Scalable Hardware Platforms for Quantum Computing

687. WE-Heraeus-Seminar

13 – 17 January , 2019
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 687. WE-Heraeus-Seminar:

The 687th WE-Heraeus Seminar on "Scalable Hardware Platforms for Quantum Computing" brings together leading quantum scientists from academia and industry concentrating on the three main potentially scalable quantum architectures — ion traps, spin qubits in quantum dots, and superconducting qubits. This interdisciplinary seminar will focus on the technical challenges and the ecosystem to be developed in order to achieve a scalable quantum computer.

Scientific Organizers:

Prof. Dr. David DiVincenzo	RWTH Aachen, Director, Theoretical Nanoscienses, Forschungszentrum Jülich, Germany
Dr. Stefan Filipp	IBM Research - Zurich, Switzerland E-mail: sfi@zurich.ibm.com
Dr. Andreas Fuhrer	IBM Research – Zurich, Switzerland E-mail: afu@zurich.ibm.com
Prof. Dr. Frank Wilhelm-Mauch	Universität des Saarlandes, Saarbrücken, Germany E-mail: fwm@lusi.uni-sb.de

Program

Sunday, January 13, 2019

17:00 – 21:00	Register and mount posters	
from 18:30	*BUFFET DINNER / Informal get together*	
20:00 – 20:15	Andreas Fuhrer Stefan Filipp	**Kick-off scientific program**

Opening Lecture (chair: S. Filipp)

20:15 – 21:00	Yoshihisa Yamamoto	**Coherent Ising Machines - Optical Neural Network operating at the Quantum Limit**
21:00	Discussions at the posters	

Monday, January 14, 2019

07:30	*BREAKFAST*	

Superconducting Qubits (chair: M. Ganzhorn)

08:30 – 09:15	John Martinis	**Software control for Google's Bristlecone Processor**
09:15 – 10:00	Andreas Wallraff	**Elements for an Extensible Quantum Information Processing Architecture with Superconducting Circuits**
10:00 – 10:30	*COFFEE BREAK*	

Spin Qubits in Quantum Dots (chair: G. Salis)

10:30 – 11:15	Lieven Vandersypen	**Quantum Computation and Simulation - Spins Inside**
11:15 – 12:00	Hendrik Bluhm	**Automated tuning of semiconductor qubits - one key to scalability**
12:00 – 12:15	**Conference Photo** (in the foyer of the lecture hall)	

Monday, January 14, 2019

12:15	*LUNCH*	

Ion Traps (chair: G. Morigi)

13:30 – 14:15	Rainer Blatt	**Quantum Information using trapped ions-status and perspectives**
14:15 – 15:00	Christopher Monroe	**A full Stack Scalable and Reconfigurable Quantum Computer**
15:00 – 15:30	*COFFEE BREAK*	

Superconducting Qubits (chair: S. de Graaf)

15:30 – 16:15	Rudolf Gross	**Quantum Microwaves for Communication in Quantum Local Area Networks**
16:15 – 17:00	William D. Oliver	**Quantum Hardware for Superconducting Qubits**

Quantum Theory and Applications (chair: C. Müller)

17:00 – 17:45	Enrique Solano	**Digital-Analog Quantum Computation**
17:45 – 18:30	Alexandre Blais	**Qubit Parity Measurement by Parametric Driving in Circuit QED**
18:30	*HERAEUS DINNER at the Physikzentrum (cold & warm buffet, free beverages)*	

Tuesday, January 15, 2019

07:30	*BREAKFAST*	

Ion Traps (chair: Ch. Monroe)

08:30 – 09:15	Ulrich Poschinger	**A Shuttling-Based Trapped Ion Quantum Processing Node**
09:15 – 10:00	Giovanna Morigi	**Quantum reservoir engineering of many-body systems**
10:00 – 10:30	*COFFEE BREAK*	

Quantum Theory and Applications (chair: F. Wilhelm)

10:30 – 11:15	Christiane Koch	**Quantum optimal control – an enabling tool for quantum technologies**
11:15 – 12:00	Barbara Kraus	**Sorting and quantifying multipartite entanglement**
12:00	*LUNCH*	

Tuesday, January 15, 2019

Superconducting Qubits (chair: R. Gross)

13:30 – 14:15	Leonardo DiCarlo	**A full-stack superconducting quantum computer**
14:15 – 15:00	Markus Brink	**Scaling Quantum Processors with Superconducting Qubits**
15:00 – 17:15	**Poster Session and** *COFFEE BREAK*	
17:15 – 17:30	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**

17:30 – 18:30 **Panel Discussion**

"Quantum Hardware and Software"

- **Is there a value in building a hardware-agnostic quantum software stack?**
- **Is there an immediate value in building application-agnostic quantum hardware?**
- **Is there a need for standardized interfaces between hardware and software?**
- **What are the challenges with regard to hardware and software? If there are limited resources, where should the focus be? Or are both aspects equally important?**
- **How many different software developments should there be?**

Panelists
John Martinis, Rainer Blatt, Markus Brink, José Ignatio Latorre, Per Delsing, Cyril Allouche

Moderator

Frank Wilhelm-Mauch

18:30 – 19:30 *DINNER*

19:30 **Poster Session, continued**

Program

Wednesday, January 16, 2019

07:30	*BREAKFAST*	

Superconducting Qubits (chair: M. Brink)

08:30 – 09:15	Jonas Bylander	**Fluctuations due to two-level systems in T_1-limited transmon superconducting qubits**
09:15 – 10:00	Sebastian de Graaf	**Chemical identification of sources of noise and decoherence in quantum devices**
10:00 – 10:30	*COFFEE BREAK*	

Quantum Theory and Applications (chair: W. Riess)

10:30 – 11:15	Michael Marthaler	**Quantum chemistry on quantum computers**
11:15 – 12:00	José Ignacio Latorre	**tba**
12:00	*LUNCH*	

Spin Qubits in Quantum Dots (chair: A. Fuhrer)

13:30 – 14:15	Andreas Landig	**Coherent spin-photon and spin-transmon coupling using circuit QED**
14:15 – 15:00	Maude Vinet	**Towards scalable silicon quantum computing**
15:00 – 16:00	Andreas Fuhrer	**Poster award and closing session**
16:00	**Walk to local sightseeing spot**	
18:30	Dinner	

End of the seminar *and FAREWELL COFFEE /* ***Departure***

For those leaving the next day Breakfast will be served at 08:00 h.

Posters

P01	Mohammad T. Amawi	**Helimagnons meet circuit quantum electrodynamics**
P02	Yoichi Ando	**ML4Q - A German Cluster of Excellence for Quantum Computing**
P03	Thomas Ayral	**Simulation of quantum programs for near-term, noisy quantum hardware**
P04	Shabir Barzanjeh	**Stationary Entangled Radiation from Micromechanical Motion**
P05	Andreas Bengtsson	**TLS induced decoherence instabilities in superconducting qubits**
P06	Ilya Besedin	**Collective and edge states in superconducting transmon chains**
P07	Gerhard Birkl	**Scalable Platform for Quantum Computing with Neutral Atoms**
P08	Ivan Boldin	**Planar electrode ion trap for microwave-based quantum information processing**
P09	Jan Brehm	**Investigating a Superconducting Quantum Metamaterial in a Waveguide**
P10	Christophe Couteau	**Development of a new platform for quantum photonics applications**
P11	Carsten Degenhardt	**Cryogenic CMOS electronics as building blocks for scalable quantum computers**
P12	Aleksei Dmitriev	**Effects of wave mixing on a single artificial atom**
P13	Arkady Fedorov	**Improving the fidelity of entangling gates via in situ characterization of qubit control lines**

Posters

P14	Gleb Federov	**Analog Ising chain simulation with transmons**
P15	Martin Friedl	**MBE Growth of Scalable Horizontal InAs Nanowire Arrays on 111B and 100 GaAs Substrates**
P16	Anton Frisk Kockum	**Decoherence-free interaction between giant atoms in waveguide QED**
P17	Marc Ganzhorn	**Gate-efficient simulation of molecular eigenstates on a quantum computer**
P18	Richard Gebauer	**FPGA-based Platform to Control and Readout Superconducting Qubits**
P19	Jan Goetz	**Platform for unconditional qubit reset based on tunable environments**
P20	Daria Gusenkova	**Implementing an inductively shunted transmon qubit with tunable transverse and longitudinal coupling**
P21	Sadik Hafizovic	**Scalable Instrumentation for Quantum Computing**
P22	Juha Hassel	**Superconducting fabrication platform for enabling solutions in quantum technology**
P23	Io-Chun Hoi	**Reflective Amplification without Population Inversion from a Strongly Driven Superconducting Qubit**
P24	Salha Jebari	**Double-sided coaxial circuit QED for Quantum Computing**
P25	Michael Johanning	**Trapped-Ion Transport Featuring High-Fidelity Preservation of Quantum Information**

Posters

P26	Jewoo Joo	**Quantum variational optimisation for nonlinear equations**
P27	Michael Kaicher	**Digital quantum simulation of a two dimensional electron gas pierced by a strong magnetic field**
P28	Matthias Krauß	**Filter effects in quantum optimal control using Krotov's method**
P29	Björn Lekitsch	**A Shuttling-Based Trapped Ion Quantum Processing Node**
P30	Xiaosong Ma	**Harnessing photonic qutrits in quantum information processing**
P31	Shai Machnes	**Scalable methodology for automated characterization and calibration for medium-scale quantum processors**
P32	Achim Marx	**Microwave remote state preparation vs. quantum cryptography**
P33	Matteo Mazzanti	**Trapped ions in optical microtraps**
P34	Matthias Mergenthaler	**Investigating coherence limitations in fixed frequency transmon quibts**
P35	Mikko Möttönen	**Qubit Measurement by Multi-Channel Driving**
P36	João Moutinho	**Quantum Link Prediction for Complex Networks**
P37	Clemens Mueller	**Passive, on-chip superconducting circulator using a ring of tunnel junctions**
P38	Krzysztof Pomorski	**Modeling quantum universal gates in semiconductor CMOS**

P39	Kitti Ratter	**Multilayer Coaxial Superconducting Circuits for Quantum Computing**
P40	Michael Renger	**Quantum Process Tomography of a 3D Quantum Memory**
P41	Nicolas Roch	**An engineered band-gap Josephson traveling wave parametric amplifier**
P42	Gian Salis	**Adiabatic quantum simulations with driven superconducting qubits**
P43	Marius Schöndorf	**Flux qubit measurement at the flux degeneracy point**
P44	Peter Ken Schuhmacher	**Gap-independent cooling and hybrid quantum-classical annealing (HQCA)**
P45	Theeraphot Sriarunothai	**Speeding-up the decision making of a learning agent using an ion trap quantum processor**
P46	Takahiro Tsunoda	**Implementing the Variational Quantum Eigensolver with native 2-qubit interaction and error mitigation**
P47	Göran Wendin	**Quantum neural networks and quantum reservoir computing for NISQ processors**
P48	Max Werninghaus	**Optimal Control of Superconducting Qubits**
P49	Nicolas Wittler	**Optimal control pulses for a scalable quantum memory**
P50	Giorgio Zarantonello	**Scalable surface-electrode trap for microwave near-field approach**

Abstracts of Lectures

(in chronological order)

Coherent Ising Machines - Optical Neural Network operating at the Quantum Limit -

Y. Yamamoto

ImPACT Program, Japan Science and Technology Agency, 7, Gobancho, Chiyoda-ku, Tokyo 102-0076, Japan

E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305, USA

In this talk, we will review the basic concept, quantum principle and performance of a novel computing machine based on the network of degenerate optical parametric oscillators. The developed machine has 2048 spins with all-to-all connections, while a next generation machine implements 10^5 spins with full (10^{10}) connections.

There are at least three quantum computational models proposed today: unitary quantum computation, adiabatic quantum computation and dissipative quantum computation. Table I compares the two quantum computational models. A gate model, or measurement based, quantum computer implements the unitary quantum computational model and is expected to solve problems with hidden periodicity or specific structure efficiently, while a coherent Ising machine (CIM) implements the dissipative quantum computational model and is suitable for combinatorial optimization problems. Table II compares the two types of CIMs, optical delay line coupling machine and measurement feedback coupling machine.

Table I. Two quantum computational models.

	Unitary quantum computation	Dissipative quantum computation
Realization	Gate/Measurement based	Neural network
Principle	Unitary rotation of state vectors in a closed system	Self-stabilized ordering in an open system
Proposal	Deutsch (1985) : quantum parallelism Shor (1994) : quantum algorithm	Zurek (2003) : quantum Darwinism and quantum chaos Verstraete, Wolf, and Cirac (2008) : quantum algorithm
Pros	Transparent physics	Robust against noise and error
Cons	Vulnerable to noise and error	Complicated physics
Applications	Problems with hidden periodicity (factoring, discrete-logarithm)	Problems with no periodicity (optimization, sampling)

Table II. Optical delay line coupling machine (DL- QNN) vs. measurement-feedback coupling machine (MF-QNN).

	DL-QNN	MF-QNN
Implementation	$(N-1)$ optical delay lines with dynamic modulation based on $[J_{ij}]$	Single measurement-feedback loop consisting of homodyne detector, ADC-FPGA-DAC circuit and optical modulator
Quantum parallel search	Quantum entanglement	Correlated spin-flip
Pros	▪ High-speed operation ▪ Both classical and quantum Hamiltonians	▪ Robust against optical loss and phase noise ▪ High-order Ising couplings ($\sigma_1\sigma_2\sigma_3\cdots$)
Cons	Sensitive to optical loss and phase error	Speed limit imposed by electronics
Applications	▪ Quantum simulation ▪ Large-scale problems with regular/sparse connections	▪ Classical Hamiltonian (combinatorial optimization) ▪ Medium-scale problems with irregular/dense connections

Software control for Google's Bristlecone Processor

John M. Martinis[1]

[1]*Google and UC Santa Barbara, Santa Barbara USA*

Calibration is the unsung hero of making high-quality qubits. I will describe the bringup methodology of our newest generation quantum processor with 72 qubits, Bristlecone. I will also discuss our ideas of "calibration science", which describes how we apply our automation tools to measure system-wide calibration metrics.

Elements for an Extensible Quantum Information Processing Architecture with Superconducting Circuits

Andreas Wallraff

Department of Physics, ETH Zurich, Switzerland

Superconducting circuits are a prime contender for realizing universal quantum computation and solving noisy intermediate-scale quantum (NISQ) problems on fault-tolerant or non-error-corrected quantum processors, respectively. In this talk, I will present elements of an architecture which allows for fast, high-fidelity, single shot qubit read-out [1], for unconditional reset [2], and can be multiplexed [3]. Integrating multiple qubits in a single device, we evaluate performance metrics such as the single and two-qubit gate fidelity and the qubit readout fidelity. We also test the performance of the architecture in parity measurements with real-time feedback, which is a basic element of a error correcting code. To provide a potential avenue for extending monolithic chip-based architectures for quantum information processing, we employ the circuit elements of our architecture to implement a deterministic state transfer and entanglement generation protocol [1]. Our protocol is based on an all-microwave process, which entangles or transfers the state of a superconducting qubit with a time-symmetric itinerant single photon exchanged between individually packaged chips connected by a transmission line. We transfer qubit states at rates of 50 kHz, absorb photons at the receiving node with near unit probability, and achieve transfer process fidelities and on demand remote entanglement state fidelities of about 80 %. We also show that time bin encoding can be used to further improve these quantum communication metrics [5]. Sharing information coherently between physically separated chips in a network of quantum computing modules may be an essential element for realizing a viable extensible quantum information processing system.

[1] T. Walter et al., Phys. Rev. Applied 7, 054020 (2017)
[2] P. Magnard et al., Phys. Rev. Lett. 121, 060502 (2018)
[3] J. Heinsoo et al., Phys. Rev. Applied 10, 034040 (2018)
[4] P. Kurpiers et al., Nature 558, 264-267 (2018)
[5] P. Kurpiers et al., arXiv:1811.07604 (2018)

This research was performed in a collaboration between J.-C. Besse, A. Akin, S. Gasparinetti, J. Heinsoo, P. Kurpiers, P. Magnard, M. Pechal, B. Royer, Y. Salathe, S. Storz, T. Walter, A. Blais, C. Eichler, and A. Wallraff.

Quantum Computation and Simulation - Spins Inside

L.M.K. Vandersypen

QuTech and Kavli Institute of Nanoscience, TU Delft, Delft, Netherlands

Quantum computation has captivated the minds of many for almost two decades. For much of that time, it was seen mostly as an extremely interesting scientific problem. In the last few years, we have entered a new phase as the belief has grown that a large-scale quantum computer can actually be built. Quantum bits encoded in the spin state of individual electrons in silicon quantum dot arrays have emerged as a highly promising direction [1]. In this talk, I will present our vision of a large-scale spin-based quantum processor, and ongoing work to realize this vision.

First, we created local registers of spin qubits with sufficient control that we can program arbitrary sequences of operations. We show the creation of each of the Bell states with fidelities up to 90% and the implementation of the four instances of the Deutsch-Jozsa and the Grover algorithms on two qubits [2].

Second, we have explored coherent coupling of spin qubits at a distance via two routes. In the first approach, the electron spins remain in place and are coupled via microwave photon. We recently observed strong coupling of a single spin to a single microwave photon in a superconducting resonator [3]. In the second approach, spins are shuttled along a quantum dot array, preserving spin coherence [4].

Third, we have developed new concepts and techniques that make quantum dot arrays a credible platform for quantum simulation of the Mott-Hubbard model. As a first demonstration, we map out the transition from Coulomb blockade to collective Coulomb blockade, the finite-size analogue of the Mott insulator transition [5]. In a second step, we study Nagaoka ferromagnetism in a 2x2 array of quantum dots.

When combined, the progress along these various fronts can lead the way to scalable networks of high-fidelity spin qubit registers for computation and simulation.

[1] L.M.K. Vandersypen, et al., Interfacing spin qubits in quantum dots and donors – hot, dense and coherent, npj Quantum Information **3**, 34 (2017).

[2] T. F. Watson, et al., A programmable two-qubit quantum processor in silicon, Nature **555**, 633 (2018).

[3] N. Samkharadze, G. Zheng, et al., Strong spin-photon coupling in silicon, Science **359**, 1123 (2018)

[4] T. Fujita, et al., Coherent shuttle of electron-spin states, npj Quantum Information **3**, 22 (2017)

[5] T. Hensgens, et al., Quantum simulation of a Fermi-Hubbard model using a semiconductor quantum dot array, Nature, **548**, 70 (2017)

Automated tuning of semiconductor qubits - one key to scalability

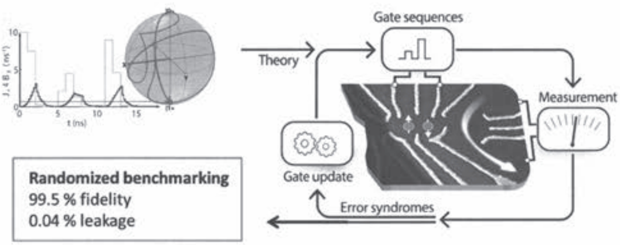
H. Bluhm[1]

[1] *JARA-Institute for Quantum Information, RWTH Aachen University Aachen, Germany and Forschungszentrum Jülich, Jülich, Germany*

The realization of scalable quantum computers will necessarily requires methods to automatically tune the operating parameters for qubits, e.g., determining the control pulses applied to qubits. For spin qubits in electrostatically defined quantum dots, these also include the gate voltages that determine the dot occupancy and tunnel couplings. Similar requirements arise for the high-throughput qubit characterization. Efficient and noise-tolerant algorithms are highly desirable to minimize the number of measurements required to complete the tuning process.

We experimentally address these issues for two-electron spin qubits in GaAs quantum dots in a way that is transferable to other types of devices. For fine-tuning the gate voltages once a dot is formed, we use a gradient-based algorithm incorporating a machine-learning approach to update the system response matrix based on a Bayesian approach. Its inputs are the dot parameters obtained from a set of fully automated measurement routines [1]. Substantial changes of the target parameters typically require about five iterations when setting two tunnel couplings and two chemical potentials using five different voltages.

For eliminating systematic errors of gate operations, we employ a self-consistent tuning procedure that is also gradient based and uses finite difference estimates of the gradient matrix [2]. The resulting gates achieve a single-qubit fidelity of 99.5%, approaching the value expected from an experimentally calibrated noise model [3]. The procedure successfully adjusted 50 parameters of the control pulses. Simulations indicated that the same approach can be applied to two-qubit gates. To this end, we use a method to automatically generate tuneup-sequences for multi-qubit operations.



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[2] Cerfontaine *et al.*, Phys. Rev. Lett. **113**, 150501 (2014)
[3] Unpublished results based on methods of Cerfontaine et al., arXiv:1606.01897

A Full Stack Scalable and Reconfigurable Quantum Computer

C. Monroe[1,2] and J. Kim[1,3]

[1]IonQ, Inc, College Park, MD USA
[2] Joint Quantum Institute, Institute for Quantum Information and Computer Science, and Department of Physics, University of Maryland, College Park, MD USA
[3] Department of Electrical and Computer Engineering, Duke University, Durham, NC USA

A quantum computer based on trapped atomic ions is inherently scalable, owing to atomic clock qubits that have nearly perfect replicability and negligible idle errors. Moreover, the trapped ion quantum computer is reconfigurable over a highly connected graph of qubits, with quantum gate operations affected by externally applied electromagnetic fields. We exploit these unique features to design, build and operate a full stack, general-purpose quantum computer. We demonstrate a family of quantum algorithms that show a path to scaling quantum computers that are not only quantum supreme but also capable of useful computational tasks. I will summarize the development and performance of room temperature ion trap systems at both university and industrial settings, including a high-level software layer that allows autonomy and remote use via a cloud service. I will also speculate on how this system can realistically be scaled to thousands of qubits and beyond.

Quantum Microwaves for Communication in Quantum Local Area Networks

S. Pogorzalek[1,2], K. G. Fedorov[1,2], M. Xu[1,2], M. Renger[1,2], M. Fischer[1,2], E. Xie[1,2], A. Marx[1], F. Deppe[1,2], and R. Gross[1,2]

[1]*Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany*

[2] *Physik-Department, Technische Universität München, 85748 Garching, Germany*

Quantum communication protocols employ non-classical correlations as a resource for a more efficient transfer of quantum states when compared to currently known classical methods. Exploiting entangled microwaves [1-4] allows one to realize a quantum local area network for distributed quantum computing without the need of any frequency conversion. As an important step towards a microwave-based quantum LAN we present the experimental realization of remote state preparation (RSP) in the microwave regime over macroscopic distances. RSP aims at the assembly of a desired and known quantum state at a remote location using classical communication and quantum entanglement. In our approach, we employ propagating two-mode squeezed microwave states [5,6] and feedforward to achieve the remote preparation of squeezed states with up to 1.6 dB of squeezing below the vacuum level. Our results represent a significant step towards microwave quantum networks between superconducting quantum processors.

We acknowledge support by the German Research Foundation through FE 1564/1-1, the Elite Network of Bavaria through the program ExQM, the EU Quantum Flagship project QMiCS, and the Excellence Cluster MCQST.

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[2] R. Di Candia *et al.*, Quantum teleportation of propagating quantum microwaves. EPJ Quantum Technol. **2**, 25 (2015).

[3] K.G. Fedorov *et al.*, Displacement of propagating squeezed microwave states. Phys. Rev. Lett. **117**, 020502 (2016).

[4] K.G. Fedorov *et al.*, Finite-time quantum entanglement in propagating squeezed microwaves. Sci. Rep. **8**, 6416 (2018).

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[6] L. Zhong *et al.*, Squeezing with a flux-driven Josephson parametric amplifier. New. J. Phys. **15**, 125013 (2013).

Quantum Hardware for Superconducting Qubits

William D. Oliver

Massachusetts Institute of Technology

In this talk, we review our progress on three aspects of quantum hardware for superconducting circuits. We begin with our progress on 3D integration technologies. This includes the integration of the Josephson traveling wave parametric amplifier (J-TWPA) for high-fidelity readout. The J-TWPA also can be used as a broadband source of squeezed microwaves. We present results of single-mode and broadband two-mode squeezing enabled by the J-TWPA. Finally, we present the demonstration of a voltage tunable transmon built from a graphene weak-link junction.

Digital-Analog Quantum Computation

E. Solano

University of the Basque Country, Bilbao, Spain
Shanghai University, Shanghai, China

Digital quantum computing offers highly-desirable features as universality, scalability, and quantum error correction. However, physical requirements to implement useful error-corrected quantum algorithms are prohibitive in the current era of NISQ devices. As an alternative paradigm to performing universal quantum computation, we propose to merge digital single-qubit operations with analog multi-qubit entangling blocks in an approach we call digital-analog quantum computing (DAQC). As a practical cases, we propose to use unitaries generated by the ubiquitous Ising Hamiltonian for the analog entangling block and we prove its universal character. Additionally, we compare a sequential approach where the interactions are switched on and off (stepwise DAQC) with an always-on multi-qubit interaction interspersed by fast single-qubit pulses (banged DAQC). The proposed DAQC approach combines the robustness of analog quantum computing with the flexibility of digital methods, establishing an avenue for achieving quantum advantage with near-term quantum hardware [1-9].

References

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Qubit Parity Measurement by Parametric Driving in Circuit QED

B. Royer[1], S. Puri[2] and A. Blais[1,3]

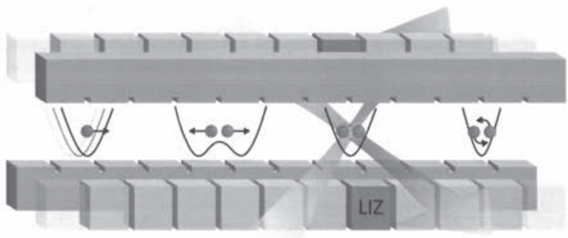
[1]*Institut quantique and Départment de Physique, Université de Sherbrooke, 2500 boulevard de l'Université, Sherbrooke, Québec J1K 2R1, Canada*
[2] *Department of Applied Physics, Yale University, PO BOX 208284, New Haven, CT 06511*
[3]*Canadian Institute for Advanced Research, Toronto, Canada*

Multi-qubit parity measurements are essential to quantum error correction. Current realizations of these measurements often rely on ancilla qubits, a method that is sensitive to faulty two-qubit gates and which requires significant experimental overhead. We propose a hardware-efficient multi- qubit parity measurement exploiting the bifurcation dynamics of a parametrically driven nonlinear oscillator. This approach takes advantage of the resonator's parametric oscillation threshold which is a function of the joint parity of dispersively coupled qubits, leading to high-amplitude oscillations for one parity subspace and no oscillation for the other. We present analytical and numerical results for two- and four-qubit parity measurements with high-fidelity readout preserving the parity eigenpaces. Moreover, we discuss a possible realization which can be readily implemented with the current circuit QED experimental toolbox. These results could lead to significant simplifications in the experimental implementation of quantum error correction, and notably of the surface code.

A Shuttling-Based Trapped Ion Quantum Processing Node

U. Poschinger, V. Kaushal, D. Pijn, J. Hilder, A. Stahl, O. Gräb, B. Lekitsch and F. Schmidt-Kaler
JGU Mainz, Institut of Physics, Staudingerweg 7, 55128 Mainz, Germany
E-mail: poschin@uni-mainz.de

Reaching scalability remains the biggest challenge to overcome for realizing useful quantum computers. For trapped ion quantum computing, a possible solution is to store atomic qubits in segmented radio-frequency traps and move these within the trap array by changing the control voltages applied to the segments [1]. This circumvents the problems of storage and addressing of ions occurring for large Coulomb crystals.
In this contribution, we present the architecture of a small shuttling-based trapped ion quantum processing node, currently capable of full control over up to six qubits. We describe the key components of the system: The segmented ion trap, the fast multi-channel arbitrary waveform generator controlling the ion movement and the $^{40}Ca^{+}$ spin qubits. We analyze the interplay of the components, address the limitations arising from these and describe required future developments.
Furthermore, we report on recent results based on our architecture: Characterization of the shuttling operations as operational building blocks [2], entanglement enhanced magnetometry [3], sequential generation of multipartite entanglement [4] and ongoing work on fault-tolerant error syndrome readout.



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Quantum reservoir engineering of many-body systems

G. Morigi

[1]Saarland University, Saarbrücken, Germany

In this talk we review recent work on the theoretical study of quantum dynamics of many-body, strongly-interacting systems. We argue that stationary quantum phases can be realised by tailoring noise and fluctuations. We bring several examples from the microscopic to the mesoscopic scale, focusing on platforms presently discussed for quantum technological applications.

Quantum optimal control
- an enabling tool for quantum technologies

Christiane P. Koch[1]

[1] *Universität Kassel, Theoretische Physik, Kassel, Germany*

Quantum advantage requires the reliable operation of quantum devices despite the presence of parameter fluctuations and noise. Optimal control of open quantum systems provides a set of tools to address this challenge [1,2]. It allows for determining the shape of electromagnetic fields to execute key tasks such as state preparation or entanglement generation. An obvious control strategy consists in beating the decoherence. It is applicable as long as the desired task can be executed on a sufficiently short time scale. I will discuss state preparation in a Rydberg atom, relevant to quantum sensing protocols and presently realized experimentally, to illustrate this strategy. An alternative approach consists in exploiting the environment as a resource. I will show how optimal control can be used to improve existing dissipative state preparation protocols and determine ultimate performance bounds for entanglement generation in trapped ions. Finally, superconducting circuits provide an ideal testing ground for exercising control via the environment, either natural or engineered. I will discuss examples for qubit reset and gate implementation.

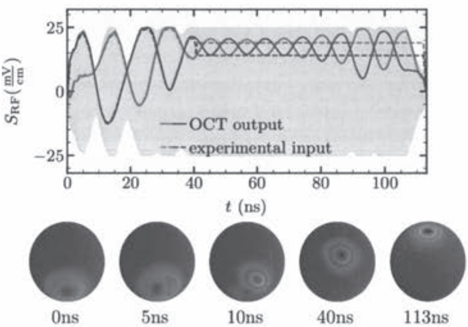

Fig. 1: Theoretically obtained and experimentally used RF quadratures to prepare the valence electron of a Rydberg atom in a circular state (top), together with the dynamics under the optimized pulse shown in the Bloch sphere (bottom).

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Sorting and quantifying multipartite entanglement

Barbara Kraus

University of Innsbruck, Department of Theoretical Physics, Innsbruck, Austria

In this talk I would like to present some recent developments in entanglement theory. I will focus on local manipulations of multipartite entanglement and on entanglement measures. In particular, I will show that deterministic local transformations among pure n-partite d-level systems are almost never possible and will discuss the consequences of this result. The maximal success probability of converting a generic state into any other as well as a complete set of multipartite entanglement measures for pure generic n-partite qudit-states will be presented.

Scaling Quantum Processors with Superconducting Qubits

Markus Brink

[1] *IBM Research, Thomas J. Watson Research Center, Yorktown Heights, USA*

Quantum processors have been scaling in size, as measured by the number of qubits, at an impressive rate in recent years. This rapid increase in the number of qubits has highlighted other metrics that need to improve simultaneously to make a quantum processor useful, such as gate and measurement fidelity and qubit connectivity. The quantum volume is a metric that attempts to assess these requirements on the same scale and measure the power of a quantum computer.

IBM's quantum hardware focuses on superconducting quantum circuits using fixed frequency Transmons and cross-resonance entangling gates. While this approach comes with some unique challenges, such as frequency crowding, so far it has been scalable and demonstrated excellent coherence times for superconducting quantum chips. Several such quantum chips are publicly available online at the IBM Q experience.

Fluctuations due to two-level systems in T_1-limited transmon superconducting qubits

Jonathan Burnett,[1,2] Andreas Bengtsson,[1] Marco Scigliuzzo,[1] David Niepce,[1] Marina Kudra,[1] Per Delsing,[1] and Jonas Bylander[1]

[1]Chalmers University of Technology, Göteborg, Sweden
[2]National Physical Laboratory, Teddington, UK

We have studied the temporal stability of relaxation and dephasing in superconducting qubits. Our qubits are transmons with a coplanar shunt capacitor (X-mon type) made of aluminum on silicon; they have reached average T_1 relaxation times of about 70 μs. The T_2^* decoherence time, as measured in a Ramsey fringe, is practically relaxation-limited. By collecting statistics during measurements spanning several days, we reveal large fluctuations of qubit lifetimes – the standard deviation of T_1 is about 15 μs – and find that the cause of fluctuations is parasitic, near-resonant two-level-systems (TLS). Our statistical analysis shows consistency with an interacting-TLS model. Interacting TLS also cause low-frequency capacitance fluctuations, ultimately leading to frequency noise and dephasing of the qubit state. These discoveries are important for creating stable superconducting circuits suitable for high-fidelity quantum gates in quantum computing applications.

Chemical identification of sources of noise and decoherence in quantum devices

S. E. de Graaf[1]

[1] *National physical laboratory, Teddington, UK*

E-mail: sdg@npl.co.uk

Eliminating the noise and decoherence due to material two-level system (TLS) defects remains an important challenge towards large-scale quantum computing applications. Most of what we know about these detrimental defects have been obtained through studying the noise and loss in the same devices (qubits, resonators) which they inhibit, however, the lack of detailed information about their chemical origin and the impact of various fabrication steps has so far limited the progress in understanding and eliminating these defects [1]. Here we present how we can learn more about the chemical and structural origin of TLS defects and their impact on the noise and decoherence in quantum devices [2, 3]. By combining high sensitivity on-chip electron spin resonance with noise and loss measurements in superconducting resonators we are able to identify the origin of some of the defects that impact the performance of quantum devices. We will also look at other techniques that can be used to learn more about TLS and, hopefully, lead to ways of eliminating them.

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Quantum chemistry on quantum computers

Michael Marthaler [1,2]

[1]*Heisenberg Quantum Simulations, Karlsruhe*
[2] *Institut für Theorie der Kondensierten Materie, Karlsruher Institute für Technologie*

Quantum computer offer tantalizing possibilities, but are currently strongly limited by their intrinsic sensitivity to errors. We discuss the prospects of using near term processor containing 50 to 100 qubits to perform ab-initio simulations of materials. At present, the overhead for quantum error correction is so large that it cannot be implemented for near term quantum computers. This means applications have to be planned with the limitation imposed by errors in mind. Material simulations seam to be the most promising near term applications. We discuss how simulations would be performed on quantum computer and how this relates to existing methods in quantum chemistry.

Coherent spin-photon and spin-transmon coupling using circuit QED

A. J. Landig[1], J. V. Koski[1], P. Scarlino[1], U. C Mendes[2], C. Reichl[1], A. Blais[2], W. Wegscheider[1], A. Wallraff[1], K. Ensslin[1], T. Ihn[1]
[1] Department of Physics, ETH Zürich, CH-8093 Zürich, Switzerland
[2] Institut quantique and Départment de Physique, Université de Sherbrooke, Sherbrooke, Québec J1K 2R1, Canada

A future quantum processor should benefit from the advantages of different qubit implementations such as fast gating or long coherence times. Two promising qubit implementations are spin qubits in semiconductors and superconducting qubits.

The first part of this talk will focus on resolving one of the major challenges for spin qubits, which is to coherently couple them to microwave photons. Coherent spin-photon coupling will enable distant qubit-qubit interaction. We demonstrate strong spin-photon coupling using circuit quantum electrodynamics technology [1]. Our spin qubit is a resonant exchange qubit (RX) [2] that is formed by three electrons in a gate defined triple quantum dot in a GaAs/AlGaAs heterostructure. The microwave photons are confined in a high impedance superconducting NbTiN microwave resonator. The qubit states are split energetically by exchange interaction naturally coupling spin and orbital degrees of freedom resulting in an electrical dipole moment of the qubit. We directly control the amount of spin-charge hybridization by electrostatic means. This allows us to tune both the qubit-photon coupling strength as well as to optimize the qubit coherence time. We resolve the vacuum Rabi mode splitting and obtain a minimum qubit decoherence rate of 10 MHz limited by hyperfine interaction in the host material.

The second part of this talk will focus on forming a coherent link between a RX qubit in a GaAs/AlGaAs heterostructure and a superconducting transmon qubit. We use a similar chip layout as in Ref. 3 and couple the two qubits capacitively to a high impedance SQUID array resonator with coupling strengths of 50 MHz and 180 MHz for the spin and transmon qubit, respectively. We demonstrate resonant and dispersive qubit-qubit interaction mediated by real and virtual photons in the SQUID array resonator.

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Towards scalable silicon quantum computing

M. Vinet1*, L. Hutin1, B. Bertrand1, S. Barraud1, J.-M. Hartmann1, Y.-J. Kim1, V. Mazzocchi1, Y. Thonnard1, A. Amisse1,2, H. Bohuslavskyi1,2, L. Bourdet2, A. Crippa2, X. Jehl2, R. Ezzouch2,! R. Maurand2, Y.-M. Niquet2, M. Sanquer2, B. Venitucci2, B. Jadot3, E. Chanrion3, P.-A. Mortemousque3, C. Spence3, M. Urdampilleta3, S. De Franceschi2 and T. Meunier3

Université Grenoble Alpes, France
[1] CEA, LETI, Minatec Campus, F-38054 Grenoble, [2] CEA, INAC, F-38054 Grenoble, [3] CNRS, Institut Néel, F-38042 Grenoble,
*e-mail: maud.vinet@cea.fr / *Phone: (+33) 438 78 99 00*

General considerations to go to large scale quantum computing in silicon request i) first to build deterministic and repeatable high quality, high fidelity single and two-qubit gates; ii) then to demonstrate high fidelity (fault-tolerant) qubit operations within 2D arrays; iii) and finally to draw a projection on what a quantum computer based on Si would look like based on the learning of the two previous conditions.
To address the first point, we will share chemical characterization of 300mm epitaxially grown ^{28}Si.
To address the second point, from a technological perspective, one main advantage of switching from lab to industry-like technology will be to provide the ability of individually controlling single spin qubits in large arrays, together with controlling the nearest-neighbor interaction. So far, to ensure individual qubit control, in an array of N qubits, some architectures demand N or more gates. We will show how by resorting to a line/column addressing architecture and a definition of the dots through the potential applied to their surrounding tunnel barriers, the number of gates can be scaled down proportionally to sqrt(N). In addition, by leveraging dense 3D integration, it will be demonstrated that the initialization and individual readout based on RF reflectometry [Cri18, Urd18, Mor18]] of the qubits can be addressed.
Finally, towards making progress regarding third point, low T° characterization of FDSOI will be shared and its potential for classical control electronics will be discussed [Boh17,18].

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Abstracts of Posters

(in alphabetical order)

Helimagnons meet circuit quantum electrodynamics

P. Schmidt[1,2,3], M. Amawi[1,2], A. Aqeel[2], C. Back[2,3], R. Gross[1,2,3], and H. Huebl[1,2,3]

[1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Walther-Meißner-Str. 8, 85748 Garching, Germany
[2] Physik-Department, Technische Universität München, James-Franck-Str. 1, 85748 Garching, Germany
[3]Nanosystems Initiative Munich, Schellingstraße 4, 80799 München, Germany

E-mail: Mohammad.Amawi@wmi.badw.de

A wealth of hybrid quantum systems is discussed in the context of converting quantum information between various frequency domains, such as from microwave to optical frequencies. Besides conversion concepts based on opto-mechanics or electromechanics, the strong coupling regime of spin excitations interacting with microwave resonators offers an alternative pathway to this goal.

We present a hybrid system consisting of tunable resonators and a helimagnonic mode . The tunable resonator is a superconducting coplanar microwave resonator shunted to ground via a dc-SQUID. Thus the resonator is frequency tunable using a magnetic field bias. At low temperatures and close to zero magnetic field helimagnetic modes form in Cu_2OSeO_3 (CSO) crystals, as the system orders magnetically in a helical spin structure. We investigate the magnetization dynamics of the CSO as millikelvin temperatures using broadband techniques and present initial results regarding the coupling of CSO to flux-tunable microwave resonators.

ML4Q - A German Cluster of Excellence for Quantum Computing

Yoichi Ando

Spokesperson of ML4Q
University of Cologne, Cologne, Germany
E-mail: ando@ph2.uni-koeln.de

The Cluster of Excellence "Matter and Light for Quantum Computing" (ML4Q) is a new research consortium funded by the Excellence Strategy for German universities. It is based on the cooperation between RWTH Aachen, University of Bonn, University of Cologne, and the Research Center Jülich to perform basic research on quantum computing and quantum communication. This poster gives an overview of ML4Q. Detailed information can be found at its website [1].

References

[1] http://ml4q.uni-koeln.de/

Simulation of quantum programs for near-term, noisy quantum hardware

Thomas Ayral

Atos Quantum Lab, Les Clayes-sous-Bois, France

We will be looking at the simulation of quantum programs on the Atos Quantum Learning Machine, taking into account the constraints and noise characteristics of an actual quantum processor. Through the concrete example of the quantum Fourier transform, we will illustrate the challenges related to the compilation of this program into a quantum circuit respecting the processor's connectivity and gateset constraints. We will discuss how hardware-specific noise models may be taken into account, how the results of the algorithm are impacted by them, and will finally hint at possible optimization strategies.

Stationary Entangled Radiation from Micromechanical Motion

S. Barzanjeh, E. Redchenko, M. Peruzzo, M. Wulf, D. Lewis, and J. M. Fink
Institute of Science and Technology Austria, 3400 Klosterneuburg, Austria
E-mail: shabir.barzanjeh@ist.ac.at

Quantum entanglement is a fascinating quantum mechanical phenomenon in which two systems essentially share an existence such that measurement of one system determines the state of the other. At the same time, individual system itself may contain no quantum signatures in it self-correlations. These properties make entangled states an ideal resource for applications in quantum information science. Here, by using a macroscopic mechanical oscillator we demonstrate the generation of continuous variable stationary entanglement between propagating microwave signals of two specially separated superconducting resonators [1-5]. We study the quantum cross-correlation between the entangled pairs and verify the generation of spatially separated two-mode squeezing in propagating microwaves, confirming the existence of entanglement. We show that the mechanical resonator is able to squeeze the electromagnetic quadratures fluctuation up to 3.6 dB below vacuum fluctuation. The results can be extended to implement quantum communication protocols such as quantum illumination (quantum radar), remote quantum state preparation, and quantum teleportation between microwave and optical frequencies.

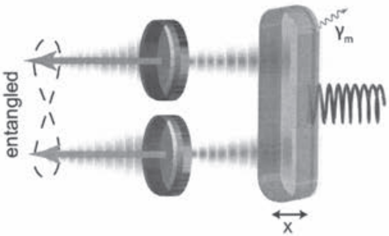

Fig1. Schematic of the electromechanical system used to generate bipartite entanglement between microwave radiations.

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TLS induced decoherence-instabilities in superconducting qubits

J.Burnett, A. Bengtsson, P.Delsing, J.Bylander

Microtechnology and Nanoscience, Chalmers University of Technology, Göteborg, Sweden
E-mail: andreas.bengtsson@chalmers.se

We study the temporal stability of relaxation and dephasing in superconducting qubits. By collecting statistics during measurements spanning multiple days, we reveal large fluctuations of qubit lifetimes and find that the main cause of fluctuations is interacting parasitic two-level-systems (TLS). Our statistical analysis also provides useful information about dynamics of TLS which could help identify possible microscopic sources of TLS, which still remain elusive. Moreover, interacting TLS also causes capacitance fluctuations, ultimately leading to frequency noise and dephasing of the qubit state. These discoveries are important for manufacturing stable superconducting circuits suitable as a scalable quantum computing platform where drift and fluctuations lead to unnecessary calibration and downtime.

Collective and edge states in superconducting transmon chains

I. Besedin[1], **I. Tsitsilin**[1,2], **and A. Ustinov**[1,3,4]

[1] National University for Science and Technology (MISiS), Moscow, Russia
[2] Moscow Institute of Physics and Technology, Dolgoprudny, Russia
[3] Physikalisches Institut, Karlsruhe Institute of Technology, Karlsruhe, Germany
[4] Russian Quantum Center, Moscow, Russia
E-mail: ilia.besedin@gmail.com

Chains of qubits coupled via nearest-neighbor interaction are expected to form a band structure similar to atoms in crystals. To achieve this regime, two requirements have to be satisfied: the number of structure periods of the qubit lattice should be large enough for the zone formalism to be meaningful and the coupling strength should exceed loss and disorder rates. When carefully engineered, such systems can exhibit interesting properties, such as topological order [1-3].
In the present work, we aim at experimentally demonstrating the emergence of band structure in linear chains of a one-dimensional chain of transmon qubits with a two-qubit unit cells with alternating coupling strength that has been suggested recently [4]. We have designed and fabricated a sample containing 11 qubits, each of them individually coupled to a coplanar waveguide resonator for dispersive readout.

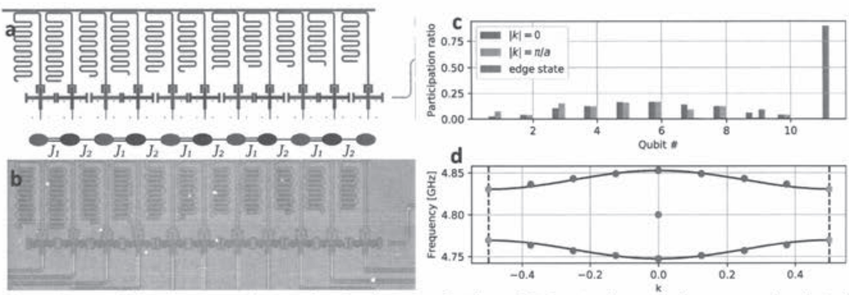

Fig 1. **a** chip layout, **b** optical photo of the fabricated sample, **c** calculated participation ratio of in-band and out-of-band states, **d** calculated spectrum of single-photon excitations (photonic bands)

We intend to explore experimentally single- and two-photon nonlocal collective excitations of the chain, which can be identified via two-tone spectroscopy with frequency multiplexing. We expect to find single- and double-photon edge states, which are identified by the one-dimensional topological order parameter, the Zak phase. We will present first experimental results obtained with these samples.

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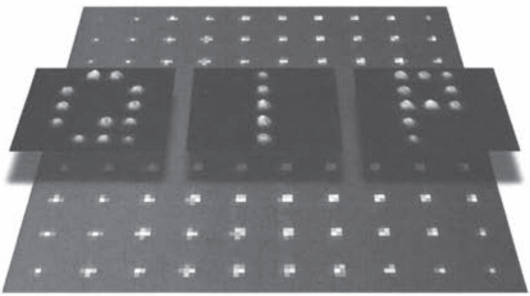
Scalable Platform for Quantum Computing with Neutral Atoms

D. Ohl de Mello[1], D. Schäffner[1], J. Werkmann[1], T. Preuschoff[1], L. Kohfahl[1], M. Schlosser[1] and G. Birkl[1]

[1]Institut für Angewandte Physik, TU Darmstadt, Darmstadt, Germany
E-mail: gerhard.birkl@physik.tu-darmstadt.de

We present a highly scalable platform for quantum computation and simulation with neutral atoms based on the combination of advanced micro-optical technologies and quantum optical methods such as optical tweezers. The use of a 2D platform of optical tweezer-traps based on microlens arrays allows for the creation of multi-site trap architectures [1] with several thousand sites capable of holding one individual laser-cooled atom at each site. In addition to being massively scalable, our platform naturally lends itself to the implementation of topological quantum computing for neutral atoms with its architecture directly suited for the application of stabilizer codes such as surface and colour codes [2].
We give an overview on the experimental investigation of ^{85}Rb atoms in 2D arrays of more than 400 individually addressable dipole traps featuring trap sizes and a tuneable site-separation in the single micrometer regime. We prepare exactly one atom per site in more than 100 sites with full control of the atom arrangement [3]. We discuss progress towards using Rydberg based interactions for the implementation of large-scale quantum computation and simulation.



Fluorescence images of rubidium atoms stored in a reconfigurable two-dimensional architecture of focused beam traps.

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Planar electrode ion trap for microwave-based quantum information processing

I. A. Boldin, A. Kraft, M. Porst, E. Esteki, B. Okhrimenko and Ch. Wunderlich

Siegen University, Siegen, Germany
E-mail: boldin@physik.uni-siegen.de

We present the current status of our experiment on the realization of a quantum processor with microwave-driven ions trapped in a novel planar ion trap. This approach uses a static spatially inhomogeneous magnetic field for MAgnetic Gradient Induced Coupling (MAGIC) between qubits and for individual addressing of the qubit states [1]. We present a newly designed trap chip (Fig. 1) that features the possibility to trap parallel strings of ions with variable ion-surface separation and separation between the ion strings. The trap chip also has built in resonator structures that enhance the microwave field amplitude and hence the speed of quantum gates. This new experimental setup incorporates an ion gun for in-situ cleaning of the trap surface in order to reduce the electric field noise and thus motional heating of the ions. The trap is enclosed into a custom-designed mu-metal magnetic field shielding in order to reduce the magnetic field noise that limits the coherence times of the qubits.

Fig. 1. A picture of the ion trap chip. The chip is 11x11 mm in size.

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Investigating a Superconducting Quantum Metamaterial in a Waveguide

J. D. Brehm[1] and A. V. Ustinov[1,2]

[1]*Karlsruhe Institute of Technology, Institute of Physics, Karlsruhe, Germany*
[2] *Russian Quantum Center, National University of Science and Technology MISIS, Moscow, Russia*
E-mail: jan.brehm@kit.edu

Metamaterials are systems composed of artificial substructures, called meta-atoms. For electromagnetic or elastic waves with wavelengths much larger than the lattice constant, the material behaves as an effective homogeneous medium with certain global parameters (e.g. refractive index). Quantum metamaterials extend the idea of classical metamaterials to a regime where the quantum coherence of the meta-atoms exceeds the typical time of a wave propagation through the medium.

In recent works, it was proposed that this regime gives rise to various collective light-matter interaction effects such as self-induced transparency, quasi-superradiant phase transitions and lasing. Superconducting qubits can be used as meta-atoms in the quantum regime because they feature well controllable properties, have sub-wavelength dimensions, and are known to have sufficiently long coherence times. First implementations of quantum metamaterials made of arrays of superconducting flux [1] and transmon [2] qubits were targeted at studying their collective interaction with a single mode of a microwave resonator.

Here, we investigate a one-dimensional quantum material which consists of an array of 80 transmon qubits coupled to a continuum of light modes of a coplanar waveguide. In order to study the collective response all qubits are required to deviate

Development of a new platform for quantum photonics applications

M. Nahra[1,] M. Ahmed[1], Robert Taylor[2], V. Davydov[3], V. Agafonov[4] & C. Couteau[1]

[1]Light, Nanomaterials, Nanotechnology-L2n ICD CNRS, University of Technology of Troyes, F-10000 Troyes, France
[2] Department of Physics, University of Oxford, Oxford, United Kingdom.
[3]GREMAN, UMR CNRS CEA 6157, Université F. Rabelais, F-37200 Tours, France;
[4]L.F.Vereshchagin Institute for High Pressure Physics, Russian Academy of Sciences, Troitsk, Moscow, 142190, Russia
E-mail: christophe.couteau@utt.fr

Very recently, the interest for quantum technologies by the scientific community and industry has strongly increased. Different types of implementations have been proposed as a practical implementation for a quantum bit. Our interest lies in using single photons and single spins in solid state host matrices such as diamond (nanodiamonds or membranes). Integration of nanosources of light is currently a major bottleneck preventing the realisation of all-photonic chips for quantum technologies and nanophotonics applications. Nanophotonics and integrated optics are vast growing fields with huge market potentials in particular for quantum technologies. Ideally, one needs optical circuitry, on-chip photodetection and on-chip generation of quantum states of light (single photons, entangled photons...). Our recent work on a new platform for quantum photonics using integrated optics can offer an easier and robust way to create fixed and compact quantum circuits that can be on chip and scalable. In this context, the coupling between waveguides and single photon emitters is critical [1]. The goal of our research is to efficiently couple single photon emitters with a new platform made of optical glass waveguides. To achieve this goal, several paths are undertaken such as the use of dielectric and plasmonic structuration in order to increase the light interaction with the waveguide or to develop fabrication techniques to insert the emitters directly inside the guide (for nanodiamonds). We will show what is our current state of the art for placing single emitters at the right place on our optical waveguides made of ion-exchange in glass and in particular what can be done to improve our first promising results in order to get near unity coupling between the optical bus and single photon emitters. We will present some promising results using negatively charged silicon-vacancy (SiV^-) centers in diamonds as they have emerged as a very promising candidate for quantum emitters due to their narrow line emission [2].

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Cryogenic CMOS electronics as building blocks for scalable quantum computers

A. Artanov[1], V. Christ[1], C. Degenhardt[1], L. Geck[1], C. Grewing[1], A. Kruth[1], D. Liebau[1], P. Muralidharan[1], D. Nielinger[1], P. Schubert[1], P. Vliex[1], A. Zambanini[1], and S. van Waasen[1]

[1]Central Institute of Engineering, Electronics and Analytics, ZEA-2: Electronic Systems, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
Email: c.degenhardt@fz-juelich.de

The Central Institute for Electronic Systems at Forschungszentrum Jülich develops, designs and tests scalable solutions for the control and readout of qubits to be used in future quantum computers. The focus lies on highly integrated system-on-chip (SoC) solutions leveraging state-of-the-art commercial semiconductor technologies.
A test chip was designed and layouted in a commercial 65nm CMOS process (see Figure 1). The chip features a DC-digital-to-analog converter (DC-DAC) that generates tuning voltages, e.g. for spin qubits, in the range of 0 V to +1 V. The integrated pulse DAC, running at 250 MHz, generates pulses with ±4 mV amplitude as gate sequences for operating the qubit.
In this presentation, we will describe the chip architecture in detail, show corresponding simulation results and measured chip performance.

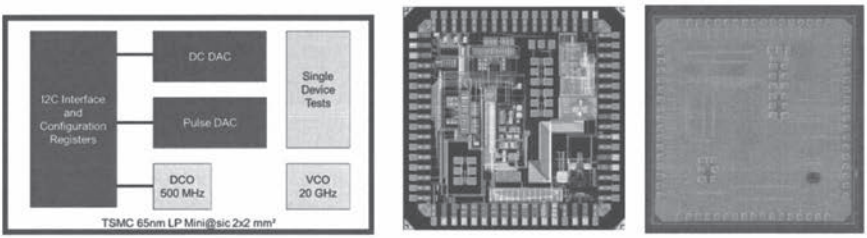

Fig. 1: High level block diagram (left), chip layout (middle) and die photograph (right) of the test chip

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Effects of wave mixing on a single artificial atom

A.Yu. Dmitriev[1,*], T. Hönigl-Decrinis[2,3], R. Shaikhaidarov[2], V.N. Antonov[2,4], S.E. de Graaf[3], O.V. Astafiev[1,2,3]

[1] *Moscow Institute of Physics and Technology, 141700 Dolgoprudny, Russia*
[2] *Royal Holloway, University of London, Egham, Surrey TW20 0EX, United Kingdom*
[3] *National Physical Laboratory, Teddington, TW11 0LW, United Kingdom*
4 Skolkovo Institute of Science and Technology,143026 Moscow, Russia
**E-mail: aleksei.j.dmitriev@phystech.edu*

A well-known effect of four and higher order wave mixing exhibits novel features when two microwave tones are scattered on a single superconducting two-level artificial atom in the strong coupling regime [1-3]. We study the effect by measuring the intensities of narrow sideband spectral components appeared from multi-photon elastic wave scattering. We derive an analytical expression for the amplitudes and show that the ratio of consequent components does not depend on the scattering order determined by the number of interacting photons per each act of scattering. We attribute this specific feature to the coherent states of input waves and suggest to use wave mixing as a tool for distinguishing non-coherent states of propagating light. Another novel feature we demonstrate is Autler-Townes-like splitting of side peaks [3], the magnitude of which depends on the scattering order. We also show the results of scattering of short microwave pulses, which lead to Bessel oscillations of side spectral components and to the mixing of classical and quantum states of light [2].

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Improving the fidelity of entangling gates via in situ characterization of qubit control lines

M. Jerger[1], A. Kulikov[1], Z. Vasseli[1] and A. Fedorov[1]

[1]ARC Centre of Excellence for Engineered Quantum Systems, The University of Queensland, St Lucia QLD 4072, Australia

E-mail: a.fedorov@uq.edu.au

One of the factors limiting the fidelity of entangling gates are distortions arising from transferring the control signals over the microwave lines. Distortions can be characterised by a transfer function and can be cancelled, in principle, if the transfer function of the control line is known. In this work we propose and experimentally realize a technique to measure the transfer function of a control line in the frequency domain using a qubit as a vector network analyzer. Our method requires coupling the line under test to the longitudinal component of the Hamiltonian of the qubit and the ability to induce Rabi oscillations through simultaneous driving of the transversal component. As a demonstration, we characterized the 'flux' control line of a superconducting Transmon qubit in the range from 1 to 450 MHz and used this characterization to improve the fidelity of an entangling CPHASE gate between two Transmon qubits.

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Analog Ising chain simulation with transmons

G. Fedorov[1,2], A. Dobronosova[3], N. Orlikovskiy[3] and A. Ustinov[1,4]

[1]Russian Quantum Center, Moscow, Russia
[2]Moscow Institute of Technology, Dolgoprudniy, Russia
[2] Bauman MSTU, Moscow, Russia
[3]Karlsruhe Institute of Technology, Karlsruhe, Germany
E-mail: gleb.fedorov@phystech.edu

Currently, the applications of medium-scale systems composed of superconducting qubits are mostly limited to testing basic principles of quantum computation, demonstrating those as proof-of-concept designs and developing scalable software and hardware interfaces to them. Although this is useful in terms of encouraging future developments in the domain, an alternative approach exists to exploit the built-in quantum properties of such devices to experiment with fundamental physical models. There already were [1], [2] some successful attempts to use small arrays of superconducting qubits to observe inherently quantum analog behaviour of these systems, and this work is aimed to continue those studies.

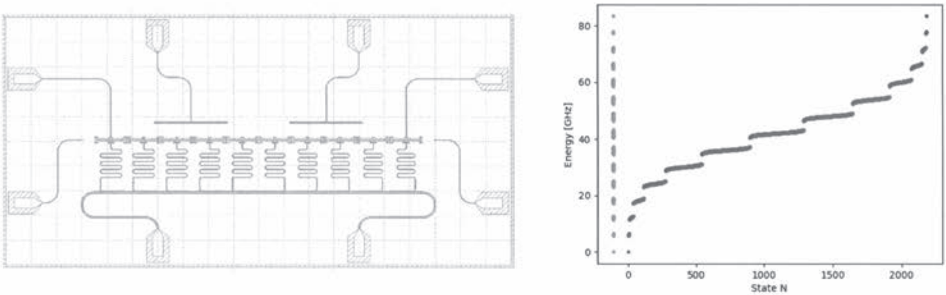

Fig. 1. The design concept **(left)**. 10 transmon quibits are arranged into a chain with transverse coupling whose state can be read out at each site. Two area-of-effect microwave drives are present, as well as full XYZ controls at the chain edges. **(Right)** Computed spectrum of the system with a slight disorder. Clearly, the energy bands are emerging even for a small transmon number of 6.

We are developing a chip to experimentally simulate crystal structure, many-body localization (MBL) and heat transport properties with a chain of XX-coupled transmons. First results will be concerning spectroscopic properties of the system.

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MBE Growth of Scalable Horizontal InAs Nanowire Arrays on 111B and 100 GaAs Substrates

M. Friedl[1], K. Cerveny[2], D. Dede[1], T. Patlatiuk[2], L. Güniat[1], W. Kim[1], N. Morgan[1], D. Zumbühl[2], A. Fontcuberta i Morral[1]

[1]*École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland*
[2]*University of Basel, Basel, Switzerland*
E-mail: martin.friedl@epfl.ch

A significant challenge in scaling up quantum computers to larger numbers of qubits is accounting for possible errors. Both qubit dephasing and gate errors can cause problems in a quantum algorithm and the more complex the algorithms become, the more important the idea of quantum error-correction becomes. Fault-tolerant architectures have been proposed in which multiple physical qubits can be used to represent a single virtual fault-tolerant qubit. An alternative approach is to explore new kinds of qubits that have inherent fault-tolerance, such as topological qubits.

Topological qubits based on Majorana Fermions have become a very popular research topic because they have been theoretically shown to have very long coherence times. Using charge-protected topological qubits to suppress quasiparticle poisoning, theoretical estimates suggest that coherence times up to several minutes are possible.[1] A measurement-based quantum computing approach in an array of in-plane InAs nanowires has been proposed as a scalable architecture for charge-protected topological quantum computing.[2]

In this work, we explore the molecular beam epitaxy growth of in-plane InAs nanowires on GaAs substrates.[3] With a patterned oxide mask to give selectivity, high-quality InAs nanowires were grown on both GaAs 111B and 100 substrates. In contrast to out-of-plane nanowire growth, this approach lends itself very well to being scaled up to the wafer-scale while maintaining low nanowire defect densities in the absence of gold growth catalysts. In this contributed work, we describe the properties of such InAs and InGaAs nanowire arrays. These were characterized by various methods, including transmission electron microscopy, Raman spectroscopy as well as magnetotransport measurements to assess the electron mean free path and coherence length. In addition, future implementations and perspectives on scalability are discussed to evaluate their feasibility in topological quantum computing architectures.

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Decoherence-free interaction between giant atoms in waveguide QED

A. F. Kockum[1,2], G. Johansson[1], and F. Nori[2,3]

[1] *Wallenberg Centre for Quantum Technology, Chalmers University of Technology, Gothenburg, Sweden*

[2] *Theoretical Quantum Physics Laboratory, RIKEN, Wako, Saitama, Japan*

[3] *Physics Department, The University of Michigan, Ann Arbor, Michigan, USA*

E-mail: anton.frisk.kockum@chalmers.se

In quantum-optics experiments with both natural and artificial atoms, the atoms are usually small enough that they can be approximated as point-like compared to the wavelength of the electromagnetic radiation they interact with. However, superconducting qubits coupled to a meandering transmission line, or to surface acoustic waves [1,2,3], can realize "giant artificial atoms" that couple to a bosonic field at several points which are wavelengths apart [4,5]. Here, we study setups with multiple giant atoms coupled at multiple points to a one-dimensional (1D) waveguide [6]. We show that the giant atoms can be protected from decohering through the waveguide, but still have exchange interactions mediated by the waveguide. Unlike in decoherence-free subspaces, here the entire multi-atom Hilbert space is protected from decoherence. This is not possible with "small" atoms. We further show how this decoherence-free interaction can be designed in setups with multiple atoms to implement, e.g., a 1D chain of atoms with nearest-neighbor couplings or a collection of atoms with all-to-all connectivity. This may have important applications in quantum simulation and quantum computing.

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Gate-efficient simulation of molecular eigenstates on a quantum computer

M. Ganzhorn[1], D. Egger[1], P. Ollitrault[1], P. Barkoutsos[1], G. Salis[1], N. Moll[1], A. Fuhrer[1], P. Mueller[1], M. Roth[2,3], S. Woerner[1], I. Tavernelli[1] and S. Filipp[1]

[1]IBM Research Zurich, Rueschlikon, Switzerland
[2] JARA Institute for Quantum Information, Forschungszentrum Juelich, Germany
[3] Institute for Quantum Information, RWTH Aachen, germany
E-mail: anz@zurich.ibm.com

A key requirement to perform simulations of large quantum systems on current quantum processors is the design of quantum algorithms with short circuit depth. To achieve this, it is essential to realize a gate set that is tailored to the problem at hand and which can be directly implemented in hardware [1]. Here, we experimentally demonstrate that exchange-type gates are ideally suited for calculations in quantum chemistry [2]. We determine the energy spectrum of molecular hydrogen using a variational quantum eigensolver algorithm based on exchange-type gates in combination with a method from computational chemistry to compute the excited states. We utilize a parametrically driven tunable coupler [3] to realize exchange-type gates that are configurable in amplitude and phase on two fixed-frequency superconducting qubits. With gate fidelities around 95% we are able to compute the eigenstates within an accuracy of 50 mHartree on average, a limit set by the coherence time of the tunable coupler.

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FPGA-based Platform to Control and Readout Superconducting Qubits

R. Gebauer[1], **N. Karcher**[1], **O. Sander**[1], **M. Weides**[2], **A. V. Ustinov**[3] **and M. Weber**[1]

[1]Institute for Data Processing and Electronics, KIT, Karlsruhe, Germany
[2] School of Engineering, University of Glasgow, Glasgow, United Kingdom
[3] Physikalisches Institut, KIT, Karlsruhe, Germany
E-mail: richard.gebauer@kit.edu

A typical measurement setup for superconducting qubits consists of arbitrary waveform generators, signal recorders, and vector network analyzers. Although sufficient for simple experiments, its applicability is limited due to long data communication delays, poor scalability, and static pulse sequences. A faster, more integrated and more flexible solution for qubit readout and control is FPGA-based custom hardware. It not only reduces costs and space requirements but also simplifies measurements and enables customized control schemes like quantum feedback where a low response time is critical.

A flexible FPGA-based integrated control and readout platform for experiments with superconducting qubits is presented which also enables fast feedback loops to control qubits depending on their measured state. Thus, it provides the basis for experiments and algorithms like quantum error correction or active reset. We demonstrated arbitrary qubit rotations around X and Y axis and can perform all standard measurements for qubit characterization. Furthermore, we present experimental results on quantum feedback and first concepts on scaling up the system.

Platform for unconditional qubit reset based on tunable environments

J. Goetz[1], V. Sevriuk[1], K. Y. Tan[1], J. Ilves[1], M. Partanen[1], J. Ikonen[1], A. Gunyho[1], M. Jenei[1], T. Li[1], M. Silveri[1,2], R. Lake[1,3], S. Masuda[4], L. Grönberg[5], J. Hassel[5], M. Möttönen[1]

[1]*QCD Labs, QTF Center of Excellence, Department of Applied Physics, Aalto University, P.O. Box 13500, FI-00076 Aalto, Finland*
[2] *Research Unit of Nano and Molecular Systems, University of Oulu, P.O. Box 3000, FI-90014 Oulu, Finland*
[3] *National Institute of Standards and Technology, Boulder, Colorado 80305, USA*
[4] *Collage of Liberal Arts and Sciences, Tokyo Medical and Dental University, Ichikawa, 272-0827, Japan*
[5] *VTT Technical Research Centre of Finland, QFT Center of Excellence, P.O. Box 1000, FI-02044 VTT, Finland*

E-mail: jan.goetz@aalto.fi

One requirement for scalable quantum computing is the preparation of well-defined qubit states in the beginning of each quantum algorithm. Typically, qubits are initialized by cooling them to very low temperatures and waiting until each qubit has approximately reached the ground state. As coherence times are improving, this technique can substantially slow down the computing process. Here, we present an unconditional reset scheme for superconducting qubits based on voltage-biased superconductor-insulator-normal metal (SIN) junctions. Our theory [1] shows that we can in-situ turn on a dissipation channel with a strength of several hundred MHz resulting in a reset time of the qubit in the nanosecond range. Our method works for transmon qubits and C-shunt flux qubits and can also be applied to superconducting resonators. In our experiments with superconducting resonators [2], we can increase the resonator decay rate by several orders of magnitude in only 3ns. By tuning the resonator coupling strength to the dissipative environment, we are furthermore able to observe a broadband Lamb shift and the generation of incoherent microwave radiation [4].

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Implementing an inductively shunted transmon qubit with tunable transverse and longitudinal coupling

Daria Gusenkova[1], Nataliya Maleeva[1], Sebastian T. Skacel[1,2] and Ioan M. Pop[1,2]
Susanne Richer[3] and David DiVincenzo[3]

[1] *Physikalisches Institut, Karlsruhe Institute of Technology, Germany*
[2] *Institute of Nanotechnology, Karlsruhe Institute of Technology, Germany*
[3] *JARA Institute for Quantum Information, RWTH Aachen University, Germany*

We present first results on the way to implement an inductively shunted transmon qubit with tunable transverse and longitudinal coupling to an embedded harmonic mode [1]. The inductive shunt acts as a coupler and it combines Josephson junction arrays with compact, linear, low-loss inductances, making use of the high kinetic inductance of granular aluminum [2, 3].

Besides overcoming fabrication challenges, originating from strict requirements on the circuit parameters, and a need to make coherent contacts between different lithographic layers [4], the main goal is to suppress phase slips in the JJ array.

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Scalable Instrumentation for Quantum Computing

S. Hafizovic

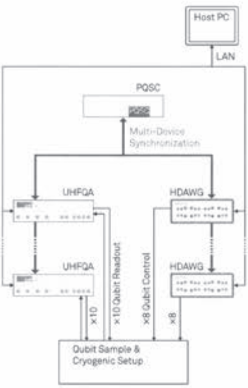
Zurich Instruments AG, Zurich, Switzerland

We present a complete system (Fig. 1) for readout and control of qubits in circuit QED and quantum dots scalable to 100 qubits. The system comprises 3 types of elements that cover readout, qubit control and classical system control.

The UHFQA Quantum Analyzer implements frequency-multiplexed pulse generation and data acquisition for measurement of up to 10 readout resonators simultaneously. Matched filters allow for optimization of both readout speed and readout fidelity. Fig. 2 details the implemented functionality, more details and measurements are shown in [1,2].

The HDAWG Arbitrary Waveform Generator generates control pulses for 1-qubit gates and 2-qubit gates [3]. The channel density of 16 ch per 2 height units allows for scaling to systems for many qubits. A trigger-to-first-sample-out latency of 50 ns and dynamic sequencing capability are beneficial for feedback experiments. The channel density of 16 channels per 2 height units also allows for

The PQSC Programmable Quantum System Controller synchronizes and orchestrates all components such that the elements integrate into a single real-time system. It also features a reprogrammable FPGA that allows for implementation of user-defined real-time algorithms for quantum processor control.



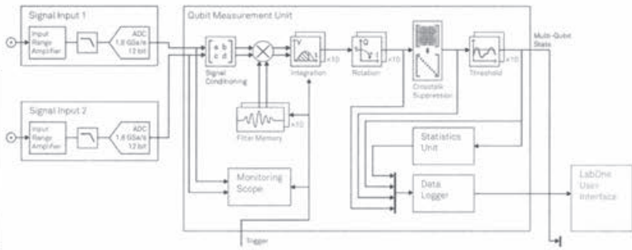


Fig 1. (left) The complete Quantum Computer Control System.

Fig 2. (above) Functional blocks of the UHFQA Quantum Analyzer readout part. Not shown is the integrated AWG that generates the readout pulses

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Superconducting fabrication platform for enabling solutions in quantum technology

J. Hassel[1], L. Grönberg[1], K. Grigoras[1], J. Lehtinen[1], V. Vesterinen[1], S. Simbierowicz[1], and M. Prunnila[1]

[1]VTT Technical Research Centre of Finland Ltd. & QTF Centre of Excellence, Espoo, Finland

VTT has established superconducting fabrication lines applied in numerous scientific experiments as well as industrial applications. In this paper, we will review the capabilities and recent developments useful in quantum systems and enabling technologies. These utilize selections of various materials deposited by sputtering, reactive sputtering, or atomic layer deposition, tunnel junction processes, and integration with micromachined structures. Example applications include low-loss resonators for qubits [1], Josephson parametric devices [2], and 3D integrated microcoolers [3] to mention a few. We will introduce the overall features of our fabrication processes. In particular, we introduce recent developments considering an improved superconducting niobium tunnel junction process based on cross-type side-wall spacer passivated (SWAPS) junctions [4], enabling lithography-limited linewidths down to < 0.5 μm with i-line UV lithography, very low parasitic capacitance, and flexible integration into multi-layer devices. We will discuss the applications of SWAPS junctions in Josephson parametric device development. Furthermore, we will describe the work and status of the development of a superconducting through-silicon via process aimed for mode suppression and signal routing in 3D integrated qubit systems. The process is based on superconducting atomic-layer deposited titanium nitride and a deep reactive etching process for through-wafer openings.

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Reflective Amplification without Population Inversion from a Strongly Driven Superconducting Qubit

Io-Chun Hoi[1]

[1]*Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan*
E-mail: ichoi@phys.nthu.edu.tw

Amplification of EM fields is often achieved by strongly driving a medium to induce population inversion such that a weak probe can be amplified through stimulated emission. Here we strongly couple a superconducting qubit, an artificial atom, to the field in a semi-infinite waveguide. When driving the qubit strongly on resonance such that a Mollow triplet appears, we observe a few percent amplitude gain for a weak probe at frequencies in between the triplet. This amplification is not due to population inversion, but instead results from a four-photon process that converts energy from the strong drive to the weak probe [1]. We find excellent agreement between the experimental results and numerical simulations without any free fitting parameters. Since our device consists of a single two-level artificial atom, the simplest possible quantum system, it can be viewed as the most fundamental version of a four-wave-mixing parametric amplifier.

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Double-sided coaxial circuit QED for Quantum Computing

S.Jebari[1], J.Rahamim[1], P.Spring[1], A.Patterson[1], M.Esposito[1], T.Tsunoda[1], G.Campanaro[1], K.Ratter[1], B.Vlastakis[1], P.J.Leek[1]

[1] *Clarendon Laboratory, Department of Physics, University of Oxford, Parks Rd, Oxford, OX1 3PU, United Kingdom*

E-mail: Salha.Jebari@physics.ox.ac.uk

A major obstacle in scaling up superconducting circuit architectures is the difficulty of having the many required control and measurement lines on the same chip as the qubits. As a solution, we present a coaxial circuit QED [1, 2] architecture in which a qubit and lumped element LC resonator are fabricated on opposing sides of a single chip, and control and readout are provided by coaxial wiring running perpendicular to the chip plane [3]. We present spectroscopic and time-resolved measurements of a fabricated device, demonstrating excellent agreement with circuit QED in the dispersive regime. The architecture allows for scaling via nearest-neighbour coupling to large arrays of selectively controlled and measured qubits, with a straight-forward fabrication procedure and without the complexity of in-plane wiring.

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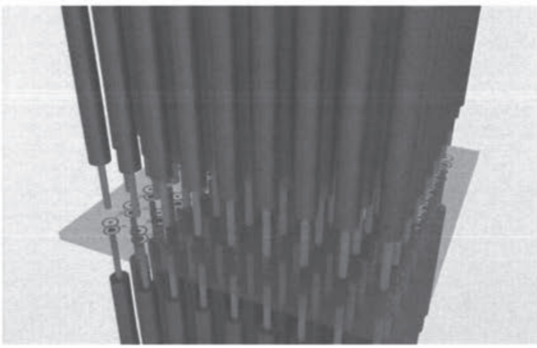

Trapped-Ion Transport Featuring High-Fidelity Preservation of Quantum Information

Peter Kaufmann[1], Timm F. Gloger[1], Delia Kaufmann[1], Michael Johanning[1], and Christof Wunderlich[1]

[1] Experimentelle Quantenoptik, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Germany
E-mail: johanning@physik.uni-siegen.de

The synthesis of a scalable system using interconnected subsystems is a promising approach for building scalable quantum simulators and computers. One prerequisite for this concept is the ability to faithfully transfer quantum information between subsystems. With trapped atomic ions, this can be realized by transporting ions with quantum information encoded into their internal states.

Here we report on high precision measurements of the fidelity of quantum information encoded into hyperfine states of a $^{171}Yb^{+}$ ion during ion transport in a micro-structured Paul trap. We infer the fidelity of the internal state upon transport from Ramsey spectroscopy interleaved with up to 4000 transport operations. Each transport spanning a distance of 280 µm takes 12.8 µs. We obtain a state fidelity of 99.9994 (+6/−7) % per ion transport [1].

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The faithful estimation of such small infidelities and of their uncertainties requires a careful calibration of our detection fidelities. With this knowledge, we infer the probability density of the state population applying Bayesian analysis.

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Quantum variational optimisation for nonlinear equations

Jaewoo Joo, **Michael Lubasch, Martin Kiffner, Dieter Jaksch**

Department of Physics, University of Oxford
E-mail: jaewoo.joo@physics.ox.ac.uk

We demonstrate a new variational optimisation approach in quantum computing framework. This enables to find the ground-state energy in nonlinear equations (e.g., Gross-Pitaevskii equation). The core task of the variational optimisation in classical numerical computation is to calculate an expectation value of an observable representing a Hermitian operator sandwiched by a variational input state (by contraction in tensor network approaches) and to update the parameters of a variational input state to obtain its minimum/maximum value over the parameters. We here replace the task of calculating the expectation values in classical computing into quantum computing, particularly to find the minimum energy of a nonlinear quantum system. We demonstrate the scheme using IBM 20Q quantum computing facility.

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Digital quantum simulation of a two dimensional electron gas pierced by a strong magnetic field

M.Kaicher[1], S. B. Jäger[1], P.-L. Dallaire-Demers[2], R. Babbush[3] and F. K. Wilhelm[1]

[1]Theoretical Physics, Saarland University, Saarbrücken, Germany
[2]Xanadu, 372 Richmond St W, Toronto ON, M5V 2L7, Canada
[3]Google Inc., Venice, CA 90291, USA
E-mail: michael.p.kaicher@gmail.com

A two-dimensional electron gas, confined to a finite disk geometry and pierced by a strong transversal magnetic field at zero temperature describes the physical setting of the fractional quantum Hall effect. We give an ab-initio roadmap on how this system may be simulated on a quantum processor. We show how the approximate ground state could be reached through a hybrid quantum-classical variational algorithm and how to extract ground state properties. This heuristic method can be extended to incorporate more physical effects, such as impurity models, to ultimately test theoretical models against experimental data beyond the limits of classical computational power.

Filter effects in quantum optimal control using Krotov's method

Matthias G. Krauß[1], **Sabrina Patsch**[1], **Daniel M. Reich**[1], **and Christiane P. Koch**[1]

[1] *Theoretische Physik, Universität Kassel, Heinrich-Plett-Straße 40, D-34132 Kassel, Germany*
E-Mail: matthias.krauss@physik.uni-kassel.de

The experimental implementation of pulse shapes obtained via optimal control theory is often complicated due to a distortion of the computed pulses, caused by a transition function characterizing the pulse generation hardware. We propose an extension to Krotov's method, which incorporates these filter functions and thus accounts for the distortion of the pulse already during the optimization process. This makes it possible to circumvent the problems arising in classical deconvolution which occur for filter functions with zeros in their spectra. We apply this algorithm to the reset of a qubit connected to a reservoir [Basilewitsch et al., New J. Phys. 19, 113042 (2017)] and to the propagation of a circular Rydberg state [Patsch et al., Phys. Rev. A 97, 053418 (2018)]. The relevant filter functions in these cases can not easily be deconvoluted. We demonstrate successful optimization for this class of filter functions.

A Shuttling-Based Trapped Ion Quantum Processing Node

B. Lekitsch, V. Kaushal, D. Pijn, J. Hilder, A. Stahl, O. Gräb, F. Schmidt-Kaler and U. Poschinger
JGU Mainz, Institut of Physics, Staudingerweg 7, 55128 Mainz, Germany
E-mail: b.lekitsch@uni-mainz.de

We present our work towards the implementation of a complete error correction algorithm in a shuttling-based trapped ion quantum system. Ions are stored in a segmented linear Paul trap with a designated laser interaction zone (LIZ). Addressed single- and two-qubit gate operations are performed by selectively transporting ions into the LIZ. A multi-channel waveform generator based on a system-on-chip device (SoC) controls the movement of ions, including shuttling, crystal separation/merging and swapping, and all laser-driven qubit operations.

Making use of this setup, four-qubit GHZ states using sequential entangling gates [1] and a dc magnetometer with quantum enhanced performance [2] have been successfully demonstrated. We will present results of ongoing work on a fault-tolerant error syndrome measurement scheme based on six fully controlled trapped-ion qubits: four data qubits, one flag and one syndrome qubit. Furthermore, we will discuss current work on extending the technical capabilities of our setup towards the implementation of a complete topological quantum error correction algorithm using up to 10 qubits.

In addition, we will describe how the current setup can be modified to include optical interconnects making it a good candidate for use as an elementary logic unit (ELU). ELUs were first proposed as a critical building block for a large-scale trapped ion quantum computer by Monroe et al. [3]. We will present a concept on how such an ELU can be realized using a linear Paul trap and selective shuttling of ions without the use of optical cavities.

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Harnessing photonic qutrits in quantum information processing

Tong Wu[1], Josh Izaac[2], Zixi Li[1], Kai Wang[1], Zhaozhong Chen[1], Lijun Xia[1], Zhiyu Chen[1], Liangliang Lu[1], Shining Zhu[1], Jingbo Wang[2], Xiaosong Ma[1*]

[1]*School of Physics, National Laboratory of Solid-State Microstructures, Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing 210093, China*

[2]*School of Physics, The University of Western Australia, Crawley, WA 6009, Australia*

E-mail: xiaosong.ma@nju.edu.cn

Three-dimensional quantum states, i.e., qutrits, have unique quantum features and offer advantages in particular quantum information tasks. Here we report two experimental endeavors by employing qutrits in: quantum walk on directed graphs, as well as finding the exact number of perfect matching with entangled qutrits.

Quantum walks [1] are of crucial importance in the development of quantum information processing algorithms. Recently, another potential application has been proposed, where one could efficiently perform network analysis with quantum walks, especially on vertex centrality ranking [2]. However, it is challenging to rank the centrality of a directed network via conventional quantum walks, since it corresponds to a non-Hermitian Hamiltonian. Here, we solved the non-unitary challenge by introducing pseudo-Hermitian evolutions [3] and report the first experimental realization of centrality ranking of a directed graph on a photonic platform with multi-photon parity-time-symmetric quantum walks. With single- and two-photon Fock states as inputs, we successfully demonstrated quantum centrality rankings on a three-vertex and a nine-vertex graph respectively, the experimental results agree well with theoretical predictions.

Integrated photonics offers high-efficiency single-photon generation as well as multi-mode, high-precision and reconfigurable quantum controls, which are particularly suited for generating, manipulating qudits [4-6]. In the second work, we experimentally realize the generation and manipulation of a pair entangled qutrits on a silicon chip. The integrated micro-ring photon-pair sources allow us to independently tune the coupling conditions of pump, signal and idler photons. A series of entangled states can be produced and re-configured on our chip, which reveals the exact number of perfect matching. These results represent a new application in functionally integrated quantum photonics, demonstrating the high potential of this platform for the progress of quantum information processing.

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Scalable methodology for automated characterization and calibration for medium-scale quantum processors

S. Machnes[1] **and F. K. Wilhelm**[1]

[1] *Theoretical Physics, Saarland University, Saarbrücken, Germany*
E-mail: shai.machnes@gmail.com

The current methodology for designing control pulses for superconducting circuits often results in a somewhat absurd situation: pulses are designed using simplified models, resulting in initially poor fidelities. The pulses are then calibrated in-situ, achieving high-fidelities, but without a corresponding model. We are therefore left with a model we know is inaccurate, working pulses for which we do not have a matching model, and a calibration process from which we learned nothing about the system. Moreover, such a process is long and arduous, and may take months for a 50+ qubit device.

We propose a novel procedure to rectify the situation by merging pulse design, calibration and system characterization: Calibration is recast as a closed-loop search for the best-fit model parameters, starting with a detailed, but only partially characterized model of the system. Fit is evaluated by fidelity of a complete set of gates, which are optimized to fit the current system characterization. The entire procedure can be fully automated, requiring human input only when the system model is not rich enough to describe observed behavior.

The end result is a best-fit characterization of the system model, and a full set of high-fidelity gates for that model. In other words – a fully working quantum device. We believe the new approach will greatly improve both gate fidelities, our understanding of the systems they drive, and our ability to swiftly utilize medium-scale quantum processors.

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Microwave remote state preparation vs. quantum cryptography

A. Marx,[1] K. G. Fedorov,[1,2] S. Pogorzalek,[1,2] M. Xu,[1,2] M. Fischer,[1,2,3] E. Xie,[1,2,3] F. Deppe,[1,2,3] and R. Gross[1,2,3]

[1]*Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany*
[2]*Physik-Department, Technische Universität München, 85748 Garching, Germany*
[3]*Nanosystems Initiative Munich (NIM), Schellingstraße 4, 80799 München, Germany*

Quantum communication protocols employ nonclassical correlations as a resource for an efficient transfer of quantum states [1]. As a fundamental protocol, remote state preparation (RSP) aims at the preparation of a known quantum state at a remote location using classical communication and quantum entanglement. We use flux-driven Josephson parametric amplifiers and linear circuit elements in order to generate propagating two-mode squeezed (TMS) microwave states acting as our quantum resource [2, 3]. Combined with a feedforward, we use the TMS states to experimentally demonstrate the continuous-variable RSP protocol by preparing single-mode squeezed states at a distant location. Furthermore, we show quantum discord consumption in the RSP protocol, suggesting that the former represents a useful quantum resource. Finally, we interpret our results as a quantum cryptographic protocol analogous to the Vernam cipher.
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Trapped ions in optical microtraps

M. Mazzanti[1], **T. Feldker**[1], **H. Hirzler**[1], **N. Ewald**[1] **and R. Gerritsma**[1]

[1]Institute of Physics, University of Amsterdam, Amsterdam, Netherlands
E-mail: m.mazzanti@uva.nl

We present progress on an experimental setup in which we aim to implement two-dimensional ion crystals in a Paul trap [1-6]. We will use novel optical microtraps – derived from spatial light modulators [see e.g. [7]] – to manipulate the phonon spectrum of the crystal [6,8]. This in turn allows us to engineer the spin-spin interactions. In particular, the pinning of a single ion can be used to create short-range spin-spin interactions. In 2D crystals, this can be used to quantum simulate spin Hamiltonians on a kagome lattice, which, at low energies, are described by emergent gauge fields [6]. Combining addressed ion operations with phonon-mode engineering, it should be feasible to equip the quantum simulator with a complete set of operations. Calculations show that the optical microtraps can also be used to deterministically prepare defect-free 2D ion crystals after a melting event.

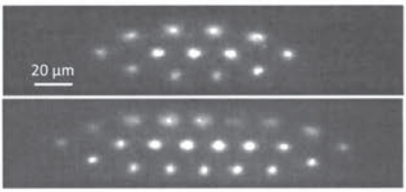

Figure: Two-dimensional ion crystals in one of our Paul traps [9].

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Investigating coherence limitations in fixed frequency transmon qubits

Matthias Mergenthaler, *Clemens Mueller, Andreas Fuhrer, Stefan Filipp*

The last decades have seen significant advances in the coherence times of superconducting qubits. This was mainly made possible by reducing the charge dispersion for transmon qubits, good thermalization and filtering of the readout and control circuitry as well as improvements in Josephson junction fabrication. Lately, efforts are being made in order to investigate the limitations of coherence due to material interfaces and two level fluctuatours.

Here we present our work towards understanding decoherence mechanisms in fixed frequency transmon qubits via participation ratio engineering, surface treatments and sample packaging. We show qubit packaging under a controlled atmosphere in UHV, discuss possible surface treatments and show coherence data from initial devices. Additionally, we discuss preliminary steps towards studying and reducing the effects of two-level fluctuators via participation ratio engineering and chip designs.

Qubit Measurement by Multi-Channel Driving

Joni Ikonen,[1] Jan Goetz,[1] Jesper Ilves,[1] Aarne Keränen,[1] Andras M. Gunyho,[1] Matti Partanen,[1] Kuan Y. Tan,[1] Leif Grönberg,[2] Visa Vesterinen,[1, 2] Slawomir Simbierowicz,[2] Juha Hassel,[2] and Mikko Möttönen[1]

[1]QCD Labs, QTF Centre of Excellence, Department of Applied Physics, Aalto University, P.O. Box 13500, FI-00076 Aalto, Finland
[2] VTT Technical Research Centre of Finland, QTF Center of Excellence, P.O. Box 1000, FI-02044 VTT, Finland
E-mail: mikko.mottonen@aalto.fi

We theoretically propose and experimentally implement a method to measure a qubit by driving it close to the frequency of a dispersively coupled bosonic mode. The separation of the bosonic states corresponding to different qubit states begins essentially immediately at maximum rate, leading to a speedup in the measurement protocol. Also the bosonic mode can be simultaneously driven to optimize measurement speed and fidelity. We experimentally test this measurement protocol using a superconducting qubit coupled to a resonator mode. For a certain measurement time, we observe that the conventional dispersive readout yields above 100% higher measurement error than our protocol. Finally, we use an additional resonator drive to leave the resonator state to vacuum if the qubit is in the excited state during the measurement protocol. This suggests that the proposed measurement technique may become useful in unconditionally resetting the resonator to a vacuum state after the measurement pulse.

Quantum Link Prediction in Complex Networks

João P. Moutinho[1], André Melo[2,1], Bruno Coutinho[1],
István A. Kóvacs[3], Albert-László Barabási[3] and Yasser Omar[1,4]

[1]Physics of Information and Quantum Technologies Group, Instituto de Telecomunicações, Lisbon, Portugal
[2]Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands
[3]Network Science Institute, Northeastern University, Boston, MA, USA
[4]Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

E-mail: joao.p.moutinho@gmail.com

In it's simplest form, link prediction in complex networks consists in determining which pairs of nodes are likely to be connected solely from the information encoded in the topology of each network. Complex networks are a general description that fits many physical, social, biological and information systems, giving the problem of link prediction multidisciplinary implications. The two main research areas are in biological networks, where the focus is to help fill in the large amounts of data still missing from biological networks [1], and social networks, where the focus is to predict interactions that will be the most fruitful for all parties in a social environment.

In this work we present a novel method for link prediction on complex networks based on continuous-time quantum walks. The control of a phase parameter allows our method to be used in different types of networks (physical, social, biological, etc.). State of the art classical methods look for specific pattern structures in the network to predict links around them, from simple triangles or squares to more complex local community structures [2, 3]. By exploiting quantum coherence we are able to outperform these methods in various datasets, indicating that our method can capture complex local patterns without the need to impose a specific structure.

One of the main challenges in network science in general is the sheer size of real world complex networks. Our results indicate there is a strong potential for combining quantum algorithms with complex network research to produce tools with direct and immediate experimental relevance, and future Quantum Hardware may become an important platform overcome these challenges and take full advantage of the potential of network science.

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Passive, on-chip superconducting circulator using a ring of tunnel junctions

C. Mueller[1,2], S. Guan[2], N. Vogt[3], J.H. Cole[3] and T. M. Stace[2]

[1] *IBM Research, Ruschlikon, Switzerland*
[2] *ARC EQuS, The University of Queensland, Brisbane, Australia*
[3] *RMIT University, Melbourne, Australia*
E-mail: clm@zurich.ibm.com

The unavailability of integrated microwave circulators is currently one of the major roadblocks on the way towards true scaling up of superconductor based quantum technology, with many recent proposals aimed at overcoming this capability gap. In general, these require additional microwave or radiofrequency components and therefore increase control complexity significantly. Here, I will present our recent proposal for a fully passive, on-chip microwave circulator based on a ring of superconducting tunnel junctions [1]. We investigate two distinct physical realizations, based on either Josephson junctions (JJ) or quantum phase slip elements (QPS), with microwave ports coupled either capacitively (JJ) or inductively (QPS) to the ring structure. A constant bias applied to the center of the ring provides the symmetry breaking (effective) magnetic field, and no microwave or rf bias is required. We find that this design offers high isolation even when taking into account fabrications imperfections and environmentally induced bias perturbations and find a bandwidth in excess of 500 MHz for realistic device parameters.

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Modeling quantum universal gates in semiconductor CMOS

Krzysztof Pomorski[1], Panagiotis Giounanlis[1], Elena Blokhina[1], Robert Staszewski[1], Dirk Leipold[2]

1: University College Dublin, The School of Electrical and Electronic Engineering, Ireland
2: Equal 1 Company, Freymont, USA

The new architecture of electrostatic charge qubit suitable for implementation in large-scale integration semiconductor circuits is given [1], [2], [3], [4]. We present the modelling methodology and preliminary results on the quantum universal gates in the chain of coupled quantum semiconductor dots that are electrically controlled by classical gates. The numerical scheme is based on the use of the time-dependent Schroedinger equation and is upgraded by the use of density matrix and non-equilibrium Green functions.

We also take into account the effects coming from the electromagnetic environment. The scheme is based on a piece-wise approximation of potential. The presented techniques allow the design quantum chip that is integrated with classical CMOS technology and operating at 4K. The relevance of the presented numerical techniques in reference to quantum annealing is drawn.

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Multilayer Coaxial Superconducting Circuits for Quantum Computing

<u>K. Ratter</u>, J. Rahamim, S. Jebari, X. Dai, P. A. Spring, A. Patterson, M. Esposito, T. Tsunoda, B. Vlastakis, G. Tancredi and P. J. Leek

Clarendon Laboratory, Department of Physics, University of Oxford,
Parks Road, OX1 3PU, Oxford, UK
E-mail: kitti.ratter@physics.ox.ac.uk

Superconducting circuits are one of the leading candidates for the realisation of quantum computing, in particular for near-term applications which may already be reached with circuits consisting of a few hundred qubits. In order to realise useful circuits at this scale, an architecture is required which implements good connectivity between qubits, and allows selective readout and control of each qubit without introducing detrimental crosstalk or new decoherence channels. Since the number of readout and control lines increases linearly with the number of qubits, scaling up a circuit which is constrained on the 2D surface of a substrate becomes increasingly difficult. We aim to overcome this challenge by taking advantage of the third, out-of-plane dimension, and entirely eliminating on-chip wiring. We recently proposed a 3-dimensional quantum circuit architecture with coaxial symmetry, and demonstrated the operation of a single unit cell [1]. The architecture consists of an LC resonator and a transmon qubit fabricated on either side of an Al_2O_3 chip. The two are capacitively coupled through the substrate. Control and readout is achieved by coaxial wires which run perpendicular to the plane of the chip, and capacitively couple to the circuit elements. 2D scaling of this circuit is simply achieved by the repetition of the unit cell without the need to redesign the control and readout wiring. The architecture also lends itself to scaling the qubit grid in the third dimension. Here we present our most recent work towards circuits with two qubit layers.

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Quantum Process Tomography of a 3D Quantum Memory

M. Renger[1,2], E. Xie[1,2,3], F. Deppe[1,2,3], P. Eder[1,2,3], M. Fischer[1,2,3], S. Pogorzalek[1,2], K.G. Fedorov[1,2], A. Marx[1], R. Gross[1,2,3]

[1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany
[2] Physik-Department, TU München, 85748 Garching, Germany
[3] Nanosystems Initiative Munich (NIM), 80799 München, Germany

E-mail: Michael.Renger@wmi.badw.de

We realize a quantum memory by coupling a transmon qubit to a rectangular 3D cavity resonator [1]. By exploiting the multimode structure of the 3D cavity, scalability is significantly enhanced in our architecture. Compared to the bare qubit, the T_1-time of the memory is 6 times longer. We accurately characterize the loss of quantum information during the storage and retrieval process by performing quantum process tomography on our memory system. To this end, we store and retrieve four distinct input states, which are reconstructed with quantum state tomography. We calculate the process matrix and find a process fidelity of 87 %. We present the corresponding tomography data and compare the measurement results with the predicted outcomes. In addition, we investigate the dynamical behavior of our system with time-resolved tomography and a master equation approach.
The authors acknowledge support from DFG through FE 1564/1-1, the doctorate program ExQM of the Elite Network of Bavaria, the IMPRS 'Quantum Science and Technology', and the EU flagship project QMiCS.

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An engineered band-gap Josephson traveling wave parametric amplifier

L. Planat[1], K. Bharadwaj[1], O. Buisson[1], R. Dassonneville[1], F. Foroughi[1], W. Hasch-Guichard[1], S. Léger[1], C. Naud[1], J. Puertas-Martínez[1], and N. Roch[1]

[1] Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France
E-mail: nicolas.roch@neel.cnrs.fr

Josephson Parametric Amplifiers (JPA) are key to research fields involving microwave signals in the quantum regime, such as superconducting quantum bits or nano electromechanical systems. Their elementary building block, the Josephson junction, is at the same time strongly non-linear and non-dissipative. Therefore they provide both large gain [1,2] and noise performances close to the quantum limit [3,4]. To obtain reasonable gain (typically 20 dB), the interaction time between the weak signal, the strong pump and the non-linear medium must be maximized. Up to now, this interaction time was increased by coupling the Josephson element to a resonant cavity, but at the expense of a reduced bandwidth. Despite continuous improvement [5,6], these resonant amplifiers still display a bandwidth below 1 GHz.

Increasing this interaction time is also possible using distributed non-linear media, similar to nonlinear optical fibers, thus overriding the limitations due to resonant cavities. This new class of devices is called Josephson Traveling Wave Parametric Amplifier (J-TWPA). It requires long arrays of Josephson junctions, at least one thousand unit cells. Fabricating such amplifiers is now technically possible [7,8]. However, these traveling-wave amplifiers suffer from what is known as phase-matching issue: not only energy conservation must be fulfilled but k-vector (or equivalently propagating phase) must also be conserved.

Here we present a device, which solves this phase-matching problem. Contrary to previous implementations [7, 8], we engineer the non-linear medium by periodically modulating the size of the Josephson junctions of the array, leading to the opening of a gap in the dispersion relation. This gap allows compensating the k-vector dispersion (both due to linear and non-linear effects). Our device shows gain greater than 15 dB while having bandwidth larger than 3 GHz.

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Adiabatic quantum simulations with driven superconducting qubits

Gian Salis[1], Nikolaj Moll[1], Marco Roth[2], Sebastian Schmidt[3], Marc Ganzhorn[1], Daniel J. Egger[1] and Stefan Filipp[1]

[1]*IBM Research - Zurich, Rüschlikon, Switzerland*
[2]*Department of Physics, RWTH Aachen University, Germany*
[3]*Institute for Theoretical Physics, ETH Zurich, Switzerland*
E-mail: gsa@zurich.ibm.com

We propose a quantum simulator based on driven superconducting qubits where the interactions are generated parametrically by polychromatic magnetic flux modulation of a tunable bus element. In this system, local bias fields as well as XX- and YY-type interactions are independently tunable over a large parameter range. We discuss an analytical derivation of the multi-qubit effective interactions between the driven qubits and complement it with numerical simulations of an adiabatic protocol that calculates the ground state of a hydrogen molecule [1]. Further applications of this technique may be found in the simulation of interacting spin system. First experimental results of adiabatic simulations realized on two superconducting qubits and one tunable bus element are presented.

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Flux qubit measurement at the flux degeneracy point

M.Schöndorf[1], **A. Lupaşcu**[2] **and F. K. Wilhelm**[1]

[1]*Theoretical Physics, Saarland University, Saarbrücken, Germany*
E-mail: marius@lusi.uni-sb.de

[2]*Institute for Quantum Computing, University of Waterloo, Ontario, Canada*

The role of measurements is crucial for the realization of real world quantum computers. A promising candidate to deliver a platform to perform quantum algorithms are superconducting qubits. There are different types of these superconducting qubits, one of which is the flux qubit. The most robust point of flux qubits against environmental effects (e.g. 1/f noise) that decohere the qubits is the so called flux degeneracy point. Because of this property one wants to operate flux qubits at this specific point. However, performing a measurement that conserves the measured observable (QND measurement) is difficult here. Typical dispersive schemes induce a huge back action on the qubit.
Here we present an indirect measurement scheme where we first entangle the qubit states with pointer states of a quantum probe. The probe is a double SQUID loop with tunable gap, which we take as an advantage to effectively decouple the qubit and the probe before the actual macroscopic readout. We show that with this protocol we are able to read out the qubit state at the degeneracy point with high fidelity and almost no back action, yielding a QND measurement

Gap-independent cooling and hybrid quantum-classical annealing (HQCA)

L.S. Theis[1], P.K. Schuhmacher[2], M. Marthaler[1], and F.K. Wilhelm[1]

[1]Saarland University, Saarbrücken, Germany
E-mail: peter@lusi.uni-sb.de

We present an efficient gap-independent cooling scheme for a quantum annealer that benefits from finite temperatures[1]. We choose a system based on superconducting flux qubits as a prominent example of current quantum annealing platforms. We propose coupling the qubit system transversely to a coplanar waveguide to counter noise and heating that arise from always-present longitudinal thermal noise. We provide a schematic circuit layout for the system and show how, for feasible coupling strengths, we achieve global performance enhancements. Specifically, we achieve cooling improvements of about 50\% in the adiabatic and a few hundred percent in the non-adiabatic regime, respectively.

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Speeding-up the decision making of a learning agent using an ion trap quantum processor

T. Sriarunothai[1], S. Wölk[2,1], G. S. Giri[3,1], N. Friis[4,2], V. Dunjko[5,2,6], H. J. Briegel[2,7] and Ch. Wunderlich[1]

[1] *Experimental Quantum Optics, University of Siegen, Siegen, Germany*
[2] *Institute for Theoretical Physics, University of Innsbruck, Innsbruck, Austria*
[3] *Institute for Experimental Physics, Heinrich-Heine-University Düsseldorf, Düsseldorf, Germany*
[4] *Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Vienna, Austria*
[5] *LIACS, Leiden University, Leiden, The Netherlands*
[6] *Max Planck Institute of Quantum Optics, Garching, Germany*
[7] *Department of Philosophy, University of Konstanz, Konstanz, Germany*
E-mail: sriarunothai@physik.uni-siegen.de

We show a proof-of-principle experiment demonstrating the speed-up of the decision-making process within autonomous learning agents of the reinforcement learning paradigm. The experiment is implemented on a small-scale quantum processor based on trapped ions using MAgentic Gradient Induced Coupling. The decision-making process is presented by a system of two qubits, which is sufficient to perform a quadratic speed-up with respect to its classical counterpart. We demonstrate that the quantum agents take $O\left(\varepsilon^{-0.57(5)}\right)$ steps instead of $O\left(\varepsilon^{-1}\right)$, where ε represents the probability to sample a desired action in the probability distribution of the learning process. Our error model successfully describes a deviation of the measured results from the theoretical estimation. This proof-of-principle experiment highlights an application of quantum information processing in the field of artificial intelligence.

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Implementing the Variational Quantum Eigensolver with native 2-qubit interaction and error mitigation

T. Tsunoda[1], B. Vlastakis[1], A. Patterson[1], X. Yuan[2], S. Endo[2], J. Rahamim[1], P. Spring[1], M. Mergenthaler[1], M. Esposito[1], S. Jebari[1], K. Ratter[1], G. Tancredi[1], S. Benjamin[2], P. J. Leek[1]

[1]*Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*

[2] *Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, United Kingdom*

E-mail: takahiro.tsunoda@physics.ox.ac.uk

The variational quantum eigensolver (VQE) is an algorithm that may provide near-term applications of small-scale quantum computers, in quantum chemistry and optimisation problems. In order for the VQE to provide accurate solutions to problems on real devices, methods have been proposed recently to mitigate the errors caused by imperfect gates [1,2].

In this presentation, we report a quantum chemistry simulation using the VQE on a 2-qubit superconducting device [3] in which we use fixed frequency qubits and build the algorithm using the native 2-qubit interaction resulting from a static capacitive coupling. The hardware ansatz of the VQE is constructed by varying the timings of echo pulses to manipulate the native ZZ coupling. This method allows us to implement a VQE algorithm without needing repeated 2-qubit-gate tune-up, and enables simple and understandable implementation of error mitigation.

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Quantum neural networks and quantum reservoir computing for NISQ processors

G. Wendin

Microtechnology and Nanoscience — MC2,
Chalmers University of Technology, SE-41296, Gothenburg, Sweden

Small quantum computers and simulators are emerging: it is now possible to implement quantum algorithms and protocols on systems with 10-20 qubits [1], and operational "NISQ" systems [2] with 50-100 qubits will be available in the near future. Such systems form real-space physical qubit networks, and the gate operations create quantum-circuit networks in state (Hilbert) space. However, a major problem for quantum computing is decoherence and loss of entanglement. This means that the present applications of digital algorithms necessarily can only have low depth and a rather small number of gates.
It is then natural to investigate the computational power of complex dynamical quantum systems in a way similar to classical reservoir computing (RC) [3,4]. Quantum reservoir computing (QRC) may then be particularly useful for quantum information processing because loss of memory - fading memory - is a key RC resource, and there is no need for global control of the reservoir network. Present and emerging quantum hardware with limited coherence could be able to serve as a fading-memory reservoir for QRC. The field is just opening up, and there are so far only a few papers on the QRC topic [5-7]. These will be discussed and related to Mitarai et al. [8] who propose a hybrid classical-quantum algorithm for machine learning - quantum circuit learning (QCL) - that they suggest can provide an alternative to the Variational Quantum Eigensolver (VQE) and the Quantum Approximate Optimization Algorithm (QAOA).

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Optimal Control of Superconducting Qubits

M. Werninghaus[1], D. Egger[1], M. Ganzhorn[1], S. Machnes[2], F. Wilhelm-Mauch[2] and S. Filipp[1]

[1]*IBM Research, Zurich, Switzerland*
[2]*Saarland University, Saarbrucken, Germany*
E-mail: maw@zurich.ibm.com

Fast and accurate two-qubit gates are a key requirement to perform complex algorithms on current quantum computers. In contrast to error rates of 0.1% or less in single-qubit gates typical error rates of two-qubit gates are above 1% in superconducting qubit architectures. Here we focus on an exchange-type gate based on a parametrically driven tunable coupler [1]. Typical gate errors are less than 5% with a gate duration around 200 ns. For longer gates the error rate increases because of the short coherence times of the tunable coupler whereas shorter gates result in unwanted leakage out of the computational qubit space caused by transitions to higher qubit levels or directly to the coupler. The latter problem can be solved by optimal control theory. This method aims to design fast control pulses which suppress unwanted side effects of the driving field [2]. To accurately predict the dynamics of the experiment we must first identify all relevant parameters of the physical system and match them with the theoretical model. However, even with an accurately calibrated system model, control pulses require a tune-up to accommodate for parameter-drifts and -inaccuracies. Here we present our work on techniques to speed up calibration routines of control pulses defined by roughly up to 20 parameters. We use an active qubit reset protocol which enables us to achieve high repetition rates [3]. Additionally, we improve the interplay of control instruments and multidimensional optimization algorithms to reduce the effect of hardware constraints such as slow updates and limited number of quantum measurements to eventually realize efficient tune-up feedback loops.

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Optimal control pulses for a scalable quantum memory

N.Wittler[1], S. Machnes[1] and F. K. Wilhelm[1]

[1] *Theoretical Physics, Saarland University, Saarbrücken, Germany*
E-mail: niwitt@lusi.uni-sb.de

Achieving high fidelities for operations on systems with low anharmonicity and complex crowded spectra, such as transmon qubits [1], is in general required for scalable quantum technologies.

A promising implementation of a quantum memory for a transmon consists of using an electromagnetic mode of the 3D cavity that is already used for readout and control of the transmon, as shown in an experiment by Frank Deppe's group at WMI in Munich [2].

The read and write operations for this memory are exchanges of excitations between the qubit and cavity. In order to profit of the life time of the cavity state (T_1 = 9.5 µs, T_2 = 13 µs) compared to the transmon (T_1 = 1.4 µs, T_2 = 3.5 µs) [2], these gates must be fast and accurate. The high power needed to reach short gate times makes it necessary to control leakage out of the computational subspace into higher transmon states.

With theoretical pulse shaping techniques such as DRAG [3] and GOAT [4] that engineer the frequency spectrum of a control pulse, unwanted transitions can be suppressed and an increase in fidelity or shortening of the gate time can be achieved.

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Scalable surface-electrode trap for microwave near-field approach

G. Zarantonello[2,1], H. Hahn[2,1], T. Dubielzig[1], S. Grondkowski[1] ,M. Wahnschaffe[2,1], A. Bautista-Salvador[2,1] and C. Ospelkaus[2,1]

[1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany
[2]QUEST Institut für experimentelle Quantenmetrologie, Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
E-mail: zarantonello@iqo.uni-hannover.de

The current challenge for quantum information processing and quantum simulation is to increase the number of qubits that can be manipulated while maintaining high connectivity between the qubits themselves. Surface-electrode ion traps can potentially overcome these limits by emulating a charge-coupled device (CCD) [1, 2] architecture. In this configuration a trap would be divided in different zones with different designations, for example: loading, storing, single and multi-qubit operations. The use of microwave electrodes [3-6] can reach every part of a CCD architecture due to their integrated nature. In this poster we will present the latest result from our group for a single site trap [7, 8] where the microwave electrodes have been embedded into a 3D structure to generate the magnetic field gradient required to drive the spin-motional couplings necessary for performing entangling gate. This fabrication capability provides advantages in terms of trap scalability since it permits to have any kind of feedlines in different layers therefore avoiding crossing electrodes on the exposed trap surface. We will present the simulation and characterization of a three layer trap operated at room temperature with $^{9}Be^{+}$ ions located at 35 µm above the surface. In addition we will present our effort towards implementing entangling gates on a single layer trap with 70 µm ion electrode distance.

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