European Quantum Technologies Conference 2023
by Quantum Valley Lower Saxony

16 - 20 OCTOBER 2023 – HANNOVER, GERMANY

BOOK OF ABSTRACTS for the EQTC 2023

Edited by:
Husemann, R., Liebisch, T. and Schnitger, A.

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RECAP OF THE EQTC 2023

The EQTC 2023 held from October 16th to October 20th, 2023, in Hannover, was an amazing week of conference and exhibition. The conference featured over 40 exhibitors, more than two-dozen plenary presentations and panel discussions, over 140 speakers and 180 poster presentations on the successes and challenges for the EU's quantum sector. With approximately 700 guests, the European quantum community made the European Quantum Technologies Conference (EQTC) Europe's quantum event of the year. The EQTC 2023 brought together a diverse community of brilliant scientists, innovative engineers, visionary leaders, and enthusiastic students, all united by their passion for quantum technologies and science.

The EQTC 2023's success was a collective endeavor, and the European Quantum Flagship as well as the local hosts Quantum Valley Lower Saxony (QVLS) express their heartfelt appreciation to all who played a role, both large and small: To the speakers who illuminated our minds with the latest breakthroughs, to the exhibitors with their insightful demos and lightning talks, to the attendees who made the event a unique community affairs, and to the sponsors and organisers who made it all possible.

ORGANISATION

The EQTC 2023 brought together science, industry and academia in an inspiring and impact-oriented setting, strengthening old and creating new connections for the success of Europe. The Quantum Valley Lower Saxony (QVLS) was selected by the European Quantum Flagship to host the EQTC 2023. The event design was led by the agency futurehain. The event program was curated, created and finalised in close cooperation between the European Commission, Programme Committee, Organising Committee and the local referees, outlined below. For example, the local referees used suggestions for invited speakers by the Programme Committee to curate the program, which was then finalised in consultation with the European Commission and Programme Committee. The submitted abstracts for talks and posters were each evaluated by two local referees. The resulting ranking was used to upgrade poster submissions to talks until all open slots for talks were filled. The resulting conference realised a unique and empowering gathering that showcased the values, merits and diversity of sectors of the European quantum community.

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Prof. Piet Schmidt, QVLS Co-Speaker, Leibniz University Hannover and German National Metrology Institute (PTB)
Prof. Andreas Waag, QVLS Co-Speaker, Braunschweig University of Technology

Local referees of the program curation and submitted abstracts
Prof. Michèle Heurs (Co-Chair), Leibniz University Hannover
Prof. Christian Ospelkaus (Co-Chair), QVLS Co-Speaker, Leibniz University Hannover
Prof. Klemens Hammerer, Leibniz University Hannover
Prof. Stefanie Kroker, Braunschweig University of Technology
Dr. Tara Liebisch, German National Metrology Institute (PTB)
Prof. Tobias Osborne, Leibniz University Hannover
Prof. Piet Schmidt, QVLS Co-Speaker, Leibniz University Hannover and German National Metrology Institute (PTB)
Dr. Nicolas Spethmann, German National Metrology Institute (PTB)
Prof. Andreas Waag, QVLS Co-Speaker, Braunschweig University of Technology

TUESDAY, 17 OCTOBER 2023

09:00 - 09:30 Official Opening and Welcome

Official Opening and Welcome by the EQTC Co-Chairs, Government of Lower Saxony, European Commission and Quantum Flagship

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Speakers:

Michèle Heurs Michèle Heurs is a professor of experimental physics at Leibniz Universität Hannover and leader of the group "Quantum Control". She is a council member of the LIGO Scientific Collaboration (LSC). She is dean of QUEST Leibniz Forschungsschule, an interdisciplinary faculty at LUH, and principal investigator in two Centres of Excellence, PhoenixD and QuantumFrontiers, as well as one of the proponents of the German Centre for Astrophysics (Deutsches Zentrum für Astrophysik, DZA). Her research interests are non-classical light sources (squeezed light), quantum radiation pressure noise reduction techniques, quantum optomechanics, precision metrology, and novel laser stabilisation techniques, metamaterials, as well as high-bandwidth high-efficiency photodetection and controls.

Christian Ospelkaus Christian Ospelkaus is a professor of physics at Leibniz Universität Hannover and PTB Braunschweig. His research group develops ion-trap quantum computers and novel quantum logic inspired spectroscopy methods with (anti-)matter in Penning traps. He is known amongst others for the first demonstration of heteronuclear Feshbach molecules in atomic gases and for the proposal and first implementation of chip-integrated entangling gates with trapped-ion qubits. He coordinates ATIQ, the largest German BMBF project for the ion-trap platform. He co-founded QUDORA Technologies GmbH to commercialize microfabricated ion traps and ion-trap quantum computing. He is co-speaker of the QVLS-Q1 project, coordinator of the BMBF clusters4future initiative QVLS-iLabs and co-host (with M. Heurs) of EQTC2023.

Minister Falko Mohrs Falko Mohrs serves as State Minister for Science and Culture in the government of Lower Saxony since 2022. He previously was a member of the Bundestag from the state of Lower Saxony from 2017 to 2022.

Roberto Viola Roberto Viola is an Italian civil servant of the European Union and has been Director-General of the European Commission's Directorate-General for Communication Networks, Content and Technologies (DG CONNECT) since 2015. He welcomed the conference participants with a video message.

09:30 - 10:30 High-level Panel: European Leadership in Quantum Technologies

Moderated panel featuring high-level representatives of the European Commission, the European Quantum Flagship, Quantum Industry Consortium (QuIC), Quantum Coordination Board (QCB) and Quantum Community Network (QCN)

Panelists:

Gustav Kalbe Dr. Gustav Kalbe studied Applied Physics at the Université Catholique de Louvain, Belgium. In 1991 he studied Applied Optics at the Imperial College of Science in London. In 1995 he completed his studies and earned a PhD in Physics at the Université Catholique de Louvain, Belgium.

Jürgen Mlynek Jürgen Mlynek, an experimental physicist, is Chairman of the Falling Walls Foundation and Prof. Emeritus of the Humboldt-Universität zu Berlin. His main fields of research are experimental quantum optics and atomic physics. He served as Vice-President of the German Research Foundation and later as President of the Humboldt-Universität in Berlin. From 2005 until 2015, he has been President of the Helmholtz Association of German Research Centres. For his own research, Mlynek was awarded the prestigious Gottfried Wilhelm Leibniz Prize.

Laure Le Bars Laure Le Bars is Research Project Director at SAP. She coordinates a Quantum Computing initiative at SAP. She is member of the Governing Board and President of the European Quantum Industry Consortium, since February 2021 (QuIC). She works on several European projects like Big Data Value Association (Board of Directors and Vice-President), Smart Data Innovation Lab, EIT Digital, Academy Cube, also the French-German cooperation on Digital Economy. She was SAP Labs Canada Managing Director since its inception in 1997 until 2008. In parallel, she conducted an analysis for a lab in Central & East Europe in 2004, established the lab in Budapest and was the Managing Director of SAP Labs Hungary until 2007. She joined SAP as a development consultant in Canada and the US in 1995

Thierry Debuisschert Thierry Debuisschert obtained his PhD from the Ecole Normale Supérieure, Paris, in 1990. He is a senior scientist at Thales Research & Technology-Fr. He actively contributed to the deployment of Europe's first quantum key distribution infrastructure in 2008 (SECOQC). He has coordinated numerous national and European research projects. He is currently coordinator of the AMADEUS project, federating the efforts of leading European groups on quantum sensors based on NV centers in diamond. Within the Quantum Industry Consortium (QuIC), he leads the expert group on quantum sensing. He is Chairman of the Quantum Coordination Board (QCB) of the European Quantum Flagship. He is the author of over 50 publications, has supervised more than 15 students and has served on several scientific boards.

Moderator:

Tommaso Calarco Tommaso Calarco has pioneered the application of quantum optimal control methods to quantum computation and to many-body quantum systems. Currently the Director of the Institute for Quantum Control of the Peter Grünberg Institute at Forschungszentrum Jülich and Prof. of Quantum Information at the Institute of Theoretical Physics of the University of Cologne, Tommaso has authored in 2016 the Quantum Manifesto, which initiated the European Commission's Quantum Flagship initiative, and is currently the Chairman of one of the Flagship's Governing Bodies: The Quantum Community Network (QCN). In 2020 he has launched an initiative towards the creation of a consortium of European quantum industries, which has been legally established in 2021 under the name of European Quantum Industry Consortium.

11:10 - 12:00 Plenary Session: Quantum Flagship Success Stories: Quantum Computing and Simulation

EUROPEAN COMMISSION IMPULSE: THE EUROPEAN VISION FOR QUANTUM COMPUTING AND SIMULATION

Oscar Diez

Oscar Diez is the Head of Quantum at the European Commission (EC), the executive branch of the Europen Union (EU). Previously, he was Head of Datacentre at the European Medicines Agency (EMA) in London. He holds a PhD in Computer Science from Universidad Politécnic Madrid and a Master's degree in Open eGovernment from University of Stockholm. He is also adjunct professor at IE University in Madrid.

KEYNOTE: QUANTUM COMPUTING AND SIMULATION

Thomas Monz

Thomas Monz is researcher at the Institute for Experimental Physics of the University of Innsbruck. He started his academic carreer focusing on the experimental implementation of an ion-photon interface during his master thesis and early PhD. Subsequently he was trained on precision spectroscopy and metrology on Calcium ions. During the second half of his PhD he then worked on the implementation of quantum algorithms on an ion-trap quantum processor. After some time working at a laser company as technical product specialist, he returned to academia and is now dedicated to quantum engineering, in particular addressing the scalability issues of ion-trap devices.

KEYNOTE: PHOTON-BASED OPTICAL QUANTUM COMPUTING

Pascale Senellart

Photons serve as excellent carriers of quantum information, inherently immune to decoherence and well-suited for long-distance communications. Our research focuses on harnessing the single-photon non-linearity of semiconductor quantum dots to advance photon-based quantum technologies. Our devices efficiently emit highly indistinguishable photons [1], enabling the implementation of small-scale quantum-computations. Notably, we recently unveiled a six-photon-based quantum computing platform that can be operated using both gate-based and photon-native protocols. This platform is accessible via the cloud [2] and supports various applications, including the variational quantum eigensolver and classification tasks [3]. To further scale up our efforts and progress toward error correction, we achieved a significant milestone: the generation of multi-photon entanglement mediated by a single spin [4]. This achievement paves the way for measurement-based computation, leveraging photonic-graph states.

[1] Thomas et al., Physical review letters 126 (23), 233601 (2021)
[2] cloud.quandela.com
[3] Maring et al., arXiv:2306.00874
[4] N. Coste et al., Nature Photonics (2023)

12:00 - 12:40 Expert Panel: The European Strategy on Quantum Computing and Simulation

Latest insights from policy, science and industry.

Panelists:

Stephan Schächer Stephan is a Senior Principal Engineer at Infineon and since 2018 responsible for developing the Infineon Ion Trap activities into a meaningful business. He is also a member of the Strategic Advisory Board of the EU Quantum Flagship, a mechanical engineer as well as a Finance MBA. After 4 years in the automotive industry he is in semiconductors for 25 years and counting. At Infineon he started in manufacturing strategy, then worked as a M&A project mgr for 5 years and finally became responsible for new applications and innovation for a €1B+ part of Infineon's Power Mgmt business. There he started a new product line of cost-effective accessory authentication ICs and grew it into a mid-double-digit business and developed new applications for Infineon like Battery Mgmt or wireless charging.

Fabio Sciarrino Fabio Sciarrino is Full Professor at the Physics Department of the University of Rome La Sapienza and Senior Research Fellow at the International School for Advanced Studies Sapienza, SSAS. He is Principal Investigator of the Quantum Information Lab, Department of Physics, Sapienza University of Rome (www.quantumlab.it). His main expertise is experimental quantum optics, computation and quantum information, and foundations of quantum mechanics. In recent years his research activity has focused on the implementation of quantum information protocols via integrated photonic circuits, with particular interest for Boson Sampling, a non-universal computational model with promising characteristics to achieve the quantum supremacy regime.

Krzysztof Kurowski Krzysztof Kurowski is the CTO of PSNC.He holds a PhD degree with a habilitation in Computer Science and graduated from Poznan University of Technology.His research activities have been focused on advanced parallel simulations of heterogeneous systems, scheduling and resource management in networked and distributed computing environments.He has recently been active in the following research domains:multi-scale modelling and hybrid GPU/CPU/QPU HPC computing simulations, quantum computing, advanced visualization and virtualisation technologies.He was involved in many R&D projects engaging different scientific and grand challenge global research communities.

Kristel Michielsen Prof. Dr. Kristel Michielsen is group leader of the Quantum Information Processing group at the Jülich Supercomputing Centre (JSC), Forschungszentrum Jülich and Professor of Quantum Information Processing at RWTH Aachen University. Kristel Michielsen and her group have ample experience in performing large-scale simulations of quantum systems. With her group and a team of international collaborators, she set the world record in simulating a quantum computer (QC) with 48 qubits. In 2019, she participated in a research collaboration that proved Google's quantum supremacy. She leads the Jülich UNified Infrastructure for Quantum computing (JUNIQ) at the JSC. Her research interests range from quantum mechanics to quantum computing architectures and applications.

Moderator:

Oscar Diez Oscar Diez is the Head of Quantum at the European Commission (EC), the executive branch of the Europen Union (EU). Previously, he was Head of Datacentre at the European Medicines Agency (EMA) in London. He holds a PhD in Computer Science from Universidad Politécnic Madrid and a Master's degree in Open eGovernment from University of Stockholm. He is also adjunct professor at IE University in Madrid.

12:40 - 14:00 Showcase Stage Talks

Presentations and lightning talks featuring highlights from the EQTC 2023 exhibitors

- 13:00 - Quantum Delta NL, Julia Feddersen
- 13:15 - EY, Dr. Jan Rosam
- 13:25 - QuantrolOx, Dr. Jelena Trbovic
- 13:35 - Quandela, William Hease

14:00 - 14:50 Plenary Session: Quantum Flagship Success Stories: Quantum Communication

EUROPEAN COMMISSION IMPULSE: THE EUROPEAN ROADMAP FOR QUANTUM COMMUNICATION.

Pascal Maillot

Pascal Maillot is deputy Head of Unit of the High Performance Computing and Quantum Technology unit in Directorate General Communications Networks, Content and Technology at the European Commission. He is in charge of the one-billion euro Quantum Flagship initiative launched in October 2018 with its first 20 projects. He graduated as a computer engineer in 1998 and had several positions in the private and public sector as telecom project manager and cyber-security analyst. He then moved to the quantum domain and focuses specifically on the future "quantum internet" interconnecting quantum computers, simulators and sensors via quantum networks to distribute information and quantum resources securely all over Europe.

KEYNOTE: TOWARDS A QUANTUM INTERNET

Tracy Northup

A future quantum internet will enable quantum communication worldwide, opening up fundamentally new capabilities for secure information transfer, distributed computing, and networked quantum sensing. I will describe the state of the art and the challenges in building prototypes that connect metropolitan networks over long distances. From the perspective of the Flagship's Quantum Internet Alliance project, I will highlight recent progress in building entanglement-based metropolitan networks, quantum repeaters, and a software and network stack.

KEYNOTE: QUANTUM KEY DISTRIBUTION: FROM SECURITY PROOFS TO IMPLEMENTATIONS

Antonio Acin

We discuss several aspects of quantum key distribution protocols, from security proofs to implementations, using continuous or discrete degrees of freedom. On the one hand, we provide a security proof for discrete-modulated continuous-variable quantum key distribution. On the other hand, we present a proposal for the implementation of device-independent quantum key distribution using single-photon sources.

14:50 - 15:30 Expert Panel: The European Strategy on Quantum Communication

Panelists:

Paolo Villoresi Full Professor of Physics and Director of the Padua Quantum Technologies Research Center, both at the University of Padova, where he studied Physics and Applied Mathematics. From 2003 he realized the first single photon exchange with a satellite at the ASI-MLRO, an then the first QC in Space, with polarization and temporal modes. Moreover, the first free-spece OAM modes for QC, QRNG using DV and CV at tens of Gbps, free-space QC at Canary-Island, and novel QKD protocols and fundamental tests of Quantum-Mechanics both in Space and in the Lab. His past research topics include Atomic Physics in the attosecond domain, multiphoton ionization, ultrafast optics in XUV and adaptive optics, beside 12 industrial patents and pat. app. Fellow of Istituto Veneto di Scienze Lettere e Arti in Venice

Johanna Sepúlveda Johanna Sepúlveda received her M.Sc. and Ph.D. degrees in Electrical Engineering – Microelectronics by the University of São Paulo, Brazil. She was a Senior Researcher in the area of security and emerging technologies at the University of South Brittany, INRIA and at the Technical University of Munich. Currently she holds a position as the Airbus Expert on Quantum-Secure Technologies, being Chief Engineer of different European quantum initiatives such as EuroQCI. Also she is the vice-chair of the Strategic Advisory Board of Quantum Technologies for the European Commission and leader of the Strategic Industry Roadmap at the Quantum Industry Consortium (QuIC). She has more than 15 years of experience in R&T and R&D in the area of security, networked systems, HPC and quantum technologies.

Stephan Ritter Stephan Ritter obtained his PhD degree in physics from ETH Zurich. He then joined the Max-Planck-Institute of Quantum Optics in Garching, Germany, to develop single atoms in high-finesse optical resonators into universal nodes of an elementary quantum network. After 15 years in academia, he joined TOPTICA Photonics, a leading manufacturer of high-tech laser systems for scientific and industrial applications, where he is currently leading the application team for quantum technologies. Stephan is a member of the Executive Team of the European Quantum Internet Alliance (QIA) and of the Advisory Board of the German joint quantum-repeater-link project QR.X.

Eleni Diamanti Eleni Diamanti is CNRS research director at the LIP6 laboratory of Sorbonne University in Paris. She received her PhD in Electrical Engineering from Stanford University in 2006 and then worked as a Marie Curie postdoctoral researcher at the Institute of Optics Graduate School in Palaiseau before joining the CNRS in 2009. Her research focuses on experimental quantum cryptography and communication complexity, and on the development of photonic resources for quantum networks. She is a recipient of a European Research Council Starting Grant, coordinator of the Paris Centre for Quantum Technologies, and an elected member of the Board of Stakeholders of the European Public Private Partnership in Photonics. She is also cofounder and scientific advisor of the start-up company Welinq.

Moderator:

Vicente Martin Vicente Martin is Full Professor of Computational Sciences at the Technical University of Madrid, Director of the Center of Computational Simulation. Coordinator of the Research Group on Quantum Information, the DIANA NATO Test Centre on Quantum Communications and the current Madrid Quantum Communications Infrastructure, built as a result of projects like the OpenQKD or CiViQ, from the European Quantum Flagship, where he led the quantum networking WPs. Current coordinator of the Spanish program on quantum communications. He also works in standards on QKD. Founding member of the ISG-QKD in ETSI and vicechair. Convener of the Quantum cryptography and Communications Workgroup in CEN. His main interest is the integration of Quantum Communications in Telco Networks and security infrastructures

15:30 - 16:00 Showcase Stage Talks

Presentations and lightning talks featuring highlights from the EQTC 2023 exhibitors.

- 15:35 - Business Finland, Dr. Pekka Pursula (BusinessQ - Finnish Quantum Ecosystem); Dr. Himadri Majumdar (SemiQon)
- 15:45 - Berlin Partner - Berlin Quantum Alliance, Dr. Katharina Witte (Berlin Quantum Alliance); Dr. Andreas Wicht (Ferdinand-Braun-Institute)

16:00 - 17:00 Interactive Session on the EU Quantum Strategy and the Role of National Initiatives

Interactive session, co-organised with the network of National Quantum Initiatives (NQI)

Speakers:

Philippe Bouyer Philippe Bouyer is professor at the University of Amsterdam and Technical University of Eindhoven. He is the coordinator of the Quantum Sensing program at Quantum Delta NL. He is the former Deputy Director of the Institute d'Optique and founding Director of the Laboratory of Photonics, Digital and Nanosciences at CNRS, IOGS, Université Bordeaux. He is co-founder of Muquans (now Exail), a France-based company dedicated to quantum sensors. Dr. Bouyer received his Ph.D. in 1995 from the École Normale Supérieure/laboratoire Kastler Brossel, Université Paris Sud. Subsequently, he was a visiting professor of physics at Stanford University in Palo Alto, California, among other positions. His current research interest concerns matter-wave interferometry for navigation and tests of general relativity.

Bjoern Schulte Dr. Bjoern Schulte works as a desk officer in the division "Quantum Technologies; Quantum Computing" at the Federal Ministry of Education and Research.

Petr Kavalir Dr. Kavalir currently holds the position of Special Envoy for Quantum Technologies under the Deputy Prime Minister for Digitalization and Minister for Science, Research, and Technology in the Czech Republic. In this role, he is responsible for overseeing the preparation of the Czech National Quantum Strategy. Since 2019 has been serving as the CEO and Chairman of the Scientific Council at the New Technologies - Research Centre of the University of West Bohemia. Throughout his career, he has demonstrated a successful track record in initiating and leading large-scale scientific projects while fostering collaborations with industry and public institutions. Additionally, he serves as Vice-chair of the Innovation and Technology Experts Group at Business at OECD and is a member of the expert committee for Research and Development at the Confederation of Industry of the Czech Republic. His dedication lies in driving transformative change and harnessing the potential of emerging technologies.

Neil Abroug Neil Abroug is the Head of the French Quantum Strategy. In 2018, he joined the Directorate General for Enterprises at the French Ministry of Economic Affairs where he contributed to setting up the national quantum agenda. In 2021, he joined the Secretary General for Investments, to coordinate the French Quantum Strategy. Neil began his career as a research engineer and project manager at CEA in the field of Industry 4.0. He is a Dr. Engineer in applied mathematics. He also graduated in Innovation Management and Competitive Intelligence.

Moderator:

Yasser Omar Yasser Omar obtained his PhD in Quantum Information at the University of Oxford. Currently, he is professor at IST, ULisbon, where he leads the Physics of Information & Quantum Technologies Group. His research interests focus on quantum computation, quantum networks, and the energetics of quantum technologies. He has won 12+ European & American projects in these domains. In 2019, he founded the Quantum Technologies Lab, where free-space QKD was implemented for the first time in Portugal. In 2022, he launched, together with colleagues in 65+ countries, the World Quantum Day. He has been involved in the creation and the coordination of the Quantum Flagship, is Co-Chair of the Advisory Board of CERN's Quantum Technology Initiative, and is the president of PQI – Portuguese Quantum Institute.

17:00 - 18:00 Next-Generation Quantum Technology Highlights from Science, Industry and Start-Ups

Fast-paced 10-min pitches showcasing the latest of European innovation

Speakers:

Cornelius C. Bultink Co-founder of Qblox

Eleni Diamanti Eleni Diamanti is CNRS research director at the LIP6 laboratory of Sorbonne University in Paris. She received her PhD in Electrical Engineering from Stanford University in 2006 and then worked as a Marie Curie postdoctoral researcher at the Institute of Optics Graduate School in Palaiseau before joining the CNRS in 2009. Her research focuses on experimental quantum cryptography and communication complexity, and on the development of photonic resources for quantum networks. She is a recipient of a European Research Council Starting Grant, coordinator of the Paris Centre for Quantum Technologies, and an elected member of the Board of Stakeholders of the European Public Private Partnership in Photonics. She is also cofounder and scientific advisor of the start-up company Welinq.

Daniel Borcherding 10/2010 – 9/2013: B. Sc. Physik, Leibniz Universität Hannover, 10/2010 – 9/2013: B. Sc. Physik, Leibniz Universität Hannover. 10/2013 – 11/2015: M. Sc. Physik, Leibniz Universität Hannover. 11/2015 – 12/2018: Ph. D., Institut für Theoretische Physik Hannover, Prof. Frahm's Arbeitsgruppe, Thema: Non-Abelian quasi-particles in electronic systems. 1/2019 – 3/2019: Postdoc, Institut für Theoretische Physik Hannover, Prof. Frahm's Arbeitsgruppe. 4/2019 – 9/2021: Software Engineer, Data Assessment Solutions GmbH, Hannover. Seit 10/2021: Junior Research Group Leader in Cloud-based Quantum Technologies, Institut für Theoretische Physik Hannover. Seit 8/2023: Head of Quantum Software at QUDORA Technologies GmbH, Braunschweig.

Magdalena Hauser & Wolfgang Lechner Magdalena is co-CEO of ParityQC - a quantum architecture company - together with Prof. Dr. Wolfgang Lechner. Previously she was co-founder and CEO of I.E.C.T. - Hermann Hauser, which focused on fostering entrepreneurship and supporting spin-offs in developing their ideas into successful companies. Alongside she managed Hermann Hauser's investment vehicle in Europe, where they mainly invested in DeepTech spin-offs. She co-founded the non-profit association AI Austria and in 2018 was selected among the Forbes 30under30 for her activities in the investment field.

18:30 - 22:00 EQTC Community Dinner + Showcase Stage

An evening dedicated to community networking - meet peers from all over Europe and connect over drinks and snacks

- 18:35 - Quantum Valley Lower Saxony, Prof. Andreas Waag
- 18:40 - QuantumFrontiers, Prof. Michelè Heurs (Leibniz Universität Hannover)
- 18:45 - TerraQ, Prof. Jürgen Müller (Leibniz Universität Hannover)
- 18:50 - DQ-mat, Prof. Klemens Hammerer (Leibniz Universität Hannover)

WEDNESDAY, 18 OCTOBER 2023

08:30 - 08:55 Showcase Stage Talks

Speakers:

- 08:30 - Portuguese Quantum Institute, Yasser Omar
- 08:40 - PicoQuant, Florian Weigert

09:00 - 10:00 Interactive Morning Panel: The Future of Quantum Technologies

Featuring experts from science, industry, policy and start-ups, this interactive panel explores the future development of Quantum Technologies in an audience-driven format.

Panelists:

Gianni Del Bimbo At Multiverse, I started as quantum machine learning specialist and later worked as head of quantum engineering managing teams and leading client projects in finance, energy, manufacturing and chemistry. As COO, I'm now responsible for designing, implementing and overseeing day-to-day operations to drive the company's strategy. MSc in Condensed Matter Physics from the Ludwig Maximilian University (LMU) of Munich. BSc in Physics and Astrophysics from the University of Florence.

Pieter de Witte Pieter de Witte serves in the executive board of Quantum Delta NL as director Research Programmes and IP. He is responsible for research collaborations, tech transfer and IP strategy. QDNL strives to create significant societal impact through technological quantum advancements. QDNL received 615 M€ government funding, it is both a foundation and a dynamic quantum technology ecosystem. Current focus points for QDNL are an ecosystem approach to technology transfer, international collaboration, realizing R&D facilities for industry, and building the House of Quantum. Pieter has worked in several positions in research funding on key enabling technologies (policy) and public private research partnerships in materials, physics and nanotechnology. Pieter has a PhD physical organic chemistry.

Chiara Macchiavello Chiara Macchiavello received her PhD in 1995 from the University of Pavia. She then spent two years at the University of Oxford with a Marie Curie postdoctoral position. In 1998 she became research assistant at the University of Pavia, where she is now Professor of the Physics of Quantum Computation. She has made relevant contributions in various aspects of theoretical quantum information science, including pioneer work in quantum error correction and quantum algorithms, quantum privacy amplification and quantum cloning. For her work she was awarded a prestigeous prize from Accademia Nazionale dei Lincei in 2006.

Robert Axmann Robert Axmann studied aerospace engineering in Munich and Cranfield, where he earned his doctorate in aerospace engineering. With 20 years of experience at the German Aerospace Center (DLR), he has been leading the DLR Quantum Computing Initiative since 2021.

Moderator:

Matyas Kovacs Matyas Kovacs currently splits his time between his own consultancy practice as Co-Founder of futurehain, a Berlin-based science strategy agency and creative studio, as well as working as the Executive Advisor to the Chairman of the Strategic Advisory Board of the Quantum Flagship and the Chairman of the Board of the Falling Walls Foundation.

10:00 - 11:00 Presentation and Discussion of the Quantum Flagship's Strategic Research and Industry Agenda (SRIA)

Presentation and Discussion of the Quantum Flagship's Strategic Research and Industry Agenda (SRIA).

Speakers:

Kristel Michielsen Prof. Dr. Kristel Michielsen is group leader of the Quantum Information Processing group at the Jülich Supercomputing Centre (JSC), Forschungszentrum Jülich and Professor of Quantum Information Processing at RWTH Aachen University. Kristel Michielsen and her group have ample experience in performing large-scale simulations of quantum systems. With her group and a team of international collaborators, she set the world record in simulating a quantum computer (QC) with 48 qubits. In 2019, she participated in a research collaboration that proved Google's quantum supremacy. She leads the Jülich UNified Infrastructure for Quantum computing (JUNIQ) at the JSC. Her research interests range from quantum mechanics to quantum computing architectures and applications.

Tommaso Calarco Tommaso Calarco has pioneered the application of quantum optimal control methods to quantum computation and to many-body quantum systems. Currently the Director of the Institute for Quantum Control of the Peter Grünberg Institute at Forschungszentrum Jülich and Prof. of Quantum Information at the Institute of Theoretical Physics of the University of Cologne, Tommaso has authored in 2016 the Quantum Manifesto, which initiated the European Commission's Quantum Flagship initiative, and is currently the Chairman of one of the Flagship's Governing Bodies: The Quantum Community Network (QCN). In 2020 he has launched an initiative towards the creation of a consortium of European quantum industries, which has been legally established in 2021 under the name of European Quantum Industry Consortium.

Oscar Diez Oscar Diez is the Head of Quantum at the European Commission (EC), the executive branch of the Europen Union (EU). Previously, he was Head of Datacentre at the European Medicines Agency (EMA) in London. He holds a PhD in Computer Science from Universidad Politécnic Madrid and a Master's degree in Open eGovernment from University of Stockholm. He is also adjunct professor at IE University in Madrid.

Felix Wissel Felix is a theoretical physicist who received his degree in solid-state physics and a PhD in statistical physics from TU Darmstadt. For over ten years, he worked in the engineering department of DT on different network concepts and architectures. Since 2016, he has been heavily involved in quantum cryptography, participating in research projects such as the Quantum Flagship, CiViQ, OpenQKD, and QCI4EU. Felix coordinated R&D collaborations and was the technical lead for the EuroQCI detailed design study QSAFE. He holds several positions in boards and bodies, including the Quantum Coordination Board and the Chair of the German QuNet Advisory Board. For the EuroQCI Coordination & Support Action PETRUS he is the project coordinator and further investigates quantum communications in the QSNP.

Anna Kaminska Dr. Anna Kaminska received her PhD from the Faculty of Physics, University of Warsaw in 2012. In 2017, after several years of research work in the field of particle physics and fundamental interactions at CERN, DESY, University of Oxford and JGU Mainz, she joined the team of Creotech Instruments S.A., a Polish company specialising in advanced electronics and systems. She is involved in business development, shaping and leading projects in the area of quantum technologies. In particular, together with a group of engineers at Creotech, she is working on control systems for quantum computers and quantum key distribution.

Moderator:

Salvatore Cinà Salvatore Cinà is Program Director for Quantum Technologies at CEA. He was previously in charge of technology transfer, building and managing strategic industrial partnerships. Earlier he was Deputy Head of the Optoelectronic Department at CEAtech-LETI, as well as Executive Director of the III-V lab, a joint venture between CEA, Thales and Nokia. As a scientist, he worked at the University of Cambridge on Si transistors, at Toshiba Cambridge Research Centre on III-V semiconductors devices, at Cambridge Display Technology on organic semiconductors optoelectronic devices, and at Thomson on the development of OLED-based displays. Salvatore has a degree in Physics from the University of Rome, and a PhD in Semiconductor Physics from the University of Cambridge.

11:00 - 11:30 Showcase Stage Talks

Presentations and lightning talks featuring highlights from the EQTC 2023 exhibitors.

- 11:05 - Munich Quantum Valley, Dr. Andrea Lenz
- 11:15 - German Aerospace Center DLR, tbc

11:30 - 13:00 Plenary Session: Investing in Quantum Technologies: Private Investment / European Innovation Council

Plenary Session: Investing in Quantum Technologies: Private Investment / European Innovation Council Session co-organised with the European Innovation Council (EIC)

Speakers:

Luuk Borg EIC Fund

Johan Maunsbach Johan is a partner at 2xN, a London-based investment firm focused on early-stage investments, including a number of investments in quantum technology. The firm recently led the seed round in Sparrow Quantum, a Danish quantum technology company renowned for its world-leading expertise in foundational quantum photonic devices. Johan has a background as a lawyer qualified in Sweden and England & Wales, and he has spent most of his career working with investments in private markets. After working in private practice, he spent 10 years at Partners Group.

Moderator:

Samira Nik Samira obtained a PhD in Materials Science from the Applied Physics Department of Chalmers University of Technology, specializing in superconducting quantum devices, nanoelectronics and materials characterization. After her postdoctoral fellowship in nanoelectronic devices, she became an R&D project manager in one of the leading foundries in the semiconductors industry in Sweden, where she developed the expertise to create proof-of-concept of innovative piezoelectric sensors and energy harvesting devices. Samira learned even more about the practical obstacles that scientists and startups face through her role in the cleanroom management team in one of the largest nanoelectronics hubs in the world, IMEC, Belgium. Samira transitioned from technical to policy work with becoming Project Manage

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13:00 - 14:30 Showcase Stage Talks

Presentations and lightning talks featuring highlights from the EQTC 2023 exhibitors

- 13:05 - SaxonQ, Prof. Dr. Marius Grundmann
- 13:15 - Berlin Partner - Berlin Quantum Alliance, Kevin-Peter Gradwohl (Leibniz-Institut für Kristallzüchtung); André Carvalho PhD (Q-CTRL); Sebastian Bock (Frauenhofer-Institute für Offene Kommunikationssysteme); Dr. Henning Schröder (Frauenhofer-Institut für Zuverlässigkeit und Mikrointegration)
- 13:35 - Business Finland/Quantum Finland, Dr. Jelena Trbovic (QuantrolOx); Dr. Valtteri Lahtinen (Quanscient); Eero Koivumäki (Vexlum); Johanna Anteroinen (VTT Technical Research Centre of Finland)
- 13:55 - AQT, Dr. Thomas Monz
- 14:10 - PETRUS/Deutsche Telekom, Felix Wissel

14:30 - 16:00 Parallel Sessions – European Showcases of Technology Maturity

Parallel Track 1: Enabling Technologies of the Quantum Industry

Curated by QuIC

ENABLING SCALABLE QUBIT CONTROL SYSTEMS FOR QUANTUM COMPUTING

Dr. Anna Kaminska, Creotech

The ARTIQ/Sinara ecosystem for qubit control in cold-atom and trapped-ion experiments and applications will be presented. Main challenges and possible solutions for enabling scalable qubit control in quantum computers will be discussed, with special focus on highly integrated and low-latency systems, as well as practical aspects related to scaling up the number of qubits. Current Creotech products and R&D projects focused on qubit control will be presented.

LET'S TAKE A QUANTUM LEAP - AND LEARN WHY FREQUENCY COMBS AND ULTRASTABLE LASERS ARE KEY INSTRUMENTS FOR THE QUANTUM REVOLUTION

Dr. Michael Mei, Menlo Systems

Technological revolutions are driven by scientific breakthroughs. The digital transformation is ongoing, led by groundbreaking research in semiconductor technology and computer science. Let's take a quantum leap and think about a future quantum revolution, and how we are refining those enabling technologies that will push the revolution forward in the next decade. In this talk, we will answer questions such as: How will future optical clocks measure time even more precisely? Why are Frequency Combs and Ultrastable Lasers core technologies for quantum computers? And what does the 2023 Nobel Prize in Physics have in common with the Prize from 2005?"

ENABLING AND ACCELERATING THE 2ND QUANTUM REVOLUTION WITH EASY-TO-USE, SUSTAINABLE, AND SCALABLE CRYOGENICS.

Dr. Tomek Schulz, Kiutra

Quantum technologies are on the rise and their development towards real world applications is at full speed. Most qubit architectures benefit from or even require low to ultra-low temperatures for their development, device qualification & operation. In particular, fast & streamlined testing tools are needed in the lab or foundry to address the growing characterization bottleneck. Mid- to long-term a scalable quantum industry will also require more cost-effective, scalable & sustainable cooling technologies that are not limited by scarce resources or critical supply chains. As a leading supplier for magnetic cooling technology, kiutra, is addressing these issues and has launched a set of innovative products and services to support the development of the quantum industry. In this talk we will showcase our recent product launches & success stories, as well as provide an outlook on our current & future product developments that will enable and accelerate the adoption of quantum technologies.

SCALABLE QUBIT CONTROL AND READOUT WITH FAST SCALABLE FEEDBACK

Dr. Yemliha Bilal Kalyoncu, Qblox

NISQ applications require improvements on gate fidelities, scalability and overcoming experimental overheads. Qblox's Cluster system is designed to support these efforts by providing fully-integrated, time-efficient and ultralow-noise control stacks. The Cluster control stacks incorporate Q1 advanced sequence processors capable of sequencing pulses and their parameters in real-time, and on-the-fly analysis of the readout signals (integration, averaging, binning and thresholding). While the system generates control pulses up to 18.5 GHz with ultra-low noise and drift, on the readout side, it allows both microwave and lockin measurements in the same device with frequency multiplexing, making it suitable for various qubit types and readout schemes. Qblox's fast scalable feedback distributes measurement outcomes with all-to-all connectivity to allow active-reset operations and error mitigation algorithms. Up to 80 control channels are linked to up to 40 input channels for feedback operations in a single device within 364 ns. This massively scalable approach brings qubit control and readout to a new level on the route to NISQ applications and further to fault tolerant quantum computing.

Anna Kaminska Dr. Anna Kaminska received her PhD from the Faculty of Physics, University of Warsaw in 2012. In 2017, after several years of research work in the field of particle physics and fundamental interactions at CERN, DESY, University of Oxford and JGU Mainz, she joined the team of Creotech Instruments S.A., a Polish company specialising in advanced electronics and systems. She is involved in business development, shaping and leading projects in the area of quantum technologies. In particular, together with a group of engineers at Creotech, she is working on control systems for quantum computers and quantum key distribution.

Michael Mei Dr. Michael Mei received his Diploma from the University of Konstanz, Germany, in 1996 working under the supervision of Prof. Mlynek and Prof. Metcalf. In 1997 he joined the Swiss Federal Institute of Technology in Zürich doing a one year research project. In February 2001, Michael received his doctoral degree with honors from the LMU Munich for experiments in multiple beam atomic interferometry and precision measurements under the supervision of Prof. Hänsch. In 2001, he founded Menlo Systems together with his colleague Dr. Holzwarth. Since the start in 2001, he is in the role of the Managing Director of the company which has grown from the founders team to a market leader in photonics with more than 175 employees.

Tomek Schulz Tomek Schulz is a physicist and entrepreneur passionate about innovative future technologies that add value to society. After receiving his diploma and PhD in physics in the field of topological non-trivial matter and novel energy-efficient data storage technologies, Tomek gaining industry experience and leadership skills at a tech consulting company as a project manager and tech lead using agile, rapid prototyping and design thinking methodologies. In 2018, he co-founded kiutra, a cryogenics company with a mission to make cryogenic cooling more user-friendly, sustainable, and scalable. His responsibilities as COO at kiutra cover a variety of strategic topics in finance, business development, corporate sustainability, HR, & marketing.

Yemliha Bilal Kalyoncu Bilal is a physicist and spends effort in bringing quantum computers to reality. As the lead application scientist of Qblox, he is specifically keen on understanding the requirements of qubit control and readout, and on matching them with Qblox's solutions. He started his studies at Bogazici university, Turkey and completed his PhD in experimental solid state physics at the University of Basel, Switzerland. He patented two applications in nanomagnetism and has experience in nanofabrication, quantum transport in 2D materials and cryogenic methods. After his PhD, he started his professional career in the scientific instruments industry to find solutions to challenging problems of experimental physics.

Parallel Track 2: Quantum Computing & Simulation

FAULT-TOLERANT QUANTUM COMPUTING: RECENT PROGRESS AND PERSPECTIVES

Prof. Markus Müller, RWTH Aachen University

Quantum computers hold the promise to efficiently solve some computationally hard problems, for which efficient solutions are intractable on classical computers. Unfortunately, noise strongly limits the capabilities of current noisy intermediate-scale quantum (NISQ) devices. To fully unlock the potential of scalable quantum computers, quantum error correction will be essential. In my talk, I will discuss recent theory work and collaborative experimental breakthroughs in fault-tolerant quantum error correction: This includes first repeated, high-performance quantum error-correction cycles on topological error correcting codes with superconducting qubits [1], and the first execution of universal and fault-tolerant logical quantum gates with trapped ions [2]. Furthermore, I will highlight alternative approaches towards robust quantum processors, based on quantum machine-learning concepts [3,4], and outline promising pathways to scale up current systems towards scalable, error-corrected quantum processors.

[1] S. Krinner et al., Nature 605, 669 (2022)
[2] L. Postler et al., Nature 605, 675 (2022)
[3] D. F. Locher et al., Quantum 7, 942 (2023)
[4] T. L. M. Guedes et al., arXiv:2309.03608 (2023)

THE ENERGETICS OF QUANTUM COMPUTERS

Prof. Yasser Omar, University of Lisbon

Exploiting quantum dynamics and quantum correlations to process information has established new forms of computation and simulation, offering significant speed-ups in the time of the computations. However, another potential advantage of quantum dynamics, still poorly explored, is the energetic performance of the computations, currently a bottleneck in classical high-performance computing. In this talk, I will discuss some recent results we have obtained in the study of the thermodynamics of quantum gates, a physics of information problem currently getting increasing attention.

INDUSTRIAL MICROFABRICATION OF ION TRAPS AT INFINEON

Dr. Silke Auchter, Infineon

To realize a useful quantum computer based on trapped ions, scaling the number of ions is an important requirement. However, scaling up to several hundreds or thousands of ions while maintaining sufficient qubit fidelity implies complex trap designs that can only be achieved by first-class industrial manufacturing. Fabrication in a productive fab offers a precise process control as well as numerous in-line measurement options to guarantee high reliability and reproducibility of the ion trap devices. In this talk, I will give an overview of the fabrication capabilities at the industrial cleanroom facilities of Infineon Technologies, and highlight 2D and 3D ion traps that have already been successfully realized. Moreover, I will present several projects towards scaling ion traps currently being pursued in collaboration with academia, and share with you our mission: We innovate and partner to make our ion trap systems the heart of the leading quantum computers.

LARGE PHOTONIC GRAPH STATES FROM SINGLE ATOMS IN A CAVITY

Dr. Olivier Morin, Max-Planck-Institute for Quantum Optics

Photonic quantum computing strongly relies on highly efficient single photon sources. This is particularly motivated by the so-called measurement-based quantum computing where the same large entangled state, in the form of a graph state, can be used for any quantum computation, the algorithm being defined by the measurement sequence. To this endeavor, a powerful strategy consists in using the photon emitter internal properties to entangle the photons directly at the emission and thus providing, ideally, a deterministic generation of an arbitrarily large number of entangled photons.
We show that a single atom in a high finesse optical cavity constitutes a suitable platform. Not only can it generate photons with high efficiency and well-controlled temporal mode, but through various atomic state manipulations we can generate streams of photons in the form of GHZ states or 1-D cluster states. Specifically, we have obtained 14-photon GHZ states at a fidelity around 80% and a rate of every 3 minutes, orders of magnitude better than the state of the art. Hence, our work represents an important step towards scalable quantum computing.

Markus Müller Prof. Markus Müller is a theoretical quantum physicist, leading the Theoretical Quantum Technology Group at the Institute for Quantum Information at RWTH Aachen University and the Peter Grünberg Institute for Theoretical Nanoelectronics at the Forschungszentrum Jülich in Germany. Main research topics include fault-tolerant quantum error correction, topological quantum computing, quantum neural networks and quantum simulation of strongly correlated quantum phases, with AMO systems, but also solid-state platforms. His group forms part of leading national and international quantum technology research collaborations, and his team enjoys working in close collaboration with leading experimental partners, to bridge the gap between theoretical models and experimental implementations.

Yasser Omar Yasser Omar obtained his PhD in Quantum Information at the University of Oxford. Currently, he is professor at IST, ULisbon, where he leads the Physics of Information & Quantum Technologies Group. His research interests focus on quantum computation, quantum networks, and the energetics of quantum technologies. He has won 12+ European & American projects in these domains. In 2019, he founded the Quantum Technologies Lab, where free-space QKD was implemented for the first time in Portugal. In 2022, he launched, together with colleagues in 65+ countries, the World Quantum Day. He has been involved in the creation and the coordination of the Quantum Flagship, is Co-Chair of the Advisory Board of CERN's Quantum Technology Initiative, and is the president of PQI – Portuguese Quantum Institute.

Silke Auchter Silke Auchter is a Technology Development Engineer at Infineon Technologies Austria AG, focusing on the development of microstructured ion traps. After her Bachelor and Master in Physics at the University of Regensburg and University of Innsbruck, she continued her academic career with a PhD at Infineon in Villach in collaboration with the Quantum Optics and Spectroscopy research group at the University of Innsbruck. Within the EU funding project PIEDMONS, she designed and realized the first industrially microfabricated 3D ion trap. Since 2022 she has a permanent position at Infineon, being responsible for the development and fabrication of ion trap chips for quantum information processing as well as for ion clocks.

Olivier Morin Postdoc at the Max-Planck Institute of Quantum Optics in the Quantum Dynamics division, Olivier Morin's research is mostly centered on cavity quantum electrodynamics with single neutral atoms coupled to high finesse optical cavities. Over the past years, he was involved in various works demonstrating this platform to be an extremely powerful and versatile building block for future quantum technologies, finding applications spanning from quantum communication to quantum computation.

Chair:

Daniel Borcherding 10/2010 – 9/2013: B. Sc. Physik, Leibniz Universität Hannover, 10/2010 – 9/2013: B. Sc. Physik, Leibniz Universität Hannover. 10/2013 – 11/2015: M. Sc. Physik, Leibniz Universität Hannover. 11/2015 – 12/2018: Ph. D., Institut für Theoretische Physik Hannover, Prof. Frahm's Arbeitsgruppe, Thema: Non-Abelian quasi-particles in electronic systems. 1/2019 – 3/2019: Postdoc, Institut für Theoretische Physik Hannover, Prof. Frahm's Arbeitsgruppe. 4/2019 – 9/2021: Software Engineer, Data Assessment Solutions GmbH, Hannover. Seit 10/2021: Junior Research Group Leader in Cloud-based Quantum Technologies, Institut für Theoretische Physik Hannover. Seit 8/2023: Head of Quantum Software at QUDORA Technologies GmbH, Braunschweig.

Parallel Track 3: Quantum Communication

SOLUTIONS FOR THE EUROQCI: A QKD PLATFORM FOR TERRESTRIAL AND SPACE DOMAINS

Dr. Simone Capeleto, ThinkQuantum

The talk is providing an overview on the ThinkQuantum QKD platform QUKY, based on DV with polarization encoding, enabling fiber, free-space and intermodal solutions fitting the needs of terrestrial and Space domains.

EXPERIMENTAL DEVICE-INDEPENDENT QUANTUM KEY DISTRIBUTION

Dr. Jean-Daniel Bancal, CEA

Cryptographic key exchange protocols traditionally rely on computational conjectures such as the hardness of prime factorisation to provide security against eavesdropping attacks. Remarkably, quantum key distribution protocols provide information-theoretic security against such attacks. However, quantum protocols realised so far are subject to a new class of attacks exploiting unmet assumptions in their practical realisation, as demonstrated in numerous ingenious experiments. Following the pioneering work of Ekert proposing the use of entanglement to bound an adversary's information from Bell's theorem, we present the experimental realisation of a complete quantum key distribution protocol relying on fewer assumptions and which is thus less exposed to these attacks. During eight hours of run time, we generate 1.5 million Bell pairs, which we use to obtain 95 628 key bits. The secrecy of this key is guaranteed device-independently. Our result shows that provably secure cryptography with real-world devices is possible, and paves the way for further quantum information applications based on the device-independence principle.

APPROACHES TO ELEMENTARY QUANTUM REPEATER LINKS

Prof. Christoph Becher, Saarland University

A quantum repeater [1] distributes entangled quantum states to remote nodes in a quantum network. Entanglement then can be used as a resource for end-to-end secure communication, entanglement-enhanced classical communication, networks of quantum sensors and for interfacing quantum computers. A quantum repeater may thus offer entanglement-enhanced security for communication without having to rely on reliable or secured classical nodes (trusted nodes), but also connects quantum computers to yield exponentially large computational spaces. The realization of an infrastructure for quantum networks and hardware components for quantum nodes and repeaters is still a technically challenging task. In my talk I will present a bottom-up approach to realizing basic elements of fiber-based quantum repeaters as pursued in the German research network "Quantum Repeater Link – QR.X" [2] and a recent experiment on entanglement of remote quantum nodes based on single Rubidium atoms via a fiber network.

[1] H.-J. Briegel et al., Quantum Repeaters: The Role of Imperfect Local Operations in Quantum Communication, Phys. Rev. Lett. 81, 5932 (1998).
[2] P. van Loock et al., Extending Quantum Links: Modules for Fiber- and Memory-Based Quantum Repeaters

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THE STATE OF QUANTUM KEY DISTRIBUTION: CLOSER LOOK TO CV-QKD

Dr. Sebastian Etcheverry, LuxQuanta

In this talk, Sebastian Etcheverry, Chief Technology Officer and co-founder of LuxQuanta, will deep dive into the current maturity state of Quantum Key Distribution technology. Even more, Sebastian will remark the added value of the QKD variant known as Continuous Variable QKD, and the features that make it interesting for the growing market. LuxQuanta's technology, based on CV-QKD, allows co-propagation and co-existance with classical communications over the same optical fiber. LuxQuanta's CTO will also review the current technological, geopolitical and socieconomic factors leading the QKD market growth.

Simone Capeleto Simone Capeleto is Co-founder and CEO of ThinkQuantum Srl (startup and spin-off of University of Padua) providing quantum solutions for cyber security, such as fiber, free-space, satellite QKD platforms and high-end high-speed QRNG devices.

Jean-Daniel Bancal Jean-Daniel Bancal obtained his Ph.D. from University of Geneva (Switzerland) in 2012. After postdoctoral fellowships at the Center for Quantum Technologies (Singapore), University of Basel (Switzerland) and University of Geneva, he has been a CEA researcher at Institut de Physique Théorique (France) since 2020. His interests lie in quantum information, quantum applications and quantum foundations. He is a recipient of the J. Wurth prize and the Paul Ehrenfest award.

Christoph Becher Christoph Becher is a full professor of experimental physics at Saarland University, Saarbrücken, Germany, leading the quantum optics research group since 2005. He received his PhD in physics from University of Kaiserslautern, Germany, in 1998 and held two postdoctoral positions: at University of California, Santa Barbara (1999-2000) and at University of Innsbruck, Austria (2001-2005), working on quantum optics and quantum computing with semiconductor quantum dots and trapped ions. His current research interests are in the field of quantum technologies for quantum communication & sensing, in particular exploration of color centers in diamond as quantum bits and single photon nonlinear optics, e.g. quantum frequency conversion for quantum networks.

Sebastian Etcheverry Dr. Sebastian Etcheverry is the co-founder and CTO of LuxQuanta, playing a pivotal role in propelling the R&D team's continuous pursuit of technological advancements. Dr. Etcheverry earned his Ph.D. in Applied Physics from KTH in Switzerland, specializing in optical fiber components. Following this, he became a part of the Optoelectronics group at ICFO, where he dedicated himself to the R&D of Continuous Variable Quantum key distribution technology (CV-QKD) systems. After three years of research and technology incubation, Sebastian co-established LuxQuanta in 2021 alongside Dr. Saeed Ghasemi. LuxQuanta has already achieved rapid growth, successfully introducing a commercial CV-QKD system to the market and solidifying its position as a reference in the field of Quantum Cryptography.

Chair:

Tara Liebisch Tara Liebisch works at Germany's National Metrology Institute PTB as a strategy officer in the Division Optics. In this role she has developed many large-scale infrastructure and collaborative initiatives. She enjoys ensuring that partners from academia, industry and government can work together to achieve scientific endeavors. Her work builds on my research in atomic physics with publications on Rydberg atoms, compact atomic devices and a thorough article on the revised SI. Currently, her work includes developing a new Clock Building and a concept for an optical fiber research network for simultaneous quantum communication and metrology operation, as well as serving as the scientific manager of the excellence cluster QuantumFrontiers and as a co-coordinator of the QVLS-iLab Ion and Atom Trap Technology.

Parallel Track 4: Quantum Fundamentals

QUANTUM CONTROL FOR QUANTUM COMPUTATION AND SENSING

Prof. Nikolay Vitanov, University of Sofia

In this talk recent results from quantum control experiments with trapped ions, doped solids, and superconducting qubits are reported. They include demonstration of broadband composite pulses – trains of pulses with well-defined relative phases – for complete (X gates) and partial (Hadamard and general rotation gates), which cancel the experimental errors to an arbitrary order. Alternatively, narrowband composite pulses which squeeze excitation to an arbitrarily narrow parameter range, are used for spatial localization in doped solids and accurate phonon counting in trapped ions. The composite idea is extended to new, very efficient dynamical decoupling sequences. Another example is the newly proposed quantum control technique of polychromatic pulse trains – sequences of pulses of appropriately chosen different frequencies. In another set of experiments, we have observed the counterintuitive phenomenon of power narrowing with driving pulses of Lorentzian shape – the squeezing of the excitation line profile when the Rabi frequency increases – by as much as a factor of 10, potentially enabling new quantum sensing tools.

SEARCHING FOR NEW PHYSICS WITH ENGINEERED QUANTUM STATES IN TRAPPED IONS

Prof. Laura Dreissen, Vrije Universiteit Amsterdam

The Standard Model of Particle Physics has known great successes but also great frustrations, as it does not account for dark matter and dark energy, does not explain the matter/antimatter asymmetry in the universe and does not include gravity. The exquisite degree of quantum control over both electronic and motional states in trapped ions have made them powerful tools for searches for physics beyond the Standard Model. With long coherence quantum metrology using engineered quantum states, unprecedented levels of sensitivity can be achieved. Here I present how a spin-echo-like Ramsey sequence has recently enabled a world-record test of Lorentz symmetry. I continue on the prospect of accurate isotope shifts measurements with entangled Ba+ ions in a decoherence-free state to explore a hypothetical long-range interaction between neutrons and electrons mediated by a new boson. The long lifetimes of meta-stable electronically excited states in Ba+ (¿10 s) enable especially long coherence times and most systematic shifts are common mode, enabling accuracies of less than 10mHz that allow for a search in yet unexplored parameter range.

OPTICALLY COHERENT NV DEFECT CENTERS IN DIAMOND NANOSTRUCTURES FOR ENHANCED ENTANGLEMENT GENERATION

Laura Orphal-Kobin, Humboldt University Berlin

In large-distance quantum networks, quantum information processing and entanglement of individual quantum nodes is mediated by single photons. A promising candidate for a quantum node is the nitrogen-vacancy defect center (NV) in diamond – the most advanced optically active quantum memory to date. Using NVs, three-node quantum network protocols were demonstrated in bulk-like micro-structured samples [1]. Entanglement generation rates could be significantly enhanced by coupling NVs to nanostructures, i.e., nanocavities, increasing the emission rate into a particular optical mode (Purcell effect) and the photon collection efficiency. However, the coupling of NVs to nanoscale photonic devices remains challenging. The NV is sensitive to charge noise, referred to as spectral diffusion, resulting in an inhomogeneously broadened optical transition and in turn preventing the generation of coherent photons – a key requirement for spin-photon entanglement generation. We demonstrated NVs coupled to nanostructures that exhibit coherent emission on the time scale of a second and spectral stability over minutes [2]. A diamond substrate with a high density of nitrogen defects incorporates natural NVs and may screen fluctuating electric fields from the surface. Moreover, long ionization times allow for resonant control sequences in which high energy pulses can be circumvented for many entanglement attempt repetitions. Finally, entanglement success rates of up to hundreds of kHz, improved by a factor of 102 to 104 compared to state-of-the-art bulk values, are proposed.
[1] M. Pompili, S.L.N. Hermans, and S. Baier et al., Science 372, 259 (2021)
[2] L. Orphal-Kobin et al., Phys. Rev. X 13, 011042 (2023)

SCALABLE MULTILAYER ARCHITECTURE OF ASSEMBLED SINGLE-ATOM QUBIT ARRAYS IN A THREE-DIMENSIONAL TALBOT TWEEZER LATTICE

Prof. Gerhard Birkl, Technical University Darmstadt

We report on the realization of a novel platform for the creation of large-scale 3D multilayer configurations of planar arrays of individual neutral-atom qubits: a microlens-generated Talbot tweezer lattice that extends 2D tweezer arrays to the third dimension at no additional costs. We demonstrate the trapping and imaging of rubidium atoms in integer and fractional Talbot planes and the assembly of defect-free atom arrays in different layers. The Talbot self-imaging effect for microlens arrays constitutes a structurally robust and wavelength-universal method for the realization of 3D atom arrays with beneficial scaling properties. With more than 750 qubit sites per 2D layer, these scaling properties imply that 10000 qubit sites are already accessible in 3D in our current implementation. The trap topology and functionality are configurable in the micrometer regime. We use this to generate interleaved lattices with dynamic position control and parallelized sublattice addressing of spin states for immediate application in quantum science and technology.

Nikolay Vitanov Nikolay V. Vitanov is a professor in physics at Sofia University in Bulgaria. He graduated in 1994, with his PhD studies conducted jointly at Sofia and Aarhus University. During 1994-2003 he was a postdoc in the groups of Peter L. Knight at Imperial College, Stig Stenholm at Helsinki Institute of Physics, and Klaas Bergmann at University of Kaiserslautern. He has supervised over 20 PhD students and over 10 postdocs. He has participated in 9 projects within the framework programs of EC, most recently as a coordinator of the MicroQC project of the Quantum Flagship. His main interests, often combining theory and experiment, are in the fields of quantum control, including resonant, adiabatic and composite methods for qubits and qudits, quantum computation and quantum sensing.

Laura Dreissen Laura Dreissen did her PhD research in the field of precision spectroscopy in simple atomic and molecular systems to test of quantum electrodynamics theory and received her degree in 2020 with honors (cum-laude) from the Vrije Universiteit Amsterdam. In 2019, she became a postdoctoral researcher at the PTB in Braunschweig and received a prestigious Humboldt fellowship to conduct a search for Lorentz symmetry violation with trapped ions. In 2023, she joined the Vrije Universiteit Amsterdam as assistant professor, where she started her own research group focused on precision trapped-ion quantum metrology for the search for new physics. She explores techniques from quantum information science and precision frequency metrology to take full advantage of the quantum system.

Laura Orphal-Kobin Laura Orphal-Kobin is presently pursuing her PhD in the Integrated Quantum Photonics group led by Prof. Tim Schröder at the Department of Physics of Humboldt-Universität zu Berlin (HUB). She studied physics at HUB and her early stage research focused on ZnO-based materials. She currently investigates the optical coherence of defect centers in diamond nanostructures for quantum information processing applications. In 2022, she spent 3 months at the Jayich Lab at UCSB. Laura's research results have led to 3 first- and 4 co-authored publications including one in PRX, alongside numerous conference presentations. She received several awards, among them the award for the best master's thesis at the Department of Physics of HUB and the Physics Study Award of the Physical Society of Berlin.

Gerhard Birkl Gerhard Birkl is professor at Technische Universität Darmstadt and chair of the 'Atoms-Photons-Quanta' group. His research interests include the investigation quantum-degenerate gases (e.g., Bose-Einstein condensates), quantum simulation, quantum computation, and quantum metrology with individual ultra-cold atoms, laser cooling and high-resolution spectroscopy of highly charged ions in ion traps and storage rings, the application of micro-optical systems to atom optics and ATOMTRONICS, and the development of advanced laser systems and control electronics. He is spokesperson of the Darmstadt-Neutral-Atom-Quantum-Technology-Platform (DaNaQTP) and member of the Helmholtz Forschungsakademie - Hessen für FAIR (HFHF).

Chair:

Markus Arndt 2020 – 2024 Director, Vienna Doctoral School in Physics 2012 – 2014 Dean of Physics, Univ. of Vienna since 2008 Full Professor of Quantum Nanophysics, Univ. of Vienna 2004 – 2008 V. Prof. of Quantum Nanophysics, Univ. of Vienna 2002 Ao. Univ. Prof. , Univ. of Vienna 1999 – 2002 Assistant, Univ. of Vienna, with A. Zeilinger 1997 – 1998 Postdoc, Univ. of Innsbruck, with A. Zeilinger 1995 – 1997 Postdoc, Ecole Normale Supérieure / Paris, with Jean Dalibard 1991 – 1995 PhD & Postdoc LMU/Munich and MPQ/Garching: with A. R. Weis & T. W. Hänsch 1990 – 1991 Diploma at LMU Munich, with H. Walther Research specialisation: • Universal matter-wave interferometry • Quantum tools for biomolecular physical chemistry • Optical cooling of nanomaterials

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Parallel Track 5: Quantum Metrology & Sensing

MITIGATING THE EFFECTS OF PHASE NOISE IN REAL-WORLD TWIN-FIELD QUANTUM KEY DISTRIBUTION

Dr. Simone Donadello

We present a study that assesses the impact of noise sources in real-world implementations of Twin-Field Quantum Key Distribution (TF-QKD), with a specific focus on phase noise originating from photon sources and connecting fibers. Our research highlights the significance of various factors, including laser quality, network topology, fiber length, interferometer arm balance, and detector performance, in determining key rates in TF-QKD systems. We demonstrate the potential to enhance the key transmission duty cycle through the use of narrow-linewidth lasers and phase-control techniques. Specifically, we provide results on the implementation of dual-wavelength fiber noise stabilization and the dissemination of a common ultrastable laser over a deployed fiber link. We emphasize the promising synergies of metrological techniques, originally developed for frequency reference dissemination, for the practical implementation of TF-QKD scenarios.

QUANTUM SENSORS ON THE ROAD TO INDUSTRIAL APPLICATIONS

Dr. Thierry Debuisschert

Quantum sensing covers a wide range of applications, including medical diagnostics, communications or positioning, navigation and timing. Quantum sensors exploit changes in the properties of single quantum objects, when coupled to an external system, to improve the sensitivity and accuracy of measurement of physical quantities. There are two main categories of quantum sensors: gas sensors and solid-state sensors. Prototypes of these sensors have been developed as part of the ramp-up phase of the Quantum Flagship program. In the main phase, several projects are continuing this development, with the aim of bringing these sensors closer to applications. These include a new generation of gravimeters based on cold atoms, optical atomic clocks with enhanced performance, the use of color centers in diamond for medical diagnostics or muscle activity monitoring. The aim is also to use these sensors in harsh environments to monitor electric car batteries or for space applications. This development is supported by a joint effort with European standardization bodies and metrology institutes to define standards in order to strengthen the position of European industry.

TNO'S TESTBED FACILITY FOR NV-BASED SENSORS

Dr. Clara Osorio Tamayo, TNO

An immense variety of quantum systems have proven to be valuable sensors, with stages of development that go from theoretical ideas to commercial products. However, to fully harness the potential of Quantum Sensing still requires a more efficient translation from current research into impactful applications. In this talk, I will discuss the efforts of TNO, the Dutch Organization for Scientific Applied Research, to accelerate the introduction of quantum sensing to the market and society. In particular, I will describe the Testbed Facility hosted in TNO and developed in collaboration with QuantumDelta NL and TU Delft. In this facility, users can co-develop and test NV-centers-based quantum sensors for applications such as semiconductor metrology, automotive, and position and navigation. Throughout this presentation, I will also elaborate on the type of instruments available, specific use cases and the partnerships that TNO has established, both on national and European levels.

Simone Donadello Simone Donadello received his Ph.D. in physics from the University of Trento in 2016, with his experimental thesis focusing on ultracold atoms and quantum gases. From 2017 to 2020, he was a Post-Doctoral Researcher Fellow at Politecnico di Milano, where he worked on innovative solutions for low-coherence interferometry and optical monitoring in high-power laser processes. Since 2020, he has been a Researcher at the Istituto Nazionale di Ricerca Metrologica (INRIM). His current research interests include the development of methods for long-range Quantum Key Distribution over optical fibers, interferometric techniques with ultrastable lasers, optical fiber sensing for distributed seismological and environmental monitoring, and optical frequency metrology.

Thierry Debuisschert Thierry Debuisschert obtained his PhD from the Ecole Normale Supérieure, Paris, in 1990. He is a senior scientist at Thales Research & Technology-Fr. He actively contributed to the deployment of Europe's first quantum key distribution infrastructure in 2008 (SECOQC). He has coordinated numerous national and European research projects. He is currently coordinator of the AMADEUS project, federating the efforts of leading European groups on quantum sensors based on NV centers in diamond. Within the Quantum Industry Consortium (QuIC), he leads the expert group on quantum sensing. He is Chairman of the Quantum Coordination Board (QCB) of the European Quantum Flagship. He is the author of over 50 publications, has supervised more than 15 students and has served on several scientific boards.

Mikael Lassen Mikael Lassen (Male) is a senior researcher at DFM. With a PhD in nonlinear and quantum optics from the Department of Physics at the Technical University of Denmark (DTU) (2007). Before joining DFM in 2012 he worked as a research fellow at DTU physics (2009-2012) and at the Max Planck institute for the science of light in Erlangen, Germany

(2007-2009) in the field of quantum information processing with CV squeezed and entangled states of light. His field of expertise is in laser-based sensors (Raman spectroscopy, photo-acoustics spectroscopy, NIR spectroscopy), nonlinear optics and quantum optics. At DFM he works on metrology for CV-QKD and traceable quantum metrology and sensing.

Clara Osorio Tamayo Clara I. Osorio Tamayo is a Senior Scientist at TNO, the Netherlands Organization for Scientific Applied Research. She is currently leading TNO's Quantum Sensing Program and is part of the core team of the Dutch Catalyst Program on Quantum Sensing. For the last 20 years, she has focused on quantum technologies, mainly quantum sensing and communications, and has contributed to R&D projects for the Semiconductor, Medical, and Defence industries. She holds a PhD in Experimental Quantum Physics from ICFO (Spain) and worked at the University of Geneva (Switzerland) and AMOLF (The Netherlands) before joining TNO.

Chair:

Dennis Schlippert Since 2021 Principle investigator in the scope of CRC 1464 TerraQ - A02: Gravity Sensing with VLBAI since 2020 Principle investigator in the scope of CRC 1227 DQ-mat - B07: Macroscopically delocalised quantum states of matter & B09: Quantum clock interferometry since 2018 Group leader - BMBF Quantum Futur group: QuIS-g 2014 - 2018 Postdoctoral researcher, Leibniz Universität Hannover

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16:00 - 16:30 Showcase Stage Talks

Presentations and lightning talks featuring highlights from the EQTC 2023 exhibitors

- 16:05 - CERN, Benjamin Frisch
- 16:15 - EMN-Q, Dr. Marco Gramegna

16:30 - 18:00 Plenary Session - Shaping Europe’s Digital Future: Chips Act and Pilot Lines // QT User Take-up: Success Stories and Infrastructure Access

Laurent Olislager Laurent Olislager graduated as an engineer in physics. He got a PhD in quantum photonics from universities in Belgium and France. He is policy officer for quantum technologies at the Directorate-General for Communications Networks, Content and Technology (DG CNECT) of the European Commission.

Gabriele Bulgarini Gabriele Bulgarini started his journey in quantum technology with a PhD at the Delft University of Technology on the topic of semiconductor non-classical light sources in photonics nanostructures. In 2014, he joined Single Quantum where he contributed in establishing the company as the global market leader for superconducting nanowire single photon detectors in the role of General Manager. Since 2019, Gabriele is Program Manager for quantum technologies at TNO covering a broad portfolio of projects in quantum computing, communication and sensing. Gabriele is coordinator of the European project Qu-Test that brings together research institutes and industry to establish the first network of distributed testbed for quantum technologies.

Moderator:

Claudius Klein VDI Technologiezentrum GmbH

18:00 - 18:30 Showcase Stage Talks

Presentations and lightning talks featuring highlights from the EQTC 2023 exhibitors.

- 18:05 - Springer Nature, Christian Caron
- 18:10 - Portuguese Quantum Institute, Yasser Omar
- 18:20 - PicoQuant, Florian Weigert

18:30 - 20:00 Poster Session 1

MACHINE LEARNING BASED INVERSE DESIGN OF SEMICONDUCTOR LASER COMPONENTS USING LOW-DATA-DEMANDING ALGORITHMS

M. R. Mahani [1], Y. Rahimof [1], I. A. Nechepurenko [1], A. Wicht [1]
[1] Ferdinand-Braun-Institut (FBH), Berlin, Germany

In this study, we demonstrate the accurate prediction of surface Bragg grating characteristics in semiconductor ridge waveguides using data-efficient machine learning (ML) models. Traditional methods of system design and optimization rely on intuition or exhaustive parameter sweeping, which can become time-consuming and challenging as systems grow more complex. Alternatively, recent approaches like machine learning-based inverse design (MLBID) and optimization-based inverse design (OBID) have emerged as state-of-the-art techniques. The selection between MLBID and OBID depends on various factors, including the specific problem, data availability, computational resources, and desired interpretability and control. In our research, we focus on the MLBID approach and utilize ML models that operate effectively on small databases, as opposed to deep learning models that require large databases. To investigate the impact of design parameters on the reflectance spectrum, we develop an automated integrated design framework for 3D and 2D finite-difference time-domain (FDTD) simulations. After creating a database with limited simulations, we employ multiple ML models to predict the shape of the central lobe in the reflectance, eliminating the need for time-consuming FDTD simulations. We compare the performance of different models, including the artificial neural network, revealing the potential of some of the shallow ML methods in accurately predicting semiconductor-based Bragg grating characteristics. Notably, our results highlight the exceptional accuracy of the optimized XGBoost method in predicting the upper portion of the main reflectance peak. These findings pave the way for the data-efficient design of integrated photonic components, in connection with time-consuming simulations.

2D AND 3D FDTD SIMULATIONS OF BRAGG GRATINGS IN GAAS-BASED RIDGE WAVEGUIDES

Yasmin Rahimof [1], Igor Nechepurenko [1], Sten Wenzel [1], Reza Mahani [1], Andreas Wicht [1]
[1] Ferdinand-Braun-Institut (FBH), Berlin, Germany

Ultra-narrow linewidth diode lasers play a crucial role in various applications such as neutral atom and ion-based quantum computers, optical atomic clocks, and atom interferometry-based quantum sensors. In order to meet the requirements regarding compactness, robustness, electro-optical efficiency, and low noise, extended cavity diode lasers (ECDL) are commonly used. A new development in this field is the monolithic ECDL (mECDL), which integrates the ECDL onto a single GaAs chip through a two-step epitaxy process, creating an active region and a low-loss passive region. While the development of mECDL components has earned significant attention, recent efforts have been focused on enhancing mECDL performance by improving the Bragg gratings to reduce frequency noise and provide frequency selective feedback. Therefore, accurately calculating of the optical response of Bragg gratings is essential. The 3D Finite-Difference Time-Domain (FDTD) method is a precise approach for this purpose. However, due to its computational complexity, it is typically not employed for large-scale structure simulations. In this investigation, we evaluate the performance of both 2D and 3D FDTD methods in simulating Bragg gratings. Our analysis reveals that the 2D FDTD method adequately handles grating structures of interest, while the 3D FDTD method proves suitable for shorter structures up to 500 μm. Moreover, we demonstrate that outcomes derived from 2D simulations can effectively be used to set up an efficient 3D FDTD simulation. Additionally, we show that the combination of the 3D FDTD method and coupled mode theory offers an efficient means of predicting the reflectance of longer Bragg gratings.

QUANTUM MACHINE LEARNING - STATUS AND PROSPECTS

Kerstin Borras [1, 2]
[1] DESY, Hamburg, Germany, [2] RWTH Aachen University, Germany

Novel technologies emerging from the second quantum revolution enable us to identify, control and manipulate individual quanta with unprecedented precision. One important area is the rapidly evolving new paradigm of quantum computing, which has the potential to revolutionize computing by operating on completely different principles. Expectations are high, as quantum computers have already solved complex problems that cannot be solved with classical computers. A very important new branch is quantum machine learning (QML), which lies at the intersection of quantum computing and machine learning. QML combines classical Machine Learning with topics concerning Quantum Algorithms and Architectures. Many studies address hybrid quantum-classical approaches, but full quantum approaches are also investigated. The ultimate goal is to find the so-called quantum advantage, where quantum models outperform classical algorithms in terms of runtime or even solve problems that are intractable for classical computers. However, in the current NISQ era (Noisy Intermediate-Scale Quantum computing), where noise in quantum computing challenges the accuracy of computations and the small number of qubits limits the size of the problem to be solved, it is difficult to achieve quantum advantage. Nevertheless, machine learning can be robust to noise and allows to deal with limited resources of present day quantum computers.

In this talk, quantum machine learning will be introduced and explained with examples. Challenges and possible transfer to practical applications will be discussed.

RESIDUAL EXCHANGE INTERACTION IN LINEAR SPIN QUBIT ARRAYS

Irina Heinz [1], Adam R. Mills [2], Jason R. Petta [2, 3], Guido Burkard [1]
[1] University of Konstanz, Konstanz, Germany, [2] Princeton University, [3] UCLA

In the NISQ era quantum computation requires short gate times due to limited coherence times of qubits and optimal control parameters to perform high fidelity gates and readout. In spin qubit devices the exchange interaction between spins enables two-qubit gates and is often regulated by a middle barrier gate voltage. However to turn off exchange interaction the voltage has to be tuned rather high on short time scales and leaves the issue of residual exchange in qubit devices of several kHz. The fidelity of quantum gates is limited in the presence of residual exchange interaction. Therefore, we investigate the time evolution of single-qubit and two-qubit gates with residual exchange. In particular we look at the gate fidelity and the error operation that is left after a gate is applied and how to reduce this effect.

GENERATING ENTANGLED PHOTONIC RESOURCE STATES WITH COLOR CENTERS IN DIAMOND

Gregor Pieplow [1], Joseph Munns [2], Mariano Monsalve [1], Tim Schröder [1]
[1] Humboldt Universität zu Berlin, Berlin, Germany, [2] PsiQuantum

Large entangled photonic states such as multiphoton Greenberger- Horne-Zeilinger (GHZ) states or cluster states (CS) play a crucial role as resource states in two key photonic quantum information applications: measurement-based quantum computing, and one-way quantum repeaters. Here, we focus on theoretically investigating the deterministic generation of photonic resource states by employing a promising class of optically active spin defects in diamond: group-IV color centers. Specifically, we investigate the generation of linear cluster states and GHZ states. Because the generation of a large entangled photonic state comprised of single photons requires many iterations of the same coherent operations on a quantum emitter, they have to be of ultra high fidelity or otherwise the quality of the state degrades exponentially. This work provides a highly detailed investigation of the optical coherent control that facilitates single qubit gates, which are used for the deterministic generation of highly entangled states. We also introduce an original GHZ state and cluster quality measure, which will underline the importance of ultrafast and high fidelity control techniques when creating large time-bin entangled photonic qubit states.

X-JUNCTION DESIGN AND SIMULATION OF ION TRANSPORT FOR IMPLEMENTATION IN THE QCCD ARCHITECTURE

Rodrigo Munoz [1], Florian Ungerechts [1], Axel Hoffmann [2], Brigitte Kaune [1], Teresa Meiners [1], Christian Ospelkaus [1, 3]
[1] Institute of Quantum Optics, Leibniz University Hannover, Hannover, Germany, [2] Institute of microwaves and wireless systems, Leibniz University, [3] Physikalisch Technische Bundesanstalt

A versatile quantum computer requires an increased amount of qubits compared to state-of-the-art quantum computers. To reach this goal scalability is essential. One possible architecture for ion based quantum computers is the quantum charge-coupled device (QCCD) architecture. This architecture requires junctions to join different computational zones of the quantum computer as well as the implementation of ion transport. We report on our x-juntion design as well as on the optimization of ion transport.

ZERO-MAGNETIC FIELD QUANTUM CONTROL AND COHERENCE MEASUREMENTS OF A TIN-VACANCY COLOR CENTER IN A DIAMOND NANOPILLAR AS A SPIN-PHOTON INTERFACE

Cem Güney Torun [1], Joseph Hugh Daekin Munns [1], Franziska Marie Herrmann [1], Mariano Isaza-Monsalve [1], Mustafa Gökçe [1, 4], Viviana Villafane [2, 5], Andreas Thies [3], Tommaso Pregnolato [1, 3], Gregor Pieplow [1], Tim Schröder [1, 3]
[1] Humboldt-Universität zu Berlin, Berlin, Germany, [2] Walter Schottky Institut, [3] Ferdinand-Braun-Institut, Berlin, Germany, [4] Karlsruher Institut für Technologie, [5] Technische Universität München

Tin-vacancy color center in diamond is a promising platform for quantum networking, information processing and sensing applications. Their advantages stem from a first-order insensitivity to Stark shifts due to inversion symmetric positioning in the diamond lattice and a large ground state splitting, reducing coupling to the phononic decoherence channels. We investigate control methods and coherence properties of two different qubit configurations selected from the orbital levels of tin-vacancy color centers under zero magnetic field at 4 K. We conduct these measurements on emitters embedded in fabricated nanopillars to enhance photon collection efficiencies. Firstly, we carry out a coherent population trapping experiment to identify phononic transition rates between the ground levels. These enable probing spin coherence properties without any Zeeman splitting and overall characterization of our system. Then, we implement resonant excitation measurements with spectrally tailored ultra-short optical pulses, and quasi-continuous driving. These pave the way for two-color detuned excitation schemes and deterministic photon retrieval in spin-photon entanglement schemes, while measuring the optical coherence of our system. These experiments set the groundwork for utilizing tin-vacancy color centers as a spin-photon interface in an integrated fashion in the world-wide quantum internet.

TIME-SERIES QUANTUM RESERVOIR COMPUTING WITH WEAK AND PROJECTIVE MEASUREMENTS

Pere Mujal [1], Rodrigo Martínez-Peña [2], Gian Luca Giorgi [2], Miguel C. Soriano [2], Roberta Zambrini [2]
[1] ICFO-Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, Castelldefels (Barcelona), Spain, [2] IFISC - Institut de Física Interdisciplinària i Sistemes Complexos (UIB-CSIC)

For time-series processing in quantum systems, particularly in quantum reservoir computing [1,2], the implementation of measurements needs to preserve the processing memory and the quantum advantage offered by large Hilbert spaces. Due to the crucial influence of measurements on the state of quantum systems, it is commonly assumed that multiple restarts of the entire dynamics are necessary in practice. In our work [3], we propose alternative measurement protocols that surpass this limitation, focusing on their efficiency in terms of resources. In one case, after each projective measurement, a partial experimental repetition is sufficient. In the other, online operation is demonstrated by employing weak measurements, at the trade-off where information can be extracted accurately and without hindering the needed memory, in spite of back-action effects. This is illustrated by a successful performance in memory and forecasting tasks. Our work establishes the conditions for efficient time-series processing, paving the way to its implementation in different quantum technologies.
[1] K. Fujii, K. Nakajima, Phys. Rev. Applied 8, 024030 (2017). [2] P. Mujal, R. Martínez-Peña, J. Nokkala, J. García-Beni, G. L. Giorgi, M. C. Soriano, R. Zambrini, Adv. Quantum Technol., 4, 2100027 (2021). [3] P. Mujal, R. Martínez-Peña, G. L. Giorgi, M. C. Soriano, R. Zambrini, npj Quantum Inf. 9, 16 (2023).

SQUEEZED LIGHT SOURCE ON LITHIUM NIOBATE ON INSULATOR WITHOUT PERIODIC POLING FOR PHOTONIC QUANTUM COMPUTING

Tummas Napoleon Arge [1], Seongmin Su [2], Francesco Lenzini [3], Renato Domeneguetti [1], Jonas Schou Neergaard-Nielsen [1], Tobias Gehring [1], Ulrik Lund Andersen [1]
[1] Technical University of Denmark, Kgs. Lyngby, Denmark, [2] University of Heidelberg, [3] University of Münster

Squeezed quantum states combined with a linear beamsplitter network and photon number resolving detectors can produce the holy grail in continuous-variable quantum computing, GKP states. Lithium niobate on insulator (LNOI) is an emerging platform suitable for producing squeezed states of light due to its ultra-low propagation loss and high non-linear chi2 coefficient. A squeezing source for a circuit generating GKP states must obey two conditions: 1) a high amount of squeezing and 2) high purity. This work presents a design for a squeezer on an LNOI platform without using periodic poling fulfilling both requirements. Perfect phase matching in a type-I OPO is achieved using a higher-order transversal mode TM2 as the pump field, producing a signal/idler pair in the TE0 mode. Using a realistic loss of 20 dBm the ring resonator cavity, -17 dB of squeezing is estimated from simulations. The method for achieving phase matching is inherently narrow band, with phase matching bandwidth of 0.3 nm. By engineering the dispersion of the light in the ring resonator, we create an asymmetry of the resonant modes of the cavity, which in moves the symmetric resonances of the SPDC process outside the cavity bandwidth, thus suppressing all unwanted non-linear effects. Preliminary experiments show low losses and non-linear effects.
In conclusion, further work is needed to demonstrate squeezing on this platform. Employing three squeezers with an on-chip interferometer shows promise for approximating a GKP state, paving the way for producing the holy grail in CV quantum computing.

CLASSIFICATION OF DATA WITH A QUDIT, A GEOMETRIC APPROACH

Aikaterini Mandilara [1], Babette Dellen [2], Uwe Jaeckel [2], Themistoklis Valtinos [1], Dimitris Syvridis [1]
[1] Department of Informatics and Telecommunications, National and Kapodistrian University of Athens, Athens, Greece, [2] Faculty of Mathematics and Technology, University of Applied Sciences

We propose a model for classifying data using isolated quantum d-level systems or else qudits.The procedure consists of an encoding phase where classical data are mapped on the surface of the qudit's Bloch hyper-sphere via rotation encoding, followed up by a rotation of the sphere and a projective measurement. The rotation is adjustable to control the operator to be measured, while additional weights are introduced in the encoding phase adjusting the mapping on the Bloch's hyper-surface. During the training phase, a cost function related with the average expectation value of the observable is minimized with gradient descent in order to adjust the weights. We show with examples and numerical estimation of lossless memory dimension that this geometrically inspired qudit model for classification is strong enough for solving complex classification problems with a low number of parameters without the need of entangling operations.

EQUALITY - EFFICIENT ‘QUANTUM ALGORITHMS FOR INDUSTRY

Wael Yahyaoui [1], **Andreas Kötter** [1]
[1] *Capgemini, Hamburg, Germany*

The EQUALITY consortium comprising Airbus, Capgemini, Da Vinci Labs, Fraunhofer ENAS, DLR, INRIA, Leiden University and PASQAL, has been selected by the EU’s key funding program for R&I, Horizon Europe, to develop innovative quantum computer algorithms that are aimed to solve strategic industrial problems.
By transforming current industrial interest into widespread adoption, EQUALITY’s objective is to solidify the link between strategic European industries and the emerging quantum ecosystem while contributing to technologies critical to the green transition.
EQUALITY targets eight industrial use cases that can benefit from the quantum-enabled speed-up – each computationally complex and faced routinely by the industrial partners. These are airfoil aerodynamics, battery design, fluid dynamics, space mission optimisation, materials design, multidisciplinary optimisation, space data analysis and fuel cell design. The computational requirements are enormous, forcing today’s engineers to use simplistic models or rely on expensive build-and-test cycles. This is exemplified in aerodynamics, where it is more feasible to test models in a wind tunnel than solving the difficult equations involved in simulations. Similarly, complex situations are also found in Li-ion batteries and fuel cell simulations.
The opportunity provided by quantum computers to tackle such questions computationally promises a competitive edge for European industry. Moreover, energy-efficient aerodynamics and more durable and affordable batteries are critical to propelling these industries towards zero emissions.

A BENCHMARK STUDY OF ADAPTATIVE VARIATIONAL QUANTUM ALGORITHMS ON QUBO INSTANCES

Gloria Turati [1], **Maurizio Ferrari Dacrema** [1], **Paolo Cremonesi** [1]
[1] *Politecnico di Milano, Italy*

Adaptative Variational Quantum Algorithms (adaptative VQAs) represent a significant advancement over traditional Variational Quantum Algorithms (VQAs). Differently from fixed-structure VQAs, adaptative VQAs not only optimize gate parameters, but also dynamically modify the circuit structure by adding or removing gates during the training process. These algorithms overcome limitations of traditional VQAs, enabling them to adapt to specific problem domains and available hardware configurations.
However, despite the existence of various adaptative VQAs, a systematic comparison among these methods is still lacking in the literature. Therefore, our study aims to fill this gap by analyzing three specific adaptative algorithms: Evolutionary Variational Quantum Eigensolver (EVQE), Variable Ansatz (VAns), and Random Adapt-VQE (RA-VQE), where the latter is introduced as a baseline. Additionally, we include the Quantum Approximate Optimization Algorithm (QAOA) in our analysis to compare the adaptative algorithms with traditional VQAs. Our evaluation involves applying these algorithms to QUBO problems and assessing the quality of the results in terms of approximation ratio, number of gates, and computational time required. Furthermore, we investigate the influence of the hyperparameters and propose a Bayesian approach to select them effectively.
Our analysis reveals that, with carefully chosen hyperparameters, all of these algorithms produce high-quality solutions with similar approximation ratios. However, the number of gates in the final circuit and the associated computational costs can differ significantly between the approaches. Therefore, we conclude that an evaluation based only on the approximation ratio is insufficient, and other dimensions should be considered for a more accurate representation of how these methods perform.

SIMULATION OF GATE FIDELITIES IN SMALL ARRAYS OF FLIP-FLOP QUBITS IN A NOISY ENVIRONMENT

Marco De Michielis [1], Elena Ferraro [1]
[1] *CNR-IMM, unit of Agrate Brianza, Agrate Brianza (MB), Italy*

This work focuses on the flip-flop (FF) qubit, a type of donor- and quantum dot-based qubit embedded in nuclear spin-free 28Si. The FF qubit exploits the antiparallel electron-nuclear spin states of a 31P donor atom and its bounded electron. In this system, the bounded electron is shared with a nearby Si/SiO2 interface quantum dot (QD) by using an electric field [1].
Rz gates have been demonstrated by electrically changing the hyperfine coupling of the bounded electron with respect to the donor nucleus, whereas Rx gates are implemented via the Electric Dipole Spin Resonance method [2]. The FF qubits could exhibit long-range two-qubit operations spanning several hundreds of nanometers exploiting dipole-dipole interaction [3]. This feature relaxes the conventional limitations on inter-qubit distances typically encountered in donor-based qubits.
Here, we present simulation results of linear and two-dimensional arrays comprising a small number of FF qubits. Our objective is to investigate the impact of various factors, including charge noise, idle qubits, and simultaneous gating [4], on the gate fidelity of these arrays. In fact, simultaneous gating plays an important role in efficiently implementing Quantum Error Correction codes, which are required for achieving fault-tolerant quantum computation. By comparing the obtained results, we gain valuable insights into the performance of the FF qubit arrays under different conditions.

[1] Tosi, G. et al., Nat. Commun. 8, 450, (2017)
[2] Savytskyy, R. et al., Sci. Adv. 9, eadd9408, (2023)
[3] Truong J. et al., arXiv:2104.07485v1 (2021)
[4] Rei, D. et al., Quantum Technol. 5, 2100133, (2022)

A MODULAR QUANTUM COMPILATION FRAMEWORK FOR DISTRIBUTED QUANTUM COMPUTING

Davide Ferrari [1], Michele Amoretti [1]
[1] *University of Parma, Italy*

Most practical applications of quantum algorithms require much more qubits than those provided by current platforms. Merely augmenting the number of physical qubits on a single device is not beneficial for the quality of the computation, because of the increasing noise. Future devices will adopt quantum error correction to extract few high-quality logical qubits from many noisy physical qubits. Therefore, to supply users with many logical qubits it will be necessary to adopt the Distributed Quantum Computing (DQC) paradigm, leveraging the functionalities provided by the Quantum Internet.
DQC efficiency and effectiveness will depend also on a well designed quantum compiler, which is responsible for finding a suitable partitioning of the quantum algorithm and then appropriately schedule remote operations to keep EPR pairs consumption to a minimum. Moreover, the quantum compiler has to compute proper local transformations for each partition.
In this work, we present a modular quantum compilation framework for DQC that considers both network and device constraints and characteristics. We also present a prototype quantum compiler and its evaluation with quantum circuits such as VQE and QFT, taking into account different network topologies and quantum processors characterised by heavy hexagon coupling maps. For scheduling remote operations, we devised a strategy to exploit both TeleGate and TeleData operations and studied their impact. The results show that TeleData operations may have a positive impact on the number of consumed EPR pairs, while choosing a more connected network topology helps reducing the number of layers dedicated to remote operations.
Preprint: arXiv:2305.02969

TRANSMISSION OF LIGHT-MATTER ENTANGLEMENT OVER A METROPOLITAN NETWORK

Samuele Grandi [1], Jelena Rakonjac [1], Sören Wengerowsky [1], Dario Lago-Rivera [1], Felicién Appas [1], Hugues de Riedmatten [1, 2]
[1] *ICFO, Castelldefels, Spain,* [2] *ICREA, Spain*

One of the principal tasks of a quantum network will be that of delivering entanglement, enabling the exchange of qubits between locations too distant to sustain direct communication between them. Any system addressing long-distance quantum communication have to overcome several hurdles to achieve quantum correlations between a quantum memory and a telecom photon.
We present a set of tests over a quantum network testbed, with the generation of entanglement between a multimode quantum memory based on a rare earth-doped crystal and a telecom photon and its transmission through up to 50 km of deployed optical fibres in a metropolitan area. One photon of the pair, the idler, is at telecom wavelength and therefore suited for propagation in optical fibres, while the other, the signal, is resonant with the same praseodymium transition used to prepare the quantum memory. We show that non-classical correlations and light-matter entanglement is maintained after the transmission, with any degradation coming only from the reduced signal-to-noise ratio. Finally, we fully decouple the photon generation from the detection by realising a transportable setup which, placed at another location, we use to demonstrate non-classical correlations between two locations separated by 20 km. We have modified our system to account for a full separation, introducing synchronisation routines and employing a transducer that allowed precise timings to be transferred over optical fibres, taking the first steps towards the realisation of fully independent quantum nodes.

QUANTUM CITY: SIMULATION OF A PRACTICAL NEAR-TERM METROPOLITAN QUANTUM NETWORK

Raja Yehia [1], **Simon Neves** [2], **Eleni Diamanti** [3], **Iordanis Kerenidis** [4]
[1] ICFO, Barcelona, Spain, [2] Université de Genève, [3] LIP6, [4] IRIF

We present the architecture and analyze the applications of a metropolitan-scale quantum network that requires only limited hardware resources for end users. Using NetSquid, a quantum network simulation tool based on discrete events, we assess the performance of several quantum network protocols involving two or more users in various configurations in terms of topology, hardware and trust choices. Our analysis takes losses and errors into account and considers realistic parameters corresponding to present or near-term technology. Our results show that practical quantum-enhanced network functionalities are within reach today and can prepare the ground for further applications when more advanced technology becomes available.

ANALYSIS OF ENTANGLEMENT-BASED QUANTUM WIFI COMPETITION RESOLUTION INREAL LIFE SCENARIOS

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As technologies evolve and resources become scarce in many environments quantum computing and communications can improve the performance of every-day used protocols and services. We developed a time-slot based medium access protocol that offers a solution to inefficient competition resolution for air-time in distributed systems. The foundation of the protocol is a special form of quantum-entanglement and it can be applied to distributed network applications. In a nutshell: in distributed wireless networks where all nodes use the same medium; the efficiency of the system can be low due to overhead in traffic management. We constructed a Quantum Medium Access Control (QMAC) that is very efficient and performs well in a static environment where all nodes are within ranges of each other. In this paper we examine the performance of our solution in real life environment scenarios where nodes are regurarly joining and leaving the network. As the results show the quantum solution significantly outperforms its classical alternatives.

DEMONSTRATION OF GHZ SEQUENTIAL TIME-BIN ENTANGLEMENT IN A METROPOLITAN FIBER NETWORK

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In the last years entanglement proved to be a valuable resource for many applications, in particular for quantum communication and computing. On one hand, high generation rates are necessary to enable fast and reliable communications. On the other hand, high-purity entanglement is needed to perform measurement-based quantum computing. Many degrees of freedom like polarization, path-entanglement or frequency can be used to generate entanglement. Time-bin entanglement is in particular interesting, as it offers the advantage of being robust along propagation in optical fibers.
We report on a setup composed of off-the-shelf components to generate sequential time-bin entangled photons at high repetition rate. It consists of a spontaneous parametric down conversion (SPDC) type-II crystal, which generates orthogonally polarized photon pairs by converting amplified laser pulses at 780nm modulated in the GHz regime. The photon pairs are sent into a commercially available Mach Zehnder interferometer (MZI) delay line. The MZI delay line, matched to the pump laser periodicity, is used to generate time-bin entangled photon pairs. The photons are distributed through a 30km long fiber link across the city of Vienna and detected by superconducting nanowire single photon detectors. By post-selecting the coincidences and phase tuning the interferometer, entanglement can be certified. A corrected quantum visibility of 93% (raw visibility of 90%) was measured after 30km fiber link. The measured visibility is clearly above the CHSH-limit of 71%, proving high quality entanglement generation, also higher than 81% (threshold for a positive secure key rate) demonstrating thus QKD capabilities in a metropolitan fiber network.

PHYSICAL LAYER SECURITY USING QKD HIGH RATE KEYS

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Recent advancements in Quantum Key Distribution (QKD) systems allow for utilization of ultra-secure and robust high-rate key exchange. Additionally, Physical Layer Security (PLS) enhance the physical layer communication, supplementing and boosting conventional cryptography. The incorporation of high-rate secure key exchange in PLS can potentially enhance the security performance to unprecedented levels. In contrast to other higher layer bit-wise cryptography schemes, PLS exploits the physical communication characteristics such as the channel, modulation and other transceiver unique characteristics.
In this work, we adopt a computational security and secret key-based approach for physical layer parameter encryption and present on-going work for a system utilizing and integrating high rate, in the order of kbps, QKD keys into conventional modulation schemes like M-QAM, OFDM in fiber and/or wireless networks, to form a robust and ultra-secure PLS ecosystem. Various parameters of the modulation can be altered and controlled using these keys, i.e., the phase of QAM symbols, OFDM subcarrier symbols and position in the spectrum etc. The main advantage of QKD exploitation to the proposed solutions comes from the application of high-rate keys which can either be used in their original form or feed a pseudo-random number generator, to modify the modulation symbols in very high rates, such that eavesdropping and decoding the encrypted information becomes almost impossible. The QKD based PLS schemes could be included in security sensitive 6G applications and networks as well as in conventional and dark fiber optical networks. By-products of PLS to the physical layer (transmission) performance are also investigated.

HIGH-RATE INTERCITY QUANTUM KEY DISTRIBUTION WITH SEMICONDUCTOR SINGLE PHOTON SOURCE BASED ON 'NIEDERSACHSEN QUANTUM LINK'

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Quantum key distribution (QKD) enables the transmission of information that is secure against general attacks by eavesdroppers. The use of quantum light sources in QKD protocols is expected to help improve security and transmission tolerant loss. Semiconductor quantum dots (QDs) are a promising building block for quantum communication applications because of the deterministic emission of single photons with high brightness and low multiphoton contribution. Here we report on the experimental demonstration of a polarisation-encoded QKD BB84 protocol using high rate single photons in the telecommunication C-band emitted by a semiconductor QD. The application of semiconductor QDs for QKD is explored for the first time on an intercity fiber testbed, the 'Niedersachsen Quantum Link', resulting in fast and robust communication. A comparison of performance with the state of the art of today's QKD protocols is performed, showcasing the competitiveness of semiconductor single photon sources for the realisation of a real-world quantum internet.

EFFICIENT CAVITY-ASSISTED STORAGE OF PHOTONIC QUBITS IN A SOLID-STATE QUANTUM MEMORY

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The realization of large scale quantum networks requires the distribution of entanglement over large distances. In this long-range regime, direct transmission is prohibitive due to losses in optical fibers. Quantum repeaters are predicted to overcome direct transmission and allow entanglement distribution over a continental scale. Most quantum repeater schemes rely on the storage of quantum bits into quantum memories. For memories to be useful in practical implementations, they must exhibit several features including a long storage time, a high storage efficiency and a large multiplexing capability. Solid-state quantum memories based on rare-earth doped solids promise excellent performances in terms of storage time and multiplexing capability. However, the efficiency for the storage of quantum bits was so far limited to around 30%.
Here, we demonstrate high efficiency multiplexed solid-state quantum memories by implementing cavity-enhanced storage in a Pr^{3+}: Y_2SiO_5 crystal. We use the atomic frequency comb (AFC) protocol, which offers intrinsic temporal multimodality.
With our setup, we reached 62% efficiency for storing weak coherent states with a mean photon number of 0.2 photons/pulse. Furthermore, we were able to store weak coherent time-bin qubits with 51% efficiency and more than 95% fidelity, representing the highest solid state quantum bit memory to date. Moreover, we report the first demonstration of cavity enhanced on-demand AFC memories at the single photon level.

SUSTAINED QKD LINK OVER A MULTIPLE ONT LOADED CARRIER-GRADE GPON FOR FTTH APPLICATIONS.

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We have successfully demonstrated the integration of a commercial Quantum-Key-Distribution (QKD) system (Toshiba) over an exact reconfigurable testbed which replicates a carrier-grade Fiber to the Home (FTTH) optical access network consisting of components and systems which are installed in real-life FTTH operational deployments. Specifically, the experiment demonstrated a QKD transmission over a 1:16 user GPON configuration at the premises of the Telecom Operator COSMOTE that followed the operator's standard FTTH topology divided in two splitting stages, with a fiber distance of 3km from the Central Office (CO) to the first splitting stage, 1km links from the first splitting stage to the second splitting stage and 80-100m fiber links to the fiber terminations. The 1310nm QKD Toshiba QKD4.2A-MB (Alice) was located in the CO and a QKD4.2B-MB (Bob) was attached through a 3dB coupler to one port of the deployed ONT side of the GPON, allowing counter-propagation of the QKD channel with the GPON uplinks (in the range of 1312-1316nm), while the GPON downlink was centred at 1490nm. The primary objective was to maximize the utilization of the connected ONTs while simultaneously maintaining an ongoing QKD channel over the 21dB power budget link. By optimizing the transmission powers of the ONTs we successfully demonstrated a QKD link with 17 kbps SKR and 4.63% QBER, while ensuring 9 operational ONTs providing up to 500Mbps high-speed internet services. The findings demonstrate the feasibility to support QKD over a real GPON and enhancing access network security in the coming years.

OPTIMAL CONFIGURATION FOR KEY MANAGEMENT IN DYNAMICALLY SWITCHED QKD NETWORKS

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When considering standard Alice-Bob based point-to-point Quantum key distribution (QKD) links, a full mesh network requires N2 pairs of Alices and Bobs for full interconnection. Dynamic QKD has been proposed to reduce the required QKD pairs using optical switches to establish a direct link between any Alice to any Bob, provided the QKD systems support such a feature. In such case, the total number of QKD pairs is reduced to N. In this work, we investigate the establishment of non-optimized QKD links between arbitrary pairs of Alices and Bobs implementing the BB84 protocol with decoy states and phase encoding (using two Alices and two Bobs off-the-shelf Toshiba QKD devices). We demonstrate a huge performance variation when connecting an Alice to an unmatched Bob, measuring average secret key rates of 936 Kb/s and 1.06 Mb/s for their matches (A1/B1 and A2/B2 respectively), while the non-optimized crossed pairs demonstrated average rates of 57 Kb/s (A1/B2) and 15 Kb/s (A2/B1) respectively. This performance variation requires advanced handling in the control plane to dynamically balance the key material across the nodes and configure the QKD links according to the network requirements. To this end we proposed a novel algorithm based on integer linear programming (ILP) that takes into account key-consumption rates, device availability, and time constraints to maximize the weighted sum of key consumption rates while respecting system constraints. The evaluation highlights the potential in reducing the number of required pairs while optimizing key generation rates.

TRUSTED NETS: HOW TO COMBINE TRUSTED NODES TO ENHANCE PRIVACY

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In QKD, trusted nodes are cheaper, technologically feasible, and can bridge intercontinental distances (as demonstrated by LEO satellites used as traveling trusted nodes). Nevertheless, the required trust poses a security risk. Most experts propose the use of untrusted nodes to reduce this vulnerability, however this can be costly and technologically challenging. Here we argue that there can be an intermediate stage between the two. If trusted node based QKD providers are cheap and abundant in a large quantum network, Alice and Bob can combine multiple keys obtained from multiple providers to calculate a final key between them which significantly boosts confidentiality. In this case no single provider knows the final key, and an attacker must obtain all their keys to learn the final key. We also examine how we could find paths in a network of trusted nodes that are secure enough. This means that we have an upper bound for the probability that an attacker can obtain the key shared through that path.

DEMONSTRATING SINGLE PHOTON EXCHANGE OVER ROOFTOP-TO-ROOFTOP LINKS AND EVALUATING PERFORMANCE IN REAL-WORLD SCENARIOS

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Physical infrastructure of the future networks will rely on both wired and wireless access domain segments operating in a seamless way. Similarly, fiber-based, and Free Space Optical (FSO) Quantum Key Distribution (QKD) links will assist on the security of these urban-communication links. To this direction, an experimental emulation of Discrete Variable QKD systems was demonstrated via a single photon exchange campaign, over a rooftop-to-rooftop FSO link, deployed on NTUA premises. Vertically polarized single photons generated within the C-band (i.e., 1550nm) were transmitted over the FSO link and detected by fiber coupled InGaAs SPADs. To comprehensively evaluate the performance of the FSO link, an extensive experimental campaign was conducted under various scenarios. These scenarios included both daytime and nighttime operation, diverse transmission distances, converged fiber-wireless transmission as well as simultaneous transmission of 10 Gbps classical data streams alongside the polarization-encoded single photons. Noise sources, such as Raman scattering, coexistence X-talk and background sky radiance were experimentally quantified through photon counting measurements, to analyze the FSO link's behavior and robustness in different real-world situations. By comparing the signal to noise counts we were able to calculate the Quantum Bit Error Rate (QBER) values of each scenario. These results were compared with a simulation modeling toolbox to determine the feasibility of each scenario in a real end-to-end deployment. It was experimentally verified, that acceptable QBER values, can be achieved for small-scale urban FSO links, even under daylight conditions, indicating that Secure Key Rate values of up to hundreds of bps can be supported.

QCI.DK: DANISH QUANTUM COMMUNICATION INFRASTRUCTURE

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The Danish Quantum Communication Infrastructure (QCI.DK) is a project within the European Communication Infrastructure (EuroQCI) framework for realising a first deployment of advanced national quantum systems in a versatile network that supports real-life applications of Quantum Key Distribution (QKD). In QCI.DK we establish a quantum secured metropolitan network between 5 Danish public authorities and 2 associated data centres in the Copenhagen area. In addition the infrastructure encompasses a 200 km long-distance link connecting three participating university partners via the metropolitan network. QCI.DK combines four different QKD technologies in one network and thereby enable a broad range of tests and applications. To explore applications of QKD, the project devotes large attention to the development of use cases in the public authorities network and analysis of best implementations. This knowledge, together with essential practical experiences from the hardware implementation, directly spill over into education, training, and outreach activities targeting the formation of a quantum aware workforce with proficiency in QKD and the creation of general quantum awareness in Denmark. Both future and existing workforce is addressed through a combination of university teaching and up-skilling.
The consortium behind QCI.DK spans a diverse group of stakeholders and unites public authorities, small and large private businesses, and academic institutions in a hitherto unprecedented strategic effort on deployment of quantum technology in Denmark. This makes QCI.DK an ideal technology demonstration project and an important spearhead for initiating large-scale deployment of quantum communication technologies with potentially far-reaching impact for the country.

DEVELOPMENT OF A MICRO-INTEGRATED OPTICALLY PUMPED MAGNETOMETER FOR MAGNETOMYOGRAPHY IN SPACE

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Monitoring and diagnosing the neuromuscular conditions of astronauts during space missions is crucial for adapting and improving their training. Current methods, such as surface or needle electromyography, are either insufficient or invasive. To broaden the range of feasible approaches, the MyoQuant project explores the use of magnetomyography facilitated by optically pumped magnetometers (OPMs), aiming to overcome the limitations of the respective conventional technique [1].
Utilizing warm alkali atom vapors interacting with external magnetic fields and laser light, OPMs allow for flexible handling and non-invasive measurements. The focus of our project is to develop a compact, single beam, Mx type magnetometer based on a cesium vapor cell delivering high-bandwidth and robustness for operation in moderately shielded environments [2], such as those encountered during extended space missions.
In this poster, we present the sensitivity response of our lab-scale setup on various parameters such as vapor temperature, optical power, and RF magnetic field amplitude. The aim is to pinpoint optimal working parameters and design requirements for a compact sensor prototype. Additionally, we report on the development status of our miniaturized OPM for biomedical applications on space-borne missions.
This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) due to the enactment of the German Bundestag under grant numbers 50WM2168 and 50WM2169.
References [1] T. Klotz et al., arXiv:2301.09494 (2023). [2] L. M. Rushton et al., Rev. Sci. Instrum. 93, 125103 (2022).

OPTICALLY PUMPED MAGNETOMETER ARRAYS FOR ELECTRIC VEHICLE BATTERY CHARACTERIZATION.

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Quantum technology is a maturing field of research that applies the principles of quantum mechanics to solve engineering problems. Optically pumped magnetometers (OPMs) are an example of a well-established technology with multiple applications including navigation, medical research, and security. Here we show the feasibility of using OPMs to non-invasively measure the current density distribution inside an electric vehicle cell and the development of magnetometer arrays with shared systems to increase sensor resolution and sensitivity.
The adoption of electric vehicles is a central pillar of the transition to environmentally friendly transport and production is estimated to pass 14 million in 2023 and to minimize the environmental cost of this transition, the efficiency of manufacturing and recycling of cells must be maximized. In this work, we present the development and application of magnetic imaging techniques to characterize electric vehicle batteries utilizing both classical fluxgate sensors in the µT-regime and quantum magnetometers down to fT sensitivity.

MAGNETIC FIELD SHAPING FOR QUANTUM SENSORS

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Quantum sensors – operating with unparalleled accuracy, speed, and flexibility – are transforming many research disciplines and industrial applications. For instance, atomic magnetometers are becoming a preeminent tool in brain mapping and non-destructive testing and atom interferometers are overhauling gravity sensing and inertial navigation. However, for all their advantages, many of these sensors are fundamentally limited by magnetic field noise. Traditionally, this is addressed by enclosing magnetically sensitive components with several layers of passive magnetic shielding. But, this shielding introduces additional weight, size, and cost, is susceptible to becoming magnetised, and distorts the fields generated by internal active current-carrying coils necessary for trapping and biassing.
We unveil new design techniques that overcome these limitations, validated with experimental results and in real-world commercial products. These include mathematical models that incorporate the electromagnetic coupling between coils and passive shields directly into the shapes of coils. We make these coils using 3D-printing and flexible-PCBs and use them in cheaper, smaller, and lighter shields optimised for specific quantum sensors; e.g. bespoke environments to design and benchmark atomic magnetometers, miniaturised circuits tailored to bias atomic vapour cells, and shields which are retrofitted to atom interferometers to control quadratic Zeeman effect induced measurement errors. Finally, we offer perspectives on magnetic field design for the next-generation of quantum sensors. Considerations include the optimisation of ultra-low noise ferrite magnetic shields; magnetic field shielding, trapping, and biassing for high-bandwidth sensors; and power-reduction by substituting optimised current-carriers for permanent magnets.

NANOSCALE NUCLEAR MAGNETIC RESONANCE WITH NV CENTERS IN DIAMOND

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Conventional nuclear magnetic resonance (NMR) is a powerful tool for the investigation of matter and finds widespread application in physics, chemistry, and medicine. However, its applicability is limited by the required sample size, preventing for example single-molecule detection.
The nitrogen vacancy (NV) center in diamond is a solid state spin quantum sensor, that allows to overcome these limitations and to investigate nanoscale samples at ambient conditions. Quantum protocols enable us to utilize the coherence of single NV centers for NMR detection on the nanoscale with increasing spectral resolution.
We combine the potential of the NV center as a sensitive quantum sensor with nanostructuring of the diamond chip hosting the defects. This enables us to perform NMR measurements on liquid samples in a new regime with sample volume on the order of zeptoliters.
Because of its versatility, nanoscale NMR with NV centers in diamond has several potential applications, for example the structure elucidation of single biomolecules, the investigation of metabolic processes and quality control in the industry.

MAGNETIC FIELD CAMERA BASED ON INFRARED ABSORPTION ODMR MEDIATED BY DIAMOND NV CENTERS

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Magnetic field sensors based on nitrogen vacancy (NV) center ensembles in diamond reveal measurement sensitivities up to several pT/sqrtHz [1]. Nowadays, their improving sensitivity allows NV-based sensors to approach magnetic field ranges solely dedicated to SQUIDs. In contrast to superconducting sensors, NV optically detected magnetic resonance (ODMR), as the magnetic field measurement principle, works at ambient conditions without any shielding from the Earth's magnetic field. Despite these outstanding properties, NV-based sensors did not expand into medical applications yet. Such applications like magnetoencephalography require the ability to resolve magnetic fields spatially. Contrarily, diamond magnetometry research has mainly focused on single-pixel NV-based sensors [1] or scanning magnetometers [2].
In our work, we propose and demonstrate a first fully-integrated multi-pixel magnetic field camera employing infrared absorption ODMR [3]. Three optical fibers attached at either side of the diamond substrate provide green light to excite the NV centers as well as infrared light to measure the infrared transmission across the diamond. Perpendicularly intersecting laser beams with wavelengths of 1042 nm and 532 nm, respectively, thus define the pixel volumes within the diamond substrate. We demonstrate our camera by imaging the magnetic field produced by a solenoid coil placed on top of the sensor.

[1] T. Wolf et al. Phys. Rev. X 5, 041001 (2015)
[2] P. Maletinsky et al. Nature Nanotech. 7, 320–324 (2012)
[3] US patent application US20220390529A1 (2022), EU patent application EP4099041A1 (2021)

STUDY OF QUANTUM SENSORS IN LATERALLY OVERGROWN HOLE ARRAYS IN DIAMOND

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Large-sized diamonds with desirable crystal properties are quintessential for quantum technology applications[1]. Sizeable dimensions are advantageous, e.g., for quantum wide-field magnetometry, and for upscaling diamond nanofabrication for quantum sensing, quantum information, and photonics. In this regard, single crystals of up to 10 cm in size have been grown using heteroepitaxy[2]. However, heteroepitaxy results in a large dislocation density due to the lattice mismatch between the substrate and the overgrown diamond. Multistep heteroepitaxy has been proposed to limit this effect, and recent work has demonstrated that a modified method of lateral growth over hole arrays reduces dislocation defect propagation[3]. The readiness of such large-sized diamonds for quantum sensing applications has not yet been investigated in detail. In this work, we report the findings based on the study of laterally overgrown diamond hole arrays. We analyze the top surface topography and study the native Nitrogen-Vacancy (NV) centers. The effect of the crystal strain field, the single-spin T2* and T2times, and the magnetic noise potentially originating from the dislocations are investigated. Additionally, applicability of advanced quantum control methods is tested to exploit favorable T2 times in the order of 102 µs for single NVs in the sample. Such diamonds with inherent size-advantage and favorable spin-defect properties can open up new avenues in the field of diamond-based quantum technologies.

[1] Nelz et al., APL Materials vol. 7, 011108, 2019. [2] Schreck et al., Scientific reports, vol. 7, 1, 2017. [3] Mehmel et al., Applied Physics Letters, vol. 118, 6, 2021.

THE DEVELOPMENT OF QUANTUM DIAMOND MICROSCOPY FOR PRECISE QUANTIFICATION OF CELLULAR FORCES

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The mechanical interactions between cells and their microenvironment through membrane receptor proteins direct a wide range of biological functions and assist the development of multicellular organisms. Therefore, precise measurement of forces ranging from pN to nN is crucial for understanding the role of forces in shaping life. To date, only a few techniques are available for measuring cell force such as traction force microscopy. However, the considerable limitations such as sensitivity and ambiguities in measurement impede our comprehensive grasp of mechanobiology. In this study, we propose a novel technique called quantum-enhanced diamond molecular tension microscopy (QDMTM) for precise quantification of integrin-based cell adhesive forces. Our approach involves creating a force-sensing platform by attaching force-responsive polymers labeled with magnetic nanotags to a diamond membrane containing nitrogen-vacancy (NV) centers. The mechanical information is then measured optically through the spin relaxation of NV centers, which is modulated by the magnetic nanotags. To validate the effectiveness of QDMTM, we conducted meticulous measurements on both control and real cell samples. By correlating the measurements with an established theoretical model, we successfully obtained quantitative mapping of cellular adhesion forces. We believe that our method holds great potential as a routine tool for studying important issues such as cell-cell or cell-material interactions and mechanotransduction.

ARTIFICIAL INTELLIGENCE FOR QUANTUM SENSING

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Algorithms from the field of artificial intelligence and machine learning have been used in recent years for a variety of applications to efficiently solve multidimensional problems. In physics, these algorithms are applied with increasing success, for example, to solve the Schrödinger equation for many-body problems, or used experimentally to generate ultracold atoms, and control lasers.
In this project we aim to work on three fundamental pillars of AI in atom interferometry: theory modeling, measurement data extraction, and operation of experiments. We will report on the results that we have obtained simulating and optimizing Bragg interferometers. Beyond this example, we will also highlight solutions to other physical problems such as the optimized shuttling of ultracold neutral ensembles or the analysis of quantum sensor absorption images.

GRAPHENE-BASED QUANTUM HALL DEVICES FOR RESISTANCE METROLOGY

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So far, GaAs/AlGaAs quantum Hall (QH) devices are used for the realization of the electrical resistance unit ohm. The outstanding properties of graphene quantum Hall resistance (QHR) devices allow for the operation under more challenging measurement conditions (e.g. temperature of 4.2 K, magnetic field approx. 5 T, current gt 200µA) in comparison to existing GaAs QHR's with equally good accuracy. This signifies great potential for a transition from GaAs to graphene-based devices in resistance metrology. We extensively tested graphene devices by means of measurements with a resistance bridge using a cryogenic current comparator (CCC). The results demonstrate resistance quantization of the value RK/2 with an accuracy on the level of 1 nOmega/Omega at magnetic flux densities around 5 T, where RK is the von Klitzing constant. The performance of the investigated QHR devices demonstrates that the technology is ready for the realization of graphene-based primary quantum standards that are used in resistance metrology and other fields that will profit from the expanded range of measurement and operation parameters.

QUANTUM ANOMALOUS HALL EFFECT DEVICES IN ZERO EXTERNAL MAGNETIC FIELD FOR RESISTANCE METROLOGY

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The quantum anomalous Hall effect (QAHE) is a phenomenon observed in ferromagnetically-doped topological insulator (TI) materials that have attracted significant interest in both fundamental physics and metrology. In particular, the quantum effect has a high potential for metrology because it allows for Hall resistance quantization in units of the von-Klitzing constant at zero external magnetic field. To investigate the QAHE, we conducted extensive experiments on Hall-bar devices made of V-doped (BiSb)2Te3 using a precision resistance bridge based on a cryogenic current comparator (CCC) that applies about four times the number of available windings (¿ 16000) compared to a previously used setup. The higher number of windings allows for significantly improved resolution, especially at low currents in the nA range. Our latest experiments on recently fabricated devices involved current and temperature-dependent measurements of magneto-transport quantities in the QAHE regime. The results of these experiments demonstrate improved performance at higher currents compared to previous investigations on V-doped (BiSb)2Te3 devices. Overall, our findings contribute to a better understanding of the QAHE and its potential applications.

CHIRAL ANDREEV EDGE STATES IN JOSEPHSON JUNCTIONS WITH AN (NF)10N MULTILAYERED WEAK LINK

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Unidirectional and backscatter-free propagation of charge carriers in three-dimensional materials is of fundamental interest in physics and high demand for quantum technologies thanks to possibility of novel excitations as chiral Majorana fermions. One of the best ways to probe spatial current distributions is Josephson interferometry in a stacked (layered) configuration where the hybrid structure under study links two superconducting (S) electrodes. Weak links inside our Josephson junctions were formed by one or two binary (NF)10N superlattices connected in the latter case by an ultra-thin oxide (I) layer, N = Al, F = Ni or Ni-Fe alloy, I = AlOx,S = Nb. The figure of merit was the maximum supercurrent (Ic) versus in-plane magnetic field (H). Using the conventional metallic nm-thin films, we have nevertheless observed SQUID-likeIc(H) oscillations instead of standard Fraunhofer patterns expected for trivial S-weak link-S junctions. Reconstruction of the spatial distribution of Andreev states inside the hybrid weak link showed their localization at the superlattice edges and strong asymmetry indicating possible chirality of the transport modes that revealed itself also in the strong upward shift of the periodic Ic(H) characteristics. The finding gives rise to hope for their potential utility as a tunable platform for non-trivial edge physics and practical implementations as quantum sensors.
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OPTIMIZED SINGLE-ELECTRON PUMPS FOR A QUANTUM CURRENT STANDARD

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A unique and elegant possible realization of the new definition of the SI unit ampere are tunable barrier single-electron pumps (SEPs). The controlled, clocked transfer of single electrons generates a current I = n e f, only depending on the number of electrons n transferred per cycle, the repetition frequency f and the elementary charge e. Beside metrological applications, these SEPs are elementary building blocks as an on-chip source of deterministic single electrons, e.g. in electron quantum optics.
In our GaAs/AlGaAs-heterostructure based SEPs, tunable barriers and a shallow-etched mesa structure define the dynamical quantum dot (QD), which allows to confine and control single electrons. This technological approach of quantum dot formation needs to be thoroughly studied in terms of reproducibility and robustness for a small series production of samples.
Here we present the results of a systematic investigation and revision of the whole sample fabrication, which enables us to fabricate quantum dots with a high yield and reproducible elementary properties like e.g., charging energy and lever-arms. These devices are then investigated as potential candidates for a quantum current standard by means of traced-back precision measurements. All 5 randomly selected samples out of a pre-qualified batch of 208 samples successfully passed a newly developed verification and validation concept based on multiples pillars.
In conclusion the presented technological approach of quantum dot formation results in robust devices with reproducible mesoscopic characteristics, suitable for a future quantum current standard.

SUPERCONDUCTING RADIOFREQUENCY RESONATOR FOR ION TRAPS

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Trapped-ion qubits are one of many approaches to realize scalable quantum computers. An ion trap has to be operated with several DC and radio frequency (RF) signals to trap and control its qubits. Many ion trap setups are operated at cryogenic temperatures to reduce thermal influences, to reach very high vacuum and to achieve high fidelity for quantum operations. A resonance circuit, consisting of a coil and the capacitance of the trap electrodes, is used to step up a low power RF signal to high amplitudes in close proximity to the ion trap. An increased quality factor (Q-factor) of the resonance circuit leads to a higher voltage gain, but the experiment also benefits from a better attenuation of parasitic frequency components in the confining electric field. The Q-factor is inversely proportional to the trap capacitance. Since ion traps are growing in size due to a larger number of qubits, the capacitance is increasing. Therefore, the development of a coil with low losses becomes even more important.
In this work, we present the setup of a superconducting coil for a high-Q resonator, measurements of the Q-factor and its temperature dependency. The coil is made of a NbTi wire wound on a threaded bobbin made of PTFE and equipped with further thermalization structures. The circuit is placed inside a copper box to minimize the influence of the coils magnetic field on the trapped ions. A connector was designed for proper connection between the wire and printed circuit boards.

SCALABLE CRYOGENIC TRAPPED-ION QUANTUM COMPUTING EXPERIMENT DESIGN

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Further progress in trapped-ion quantum computing requires a significant increase in the number of ion qubits and splendid interconnectivity. On our poster we describe the design of cryogenic demonstrator machines for this task, implementing surface-electrode ion traps mounted on a universal interchangeable socket. The apparatus design is based on a vibration isolated cold head to cool a cryogenic vacuum system to temperatures around 5K. The system features several hundreds of DC control lines to support transport of qubits through dedicated trap structures including junctions, storage, detection and manipulation registers. Multi-qubit quantum gates will be implemented through the use of chip-integrated microwave methods. The system has been designed to accommodate the integration of new components for scaling as the development of the underlying enabling technologies progresses. One setup is based on 9Be+ qubits and 40Ca+ ions for sympathetic cooling; a second setup will be based on 43Ca+ qubits and 88Sr+ cooling ions. Both setups are currently under construction.

NEW PHOTON SCANNING TUNNELLING MICROSCOPE FOR INVESTIGATION OF ELECTROLUMINESCENCE OF SINGLE PHOTON EMITTERS

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Scanning tunnelling microscopy (STM) is a widely used method where the quantum properties of electrons to tunnel through a vacuum barrier are used to characterize for example surface topography, electronic density states and vibrational excitations. New setups with optical access to the tunnelling junction also offer the possibility to study electrical excitations and recombination processes of individual atoms and molecules by STM-induced luminescence (STML). In these measurements, the tunnelling current in STM is utilized to electrically excite individual atoms or molecules directly below the tip apex and to study the excitation process at the individual molecular level.
Our STML is a relatively compact design and a state-of-the-art, self-build, low-temperature, ultra-high vacuum STM. In our setup we employ a parabolic mirror to collect photons in an area of about 50 % of the hemisphere above the tunnelling junction. We use high frequency cabling from and towards the junction with a band with of 20GHz. This setup will give the possibility to study charge carrier and exciton dynamics in different single-photon emitter systems – especially in organic molecules – below the nanosecond range and this allows to gain further insight into its exciton decay.
The system also allows spectroscopic measurements of the electroluminescence by a Czerny-Turner spectrometer in combination with a LN2 cooled detector.

AN EXPERIMENTATION PLATFORM TOWARDS STANDARDIZED CHARACTERIZATION OF ION TRAPS FOR INDUSTRY AND RESEARCH

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Ion traps are enabling technologies for quantum technologies (QT) and have nowadays become indispensable in the fields of quantum computing, quantum sensing and quantum metrology. To successfully commercialize QT key components, knowledge transfer between research and industry is required.
The Quantum Technology Competence Center (QTZ) at PTB has the central goal of becoming the bridge between research and industry in Germany for quantum technologies. The user facility "Ion Traps" of QTZ will provide a user-friendly experimentation platform for the characterization of ion traps, enabling intuitive access for partners from academia and industry. Being a consortium partner in national and European QT programmes, the QTZ strives for the recommendation of a standardized procedure for the characterization of ion traps. This involves a standardized set of measurement parameters, e.g. ion micromotion and heating rate, and the implementation of automated routines in the European QuTest project.
To make the trapped ion systems scalable and robust against environmental influences, the integration of photonic components will play a key role in guiding and manipulating the laser light at the chip level. During the BMBF ATIQ project and activities in Quantum Valley Lower Saxony facilities for the connectorization and characterization of photonic-integrated circuits from UV to IR have been established at PTB.
In the BMBF project QVLS-iLabs "Scalable integrated ion traps", a standardized connection socket will be developed together with Infineon Technologies Austria AG towards the characterization of photonic integrated ion traps. Different materials for ion traps will be investigated by Infineon and tested at PTB.

HYBRID INTEGRATION AND MICROFABRICATION TECHNOLOGY FOR SCALABLE ION TRAP QUANTUM COMPUTER

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Ion traps have emerged as a prominent platform for achieving scalable quantum computing. The physical realization of these traps relies on microfabricated surface-electrode ion traps, wherein a multilayer fabrication technique [1] enables the creation of geometries that were previously unattainable with single-layer traps. This method involves the deposition of thick and planarized dielectric-metal layers, which offer flexibility and improved signal routing capabilities. To enhance the efficiency and yield of the fabrication process, it is necessary to systematically analyse and update various microfabrication techniques such as UV photolithography, reactive ion etching (RIE), and electroplating.
To facilitate scalability and enable hybrid integration of diverse control techniques, we explore the implementation of Integrated photonics, Interposer technology, Through substrate vias, and packaging technologies like flip-chip bonding. A solder-free thermocompression method [2] which utilizes plastic deformation of gold stud bumps for bonding is being tested and characterised. This method is a potential alternative which offers higher packaging densities, unlike the conventional method of wire bonding. Preliminary process optimisation concerning the integration of optical components is also investigated.

[1] A. Bautista-Salvador et al., New J. Phys. 21, 043011, Patent DE 10 2018 111 220 (2019).
[2] M. Usui et al., "Opto-electronic hybrid integrated chip packaging technology for silicon photonic platform using gold-stud bump bonding", (ICEP-IAAC) pp. 660-665 (2015).

MINIATURIZED CROSSED BEAM OPTICAL DIPOLE TRAP AND ENABLING TECHNOLOGIES FOR COMPACT ATOM-BASED QUANTUM SENSORS

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Cold atomic quantum sensors leverage on the generation, manipulation, and detection of atomic quantum gases and are well proven within laboratory environments. But for many applications in the areas of sensing, timekeeping and fundamental physics, these setups need to be transferred into mobile and field compatible, miniaturized devices. We aim to develop compact and rugged atomic quantum sensing devices and specifically address the physics package, including the atom source, ultra-high vacuum system and optical systems for atom manipulation. Using micro-integration methods, we assembled a miniaturized crossed beam optical dipole trap (volume ca. 25 ml), to trap and manipulate an atomic ensemble. Two high-power laser beams (1064 nm, 2 W total power) precisely overlap in their focal points (32 µm beam waist), and the system exhibits a high mechanical and thermal alignment stability. We present the optical system and results from its characterization and operation in a rubidium cold atom experiment.
One approach to further reduce the overall size of an atomic quantum sensor is to integrate optical setups for atom trapping and manipulation within the UHV system, requiring ultra-low outgassing optical systems. We present our development and qualification efforts for future in-UHV optics and enabling technologies for compact physics packages, such as additive manufacturing.
This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) due to an enactment of the German Bundestag under grant number DLR50WM1949, 50RK1978, 50WM2070 and 50WM2268.

COMPACT CHIRPED FIBER BRAGG GRATINGS AT 800 NM FOR ROBUST SINGLE-PHOTON GENERATION FROM QUANTUM DOTS

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A scalable source of single photons is a key constituent of an efficient quantum photonic architecture. To realize this, it is beneficial to have an ensemble of quantum emitters that can be collectively excited with high efficiency. Semiconductor quantum dots hold great potential in this context, due to their excellent photophysical properties. Spectral variability of quantum dots is commonly regarded as a drawback introduced by the fabrication method. However, this is beneficial to realize a frequency-multiplexed single-photon platform. Chirped pulse excitation is the most efficient scheme to excite a quantum dot ensemble due to its immunity to individual quantum dot parameters. Yet, the existing methods of generating chirped laser pulses to excite a quantum emitter are bulky, lossy, and mechanically unstable, which severely hampers the prospects of a quantum dot photon source. Here, we demonstrate a compact, high-efficiency, plug-and-play alternative for chirped pulse excitation of solid-state quantum emitters. Our technique is based on chirped fiber Bragg gratings (CFBGs) developed around 800 nm -for the first time to the best of our knowledge- enables precise control of the dispersion characteristics of the laser pulses and couple them to a GaAs quantum dot. We establish the versatility of our method by demonstrating a high-fidelity, frequency-multiplexed single-photon generation. Our work is a significant breakthrough toward realizing a practical quantum dot photonic device.

BRAGG GRATING BASED FREQUENCY REFERENCE MODULE FOR OPERATION IN QUANTUM TECHNOLOGY APPLICATIONS

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Specifically tailored to meet the requirements of automated laser operation in quantum technology applications, a compact and robust frequency reference module has been developed. The reference module is based on the spectroscopy of a volume holographic Bragg grating. The measured incident, transmitted and diffracted laser powers are used to generate an error signal, which enables the stabilization of the laser frequency.
The micro-integrated module is fiber-coupled and fits into a volume of 96x96x35mm3. A frequency accuracy of 50MHz and a tuning range of more than 20GHz will be achieved by placing a Bragg grating with a steep slope on a Peltier element and isolating it from the surrounding environment with a thermally conductive cover attached to a temperature stabilized micro-optical bench.
The reference module is designed to be operated in two different modes: (i) stabilization of a laser to the frequency reference for achieving an accelerated lock-acquisition and (ii) operation of the frequency reference as a wavemeter to measure the emission frequency of a free-running laser. In its first application the frequency reference is intended to complement a laser module by facilitating accurate control of the laser frequency in an atom interferometer application with ultra-cold potassium atoms.
We will present the design of the novel micro-integrated frequency reference module as well as first characterization results.
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INDUSTRIALLY MICROFABRICATED ION TRAPS FOR QUANTUM INFORMATION PROCESSING AND METROLOGY

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Infineon Technologies is fabricating 2D and 3D ion trap chips in its industrial facilities [1,2]. This poster gives an overview of our work towards scalable, reliable ion traps.
We are developing multiple fabrication processes on silicon and dielectric substrates for multi- and single-layer metal stacks with low resistance at cryogenic temperatures. Additionally, we are realizing 3D trap architectures using MEMS wafer bonding technology. Together with our partner, the PTB, we are working on several joint projects incorporating new materials and designs in industrial ion trap production. In the BMBF project "ATIQ" Infineon Technologies has committed to the goal of fabricating ion traps with integrated optics on industrial scale, further pathing the way to the scalable use of ion traps. In the BMBF project "QVLS ILabs SiQT" we integrate single photon avalanche detectors into ion traps to miniaturize the detection system fort trapped ions thereby decreasing the size of whole setup.
1. Ph. Holz, S. Auchter et al., Adv. Quantum Technol. 3, 2000031 (2020) 2. S. Auchter, C. Axline at al., Quantum Sci. Technol. 7, 035015 (2022)

CRYOGENIC ELECTRONICS FOR INTEGRATED SNSPDS

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Quantum optics require generation, manipulation, and detection of single photons. Due to their excellent performance characteristics, superconducting nanowire single-photon detectors (SNSPDs) are now widely used for measurement at the single-photon level. These detectors require cryogenic operation temperatures since they are based on the breakdown of superconductivity, while a bias current is flowing through the SNSPD.
Conventionally, these detectors are operated in a free running mode with a DC bias generated at room temperature. However, the interconnects between room and cryogenic temperature introduce parasitic effects limiting the number of operation modes of the SNSPD. In this contribution, we show how implementing a cryogenic current source removes the limitation of the cryogenic-room temperature interconnect, which increases the electrical bandwidth and reduces electrical noise. This enables different operation modes including deterministic gating of an SNSPD, since the modulation bandwidth of the bias current is no longer limited by the cryogenic-room temperature interconnect. We show a cryogenic current source that enables gated operation of an SNSPD with a detection window down to 5.0 ns with a rise- and fall time of 2.4 ns, without degrading the SNSPD performance. To do so, we designed an electrical circuit cable of generating current pulses while at a temperature of 2.4 K. This circuit is controlled with room temperature electronics.
These electrical biasing circuits can be expanded with cryogenic compatible readout circuits, enabling cryogenic processing of SNSPD detection events. This enables full cryogenic feed forward modulation.

ALL-OPTICAL OPERATION OF A SUPERCONDUCTING OPTO-ELECTRONIC CIRCUIT

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Advanced quantum photonic circuits require the combination of quantum light sources, optical modulation, and single photon detection. High performance optical devices are required to pursue the realization of desired quantum optical processes. Superconducting nanowire single photon detectors (SNSPDs) play a vital role to achieve these capabilities due to their near unity detection efficiency, low dark count rates and low timing jitter. However, their operation demands an adaptation of the photonic circuits for cryogenic operation temperatures. Typically, the operation power and the signal readout for these single photon detectors is achieved by coaxial cables. Unfortunately, the coaxial cables introduce parasitic effects such as electronic noise and a thermal power dissipation. To mitigate these risks, we replace the coaxial cables with single mode fibers and opto-electronic components. In this work, we show an all-optical operation of an SNSPD with a cryogenic photodiode for the optical power delivery and an electro-optic modulator for the optical readout. The all-optical implementation allows us to electronically decouple the superconducting single photon sensitive circuit. Furthermore, we achieved a low power operation of the SNSPD at 1K with a total consumption of approximately 75µW. The applied optical methods allow us to fully operate more advanced superconducting circuits across the room temperature to cryogenic environment. A key aspect in the implementation can be to optimize the signal transformation from the single photon detectors to the electro-optic modulator which can enable feed-forward modulation for various quantum optical processing tasks.

SUPERCONDUCTING NANOWIRE SINGLE-PHOTON DETECTORS INTEGRATED IN SUBWAVELENGTH GRATING METAMATERIAL WAVEGUIDES

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Superconducting nanowire single-photon detectors (SNSPDs) play a pivotal role in applications, such as quantum communication, where efficient photon counting is essential. SNSPDs allow for taking advantage of nanophotonic integration, enabling compact and stable devices while also holding potential for engineering the detector absorption efficiency by increasing the interaction length between the nanowire and the evanescent field of an optical mode propagating along a waveguide. Additionally, embedding SNSPDs with photonic-integrated-circuit components has opened up new possibilities for advancing quantum technologies.
Conventional waveguide-integrated SNSPDs have limited detection speed due to increased kinetic inductance resulting from long nanowire geometries. Furthermore, U-shaped nanowire designs introduce timing jitter due to current distribution alterations caused by bends. Previous attempts to overcome these issues involve embedding short, straight nanowires in optical cavities. However, this approach requires waveguide crossings, leading to light scattering and reduced absorption efficiency.
Here, we propose a novel waveguide-integrated SNSPD concept that leverages refractive index engineering of subwavelength grating (SWG) metamaterials to suppress the scattering caused by waveguide crossings. The structure is simulated using a finite-element-method tool by substituting the lateral SWG cladding of the waveguides with an isotropic equivalent material, yielding an absorption of 0.23 dB per 100-nm-long NbTiN nanowire. The nanowires are integrated with the waveguides by sputtering a 5-nm-thin superconducting layer on a silicon nitride sample. Then, the nanowires and subsequently the waveguides are dry etched. This novel approach holds great promise for achieving high absorption efficiency while maintaining fast detection speeds with high timing accuracy by utilizing short, straight nanowires.

TRADE-OFF DESIGN CONSIDERATIONS FOR LASER SYSTEMS FOR HIGH-END QUANTUM SENSOR APPLICATIONS

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We present the design trade-offs for our laser modules tailored for high-end quantum sensing applications such as atom interferometry. Based on requirements such as high optical output power, narrow linewidth, frequency agility and suppression of amplified spontaneous emission, we derive the design trade-offs for our laser architecture based on an extended-cavity diode laser (ECDL) as local oscillator and a power amplifier within a single platform with a footprint of 125 x 75 mm^2.
Furthermore, investigations about the behaviour of both the semiconductor power amplifier and ECDL towards unwanted feedback are presented and we discuss the considerations to lower the sensitivity of the whole module to external feedback.
Especially for space related projects, reliability and longevity are becoming increasingly important. Therefore, we show test results, approving that we meet the demanding requirements for currently planned missions.
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A FAST QKD PROTOTYPE BASED ON PHOTONIC INTEGRATED CIRCUITS

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QKD can play a significant role in improving security in communication networks in the near future. Multiple QKD experiments have been carried out, the majority being proof-of-concept demonstrations. However, for large-scale applications of this technology in communication networks, compact and scalable integrated units are needed. To pursue this effort, we developed a compact, portable, ready-to-use high-speed (1.25 GHz) QKD platform based on Photonic Integrated Circuits (PIC). Our practical integrated QKD system can generate secret keys at high speeds and with low Quantum Bit Error Rates (QBER) by implementing the 3-state, one-decoy BB84 protocol with time-bin encoding.
A silicon-based PIC is responsible for producing the three states needed for the protocol at the transmitter unit. In addition, a laser, an in-house-made PCB and an FPGA are all placed inside a 1U 19" frame.
The receiver's PIC is based on silica, features low loss and is polarization-insensitive. The receiver's unit comprises two NFADs, a PCB and an FPGA, placed inside a 2U 19" frame. The NFADs, cooled to -50°C, with a standard Peltier, are integrated into a compact package resulting in a total volume of 125 cm3.
As preliminary results, we obtained QBERZ = 1.8
We look forward to presenting our newest results at the conference.

FABRICATION OF SUSPENDED "SAWFISH" PHOTONIC CRYSTAL CAVITIES IN DIAMOND

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Color centers in diamond are a promising candidate for the development of photonic quantum networks, because of their quantized spin-states that can be coupled to optical transitions and present long coherence times [1]. An efficient interface between spins and photons is key for the success of such a network, as it enables the transfer of information between the distributed quantum systems. Such an interface can be achieved by coupling a color center to a photonic crystal cavity [2].
We recently proposed a new cavity design based on the periodic corrugation of the width of a fully suspended diamond nanobeam [3]. Our simulations, which use parameters that are achievable in state-of-the-art fabrication processes, show that such a device has the potential to not only enhance the emission rate of the coherent photons from an embedded tin vacancy color center by almost 50 times, but also to couple them into a single-mode waveguide with an efficiency of 92.9%. Here, we report on our progress on fabricating such photonic crystal cavities. We present our fabrication procedure to obtain these suspended devices and the results of our first optical characterizations, where we show that the spectral positions of the measured resonances follow the expected design parameters and the optical properties of the devices are robust against fabrication imperfections.

[1] M. Atatüre, et al., Nat. Rev. Mater. 3, 38–51 (2018)
[2] T. Schröder, et al, J. Opt. Soc. Am. B 33, B65-B83 (2016)
[3] J. M. Bopp, et al., arXiv:2210.04702 (2022)

IQUBITS: AN ALL-IN-ONE INTEGRATED QUBIT PLATFORM IN COMMERCIAL ULTRA-SCALED SILICON FOUNDRY TECHNOLOGIES FOR SCALABLE MONOLITHIC QUANTUM PROCESSORS

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IQubits is a European FET Open project addressing the implementation of an integrated qubit platform with electron/hole spin qubits, control and readout circuits integrated together onto the same chip fabricated in commercial ultra-scaled Silicon foundry technologies enabling scalable monolithic quantum processors operating at acceptable cryogenic temperatures.
IQubits is a joint effort between Europe (EU H2020) and Canada (NSERC), which brings together quantum physicists, material scientists, semiconductor technologists of pilot prototyping lines and large production fabrication facilities, electronic circuit designers and measurement scientists and engineers from leading universities, research institutes and large multinational enterprises - to work together in a full-stack approach from basic research to applied research and innovation encompassing theory, modeling, design, simulation, fabrication and measurement, toward the hardware implementation of a scalable integrated technology platform for monolithic quantum processors fabricated in commercial Silicon technologies and operating at 2-12 K.
This presentation reports the key features and the main results of the research conducted so far by the consortium and its impact on the international research landscape. It highlights the main achievements and results from the design and fabrication to the measurements of the integrated qubit devices and circuits in ultra-scaled FDSOI and FinFET CMOS technologies ranging from the 22 nm to 3 nm nodes currently in production. Cryogenic measurements at 2 K show excellent repeatability of Coulomb peaks and subthreshold characteristics for both p-type and n-type quantum dots and superior performance of innovative compact low-power microwave/mm-wave control and readout circuits.

NATIVE 3-BODY INTERACTIONS FOR QUANTUM ANNEALING WITH TRAPPED IONS

Sebastian Nagies [1, 2, 3], Kevin Geier [1, 2, 3], Philipp Hauke [1, 2, 3]
[1] University of Trento, Trento, Italy, [2] Pitaevskii BEC Center, [3] INFN-TIFPA, Trento Institute for Fundamental Physics and Applications

Using quantum annealing algorithms to solve optimization problems represents a promising path to achieving a practical quantum advantage in the NISQ era. Problems of interest are typically formulated as a quadratic unconstrained binary optimization (QUBO) and then encoded into a spin glass Hamiltonian with two-body spin interactions.
Recently the inclusion of higher-order terms into the formulation of optimization problems (PUBO's) has garnered much interest due to the promise of increased ressource effiency and potential speedups.
We study examples of relevant optimization problems that are naturally formulated as PUBO's and calculate the associated ressource savings when solving them using quantum annealing protocols with three-body spin interactions. Specifically we show that one can save up to an order of magnitude in for the encoding required logical qubits as compared to a QUBO formulation for certain problems like 3SAT.
We propose and discuss different approaches to engineer these higher-order interactions within a trapped ion quantum computer. These schemes are feasible to implement on current hardware and allow quantum annealing algorithms to solve larger optimization problems with relevance to industry.

CONSTRAINED QUANTUM GENETIC ALGORITHM FOR MAXIMIZING ENERGY EFFICIENCY IN DOWNLINK MASSIVE MIMO NETWORK FOR 5G APPLICATIONS

Sara El Gaily [1], Mohammed Almasaoodi [1, 2], Abdulbasit Sabaawi [1, 3], Sándor Imre [1]
[1] Budapest University of Technology and Economics, Budapest, Hungary, [2] Kerbala University, [3] College of Electronics Engineering, Ninevah University

In practical real-application scenarios, the database is unsorted and enormously large, such that there is no currently available quantum computer the qubit size of the current universal quantum computer does not support a vast database or classical computer globally connected traditional computers via a classical network or a supercomputer may consume millions of years to find the solution, which can perform the search for the extreme (maximum or minimum) value in this database.
We proposed a constrained quantum genetic algorithm (CQGA) that utilizes the advancements of blind quantum computing which enables delegating computation to quantum remote devices, and a constrained quantum optimization algorithm that finds the extreme value for a constrained goal function to improve and speed up the search capabilities in enormously large and unsorted database of the constrained classical genetic algorithm.
The primary objective of our proposed algorithm is to enhance the likelihood of discovering the global solution while effectively circumventing local minima. A downlink multi-cell massive multiple-input multiple-output (MIMO) application is employed as a representative example for testing and validating the efficiency of the CQGA. Through rigorous experimentation and analysis, we showed that the CQGA can maximize the energy efficiency with respect to the target bit rate of the active users in the massive MIMO system with low computational complexity.
Our findings can contribute to the advancement of quantum computing techniques for solving complex problems in the field of wireless communication.

INTUITIVE AND VERSATILE SOFTWARE FOR REAL-WORLD QUANTUM SENSORS

Jan-Niclas Kirsten-Siemß [1], Stefan Seckmeyer [1], Gabriel Müller [1], Christian Struckmann [1], Gina Kleinsteinberg [1], Naceur Gaaloul [1]
[1] Leibniz Universität Hannover, Institut für Quantenoptik, Germany

Quantum sensors measure electromagnetic, gravitational and inertial forces with unparalleled accuracy and precision. Their commercialization is therefore a crucial aspect for ensuring the European Union's sovereignty in the field of quantum technologies.
Numerous real-world applications, such as in civil engineering, inertial navigation, and Earth Observation, have already demonstrated the utility of quantum sensing with atom interferometers. Today, the biggest challenge to broader market adoption of these sensors is the in-depth knowledge of quantum mechanics required by both the manufacturers and users of these devices.
We aim to make the design, construction, and operation of atom interferometers more intuitive using software that incorporates our years of experience in atom interferometry simulation.
Here, we provide an overview of the versatile components of our simulation software. In addition to optimizing sensor operation and facilitating data analysis and interpretation, we view it as an invaluable tool for next-generation hardware development. Our versatile numerical toolbox enables efficient simulation of atomic test masses interacting with realistic electromagnetic, gravitational and optical forces, as well as prediction of sensor performance in realistic deployment scenarios, e.g., on air, land, and water vehicles.
This work was funded by the Deutsche Forschungsgemeinschaft (German Research Foundation) under Germany's Excellence Strategy (EXC-2123 QuantumFrontiers).

EFFICIENT MIXED-INTEGER LINER PROGRAMMING DECOMPOSITION METHODS FOR QUANTUM COMPUTING

Nicola Franco [1], **Jeanette Miriam Lorenz** [1]
[1] *Fraunhofer IKS, Munich, Germany*

New developments in quantum computing technology have the potential to revolutionize the resolution of mathematical optimization problems. However, practical applications are constrained by factors such as the scarcity of qubits, noise, and errors. Our research centers around two techniques for decomposing Mixed-Integer Linear Programming (MILP) problems with the goal of reducing the size and enhancing the performance of NISQ devices. We focus on subdividing the initial problem into minor subproblems, which are then solved iteratively using a combined quantum-classical hardware approach. We provide an in-depth evaluation of the Benders and Dantzig-Wolfe decomposition methods for MILP. Our findings indicate that in the worst-case scenario, Benders' decomposition requires a significant number of qubits, while the need for qubits remains constant for Dantzig-Wolfe. Significantly, the master problem's solution in Benders decomposition greatly impacts the entire problem's feasibility. Additionally, the heuristic nature of quantum optimization algorithms, like VQE or QAOA, could potentially lead to improper cut generation in the associated subproblem, causing infeasible solutions. Conversely, a primary benefit of the Dantzig-Wolfe decomposition is its inherent correlation with the solution to the master problem. Given that this problem is solved using traditional methods, the condition of coupling constraints is constantly met, resulting in more feasible solutions. As a standard practice, the application of efficient heuristics is promoted in the context of Dantzig-Wolfe decomposition to speed up the overall search process. Our experimental results demonstrate that Dantzig-Wolfe can save up to 90% of qubits compared to Benders on quantum annealing and gate-based quantum computers.

MICRO TECHNOLOGICAL FABRICATION OF LOW OUTGASSING ATOM CHIPS FOR THE USE IN UHV ENVIRONMENT

Christoph Kuenzler [1], **Alexander Kassner** [1], **Lauritz Keinert** [1], **Sascha de Wall** [1], **Hendrik Heine** [2], **Ernst Maria Rasel** [2], **Folke Dencker** [1], **Marc Christopher Wurz** [1]
[1] *Institute of Micro Production Technology, Leibniz University Hannover, Germany,* [2] *Institute of Quantum Optics, Leibniz University Hannover, Germany*

The generation of Bose-Einstein condensates (BEC) in ground-based laboratory systems is widely shown. With the intention to use Bose-Einstein condensates for quantum sensors like accelerometers or gravimeters in aerospace systems, developing a mobile system becomes a very important task.
To achieve a mobile system, its miniaturisation and reduction of complexity is immanent. The activities are aiming to create an all in one compact system with both smaller outer dimensions and less weight. As part of the magneto-optical trap these efforts also affect the atom chip. The atom chip consisting of a multi chip layout has to combine a small and robust design with the needed conductor tracks. In order to achieve this, the conductor tracks are embedded into the chip and have to be insulated to the surrounding substrate. To provide an adequate surface for the later functionalisation there are high requirements for surface parameters. Furthermore, the connectivity to the macroscopic outer electronic parts has to be secured via a pin connection. To finalise the atom chip system a mesoscopic ceramic structure is build. The ceramics serve as a socket for the chips as well as a mount for the mesoscopic wires, which are guided in the structures. They also provide the connection to the vacuum chamber for the whole atom chip system. The connection between the individual components is realised by non-adhesive methods to achieve better vacuum compatibility.

BESPOKE FIELD ENVIRONMENTS FOR QUANTUM COMMERCIALISATION

Alister Davis [1], **Peter Hobson** [1], **Christopher Morley** [1], **Thomas Smith** [1], **Mark Fromhold** [1]
[1] *University of Nottingham, United Kingdom*

Over the last decade, quantum sensing and timing applications have increased dramatically. Moving such quantum technologies from lab-based research into commercialisation requires low Size, Weight, Power and Cost (SWaP-C) magnetic field shielding and biasing systems that reduce measurement noise and drift. We present new design methodology for active cancellation coils that can be optimised to suit user-specified SWaP-C requirements. We are able to explicitly define target regions, optimise the power and inductance of continuum coils and create simple models for discrete designs; changing the parameters and designing new shielding systems as required.
We compare coils wound on 3D printed formers with flexible Printed Circuit Boards (flex-PCBs), highlighting their respective advantages and disadvantages for performance and scalable manufacture and showcasing how our coil design methodologies can transform the performance of key quantum technology sub-systems. Our methods provide highly flexible solutions throughout the entire design and manufacturing process, generating distinctive solutions for bespoke quantum systems. This adaptability enables us to keep pace with the diverse magnetic field shaping requirements inherent in the evolving quantum commercialisation landscape.

EMPOWERING QUANTUM TECHNOLOGY ECOSYSTEM WITH TRANSVERSAL SKILLS

Shaeema Zaman [1]
[1] *Science Melting Pot, Aarhus, Denmark*

We, Science Melting Pot, would like to present our academia-startup collaborations that provide consultancy and training services to the quantum science & technology ecosystem in two areas: (a) science communication and (b) diversity & inclusion.
At this talk/poster presentation, we will present some of our current work crafted for researchers and universities in quantum science & technology, especially, focussing on the training of practical and transversal skills under the Quantum Technology Competence Framework [1]. For example, we will present the work that we have been doing in the DigiQ project [2]. Science Melting Pot is providing outreach training modules that will facilitate DigiQ students to gain science communication skills relevant to career paths in quantum technology. Students will also receive training in professional open-source digital tools to create innovative outreach material. In addition to outreach, our Equity, Diversity, and Inclusion (EDI) workshops in DigiQ aim to prepare students for future management and leadership roles in the Quantum Technology community.
About us: Science Melting Pot [3] is a startup based in Denmark that offers services in science communication and diversity & inclusion training for scientists, research organisations, universities, and industries in science & technology. Our team comprises quantum physicists, science communicators, EDI specialists, and theatre artists. We have worked previously with Danish and EU research networks as science outreach partners and collaborators.
References:
[1]: Franziska Greinert and Rainer Muller, Competence Framework for Quantum Technologies: Methodology and Version History. https://op.europa.eu/en/publication-detail/-/publication/93ecfd3c-2005-11ec-bd8e-01aa75ed71a1/language-en
[2]: DigiQ Website: https://www.digiq.eu/
[3]: Science Melting Pot Website: https://www.sciencemeltingpot.com/

ON FINDING GOOD QUANTUM-ENHANCED SOLUTION PATHS FOR OPTIMIZATION PROBLEMS

Benedikt Poggel [1], **Nils Quetschlich** [2], **Lukas Burgholzer** [3], **Robert Wille** [2, 4], **Jeanette Miriam Lorenz** [1]
[1] *Fraunhofer Institute for Cognitive Systems IKS, Munich, Germany,* [2] *Chair for Design Automation, Technical University of Munich,* [3] *Institute for Integrated Circuits, Johannes Kepler University,* [4] *Software Competence Center Hagenberg GmbH*

From an application viewpoint, quantum computing (QC) is a topic with a high barrier of entry. In a fast-moving research field, domain knowledge from physics, mathematics and computer science is required to implement quantum-assisted solutions and estimate their potential impact. For noisy intermediate-scale quantum (NISQ) devices, even the question what kind of advantage to aim for and what applications are suitable is still open.
Optimization problems, relevant for industry in many variations, are under heavy investigation with algorithms based on the variational quantum eigensolver (VQE) and the quantum approximate optimization algorithm (QAOA) in the focus. Setting up working solutions requires decisions at different levels, from the problem formulation, over encoding and decomposition, to the variational algorithm and its hyperparameters. We propose to model this process as a decision tree. Navigating it requires a modular recommendation framework providing guidance based on application-centric performance metrics. We find that the decision levels are highly interdependent and impact the solution quality in non-trivial ways. However, integrating methods and ideas into one framework is necessary to focus on the benefit for real applications and channel the efforts towards practical quantum advantage. We demonstrate the necessary steps with the highly relevant capacitated vehicle routing problem (CVRP), a multi-vehicle variant of the travelling salesperson problem (TSP) that occurs frequently in logistics. Its solution with VQE and QAOA is furthermore examined in depth. The study indicates that VQE may be better suited for the problem and once again highlights the need for the systematic comparison of decision paths.

VIRTUAL USER PLATFORM AS A LOW-THRESHOLD, TIME- AND LOCATION-INDEPENDENT QUANTUM TECHNOLOGY TRAINING FORMAT

Daniel Stuhlmacher [1], **Oliver Bodensiek** [1]
[1] *PTB, Braunschweig, Germany*

The realization of high-precision quantum technologies (QT) like the quantum clocks is a consequence of the so-called "second quantum revolution". To maintain Europe's leading role in QT, it is essential to ensure the transfer of knowledge and technology from research to industry in the field of QT. Due to the complexity of the subject, innovative education and training formats, like interactive hands-on learning, are necessary for the transfer of knowledge. With regard to QT hardware, however, there are currently no correspondingly practical and at the same time low-threshold and scalable offers.
Here we present a concept to develop a digital, interactive, and three-dimensional learning environment for education and training purposes, in which realistic virtualizations of ion-trap facilities for users, that will be available in the near future, are embedded.
The learning environment will be accessible online via a web browser and will also be made available for Virtual Reality to enable an ever more realistic learning experience. This enables potential QT users and developers to benefit from a low-threshold, time- and location-independent education and training format that can address the foreseeable problem of severely limited laboratory capacities and complement the real user platforms.

PRESENTING THE EUROPEAN COMPETENCE FRAMEWORK FOR QUANTUM TECHNOLOGIES - VERSION 2.0

Franziska Greinert [1], Rainer Müller [1], Simon Goorney [2, 3], Riccardo Laurenza [1], Jacob Sherson [2, 3], Malte Ubben [1]
[1] *Institut für Fachdidaktik der Naturwissenschaften, TU Braunschweig, Braunschweig, Germany,* [2] *Department of Management, Aarhus University,* [3] *Niels Bohr Institute, Copenhagen University, Denmark*

The European Competence Framework for Quantum Technologies (DOI 10.5281/zenodo.7827254) has been updated within the Quantum Flagship coordination project QUCATS. It provides a common language in quantum technology education and serves as a basis for standardising training. The poster shows extracts from version 2.0, published in April 2023. This updated version includes new key skills for the quantum workforce, as well as descriptions of proficiency levels that are necessary for mapping and comparing training or qualifications.

DEVELOPING EUROPEAN QUANTUM ECOSYSTEMS FOR THE EURO-QUANTUM COMMUNICATIONS INFRASTRUCTURE

Antonio Manzalini [1]
[1] *TIM, Turin, Italy*

The transformative role of Telecommunications and ICT has long been observed as a precursor of scientific progress and economic growth. Today, like never before, we are witnessing a pervasive diffusion of ultra-broadband fixed-mobile connectivity, the deployment of cloud-native 5G network and service platforms and a wide adoption of Artificial Intelligence (AI). This "Digital Transformation" is bringing far reaching techno-economic impacts on our society. Sustainability of such network scenarios will have to face several techno-economic challenges, such as the transmission and processing of enormous and increasing quantity of data with ultra-low latencies, automation of management and control processes, the fulfillment of strict requirements of resilience, security, and privacy, optimization of energy consumption, etc. Quantum technologies are expected to address some of these challenges. In fact, we are currently witnessing an impressive growth of interests for quantum technologies and services, with several investments from public and private organizations worldwide targeting the exploitation of new applications and services in the areas of quantum communications, computing, simulations, and sensing and metrology. Quantum-secure communications is the more mature area today as it relies on systems such as Quantum Key Distribution (QKD) which have a quite high Technology Readiness Level. This paper provides an overview of the vision and the preliminary achievements of the EQUO DEP project funded by European Commission. Main scope of the project is to design, develop and test production ready QKD nodes and networks based on cutting-edge technology developed in Europe, ready for integration in telecommunication networks, supporting Euro-QCI developments.

QUANTUM LEAP: EMPOWERING ENTREPRENEURSHIP AND TRAINING IN SPAIN'S QUANTUM COMMUNITY AT THE TECHNICAL UNIVERSITY OF MADRID

Jose Luis Rosales [1], Vicente Martín [1], Juan Pedro Brito [1], Laura Ortiz [1]
[1] *Universidad Politécnica de Madrid, Spain*

The MadQ (Madrid Quantum) project catalyzes entrepreneurship and training in the quantum technology domain. Led by the Community of Madrid and the National Plan for Quantum Communications, it establishes the Madrid Quantum Communication Infrastructure (MadQCI), a cutting-edge quantum communication network.Objective 1 focuses on transitioning from research to entrepreneurship, developing a comprehensive calendar and catalog of innovation and entrepreneurship courses. It includes international industrial workshops, fostering collaboration among autonomous communities, and facilitating spin-off ventures based on mature technologies. Scholarships are offered for implementing quantum key distribution (QKD) use cases. Objective 2 attracts and retains research talent by exposing researchers to real-world challenges and fostering collaborations between universities and businesses. The project integrates into the UPM2T program, providing specialized R and D training in quantum computing entrepreneurship with industry involvement. It builds a robust quantum security network within the Madrid Quantum Communication Infrastructure, recognizing exceptional contributions.The project addresses research challenges, establishing a dedicated quantum technology laboratory and implementing quantum networks in commercial, industrial, and governmental settings. It creates prototypes and deployments for networks, analyzing large-scale optical fiber behavior and conducting comprehensive tests on quantum communication systems.Collaboration with companies occurs through public tenders, allowing contributions from quantum technology and communication companies. The objective is to consolidate and stabilize the Complementary Plan for Quantum Communications while facilitating technology transfer to other sectors.The MadQ project drives entrepreneurship, empowers the quantum workforce, and positions Madrid as a hub for quantum technologies and communication infrastructure.

MONOLITHIC INTEGRATION OF SION PHOTONIC CIRCUITS WITH SI SINGLE-PHOTON DETECTORS FOR NIR-RANGE AND ROOM-TEMPERATURE OPERATION

Martino Bernard [1], Fabio Acerbi [1], Giovanni Paternoster [1], Gioele Piccoli [1], Alberto Gola [1], Georg Pucker [1], Mher Ghulinyan [1]
[1] *Center for Sensors & Devices, Fondazione Bruno Kessler*

We report on the realization and characterization of an on-chip direct coupling of reconfigurable photonic integrated circuits (PIC) to Si substrate-integrated linear photodetectors and single photon avalanche diodes (SPAD) [1]. This monolithic integration has been realized for the first time within a top-down approach by means of a 3D structuring of the bottom cladding of the PIC through an efficient, CMOS-compatible process using a single-lithography and wet-etching step [2]. A first-run 44% external quantum efficiency at 850 nm wavelength is shown for a silicon oxynitride (SiON) PIC coupled to photodetectors at room temperature. In photon-counting regime [3], using waveguides coupled to SPADs, we have measured a photon detection efficiency of 18% with dark count rates below 100 Hz at 20°C and 5V excess bias [4]. Simulations predict a margin of improvement of the coupling efficiency up to 90% both for photodetector and SPAD devices operating at NIR wavelengths upon further optimization. The developed PIC-to-detector coupling approach can be readily implemented with commonly used Silicon Nitride PICs. Our monolithic platform is the cornerstone technology of H2020 EPIQUS project, aiming to demonstrate a cheap, compact, and performant Quantum Simulator based on full integration of silicon SiON/SiN photonics with silicon electronics and operating at room temperature. References 1. M. Bernard et al., Optica 8, 1363 (2021). 2. M. Ghulinyan et al., Appl. Surf. Sci. 359, 679 (2015). 3. F. Acerbi et al., Nucl. Instrum. Methods Phys. Res. A 912, 309 (2018). 4. F. Acerbi et al., (2023, under preparation)

THURSDAY, 19 OCTOBER 2023

09:00 - 10:45 Morning Plenary: Future Challenges in Fundamental Quantum Science

Two expert keynotes, followed by a moderated panel on the frontiers of fundamental Quantum Science

Keynotes:

KEYNOTE: UNIVERSAL MATTER-WAVE PHYSICS: FROM THE FOUNDATIONS OF QUANTUM MECHANICS TO TECHNOLOGIES FOR BIO-PHYSICAL CHEMISTRY.

Markus Arndt

In 2023, we celebrate the 100th anniversary of de Broglie's idea that every piece of matter is associated with a wave. This idea inspired the Schrödinger equation, which has become basis for modern technology including quantum computing, simulation, communication, metrology or quantum sensing. A growing research community has set out to explore the quantum behavior of systems of increasing mass, size, complexity, or excitation. These efforts aim at either finding a limit or to expand the verified validity of quantum theory, at the interface to classical phenomena, chemistry, biology, materials science, gravity, or cosmology. Our universal matter-wave interferometers, built to demonstrate the quantum wave nature of matter, prove to be also highly sensitive force sensors, with applications in measurements of electric, magnetic or structural nanoparticle properties . Exploring the foundations of quantum mechanics, relies itself on advanced quantum technologies: I will also illustrate advances by the EU consortium "SuperMaMa" on how to use single-photon chemistry and superconducting nanowires technology to achieve charge control and sensitive detection of individualized proteins in the gas phase.

KEYNOTE: TESTING AND VERIFYING QUANTUM DEVICES

Barbara Kraus

I will discuss here several protocols designed for the verification and the characterization of quantum devices. They range from protocols which were designed to verify the output of a quantum cloud computer using only classical means to practical testing and verification protocols of quantum devices.

Panelists:

Reinhard Werner Prof. Reinhard Werner is notable for his contributions to the field of quantum information theory such as foundational concepts in the theory of quantum correlations including the concept of separable quantum states and mixed entangled states now known as Werner state, finitely correlated states aka matrix product states, mean field theory and entanglement area laws.

Dagmar Floeck Dr. Dagmar Floeck is a Scientific officer at the European Scientific Council Executive Agency (ERCEA) since early 2022. From 2017 until 2022 she was a Policy officer at DG CNECT where she closely followed and worked for the Quantum Technologies Flagship e.g. as project officer for the Flagships coordination and support actions. Dagmar graduated in physics from the FU Berlin, received her PhD in physics from the Goethe University Frankfurt and moved then on to a Post-doc at La Sapienza in Rome. She has now more than 12 years experience in national and European research funding activities.

Nikolay Vitanov Nikolay V. Vitanov is a professor in physics at Sofia University in Bulgaria. He graduated in 1994, with his PhD studies conducted jointly at Sofia and Aarhus University. During 1994-2003 he was a postdoc in the groups of Peter L. Knight at Imperial College, Stig Stenholm at Helsinki Institute of Physics, and Klaas Bergmann at University of Kaiserslautern. He has supervised over 20 PhD students and over 10 postdocs. He has participated in 9 projects within the framework programs of EC, most recently as a coordinator of the MicroQC project of the Quantum Flagship. His main interests, often combining theory and experiment, are in the fields of quantum control, including resonant, adiabatic and composite methods for qubits and qudits, quantum computation and quantum sensing.

Jelena Trbovic Jelena is a physicist and an expert in quantum, nanotechnology, and material science. She graduated from Florida State University in the USA and held a postdoctoral position at the University of Basel, Switzerland before joining Zurich Instruments as an Applications Manager for nanotechnology and magnetism. She has collaborated closely with top universities worldwide as a Product Manager for lock-in amplifiers and developed businesses for quantum systems control electronics in the UK and EMEA region. She is passionate about quantum technologies and helping physicists and engineers develop good measurement practice.

Moderator:

Tobias Osborne I am a leader of the Quantum Information Group, Hannover since 2010. I obtained my PhD with Michael Nielsen in 2003. I have a twenty year track record in quantum algorithm design as co-discoverer of the Quantum Metropolis Sampling algorithm. I also have extensive experience in variational methods and their experimental implementation as co-author of one of the first analog variational quantum simulation algorithms. I am also an early innovator in Quantum Machine Learning.

10:45 - 11:30 Showcase Stage Talks

Presentations and lightning talks featuring highlights from the EQTC 2023 exhibitors

- 10:50 - powerBridge, Friedrich Fix
- 11:00 - Qudora, Dr. Amado Bautista
- 11:10 - Qruise, Nicu Becherescu
- 11:20 - Qlibri, Thomas Hümmer

11:30 - 13:00 Parallel Sessions – Scientific Advances Across the Quantum Domains

Parallel Sessions – Scientific Advances Across the Quantum Domains

Parallel Track 1: Deployment of QT: Pilot lines, Test & Measurements and Standardization

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Prof. Ivo Pietro Degiovanni, INRIM, EMN-Q Coordinator Ivo Pietro Degiovanni is a Senior Researcher at Istituto Nazionale di Ricerca Metrologica (INRIM). He has developed his scientific competences in the fields of Quantum Metrology, Quantum Communication and Quantum Optics as testified by his publications (more than 90 papers, h-index 36). He is the Chairman of the EURAMET European Metrology Network for Quantum Technologies (EMN-Q), and he serves as a Member of the "Consiglio di Direzione Scientifica" of INRIM. He is an Associate Editor of EPJ D, and of the EPJ QT. He is Lecturer of the course "Quantum Communication" at University of Torino (Torino Graduate School in Physics and Astrophysics). He is the INRIM representative in the ETSI ISG-QKD. He is eligible as University Full Professor following a Italian Evaluation (2018-2020)

Dr. Oskar van Deventer, CEN-CENELEC Dr. M. Oskar van Deventer is chair of CEN-CENELEC JTC22, which has been developing European standards for quantum technologies since early 2023. He was also chair of the CEN-CENELEC Focus Group on Quantum Technologies (FGQT, 2020-2022), where a group of experts developed the European Standardization Roadmap on Quantum Technologies. Oskar is a senior scientist with TNO, the largest research institute of The Netherlands. He graduated in electrical engineering in 1987, and obtained his PhD in optical-fibre communication in 1994, both at the TU Eindhoven. He has been active contributor to a wide variety of international standards bodies (ITU, ETSI, ISO, MPEG, HbbTV, DVB, Hyperledger, W3C, . . .).

Dr. Gabriele Bulgarini, Qu-Test Gabriele Bulgarini started his journey in quantum technology with a PhD at the Delft University of Technology on the topic of semiconductor non-classical light sources in photonics nanostructures. In 2014, he joined Single Quantum where he contributed in establishing the company as the global market leader for superconducting nanowire single photon detectors in the role of General Manager. Since 2019, Gabriele is Program Manager for quantum technologies at TNO covering a broad portfolio of projects in quantum computing, communication and sensing. Gabriele is coordinator of the European project Qu-Test that brings together research institutes and industry to establish the first network of distributed testbed for quantum technologies.

Prof. Wolfgang Lechner, QuIC Wolfgang Lechner is Professor at the University of Innsbruck and co-founder/CEO at ParityQC. Wolfgang Lechner received his PhD at the University of Vienna in 2009 and after a PostDoc he joined Prof. Peter Zollers group in Innsbruck where he contributed to the fields of quantum simulation and quantum computing. In 2017 he has established his own research group dedicated to the development of quantum computing and simulation. He is best known for the introduction of the parity architecture, a quantum computing architecture for near term as well as universal digital computing on realistic quantum hardware.

Dr. John Devaney, National Physics Laboratory John is responsible for delivery of the standards-related objective of the NPL Quantum Programme. NPL is the national metrology institute for the UK, which is developing test and characterisation methods for quantum technologies such as quantum key distribution, quantum random number generation and qubit technologies, alongside fundamental quantum technology research. John chairs the UKQuantum working group on standards, is convenor of the CEN/CENELEC working group on metrology, sensors, imaging and quantum enabling technologies, and co-convenor on the IEC working group developing a roadmap for quantum technology standards. John worked for the British Standards Institution for 18 years before joining NPL. He has background in physics and photonics.

Moderator:

Dr. Nicolas Spethmann, PTB Braunschweig Nicolas Spethmann is head of the Quantentechnologie-Kompetenzzentrum (QTZ) at Physikalisch-Technische Bundesanstalt (PTB). He obtained his PhD in 2012 in the group "quantum technology with single neutral atoms" at University of Bonn. Subsequently he attained a Marie-Curie outgoing fellowship at University of California, Berkeley. Since 2019 he heads QTZ at PTB, which pursues the transfer of quantum technology from the fundamental research laboratory into application together with partners from industry and academia. From 2020 to 2023, he was vice-chair of the focus group quantum technology of CEN/CENELEC, and since 2023 Nicolas Spethmann is vice-chair of the new Joint Technical Committee 22 Quantum Technology of CEN/CENELEC.

Parallel Track 2: Quantum Computing & Simulation

TOWARDS MORE EFFICIENT TRAINING IN QUANTUM MACHINE LEARNING

Dr. Eileen Kühn, KIT (QML)

Today, quantum machine learning utilizes hybrid training methods and models. On the one hand, hybrid training benefits from established classical workflows. The classical training pipeline, based on calculating parameter gradients with respect to a given cost function can be directly applied to parameterized quantum circuits (PQCs) due to the well-known parameter-shift rule. On the other hand, hybrid quantum-classical models are used. These models extend established machine learning models by introducing PQCs into the given structure. Both methods combine differing computational technologies which creates new challenges regarding the efficiency of training. In our group, we explore the trainability of hybrid quantum machine learning by focusing on different aspects of the training workflow. These include using selected optimizers for a given part of the hybrid model. This allows to i) having separate parameters for training; and ii) addressing specific properties of the single parts. To be precise, we use gradient-free optimization focusing on quantum mechanical properties for PQCs to reduce the number of evaluations that need to be performed on a quantum computer. Furthermore we will report on our experience with hybrid model construction focusing on how quantum and classical layers can be constructed to a hybrid model and which influence this has on the handling of input data as well as performance in terms of training efficiency. In this contribution, we will present our methods and experiences with varying combinations of these for different use cases including some from high energy physics.

ENCODING-INDEPENDENT OPTIMIZATION PROBLEM FORMULATION FOR QUANTUM COMPUTING

Dr. Christian Ertler, ParityQC

We present an extension of an encoding-independent formulation of optimization problems for quantum computing [1, 2]. The abstract problem formulation allows an automatic construction of different spin glass Hamiltonians by identifying common building blocks and following a decision tree on choosing appropriate qubit and side conditions encodings. Only after specifying the encoding for the problem's variables, a spin Hamiltonian is obtained ready to be fed into algorithms such as quantum annealing or QAOA. The presented freedom in the problem formulation is key for tailoring optimal spin Hamiltonians to be solved on specific hardware platforms. Ultimately, this freedom arises from the fact that the solution to the problem is only encoded in the ground state of the Hamiltonian and the excited states are not fixed. The approach is elaborated for a wide variety of important use cases.

[1] N. PD Sawaya, A. T. Schmitz, and S. Hadfield, arXiv:2203.14432 (2022)
[2] F. Dominguez, J. Unger, M. Traube, B. Mant, C. Ertler, and W. Lechner, arXiv:2302.03711 (2023)

EUROPEAN INFRASTRUCTURE FOR RYDBERG QUANTUM COMPUTING – EURYQA

Prof. Guido Pupillo, University of Strasbourg

Neutral atoms have emerged as a highly competitive platform for digital quantum simulations and computing. In this presentation we review recent key advances in the field and present the European Quantum Flagship program to establish a "European Infrastructure for Rydberg Quantum Computing – EuRyQa".

Eileen Kühn Eileen Kühn holds a doctoral degree in computer science from Karlsruhe Institute of Technology (KIT) where she did research in machine learning on online analysis of big data streams. Since 2020 she primarily conducts research in the area of Quantum Machine Learning (QML) in general and hybrid QML models and their integrated and transparent use on different hardware architectures in specific. She leads a group that is focused on trainability of QML with a focus on High Energy Physics use cases. Since 2022 she holds a lecture on hybrid algorithms for QML at KIT. Besides living in the quantum realm, she is active in a variety of topics including High Performance Computing, Opportunisti

Christian Ertler I am theoretical physicist by training and conducted several years of research on the dynamics of open quantum systems at different university research groups in Germany, Austria and US. After that I worked for six years as a project coordinator at the German Aerospace center, managing large scale research projects in the field of energy research. Since two years I am Head of Technology Partnerships at ParityQC Germany GmbH being in charge of the scientific management of the German subsidiary of ParityQC.

Guido Pupillo Guido Pupillo is Distinguished Full Professor at the University of Strasbourg and Director of the "Centre Européen de Sciences Quantiques" in Strasbourg. His research interests are in atomic, molecular and optical physics, quantum simulations and computing. He obtained a PhD in Physics in 2005 at the University of Maryland and the National Institute of Standards and Technology. Until 2011 he was scientist at the Austrian Academy of Sciences. Since 2012 he is professor in Strasbourg, where he is involved in the development of research and teaching programs in QST. He is co-coordinator of the French public platform “aQCess – Atomic quantum computing as a service” and coordinator of the Horizon Europe program “EuRyQa – European Infrastructure for Rydberg Quantum Computing”.

Chair:

Tobias Osborne I am a leader of the Quantum Information Group, Hannover since 2010. I obtained my PhD with Michael Nielsen in 2003. I have a twenty year track record in quantum algorithm design as co-discoverer of the Quantum Metropolis Sampling algorithm. I also have extensive experience in variational methods and their experimental implementation as co-author of one of the first analog variational quantum simulation algorithms. I am also an early innovator in Quantum Machine Learning.

Parallel Track 3: Quantum Communication

A HETEROGENEOUS AND SCALABLE SDN QKD NETWORK DEPLOYED IN MADRID

Prof. Vicente Martin, Universidad Politécnica de Madrid

Current Quantum Communications Networks are largely focused in isolating the quantum channel for maximum performance. As a consequence, they are built as physically and logically separated infrastructures. While this is reasonable for early trials or cost-no-object limited settings, its supporting architecture might differ considerably from the one needed for the effective use in real world networks and applications, which are subject to a variety of constraints imposed by other requirements. Here we present a QKD network whose structure follows modern paradigms designed for flexibility that facilitates the integration in the physical and logical telecommunications network infrastructure as well as in the security one. These concepts have been tested deploying a large number of QKD systems from several manufacturers in a real-world, multi-tenant telecommunications network, installed in production facilities and sharing the infrastructure with commercial traffic.

A QUANTUM INTERFACE BETWEEN NV CENTER MATTER QUBITS AND THULIUM RARE-EARTH ION QUANTUM MEMORY COMPATIBLE LIGHT

Dr. Marie-Christine Slater, AIT

Quantum networks, connecting quantum devices over large distances, promise to enable a range of new applications ranging from secure communication to fundamentally new kinds of computation. However, the individual components of (future) quantum networks may be realized with different kinds of physical systems, requiring specialized interfaces between these systems. Here we will present our work on interfacing a diamond Nitrogen Vacancy (NV) center, well suited as a local quantum processing network node [1], with light compatible with Tm-based rare-earth ion quantum memories, well suitable for long-range quantum repeaters [2].
To this end we demonstrate two-photon quantum interference between photons emitted from an NV center with weak coherent light resonant with a Tm-based memory, probing the indistinguishability of the photons created by these disparate sources. Furthermore, we present latest results on teleporting memory-compatible time-bin qubits into the spin-state of the NV center. With this quantum interface between different physical systems, we aim to bridge the gap between two key network components, an important step towards future quantum networks.

[1] Hermans, S.L.N. et al. Nature 605 (2022)
[2] Davidson J.H. et al.

QUANTUM KEY DISTRIBUTION AND TIME AND FREQUENCY TRANSFER ON THE NIEDERSACHSEN QUANTUM LINK

Dr. Ann-Kathrin Kniggendorf, PTB Braunschweig

The extreme imbalance in signal intensity between classical and quantum communication currently limits quantum-secured communication to a select high-end userbase such as national governments, financial institutions, and the military, who can afford to allocate long-haul fibres specifically for this purpose. If quantum keys could be distributed along the long-range international fibre links that disseminate time- and frequency references between the national metrology institutes and research centres, the costs of allocating fibres would be reduced. At the same time, quantum key distribution (QKD) benefits from a well-known and tightly controlled fibre environment and an ultra-stable time signal that allows for tighter temporal binning. However, for this to work, QKD must coexist with time and frequency transfer. We present initial work to use a commercial single-photon source QKD system alongside time and frequency transfer operation via electrically stabilized amplitude-modulation (ELSTAB) or phase-coherent light on the Niedersachsen Quantum Link, a testbed of 78 km deployed fibre linking PTB in Braunschweig with Leibniz University in Hannover, Germany, including 10 km of high-loss municipal fibre.

Vicente Martin Vicente Martin is Full Professor of Computational Sciences at the Technical University of Madrid, Director of the Center of Computational Simulation. Coordinator of the Research Group on Quantum Information, the DIANA NATO Test Centre on Quantum Communications and the current Madrid Quantum Communications Infrastructure, built as a result of projects like the OpenQKD or CiViQ, from the European Quantum Flagship, where he led the quantum networking WPs. Current coordinator of the Spanish program on quantum communications. He also works in standards on QKD. Founding member of the ISG-QKD in ETSI and vicechair. Convener of the Quantum cryptography and Communications Workgroup in CEN. His main interest is the integration of Quantum Communications in Telco Networks and security infrastructures

Marie-Christine Slater Marie-Christine Slater is a Scientist at the Austrian Institute of Technology. In 2020 Slater graduated in Physics at the University of Vienna, Austria. This was followed by a Postdoc in the Lab of Prof. Ronald Hanson at QuTech, Delft University of Technology in the Netherlands. Since 2023 she has been a member of the Security & Communication Technologies Team of the AIT and is involved in several national and international research projects in the area of Quantum-Technologies.

Ann-Kathrin Kniggendorf Ann studied physics at the University of Hannover with a focus on non-linear optics and biophysics, earning her doctorate with applied resonance Raman micro-spectroscopy. She was a post-doctoral fellow at the Hannover Centre for Optical Technology, researching non-invasive environmental and biomedical applications of Raman and related spectroscopic methods. Together with her team, she received the Kaiser-Friedrich-Forschungspreis in 2020 for the online detection of microplastics in streaming tap water.

Chair:

Jochen Kronjäger From 1995 to 2001 Jochen Kronjäger studied physics at the University of Marburg (Germany). He graduated in April 2001 after completing a one-year diploma thesis on "numerical studies of viscoelelastic shear turbulence" in the Complex Systems research group. From May 2002 through June 2007, he worked towards a PhD in the Quantum Gases Group of Prof. Sengstock at the Institute for Laser Physics at the University of Hamburg. His PhD thesis, "Coherent Dynamics of Spinor Bose-Einstein Condensates", treated aspects of the physics of ultracold atomic gases. Starting October 2008 he was a postdoc in the "Cold Atoms" group of Prof. Kai Bongs at the University of Birmingham (UK). Thereafter he moved to NPL and in 2022 to PTB, to work on Frequency Dissemination with Fibres. He is currently the head of the working group on this topic in the Department Quantum Optics and Unit of Length.

Parallel Track 4: Quantum Fundamentals

ERROR CORRECTION FOR SUPERCONDUCTING QUANTUM PROCESSORS*

Prof. Andreas Wallraff, ETH Zürich

Superconducting circuits are ideally suited for studying both the foundations of quantum physics and its applications. Since complex circuits combining hundreds or thousands of elements can be designed, fabricated, and operated with ease, superconducting quantum circuits are one of the prime contenders for realizing quantum computers. For fault-tolerant operation, universal quantum computers must correct errors occurring due to limited control accuracy and unavoidable decoherence. Therefore, quantum error correction is a prime target of current research and development across academia and industry. Recently, our lab has demonstrated quantum error correction in the surface code. Using 17 physical qubits we encode quantum information in a distance-three logical qubit. In an error correction cycle of only 1.1 μs duration, we demonstrate the preservation of the logical qubit with a logical error probability of only 3% per cycle. In the process, we detect both bit- and phase-flip errors and decode using a minimum-weight perfect-matching algorithm. The demonstration of repeated, fast, and high-performance quantum error correction supports our understanding that fault-tolerant quantum computation will be practically realizable.

HARDWARE-EFFICIENT QUANTUM COMPUTING USING QUDITS

Prof. Christine Muschik, University of Waterloo

Computing today is almost exclusively based on binary information encoding. This holds true for classical computers operating with bits, as well as for the emerging area of quantum computing that uses qubits to exploit quantum superposition and entanglement for information processing. However, the quantum systems underpinning today's quantum computers offer the possibility to process information in several different energy levels so-called qudits. A key to unlocking the potential of this approach, and to realsing qudit algorithms in practice is the availability of programmable, high-fidelity qudit entangling gates. This capability is now becoming available in trapped-ion quantum processors with all-to-all connectivity. These new resources open up exciting avenues for native quantum simulation of d-evel systems with smaller registers and reduced gate depth compared to a qubit approach. We use qudit quantum circuits to perform quantum computations of problems in particle physics. These results open the door for hardware-efficient quantum simulations with qudits in near-term quantum devices.

SEMICONDUCTOR FLYING ELECTRON QUBITS AND QUANTUM METROLOGY

Dr. Masaya Kataoka, National Physical Laboratory (NPL)

The progress of charge manipulation in semiconductor-based nanoscale devices opened up a novel route to realise a flying qubit with single electrons. In this presentation, we introduce the concept of these flying electron qubits, discuss their most promising realisations and show how numerical simulations are applicable to accelerate experimental experimental development cycles, an activity developed within the EU FET-OPEN project UltraFastNano (https://ultrafastnano.eu). Recent technological advances in electron quantum optics have enabled several single-electron sources and detectors with efficiencies far beyond currently available single-photon technology. One of the promising aspects of flying qubits is the reduced footprints required for the qubits, on-the-fly error correction and ultrafast logic operations. However, the challenge remains to control the single quantum operation to a single electronic excitations level and generate non-local entangled states. As an example, we will show for the first time controlled collision experiments between two individual electrons [1-3] that enable the use of the Coulomb interaction for high-speed sensing or gate operations on flying electron qubits.

[1] Wang, J., et al. Coulomb-mediated antibunching of an electron pair surfing on sound. Nat. Nanotechnol. (2023). https://doi.org/10.1038/s41565-023-01368-5
[2] Fletcher, J.D., et al. Time-resolved Coulomb collision of single electrons. Nat. Nanotechnol. (2023). https://doi.org/10.1038/s41565-023-01369-4
[3] Ubbelohde, N., et al. Two electrons interacting at a mesoscopic beam splitter. Nat. Nanotechnol. (2023). https://doi.org/10.1038/s41565-023-01370-x

SINGLE-ELECTRON QUANTUM TECHNOLOGIES: A QUANTUM OPTICS ANALOGUE WITH STRONG NON-LINEARITY

Prof. Vyacheslavs Kashcheyevs, University of Latvia

Universality of electrical charge quantization and the fundamental nature of the Planck constant are the foundational principles of electrical quantum metrology where macroscopic quantum phenomena (quantum Hall and Josephson effects) are routinely employed in commercial high-precision measurements systems. Here we argue that more recent advances in high-fidelity manipulation of discrete electrons for metrological current sources open up a new resource for quantum technologies 2.0 [1-4] with individual electrons propagating in semiconductor circuits in direct analogy to photons. We discuss an electron quantum optics toolbox of circuit elements for on-demand emission, transformation, and readout of single electron wavepackets, emphasizing the unique advantages [3-4] of beamsplitters with the dispersion tuneable by the field

effect and the non-linearity mediated by controlled Coulomb interaction. Envisioned applications are quantum-limited sensors for picosecond scale electrical signals and eventually an all-electronic quantum information platform interfaceable with other cryogenic on-chip technologies.
Developing the full potential of single-electron quantum technologies calls for alignment and collaboration between the European metrology community and the corresponding basic science tracks of several national quantum technology initiatives.

[1] J.D.Fletcher et al., Continuous-variable tomography of solitary electrons, Nature Comm. 10, 5298 (2019).
[2] D.Reifert et al., A random-walk benchmark for single-electron circuits, Nature Comm. 12, 285 (2021).
[3] J.D.Fletcher et al., Time-resolved Coulomb collision of single electrons, Nat. Nanotechnol. (2023). DOI:10.1038/s41565-023-01369-4
[4] N.Ubbelohde et al., Two electrons interacting at a mesoscopic beam splitter, Nat. Nanotechnol. (2023). DOI: 10.1038/s41565-023-01370-x

Andreas Wallraff Andreas Wallraff is Full Professor for Solid-State Physics in the Department of Physics at ETH Zurich. His work focuses on the experimental investigation of quantum effects in superconducting electronic circuits for fundamental quantum optics experiments and for applications in quantum information processing. His group at ETH Zurich researches micro- and nano-electronics as well as hybrid quantum systems combining superconducting electronic circuits with semiconductor quantum dots, making use of fast and sensitive microwave techniques at ultra-low temperatures.

Christine Muschik Prof. Christine Muschik holds a University Research Chair at the University of Waterloo, a faculty position at the Institute for Quantum Computing, and an associate faculty position at the Perimeter Institute for Theoretical Physics. Christine Muschik received a number of awards for her work on quantum computers, including an Ontario Early Researcher Award, a CIFAR Azrieli Global Scholar Fellowship for “Research Leaders of Tomorrow”, and a Sloan Fellowship for outstanding early career researchers. Her work on quantum simulations has been featured by Scientific American and Forbes. In 2016, her pioneering results on simulating particle physics on quantum computers has been named as one of the “Top 10 breakthroughs in Physics” of this year.

Masaya Kataoka Dr Masaya Kataoka obtained his PhD degree from the Department of physics, University of Cambridge in 2000. He worked as a postdoctoral researcher at the Cavendish Laboratory and Cambridge-MIT Institute. He joined National Physical Laboratory in 2009, and currently leads the Quantum Electrical Metrology Group as the Science Area Leader. He is also a visiting professor at the University of Strathclyde. His main research interest is the development of single-electron devices towards applications in metrology and quantum technologies.

Vyacheslavs Kashcheyevs Vyacheslavs Kashcheyevs is a professor of physics at University of Latvia. He holds a Ph.D. from Tel Aviv University (2007) and leads nanoelectronics theory group at University of Latvia since 2013. Vyacheslavs Kashcheyevs is known for theory of single-electron semiconductor devices in application to fundamental electrical metrology. His current research is focused on solid-state electron quantum optics in collaboration with multiple experimental labs across Europe. Professor Kashcheyevs is a co-director of Latvian Quantum initiative.

Chair:

Rolf Haug Rolf Haug is a professor at the Leibniz University Hannover. At the Institute of Solid State Physics his research focuses on quantum effects in low-dimensional electron systems.

Parallel Track 5: Quantum Metrology & Sensing

SUPERCONDUCTING QUANTUM METROLOGY AT PTB

Dr. Mark Bieler, PTB Braunschweig

Quantum-accurate generation and quantum-limited detection of electrical signals are among the key topics in electrical quantum metrology. Such techniques gained further attention during the last decade, especially due to emerging applications in quantum technology (QT). In my talk I will briefly describe the activities at PTB with regards to such generation and detection techniques. First, this concerns the development of Josephson Arbitrary Waveform Generators (JAWS), effectively denoting a quantum-accurate digital-to-analogue converter. While JAWS circuits have been established at kHz and MHz output frequencies for a long time, the development of GHz JAWS circuits poses several challenges, yet, also offers completely new applications in metrology and QT. Second, high-fidelity readout of small electrical signals at the quantum limit requires parametric amplifiers. Such amplifiers, which do not possess resistive elements, exhibit noise, which is one order of magnitude lower than the best available semiconducting amplifiers. Some recent studies regarding travelling-wave parametric amplifiers based on three-wave mixing will be shown.

DARK MATTER AND NEW PHYSICS SEARCHES WITH QUANTUM SENSORS

Jun.-Prof. Dr. Elina Fuchs, Leibniz University Hannover

Feebly interacting, light new particles are predicted in a range of well-motivated scenarios beyond the Standard Model and can be candidates for Dark Matter. In order to make their small effects detectable, novel approaches are in demand. I will present an overview of the use of quantum sensors for particle physics questions, with a focus on the sensitivity of atomic clocks to light new bosons that can arise in extensions of the Standard Model of particle physics as candidates for dark matter or as mediators to a dark sector.

TOWARDS QUANTUM CONTROL OF AN ULTRACOHERENT MECHANICAL RESONATOR WITH A FLUXONIUM QUBIT

Himanshu Patange, Laboratoire Kastler Brossel

Superconducting quantum circuits are one of the most promising platforms for the realization of a scalable quantum computer. On the other hand, owing to recent advances in phononic engineering, chip-scale mechanical resonators with lifetimes in excess of 100s at cryogenic temperatures have been recently demonstrated [1]. A resonant coupling between these two platforms would enable a 3-orders of magnitude boost in coherence time in the quantum computing regime. Furthermore, mechanical resonators could play an important role in microwave to optical signal conversion [2]. On a more fundamental level, such a hybrid platform would be ideal to test gravitational collapse models in an unprecedented regime [3]. One of the biggest challenges to these proposals is bridging the frequency gap between these resonators that typically oscillate below 10 MHz, and superconducting qubits in the GHz domain. We plan to overcome the frequency gap by coupling the former to a cutting-edge fluxonium qubit [4]. This highly non-linear circuit is composed of a Josephson junction shunted by a large inductance in the high-impedance regime and has recently outperformed the transmon architecture, which constitutes the current quantum computing standard. In addition, we have lowered the transition frequency of the qubit to below 2 MHz, where it matches the mechanical resonance frequency of the ultracoherent mechanical membranes envisioned in this project. In this talk, I will present results obtained on phononic crystal membrane resonators and the fluxonium qubit, and the flip chip assembly which is required to couple the two systems.

Mark Bieler Mark Bieler received the diploma and Ph.D. in electrical engineering from the Technical University of Braunschweig, Germany, in 1999 and 2003, respectively. He was a Post-Doctoral Fellow with the University of Toronto from 2003 to 2004. Since 2004, he has been with the Physikalisch-Technische Bundesanstalt, Braunschweig, where he is currently the head of the Quantum Electronics Department. He has co-authored over 160 journal and conference papers and coordinated three European research projects. His scientific interests include ultrafast light-matter interaction and superconducting quantum technology.

Elina Fuchs Junior Professor at Leibniz University Hannover & PTB Braunschweig, Germany, since 2021 Senior Research Fellow at CERN and Theory Coordinator of the CERN Quantum Technology Initiative, Switzerland, 2021-2023 Feodor Lynen-Fellow/ Postdoc at Fermilab & University of Chicago, USA, 2019-2021 Minerva Fellow/ Postdoc at Weizmann Institute of Science, Israel, 2015-2019 PhD at DESY & University of Hamburg, Germany, 2012-2015 B.Sc. & M.Sc. in physics at Georg-August-University Göttingen, Germany, 2006-2012, with studies abroad at Helsinki University, Finland (2009-2010) & UC Santa Cruz, USA (2011) Awards: Heinz-Maier-Leibnitz Price 2023, Outreach Award of Göttingen University, Science Award Lower Saxony 2009, Fellowships of the Humboldt Foundation, Minerva Foundation, German National Academic Found

Himanshu Patange I am a PhD student with CNRS in Paris. My interests lie in the field of Quantum Optomechanics and Metrology & Sensing, as well as fundamental questions about Quantum mechanics. I received my Masters degree from IISER Mohali, India in 2019. My thesis focused on the theory of Quantum Metrology, which I followed up with a Masters degree (2021) from the University of Tuebingen in Germany in experimental Quantum Optomechanics. From the end of 2021, I have joined a PhD program in Paris with the Kastler Brossel Laboratory. I work on a new platform meant to couple a micromechanical membrane to a low frequency qubit. In future, I would like to continue working on hybrid systems to uncover new and exciting interplays between the principles of quantum physics.

Chair:

Naceur Gaaloul Dr. Naceur Gaaloul is the head of the "Theory of Quantum Sensing" group at the Institute of Quantum Optics. He is pushing the quantum engineering of ultracold gases to realize precision measurements for fundamental physics and inertial sensing applications since 15 years. He started supporting the QUANTUS project (DLR) which pioneered the deployment of Bose-Einstein condensates (BEC) in microgravity. Later, he delivered theory support to several space projects such as the MAIUS (DLR) sounding rocket mission putting the first BEC in space in 2017 and is active at the core team of ESA's STE-QUEST proposal for an M-mission (phase 0 and A). Presently, he is coordinating a number of national, European and international activities (NASA's ISS Cold Atom Lab) and projects aiming to strengthen the presence of quantum sensors in the space environment by unlocking their quantum advantage.

13:00 - 14:00 Showcase Stage Talks

Presentations and lightning talks featuring highlights from the EQTC 2023 exhibitors.

- 13:05 - TOPAG, Kilian Parzinger
- 13:10 - Toptica, Stephan Ritter
- 13:20 - Kiutra, Jasper Kölling
- 13:35 - Single Quantum, Benedetta Valerio
- 13:40 - NKT Photonics, Thorge Holm

14:00 - 15:30 Parallel Sessions – Scientific Advances Across the Quantum Domains

Featuring invited and contributed talks.

Parallel Track 1: Equity, Diversity and Inclusion in Quantum Technology

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DIVERSITY DIARIES: A THEATRE SHOW

Dr. Shaeema Zaman, Science Melting Pot, Dr. Nena Vandeweerdt, Science Melting Pot, Anna Carla Maria Penati, HumanLab, Aarhus, Denmark, Marco Zavarise, HumanLab, Aarhus, Denmark

Creating an inclusive environment is a multifaceted endeavour that requires collective effort and continuous commitment. Our interactive theatre session offers a crucial starting point in this direction. We will cover the general state of equity, diversity and inclusion (EDI) and explore the role of bias in the issues occurring regarding EDI. Using interactive theatre pieces, we will empower participants to recognise and remediate microaggressions and biased behaviour. This varied and interactive session encourages participants to keep thinking about the origins and challenges of EDI injustices while suggesting actionable steps towards allyship of inclusion.

Shaeema Zaman Dr. Shaeema Zaman, CEO of Science Melting Pot, is a quantum physicist and science communicator based in Denmark and India. Her research experience spans quantum physics education and outreach using games and simulations, and quantum control. Furthermore, she also co-mentored a quantum physics outreach training program in an H2020 MSCA-ITN research project, QuSCo, during her Ph.D. After her PhD, she started Science Melting Pot driven by her passion for science outreach and achieving diversity and inclusion in the scientific community. She was also one of the nominees for the Kvinder i Fysik (KIF) / Danish Women in Physics 2021 prize for her dedication to physics teaching and outreach.

Nena Vandeweerdt Nena Vandeweerdt works as a communication and inclusion specialist at Science Melting Pot. In her former role as a Ph.D. researcher in medieval gender history, she studied mechanisms that influenced women's work in past societies. She strived for the dissemination and popularisation of this topic in public presentations, actions, and publications. Her topic led straight to her current position at Science Melting Pot, where she has started to set up projects and collaborations striving for EDI in academia and the quantum technology community.

Anna Carla Maria Penati Anna Carla Maria Penati is an Italian actress, director, theatre lecturer based in Denmark where she pursued her MFA in Performing Arts (acting specialization) at The Danish National School of Performing Arts. Moreover, she pursued a two-year specialization in theatre pedagogy: Anatolij Vasiliev/Stanislavskij/Maria Knebel-ActiveAnalysis. She designs theatre-based learning workshops and research projects for higher education (fx "VIA Drama Laboratorium" project at VIA University College/Marketing Dpt and Software Eng Dpt). She is co-founder of the HumanLab theatre company (humanlab.studio) which brings shows, short films, workshops, lectures, research projects, and site-specific performances to theatres, universities, schools, art galleries, museums in Denmark, Italy, France, UK, Brazil.

Marco Zavarise He graduated as an actor from the Italian Academy of Dramatic Arts "Nico Pepe" and has since performed in numerous theater festivals across Italy, France, the UK, Denmark, and Russia. In 2017, he moved to Denmark where he teaches physical theatre, mask technique, and training methods at various educational institutions and cultural organizations throughout the country, including Aarhus University, CISPA, the Actors' Academy, VIA University, and Kongernes Jelling/National Museum.In 2019, he founded the theater company HumanLab, dedicated to producing performances, designing workshops and research projects in collaboration with institutions across Europe. HumanLab's research project, NORDICOMÆDIA, received support from the Italian Cultural Institute and the European Cultural Region.

Moderator:

Oxana Mishina PhD in physics (Russia) Experiments models at NBI (Denmark) and LKB (France) Theory for cooling and squeezing atoms at USAAR (Germany) Quantum ambassador in schools (Germany) Teaching QT to teacher-students at TUBS (Germany) QTEdu.eu portal creation and management management, QT training for European Policymakers, EDI proactive within European Quantum Flagship's coordination action (QTEdu, QFlag, QUCATS) at CNR-INO, Trieste (Italy) Trieste section of the Italian Quantum Weeks - IQW2022 - a National outreach event

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Parallel Track 2: Quantum Computing & Simulation

NEW DEVELOPMENTS IN QUANTUM ALGORITHMS AND LOWER BOUNDS

Prof. Andris Ambainis, University of Latvia

Developing new quantum algorithms is among the most central challenges in quantum computing. In this talk, we describe new developments in quantum algorithms for dynamic programming and quantum walks, as well as new results about quantum lower bounds that illuminate for what problems exponential and superexponential quantum speedups can be found.

QUANTUM-HPC INTEGRATION: CHALLENGES AND OPPORTUNITIES

Dr. Alba Cervera-Lierta, Barcelona Supercomputing Center

In this talk, I will present the BSC-CNS roadmap to integrate quantum computers into our HPC infrastructure. I will discuss what are the challenges that a supercomputing center faces when installing and operating a quantum device that is still in its early technological development, as well as what are the necessary features that quantum computing providers need to develop and include when facing such installation. I will also present what we understand as ”quantum-HPC integration” and what potential applications will require from quantum computers and standard HPC devices.

ADAPTIVE CHARACTERISATION OF A FLUX TUNABLE SUPERCONDUCTING QUBIT PROCESSOR WITH MODEL BASED REINFORCEMENT LEARNING

Anurag Saha Roy, Qurise

Despite significant progress made in the number and lifetime of superconducting qubits, gate fidelities have not experienced a proportionate improvement over the last decade. Detailed device characterisation is necessary for both obtaining the optimised gatesets on a given hardware as well as identifying device imperfections and error sources to improve the next design iteration. Textbook calibration and characterisation techniques become unsuitable and unscalable when we progress from fixed frequency few qubit prototypes to fully flux tunable multi qubit processors. One approach to solve this scaling issue is the use of Bayesian Optimal Experiment Design (BOED) which uses existing experimental data to identify the next experiments with the maximal expected information gain for the model parameters of interest to us. As shown in recent developments in policy-based design, the typical computational intractability of BOED can be overcome by using a model-based Reinforcement Learning agent in an Actor-Critic network that simultaneously learns both optimal design policies as well as lower bounds on the information gain metric. We study the application of these techniques to the characterisation of a tunable qubit - tunable coupler superconducting processor, demonstrating significant speed-up over existing methods. This additionally allows for fully parallelised system-identification by designing unique pulse sequences that simultaneously maximise the information gain for several relevant model parameters. This entire workflow is built on top of a fully differentiable digital twin that simulates the physics of not just the quantum processor but also all of the associated control electronics stack.

Andris Ambainis Andris Ambainis (Ph.D., University of California, Berkeley, 2001) is a professor of computer science at the University of Latvia. He is known for developing quantum algorithms and studying limits of quantum computation. Ambainis has developed quantum walks (quantum counterparts of random walks) into a major method for constructing new quantum algorithms, used by scientists worldwide. He invented the quantum adversary method, the most widely used method for quantum lower bounds and has constructed record-breaking examples of advantage for quantum computers. His research has been recognized by an ERC Advanced Grant and the Grand Medal of the Latvian Academy of Sciences.

Alba Cervera-Lierta Alba Cervera-Lierta is a Senior Researcher at the Barcelona Supercomputing Center. She earned her PhD in 2019 at the University of Barcelona, where she studied physics and an MSc in particle physics. After her PhD, she moved to the University of Toronto as a postdoctoral fellow at the Alán Aspuru-Guizik group. She works on near-term quantum algorithms and their applications, high-dimensional quantum computation, and artificial intelligence strategies in quantum physics. Since October 2021, she is the coordinator of the Quantum Spain project, an initiative to boost the quantum computing ecosystem that will acquire and operate a quantum computer at the BSC-CNS.

Anurag Saha Roy Anurag’s current research at Qruise is focused on the automated adaptive characterisation of quantum devices using tools in statistical machine learning and reinforcement learning. Previously he worked on the experimental control of cold atom quantum systems at the Centre for Quantum Technologies in Singapore before moving to the Forschungszentrum Juelich in Germany where he focussed on Quantum Optimal Control with Prof Frank Wilhelm-Mauch.

Chair:

Christian Ertler I am theoretical physicist by training and conducted several years of research on the dynamics of open quantum systems at different university research groups in Germany, Austria and US. After that I worked for six years as a project coordinator at the German Aerospace center, managing large scale research projects in the field of energy research. Since two years I am Head of Technology Partnerships at ParityQC Germany GmbH being in charge of the scientific management of the German subsidiary of ParityQC.

Parallel Track 3: Quantum Communication

QUANTUM CONTROL STACKS FOR QUANTUM NETWORKS

Dr. Fokko de Vries

Quantum networks will revolutionize our classical Internet by supplementing it with capabilities such as quantum secure communications, quantum sensing, secure quantum computing in the cloud, and distributed quantum computation. Current efforts by academia and industry investigate feasible frameworks that can support such applications, for example by connecting quantum nodes via a standard telecommunication line and a quantum link that is enhanced by quantum repeaters. To develop this technology further, a European testbed is being created by the Quantum Internet Alliance. However, there are great challenges at the level of technology and integration in a full network stack. Qblox offers a solution for the quantum control and operation of various types of qubits, and to connect them across Europe as part of this Alliance. We will present our solutions for building quantum control stacks for quantum networks of various distances. In particular, we focus on the quantum device control stacks which are responsible for sending control signals to the quantum hardware, as well as the synchronization and low-level communication between the nodes. We discuss our approach to tackle the technological challenges on this physical layer, as well as the challenges that come with integrating this with the other layers in a full network stack.

SILICON-INTEGRATED MULTIPLEXED SOURCE OF ENTANGLED PHOTON PAIRS WITH EMISSION RATE OVER 1 GHZ

Linda Gianini

Low-loss high-rate sources of non-classical states of light are crucial for quantum communications, most notably in quantum key distribution. Such sources would be of great relevance for high-loss channels, especially for satellite-based applications. Realizing high-rate sources on a silicon-integrated platform would allow the production of devices that are cheap, scalable and compatible with fabrication in most of the already existing foundries. We report on a source of entangled photon pairs operating in the gigahertz regime, consisting of a resonator with loaded Q-factors approx. 250k and a small FSR (80 pm) which allows us to observe generation of photon pairs via spontaneous four-wave mixing on about 400 frequency modes on each side. We also realize a broadband on-chip DEMUX to separate the signal and idler combs. We measure a generation rate of 8 GHz (2.5 GHz after the DEMUX). Entanglement is proven using frequency-bin encoding, with a two-photon interference visibility of 95%. Finally we reconstruct one of the maximally entangled Bell states via quantum state tomography with a fidelity of 98% and a purity of 96.5%. This improves the state of the art for Si-integrated sources of entangled photon pairs of over an order of magnitude.

Fokko de Vries As a roadmap leader Fokko is part of Qblox' strategic team that takes care of the product planning and management. Within this role he is responsible for business development as well as engaging with the scientific community. He specializes in the quantum network area, for example through leading the development of the Qblox quantum control stacks within the european Quantum Internet Alliance.

Linda Gianini Lind Gianni received her Master's Degree in Electronics with specialization in Photonics from the Faculty of Engineering of the University of Pavia, Italy, in 2020. In the same year, she started a Ph.D. at the Doctoral School of Microelectronics of the University of Pavia, Italy, in partnership with the Department of Optics and Photonics at CEA Leti in Grenoble, France. Her current research focuses on integrated photonics with Quantum applications.

Chair:

Vicente Martin Vicente Martin is Full Professor of Computational Sciences at the Technical University of Madrid, Director of the Center of Computational Simulation. Coordinator of the Research Group on Quantum Information, the DIANA NATO Test Centre on Quantum Communications and the current Madrid Quantum Communications Infrastructure, built as a result of projects like the OpenQKD or CiViQ, from the European Quantum Flagship, where he led the quantum networking WPs. Current coordinator of the Spanish program on quantum communications. He also works in standards on QKD. Founding member of the ISG-QKD in ETSI and vicechair. Convener of the Quantum cryptography and Communications Workgroup in CEN. His main interest is the integration of Quantum Communications in Telco Networks and security infrastructures

LEVITATION WITH FAST NONLINEAR QUANTUM CONTROL

Dr. Mario Arnolfo Ciampini, University of Vienna

Optical levitation has shown that it is possible to control the emotional state of massive solid objects to the quantum level. Recently, multiple levitation experiments have shown ground-state cooling of a dielectric nanoparticle in the mass range of 10^8 atomic mass units. Mechanical squeezing, non-gaussian states and even spatial superposition of massive objects manifest truly quantum features that can be exploited for a wide range of applications, from force sensing to investigating the quantum-gravity interface. Here, I will present a scheme to prepare and detect non-gaussian quantum states of an optically levitated particle via the interaction with a light pulse that generates cubic and inverted potentials. I will show that this approach allows operating on short times- and length scales, significantly reducing the demands on decoherence rates in such experiments. I will discuss the prospect (and the many challenges) of using this approach for coherently splitting the wavepacket of massive dielectric objects using neither projective measurements nor an internal level structure.

DISTRIBUTED QUANTUM SENSING

Prof. Augusto Smerzi, LENS

I discuss the problem of distributed quantum sensing, which is the detection of a spatially distributed field with a network of sensors. I show how entanglement among the nodes can provide decisive advantages with respect to protocols based on independent sensors. I therefore present a novel approach for the detection and characterization of multipartite entanglement and demonstrate a profound connection between the ability to statistically differentiate quantum states and the class of entangled states that can enhance the sensitivity of multi-phase interferometers.

ELECTRON-PHOTON PAIR STATES GENERATED AT A SILICON NITRIDE INTEGRATED PHOTONICS MICRORESONATOR

Dr. Armin Feist, MPI Multidisciplinary Sciences Göttingen

Integrated photonics facilitates supreme control over fundamental light-matter interactions in manifold quantum systems. Recent work could extend these capabilities to electron beams [1]. However, the coupling of single photons to electrons and their entanglement [2] remains a standing challenge.

Here, we generate electron-photon pair states via spontaneous inelastic scattering of free electrons at a high-Q photonic-chip-based microresonator [3]. Inside a transmission electron microscope, a continuous electron beam (120-keV beam energy) passes parallel to a fiber-coupled Si3N4 microresonator. The air-cladded photonic chip is fabricated using the photonic Damascene process (∼150-MHz linewidth, ∼194-GHz FSR, quasi-TM fundamental mode). The stream of single electrons interacts with the empty resonator, generating cavity photons by inelastic electron-light scattering [4], which are detected with a SPAD. Event-based electron spectroscopy, using the photon arrival for time tagging, yields time and energy-resolved correlation histograms. A strong coincidence peak appears for a loss of about 0.8 eV—the energy of the generated photons (1550-nm wavelength).

In analogy to spontaneous parametric down conversion, this mechanism enables heralded single electron or photon sources. This provides an essential step toward novel hybrid quantum technology with entangled electrons and photons, as well as the capability for quantum-enhanced electron imaging and Fock-state photon sources.

References

1. J.-W. Henke et al., Nature 600(7890), 653 (2021).
2. O. Kfir, Phys. Rev. Lett. 123(10), 103602 (2019).
3. A. Feist et al., Science 377, 777–780 (2022).
4. X. Bendaña et al., Nano Lett. 11(12), 5099 (2011).

Mario Arnolfo Ciampini Dr. Mario Arnolfo Ciampini is a postdoc at the Institute for Quantum Optics and Quantum Information – Vienna (IQOQI-Vienna) of the Austrian Academy of Sciences.

Augusto Smerzi Augusto Smerzi is Director of Research at the INO-CNR institute. He got his PhD at the University of Catania in nuclear physics and spent a post-doc at the University of Urbana-Champaign. Back to Italy he shifted his research interests to ultra-cold quantum gases and entanglement assisted phase estimation. He has been consultant and visiting staff member at the Los Alamos national laboratory, visiting professor at the University of Hannover and currently is "Mercator Fellow" of the Deutsche Forschungsgemeinschaft (DFG) and visiting professor at the University of Bordeaux. Main research contributions include the characterization of "useful entanglement" in sensing and metrology and the dynamical characterization of superfluidity in gaseous Bose-Einstein condensates.

Armin Feist Armin Feist is a research scientist at the Max Planck Institute for Multidisciplinary Sciences, where he works at the junction between solid-state physics, electron microscopy, and quantum optics. He studied Physics in Leipzig, Leeds, and Göttingen before pursuing his Ph.D. with Claus Ropers at the University of Göttingen. He received various awards, including the Optica Li Innovation Prize 2022, the 2019 EPS-QEOD Thesis Prize, and the Jan Peter Toennies Physik-Preis 2018. Currently, his research interests range from ultrafast materials dynamics to optically-enhanced electron microscopy, aiming to merge free electrons with photonic and solid-state quantum technology.

ADVANCES IN QUANTUM SENSING OF MAGNETIC FIELDS

Prof. Morgan Mitchell, ICFO

Precise measurement of magnetic fields has applications from space science to resource extraction to medical imaging to searches for dark matter. Magnetometers are also an excellent proving ground for quantum sensing methods, because practical magnetometers can be quantum noise limited and thus benefit directly from quantum tricks such as squeezing and quantum non-demolition measurement. I will first describe recent work toward high-performance, mass-manufacturable magnetometers for brain imaging. I will then describe how the optimization of such sensors requires the standard quantum limit to be reformulated, which implies also a reformulation of the idea of quantum sensitivity enhancement. I will then describe very recent experiments that apply squeezed light to high-sensitivity, optimized magnetometers, to achieve quantum sensitivity enhancement by this new formulation. The results reveal an unexpected link between squeezed light probing and quantum non-demolition measurement, and demonstrate the practical utility of quantum enhancement for a broad class of atomic and opto-mechanical sensors.

MAGNETIC MUSCLE SIGNALS MEASURED IN A MOBILE SETUP WITH OPTICALLY PUMPED MAGNETOMETERS

Dr. Thomas Middelmann, PTB

Analysis of electrical muscular activity is crucial for the diagnosis and investigation of numerous neuromuscular diseases. However, typically employed needle electromyography (nEMG) is invasive and painful, while surface EMG (sEMG) suffers from low spatial resolution due to distortions from tissue conductivity. A possible non-invasive alternative is provided by magnetomyography (MMG) with optically pumped magnetometers (OPMs). Since magnetic fields penetrate the tissue largely undistorted, a higher spatial resolution can be achieved than with sEMG. Exemplarily, we have measured the voluntary activity of the lower arm musculature during weak and strong contractions and also the electrically evoked magnetic activity of the abduction muscle of the little finger with commercial zero-field OPMs inside a four-layer table-top cylindrical magnetic shield, open on both ends. The comparison with measurements in PTB's heavily shielded room (BMSR-2) demonstrates that despite stronger disturbances from external fields, the magnetic muscle signals are measurable and behave as expected with increasing contraction or stimulation strength. From these measurements and a systematic analysis of the setup we deduce both, (1) implications for an MMG specific magnetic shielding, to access a wider variety of muscles and (2) requirements for magnetic field sensors specifically suited for MMG. In this context, we also report on our recent OPM development towards enabling high-bandwidth MMG in harsh environments such as a hospital or even on a space station. This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) under grant number 50WM2168.

RYDBERG ATOM-BASED RADIO FREQUENCY SENSING FOR COMMUNICATIONS, METROLOGY AND RADAR

Dr. James Shaffer, Quantum Valley Ides Laboratories

We will present an overview of Rydberg atom-based sensing for applications in metrology, communications and radar. Rydberg atom sensors are a new type of radio frequency sensor that promise to have a wide range of uses. Rydberg atom-based sensors have advantages like electromagnetic transparency, self-calibration, broad carrier bandwidth, and optical readout that are unique when compared to conventional antennas. Experiments on a novel approach to Rydberg atom-based sensing that uses a collinear three-photon read-out and detection scheme will be described in this presentation. The experiments show that the collinear three-photon scheme extends the sensing range of the self-calibrated, Autler-Townes sensing mode to lower electric field strengths, while simultaneously improving sensitivity. We demonstrate proof of concept and present concrete results from first experiments, where the spectral resolution is increased by ¿18 over conventional methods and the sensitivity is increased by ¿15 over other all-optical readout experiments. Approaches to engineering vapor cells for specific applications will also be described. Experiments on vapor cells that integrate amplification of the RF target signal will be presented. The vapor cell designs are centered on photonic crystal and metamaterial concepts. Vapor cell engineering is a critical element in the development of any Rydberg atom-based sensor.

Morgan Mitchell Morgan obtained his PhD from the University of California at Berkeley, and he is a ICFO Group Leader in "Atomic Quantum Optics" since 2004 and ICREA professor since 2011. He has obtained the ERC Starting Grant "Atomic Quantum Metrology" and ERC Advanced Grant "Field Sensors with Exceptional Energy Resolution." Morgan holds a leadership position of the optically-pumped magnetometer activities in Quantum Technologies Flagship project "Miniature Atomic vapor-Cell Quantum devices for Sensing and Metrology Applications" and he is a PI in the EIC Transition project "Optically-Pumped Magnetometers for Magnetoencephalography". Lastly, he co-founded Quside Technologies SL in 2017.

Thomas Middelmann Thomas Middelmann studied physics at the Technical University of Berlin (Germany), the Rijksuniversiteit Groningen (Netherlands) and the Fritz-Haber-Institute of the Max-Planck-Society, Berlin. He received the Diploma in physics in 2007 from the Technical University of Berlin and the PhD degree in physics for his work on the high-accuracy correction of the blackbody radiation shift in optical atomic strontium clocks from the Leibniz University of Hannover (Germany) in 2013. Since 2008 he has been a staff member of the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, and later Berlin (both Germany) where he has worked in the fields of quantum optics, interferometry and (bio-) magnetic measurements. Since 2019 he has been leading the “Optical Magnetometry” group at PTB in Berlin.

James Shaffer a. Professional Preparation University of Illinois-Champaign Physics B.S. The University of Rochester Optics Ph.D National Research Council, Canada Ultrafast Spectroscopy Visiting Fellow b. Appointments 2023-Present Chief Technology Officer, WaveRyde Instruments, Waterloo, Canada 2018-present Senior Technical Fellow, Quantum Valley Ideas Laboratories, Waterloo, Canada. 2001-2018 Homer L. Dodge Professor of Atomic, Molecular and Optical Physics, University of Oklahoma, Norman Oklahoma

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Chair:

Stefanie Kroker Stefanie Kroker studied Physics at Friedrich Schiller University in Jena/Germany and Universidad de Granada/Spain. She did her PhD with the Institute of applied Physics at Friedrich Schiller University in 2014 and became assistant professor at TU Braunschweig and the German national metrology institute, PTB, in 2016. In 2020 Stefanie Kroker received the Science Award Lower Saxony and in 2021 she was appointed to a full professorship at TU Braunschweig. She is a member of the German clusters of excellence QuantumFrontiers and PhoenixD.

15:30 - 16:00 Showcase Stage Talks

Presentations and lightning talks featuring highlights from the EQTC 2023 exhibitors

- 15:35 - AUREA Technolgy, Benjamin Pages
- 15:40 - ConScience, Marcus Rommel
- 15:45 - Euris Semiconductors - Formfactor, Reza Kakavandi

16:00 - 17:30 Plenary Session - Assuring a Successful European QT Ecosystem

Keynotes and moderated, interactive panel conversations on the European development of an ecosystem based on diversity, access, training & next generation talents.

KEYNOTE: EDUCATION AND TRAINING IN THE QUANTUM FLAGSHIP'S QUCATS CSA

Prof. Rainer Müller, QUCATS

We will give an overview over the education and training activities in the Qucats CSA. In particular, we will describe the Strategic Infrastructures for workforce development that were developed, the standards for workforce development (with the European Competence Framework for QT) and the career training opportunities.

KEYNOTE: QTINDU PROJECT, BUILDING QUANTUM COURSES FOR INDUSTRY

Dr. Araceli Venegas-Gomez, QTIndu

QTIndu is the answer to the increasing demand for quantum-ready professionals by offering specialized training courses at various levels. Our goal is to transform non-specialists into quantum experts, with a focus on harmonizing European training efforts and aligning with industry standards.

Speakers:

Rainer Müller Professor of Physics Education at Technische Universität Braunschweig, Germany. Member of the Quantum Flagship Communication and Support Action (Qucats CSA)

Araceli Venegas-Gomez Araceli spent several years working for Airbus in Germany and France as an aerospace engineer, before falling in love with quantum mechanics. She then decided to follow her passion for physics, and moved to Scotland to pursue a PhD in quantum simulation at the University of Strathclyde. Araceli identified the need to bridge the gap between businesses and academia, as well as to raise the quantum awareness to the general public. Continuing her work on outreach advocating quantum technologies, she was named the quantum ambassador, after winning the OPTICA Milton and Rosalind Chang Pivoting fellowship in 2019. Araceli founded her own company called QURECA (Quantum Resources and Careers) to create a link between the different stakeholders in the quantum community through a common language.

Panel: Assuring a Successful European QT Ecosystem: Diversity,Equity, Access, Next Generation Talents

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Panelists:

Barbara Tautz Barbara Tautz studied English literature, theology, philosophy, and comparative literature in Munich, London, and Caen Basse-Normandy. In her PhD she explored different philosophical concepts of humility as a response to gender and postcolonial studies. Her PhD was awarded Doctor Europaeus as the thesis brought together three European languages and cultures. Since 2019 she has been responsible for the Equal Opportunity Programs at the Munich Center for Quantum Science and Technology (www.mcqst.de). She focuses on combining leadership skills with an awareness for diversity aspects.

Elif Kiesow Cortez Dr. Elif Kiesow Cortez is the director of Quantum & AI at Ethicqual leading international projects. Elif is also a researcher for Stanford University currently working on her project focusing on a transatlantic governance framework for Quantum technologies. She has been appointed as an advisory board member for projects of leading institutions including the UNFCCC, IAPP and European Research Council. Elif has acquired research grants for projects commissioned by the German Research Association (DFG), Dutch Research Council (NWO) and the US National Science Foundation (NSF) among others. Previously, Elif was a John M. Olin Fellow in Law and Economics at Harvard Law School. Elif is an expert on behavioral strategies for designing effective policy regarding emerging technologies.

Shaeema Zaman Dr. Shaeema Zaman, CEO of Science Melting Pot, is a quantum physicist and science communicator based in Denmark and India. Her research experience spans quantum physics education and outreach using games and simulations, and quantum control. Furthermore, she also co-mentored a quantum physics outreach training program in an H2020 MSCA-ITN research project, QuSCo, during her Ph.D. After her PhD, she started Science Melting Pot driven by her passion for science outreach and achieving diversity and inclusion in the scientific community. She was also one of the nominees for the Kvinder i Fysik (KIF) / Danish Women in Physics 2021 prize for her dedication to physics teaching and outreach.

Moderator:

Jacob Sherson Jacob Sherson holds professorships of Management at Aarhus University and Physics at the Niels Bohr Institute, Copenhagen University and is Director of the Center for Hybrid Intelligence and the game-based citizen science platform ScienceAtHome with +300,000 contributors. Jacob co-leads the pan-European Quantum Technology workforce efforts, coordinates the 17mio€ EU project, DigiQ, on Pan-European Quantum Master's education and is the director of the European Quantum Readiness Center. Jacob advises public and private institutions on AI and quantum technologies, is a TedX speaker (+300k views) and won the 2020 Falling Walls in Science and Innovation Management, 2019 Bold Award on Boldest AI + Boldest Scientific Project, 2018 Grundfos Prize and 2017 Ministerial Research Communication Prize.

17:30 - 17:50 Day 3 Wrap-up

Speaker:

- Ana Filipa Carvalho, Quandela

18:00 - 18:40 Showcase Stage Talks

Presentations and lightning talks featuring highlights from the EQTC 2023 exhibitors

- 18:05 - IOP Publishing, Sara Bebbington
- 18:20 - QuantumAlliance, Tara Cubel Liebisch
- 18:30 - SquaD, Dr. Luminita Mihaila
- 18:35 - NEASQC, Pascale Bernier-Bruna

18:30 - 20:00 - Poster Session 2

CHARGE- AND SPIN- DIPOLE EXCITATIONS PRODUCED ON-DEMAND IN THE FERMI SEA

Mykhailo Moskalets [1, 4], **Pablo Burset** [2], **Benjamin Roussel** [3], **Christian Flindt** [3]
[1] Instituto de Física Interdisciplinar y Sistemas Complejos IFISC (CSIC-UIB), Palma de Mallorca, Spain, [2] Department of Theoretical Condensed Matter Physics, Condensed Matter Physics Center (IFIMAC) and Instituto Nicolás Cabrera, Universidad Autónoma de Madrid, [3] Department of Applied Physics, Aalto University, [4] Deprtmemnt of Metal and Semiconductor Physics, NTU "Kharkiv Polytechnic Institute"

The single-particle injection from the Andreev level and how such an injection can be simulated using a voltage pulse are discussed. Recently, high-speed quantum-coherent electron sources injecting one- to few-particle excitations into the Fermi sea have been experimentally realized. The main obstacle to using these excitations as flying qubits for quantum-information processing purposes is decoherence due to the long-range Coulomb interaction. An obvious way to get around this difficulty is to generate electrically neutral excitations. Here it is discussed how such excitations can be generated on-demand using the same injection principles as in existing coherent electron sources. Namely, with the help of a voltage pulse of a certain shape applied to the Fermi sea, or using a driven quantum dot with superconducting correlations. The advantage of the latter approach is the possibility of varying the electron-hole content in the excitation and the possibility of creating a charge-neutral but spin-dipole excitation.

EDGE EMITTING SEMICONDUCTOR LASER EMITTING AT 626 NM AND 619 NM FOR USAGE IN QUANTUM INFORMATION PROCESSING

Felix Mauerhoff [1], **Hans Wenzel** [1], **André Maaßdorf** [1], **Tim Schröder** [1, 2], **Katrin Paschke** [1], **Günther Tränkle** [1]
[1] Ferdinand-Braun-Institut, Berlin, Germany, [2] Humboldt-Universität zu Berlin

Extending the emission wavelength range of GaAs-based diode lasers towards orange improves the scaling possibility of quantum information processing applications significantly. Especially 626 nm and 619 nm are in high demand for investigations of qubits based on 9Be+ or color centers in diamond. Currently, this wavelength range can be accessed by different techniques. It can be either done by continuous wave nonlinear frequency conversion or by semiconductor lasers cooled down to below the dew point. All these techniques have substantial disadvantages regarding size, handling and efficiency, compared to diode lasers operating at room temperature. This contribution focuses on the development of epitaxial structures, especially on the active zone, in order to achieve room-temperature operation of diode lasers emitting at 626 nm and 619 nm. The theoretical design is based on the kp theory of strained semiconductors taking the removal of the degeneration of the X band valleys into account. The energy band structure, the vertically guided mode, and the modal gain in dependence of carrier density as well as threshold sheet densities and wavelengths are calculated. The simulation results are validated experimentally. Promising simulated designs are selected and grown on three-inch wafers by metal-organic vapor-phase epitaxy for experimental investigations. Broad area lasers are fabricated to investigate the laser performance. Simulation and experimental results are presented at the conference.

ITERATIVE SCHRÖDINGER CAT STATES GENERATION SCHEME USING A QUANTUM MEMORY CAVITY.

Hector SIMON [1], **Viviane Cotte** [1], **Rosa Tualle-Brouri** [1], **Benjamin Pointard** [1]
[1] Laboratoire Charles Fabry, Palaiseau, France

Used either as direct resource or as a step to generate more complex quantum states, "Schrödinger cat states" (SCS) have been proven to be a valuable resource for quantum computing and quantum communication.
In this work we present an experimental implementation of an iterative scheme to generate such states. We use a pulsed Ti:Sa Laser at 850nm (76MHz, 4ps), a second harmonic generation cavity and a spontaneous parametric down conversion cavity to generate single photon pairs. An avalanche photodiode (APD) detects the first photon while the second one propagates through a 60m free space optical delay line. The APD trigger signal drives a quantum memory cavity comprising a fast Pockels cell (rise time less than 10ns) and a polarizing beam splitter (PBS) allowing us to store a first single photon waiting for a second one to be generated. We entangle the stored photon and the incoming photon using a PBS and the Pockels cell to perform polarization manipulation. A homodyne detection then performs a quadrature measurement on one part of the entangled state that project the other part on a SCS, which is stored up to 184ns in the quantum memory before being characterized with the homodyne detection.
Preliminary measurements allowed us to generate SCS at a rate of 97 Hz with a fidelity of 47%. The major point of this experiment is the quantum memory cavity that increases the generation rate by storing the first photon. Furthermore the stored cat states could be used in a growing protocol.

PRECISION SPECTROSCOPY OF HIGHLY CHARGED IONS WITH SUB-HZ UNCERTAINTY

Alexander Wilzewski [1], Lukas J. Spieß [1], Malte Wehrheim [1], Shuying Chen [1], Steven A. King [1], Michael K. Rosner [2], Nils-Holger Rehbehn [2], Agnese Mariotti [3], Jan Richter [1], Elina Fuchs [1,3,7], Anna Viatkina [1,5], Andrey Surzhykov [1,5], Erik Benkler [1], Nils Huntemann [1], José R. Crespo López-Urrutia [4], Piet O. Schmidt [1,6]
[1] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, [2] Max-Planck-Institut für Kernphysik, [3] Institut für Theoretische Physik, Leibniz Universität Hannover, [4] Max-Planck-Instituts für Kernphysik, [5] Technische Universität Braunschweig, [6] Institut für Quantenoptik, Leibniz Universität Hannover, [7] Theoretical Physics Department, CERN

Highly charged ions (HCI) are promising candidates for a next generation of optical clocks with applications for frequency metrology and tests of fundamental physics. Typically, the megakelvin environment in which HCI are produced does not allow for high precision spectroscopy. In our experiment, HCI are extracted from an electron beam ion trap (EBIT) and transferred to a linear Paul trap. There, a single HCI is confined together with laser cooled beryllium ions for sympathetic cooling. After preparation of an HCI-Be+ two-ion ion crystal, we employ quantum logic techniques for further cooling as well as readout of the HCIs internal state. This enabled us to construct the first optical clock based on an HCI. By comparison to the established Yb+ clock at PTB, we measured the absolute frequency of Ar13+ with a fractional statistical uncertainty of 1x10-16 and a systematic uncertainty of 3x10-17. Recently, we applied the developed techniques to determine the isotope shift of a narrow M1 transition in five stable even isotopes of Ca14+. This can be used for the search of a hypothetical fifth force coupling neutrons and electrons and to probe fundamental physics in combination with existing data of the clock transition in Ca+. Here, we present improved constraints on such a hypothetical coupling based on the results of recent isotope shift measurements in Ca14+.

CERTIFYING LONG-RANGE QUANTUM CORRELATIONS THROUGH ROUTED BELL TESTS

Edwin Peter Lobo [1], Jef Pauwels [1], Stefano Pironio [1]
[1] Université libre de Bruxelles, Brussels, Belgium

Losses in the transmission channel, which increase with distance, are a major obstacle to photonics demonstrations of quantum nonlocality. They also pose a daunting challenge for long-distance applications that rely on nonlocality, such as device-independent quantum key distribution (DIQKD). CVP recently proposed the idea of a routed Bell experiment [arXiv:2211.14231] where, in addition to the usual distant parties Alice and Bob, a switch is placed between the source and Bob, which can relay quantum particles coming from the source either to Bob or to a closer 'test' party. In this work, we point out an important distinction between two questions: (i) whether the correlations in a routed Bell test can be traced back to quantum measurements (short-range quantum correlations) and (ii) whether those measurements are performed at distant locations (long-range quantum correlations). Through an explicit example, we illustrate that the analysis of CVP only addresses question (i), while (ii) is the relevant question for studying the efficiency requirements for nonlocality. We use the concept of joint measurability to analytically derive novel trade-off relations between short- and long-range correlations, which imply a reduction in the critical efficiency when the close parties have perfectly self-testing quantum correlations. We furthermore show how the correlations in a rooted Bell test can be characterized through NPA and apply these methods to derive new bounds on the critical efficiency for nonlocality in the absence of perfect self-testing. Finally, we discuss how these ideas can be applied to DI applications.

DETECTION OF SINGLE IONS IN A NANOPARTICLE COUPLED TO A FIBER CAVITY

Samuele Grandi [1], Chetan Deshmukh [2], Eduardo Beattie [1], Bernardo Casabone [1], Diana Serrano [3], Alban Ferrier [3], Philippe Goldner [3], David Hunger [4], Hugues de Riedmatten [1,5]
[1] ICFO, Castelldefels, Spain, [2] ICFo, [3] Chimie ParisTech, France, [4] KIT, Germany, [5] ICREA, Spain

Rare earth ion-doped crystals constitute a promising platform for quantum information processing and networking. Among the rare-earth ions, erbium offers direct operation at telecommunication wavelengths, as well as long optical and spin coherence times at low temperature and with suitable magnetic fields.
We report the first demonstration of single ion detection within a nanoparticle coupled to a fiber-microcavity. Our cavity is composed of a planar dielectric mirror, on which the nanoparticles are deposited, and a concave mirror on the tip of a single mode fiber. The cavity was assembled on a home-made nanopositioner placed inside a closed-cycle cryostat, allowing full 3D positioning of the fiber. The nanoparticles are of Y2O3and are doped with a concentration of 20 ppm of erbium ions, with a mean diameter of 110 nm.
Through fluorescence decay measurements we verified the presence of erbium ions and measured a decay constant of 88(10) µs corresponding to a Purcell factor C = 123(14). We investigated a single spectral feature with a minimum linewidth of 3.8(3) MHz. The autocorrelation function of the collected light shows a strong dip at tau = 0 which goes below the threshold value of 0.5 for single photons, proving that we have a single emitter.
In our experiments, hundreds of ions were confined to a volume 2 orders of magnitude smaller than previous realizations, strongly increasing the probability to find ions within a distance that allows strong dipolar interaction.

SPECTROSCOPY OF SINGLE PHOTON EMITTERS FOR QUANTUM TECHNOLOGY

Andreas Schell [1]
[1] *JKU Linz, Austria*

Single photon emitters play a central role in the rapidly developing field of integrated quantum technologies. While single atoms and ions are very well understood emitters, solid-state emitters are more complex. Understanding the properties of these emitters with advanced spectroscopy techniques makes them a resource for quantum sensing and information.
Here, we are reporting on our ongoing efforts to understand nano-sized solid-state quantum emitters such as defect centers in diamond and hexagonal boron nitride, quantum dots, and molecules. A variety of optical spectroscopy techniques is used to achieve this goal, such as time resolved single photon correlation spectroscopy, multi-photon and cryogenic microscopy, and multi-wavelength excitation.
In our experiments we are extending the wavelength range as well as the number of investigated emitters in order to provide reliable information on the emitter properties for their use in quantum technologies.

IMAGING AND LASER SYSTEMS FOR SURFACE-ELECTRODE ION TRAP EXPERIMENTS

Emma Vandrey [1], **Timko Dubielzig** [1], **Sebastian Halama** [1], **Christian Ospelkaus** [1]
[1] *Leibniz Universität Hannover, Germany*

Trapped ion qubits are a promising hardware platform for quantum computing. One ion species is used as logic ions or qubits and a second, different ion species can be used for sympathetic cooling, a way to control the logic ion's motion without destroying the qubit state. While it is sufficient to detect a single wavelength for qubit state readout, many different lasers are involved in state preparation, sympathetic cooling and ionization procedures. Therefore, totally achromatic imaging optics are advantageous for calibration and debugging purposes. We present such a system of imaging optics with two switchable magnifications and fast single ion detection and discrimination capabilities.
Qubit control and state preparation require stable laser light delivery systems with potentially variable frequency control. We present a double-pass acousto-optic modulator setup with a geometry that is inherently stable with respect to thermal effects due to duty cycle or rf input power fluctuations.
Both developments were implemented in the context of a cryogenic surface-electrode ion trap apparatus. We will report on the status of the project and on a new generation of segmented multi-ion trap chips to be implemented in this evironment.

ASSESSING HOW THE STRUCTURE OF THE QUBO PROBLEM AFFECTS THE EFFECTIVENESS OF QUANTUM ANNEALING

Riccardo Pellini [1], **Maurizio Ferrari Dacrema** [1, 2], **Paolo Cremonesi** [1]
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In recent years there has been significant interest in exploring the potential of Quantum Annealers (QA) as heuristic methods to solve Quadratic Unconstrained Binary Optimization (QUBO) problems. It is known that some problems are more difficult to solve effectively on a QA compared to others. However, studying this analytically is very challenging unless the problem is small and it is often not clear how to use these findings to develop new general QUBO formulations that are easier to solve on QA.
This work studies with an empirical perspective the characteristics making a QUBO problem difficult to solve on QA when it requires too many qubits for the analytical study of the Hamiltonian. We consider the Maximum Cut, Minimum Vertex Cover, Graph Coloring, Set Partitioning, Number Partitioning problems with instances requiring 30-32 QUBO variables, corresponding to 100-150 qubits.
For all instances we compute several features based on the energy distribution of their solutions and on the spectral representation of the QUBO problem as a graph. Each instance is solved with the D-Wave Advantage QA, Simulated Annealing and Tabu Search. The problem instances are clustered based on their features and the clusters validated with Silhouette Coefficient and Elbow. The analysis reveals correlations between the clusters and the ability of QA to solve the instances effectively. Furthermore, we evaluate if these findings generalize to other problems, in particular for a Feature Selection problem. These results open new research opportunities to develop better QUBO formulations that are easier to solve on QA.

MODIFICATION OF GLASS BY A LASER FOR THE USE IN MICRO-ELECTRIC SYSTEMS AND QUANTUM DEVICES

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Since the invention in 1960, the variety of applications of lasers has increased more and more. In addition to data transmission, in medicine and the entertainment industry, lasers can also be used for material processing. The Lightfab 3D Printer, which has been available to the Institute of Micro Production Technology at the University of Hannover since the beginning of 2023, makes use of this property. The machine uses a femtosecond laser for the selective modification of glass to transfer three-dimensional structures. In addition to modification, the laser can be used for welding of two glass components. A system consisting of two chips with an integrated fluid channel has already been realized in this way. In the future, hermetic packages, for example, are to be realized on the basis of the system's capabilities. The focus is not only on pure glass-based systems, but also on heterogeneous material systems made of glass and non-glass materials. Likewise, the applicability for the production and integration of quantum systems such as the atom chip or vapor cells will be evaluated. The atom chip serves as a carrier system for quantum experiments. In order to realize the integration of this chip into a miniaturized vacuum setup, hermetic welded joints between glass and silicon are investigated. Furthermore, vapor cells are used to precisely control a defined atmosphere. With their help, the gas composition and concentration in a volume can be controlled. The vapor cells are central components of optically pumped magnetometers and atomic clocks.

SIZE AND DIMENSIONALITY EFFECTS IN SUPERCONDUCTING NBN THIN FILMS

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Thin superconducting niobium nitride layers are known to be the material of choice in developing future quantum devices and at the same time, can offer a comprehensive platform for investigating longstanding debates on the role of dimensionality in superconducting samples. In this work, we have used magnetotransport measurements of nm-thick NbN films in order to probe their effective dimensions. Electrical non-local probing was carried out using a four-point configuration in the temperature range near the normal-to-superconductor transition. The temperature effect on the upper critical field Hc2 of NbN layers with thicknesses from 50 to 100 nanometers certainly pointed to three-dimensionality of the samples. Nevertheless, an application of a new criterion based on the dependence of Hc2 on the angle Theta between the normal to the film and its surface unexpectedly revealed behavior typical for 2D samples with almost isotropic Hc2(Theta) characteristics. Even a shallow dip in the Hc2(Theta) curves for 50 and 100 nm-thick samples at Theta = 30o and 60o, intermediate between out-of-plane and in-plane field orientations were well reproduced by the 2D theory. The seeming contradiction is explained by the interplay of three length scales: the film thickness, the Ginzburg-Landau coherence length, and the magnetic field penetration depth. Our results provide new insights into the two-dimensional physics of NbN superconducting films and their practical applications as elements of quantum integrated circuits.
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PRECISE QUANTUM ANGLE GENERATOR DESIGNED FOR NOISY QUANTUM DEVICES

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The Quantum Angle Generator (QAG) is a new quantum machine learning model designed to produce precise images on current NISQ devices. The QAG model uses variational quantum circuits and multiple circuit architectures are evaluated. With the addition of the MERA-upsampling architecture, the QAG model achieves exceptional results that are analyzed and evaluated in detail. To the best of our knowledge, this is the first quantum model to achieve such accurate results.
This study explores the QAG model's noise robustness through an extensive quantum noise study. The results indicate that the model when trained on a quantum device, can learn the hardware noise behavior and produce excellent outcomes. When simulated quantum hardware noise is included, the model's results remain stable until approximately 1.5% of noise during inference and almost 3% in training. However, running the noise-less trained model on real quantum hardware leads to a decrease in accuracy. If the model is trained on hardware, it can learn the underlying noise behavior, where the same precision is achieved by the noisy simulator. Additionally, the training showed that the model can recover even with significant hardware calibration changes during training with up to 8
This work demonstrates the QAG model's ability to learn hardware noise behavior and deliver accurate results in the presence of realistic noise levels. The QAG model aims at simulated calorimeter shower images, being at the core of particle physics to determine particle energies and to discover new physics at CERN's Large Hadron Collider.

QUANTUM ANNEALING-ASSISTED BIPARTITE COMMUNITY DETECTION FOR RECOMMENDER SYSTEMS

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Detecting communities within networks is an important task with practical implications across various disciplines and can be part of a more complex machine learning pipeline. Among the available methods, one well-established approach is modularity maximization, which has been demonstrated to be NP-complete to solve exactly. While classical optimizers can yield near-optimal candidate solutions for small-scale networks, their efficacy may diminish when confronted with larger instances, which may become insufficient for the given task. The recent emergence of cloud-based Quantum Annealers as accessible services holds promise for addressing this challenge by providing solutions that closely approach optimality and offer improved scalability. This study aims to understand the effectiveness of currently available Quantum Annealers within the context of Recommendation Systems. Recommender systems are a widely used technology whose purpose is to help the user explore the large catalogues available in today's web services. The goal is to assess whether Quantum Annealers can be used to solve a community detection problem as part of a recommendation system pipeline. The evaluation task is to provide movie recommendations based on the movies popularity, differentiating them according to the community the user belongs to. The user communities are identified through an optimization problem formulated as a Quadratic Unconstrained Binary Optimization (QUBO) and solved using both the D-Wave Advantage quantum annealer and the D-Wave Leap Hybrid solvers. The findings show a substantial improvement in the quality of recommendations through community detection, indicating that Quantum Annealers can be used effectively for this task.

OPTIMIZING HYPERPARAMETERS USING THE GEOMETRIC DIFFERENCE

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Quantum kernel methods (QKM) are a promising method in Quantum machine learning (QML) thanks to the guarantees connected to them. Their accessibility for analytic considerations also opens up the possibility of prescreening datasets based on their potential for a quantum advantage. To do so, earlier works developed the geometric difference, which can be understood as a closeness measure between two kernel-based ML approaches, most importantly between a quantum kernel and classical kernel. This metric links the quantum and classical model complexities. Therefore, it raises the question of whether the geometric difference, based on its relation to model complexity, can be a useful tool in evaluations other than the potential for quantum advantage.
In this work, we investigate the effects of hyperparameter choice on the generalization gap between classical and quantum kernels. The importance of hyperparameter optimization is well known also for classical ML. Especially for the quantum Hamiltonian evolution feature map, the scaling of the input data has been shown to be crucial. Still, there are additional parameters left to be optimized, like the order of the features or the selection of the best number of qubits to trace out (subsystem size), before computing a fidelity or distance kernel. For choosing those parameters, we compare the classically reliable method of cross validation with the method of choosing based on the geometric difference. These findings lead to better understanding of the applicability of the geometric difference.

ROBUSTNESS OF QUANTUM ALGORITHMS AGAINST APPROXIMATE DATA REPRESENTATIONS

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Quantum algorithms face practical difficulties and overheads in execution on realistic devices, potentially thwarting their theoretical advantages. A key practical challenge is efficiently encoding classical data, since data embedding layers, often exponential in the number of qubits, can consume a significant portion of the circuit depth. One possible strategy to address this is to compress the standard data embeddings using variational circuits. The approximate amplitude encoding (AAE) algorithm successfully applies this approach to financial calculations and image pattern matching, achieving only polynomially deep embedding layers. Tensor network methods have also been explored for efficient quantum state preparation. While prior works focus on optimizing the approximate embedding in isolation, the ultimate goal is the compound algorithm's performance.
This study systematically examines the impact of embedding compression on the fidelity of the subsequent quantum algorithm in a noiseless setting, specifically investigating amplitude encoding and its dependence on input dataset size and complexity. Trainability of the different variational ansätze, their output state fidelity, and the degree of the embedding layer depth compression are investigated. Performance benchmarks of standard quantum algorithms, e.g. Grover search, amplitude estimation, and quantum Fourier transform (QFT), are conducted based on the degree of compression and quality of the compressed input state. Results show that the amplitude encoding circuit can be compressed by up to 50% in depth, for generic data and a small number of qubits, with only marginal loss in state fidelity. Certain algorithms, most notably the QFT, demonstrate robustness to such approximations.

FIELD EMISSION CURRENT-VOLTAGE CHARACTERISTICS OF FIELD EMITTERS FABRICATED BY WAFER DICING.

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Electron sources in the form of arrays of silicon microstructures are typically fabricated by photolithography followed by reactive ion etching or laser micromachining. In 2016 we proposed a new fabrication method for silicon field emitters by dicing technique in a two-step process. Thanks to the brittleness of silicon, not only one emitter but numerous secondary tips are fabricated during the process. We have optimized the process by using a trapezium-dicing blade, enabling the fabrication of high-density Field Emitter Arrays (FEAs) of 57x57 (3249) emitters in a one-step process.
This research aims to characterize the field emission properties of diced emitters depending on the variation of the fabrication parameters, the number of emitters, and the doping of the substrate. The current-voltage characteristics were conducted in a test set-up comprising a metal electrode about 100 µm away from the FEA. All tests were conducted in an ultra-high vacuum chamber. Each sample was tested for about 8 hours. The voltage was applied to the metal electrode throughout the experiments, whereas the silicon FEA was at 0 V potential.
The dicing parameters, such as grooving speed, depth, and so-called overlapping of the grooves, influence the height and geometry of the emitters. By variating the cutting speed, a sharpening effect was observed. Emission currents can be measured at lower voltages at bigger FEAs (57x57, 9.9 ± 4.5 µA at 1.75 kV) compared to the smaller ones (41x41, 2.4 ± 1.3 µA at 2.35 kV). The n-doped silicon FEAs show higher emission currents but with higher deviation.

ON THE QUANTUM-CLASSICAL SOLVERS: HYBRID OR IMBRICATED?

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Hybrid quantum-classical schemes are sometimes wrongly conceived as mechanisms to materialize unfeasible pure-quantum algorithms by introducing classical methods as wrappers and controllers of quantum procedures, habitually in charge of orchestrating the whole solving workflow and/or providing decomposers for large problems not affordable by current QPUs. Quality and capacity of quantum hardware in this NISQ era has promoted an indissoluble partnership when facing real-world oriented problems. Nonetheless, the classical and quantum methods must prove own contributions in terms of non-trivial intelligence to be properly named hybrid. This specification makes perfect sense since classical and quantum computing will be playing collaborative, not competitive, roles in the mid-term horizon. As a step further, both would need to fuse their intelligence to be called as an imbricated solver. On this basis, adding a parallel thread launching a classical algorithm to assure near-optimum solutions or supplying intelligent, yet self-sufficient, classical tools to decompose large problems fall short in meeting this last condition. Indeed, they are doomed to disappear when intermediate becomes fault-tolerant large-scale quantum hardware. In turn, imbricated solvers will remain as far as scientists coming from classical and quantum AI learn to share the playing field by reaching consensus in fact-based contributions. This work will: (1) review most prominent efforts in the broad definition of hybrid methods while distinguishing between classical-assisted quantum workflows and legitimate and cooperative hybrid schemes; and (2) envision potential synergies in an imaginary future when mastering the industrial market will be decided on applicability and usability metrics.

ADVANCED QUANTUM COMPUTING AND QUANTUM ERROR CORRECTION WITH A SCALABLE, DISTRIBUTED QUANTUM CONTROL STACK

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Scaling up the number of qubits is a necessary step towards reaching quantum advantage. This makes the quantum control stack of critical importance, as this is the central hub between the user and the qubits, between nodes in a quantum network and between quantum computers and classical supercomputers. As the current generation of quantum computers is limited by errors, quantum error correction will be essential to achieve fault tolerance. A critical part of this process is the decoder, which uses syndrome measurement outcomes to output a correction. However, the decoder has to run extremely fast to minimize additional decoherence in the qubits during the decoding. Hence, for qubits with 100s microseconds of decoherence time (e.g. superconducting qubits) it needs to compute and communicate within 100s nanoseconds. As the number of qubits increases, multiple control and readout units are needed to control the qubits, making low-latency communication key to realize real-time decoding. Traditional quantum control stacks rely on a single-chip architecture, leading to control-flow bottlenecks. Instead, we present a highly distributed architecture that leads to a scalable approach where our dedicated LINQ protocol allows for sharing information across the stack within a few 100s nanoseconds. Furthermore, we develop a decoding module that can run state-of-the-art decoding algorithms. We identify the most promising developments in the field of real-time decoding algorithms that can run within a few 100s nanoseconds. These algorithms together with our fast communication protocol constitute a crucial step towards bringing fault tolerance and quantum advantage close to experimental reality.

TENSOR-NETWORK ASSISTED QUANTUM ALGORITHMS FOR QUANTUM SIMULATIONS

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Quantum simulations stand out as a particularly promising application of quantum computers. The noisy intermediate-scale quantum (NISQ) devices pave the way for the development of fault-tolerant quantum computers. However, the presence of noise and decoherence in current noisy quantum devices necessitates the use of hybrid quantum algorithms based on low-depth circuits to achieve promising results. In this context, the initialization of quantum algorithms with a suitable initial ansatz becomes crucial. Tensor network methods, well-established techniques for classical simulations of quantum many-body systems, offer a valuable approach to enhance state preparation in quantum algorithms. In this presentation, we demonstrate how tensor network methods can improve the performance of a specific quantum algorithm. By using these methods to prepare an optimized ansatz and feeding it into the algorithm, we show significant enhancements in the results obtained.

REAL-TIME HYBRID QUANTUM-CLASSICAL COMPUTATIONS FOR TRAPPED IONS WITH PYTHON CONTROL-FLOW

Tobias Schmale [1], **Bence Temesi** [1], **Niko Trittschanke** [1], **Nicolas Pulido-Mateo** [1, 3], **Ilya Elenskiy** [2], **Ludwig Krinner** [1, 3], **Timko Dubielzig** [1], **Christian Ospelkaus** [1, 3], **Hendrik Weimer** [1, 4], **Daniel Borcherding** [1]
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In recent years, the number of hybrid algorithms that combine quantum and classical computations has been continuously increasing. These two approaches to computing can mutually enhance each others' performances thus bringing the promise of more advanced algorithms that can outmatch their pure counterparts. In order to accommodate this new class of codes, a proper environment has to be created, which enables the interplay between the quantum and classical hardware.
For many of these hybrid processes the coherence time of the quantum computer arises as a natural time constraint, making it crucial to minimize the classical overhead. For ion-trap quantum computers however, this is a much less limiting factor than with superconducting technologies, since the relevant timescale is on the order of seconds instead of microseconds.
In fact, we show that the operating time-scales of trapped-ion quantum computers are compatible with the execution speed of the Python programming language, enabling us to develop an interpreted scheme for real-time control of quantum computations. This keeps the implementation of hybrid algorithms simple and also lets users benefit from the rich environment of existing Python libraries.
In order to show that this approach of interpreted quantum-classical computations (IQCC) is feasible, we bring real-world examples and evaluate both the interpreted and compiled schemes in realistic benchmarks.

REDUCTION OF FINITE SAMPLING NOISE IN QUANTUM NEURAL NETWORKS

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Quantum machine learning leverages the power of quantum computers to enhance traditional machine learning models. On strongly investigated model in this field are Quantum neural networks (QNNs) which utilize parameterized quantum circuits with data-dependent inputs and generate outputs through the evaluation of expectation values. Calculating these expectation values necessitates repeated circuit evaluations, thus introducing fundamental finite-sampling noise even on error-free quantum computers. We show how to reduce this noise by introducing the variance regularization, a technique for reducing the variance of the expectation value during the quantum model training. This technique requires no additional circuit evaluations if the QNN is properly constructed. Our empirical findings demonstrate the reduced variance speeds up the training and lowers the output noise as well as decreases the number of measurements in the gradient circuit evaluation. This regularization method is benchmarked on the regression of multiple functions. We show that in our examples, it lowers the variance by an order of magnitude on average and leads to a significantly reduced noise level of the QNN. We finally demonstrate QNN training on a real quantum device and evaluate the impact of error mitigation. Here, the optimization is practical only due to the reduced number shots in the gradient evaluation resulting from the reduced variance.
The talk will present the main results of recent preprint: Kreplin, David, and Marco Roth. "Reduction of finite sampling noise in quantum neural networks." arXiv preprint arXiv:2306.01639 (2023).

QUANTUM COMPUTING FOR MULTIOBJECTIVE OPTIMIZATION PROBLEM: A FIRST APPROACH

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Multiobjective optimization is a rapidly evolving research field that addresses complex real-world problems that have multiple, often conflicting, objectives that have to be optimized simultaneously. Unlike traditional optimization, multiobjective optimization problems usually have not one but several optimal solutions, so-called Pareto-optimal solutions representing trade-offs between different objectives. However, finding these solutions is computationally intensive, exacerbated by the potential vast number of Pareto-optimal solutions. This characteristic makes multiobjective optimization problems ideal candidates for quantum computing. In this talk, we present a pioneering approach to solving multiobjective problems using quantum computing.
Our focus lies in applying known quantum algorithms for single-objective optimization, such as variational algorithms (VQE, QAOA) and Grover adaptive search. We enhance and adapt these algorithms with classical optimization tools, like branching, bounding, or cutting, and known results about the structure of multiobjective problems to tackle multiobjective optimization problems. Initially, we address scalarized and parametrized problems, such as the weighted sum problem, and subsequently extend our methods to more general multiobjective problems. To demonstrate both functioning and effectiveness of our approach, we employ the biobjective variant of the classical Markowitz portfolio optimization problem as our benchmark problem.
By leveraging the inherent parallelism and superposition properties of quantum computing, our research marks a significant step forward in utilizing quantum computing for multiobjective optimization problems, trying to overcome the limitations faced by classical computing approaches. Thus, our research opens up new avenues for solving complex real-world challenges.

THE NEASQC BENCHMARK SUITE: BENCHMARKING QUANTUM COMPUTERS ACROSS NEXT APPLICATIONS OF QUANTUM COMPUTING

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The NEASQC Benchmark Suite (TNBS) aims to evaluate the performance and accuracy of Quantum Computing (QC) platforms. The suite is built around the benchmark case concept, each targeting a kernel of QC and requiring the definition of a test case that involves the execution of the kernel.
The kernel is a task that needs to be usually done in QC, such as the state preparation, the Quantum Amplitude Estimation (QAE), or the loading of a probability distribution in a quantum circuit. The test case is a small application in which, the execution of the kernel plays a central role. The output of the test case must be verifiable using classical means.
The definition of each benchmark case is done mathematically and/or procedurally. This approach aims to avoid linking each case to a given existing solution, this could bias the kernel definition to favor a certain kind of platform against others. For instance, there are many possible implementations of the QAE kernel and some of them could be more suitable for a certain kind of QC platforms.
The definition of each case also involves an standarized process of execution, and a procedure to measure the computational performance and the accuracy of the output.
Although the definition of each kernel is done mathematically we provide a reference implementation in myQLM, although each manufacturer can generate its own implementation. So far, we have proposed and formalized three benchmark cases: probability loading, Quantum Amplitude Estimation, and Quantum Phase Estimation.

MULTIOBJECTIVE VARIATIONAL QUANTUM OPTIMIZATION FOR CONSTRAINED PROBLEMS

Pablo Díez-Valle [1], **Jorge Luis-Hita** [2], **Senaida Hernández-Hita** [2], **Fernando Martínez-García** [1], **Álvaro Díez-Fernández** [2], **Eva Andrés** [2], **Juan José García-Ripoll** [1], **Escolástico Sánchez-Martínez** [2], **Diego Porras** [1]
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Combinatorial optimization problems (CO) have a strong impact on a wide range of disciplines such as finance, machine learning, logistics, etc. In addition to finding a solution with minimum cost, problems of high relevance involve a number of constraints that the solution must satisfy. Variational quantum algorithms (VQA) have emerged as promising candidates for solving these problems in the noisy intermediate-scale quantum stage. However, the constraints are often complex enough to make their efficient mapping to quantum hardware difficult or even infeasible. Our work introduces the Multi-Objective Variational Constrained Optimizer (MOVCO), a new method for improving VQA solving of problems with difficult constraints. [1]. MOVCO combines the quantum variational framework with a genetic multi-objective optimization to simultaneously optimize the projection of the variational wave function onto the subspace of solutions satisfying all constraints, and the energy of the feasible solutions. This procedure allows the algorithm to progressively sample states within the in-constraints space while optimizing the energy of these states. We test our proposal on a real-world problem with great relevance in finance and compare the performance of MOVCO versus a penalty-based optimization. Our empirical results show a significant improvement in terms of the cost of the achieved solutions, but especially in the avoidance of local minima that do not satisfy any of the mandatory constraints.
References: [1] Pablo Díez-Valle et al., arxiv preprint 2302:04196 (2023).

HIGH ACCURACY TIME SYNCHRONIZATION FOR QUANTUM NETWORKING. WHITE RABBIT / IEEE 1588 (PTP) HIGH ACCURACY PROFILE

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White Rabbit (WR) is a synchronization technology developed as an open-source project born in 2009 involving multiple international public scientific institutions, i.e., CERN, GSI, University of Granada and private companies as Seven Solutions (currently part of SED).
The main characteristic of the WR technology is that it ensures sub-nanosecond time synchronization accuracy using conventional optical fiber network technology and frequency distribution with picosecond-level precision. WR has integrated Low Jitter circuitry more recently.
The typical WR link has a master/slave model where the time information from the master is distributed to slave nodes. WR is distributed using standard 1 Gigabit (G) Ethernet links. It can be deployed using regular DWDM/CWDM or SyncE compliant fiber infrastructure and shows no timing degradation when combining data packets with WR packets in the link. This technology has been widely adopted in many scientific applications (High Energy Physics, radio telescopes, metrology) and industry segments (fintech, telecom, industrial control) over the past decade in which ultra-accurate timing is key. Now, it is starting to be used with Quantum Networks. In this new field, every quantum node in the network is spatially distributed, forcing independent receivers to evaluate network performance and perform quantum communications. High accuracy distributed timing synchronization presents a critical technical challenge as it needs to coexist with quantum channels. For photon coincidence counting, all time-to-digital converters in the network must be synchronized to extend quantum networking from experiments to more extensive deployments.

DYNAMICAL SIMULATION OF QUANTUM REPEATER SATELLITE CONSTELLATIONS

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Quantum repeaters and satellite-based free-space optical links are complementary technological approaches slated to overcome the exponential photon loss occurring in optical fibers and thus allow quantum communication at global scales. Here, we analyze scenarios where these approaches are combined: satellites are used as quantum repeater nodes and are employed to distribute entangled photon pairs to far-away optical ground stations. The satellites have to mount optical communication terminals in order to allow the exchange of photonic states over free space, as well as quantum memories and optical Bell-state measurement setups to perform entanglement swapping. Here we report on the development of a full end-to-end simulator of quantum repeater satellite constellations, including detailed orbit dynamics, optical link quality evaluation, calculations of the downstream entanglement generation rate, latency and fidelity. Using only three satellites enables the distribution of entangled states at intercontinental distances; the small number of links in the repeater chain allows us to forgo entanglement purification altogether, resulting in a favorable entanglement swapping rate and state fidelity. We perform numerical simulations of time-varying satellite positions and compare the results to analytical estimates of the entanglement distribution rate based on the average values of the link parameters. The goal is to maximize performance through optimization of the orbits and other system parameters.

ACCURATE METROLOGY TO EVALUATE THE SECURITY OF QKD MODULES

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Quantum key distribution (QKD) systems create shared secret encryption keys between two distant parties by generating, transmitting and detecting quantum signals at the single-/few-photon level, together with supporting classical communication. Protocols based on time-bin and relative phase between consecutive optical pulses have been implemented and are commercially available. The security of a QKD system relies on the hardware correctly implementing the protocol, or the protocol being modified to account for non-idealities in the implementation hardware.
The physical parameters of the QKD system are therefore critical to evaluating its security and its resilience against attacks. Examples for the transmitted states are the mean photon numbers of signal and decoy states (which are important for countering the photon-number-splitting attack), the correct phase relationship between pulses, the correct coding of pulses into time bins. Examples for the receiver (detector) are parameters of the single-photon detectors – such as detection efficiency, dead-time and after-pulse probability.
Methods and instrumentation have been developed to measure the physical security parameters for discrete-variable QKD modules operating at GHz pulse rates over optical fibre; these require high-speed, low-jitter measurements at the single-photon level. We will describe the methods and instrumentation used to deliver measurements traceable to SI units with a quantified uncertainty, focussing on the parameters stated above.
This work was funded by H2020 Projects OPENQKD (Grant 857156) and EMPIR 19NRM06 'MeTISQ', and the UK EPSRC Quantum Communication Hub (EP/T001011/1).

QUANTUM-SECURED COMMUNICATION SYSTEMS FOR ALL: MERQURY CYBERSECURITY AND A CASE STUDY FROM MALTA.

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Quantum safe communication is at the top of the agenda for most countries and companies that handle sensitive data, driven by the increase in computational power together with the availability and progress in quantum computing. Asymmetric cryptography, which is the backbone of today's Internet, is known to be only computationally secure. Advancements in high-performance and quantum computing threaten the security of the data protected through asymmetric cryptography. Without the security guarantees offered by asymmetric cryptography, the Internet will be incapable of handling sensitive transactions, such as bank transfers, in a safe and secure manner. Merqury, together with its partners, was set up to help with the provision of quantum-safe solutions. As the technical lead for the PRISM (Maltese EuroQCI) project, we at Merqury are developing and deploying a QKD-based network comprising 20 nodes with an easy-to-use, vendor-agnostic, source-available configuration and management suite; something that the current ecosystem is lacking but severely needs. As part of our efforts towards the goal of bringing quantum safe solutions to everyone we have released two products: a test suite and reference implementation of the ETSI GS QKD 014 standard. The test suite ensures that a QKD device is compatible with the standard while stress tests ensure that the device continues to work reliably even under heavy loads. The reference implementation is a pedagogical resource aimed at lowering the barrier to entry. Both products are developed in Rust to ensure memory safety and unrivalled performance.

CONTINUOUS-VARIABLE QUANTUM KEY DISTRIBUTION AT 10 GHZ USING AN INTEGRATED PHOTONIC-ELECTRONIC RECEIVER

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Quantum key distribution (QKD) is a cornerstone of quantum information which guarantees information-theoretically secure key exchange. However, commercial viability of QKD systems is currently impeded by issues such as scalability, network integration, and high manufacturing costs. Low-cost, high-volume production of photonic and electronic integrated circuits could be the breakthrough needed for broad-scale deployment of cutting-edge QKD systems.
Here, we present a continuous-variable (CV) QKD system that is based on an integrated photonic-electronic receiver. It combines a silicon photonic integrated circuit, featuring a phase-diverse receiver, with custom-designed GaAs pHEMT transimpedance amplifiers. Operating at a classical telecom symbol rate of 10 GBaud, our QKD system generates high secret key rates - exceeding 0.7 Gb per second over 5 km distance and 0.3 Gb per second over 10 km. The secret keys are secure against collective attacks, even when accounting for finite-size effects. Apart from the high-bandwidth and the high electronic noise clearance achieved through our receiver integrated circuits the results were made possible by well-designed digital signal processing (DSP) that supports high-speed operation. Utilizing DSP is at the foundation of the new paradigm of digital CV-QKD which aims at operating with the simplest possible photonic-electronic circuits by leveraging complex but flexible DSP algorithms in the digital domain.
Our experiment sets a new record for secure key-exchange and paves the way for the evolution of next generation CV-QKD systems.

PHOTONIC INTEGRATED QUANTUM COMMUNICATION RECEIVERS WITH SUPERCONDUCTING NANOWIRE DETECTORS.

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Efficient single photon detectors are of paramount importance for quantum technology as they provide crucial measurement capabilities for quantum communication, sensing and information processing. The high detection efficiency, low dark count rates, high operation speeds and accurate timing performance of superconducting nanowire single photon detectors (SNSPDs) are especially beneficial for quantum cryptography, where they enable long range communication and high key generation rates. Embedding SNSPDs into photonic integrated circuits further allows for compact next generation quantum network devices that combine several active and passive functionalities with photon counting on a large number of parallel quantum communication channels.
Here we show how large numbers of SNSPDs can be integrated with nanophotonic waveguides, all of which can simultaneously be optically and electrically addressed for independent parallel operation. We leverage the possibilities for providing photonic integrated SNSPDs with additional nanophotonic functionalities, such as switching capabilities via low-voltage optomechanical phase shifting, on silicon chips and maintain greater than 80% detection efficiency and sub-15 ps jitter performance. Similarly, we configure serial multi-element SNSPDs for achieving photon number resolution in photonic integrated beam splitter networks with up to 16 channels, which could provide receivers for quantum key distribution with resilience to quantum hacking attacks. All such devices can be equipped with efficient optical fiber-chip interconnects produced in 3D direct laser writing that allow for taking advantage of the attractive broad-bandwidth waveguide-integrated SNSPD features and photonic integrated circuit functionalities in fiber-optic networks. We exploit these capabilities for demonstrating Mbit/s rate quantum key generation with a multi-channel receiver unit.

MEGA-SCALE QUANTUM DETECTOR TOMOGRAPHY USING HIGH-PERFORMANCE COMPUTING

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As quantum states become larger, it becomes necessary to develop more advanced tools to handle them, as well as refine the techniques used to characterize these tools. Recent advancements in the field have focused on large-scale arrays of single-photon detectors, aimed at over a million pixels. Furthermore, for photonic quantum computing, logical qubits require hundreds of millions of detectors. These devices are able to cover a very large Hilbert space. Recent research has successfully demonstrated detectors capable of detecting single photons up to millions of photons, covering a wide dynamic range and therefore also a very large Hilbert space. However, accurately characterizing these devices quantum mechanically presents considerable challenges. In this study, we show an approach that utilizes high-performance computing on a supercomputer to reconstruct the positive-operator-valued measure (POVM) of a high-dynamic range detector, covering a Hilbert space of 1.2·106. The number of variables that need to be determined is in the order of 108. These methods hold potential for application in other fields that involve reconstructing quantum systems of similar mega-scale proportions.

DYNAMICAL DECOUPLING TECHNIQUES FOR LONG-LIVED SINGLE-PHOTON LEVEL STORAGE IN PR-BASED QUANTUM MEMORIES

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The realization of quantum networks is a long-standing goal of the field of quantum communications with envisioned applications ranging from secure communications to distributed quantum computing, simulation and sensing. However, at long distance, losses ultimately limit the achievable rate of distribution of entanglement between nodes. This limitation can be overcome in a quantum repeater architecture where entanglement is heralded from entanglement sources then stored in quantum memories (QM). In this work we report on recent progress on long-lived single-photon-level storage in Pr3+:YSO rare-earth doped crystal solid-state quantum memories using the atomic frequency comb (AFC) protocol. This storage method combines multimodality with the possibility of long-lived on-demand storage in the hyperfine ground state spin levels thanks to dynamical decoupling techniques. Using such a scheme, we store weak pulses of light tailored to match the temporal waveforms of single photons produced by cavity-enhanced SPDC sources for up to 300 us, the longest storage time demonstrated so far at the few photon level in a multimode Pr3+:YSO QM. The achieved low noise levels represents a promising advance towards storage of genuine single photons, confirming the suitability of Pr-based solid-state quantum memories for metropolitan-scale quantum repeater links.

RECENT ADVANCES IN FREE-SPACE AND FIBER QUANTUM KEY DISTRIBUTION

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Free-space links will be an integral part of future global quantum communication networks.
Here we present the recent development at the University of Padova in the modeling and experimental realization of free-space and fiber quantum key distribution (QKD) system based on the efficient-BB84 protocol with active decoy states.
In the past years we realized daylight QKD at 1550 nm enabled by integrated silicon photonics [npj Quantum Information 7, 93 (2021)], we proposed new schemes (iPognac, patented) for the realization a stable, low-error, and calibration-free polarization modulation scheme at 1550nm [Optics Letters 45, 4706 (2020)] and its extension to 800nm [EPJ Quantum Technology (in press). Preprint at [arXiv:2301.12882]], for both intensity and polarization encoding. The iPognac was also used to generate time-bin state by exploiting a polarization-to-time-bin converter [Adv. Quantum Tech 2200051 (2022)] The QKD source was also tested in complete QKD system in lab [Optica 7, 284 (2020)], in deployed-fiber enviroment [Optics Letters 46, 2848 (2021)] and with the copropagation of classical signal [Jour. of Lightwave Technology 40, 1658 (2022)].

SATELLITE-BASED QUANTUM COMMUNICATION AND EXTENDED PHYSICAL THEORY TESTS IN SPACE

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We present a compact, fully space-qualified, room temperature single photon source based on a color center in the 2D material hexagonal boron nitride (hBN) for future long-distance satellite-based quantum networks. The performance of this quantum light source is sufficient to outperform conventional laser-based decoy quantum key distribution (QKD) protocols. The emitter is directly coupled with a photonic integrated circuit that routes the single photons to different experiments. This includes the verification of the single photon source by measuring the photon statistics as well as performing a fundamental test of quantum gravity. The payload is currently being integrated on a 3U CubeSat and launched in 2024 as part of the QUICK3 mission. In addition, we also show results of our daylight QKD experiments, where our hBN emitter is coupled to a micro-photonic resonator. The output spectrum of this photon source can be fine-tuned to one of the Fraunhofer lines in the solar spectrum. If a narrow bandpass filter is applied in a QKD receiver, the background light from the sun can be fully suppressed and quantum information can be exchanged during ambient daylight conditions. For space-to-ground quantum links this means that every satellite pass can be used and not only those during the night. This has great potential for highspeed and high availability quantum networks in the near future.

A PORTABLE WARM VAPOUR QUANTUM MEMORY

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Warm vapor quantum memories have seen significant progress in recent years. Their low complexity makes them a promising candidate for operation in non-lab environments including space-based applications. As a necessary element of quantum repeaters, memories operating in space could advance global quantum communication networks [1].
We will present the implementation and performance of a portable rack-mounted system. The optical memory is based on long-lived hyperfine ground states of Cesium which are connected to an excited state via the D1 line at 895 nm in a lambda-configuration [2]. Cesium atoms are confined in a temperature-controlled vapor cell enclosed within a three-layer magnetic shielding. Three separate lasers are frequency stabilized via FPGA-based tools [3] to provide pump, signal and control pulses.
We observe memory efficiencies of greater than 40% for storage times of greater than 500 ns. By using attenuated coherent pulses, we observe storage and retrieval fidelities that surpass the classical threshold even after considering the Poissonian statistics and the finite memory efficiency [4]. Our results suggest that storing non-classical states with these parameters would be possible. Possibilities of micro-integration of this platform are also being investigated.
This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number 50RP2090.
[1] M. Gündoğan et. al., npj Quantum Information 7, 128 (2021)
[2] L. Esguerra et al., Phys. Rev. A 107, 042607 (2023)
[3] B. Wiegand et al., Review of Scientific Instruments 93, 063001 (2022)
[4] M. Jutisz et. al., in preparation (2023)

TOWARDS FUNCTIONAL QUANTUM REPEATER LINKS USING RARE-EARTH DOPED CRYSTALS

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Future quantum networks will rely on the distribution of entanglement between distant material quantum nodes (Duan, et al., 2001). Several physical systems have been entangled already (Chou, et al., 2007, Yu, et al., 2020, Hensen, et al., 2015, Lago-Rivera, et. al., 2021) but none of these demonstrations satisfied all the requirements for a network operation, such as: heralded operation compatible with the telecom network, high heralding rate, resilience against losses, multiplexed operation, on-demand read-out of the stored entanglement, encoding in a functional basis, etc.
Here, we show the status and progress of our efforts towards realizing functional entanglement between solid-state multimode quantum memories based on praseodymium doped crystals, heralded by single photons at telecommunication wavelengths.
Our quantum memories, show a large capacity for multiplexing in several degrees of freedom (Seri, et al., 2019) and spin/optical coherences that have allowed long storage times (Heinze, et al., 2021). As an entanglement source, we use highly non-degenerate (telecom compatible) SPDC where the non-linear crystal (ppLN) is embedded in a cavity, to match the produced photon pairs linewidth with the absorption of our memories.
Entanglement can be propagated through two nodes via entanglement swapping between the two SPDC generated states in the Fock basis where half of the state is stored in the quantum memory. Our next step will be to demonstrate on-demand read-out of the stored entanglement resulting from this swapping. A more functional two-photon encoding can be achieved with a second parallel link.

LONG-DISTANCE MULTIPLEXED QUANTUM TELEPORTATION FROM A TELECOM PHOTON TO A SOLID-STATE QUBIT

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Transferring quantum information between remote parties is a basic and still challenging requirement in the field of quantum communication. Quantum teleportation is the main protocol for quantum information transfer, based upon a shared entangled state between the transmitter and the receiver. Here we demonstrate the teleportation of a photonic time-bin qubit in the telecom wavelength to a solid-state quantum memory, over 1 km of optical fibre, featuring active feedforward. Our setup is divided into two portions. At Alice's side, there is a source of energy-time entangled photon pairs, based on cavity-enhanced spontaneous parametric down conversion. One photon of the pair is stored in a praseodymium-doped crystal as a collective excitation. The second photon is at telecommunication wavelength, and it is sent to Bob over a long communication link. Bob is able to generate time-bin qubits also at telecom wavelength. A Bell state measurement is then performed on this qubit and on the entangled telecom photon. Depending on the result of the Bell state measurement, a unitary transformation is applied to the photon stored at Alice's after it has been retrieved, therefore completing the teleportation protocol.
We prepared and teleported a full set of qubits in the time-bin basis. We measured an average fidelity of the teleported qubit of 86(4)%, for a storage time of 17 μs in the memory and a distance of 1 km between Alice and Bob, which is significantly above the classical limit.

TESTING THE INTEGRATION OF A CONTINUOUS VARIABLE QUANTUM KEY DISTRIBUTION SYSTEM

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Quantum Key Distribution (QKD) with the One-Time Pad symmetric encryption scheme promises a way for two parties to create a shared secret key, that is only known to them and with the help of quantum mechanics they can even detect when a malicious party tries to eavesdrop during the key sharing process. Many QKD protocols require special equipment, like Single Photon Detectors (SPDs) that need extra cold environments to work properly. In contrast, Continuous-Variable QKD (CV-QKD) uses only optical devices that are found in any modern optical network. This can facilitate their deployment, but an important consideration is how well they can be integrated into an existing optical network.
At the Budapest University of Technology and Economics, we developed a Continuous-Variable QKD (CV-QKD) system. The system uses coherent states and homodyne detection. Post processing is performed with LDPC codes. Recently, were carried out two field tests using a real optical line. The two links were part of a Hungarian telecommunication operator's network, and their length was 1 km and 20 km. The results show that CV-QKD is an attractive candidate for future integration.

SQUEEZING RECOVERY BY PHASE COMPENSATION IN FREE-RUNNING DETECTION OF SQUEEZED LIGHT

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Squeezed state of light plays a crucial role in quantum optics with a wide range of applications to quantum computing, quantum communication and quantum sensing. However, practical utilisation of squeezed light often requires phase locking of the local oscillator (LO) to the squeezed quadrature. These complex locking schemes pose challenges, limiting the widespread implementation of squeezed light in real-world scenarios. Furthermore, the distribution of squeezed light over long distances which is crucial for applications like quantum communication and quantum sensing, makes optical phase lock loops much more difficult. Alternatively, many quantum information tasks use heterodyne detection providing information on conjugate quadratures enabling compensation for squeezed light's phase drift over the propagation distance. Here, we report a phase compensation scheme which allows us to recover the squeezed and anti-squeezed quadratures after heterodyne detection without optical phase locking. We utilised a 90o optical hybrid to measure the squeezed light and devised a digital signal processing procedure for phase compensation. Our proof-of-concept experiment shows the post-processing procedure can give us 0.8 dB of squeezing in comparison with 1 dB of squeezing achieved by an optical phase lock loop. Our method can simplify how we measure squeezed light and thus pave the way for the wider applications of squeezed light beyond the confines of the laboratory.

CRYOGENIC DEGENERATE SPONTANEOUS PARAMETRIC DOWN-CONVERSION

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While integrated spontaneous parametric down-conversion (SPDC) is a well-established method for quantum light generation, it is typically operated at room temperature. This limits the integration with components such as superconducting detectors which are incompatible with room temperature operation, since all integrated devices must be functional under the same conditions. To address this, we demonstrate cryogenic compatibility and customization for SPDC, which paves the way for combined integration with highly efficient superconducting detectors, the golden standard for single-photon detection. Our SPDC source does not only present good cryogenic source performance, but we can also design the spectral properties to obtain degenerate photon pairs in the telecom C-band.
We show signal and idler photons centered at (1559.33 ± 0.05) nm from type-II SPDC in a periodically poled titanium in-diffused lithium niobate waveguide. The waveguide is characterized at 6.4 K in a free-space coupled cryostat. Thorough investigation of the shift in the phase-matching during temperature change allows us to develop an empirical model, defining the room temperature poling period required for a desired cryogenic wavelength interaction. With this, our experimental cryogenic phase-matched wavelengths are within 1.5 nm of our design. We characterize the joint spectral intensity and further verify degeneracy by performing a Hong-Ou-Mandel interference measurement which gives us a visibility of (66.3 ± 0.5) %. Furthermore, we obtain high source brightness of (6.0 ± 0.3) x 105 pairs/smW and a low heralded second-order correlation function of 0.017 ± 0.002, which verifies cryogenic single-photon generation. Our results demonstrate a valuable understanding of the cryogenic nonlinear interaction.

RADIOMETRIC APPLICATION OF A SINGLE-PHOTON SOURCE BASED ON A GERMANIUM-VACANCY CENTER IN DIAMOND

Justus Christinck [1, 6], Franziska Hirt [1, 6], Helmuth Hofer [1], Zhe Liu [2, 6], Markus Etzkorn [2, 6], Toni Dunatov [3], Milko Jaksic [4], Jacopo Forneris [5, 7, 8], Stefan Kück [1, 6]
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We present the metrological characterization of a single-photon source based on a germanium-vacancy (GeV-) center in diamond under a solid immersion lens in a confocal microscope setup at room temperature. Solid immersion lenses have been fabricated into the diamond surface by the focused ion beam (FIB) technique. The single-photon source was then investigated in terms of the emission's spectral distribution, single-photon purity, temporal stability and the emitter's excited state lifetime and saturation behavior. A simultaneous count rate of 580 x 103 counts per second and a g(2)(tau=0) = 0.12 ± 0.06 were found. The saturation count rate was (854 ± 8) x 103 counts per second. The relative overlapping Allan deviation of the temporal stability measurement was calculated. From the minimum of the deviation, the integration time for a calibration measurement of the relative detection efficiency of two single-photon avalanche diode (SPAD) detectors was determined. This calibration was performed for a spectral width of 2.88 nm around the zero-phonon line of the GeV-center emission with a g(2)(tau=0) = 0.02+0.09-0.02. The result of the calibration using the single-photon source was compared to the result received from the conventional method using attenuated laser light for the calibration of SPAD detectors.

MONOLITHIC INTEGRATION OF EXTENDED CAVITY DIODE LASERS AT 778 NM AND 1064 NM

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Photonic integrated systems for applications such as atom interferometry, gravitational wave detection, satellite-based navigation, coherent free space communication and optical quantum sensing require a light source with ultra-low frequency noise. The deployment of such systems in challenging environments outside of laboratories imposes additional requirements such as compact dimensions, mechanical robustness and high electro-optical conversion efficiency. Narrow-linewidth semiconductor lasers are ideally suited to meet these demands. A commonly used approach to reduce the linewidth of semiconductor lasers is to extend the optical cavity by a low loss propagation section. So far, this extended cavity diode laser (ECDL) concept has been realized by hybrid micro-integration of external optical components such as lenses, mirrors and grating structures. In this work, we demonstrate the monolithic integration of the ECDL concept on a single chip. This is accomplished by a two-step epitaxy to combine an active waveguide featuring quantum wells for photon generation and a low-loss passive waveguide in the gallium arsenide (GaAs) material system. The monolithically integrated extended cavity diode laser has several advantages such as low manufacturing cost due to wafer scale production, high mechanical stability of a more compact cavity and on-chip wavelength tuning with a timescale of milliseconds. We demonstrate the performance of two devices at 778 nm and 1064 nm and discuss challenges in the manufacturing process of a low loss passive waveguide based on AlGaAs (778 nm) and GaAs (1064 nm) optical confinement layers, including an outlook on further optimization potential of the devices.

ADVANCING MICROSTRUCTURED MIRRORS FOR NEXT-GENERATION ULTRASTABLE LASERS

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In this talk, we showcase the theoretical and experimental outcomes of our research on low-noise microstructured mirrors made from silicon on silica, designed specifically for employment in ultrastable lasers. Our focus lies on the practical implementation of a hybrid etalon featuring a combination of microstructured and conventional mirrors. We delve into various aspects including the measurement of reflectivity using cavity ringdown spectroscopy, the calculation of noise contributions, and the evaluation of scattered light measurements on the mirror. By presenting these findings, we aim to contribute to the advancement of ultrastable laser applications and pave the way for future developments in the field.

ON-CHIP INTEGRATED PHOTONICS FOR HIGH-PERFORMANCE QUANTUMCOMPUTING, ATOMIC CLOCKS AND QUANTUM SENSING APPLICATIONS

Steffen Sauer [1, 4], Anastasiia Sorokina [1, 4], Pascal Gehrmann [1, 4], Carl-Frederik Grimpe [2], Guochun Du [2], Elena Jordan [2], Dennis Schlippert [3], Tanja Mehlstäubler [2, 3, 5], Stefanie Kroker [1, 2, 4]
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Integrated optics in chips in the field of quantum technology (QT) open up completely new application possibilities. They push the limits of the complexity of quantum systems while maintaining the reliability and robustness of the experiments. They also reduce the cost, ecological footprint and power consumption compared to experiments with bulk optics.
Our focus is to develop photonics in chips and chip traps in the field of quantum sensing with ions & neutral atoms [1, 2] and trapped-ion quantum computers (QC) [3, 4]. Through the advantages of integrated photonics, in the future QC's can be produced in a scalable and cost-effective way, or optical clocks and atom interferometers can be developed for robust and compact quantum sensors for space missions. We are revolutionising these quantum technologies with our optics that enable fundamentally new approaches.
In this contribution we provide an overview on integrated photonic components for QT such as coupling laser light from the fiber into the chip, light routing inside the chip, decouplers for linear and circular polarized light to address the atoms. Our goal is to cover the wavelength range from 370 to 1650 nm for integrated optics. Therefore, we simulate and characterise integrated optics such as waveguides, splitters, mode converters and grating outcouplers as well as the chips.

[1] Isichenko et al., Nat. Com. 14, 3080 (2023)
[2] Ropp et al. Light: Science & Applications 12, 83 (2023)
[3] Niffenegger et al., Nat. 586, 538 (2020)
[4] Mehta et al., Nat. 586, 533 (2020)

QUANTUM TECHNOLOGIES FOR OPTICAL COHERENCE TOMOGRAPHY

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Optical coherence tomography (OCT) presents an indispensable, non-contact, high resolution 3D imaging technique. Its main application, retinal imaging, has helped to save the sight of millions of people worldwide. However, classical OCT seems to have reached its practical axial resolution limit at 1 μm and further improvement is heavily impacted by dispersion. The SEQUOIA project develops sensing combining quantum OCT (QOCT) with artificial intelligence. A quantum benefit is expected by using entangled photon pairs instead of classical light, which allows for immunity against even-order dispersion and further promises a factor of two improvement in axial resolution. These photon pairs are produced by spontaneous parametric down-conversion. Controlling and entangling the photon pairs in additional quantum degrees of freedom such as orbital angular momentum may foster the robustness against noise and thus improve edge and surface profile recognition. Finally, machine learning techniques are applied for further noise reduction. Overall, this promises to demonstrate an OCT system with the highest resolution yet.
Here, we will present an overview of the project giving insights into the ongoing research and development of quantum technologies for OCT. We will further show first results regarding the noise characterization and stabilization of the supercontinuum source used in this project. It currently spans from 700 nm to 1400 nm and is analyzed with respect to its application in QOCT and, more generally, as ultra-stable, broadband phase-coherent frequency comb.

MICRO-INTEGRATED DIODE LASER MODULES FOR OPERATION IN QUANTUM TECHNOLOGY APPLICATIONS

Christoph Tyborski [1], Martin Gärtner [1], Stephanie Gerken [1], Sriram Hariharan [1], Nora Goossen-Schmidt [1], Janpeter Hirsch [1], Simon Kubitza [1], Norbert Müller [1], Mathis Müller [1], Max Schiemangk [1], Andreas Wicht [1]
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The Ferdinand-Braun-Institute has been developing micro-integrated, high-power, narrow-linewidth semiconductor laser sources for precision spectroscopy applications for more than ten years. As the next step, we now develop, qualify, and deliver whole laser modules for applications on ground and on space-borne platforms (e.g. small satellites). Here, we will present the latest generation of our micro-integrated diode laser modules and give an outlook on other photonic modules we are currently developing.
We present ECDL-MOPA modules, where the laser architecture consists of an extended cavity diode laser (ECDL) and a semiconductor optical amplifier, both hybrid-integrated into a package with a footprint of a conventional smartphone. The single-mode, polarization-maintaining optical output delivers a few hundred milliwatts (wavelength dependent) with low frequency noise.
In the near future the modules will be upgraded with a hermetically sealed housing, which will facilitate or enable the deployment in applications in the field and in space. In addition, specially developed control algorithms shall ensure enhanced functionality and user-friendliness of our laser modules. This includes a sophisticated spectroscopy setup for the frequency selective element of the ECDL, which will enable the generation of an error signal to extend the laser's mode-hop free tuning range beyond the limit given by the free spectral range.
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SENSING BEYOND THE SHOT-NOISE LIMIT WITH SQUEEZE LASERS

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Photon shot noise poses limitations on high-precision laser-based measurements. Squeeze Lasers can circumvent the need for even higher powers and the associated side effects.
Conventional methods in high-precision measurements rely on increasing optical power to enhance the signal-to-noise ratio limited by photon shot noise. However, this approach has inherent side effects. Exposing biological samples to high powers results in their destruction or photo-bleaching. Delicate mechanical devices experience adverse heating effects. Operating outside the realm of eye-safe laser powers necessitates the implementation of laser-safety measures, entailing additional costs and efforts. At high laser power levels, the challenge persists, as further power increase can induce thermal effects like thermal lensing and lead to misalignment of the measurement device.
Squeeze lasers do not increase the signal power but reduce the photon shot noise – with almost zero additional optical power. After several decades of research, a noise reduction by a factor of more than 10 [Phys. Rev. Lett. 117, 110801 (2016)] [Opt. Lett. 43, 110-113 (2018)] is feasible if most of the light is detected. Use cases can be found, for example, in [Nature 594, 201-206 (2021)], [Phys. Rev. Lett. 123, 231107 (2019)] and [Quantum Sci. Technol. 8, 01LT01 (2023)]. Compact, portable and user-friendly systems are now available at Noisy Labs GmbH.

QUANTUM GHOST IMAGING OF TRANSPARENT PHASE PATTERNS WITH HYPER-ENTANGLED PHOTONS

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Quantum ghost imaging method for light-absorbing objects is based on the nonlocal correlations of quantum entangled photons. Where an image is constructed by correlating a measurement of a single photon, after its interaction with the object with a measurement of a quantum entangled photon on the camera, which has never interacted with the object. However, this conventional method does not work for transparent phase objects, which exhibit a phase shift in the transmitted light without absorbing it. We have introduced quantum ghost imaging of polarization-dependent phase patterns, which exhibit a phase shift of transmitted photons depending upon their polarization state. Since the pattern is invisible to these photons therefore, in contrast to conventional ghost imaging methods this new method requires hyper-entanglement of photons. We performed experiments to produce a quantum ghost image of a few millimetres size polarization sensitive phase pattern from a distance of 19.16 meters in free space. Photons are quantum entangled in two different degrees of freedom, which are initially uncoupled and resulting in a hyper-entangled state consisting of Einstein Podolsky Rosen (EPR) entanglement and polarization entanglement. A quantum ghost image is formed by correlating the joint measurements of momentum-polarization of the interacting photon and position-polarization of the non-interacting photon. In this experiment, position-polarization information of a photon interacting with the pattern is not available.

QUANTUM COMPUTING FOR GENERATIVE ART & DESIGN

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Here we present techniques and examples of generative art and design based on quantum algorithms and tools. After a brief history of existing work, we show the applications that can be realized using Quantum Blur, quantum random numbers and other quantum algorithms. More specifically, we describe some generative quantum experiments around tools included in Blender, Rhino 3D, and numerous examples with Qiskit, IBM's Python module. Some examples are explained, including generative artwork, video game environments and 3D object designs. Finally, the use of Quantum Machine Learning algorithms, and Quantum GAN in particular, is discussed.

THE QUMIC PROJECT - TOWARDS A SCALABLE ION TRAP WITH INTEGRATED HIGH-FREQUENCY CONTROL

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Ion traps are a promising candidate for a scalable quantum computer [1]. A major challenge is the integration of qubit control into the device. With the microwave near-field approach [2], qubit control realized by microwave conductors that are integrated into the ion trap naturally scale with the trap itself. However, the microwave signal generation currently takes place outside of the vacuum chamber in which the ion trap is located. The QuMIC project researches and develops novel highly integrated BiCMOS chips at high frequencies and their hybrid integration with quantum electronics like ion traps. This approach enables the scalability of a quantum computer to a large number of qubits and a drastic reduction in the number of required high-frequency lines, which also benefits the cooling capabilities of the cryostat used to cool down the ion trap to around 4K. We describe the setup of a cryogenic ion trap apparatus with the associated laser systems for 9Be+. The goal is to build a testing stand for rapid trap testing, such as the ion traps with integrated microwave sources developed for QuMIC. We will report on the current status of the project.
[1] Chiaverini et al., Quantum Inf Comput 5, 419-439 (2005)
[2] Ospelkaus et al., Phys. Rev. Lett. 101, 090502 (2008)

CALCULATING AN ERROR BUDGET FOR AN ION-TRAP BASED QUANTUM PROCESSOR

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Fault tolerance is an important milestone in quantum computing. A promising candidate platform for achieving this goal are trapped ions, which can enable long coherence times and low error-rates per computational gate [1]. Our group has been able to drive high-fidelity entangling gates making use of near field magnetic gradients [2][3]. We investigate ways of lowering two-qubit entangling gate infidelities below the 10-4 threshold by constructing error models and using them in simulations of open quantum systems.
[1] C. R. CLark et al., Phys. Rev. Lett. 127, 130505 (2021)
[2] M. Duwe et al., Quant. Sci. and Techn. 7.4, 045005 (2022)
[3] G. Zarantonello et al., Phys. Rev. Lett. 123 260503 (2019)

PERFORMANCE EVALUATION OF NOVEL ACCELEROMETERS FOR FUTURE GRAVIMETRY MISSIONS

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Dedicated satellite gravimetry missions from the beginning of the 21-st century have provided unique data on mass redistribution processes in the Earth system, e.g., melting of the Antarctic and Greenland ice sheets, sea level changes, droughts, etc. Ongoing climate change underlines the need to continue this kind of measurements with enhanced concepts and sensors. For example, the Mass Change mission is planned to be launched within the next decade in a DLR-NASA partnership.
Drifts of the electrostatic accelerometers (EA) at low frequencies (less than 1mHz) are one of the limiting factors in current space gravimetry missions. The focus of this study is on the assessment of enhanced ACCs for future gravimetry missions. For example, an improved EA with laser-interferometric readout, a so called 'optical accelerometer' was modelled. Its performance at Low Earth Orbit has been evaluated. Contrary to present-day EAs, which measure capacitively the test mass (TM) displacement and actuate it electrostatically, optical ACC, beside a similar actuation scheme, track the TM with laser interferometry.
Here, we introduce general workflow of simulations including the propagation of the satellite dynamics and the modeling of optical ACCs including major noise sources. Also, parametrization of the developed ACC model will be discussed including the effect of different TM weights and TM-electrode housing gaps. Finally, improved results of the recovered gravity field will be shown for various mission scenarios applying optical accelerometry and gradiometry. They are compared to the present-day EAs and quantum sensors performance.
This project is funded by: Deutsche Forschungsgemeinschaft(DFG)–Project-ID 434617780-SFB 1464.

EXTENSIVE STUDY OF MAGNETO-OPTICAL AND OPTICAL PROPERTIES OF CD1-XMNXTE BETWEEN 675 NM AND 1025 NM

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We determine Faraday rotations and measure the optical reflection and transmission from magneto-optical Cd1-xMnxTe crystals with Mn contents ranging from x=0.14 to x=0.50. For wavelengths between 675nm and 1025nm we derive Verdet constants, optical loss coefficients, and the complex indices of reflection that are relevant measures to find suitable stoichiometric ratios of Cd1-xMnxTe for the realization of miniaturized optical isolators. Depending on the stoichiometric ratio we find Verdet constants of several -100Deg/Tmm close to the absorption edge and optical loss coefficients of 0.2 1/mm and less that are assumed to be dominated by scattering on Te inclusions rather than by an intrinsic absorption. By reflection and transmission measurements we determine the stoichiometric ratios of several different Cd1-xMnxTe crystals and discuss the observed dependence of the optical properties on the stoichiometric ratio with respect to their use in optical isolators. We find differences of the respective Mn contents of more than one percentage point for nominal identical stoichiometric ratios and relate the observed behaviour to the growth process of Cd1-xMnxTe. In the end we show the relevant figure of merit, i.e. the ratio of Verdet constants V(lamda) and optical loss coefficients alpha(lambda) for Cd1-xMnxTe crystals and calculate wavelength-dependent optical losses when Cd1-xMnxTe is used in a miniaturized optical isolator based on the Faraday effect.
This work was supported by VDI Technologiezentrum GmbH / Federal Ministry of Education and Research (grant numbers: 13N14906 and 13N15724) and by DLR Space Administration / Federal Ministry for Economic Affairs and Climate Action (grant umber: 50WM2261B).

HIGH PERFORMANCE VIBRATIONAL NOISE MITIGATION FOR ATOM INTERFEROMETRY WITH AN ACCELEROMETER INTEGRATED REFERENCE MIRROR

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Quantum inertial sensors based on atom interferometry possess the potential for high precision and reliable measurements of inertial effects for real world applications in high noise environments. Vibrational noise is the most prominent noise source that hinders its measurement sensitivity apart from introducing ambiguities. We have successfully demonstrated using a compact opto-mechanical resonator on a T = 10 ms atom interferometer [1] which resolves measurement ambiguity and measures the local gravitational acceleration with an uncertainty of 4 × 10-6 ms-2 after an integration time of 18000 seconds. We have taken the next step of fully integrating an accelerometer which comprises a harmonic mechanical oscillator and a Fabry–Perot interferometer with the inertial reference mirror of the atom interferometer aiming for higher accuracy hybridization. The optical interferometer is used to directly measure the test mass displacement of the mechanical oscillator which is also the inertial reference mirror for the atom interferometer. This therefore enables both the atom and optical interferometers to measure acceleration with respect to the same inertial reference. High reflective optical coating for the optical interferometer will enhance its measurement sensitivity which will enable hybridization with highly sensitive atom interferometers with longer interrogation times.
Funded by the DFG EXC2123 QuantumFrontiers - 390837967 supported by the DLR with funds provided by BMWK under Grant No. DLR 50NA2106 (QGyro+) and TerraQ.
Reference:
1. Richardson, L.L., Rajagopalan, A., Albers, H. et al. Optomechanical resonatorenhanced atom interferometry. Commun Phys 3, 208(2020). https://doi.org/10.1038/s42005- 020-00473-4

TOWARDS A HIGH-FLUX SINGLE-BEAM BEC SOURCE FOR QUANTUM TECHNOLOGIES

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Bose-Einstein condensates (BECs) are of high interest to many fields of physics due to their unique quantum properties. They are typically created by laser cooling and trapping of neutral atoms in a magneto-optical trap with subsequent evaporative cooling in a complex experimental sequence. In particular, atom chips have proven their excellent performance to create BECs with a high flux, even in demanding environments such as a sounding rocket or the International Space Station. This opens up the possibility to use them in metrological applications such as inertial sensing using matter-wave interferometry though further improvements on these complex systems are necessary to apply them on a broader scale. In an attempt to simplify these sources, we have combined an atom chip with a nano-structured surface to perform magneto-optical trapping with a single optical beam. This strongly reduces the complexity of the setup, its surroundings and allows to drastically shrink the overall size. We demonstrate magneto-optical trapping, optical cooling, magnetic state preparation and finally magnetic trapping with the simplified setup.
In the future, we will extend the chips' capability with fast evaporative cooling towards BEC generation. This will drastically shrink BEC machines and make them available for applications outside of laboratory environments.

CARIOQA-PMP: A SPACE GRAVIMETRY QUANTUM PATHFINDER MISSION

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Quantum sensors based on the interference of matter waves provide an exceptional measurement tool for inertial forces, and are considered next generation accelerometers for applications in geodesy, navigation, or fundamental physics due to the absence of drifts. Space-borne atom interferometers promise to exploit the full potential of these sensors due to long free-fall times, and to reach unprecedented sensitivity at low frequencies.
In this context, the European Consortium CARIOQA-PMP aims to design and launch a Quantum Pathfinder Mission unlocking key features of atom interferometry for space and paving the way for future ambitious space missions utilising this technology. In this contribution, we will report on the mission concept, the progress of the Engineering Model construction and the scenario building of a quantum space gravimetry mission.
CARIOQA-PMP is funded by the Horizon Europe Programme and brings together leading players from five EU countries. These include experts in satellite instrument development (Airbus, Exail, TELETEL, LEONARDO), in quantum sensing (LUH, SYRTE, LP2N, LCAR, ONERA, FORTH), space geodesy, Earth sciences and users of gravity field data (LUH, TUM, POLIMI, DTU), as well as in impact maximisation and assessment (G.A.C. Group). The pathfinder mission preparation is coordinated by the French and German space agencies CNES and DLR under CNES lead.

QUANTUM INERTIAL ACCELEROMETER FOR MOBILE APPLICATION

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Today, precise inertial navigation and positioning systems are the basis for controlling vehicles such as aircraft, ships, or satellites. However classical inertial sensors suffer from device-dependent drifts and re-quire GNSS corrections that themselves rely on the availability of the signal broadcasted by the satellites. This leads to the non-usability of classical sensors in some environments like in-between buildings, underground, or space.
Hybrid quantum navigation, based on the combination of classical Inertial Measurement Units with quantum sensors based on atom interferometry are a serious candidate for a new technology that meets the demand of our time requirements for inertial navigation.
Atom interferometers have proven to measure drift-free at very high sensitivities. The main challenge is to transfer a complex laboratory-based device to a robust and compact measurement unit that can be used regardless of its small bandwidth and dynamic range to subtract the drifts of the classical devices.
We present the current status of our inertial quantum accelerometer based on an atom interferometer in a Mach-Zehnder geometry using a compact and robust laser system made from off- the-shelf fiber-based components along with a commercial vacuum system from ColdQuanta and new optics geometry that enhances the quantum sensor sensitivity while the final device is employed on a gyro-stabilized platform.
This work is supported by the Federal Ministry of Economics and Climate Protection (BMWK) due to the enactment of the German Bundestag under Grand No. DLR 50RK1957 (QGyro) and DLR. 50NA2106 (QGyro+)

APPLICATIONS OF TUNABLE INTERACTIONS AND TIME-AVERAGED POTENTIALS IN ATOM INTERFEROMETRY SOURCES

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Cold atom interferometry has become a central tool for sensing inertial effects and investigating fundamental physics. Using Bose-Einstein condensates a new generation of devices aim for previously unreached levels of precision. Fundamentally, the sensitivity of these sensors is limited by shot noise, motivating high-flux atomic sources. Furthermore, control over the ensemble's initial conditions and its expansion dynamics is key for systematic error mitigation.
We report on an all-optical high flux source of ultra-cold 39K with nearly Heisenberg limited expansion rates. Using time-averaged potentials we overcome the typical limitations of optical dipole traps, increasing the trapping volume and decoupling trap frequencies from trap depth. Moreover, we utilize external magnetic field as an additional experimental parameter, controlling atomic interactions via magnetic Feshbach resonances. By dynamically tuning interactions along the evaporation trajectory we achieve quantum degeneracy in below 200 ms evaporation time, maintaining a high flux comparable to the most recent magnetic chip traps. Subsequently, minimizing interactions reduces the ensembles mean-field energy, hence offering a simple and robust way to decrease its expansion rate. We apply the same method to enhance optical matter-wave lensing. Here we improve on previous results we obtained with 87Rb and realize an effective temperature equivalent of 500 pK.

GRAVIMETRY WITH THE VERY LONG BASELINE ATOM INTERFEROMETRY FACILITY

Ali Lezeik [1], Mario Montero [1], Justus Stannek [1], Klaus Zipfel [1], Dorothee Tell [1], Vishu Gupta [1], Sebastian Bode [1], Jonas Klussmeyer [1], Bjarne Herrmann [1], Christian Schubert [2], Dennis Schlippert [1]
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Light-pulse atom interferometry is a powerful tool to extract the phase differences in coherent matter waves. Quantum sensors employing this technique allow high-precision measurement of inertial forces caused by e.g. acceleration and rotation, paving the way towards tests of fundamental physics and metrological applications1,2. Their sensitivity scales with many factors one of which being the free fall time of the atomic ensemble.
In this talk we go through the principles, advantages and challenges of long baseline atom interferometry and present solutions implemented at the 15 m high Very Long Baseline Atom Interferometry (VLBAI) facility in Hannover.
Featuring a high-performance seismic attenuation system and a well controlled environment3,4, the VLBAI facility aims for sub nm/s2 gravity measurement sensitivity. Such a sensitvity allows the VLBAI facility to transfer its measured gravity values to nearby positions, becoming a reference station for calibrating mobile gravimeters.

[1]: C. Ufrechtet al,Phys. Rev. Research 2, 043240
[2]: M. Schilling et al, Journal of Geodesy 94, 122 (2020)
[3]: É. Wodey et al, Review of Scientific Instruments 91, 035117 (2020)
[4]: A. Lezeik et al 2022 arXiv:2209.08886

CHANCES AND CHALLENGES OF QUANTUM INERTIAL NAVIGATION SYSTEMS

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Atom interferometry (AI) is a comparably novel concept for high accuracy inertial sensing. Experiments based on cold atoms and Bose-Einstein condensates in static settings demonstrated a superior long-term stability and sensitivity, making AI a promising option for future navigation systems. Commercially available options for the measurement of gravity indicate that the realization of a full six-degree of freedom quantum inertial sensor is close.
Challenges for applying the novel sensors are the low data rate and small dynamic range, which yields severe limitations; especially for an application in terrestrial navigation, where accelerations and angular rates are varying over time, and vibrations of the vehicle frame lead to oscillations of the inertial quantities on all sensor axes. Hybrid solutions where the AI is used in conjunction with complementary sensors are state of the art.
In this contribution, we present the current status of our work on a hybrid solution of AI with conventional accelerometers and gyroscopes. The conventional sensors are used to predict the AI phase shift and increase the dynamic range, while the AI is used in order to improve the long term stability of the navigation solution. We elaborate on the ability of the AI to resolve different input signals and examine the limits introduced by the hybridisation. Furthermore, we demonstrate the performance of the quantum inertial navigation system with realistic trajectories derived from actual terrestrial inertial measurement.

TWO-DIMENSIONAL GRATING MAGNETO-OPTICAL TRAP

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Matterwave interferometry with Bose-Einstein Condensates (BEC) provides great opportunities for precision measurements and tests of fundamental physics. BECs are generally produced via laser cooling and confinement of a bosonic gas in a magneto-optical trap (MOT). The cold trapped atoms are then evaporatively cooled to a BEC. One approach to achieve faster MOT loading and higher atom numbers is to use Two-dimensional magneto-optical traps (2D-MOTs) as separate source chambers, which slow down atoms to velocities low enough to be captured by the 3D-MOT directly. Currently existing lab based experimental systems are however still very complex and unstable in the long term thereby limiting their applications in certain scenarios. Therefore, there is need for design simplification and room for stability improvements.
In this poster, I will present a design of a two-dimensional grating magneto-optical trap (2DgMOT) requiring only a single input cooling beam. The cold atomic beam from the 2D-gMOT will load atoms in a 3D-gMOT implemented on a novel atom chip for efficient generation of Bose-Einstein Condensates. The use of a grating in this setup simplifies the optical system thereby reducing the complexity and size of the atomic source thus providing an avenue for further miniaturisation.

QUANTUS-2: ATOM INTERFEROMETRY IN MICROGRAVITY

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Atom interferometry allows for precise quantum sensors with a wide range of applications including geodesy and tests of fundamental physics such as Einstein's equivalence principle.
Long free propagation times are one key-element to achieve high sensitivities, but it's strongly limited by gravity. Therefore, space-based experiments are of special interest.
QUANTUS-2 is an experiment created as a testbed for future space missions. It performs atom interferometry on long time scales under microgravity at the ZARM drop tower in Bremen.
In order to be able to detect the atoms after long times it's crucial to have slowly expanding Bose-Einstein Condensates (BECs). Using a quadrupole enhanced magnetic lens, we are able to reduce the 3D expansion of an BEC down to a total internal kinetic energy of 3/2 kB*38 pK [1].
Here, we present the buildup and function of the system and the latest results of asymmetric Mach-Zehnder atom interferometry with time scales up to 1.7 s.
The QUANTUS-2 project is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) under grant numbers DLR 50WM1952-1957.

QUANTUM SENSORS IN SPACE FOR FUNDAMENTAL PHYSICS AND APPLICATIONS

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Quantum sensors based on the interference of matter waves provide an exceptional measurement tool for inertial forces, and are considered next generation accelerometers for applications in geodesy, navigation, or fundamental physics due to the absence of drifts. Space-borne atom interferometers promise to exploit the full potential of these sensors due to long free-fall times, and to reach unprecedented sensitivity at low frequencies.
In this contribution, we present the STE-QUEST mission scenario, a satellite test of the universality of free fall with ultracold atoms to 10-17 as proposed to the ESA Medium mission frame [https://arxiv.org/abs/2211.15412]. Moreover, we will highlight the application to Earth Observation missions going beyond state of the art such as the CARIOQA concept [https://arxiv.org/abs/2211.01215].

TOWARDS A SPACEBORNE TWO-PHOTON RUBIDIUM FREQUENCY REFERENCE

Daniel Emanuel Kohl [1, 2], **Julien Kluge** [1, 2], **Moritz Eisebitt** [1, 3], **Klaus Doeringshoff** [1, 2], **Nicolas Manrique** [1, 2], **Markus Krutzik** [1, 2]
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Optical frequency standards based on spectroscopy using hot atomic vapor are a promising candidate for realization of simple and compact optical clocks for application in next generation global navigation satellite systems. Two-photon transitions in hot rubidium vapor offer narrow linewidths and are inherently free of Doppler broadening.
We present the development of a rubidium two-photon frequency reference using FM spectroscopy of the 5S1/2 - 5D5/2 transition at 778.1 nm, developed in the frame of the CRONOS project. The projects goal is to demonstrate a microsatellite-based optical clock in low earth orbit. Recent results of our lab-based reference show a fractional instability below 1.5 * 10-13 per sqrt(tau) for up to 1000 s. We present our laboratory setup as well as the first prototype of a compact spectroscopy module. Additionally, a future module design comprises a projected volume below half a liter, weight below one kilogram and a planned power budget of under 10 W for accommodation on a satellite. Details of the vapor cell assemblies as well as of the laser systems will be highlighted, including power stabilization and suppression of residual amplitude modulation.
This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) due to an enactment of the German Bundestag under grant numbers 50RK1971, 50WM2164.

AEROQGRAV - ABSOLUTE AIRBORNE GRAVIMETRY USING QUANTUM SENSORS

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Airborne gravimetry fills the gap between local measurements and global gravity field recovery with satellite missions.
In this context, quantum sensors based on atom interferometry offer a new tool for absolute measurements of gravity with the perspective of superior performance in comparison to conventional methods. This contribution will introduce the AeroQGrav consortium and our approach for the concept of the quantum sensor to recover the gravity signal, aiming for a resolution of 1 μm/s2 after 5 s of averaging.
AeroQGrav is a collaborative research project of iMAR Navigation, Geo++, TU Braunschweig, Leibniz Universität Hannover, Humboldt-Universität zu Berlin, BKG, TU Clausthal, and DLR, funded by the Federal Ministry of Education and Research (BMBF), FKZ 13N16519.

GRAVIMETRY WITH VERY LONG BASELINE ATOM INTERFEROMETER

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Quantum sensors based on atom interferometry allow the high-precision measurement of fundamental physical properties. The Very Long Baseline Atom Interferometry (VLBAI) facility in the Hannover Institute of Technology is working towards the measurement of inertial effects, which can be used for tests of fundamental physics and metrology. The sensitivity of atom interferometers depends on several factors one of which being the interferometer time and the large base- line of VLBAI facility provides longer interferometer time which leads to higher sensitivity. Here we present the current status of the 15 m high VLBAI facility which aims for sub nm/s2 gravity measurement sensitivity. It includes a 10 m high magnetically shielded baseline to reach gradients below 1.5nT/m and a seismic attenuation system for inertial referencing which allows for excellent control over external perturbations of the inertial reference mirror. The long baseline at the VLBAI facility uses rubidium and ytterbium BEC source based atom interferometers with possible interferometer time of 2.8s. After the demonstration of small-scale interferometer, the rubidium BEC source is currently being inserted as fountain source on long baseline. This work is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation): Project-ID 274200144 - SFB 1227 DQ-mat (projects B07 and B09), Project-ID 434617780 - SFB 1464 TerraQ (project A02), and Germany's Excellence Strategy – EXC-2123 QuantumFrontiers - Project-ID 390837967.

MULTI-AXIS QUANTUM GYROSCOPE WITH MULTI-LOOP ATOMIC SAGNAC INTERFEROMETRY

Ann Sabu [1], Yueyang Zou [1], Mouine Abidi [1], Philipp Barbey [1], Ashwin Rajagopalan [1], Christian Schubert [2], Matthias Gersemann [1], Dennis Schlippert [1], Ernst M. Rasel [1], Sven Abend [1]
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The sensitivity of matter-wave interferometers to rotations is based on the Sagnac effect and increases with the area enclosed by the interferometer. Twin-lattice atom interferometers promise to provide absolute measurements of inertial forces with high long-term stability. We aim at developing a portable device capable of multi-axis inertial sensing, enabling measurement of rotations and accelerations. In this setup, areas of up to 0.2m2 can be enclosed with the help of a multi-loop scheme. We present a brief theory of twin-lattice atomic Sagnac interferometry and the current status of the preliminary system design using Bose-Einstein condensates (BECs) of 87Rb atoms. We also present the design of the laser system for beamsplitting, cooling and detection.
We acknowledge financial support from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC-2123 QuantumFrontiers - 390837967 and through the CRC 1227 (DQ-mat), as well as support from DLR with funds provided by the BMWi under grant no. DLR 50RK1957 (QGyro) and DLR 50NA2106 (QGyro+)

EXPERIMENTAL PLATFORM FOR MULTI-AXIS QUANTUM INERTIAL SENSING

Matthias Gersemann [1], Ann Sabu [1], Mouine Abidi [1], Philipp Barbey [1], Ashwin Rajagopalan [1], Yueyang Zou [1], Christian Schubert [2], Dennis Schlippert [1], Sven Abend [1], Ernst M. Rasel [1]
[1] Leibniz Universität Hannover, Institut für Quantentoptik, Hannover, Germany, [2] Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institut für Satellitengeodäsie und Inertialsensorik

In light pulse atom interferometry, ultracold atoms open up the prospect of developing new techniques and concepts, for increasing the sensitivity of inertial measurements.
We perform correlated interferometry with two Bose-Einstein condensates generated out of one by large momentum transfer through double Bragg diffraction and Bloch oscillations. These methods also serve to create interferometers with large space-time areas. So far, most measurements demonstrated with atom interferometers sense along one direction. However, for inertial navigation, one must be able to reconstruct the three-dimensional trajectory of a moving body. The here presented scheme, can be employed to measure accelerations and rotations in three mutually orthogonal directions and form the basis for a compact six-axis quantum inertial measurement unit.
This contribution presents the underlying concept in detail and a planned system design based on a 3D-printed compact ultra-high vacuum chamber including atom-chip technology.
We acknowledge financial support from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC-2123 QuantumFrontiers – 390837967 and through the CRC 1227 (DQ-mat), as well as support from DLR with funds provided by the BMWi under grant no. DLR 50NA2106 (QGyro+).

INERTIAL SENSING UTILISING PAINTED OPTICAL POTENTIALS

Knut Stolzenberg [1], Sebastian Bode [1], Alexander Herbst [1], Daida Thomas [1], Wei Liu [1], Henning Albers [1], Ernst Rasel [1], Dennis Schlippert [1]
[1] Leibniz Universität Hannover, Germany

In GNSS-denied environments, inertial sensors based on atom interferometers can become a viable addition to classical IMUs, e.g., for autonomous driving or aviation. While they are superior with respect to their accuracy and long-term stability, it remains challenging to simultaneously measure accelerations and rotations in one or more axes in present experiments.
In our experiment we use a 1064 nm crossed optical dipole trap (ODT) for creation of quantum-degenerate ensembles. By using acousto-optical deflectors in both ODT beam paths, we add versatile control over the trapping potentials with respect to position and trap depth. This allows for the creation of one or more BECs amounting to a total number of up to 300 x 103 ultracold 87Rb atoms prepared in the magnetically insensitive state $|F = 1, mF = 0 >$. We report on prospects of implementing guided quantum inertial sensors by light-pulse atom interferometry in waveguides and by atomtronics in painted potentials.

ADVANCED METHODS FOR ATOM INTERFEROMETRY WITH ULTRACOLD ATOMS.

Mikhail Cheredinov [1], Ekim T. Hanımeli [2], Simon Kanthak [3], Matthias Gersemann [1], Sven Abend [1], Ernst M. Rasel [1]
[1] Institut für Quantenoptik, Leibniz University Hannover, Hannover, Germany, [2] ZARM, Universität Bremen, [3] Institut für Physik, HU Berlin

Inertial sensors based on ultra-cold matter waves are well-proven tools for measuring accelerations and rotations as well as testing fundamental physics. Due to their small spatial and momentum width, Bose-Einstein condensates (BECs) present ideal sources for precision measurements. The sensitivity of the interferometer to the inertial effects scales both with interrogation time T and with difference in momentum between the two arms of the interferometer. This contribution presents novel interferometry geometries and manipulation techniques. These can be divided into three categories as follows.
First, we aim to study interferometry topologies based on a combination of Raman and Bragg beam splitters by utilizing control over both internal and external states and exploit their complementary advantages.
Second, we investigate the current limitations of twin-lattice atom interferometry and present mitigation strategies. With this method, symmetric interferometers with matter waves of large relative momentum can be generated by using two optical lattices, propagating in opposite directions.
Third, we present our approach of optically guided BEC interferometry at a single wavelength inside a horizontally aligned atomic waveguide. A far-detuned focused beam in a retro-reflector configuration provides both tools to levitate and symmetrically split the wave packets via double Bragg diffraction.
This work is supported by the DLR with funds provided by the BMWi under grant no. DLR 50WM1952-1957 (QUANTUS-V-Fallturm), 50WM2250 (QUANTUS +), 50RK1957 (QGyro), 50NA2106 (QGyro+) and by the Deutsche Forschungsgemeinschaft (DFG,German Research Foundation) under Germany's Excellence Strategy – EXC-2123 QuantumFrontiers – 390837967.

MEASUREMENT OF THE FREQUENCY RATIO BETWEEN NEUTRAL 87SR AND 115IN+ AT THE 10-18 LEVEL

Kilian Stahl [1], Nimród Hausser [1], Jonas Keller [1], Sören Dörscher [1], Erik Benkler [1], Tabea Nordmann [1], Joshua Klose [1], Moritz von Boehn [1], Christian Lisdat [1], Tanja Mehlstäubler [1, 2]
[1] *Physikalisch Technische Bundesanstalt, Braunschweig, Germany,* [2] *Leibnitz Universität Hannover*

We report on a frequency ratio measurement between an ion clock using the 1267 THz transition in 115In+, which is based on a mixed-species Coulomb crystal containing 172Yb+ cooling ions, and a lattice clock realising the 429 THz transition in neutral 87Sr.
The new In+/Yb+ clock has been evaluated with a relative systematic uncertainty of 2.5x10-18 and achieved a fractional frequency instability of 1.6x10-15 / (tau/s)1/2 for operation with a single In+ ion. It incorporates novel techniques which enable scaling to ion crystals with multiple clock ions without compromising accuracy, thus obtaining lower instabilities than the current generation of ion clocks. We discuss planned measurements of atomic constants and further near-term improvements to reduce the fractional frequency uncertainty below 1x10-18.
The strontium clock's fractional frequency instability (less than 2x10-16 / (tau/s)1/2) was well below that of the ion clock. Systematic effects have been evaluated with fractional uncertainty below 4x10-18 for the measurement interval. Operating near room-temperature, the uncertainty of the frequency shift from blackbody radiation was close to the limit set by present knowledge of the atomic parameters. We also discuss long-term evaluation of systematic effects like the DC-Stark shift caused by static electric fields.
The 115In+/87Sr frequency ratio is determined with a relative systematic uncertainty below 5x10-18, surpassing previous measurements by more than two orders of magnitude. The observed fluctuations of the frequency ratio are consistent with white frequency noise. This demonstrates the level of control recommended for the eventual redefinition of the second using optical clocks.

TOWARDS HIGH PRECISION QUANTUM LOGIC SPECTROSCOPY OF SINGLE MOLECULAR IONS

Maximilian J. Zawierucha [1], Till Rehmert [1], Fabian Wolf [1], Piet O. Schmidt [1, 2]
[1] *Physikalisch-Technische Bundesanstalt, Braunschweig, Germany,* [2] *Institut für Quantenoptik, Leibniz Universität*

We are currently setting up an experimental apparatus for the investigation of molecular ions. The main goal of the experiment is precision spectroscopy on a vibrational overtone transition of a single molecular ion to probe for new physics effects such as a possible variation of fundamental constants. For this purpose, we are implementing quantum logic spectroscopy that was already successfully used for the aluminum optical clock [1] and the first clock based on highly charged ion [2]. We plan to implement a modified version of the classical quantum logic spectroscopy by using optical forces from bichromatic Raman interactions on the molecular ion, that allow to entangle the internal state of the molecule with the motional state [3]. The motional state is shared between the molecule and a co-trapped atomic ion and can therefore be used as a bus to transfer information from one ion to the other. Detection of the motional excitation on the atomic ion will allow us to infer the molecules internal state [4].
On my poster I will show the status of the experiments and present some ideas for experiments with trapped atomic and molecular ions in the context of time and frequency measurements.

[1] S. M. Brewer et al., Physical Review Letters 123, 033201 (2019)
[2] S. A. King et al., Nature 611, 43-47 (2022)
[3] F. Wolf et al. arXiv:2002.05584 (2020)
[4] F. Wolf et al., Nature 530, 457-460 (2016)

THE UPGRADED TRANSPORTABLE OPTICAL LATTICE CLOCK AT PTB

Chetan Vishwakarma [1], Ingo Nosske [1], Tim Lücke [1], Sofia Herbers [1], Christian Lisdat [1]
[1] *Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

After laboratory optical atomic clocks have reached fractional frequency uncertainties in the 10-18 regime, it is an ongoing task to miniaturize these complex devices and to make them transportable and in-field deployable. This effort is primarily motivated by promising prospects in geodesy. Together with accurate frequency transfer via e.g., fiber links, these clocks can measure gravitational potential differences in the 0.1 m2 / s2 regime (corresponding to cm height differences on Earth's surface) with high spatial and temporal resolution. Thus, they could help to establish an accurate height reference system. At PTB, we have been operating a transportable optical clock based on neutral strontium atoms in a 1-D optical lattice. This clock had been to international measurement campaigns in Modane, Turin, Paris, and Munich..
Here we present the development and ongoing evaluation of our new transportable clock. The upgrades come in the form of a new physics package employing a single-beam pyramid MOT for the first and second stages of cooling, better stray magnetic field shielding, a lower background pressure in the science chamber and a temperature shield for thermal homogeneity during the clock interrogation phase. With the ability to cool the temperature shield to cryogenic temperatures, the clock achieves blackbody radiation induced uncertainties below 10-18. Using the latest transportable cavity operating at the subharmonic of the clock transition, the new system achieves an instability below 5*10-16 tau -1 / 2. By careful characterization of various perturbations, we expect the clock to be able to reach total uncertainties well below 10-17.

OPTICAL AND MAGNETIC SIMULATIONS FOR QUANTUM SENSORS IN SPACE

Gabriel Müller [1], Stefan Seckmeyer [1], Naceur Gaaloul [1]
[1] *Leibniz University Hannover, Institut für Quantenoptik, Germany*

Ultra-cold atoms are an excellent source for quantum sensors performing atom interferometry experiments. Deploying such quantum sensors in space offers the opportunity to achieve free fall times not achievable with ground-based experiments. However, to ensure high sensitivities, in addition to long interferometry times, we require distortion-free interferometry beams and large numbers of atoms.
To meet these requirements, we employ optical and magnetic simulations. Our optical simulations use Fast-Fourier-transform beam propagation methods, allowing us to efficiently simulate the realistic atom interferometry beams. Our magnetic simulation tool offers a simple and efficient method to optimize atom chip traps and to characterize undesired magnetic forces on the atoms. We use these tools to operate current ISS experiments and applied them to help design the next-generation missions targeting larger atom numbers and clean interferometry beams.
These tools are highly valuable for current and future cold-atom experiments, particularly when combined with universal atom interferometry simulations.

REDUCTION OF THE BLACKBODY RADIATION AND LATTICE LIGHT SHIFT UNCERTAINTY OF STRONTIUM LATTICE CLOCKS

Sören Dörscher [1], Joshua Klose [1], Christian Lisdat [1]
[1] *Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

To accurately control frequency shifts of the clock transition (5s5p) 3P0 – (5s2) 1S0 in neutral strontium and operate a clock at a fractional uncertainty below 10-17, detailed understanding of the lattice light shift and the blackbody radiation (BBR) shift is necessary. We present recent improvements of the systematic lattice light shift in our strontium lattice clock, reaching a fractional uncertainty on the order of 1*10-18. A series of independent determinations of the E2-M1 polarisability deltaaplphaqm by different groups, including our own experimental measurement, has narrowed down the limits for the correct value of deltaalphaqm. The reduced fractional uncertainty of the lattice light shift benefits the strontium lattice clocks in the community.
Further improvements of our system are planned by operating at cryogenic temperature of about 80 K. The fractional frequency correction of the BBR shift with respect to the clock transition frequency is in the order of 10-15 at room temperature, and therefore the largest correction in most strontium lattice clocks. To shield the atoms from BBR and to operate at cryogenic temperature, we designed and installed a dual layer copper heat shield. Currently, apertures to inject an atomic beam still cause a direct line of sight from the atoms to the external environment, which causes a fractional uncertainty of our clock at 1*10-18 for operation at 80 K. Blocking the atomic beam holes during the interrogation is planned by installing additional beam shutters. This modification is estimated to reduce the uncertainty to less than 2*10-19.

TOWARDS (ANTI-)PROTON G-FACTOR MEASUREMENTS USING QUANTUM LOGIC SPECTROSCOPY

Moritz von Boehn [1], Julia-Aileen Coenders [1], Jan Schaper [1], Juan Manuel Cornejo [1], Stefan Ulmer [2, 3], Christian Ospelkaus [1, 4]
[1] Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany, [2] Ulmer Fundamental Symmetries Laboratory, RIKEN, [3] Heinrich-Heine Universität, [4] Physikalisch-Technische Bundesanstalt

Comparisons of fundamental properties of matter and antimatter provide stringent tests of CPT symmetry [1]. Throughout the last years, measurements of proton and antiproton g-factors in Penning traps have been carried out with outstanding precision, setting new constraints on CPT violating coefficients of the SME [2,3]. However, these experiments rely on time consuming particle cooling and state detection schemes based on image current detection (see e.g. [3]), currently limiting measurement sampling rate and accuracy. To overcome these limitations, we develop new cooling and state readout techniques following a proposal by Heinzen and Wineland [4,5]. In our approach, we want to couple an (anti-)proton to a laser (ground-state) cooled 9Be+ using free-space Coulomb-coupling in a double well potential. This should allow to ground-state cool the (anti-)proton and detect its spin state by means of a quantum-logic inspired readout protocol [6]. In this contribution, we present the basic concept of our approach as well as the current status and latest advances of our experiment.

[1] V. A. Kostelecký and Neil Russell, Rev. Mod. Phys. 83, 11 (2011) [2] C. Smorra et al., Nature 550, 371–374 (2017) [3] G. Schneider et al., Science 358, 1081 (2017) [4] D. J. Heinzen and D. J. Wineland, Phys. Rev. A 42, 2977 (1990) [5] D. J. Wineland et al., J. Res. NIST 103, 259 (1998) [6] J. M. Cornejo et al., New J. Phys. 23 (2021) 073045

A TRANSPORTABLE ACCURATE OPTICAL LATTICE CLOCK FOR GEODESY AND FUNDAMENTAL PHYSICS STUDIES

Dongliang Cong [1], Pramod Mysore Srinivas [1], Chang Jian Kwong [1], René Oswald [1], Eugen Wiens [1], Stephan Schiller [1], Sören Dörscher [2], Christian Lisdat [2], Uwe Sterr [2], Yeshpal Singh [3], Kai Bongs [4]
[1] Institut für Experimentalphysik,Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany, [2] Physikalisch-Technische Bundesanstalt, [3] University of Birmingham, [4] Institute of Quantum Technologies (DLR Ulm)

We are planning to install an accurate optical lattice clock based on 88Sr atoms at the Geodätisches Observatorium Wettzell (GOW). This clock will be integrated with the Satellite Laser Ranging system for optical time transfer to the ESA mission ACES, via the European Laser Timing link. It will also be integrated with the GOW timing system and the ACES microwave link. The goal is to demonstrate the use of precise time transfer in geodesy and relativistic geodesy via an optical space link by repeated comparisons between our clock and the optical clocks at PTB. One application could be to perform a test of gravitational time dilation.

In earlier work, we demonstrated 2E-17 fractional uncertainty with our apparatus [1]. We are currently revising and updating the apparatus to make it fit for transportation to GOW, scheduled in late 2024. We are introducing several new sub-systems: a new Ti:Sapphire lattice laser; higher power cooling lasers; a transportable clock laser based on a NEXCERA resonator; a transportable comb; transportable reference lasers based on cryogenic Silicon cavities; etc. The expected fractional uncertainty will reach 1e-17. The characterization of the updated apparatus is in progress. We are also analyzing the instability contributions from Dick effect, QPN, detection noise, bias magnetic field noise, and probe light noises etc. At this conference, we will present the latest status and results of our apparatus.

This work was done in the framework of DFG Forschungsgruppe FOR 5456.

[1] S. Origlia et al,Phys. Rev. A 98, 053443 (2018)

FRIDAY, 20 OCTOBER 2023

09:00 - 9:30 Morning Keynote: Quantum Computing

KEYNOTE: AN ECOSYSTEM FOR SUPERCONDUCTING QUBITS IN EUROPE: OPENSUPERQPLUS

Prof. Frank Wilhelm-Mauch, FZ Jülich

Superconducting qubits are a leading platform for implementing quantum computers. I will highlight how the OpenSuperQ project brings together the leading players in Europe with the goal to develop quantum computing systems with all their enabling technology that can reach low error rate at ever increasing sizes.

Frank Wilhelm-Mauch Studied physics with Diplom/MSc (1996) and doctoral degree (1999) at Karlsruhe University (now KIT) in theoretical condensed matter Postdoctoral reseracher at Delft University of Technology (1999-2001) Senior researcher / lecturer, Ludwig-Maximilians-University Munich (2001-2005) with habilitation in theoretical physics (2004) Associate Professor, University of Waterloo (2006-2011) Full Professor, Saarland University (since 2011) Director, Institute for Quantum Computing Analytics (PGI-12), Forschungszentrum Jülich (since 2020) Founder and managing director, Qruise GmbH (since 2021).

09:30 - 11:00 Morning Plenary: Future Challenges in Metrology and Sensing

KEYNOTE: FUTURE CHALLENGES IN OPTICAL QUANTUM METROLOGY – DETECTORS AND SOURCES

Dr. Stefan Kück, Physikalisch-Technische Bundesanstalt

The talk will address the current state-of-the art in metrology concerning single photon sources and detectors as well as entangled photon sources. For single-photon detectors, like e.g., Si- and InGaAs-single-photon avalanche detectors (SI-SPAD, InGaAs-SPAD), superconducting single-photon nanowire detectors (SNSPD) and transition edge sensor (TES-) detectors, which are already commercially available, the metrological characterization has been evolved in the recent years to a large extend at national metrology institutes. The situation is different for single-photon sources. Commercial availability is still scarce, although especially start-up companies are push into the market, and so also the metrology has developed only recently, mainly within the frame of European funded metrology projects. In this presentation, the actual status at national metrology institutes concerning traceability for several parameters will be addressed. Furthermore, an outlook for the metrology for entangled photon sources will be given. Here, even the description of the performance and the definition of an adequate metrics and vocabulary is missing, however, these aspects are a prerequisite for products and applications based on these kinds of sources.

KEYNOTE: FUNCTIONAL BRAIN IMAGING WITH OPTICALLY-PUMPED MAGNETOMETERS

Prof. Svenja Knappe, University of Colorado

We present our ongoing effort in developing imaging systems with microfabricated optically-pumped magnetometers (OPMs). By use of microfabrication technologies and simplification of optical setups, we aim to develop manufacturable sensors of small size and low power. Our zero-field OPMs require a shielded environment but reach high sensitivities of less than 10 fT/rtHz. Target applications lie in the field of non-magnetic brain imaging, specifically magnetoencephalography (MEG). The attraction of using these sensors for non-invasive brain imaging comes from the possibility of placing them directly on the scalp of the patient, very close to the brain sources. We have built several multi-channel test systems to validate the prediction of very high signal-to-noise ratios in standard MEG paradigms.

Speakers:

Stefan Kück Stefan Kück is the head of the division of optics at the Physikalisch-Technische Bundesanstalt.

Svenja Knappe Knappe is one of the world's leading researchers in the field of magnetic field measurement using optically pumped magnetometers, which enable high-precision measurements of brain waves.

Panel

Panelists:

Philippe Bouyer Dr P. Bouyer is professor at the University of Amsterdam and Technical University of Eindhoven. He is the coordinator of the Quantum Sensing program at Quantum Delta NL. He is the former Deputy Director of the Institute d'Optique and founding Director of the Laboratory of Photonics, Digital and Nanosciences at CNRS, IOGS, Université Bordeaux. He is co-founder of Muquans (now Exail), a France-based company dedicated to quantum sensors. Dr. Bouyer received his Ph.D. in 1995 from the École Normale Supérieure/laboratoire Kastler Brossel, Université Paris Sud. Subsequently, he was a visiting professor of physics at Stanford University in Palo Alto, California, among other positions. His current research interest concerns matter-wave interferometry for navigation and tests of general relativity.

Albert Schliesser Albert Schliesser obtained a PhD in 2009 from Ludwig-Maximilians University Munich, for research done at the Max-Planck Institute of Quantum Optics. After a postdoc at the École Polytechnique Fédérale de Lausanne, he joined the Niels Bohr Institute at Copenhagen University, where he has been a full professor since 2016. There, he leads a group in the area of Quantum Optics and Optomechanics. The significance of his work has been recognized by several prizes, including the Otto Hahn Medal of the Max Planck Society, an Early Career Prize of the European Physical Society, the EPFL Latsis Prize and a Young Scientist prize in Optics of the International Union of Pure and Applied Physics. He is a fellow of Optica and double ERC grantee.

Tara Liebisch Tara Liebisch works at Germany's National Metrology Institute PTB as a strategy officer in the Division Optics. In this role she has developed many large-scale infrastructure and collaborative initiatives. She enjoys ensuring that partners from academia, industry and government can work together to achieve scientific endeavors. Her work builds on my research in atomic physics with publications on Rydberg atoms, compact atomic devices and a thorough article on the revised SI. Currently, her work includes developing a new Clock Building and a concept for an optical fiber research network for simultaneous quantum communication and metrology operation, as well as serving as the scientific manager of the excellence cluster QuantumFrontiers and as a co-coordinator of the QVLS-iLab Ion and Atom Trap Technology.

Ted Santana Ted Silva Santana is a Higher Scientist in the Quantum Photonics team at the National Physical Laboratory (NPL), the UK's national metrology laboratory. He received a PhD in Physics from Heriot-Watt University. After his PhD, Ted worked as a post-doctoral researcher, physics teacher, lecturer, and temporary faculty member. He joined NPL in 2021 and his current interests are metrology of solid-state single-photon emitters and quantum key distribution hardware. Ted has a wealth of experience in dark field confocal microscopy, photoluminescence detection, resonance fluorescence from quantum dots, and correlation measurements using ultrafast electronic devices. His theoretical expertise includes the derivation and resolution of master equations, and modelling of photon statistics measurements.

Moderator:

Thierry Botter Executive Director, European Quantum Industry Consortium

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11:00 - 11:30 Showcase Stage Talks

Presentations and lightning talks featuring highlights from the EQTC 2023 exhibitors

- 11:05 - Qblox, Yemliha Bilal Kalyoncu
- 11:15 - Quantware, Pepijn Rot

11:30 - 13:00 Parallel Sessions – Scientific Advances Across the Quantum Domains

Parallel Track 1: Education, Training & Careers in Quantum Technology

Intro to Education and Training in the Strategic Research and Industry Agenda (SRIA).

EDUCATION AND TRAINING IN THE QUANTUM FLAGSHIP'S QUCATS CSA

Prof. Rainer Müller, QUCATS and Prof. Jacob Sherson, DigiQ

We will give an overview over the education and training activities in the Qucats CSA. In particular, we will describe the Strategic Infrastructures for workforce development that were developed, the standards for workforce developent (with the European Competence Framework for QT) and the career training opportunities.

TWO-STATE SYSTEMS IN SECONDARY SCHOOL

Prof. Sergej Faletic, University of Ljubljana

Our goal is to bring to secondary school the discovery of quantum mechanics in an interactive and investigative environment that can rekindle the natural curiosity of students. In our experience, a two-state approach to quantum mechanics can do that. There is a big difference between countries in their quantum curriculum for secondary schools. Some only adress atomic physics (photoelectric effect and energy levels of atoms), and others go as far as the Schrödinger equation and tunnelling. But rarely are two-state systems expicitly in the curriculum. Yet, a big part of quantum technology can be understood through two-state systems. Addressing two-state systems requires little mathematics and can be done in multiple contexts (polarization, spin, double well). We have shown in class that students are able to come up with appropriate models for quantum phenomena largely on their own. We will present our approach and touch on related approaches on our quest to create a quantum-aware general public.

QUANTUM LIFELONG LEARNING - DEVELOPING A STRUCTURED TRAINING AND FURTHER EDUCATION PROGRAM IN QUANTUM TECHNOLOGIES

Dr. Judith Gabel, LMU

Quantum technologies are already an established and still rapidly growing scientific research field with great application potential for industry. The current challenge for Germany and Europe is to transfer the knowledge and technological expertise on quantum systems from the research laboratories to the industrial sector. A key role here is played by the experts and executives in the high-tech industry, who must recognize and implement the specific potential of quantum technologies for their respective companies. We present the project Quantum LifeLong Learning (QL3), a structured training and further education program of the Munich universities in the field of quantum technologies with the target group of specialists and executives in the high-tech industry. We acknowledge financial support from the Bundesministerium für Bildung und Forschung (BMBF) of Germany.

Speakers:

Rainer Müller Professor of Physics Education at Technische Universität Braunschweig, Germany. Member of the Quantum Flagship Communication and Support Action (Qucats CSA)

Jacob Sherson Jacob Sherson holds professorships of Management at Aarhus University and Physics at the Niels Bohr Institute, Copenhagen University and is Director of the Center for Hybrid Intelligence and the game-based citizen science platform ScienceAtHome with +300,000 contributors. Jacob co-leads the pan-European Quantum Technology workforce efforts, coordinates the 17mio€ EU project, DigiQ, on Pan-European Quantum Master's education and is the director of the European Quantum Readiness Center. Jacob advises public and private institutions on AI and quantum technologies, is a TedX speaker (+300k views) and won the 2020 Falling Walls in Science and Innovation Management, 2019 Bold Award on Boldest AI + Boldest Scientific Project, 2018 Grundfos Prize and 2017 Ministerial Research Communication Prize.

Sergej Faletič Sergej Faletič is assistant professor at University of Ljubljana Faculty of Mathematics and Physics. He works in Physics Education Research and he has been involved in Physics Teacher education since 2007. His main research area is teaching and learning quantum mechanics (T&LQM) at pre-university level. He has been developing and implementing quantum mechanics courses for high-school students since 2014. He has been involved in two pilot projects of the education innitiatives of Quantum Flagship and is one of the responsibles for the thematic group on T&LQM of the International Research Group on Physics Teaching (GIREP). Since 2019 he has co-organised several symposia on T&LQM to bring experts together and facilitate exchange of knowledge and ideas.

Judith Gabel Dr. Judith Gabel studied physics in Würzburg, Germany, and Stony Brook, USA. Afterwards, she did her Ph.D. in experimental physics at Würzburg University, investigating how oxide quantum materials can be manipulated and used in novel electronic applications. She followed up that research as a postdoctoral researcher at Diamond Light Source, a large-scale science facility in the UK near Oxford. In 2022, Judith Gabel joined the Quantum Lifelong Learning (QL3) project, a project of the Technical University of Munich and the Ludwig-Maximilians-Universität München. She develops courses about quantum technologies for professionals in industry, to help along the transfer of ideas from the university research groups to industry.

Moderator:

Oxana Mishina PhD in physics (Russia) Experiments models at NBI (Denmark) and LKB (France) Theory for cooling and squeezing atoms at USAAR (Germany) Quantum ambassador in schools (Germany) Teaching QT to teacher-students at TUBS (Germany) QTEdu.eu portal creation and management management, QT training for European Policymakers, EDI proactive within European Quantum Flagship's coordination action (QTEdu, QFlag, QUCATS) at CNR-INO, Trieste (Italy) Trieste section of the Italian Quantum Weeks - IQW2022 - a National outreach event

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Parallel Track 2: Quantum Computing & Simulation

FAULT-TOLERANT QUANTUM COMPUTATION IN PLANAR ARCHITECTURES

Prof. Robert Raußendorf, Leibniz University Hannover

Decoherence is a severe obstacle to quantum computation at large scale, but it can be overcome by a software technique—quantum error correction. I describe how to apply these techniques in the presence of geometrical constraints, namely a two-dimensional grid of qubits with only short-range interaction. A very high error threshold of 1% is possible in such a setting, and the scaling of the overhead caused by fault-tolerance is moderate.

EXPERIMENTAL QUANTUM SIMULATIONS IN "ARTIFICIAL" ARRAYS OF TRAPPED IONS

Prof. Tobias Schätz, University Freiburg

Direct experimental access to the most intriguing quantum phenomena is difficult due to their fragility to noise. To reach beyond the capabilities of very powerful numerical methods and approximations, leading theorists demand more than one-dimensional systems linked via interactions at long range. Trapped atomic ions are among the most promising candidates to provide a platform for experimental quantum simulations, featuring unique control and operational fidelities in one-dimensional systems of few-ions. We aim to extend this platform to larger size and dimensionality while preserving the unique controllability via trapping individual ions at individual sites of arrays - by trapping above surface traps with electrodes of the micrometer scale. We present results on coupling coherently excited ions within a basic-triangular array, observing transfer and interference. Recently, we achieved automated loading of single Mg+ ions within our array containing up to 13 trapping sites in a three-dimensional arrangement. Shuttling ions from a loading hub to multiple sites, we achieve a success rate ¿0.99 999 and demonstrate coherence preservation and coherent manipulation of superposition states of a hyperfine qubit during the process.

SIMULATING QUANTUM FIELDS WITH A CONTINUOUS VARIABLES PHOTONIC VQE

Dr. Federico Centrone, ICFO

This work introduces a novel approach to quantum simulations using a continuous variables photonic hardware-inspired variational quantum eigensolver (VQE) framework. By leveraging the infinite degrees of freedom inherent in continuous variables systems, namely bosons, we aim to simulate infinite-dimensional quantum fields without imposing a cutoff on the Hilbert space. Our focus lies in exploring applications in many-body physics and quantum field theory, specifically the Bose-Hubbard and lattice gauge theory models. In evaluating the performance of our simulator, we consider realistic experimental constraints. This encompasses limitations on squeezing, a technique that enhances measurement precision, as well as incorporating photon subtraction, the simplest non-Gaussian operation in photonics systems, which is crucial for aspiring towards quantum advantage. Additionally, we employ variational optimization over passive optics elements to manipulate and control quantum states. Through our study, we effectively demonstrate the practicality and viability of our simulation methodology. By successfully determining ground states of Hamiltonians under realistic experimental conditions, we highlight the potential of continuous-variable quantum simulations in addressing complex problems within the realm of quantum physics. This research serves as a valuable contribution to the field of quantum simulations by bridging the gap between theoretical concepts and experimental implementation. Furthermore, our approach unlocks new possibilities for investigating unbounded complex quantum systems and may pave the way for advancements in continuous variables quantum computing and quantum information processing.

DRUG DESIGN ON QUANTUM COMPUTERS

Dr. Nikolaj Moll, Quantum Lab Boehringer Ingelheim

Quantum computers promise to disrupt industrial applications. Especially researchers could be able to perform quantum chemistry calculations with high accuracy. Here we explore the challenges and opportunities of applying quantum computers to drug design, discuss where they could transform industrial research, and elaborate on what is needed to reach this goal.

Speakers:

Robert Raussendorf Robert Raussendorf is a physicist and quantum information scientist. He has invented the one way quantum computer, aka measurement based quantum computation, jointly with Hans Briegel. He is Humboldt Professor at LUH since 2023.

Tobias Schaetz I have studied physics at the Technical University of Munich (& master at the Ecole Normale Supérieure in Paris), focussing in my Diploma thesis on nuclear physics. During my PhD thesis, I have investigated whether ions in storage rings could get laser cooled to form crystalline ion beams. For my Postdoc, I had the privilege to learn from Dave Wineland and Dietrich Leibfried at NIST/Boulder about the possibilities of further improving the control of (molecular) ions on the quantum level. I started an independent research group at the Max Planck Institute for Quantum Optics in Garching, to demonstrate that trapped ions are suited to provide an experimental quantum simulator – and we additionally showed that ions can be trapped by light. In 2011, we joined the University of Freiburg.

Federico Centrone I am a postdoctoral researcher based at ICFO research institute in Barcelona. With a primary focus on quantum optics and continuous variables paradigms, my scientific research centers on theoretical conception and simulation of quantum information protocols. I place particular emphasis on the experimental realization of these protocols using state-of-the-art photonic technology, while also addressing their energetic efficiency. Currently, I am engaged in developing the optical implementation of NISQ variational algorithms in the non-Gaussian continuous variables framework. My strong background in experimental physics allows me to engage in meaningful discussions with experimentalists, facilitating the design of realistic theoretical models for practical applications.

Nikolaj Moll Dr. Nikolaj Moll is a Quantum Computing Scientist at Boehringer-Ingelheim, where he is responsible for developing quantum algorithms for pharmaceutical research and development. Before this, he was a scientist at IBM Research in Zurich for 20 years. Dr. Moll received his doctorate in physics from the Technical University of Berlin in August 1998, performing research at the Fritz Haber Institute of the Max Planck Society. He then spent two years at the Massachusetts Institute of Technology. He has authored over 20 issued patents and over 100 scientific articles on semiconductor technology, nanophotonics, scanning probe microscopy, and quantum computing.

Chair:

Giorgio Zarantonello Physicist with experience in trapped ion technology. Obtained a PhD in physics at Hannover university and PTB Braunschweig in implementing microwave driven entangling gates on trapped ions. Following this, he extended his experience with a Postodoc in the NIST ion storage group in Boulder where he worked on designing large scale.

Parallel Track 3: Quantum Communication

EUROQCI AND EUROQCS INFRASTRUCTURES INTEGRATION.

Dr. Piotr Rydlichowski, Poznan Supercomputing and Networking Center

EuroQCI and EuroQCS national infrastructures require significant effort in terms of the technical implementation effort, integration, development roadmap and management. These are expected to be inline also with other projects both on the national and European levels. It can be noted that EuroQCI and EuroQCS national infrastructures can be potentially locally integrated on multiple levels and both from technical, organizational and management point of views. Similar framework of these initiatives and overall program goals allow to achieve synergy in terms of the expected project results. Especially interesting aspects are potential joint use cases, application scenarios, management and training. It brings also new opportunities for integration with classical communication and HPC infrastructures.

QUANTUM AUTHENTICATION, QUANTUM COMMUNICATION, AND QUANTUM INFORMATION PROCESSING

Prof. Dr. Pepijn Pinkse, University of Twente

In this contribution we will report about our results in the areas of quantum authentication, authenticated communication and quantum information processing with integrated photonics. A physical unclonable function (PUF) is a unique physical key which cannot be physically copied with existing technology. Multiple-scattering samples form good optical PUFs. We have demonstrated authentication by quantum-secure optical readout of a PUF [1] and more recently, we have devised a quantum communication scheme based on PUFs [2]. In order to investigate the limits of state-of-the-art nanofabrication techniques, we started making multiple-scattering media by direct laser writing, as illustrated in the figure. A new class of PUFs we realize in the form of complex integrated photonic circuits. For the purpose of achieving and exploiting a quantum advantage for computational tasks, scalable multiphoton interference with extreme programmability and ultralow loss is required. We believe the best way for that purpose is large-scale integrated photonics, which we are pursuing together with UT spin-off Quix Quantum. A programmable integrated photonic processor [3] recently allowed us to demonstrate quantum thermodynamics [4], an indistinguishability witness [5] and an analog simulation of open scattering channels [6].
References

1. S. A. Goorden, et al., Optica 1, 421 (2014).
2. R. Uppu et al., Quantum Sci. Tech. 4, 04501 (2019).
3. C. Taballione et al., ArXiv 2203.01801
4. F.H.B. Somhorst et al., Nat. Commun. 14, 3895 (2023).
5. R. van der Meer et al., arXiv: 2112.00067
6. R. van der Meer et al., arXiv: 2110.04380

DEMONSTRATION OF QUANTUM-DIGITAL PAYMENTS

Dr. Mathieu Bozzio, Uni Wien

Digital contactless payments have replaced physical banknotes in many aspects of our daily lives. Similarly to banknotes, they should be easy to use, unique, tamper-resistant and untraceable, but additionally have to withstand attackers and data breaches in the digital world. Current digital payments require a binding commitment between the customer, merchant and bank or payment network to guarantee the validity of a transaction. Such a bond usually comes in the form of a cryptogram, which is the output of a hash function that guarantees the one-time nature of each purchase. However, computationally powerful attackers can violate the security of such functions. In this work [1], we show how quantum light can secure daily digital payments by generating inherently unforgeable quantum cryptograms. We conceal the customer's sensitive information by using an information-theoretically secure cryptographic function, while the commitment to the purchase is intrinsically guaranteed by the laws of quantum mechanics. We implement the scheme over an urban optical fiber link, and show its robustness to noise and loss-dependent attacks. Unlike previously proposed protocols, our solution does not depend on challenging long-term quantum storage [2], or a network of spacetime-constrained agents and authenticated channels [3].
References:

[1] P. Schiansky et al.,final revisions for Nature Communications (ArXiv: https://arxiv.org/abs/2305.14504).
[2] M. Bozzio et al.,npj Quantum Information 4, 5 (2018).
[3] A. Kent et al.,npj Quantum Information 8, 28 (2022).

Speakers:

Piotr Rydlichowski Coordinator for quantum technologies projects at PSNC. Researcher in the area of optical transmission systems, quantum communication technologies especially QKD. Involved in projects related to GNSS systems, photonics and microwave theory and techniques. Completed studies in the areas of Telecommunication Systems and PhD studies in the area of Modern Information Technologies. Involved in Quantum Computing hub at PSNC, hybrid quantum-classical algorithms, EuroQCI and EuroQCS projects. Responsible for network requirements specification, QKD systems testing and integration with existing operational network environment. Running operational and laboratory network environment to perform the integration and validation tests of solutions.

Johanna Sepúlveda Johanna Sepúlveda received her M.Sc. and Ph.D. degrees in Electrical Engineering – Microelectronics by the University of São Paulo, Brazil. She was a Senior Researcher in the area of security and emerging technologies at the University of South Brittany, INRIA and at the Technical University of Munich. Currently she holds a position as the Airbus Expert on Quantum-Secure Technologies, being Chief Engineer of different European quantum initiatives such as EuroQCI. Also she is the vice-chair of the Strategic Advisory Board of Quantum Technologies for the European Commission and leader of the Strategic Industry Roadmap at the Quantum Industry Consortium (QuIC). She has more than 15 years of experience in R&T and R&D in the area of security, networked systems, HPC and quantum technologies.

Pepijn Pinkse Pepijn Pinkse obtained his Ph.D. in 1997 at the University of Amsterdam. Thereafter, he performed seminal cavity QED experiments at the University of Konstanz and at the Max Planck Institute for Quantum Optics (MPQ). Here he also pioneered new ways of cooling and trapping ultracold molecules in a project he initiated in 2002. After his habilitation in 2008 at the TU München, he moved in 2009 to Twente. Here he pioneered quantum-secure readout of a scattering key as so-called Physical Unclonable Function (PUF). He now is the chair of the Adaptive Quantum Optics group and director of the center for QUAntum Nanotechnology Twente (QUANT). Presently he is combining ideas from quantum optics and with nanofabricated media, multimode fibers and complex integrated photonic circuits.

Mathieu Bozzio After completing his PhD in quantum cryptography at the University Paris-Saclay, Mathieu Bozzio is now developing practical security proofs and experimental demonstrations of mistrustful quantum primitives at the University of Vienna.

Chair:

Stefan Kück Stefan Kück is the head of the division of optics at the Physikalisch-Technische Bundesanstalt.

Parallel Track 4: Quantum Fundamentals

QUANTUM NETWORKING WITH QUANTUM NODES BASED ON RARE-EARTH DOPED SOLIDS

Dr. Hugues de Riedmatten, ICFO

The distribution of entanglement in quantum networks will allow new advances in long distance quantum communication, distributed quantum computing and quantum sensing. To distribute entanglement over long distances, quantum repeaters have been proposed. The nodes of a quantum repeater are matter systems that allow entanglement with photons at telecom wavelengths and serve as efficient and long-lived quantum memory for (entangled) quantum bits. In addition, the nodes should allow multiplexed operation and ideally enable quantum processing capabilities between stored qubits. In this talk, I will describe our recent progress towards quantum the realization of quantum repeaters with multiplexed quantum memories, using cryogenically cooled rare-earth ion doped solids. Recent experiments include the demonstration of long-distance multiplexed quantum teleportation from a photonic telecom qubit to a solid-state collective qubit with active feed-forward and the distribution of light-matter entanglement over the Barcelona metropolitan fiber network. Finally, I will explain our current work to build quantum processing nodes and spin-photon interfaces using single rare-earth ions in nanoparticles embedded in fiber-based microcavities.

GE/SI BASED GATEMON AS AN ALTERNATIVE QUBIT

Prof. Christian Schoenenberger, University of Base

Transmon qubits based on superconducting circuits are currently the most popular platform for small and intermediate scale quantum technology applications. However, there are several challenges, such as the large size and hence the difficulty in scaling to many qubits, the sensitivity to flux noise and the associated power load for driving qubits through flux lines.

A possible solution are semiconductor-superconductor hybrid systems called gatemon qubits where the Josephson junction is realized by a gate-tunable weak link (gatemon). Such gatemons have intensively been studied in III-V semiconductor 2D and 1D platforms and, recently, work has been started also on using type-IV semiconductors, such as Si and/or Ge. Here, we present a gatemon qubit based on a Ge/Si core-shell nanowire Josephson junction. On this new platform we demonstrate the electrical tunability and coherent manipulation, with coherence times on par with other gatemon platforms. We also study the current-phase relation of Ge/Si Josephson junctions and demonstrate, that the narrow core of Ge allows for junctions with one or two channels only. In short junctions the electric current carrying channels are ballistic and highly transmissive opening a way to realize parity protected 4e gatemon devices.

QUANTUM LIGHT SOURCES: ENTANGLEMENT GENERATION AND CHARACTERIZATION

Dr. Ana Predojevic, Uni Stockholm

Single quantum dots are established emitters of single photons and entangled photon pairs. However, the achievable degree of entanglement and the source readiness to be deployed in quantum communication protocols depend on additional functionalities, including high photon collection efficiency. I will present engineered photonic systems that allow for entangled photon pair sources to be more efficient. Also, I will introduce a novel method to achieve potentially scalable photonic sources that can be accomplished without need for costly and complex deterministic nanofabrication and lithography techniques.

Speakers:

Hugues de Riedmatten Hugues de Riedmatten (PhD 2003, University of Geneva) is ICREA professor and head of the Quantum Photonics group at ICFO since 2010. His group´s research focuses on building experimental hardware for quantum networks and quantum repeaters, including quantum memories for light, quantum light sources, quantum network nodes and quantum frequency conversion. He contributed to key milestones in quantum repeater technology, including the first demonstrations of long distance quantum teleportation, and of quantum repeater links using cold atoms and solid-state quantum memories. Hugues is a member of the executive team of the European Quantum Internet Alliance.

Christian Schönenberger Christian Schönenberger is both an electrical engineer and a physicist by training. He worked at the ETH-Zurich, the IBM Zurich Research Laboratory and later at the Philips Research Laboratory in Eindhoven. Since 1995 he is a full professor in experimental physics at the Department of Physics of the University of Basel. He was a co-initiator of the Swiss Nanoscience institute (https://nanoscience.ch/) and till summer 2022 its director. The research in his group is targeted towards electrical properties of nano-scaled quantum devices. Such devices are currently central in developing quantum computers and other quantum-based electronic applications. In their research, the group often explores fundamental quantum effects in new material systems with reduced dimensions. Website: www.nanoelectronics.ch

Ana Predojević Ana Predojević is Associate Professor at Stockholm University. Her research focuses on quantum optics, quantum photonics, and use of quantum light for quantum technologies. Prior to her current appointment she held the position of Junior Professor at Ulm University. She received her Habilitation from University of Innsbruck in 2016, where she was recipient of Lise Meitner and Elise Richter fellowships. She received her doctoral degree from the Institute of Photonics Sciences (ICFO), Barcelona.

Chair:

Klemens Hammerer Hammerer is a professor at Leibniz Universität Hannover and carries out research in the field of theoretical quantum optics

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Parallel Track 5: Quantum Metrology & Sensing

MEASUREMENT AND CONTROL OF MECHANICAL MOTION AT AND BEYOND THE QUANTUM LIMIT

Prof. Albert Schliesser, Niels Bohr Institute

The Heisenberg microscope illustrates that quantum mechanics imposes constraints on the precision of measurements. In precision interferometry—as implemented for example in laser-based gravitational wave antennae—this entails the so-called Standard Quantum Limit (SQL). It arises from a trade-off of measurement imprecision and the backaction of the measurement. Here we describe table-top experiments in which we measure the motion of a micromechanical membrane oscillator at the SQL in practice. We also demonstrate methods to overcome the SQL by exploiting quantum correlations directly generated in the system. Furthermore, by implementing quantum feedback, we can control the motional state of the measured object at the quantum limit, even at room temperature. We conclude with an outlook on applications in, e.g., spin sensing.

PULSED PROTOCOLS IN NV MAGNETOMETRY FOR IMPROVED SENSITIVITY IN SCANNING APPLICATIONS

Bjorn Josteinsson, QZabre

The combination of high spatial resolution and high sensitivity at ambient conditions makes scanning NV an ideal candidate for magnetometry with applications in measuring e.g. antiferromagnets, multiferroics and current distributions. Recent advances, using demodulation techniques, have enabled scanning rates of 200 pixels/s or more, with megapixel scans now possible in under two hours. However, the sensitivity using continuous wave ODMR protocol, driving microwaves and laser at the same time, remains limited to about 1 uT/sqrt(hz). Using pulsed protocols enables an increase in sensitivity by almost an order of magnitude, at the cost of higher setup complexity. We show how two such protocols, pulsed ODMR and gradiometry, implemented on a quantum scanning microscope (QSM), a commercial scanning NV system, compare when measuring samples with uT and sub uT magnetic fields.

DETECTION SCHEMES FOR MICROWAVE QUANTUM ILLUMINATION

Prof. David Vitali, University of Camerino

The quantum illumination protocol has demonstrated that its advantage can survive even when entanglement is destroyed by the effect of a noisy environment. However, designing a measurement system that realizes this advantage is challenging since the information is hidden in the weak correlation embedded in the noise at the receiver side. Recent progress in a correlation-to-displacement conversion module provides a route towards an optimal protocol for practical microwave quantum illumination. Here we extend the conversion module to accommodate experimental imperfections that are ubiquitous in microwave systems. To mitigate loss, we propose amplification of the return signals. In the case of ideal amplification, the entire six-decibel error-exponent advantage in target detection error can be maintained. However, in the case of noisy amplification, this advantage is reduced to three decibels. We analyze the quantum advantage under different scenarios with a Kennedy receiver in the final measurement. Empowered by photon-number-resolving detectors, the performance is further improved and also analyzed in terms of receiver operating characteristic curves.

Speakers:

Albert Schliesser Albert Schliesser obtained a PhD in 2009 from Ludwig-Maximilians University Munich, for research done at the Max-Planck Institute of Quantum Optics. After a postdoc at the École Polytechnique Fédérale de Lausanne, he joined the Niels Bohr Institute at Copenhagen University, where he has been a full professor since 2016. There, he leads a group in the area of Quantum Optics and Optomechanics. The significance of his work has been recognized by several prizes, including the Otto Hahn Medal of the Max Planck Society, an Early Career Prize of the European Physical Society, the EPFL Latsis Prize and a Young Scientist prize in Optics of the International Union of Pure and Applied Physics. He is a fellow of Optica and double ERC grantee.

Bjorn Josteinsson Before moving to Switzerland, I pursued my Bachelor's degree in Engineering Physics at the University of Iceland. Recently, I finished my master's studies at ETH where I studied Quantum Engineering. During my time at ETH, I first came into contact with QZabre, a spin off company from the Spin Physics group at ETH. At QZabre I did a project as an intern, initially originating as a semester thesis at the Spin Physics lab. For my Master's thesis I worked with the Trapped Ion group at ETH where my project was on an experiment doing quantum logic spectroscopy on the hydrogen molecular ion. Since last May I work full time as a quantum software engineer at QZabre where I am responsible for control software, system assembly, testing and installation.

David Vitali Phd in Theoretical Physics at Scuola Normale Superiore (Pisa, Italy) in 1994. Full professor of Theoretical Physics at the University of Camerino since 2001. He has carried out research in many subfields of Quantum Optics and Quantum Information Theory, such as entanglement manipulation, quantum communication and quantum key distribution, quantum optics implementation of quantum technologies. He has been one of the pioneers in the study of quantum effects in optomechanical systems, suggesting the possibility to utilize microresonators for quantum information processing, and he has been nominated 2015 APS Fellow with this motivation. He has published more than 190 articles in international journals with referee, and he has an h-index of 52 (Scopus, more than 10200 citations).

Chair:

Philippe Bouyer P. Bouyer is professor at the University of Amsterdam and Technical University of Eindhoven. He is the coordinator of the Quantum Sensing program at Quantum Delta NL. He is the former Deputy Director of the Institute d'Optique and founding Director of the Laboratory of Photonics, Digital and Nanosciences at CNRS, IOGS, Université Bordeaux. He is co-founder of Muquans (now Exail), a France-based company dedicated to quantum sensors. Dr. Bouyer received his Ph.D. in 1995 from the École Normale Supérieure/laboratoire Kastler Brossel, Université Paris Sud. Subsequently, he was a visiting professor of physics at Stanford University in Palo Alto, California, among other positions. His current research interest concerns matter-wave interferometry for navigation and tests of general relativity.
