European Quantum Technologies Conference 2024

a Quantum Flagship event

18 to 20 November 2024
Lisbon, Portugal

BOOK OF ABSTRACTS

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DAY 1 - MONDAY 18 NOVEMBER

Opening Session

Monday, 18 November - 14:00 – 14:45

Chair: **Yasser Omar** (PQI & IST, ULisbon)

09:00 - **Welcome address by Gustav Kalbe** (European Commission)

09:15 - **Welcome address by Ana Paiva** (Secretary of State for Science)

09:30 - **Quantum Gravimetry for Archaeology**
António Marques (Centro de Arqueologia de Lisboa / CML)
Camille Janvier (Exail)

10:00 - **Live Demonstration of Quantum Communications**
Pierangela Pitzolu (Telsy)
Ana Carla Sousa (MEO)
Alessandro Zavatta (QTI)

Panel discussion:
The European Quantum Declaration

Monday, 18 November - 11:00 – 12:00

Chair: **Tommaso Calarco** (Forschungszentrum Jülich)

Thierry Botter (QuIC - European Quantum Industry Consortium)

Eleni Diamanti (Centre National de Recherche Scientifique, Sorbonne University)

Julia Feddersen (Quantum Delta NL)

Stella Mitsche (Federal Funding Agency Austria)

Yasser Omar (PQI & IST, Ulisbon)

LUNCH TALKS
Monday 18 November

12:10 – 13:50

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Lunch Talks

(Monday, 18 November - 12:00 – 14:00)

1. 12:10 **- AMIRES:** AMIRES as a quantum ecosystem builder
2. 12:20 - **Baden-Württemberg International:** From Lab to Fab: Shaping an Ecosystem to Bring Quantum Technologies to the Market
3. 12:30 - **NVision Imaging Technologies GmbH:** Mastering spin control for medical imaging and scalable quantum computing
4. 12:40 – **CERN:** The CERN Quantum Technology Initiative
5. 12:50 - **Delft Circuits:** A route to scalable Quantum Computer
6. 13:00 - **DEMCON high-tech systems:** Engineering for Quantum: bridging the gap from prototype to product
7. 13:10 - **Dynex Moonshots:** A Quantum-Centric Future: Silicon Quantum Computing
8. 13:20 - **EURAMET EMN-Q European Metrology Network for Quantum Technologies:** Metrology in the Quantum Era: Perspectives on the EURAMET European Metrology Network for Quantum Technologies
9. 13:30 - **Fraunhofer Institute for Applied Optics and Precision Engineering IOF:** Quantum technologies for satellite-based Quantum Communication
10. 13:40 - **Qblox:** Controlling quantum computers at utility scale

13:50 - *End*

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AMIRES

AMIRES as a quantum ecosystem builder

Baden-Württemberg International

Alexander-C. Heinrich
Head of QuantumBW office,
Baden-Württemberg International

From Lab to Fab: Shaping an Ecosystem to Bring Quantum Technologies to the Market

QuantumBW is Baden-Württemberg's innovation initiative to promote the transfer of quantum science to market applications. By pooling the region's unique scientific and economic expertise, it fosters a dynamic ecosystem to tackle the challenges of developing quantum products. Strategic ten-year technology roadmaps, defined by experts from science and industry, provide coherent guidelines and binding schedules. Focusing on quantum sensor technology, Baden-Württemberg aims to deliver market-driven quantum devices in the next 3-5 years in fields like healthcare and medical diagnostics, while stimulating the entire quantum ecosystem. Join us to experience the power of an academia-industry ecosystem. Visit us at booth no. 4.

NVISION

Mastering spin control for medical imaging and scalable quantum computing

NVision is a quantum biotech startup from Ulm, Germany. We use quantum material (parahydrogen) to enable real-time detection of biomolecules in standard MRI scanners. This medical imaging technique provides deep insights into metabolic processes - e. g. fast assessment of whether a tumor is responding to treatment.
We are also developing a quantum computer based on photoactive organic molecules, which offer a very wide range of tunability. As part of this effort, we are building a 50-qubit demonstrator with molecular spin based qubits for the German Space Agency (DLR).

CERN

CERN, the European Organization for Nuclear Research, provides unique accelerator, detector and computing facilities, pushing the frontiers of science and technology to enable world-class research in fundamental physics.
Our Quantum Technology Initiative fosters opportunities that quantum technologies can provide to the particle physics community, and conversely identifies how CERN know-how can uniquely contribute to the further development of quantum technologies.
Discover CERN's R&D to solve concrete challenges in quantum computing, communication, and the development of enabling technologies, and learn how to collaborate with us!

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Delft Circuits

Artem Nikitin

A route to scalable Quantum Computer

One of the imminent roadblocks towards realizing a quantum computer is the input and output wiring system. Cri/oFlex® technology developed by Delft Circuits removes the barriers and enables scaling for quantum computing. Designed specifically for cryogenic setups, it provides excellent microwave performance, low thermal load, flexibility, ease of installation and reliability

DEMCON

Martijn Krijnen

Engineering for Quantum: bridging the gap from prototype to product

Dynex

A Quantum-Centric Future: Silicon Quantum Computing

Dynex pioneered emulated Quantum-as-a-Service (QaaS) to address complex, large-scale challenges beyond the limits of classical computing. Now, the focus shifts to Silicon Quantum Chips, targeting real-time quantum computing by 2025. This talk will cover our technology's evolution and what lies ahead.

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EURAMET

Metrology in the quantum era: perspectives on the EURAMET European metrology network for quantum technologies

The EURAMET's European Metrology Network (EMN) for Quantum Technologies provides active coordination of European measurement science research to maintain competitiveness in the field of quantum technologies. By promoting and facilitating knowledge sharing, collaboration and the uptake of measurement science in the development of quantum technology, the EMN Quantum Technologies will establish globally accepted measurement services for quantum technologies and devices.

To support competitiveness of the emerging European quantum industry, EMN-Q develops a European quantum metrology infrastructure by coordinating, pooling, and strengthening the national quantum metrology infrastructures.

Fraunhofer Institute

Quantum Technologies for satellite-based Quantum Communication

Optical satellite links are a promising approach to ensure secure communication over large distances. Several proof of concept experiments have demonstrated the feasibility but a number of challenges remain towards industrial scale applications. Here, we report on recent advances in engineering space qualified quantum technologies as well as on proof of concept experiments of high-dimensional Quantum Key Distribution over an intra-city free space test bed in Jena, Germany.

Qblox

Controlling quantum computers at utility scale

Quantum utility will require improving the current state-of-the-art quantum systems by increasing their qubit count and reducing the error rates by multiple orders of magnitude. On top of that, the systems need to be employed with real-time error decoding and correction to make them fault tolerant. Qblox builds control stacks with the highest channel density, record-low noise levels and advanced error decoding capabilities to overcome these challenges.

Plenary talk on Quantum Computation

Monday, 18 November - 14:00 - 14:45

Quantum software: capabilities, challenges, and a path to trustworthiness

Laura Mančinska
University of Copenhagen

Quantum hardware is advancing rapidly, but its true potential can only be realized through tailored quantum algorithms, protocols, and software that harness the power of quantum bits. In this talk, I will explore the expected impact of quantum technologies on computation, communication, and cryptography. I will also discuss device-independent quantum software and how it addresses the challenge of reliably operating untrusted quantum devices and keeping our data secure.

Panel discussion: Widening Participation in Quantum Technologies

Monday, 18 November - 14:45 – 15:30

Chair: **Enrique Sánchez** (Quantum Community Network, Quantum Flagship)

Ticijana Ban (Institute of Physics, Zagreb)

Konrad Banaszek (National Science Centre Poland)

Radu Ionicioiu (IFIN-HH - National Institute of Physics and Nuclear Engineering)

Rui Semide (Entangled Space)

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Panel discussion:
Quantum Education & Workforce Development

Monday, 18 November - 16:00 – 16:45

Chair: **Jacob Sherson** (Aarhus University)

16:00 - **Rainer Müller** (TU Braunschweig): Recent advances in quantum education and workforce development

16:10 - Introductory statements:

Maria Bondani (CNR - Istituto di fotonica e nanotecnologie)

Aurél Gábris (Czech Technical University in Prague)

Araceli Venegas-Gomez (Qureca)

16:20 - Panel discussion on Quantum Technologies Education & Workforce Perspectives

PITCH TALKS
Monday 18 November

16:45 – 17:30

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Pitch Talks from Exhibitors & Sponsors

Monday 18 November, 16:45 – 17:30

NVision Imaging Technologies GmbH

AMIRES

Baden-Württemberg International

CERN

Delft Circuits

DEMCON high-tech systems

Dynex Moonshots

EURAMET EMN-Q European Metrology Network for Quantum Technologies

Fraunhofer Institute for Applied Optics and Precision Engineering IOF

Kwan-Tek

PQI – Portuguese Quantum Institute

Qblox

QPerfect

Qruise

Quantum Industries GmbH

Quantum Technology Laboratories (qtlabs)

QuantWare

Quobly

Qutools

SingleQuantum

ThinkQuantum srl

Conference Dinner: Special after dinner talk

Monday, 18 November – 19:45, Pátio da Galé

Some aspects of the history of Portugal that should interest scientists of today.

Henrique Leitão

University of Lisbon

The history of Portugal is closely linked to sea voyages and maritime expansion in the 16th century. Interestingly, these historical events had a significant scientific and technical dimension. In this presentation, I will try to show that some of the scientific challenges faced during that period and the solutions implemented at the time are still of interest to scientists today. This is a light-hearted – but rigorous – presentation for those who are scientifically-minded and curious about the history of Portugal.

DAY 2 - TUESDAY 19 NOVEMBER

Plenary talk on Quantum Simulation

(Tuesday, 19 November - 09:00 - 09:45)

Quantum computing and simulation in the presence of errors

Ignacio Cirac

Max Planck Institute of Quantum Optics

Quantum computing and related technologies are grounded in a robust understanding of quantum physics, yet their potential remains largely untapped without further innovation and development. To fully harness the capabilities of these technologies, we must also address fundamental questions, including the creation of scalable hardware, the development of advanced error correction codes, a deeper comprehension of the factors that differentiate quantum and classical computing, and the development of new quantum algorithms. In this talk, we will review these critical questions and highlight recent advancements regarding some of them. Specifically, we will examine the feasibility of achieving quantum computational advantages in simulation in the presence of errors.

Panel discussion: Innovation in Quantum Technologies

Tuesday, 19 November – 09:45 – 10:30

Chair: **Carlos Kuchkovsky** (QCentroid)

Salvatore Cinà (CEA - Commissariat a l'Energie Atomique et aux Energies Alternatives)

Sebastian Etcheverry (Luxquanta)

Thomas Ferré (EIB/EIC)

Emily Meads (Quantonation)

Plenary talks on Pilot Lines for Quantum Technologies

Tuesday, 19 November - 11:00 - 12:00

Chair: **Laure Le Bars** (SAP & QuIC)

Introduction, **Laure Le Bars** (SAP & QuIC)

Christian Trefzger (European Commission): Quantum Pilot Lines: The EU approach

Mika Prunnila (VTT): QU-PILOT

Gabriele Bulgarini (TNO): QU-TEST: open testing and experimentation for quantum technologies in Europe

Quantum Pilot Lines: The EU approach

Christian Trefzger

European Commission

The European Union is driving innovation in quantum technologies through a robust ecosystem and strategic initiatives.
The Quantum Flagship program, including the projects QU-PILOT and QU-TEST, fosters cutting-edge research and application development.
The EU Chips Act and the Chips for Europe Initiative focus on accelerating quantum chip production, a key enabler for next-generation technologies.
Through the Chips Joint Undertaking (JU), the EU has launched calls for quantum pilot lines, advancing industrial scalability and strengthening Europe's leadership in quantum and semiconductor innovation.
In my talk, I will discuss these efforts that collectively pave the way for transformative progress in quantum technologies.

QU-PILOT

Mika Prunnila

VTT

In this communication we introduce Qu-Pilot Europen Quantum Flagship project. The project is intimate part of European strategic actions in quantum technologies and quantum chips. We dive into the project's overall approach and recent developments of internal and external industrial use-cases. In the latter we have just closed an open call that brings Qu-Pilot manufacturing technologies to disposal of European quantum industry.
Further details about Qu-Pilot can be found from our www-page https://qu-pilot.eu that we manage jointly with our twin project Qu-Test focusing on quantum component testing services. Qu-Pilot (and also Qu-Test) services can be found through pages https://ecosystem.qu-pilot.eu/technical-marketplace.

QU-TEST: open testing and experimentation for quantum technologies in Europe

Gabriele Bulgarini

TNO

LUNCH TALKS
Tuesday 19 November

12:10 – 13:20

Lunch Talks

Tuesday, 19 November - 12:00 – 13:30

1. 12:10 - **Kwan-Tek:** KWAN-TEK's solutions in Education and Quantum Metrology
2. 12:20 – **PQI – Portuguese Quantum Institute:** The International Year of Quantum 2025
3. 12:30 - **Qperfect:** Large-Scale Tensor Network Simulations of Error-Corrected Quantum Circuits with MIMIQ
4. 12:40 - **Qruise:** Physics-based AI - accelerating R&D of new hard tech
5. 12:50 - **Quantum Flagship:** Quantum Technologies in Europe
6. 13:00 - **Quantum Industries GmbH:** Enabling secure quantum networks with entanglement-based QKD
7. 13:10 - **Quantum Internet Alliance (QIA):** Quantum Network Explorer

   13:20 - *End*

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KWAN-TEK

KWAN-TEK's solutions in Education and Quantum Metrology

PQI – Portuguese Quantum Institute

The International Year of Quantum 2025

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QPerfect

Large-Scale Tensor Network Simulations of Error-Corrected Quantum Circuits with MIMIQ

We discuss how QPerfect's Matrix-Product-States (MPS) simulator, MIMIQ, can be used to simulate practically relevant logical circuits with 100s of qubits in minutes. Since MPS is a universal simulator, it can simulate both Clifford and non-Clifford operations, allowing to study realistic noise and universal error-corrected algorithms. This can help understand the effect of different hardware and algorithmic choices on the final performance of QEC, and lead to the co-development of better solutions in the road towards fault tolerance.

Qruise

Nicu Becherescu

Physics-based AI - accelerating R&D of new hard tech

Qruise is developing an AI-powered simulation software aimed at enhancing the performance and reliability of quantum devices. In essence, we are creating an "AI physicist" designed to integrate AI into quantum labs, augmenting the capabilities of human researchers and accelerating the development of new technologies. Our simulations are designed to close the reality gap between the digital representation of the hardware and the actual hardware by utilizing differentiable simulations that can learn, improve, and predict real system behavior.

Quantum Flagship

Quantum Technologies in Europe

Quantum Industries

Fully connected quantum networks with Quantum Industries
Enabling secure quantum networks with entanglement-based QKD

Quantum Industries offers entanglement-based quantum networks with up to 20 users. In such a network, every user shares quantum information with every other one by establishing only a single fiber connection to a central server. Therefore, the equipment resources required for the network scale linearly with the number of users (instead of quadratically, as they would for point-to-point connections). Our network solution is ideally suited for sharing entanglement in metropolitan networks, e.g. for entanglement-based Quantum Key Distribution (eQKD).

QIA

Quantum Network Explorer

How can quantum technology be made accessible to people from broad and varied backgrounds? We present the Quantum Network Explorer (QNE), an open platform designed to enable users to explore, learn, and innovate with quantum networks. Featuring powerful simulation tools and an intuitive interface, QNE reveals the potential of quantum networks. Our high-level application development kit (ADK) and Community Application Library empower users to develop and share ideas, inviting a collaborative vision for future applications in quantum networking.

Plenary talks on Quantum Communication and Networks

Tuesday, 19 November - 13:30 – 14:30

Chair: **Eleni Diamanti** (Centre National de Recherche Scientifique, Sorbonne University)

Christoph Marquardt (Friedrich-Alexander-Universität Erlangen-Nürnberg and Max Planck Institute for the Science of Light): Practical Aspects of Quantum Safe Networks in Space and on Ground

Stephanie Wehner (TUDelft)

Julien Laurat (Sorbonne University): Quantum Networking with Cold-Atom Optical Memories

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Practical Aspects of Quantum Safe Networks in Space and on Ground

Christoph Marquardt

Friedrich-Alexander-Universität Erlangen-Nürnberg and Max Planck Institute for the Science of Light

I will highlight practical aspects concerning architecture and implementations of quantum safe networks.
These need to fulfil several conditions as security considerations, upgradability, resilience and also economical aspects. I will show some examples from two German national quantum communication projects: QuNet, which aims at developing technology and architecture towards government use cases and QUBE, which recently launched a nano satellite to test quantum communication in space. These projects generate natural synergy with European level projects as those from EuroQCI and the quantum flagship project QSNP that aim at quantum safe networks. The lesson learned in these projects is the need for highly interdisciplinary research and addressing different aspects of near and long term challenges at the same time.

Stephanie Wehner

TUDelft

Quantum Networking with Cold-Atom Optical Memories

Julien Laurat
Sorbonne University

Panel discussion:
HPC and Quantum Computation in the EU

Tuesday, 19 November - 14:30 – 15:15

Chair: **Julia Feddersen** (Quantum Delta NL)

Jacques-Charles Lafoucrière (CEA - Commissariat a l'Energie Atomique et aux Energies Alternatives)

Irene López de Vallejo (Fundación CTIC)

Matteo Mascagni (EuroHPC-JU, European Commission)

Stephan Schächer (Infineon Technologies AG)

Panel discussion: EuroQCI, the European Quantum Communications Infrastructure

Tuesday, 19 November - 14:30 – 15:15

Chair: **Felix Wissel** (Deutsche Telekom)

Keith Elder (PETRUS/Nostradamus)

Augusto Fragoso (ANACOM - Portuguese Telecom Regulator)

Harald Hauschildt (ESA - European Space Agency)

Josef Lazar (Technical University Brno and Palacký University Olomouc)

Ingrid Linnas (Estonian State Telecom)

Aymard de Touzalin (European Commission)

Panel discussion: Quantum Sensing & Infrastructures

Tuesday, 19 November - 14:30 – 15:15

Chair: **Philippe Bouyer** (Quantum Delta NL)

Camille Janvier (Exail)

Damian Markham (CNRS, Sorbonne University)

Marvin Reich (GFZ Potsdam)

Panel discussion:
Quantum for Society: a diverse community contributing to sustainability

Tuesday, 19 November - 14:30 – 15:15

Chair: **Clifford Murray** (VDI Technologiezentrum)

Natalia Bruno (CNR)

Pieter Vermaas (TU Delft, Quantum Delta NL and PQI - Portuguese Quantum Institute)

Raja Yehia (ICFO)

Shaeema Zaman (Science Melting Pot)

Parallel Session: Basic Science and New Directions for Quantum Technologies

Tuesday, 19 November - 14:30 – 15:15

Ivan Favero: Towards an atomic force probe operating in the quantum regime

Marco Pezzutto: Towards energetic quantum advantage in trapped-ion quantum computation

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Towards an atomic force probe operating in the quantum regime

Ivan Favero
Université Paris Cité, CNRS

We will discuss our efforts towards the realization of a mechanical probe capable of detecting atomic forces with a resolution fixed by the mere quantization of its vibrational energy. This idea draws on the concepts and tools of quantum optomechanics to implement phonon counting experiments, while transforming optomechanical resonators into all-optically controlled atomic force probes.

Towards energetic quantum advantage in trapped-ion quantum computation

Marco Pezzutto
Istituto Nazionale di Ottica - CNR, Florence, Italy and
PQI – Portuguese Quantum Institute, Lisbon, Portugal

The question of the energetic efficiency of quantum computers has gained some attention only recently. A precise understanding of the resources required to operate a quantum computer with a targeted computational performance and how the energy requirements can impact the scalability is still missing.
In this work, one implementation of the quantum Fourier transform (QFT) algorithm in a trapped ion setup was studied. The main focus was to obtain a theoretical characterization of the energetic costs of quantum computation.
The energetic cost of the experiment was estimated by analyzing the components of the setup and the steps involved in a quantum computation, from the cooling and preparation of the ions to the implementation of the algorithm and readout of the result. A potential scaling of the energetic costs was argued and used to find a possible threshold for an energetic quantum advantage against state-of-the-art classical supercomputers.

Plenary Talks on Standardisation on Quantum Technologies

(Tuesday, 19 November - 15:45 - 16:30)

Chair: **Florent Staley** (CEA - Commissariat a l'Energie Atomique et aux Energies Alternatives)

Standardisation on quantum technologies, **Florent Staley** (CEA - Commissariat a l'Energie Atomique et aux Energies Alternatives)

Business Involvement in Standardization Activities : How, Why, and Key Issues at Stake, **Alexandra Paul** (Pasqal)

Supporting the quantum technologies standardization through measurement and testing, **Ivo Pietro Degiovanni** (INRIM, EURAMET EMN-Q)

Standardisation on quantum technologies

Florent Staley

Commissariat a l'Energie Atomique et aux Energies Alternatives

Business Involvement in Standardization Activities : How, Why, and Key Issues at Stake,

Alexandra Paul

Pasqual

Supporting the quantum technologies standardization through measurement and testing

Ivo Pietro Degiovanni

INRIM, EURAMET EMN-Q

Driven by recent great advances achieved in research laboratories, the technologies emerging from the second quantum revolution are now considered strategic for commerce and traditional markets, with large companies and start-ups that have begun to develop and integrate quantum devices into their lines of products.

Increasing trust in these technologies is crucial to their success. This path in turn is based on test, validation and certification processes, defined on internationally agreed standards and on metrological traceability, implemented by independent experts.

The European National Metrology Institutes organized in the European Metrology Network for Quantum Technologies (EMN-Q), together with key European RDOs and academic institutions are developing measurement and testing facilities, also in the context of the project Qu-Test, that are the seeding the creation of a European quantum measurement and testing infrastructure. Such an infrastructure aims at supporting quantum technologies innovation and the development of new quantum technologies products and their successive commercialisation, also through developing the tests and measurements required to demonstrate that the quantum products are standards compliant.

In general, the EMN-Q members and the RDOs are actively promoting and contributing to the quantum technologies standardization effort, including regular and constructive dialogues with relevant standardization organizations, so that the needs of these organizations can be accommodated. This will ensure that industry and R&D take up the metrology tools offered at an early stage and ultimately provide assurance to end-users that their devices have been appropriately certified against standards.

Parallel Session: Quantum Software

Tuesday, 19 November - 16:30 – 17:30

Stacey Jeffery: Composing quantum subroutines

András Gilyèn: A quantum speed-up for approximating the top eigenvectors of a matrix

Miguel Murça: On Limited Fault-Tolerant Quantum Computers

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Composing quantum subroutines

Stacey Jeffery

CWI - Centrum Wiskunde & Informatica

Subroutines are ubiquitous in classical programs, making algorithms easier to design, analyze, and implement. Quantum algorithms can also have subroutines, but it is not as straightforward to think about them. For example, what is the complexity of a superposition of calls to different subroutines, with different running times? With the right way of looking at quantum programs, these difficulties can be overcome, and we can even get something that is not possible with classical programs: composing bounded-error algorithms without incurring log factor overhead.

In this talk, I will discuss joint work with Aleksandrs Belovs and Duyal Yolcu.

A quantum speed-up for approximating the top eigenvectors of a matrix

András Gilyèn

Rényi Institute

Finding a good approximation of the top eigenvector of a given $d \times d$ matrix A is a basic and important computational problem, with many applications. We give two different quantum algorithms that, given query access to the entries of a Hermitian matrix A and assuming a constant eigenvalue gap, output a classical description of a good approximation of the top eigenvector: one algorithm with time complexity ~O(d^1.75) and one with time complexity d^{1.5+o(1)} (the first algorithm has a slightly better dependence on the ℓ_2-error of the approximating vector than the second, and uses different techniques of independent interest).

Both of our quantum algorithms provide a polynomial speed-up over the best-possible classical algorithm, which needs Ω(d^2) queries to entries of A, and hence Ω(d^2) time. We extend this to a quantum algorithm that outputs a classical description of the subspace spanned by the top-q eigenvectors in time qd^{1.5+o(1)}. We also prove a nearly-optimal lower bound of ~Ω(d^1.5) on the quantum query complexity of approximating the top eigenvector.

Our quantum algorithms run a version of the classical power method that is robust to certain benign kinds of errors, where we implement each matrix-vector multiplication with small and well-behaved error on a quantum computer, in different ways for the two algorithms. Our first algorithm estimates the matrix-vector product one entry at a time, using a new ``Gaussian phase estimation'' procedure. Our second algorithm uses block-encoding techniques to compute the matrix-vector product as a quantum state, from which we obtain a classical description by a new time-efficient unbiased pure-state tomography procedure.

Joint work with: Yanlin Chen and Ronald de Wolf

On Limited Fault-Tolerant Quantum Computers

Miguel Murça
PQI – Portuguese Quantum Institute and
Instituto Superior Técnico, Universidade de Lisboa, Portugal

While not a realistic model of current noisy quantum computers, limited fault-tolerant quantum circuits provide insight on the possible power of noisy computers, while remaining theoretically tractable. This limitation can be imposed on, for example, the number of queries allowed to be performed coherently. In this talk, we present some results on query-limited quantum computers, drawing connections to Quantum Signal Processing [Low, Chuang, 2019]. Namely, we discuss a method that leverages QSP to establish families of hybrid algorithms admitting variable coherent query limitations. We then present some prospective results that go beyond the query model. We do so by drawing from connections to Quantum Singular Value Transformations [Gilyén et al., 2019] and dequantization results [Tang, 2019]. We define an access model that is economical, and amenable to both classical and quantum agents. We show that this access model is both compositional and computationally useful. Finally, we illustrate this with an application to distributed inner product estimation.

Parallel Session: Quantum Simulation

Tuesday, 19 November - 16:30 - 17:30

Chair: **João Seixas** (PQI & IST, ULisbon)

Emergent quantum simulators, **Jörg Schmiedmayer** (TU Wien)

Quantum and quantum-inspired simulations of lattice gauge theories, **Simone Montangero** (Padova University)

Gadgets and scalability for analogue quantum simulators, **Dylan Harley** (University of Copenhagen)

Emergent quantum simulators

Jörg Schmiedmayer
Vienna University of Technology

Quantum Simulation promises insight into quantum physics problems which are beyond the ability to calculate with conventional methods. Quantum simulators can be built either using a 'digital' Trotter decomposition of the problem or by directly building the Hamiltonian in the lab and performing 'analogue' experiments. I will present here a different approach, by which the model to simulate emerges naturally from a completely different microscopic Hamiltonian. I will illustrate this in the example of the emergence of the Sine-Gordon quantum field theory from the microscopic description of two tunnel coupled super fluids [1] and in the emergence of Fermionic Pauli blocking in a weakly interacting Bose gas [2]. Special emphasis will be put on how to verify such emergent quantum simulators and how to characterize them through the evaluation of the quantum effective action of the emerging quantum field theory [3] and by learning the emerging Hamiltonian [4]. Together they establish general methods to analyse quantum systems through experiments and thus represents a crucial ingredient towards the implementation and verification of quantum simulators.

[1] T. Schweigler et al., Nature **545**, 323 (2017), arXiv:1505.03126
[3] F. Cataldini et al. Phys. Rev. X **12**, 041032 (2022)
[3] T. Zache et al. Phys. Rev. X **10**, 011020 (2020)
[4] R. Ott et al., arXiv:2401.01308

Quantum and quantum-inspired simulations of lattice gauge theories

Simone Montangero
University of Padova

We review some recent results on the development of efficient tree tensor network algorithms and their applications to high-dimensional many-body quantum systems. In particular, we present recent results on two and three-dimensional lattice gauge theories in presence of fermonic matter at finite densities. Moreover, we show how to compute the entanglement of formation in critical many-body quantum systems at finite temperature, resulting in the generalization of the logarithmic formula for entanglement to open systems. We present one and two-dimensional simulations of out of equilibrium dynamics and how to implement them on different quantum simulation platforms. Finally, we present a resources estimations for quantum and quantum-inspired for future simulation of lattice gauge theories.

Gadgets and scalability for analogue quantum simulators

Dylan Harley

University of Copenhagen

Analogue quantum simulation, the use of one quantum system to mimic another, is both a promising near-term use case for quantum technology and a mathematically rich area of study. Its applicability hinges on the central question: which sorts of systems can actually simulate one another? In the context of Hamiltonian complexity theory, it is known that lots of very simple families of Hamiltonians are expressive enough to capture all of many-body physics. In this work, we discuss whether these conclusions still hold when one imposes the physically reasonable requirement of bounded-strength interactions, which is necessary for any scalable implementation in a lab. By developing a theory of Hamiltonian gadgets used widely in complexity theory, we prove that locality reducing gadgets cannot possibly satisfy this constraint — this creates a fundamental barrier for realistic simulators. Moreover, we discuss a general mathematical framework for analogue quantum simulators which captures the full scope of experimentally realisable devices, based on criteria introduced by Cirac and Zoller. In this broader setting, where we allow ourselves the additional resource of engineered dissipation, we demonstrate a scheme which partially circumvents the locality reduction no-go theorem by using the quantum Zeno effect.

This talk is based on arXiv:2306.13739, which is joint work with Ishaun Datta, Frederik Ravn Klausen, Andreas Bluhm, Daniel Stilck França, Albert Werner, and Matthias Christandl.

Parallel Session: Quantum Networks

Tuesday, 19 November - 16:30 - 17:30

Chair: **Julien Laurat** (Sorbonne University)

An entanglement-based quantum network test-bed for QKD applications, **Djeylan Aktas** (Slovak Academy of Sciences)

Stephanie Barz (University of Stuttgart)

Quantum networks utilizing multipartite entanglement, **Wolfgang Dür** (University of Innsbruck)

An entanglement-based quantum network test-bed for QKD applications

Djeylan Aktas

IP SAS - Slovak Academy of Sciences

Quantum Key Distribution (QKD) promises an unconditional security based on the laws of quantum physics ensuring that eavesdroppers cannot retrieve key information without introducing detectable errors. This allows for two remote parties to share lists of private random bits, called Private Key Exchange (PKE), which are essential primitives to advanced encryption standards protocols. As of late, recent work has demonstrated that entanglement-based QKD is one of the most suitable candidates for creating fully connected topologies, which greatly reduces the overhead cost of adding a new user to a bespoke network. We plan to develop this quantum technology to maturity in order to secure critical infrastructures.

Stephanie Barz

University of Stuttgart

Quantum networks utilizing multipartite entanglement

Wolfgang Dür

University of Innsbruck

Coupling quantum devices opens new possibilities, and allows one to unlock their full potential. Such quantum networks exist at different scales, and we describe methods to realize and operate them. We show how multipartite entangled states can serve as a valuable resource to fulfill network requests on demand [1]. Such entanglement-based or entanglement assisted quantum networks offer new features such as speeding up network requests, and network optimization independent of the underlying physical structure [2]. We show how to simulate, design and optimize such entanglement-based networks, and study their performance under noise. To this aim, we introduce efficient classical simulation methods [3] that we utilize to study networks with thousands of nodes [4,5]. We also outline how present-day quantum computers can be used to simulate and optimize large-scale quantum networks.

[1] Julia Freund, Alexander Pirker and Wolfgang Dür, Phys. Rev. Research 6, 033267 (2024), Flexible quantum data bus.

[2] Jorge Miguel-Ramiro, Alexander Pirker and Wolfgang Dür, Quantum 7, 919 (2023); Optimized quantum networks.

[3] Maria-Flors Mor-Ruiz and Wolfgang Dür, Phys. Rev. A 107, 032424 (2023); Noisy stabilizer formalism.

[4] Maria-Flors Mor-Ruiz and Wolfgang Dür, IEEE Journal on Selected Areas in Communications 42, 1793 (2024); Influence of noise in entanglement-based quantum networks.

[5] Maria-Flors Mor-Ruiz, Julius Wallnöfer and Wolfgang Dür, E-print arXiv:2403.19778, Imperfect quantum networks with tailored resource states.

Parallel Session:
Basic Science and Future Directions for Quantum Technologies

Tuesday, 19 November - 16:30 - 17:30

Chair: **Markus Arndt**

Chiara Macchiavello: Multiple-observable entropic uncertainty relations and complementarity

Julen Pedernales: Levitated force sensors as a platform to test fundamental aspects of gravity

Ekkehard Peik: Laser excitation of the Th-229 nucleus - towards a nuclear clock

Multiple-observable entropic uncertainty relations and complementarity

Chiara Macchiavello

University of Pavia

We review the concepts of entropic uncertainty relations (EUR) and consider the case of multiple observables. We investigate the corresponding additivity properties for both bipartite and multipartite systems where the EUR are defined in terms of the joint Shannon entropy of probabilities of local measurement outcomes. We show that the additivity of EUR holds only for EUR that involve two observables, while this is not the case for inequalities that consider more than two observables or the addition of the von Neumann entropy of a subsystem.

Moreover, we address also the case of a single high dimensional system and show that the amount of complementarity that a quantum system can exhibit depends on which complementary properties one is considering. Complementary properties can be connected to mutually unbiased bases (MUBs): if the value of one property is known (i.e. the system state is in one of the basis states), then the complementary properties are completely unknown: the measurement of another property will find any of its possible outcomes with uniform probability. We show that a 5-dimensional system can have different degrees of complementarity, depending on which three of the six MUBs we choose. The degree of complementarity is assessed using EUR and variance. Interestingly, this result was first found and demonstrated experimentally.

Levitated force sensors as a platform to test fundamental aspects of gravity

Julen Pedernales

Ulm University

Recent advancements in the quantum control of solids suspended in a vacuum, each containing billions of atoms, have established a novel, quantum platform in the large-mass regime of quantum mechanics, with applications ranging from force sensing to fundamental tests of physics. Although very challenging, one particularly exciting application is the possibility of testing gravity in unprecedented regimes. In particular, enabled by their high mass density and exceptional sensitivity to external forces, it is predicted that such systems will be able to detect gravitational forces sourced by matter in quantum states. In this regard, the notion of "gravitationally induced entanglement" between two levitated objects has gained considerable attention in recent years as a potential experimental pathway for probing semiclassical models of gravity that cannot produce entanglement. In my talk, I will explore the potential of these levitated quantum platforms as exceptionally precise force sensors, focusing on their prospects for falsifying several semiclassical gravity models. To this end, I will introduce a novel approach that tests LOCC-based gravity models without requiring the generation of gravitationally mediated entanglement, thereby reducing the experimental demands of these tests.

[1] J. S. Pedernales and M. B. Plenio, *On the origin of force sensitivity in tests of quantum gravity with delocalised mechanical systems,* Contemporary Physics, 64:2, 147-163 (2023).

[2] L. Lami, J. S. Pedernales, M. B. Plenio, *Testing the quantum nature of gravity without entanglement*, Phys. Rev. X 14, 021022 (2024).

Laser excitation of the Th-229 nucleus - towards a nuclear clock

Ekkehard Peik

PTB – the National Metrology Institute in Germany, Braunschweig

Motivated by the prospect of building a nuclear clock, we have demonstrated laser excitation of the low-energy (8.4 eV) nuclear isomer in Th-229, using Th-doped calciumfluoride crystals and a tabletop tunable laser system at 148 nm wavelength. A nuclear resonance fluorescence signal has been observed in two crystals with different Th-229 dopant concentrations, while it was absent in a control experiment using a crystal doped with Th-232.
The isomer radiative lifetime in the crystal is 630(15) s, corresponding to an isomer half-life of 1740(50) s for a nucleus isolated in vacuum. These results open the door towards applications like laser Mößbauer spectroscopy and ideas of "quantum nucleonics". A highly precise nuclear clock would show high sensitivity to "new physics" for example in tests of the Einstein equivalence principle.

This is work done in a cooperation of PTB and TU Wien: J. Tiedau et al., Phys. Rev. Lett. 132, 182501 (2024)

DAY 3 - WEDNESDAY 20 NOVEMBER

Plenary talk on Quantum Sensing & Metrology

Wednesday, 20 November – 09:00 – 10:00

Space, time, and temperature - new considerations in quantum sensing of fields

Morgan Mitchell
ICFO

As quantum sensing and metrology extend their reach in challenging applications such as brain imaging, materials characterization and non-destructive battery testing, new figures of merit emerge, figures of merit that combine sensitivity with other key factors such as spatial resolution and bandwidth. In magnetic sensing, for which the situation has been most extensively studied, both experimental results and detailed noise models suggest that new quantum limits govern such figures of merit. These limits are consistent with the well-known standard quantum and Heisenberg limits, but incorporate many-body features such as two-body interaction of sensing particles, and arrive at number-resource-independent quantum limits. I will describe the nature of such “energy resolution" limits, their origin in sensor self-interaction effects, and non-traditional sensing methods that may escape these limits. As a proof-of-principle, I will describe our work with a spinor Bose-Einstein condensate to escape the energy resolution limit, and speculate about future technologies that build upon this new perspective in quantum sensing.

Special session on Benchmarking of Quantum Computing

Wednesday, 20 November - 10:00 – 12:15

Jeanette Lorenz: Application-driven benchmarking of quantum computers – what benchmarking tells us for the further development of quantum computing

Félicien Schopfer: The BACQ project as part of the European effort for quantum computing benchmarking

Shannon Whitlock: Application-oriented benchmarking of tensor networks as a challenge to future quantum computers

Zoltán Zimborás: Scalable volumetric benchmarks based on Clifford and free-fermion operations

Panel Discussion

Chair: **Frank Wilhelm-Mauch** (Saarland University)

Jeanette Lorenz (Fraunhofer IKS, Munich)

Yasser Omar (PQI & IST, ULisbon)

Félicien Schopfer (LNE, France)

Shannon Whitlock (University of Strasbourg)

Zoltán Zimborás (Wigner Research Centre for Physics)

Application-driven benchmarking of quantum computers – what benchmarking tells us for the further development of quantum computing

Jeanette Lorenz

Fraunhofer IKS, Munich

Although the development of quantum computing hardware and software is progressing fast with many papers appearing on arXiv daily, the advantage of using quantum computing for real-life (industry and academic) applications remains unclear.

Present quantum computers remain to be limited in the number of qubits, in the connectivity and are affected by noise, although we see first progress in the direction of fault-tolerant quantum computers being made.

Looking at the capabilities of quantum algorithms and hardware from the application side provides us with important information into which direction we should develop the technology further. In this context, an increasing number of application-centric benchmarks are developed that explicitly test the interplay between quantum hardware, software and algorithms. But these benchmarks need to be carefully crafted, need to be reproducible and need to come along with an evaluation procedure and sample datasets.

This talk first introduces as an example the German initiative Bench-QC – Application-driven benchmarking of quantum computers, to then put this into the bigger context of the newly established European Quantum Computing Benchmarking Coordination Committee, and closes with first recommendations from these coordination activities.

The BACQ project as part of the European effort for quantum computing benchmarking

Félicien Schopfer

LNE, France

As part of MetriQs-France, the National program on measurements, standards, and evaluation of quantum technologies, within the French national quantum strategy, the BACQ project is dedicated to application-oriented benchmarks for quantum computers [1]. The consortium gathering THALES, EVIDEN, CEA, CNRS, TERATEC, and LNE aims at establishing a set of recognized benchmarks close to real applications and meaningful for industrial end-users, for objective multicriteria evaluation of the practical performance of any type of quantum computer. The methodology encompasses the definition of reference problems to be solved (simulation of quantum physics, optimization, linear system solving and factorization), of technical metrics related to their resolution (computation time, problem size, accuracy, fidelity, Q-score, energetic consumption…), as well as the aggregation and analysis of these metrics using a dedicated model, Myriad-Q, providing high-level operational indicators. The final notation allows comparisons between different quantum computers and with classical computers, as well as reliable evaluation of progress towards useful quantum computing. This project is part of the European effort now coordinated within the recently established European quantum computing benchmarking coordination committee (EQCBC). Indeed, collaborations are key to address all the challenges of quantum computing benchmarking and to contribute significantly to this important topic. In addition, standardization, within e.g., CEN-CENELEC JTC22 and IEC/ISO JTC3, is considered to support progress towards globally harmonized and recognized quantum computing benchmarking protocols providing reproducible, transparent, and comparable results.

[1] https://arxiv.org/pdf/2403.12205

Application-oriented benchmarking of tensor networks as a challenge to future quantum computers

Shannon Whitlock

University of Strasbourg

Utility-scale quantum computing refers to quantum computers that are powerful and reliable enough to solve real-world problems that classical computers cannot. However, advancements in quantum emulation, particularly through tensor-network methods, enable efficient simulation of quantum algorithms with hundreds of qubits and high entanglement on classical computers, making the concept of ``quantum utility'' a moving target. For this reason we present comprehensive benchmark results on utility scale quantum emulators for evaluating complex quantum algorithms with 100 qubits or more. This provides insights into the performance of such emulators on real-world quantum computing tasks, highlights possible areas to improve performance and applicability of quantum emulators and sets a reference point for application oriented benchmarking of quantum computer systems beyond the limits of classical computing.

Scalable volumetric benchmarks based on Clifford and free-fermion operations

Zoltán Zimborás

HUN-REN Wigner Research Centre for Physics

The present generation of quantum computers spans diverse platforms with qubit counts approaching the limits of classical simulation. Benchmarking these processors requires a scalable, platform-independent approach. We propose a volumetric benchmarking framework based on randomly sampling operations from two important groups of unitaries: The Clifford and the free-fermion groups, that are both separately classically simulable but together yield a universal gate set. A key strength of the proposed benchmark framework lies in its inherent flexibility: Our approach avoids platform-specific rules, enabling the benchmark circuits to be optimized directly for the device being tested. Moreover, these benchmarks are application-oriented, due to the importance of these operations in various tasks such as shadow tomography and quantum chemistry simulations. Our framework is based on measuring appropriate fidelity witnesses thereby eliminating the need for a general state tomography—a process that would otherwise require an exponential number of measurements as the number of qubits increases.

LUNCH TALKS
Wednesday, 20 November

12:15 – 13:15

Lunch Talks

Tuesday, 20 November - 12:00 – 13:30

1. 12:15 - **Quantum Technology Laboratories (QTLabs):** Satellite-based quantum communication
2. 12:25 - **QuantWare:** Engineering strategies to enable flexible superconducting qubit fabrication at scale
3. 12:35 - **Quobly:** Leveraging semiconductors for quantum computing
4. 12:45 - **Qutools:** Grasp the Spooky! Quantum Education by Qutools
5. 12:55 - **SingleQuantum:** SNSPDs - New developments, from the lab to the market
6. 13:05 - **ThinkQuantum srl:** NA

13:15 - *End*

QTLabs

Satellite-based quantum communication

We will provide an overview of satellite-based quantum communication systems. Starting from the basic ideas, we will present an overview past and recent developments in the field starting from free-space experiments to current quantum-communication space missions. This includes optical ground stations as the user segment and connection to terrestrial networks as well as space payloads for quantum communication. Both quantum key distribution (QKD) as well as more involved quantum communication applications (e.g. quantum internet) will be considered. We will round up by providing current state-of-the-art technology.

QuantWare

Engineering strategies to enable flexible superconducting qubit fabrication at scale

As superconducting quantum circuits grow increasingly complex, ensuring reliable and scalable fabrication becomes critical to advancing quantum hardware. In this presentation, we discuss key engineering strategies that enable our fabrication platform to meet these challenges. The core of the presentation delves into how we optimize Josephson junctions, ensuring cross-platform compatibility while maintaining precise control over critical parameters. We also present coherence results, focusing on T1 as implemented in realistic quantum processors, showcasing our capability to meet the demands of practical quantum computing applications.

Quobly

Jayshankar Nath

Leveraging semiconductors for quantum computing

Qutools

Slava Tzanova

Bridging Theory and Practice: Turnkey Quantum Devices for the Engineers of the Revolution

The second quantum revolution requires engineers equipped with practical experience in quantum mechanics, moving beyond simulations and theory alone. Key concepts—such as superposition, entanglement, and quantum interference—are abstract and resist intuitive understanding, demanding specialized tools for effective teaching. We propose that a project-based approach using turnkey quantum devices can bridge the gap between complex theory and practical skills, effectively preparing a new generation of engineers to lead in quantum technology across Europe.

Single Quantum

Mario Castaneda

SNSPDs - New developments, from the lab to the market

Contents

ThinkQuantum

Pannel Discussion:
Ethics and Disruptions of Quantum Technologies

Wednesday, 20 November - 13:30 – 14:30

Chair: **Pieter Vermaas** (TU Delft & PQI – Portuguese Quantum Institute)

13:30 - **Magda Cocco** (VDA - Vieira de Almeida & Associados)

13:50 - **Marco Lamonato** (ThinkQuantum)

14:10 - **Zeki Seskir** (Karlsruhe Institute of Technology)

Parallel Session: Quantum Computing Hardware

Wednesday, 20 November - 13:10 – 15:15*

*Note exceptional starting time to cover the 6 hardware platforms

Chair: **Shannon Whitlock**

Jay Nath: FDSOI platform for quantum computing

Anil Murani: Dissipative stabilization of a squeezed-like cat qubit

Christine Silberhorn: Photonic quantum technologies: from integrated quantum devices to designing large complex system

Christof Wunderlich: Laser-free universal entangling gates for trapped-ion quantum computing

Tilman Pfau: Novel qubits for the neutral atom platform

Milos Nesladek: Diamond quantum chips: towards scalable approaches

FDSOI platform for quantum computing

Jay Nath

Quobly

Si-based qubits are considered the most promising experimental system for scaling quantum computing. FDSOI CMOS technology is demonstrated as a platform to co-integrate spin qubits with cryo-electronics. Considering the requirement for quantum computing, Quobly's strategy is to design and engineer good qubits in a technology as close as possible to the most advanced industrial technological nodes. Advancement in qubit manipulation for both electrons and holes will be discussed, with demonstration of the elementary operations for running a quantum computer at µs-timescale and with state-of-the-art noise figure. For cryo-control, we show voltage gain as high as 75dB for long devices, noise of 10-11V2·µm2/Hz, and 1.29mV·µm threshold voltage variability. Based on these characteristics, realisation of elementary control and read-out based on FdSOI-cryoelectronic systems will be presented and their performance will be discussed. Different strategies for co-integration of qubit and control cryo-electronics will be presented and their realization will be discussed.

This research was supported by funding from the European Union under Horizon Europe programme, project MCSquare grant number 101136414.

Dissipative stabilization of a squeezed-like cat qubit

Anil Murani
Alice&Bob

Dissipative cat-qubits are a promising architecture for assembling a quantum processor due to their built-in quantum error correction properties. Owing to the two-photon dissipation, their bit-flip error rate is exponentially suppressed by a factor $\exp(-\gamma n)$ as the cat size n is increased, only at a linear cost in phase-flip rate. This results in a significant reduction of the number of qubits required for fault-tolerant quantum computation. A deformation of the basis states increasing their separation could result in a further reduction of the bit-flip error rate. In this work, we propose and implement a squeezing-like deformation of the cat qubit basis states, achieved with the same longitudinal interaction used to perform ancilla-free parity measurement. We demonstrate an unprecedented exponential suppression of the bit-flip error rate with a scaling factor up to $\gamma = 4$, at a limited cost in phase flip rate. We measure bit-flip times of 60s for a 1 μs phase flip time for a cat of size $n = 5$.Moreover, we demonstrate that squeezing also improves the qubit Rabi flopping performance, dividing the phase-flip rate by a factor two. This simple yet effective technique enhances cat qubit performances, and brings multi-cat architectures a step closer to the error correction threshold.

Photonic quantum technologies: from integrated quantum devices to designing large complex system

Christine Silberhorn

Integrated Quantum Optics, Department Physics, Institute for Photonic Quantum Systems (PhoQS), Paderborn University, 33098 Paderborn, Germany

Quantum technologies promise a change of paradigm for many fields of application, for example in communication systems, in high-performance computing and simulation of quantum systems, as well as in sensor technology. Current efforts in photonic quantum science target the implementation of practical devices and scalable systems, where the realization of quantum devices for real-word deployment and controlled quantum network structures is key for many applications.

Here we present our work on three different fields in this area: non-linear integrated quantum optics, pulsed temporal modes and photonic quantum computation.

Laser-free universal entangling gates for trapped-ion quantum computing

Christof Wunderlich

Universyt of Siegen

Trapped atomic ions are well suited to investigate fundamental questions of quantum physics that require access to, and detailed control of individual quantum systems. In addition, this physical platform has set standards for quantum information processing for decades. Here, a novel two-qubit entangling gate for radio frequency (RF)-controlled trapped-ion quantum processors is proposed theoretically and demonstrated experimentally. The speed of this double-dressed gate is an order of magnitude higher than that of previously demonstrated two-qubit entangling gates using magnetic gradient induced coupling (MAGIC) in a static gradient field. At the same time, the phase-modulated field driving the gate dynamically decouples hyperfine qubits in 171Yb+ ions from amplitude and frequency noise, increasing the qubits' coherence time by three orders of magnitude. The gate requires only a single continuous RF field per qubit, making it well suited for scaling a quantum processor to large numbers of qubits. Implementing this entangling gate, we generate Bell states in ≤ 313 μs with fidelities up to 98+2 −3 % in a static magnetic gradient of only 19.09 T/m. At higher magnetic field gradients in micro-structured ion traps, the entangling gate speed can be further improved to match that of laser-based counterparts.

Novel qubits for the neutral atom platform

Tilman Pfau
University of Stuttgart

In the first part of the talk, I will discuss our endeavor to realize a gate-based quantum computer involving a novel fine-structure qubit encoded in the metastable 3P0 and 3P2 states of strontium [1]. We have recently implemented this qubit for the first time and measured its coherence in a magic optical tweezer, which is enabled by tuning the tensor polarizability of the 3P2 via a control magnetic field.
In the second part I will present work on a novel Rydberg qubit encoded in circular states of strontium atoms in optical tweezers. Circular Rydberg states promise orders-of-magnitude longer lifetimes compared to their low-L counterparts, which allows for overcoming fundamental limitations in the coherence properties of Rydberg atom based quantum simulators. We have recently demonstrated efficient transfer into high-n circular Rydberg atoms with n=79, and showed trapping of the circular state enabled via the second available valence electron of the Sr atom [2]. These results open exciting prospects for exploiting the unique properties of two-valence electron atoms for quantum computation and simulation.

References

[1] G. Unnikrishnan et al., Phys. Rev. Lett. **132**, 150606 (2024)

[2] C. Hölzl et al., Phys. Rev. X **14**, 021024 (2024)

Diamond quantum chips: towards scalable approaches

Milos Nesladek

Institute for Materials Research, Hasselt University, imomec division, imec vzw, Weteschapspark 1, B 3591 Hasselt, Belgium

Diamond is considered one of the leading materials for quantum technologies operating at room temperature. This talk focuses on the key challenges in fabricating diamond quantum processors based on NV spin qubits in the solid state, in particular the scalability of the system in terms of the maturity of diamond NV technologies and the scalability of the readout. The talk discusses ultrapure diamond crystal CVD technology and the fabrication of individual NV qubits and presents the implications for color center properties such as coherence and charge states.

We compare methodologies for electrical and optical readout of spin states and related algorithms for high-fidelity 2-qubit gates for nuclear spin control and concepts for the construction of correlated states that can be used for both sensing and computation. Also, practical aspects as electrical signal amplifiers and integration on chip are discussed.

References:

1. Siyushev P., Nesladek M. et al Science, 363,728-731, (2019)
DOI: 10.1126/science.aav2789,

2. M. Gulka, D. Wirtitsch et al, Nature Comm., 12, 4421 (2021),
doi.org/10.6084/m9.figshare.14748138.v1.

Parallel Session:
Quantum Sensing

Wednesday, 20 November - 13:30 - 15:15

Chair: **Thierry Debuisschert**

Martin B. Plenio: Quantum technologies for metabolic MRI

Radim Filip: Quantum non-gaussianity

Nicole Fabbri: Diamond quantum magneto microscopy towards cardiac imaging

Fedor Jelezko: Quantum sensing at nanoscale enabled by diamond spin qubits

Florian Schreck: Optical atomic clocks

Quantum technologies for metabolic MRI

Martin B. Plenio

Ulm University & NVision Imaging Technologies

Magnetic resonance, a leading spectroscopic technique, is fundamentally limited by its low sensitivity due to the weak nuclear spin polarisation in thermal equilibrium. The most promising solution to this problem relies on nuclear spin hyperpolarisation which can enhance polarisation levels by up to five orders of magnitude. This has the potential to open the path towards metabolic imaging at physiologically relevant concentrations, promising major advances in cancer diagnostics and treatment.

This talk discusses key requirements for hyperpolarisation technologies and identifies parahydrogen-induced polarization (PHIP) as the most promising approach. PHIP involves a chemical reaction between parahydrogen and a target molecule, followed by the quantum control enabled transformation of nuclear singlet spin order into magnetisation of a designated target nucleus.

Quantum control methods are essential to PHIP. I will demonstrate the mathematical equivalence between PHIP and dynamical nuclear polarisation based on colour centers in diamond (NV-DNP). Based on this equivalence, I show that the PulsePol sequences originally discovered in NV-DNP can be translated to deliver exceptional robustness and efficiency for PHIP polarisation transfer in preclinical polarisers.

For clinical applications larger doses and higher concentrations are required which impose unexpected challenges due to the backaction of the demagnetisation field on the nuclei. This leads to non-linear, even chaotic dynamics and disrupts known quantum control sequences. This results in severe limits on the achievable product of polarisation and concentration. I introduce pulse sequences to overcome this challenge and present their experimental demonstration. This contributes to the development of commercially available clinical polarisers.

Quantum non-gaussianity

Radim Filip

Palacky Universit

The bosonic systems currently have applications in all pillars of quantum technology. This stimulates further studies of the fundamental features of bosonic states. The talk will present an overview of the theoretical and experimental development of quantum non-Gaussian states of many bosons, their generation, manipulation, detection, identification, scalability, and applications for different experimental platforms: nonlinear optics and cavity QED, microwaves in superconducting circuits, and mechanical motion of trapped ions. The particular focus will be on conclusive benchmarking and scalability of quantum non-Gaussian states of light, microwaves and mechanics in recent experiments.

Diamond quantum magneto microscopy towards cardiac imaging

Nicole Fabbri

CNR and LENS

Heart rhythm disorders are the leading cause of mortality globally. Yet, cardiac arrhythmias suffer from a very low predictability due to the difficulty in obtaining multiscale models of spatiotemporal dynamics. The MUQUABIS Project investigates synergetic quantum tools for sensing and imaging of cardiac processes, from molecule to cell to tissue scales. On one side we develop low-light-level spectro-imaging tools to detect cell-membrane proteins and gaseous metabolites nearby cell tissues, on the other side we develop a comprehensive quantum magnetic sensing and imaging platform based on NV centers in diamond, tailored for biological tissue investigation and potentiated by quantum control and deep learning tools. A newly built diamond quantum magneto-microscope has the goal of mapping the magnetic field originated from the activity of cardiac tissues and correlating it with voltage maps to investigate vortex excitations that are responsible of cardiac arrhythmias.

Quantum sensing at nanoscale enabled by diamond spin qubits

Fedor Jelezko

Institute of Quantum Optics, Ulm University, Germany

Synthetic diamond has recently emerged as a candidate material for a number of quantum applications, including quantum information processing and quantum sensing. In this talk, I will show how single nitrogen-vacancy (NV) colour centres can be created near the diamond surface and used as nanoscale sensors of electric and magnetic fields. I will also demonstrate novel dynamical decoupling techniques allowing to improve the sensitivity of diamond quantum sensors and discuss applications of small-scale quantum registers for nanoscale NMR. Applications of NV centres for hyperpolarisation of nuclear spins and application of optical spin polarisation in MRI will be presented.

Optical atomic clocks

Florian Schreck

University of Amsterdam

Optical clocks are amazingly stable frequency standards, which would remain accurate to within one second over the age of the universe, a precision of 10^-18. Bringing these clocks from the lab to the market offers great opportunities for telecommunications, navigation, sensing, and science. We participate in three developments to make this a reality.

1) The Quantum Flagship project AQuRA (Advanced Quantum Clock for Real World Applications) is developing a transportable strontium optical lattice clock. Industry partners are building and integrating most components. National metrology institutes and academic partners provide the physics package, benchmark the clock and apply it to geodesy and to radio astronomy.

2) Conventional optical clocks operate in a pulsed manner and need to average for hours to reach their ultimate precision. We develop continuously operating optical clocks, which promise to reach high measurement precision after minutes or alternatively to render transportable clocks more robust.

3) We participate in an initiative by GÉANT, the collaboration of European National Research and Education Networks, to create a European optical frequency distribution network, providing precise optical clock frequencies also to partners that do not operate their own optical clocks.

Parallel Session: Quantum Secure Communications

Wednesday, 20 November - 13:30 - 15:15

Chair: **Marco Avesani**

Tobias Gehring: Continuous-variable quantum key distribution for telecom access networks

Giuseppe Vallone: Development in satellite quantum communication

Mariana Ferreira-Ramos: Next-generation quantum cryptography: innovations beyond QKD and chiplet solutions for widespread integration

Johannes Pseiner: Developments in satellite-based quantum communication

Adomas Baliuka: A side channel attack on QKD sender electronics using convolutional neural networks

Continuous-variable quantum key distribution for telecom access networks

Tobias Gehring

University of Denmark

Continuous-variable quantum key distribution (CV-QKD) employs technology similar to coherent telecommunication to ensure future-proof distribution of encryption keys. An important aspect for the success of QKD is its integration into telecom access networks, such as passive-optical networks, where an access node exchanges secret keys with multiple end-nodes. In the down-stream configuration within a passive-optical network a transmitter connects to multiple receivers via an optical splitter. The wave-nature thereby allows the CV-QKD systems to simultaneously generate secret keys between the end-nodes and the access node. In this talk I will discuss an experiment involving 8 users and highlight how the new paradigm in CV-QKD, based on digital-signal-processing, supports these advancements.

Development in satellite quantum communication

Giuseppe Vallone
Padova University

Free-space and satellite links will be an integral part of future global quantum communication networks. Within the EU project QUDICE (www.qudice.eu), we report on the development of components and subsystems for quantum communication and optical systems for space-based QKD enabling the realization of a European network of satellites with quantum key distribution as the main service.

Next-generation quantum cryptography: innovations beyond QKD and chiplet solutions for widespread integration

Mariana Ferreira-Ramos

AIT - Austrian Institute of Technology

As global travel security and privacy issues continue to rise, the demand for robust and reliable identity verification systems has become crucial. Biometric systems are increasingly being adopted to secure borders at airports and other high-security sites. These systems play a key role for entities like national governments, which require effective methods for identity verification. In this context, multi-party computation is particularly well-suited, as it provides a solution that addresses both security and privacy requirements. This talk presents an experimental implementation of quantum oblivious transfer (QOT) as a critical building block for secure multi-party computation. We present the full-stack implementation of QOT, addressing all layers from physical hardware to application-level protocols. New experimental results validate the system's practicality and performance in a real biometrics application, while highlighting the challenges encountered and the solutions applied at each stage.

Additionally, we present a recent advancement in the integration of quantum key distribution (QKD) transmitters monolithically on a silicon platform. This enables seamless co-integration with classical electronic systems, reducing both cost and complexity. By adopting silicon-based QKD, we move toward making QKD a commodity technology, supporting its broader use in practical cryptographic applications. Our findings suggest that this approach offers a path to scalable, secure communication systems that can be deployed efficiently, advancing quantum-enhanced security in everyday technologies. The talk concludes by outlining potential applications and future directions for expanding the accessibility and practicality of quantum cryptography.

Developments in satellite-based quantum communication

Johannes Pseiner

QTLabs

Satellite-based quantum communication represents a frontier in achieving secure global data exchange, leveraging the advantage of lower photon loss in free-space optical links compared to traditional terrestrial fiber networks. Quantum Technology Laboratories GmbH (qtlabs) is at the forefront of this field, contributing advanced technologies and expertise to drive the successful deployment of a space-based quantum communication network. We are engaged in the development of high-performance quantum communication solutions such as Optical Ground Stations (OGS), space-qualified quantum sources, and free-space terrestrial links.

qtlabs is also actively involved in two major EU Horizon Europe projects, LaiQa and QuTechSpace. QuTechSpace is dedicated to advancing space-ready QKD technologies by enhancing high-brightness entangled photon sources, prepare-and-measure sources, and post-processing software, while achieving space qualification of key components and pushing towards European sovereignty in space quantum technology. Meanwhile, the LaiQa project aims to develop the critical components needed for a global space-based quantum network, including both entangled photon and prepare-and-measure sources, advanced photonic integration, and quantum memories for long-distance entanglement distribution. Efforts also focus on optimizing fiber-to-space coupling techniques, conducting field trials, and pioneering standardization initiatives to ensure interoperability across the European quantum ecosystem.

These initiatives underscore qtlabs' commitment to leading the transition from lab-scale experiments to fully deployable quantum communication systems in space. By combining in-house research expertise with international collaboration, qtlabs is poised to help establish a secure and resilient quantum communication infrastructure that extends beyond national borders, setting the stage for a future quantum internet.

Contents

A side channel attack on QKD sender electronics using convolutional neural networks

Adomas Baliuka

Ludwig-Maximilians-University of Munich

Parallel Session:
Quantum Computation and Artificial Intelligence

Wednesday, 20 November - 13:30 - 15:15

Chair: **Andris Ambainis** (University of Latvia)

Jens Eisert (Freie Universität Berlin)

Iordanis Kerenidis (CNRS): Quantum machine learning for algorithmic discovery

Philip Walther (University of Vienna): Photonic quantum computing and cybersecurity development

Philipp Slusallek (Saarland University): Quantum & AI: do we need a "CERN for AI"?

Panel discussion with the speakers

Jens Eisert

Freie Universität Berlin

Quantum machine learning for algorithmic discovery

Iordanis Kerenidis

CNRS

We define quantum intelligent agents that can be used in quantum supervised and reinforcement learning frameworks. We provide evidence of their learning capabilities by showing how they can discover a number of seminal quantum algorithms and protocols and in particular: efficient logarithmic-size quantum circuits for the Quantum Fourier Transform; Grover's search algorithm; optimal cheating strategies for strong coin flipping protocols; and optimal winning strategies for the CHSH and other nonlocal games. These results pave the way for a new paradigm in developing quantum algorithms and protocols through the aid of quantum intelligence and we expect they can be pushed much further to the development of novel quantum algorithms.

Photonic quantum computing and cybersecurity developments

Philip Walther
University of Vienna

After providing a brief overview of recent advancements in the generation and processing of multi-photon states, I will highlight the advantages of quantum dot sources for quantum cryptography, as well as applications that extend beyond the capabilities of quantum key distribution. Following this, I will explore the potential of photonic quantum machine learning by presenting quantum-enhanced reinforcement learning using a tunable integrated processor. Finally, I will discuss our development of a so-called quantum memristor for single photons. These devices, which can mimic the behavior of neurons and synapses, hold great promise for the realization of quantum neural networks.

I

Quantum & AI: do we need a "CERN for AI"?

Philipp Slusallek
Saarland University

Artificial Intelligence is currently developing at breakneck speed and is already influencing our lives in many areas: AI systems already understand and generate language, images and many other data amazingly well and can be used in a variety of ways. But what are their limits, how can we control and trust them? At the same time, Quantum Technologies are becoming more and more relevant and there is a strong link also to AI and its applications that we need to explore in more detail.
Ultimately, modern AI is opening up a completely new world whose laws we do not yet know. In view of the very direct effects on us all, do we not need a large-scale, joint European research program that systematically investigates the fundamental laws of this new world and makes them controllable and safe to use for all of us? Just as physicists have been doing with CERN for a long time? Don't we need a European “CERN for AI”? And which role should Quantum Computing and Quantum-AI play there?

EU Inauguration of the International Year of Quantum Science and Technologies and launch of the Quantum Cities initiative

Wednesday, 20 November - 15:45 – 16:45

Hyoung Joon Choi (Yonsei University)

Yasser Omar (IST and PQI)

Amal Kasry (UNESCO): Quantum Science and Technology: Building Capacity and Raising Awareness.

Announcement of EQTC 2025 & Closing Ceremony

Wednesday, 20 November - 16:45 – 17:00

POSTER SESSION
Monday, 18 November

17:45 - 18:45

Education & Outreach

Education & Outreach | Poster

A quantum physics exhibition: students and visitors engagement evaluation

Diana Tartaglia[1]; Costanza Toninelli[1,2]
1 - CNR-INO;
2 – Lens

The second quantum revolution is expected to bring new technologies in use in the next 5 to 10 years. Investments in Quantum Technology (QT) research in Europe and all over the world include outreach and educational actions towards several sections of the public in order to create awareness on the subject and interest that will hopefully lead to a quantum ready workforce.

In November 2023, CNR-INO organized an exhibition on quantum physics and the second quantum revolution that took place in Florence. The exhibition was part of the activities of the Italian Quantum Weeks National coordination, which celebrates the world quantum day in Italy with several events aimed to non scientists.The aim of the event organized in Florence was to engage students and the general public with the Institute's research focus and to share interest in the topic.

To assess visitors' perception of quantum related topics, a survey was shared with the public after their visit. In addition, schools that booked a visit, were asked to answer a survey before and after that. The survey focused on the expectations and views the visitors have regarding quantum technologies and their development in industry. The results of this research shed light on the landscape of citizens' interest in and views on the implementation of quantum technologies in their daily lives.

Education & Outreach | Poster

Evaluation of learning material on quantum technologies in terms of interest and motivation: the iooi-method in application

Ismet Nurullah Dogan; Dagmar Hilfert-Rüppell; Franziska Greinert; Malte Steve Ubben; Rainer Müller
TU Braunschweig

Quantum technologies are on the rise, leading to an increased demand for appropriately trained and educated professionals in the industry. The innovative QTIndu (Quantum Technology Courses for Industry) project, an EU-founded initiative, is working to close this gap. It pursues the goals to develop training programmes, to evaluate them and to provide guidelines to scale up the work. As part of this project, an introductory module on quantum technologies is developed, connecting theoretical and didactically valuable aspects of quantum physics with different quantum technologies. Currently, the module is being evaluated in terms of interest in quantum technologies and motivational impact of the learning material, accessing motivational aspects in a groundbreaking way. Due to the IOOI-method (Input-Output-Outcome-Impact method, based on Riess 2010), data on motivation and interest in the module are collected to enable evidence-based improvements of the learning material. This study employs a pre-post design, incorporating self-report measures of interest and self-efficacy. Additionally, a semi-structured interview with participants offers insights into their motivation.
This poster will present the work done in the past, the current status of the evaluation and an outlook. It provides an overview of the development of the module, its structure and the topics that are taught. Furthermore, the evaluation plan is going to be shown and insights into up-to-date results are granted.

Education & Outreach | Poster

An integrated view of quantum technology? Mapping media, business, and policy narratives

Viktor Suter; Charles Ma; Gina Pöhlmann; Miriam Meckel; Lea Steinacker
University of St. Gallen

Quantum technologies (QT) are advancing rapidly, making it necessary to have both, a well-informed public and a quantum-ready workforce capable of understanding and leveraging this innovation. We examined QT discourse across government, business, and media sectors over the past two decades, analyzing an extensive dataset to uncover prevalent topics and narratives surrounding this promising frontier. Our analysis shows that the discourse surrounding QT is layered, with a broad spectrum of narratives in the business, media, and government sectors. While technical aspects and applications dominate the overall discussion, highlighting QT's potential to revolutionize various industries, there are notable gaps in the treatment of political and societal issues in both corporate and governmental discussions, while media showed a very multi-faced distribution of topics. Businesses that ignore the political dimensions of QT risk missing regulatory opportunities and being unprepared for new regulations. Similarly, neglecting societal concerns can lead to low public confidence in QT, hindering its adoption. Looking more closely at educational aspects around QT concepts, topics in our data highlight themes including the workforce skills required by businesses, the need for STEM education investment, gender equality, and the importance of partnerships with academia, startups, and established technology providers for expertise, resources, and commercialization. However, we observed that the proposed measures for educational reform and workforce up-skilling lack specificity, with a notable absence of detailed strategies and concrete, actionable ideas to effectively address these challenges and bridge the knowledge gap.

Education & Outreach | Poster

Investigating industry perspectives:
quantum technology workforce development and training needs

Franziska Greinert; Malte Steve Ubben; Ismet Nurullah Dogan;
Dagmar Hilfert-Rüppell; Rainer Müller
Technical University Braunschweig

With the growing quantum industry, there are a variety of emerging educational needs. The study presented on this poster aims to identify these needs and provide a picture of the industry's requirements in terms of workforce development and (external) training and materials. This includes also requirements or preferences for training formats and conditions. Conducted for the QUCATS project, the study consists of 34 semi-structured interviews with industry representatives and a follow-up questionnaire to validate some of the issues raised in the interviews. The results have influenced activities in EU projects, including an update of the European Competence Framework for Quantum Technologies.

Education & Outreach | Poster

Proficiency triangle and qualification profiles: updated European competence framework for quantum technologies

Franziska Greinert[1]; Rainer Müller[1]; Malte Steve Ubben[1]; Simon Richard Goorney[2,3]
1 - Technical University Braunschweig;
2 - Aarhus University;
3 - Copenhagen University

The European Competence Framework for Quantum Technologies is the reference tool for planning, mapping and comparing educational activities such as master programmes or training objectives, personal qualifications, and job requirements. A first version has been compiled within the QTEdu CSA, and annual updates are delivered within the QUCATS project. Based on the analysis of 34 interviews with industry representatives and further refinement, the 2024 version 2.5 provides an extension with two new parts. While the previous version consisted mainly of a content map structuring topics around QT, the new version adds the second dimension of a proficiency triangle: six proficiency levels are specified for each of the three proficiency areas (I) quantum concepts, (II) QT hardware and software engineering, (III) QT applications and strategies. In addition, nine qualification profiles show prototypical job roles with example personas and additional needs and suggestions, such as what training would be suitable to reach this qualification. (Associated document available on Zenodo: https://doi.org/10.5281/zenodo.10976836, to be published 'officially' soon through the Publications Office of the European Union)

Education & Outreach | Poster

Preparing the industry for a quantum communicating future: a strategic training

Riccardo Laurenza
Technische Universität Braunschweig

Quantum communication (QC) represents a leading-edge technology increasingly adopted by the market. Unlike other quantum technologies, QC applications, such as QKD, do not require a full-scale quantum computer for implementation. QKD systems are already commercialized, providing robust and secure solutions for protecting critical information. While the long-term vision for QC is the establishment of a global quantum internet, intermediate-stage quantum networks already offer viable solutions for real-world applications.

This course, "Quantum Communication and Networks: A Strategic Guide for Industries" part of the QTIndu project funded by the European Union's Digital Europe Programme, provides an exploration of QC protocols and their technological implementations. It offers a comprehensive roadmap for understanding the development stages of quantum networks and their specific applications across various sectors.

Preparing the industry for quantum communication is critical for several reasons:

Strategic Readiness: Early adoption secures a competitive edge, fostering innovation and leadership in a rapidly evolving market.

Economic Potential: The global quantum tech market is projected to reach billions by the end of the decade, driven by demand for secure and efficient communication solutions.

Security Enhancement: Quantum communication protocols offer unparalleled security, essential for safeguarding sensitive data against future quantum computer-based threats.

The course includes interactive learning tools, real-world case studies, and strategic planning sessions, enabling participants to make informed decisions about investment, policy, and implementation of quantum technologies. By fostering a deep understanding of quantum principles and applications, industries can optimize operations, enhance cybersecurity measures, and drive technological innovation.

Education & Outreach | Poster

Modelling innovation in quantum technology curricula

Stefan Heusler[2]; Jacob Sherson[1]; Simon Goorney[1]; Jonas Bley[3]
1 - Aarhus University;
2 - WWU Münster;
3 - RPTU Kaiserslautern-Landau

To satisfy the increasing demand for education opportunities in the field of quantum technologies, over 16 master's degrees are being created within the European project DigiQ. Courses created therein entail didactical innovations using interactive digital learning modules, cooperative teaching, and digitalization.. We present the first version of a didactical framework for modelling quantum curriculum development and transformation, based on five levels: the content, the targeted skills, the cognitive learning outcomes (Bloom's taxonomy), the representations used, and the concrete teaching approach. We show empirical results that identify the value that the framework adds in these different areas of didactical innovation while determining its current limitations. We present an approach to quantum curriculum development that is based on both theory and practice, to steer the quantum education ecosystem in a direction most effective for the learning outcomes of students in the field.

Education & Outreach | Poster

Tailoring quantum technology training programs for industry professionals: insights and experiences

Judith Gabel[1]; Björn Ladewig[1]; Christos Paspalides[2]; Stefan Küchemann[1]; Jochen Kuhn[1]; Tatjana Wilk[1]; Alexander Holleitner[2]; Jan Von Delft[1]
1 - Ludwig-Maximilians-Universität München;
2 - Technische Universität München

As quantum technologies continue to mature, there is an increasing demand to upskill professionals in industry in these fields. For the past three years, we have focused on creating quantum technology training programs for industry professionals through the Quantum LifeLong Learning project. I will present our findings from this development process, from our efforts to gauge industry demand, over the design of the training programs to their testing and refinement. I will particularly emphasize our approach to tailoring these programs in format, content and instructional methods for different target audiences, such as managers without a technical background or engineers with a technical but no quantum physics background.
I will share lessons learned, offering insights into the challenges and successes encountered along the way. This evaluation will highlight key strategies for creating impactful educational initiatives in the rapidly evolving field of quantum technologies.

Education & Outreach | Poster

Experimental courses in quantum technologies for working professionals

Alda Arias; Eva Rexigel; Jonas Bley; Artur Widera
University of Kaiserslautern-Landau

The rapid expansion of quantum technologies in the industry has created a growing demand for qualified specialists, a need that extends beyond the capacity of traditional university programs. To address this, the project QuanTUK at the University of Kaiserslautern-Landau has developed an interdisciplinary distance master program tailored for working professionals. The program is structured around three key components: foundational courses on the mathematical and physical principles of quantum technologies, practical courses featuring experiments and numerical projects, and advanced courses in both theoretical and applied domains such as quantum computing and quantum sensing.

This poster highlights the experimental courses within the master program, detailing their conceptual framework and educational methodologies. The modules are designed to enhance the comprehension of theoretical concepts from the foundational courses through hands-on experimentation. Furthermore, we examine the challenges faced in these experimental courses, such as students' diverse learning backgrounds and resource limitations, and present our strategies to overcoming these challenges.

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From color centers in salts to the NV center - An experimental introduction to quantum sensing

Philipp Scheiger; Simon Koppenhöfer; Kim Kappl; Ronny Nawrodt
Physics Didactics Research, 5th Institute of Physics, University of Stuttgart

First and second generation quantum technologies represent a great opportunity for our modern society. At the same time, they pose new challenges for our education system in terms of making quantum mechanical principles accessible to a wider audience. Future generations of physicists, engineers, technicians, etc. must learn to assess in which contexts quantum technologies have an advantage over classical technologies and in which contexts classical technology is preferable. In preparation for this, we are developing educational magnetometers based on NV centers. These color centers in diamond are very well suited as an introduction to quantum sensor technologies in schools. On the one hand, because they do not require cryogenic temperatures to demonstrate quantum mechanical effects and, on the other hand, because essential content for understanding NV centers is already covered, for example, in the upper secondary school. Nevertheless, this topic is complex and a well-designed educational concept is necessary for the introduction to quantum sensing. In addition to the NV magnetometers, we would like to present a proposal for such a concept in this contribution. It is based on experiments with color centers of salts to explain quantum particles in the potential well, analogy experiments to illustrate the Zeeman effect and ESR measurements of unpaired spins in salts.

Education & Outreach | Poster

QArt: Applying quantum computing technologies to reinterpret classical masterpieces

Yahui Chai[2]; Arianna Crippa[2,4]; Omar Costa Hamido[1];
Paulo Vitor Itaboraí[2,3]; Karl Jansen[2,3]
1 - CEIS20, University of Coimbra;
2 - CQTA, DESY;
3 - CaSToRC, The Cyprus Institute;
4 - Humboldt University Berlin

In this project, we aim to apply a quantum computing technique to compose artworks. The main idea is to revisit three paintings of different styles and historical periods: "Narcissus", painted circa 1597–1599 by Caravaggio, "Son of Man", painted 1964 by Magritte and "192 colors", painted 1966 by Richter. We consider the time evolution of an Ising Hamiltonian to modify the paintings, or part of them, with the output of the quantum computation. In particular, the figures are discretized into square lattices and the order of the pieces is changed according to the result of the simulated time evolution.
From a renaissance subject to abstract forms, we seek to combine classical and quantum aesthetics through these three art pieces.
Besides experimenting with hardware runs and circuit noise, our goal is not only to render digital media but to reproduce these works as physical oil paintings on wooden panels. With this process we complete a full circle between classical and quantum techniques and contribute to rethinking Art practice in the Era of Quantum Computing Technologies.

Education & Outreach | Poster

QWorld: Building a global quantum technology community via education

Aurél Gábris[1,2,3]; Paweł Gora[3]; Agnieszka Wolska[3]; Abuzer Yakaryilmaz[3,4]; Maksims Dimitrijevs[3,4]; Zoltán Zimborás[2,3]; Özlem Salehi Köken[3]; Jibran Rashid[3]; Aritra Sarkar[3]; Lorraine Majiri[3]; Abdullah Khalid[3]
1 - Czech Technical University in Prague;
2 - Wigner Research Centre for Physics;
3 - QWorld Association;
4 - University of Latvia

QWorld has been operating as a volunteer organization since 2019, with a mission to enable non-privileged groups and regions to be part of the global quantum ecosystem. Since its foundation it has grown into an organization present in 32 countries, and has conducted nearly 200 events, handing out over 4000 diplomas. It has developed and maintains a curriculum of consisting of five on-line workshops (with more in the works), and which have been used in over a hundred of free on-line workshops organized by QWorld and its local groups, as well as delivered by QWorld at events organized by third parties. In partnership with universities, including the Czech Technical University and University of Latvia, it has provided four on-line master-level courses. In 2024 QWorld is organizing its global on-line internship programme for the fifth time. QWorld is also partnering with other stakeholders in the QT ecosystem, including startups and large industry, employing their educational tools to implement its mission.

Enabling Technologies

Enabling Technologies | Poster

Delta-T noise, a new tool for detecting temperature fields in superconducting films

Elena Zhitlukhina[1]; Paul Seidel[2]
1 - Comenius University Bratislava;
2 - Friedrich-Schiller-Universität Jena

A key area of improvement for quantum devices is the optimization of superconducting film materials used to create qubit elements and resonators. In this contribution, we discuss our current approach to probing temperature fields in superconducting layers with nanometer resolution based on the measurements of the delta-*T* noise, current fluctuations at zero voltage bias generated by probabilistic quantum scattering processes due to a temperature gradient. The aim of the work has been to study how the delta-*T* noise spectral density is modified in metallic superconductor-based heterostructures. Our theoretical analysis based on the extension of a conventional scattering approach to hybrid mesoscopic systems with Andreev (electron-into-hole and inverse) retroreflections subjected to periodic voltage fluctuations showed that related zero-frequency as well as frequency-dependent noise spectra directly reflect the amplitude and the frequency of the AC fluctuations. We show that measurements of the non-equilibrium delta-*T* noise can be used for identifying dynamical finite-frequency processes inherent in the superconducting devices. Such probing, which is most effective at ultra-low temperatures, can provide valuable information about local thermally induced dynamics in small samples, important for quantum sensing technologies. The on-surface control in mesoscopic superconductors by operating in a current-less temperature-induced noise mode may serve as a powerful alternative to electrical transport usually used for monitoring nanoscale quantum materials under cryogenic conditions. The main advantages of such technology are *in situ* study of as grown nanostructures, flexible positioning of the counter-electrode tips, and non-invasive probing with only two point contacts.

Enabling Technologies | Poster

Towards hybridization of photonic and superconducting quantum platforms with transparent superconductors

Mikhail Belogolovskii[1]; Ali Aliev[2]; Paul Seidel[3]
1 - Comenius University Bratislava;
2 - University of Texas at Dallas;
3 - Friedrich-Schiller-Universität Jena

Hybridization of two outstanding quantum chip platforms, photonic and superconducting, and their further integration with other potential components on a single chip have become critical for future scalable quantum processors, distributed quantum computing, and quantum networks. Using a transparent superconducting material would be an ideal solution to prevent significant photon absorption in hybrid on-chip circuits. In this contribution, we present an analysis of how the complex interaction of free carrier absorption and interband transitions can lead to the coexistence of a relatively high carrier density at the Fermi level with quite satisfactory transparency to visible light and, at the same time, a conventional superconducting state. Using doped indium-tin oxide (ITO) layers as an example, we found characteristic features responsible for the transparency phenomenon already observed in some superconductors as well as the design principles for potential candidates. The efficiency of the electrochemical intercalation method for converting commercially available ITO films into superconductors has been demonstrated. The highest transition temperatures of about 5 K and the sharpest resistive transitions were obtained for ITO films intercalated with sodium and magnesium ions. Magneto-transport measurements made it possible to determine temperature and angular dependences of the upper critical fields, which in a certain way demonstrate the three-dimensional nature of superconductivity in the studied samples. Point-contact conductance spectra of the films revealed the presence, in addition to the main phase, of a phase with the critical temperature of about 10 K, localized, apparently, near the surface of the doped ITO layers.

Enabling Technologies | Poster

Towards atomically thin single photon detection

Alessandro Palermo[1]; Lucio Zugliani[1]; Aniket Patra[2]; Matteo Barbone[1]; Jonathan J. Finley[3]; Kai Müller[1]
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2 - Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany;
3 - Walter Schottky Institute, TUM School of Natural Sciences, Technical University of Munich, Germany

Superconducting Single Photon Detectors (SSPDs) are promising building blocks for photonic quantum technologies, due to their high efficiency, low dark counts and low timing jitter. Transition Metal Dichalcogenides (TMDs) are a class of Van der Waals materials comprising a broad spectrum of thickness-dependent optoelectronic properties. Amongst them, Niobium Diselenide ($NbSe_2$) is superconducting down to the monolayer limit [1], can be processed with standard nanofabrication techniques, where 30nm-wide nanowires have been demonstrated [2] and shows an energy-dependent response when the superconducting state is optically perturbed [3]. These properties make $NbSe_2$ a promising material for new SSPD concepts due to its extremely low thickness, beneficial for the sensitivity of SSPDs, and the integration possibilities of TMDs.
In this contribution, we present our progress on the fabrication, electrical characterization and optical response analysis of $NbSe_2$ devices. A few-layers $NbSe_2$ and hexagonal boron nitride heterostructure is transferred on pre-patterned gold contact pads on a Si/SiO_2 substrate. Our devices show a superconducting critical temperature up to 6.5 K, depending on the number of layers. Further, the heterostructures are patterned to obtain bridge-like devices with a constriction width between 200 nm and 1000 nm, designed to accentuate the photosensitivity in a confined area. Finally, the electro-optical response of the devices is characterized regarding the figures of merit of state-of-the-art SSPDs.

[1] Khestanova et al, Nano Lett. 2018, 18, 2623−2629
[2] Mills et al., Appl. Phys. Lett. 104, 052604 (2014)
[3] Orchin et al., Appl. Phys. Lett. 114, 251103 (2019)

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Development of $In_{0.53}Ga_{0.47}As$-$Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ SPAD for 1550 nm detection at 200 K

Jonathan Taylor-Mew[1]; Xiao Collins[2]; Ben White[2]; Chee Hing Tan[1]; Jo Shien Ng[1]
1 - Department of Electronic and Electrical Engineering, University of Sheffield, UK;
2 - Phlux Technology Ltd, Sheffield, UK

Single photon detection around 1550 nm wavelength is increasingly important due to applications such as Quantum Key Distribution, laser ranging, and remote gas sensing, which require or benefit from using a single photon detector. Single Photon Avalanche Photodiodes (SPADs) are commonly used for such applications due to their ease of use and high operating temperature compared to other single-photon detectors. However, SPADs for 1550 nm wavelength exhibit a Dark Count Rate (DCR) higher than their Si counterparts. Also, their operating voltage can vary significantly with temperature, leading to challenges in the design of the external bias circuitry. Linear mode AlGaAsSb APDs have exhibited excellent temperature stability, significantly lower than both InP and InAlAs. This has made it of interest for SPAD application due to the potential of reducing the design challenges of both the external bias circuitry and temperature stability solution required.

In this work, we characterised multiple 50 μm diameter $In_{0.53}Ga_{0.47}As/Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ APDs as SPADs, covering temperature-dependent avalanche breakdown, DCR, and Single Photon Detection Efficiency (SPDE). For DCR and SPDE measurements, the SPAD was operated using passive quenching and electrical gating. The breakdown voltage increases with temperature at a rate of 13.5 $mV.K^{-1}$ (over 200 - 300 K). When the SPADs were overbiased using 20 ns voltage pulses at 100 kHz repetition, they achieved SPDE of 5-15 % at DCR of 1-20 $Mc.s^{-1}$. This is comparable to performance of InAlAs and early InP-based SPADs.

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Enhancing Rydberg atom quantum computing with digital twin models and machine learning techniques

Lorena Bianchet[1]; Marco Rossignolo[1]; Satyanarayana Bade[1]; Anurag Saha Roy[1]; Shai Machnes[1]; Andrea Alberti[2]
1 - Qruise;
2 - Max Planck Institute for Quantum Optics

An array of Rydberg atoms trapped by optical tweezers presents a promising platform for quantum computing. Recent advancements have demonstrated high-fidelity gates within Rydberg atom systems. However, further gate fidelity improvements are essential to achieve fault-tolerant computation. Various error sources, such as phase and intensity fluctuations in lasers, alignment errors, optical potential variations, the finite lifetime of Rydberg atoms, and significant atomic motion during gate operations, must be addressed to enhance fidelity.
Our developed digital twin of the Rydberg atom device is designed to tackle these challenges, incorporating a comprehensive system model. We utilize techniques such as automatic differentiation, ensemble averaging, and adjoint equation-based methods. These approaches enable us to create protocols with state-of-the-art fidelities that are robust and resilient to the identified noise sources. We also employ model learning techniques, using experimental data to characterize Hamiltonian parameters and provide a detailed error budget for the optimized protocols, offering valuable insights for experimental implementation. We also apply supervised learning for frequency trapping homogenization, further enhancing the robustness of our system against frequency variations. Both Markovian and non-Markovian noise sources are considered in our fidelity enhancement strategies.
Furthermore, we have demonstrated the capability to simulate analog computing and have tested our model on the Aquila neutral atoms QPU platform, validating its effectiveness in practical scenarios. Our versatile toolbox is adaptable to similar challenges in other qubit modalities, such as trapped ions, showcasing its broad applicability in quantum computing.

Enabling Technologies | Poster

Miniaturised optical isolators for realising micro-integrated laser distribution modules in quantum technology applications

Marcel Bursy; Jonas Hamperl; Bassem Arar; Ahmad Bawamia;
Thomas Flisgen; Nora Goossen-Schmidt; Sriram Hariharan; Armin Liero;
Charleen Luplow; Sonja Nozinic; Max Schiemangk; Sandy Szermer;
Christoph Tyborski; Andreas Wicht[1]
Ferdinand-Braun-Institut (FBH)

The Ferdinand-Braun-Institut (FBH) has more than a decade of experience in the development and realisation of ultra-compact diode laser modules for quantum applications. Currently we are expanding our unique and flexible hybrid micro-integration technology towards new applications in quantum sensing and computing. This includes both the extension of the wavelength range of our laser modules and the development of novel distribution modules to efficiently split and shift laser beams of one or multiple wavelengths. Ultra-compact, robust optical components are crucial for the realisation of these systems. For example, optical isolators with high isolation and compact dimensions are required for a variety of photonic modules to suppress unwanted back reflections. For this purpose, we have developed a technology platform for miniaturised optical isolators in the wavelength range from 400 to 950 nm with a volume smaller than 0.5 ml. First isolators at 461 and 689 nm typically achieve an isolation of more than 30 dB and have an insertion loss of less than 1.5 dB. We present the design and performance of our isolators and show their utilisation in one of our latest distribution modules. As part of a compact and rugged strontium optical lattice clock, its purpose is to provide the two wavelengths 679 and 707 nm emitted by two distributed Bragg reflector (DBR) laser chips via a single output fibre. To enable fast intensity modulation, two acousto-optical modulators (AOM) are included. The isolators developed specifically for these wavelengths offer the necessary feedback suppression to ensure stable single-frequency laser operation.

Enabling Technologies | Poster

Advances in SNSPDs and their novel applications

Mario Castaneda
Single Quantum

Superconducting nanowire single photon detectors (SNSPDs) have become an important player in diverse research fields such as quantum communication, quantum computing, and generally in quantum optics experiments. In fact SNSPDs they have established themselves as the detector of choice in those applications as they have outperformed more traditional single photon detectors due to their improved efficiency, high count-rates, excellent timing resolution, minimal dark count rates (DCR) and broad spectral span.
Here we will present some developments that can enable new functionalities in those research areas and we will present novel applications that demonstrate that SNSPDs can be useful even beyond traditional quantum technologies.

Enabling Technologies | Poster

Assessment criteria for quantum technology projects in industry

María Begoña Peña-Lang[1]; Tomas Iriondo Astigarraga[2]; Aritz Balerdi Blanco[3]; Francisco Javier Fernández-Curtiella[3]
1 - University of the Basque Country UPV/EHU;
2 - Gaia;
3 - BASQUE Data

According to the European Commission's Strategic Research Agenda on Quantum Technologies, the aim of this research is to determine the key factors in the development of projects that apply Quantum Technologies in industry. Having well-defined selection criteria ensures that Quantum projects are viable, and have the capacity to contribute to industry and society. This can also provide informed decisions and optimise resources.
Based on a review of the literature and the use of scientific methodology, the basic criteria for their evaluation are established, including technical, economic and regulatory aspects. Likewise, the methodology employed incorporates both a qualitative and quantitative approach, using content analysis and statistical techniques to systematize the information gathered. In accordance with these criteria and the methodology, a rubric is outlined to assess whether a project meets the requirements of a Quantum project.
The research results suggest that aspects such as technical feasibility, performance and efficiency, innovation, impact, data security and confidentiality, management, sustainability, ethics and regulatory compliance are critical factors for evaluating Quantum projects. In addition, the importance of training and retention of specialized talent is highlighted, as well as the need to develop adequate infrastructures for experimentation and scalability of Quantum Technologies.
On the other hand, a number of specific use cases illustrating the application of Quantum Technologies in some international Quantum centers and in different industrial sectors, according to previously established criteria; its implementation, challenges faced, benefits observed, best practices and lessons learned are discussed.

Enabling Technologies | Poster

Opportunities for quantum technology at European synchrotron radiation facilities

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1 - Helmholtz-Zentrum Berlin;
2 - KU Leuven;
3 - Synchrotron Soleil

Synchrotron radiation can support quantum technology in many ways. Examples are 2D and 3D imaging using contrast based on chemical sensitivity, oxidation states, and magnetic dichroism, the characterization of impurities in semiconductors by spectroscopy, of strain conditions for Si quantum dot qubits and for nanowires, materials issues in superconducting qubits that lead to decoherence and broken Cooper pairs, the investigation, orbitals involved in single photon emission from hBN defects and transition metal dichalgogenides, However, use of synchrotron and free-electron laser (FEL) radiation for quantum technology occurs only punctually with the exception of research on quantum materials. We will provide an overview of European synchrotron radiation and FEL sources and instrumentation that is particularly suited for quantum technology. Moreover, we will give information on access schemes and engage in discussions on the special needs of researchers in quantum technology in terms of instrumentation, proposal submission, experiment, and data analysis.
This project is part of the LEAPS-INNOV WP9. Funded from the European Union´s Horizon 2020 programme under grant no. 101004728.

Enabling Technologies | Poster

QLASS project: Scaling up the photonic platform

Giulia Acconcia[1]; Jean-Sebastien Filhol[2]; Roberto Osellame[3]; Fabio Sciarrino[4]; Jens Ulrich Thomas[5]; Nicolai Walter[6]

1 - Politecnico di Milano;

2 - University of Montpellier;

3 - Ephos srl;

4 - Sapienza Università di Roma;

5 - Schott AG;

6 - Pixel Photonics GmbH

QLASS is a Quantum Flagship backed consortium that unites experts from leading research institutions and industry to leverage integrated quantum photonics for generating, manipulating, and detecting quantum states of light. Our initiative centers on developing a quantum photonic integrated circuit (QPIC) using femtosecond laser writing (FLW) to create 3D waveguides in glass, optimized for photonic performance and supporting 200 reconfigurable optical modes. This approach offers minimal interface losses, making it ideal for modular architectures with superior speed, affordability, and end-user optimization.

Our QPIC platform will integrate high-performance single-photon sources (SPSs), superconducting nanowire single-photon detectors (SNSPDs), and electronics for reconfigurable state manipulation, enabling control over 200 cryogenic-detector channels and 1000 phase shifters. Our primary use case targets lithium-ion battery design improvements, crucial for EU technological and sustainability objectives.

Enabling Technologies | Poster

From lasers for quantum technologies to optical clocks

Juergen Stuhler
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Lasers are one of the most important enabling technologies for applied and fundamental quantum technologies. They enable applications like quantum networks, quantum computers, quantum sensing, and quantum metrology.
Over the last years, TOPTICA has developed lasers and laser systems that feature the high-end specifications required by by research laboratories while meeting industry standards like ease-of-use, remote control and 19" rack footprint. In addition, TOPTICA provides complete solutions and customized developments for quantum industry and quantum academia. The quantum technology solutions comprise tunable diode lasers including amplification and frequency conversion, low phase-noise lasers, frequency-stabilization to high-finesse ultra-stable optical cavities, optical frequency combs, electronics modules for laser phase and frequency stabilization, and light processing units. They are used, qualified, or partially developed within quantum flagship projects such as "Aqtion", "iqClock", "PASQuanS", "QIA", "Millenion", "PASQuanS2" or within German quantum technology projects.
We will describe solutions that have been realized for quantum computing with neutral atoms, quantum computing with ions, quantum networks, and optical clocks. We will discuss the obtained results in the context of the mentioned applications. Finally, we will present the status of our currently most complex complete solution that is being developed on demand for a customer as a research demonstrator: a single ytterbium ion optical frequency standard.

Quantum Computing Hardware

Quantum Computing Hardware | Poster

Enhancing quantum technologies with 3D fabrication: the role of femtosecond laser assisted chemical etching in creating glass ion traps and TGVs

Cesare Alfieri, Enrico Casamenti
FEMTOprint SA

Femtosecond laser induced chemical etching (FLICE) is emerging as a mature technology in the field of 3D manufacturing of glass at the micron-scale. During the last years, its application to the quantum technology domain has grown significantly, with a special focus on the fabrication of glass ion traps and through-glass-vias (TGVs).

FLICE leverages the ultra-short pulse duration of femtosecond lasers to induce precise modifications in glass substrates, which are subsequently subjected to chemical etching to achieve complex three-dimensional structures with high spatial resolution. The inherent flexibility of FLICE technology and the possibility of integrating directly written 3D waveguides are pivotal for applications in quantum technology, where the precise manipulation and control of ions and photons are crucial. The ability to create intricate, high-precision geometries in glass enables the development of sophisticated ion traps, targeting a higher stability that is essential for quantum computing and advanced sensing technologies. Additionally, TGVs fabricated using FLICE facilitate high-density interconnects, crucial for integrated quantum systems.

This flexibility not only enhances the design and performance of quantum devices but also accelerates the pace of innovation by allowing for rapid prototyping and customization.

We will present quantum devices produced by the company FEMTOprint, demonstrating that FLICE technology stands out as a versatile tool in the advancement of quantum technologies, fostering the development of next-generation quantum devices and systems.

Quantum Computing Hardware | Poster

The SPINUS project

Martin Koppenhoefer
Fraunhofer Institute for Applied Solid State Physics IAF

We present the Horizon Europe project SPINUS - spin based quantum computer and simulator (https://spinus-quantum.eu/). SPINUS is a collaboration of 12 research institutions across Europe and its mission is to significantly advance solid-state quantum computation and quantum simulation based on nuclear spin networks and dipole-dipole entangled electron spin qubits. We seek to establish experimental platforms for quantum simulation (>50 quantum units) and room-temperature quantum computation (>10 qubits), as well as to address scalability challenges to push to even larger devices. SPINUS address these goals through cutting-edge material engineering using isotopically engineered diamond and ultrapure silicon carbide, as well as through the development of novel readout techniques enabling single-shot electrical readout of magnetic resonances.

Our experimental efforts are complemented by the development of tailored algorithms to control, characterize, and read out the quantum simulation and computation hardware. Moreover, we will develop a software stack of quantum algorithms for practically relevant use cases. These algorithms will be adapted to the requirements and properties of solid-state quantum hardware and will be used to evaluate the potential for realizing quantum advantage on this platform.

SPINUS aims to mature diamond-based quantum devices and build a European diamond ecosystem. This will enable compact and robust room-temperature quantum hardware without the need for complex cooling infrastructure or vacuum technology, promising significant energy savings. Our efforts are flanked by a comprehensive communication and dissemination program, which will raise awareness for the potential of quantum technologies.

Quantum Computing Hardware | Poster

Machine learning based characterizing of wafer-scale superconducting qubits

Manognya Acharya[1]; Juan Carlos Calvo[2]; Marco Caselli[2]; Nathan Korda[2]; Tobias Lindstrom[1]; Thomas Sweetnam[1]
1 - National Physical Laboratory;
2 - Mind Foundry Ltd.

The ability to scale from experiments on small quantum circuits to where large-scale quantum processors can not only be fabricated but also effectively controlled is a fundamental requirement for a practical quantum computer. As part of the ISCF AutoQT project funded by Innovate UK, NPL in collaboration with Mind Foundry has developed an ML-based automated qubit calibration pipeline, delivering a fully calibrated qubit and 2-orders of magnitude speed up in total calibration time. The calibration pipeline was built leveraging Mind Foundry's Dioscuri orchestration, data management, and callback functionality, among others. This results in an informative view of live runs, easy inspection of data generated at intermediate steps, and ease of integration with other tools. The pipeline is being tested on hardware at NPL, where we are establishing a capability to scale from single superconducting qubits to small-scale quantum processor systems. Our approach involves sophisticated measurement methods to allow rapid, accurate characterization of large-scale circuits. Developing and benchmarking automated qubit calibration method is an integral part of this approach.

Quantum Computing Hardware | Poster

An industry-centric approach: Quobly's viable path to large-scale quantum computing

Alain Champenois; Xavier Thibault
Quobly

Quobly, a pioneer in silicon spin qubit technology, was founded in 2022 in the French Alps. The company originated from a 15-year collaboration between renowned research labs CEA and CNRS on quantum computing led by CEO Maud Vinet and supported by a €30 million investment. A pivotal development in this journey was the FD-SOI CMOS technology in Grenoble, which led to the creation of SOITEC.

Quobly is committed to addressing the fault-tolerant quantum computing race, necessary for achieving quantum advantage. This involves scaling up to the estimated million physical qubits required for qubit-intensive error-correction protocols. Unlike other quantum technologies, Quobly's approach uses semiconductor devices to create arrays of electrostatic-potential traps, isolating single electrons with quantum information encoded in their spin.

The transition from "building the best qubits" to "scaling up" poses new system engineering challenges. Industrial-scale production demands balancing precision with scalability, a significant departure from the bespoke fabrication techniques used in academic settings. Quobly leverages existing VLSI-compatible technologies, such as the proven FD-SOI technology, to shorten the time to market, avoiding lengthy development cycles and produce the cheapest QPU in the market.

Key technological choices, like using 28nm CMOS FD-SOI, offer technical advantages for quantum circuits, including demonstrated control for two-qubit gates and integration with cryo-CMOS for low-temperature operations. These innovations address the main hurdles of variability, decoherence, control, and connectivity, paving the way for scalable, industrial quantum computing.

Quantum Computing Hardware | Poster

Calibrated scattering parameter measurements of a Josephson travelling wave parametric amplifier

Sang-Hee Shin[1,2]; Manoj Stanley[1]; Wang Wong[1]; Asem Elarabi[1]; Thomas Sweetnam[1]; Tobias Lindstrom[1]; Nick Ridler[1]; Sebastian De Graaf[1]

1 - National Physical Laboratory;

2 - Sejong University

Josephson travelling wave parametric amplifiers (JTWPAs) are widely used for the readout of quantum circuits, but their individual device performance is not easily investigated without including the effects of auxiliary components such as isolators and circulators. Using a custom low-power microwave calibration setup at millikelvin temperatures, the scattering (S) parameters of a JTWPA in various network configurations have been measured, enabling extraction of the S-parameters of the device itself. With the addition of a pump tone over a large range of pump powers and frequencies, the device was measured to find the gain and S-parameters under working conditions. These results give new insights into the impact of a slight impedance mismatch on the behaviour of a device at different gain levels and signal powers, with implications for parametric amplifier design and modelling improvements.

Quantum Computing Hardware | Poster

Integrated squeezed light sources for photonic quantum computing

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Quantum computing offers an exciting technology which can revolutionize classical computation, secure communication, metrology and many other fields. One of the platforms where a quantum advantage could already be realized is photonics, which stands out due to large scalability, room temperature performance and computational speed in current generation photonic integrated circuits (PICs).
Squeezed light, characterized by reduced quantum noise in one of its quadratures, is a crucial resource for generating entangled states and implementing quantum gates. The integration of these sources into photonic circuits represents a significant step towards scalable and practical quantum computing solutions.
Within our work we use thin-film lithium niobate combined with large bandwidth 3D-printed fiber-to-chip couplers to realize flexible and low loss squeezed light sources. Different design approaches based on periodically poled lithium niobate for spontaneous parametric down conversion and micro-ring resonators are discussed. Their characteristics are compared regarding reproducibility, fabrication complexity alongside with their performance in terms of squeezing level, threshold power and scalability.
The as presented platform for squeezed light sources has the capability for versatile large low-loss integrated quantum circuits and thus provides an important step towards fully integrated photonic quantum computing hardware.

Quantum Computing Hardware | Poster

**Microelectronics research fab:
enabling and scaling quantum computing**

Tim Rom[1,2]
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2 - Fraunhofer Group for Microelectronics

Nanoelectronics, microelectronics, and photonics are playing an increasingly important role in the quest for commercially viable quantum computers. These advanced enabling and process technologies are essential for the continuous improvement of qubit quality and scalability, as well as for the precise, low-latency control and readout necessary for all physical qubit platforms.
We provide an overview of the typical challenges in quantum hardware development and demonstrate how microelectronics can address these challenges at all system levels, driving further hardware scaling and integration. The Research Fab Microelectronics Germany (FMD) with its extension module for quantum and neuromorphic computing (FMD-QNC) supports the community with agile research and development in these areas, ensuring the highest quality standards.
Additionally, we illustrate how quantum hardware can leverage advancements in adjacent fields such as neuromorphic computing and deep-tech applications like animated holography. Through its modular approach, the Research Fab can harness synergies between various developments in microelectronics and the underlying sophisticated manufacturing processes.
The FMD-QNC provides research groups, start-ups, and industrial companies across Europe with access to advanced microelectronics facilities and extensive process expertise for the development of quantum and neuromorphic computing hardware. This network of 19 institutions, including Fraunhofer Society, Leibniz Association, Forschungszentrum Jülich, and AMO GmbH, is coordinated by a joint business office serving as a one-stop shop. Funded by the German Federal Ministry of Education and Research (BMBF), this initiative is crucial for the advancement of Next Generation Computing in Europe.

Quantum Computing Hardware | Poster

Quantum technology platform beyond 1000 atomic qubits for quantum simulation, computation, and metrology

Malte Schlosser; Gerhard Birkl
TU Darmstadt

Arrays of neutral atoms in optical tweezers offer a versatile platform for quantum technologies due to their inherently non-interacting nature and identical intrinsic properties. We present the realization of a large-scale quantum technology platform beyond the 1000 qubit level. By scaling tweezer arrays using a micro-optical approach, we achieve 2D configurations comprising 3000 sites, providing an average of 1167 single-atom qubits. We demonstrate the technique of supercharging the main QPU array with atoms from a secondary array, which significantly increases the initial filling fraction. This enables the assembly of defect-free clusters containing up to 441 qubits with stabilized near-unity filling over multiple detection cycles. To address atom loss, a modular scheme with an additional cold-atom reservoir and buffer sites decouples cold-atom accumulation from QPU operation, increasing data rates and enabling continuous operation. For extension to 3D, we introduce a novel architecture for multilayer configurations of planar arrays using a microlens-generated Talbot tweezer lattice, which extends 2D quantum arrays to the third dimension at no additional cost, accessing 10000 sites in the current setup. Applications in quantum sensing are demonstrated by mapping an externally applied DC gradient magnetic field with submicron resolution using a selected planar array. Real-time control of quantum states and interactions is achieved through fast laser addressing, enabling parallelized universal quantum operations. These advances facilitate the continuous operation of highly scalable quantum registers, with immediate applications in Rydberg-mediated quantum simulation, computation, sensing, and metrology.

Quantum Computing Hardware | Poster

Semi-device independent characterization of multiphoton indistinguishability

Ernesto Galvão[1]; Giovanni Rodari[2]; Leonardo Novo[1]; Riccardo Albiero[3]; Alessia Suprano[2]; Carlos Tavares[1]; Eugenio Caruccio[2]; Francesco Hoch[2]; Taira Giordani[2]; Gonzalo Carvacho[2]; Marco Giardina[4]; Niki Di Giano[5]; Serena Di Giorgio[4]; Giacomo Corrieli[5]; Francesco Ceccarellli[5]; Roberto Osellame[5]; Nicolò Spagnolo[2]; Fabio Sciarrino[2]

1 - International Iberian Nanotechnology Laboratory;
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3 - Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche, Milan;
4 - EPHOS;
5 - Politecnico di Milano

Multiphoton indistinguishability is a central resource for quantum enhancement in sensing and computation. Developing and certifying large scale photonic devices requires reliable and accurate characterization of this resource, preferably using methods that are robust against experimental errors. Here, we propose a set of methods for the characterization of multiphoton indistinguishability, based on measurements of bunching and photon number variance. Our methods are robust in a semi-device independent way, in the sense of being effective even when the interferometers are incorrectly dialled. We demonstrate the effectiveness of this approach using an advanced photonic platform comprising a quantum-dot single-photon source and a universal fully-programmable integrated photonic processor. Our results show the practical usefulness of our methods, providing robust certification tools that can be scaled up to larger systems.
This is joint work with Giovanni Rodari, Leonardo Novo, Riccardo Albiero, Alessia Suprano, Carlos T. Tavares, Eugenio Caruccio, Francesco Hoch, Taira Giordani, Gonzalo Carvacho, Marco Gardina, Niki Di Giano, Serena Di Giorgio, Giacomo Corrielli, Francesco Ceccarelli, Roberto Osellame, Nicolò Spagnolo, and Fabio Sciarrino, and has appeared as preprint https://arxiv.org/abs/2404.18636 .

Quantum Computing Hardware | Poster

Quantum gates between distant atoms mediated by a Rydberg excitation antiferromagnet

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We present a novel protocol to implement quantum gates between distant atomic qubits connected by an array of neutral atoms playing the role of a quantum bus. The protocol is based on adiabatically transferring the atoms in the array to an antiferromagnetic-like state of Rydberg excitations using chirped laser pulses. Upon exciting and de-exciting the atoms in the array under the blockage of nearest neighbors, depending on the state of the two qubits, the system acquires a conditional geometric π-phase, while the dynamical phase cancels exactly, even when the atomic positions are disordered.

Quantum Computing Hardware | Poster

Robust dynamical decoupling on IBM Quantum

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Dynamical decoupling (DD) is one of the simplest and least resource-intensive methods for suppression of decoherence and has proven to be an essential tool on today's noisy intermediate-scale quantum (NISQ) devices. In this work we derive general formulas for two new classes of DD sequences which are constructed to be robust against detuning. We present numerical simulations showing increasing detuning frequency bandwidth with minimal error compared to CMPG. The robustness of the sequences to pulse area errors is also studied. Experimental results are presented from the 127-qubit open-access IBM Quantum processors, showing substantial increase in qubit fidelity compared to periods of free evolution and increased robustness to detuning and pulse area errors than the most widely used DD sequences.

Quantum Computing Hardware | Poster

Investigation of Yb-Rb Rydberg pair interactions and progress toward dual-type dual-element atom arrays

Wenchao Xu
ETH Zurich

Rydberg atoms are central to the current quantum technology revolution, from quantum sensing and metrology to quantum information processing with atom-array-based architectures. Recent breakthroughs have demonstrated the execution of an error-detectable complex sampling circuit with 48 logic qubits. Despite this rapid progress, several key challenges remain, such as performing rapid repetitive error syndrome detection and reusing atoms after an experimental run. Overcoming these difficulties is essential for the efficient implementation of fault-tolerant quantum protocols.

Our group aims to advance quantum technology by using dual-element atom arrays that combine two-electron valence atoms (171Yb) with alkali species (87Rb). We report on the ongoing development of an experimental system combining these two types of atoms. Our research focuses on studying and calibrating the heteronuclear dipole-dipole interactions and identifying Förster resonances between Yb-Rb Rydberg pairs through spectroscopic techniques. By leveraging these heteronuclear interactions, novel gate and measurement schemes developed in our group, we aim to demonstrate efficient, high-fidelity multi-quit gate operations and repetitive stabilizer measurements, paving the way for efficient fault-tolerant quantum computation.

Quantum Computing Hardware | Poster

Automated calibrations of spin devices in Silicon

Pieter Eendebak; Lieven Vandersypen; Tumi Makinwa; Onder Gul; Giordano Scappucci; Toufik Salhioui; Yoram Vos; Pieter Wasserman; Larysa Tryputen; Saurabh Karwa; David Michalak; Harold Meerwaldt; Daniel Van Der Velde; Michiel Haye; Jasper Winters; Peter Verhoeff
QuTech

Quantum Inspire is a cloud platform giving access to quantum computers based on superconducting and semiconducting qubits. Structured tune-up and automated calibration techniques are vital for keeping these systems available online. We will discuss the tune-up and automated calibration techniques utilized in our six-qubit device architecture [1] based on electron spins in silicon. The qubits are hosted in a linear array of six quantum dots in a SiGe/^{28}Si/SiGe heterostructure grown inhouse at QuTech [2]. Readout is done using Pauli Spin Blockade (PSB), single qubit operation through EDSR, and two-qubit gates are symmetric CZ gates.
The requirements and frequency of automated calibrations to keep spin qubits up-to-spec are different from the more well-known superconducting qubits. We perform these automated calibrations using a directed acyclic graph. Nodes in the graph represent different calibrations ranging from calibrating the sensing dot up to compensating for qubit crosstalk. We will discuss the calibrations necessary for spin qubits, the frequency of these calibrations and the final qubit performances we achieve after calibrations. Finally, based on this data, we will share the future challenges for calibrating spin qubits.
This work was partly supported by the EU through the H2020 QLSI project under agreement 951852.
[1] Philips, Stephan GJ, et al. "Universal control of a six-qubit quantum processor in silicon." *Nature* 609.7929 (2022): 919-924.
[2] Degli Esposti, Davide, et al. "Wafer-scale low-disorder 2DEG in 28Si/SiGe without an epitaxial Si cap." *Applied physics letters* 120.18 (2022).

Quantum Computing Hardware | Poster

Robust composite Molmer-Sorensen gate

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The Molmer-Sorensen(MS) gate is a two-qubit rotational gate in ion traps that is highly valued due to its ability to preserve the motional state of the ions. However it's fidelity is obstructed by errors affecting the motion of the ions as well as the rotation of the qubits. In this work we investigate a combination of amplitude modulation and composite MS gates that eliminate specific motional and rotational errors. In addition, based on the specific amplitude modulation we demonstrate how this protocol can be used as a quantum sensor.

Quantum Computing Hardware | Poster

Multi-pass quantum process tomography: precision and accuracy enhancement

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Sofia University

We introduce a method to enhance the precision and accuracy of Quantum Process Tomography (QPT) by mitigating the errors caused by state preparation and measurement (SPAM), readout and shot noise. Instead of performing QPT solely on a single gate, we propose performing QPT on a sequence of multiple applications of the same gate.

The method involves the measurement of the Pauli transfer matrix (PTM) by standard QPT of the multipass process, and then deduce the single-process PTM by two alternative approaches: an iterative approach which in theory delivers the exact result for small errors, and a linearized approach based on solving the Sylvester equation.
We examine the efficiency of these two approaches through simulations on IBM Quantum using ibmq_qasm_simulator.

Compared to the Randomized Benchmarking type of methods, the proposed method delivers the entire PTM rather than a single number (fidelity). Compared to standard QPT, our method delivers PTM with much higher accuracy and precision because it greatly reduces the SPAM, readout and shot noise errors. We use the proposed method to experimentally determine the PTM and the fidelity of the CNOT gate on the quantum processor ibmq_manila(Falcon r5.11L).

Quantum Computing Hardware | Poster

A globally driven superconducting quantum computing architecture

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Traditional quantum computing (QC) architectures require addressing each qubit individually, resulting in numerous control lines entering the quantum processor—a challenge known as the "wiring problem." Superconducting qubits often experience undesirable "residual" longitudinal ZZ interactions between neighboring qubits, leading to phase accumulations that must be managed during computation. To address these issues, we present a universal superconducting QC architecture that leverages always-on ZZ coupling terms. This approach replaces the local driving of individual qubits with global pulses controlling a large collection of memory registers, thereby drastically reducing the number of wires needed for computation. Although pioneering global QC schemes have been proposed, they have not achieved the readiness level necessary to compete with local control models. Our scheme is inspired by recent advancements made by Cesa and Pichler (2023), who presented a universal quantum computer based on globally-driven Rydberg atoms. We generalize their results to a solid-state, superconducting platform featuring a 2D ladder with three different species of superconducting qubits and only three control lines. Unlike existing literature, our scheme exploits always-on longitudinal ZZ coupling combined with specific driving frequencies to achieve a blockade regime emulating the Rydberg blockade, crucial for the computing scheme. Compared to the model by Cesa and Pichler, our proposal significantly reduces the number of physical qubits required for universal computation and initialization.

Quantum Computing Hardware | Poster

Energy analysis of a fault tolerant implementation of the Quantum Fourier Transform encoded with the Steane code on a trapped-ion quantum computer

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4 - Instituto Superior Técnico, Universidade de Lisboa, Portugal;
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The practical implementation of quantum algorithms on physical systems necessitates a rigorous evaluation of the energy consumption. Despite indications of quantum technologies' potential efficiency, this aspect is often overlooked in discussions of quantum computation. To address this gap, this project studies the energy use of a fundamental algorithm in a highly realistic setting.

To carry out this study, we have chosen a trapped ions platform with a quantum charge-coupled device architecture. The latter is one of the most promising configurations, as it can manage many qubits, offer high connectivity, enable parallel manipulation, and operate with high fidelity. However, the effectiveness of quantum devices is often challenged by significant noise from undesired interactions: the strategy is to employ a quantum error correction code to tackle this challenge and ensure fault-tolerant computation. Specifically, we have selected the Steane [[7,1,3]] code, which is well-suited for this platform, using flag-based error correction gadgets. Our analysis concentrates on the Quantum Fourier Transform, a crucial circuit for important algorithms such as Shor's factorization and Phase estimation. This circuit is noteworthy for requiring exponentially fewer gates compared to its classical counterpart, the discrete Fourier transform.

Overall, this study provides a comprehensive energy analysis of all aspects of quantum computation, including gate application, ion transport, cooling, and qubit measurement. By understanding how these operations affect the energy consumption, we aim to give some insights into the energy characterization of quantum algorithms on trapped ion quantum computers.

Quantum Computing Hardware | Poster

Fast and high-fidelity composite gates in superconducting qubits

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We present a method for quantum control in superconducting qubits, which overcomes the Fourier limit for the gate duration imposed by leakage to upper states. The technique utilizes composite pulses, which allow for the correction of various types of errors, that naturally arise in a system. We simulate the approach to produce complete and partial population transfers between the qubit states, as well as two basic single-qubit quantum gates. Our simulations show a substantial reduction of the typical errors and a gate speed-up by an order of magnitude. Three different independent verifications are made to justify these claims.

Quantum Computing Hardware| Poster

Standardized strategies for quantum benchmarks

Zoltán Zimborás
HUN-REN Wigner Research Centre for Physics

As quantum computers advance in size and capabilities, accurately predicting their capability—specifically, which circuits they can execute and how efficiently they can do so—becomes increasingly important. This is the fundamental goal of quantum benchmarking. We need to create precise and scalable predictive capability models to aid researchers and stakeholders in making informed decisions about which quantum computer architectures to develop and utilize. In this work, we outline a set of characteristics that any benchmark should follow and also present the framework for the standardization procedures. These ideas are exemplified for our new mixed cross-entropy/mirror-circuit random Clifford benchmark that we developed within the Quantum Flagship projects.

Quantum Computing Hardware | Poster

EPIQUE: European Photonic Quantum Computer

Fabio Sciarrino
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EPIQUE is a research project funded with €10,340,000 by the European Commission under the call HORIZON-CL4-2023-DIGITAL-EMERGING-01-CNECT within the European Quantum Flagship initiative. It is carried out by 18 partners from 12 countries. Our final ambitious goal is to build a European quantum computer based on scalable photonic technology that will be made available to the European industry and academia to tap into the potential markets and applications of quantum computing. In EPIQUE, academic laboratories and deep-tech start-ups will work in synergy to assemble photonic platforms for quantum computing based on photonic cluster states and measurement induced operations.

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Quantum Computing Hardware | Poster

Quantum walks with Rydberg atoms

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Rydberg atoms provide a highly promising platform for quantum computation, leveraging their tunable interactions to encode information in the electronic states of individual atoms. Quantum gates are executed through controlled atom-light interactions and strong interatomic Rydberg interactions. Key advantages of Rydberg atoms include scalability, arbitrarily reconfigurable connectivity, and native multi-qubit gates, making them particularly well-suited for addressing complex network problems. Such problems can often be framed as graph-based tasks, efficiently tackled using quantum walks. In this work, we propose a general implementation of staggered quantum walks with Rydberg atoms, especially applicable to spatial networks. We compare this approach to coined quantum walks and find that our implementation yields reduced circuit depth and faster execution times, albeit with an increased qubit overhead. Additionally, we developed an efficient algorithm for constructing a set of tessellations required for the staggered quantum walk.

Quantum Computing Hardware | Poster

Compact milliKelvin solid-state refrigeration platforms for quantum technologies

Stephen Rowley
University of Cambridge

We present an overview of compact milliKelvin refrigeration platforms based on advanced solid-state magneto and electro-caloric materials. In current single-stage magnetic embodiments base temperatures below 50 mK are possible starting at around 2 Kelvin with fields of a few Tesla. Two and multiple stage versions allow for continuous cooling and/or lower base temperatures below 5 mK. When combined with recent versions of particularly compact liquid-cryogen-free Gifford-McMahon, pulse-tube or Sterling-cycle refrigerators, essentially desktop-sized mK refrigerators are realized suitable for a wide range of applications in quantum technologies including sensing and computation.

Quantum Sensing and Metrology

Quantum Sensing and Metrology | Poster

Quantum nature of high harmonic generation: from correlation to homodyne measurements

Viviane Cotte; Houssna Gringer; Mateusz Weis; David Theidel; Hamed Merdji
LOA - Institut Polytechnique de Paris

Among the numerous quantum photonic sources currently available, high harmonic generation (HHG) remains a relatively unexplored area. Recent studies have demonstrated its potential for quantum imaging through the generation of high-energy frequency-entangled states and, more generally, for quantum information through the generation of new states of interest. Indeed, some non-classical effects present in HHG have led to the experimental generation of optical Schrödinger cat states. Futhermore our team has recently provided the first evidence for the existence of superbunching and entanglement between two high harmonics (H3 and H5) generated in semiconductors with a femtosecond laser in a Hanbury-Brown-Twiss (HBT) like experimental setup.
We will present our main advances in the quantum characterisation of the HHG through two key experiments: an upgraded version of our HBT-like setup and a self-homodyning experiment. The upgraded version of the HBT setup enables us to perform measurements up to the 11th harmonic in the ultraviolet region, thanks to a new laser and new single-photon detectors. We will discuss both the presence of squeezing (and more generally the statistical nature of the harmonics) as a function of their order, and the entanglement between the harmonics over a wide spectrum (from the visible to the UV). The aim of the self-homodyning experiment is to reconstruct the Wigner function of each individual harmonic, which will enable us to gain a deeper understanding of the quantum nature of HHG. We will present our technique for performing such an experiment with HHG and discuss the most recent results.

Quantum Sensing and Metrology | Poster

Private and robust states for distributed quantum sensing

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Distributed quantum sensing allows one to characterize estimation scenarios where each of the parameters is encoded in spatially separated probes. While in quantum sensing, the goal is most often to estimate one parameter with maximum precision, in the distributed setting one might be interested in more than maximum precision. As we move to multiple parameters, the concept of functions of parameters appears and the information accessible to each of the parties involved in the estimation scenario becomes a pressing question. To analyze this problem we resort to the concept of privacy with respect to a function, meaning that only information about the target function is available to the parties involved in the estimation scenario. Given a privacy measure, we proceed to construct all the states that achieve privacy for a given function, taking different considerations for the resource dis- tribution, and for different encoding dynamics characterized by an Hamiltonian evolution. For separable and parallel Hamiltonians, we verify and prove that the GHZ state with the minimum amount of resources required for a certain linear function is the first and only private state. Given that this state is not robust against particle loss, we proceed to build a method to create private and robust states against multiple types of noises by adding extra resources. We then generalize our privacy proof for the different regions of resources distributions and different considerations on the Hamiltonians, resulting in a set of private and robust states for distributed estimation scenarios.

Quantum Sensing and Metrology | Poster

AION: Probing the cosmos with long baseline atom interferometers

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Atom interferometers can be used as ultraprecise sensors with applications ranging from navigation to geophysics and searching for new physics beyond the standard model. The Atom Interferometer Observatory and Network (AION) project aims to develop next-generation differential atom interferometers for detecting ultra-light dark matter (ULDM) and mid-frequency range gravitational waves (GWs), while simultaneously embarking on a programme of quantum technology development with neutral strontium atoms. The project comprises several stages, starting with a 10 m baseline atom interferometer paving the way to a 100 m detector, and eventually a km-scale terrestrial detector, with the final stage being the development of a satellite-based detector. This multidisciplinary initiative involves researchers from seven institutions across the UK.

This poster presentation will give an overview of the AION project detailing the detection mechanisms for GWs and ULDM. The technological progress made to date, with a focus on the work of our team at Imperial College London, will be highlighted. Long-baseline atom interferometers, such as the one built by the AION collaboration, require ultra-cold atomic clouds. Our initial results have demonstrated the production of a strontium atomic cloud at sub-microkelvin temperatures. Additionally, we will discuss progress towards achieving interferometry using the 87Sr clock transition.

Quantum Sensing and Metrology | Poster

EURAMET Projects Qadet and Noqtes: supporting measurement testing & standardization of colour-centre-based quantum sensing technology

Paolo Traina
INRIM - Istituto Nazionale di Ricerca Metrologica

Solid-state quantum sensors (QSs) have the potential to measure several physical quantities with unprecedented spatial resolution and sensitivity. As such, they are emerging candidates for potential applications in e.g. electromagnetic and radiofrequency measurements, gravimetry, climate research, navigation, medicine (brain imaging, heart imaging) and metrology. Nitrogen-Vacancy (NV) centres are photoluminescent point defects in diamond, which have high potential for future uptake as they present the highest Technology Readiness Level (TRL) amongst solid state atomic-scale sensors, as recognized by the CEN/CENELEC Focus Group on Quantum Technologies [1] and its successor dedicated technical committee in 2022 (CEN-CLC JTC-22 QT) [2].
INRIM coordinated EMPIR project 20IND05 QADeT [3] (2021-2024) developed methods for: (i) engineering individual colour centres in a controlled way; (ii) characterising colour-centre based QSs and (iii) developing of dedicated detectors for measurement traceability in the photon-counting regime.
The followup project 23NRM04 NoQTeS [4], kicked-off in June 2024, has the overall objective to move forward to support effective standardisation of devices based on colour centres in diamond and also colour centres in other bulk or 2-D semiconductor materials (e.g. Si, SiC, hBN).
This will be done in synergy with the needs expressed by CEN-CLC JTC-22 QT.

[1] van Deventer, O., et al., EPJ Quantum Technol. 9, 33 (2022).
[2]https://www.cencenelec.eu/areas-of-work/cen-cenelec-topics/quantum-technologies/
[3] https://qadet.cmi.cz/
Project Partners: INRIM, CMI, DFM, PTB, Aalto University, UNITO, DTU, ENS Paris-Saclay, QNAMI, SPARROW QUANTUM, THALES
[4] Project Partners: INRIM, CMI, DFM, PTB, Aalto University, Metrosert, UNITO, ENS Paris-Saclay, Herriott-Watt University, SPARROW QUANTUM, THALES. Chief Stakeholder: CEN-CLC JTC 22 QT WG2.

Quantum Sensing and Metrology | Poster

Quantum diamond nanosensor detects local temperature variation in single-neuron scale.

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Temperature is one of the most relevant parameters for the regulation of intracellular processes. Measuring localized subcellular temperature gradients is fundamental for a deeper understanding of cell function, such as the genesis of action potentials, and cell metabolism.
This poster reports our latest progresses in nanodiamond-based thermometry, resulting in the first localized temperature increase detection in a firing neuronal network with precision under 0.1 K [1].
By exploiting Optically Detected Magnetic Resonance (ODMR), such temperature variations are probed in cultured hippocampal neurons at the single-cell scale using NV color centers in nanodiamonds. Our data show that, 1 K local temperature increases can be detected in association to a significant potentiation of the firing rate, whereas ODMR stimulation protocols do not affect cell viability and functionality.
In perspective, this techniques provides an extremely promising mean of indirect detection of the action potential and can be potentiated to study temperature variations in proximity of particular cell regions by targeting specific cell components (e.g. ion channels, mitochondria, etc) via nanodiamond functionalization.

[1] G. Petrini et. al., Nanodiamond–Quantum Sensors Reveal Temperature Variation Associated to Hippocampal Neurons Firing. Adv. Sci. 2022, 9, 2202014.

Quantum Sensing and Metrology | Poster

Endoscopy-type quantum ghost imaging

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Microendoscopy is a powerful imaging modality that allows visualising hard-to-reach samples - such as the inside of an organ.
Modern endoscopes utilize flexible optical fibres, and have found many applications in biomedicine, as well as remote monitoring in hazardous environments.

In this work, we show the first demonstration of a quantum ghost imaging (QGI) endoscope.
QGI is a quantum optics technique in which an image is formed from photons that have not interacted with the sample.

Our QGI endoscope harnesses spatial correlations between pairs of photons, generated via spontaneous parametric down-conversion in a non-linear crystal: One photon from the pair illuminates the sample through an optical fibre, and its detection is registered without spatial resolution using a standard single-photon avalanche diode (SPAD). Simultaneously, we image the other photon directly, using a novel SPAD array camera specifically designed for QGI applications.
We employ the backwards-looking-in-time logic in each pixel of this low-power SPAD array camera to identify photon pairs by exploiting the fixed time delay between them. This eliminates the need for commonly used bulky image-preserving delay stages, resulting in a compact and stable setup suitable for practical applications.
We visualize a sample in reflection through a commercially available, meter-long, flexible image fibre bundle.
Our technique may facilitate high signal-to-noise ratio low-light endoscopy, especially at wavelengths where conventional cameras are not readily available.

Quantum Sensing and Metrology | Poster

AQuRA - Advanced quantum clock for real world applications

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1 - University of Amsterdam; 2 - NKT Photonics A/S; 3 - EXAIL SAS; 4 - Vexlum Oy; 5 - QuiX Quantum BV; 6 - Uniwersytet Mikolaja Kopernika w Toruniu; 7 - Centre National de la Recherche Scientifique; 8 - Physikalisch-Technische Bundesanstalt; 9 - Vrije Universiteit Amsterdam; 10 - Menlo Systems GmbH

AQuRA, the Advanced Quantum Clock for Real World Applications, is a European Quantum Flagship consortium of five industry leaders, two national measurement institutes and three universities. We are building the AQuRA clock, which will be the first European optical lattice clock product prototype, aiming for instability and uncertainty at around a second over the age of the universe. Such precise and accurate clocks are crucial for the precise navigation, communications and sensing challenges that underpin our modern society. We will present our progress in building the AQuRA clock.

Quantum Sensing and Metrology | Poster

Microfabrication of Fresnel lens array for ultraviolet fluorescence detection of trapped ions

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Ion traps have a wide range of applications in quantum technologies including quantum metrology, quantum computing, quantum simulation and sensing. Currently, a major research interest is to realise scalability to large qubit numbers. Microfabrication has been used extensively to produce chip integrated waveguides and other photonic elements that help the scalability of ion-trap systems, but very little has been reported on compact detection mechanisms. Our compact and scalable ultraviolet (UV) detection scheme is based on an array of single photon avalanche detectors (SPAD's) and micro-fabricated Fresnel lenses to support scaling and imaging of an extended array of ions [1]. UV Fresnel lenses are rarely reported as they have several disadvantages regarding significant absorption losses for most materials and small feature sizes for concentric structures on the scale of the UV wavelength. Here we report on the fabrication of a UV Fresnel lens array using electron beam lithography technique that will enable individual readout of ions [2] to the SPAD's and simultaneously improve the overall numerical aperture (NA).

[1] Atasi Chatterjee, Leonie Vieler, Markus Kromrey, Andrey Kravchenko, Heiko Fröhlich, Thoralf Kautzsch, Elena Jordan, Jens Repp, Tanja Mehlstäubler, *Integrated detection optics for scalable ion traps for quantum technologies,* Accepted for publication in Measurement : Sensors by Elsevier.
[2] E. W. Streed, B. G. Norton, A. Jechow, T. J. Weinhold, and D. Kielpinski, Imaging Trapped Ions with a Microfabricated Optic for Quantum Information Processing, *Phys. Rev. Lett.* 106, 010502 (2011)

Quantum Sensing and Metrology | Poster

Error mitigation in noisy qubits using qubit interference

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We have developed an optimized hardware strategy to mitigate errors in noisy qubits. Our scheme leverages error filtration principles and utilizes auxiliary qubits. Both the signal and ancillary qubits experience local noise, but constructive interference and post-selection reduce noise in the signal qubit. To find the optimal unitary transformation for effective qubit interference, we start with universal gates and optimize functionals using gradient descent or stochastic approximation.
Our approach is evaluated against various metrics tailored to different applications, including entanglement fidelity, quantum Fisher information (for quantum sensing), and Bell functionals (for non-locality tests and quantum cryptography), using one, two, and three ancillary qubits. For configurations with one and two ancillary qubits, we provide explicit expressions derived from an ansatz for the optimal unitary transformation.
We systematically analyze the performance of our error mitigation strategy across different noise models and quantum circuit architectures. Our approach not only enhances the fidelity of quantum operations but also significantly improves the robustness of quantum states against decoherence. Extensive simulations show that our method can be adapted to various quantum technologies, including superconducting qubits and trapped ions. Additionally, we discuss the scalability of our technique and its potential impact on the development of fault-tolerant quantum computers. Our findings suggest that incorporating auxiliary qubits and optimizing interference patterns can lead to substantial advancements in quantum error correction, paving the way for more reliable and efficient quantum computations.

Quantum Sensing and Metrology | Poster

Rb-filled hollow-core fibres: a novel approach to atomic sensing

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Developed over the last 3 decades, atom interferometry, i.e. interferometry performed with atomic matter wave, has generated gravimeters and gyroscopes of unprecedented precision.

While a few commercial instruments based on atom interferometer already made their way to the market, in general the instrumentation is cumbersome, delicate and hardly movable, when realised in a "standard" way. We aim at making the experimental setups much more compact, economic and easily transportable. We plan to prepare laser-cooled atoms inside a Hollow Core Photonic Crystal Fibre (HCPCF). Once in the core, using light guided by the fibre, an Atom-light Crystal is created, where collective radiative effects can be observed and used for various purposes including magnetometry and interferometry.

Our experimental setup is composed of a vacuum chamber to generate a magneto-optical trap (MOT) of Rubidium (Rb) atoms in proximity of the tip of a HCPCF. The fibre has one sealed end sticking out of the chamber, for easier light injection with and external laser source. After the atoms are in place, their interaction with the fibre will be studied in order to understand how to prevent them being adsorbed by the walls, and to ensure the realisation of a proper atom-light crystal. With such a device, gravimetry measurements could be performed with state-of-the-art sensitivity of 10^−7m/s2 (enough to detect a ~1kg nearby mass around the fibre). Magnetometry measurements with high spatial resolution and sensitivity would also be possible (~100µm and 10^-11T/sqrt(Hz) respectively).

Quantum Sensing and Metrology | Poster

NV centers in diamond for quantum sensing and imaging

Philipp D'astolfo; Niklas Mathes; Felix Hahl; Lukas Lindner; Tingpeng Luo; Rebekka Eberle; Sebastian Heuft; Florian Schall; Yves Rottstaedt; Peter Knittel; Jan Jeske
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Nitrogen-Vacancy (NV) centers in diamond have become versatile tools across various scientific and technological domains due to their distinctive quantum properties. These centers consist of point defects in the diamond lattice, where a nitrogen atom replaces a carbon atom adjacent to a vacancy. Their remarkable optical and magnetic characteristics position them as excellent candidates for applications in quantum computing, quantum sensing, and high-resolution imaging.

At Fraunhofer IAF, NV centers are employed in Laser-Threshold-Magnetometry, Widefield- and Scanning-Probe Magnetometry. Implemented into a laser cavity, NV centers in diamond significantly enhance magnetic sensitivity, pushing it to a theoretical limit of 10 fT/sqrt(Hz) . This heightened sensitivity makes them viable for detecting even the smallest magnetic signatures produced by brain activities, with profound implications for neuroscience and medical diagnostics.

High-resolution imaging leverages the photostability and brightness of NV centers, enabling super-resolution microscopy techniques that surpass the diffraction limit of light. These advanced imaging techniques facilitate fast magnetic imaging, providing detailed insights into biological processes and material properties at the micro- and nanoscale. In biology, NV centers can be used to observe cellular and subcellular structures with unprecedented clarity. In materials science, they enable the study of the magnetic properties of novel materials and nanostructures.

These methods find applications in a wide range of fields, from fundamental research to practical applications, underscoring the versatility and potential of NV centers in diamond as powerful tools for scientific exploration and technological innovation.

Quantum Sensing and Metrology | Poster

News from project QuAHMET: Quantum anomalous hall effect materials and devices for metrology

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Quantum Hall Effect (QHE) is the basis of the realisation of the SI unit of electrical resistance, the ohm. Present QHE devices require low temperatures and high magnetic fields to operate. The Quantum Anomalous Hall effect (QAHE) in topological insulators is a good candidate to simplify the realisation of the resistance unit and the development of a ‘quantum electrical metrology toolbox’ for universal adoption of quantum electrical SI standards, beyond just the NMIs.
The aim of the Joint Research Project QuAHMET: "Quantum Anomalous Hall Effect Materials and Devices for Metrology" is to investigate and implement novel technologies for the development of QAHE devices and measurement systems for metrology. The project started in June 2024: the poster will report on its advancements and results.
The project is open to collaborations and interest from stakeholders. You can connect to the project via its website (sites.google.com/inrim.it/quahmet/home), its LinkedIn group (www.linkedin.com/groups/8824119/), the YouTube channel (www.youtube.com/channel/UCaHuyb8YzrjPnLUz7nSiauA). If you want to be informed of future developments, send an email to the Impact manager Martina Marzano (m.marzano@inrim.it).
Acknowledgement: The project 23FUN07 QuAHMET has received funding from the European Partnership on Metrology, co-financed from the European Union’s Horizon Europe Research and Innovation Programme and by the Participating States.

Quantum Sensing and Metrology | Poster

Higher-order corrections to the quantum Cramér-Rao bound

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The Quantum Cramér-Rao Bound (QCRB) is crucial in quantum metrology. However, like its classical counterpart, it is a local quantity that only depends on the first derivative, overlooking higher-order information. Although it can identify a unique optimal state for a specific unitary transformation, it fails to do so for arbitrary unitary transformations within a given group, such as SU(2), where there exists a family of optimal states. Furthermore, the optimal measurement that saturates the QCRB is generally not unique. Additionally, the QCRB only informs us about performance in the asymptotic limit; however, in the real world, resources are not unlimited.
To address these issues, we employ higher-order asymptotic theory, which provides corrections beyond the Classical Cramér-Rao Bound. Although well-established in statistical literature, its results have not been applied to quantum metrology. This approach will allow us to evaluate performance before reaching the asymptotic limit and to identify optimal states and measurements within the family that are equivalent according to the QCRB.

Quantum Sensing and Metrology | Poster

Bringing photonic quantum-enhanced sensors to the next level of integration and usability: the QUANTIFY project

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Istituto Nazionale di Ricerca Metrologica

Over the years, sensors have expanded their use from scientific exploration to consumer electronics, and their market has evolved accordingly. Quantum technologies are expected to further enhance sensor performance, unlocking more application domains by exploiting non-classical correlations of light and matter. This allows extraction of relevant information beyond the limits dictated by classical noise processes, improving sensitivity, specificity, and uncertainty. The ability to produce, control, and measure quantum states in portable devices is key to extending sensors' operating environments, lifetimes, power consumption, and costs. QUANTIFY aligns with this vision and the goal of demonstrating quantum sensing beyond classical capabilities for real-world applications, as outlined in the Quantum Flagship Program's Strategic Research Agenda. QUANTIFY aims to advance photonic quantum-enhanced sensors by developing essential building blocks and novel quantum-enhanced techniques for future chip-scale optical clocks, optically pumped magnetometers, and optomechanical temperature sensors. QUANTIFY leverages different photonic platforms combined with a novel hybrid integration technique to bring key optical and optomechanical functionalities onto a single chip. To increase clock and magnetometer performance, the project introduces a photonic integrated squeezed light source, an important step toward realizing a universal quantum computer based on photonics. Additionally, it demonstrates a novel absolute temperature sensor with an extended detection range, from cryogenic to room temperature, leveraging a nanoscale optomechanical approach that couples photonic and phononic degrees of freedom. All developed sensors will be assessed using metrological protocols and national primary standards in NMI laboratories to foster their feature exploitation in real applications for end-users.

Quantum Sensing and Metrology | Poster

A compact radiofrequency spectrum analyser based on nitrogen-vacancy centers in diamond

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We present a compact architecture of a radiofrequency (RF) spectrum analyser based on an ensemble of nitrogen-vacancy (NV) centers in diamond. The device covers a frequency range from 0.1 MHz to 10 GHz with a maximum real-time bandwidth of 1 GHz, a frequency resolution of a few tens of MHz and a temporal resolution of 10 µs. As use-case, we detect the Bluetooth signals from mobile phones.

The RF spectral analysis based on NV centers in diamond relies on the spatial encoding of the NV centers spin resonance frequency by means of a static magnetic field gradient. The NV centers are continuously pumped by a 532 nm laser and their photoluminescence (PL) is collected by an imaging system and detected by a CMOS camera. A static magnetic field gradient is aligned along one NV center family so that different pixels of the camera image NV centers resonating at different frequencies. The incoming RF signal induces a drop of PL for those pixels imaging NV centers on resonance with it, thus revealing its spectrum. The compactness of the system is achieved by properly designing the diamond, the imaging system and the magnet.

The RF spectral analysis based on spin defects allows overcoming the electronic bottleneck imposed to the real-time wideband spectrum analysers by the limited dynamics at high sampling rate of analog-to-digital converters and the high power consumption required to perform fast Fourier transforms. The compactness of the device makes it an interesting tool for on-board communications and radar applications.

Quantum Sensing and Metrology | Poster

Photoelectric detection of Nitrogen-Vacancy center magnetic resonance using Schottky contacts

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Nitrogen-vacancy (NV) centers in diamond offer a specific approach for quantum sensing owing to the optical polarization, optical readout and room temperature manipulation of its electronic spin state. In recent years, an alternative method to the traditional optical readout technique (ODMR) based on the photoelectric detection of the spin magnetic resonance (PDMR) has been investigated as it allows a more compact implementation.
PDMR readout relies on the relationship between the intensity of the collected photocurrent and NV spin state under intense green laser illumination of the diamond crystal. The photocurrent is collected by graphitic electrodes fabricated with a focused-ion-beam (FIB). The electrical scheme behavior is equivalent to a back-to-back Schottky diode scheme, which thus differs from previous measurements where a photoconductive current was detected using ohmic contacts. Since the research using ODMR is more mature, a complete setup that enables ODMR and PDMR measurements has been developed to compare both techniques. From there, the detected PDMR signal is observed to be localized close to the reverse polarized contact, corresponding to the positive electrode in our situation. The photocurrent is now controlled by the reduction of the Schottky barrier, resulting in a PDMR contrast of up to 20%, higher than the values reported in literature for ohmic contacts.
The research shows the significant potential of photoelectric detection of magnetic resonance through Schottky contacts, allowing for a high PDMR contrast and a localized signal detection. This paves the way for advanced, more compact, and high-performance quantum sensors.

Quantum Sensing and Metrology | Poster

Defying conventional wisdom in spectroscopy: power narrowing

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Commonly used pulse shapes, such as constant pulses, cause power broadening in the excitation landscape of the qubit. However, special shapes, such as Gaussian pulse shapes, reduce power broadening significantly; hyperbolic secant pulses go even further, maintaining a constant transition linewidth independent of the Rabi frequency of the pulse. Our study reveals that Lorentzian pulses induce power narrowing, reversing the common power broadening effect. We manage to perform the first experimental demonstration of power narrowing by moving the truncation point further from the center of the Lorentzian pulse, observing a shift from power broadening to pronounced power narrowing. The effect was predicted and experimentally validated using IBM Quantum hardware, showing a tenfold decrease in the 4th maximum width. Further truncation is theoretically predicted to reduce the width by the astounding two orders of magnitude, enabling more precise spectroscopic measurements with increased power of the pulse (in this case high powers are desirable, contrary to traditionally used pulse shapes).

Quantum Sensing and Metrology | Poster

Multi-parameter quantum sensing and magnetic communications with a squeezed-light enhanced hybrid DC/RF optically-pumped magnetometer

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Optically-pumped magnetometers (OPMs) are paradigmatic quantum sensors that provide insight into quantum sensitivity limits and have applications in bio-medicine, space science and fundamental physics [1]. Multi-parameter quantum sensing [2] aims to extend quantum enhancement to simultaneous measurement of multiple physical parameters. Here we report an OPM capable of simultaneously measuring dc and rf fields with quantum-limited sub-pT/√Hz sensitivity, making it a practical test-bed for quantum multi-parameter estimation (MPE) [3].
We demonstrate MPE-enabled spread spectrum magnetic communication, with possible application in ultra-compact radio receivers for communication underwater and underground. Finally, we demonstrate dc and rf sensing beyond the shot noise limit, using squeezed light to reduce the optical quantum noise (optical shot noise) in the hOPM, and demonstrate a sensitivity improvement consistent with the amount of squeezing available.

[1] D. Budker and M. Romalis, Nature Physics 3, 227 (2007).\\
[2] M. Szczykulska, T. Baumgratz, and A. Datta, Advances in Physics: X 1, 621 (2016).\\
[3] M. Lipka, A. Sierant. C. Troullinou, M. W.Mitchell, Physical Review Applied 21.3 (2024): 034054.

Quantum Sensing and Metrology | Poster

On-chip cold atom interferometer for inertial sensing

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For over thirty years, many laboratories have developed atom interferometers to sense accelerations and rotations. For many applications, small compact devices are desirable, and the atom chip appears to offer a path towards miniaturization. Additionally, implementing the interferometry sequence on-chip with trapped atoms decouples the sensitivity of the sensor from its size, potentially enabling longer interrogation times while reducing the device's dimensions. It has been shown that accelerations can be sensed from a Ramsey's interferometer by spatially splitting the two states of the atoms during the interrogation period. This can be done by separating the two states, using state selective near-field microwave gradients from a coplanar waveguide.
We have demonstrated the ability to selectively displace different internal states of a two-component thermal cloud using coplanar waveguides. The separation between these internal states spans several microns, while keeping the coherence of the interference fringes. This leads to a sensitivity to accelerations of our on-chip cold atom interferometer.

Quantum Sensing and Metrology | Poster

Ramsey interferometry with qudits

Branislav Ilich
Sofia University "St. Kliment Ohridski"

Ramsey interferometry, a cornerstone technique in quantum mechanics, traditionally employs qubits for high-precision measurement. We explore the extension of Ramsey interferometry to qudits, quantum systems with d-levels, which are predicted to offer enhanced resolution of the transition frequencies. A comprehensive theoretical extension to higher-level systems is provided via the Wigner-Majorana(WM) representation. Our approach leverages the unique properties of WM systems to achieve superior resolutions, compared to qubit-based systems. Implementation of the Ramsey protocol in WM qudit systems is explored and analysed.

The theoretical predictions are supported by simulations and analytical solutions, demonstrating the feasibility and advantages of using qudits in Ramsey interferometry. Results show improved resolution and precision, making qudits a promising candidate for advanced quantum sensing applications. However, such improvements are not without drawbacks, as decreases in the overall contrast of the oscillations is observed in higher-level systems. Differences between odd-level and even-level systems are considered, culminating in a golden middle of where the increase in resolution is substantial enough to justify the decreased contrast. Most notably, three-level systems, qutrits, are observed to have the highest increase in effectiveness of all qudit systems, doubling the resolution, with no decrease in contrast of the oscillations. Ultimately, a conclusion is made that odd-level WM systems seem to cope better with the Ramsey protocol, with qutrits (three-level) and quinits (five-level) systems as the best performers.

Quantum Sensing and Metrology | Poster

Memristive devices for quantum metrology

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Memristive devices or memristors (from the contraction of memory + resistor) are a recent type of nanoscale devices where ionics is coupled with electronics and their functionalities rely on nanoionic effects. These are two-terminal devices where a switching film (usually a metal-oxide) is sandwiched in between two metal electrodes in a metal-insulator-metal structure. When operated under specific conditions, a conductive filament is formed between the metal electrodes and low resistance states can be activated in the device corresponding to values multiple (or half-integer multiples) of the fundamental conductance value, $G_0 = 2e^2/h$. These quantized values of conductance agree with the principle and fundamental characteristic of the last revision in 2019 of the International System of Units (SI) to the definition of the measurement units depending on only the fixed values of fundamental constants, e, the elementary charge and h, the Plank constant, in the case. The recent European EMPIR project 20FUN06 MEMQuD - "Memristive devices as quantum standard for nanometrology" explored for the first time the potential of the quantum conductance effect in memrisitve devices to be applied in the metrology field as a quantum resistor standard. In this work, it is presented the operation of memristive devices to produce quantized conductance states, a model for the related measurement uncertainty and their metrological characterization based on experimental measurements. ACKNOWLEDGEMENT: This work was supported by the European project MEMQuD, code 20FUN06, funded by the EMPIR programme co-financed by the Participating States and from European Union's Horizon 2020 research and innovation programme.

Contents

Quantum Sensing and Metrology | Poster

Arbitrary gates on the double transition of NV ground state for low field or high frequency sensing

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We present a scheme for the implementation of fast arbitrary qubit gates in the ground state of the negatively charged nitrogen-vacancy (NV) defect in diamond [1]. The protocol is especially useful in the low-field regime and for high-frequency sensing applications. It constitutes an extension to the NV-ERC technique [2], which has demonstrated efficient initialization and readout of the double quantum transition with no leakage to any third level thanks to an effective Raman coupling [3]. Here we derive a full theoretical framework of the scheme, identifying the complete unitary associated to the approach, and more specifically the relevant basis transformation for each of two characteristic pulse durations. Based on this insight, we propose a scheme to perform fast single qubit gates in the double quantum transition. We study its robustness with respect to pulse-timing errors resulting from faulty identification of system parameters or phase-control limitations. We finally demonstrate that the technique can also be implemented in the presence of unknown electric or strain fields.

[1] Alberto López-García and Javier Cerrillo; Full Qubit Control in the NV^- Ground State for Low Field or High Frequency Sensing, arXiv:2407.17461
[2] J. Cerrillo; S. Oviedo Casado; J. Prior. Low Field Nano-NMR via Three-Level System Control. Physical Review Letters 126, 220402 (2021)
[3] Philipp J. Vetter; Alastair Marshall; Genko T. Genov; Tim F. Weiss; Nico Striegler; Eva F. Großmann; Santiago Oviedo-Casado; Javier Cerrillo; Javier Prior; Philipp Neumann et al. Zero- and Low-Field Sensing with Nitrogen-Vacancy Centers. Physical Review Applied 17, 044028 (2022).

Quantum Sensing and Metrology | Poster

A CMOS 472X456 SPAD array chip using in-pixel temporal correlation and address-based readout for quantum ghost imaging

Seyed Rasoul Aghazadeh[1]; Massimo Gandola[1];
Enrico Manuzzato[1,2]; Leonardo Gasparini[1]
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2 - University of Trento

Ghost imaging allows visible sensors to acquire images of objects at non-visible wavelengths, but practical implementations of ghost imaging systems suffer from poor miniaturization due to the need for long optical delay lines. We here propose a new Single Photon Avalanche Diode (SPAD)-based detector integrating on-chip the logic required to measure spatio-temporal correlations with an external bucket detector. To collect signal photons, we have designed a large image sensor based on SPADs offering appropriate signal-to-noise ratio and photon detection efficiency, high frame rate, etc. The 472x456 SPAD array chip fabricated in a 110-nm CMOS process achieves a 17-µm pixel pitch and a fill factor of 31.3% while the chip area is 8600 µm x 9000 µm. The sensor performs In-pixel temporal correlations through a compact electrical delay circuit, a correlation network, and a 1-bit memory cell. The delay circuit produces a tunable time delay, from 8 ns to 30 ns, and thus compensates for the intrinsic electrical delay generated by the bucket detector and other optical and/or electrical elements in the system. Once the SPAD detects a photon, the correlation network generates a tunable correlation window ranging from 2 ns to 10 ns. If the bucket trigger and the correlation window are in-phase, a correct correlation is detected and thus is stored inside the in-pixel memory cell. A robust address-based readout scheme has been exploited to address the pixels detecting correct correlations. The chip has been experimentally verified in a ghost imaging setup, promising for high-resolution quantum ghost-images.

Quantum Sensing and Metrology | Poster

Towards coherent interaction between a solid-state spin and a macroscopic mechanical resonator

Anna Olofsson; D. M. Kara; D. M. Høj; R. H. Jensen; A. Huck; U. L. Andersen
Center for Macroscopic Quantum States (bigQ), Department of Physics, Technical University of Denmark

Mechanical resonators from the nano- to cm-scale are interesting for a range of applications including force sensing, intertial navigation, to searches for quantum gravity and dark matter. With improved fabrication techniques and understanding of mechanical losses over the past decade the Q-factor, which is the ratio of mechanical frequency, $f_\rm{m}$, to mechanical damping rate, $\gamma_\rm{m}$, of some resonator devices now surpass the billions. This has opened up the potential of using functionalised resonators for the transduction of information in quantum computing architectures and also scanning-probe based quantum sensing.

To date opto-mechanical interactions, such as radiation pressure, have typically been used for investigating these systems, and have proved extremely successful, for example leading to demonstrations of cooling to the ground-state, mechnical squeezing, entanglement of distant phonon-modes, and conversion between optical and microwave photons. We are exploring interfacing micro-scale resonators with the electronic spin state of nitrogen-vacancy centres in diamond, via magnetic gradients. Coupling resonators to what is effectively a two-level system, would enable the creation of non-gaussian mechanical states, including phonon-superpositions to allow the study of phonon quantum-coherence, quantum enhanced gyroscopes, and the possibility of interconnecting superconducting qubit processors with optical quantum networks.

If accepted, I will present recent work characterising shallow (within $10\,\rm{nm}$ of the surface) NVs in diamond and our progress toward using them to sense the motion of a nearby magnetic force microscopy probe with high spectral resolution by implementing a quantum heterodyne technique. Further, I will discuss our initial results in functionalising high-Q trampoline resonators with nanoscale magnetic structures.

Quantum Sensing and Metrology | Poster

Towards a variable-geometry multiplexed strontium optical atomic clock

Ivana Puljić; Johnn Erick Toro Rojo; Marko Mandarić; Damir Aumiler; Ticijana Ban; Neven Šantić
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In the last two decades, experimental platforms based on alkaline earth atoms in optical lattices have developed rapidly. Current state-of-the-art op- tical lattice clocks can reach levels of accuracy below 10–18, making these clocks a unique platform for metrology and precision measurements. Meanwhile, in the last few years optical tweezers have pushed the possibilities of single optical qubit control and detection, opening new research possibilities for quantum simulation, quantum computing and metrology.

We are developing a new experiment with strontium atoms in optical lattices in which we plan to combine the unique flexibility offered by techniques used in optical tweezers with the high accuracy of 1D optical lattice clocks.

Here, we report on the current state of our experiment and offer an outlook for our clock.

Additionally, we present the first direct measurement of the lifetime of the 5s5p 1P1 state of 88Sr. We achieve this by exciting a hot atomic beam of strontium using a femtosecond laser at ≈461 nm and collecting the fluorescence with a single-photon detector, employing the time-correlated single-photon counting (TSCPC) technique.

Quantum Sensing and Metrology | Poster

A theoretical framework of Hong-Ou-Mandel microscopy

Dominic Branford[1,2]; Niclas Westerberg[3]; Erik Gauger[2]
1 - Università degli Studi di Firenze;
2 - Heriot-Watt University;
3 - University of Glasgow

The Hong-Ou-Mandel (HOM) effect is a two-particle interference phenomenon driven by the indistinguishability of particles. This creates a sensitivity to properties which reduce the similarity of photons, such as a relative delay. HOM sensing has been demonstrated to have nanometre-resolution, while also being tunable to have a wide dynamic range. We extend the theory of HOM sensing to spatially-resolved interference, giving a model of HOM imaging. This can be used to apply statistical inference to reconstruct samples, and use two-photon correlations to detect beyond the resolution of the detector array.

Quantum Sensing and Metrology | Poster

Ultracold molecules for metrology and quantum science

Tim Langen
Atominstitut / TU Wien

Molecules promise a large variety of applications ranging from precision measurement science to many-body physics. A major requirement towards realizing these applications is the precise control of molecules and their quantum states. To achieve this, important recent advances have been made in the cooling, trapping and manipulation of molecules using laser cooling techniques. I will present three lines of research that exemplify the rapid progress in this field.

First, I will present our recent advances towards the first laser cooling of barium monofluoride molecules, which are promising sensors for many different types of precision measurements. I will discuss how to realize novel laser cooling schemes in this species, which paves the way for studies of electron electric dipole moments, weak parity violation and nuclear anapole moments.

Second, I will present an experiment aiming at cooling calcium monofluoride molecules to quantum degeneracy. In this regime, tunable interactions between the molecules will allow the exploration of quantum states with enhanced metrological sensitivity. Moreover, I will also highlight the possibilities that such strongly dipolar molecular systems open up for quantum simulation and dipolar many-body physics.

Finally, I will introduce a new approach to realize optical tweezers for single atoms and molecules, which is based on micrometer-scale lenses that are 3D printed directly onto the tip of standard optical fibers. Their compactness and simplicity make these tweezers promising components for future portable quantum devices, such as single-photon sources and optical clocks.

Quantum Sensing and Metrology | Poster

Single-Photon detectors with room-temperature operation, high quantum efficiency, and low noise

Eunsung Park[1]; Hyo-Sung Park[1]; Hyun-Seung Choi[1]; Jae-Young Kim[2]; Sung Chul Shin[2]; Myung-Jae Lee[1]

1 - Yonsei University, TruPixel;

2 - TruPixel

Single-photon avalanche diodes (SPADs) are semiconductor devices that enable single-photon detection based on the avalanche-multiplication mechanism and have been in the spotlight in light detection and ranging (LiDAR) as well as various biomedical applications. In addition, recently, it has attracted great attention as a key element technology for various quantum applications such as quantum key distribution (QKD), quantum random number generator (QRNG), optical quantum computing, etc. While superconducting nanowire single-photon detectors (SNSPDs) require cryogenic operation temperatures, SPADs can operate at room temperature.

SPADs especially based on standard CMOS technology are of great interest due to such advantages as cost-effective fabrication, high-volume production, high reliability, and monolithic integration capability with circuitry. Here, we present the recent achievements of CMOS SPADs, achieving room-temperature operation, high quantum efficiency, and low noise [1-3]. It is expected that the high-performance CMOS SPADs will open up new possibilities for advancing quantum technologies and applications.

This work was supported by the DIPS 1000+ program funded by MSS (Grant No. 20242237).

[1] E. Park et al., IEEE J. Sel. Topics Quantum Electron., 3800207 (2024).
[2] W.-Y. Ha et al., IEEE J. Sel. Topics Quantum Electron., 3800410 (2024).
[3] E. Park et al., IEEE J. Sel. Topics Quantum Electron., 3800809 (2024).

Quantum Simulation

Quantum Simulation | Poster

A quantum walk-based scheme for distributed searching on arbitrary graphs

Mathieu Roget[1,2]; Giuseppe Di Molfetta[1,2]
1 - Aix-Marseille University;
2 - Laboratoire d'informatique et des systèmes (LIS)

A discrete time quantum walk is known to be the single-particle sector of a quantum cellular automaton. Searching in this mathematical framework has interested the community since a long time. However, most results consider spatial search on regular graphs. This work introduces a new quantum walk-based searching scheme, designed to search nodes or edges on arbitrary graphs. As byproduct, such new model allows to generalise quantum cellular automata, usually defined on regular grids, to quantum anonymous networks, allowing a new physics-like mathematical environment for distributed quantum computing.

Quantum Simulation | Poster

Simplification of tensor updates for quantum computer simulation

Koichi Yanagisawa; Aruto Hosaka[1]; Tsuyoshi Yoshida[1];
Tsuyoshi Okubo[2]; Synge Todo[2]
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2 - The University of Tokyo

Quantum computing hardware is rapidly evolving, which makes its simulation highly complex. Herein, tensor network takes attentions to reduce the complexity. Especially, a one-dimensional tensor network of the matrix product state is employed with a tensor update method called canonical form. Quantum computing simulation generally has distant time-consecutive gates, leading to high complexity of the tensor updates with the canonical form because it would require to update many tensors depending on the position of the quantum gate.

There can be several alternative methods for simplifying the tensor updates, intended to reduce the computational complexity at an expense of the fidelity reduction. For example, simple update utilizes the information of local tensors only. This work numerically and quantitatively evaluates those tensor update methods in terms of the fidelity and computational complexity for quantum computing simulation. In a scenario, simple update reduces the computational complexity by the order of the number of qubits without significant degradation in the fidelity compared with the canonical form.

Quantum Simulation | Poster

Quantum variational simulation of non-perturbative QED

Óscar Amaro; Lucas Gamiz; Marija Vranic
GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal

Advances in digital and analog quantum simulation hardware hold the potential to enable scalable numerical modeling of quantum many-body physics, particularly in the context of relativistic plasmas in strong background fields. However, current devices face significant limitations due to decoherence and the absence of quantum error correction, restricting the depth of quantum circuits.

Variational algorithms, a type of hybrid classical-quantum method, involve using quantum devices to compute computationally intensive cost functions (such as the system's average energy), while classical components optimize the variational parameters of the wavefunction. This approach, which accommodates the constraints of today's noisy quantum hardware, has been successfully used to model general stochastic differential equations [2].

In this study, we apply these techniques to simulate quantum radiation reaction of electrons in a one-dimensional simple setup. We investigate various aspects of the simulation: the optimized wavefunction ansatz, the depth of single time-step evolution, and the extraction of observables. Future work may extend to higher-dimensional problems, more complex collision operators (such as the Boltzmann equation), and the inclusion of additional Strong-Field QED processes (see [2]).

[1] Alghassi, H, et al, Quantum 6, 730 (2022)
[2] Luis Hidalgo and Patrick Draper, Phys. Rev. D 109, 076004 (2024)

This work was supported by the European Research Council (ERC-2015-AdG Grant No. 695088) and Portuguese Science Foundation (FCT) Grant Nos. CEECIND/01906/2018, PTDC/FIS-PLA/3800/2021 DOI:https://doi.org/10.1103/10.54499/PTDC/FIS-PLA/3800/2021, and UI/BD/153735/2022. We acknowledge use of the Marenostrum (Spain) and LUMI (Finland) supercomputers through PRACE/EuroHPC awards. Simulations were also performed at the IST cluster (Lisbon, Portugal)

Quantum Simulation | Poster

Non-linear quantum computing for simulation of non-linear physical problems

Efstratios Koukoutsis[1]; Kyriakos Hizanidis[1]; Abhay Ram[2]; George Vahala[3]
1 - School of Electrical and Computer Engineering, National Technical University of Athens;
2 - Plasma Science and Fusion Center, Massachusetts Institute of Technology;
3 - Department of Physics, William & Mary

We propose a quantum simulation process for a specific class of non-linear physical problems, where the non-linear evolution is managed by a two-component Bose-Einstein
condensate coupled with the qubit space. In that way, a composite computational space is created consisting of a non-linear qubit which allows for state dependent non-linearrotations, based on the Gross–Pitaevskii mean field dynamics, and the standard qubit space for linear unitary operations. We demonstrate the effectiveness of the algorithm by applying it into suitably transformed non-linear problems such as the Hydrodynamic Schrödinger equation† as well as to non-linear-in-normalization-only quantum channels. Finally, we discuss the potential realization of the proposed quantum computational structure.

Th. Meng and Y. Yang, Phys. Rev. Research 5, (2023).

Quantum Simulation | Poster

Demonstration of system-bath physics on gate-based quantum computer

Rolando Reiner; Pascal Stadler
HQS Quantum Simulations

We demonstrate algorithmic cooling on IBM-Q devices. We utilize inherent qubit noise to simulate the equilibration of an interacting spin system towards its ground state, when coupled to a dissipative auxiliary-spin bath. The steady-state correlations in the system are defined by the system Hamiltonian and are stable as long as the algorithm can be executed. In particular, we demonstrate the relaxation of system spins to ferromagnetic and antiferromagnetic ordering, controlled by the definition of the Hamiltonian. We are able to perform simulated cooling for global systems of up to three system spins and four auxiliary spins.

Quantum Simulation | Poster

QML framework with QKE algorithm for benchmarking quantum computer in context of application

Stefan Kister; Martin Ruefenacht

Quantum benchmarks considering applications running in a hybrid quantum-classical environment are today an emerging field of research. In era of NISQ computing it is very likely that hybrid workloads may show first kind of advantage. Therefore, it is necessary to understand better, how certain level of noise will impact applications results in such a hybrid setup.
However, today standardized benchmarks focusing on assessing the quantum hardware stack only. For assessing quality from application perspective, it is hard to estimate how these metrics will affect application results.
As a first approach, we show a quantum machine learning benchmark framework using quantum kernel estimation algorithm (QKE) in a standardized classification procedure with support vector classifier. We think QKE is an ideal candidate for such an application benchmark: It has a hybrid setup and needs to run over the entire classic-quantum workflow, with the most time-consuming part running on quantum. It can be easily tuned to investigate scale, quality and speed of a hybrid system in context of the accuracy of a trained model. The in ML widely used MNIST dataset delivers high accuracy results without relying on the quality of data engineering.
We show the results of series of emulations on a pre-version of ParTec's quantum workbench varying number of qubits, data samples sizes, quantum feature maps and circuit depths. Our baseline work will show results without noise on a fake backend. The same emulations are then done under same conditions, but noise models applied to this backend.

Quantum Simulation | Poster

A Qiskit framework for qLSTM to predict real world time series data

Stefan Kister; Jonas Michel; Felix Lehner

Long Short-Term Memory (LSTM) methods were introduced to overcome the vanishing gradient problem of recurrent neural networks in the 90's. LSTM is still valuable method in deep learning and got recently enhanced by an extended LSTM method. LSTM can be used in different use cases, e.g. language modeling, machine translation (sequence to sequence learning), image captioning, handwriting generation, image generation using attention models.
On basis of first published approaches of quantum LSTM we introduce a qLSTM framework utilizing the integrated PyTorch workflow in Qiskit. In our demonstrator we use LSTM for predicting time series data in a hybrid quantum-classical workflow. We use variational quantum circuits (VQA) for representing the weights in the classical LSTM cell. The variational quantum circuits are built of 2 parts: An encoding layer (quantum feature map) to load classical data points into quantum feature space, and a variational layer (ansatz) which contains the tunable parameters.
We will show illustrative examples utilizing the Aer state vector simulator for noise free QC simulations as well as fake backends with noise models from current IBM eagle devices. To illustrate functionality of the qLSTM framework results will be presented with toy data of a damped oscillator, but also with real world data which were used to create global warming stripes.

Quantum Simulation | Poster

Quantum simulation of bound state scattering

Matteo Turco[1]; Gonçalo Quinta[2]; João Seixas[1]; Yasser Omar[1]
1 - CeFEMA & IST & PQI;
2 - Instituto de Telecomunicações

The last few years have seen rapid development of applications of quantum computation to quantum field theory. The first algorithms for quantum simulation of scattering have been proposed in the context of scalar and fermionic theories, requiring thousands of logical qubits. In this paper we present a strategy to excite wavepackets of the interacting theory directly from the vacuum of the interacting theory, allowing the preparation of states of composite particles. This is an important step towards digital quantum simulation of scattering of composite particles. The approach is based on the Haag-Ruelle scattering theory, which provides a way to construct creation and annihilation operators of a theory in a full, nonperturbative framework. We provide a quantum algorithm requiring a number of ancillary qubits that is logarithmic in the size of the wavepackets, and with a success probability vanishing at most like a polynomial in the lattice parameters and the energy of the wavepacket. The gate complexity for a single iteration of the circuit is equivalent to that of a time evolution for a fixed time. Furthermore, we propose a complete protocol for scattering simulation using this algorithm. We study its efficiency and find improvements with respect to previous algorithms in the literature.

Quantum Simulation | Poster

Squared overlap calculations with linear combination of unitaries

Michelle Sze; Nathan Fitzpatrick; David Muñoz Ramo
Quantinuum

Linear combination of unitaries (LCU) method has proven to scale better than existing product formulas in simulating long time Hamiltonian dynamics. However, given the number of multi-control gate operations in the standard prepare-select-unprepare architecture of LCU, it is still resource-demanding to implement it on the current hardware machines. For a special purpose of calculating squared overlaps of two wave functions, we propose an optimized LCU method, based on pre-selecting relevant unitaries, that leads to a significant reduction in the circuit depths and two-qubit counts. We test this approach in simulating Rabi-Hubbard Hamiltonian.

Quantum Simulation | Poster

Simulating chemical reactions with fault-tolerant quantum computers

Wojciech Burkot; Witold Jarnicki; Paulina Mazurek; Emil Zak
BEIT sp. z o.o

The conversion of nitrogen into ammonia accounts for up to 3% of global energy consumption. One solution to the high energy demands of ammonia (fertilizers) production is to perform comprehensive simulations that guide the design of new catalysts. One such molecule is the FeMo cofactor ("FeMoCo") in the nitrogenase enzyme, which steers the biological nitrogen fixation. To date however, classical high-performance computing simulations of chemical reaction dynamics are prohibitively expensive for many industrially relevant molecules, including FeMoCo. We took the challenge of designing a blueprint for fault-tolerant quantum computer simulations of chemical reaction dynamics. We thus present a comprehensive software suite solution, BQCHEM, offering a portfolio of quantum simulation algorithms along with customized procedures tailored to specific applications, such as catalyst design. BQCHEM is informed by the hardware layer, integrating quantum error-correcting codes (QEC) developed and optimized for specific quantum circuits and architectures. Each simulation algorithm is supported with resource estimation metrics such as T-gate and Qubit count. Our solution returns predictions of the quantum computational complexity and guidelines for QEC schemes.

As a demonstration of BQCHEM, we present a quantum algorithm for simulating the electronic energies of the FeMoCo molecule, incorporating relativistic effects. For FeMoCo electronic structure calculations, we achieved a 60% reduction in quantum computing resources. These algorithmic advancements carry the potential to aid the design of more efficient catalysts with impact on agriculture, the design of pharmaceuticals, advanced materials for efficient artificial photosynthesis, and innovative catalysts for CO2 conversion into methanol, among other applications.

Quantum Simulation | Poster

Simulating electron-positron pair production using quantum Monte Carlo

Lucas Inigo Gamiz; Óscar Amaro; Marija Vranić
GoLP / IPFN, Instituto Superior Técnico, Universidade de Lisboa

Monte Carlo (MC) simulations are fundamental for modelling stochastic processes in fields ranging from quantum electrodynamics and biology to finance. However, the computational demands of classical MC simulations can be prohibitive, and reliance on pseudorandom numbers may introduce bias. Quantum computing offers a potential solution through quantum amplitude amplification (QAA) and estimation (QAE) techniques, which have demonstrated the potential for quadratic speedup and improved accuracy in quantum Monte Carlo (QMC) simulations for applications like pricing financial options[1,2] and risk analysis[2]. Moreover, the impending commissioning of next-generation petawatt lasers implies that QED effects will become relevant in laser-plasma interactions, highlighting the need for efficient and accurate computational tools to study QED processes in plasmas. In this work, we explore the application of QAA and QAE to calculate expectation values from electron-positron pair production in the Breit-Wheeler process, a fundamental process in quantum electrodynamics. By leveraging quantum simulators and, if feasible, quantum hardware, we aim to perform QMC simulations and compare the results with classical calculations. This research contributes to the growing body of work demonstrating the potential of quantum computing for accelerating computationally intensive simulations with real-world applications, particularly in high-field physics. Furthermore, the methods developed in this study can serve as illustrative examples for other scientific fields that rely on MC simulations.

[1] Rebentrost, P., Gupt, B. & Bromley, T. R. Quantum computational finance: Monte Carlo pricing of financial derivatives. *Phys. Rev. A* 98, 022321 (2018).

[2] Woerner, S. & Egger, D. J. Quantum risk analysis. *npj Quantum Inf* 5, 1–8 (2019).

Quantum Simulation | Poster

Method of fragment molecular orbital and variational quantum eigensolver for quantum chemistry using quantum computing

Doo Hyung Kang
Qunovacomputing

Quantum computers hold great promise for analyzing complex systems, but their application to larger systems is constrained by limited qubit availability and quantum hardware noise. Although the variational quantum eigensolver (VQE) was designed to tackle these challenges, its scalability remains restricted. Numerous approaches, including new ansätze and Hamiltonian modifications, have been explored to improve VQE performance. Here, we introduce the Fragment Molecular Orbital/Variational Quantum Eigensolver (FMO/VQE) algorithm, which combines the fragment molecular orbital (FMO) approach with VQE to optimize qubit usage in quantum chemistry simulations. Using the UCCSD ansatz, the FMO/VQE achieved remarkable accuracy in simulations with minimal qubit requirements across different basis sets, representing a notable improvement in scalability over conventional VQE. This integration of fragment-based quantum chemistry with quantum algorithms in our FMO/VQE method demonstrates how scalability can be enhanced, paving the way for more complex molecular simulations in line with advances in quantum computing.

POSTER SESSION
Tuesday, 19 November

17:45 – 18:45

Basic Science

Basic Science | Poster

Optical repulsive potential for DY DEC and supersolid in the 400 nm region

Niccolò Preti[2]; Nicolò Antolini[3]; Giulio Biagioni[3]; Andrea Fioretti[1]; Giovanni Modugno[2]; Luca Tanzi[1]; Carlo Gabbanini[1]

1 - CNR INO, Pisa;

2 - Dipartimento di Fisica e Astronomia, Università di Firenze;

3 - Dipartimento di Fisica e Astronomia, Università di Firenze

Repulsive optical potentials are important tools to study fundamental phenomena in ultracold quantum gases, as uniform Bose and Fermi gases, device-like systems, and controllable vortexes. The use of blue light allows to achieve high spatial resolution. We realized a repulsive potential in the 400 nm region for dysprosium Bose-Einstein condensate, where the presence of the long ranged dipolar interaction leads to novel phenomena and phases, as the supersolid state [1]. Using a spectrally filtered diode laser, we measured both scalar and tensorial components of the polarizability of dysprosium, finding a good agreement with the theoretical predictions. We demonstrated the realization of potential strengths appropriate to manipulate BECs, with lifetimes exceeding one second [2]. This kind of optical potentials opens interesting directions for investigating dipolar superfluids and supersolids. In particular we are interested in realizing an annular geometry to test the differences between superfluids and supersolids under rotation.

[1] L. Tanzi, E. Lucioni, F. Famà, J. Catani, A. Fioretti, C. Gabbanini, R. N. Bisset, L. Santos, and G. Modugno, Observation of a dipolar quantum gas with metastable supersolid properties, Phys. Rev. Lett. 122, 130405 (2019)

[2] N. Preti, N. Antolini, G.Biagioni, A.Fioretti, G. Modugno, L. Tanzi,and C.Gabbanini, A blue repulsive potential for dysprosium Bose-Einstein condensates, arXiv:2403.18677v1

Basic Science | Poster

Controllable coupling between fundamental modes in an asymmetric superconducting coplanar waveguide resonator

Evgeniya Mutsenik; Aidar Sultanov; Sven Linzen; Matthias Schmelz; Gregor Oelsner; Mario Ziegler; Uwe Hübner; Ronny Stolz; Evgeni Il'ichev
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Controllable coupling between the even and odd fundamental modes of an asymmetric half-wavelength superconducting coplanar waveguide (CPW) resonator is demonstrated. The CPW resonator was fabricated of niobium nitride thin film and galvanically coupled with an array of aluminium-based rf-SQUIDs (radio frequency superconducting quantum interferometer device), which were placed in only one CPW resonator gap, ensuring its strong asymmetry. In such a way, adjusting an external magnetic field Φ, the even mode resonant frequency could be tuned. Meanwhile, the resonant frequency of the odd mode stays constant. Approaching a certain Φ value, the resonant frequencies of both fundamental modes become identical and anti-crossing is experimentally observed, establishing the even and odd mode coupling. Also, a fitting model, describing the measured data, is introduced.

Basic Science | Poster

Quantum light from solid-state high-harmonic generation

David Theidel[1]; Viviane Cotte[1]; René Sondenheimer[2]; Mateusz Weis[1]; Hamed Merdji[1]
1 - Institut Polytechnique de Paris;
2 - Fraunhofer Institute for Applied Optics and Precision Engineering IOF,

The second quantum revolution hinges on platforms that efficiently generate non-classical states of light, which is crucial for advancing quantum technologies. Photonic systems have gained interest due to their scalability and compatibility with existing communication hardware. However, current non-classical light sources are limited by brightness and spectral range. In our research, we present a novel quantum photonic system that addresses these limitations.
We experimentally demonstrate that solid-state high-harmonic generation can serve as a quantum light source. Our setup identifies the signatures of squeezed light states by analyzing photon statistics. We perform broadband, multimode detection of the second-order intensity correlation function on a three-partite state, which includes discrete harmonic orders and spans a spectral range of over 1000 THz. We evaluate the modal distribution of the multimode squeezer, comparing experimental results with theoretical predictions. Furthermore, we confirm the presence of entanglement through the violation of the Cauchy-Schwarz inequality in bipartite reductions.
Additionally, we introduce a magnetic field to induce spin-orbit splitting of electronic orbitals and investigate its effects on non-classical properties. This research advances the understanding of quantum light sources, with potential applications in quantum communication and computation.

Tailoring a local oscillator for quantum interference with single-photon sources

Petr Steindl[1]; Hubert Lam[1]; Juan R. Alvarez[1]; Dario Fioretto[1]; Ilse Maillette De Buy Wenniger[2]; Stephen Wein[3]; Nadia Belabas[1]; Wolfgang Löffler[4]; Pascale Senellart[1]

1 - C2N, Photonics Department, Université Paris-Saclay, 10 Bd. Thomas Gobert, 91120 Palaiseau, France;
2 - Imperial College London, Quantum Optics and Laser Science, Exhibition Rd, London SW7 2BX, United Kingdom;
3 - Quandela, 7 Rue Léonard de Vinci, 91300 Massy, France;
4 - Leiden Institute of Physics, Leiden University, 2333 CA Leiden, The Netherlands

Quantum photonic technologies, including photon-number-statistic engineering [1], photonic state metrology [2], and the efficient development of quantum networks [3] require optimal wavepacket overlap between dissimilar photonic fields. Customarily, benchmarking the similarity between two fields is made via their Hong-Ou-Mandel (HOM) interference, where the overlap is retrieved from two-photon-correlation visibility measured at the outputs of a beam-splitter.
We measure the HOM visibility to determine the wavepacket overlap between high-quality single photons emitted by a quantum-dot (QD) device [4] and weak laser pulses. By tailoring laser light in different degrees of freedom, we maximize the overlap up to 77%. This represents a record value reported with semiconductor-QD sources, slightly limited by the mismatch between the temporal profile of the two fields and the low-frequency charge noise of the single-photon source. Additionally, we implement a simultaneous and complementary photon-correlation technique where the correlations are recorded from one beam-splitter output. Here, we observe an antibunching to bunching transition controlled by the coherent state amplitude and the indistinguishability between both fields. We use the transition profile to characterize and, benefiting from the high brightness of the single-photon source, also optimize the wavepacket overlap live. Since a direct Wigner function reconstruction method uses the same experimental scheme, the overlap control achieved with both techniques improves its accuracy.

[1] Lvovsky, PRA 66, 011801 (2002); Shen, PRA 95, 053851 (2017)
[2] Walschaers, PRX Quantum 2, 030204 (2021); Vogel, PRA 51, 4160 (1995)
[3] Iuliano, arXiv:2403.18581 (2024)
[4] Somaschi, Nat. Photonics 5, 340 (2016)

Basic Science | Poster

Non-positive energy quasidistributions in coherent collisional models beyond the small interaction-time limit

Marco Pezzutto[1]; Gabriele de Chiara[2]; Stefano Gherardini[1]
1 – Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche
2 – Queen's University Belfast

Collisional models have proven to be insightful tools for investigating open quantum system dynamics in regimes beyond those typically accessible with the techniques commonly employed. Recently, collisional models were applied to the scenario where a system interacts with elements of an environment prepared in states which are approximately thermal but possess a degree of coherence, in the short system-environment interaction time limit. A clear formulation of the first and second laws of thermodynamics emerges, modified to include contributions due to the presence of quantum coherence. Here we go beyond the short interaction time limit, and obtain the distributions of the stochastic instances of internal energy variation, work and heat. We show that the corresponding Kirkwood-Dirac Quasiprobability distributions (KDQ) can take into account of non-commutativity, and return the statistical moments of the distributions, in a context where the two-point measurement scheme would not be adequate. We certify the conditions under which the collision process under scrutiny exhibits genuinely quantum traits, using as quantumness criteria the negativity of the real part of a KDQ, and the deviations from zero of its imaginary part. We test our results on a qubit case-study, amenable to analytical treatment as far as the KDQ for thermodynamic quantities are concerned, whereas the full qubit dynamics over repeated collisions is accessible numerically. Our work represents an instance where thermodynamics can be extended beyond thermal systems, as well as an example of application of KDQ distributions in a thermodynamic context where quantum effects play a significant role.

Basic Science | Poster

Haldane spheres

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The current understanding of the Quantum Hall Effect (QHE) relies on the old Landau problem. Landau studied the problem of non-relativistic electrons moving in the background of a magnetic field transversal to a plane. The energy spectrum consists of bands with huge degeneracies known nowadays as Landau levels. An alternative geometry of the planar Landau problem is the Haldane sphere. We investigate the connection between the Landau levels in spherical and planar geometry. The exact eigenfunctions provide us with toolkits for numerical simulations of the fractional QHE. The Haldane spherical model for multilayer graphene is explored in view of its potential applications in quantum technologies. In particular this model can be harnessed to design topologically protected qubits, enabling robust quantum computation and storage.

Quantum Communication and Networks

Quantum Communication | Poster

Improved finite-size key rates for discrete-modulated continuous variable quantum key distribution under coherent attacks

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Continuous variable quantum key distribution (CVQKD) with discrete modulation combines the benefits of CVQKD, such as the implementability using current telecom technologies, with the advantages of discrete variable quantum key distribution, such as easier error correction procedures and simplified digital signal processing. In this work, we consider a phase-shift keying protocol using four coherent states (4-PSK protocol) and coarse-grained heterodyne measurements both for the key distillation and parameter estimation. We derive a composable security proof against coherent attacks, and compute the achievable secret key rate in a finite-size setting, i.e. with a limited number of rounds. To this end, we employ the generalized entropy accumulation theorem, which provides a framework for the coherent security of prepare-and-measure QKD protocols, together with corrections for the statistical fluctuations in the finite regime. In addition, we employ a new method from conic optimisation that provides a speedup compared to previous approaches. Our technique provides us with improved generation rates compared to previous works---we report secret key rates greater than 10^(-2) bits per channel use with less than 10^9 rounds at distances beyond 20 km.

Quantum Communication | Poster

Quantum communications in complex quantum key distribution netwoks

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Quantum Key Distribution (QKD) provides information-theoretic security for the generation of secret keys at distance. Thanks to its approach based on commercial hardware, protocols based on Continuous Variables (CVQKD) represent a suitable scope towards the practical implementation of QKD. As it provides affordability, scalability and high generation rates at intercity distances, CVQKD naturally suggests interest about its feasibility and optimal conditions in the case of many-user networks---which would constitute a first step towards a future quantum Internet.

With this work, we bridge the fields of QKD and Complex Network Theory, and use a model from the existing classical Internet in order to simulate a CVQKD network of trusted nodes. We provide an analysis of the collective properties that arise in the model, such as the connectivity, average secret key rate and clustering---as well as their variations according to the density of users and the characteristics of the channels connecting them. We complement the analysis by considering a discrete variable QKD protocol where it provides an enhanced performance, which improves several properties of the network.

Quantum Communication | Poster

Datacom-blind shortwave QKD: enhancing security for short-reach links

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In recent years, the practical application of quantum key distribution (QKD) in telecom networks has been extensively explored, with numerous field trials successfully demonstrating its feasibility. The urgency for implementing QKD is increasingly underscored by the rapid expansion of datacenters, which are transitioning from traditional perimeter security models to a zero-trust model, where no internal resource is inherently trusted. The datacenter interconnects, typically characterized by an optical budget of around 6 dB and limited fiber reach, allows for the adoption of shortwave QKD schemes. By operating at the border of the visible-light and near-infrared regions, shortwave QKD takes advantage of highly efficient silicon SPADs, circumventing the dead-time limitations inherent in InGaAs SPADs while sustaining key exchange over lossy channels, thanks to their lower dark count rate. Shortwave QKD has primarily been demonstrated in free-space scenarios. However, its application in fiber-based telecom networks holds significant promise for enhancing security in these rapidly evolving datacenter environments.

We experimentally demonstrate datacom-blind QKD operation at 852 nm over a 1-km short-reach optical interconnect, co-existing with a 100-Gb/s LAN-WDM link across four unattenuated classical O-band channels. Our results indicate that QKD performance remains unaffected by Raman noise, and only minimal spectral filtering is required for co-existence. Additionally, we explore the impact of few-mode transmission on the shortwave quantum channel using standard telecom fiber and compare its performance to a 1550-nm QKD setup. Our findings contribute to the advancement of shortwave QKD in datacenter environments, emphasizing its robustness and compatibility with existing high-speed data transmission infrastructure.

Quantum Communication | Poster

Quantum key distribution to support secure communication and computation services

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We propose a generic framework designed to distribute cryptographic keys for secure communication and computation services. In this framework, secure communication services are supported by symmetric keys, while secure computation services rely on oblivious keys. Symmetric keys ensure the privacy of data in transit, facilitating secure communication. Oblivious keys, on the other hand, enable secure computation by maintaining the privacy of input data used in computations.
The framework incorporates a key management layer that delivers both types of cryptographic keys to applications upon request. This layer can forward the keys to extend their reach. Applications ensure the security of services by operating in a hybrid mode, combining post-quantum cryptographic keys with quantum keys. We discuss the advantages of this hybrid approach with relation to purely post-quantum or purely quantum solutions.
We explore two potential implementations for the key management layer. The first implementation uses only oblivious keys, deriving symmetric keys from them. The second implementation manages both symmetric and oblivious keys independently. In both implementations, the key reconciliation layer generates secure cryptographic keys from raw material provided by quantum key distribution (QKD) systems.
The reconciliation layer, grounded in quantum and information theory, distills secure cryptographic keys from various types of quantum communication systems, including discrete, continuous, and entangled systems. This approach leverages the strengths of both classical and quantum cryptography, providing a robust solution for secure communication and computation.

Quantum Communication | Poster

High fidelity distribution of telecom polarization entangled photons through a 7.7 km antiresonant hollow-core fiber

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The field of quantum communication has developed significantly over the last two decades and quantum networks have emerged offering ultimately secure communications. The distribution of entangled quantum states in such networks has important applications in entanglement-based and beyond QKD protocols.
Silica fibers have so far been the work-horse for quantum communication demonstrations, due to the low propagation loss in the C-band. However, they suffer from several limitations, such as: Rayleigh scattering (maximum distance few hundred kilometres), Raman scattering (challenging co-existence classical and quantum signals), chromatic dispersion (temporal broadening) and various depolarizing effects. Recently, novel types of optical antiresonant hollow-core fibers have been proposed such as Nested Antiresonant Nodeless Fibers (NANFs). Since the optical mode predominantly propagates in air, antiresonant hollow-core fibers are characterized by vacuum-like speed, suppressed dispersion effects and nonlinear optical effects and, recently, ultra-low propagation loss.
In this work, an experimental investigation of entanglement distribution through a NANF with an overall length of 7.72 km is presented. Remarkably, substantial reduction of latency (about 13µs) and suppressed chromatic dispersion (about one order of magnitude) of the studied NANF compared to a telecom single-mode fiber (Corning's SMF28) of equal length are measured for different bandwidths of the distributed entangled photons. Moreover, by encoding entanglement in polarization, high fidelity (>95%) distribution of narrow-bandwidth entangled photons is demonstrated. This result paves the way to the exploitation of NANF as a superior transmitting medium for quantum technology applications relying on the distribution of entanglement encoded in polarization over inner-city distances.

Quantum Communication | Poster

Development of an entanglement-based free-space quantum communication system

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Due to the limitation of optical fibers, we need satellites to connect distant cities to share secret keys using quantum key distribution (QKD). The maturity of the technology has been demonstrated by the Chinese Micius satellite and there are many ongoing developments including the European Eagle-1 and the Asian SpeQtral-1.

At the Budapest University of Technology and Economics (BME), we have more than 20 years of experience in quantum communication. At Mobile Communication and Quantum Technologies Laboratory, we are developing four different quantum key distribution systems (fiber-based BB84, fiber-based CV-QKD, entanglement-based fiber system and entanglement-based free-space system) with the support of the national project of the European Quantum Communication Infrastructure named QCIHungary and the Quantum Information National Laboratory of Hungary.

As a high-level architectural overview, an entanglement-based free-space quantum communication systems requires a laser source, detectors, free-space channel, and time synchronization solutions. Our system was developed entirely in-house with the appropriate hardware and software components. At the Faculty of Natural Sciences, a polarization entangled photon source based on parametric down conversion and type I phase matching has been built. Detector modules with an integrated polarization analysis system have been developed at Faculty of Electrical Engineering and Informatics. GPS disciplined oscillators and a laser-based synchronization system capable of transmitting the clock signal through a free-space channel have been developed as well. We tested our photon source and communication system in short range free-space links and successfully demonstrated viable communication. Our system architecture and test results are presented in the poster.

Quantum Communication | Poster

A cavity-enhanced solid-state spin wave quantum memory

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The realization of large-scale quantum networks necessitates entanglement distribution over long distances. Direct transmission is impractical due to optical fibre losses, making quantum repeaters a potential alternative for continental-scale entanglement. Most quantum repeater protocols rely on quantum memories, which need long storage times, high efficiencies, and large multiplexing capabilities. Solid-state quantum memories based on rare-earth doped solids are promising in these aspects.
However, longer storage times often lead to an exponential efficiency decay due to material coherence time, limiting memory applicability. Spin-state storage, with spin-rephasing techniques, can address this efficiency decay. Previously, rare-earth based memories achieved a maximum of 31% efficiency for spin-wave storage at the single-photon level using the spectral-hole memory protocol, which is not temporally multimode. The highest reported efficiency for spin-state storage with the atomic frequency comb (AFC) protocol allowing temporal multimodality was 12% for classical-level coherent states.
We used the AFC protocol to implement a quantum memory in an impedance-matched cavity surrounding our cryostat's vacuum chamber. Our device achieved >50% efficiency for storing weak coherent states at the single-photon level in the excited state for 8 μs and >38% for spin-state storage for an additional 5 μs. Maintaining a high signal-to-noise ratio (SNR) is more challenging for spin-state than for excited-state storage. We achieved an SNR of 16 with a mean input photon number of 0.44, suitable for photon storage from spontaneous parametric down-conversion sources. We characterized efficiency and SNR relative to photon bandwidth and storage time and examined the impedance-matched cavity's effect on noise levels.

Quantum Communication | Poster

A flexible quantum data bus

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We consider multi-path generation of Bell-states in quantum networks, where a pre-prepared multipartite entangled 2D cluster state serves as a resource to perform different tasks on demand. We show how to achieve parallel connections between multiple, freely chosen groups of parties by performing appropriate local measurements along a diagonal, staircase-shaped path on a two-dimensional cluster state. Remarkably, our measurement scheme preserves the entanglement structure of the cluster state such that the remaining state is again a two-dimensional cluster state. We demonstrate strategies for generating crossing, turning and merging of multiple measurement lines along the two-dimensional cluster state. The results apply to local area as well as to long-distance networks.

Quantum Communication | Poster

Kramers-Kronig detection in the quantum regime

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Coherent detection is a family of measurement protocol allowing one to characterize an electric field. They are widely used both in classical communications and in quantum technologies like, e.g., homodyne, double homodyne or heterodyne detections. We investigate, in this presentation, an alternative coherent detection protocol called Kramers-Kronig detection. It relies on digital signal processing and aims at measuring both quadratures of the electric field. Such scheme, already well mastered classically and used, notably, for communications, is extended into a quantum version by use of the standard quantum description of linear optics. The main feature of Kramers-Kronig detection is that it allows to reconstructs the phase of the field from the measured intensity. In the quantized version, we define, at the first order, a KK phase operator that represent such reconstruction and which allows, together with the intensity measurement, to also reconstruct the quadratures. We also investigate the validity of Kramers-Kronig detection for some particular quantum states like coherent states and single-photon states.

Quantum Communication | Poster

Simulation of entanglement-based quantum communication using satellites on different orbits

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Today, there is a growing emphasis on integrating quantum communication into everyday practice. One plan is to build a global quantum internet. In the case of terrestrial quantum communications, the system suffers large signal attenuation over long distances, during which quantum information can be lost. To overcome this problem, a satellite-based quantum channel could be a good solution, as there are fewer sources of decoherence in space communication and the same quantum state is more likely to preserved.

To ensure the highest possible state fidelity during communication, quantum memories are needed, to store the state of the quantum bit without measurement and then send it to the appropriate node on request. Several quantum memory platform candidates have been studied in laboratory environments. Based on the available results, we are working on the design of a complex satellite system that will enable global quantum internet using quantum memories. As part of our research, we have developed a simulation framework which utilizes the properties of different quantum memories (e.g., decoherence time) and the properties of satellites on different orbits including LEO (Low Earth Orbit) and GEO (Geostationary Earth Orbit). We have investigated the potential application of entanglement swapping protocol for complex satellite constellations, i.e., systems consisting of several satellites. Using the decoherence time of quantum memories as a determining parameter, we have calculated the optimal number of satellites required for different use cases in such constellations.

Quantum Communication | Poster

Highspeed polarization preparation scheme for quantum key distribution for visible light

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For free-space quantum key distribution (QKD), the degree of freedom in which the quantum states are usually encoded is polarization. For visible light, however, no fast polarization modulators are available (that can compete with telecom devices). On the other hand, visible wavelengths can enable faster communication in daylight conditions when Fraunhofer lines are exploited. We present a novel polarization preparation scheme for the B92 QKD protocol and demonstrate its implementation in a prototype system. The B92 protocol, a simplified variant of BB84, utilizes only two non-orthogonal polarization states (horizontal and +45 degrees), reducing complexity while maintaining security. Our experimental setup consists of a transmitter (Alice) and a receiver (Bob) precisely aligned on an optical bench in a laboratory environment. Key features of our implementation include high-speed key generation facilitated by acousto-optic modulators, potentially increasing practical viability. The scalable design offers the potential for extension to BB84 and six-state protocols. This work contributes to the ongoing effort to bridge the gap between theoretical QKD protocols and their practical, real-world implementations. Our findings suggest that this approach could pave the way for more efficient and cost-effective QKD systems, which are crucial for the widespread adoption of quantum-secure communication technologies. This is particularly relevant for satellite-to-ground quantum channels using visible light and operating in daylight conditions.

Quantum Communication | Poster

N-Qubit GHZ state distillation utilizing non-linear iterative quantum algorithm

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Advances in quantum technology enable communication between remote quantum devices using highly entangled quantum bits. Entangling qubits to a high degree is challenging, requiring error correction for partially entangled pairs. Nonlinear protocols were introduced for entanglement distillation, involving local operations and classical communication. Iterative application of these protocols enhances entanglement.
The protocol involves an ensemble of two pairs of n-qubits in the same state. Initially, the parties agree on which qubits to measure. They then perform local unitary operations on their qubits before measuring them. Using classical communication, they post-select the zero measurement outcome on both sides; otherwise, they discard the results. The non-linearity arises from the feedback based on this selection-conditioned measurement. With repeated application, the remaining qubits may achieve higher order entanglement.
Recently, quantum networks have garnered significant research interest, particularly in connecting distant quantum chips. We explore the extension of uniform protocols from the well-studied bipartite case to multipartite systems involving many parties and n-qubits.
We introduce the alternating double iteration protocol, using specific single and two-qubit operators (CNOT-X and CNOT-H) to mitigate errors linearly. It achieves sub-exponential noise reduction in GHZ state distillation, purifying slightly noisy states. We analyze its performance with imperfect components like noisy gates and measurements.
Our hardware-efficient design is implementable on recent quantum computers, requiring a low number of qubits and minimal 1- and 2-qubit gates. We validate its performance using the IBM Qiskit quantum simulator and actual quantum hardware.

Quantum Communication | Poster

Quantum storage in a solid-state memory array

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A long-distance quantum network requires quantum repeaters dispersed between the end-nodes and entanglement to be distributed across the network. Successful entanglement events are heralded by detections at intermediate stations placed between the nodes. However, in a sequence of entangling attempts, the repeater nodes must wait for the heralding signal to return from the intermediate station before the next attempt. At intercity distances, the entangling rate consequently may be limited by the time of the photon travel and the classical communication. Quantum repeaters based on rare-earth-doped crystals overcome this limitation, as the atomic frequency comb protocol preparing these memories allows for temporal multiplexing, leading to a linear increase in the entanglement rate with the number of modes. The entanglement rate is further increased by combining temporal multiplexing with spatial and frequency multiplexing.

In this poster, I will present experiments on quantum storage in a novel spatially-multiplexed solid-state memory array. We use acousto-optical deflectors to store and manipulate ten individual memory cells. We characterize the efficiency of the array, determine the cross-talk between the cells, and demonstrate on-demand storage at the single-photon level in 250 spatial-temporal modes. Furthermore, we encode qubits in the time and path degrees-of-freedom and store the qubits. The fidelities of the retrieved qubits are assessed via quantum tomography and violate the classical bound for all memory cells. In near future, we will entangle each cell with a telecom photon traveling 50km of fiber and demonstrate an increase of the entanglement rate due to the multiplexing.

Quantum Communication | Poster

Requirements for teleportation in an intercity quantum network

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Connecting nodes across large distances in a quantum network presents a multifaceted challenge, intricately linked to the diverse properties of different hardware platforms. Some being ideal as processing nodes, while others serve as efficient repeaters. From distributing entanglement over short distances in a metropolitan network (50 km) to facilitating quantum communication across intercity scales, each network segment demands tailored requirements and improvement over the current state-of-the-art. We investigate high-level parameter trade-offs in the requirements for achieving quantum teleportation deterministically with an average fidelity surpassing the classical bound of 2/3 on an intercity quantum network, a large-scale network bridging two metropolitan-scale networks via a long-distance linear repeater chain. In particular, we examine the interplay between the coherence time of quantum memory, entanglement generation rate, and fidelity. We do so for two scenarios: one where the to-be-teleported state needs to be stored in memory until the required entanglement is established, and one where this is not necessary. Employing both simplified analytical models and an extensive simulation framework implemented with NetSquid, a discrete-event simulator for quantum networks, and using baseline parameters based on the state-of-the-art networked ion traps and atomic-ensemble memories, we identify the requirements imposed on the metropolitan link by the long-distance setup. Our work sheds light on the trade-offs between different hardware improvements and provides practical regimes for target requirements that could be made in order to realize quantum teleportation in deployed quantum networks.

Quantum Communication | Poster

Development of single-photon sources in hBN for free-space QKD applications

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Quantum key distribution (QKD) networks, in combination with post-quantum cryptography, are essential to ensure secure communications for critical infrastructure in the near future, addressing the threats posed by rapidly advancing quantum computers to classical cryptography. Deterministic single-photon sources (SPS) are the essential resource for realizing practical QKD. In this work, we present our research on the development of hexagonal boron nitride (hBN) -based SPS for free-space QKD applications. The two-dimensional hBN is known for hosting ultrabright optically active color centers with emission wavelengths spanning from UV to infrared, exhibiting high single-photon purity and room-temperature operation. Despite many favorable properties of hBN, the atomic origin of only a handful of observed SPS are known; however, these particular SPS are not suitable for free-space QKD due to their UV-range emission or wide phonon-side bands. Our research presents an experimental and theoretical approach to create defect-based SPS in hBN suitable for atmospheric optical window QKD applications. We use a combination of ion implantation and laser-based creation and activation, SPS properties measurements, atomic-resolution materials characterization, and density functional theory calculations to elucidate the atomic origin of the SPS in hBN needed for practical QKD device manufacturing and applications.

Quantum Communication | Poster

Entangled photon sources for quantum communication and sensing

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Entangled photon sources (EPS) are crucial for many applications in quantum information processing, quantum sensing, and quantum communication. The development of practical, high-performance EPSs is therefore crucial to facilitate adoption of quantum technology in real-world scenarios. However, different EPS technology platforms each inherit their own advantages and weaknesses, and it is thus important to make the optimal choice for a given use case.

In this work, we show recent advances in development of EPS technology in the Optoelectronics group at ICFO. In particular, we present results on novel EPSs implemented in three different technologies – bulk optics, fibre-integrated components, and photonic integrated circuits:

Firstly, our bulk optics EPS is optimized for free-space quantum communication, including space-based, as well as metropolitan link, use cases. This compact and robust EPS takes advantage of the near-ideal outcoupling efficiencies possible in bulk optics, as well as the availability of highly mature off-the-shelf components. Secondly, our research on fibre-integrated EPS focuses on generating photon pairs both in nonlinear waveguide devices, as well as in strongly nonlinear fibres. Here, the advantages of our systems are facile connection to existing optical fibre networks, including minimized inter-fibre coupling losses, resulting in near-passively stable EPS. Lastly, quantum sensing requires highly stable EPSs with small physical footprints, in applications where portability is key. We have developed a fully on-chip source of quantum states of light that is suitable for quantum-enhanced gas sensing and spectroscopy.

Developing metrology at the single photon level for QKD: the effort of the EURAMET European metrology network for quantum technologies

Marco Gramegna
INRIM

The deployment of EuroQCI [1], the EU secure quantum communication infrastructure, is underway and relies on "quantum safe" cryptographic techniques, most notably Quantum Key Distribution (QKD) [2], that operating at the single-photon level, distributes secret digital keys over optical links. Uniquely, QKD provides protocols whose security can be proven by the laws of quantum mechanics, rather than by relying on unproven assumptions about the computational resources available to an adversary.

Although QKD protocols can be proven unconditionally secure in theory, in practice any deviations of the real system from the idealised model could introduce vulnerabilities [2]. For QKD technology to become a viable real-world solution, end-users need confidence in it, and this requires its metrological characterisation of physical parameters of the practical QKD system devices [3-4]. This work reports on the on-going effort of the National Metrology Institutes [5] coordinated by the EURAMET EMN-Q [6] to establish a reliable metrology for quantum communication [7], providing an overview of recent developments [3] of SI-traceable measurements, at the single-photon level, to characterise QKD technologies and hardware vulnerabilities of practical QKD systems for the main prominent cyber-attacks, in alignment with the actual standardisation [9] and certification process for QKD.

The EMN Quantum measurement services and facilities portfolio database will be soon available on the new website of the EMN-Q [1].

References:

[1] https://qt.eu/ecosystem/quantum-communication-infrastructure
[2] www.etsi.org/technologies/quantum-key-distribution
[3] www.euramet.org/project-19nrm06
[4] www.euramet.org/project-14ind05
[5] Nat. Phys. 18, 724–727 (2022)
[7] https://www.euramet.org/quantum-technologies/
[8] Nat. Commun. 13, 157 (2022).
[9] EPJ Quantum Technol., 9 1 (2022) 33

QUID: The deployment of the quantum communication infrastructure in Italy

Ivo Pietro Degiovanni
INRIM

The project QUID [1] proposes to start the deployment of the Quantum Communication Infrastructure (QCI) in Italy, as national implementation of EuroQCI [2]. Taking advantage of the Italian Quantum Backbone [3], QUID deploys systems and networks on the national territory to test quantum distribution of cryptographic keys, with attention to integrating them with existing communications [4]. On the other hand, QUID foster the uptake of these systems and networks from use cases. QUID is based on the deployment of several Nodes in Metropolitan Area Networks based on Discrete Variable QKD, connected by a fibre backbone. During the project, several nodes will test QKD systems, while long-distance deployment will use techniques based on Trusted Nodes, or Twin Field QKD (Untrusted Nodes).

QUID will connect also sites relevant for interconnection with the space segment of the European QCI. Last, since QKD still offers relevant possibilities of innovation, QUID devotes activities towards improving QKD features, in particular high-rate, use of innovative fibres, and the use of free-space QKD, to be implemented for mobility and where fibre is not present. QUID consortium is composed of leader Italian companies in the field, integrating systems, manufacturing QKD devices, operating telecommunication networks, and offering cyber security integrated solutions.

As well, the main research institutes involved in quantum communication in terrestrial and space segment are present, as well as five among the more relevant universities, committed to innovation and training [5-6].

References:

[1] https://www.inrim.it/en/research/projects/quid

[2] https://qt.eu/ecosystem/quantum-communication-infrastructure

[3] https://www.inrim.it/en/research/scientific-sectors/time-and-frequency/laboratories-and-activities/italian-quantum-backbone

[4] https://securecommunications.airbus.com/en/newsroom/news/2023-04-towards-a-better-approach-for-quantum-key-distribution-qkd-networks-key

[5] https://petrus-euroqci.eu/

[6] https://www.telekom.com/en/media/media-information/archive/eu-launches-nostradamus-prepares-europe-for-a-quantum-world-1056746

Quantum Communication | Poster

Entanglement of spin-wave on-demand solid-state quantum memories for quantum repeater links

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Heralded entanglement of shared excitations between two remote matter nodes is a primitive for quantum repeater links. This type of architecture relies on quantum nodes consisting of sources of entanglement and quantum memories (QM). Some of the main requirements for practical quantum links are high heralding rates with photons at telecom wavelength and multiplexed operation. Most importantly, the ability to retrieve stored excitations on-demand is a crucial feature for synchronization of repeater links across a network. In this work, we report on recent progress towards remote entanglement of two on-demand solid-state quantum memories using cavity-enhanced non-degenerate spontaneous parametric downconversion (cSPDC) sources and Pr^{3+} rare-earth doped QM. Upon detection of an idler click at one of the detectors of the central station, an entangled state is heralded at the memories. To verify entanglement, it is necessary to show that we operate in the single excitation regime and that the excitation is in a coherent superposition of the two memories By retrieving the excitations from the QMs and interfering the photons at a beam splitter, state tomography can be carried out. The estimated concurrence of the detected heralded state is of (4.95±2.12)x10^-5 with single photon suppression of 0.295±0.028 and associated total heralding rate of around 540 cps indicating the successful heralding of a genuinely entangled state at high rate. Together with the high multiplexing capability of Pr^{3+} QM, our system combines most requirements for efficient quantum repeater links thus paving the way towards real-world deployment of quantum networks.

Quantum Communication | Poster

Noisy squeezing in continuous-variable secure quantum communication

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We address the crucial role of noisy squeezing in security and performance of continuous-variable (CV) quantum key distribution (QKD) protocols. Squeezing has long been recognized for its numerous advantages in CV QKD, such as enhanced robustness against channel noise and loss, and improved secret key rates. However, the excess noise of the squeezed states, that unavoidably originates already from optical loss as well as other imperfections in the source, raises concerns about its potential exploitation by an eavesdropper. For the widely adopted trust assumption on the excess noise in the signal states, we confirm the stability of the protocol against the noisy squeezing in both purely attenuating as well as noisy channels in the asymptotic limit, which implies perfect parameter estimation. In the finite-size regime we show that this stability largely holds at up to 10 to power 7 of data points using optimal biased homodyne detection for key distribution and parameter estimation. Untrusted assumption on the noisy squeezing, on the other hand, introduces additional security bounds on the squeezing excess noise already in the asymptotic regime, which is further enforced by the finite-size effects. Additionally, we show the critical negative role of noisy squeezing in the case of atmospheric free-space channels, already in the trusted-noise and asymptotic assumptions, which emphasizes the importance of squeezing purity in the free-space quantum channel. Our results pave the way towards practical realization of squeezed-state CV QKD protocols in both fibre and free-space channels.

Towards a global quantum communication network – The HyperSpace project

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Entanglement is a fundamental resource for the information age, enabling applications such as enhanced sensing technologies, quantum computing, and secure communication. It is particularly crucial for satellite-based quantum key distribution, allowing secure and reliable quantum information transfer over long distances and overcoming the limitations of terrestrial networks. The quantum space race has already led to several successful experiments with satellite-optical links [1]. However, scaling these experiments in terms of both distance and connectivity remains an ongoing scientific and technological challenge.
This contribution discusses the scientific and engineering requirements in developing efficient, space-qualified quantum hardware and explores potential improvements for further deployment on an intercontinental quantum link. In particular, we address challenges and benefits of using entanglement in multiple photonic degrees of freedom. Encoding high-dimensional quantum states ("qudits") in the time and frequency domain presents a promising approach to process more information and enhance resilience to noise and eavesdropping, e.g. [2,3]. Additionally, simultaneous entanglement in multiple photonic degrees of freedom, known as hyperentanglement, can increase the quantum channel capacities towards more resource-efficient quantum communication. These approaches are currently being investigated in the EU-Canadian project HyperSpace [4], a strategic collaboration aiming to harness the benefits of hyperentangled states for satellite links within a transatlantic quantum network.

References:

1. Yin, J. et al. https://doi.org/10.1038/s41586-020-2401-y, Nature, 2020.
2. Cabrejo-Ponce, M. et al, https://doi.org/10.1002/lpor.202201010, Laser Photonics Rev, 2023.
3. Ecker, S. et al, https://doi.org/10.1103/PhysRevX.9.041042, Phys Rev X, 2019.
4. Fraunhofer IOF, Press release, https://www.iof.fraunhofer.de/en/pressrelease/2022/hyperspace.html, 2022, October 17th.

Quantum Communication | Poster

Remote entanglement of spin-wave quantum memories

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ICFO

Future quantum networks will rely on the distribution of entanglement between distant material quantum nodes. Several physical systems have been entangled already, but none of these demonstrations satisfied all the requirements for a network operation. Some of these requirements are: heralded operation compatible with the telecom network, high heralding rate, resilience against the losses that a long distance scenario would imply, multimode operation, on-demand read-out of the stored entanglement, encoding in a functional basis, etc. We use rare-earth doped crystals as quantum memories. They are playing a very important role in the storage of quantum information. Among their advantages, there is a large capacity for multiplexing in several degrees of freedom and spin/optical coherences that have allowed storage for very long times.
We show status and progress towards functional entanglement between solid-state multimode quantum memories based on praseodymium doped crystals, heralded by a single photon at telecommunication wavelengths. We report the entanglement between two such memories, sharing a single photon in a delocalised spin-wave. We exploit the on-demand readout to perform feedforward operation, scanning the phase of the recalled state and applying a fixed heralding-dependent shift, to ensure a constant recalled state. Finally, we propose a scheme to extend this to a functional quantum repeater link.

Quantum Communication | Poster

Long-distance photonic device-independent quantum key distribution

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Device-independent quantum key distribution (DIQKD) offers the strongest form of quantum security for two fully uncharacterized users. However, its implementation, especially over long distances, poses significant challenges as losses make Bell test difficult to conduct successfully. In this work, we propose a photonic realization of DIQKD that offers significant advantages with respect to existing proposals. In particular, our scheme leads to positive key rates over distances of hundreds of kilometers for state-of-the-art parameters, making the proposed setup a promising candidate for securing long-distance communication in quantum networks.

Results have been obtained and the manuscript is nearing completion; we anticipate publication on arXiv prior to the conference. Further details will be provided during the presentation.

Integration of a 3-node OTN secure network with a hybrid QKD/centralized symmetric classical key management

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The quantum threat necessitates effective countermeasures and in response, Quantum Key Distribution (QKD) over optical networks provides an information theoretic secure paradigm for mitigating these emerging threats. In this respect, we report on a recent field demonstration of a fully managed quantum network that is simultaneously orchestrated with a classical optical network and employs a hybrid key scheme using both QKD keys and a commercial solution relying on a centralized symmetric classical key management. This QKD network was proficiently developed in a three-node full ring configuration over a field-deployed testbed. In this proof-of-concept QKD network – Athens PoC Quantum Network - each node comprises a fully integrated vertical stack featuring a Quantum layer, a separate Key Management (KMS) layer, and an Application layer comprising L1/OTNsec encryptors. In the proposed scheme, the SAEs in the Athens PoC Quantum Network consume keys at all three nodes of the relayed network, while enabling the application of priorities or QoS attributes to the key consumption. This was achieved by simultaneously orchestrating the encryption needs of the classical network with the KMS. The quantum network's security and continuity were further enhanced by implementing a robust secure management system, allowing the network to operate in a hybrid mode by centrally generating and distributing symmetric quantum-safe classical keys to the SAEs. This is the first demonstration to showcase a quantum-secured network that can seamlessly transition to classical encryption methods in the event of a DDoS attack on the QKD layer or any failure in key generation or distribution.

Quantum Communication | Poster

Universal, unambiguous preparation of Bell pairs

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The ability of preparing perfect Bell pairs with a practical scheme is of great relevance for quantum communication, distributed quantum computing, as well as multi-core quantum computing. We propose a scheme which probabilistically, but universally and unambiguously produces the Phi_{+} Bell pair from four copies of qubit pairs initially in the same unknown pure quantum state. The same scheme, extended to eight qubit pairs initially in the same, moderately mixed quantum state, unambiguously produces the Phi_{+} Bell pair with quadratically suppressed noise. The core step of the proposed scheme consists of a pair of local two-qubit operations applied at each of the two distant locations, followed by a partial projective measurement and postselection at each party, with results communicated classically. While the scheme resembles standard entanglement distillation protocols, it achieves success within just three iterations, making it attractive for real-world applications.

Quantum Communication | Poster

Exciton and biexciton emission in colloidal quantum dots

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Quantum dots exhibit two fundamental decay processes: exciton emission or biexciton emission. De-excitation through exciton emission produces a single photon, which is crucial for the development of single-photon sources. On the other hand, biexciton emission, which involves the sequential emission of two photons, is essential for generating entangled photons, useful in quantum computing and cryptography applications. The main challenge lies in the probabilistic nature of these decay processes, i.e. it is impossible to predict with certainty which of the two transitions will occur during the de-excitation of a quantum dot. We address the issue by developing a method to deterministically separate the two emissions. Additionally, procedures for characterising each type of emission are detailed, allowing for more precise control over the properties of the quantum dots and optimising its use in advanced quantum technologies.

Quantum Communication | Poster

Practical randomness amplification and privatization with implementations on quantum computers

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One exclusively quantum feature is the ability to run certain protocols whilst considering the devices that are used as black boxes only, i.e. in a way that does not rely on correctly modelling the hardware. Security is then guaranteed in a *device-independent (DI)* manner. Despite being the "gold standard" of security, DI protocols are notoriously hard to implement. Our work aims at making few, well justified and testable, added assumptions combined with state-of-the-art security proof techniques to develop highly secure semi-DI protocols that are simpler to implement.

We develop a protocol for device-independent randomness amplification and privatization (DI-RAP) based on Bell tests [1]. Such protocols are impossible to achieve classically and solve the central problem of generating perfect randomness from weak (or imperfect) random sources only. Other protocols assume access to perfect randomness to generate more of it, leading to a circularity and thus security loophole. We then show how DI-RAP can be made semi-DI under well justified assumptions and implement it on existing quantum computers [1]. A version of this protocol has been turned into a product by Quantinuum, showcasing that it is real-world technology available today.

[1] Practical randomness amplification and privatization with implementations on quantum computers, C. Foreman et al., Quantum (2023).

Quantum Communication | Poster

Energetic cost of quantum networks

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With the rapid development and the beginning of the industrialization of quantum networks, it is of great interest to analyze their overall energy consumption, before planning for wide-scale implementations. While it is widely known that such a cost is present, just like for classical computation, the intricate nature of quantum technologies makes evaluating the total energy requirements of quantum networks challenging. Indeed, they require very disparate techniques to create quantum signals and different methods to distribute, manipulate, detect, and process them.
In this work, we lay the foundations of a framework to estimate the energy cost of network protocols. We then give a first estimation of the energy requirement of basic network functionalities, namely Quantum Key Distribution (QKD) and Conference Key Agreement (CKA). The goal of these two protocols is to generate a private key among end users of a quantum network. While these applications are within the quantum cryptography realm, the methods and hardware we use are generic to most network protocols based on photonic implementation. In particular, the creation and sharing of entangled states among distant parties, believed to be the main goal of any network architecture, are the building blocks of many other network protocols.
We adopt a hardware dependent approach. Our goal here is to give concrete figures of merits that reflect the energy cost of basic quantum networks and discuss how to engineer and construct them efficiently. We compare the hardware commonly used in current implementations of different bipartite and multipartite communication tasks.

Quantum Communication | Poster

The Rome quantum key distribution network and the EuroQCI program

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Quantum key distribution (QKD) is an innovative technology that allows secure sharing of cryptographic key among distant users relying only on fundamental rules of quantum physics. Unlike classical key exchange protocols, QKD provides information-theoretic security, meaning it's theoretically impossible for an attacker to intercept the key, even if it has very high computational power. Different variants of this technology led to several QKD testbeds worldwide, for institutional and commercial purposes. Among the remaining challenges, its integration in existing infrastructure is a critical one, together with the hybridization with different technologies.

As part of the Quantum Italian Deployment (QuID) project, that begins the deployment of the Italian segment of the European Quantum Communication Infrastructure (EuroQCI), Leonardo is the leader of the design and implementation of the Rome QKD Metropolitan Area Network (QMAN). The network connects several important industrial sites in Rome, including facilities operated by Leonardo, Telespazio, and Thales Alenia Space.

This work presents the architecture of the network and how it interconnects with the different Italian QMAN deployed in QuID. The poster shows the different layers required to sustain such network, including a Key Management System developed by Leonardo. The network is hybrid, including fiber and free-space optical links. Notably, commercial QKD devices are deployed in the network alongside QKD prototypes developed internally by Leonardo, a rare case among defence companies. An additional connection towards the city centre allows to connect the QMAN to the Italian Quantum Backbone (IQB), and therefore to the rest of the Italian QMAN networks.

Quantum Communication | Poster

ERBIUM doped Silicon nanophotonics for scalable quantum networks

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The creation of quantum links between individual units promises to enable secure communication channels and scalable quantum computation in networks. Such a link is most practically realized with photons in the telecommunication regime, where transmission with minimal loss is achievable. This requires efficient photonic interfaces to local quantum devices. Long coherence times and optical transitions in the telecom regime make erbium ions integrated into solid state crystals a prime candidate. We directly implant erbium into silicon nanophotonic devices and achieve reliable integration of the dopants in the silicon crystal at newly discovered sites providing narrow inhomogeneous linewidths below 1 GHz and good optical coherence up to temperatures of several Kelvin. These results have been reproduced in commercially fabricated silicon-on-insulator waveguides promising rapid transfer to technological applications. In addition, we are able to resolve single ions spectroscopically by incorporating the ions into nanobeam cavities with quality factors close to 10^5. In this structure, we observe Purcell enhancements of up to 177-fold and demonstrate coherent optical control with Rabi oscillations. Using external magnetic fields, we lift the spin-degeneracy of the ground state and find electronic spin lifetimes above one second for temperatures accessible by conventional ^{4}He cryocoolers. We initialize and read out the electronic spin state by optical means with fidelities approaching 90%. Overall, these results establish erbium-doped silicon nanostructures as a promising platform for spin-photon interfaces that can be used as the basis for scalable quantum networks.

Quantum Communication | Poster

High-efficiency coupling of polarization-entangled photon pairs in multi-core fiber via spatial light modulator

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The development and wide application of quantum technologies highly depend on the capacity of communication channels to distribute entanglement. Space-division multiplexing (SDM), recognized for augmenting data transmission capacity in classical telecommunication, holds the potential to revolutionize quantum communication. Multi-core fibers (MCFs), a key enabling technology for SDM, are therefore anticipated to be integral components of future fiber networks, making it logical to exploit this capability for quantum communication.

This study presents a novel approach to coupling polarization-entangled photons generated through type-0 spontaneous parametric down-conversion (SPDC) into an MCF, by means of a spatial light modulator (SLM). The SLM effectively manipulates the spatial properties of the entangled photons, facilitating efficient coupling into the MCF, and fully harnessing the potential of SDM techniques. The detection of the entangled photon pairs is achieved via a single-photon avalanche diode (SPAD) camera, ensuring a wide-field and accurate spatial resolution of the entangled pairs transported by the fiber.

Our system achieved a maximal Bell inequality violation, with an average entanglement visibility surpassing 90%.

Potential enhancements in performance and stability are discussed, emphasizing the scalability and adaptability of the system for various quantum information processing tasks. This work not only improves on current coupling capabilities in MCFs, also significantly enhancing the potential and applicability of multi-core fibers in quantum communication and quantum sensing, opening new avenues and possibilities for their use.

Quantum Communication | Poster

Advancing quantum communication: establishing a cutting-edge industrial and commercial ecosystem with MadQuantum-CM

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This abstract presents the projects under the MadQuantum-CM program, which aim to establish a comprehensive industrial and commercial ecosystem for quantum technologies. The projects involve extensive research and development in quantum communication and cryptography within the Madrid Quantum Communication Infrastructure (MadQCI) and its integration with a satellite-based Quantum Key Distribution network (satelital QKD network). INDRA SCS will develop advanced hardware for managing cryptographic materials and end-to-end encryption in the MadQCI network, while TELEFÓNICA INNOVACIÓN DIGITAL will focus on the seamless interconnection between MadQCI and an industrial quantum network, developing innovative use cases and ensuring robust connectivity. UTE INDRA SCS e INDRA will work on the crucial interconnection between MadQCI and the satelital QKD network, developing essential functionalities for QKD connectivity and management. GMV AEROSPACE AND DEFENCE, S.A.U. will concentrate on secure telecommunications via MadQCI and a global satelital QKD network, developing comprehensive systems for network mediation, supervision, and cybersecurity.
The MadQuantum-CM program also includes the MadQ Business Venture (MadQ BV) initiative, which supports small and medium-sized enterprises (SMEs) in developing cutting-edge quantum technology solutions. This initiative is facilitated through the Quantum Technology Laboratory at the Universidad Politécnica de Madrid (UPM) on the Montegancedo campus, offering a dedicated testing ground for proof of concept (PoC) experiments by participating SMEs. These projects are critical for advancing quantum technology infrastructure and applications, aligning seamlessly with the European Quantum Flagship and EuroQCI initiatives, and paving the way for future advancements in the field.

Quantum Communication | Poster

Adaptive polarization drift compensation in polarization-encoding quantum key distribution using QBER tracking

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Polarization drift due to fiber birefringence is a primary cause of increased quantum bit error ratio (QBER) in polarization-encoding quantum key distribution (QKD). The random nature of polarization drift and environmental instabilities cause it to vary over time, necessitating adaptive algorithms for effective polarization drift compensation in polarization-encoded QKD links. Existing algorithms typically employ time- or wavelength multiplexing with relatively strong signals to measure the incoming state of polarization (SOP) and compensate for polarization drift, or they track QBER and interrupt communications to estimate SOP via additional measurements, disrupting quantum key exchange. We propose an algorithm based on QBER tracking using the Jones matrix formalism that eliminates the need for additional measurements applicable to BB84-like protocols. Our algorithm can compensate for polarization drift caused by environmental changes, provided the SOP does not change drastically within a millisecond timescale. We evaluated the robustness of our algorithm under various conditions, including channel losses, random polarization drift speeds, and additional noise due to dark counts in single-photon and weak-coherent QKD systems, to determine the applicability limits of the proposed algorithm. Our findings demonstrate the effectiveness of the algorithm in maintaining low QBER and ensuring reliable QKD performance under diverse and dynamic conditions.

Quantum Communication | Poster

Linking QKD testbed across Korea for verifying the function of quantum cryptography communication devices

Sangkil Park
ETRI

Quantum key distribution (QKD) networks are becoming increasingly important, and it is now necessary to analyze the most appropriate method for the interconnection of solutions of heterogeneous operators. ETRI and NIA have been operating quantum cryptography communication testbeds since 2020 to verify the functionality and stability and security of quantum cryptography communication equipment. The quantum cryptography communication testbed consisted of three types of quantum cryptography communication equipment installed at the main nodes of the KOREN network operated by the NIA. Quantum cryptography communication equipment is classified into quantum key distribution equipment (QKD), quantum key management equipment (QKMS), and quantum communication encryption equipment (QENC). The testbed was composed of three types of QKD, two types of QKMS, and two types of quantum communication encryption equipment. In this paper, using the quantum cryptography communication testbed, the criteria for function verification, interoperability, and security verification in disappointment were developed for the same and heterogeneous quantum cryptography communication solutions and long-term demonstrations were conducted. In particular, in cooperation with security agencies in Korea, the security verification procedure for quantum cryptography communication equipment was institutionalized. ETRI and NIA are performing their functions as a supplement and convergence of QKD and PQC technologies in various ways in the future.

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Quantum Communication | Poster

Suspended "Sawfish" photonic crystal cavities in diamond for efficient spin-photon interfaces

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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 that 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 developed and fabricated a new cavity design based on periodically corrugating the width of a fully suspended diamond nanobeam [3,4]. Our simulations show that such a device has the potential to simultaneously enhance by 46 times the emission rate of the coherent photons from an embedded tin vacancy color center and to couple them into a single-mode waveguide with an efficiency of 88%. Here, we report on our methods to fabricate these devices and on the results of our first optical characterizations. We show that the measured cavity resonances follow the expected behavior and quality factors as high as 3800 could be measured. Furthermore, we investigate the effects of nanofabrication and show that their optical properties are robust against fabrication imperfections.

References:
[1] M. Atatüre, *et al.*, Nat. Rev. Mater. 3, 38-51 (2018)
[2] T. Schröder, *et al.*, J. Opt. Soc. Am. B 33, B65 (2016)
[3] J. M. Bopp, *et al.*, Adv. Opt. Mater. 2301286, 1–11 (2023)
[4] T. Pregnolato, *et al.*, APL Photon. 9, 036105 (2024)

Quantum Communication | Poster

Hybrid quantum state sharing of qubit states using gaussian entanglement

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Quantum state sharing is a cryptographic protocol to distribute the quantum information describing a single (unknown) secret state across a number of auxiliary modes, such that no single mode contains accessible information. Crucially, not all of these shares are required to reconstruct the secret state and so the information is not lost should a small number be lost to an adversary. A protocol such as this provides guaranteed security against small groups of dishonest actors, guarding both against unauthorised access to secret information and against the blocking of access to authorised groups.

We consider the case in which the secret state is split across 3 modes, with any 2 of those required to reconstruct it. We have previously shown this protocol to be effective for the secure sharing of Gaussian states using a Gaussian resource.

In this poster, we discuss the use of the protocol for discrete-variable secret states: Fock eigenstates and qubit-like superpositions of Fock states. A "hybrid protocol" such as this - using continuous-variable entanglement to share discrete-variable states - may present a best-of-both-worlds solution to quantum communication, allowing for the use of discrete-variable information carriers while exploiting the relative simplicity with which continuous-variable entanglement an be generated. We show that this protocol remains effective for the sharing of the full space of Fock eigenstates and discuss the levels of entanglement required to share these states. We further discuss the use of this protocol for select Fock superposition states, enabling the use of this protocol for qubit state transmission.

DISCRETION: first demonstration of a quantum enabled- software defined network in the context of a military exercise

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DISCRETION is a prototype Software Defined Network (SDN) solution that integrates Quantum Key Distribution (QKD) capabilities for quantum-safe secure communications, in a way that European Defence can benefit from the flexibility, security, and resilience that these technologies bring to the networks. DISCRETION implements and integrates these disruptive technologies with military and Defence communication doctrines, considering the red-black separation principle of military networks. Encryption of all data between red and black networks is realized through dedicated cipher machines developed to use cryptographic keys obtained from QKD systems integrated by the SDN and a key management service (KMS). Both SDN and KMS were developed in DISCRETION in compliance with the ETSI GS QKD015 and QKD004 standards. We explore the Continuous-Variables (CV) QKD technology, which is currently regarded as one of the main building blocks for large-scale deployment of quantum cryptography, since it facilitates coexistence with traditional optical networks, using classical photonics platforms. In this work, we present a in the field live demonstration of the DISCRETION project in the context of the Robotic Experimentation and Prototyping using Maritime Uncrewed Systems (REPMUS) organized annually by the Portuguese Navy and NATO. We also show how Software Defined Radios can be securely connected to the DISCRETION's system from various locations to get a set of keys generated and distributed by a CV-QKD and use them for encrypted communications in a mission. We also show how we can use the Quantum generated keys to feed cipher machines protect Red side messages passing through black connections.

Quantum Communication | Poster

A low-swap GHZ quantum random number generator for satellite quantum key distribution

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Toshiba Europe Ltd.

Quantum key distribution (QKD) systems require a source of truly random numbers, ideally provided by a quantum random number generator (QRNG), which provide the strongest guarantees of the unpredictability of their outputs. These QRNGs often demand high power consumption to achieve Gbps generation rates, making them unsuitable for satellite applications. We develop a low size, weight, and power (SWaP) QRNG for satellite QKD using compact integrated photonic interferometers, housed on a small PCB that consumes only 6 watts, yet is capable of generating random numbers at rates up to 2 Gbps. Our QRNG exploits the phase diffusion of two gain-switched distributed feedback (DFB) lasers, driven by an FPGA. Each lasers' pulses travel through a silicon waveguide asymmetric Mach-Zehnder interferometer (AMZI), such that each pulse interferes with a subsequent pulse, yielding a random output intensity at the output of each AMZI. These intensities are measured with fast photodetectors, whose outputs are converted into binary data by comparators. The FPGA performs an XOR operation on the comparators outputs to produce the final output. This post-processing approach significantly reduces the power consumption compared to the hashing algorithms typically employed. The performance of the QRNG was verified through characterization of laser phase randomization and randomness testing with the NIST randomness test suite. We demonstrated the long-term stability and uniformity of the generated random numbers in real-time operation, highlighting the QRNG's suitability for practical low-SWaP QKD systems. To demonstrate this, our QRNG was operated in tandem with a free-space decoy-state QKD system in real-time operation.

Quantum Communication | Poster

Modelling of relativistic effects in quantum space communications

Isabella Cerutti; Petra Scudo
European Commission Joint Research Centre

Space-based quantum transmissions can enable secure communication over distances beyond ground-based ones but are, at the same time, extremely challenging.
Indeed, by using specific protocols, quantum key distribution (QKD) systems on board satellites can transmit quantum states encoded in photons to far-located sites on Earth.
However, the satellite to ground links are impaired by different effects. Besides atmospheric effects, such as turbulence, attenuation and backscattering of solar radiation, the photons transmitted by non-geostationary satellites experience relativistic effects. These effects can be grouped in two macro-categories: special relativity effects (caused by the relative satellite vs optical ground station motion) and general relativity effects (caused by variations of trajectory induced by Earth's gravitational field). Special relativity effects caused by the satellites moving with respect to ground impact photon polarization states through the so called 'Wigner rotation' in the representation of Lorentz transformations for massless particles.

Estimation of the relativistic effects on photon polarization in space links is essential to estimate performance and guarantee the security of the QKD link. Currently only the most renowned space quantum communication experiment using the Micius satellite provides measurements of the polarization performance.
Some relevant theoretical works are available but they fail to provide a complete framework and assessment of the relativistic effects on the polarization.

The presentation will discuss the state-of-the art in the field and introduce a suitable framework for modelling the relativistic effects on photon polarization establishing the conditions under which it is rotate and its entity.

Quantum Communication | Poster

Portuguese Quantum Communication Infrastructure: seed of EuroQCI in Portugal

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5 - IPTELECOM;
6 - Gabinete Nacional de Segurança;
7 - Instituto Superior de Engenharia de Lisboa; 8 - Warpcom; 9 - Omnidea; 10 - Instituto Português da Qualidade; 11 - FCCN; 12 - Instituto Superior Técnico; 13 - INESC-ID; 14 - PQI

Portuguese Quantum Communication Infrastructure (PTQCI) will be the first terrestrial segment of the European Quantum Communication Infrastructure (EQCI) in Portugal. PTQCI, making exclusive use of European technology, will be the first quantum enabled network testbed for which sovereign authorities can run use cases that demand high security levels in the Lisbon metropolitan area. Moreover, PTQCI will pave the way for next generation of highly secure networks in Portugal acting as testbed for other critical projects in Portugal. For instance, Égide which is the new secured network of National Security Agency to manage classified information up to Secret. PTQCI's use cases are based on: sharing quantum secure generated keys to enable applications like secure multiparty computation, secret sharing and other state-of-the-art cryptographic protocols; Connecting and extending secure networks using cipher machines feed by the quantum key to provide harden confidentiality and authentication; Connecting relevant data centres to share privately information. PTQCI will prepare the network expansion to farther locations in Portugal and to Spain, including the assessment of the ground locations to space segment infrastructures. Furthermore, it will be designed from the start with a strong engagement with Spanish EQCI counterparts, building on joint knowledge and fruitful collaboration to achieve full EQCI interoperability at Iberian scale. The testbed, that shall be developed in the metropolitan Lisbon area, involves both academic, public and private stakeholders, will be testing new or different technologies, including free-space links and networking, as well as long-distance terrestrial and spatial solutions, including the connection to Space assets.

Quantum Communication | Poster

End-to-end hybrid quantum-secured terrestrial and space networks for defence environments

Johanna Sepulveda; Jonas Vith; Joel Jurado
Airbus Defence and Space

Quantum-secured communications are required to ensure the protection against the quantum computer threat for a wide variety of sectors, including defence. There are two quantum-secure technologies: post-quantum cryptography (PQC) and quantum communication. These two security technologies are complementary, covering different security needs. The integration of these technologies to defence scenarios is challenging due to the tight security requirements and different operational conditions. Therefore, it is required the exploration of hybridization methods of (PQC and quantum communication) as well as the fast design of quantum-secured networks that meet the security and performance requirements. These two technologies (PQC and Quantum) are expected to work together while spanning through terrestrial and aerospace networks, securing a wide variety of assets.

In this talk we describe our experience on designing quantum-secured networks that hybridize the post-quantum and quantum communication through the terrestrial and aerospace segments targeting highly secure applications. It includes the characterization of the terrestrial and aerospace quantum-secured networks, the exploration of hybridization methods as well as the exploration of the partition of the different quantum network segments in order to meet the different SLAs (Service Level Agreements) set together with future users. In the talk we describe our methodology, as well as a wide variety of experiments which report the performance as well as the security of different network configurations.

Quantum Communication | Poster

Critical current targeting in wafer-scale fabrication of Josephson parametric circuits

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1 - Walther-Meißner-Institut der Bayerischen Akademie der Wissenschaften;
2 - Technical University of Munich, TUM School of Natural Sciences, Physics Department;
3 - Munich Center for Quantum Science and Technologies (MCQST)

The scalable production of Josephson junctions with uniform and reproducible characteristics is one of the main challenges for quantum information processing and quantum communication with superconducting circuits. In this work, we identify and investigate various inhomogeneities affecting the wafer-scale fabrication process of Josephson junctions, with a particular focus on their critical current values. Through an automated image analysis of geometric dimensions of thousands of Al/AlOx/Al Josephson junctions fabricated on 4-inch silicon wafers, we quantify finite-size geometry effects and center-to-edge variations of the Josephson critical current. We develop an effective model to mitigate these effects at the design stage. By compensating for geometric effects, we can further identify additional sources of undesired parameter spread, such as dimensional variations of junction size and inhomogeneous oxidation. Our model's corrections systematically reduce parameter spread and enhance the reproducibility of Josephson junction fabrication, thereby enabling precise frequency targeting of superconducting quantum circuits based on Josephson junctions.

Quantum Communication | Poster

A Quantum-Network register based on atom tweezers arrays in a cavity

Lukas Hartung[1]; Matthias Seubert[1]; Stephan Welte[1,2,3];
Emanuele Distante[4]; Gerhard Rempe[1]
1 - Max Planck Institute of Quantum Optics;
2 - Institute for Quantum Electronics, ETH;
3 - Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart;
4 - ICFO - The Institute of Photonics Science

Quantum networks offer vast potential for secure communication, distributed computing, and precision sensing. Their architecture requires nodes with stationary qubits connected via optical fibres. However, optical losses and errors make quantum information exchange slow and unreliable. A solution is using larger qubit registers per node, enabling multiplexed communication and error correction. The challenge lies in creating a scalable register of individually controllable qubits coupled to an optical cavity for network connectivity.

In this talk, I will present our recent results [1] showing the potential of a platform combining arrays of optical tweezers with a microscopic optical cavity for scalable quantum networks. We create one- and two-dimensional registers of up to 6 atoms and address each atom individually to generate atom-photon entanglement using vacuum Stimulated Raman Adiabatic Passages. The entanglement fidelity remains constant as the number of qubits in the register increases, indicating scalability. By implementing a multiplexing scheme, we generate atom-photon entanglement with a source-to-detection probability of up to ~90% per attempt, an important step towards the deterministic distribution of entanglement across networks. This is achieved by exploiting the advantages of a Fabry-Pérot cavity that allows for optical access in a thin sheet perpendicular to the symmetry axis.

[1] L. Hartung et al. Science Vol 385, Issue 6705 pp. 179-183 (2024)

Quantum backdoor - Performing electronic side-channel analysis on QKD systems

Beatriz Lopes Da Costa[1]; Matías R. Bolaños Wagner[4]; Ricardo Chaves[1,5]; Claudio Narduzzi[4]; Marco Avesani[4,6]; Davide Giacomo Marangon[4,6]; Andrea Stanco[4,6]; Giuseppe Vallone[4,6]; Paolo Villoresi[4,6]; Yasser Omar[1,2,3]

1 - Instituto Superior Técnico, Universidade de Lisboa;

2 - Physics of Information and Quantum Technologies Group, Centro de Física e Engenharia de Materiais Avançados (CeFEMA);

3 - PQI — Portuguese Quantum Institute;

4 - Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Padova;

5 - Instituto de Engenharia de Sistemas e Computadores – Investigação e Desenvolvimento (INESC-ID);

6 - Padua Quantum Technologies Research Center, Università degli Studi di Padova

Over the last decades, Quantum Key Distribution (QKD) has risen as a promising solution for secure communications, a pressing subject in the aftermath of the security threat posed by Quantum Computers and the Shor's Algorithm. Offering a theoretically secure way to share secret keys between parties, QKD state of the art has witnessed remarkable progress in the last years. Nonetheless, cryptographic protocols are not implementation-secure. Although theoretically secure, even QKD is not implementation-secure. Until now, the study of physical vulnerabilities in QKD setups has mainly focused on the optical channel. The concept of hacking a cryptographic system via its physical characteristics and associated leakages, known as side-channel analysis, was firstly introduced in classical cryptography, with the seminal work of Paul Kosher. Since then, power and electromagnetic side-channel analysis have become a staple in classical cryptanalysis. However, these concepts have hardly been applied to QKD. In this work, we propose and implement a new method for side-channel analysis on QKD systems, by exploiting the power consumption of the electronic driver controlling the electro-optical components of the QKD transmitter. QKD modules typically require very precise electronic drivers, such as Field Programmable Gate Arrays (FPGAs). Here, we show that the FPGA's power consumption can leak information about the QKD operation, and consequently the transmitted key. The analysis was performed on the QKD transmitter at the University of Padua. Our results show critical information leakage, having reached a maximum accuracy of 73.35% in the prediction of transmitted random keys at 100 MHz repetition frequency.

Simple and low-error encoder for time-bin QKD

Davide Scalcon; Elisa Bazzani; Giuseppe Vallone; Paolo Villoresi; Marco Avesani
University of Padova

The emergence of quantum computing poses a significant threat to classical cryptography, necessitating the adoption of Quantum Key Distribution (QKD) protocols to ensure unconditional security. Time-bin encoding is as a robust solutionfor fiber-optical QKD links, overcoming the issue of birefringence and so of polarization drifts. On the other hand, time-bin encoding requires to stabilize the relative phase between time bins, leading usually to a higher intrinsic QBER, compared to polarization implementations. This work introduces MacZac, an all-fiber encoder that leverages a Mach-Zehnder interferometer nested within a Sagnac loop to generate time-bin states of arbitrary dimensions and photon numbers.

MacZac simplifies the encoding process by allowing the preparation of photonic states in phase-randomized attenuated laser pulses and preserving communication security using the decoy state method. The encoder uses a single phase modulator for both state encoding and decoy generation, reducing optical and electronic complexity. We constructed a prototype with Commercial-Off-The-Shelf components, achieving a record-low intrinsic QBER of 2 × 10^(-5). Integrating MacZac into a complete QKD system and employing the efficient three-state BB84 protocol with one-decoy method, we demonstrated a steady secret key distillation with a QBER of less than 0.03% in the key basis. Experimental results show that MacZac achieves record-low intrinsic QBER, excellent stability, and low complexity. Our work highlights MacZac's potential in enhancing the performance and reliability of QKD systems, making it a significant advancement in the field of quantum cryptography.

QKD implementations of QKD security for the G7 summit in Italy

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1 - QTI s.r.l.; 2 - University of Florence

The advances in quantum key distribution (QKD) during the last 30 years have been outstanding in terms of reachable distance and key generation rate. However, the implementation and integration of quantum systems in real telecommunication networks generate multiple challenges. Along with well-known challenges, including the fiber or wavelength availability between remote locations and the complexity of schemes and topology of the current telecommunication networks (which include optical amplifiers), other practical problems have to be taken into account. Examples are the temperature range of telecom data centers, the amount of noise emitted by the equipment, as well as the optical crosstalk coming from commercial signals into the quantum channels due to spurious effects on fiber.
Here, we will present the latest implementation we have conducted to both improve current quantum technology and integrate commercial QKD systems in standard telecommunication networks. Thanks to our unique value proposition, which includes in the same family a quantum vendor (QTI), a cryptographic company (Telsy), and the largest Italian telecom operator (TIM), we present the implementation of a concrete and existing use case for the G7 summit located in Apulia a few weeks ago. In particular, we will show how quantum technology can be combined with standard network layer-three encryptors for real-time use of the link. The cryptographic solution demonstrated the ability to use QKD in a critical scenario to ensure the highest level of security in data communication.

Quantum Computing Software

Quantum Computing Software | Poster

Compiling quantum circuits with quantum computers

Davide Rattacaso; Daniel Jaschke; Marco Ballarin;
Ilaria Siloi; Simone Montangero
University of Padova, Italy

Executing quantum algorithms on actual quantum computers requires a compilation process that generates a circuit implementation optimized for minimal infidelity or runtime specific to the target hardware. This circuit optimization problem is crucial for advancing quantum computing, but its NP-complete nature makes finding optimal solutions difficult. We propose a novel paradigm for compiling quantum circuits using quantum computers, analogous to how classical algorithms are compiled with classical computers. We map the compilation problem to the search for the ground state of a suitable many-body Hamiltonian, constrained to states representing circuits that implement the same quantum algorithm. This search can be performed via quantum algorithms such as Quantum Annealing, Optimal Control, and the Quantum Approximate Optimization Algorithm, potentially offering a quantum advantage in finding low-infidelity circuit implementations of the target algorithm. We validate our approach by introducing a Quantum Annealing based quantum compiler and simulating its dynamics using tensor network techniques. Additionally, we implement Simulated Annealing to compile circuits involving up to 64 qubits, demonstrating that the benefits of our many-body approach to quantum compilation increase with circuit volume.

Quantum Computing Software | Poster

Resource estimation architecture for distributed quantum applications

Waldemir Cambiucci; Regina Melo Silveira; Wilson Vicente Ruggiero
USP - University of São Paulo

Recent advancements in quantum computing and trends towards distributed quantum systems have underscored the importance of efficient resource estimation and circuit partitioning techniques for distributed environments. A significant challenge in this context lies in balancing the minimization of communication overhead between partitions while maximizing parallelism and resource utilization during runtime. As quantum circuits grow in size and complexity to support real-world problems, determining the optimal partitioning strategy becomes increasingly difficult, especially given hardware constraints and noise characteristics. To address these challenges, this paper introduces a novel resource estimator architecture designed for distributed quantum applications. Our approach incorporates hyper graphic representation and partitioning heuristics to optimize the allocation of quantum circuits across multiple quantum processing units. By partitioning circuits into subcircuits with minimized communication overhead, our method enhances parallelism and resource utilization, thereby improving overall system performance and scalability. Key features include detailed analysis of quantum algorithms and their dimensions, consideration of topology and noise characteristics of target hardware, and hyper graphic partitioning to reduce inter-QPU communication costs. By considering the complexities of the problem, algorithms, and constraints from distributed hardware, our resource estimator aims to enhance scalability and performance with noisy intermediate-scale quantum devices. This architecture seamlessly integrates into the quantum computing development workflow, providing a robust tool for simulation, optimization, and execution planning. Through experimental validation, we demonstrate how the estimator can provide resource predictions and insight for practical deployment of distributed quantum applications in different domains.

Quantum Computing Software | Poster

An exponential reduction in training data sizes for machine learning derived entanglement witnesses

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2 - Tulane University

We propose a support vector machine (SVM) based approach for generating an entanglement witness that requires exponentially less training data than previously proposed methods. SVMs generate hyperplanes represented by a weighted sum of expectation values of local observables whose coefficients are optimized to sum to a positive number for all separable states and a negative number for as many entangled states as possible near a specific target state. Previous SVM-based approaches for entanglement witness generation used large amounts of randomly generated separable states to perform training, a task with considerable computational overhead. Here, we propose a method for orienting the witness hyperplane using only the significantly smaller set of states consisting of the eigenstates of the generalized Pauli matrices and a set of entangled states near the target entangled states. With the orientation of the witness hyperplane set by the SVM, we tune the plane's placement using a differential program that ensures perfect classification accuracy on a limited test set as well as maximal noise tolerance. For N qubits, the SVM portion of this approach requires only O(6^N) training states, whereas an existing method needs O(2^4^N). We use this method to construct witnesses of 4 and 5 qubit GHZ states with coefficients agreeing with stabilizer formalism witnesses to within 6.5 percent and 1 percent, respectively. We also use the same training states to generate novel 4 and 5 qubit W state witnesses. Finally, we computationally verify these witnesses on small test sets and propose methods for further verification.

Quantum Computing Software | Poster

Unified framework for inter-chip quantum teleportation and clock synchronization

Muhammad Asad Ullah; Ahsan Javed Awan
Ericsson

Executing a quantum algorithm on the multi-chip quantum computer requires accurate teleportation of the quantum states between the chips, which in turn depends on the precision of clock synchronization between them. Prior art necessitates separate hardware and the system configuration for both synchronization and teleportation [1, 2]. This leads to increased hardware costs, latency overhead and computation errors arising from recurrent system reconfigurations.

To overcome these limitations, we propose a variant for entanglement-based synchronization that follows the same steps as quantum teleportation [2]. On the sender side (Alice), we propose a) triplet sampling instead of singlet to allow evolving states [1], b) Bell basis measurement instead of single-qubit measurement, and c) an ancilla qubit in a superposition state. Correspondingly on the receiver side (Bob), we perform state corrections using conditional Pauli-X and Pauli-Z gates. This scheme would enable utilizing the same hardware and the system configuration for both tasks.

[1] C. H. Bennett, et al., "Purification of noisy entanglement and faithful teleportation via noisy channels," in Phys. Rev. lett., vol. 76(5), pp. 722-725, 1996.
[2] R. Jozsa, et al., "Quantum Clock Synchronization Based on Shared Prior Entanglement" in Phys. Rev. lett., vol. 85(9), pp. 2010-2013, 2000.

Quantum Computing Software | Poster

Quantum control without quantum states

Nguyen Le; Modesto Orozco-Ruiz; Florian Mintert
Imperial College London

We show that combining ideas from the fields of quantum invariants and optimal control can be used to design quantum control of quantum systems without explicit reference to quantum states. The scaling in numerical effort of the resultant approach is given by commutation relations of system operators, and it can be polynomial in the number of subsystems despite the general quantum mechanical exponential scaling of the Hilbert space. As explicit applications, we discuss state preparation and quantum simulation with Hamiltonians including three-body and many-body interactions with spin chains of up to 50 constituents, and the perspective of use for topologically protected quantum information processing. arXiv:2405.15609

Quantum Computing Software | Poster

Quantum artificial intelligence meets geoinformation systems (QAI meets GIS)

Roland Degelmann
Takatoa

Business, science and administration, but also politics and society are increasingly using analyzes of geo- and time-referenced data to make hidden patterns in existing information visible, gain new insights and stay one step ahead of the competition. Comprehensive knowledge of existing conditions and values is an essential basis for planning, realignment and usage processes.
The competence field of Spatial Business Intelligence (SBI) realizes the connection between geographic information systems (GIS) and business intelligence (BI). SBI makes it possible to integrate systems and technologies from both areas, visualize, structure and optimize resources, streamline workflows, minimize risks and make strategic decision-making sustainable.
Combining Quantum computing with GIS tools will enable a wide range of further advances in location analysis. Quantum computing will handle more complex computational tasks and produce results that either cannot be achieved with the most powerful classical high-performance computers or cannot be achieved within a reasonable time frame.
Examples using such technologies are the prediction of condition changes for assets or the derivation of object labels from laser scan data (LIDAR point clouds). Consideration of permanently updated data are increasingly being included in such studies as well. The activities uses, among others, such data from the German Weather Service (DWD) or mobility data as they are available worldwide nowadays.
The presentation shows results of the future-oriented studies that use artificial intelligence, especially Deep Learning from Big Data, in combination with upcoming technologies on quantum hardware.

Quantum Computing Software | Poster

Automated translation of Qiskit quantum circuit into Intel quantum simulator.

Daniel Talaván; Pablo Fernández-Alonso; Moisés Gaitán-Fernández;
Paloma Rodríguez-Oliver; Javier Corral-García; Juan Antonio Rico-Gallego
COMPUTAEX Foundation

We have developed a parser that adapts circuits from the most commonly used quantum computing languages, such as Qiskit, to Intel's IQS simulator (C/C++), thus facilitating access to this simulator for Qiskit users. Qiskit is an IBM library widely used by the scientific community for quantum circuit programming. In fact, IBM was a pioneer in providing public access to real quantum processors of up to 5 qubits in 2016. Since IQS requires the use of programming languages like C/C++, and most quantum circuits are programmed with Qiskit in Python, we have developed a parser that automatically translates Qiskit quantum circuits into a format compatible with IQS. This parser, implemented in Python, ensures the reliability of the translation and facilitates the use of the IQS simulator. Additionally, it allows performing translations from any QASM circuit. As a result, it generates a .cpp file that is compilable and executable in IQS, with a circuit equivalent to the original. We have tested the parser with circuits ranging from simple Hadamard gates to more complex implementations of Grover's algorithm, where we marked and amplified 1/4 of the total states, up to 34 qubits, and executed on systems with up to 256 cores, demonstrating its accuracy and efficiency.

Quantum Computing Software | Poster

Fast decoders for quantum surface codes

Lorenzo Valentini; Diego Forlivesi; Marco Chiani
University of Bologna

The primary challenge in constructing a quantum computer is the unavoidable presence of errors, which, if not properly managed, quickly degrade quantum information. Consequently, error correction is essential for effective quantum computation. To this aim, we introduce new decoding techniques for surface codes to decrease the decoding complexity, although guaranteeing the error correction capability up to the code's designed distance. By theoretical analysis on quantum codes, we have that the logical error rates asymptotically depend on the number of non-correctable error patterns of the minimum weight. Our approach integrates concepts from graph theory to design our decoders, focusing on these critical error patterns to achieve a good performance, and not optimizing the decoding of heavier error patterns to obtain fast decoding speed. The code distance is preserved through graph-theoretic theorems, while improvements in decoding time and potential performance degradation are evaluated via numerical simulations. We compare our proposed methods with the widely used minimum weight perfect matching (MWPM) and union-find (UF) decoders, highlighting their efficiency and effectiveness. As an application example, in the context of quantum memory, improving decoding speed could reduce the decoherence suffered by the quantum information we aim to preserve.

Quantum Computing Software | Poster

RIVET: an open-source toolkit for quantum computing workflows optimisation

Yuriy Pryyma[1]; Mykhailo Ohorodnikov[1,2]; Vladyslav Bohun[1]; Volodymyr Sergeyev[1]; Mykola Maksymenko[1]

1 - Haiqu Inc.;

2 - SoftServe Inc.

The efficient execution of quantum algorithms remains a critical challenge in the advancement of quantum computing. The transpilation of quantum circuits into a form executable on quantum hardware often acts as a significant bottleneck, consuming substantial computational resources and session time in the quantum cloud. This becomes critical for workflows where a large number of quantum circuits have to be executed. To address this, we introduce Rivet (https://github.com/haiqu-ai/rivet) – an open-source toolkit designed to optimize and expedite the transpilation process.

Rivet is engineered to provide quantum developers with flexibility and control over their transpilation routines. By allowing users to segment circuits into modular blocks, Rivet supports the precise management of quantum resources, enabling efficient debugging and optimization. This toolkit integrates with industry-standard transpilation stacks such as Qiskit, BQSKit, and Pytket, and supports the selection of different stacks for specific circuit segments, offering customized and optimized transpilation solutions.

Key features of Rivet include the ability to concatenate adjacent circuits with consistent transpilation settings, manage efficient qubit usage, and facilitate modular transpilation and hashing. In practice, these added capabilities enable a significant reduction in transpilation times from hours to minutes, enhancing the overall efficiency of quantum computing workflows.

In this presentation, we will explore the technical underpinnings of Rivet and its application in various quantum computing domains, including shadow state tomography, quantum machine learning (QML), and error mitigation. We will showcase how more effective algorithm execution can facilitate research and prototyping cycles.

Quantum Computing Software | Poster

Optimized quantum compilation for distributed quantum computing

Michele Bandini; Davide Ferrari; Stefano Carretta; Michele Amoretti
University of Parma

Most practical applications of quantum algorithms require much more qubits than those provided by current Noisy Intermediate-Scale Quantum (NISQ) platforms. To supply users with many logical qubits it could prove advantageous to exploit the Distributed Quantum Computing (DQC) paradigm, which consists in splitting the circuits into subprograms that are spread for execution over networked quantum processing units (QPUs).

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 (i.e., two-qubit gates across different QPUs) to keep network resources to a minimum. Moreover, the quantum compiler must compute proper local transformations for each partition.

In a previous work, we introduced a modular compilation framework for DQC and we presented the experimental evaluation of a compiler prototype. In that case, we considered network topologies with sparse connectivity, with EPR pairs between non-adjacent QPUs established by making intermediate QPUs play the role of quantum repeaters -- an assumption that fits network-on-chip and local area network scenarios.

In this work, we present an improved compiler that copes with all networking scenarios. For the Quantum Internet one, entanglement between remote nodes is a resource provided by the network infrastructure. Therefore, the compiler can assume that the network topology is completely connected and computes the quantum circuit partitioning more quickly. Moreover, the compiler can recognize when multiple remote gates can be implemented with just one EPR pair, thus optimizing the consumption of network resources.

Quantum Computing Software | Poster

Efficient compilation strategies for zoned neutral atom architectures

Yannick Stade[1]; Ludwig Schmid[1]; Lukas Burgholzer[1]; Robert Wille[1,2]
1 - Technical University of Munich;
2 - Software Competence Center Hagenberg GmbH

Besides superconducting electronic circuits and trapped ions, neutral atoms are among the most promising quantum computing technologies. They offer long coherence times, dynamic atom rearrangement and highly-parallel gate execution. In the following, we particularly focus on a zoned neutral atom architecture, in which idling atoms can be protected from interfering influences in a storage zone and entangling gates are executed in a dedicated entangling zone—necessitating shuttling of atoms between the zones to perform computations. Recent experimental achievements promise ongoing growth in the number of available qubits, making first realizations of fault-tolerant quantum computing, including error detection and correction, feasible. As the number of qubits continues to rise, the complexity of the quantum computations to be executed increases, which makes manual compilation of the respective quantum circuits impractical. Even for automatic tools, the diverse physical capabilities, such as shuttling and native multi-qubit as well as global gates, present challenging optimization problems.
Here, we present an efficient solution to the routing problem of entangling gates that considers these unique restrictions and makes use of techniques from the design automation community to efficiently tackle the underlying problem. The objective is to enhance the parallel execution of entangling gates while minimizing the routing overhead associated with moving atoms between zones. We particularly focus on the implications for fault-tolerant quantum computing in the form of logical qubit arrays, where each array represents a single logical qubit. The tool developed within this project is publicly available as part of the Munich Quantum Toolkit (MQT) at https://github.com/cda-tum/mqt-qmap.

Quantum Computing Software | Poster

Fully automated comprehensive characterization and bring-up of superconducting quantum computers

Alastair Marshall; Anurag Saha Roy; Nicu Becherescu;
Roman Razilov; Shai Machnes
Qruise

Bringing up, characterizing and calibrating devices is a time-consuming, but essential step in experimental quantum computing. To tackle this problem, most laboratories still rely on home-brewed scripts that require significant manual intervention. While this approach may work for devices of modest sizes, it is inefficient and will not scale to processors with larger numbers of qubits.

In this talk, we introduce the Qruise scalable framework for automated bring-up and characterization of superconducting quantum processors. A user-defined directed acyclic graph of an atomic experiment is automatically traversed in a parallelized fashion. Atomic experiments can be either user-defined, or drawn from a library of over 30 distinct pre-defined experiments. The results at each stage are stored in a local database, and may be viewed through a web browser in real time. Concomitantly with the experiments, the Qruise framework also gradually builds up a detailed physical model of the device, along with an error budget designed to inform future experiments.

We showcase results of our bring-up framework and show how the resulting models are able to predict nontrivial device properties such as flux line transfer functions.

Quantum Computing Software | Poster

Bayesian amplitude estimation

Alexandra Ramôa[1,2,3]; Luís Santos[1,2,3]; Ernesto Galvão[3,4]
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2 - INESC TEC;
3 - International Iberian Nanotechnology Laboratory;
4 - Instituto de Física, Universidade Federal Fluminense

Quantum amplitude estimation (QAE) is a fundamental routine with a quadratic quantum speed up relative to the classical case. It can be used for expected value estimation and Monte Carlo integration, with applications in chemistry, finance, and other fields. The first QAE proposal relied on performing phase estimation on an amplitude amplification operator. The corresponding circuit is prohibitively deep and wide for current quantum devices.
Alternatives have been proposed in the literature, often hybrid quantum-classical algorithms where simpler circuits are embedded in a classical feedback loop. The simpler circuits typically consist of a sequence of non-controlled applications of the amplification operator. It is known that such schemes can achieve the full quadratic advantage. However, the implementation details remain an open question. They are determinant for performance factors such as the classical processing cost, parallelizability, cost offset, and noise resilience. Even when requiring simpler circuits, most algorithms assume ideal executions and are evaluated accordingly, rendering their behavior unpredictable in the presence of noise.
Bayesian inference can be applied to this problem in a noise-aware fashion, but the processing costs are high. The classical cost of a naive approach increases exponentially with the total iterations. We propose Bayesian amplitude estimation, a noise-aware algorithm combining problem specific insights awith a statistical backbone to cut down processing costs while preserving the quantum advantage and potential for scalability. Numerical simulations show that our algorithm achieves Heisenberg-limited estimation. We additionally assess its performance against others in the absence and presence of noise, demonstrating its competitiveness.

Quantum Computing Software | Poster

Quantum bayesian reinforcement learning

Michael Oliveira[1,2,3]; Alexandra Ramôa[2,3]; Gilberto Cunha[4];
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2 - University of Minho;
3 - International Iberian Nanotechnology Laboratory;
4 - Continental;
5 - INESC TEC

Reinforcement learning agents can be a valuable tool for dealing with partially observable environments. These can be modelled as Markov decision processes, which in turn can be represented by dynamic decision Bayesian networks.
It has been shown that there is a quantum speed-up for performing inference on sparse Bayesian networks via rejection sampling. Quantum amplitude amplification can be used to improve the acceptance rate, offering the same quadratic advantage as Grover searching for this sub-routine. This speed-up can transfer to reinforcement learning algorithms under certain conditions. In practice, this means that quantum resources can improve the decision making, or conversely, make it faster.
We propose a hybrid quantum-classical look-ahead algorithm for model-based reinforcement learning in partially observable environments. We do a theoretical complexity analysis of the quantum algorithm as compared to the classical one. We furthermore analyse its performance numerically, testing it against its classical counterpart. In both cases we demonstrate the potential for quantum advantage and discuss the scenarios where it is most likely to present and be most relevant.

Contents

Quantum Computing Software | Poster

Construction of SIC-POVMs in various dimensions using quantum circuits

Ashwin Bhattathiripad; P Devraj
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Symmetric Informationally Complete Positive Operator-Valued Measures (SIC-POVMs) are an important part of the math used in quantum computing. This paper introduces a method for creating SIC-POVMs of various dimensions using Qiskit, a popular software framework for quantum computing. Qiskit allows direct access to quantum systems, making it perfect for practical applications and exploring quantum information protocols. This approach takes advantage of the special mathematical properties of the Weyl-Heisenberg group to systematically build quantum circuits that can produce SIC-POVMs of any given dimension. By using the algebraic structure of the Weyl-Heisenberg group, the aim is to simplify the traditionally complex process of creating SIC-POVMs. The paper looks into both the theory and practical implementation of these quantum circuits, addressing the challenges and solutions involved in constructing SIC-POVMs in higher-dimensional quantum systems. This includes analyzing the mathematical principles behind SIC-POVMs and their implications for quantum information theory. In addition to the theory, simulations are run using Qiskit to validate the effectiveness of the designs. This involves creating quantum circuits that accurately perform state preparation and measurement processes, ensuring they meet the criteria required for SIC-POVMs. The simulations provide insights into the performance and limitations of the built quantum circuits, guiding further improvements and optimizations.

Quantum Computing Software | Poster

EQUALITY - Efficient quantum algorithms for industry

Hendrik Meer; Pranjal Dhole; Kirill Shiianov; Andreas Kötter
Capgemini Engineering, 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 computing algorithms that are aimed to solve strategic industrial problems.

EQUALITY targets six industrial use cases that can benefit from the quantum-enabled speed-up in the near- and mid-terms: computational fluid dynamics for aerospace and energy applications, design of batteries and fuel cells, development of new materials for energy applications, multidisciplinary optimization, space mission optimization, space data analysis. Each of these tasks, faced routinely by the industrial partners, is highly demanding on computational resources. Thus, today's engineers are forced to use simplistic models or rely on expensive build-and-test cycles. The opportunity provided by quantum computers promises a competitive edge for European industries.

EQUALITY develops a set of complementary NISQ technologies, from mid-ware to application-specific algorithms, oriented at delivering near-term value to the industry. In addition to the algorithms that can be applied for the use-cases directly, the project develops a set of hardware utilisation strategies and techniques, maximising utility of NISQ machines for industrial applications.

By transforming current industrial interest into widespread adoption, EQUALITY solidifies the link between strategic European industries and the emerging quantum ecosystem while contributing to technologies critical to the green transition.

Quantum Computing Software | Poster

A flexible, modular framework for quantum-enhanced solutions

Benedikt Poggel
Fraunhofer IKS

Applying quantum-enhanced algorithms to industrial optimization problems requires carefully evaluating countless options between encoding the application case and selecting the quantum and classical parts of the algorithm, as well as tuning their hyperparameters. The missing abstraction layers between hardware and business cases prevent end users from exploring the potential of quantum computing (QC) and applied researchers from gaining valuable insights into the needs of the industry.

To simplify the application-specific design of hybrid quantum algorithms, we present a prototypical implementation of a decision tree (DT) designed to bridge the gap between QC and the application. It allows adaptation to customers' needs, easy insertion and removal of new algorithmic options and methods without the need to modify the entire DT. Across the various layers concerning the formulation, decomposition, and encoding of the use case, as well as the algorithm, hyperparameter, and backend selection, options can be chosen interactively or handled by modular automation routines. Once the algorithms have been executed or passed on to external compilation and optimization routines, the DT interprets the quantum output for a direct solution to the application.

The DT allows for automating the application-oriented design of quantum-enhanced solutions. Its modular structure ensures new algorithms, computational methods, and evaluation tools can be quickly integrated by researchers and evaluated directly on the application level. In the quest for quantum utility, it further narrows the gap between application and state-of-the-art technology and lowers the practical barriers in applying QC for end users and exploring industrial applications for researchers.

Quantum Computing Software | Poster

Large-scale simulation of quantum error correction circuits with realistic noise using matrix-product states

Asier Pineiro Orioli; Shannon Whitlock; Guido Masella
QPerfect

Implementing efficient quantum error correction (QEC) is the most important open challenge of current quantum computers. In theory, many solutions for QEC codes and techniques to implement fault-tolerant logical circuits have been developed. However, practical implementations differ wildly in performance when taking hardware limitations and realistic errors into account. How do we test and develop QEC algorithms at scale to bring fault-tolerant quantum computing closer to reality?

In this poster, I will present QPerfect's efforts towards estimating the logical performance of QEC and magic state distillation circuits using realistic noise models. The simulations are made with MIMIQ, a ground-breaking quantum emulator developed by QPerfect and the only platform capable of running complex quantum algorithms with thousands of qubits and millions of gates. Powered by a state-of-the-art matrix-product-state (MPS) engine, it allows to simulate large-scale circuits including arbitrary non-Clifford noise and operations. Our simulations allow us to estimate the feasibility of implementing these circuits in current hardware, and elucidate the path towards improved implementations with better logical performance.

Quantum Computing Software | Poster

Benchmarking quantum computers: towards a standard performance evaluation approach

Ruben Pena
Basque center for applied mathematics

The technological development of increasingly larger quantum processors on different quantum platforms raises the problem of how to fairly compare their performance, known as quantum benchmarking of quantum processors. This is a challenge that computer scientists have already faced when comparing classical proces- sors, leading to the development of various mathematical tools to address it, but also to the identification of the limits of this problem. In this work, we briefly review the most important aspects of both classical processor benchmarks and the metrics comprising them, providing precise definitions and analyzing the quality attributes that they should exhibit. Subsequently, we analyze the intrinsic properties that characterize the paradigm of quantum computing and hinder the naive transfer of strategies from classical benchmarking. However, we can still leverage some of the lessons learned such as the quality attributes of a good benchmark. Additionally, we review some of the most important metrics and benchmarks for quantum processors proposed in the literature, assessing what quality attributes they fulfill. Finally, we propose general guidelines for quantum benchmarking and its associated test suite. These guidelines aim to pave the way for establishing a roadmap towards standard- izing the performance evaluation of quantum devices, ultimately leading to the creation of an organization akin to the Standard Performance Evaluation Corporation (SPEC).

Quantum Computing Software | Poster

Benchmarking PQC ansaetze in realistic device topologies

Oleksa Hryniv[1]; Vladyslav Los[1,2]; Yuriy Pryyma[1];
Maciej Koch-Janusz[1,3]; Mykola Maksymenko[1]
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3 - University of Zurich

Parametrized quantum circuits (PQCs) serve as a flexible framework for implementing various quantum algorithms, particularly in quantum machine learning and optimization tasks. However, their training is challenging due to both theoretical constraints and the inherent limitations in current quantum hardware. Employing a correct architecture of PQCs is crucial for accurately representing the solution space and achieving the desired accuracy. Several works introduced descriptors of expressibility and entanglement capability for PQCs, and compared these metrics across different circuit structures, providing insights into how different architectures impact performance and efficiency.

Hardware-efficient Ansaetze have been developed to align with the native topology of quantum devices. However, the measurement of descriptors like expressibility and entanglement capability has often assumed ideal, all-to-all qubit connectivity, which is not applicable to most real hardware architectures.

In our work, we extend the concept of measuring PQC efficiency using descriptors to include more realistic quantum hardware models. We examine several popular hardware topologies, including hexagonal, square, circular, linear, and all-to-all. We evaluate the expressibility and entanglement capability of circuits with different connectivity types and various structures of rotation gates. Additionally, we identify the preferred rotation gate structure for each connectivity type and assess the performance of these PQCs during training. This approach provides a more realistic evaluation of PQC performance, thus offering practical insights into their applications on existing quantum devices.

A hybrid quantum-classical approach to complex optimization using a variational quantum classifier

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2 - Department of Electronic Systems, Aalborg University;
3 - Rosen Center for Advanced Computing, Purdue University

In this work, we develop, implement, and analyze a 50-qubit Variational Quantum Classifier (VQC) within a hybrid quantum-classical framework to tackle complex optimization problems. The VQC is employed to map classical data into a high-dimensional quantum feature space, leveraging quantum entanglement and superposition to capture complex patterns that are challenging for classical models to discern. This quantum feature mapping, achieved through a parameterized quantum circuit, is integrated with classical machine learning techniques for subsequent post-processing and optimization.

Our hybrid approach combines the computational strengths of both quantum and classical paradigms. The VQC executes the quantum circuit to transform the input data, generating classical features via quantum measurements. These features are then utilized as input for classical machine learning models for training and optimization, effectively reducing quantum resource requirements by minimizing the number of quantum circuit executions while exploiting the robust optimization capabilities of classical algorithms.

We address several practical challenges associated with the implementation of the VQC, including mitigating noise and decoherence in current quantum hardware, implementing efficient error correction techniques, and managing the classical-quantum interface for handling large datasets. Specifically, the 50-qubit GHZ state plays a significant role in enhancing the system's capability to process complex information.

Our results indicate that, despite existing hardware limitations, the hybrid quantum-classical approach presents significant potential for enhancing the efficiency of solving optimization problems compared to fully classical methods. This potential is particularly pronounced as advancements in quantum technology continue to emerge, highlighting the superiority of hybrid methods over classical ones.

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RYSP: A versatile digital-twin for neutral atom quantum computing devices

Raul Santos; Robert De Keijzer; Emre Akatur; Jasper Postema; Madhav Mohan; Servaas Kokkelmans
Technical University of Eindhoven

The neutral atom quantum computing platform holds impressive capabilities, such as reconfigurable geometry and long coherence times. It is therefore a promising platform for quantum computation towards solving problems for real-world applications with quantum advantage. These NISQ-era (Near-term Intermediate Quantum) devices have to be designed and optimized to assure favorable performance of the quantum program, such that it approaches its theoretical expectations. Towards this end, in this poster we showcase a fast and versatile digital-twin designed towards the accurate emulation of neutral atom quantum computers, built up from the pulse level and towards the implementation of dynamical quantum circuits. It is capable of interpreting QASM (Quantum ASseMbly) files and translating it into a pulse level implementation using the rearrangeable atom array architecture. Furthermore, it considers a series of optimizations that bring the simulation time closer to gate level simulation, while retaining the accuracy of pulse-level.

Quantum Computing Software | Poster

Unitary-Invariant witnesses of quantum imaginarity

Rafael Wagner; Leonardo Novo; Ernesto Galvão; Carlos Fernandes
International Iberian Nanotechnology Laboratory

Quantum theory is traditionally formulated using complex numbers. This imaginarity of quantum theory has been quantified as a resource with applications in discrimination tasks, pseudorandomness generation, and quantum metrology. Here we propose witnesses for imaginarity that are basis-independent, relying on measurements of unitary-invariant properties of sets of states. For 3 pure states, we completely characterize the invariant values attainable by quantum theory, and give a partial characterization for 4 pure states. We show that simple pairwise overlap measurements suffice to witness imaginarity of sets of 4 states, but not for sets of 3. Our witnesses are experimentally friendly, opening up a new path for measuring and using imaginarity as a resource.

This is joint work of Carlos Fernandes, Rafael Wagner, Leonardo Novo, Ernesto F. Galvão, and has appeared as preprint https://arxiv.org/abs/2403.15066

Quantum Computing Software | Poster

Making the cut: two methods for breaking down a quantum algorithm

Miguel Murça
Instituto Superior Técnico, Universidade de Lisboa

Despite the promise that fault-tolerant quantum computers can efficiently solve classically intractable problems, it remains a major challenge to find quantum algorithms that may reach computational advantage in the present era of noisy, small-scale quantum hardware. Thus, there is substantial ongoing effort to create new quantum algorithms (or adapt existing ones) to accommodate depth and space restrictions. By adopting a hybrid query perspective, we identify and characterize two methods of ``breaking down'' quantum algorithms into rounds of lower (query) depth, designating these approaches as ``parallelization'' and ``interpolation''. To the best of our knowledge, these had not been explicitly identified and compared side-by-side, although one can find instances of them in the literature. We apply them to two problems with known quantum speedup: calculating the k-threshold function and computing a NAND tree. We show that for the first problem parallelization offers the best performance, while for the second interpolation is the better choice. This illustrates that no approach is strictly better than the other, and so that there is no single systematic way of breaking down a quantum algorithm into a hybrid quantum-classical algorithm.

Quantum Computing Software | Poster

Quantum state preparation for multivariate functions

Matthias Rosenkranz; Eric Brunner; Gabriel Marin-Sanchez; Nathan; Silas Dilkes; Yao Tang; Yuta Kikuchi; Marcello Benedetti
Quantinuum

A fundamental step of any quantum algorithm is the preparation of qubit registers in a suitable initial state. Often qubit registers represent a discretization of continuous variables and the initial state is defined by a multivariate function. We develop protocols for preparing quantum states whose amplitudes encode multivariate functions by linearly combining block-encodings of Fourier and Chebyshev basis functions. Without relying on arithmetic circuits, quantum Fourier transforms, or multivariate quantum signal processing, our algorithms are simpler and more effective than previous proposals. We analyze requirements both asymptotically and pragmatically in terms of near/medium-term resources. Numerically, we prepare bivariate Student's t-distributions, 2D Ricker wavelets and electron wavefunctions in a 3D Coulomb potential, which are initial states with potential applications in finance, physics and chemistry simulations. Finally, we prepare bivariate Gaussian distributions on the Quantinuum H2-1 trapped-ion quantum processor using 24 qubits and up to 237 two-qubit gates.

Quantum Computing Software | Poster

Guppy: Pythonic quantum-classical programming

Mark Koch; Seyon Sivarajah
Quantinuum

Python is by far the most popular programming language in the quantum domain. According to a recent poll, it is used by over 90% of researchers and practitioners in the field [1]. However, most Python frameworks are limited by the fact that they describe quantum programs at the abstraction level of circuits, with only limited support for algorithms with high-level control flow. For example, repeat-until-success protocols use mid-circuit measurements to decide which quantum gates to apply next, which is quite cumbersome to express in the traditional circuit picture.
To alleviate these issues, we introduce Guppy: a domain-specific language embedded in Python that allows users to write high-level hybrid quantum programs with complex control flow in Pythonic syntax. While most Python-based frameworks trace the Python interpreter to build the representation of a quantum program, Guppy code is parsed separately and statically compiled to a novel quantum intermediate representation, which can express and optimise these real-time quantum-classical programs. This gives us the flexibility to add new syntactic constructs, custom type checking, and better error messages to the language.
The main features of Guppy include:
* Native pythonic control-flow syntax (if, for, while, break, etc.) inside quantum programs
* Static typing, including a linear type system to ensure correctness of quantum operations
* Higher-order functions and polymorphism
* Interoperability with Python
* Program optimisation within and across the quantum-classical boundary
Guppy is open source and available at https://github.com/CQCL/guppylang. An extended abstract is available at https://ks.cs.uchicago.edu/publication/guppy-planqc.

[1] Unitary Fund, 2023, https://unitary.fund/posts/2023_survey_results/

Quantum Computing Software | Poster

Classical simulation and barren plateau detection powered by the ZX calculus

Mark Koch[1]; Richie Yeung[1,2]; Quanlong Wang[1]
1 - Quantinuum;
2 - University of Oxford

Bravyi et al.'s Stabiliser Decomposition method [1] is an algorithm to classically simulate universal Clifford+T quantum circuits. Unlike state vector based simulation methods whose runtime and memory requirements scale exponentially with increasing number of qubits, stabiliser decomposition methods only scale exponentially in the number of T gates, making it feasible to simulate circuits with large numbers of qubits. We develop a novel extension of the traditional stabiliser decomposition algorithm based on the ZX-caclulus that greatly speeds up simulation of circuits containing multi-controlled gates like the Toffoli, demonstrating 2-3 orders of magnitude speed-ups compared to a previous state-of-the-art implementation.

Besides classical simulation, our algorithm also enables exact computation of the gradient variance of parameterised quantum circuits. This metric is important in the domain of Quantum Machine Learning as it characterises the existence of barren plateaus which make variational optimisation infeasible. Our algorithm allows us to numerical detect barren plateaus in quantum ansatze significantly faster than existing techniques.

Our method builds on previous work encoding stabiliser decompositions in the ZX-calculus [2]. We improve on these previous ideas by studying optimisation and decomposition techniques for ZX diagrams enriched with a special non-unitary operation called the "triangle node". It allows us to naturally represent both multi-controlled gates and integrals of expectation values that are needed to compute gradient variances.

A preprint of this work is available at arXiv:2307.01803.

[1] Bravyi et al. Quantum 3, 181 (2019)
[2] Aleks Kissinger and John van de Wetering 2022 Quantum Sci. Technol. 7 044001

Quantum Computing Software | Poster

HUGR: A quantum-classical intermediate representation

Mark Koch[1]; Agustín Borgna[1]; Seyon Sivarajah[1]; Alan Lawrence[1]; Alec Edgington[1]; Douglas Wilson[1]; Craig Roy[1]; Luca Mondada[1,2]; Lukas Heidemann[1]; Ross Duncan[1]
1 - Quantinuum;
2 - University of Oxford, Oxford, UK

We introduce the Hierarchical Unified Graph Representation (HUGR): a novel graph based intermediate representation for mixed quantum-classical programs. HUGR's design features high expressivity and extensibility to capture the capabilities of near-term and forthcoming quantum computing devices, as well as new and evolving abstractions from novel quantum programming paradigms. The graph based structure is machine-friendly and supports powerful pattern matching based compilation techniques. Inspired by MLIR, HUGR's extensibility further allows compilation tooling to reason about programs at multiple levels of abstraction, lowering smoothly between them. Safety guarantees in the structure including strict, static typing and linear quantum types allow rapid development of compilation tooling without fear of program invalidation. A full specification of HUGR and reference implementation are open-source and available online.

Quantum Computing Software | Poster

Introducing BRAT

Craig Roy
Quantinuum

As the capabilities of quantum computers advance, they allow more sophisticated computation to be done while a circuit is running (i.e. "online''). Quantum programming languages are tasked with interleaving quantum and classical execution, while avoiding costly runtime errors in the online fragment of the program.

To this end, we introduce BRAT: A strongly typed programming language for writing quantum experiments, with an emphasis on safety and compositionality. In BRAT programs, both classical functions and quantum circuits are written in an ergonomic, compositional syntax. However, they reside in separate worlds, with different typing rules and base types. Circuits must use their quantum variables linearly, whereas classical functions have no such requirement.

BRAT leverages dependent types so that the classical world can make guarantees about the quantum circuits that it generates. For example, the size of vectors used in circuits is parameterised by classical variables using an ergonomic language of number and vector patterns. In BRAT circuits, the only pattern matches allowed are irrefutable ones, and this is guaranteed by giving sufficient data in the type system.

Additionally, BRAT is designed with mid-circuit measurement in mind. Measuring a "Qubit" yields "Money", which can be used to instantiate a fresh qubit in the |0> state. BRAT maintains a distinction between these two types. Thus, circuits can be prevented from instantiating more qubits than are available on a device, and it's unambiguous which arguments to circuits are fresh ancillae.

Brat is open source and available at https://github.com/CQCL/brat.

Quantum Computing Software | Poster

Fast quantum computation optimisation using concurrent graph rewriting

Luca Mondada[1,2]; Agustín Borgna[2]
1 - University of Oxford;
2 - Quantinuum Ltd

Graph rewriting is a powerful and general technique for optimisation problems on graphs. In the quantum computing domain, complete equational theories for quantum circuits provide strong theoretical foundations for rewriting. Unfortunately, rewriting-based circuit optimisation using a naive backtracking search is slow in practice, due to its poor scaling both in the number of rewrite rules and in the input circuit size, as well as being hard to parallelise.
We propose concurrent graph rewriting to address these issues, inspired from equality saturation for term rewriting. Rewrites can be applied in parallel on a persistent data structure. The data structure stores rewrites that can be applied either on the input circuit directly or following a sequence of previous rewrites. After an initial exploration phase, in which all possible rewrites are identified and added to the data structure, an extraction phase determines the set of rewrites that should be applied to optimise the circuit cost function. The exploration phase is designed to scale to large distributed systems, whilst the optimisation problem in the extraction phase can be solved using an off-the-shelf SMT solver.

Quantum Computing Software | Poster

Application of gate teleportation for routing of near-term quantum algorithms

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2 - Faculty of Information Technology, University of Jyväskylä, Finland

In near-term quantum processors, the limited qubit connectivity poses a significant challenge for deploying practical quantum algorithms and logical gates, necessitating efficient qubit mapping and routing strategies. When implementing a gate that requires additional connectivity beyond the native connectivity, the qubit state must be moved to a nearby connected qubit to execute the desired gate. This is typically achieved using a series of SWAP gates creating a SWAP path, but this method increases depth and gate number. An alternative approach is to use quantum teleportation, which allows the qubit state transfer or the gate execution over a distance with minimal overhead. This method can be particularly useful in a quantum computer topology where certain qubits act as bridge qubits for teleporting gates. The long-range teleportation of the CNOT gate has recently been experimentally demonstrated on the IBMQ quantum computer [1].
In this work, we perform an in-depth theoretical and numerical analysis of how teleported gates can enhance qubit routing efficiency for specific hardware topologies. We evaluate routing performance for various near-term algorithms, highlighting how the creation of virtual edges through gate teleportation paths can reduce circuit depth and the number of two-qubit gates required. Also, we focus on error budgeting and strive to predict error thresholds associated with teleported gates to optimize routing performance. Finally, we showcase a practical demonstration of the implementation of gate teleportation-assisted routing on a cloud-based quantum computer.

[1] E. Bäumer, et al., Efficient long-range entanglement using dynamic circuits, arXiv:2308.13065 (2023).

Quantum Computing Software | Poster

On music and quantum computing technologies

Omar Costa Hamido
CEIS20, University of Coimbra

In this sound poster I will present recent work integrating Music practice and Quantum Computing technologies. This work is the result of the continuing development of The QAC Toolkit, a software toolkit that allows musicians and artists to build, run, and simulate quantum circuits inside the Max/MSP visual programming environment. Integrating Music and QC means not only to put the technology in the hands of creative practitioners but also to rethink the creative practice itself in the light of a new computational paradigm. It is a goal of this work to find ways to connect and better articulate current technological tools in both computer music and computer science. The quantum computing technological revolution is transversal to many fields. The field of creative practices integrating Art, Science, and Technology is a window to the QC-enabled future.

Quantum Computing Software | Poster

Piquasso: a photonic quantum computer simulation software platform

Zoltán Kolarovszki; Ágoston Kapos; Szabolcs Jóczik; Zoltán Zimborás
HUN-REN Wigner Research centre for physics

We introduce the Piquasso quantum programming framework, a full-stack open-source software platform for the simulation and programming of photonic quantum computers. Piquasso can be programmed via a high-level Python programming interface enabling users to perform efficient quantum computing with discrete and continuous variables. Via optional high-performance C++ backends, Piquasso provides state-of-the-art performance in the simulation of photonic quantum computers. The Piquasso framework is supported by an intuitive web-based graphical user interface where the users can design quantum circuits, run computations, and visualize the results.

Quantum Computing Software | Poster

Munich quantum software stack:
seamlessly integrating quantum computing into HPC

Jorge Echavarria[1]; Muhammad Nufail Farooqi[1]; Lukas Burgholzer[2]; Robert Wille[2]; Laura Schulz[1]; Martin Schulz[2]
1 - Leibniz Supercomputing Centre (LRZ);
2 - TU-Munich

Quantum accelerators are increasingly being integrated into HPC centres. However, new technologies used to build quantum devices and their limited availability as shared resources create significant integration challenges. These challenges extend to the efficient execution of hybrid HPCQC applications within HPC environments.

We introduce the Munich Quantum Software Stack (MQSS), a JIT compilation and execution software stack designed for the EuroHPC Euro-Q-Exa system, soon to be integrated with SuperMUC-NG, the flagship supercomputer of the Leibniz Supercomputing Centre (LRZ). Its main goal is to seamlessly integrate quantum accelerators into traditional HPC workflows. Our comprehensive stack offers solutions for programming interfaces, hybrid classical-quantum computation, and circuit cutting to ensure circuits fit into available quantum accelerators. It includes schedulers for selecting a target accelerator and a compiler based on LLVM IRs. Specifically, our stack parses a quantum job described in any supported programming interface into MLIR for subsequent compilation. Once the circuit is compliant with the target architecture, it is converted into Quantum Intermediate Representation (QIR) for submission to the accelerator.

Our stack maps the circuit to the appropriate topology, transpiles it to the native gate set, and performs further optimisations through a pipeline of LLVM passes, delivering the performance needed in HPC environments. The MQSS also features the Quantum Device Management Interface (QDMI) to interface with quantum accelerators from the compiler while abstracting the underlying technology. This stack can abstract various aspects of targeted quantum accelerators while tailoring circuit compilation to the specific architecture, making it both target-agnostic and target-specific as needed.

Quantum Computing Software | Poster

QDMI – Quantum device management interface: hardware-software interface for the Munich quantum software stack

Robert Wille[1]; Ludwig Schmid[1]; Yannick Stade[1]; Jorge Echavarria[2]; Martin Schulz[1]; Laura Schulz[2]; Lukas Burgholzer[1]

1 - Technical University of Munich, Germany;

2 - Leibniz Supercomputing Center, Germany

Quantum computing is a promising technology that requires a sophisticated software stack to connect end users to the wide range of possible quantum backends.

However, current software tools are usually hard-coded for single platforms and lack a dynamic interface that can automatically retrieve and adapt to changing physical characteristics and constraints of different platforms.

With new hardware platforms frequently introduced and their performance changing on a daily basis, this constitutes a serious limitation.

In this poster, we showcase a concept and a prototypical realization of an interface, called the Quantum Device Management Interface (QDMI), that addresses this problem by explicitly connecting the software and hardware developers, mediating between their competing interests.

QDMI allows hardware platforms to provide their physical characteristics in a standardized way, and software tools to query that data to guide the compilation process accordingly.

This enables software tools to automatically adapt to different platforms and to optimize the compilation process for the specific hardware constraints.

QDMI is a central part of the Munich Quantum Software Stack (MQSS)—a sophisticated software stack to connect end users to the wide range of possible quantum backends.

Quantum Computing Software | Poster

Enhancing quantum annealing with statistical qubit freezing

Jeung Rac Lee[1]; June-Koo Kevin Rhee[1]; Changjun Kim[2]; Bo Hyun Choi[2]
1 - Qunova Computing;
2 - LG UPlus

Interest in quantum annealing technology has been growing, given its potential to address classically hard combinatorial problems, with case studies from various industries highlighting its applications in solving real-world challenges. Adiabatic quantum annealers, however, face scalability issues as energy gaps between ground and excited states shrink rapidly with an increasing number of qubits. This narrowing of energy gaps makes it harder to identify ground states accurately and is further affected by thermal noise. We introduce a new algorithm called statistical qubit freezing (SQF), which selectively fixes the state of statistically predictable qubits within the annealing Hamiltonian for a given problem. By repeatedly applying qubit freezing, SQF expands the spectral gap during the annealing process, achieving notable improvements in performance over conventional annealing technique used by D-Wave quantum annealer.

Quantum Computing Software | Poster

Lattice Boltzmann inspired quantum walk for solving PDEs

Lara Janiurek
University of Strathclyde

We present a discrete-time quantum walk (DTQW) model inspired by the classical lattice Boltzmann (LB) method, designed as a foundational step toward quantum-based fluid dynamics simulation. Classical LB algorithms, which use streaming and collision operations to approximate fluid flow, recover the Navier-Stokes equations in the continuum limit but are computationally intensive. In a parallel approach, DTQWs combine streaming and coin operations and conventionally produce relativistic wave equations at the continuum level.

Our model introduces decoherence into the DTQW framework, resulting in a continuum limit that yields nonlinear partial differential equations (PDEs). This positions the quantum walk as a new type of PDE solver with adjustable parameters, allowing it to approximate fundamental fluid dynamics equations, including the Navier-Stokes equations. While this model currently establishes core principles, it provides a platform for future quantum software to explore and extend the possibilities for fluid dynamics and PDE simulation, particularly as quantum technology advances toward handling more complex systems.

Quantum Computing Software | Poster

Benchmarking PQC ansaetze in realistic device topologies

Oleksa Hryniv[1]; Vladyslav Los[1,2]; Yuriy Pryyma[1]; Maciej Koch-Janusz[1,3]; Mykola Maksymenko[1]

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Parametrized quantum circuits (PQCs) serve as a flexible framework for implementing various quantum algorithms, particularly in quantum machine learning and optimization tasks. However, their training is challenging due to both theoretical constraints and the inherent limitations in current quantum hardware. Employing a correct architecture of PQCs is crucial for accurately representing the solution space and achieving the desired accuracy. Several works introduced descriptors of expressibility and entanglement capability for PQCs, and compared these metrics across different circuit structures, providing insights into how different architectures impact performance and efficiency.
Hardware-efficient Ansaetze have been developed to align with the native topology of quantum devices. However, the measurement of descriptors like expressibility and entanglement capability has often assumed ideal, all-to-all qubit connectivity, which is not applicable to most real hardware architectures.
In our work, we extend the concept of measuring PQC efficiency using descriptors to include more realistic quantum hardware models. We examine several popular hardware topologies, including hexagonal, square, circular, linear, and all-to-all. We evaluate the expressibility and entanglement capability of circuits with different connectivity types and various structures of rotation gates. Additionally, we identify the preferred rotation gate structure for each connectivity type and assess the performance of these PQCs during training. This approach provides a more realistic evaluation of PQC performance, thus offering practical insights into their applications on existing quantum devices.