Advances in Scalable Hardware Platforms for Quantum Computing

737. WE-Heraeus-Seminar

11 - 13 January 2021
ONLINE

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 737. WE-Heraeus-Seminar:

Quantum computing is in the middle of the Noisy Intermediate-Scale Quantum (NISQ) computing era that is characterized by architectures that do not yet feature full error correction, but are already powerful enough to serve as a testbed for a wide variety of algorithms with potential scientific and commercial applications such as quantum chemistry or finance. Signatures of quantum advantage become already visible on first quantum processors, and several platforms are made available as cloud services that serve a fast-growing user community. The 737th WE-Heraeus Seminar on "Advances in 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. It will focus on recent hardware developments made in these fields in the business sector, which has grown rapidly in the recent past, and at university and government labs. The seminar furthermore aims to discuss advances in algorithms that make best use of the available quantum hardware on the path to identify promising fields of first quantum applications.

Introduction

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Program

Program

Monday, January 11, 2021

08:45 – 09:00	Stefan Filipp	**Kick-off scientific program**

Ion Traps (Chair: Stefan Filipp)

09:00 – 09:45	Rainer Blatt	**Quantum Computation and Quantum Simulation with Strings of Trapped Ca+ Ions**
09:45 – 10:30	Christopher Ballance	**Networking Trapped-Ion Quantum Computers**
10:30 – 10:45	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
10:45 – 11:00	*COFFEE BREAK*	

Spin Qubits in Quantum Dots (Chair: Andreas Fuhrer)

11:00 – 11:45	Hendrik Bluhm	**Asymmetric sensing dots – a scaling oriented approach to boost quantum dot qubit readout**
11:45 – 12:30	Andreas Kuhlmann	**Scalable silicon quantum computing**
12:30	*LUNCH*	

Quantum Theory and Applications (Chair: Frank Wilhelm-Mauch)

14:00 – 14:45	Christiane Koch	**Quantum optimal control for fast and accurate state preparation**
14:45 – 15:30	Stefan Woerner	**Towards Quantum Advantage in Finance**
15:30 – 15:45	*COFFEE BREAK*	

Program

Monday, January 11, 2021

Poster Session I

15:45 – 16:30	**Flash Talks**	
16:30 – 17:00	**Poster Session**	

Quantum Theory and Application (Chair : Frank Wilhelm-Mauch)

17:00 – 17:45	Harry Buhrmann	**Musings on the Future of Quantum Software**

Evening Lecture (Chair: Stefan Filipp)

17:45 – 18:30	Charlie Marcus	**Topological superconductivity in epitaxial superconductor-semiconductor-ferromagnetic materials**

Program

Tuesday, January 12, 2021

Ion Traps (Chair: Christopher Ballance)

08:30 – 09:15	Jonathan Home	**Quantum error correction of a logical qubit using autonomous dissipation**
09:15 – 10:00	Christof Wunderlich	**Trapped Ions and MAGIC for Quantum Computing**
10:00 – 10:15	*COFFEE BREAK*	

Superconducting Qubits (Chair: Per Delsing)

10:15 – 11:00	Andreas Wallraff	**tba**
11:00 – 11:45	John Martinis	**Quantum supremacy using a programmable superconducting processor**
11:45 – 12:30	Kuan Tan	**Towards scalable superconducting quantum computers: IQM's perspective**
12:30	*LUNCH*	

Control of Qubits (Chair: Hendrik Bluhm)

14:00 – 14:45	Hannes Töpfer	**Energy-efficient microelectronics using flux-quantum based information processing – current state-of-the-art and potential in Europe**
14:45 – 15:30	Edoardo Charbon	**Cryo-CMOS Electronics for Quantum Computing**
15:30 – 15:45	*COFFEE BREAK*	

Tuesday, January 12, 2021

Poster Session II

15:45 – 16:30	**Flash talks**
16:30 – 17:00	**Poster session**

Superconducting Qubits (Chair: Mikko Möttönen)

17:00 – 17:45	Jonas Bylander	**Ubiquitous TLS fluctuations, and a depth-2 implementation of QAOA**
17:45 – 18:30	William Oliver	**Quantum Engineering of Superconducting Qubits**

Program

Wednesday, January 13, 2021

Quantum Theory (Chair: Stefan Wörner)

09:15 – 10:00	Chiara Macchiavello	**Hypergraph states in quantum computing**
10:00 – 10:45	Barbara Terhal	**Stoquastic Hamiltonians in Circuit-QED**
10:45 – 11:00	*COFFEE BREAK*	

Poster Session III

11:00 – 11:45	**Flash talks**	
11:45 – 12:30	**Poster session**	
12:30	*LUNCH*	

Spin Qubits (Chair: Maude Vinet / Andreas Fuhrer)

14:00 – 14:45	Romain Maurand	**Scaling spin-based silicon quantum computing using CMOS technology: electron and hole quantum dots**
14:45 – 15:30	Lieven Vandersypen	**Scaling up semiconductor spin qubits**
15:30 – 16:15	Jason Petta	**Towards high fidelity quantum gates in silicon quantum dot arrays**
16:15 – 16:30	Scientific organizers	**Closing remarks and poster awards**

End of seminar

Posters

Posters

Poster Session 1 / Monday, Jan. 11 / 15:45 – 17:00 h (15 Posters)

P01	Ondrej Cernotik	**Microwave entanglement created using swap gates with biased noise**
P02	Ivari Pietikäinen	**Microwave swap gates with a Kerr-cat ancilla**
P03	Yuki Nojiri	**Time-Resolved Quantum Process Tomography in the Compact 3D Quantum Memory**
P04	Max Werninghaus	**Optimal Control of Superconducting Qubits**
P05	Gaurav Bhole	**Rescaling Interactions for Quantum Control**
P06	*(Cancelled at short notice)*	
P07	Tobias Hangleiter	**Filter Function Formalism for Quantum Operations**
P08	Ashish Mani	**Towards quantum evolutionary search and optimization on NISQ devices**
P09	Göran Wendin	**Benchmarking the Variational Quantum Eigensolver for Quantum Chemistry on High-Performance Computers**
P10	*(Cancelled at short notice)*	
P11	Rebekka Garreis	**Charge detection in electrostatically defined quantum dots in bilayer graphene**
P12	Chuyao Tong	**Tunable Valley Splitting in Bilayer Graphene Quantum Dots**

P13	Amin Hosseinkhani	**Theory of valley splitting and valley-induced relaxation of a single silicon spin qubit in the presence of interface disorder**
P14	Riccardo Borgani	**Adapting 5G-telecom hardware for the control of quantum computers**
P15	Seref Kalem	**Silicon quantum pillars for possible scalable HW platforms**
P16	Mats Tholén	**General-Purpose firmware for controlling quantum processors**
P17	Robert Gartmann	**Highly integrated RF electronics to interface superconducting qubits**

Poster Session 2 / Tuesday, Jan. 12 / 15:45 – 17:00 h (18 Posters)

P01	Daniel Jirovec	**A depletion mode hole spin-qubit in Ge**
P02	Theodor Lundberg	**Accurate Readout of Spin States in Silicon Nanowire Quantum Dots**
P03	Andras Palyi	**Charge noise and overdrive errors in reflectometry-based qubit readout**
P04	Adrien Morel	**Cryogenic current-steering DAC for biasing of quantum dots**
P05	Réouven Assouly	**Number-resolved photocounter for propagating microwave mode**
P06	Michael Renger	**Beyond the standard quantum limit of parametric amplification**
P07	Clemens Müller	**Quantum rifling - Protecting a qubit from measurement back action**
P08	Mikko Möttönen	**Radio frequency quantum-circuit refrigerator and the resulting photon-number-dependent Lamb shift**
P09	Jeremy Stevens	**Cavity-photon induced state transitions in a coupled Fluxonium qubit system**
P10	Florentin Reiter	**Parametric dissipation engineering for quantum information processing**
P11	Federico Roy	**Control, Calibration and Characterization of superconducting qubits**
P12	Richard Gebauer	**Integrated scalable electronics platform to interface superconducting qubits**

Posters

P13	Oliver Sander	**Partitioning of functionality for superconducting qubit control and readout**
P14	Camille Chartrand	**A silicon-integrated telecommunications photon-spin interface**
P15	Albert Hertel	**Electrical properties of selective area grown superconductor-semiconductor hybrid structures on silicon**
P16	Matthias Rößler	**Top-down Topological Insulator Nanowires for Majorana-Qubits**
P17	Rubén Seoane Souto	**Optimal manipulation of Majorana bound states using quantum dots**
P18	Manohar Kumar	**Anyonic statistics in collider geometry**

Posters

Poster Session 3 / Wednesday, Jan. 13 / 11:00 – 12:30 h
(17 Posters)

P01	Janine Hilder	**A shuttling-based trapped-ion quantum information processing node**
P02	Christian Melzer	**Control Software Stack for Shuttling-Based Trapped-Ion Quantum Computing**
P03	Daniel Wessel	**Components for scalable quantum logic with trapped ions**
P04	Matthias Mergenthaler	**Effects of surface treatments and packaging on transmon qubits**
P05	Uwe von Lüpke	**Flip chip technique for hybrid quantum systems**
P06	Martin Weides	**Coherent superconducting qubits from a subtractive junction fabrication process**
P07	Benedikt Kratochwil	**The CQ3 Qubit spectroscopy and coherence**
P08	Jacob Koenig	**Selectively Activated Photon-Hopping, Cross-Kerr, and Two-Mode Squeezing via Flux Modulation of a Tunable Coupler**
P09	Benjamin Schiffer	**Faster adiabatic ground state preparation with few measurements**
P10	Nicolas Wittler	**An integrated tool-set for Control, Calibration and Characterization of quantum devices applied to superconducting qubits**
P11	Xiaosong Ma	**An integrated heterogeneous superconducting-silicon-photonic platform for quantum network**

photonic platform for quantum network

P12	Hugo Doeleman + Tom Schatteburg	**Towards quantum optomechanics using bulk acoustic wave resonators**
P13	Tomas Ramos	**Scalable multiphoton generation from cavity-synchronized single-photon sources**
P14	Rene Otten	**Scalable Cryogenic Control of Spin qubits**
P15	Florian Ginzel	**Spin shuttling in a silicon double quantum dot**
P16	Cécile Yu	**High-Impedance NbN Microwave Resonator as a Quantum Bus for Si Hole Spin Qubits**
P17	Jann Hinnerk Ungerer	**Engineering of a semiconductor charge qubit coupled to a resonator – From coherence protection to ultrastrong coupling**

Abstracts of Lectures

(in alphabetical order)

Networking Trapped-Ion Quantum Computers

C. Ballance[1]

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Experiments on small numbers of trapped-ion qubits are approaching the error-rate needed for large scale computation. The challenge to building a large-scale quantum computer out of trapped ions is maintaining these low error rates as many more qubits are added.

A naive approach to scaling to large numbers of qubits is to simply use ever larger crystals of ions. However, due to spectral crowding, as the ion number increases it rapidly becomes difficult to precisely control the quantum state of the system. The approach we are pursuing is to instead quantum-optically network many smaller trapped-ion quantum processors. In this networked architecture, one makes each network 'node' as powerful as easily possible, then scales to a large number of qubits by networking many identical nodes.

Here we present results from a two-node networked quantum processor [1], and demonstrate the ingredients required to purify the photonically distributed entanglement using only zone-global operations [2].

References

[1] L. J. Stephenson, Phys. Rev. Lett. **124**, 110501 (2020)
[2] R. Nigmatullin et al., New J. Phys. **18**, 103028 (2016)

Quantum Computation and Quantum Simulation with Strings of Trapped Ca^+ Ions

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The state-of-the-art of the Innsbruck trapped-ion quantum computer is briefly reviewed. We present an overview on the available quantum toolbox and discuss the scalability of the approach. Fidelities of quantum gate operations are evaluated and optimized by means of cycle-benchmarking [1] and we show the generation of entangled states with fully controlled strings of 20 to 50 ions [2], which are used for quantum simulations.

In the second part, we present both the digital quantum simulation and a hybrid quantum-classical simulation of the Lattice Schwinger model, a gauge theory of 1D quantum electrodynamics. Employing universal quantum computations, we investigate the dynamics of the pair-creation [3] and using a hybrid-classical ansatz, we determine steady-state properties of the Hamiltonian. Hybrid classical-quantum algorithms aim at solving optimization problems variationally, using a feedback loop between a classical computer and a quantum co-processor, while benefitting from quantum resources [4]. With randomized measurements, we describe a protocol for cross-platform verification of quantum simulators and quantum computers [5].

[1] A. Erhard et al., Nat. Commun. **10**, 5347 (2019)
[2] N. Friis et al., Phys Rev **X 8**, 021012 (2018)
[3] E. A. Martinez et al., Nature **534**, 516 (2016)
[4] C. Kokail et al., Nature **569**, 355–360 (2019)
[5] A. Elben et al., Phys. Rev. Lett. **124**, 010504 (2020)

Asymmetric sensing dots – a scaling oriented approach to boost quantum dot qubit readout

Lars Schreiber[1], Dominique Bougeard[2], H. Bluhm[1]

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[2] *Institut für Experimentelle und Angewandte Physik, Universität Regensburg, Regensburg, Germany*

For scalable quantum computing, high fidelity readout with a short integration time is highly desirable. For qubits based on semiconductor quantum dots, charge sensing is widely adopted. The best sensitivity to date is achieved with readout quantum dots operated as single electron transistors in combination with RF reflectometry and cryogenic amplification. However, such a readout chain requires bulky, power-hungry components and is thus not ideal to scaling up. Dispersive gate readout enables a simpler device layout without sensing dot, but is less sensitive and thus further increases the requirements for the amplification chain.
An arguably more scalable alternative is to use a baseband amplifier placed close to the qubit. For best performance and lowest power consumption, a high output swing of the charge sensor is then desirable. We have developed a sensing dot design termed “asymmetric sensing dot” (ASD) whose drain potential is shaped such that the drain-dot capacitance is strongly reduced, which enhances the achievable output swing by suppressing negative feedback.
Transport measurements on a GaAs-based device show a tenfold reduction of the dot-drain capacitance and a factor 15 increase in the sensor response. When used as a current biased charge sensor, it provides an output swing of more than 2 mV for the (1,1)→(2,0) charge transition of a nearby double quantum dot. This opens up the possibility to use very simple, low power amplifiers as first readout amplification stage. We also demonstrate a realization in a Si/SiGe device.

Furthermore, I will present charge noise measurements on a Si/SiGe qubits which exhibit excess low frequency noise compared to an extrapolation of the 1/f like spectrum found above about 1 Hz [1]. These results show that very low frequencies need to be considered very carefully when assessing the impact of qubit recalibration intervals on qubit fidelity.

References

[1] T. Struck, npj Quantum Information **6**, 40 (2020)
[2] See quantuminfo.physik.rwth-aachen.de/code for our open source software packages for qubit control and simulation.

Musings on the Future of Quantum Software

Harry Buhrmann

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Quantum computers promise to have a great impact on how we do information processing tasks. The extra power comes the quantum mechanical effects of superposition, interference, and entanglement.
Quantum computers require a fundamentally different hardware. The basic building block is a the qubit and operations on these qubits are fundamentally different from the operations that one performs on classical bits. Hence the software that runs on quantum computers is also fundamentally different from the way we are used to program computers. A major driving (research) question is the following: For which computational problems does a quantum computer have an advantage and how big is that advantage? This question is deeply intertwined with fundamental questions in computer science and only a partial answer has been found so far.

Recent years has seen great progress in the fabrication of reasonably stable qubits: 50-100 qubits are available now, with a projected growth to a 1000 qubits within the next 5 years. These qubits however are physical qubits that deteriorate and decohere over time. It is known that error correction in combination with fault tolerant computation offer a solution to this decoherence problem. However, this comes at a the price of using a multitude of physical qubits to implement a single stable or logical qubit. This overhead is at the moment and in the near future prohibitively large. We therefore have to develop applications for quantum computers that have a relatively large amount of qubits that decohere over time. I will describe what the impact of the above considerations is on the design of quantum algorithms.

Ubiquitous TLS fluctuations, and a depth-2 implementation of QAOA

Jonas Bylander

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Wallenberg Center for Quantum Technology

All modern superconducting quantum circuits suffer from both decoherence and parameter fluctuations. A significant part of this noise originates in two-level-system (TLS) defects that reside within the device dielectrics. The characterization and mitigation of TLS is a prerequisite for building larger-scale quantum processors with high-fidelity gates and manageable tune-up routines.

We have performed a thorough characterization of qubit relaxation, resonator Q, and frequency fluctuations. In this talk I will present the new insights that we have gained into the behavior of these TLS, including motional narrowing of resonator frequency fluctuations due to the driving of Landau-Zener transitions and universal scaling independent of material (Al and NbN) and geometry (superinductor, coplanar, and cavity resonator).

I will also show high-fidelity two-qubit gates enabling us to implement the QAOA algorithm up to a circuit iteration level of depth 2, as well as recent progress toward developing a superconducting quantum processor.

This work is part of the quantum computer efforts within the Wallenberg Center for Quantum Technology in Sweden and also within the OpenSuperQ project of the EU Flagship program on Quantum Technology.

References

[1] D. Niepce, J. Burnett, M. Kudra, J. H. Cole, and J. Bylander, "Stability of superconducting resonators: motional narrowing and the role of Landau-Zener driving of two-level defects," arxiv:2008.07038 (2020)

[2] A. Osman, J. Simon, A. Bengtsson, S. Kosen, P. Krantz, D. Perez, M. Scigliuzzo, J. Bylander, and A. Fadavi Roudsari, "Simplified Josephson-junction fabrication process for reproducibly high-performance superconducting qubits," arXiv:2011.05230 (2020)

[3] A. Bengtsson, P. Vikstål, C. Warren, M. Svensson, X. Gu, A. Frisk Kockum, P. Krantz, C. Križan, D. Shiri, I.-M. Svensson, G. Tancredi, G. Johansson, P. Delsing, G. Ferrini, and J. Bylander, "Improved success probability with greater circuit depth for the quantum approximate optimization algorithm," Phys. Rev. Appl. **14**, 034010 (2020)

[4] D. Niepce, J. Burnett, M. Gutierrez Latorre, and J. Bylander, "Geometric scaling of two-level-system loss in superconducting resonators," Supercond. Sci. Technol. **33**, 025013 (2020)

[5] J. J. Burnett, A. Bengtsson, M. Scigliuzzo, D. Niepce, M. Kudra, P. Delsing, and J. Bylander, "Decoherence benchmarking of superconducting qubits," npj Quantum Inf. **5**, 54 (2019)

[6] D. Niepce, J. Burnett, and J. Bylander, "High kinetic inductance NbN nanowire superinductance," Phys. Rev. Appl. 11, 044014 (2019)

Cryo-CMOS Electronics for Quantum Computing

Edoardo Charbon

EPFL, AQUA, Neuchatel, Switzerland

An array of qubits, at the core of a quantum computer, needs to be controlled and read out by a classical processor operating on the qubits by means of radio-frequency signals with nanosecond latency, several millions of times per second. Due to the extremely weak signals involved in the process, ultra-low-noise, highly sensitive circuits and systems are needed, along with very precise timing capability. We advocate the use of CMOS technologies to achieve these goals, whereas the circuits will be operated at deep-cryogenic temperatures. We believe that these systems, collectively known as cryo-CMOS control, will make qubit arrays scalable, enabling a faster growth of the qubit count. In the talk, the challenges of designing and operating complex circuits and systems at 4K and below will be outlined, along with preliminary results achieved in the control and read-out of qubits by *ad hoc* integrated circuits that were optimized to operate at low power in these conditions. The talk will conclude with a perspective on the field and its trends.

Quantum error correction of a logical qubit using autonomous dissipation

B. deNeeve, T-L. Nguyen, T. Behrle, K. Mehta, M. Malinowski, C. Zhang, M. Stadler, S. Jain, J. Alonso, M. Grau and J. Home[1,2]

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[2] *Quantum Center, ETH Zürich, Switzerland*

Quantum error correction is key to realizing large-scale quantum computers. Storing information in continuous variables provides a means for implementing quantum error correction in single physical systems. I will describe stabilization of a logical qubit encoded in a trapped-ion oscillator using the Gottesman-Preskill-Kitaev “grid” state encoding. We introduce measurement variables which account for the finite extent of our code states, and then use this to construct a two-step dissipative map which corrects errors. We achieve an extension of coherence of a factor of 3.4 over all logical variables [1]. I will also provide an overview of recent results towards scaling ion trapped systems up, including multi-qubit gates implemented using integrated waveguide optics [2], and 2-dimensional arrays of ions in Penning traps [3].

References

[1] B. deNeeve, T-L Nguyen, arXiv:2010.09681 (2020)
[2] K. Mehta et. al. Nature 586, 7830 (2020)
[3] S. Jain et al. PRX 10,3 (2020)

Quantum optimal control for fast and accurate state preparation

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Fast and accurate state preparation is a key challenge in scalable hardware platforms, in some cases presently limiting device operation clock speed. In this talk, I will show how to use the quantum optimal control toolbox to address this challenge from both a fundamental and a practical point of view. Fundamentally, quantum optimal control allows us to identify bounds on the minimal duration and maximal fidelity for resetting a qubit when coupling it to an ancilla to export entropy. Remarkably, we find the minimum duration to depend on the qubit-ancilla coupling and the maximal fidelity to depend on the dimension of the ancilla Hilbert space [1]. Practically, quantum optimal control allows us to derive pulse shapes that implement fast state preparation to the desired accuracy, as demonstrated in a recent experiment with Rydberg atoms [2]. I will discuss how to adapt these concepts to state preparation for cat codes in superconducting circuits-based platforms.

References

[1] D. Basilewitsch, J. Fischer, D.M. Reich, D. Sugny, C.P. Koch, arXiv:2001.09107

[2] A. Larrouy, S. Patsch, R. Richaud, J.-M. Raimond, M. Brune, C.P. Koch, S. Gleyzes, Physical Review X **10**, 021058 (2020)

Scalable silicon quantum computing

S. Geyer[1], L. C. Camenzind[1], M. de Kruijf[1], L. Czornomaz[2], V. Deshpande[2], A. Fuhrer[2], R. J. Warburton[1], D. M. Zumbühl[1] and A. V. Kuhlmann[1,2]

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A worldwide effort is currently underway towards constructing a full-scale quantum computer that exploits quantum-mechanical phenomena, like superposition and entanglement, to perform computations. The basic building block of a quantum computer is represented by the qubit, which is the quantum analogue of a classical bit. Qubits are defined by quantum two-level systems that can be realized with different physical systems. In 1998, Loss and DiVincenzo [1] proposed to encode quantum information in the spin state of a single electron or hole confined to a semiconductor quantum dot [2,3]. This approach promises a high density integration of fast and coherent qubits that can be controlled by purely electrical means.

Silicon is a particularly promising material platform for scalable spin-based quantum computing because of its fully developed, industrial manufacturing processes, which enable reliable and reproducible fabrication at the nanometer scale. Furthermore, natural silicon consists of 95% nonmagnetic nuclei and a nearly nuclear-spin-free environment, suppressing hyperfine-induced decoherence, can be engineered by means of isotopic purification [4].

We integrate tunable double quantum dots in silicon fin field-effect transistors with two layers of gate electrodes [5,6]. In this talk, I will discuss how we implement a multi-layer gate stack using self-alignment, and demonstrate the great potential of self-aligned gates for integrating spin-based multi-qubit devices. In addition, I will present all-electrical control of a fast and coherent hole spin qubit (coherence time $T_2^* \sim 200$ ns, Rabi frequency $f_{Rabi} \sim 50$ MHz) at "ultra-hot" operation temperatures (T>4K). These results demonstrate that hole spins in silicon are prime candidates for scaling up quantum circuits

References

[1] D. Loss and D. P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).
[2] C. Kloeffel and D. Loss, Annu. Rev. Condens. Matter Phys. **4**, 51 (2013).
[3] R. Hanson et al., Rev. Mod. Phys. **79**, 1217 (2007).
[4] M. Veldhorst et al., Nat. Nanotechnol. **9**, 981 (2014).
[5] A. V. Kuhlmann et al., Appl. Phys. Letts. **113**, 122107 (2018).
[6] S. Geyer et al., arXiv:2007.15400 (2020).

Quantum supremacy using a programmable superconducting processor

John Martinis

Google and UCSB, USA

The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here we report the use of a processor with programmable superconducting qubits to create quantum states on 53 qubits, corresponding to a computational state-space of dimension 2^53 (about 10^16). Measurements from repeated experiments sample the resulting probability distribution, which we verify using classical simulations. Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years. This dramatic increase in speed compared to all known classical algorithms is an experimental realization of quantum supremacy for this specific computational task, heralding a much-anticipated computing paradigm.

Scaling spin-based silicon quantum computing using CMOS technology: electron and hole quantum dots

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Silicon spin based quantum computing hardware appears as a promising approach to build a quantum processor: thanks to the size of the qubits, the quality of the demonstrated quantum gates as well as the VLSI ability to fabricate billions of closely identical objects. Even if the quality of silicon spin qubits has improved very fast during the past eight years thanks to material and technology developments, the way towards scalability present many hardware open questions on qubit architecture, qubit readout and cryogenic electronics for control. Here we will first present the joined effort of the Quantum Silicon Grenoble laboratories working around fully-depleted silicon-on-insulator (FDSOI) technology going from CryoCMOS electronics to packaging. Then we will focus on recent measurements on FDSOI electron or hole based spin qubits going from double dot device [1,2] to small two-dimensional arrays [3].

References

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Quantum Engineering of Superconducting Qubits

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Quantum computers are fundamentally different than conventional computers. They promise to address problems that are practically prohibitive and even impossible to solve using today's supercomputers. The challenge is building one that is large enough to be useful. In this talk, I will discuss aspects of engineering high-performance superconducting qubits, with an eye toward extensible applications. After a brief introduction to superconducting qubits [1] and 3D integration of high-fidelity devices [2], I will discuss the impact of ionizing radiation on qubit performance [3], and (time permitting) experimental results of waveguide quantum electrodynamics with giant artificial atoms [4].

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Towards high fidelity quantum gates in silicon quantum dot arrays

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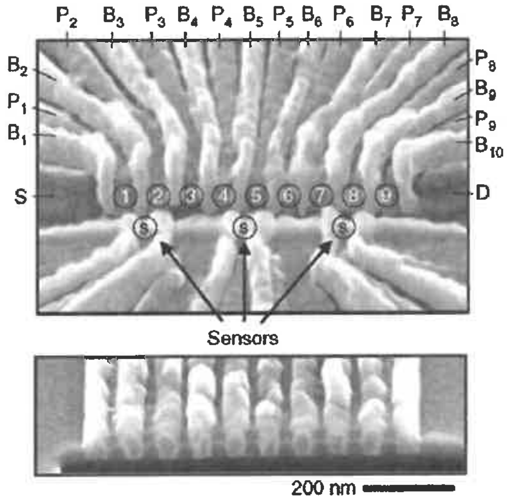
Intense research on electron spin qubits defined in silicon quantum dots has led to increasingly impressive levels of quantum control, with recent demonstrations of >99.9% single qubit gate fidelities and >90% two-qubit gate fidelities. Progress has been fueled by an investment in high quality Si/SiGe heterostructures, coupled with the advent of accumulation-mode device designs that are less sensitive to disorder and enable fine control over quantum dot electrons. At Princeton, we have developed a device architecture that allows for the scalable fabrication of one-dimensional silicon spin qubit arrays [1,2]. Devices fabricated on isotopically enriched ^{28}Si quantum wells allow for high fidelity control of four individually addressable spin qubits. Single qubit gate fidelities exceed 99.9% and we demonstrate ac-driven SWAP gates to transfer spin eigenstates with a fidelity of 98% [3]. The high degree of control offered by the device design allows for the transfer of a single electron across a linear array of nine quantum dots in ~50 ns. With more complex control sequences we perform parallel shuttling of two and three electrons through the array [4]. As a demonstration of automated tuning of dot arrays, we use an image analysis toolbox to automate the calibration of virtual gates in these devices [5].



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Towards scalable superconducting quantum computers: IQM's perspective

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In this talk, we will present the recent updates on the technological development at IQM Quantum Computers in developing scalable superconducting quantum processors. We will discuss our approach towards reducing the clock cycle of the quantum processor through faster reset, gating, and readout. In particular, we will describe the concept of using a quantum-circuit refrigerator (QCR) as a tunable dissipation in the qubit environment, and how it could be utilized to reset the qubit unconditionally to the ground state. We will then present our latest experimental results in qubit reset with the QCR, and ways to improve undesired dissipation in the system. On the broader scope, we will also present our results in qubit and quantum processor development.

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Stoquastic Hamiltonians in Circuit-QED

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Quantum computational physics and quantum complexity theory aim at simulating quantum physical systems effectively or capturing the computational hardness of quantum physical problems. An important class of possibly 'easier' problems are quantum systems without a sign problem, sometimes referred to as stoquastic Hamiltonians. We discuss whether Hamiltonian descriptions of superconducting qubit devices, in particular of coupled flux qubits, do or do not have a sign problem and the computational consequences thereof for a task such as quantum annealing.

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Energy-efficient microelectronics using flux-quantum based information processing – current state-of-the-art and potential in Europe

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One of the options for realizing microelectronics with very low power consumption is given by the Rapid Single Flux Quantum (RSFQ) technique [1,2]. Although the energy consumption per logical switching is very low – typically in the range of 10^{-19} J and thus lower than the "ultimate CMOS" projections at the limits of scaling [3] – the operation speed can be quite high, allowing circuits to be operated at tens of GHz clock speed. The realization of RSFQ integrated circuits and systems based on this principle is reported by various sites.
After a brief introduction in the operation of RSFQ electronics, the current state of engineering such circuits in Europe / Germany is described. In particular, capabilities of modeling, simulation, and implementation will be addressed. Examples of realizations and practical use cases illustrating the current state-of-the-art will be given. Furthermore, the current understanding and possibilities of systematic design of such circuits from single gates / cells towards systems as well as the connection to fabrication processes will be discussed. After some remarks on the existing European collaboration network, an assessment on already known and potential limits, resulting research topics to overcome them and – based on this – the prospective level of integration, i.e. the suitability of RSFQ as a scalable hardware platform for quantum information systems will be given.

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Scaling up semiconductor spin qubits

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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 create local registers of increasing numbers of spin qubits with sufficient control that we can program arbitrary sequences of operations. Furthermore, in close collaboration with Intel, we have fabricated and measured quantum dot qubits using all-optical lithography on 300 mm wafer, using industry-standard processing. This industrial approach to nanofabrication will be critical for achieving the extremely high yield necessary for devices containing hundreds or thousands of qubits. Second, we explore the coherent coupling of spin qubits at a distance via two routes. In the first approach, the electron spins remain in place and our coupled via superconducting resonator. In the second approach, spins are shuttled along a quantum dot array, preserving both the spin projection and spin phase. Third, we work towards the integration of quantum bits and classical electronics on the same chip or package, where qubits are operated above 1 K and the electronics is designed for cryogenic operation. 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.

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Towards Quantum Advantage in Finance

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Quantum computing promises unprecedented computational capabilities for many industries and science. In this talk, we discuss potential applications of quantum computing in the financial service sector, their expected quantum advantage as well as hardware requirements. Applications range from fraud detection, to portfolio management, to risk analysis and pricing [1].
Quantum computing has the potential to increase accuracy and performance in machine learning and optimization [2, 3], which may lead, for instance, to reduced cost, improved customer satisfaction, increased returns. In addition, it may allow unprecedented speed and accuracy for Monte Carlo simulation [4, 5, 6], as used for risk analysis and pricing, enabling new financial products and services and lower capital requirements.
We discuss the different quantum algorithms applicable to such problems, analyze their requirements on quantum hardware for real-word applications, and discuss what kind of quantum advantage to be expected. First applications may benefit already from near-term quantum computers. Future progress in hardware and algorithms will continue to significantly broaden the spectrum of applications.

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Trapped Ions and MAGIC for Quantum Computing

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Trapped atomic ions are an advanced physical system for quantum information processing with well-established methods for preparation and read-out of qubits and for quantum gates, all with high fidelity. When scrutinizing the scalability of this system, it is evident that the use of laser light for coherent operations gives rise to technological issues, and to challenges rooted in the physics of trapped ions. Suitably modified ion traps allow for magnetic gradient induced coupling (MAGIC) [1], such that laser light can be replaced by radio-frequency (RF) radiation, thus avoiding numerous potential sources of error. It has been demonstrated that the MAGIC scheme, in addition, allows for unprecedented low cross-talk between qubits [2], advantageous connectivity, and on-the-fly conversion between qubits that can serve as quantum memory or processor, respectively [3].

Using trapped $^{171}Yb^{+}$ ions and MAGIC, we have implemented a freely programmable quantum computer with a few qubits: We showed that the deliberation process in the framework of reinforcement learning can be sped up on a quantum computer [4] employing an algorithm of computational depth up to 43. Here, we report on experimental progress in realizing novel types of 2-qubit RF quantum gates. In particular, (fast) 2-qubit RF quantum gates that are robust against variations in the secular trap frequency, motional excitation (varied by RF sideband cooling), and Rabi frequency are demonstrated. In future traps such gates will increase the speed as well as the fidelity of multi-qubit RF gates. Furthermore, the gate fidelity is enhanced by precisely tracking the ions' qubit resonances.

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Abstracts of Posters

(in alphabetical order)

Number-resolved photocounter for propagating microwave mode

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The first detectors of propagating microwave photons have been realized using superconducting circuits a decade ago[1]. However a number-resolved photocounter is still missing. We demonstrate a single-shot counter for propagating microwave photons that can resolve up to 3 photons. It is based on a pumped Josephson Ring Modulator that can catch an arbitrary propagating mode by frequency conversion and store its quantum state in a stationary memory mode. A transmon qubit then counts the number of photons in the memory mode using a series of binary questions. Using measurement based feedback, the number of questions is minimal and scales logarithmically with the maximal number of photons. The detector features a detection efficiency of 0.96 ± 0.04, and a dark count probability of 0.030 ± 0.002 for an average dead time of 4.5 µs. To maximize its performance, the device is first used as an in situ waveform detector from which an optimal pump is computed and applied. Depending on the number of incoming photons, the detector succeeds with a probability that ranges from 54 ± 2 % to 99 %.[2]

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Rescaling Interactions for Quantum Control

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A powerful control method in experimental quantum computing is the use of spin echoes, employed to select a desired term in the system's internal Hamiltonian, while refocusing others. Here, we address a more general problem, describing a method to not only turn on and off particular interactions but also to rescale their strengths so that we can generate any desired effective internal Hamiltonian. We propose an algorithm based on linear programming for achieving time-optimal rescaling solutions in fully coupled systems of tens of qubits, which can be modified to obtain near-time-optimal solutions for rescaling systems with hundreds of qubits. Further, we propose an analytic method based on graph colouring to address the rescaling problem in systems with any number of qubits, however, with only nearest/next-nearest neighbour couplings.

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Adapting 5G-telecom hardware for the control of quantum computers

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An important figure of merit for scalable quantum-computing technology is the cost per channel per MHz of bandwidth of its classical control electronics. Fortunately, there is a major market force pushing this cost down as digital wireless telecom and the control of quantum computers both share many of the same technical requirements. Some of these requirements are: multiple channels of wide-band signal output and input, with all channels sharing a common phase reference; low noise and low distortion or highly linear signal analysis with good isolation or low cross-talk between channels; easy to reconfigure and field-programmable, with high-speed logic for feedback and feed-forward control.

These requirements have driven the development of a new series of radio-frequency system-on-a-chip (RFSoC) devices from Xilinx. Released in 2020, the third generation of Zynq UltraScale+ RFSoC devices allows for direct digital synthesis and sampling of signals up to 6 GHz, without external analog mixers. With 16 channels of input and output coupled to one very large field programmable gate array, these circuits allow for multiple, synchronous signal generation and readout at a cost well below $1.00 / channel / MHz.

We have successfully adapted a Gen3 RFSoC platform for the characterization and control of superconducting qubit circuits. We describe the hardware modifications and firmware extensions needed for this adaptation. We demonstrate the use of our platform in characterizing a superconducting qubit.

Microwave entanglement created using swap gates with biased noise

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Bosonic codes provide an interesting approach to fault-tolerant quantum computing. By redundantly encoding a quantum bit into the infinite Hilbert space of a harmonic oscillator, the stored information can be naturally protected against decoherence. Each of the existing bosonic codes needs a set of quantum gates allowing full control of individual qubits and efficient interactions between them. Swap-based gates are a particularly attractive class as they can operate on any two qubits irrespective of encoding but their performance is so far limited by noisy transmon ancillas. Here, we show that swap gates with ancillas exhibiting biased noise can be used to efficiently generate and verify entanglement between two microwave fields. The ancilla qubit—encoded as a Kerr cat—suffers from phase flips but is protected from bit flips which helps to create strong entanglement between the microwave fields as we show for the particular example of coherent states. With all necessary ingredients readily available, experimental realization of our proposal is within reach of existing technology. With the progress in manipulation of bosonic qubits, our work presents an important step towards scaling these systems up in a hardware-efficient and error transparent manner.

A silicon-integrated telecommunications photon-spin interface

C. Chartrand[1], L. Bergeron[1], A. T. K. Kurkjian[1], K. J. Morse[1], H. Riemann[2], N. V. Abrosimov[2], P. Becker[3], H.-J. Pohl[4], M. L. W. Thewalt[1] and S. Simmons[1]

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Robust quantum memories with photonic coupling are instrumental to the development of the future quantum internet. A spin-photon interface fulfills both those requirements, but to be useful, such an interface needs to be embedded in a scalable platform. Silicon stands out as a mature hardware platform for integrated electronics and photonics applications. Moreover, isotopically purified silicon is an excellent quantum host material that has underpinned a variety of record-breaking quantum lifetime demonstrations. Yet to date, silicon had the reputation of lacking fast, efficient, and spin-active optical emitters in the technologically advantageous telecommunication bands that could be easily coupled to integrated photonic structures.

Our recent investigation into the optical and quantum properties of the T radiation damage centre in isotopically purified silicon reveals that it is a sub-us optical emitter in the telecommunications O-band, with 33(2) MHz ensemble optical linewidth at 1.5K, as well as spin states with electronic and nuclear coherence times of at least 2.1 ms and 1.1 s, respectively [1]. This work is a significant step towards the realization of a scalable, all-silicon quantum computing and communication platform capable of providing spin-entangled single photons and spin-selective optical interactions.

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Towards quantum optomechanics using bulk acoustic wave resonators

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Superconducting circuits are one of the most sophisticated architectures for quantum information processing to date. Their operation at microwave (MW) frequencies, however, confines these circuits to the base stages of dilution refrigerators. MW-to-optical conversion in the quantum regime could enhance the scalability and range of applications of superconducting circuits, since optical photons can be used as noise-free carriers of quantum information that connect circuits in different refrigerators. This requires a conversion process that is coherent, efficient, and with minimal added noise, which has not been demonstrated yet.

We present our advances in developing a cryogenic cavity optomechanical device based on a bulk-acoustic-wave (BAW) mechanical resonator, which can act as an essential part of a MW-to-optical transducer. Strong coupling to BAWs has been demonstrated both for microwave photons [1] and for optical photons [2]. Building on these works, we are developing an optomechanical system for operation at mK temperatures inside a dilution fridge that is also compatible with coupling to superconducting circuits. We discuss the requirements for such a system, and our progress on meeting these.

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Charge detection in electrostatically defined quantum dots in bilayer graphene

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Graphene is a promising candidate for future nano-electronic devices including building blocks for quantum information processing. Reasons are the expected long spin lifetimes and high carrier mobilities. Experimentally these spin lifetimes have not been demonstrated yet. For progress in this direction a device is needed that allows to confine charges and simultaneously measure their dynamics in a time-resolved way. This is possible with a charge detector in close proximity to a graphene quantum dot (QD).

Here, we use bilayer graphene with its electrostatically induced band gap to fabricate a fully gate-defined device with quantum dots [1,2], that are also used as charge detectors [3]. The Coulomb resonances in the detecting dot are sensitive to individual charging events on the nearby quantum dot. The potential change due to single electron charging causes a step-like change in the current through the charge detector which matches the quality of the traditional semiconductors Si and GaAs. This high-quality detection signals allow us to show complete depletion of one of the quantum dots. Furthermore, we were able to observe the changes in the charge state of a quantum dot with tunable tunneling barriers, and of a multi-dot system. In the multi-dot regime [4], the charge detection enables us to determine the number of charge carriers in each of the dots.

Our experiments demonstrate a device that is needed as the starting point for time-resolved measurements in graphene quantum dots, which may allow us to investigate the spin-lifetime in graphene.

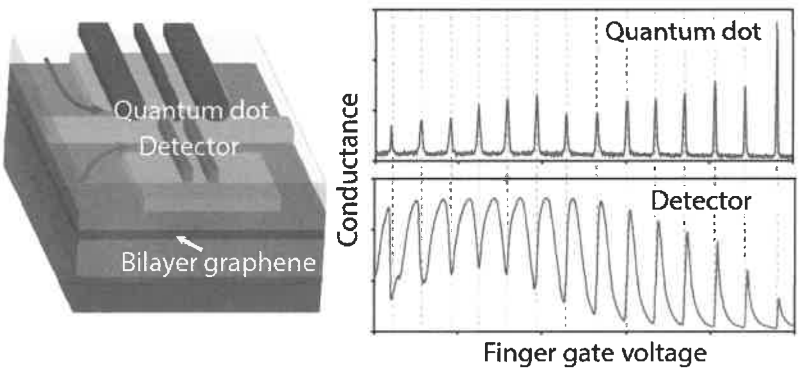

Figure 1 Left: Schematic picture of the different layers in the bilayer graphene device and the gate structure on top. Right: Conductance of the signal dot (upper panel) and the sensing dot (lower panel) as a function of the finger gate voltage for a fixed back gate and split gate voltage.

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Highly integrated RF electronics to interface superconducting qubits

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Superconducting circuits require precise signaling to control experiments within a cryostat, without introducing noise and thus errors. Millimeter radio frequency signals are typically used to interface superconducting qubits. Reading out multiple qubits at the same time can be simplified by using multiple tones propagating through a single wire, also known as frequency division multiplexing. [1, 2]

In the RF approach, possible sources of error shift towards amplitude stability and phase noise. Providing flexibility in signal parameters hence becomes a key challenge. The signal needs to cover a wide, multi-gigahertz band, feature high dynamic range and offer more than 100MHz of instantaneous bandwidth to support a wealth of pulse durations from nanoseconds to continuous wave operation (e.g. [3-5]). However, phase-noise and amplitude deviation should not be compromised. General purpose measurement equipment satisfies signal fidelity but lacks scalability. An alternative, alleviating cost and size limitations of said setup, is proposed, featuring a custom circuit assembly. This signal conditioning frontend allows for 4 to 12 GHz operation covering aforementioned requirements in level and accuracy.

The integrated PCB is based on a novel two-step mixing process and tailored for stand-alone operation. It integrates all components for the frequency conversion and thus does not require external clock references, local oscillators, synthesisers or vector signal generators. We will present the concept of the integrated RF board, as well as performance benchmarks and proof-of-concept measurement results with a superconducting qubit. We will also outline our ongoing efforts to integrate all further necessary electronics components which will allow the system to form a complete quantum-classical interface.

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Integrated scalable electronics platform to interface superconducting qubits

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Superconducting circuits, as used for quantum computing experiments, are commonly interfaced by microwave signals with gigahertz frequencies [1]. The readout is performed using microwave probe pulses. Likewise, qubit gate operations are realized by nanosecond-shaped microwave and current pulses. Due to the high requirements on sampling quality and speed, as well as accurate timing and low phase jitter, special electronics is needed. Typical measurement setups combine arbitrary waveform generators with low-noise DC current sources, high quality local oscillators, discrete radio frequency electronics and signal digitizers. While feasible for small systems, this approach becomes impractical when increasing the qubit count due to high relative cost, susceptibility to errors and space requirements.

A more promising approach is to integrate all necessary room-temperature components into a flexible FPGA-based electronics platform. It not only dramatically reduces potential errors, costs, and space requirements but also simplifies measurements and enables customized control schemes. First steps in this direction have already been taken by research groups performing real-time feedback operations and correlation measurements [2-4], as these require low-latent and highly parallel computation capabilities provided by an FPGA. Also first commercial activities arose that integrate baseband signal generation and processing into a single device. We developed a platform that aims at integrating all required room-temperature components. In a first stage, it therefore also includes the frequency conversion to the gigahertz regime. Different groups in the field already use our platform (e.g. [4-5]) and we will show some examplary experiment results with superconducting qubits. We will also present our plans for further integration, as well as scalability to operate up to 6 qubits with one single platform. Further scaling is planned through synchronization between multiple platforms.

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Spin shuttling in a silicon double quantum dot

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The transport of quantum information between different nodes of a quantum device is among the challenging functionalities of a quantum processor. In the context of spin qubits, this requirement can be met by coherent electron spin shuttling between semiconductor quantum dots. Here we theoretically study a minimal version of spin shuttling between two quantum dots. To this end, we analyze the dynamics of an electron during a detuning sweep in a silicon double quantum dot occupied by one electron. Possibilities and limitations of spin transport are investigated. This research is motivated both by the demand for long and intermediate range interactions in quantum information devices and by recent experimental progress [1,2]. Spin-orbit interaction and the Zeeman effect in an inhomogeneous magnetic field play an important role for spin shuttling and are included in our model. Interactions that couple the position, spin and valley degrees of freedom open a number of avoided crossings in the spectrum allowing for diabatic transitions and interfering paths. The outcomes of single and repeated spin shuttling protocols are explored by means of numerical simulations and an approximate analytic model based on the solution to the Landau-Zener problem. We find that a spin infidelity as low as $1 - F_s \lesssim 0.002$ with a relatively fast level velocity of $\alpha = 600$ μeV/ns is feasible for optimal choices of parameters or by making use of constructive interference.

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Filter Function Formalism for Quantum Operations

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While the quantum operations formalism provides a natural framework for describing the concatenation of quantum operations, it is of limited use when describing the effects of correlated noise. Here we present an extension of the filter function formalism which so far has mostly been used to model gate fidelities [1] and the effects of dynamical decoupling sequences [2]. Our extension enables the calculation of full quantum operations in the presence of correlated noise, e.g. the 1/f-like noise found in many host systems for spin qubits.

We show that a simple composition rule arises for the filter functions of gate sequences. This enables the investigation of quantum algorithms affected by correlated noise with moderate computational resources. Lastly, we present a performant and easy-to-use open source software framework [3] which facilitates the calculation of quantum operations and fidelities for arbitrary system dimensions. Other features include the efficient concatenation of several operations and an optimized treatment of periodic Hamiltonians such as the Rabi Hamiltonian.

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Electrical properties of selective area grown superconductor-semiconductor hybrid structures on silicon

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We present a superconductor-semiconductor materials system that is both scalable and monolithically integrated on a silicon substrate. It utilizes selective area growth of Al-InAs hybrid structures [1] on a planar III-V buffer that is directly grown on a high resistivity silicon substrate. We characterized the electrical properties of this material system at millikelvin temperatures and observed a high average field-effect mobility of $\mu \sim 3200\ cm^2/Vs$ for the InAs channel, a hard induced superconducting gap, high transparency Josephson junctions $T \sim 0.75$ and signatures of multiple Andreev reflections. Josephson junctions exhibited a gate voltage tunable switching current and an $I_C R_N \sim 83\ \mu V$. These results pave the way for scalable gate voltage tunable transmon devices [2] and other superconductor-semiconductor hybrids fabricated directly on silicon.

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A shuttling-based trapped-ion quantum information processing node

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Trapped ion quantum technology is among the most promising candidates for the realization of a scalable quantum processor. To address individual ions and perform high-fidelity two-qubit entangling gates in a linear segmented Paul trap, we employ dynamical register reconfiguration operations to place specific qubits in a laser interaction zone. Using this shuttling-based approach, we demonstrated the sequential generation of four-qubit GHZ states using subsequent entangling gates [1]. To realize fault-tolerant quantum information processing, it is of crucial importance to be able to perform quantum error correction [2]. Realization of quantum error correction circuits requires novel technological approaches. A magnetic field stabilization system around the trapped ion processor has been developed to significantly enhance the qubit phase stability in a noisy magnetic field environment. Calibration routines were automated and measurement cycle times reduced, to allow for faster data acquisition. Additional ongoing technological and methodological improvements are discussed in this contribution. We show recent results from work towards the realization of fault-tolerant stabilizer measurements using a flag-based readout with four data and two ancilla qubits.

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Theory of valley splitting and valley-induced relaxation of a single silicon spin qubit in the presence of interface disorder

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In silicon spin qubits, the qubit must be tuned away from spin-valley hotspot, where the valley splitting matches the Zeeman splitting, to prevent fast qubit relaxation. In this work, we study in detail how the valley splitting depends on the electric and magnetic fields as well as the quantum dot geometry for both ideal and disordered Si/SiGe interfaces. Importantly, our modeling makes it possible to analyze the effect of arbitrary configurations of interface steps. We show that the electromagnetic response of the valley splitting strongly depends on the interface roughness [1].

We then extend our analysis by developing a valley-dependent envelope function theory. One crucial set of parameters for understanding the behavior of spin relaxation is the inter-valley and intra-valley dipole matrix elements. Our analysis enables us to calculate the dipole matrix elements as a function of interface roughness, the in-plane orbital splitting as well as the electromagnetic field. Interestingly, we find some specific highly disordered interfaces where the valley splitting is suppressed but remains finite whereas the inter-valley dipole matrix elements vanish. This, in turn, offers a possibility of cooling the spin relaxation hot-spot.

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A depletion mode hole spin-qubit in Ge

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Abstract

Spin qubits are considered to be among the most promising candidates for building a quantum processor[1]. Group IV hole spin qubits have moved into the focus of interest due to the ease of operation and compatibility with Si technology [2;3;4;5;6]. In addition, Ge offers the option for monolithic superconductor-semiconductor integration. Here we demonstrate a hole spin qubit operating at fields below 10 mT, the critical field of Al, by exploiting the large out-of-plane hole g-factors in planar Ge and by encoding the qubit into the singlet-triplet states of a double quantum dot[7;8]. We measure g-factor differences as large as 2 which enables electrically controlled X rotations with tunable frequencies exceeding 100 MHz and dephasing times of 1 µs which we extend beyond 15 µs with echo techniques. Moreover, we demonstrate a gate dependence of the g-factors resulting in a 30% reduction of their difference over a voltage change of only 50 mV. Precise tuning of the exchange interaction and g-factor differences allow to tune the device to an optimal configuration where rotations speed and coherence are optimized. Our results show that Ge hole singlet triplet qubits outperform their electronic Si and GaAs based counterparts in speed and dephasing time, respectively. In addition, their coherence is on par with Ge single spin qubits, but they can be operated at much lower fields underlining their potential for on chip integration with superconducting technologies.

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Silicon quantum pillars for possible scalable HW platforms

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This work outlines the issues related to the fabrication of silicon quantum pillars for possible use in scalable HW platforms [1] for quantum computing applications. These quantum structures could be an efficient way of routing quantum information carriers. But also they might be very efficient photon sources, which are made of silicon as shown in Fig. 1d. The emission energy is well under the Si bandgap, therefore suitable for Si waveguides. Having carrier lifetimes close to femtosecond range would be suitable for the realization of ultrafast switching devices for use in scalable quantum networks. The platform can support the development of qubit systems.

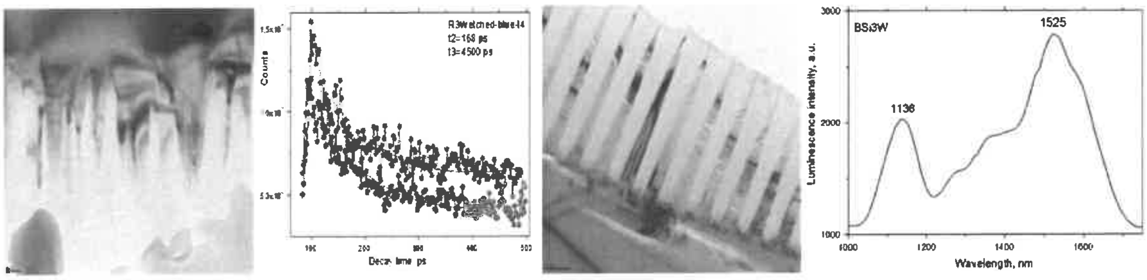

Fig.1 Silicon pillars and optical response to excitation light. a) randomly distributed silicon pillars, b) lifetime of carriers with ultrafast time decay, c) regularly spaced and smoothed pillars, d) Mid infrared photon emission from the pillars in (a).

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Selectively Activated Photon-Hopping, Cross-Kerr, and Two-Mode Squeezing via Flux Modulation of a Tunable Coupler

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Access to a wide variety of qubit-qubit interactions on a single device is desirable in order to effectively simulate a host of quantum systems. At the most basic level, a plaquette containing two superconducting transmon qubits connected both capacitively and inductively by a flux tunable coupler containing a SQUID has shown promise for accessing disparate coupling regimes, such as those in which the single excitation transfer coupling dominates over the cross-Kerr (ZZ) coupling, and vice versa[1]. Access to these regimes and others on a larger device is expected to allow for the simulation of several physical phenomena including fractional Bloch oscillations, various spin-spin interactions, and lattice gauge theories[2-4]. In this work, we show theoretically and demonstrate experimentally the ability to selectively enter into regimes in which the system dynamics are dominated by either single photon-hopping, two-mode squeezing, or cross-Kerr interactions. The primary interaction is determined by the DC flux bias point and choice of modulation frequency for the AC flux threading the tunable coupler. The ability to tune into and out of these coupling regimes reinforces the promising nature of superconducting devices based on transmon qubits and tunable couplers as versatile analog quantum simulators.

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The CQ3 Qubit spectroscopy and coherence

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We implement a single electron charge qubit in a gate defined linear triple quantum dot (TQD) array on a GaAs/AlGaAs heterostructure. The TQD is capacitively coupled to a frequency tunable high impedance SQUID array resonator. The qubit has four control parameters, the strength of the left and right tunnel barriers t_L and t_R as well as the quadrupolar E_M and dipolar detuning δ. We explore a charge qubit operation point which has a third order sweet spot along the detuning parameter δ , however the qubit is susceptible to fluctuations in E_M. These so-called sweet spots are beneficial for charge coherence, since the decoherence effects caused by small fluctuations of gate voltages or surrounding charge fluctuators are minimized. We show strong coupling of the qubit to single photons in a frequency tunable high impedance SQUID array resonator. In the dispersive regime we investigate the qubit linewidth in the vicinity of the proposed operating point. In contrast to the expectation of a higher order sweet spot we find a local maximum in the linewidth at the proposed working point. We develop a detailed noise model for this qubit which explains our observations. These results indicate that, in contrast with the original assumption that noise is mostly originating from long-distance sources, the noise affecting the qubit has a non-negligible contribution coming from short-distance noise sources.

Anyonic statistics in collider geometry

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Two-dimensional systems at low temperatures and the high magnetic field can host exotic particles with elementary excitations carrying fractional charge $e^* = e/q$ such as in fractional quantum Hall effect[1]. These exotic particles are anyonic particles, whose quantum statistics are neither bosonic nor fermionic; instead, they are predicted to obey fractional statistics[2]. The fractional charge of these anyons has been studied successfully using low-frequency shot noise measurement[3,4]. However, no universal method for sensing them unambiguously exists[5]. Also, a clear signature of the fractional statistics remains elusive. Here we exploited the Josephson relation of these anyonic states to determine the fractional charge of exciting quasiparticles. The microwave photons emitted by voltage biased anyonic system obey the Josephson relation, like superconducting Josephson junction but with the charge $q = e^*$ rather than 2e. This provides direct evidence of fractional charge in the fractional quantum Hall effect[6]. Lastly, we also probed the fractional statistics in mesoscopic anyonic collider[7]. Our collision results explicitly extract the quantum phase of $\phi = \pi/3$ for the exchange of two anyonic quasiparticles with $q = e/3$. This is the very first smoking gun result on fractional statistics of anyon. This collider geometry could be extended to perform the ultimate braiding experiment to the realized full potential of a special kind of anyon called non-Abelian anyons in topological quantum computation.

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Accurate Readout of Spin States in Silicon Nanowire Quantum Dots

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Spins in gate-defined silicon quantum dots are promising candidates for implementing large-scale quantum computing. To read the spin state of these qubits, the mechanism that has provided highest fidelity is spin-to-charge conversion via Pauli spin blockade [1]. However, given the valley degree of freedom in silicon quantum dots, which can lead to complex energy spectra, accurate identification of when singlet-triplet Pauli spin blockade occurs is a key requirement for reliable readout of silicon spin qubits. Here, we present a pathway for achieving accurate, fast and scalable readout in a tunnel-coupled silicon CMOS double quantum dot (DQD) defined in the corners of a split-gate nanowire transistor.

In the first part of the poster, we expand the standard description of Pauli spin blockade in a DQD to include multiparticle states with large total spin angular momentum *S*. Using gate-based dispersive readout and magnetospectroscopy, we show successive steps of spin blockade and spin blockade lifting involving spin states up to *S*=3 as well as the formation of a novel spin-quintet state [2]. These results demonstrate the use of magnetospectroscopy as a powerful tool for accurately identifying when Pauli spin blockade occurs and open the possibility for further studies of high-spin systems.

In the second part, we use a multi-chip approach to couple the DQD to a high-impedance lumped-element resonator. We report a large coherent coupling rate of $g/(2\pi)=163$ MHz between the DQD charge state and the microwave photons of the resonator and achieve rapid high-fidelity charge readout with an SNR=3.3 in 50 ns. We predict this method could achieve a projected readout fidelity of 99.7% in 300 ns for singlet-triplet readout. Through frequency multiplexing experiments we display the scalability of this readout approach [3].

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An integrated heterogeneous superconducting-silicon-photonic platform for quantum network

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Integrated quantum photonics (IQP) is a promising platform for realizing scalable and practical quantum information processing. Here we realize a server for measurement-device-independent quantum key distribution (MDIQKD) based on a heterogeneous superconducting-silicon-photonic chip. The unique design of the waveguide integrated superconducting nanowire single-photon detector enables an ultra-short dead time for single-photon detection, allowing us to perform time-bin-encoded two-outcome Bell state measurements (BSM) between two independent lasers. This provides twice the key rate than the one-outcome BSM MDI-QKD. We show on-chip Hong-Ou-Mandel interference between weak coherent states with a visibility of 48%±2%. Our system generates 733 sifted bits at about 71 dB attenuation (equivalent to 358 km standard fiber) with a quantum bit error rate of 3.5%±0.7%. The fabrication processes of our device are compatible with standard thin-film technology. Together with integrated transmitters, a scalable, chip-based, cost-effective and higher-performance quantum network can be realized in the near future.

Towards quantum evolutionary search and optimization on NISQ devices

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Quantum inspired evolutionary algorithms (QEA) [1] are a class of population-based multi-model estimation of distribution algorithms [2], which have been successfully applied for solving wide variety of search and optimization problems. They have been developed by integrating some of the principles of quantum mechanics into the framework of evolutionary algorithms. QEA uses qubit representation, unitary rotation gates and measurement operators, which are simulated on classical digital computers [3]. The noisy intermediate scale quantum (NISQ) [4] device has been used to show case selective quantum supremacy in sampling probability distributions, which are hard to simulate for classical digital computers [5]. NISQ devices can be used to implement genotype qubit representation, rotation gates and for performing measurement operations in QEA more efficiently as compared to classical digital computer. It is conjectured that NISQ devices may help in inherently better estimation of the multiple-model probability distribution in QEA, which may lead to faster search and optimization as compared to implementation on digital computers. This paper proposes a hybrid classical-quantum implementation of QEA on digital computer and NISQ devices shown in fig. 1, with evolutionary framework running on digital computer and quantum inspired representation and operators running on low depth quantum circuits of NISQ devices.

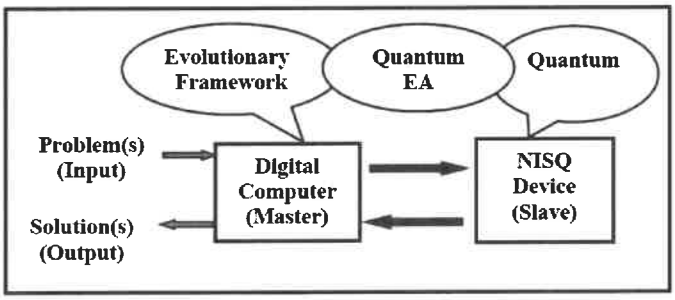

Fig.1: Block Diagram of Proposed Hybrid Classical-NISQ Computing System for Quantum Evolutionary Algorithms

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Control Software Stack for Shuttling-Based Trapped-Ion Quantum Computing

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Aiming at the realization of a shuttling-based trapped-ion NISQ quantum processor, a complex software control stack is required. This stack is supposed to generate sequences of hardware-level commands from established quantum programming frameworks such as Qiskit. It requires compilation to a native gate set sequence, from which shuttling sequences are to be generated, which determine the dynamical reconfiguration of the register via shuttling operations. These sequences ought to be optimized in terms of resources such as overall runtime. Error suppression techniques such as dynamical decoupling, conditional feedback and dual-species operation capabilities allowing for in-sequence cooling are to be integrated into this framework. A back-end assembler, generating hardware level commands, allowing for complex diagnostics, concludes the stack. We discuss the layout of the overall stack, the requirements imposed on its components, the current state-of-the-art and future extensions, e.g. additional levels allowing for fault-tolerance via quantum error correction.

Effects of surface treatments and packaging on transmon qubits

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The last two decades have seen significant advances in the coherence times of superconducting qubits. However, further progress in transmon coherence times seems to require substantial effort in understanding the remaining limitations due to material interfaces and imperfections, which give rise to two level fluctuators [1-3]. Often, ion milling is an integral part of Josephson junction fabrication and possibly damages the material surface, but its impact on qubit coherence is not well understood and needs experimental investigation.

Here, we present our work towards understanding decoherence mechanisms in flux-tunable transmon qubits. We study the effects of qubit packaging under UHV and controlled atmospheres on the qubit coherence. In addition, we analyze the impact of surface treatments, such as UV light exposure and ion milling, on the qubit parameters. For further insight, qubit coherence and parameter fluctuations are investigated by tracking the coherence times and transition frequencies of multiple qubits over several hours. The resulting noise spectra for different packaging and treatment methods are then compared.

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Cryogenic current-steering DAC for biasing of quantum dots

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Future quantum computers will require thousands or even millions of qubits in order to address any practical problem. Scaling to such a large number of qubits will be unpractical using the current "brute-force" approach, as it will become infeasible to wire the thousands of cables required to connect the cryogenic qubits to the room-temperature electronics. In order to overcome these constraints, the control, biasing and readout electronics has to be placed at low temperature stages in close proximity to the qubits, but this requires low-power electronic blocks operating at cryogenic temperature.

In order to face the lack of existing CMOS transistor model at cryogenic temperature, we designed an integrated on-chip matrix of individually addressable transistors in order to massively characterize the FDSOI 28nm technology [1]. The development of systematic characterization and models of this technology enabled the design of building analog and digital blocks co-integrated with a silicon-based electron double quantum bot, in order to expose quantum dynamic phenomena such as charge pumping [2].

During this conference, we will present the last results of our research group concerning the design of cryogenic-operating CMOS electronics [3]. In particular, we will present the design and experimental results of a current-steering digital-to-analog converter (DAC) made in FDSOI 28nm Si MOSFET technology and operating at 4.2K. Our DAC is made of an 8-bits fine-grained DAC [3] (4µV step voltage) working in parallel with a 10-bits coarse-grained DAC (1mV step voltage), featuring an effective resolution of about 16bits. The DAC output is followed by an analog 1-to-4 multiplexer, four high-retention sample-and-hold blocks and four voltage followers. Experimental results on the performance of the DAC at 4.2K will be presented for the gating of quantum dot devices with a power consumption as low as 1mW. According to the retention time of the sample-and-hold circuit, we envision that our solution could bias more than hundreds of quantum devices simultaneously, paving the way toward fine-grain biasing of Si-based qubit arrays.

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Radio frequency quantum-circuit refrigerator and the resulting effective photon-number-dependent Lamb shift

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The Lamb shift, an energy shift arising from the presence of the electromagnetic vacuum, has been observed in various quantum systems and established as the part of the energy shift independent of the environmental photon number. However, this argument is based on a simplistic bosonic model and may be challenged in practical quantum devices. We demonstrate a hybrid bosonic-fermionic environment for a linear resonator mode and observe that the photon number in the environment can dramatically increase both the dissipation and the effective Lamb shift of the mode. Our observations are quantitatively described by a first-principles model which potentially enhances the device design for future quantum technological applications. The device demonstrated here can be utilized as a fully rf-operated quantum-circuit refrigerator to quickly reset superconducting qubits. [1–8]

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Quantum rifling - Protecting a qubit from measurement back action

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Quantum mechanics postulates that measuring the qubit's wave function results in its collapse, with the recorded discrete outcome designating the particular eigenstate that the qubit collapsed into. We show that this picture breaks down when the qubit is strongly driven during measurement. More specifically, for a fast evolving qubit the measurement returns the time-averaged expectation value of the measurement operator, erasing information about the initial state of the qubit, while completely suppressing the measurement back-action. We call this regime `quantum rifling', as the fast spinning of the Bloch vector protects it from deflection into either of its eigenstates. I will explain the basic physics behind this effect and show experimental results from two superconducting qubits coupled to the same probe field, demonstrating that quantum rifling allows us to measure either one of the qubits on demand while protecting the state of the other from measurement back-action. These results may allow for the implementation of selective read out multiplexing of several qubits, contributing to the efficient scaling up of quantum processors for future quantum technologies.

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Time-Resolved Quantum Process Tomography of a Compact 3D Quantum Memory

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Storing a photonic state in a 3D superconducting cavity as long as possible and reading out its information as fast as possible is a challenging task due to the conflicting requirements regarding the coupling strength between the cavity and readout circuit. This problem can be solved by a multimode compact3D memory scheme employing a weakly and strongly coupled storage and readout mode with both coupled to a transmon qubit [1]. However, comparing the experimental data of the time evolution of the quantum process tomography with an empirical simulation, we saw difference in the relaxation behavior become obvious. To clarify this issue we perform an ab initio quantum simulations. In particular, these simulations allow us to understand yet unknown physics behind the compact 3D memory design and improve the protocol for the quantum memory process.

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Scalable Cryogenic Control of Spin qubits

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In order to realize qubit numbers required for large scale quantum computation, a control interface that is tightly integrated with the qubits is essential.
However, the power dissipation of existing CMOS circuits hinders the qubit operation at mK temperatures. While solutions exist, where the control electronics are placed at a higher temperature stage of a cryostat this approach significantly increases wiring complexity [1].
Here, we present our progress on developing a scalable, ultra-low-power control interface that can be directly integrated with the qubit chip at mK temperatures using state of the art packaging techniques.
As a first step, a capacitive, cryogenic DAC will be placed on an interposer chip directly next to a GaAs qubit and generate the DC voltages required for defining quantum dots [2].
Additionally, off-the-shelf heterojunction bipolar transistors (HBTs) are evaluated as an integrated option for time multiplexed readout of many qubits with a limited number of connections.
In the long run, we plan to operate a chip with on the order of 50 qubits using cryogenic control and readout, as well as 3D integration, in order to validate these concepts. I would like to emphasize that our work is in large parts agnostic to the specific type of spin quit and can be quickly adopted to the most promising candidate in the future.

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Charge noise and overdrive errors in reflectometry-based qubit readout

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Solid-state qubits incorporating quantum dots can be read out by gate reflectometry. In this study [1], we theoretically describe physical mechanisms that render such reflectometry-based readout schemes imperfect. We discuss charge qubits, singlet-triplet spin qubits, and Majorana qubits. In our model, we account for readout errors due to slow charge noise, and due to overdriving, when a too strong probe is causing errors. A key result is that for charge and spin qubits, the readout fidelity saturates at large probe strengths, whereas for Majorana qubits, there is an optimal probe strength which provides a maximized readout fidelity. We also point out the existence of severe readout errors appearing in a resonance-like fashion as the pulse strength is increased, and show that these errors are related to probe-induced multi-photon transitions. Besides providing practical guidelines toward optimized readout, our study might also inspire ways to use gate reflectometry for device characterization.

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Microwave swap gates with a Kerr-cat ancilla

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Quantum computation requires coherent highly controllable gates with low error rates. A long-standing target is an exponential-swap gate which requires an ancilla qubit to entangle two microwave fields. A transmon ancilla has been previously used [1]; it introduces a back propagation of ancilla errors into the fields. We propose a new way of doing a controlled beam splitter with a SNAIL-based Kerr cat that is transparent to the dominant error channel. We show that one can implement a beam splitter with a phase that depends on the state of the ancilla cat using suitable driving fields. Encoding quantum information into coherent states of the Kerr cat biases its decoherence towards phase flips, allowing significantly improved performance compared to the transmon setup. With this controlled beam splitter, it is possible to implement controlled-swap and further exponential-swap gates for microwave fields, which allows further applications such as swap tests or quantum random access memory protocols. This work is supported by the grants ARO W911NF-18-1-0212 and LTAUSA19099.

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"Scalable multiphoton generation from cavity-synchronized single-photon sources"

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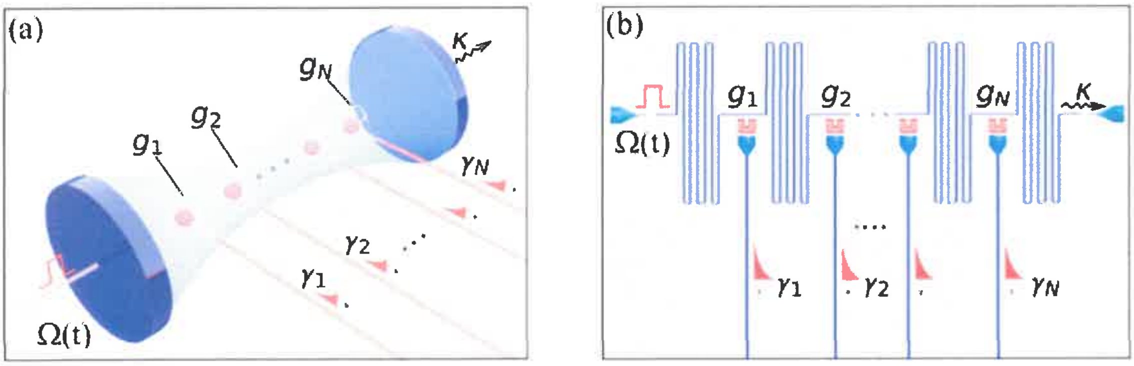
Photonic technologies are a promising platform for processing quantum information, because it combines the resilience of the photon with simple but powerful tools for its manipulation. Nevertheless, to perform practical quantum information applications, photonic circuits need to be fed with a very large number of identical photons. A promising route to generate these quantum resources is by synchronizing many single-photon sources to emit a large non-classical multiphoton state, but the low efficiencies achieved so far has strongly limited the scalability of this approach.
In my poster, I propose a novel cavity-mediated synchronization scheme that efficiently generates up to hundreds of indistinguishable photons. For a state-of-the-art circuit QED implementation, we show that the scheme generates single photons with purity, indistinguishability, and efficiency of 99% at rates of ~MHz, and a simultaneous 30-photon state with efficiency above 70% at a rate of hundreds of kHz. This is seven orders of magnitude more efficient than current demultiplexed sources and may enable the realization of large-scale quantum information processing with photons, such as boson sampling or quantum metrology.



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Parametric dissipation engineering for quantum information processing

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Dissipation engineering provides a versatile framework for quantum information processing tasks ranging from entanglement preparation to quantum error correction, ultimately allowing for universal quantum computation. Theoretical works have demonstrated improved robustness to decoherence, and proof-of-principle experiments have shown the feasibility of the approach.

We propose a new framework for dissipation engineering that combines the advantages of static dispersive couplings with strong parametric driving. Parametric dissipation engineering offers high fidelity *and* fast operation, overcoming constraints in previous protocols. First schemes for entanglement generation [1] and quantum error correction are readily accessible with superconducting qubit and trapped-ion technology. The paradigm holds promise for application in near-term quantum information processing tasks performed on noisy hardware.

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Beyond the standard quantum limit of parametric amplification

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The low noise amplification of weak microwave signals is crucial for many protocols in quantum information processing. Quantum mechanics sets an ultimate lower limit of half a photon to the added input noise for phase-preserving amplification of narrowband signals, also known as the standard quantum limit (SQL). This limit, however, can be circumvented by employing non-degenerate parametric amplification of broadband signals [1]. We show that, in theory, a maximum quantum efficiency of 1 can be reached. Experimentally, we detect the quantum efficiency of 0.69 beyond the SQL of 0.5 by employing a flux-driven Josephson parametric amplifier and broadband thermal signals. Thus, we demonstrate the violation of the SQL for non-degenerate parametric amplification of broadband input signals, a result which can be exploited for improvement of various qubit readout techniques.

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Top-down Topological Insulator Nanowires for Majorana-Qubits

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With proximity-induced superconductivity (SC), bulk-insulating topological insulator (TI) nanowires (NWs) are expected to serve as a robust platform to realize Majorana bound states (MBS), which are of interest for topological quantum computation schemes. Compared to work on Rashba nanowires, a TI-based platform for MBS is predicted to have significantly relaxed constraints on the tuning of the relevant parameters in terms of chemical potential and magnetic field [1,2].

So far, experimental progress in TI NWs has been hindered by bulk contribution and imperfect contact interfaces in devices. Here we report transport measurements of highly gate-tuneable bulk insulating TI NWs based on a scalable approach using high quality MBE-grown $(Bi_{1-x}Sb_x)_2Te_3$. We observed the predicted quasi-1D surface subband structure from circumferential quantization in magnetoresistance measurements and study Josephson junctions on such NWs. Showing first results on unconventional superconductivity, we have the second ingredient at hand required to study MBS-physics and to eventually realize various related qubit proposals [3].

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Control, Calibration and Characterization of superconducting qubits

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Efforts to scale-up quantum computation have reached a point where the principal limiting factor is not the number of qubits, but the entangling gate infidelity. However, a highly detailed system characterization required to understand the underlying errors is an arduous process and impractical with increasing chip size. Open-loop optimal control techniques allow for the improvement of gates but are limited by the models they are based on.

To rectify the situation, we provide a new integrated open-source tool-set for Control, Calibration and Characterization (C^3), capable of open-loop pulse optimization, model-free calibration, model fitting and refinement.

In this talk I will present a methodology to combine these tools to find an accurate system model and high-fidelity gates. I'll illustrate our methods using fixed-frequency superconducting qubits for which we learn model parameters to an accuracy of <1% and derive a coherence limited cross-resonance (CR) gate that achieves 99.6% fidelity without need for calibration.

Partitioning of functionality for superconducting qubit control and readout

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Even a quantum chip with thousands of qubits is not enough to realize a quantum computer based on superconducting qubits. Interfacing all these qubits reliably and efficiently is a challenge on its own. It requires careful tuning on all system levels. Technical trade-offs steer the system partitioning. For example, while having as much of the control logic close to the qubits is highly attractive from the functional point of view, this might not be possible due to the power dissipation of the same electronics and cooling limitations. In conclusion, parts of the low-level functionality will be realized close to the qubit. In contrast, less time critical functionalities are better handled outside the cryostat.

Based on this belief, my research group started working on highly integrated and customized control and readout electronics for superconducting qubits a few years ago. Our system is based on an RFSoC device that integrates various processors, an FPGA and high-speed ADCs and DACs on one single chip. We developed a custom FPGA design and software architecture on top of that hardware. It supports a wide variety of qubit experiments, including real-time feedback. Ease of use is achieved through Python descriptions of experiments. Wherever needed, low-level code is generated automatically from these high-level descriptions utilizing custom tools. We also provide a custom RF interface to the superconducting qubits. It is realized on a single custom PCB, including the local oscillators. Thereby we provide a lean and easy to use platform for qubit experiments.

We will introduce the platform's current status and outline the next significant development steps we are currently pursuing. These are related to scalability, cryogenic electronics, and conceptual integration into quantum computing stacks.

Faster adiabatic ground state preparation with few measurements

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Preparing the ground state of a Hamiltonian is a problem of great significance in physics with deep implications in combinatorial optimization. While the quantum adiabatic algorithm (QAA) [1] is known to return the ground state for sufficiently long preparation times, the decoherence times of noisy, intermediate-scale quantum devices [2] render the QAA infeasible. Variational approaches such as the quantum approximate optimization algorithm [3] sparked intensive research interest [4], however, optimization of a multiparameter cost function requires billions of measurements already for a moderate number of qubits and can be prone to noise-induced barren plateaus [5], thus forsaking any practical quantum advantage. In our work, we aim at combining the strengths of the adiabatic and the variational approaches for fast and high-fidelity ground state preparation by keeping the number of measurements as low as possible (Fig. 1), benchmarking our algorithm for a spin-1/2 transverse and longitudinal Ising chain (ZZXZ model) with $N = 100$ sites. Our preliminary results already show a promising significant increase in the overlap with the ground state from 5.7% to 17.4% when compared to naive QAA for fixed total evolution time.

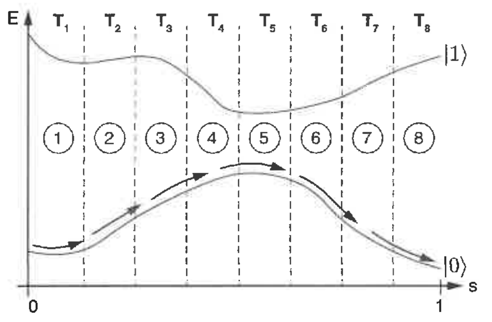

FIG. 1: Illustration of the hybrid algorithm by dividing the adiabatic path into eight chunks. The ground state and first excited state energies are shown for parametrized time $s = t/T$ from 0 to 1. For the black box optimization shown below, the adiabatic evolution time T is allocated evenly between the chunks of the adiabatic path (here $T_i = T/8\ \forall i \in \{1, 8\}$), so that the chunk positions become the variational parameters to be optimized, effectively controlling the density of adiabatic steps.

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Optimal manipulation of Majorana bound states using quantum dots

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By now, there has been a lot of evidence of the existence of Majorana bound states (MBSs) at the ends of topological superconductors (TSs) [1]. However, a definitive proof of their topological origin will rely on the demonstration of their non-abelian statistics, which emerge after the exchange of two or more MBSs in real space. Alternatively, MBSs can be exchanged in parameter space using charge-transfer based operations performed with a quantum dot (QD) coupled to two TSs. In a successful operation where the QD energy is ramped up, the QD transfer its charge to the two TSs leading to a superposition of states [2].

In this presentation I will analyze the efficiency of charge-transfer based operations between a QD and to two TSs [3], analyzing the unique signature provided by non-abelian particles. Using a full counting statistics analysis, we set bounds to the operation time scales. The lower bound depends on the phase difference, due to a partial decoupling of the different parity sectors. In contrast, the upper bound is determined by poisoning processes due to the tunneling of quasiparticles to the MBSs. Using realistic parameters, we find that operations can be performed with a fidelity close to unity in the ms to μs timescales, demonstrating the absence of dephasing and accumulated dynamical phases for a given superconducting phase difference. I will analyze the accumulation of the geometrical phases away from the fine-tuned ideal point, deriving ways to minimize errors in the system [4].

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Cavity-photon induced state transitions in a coupled Fluxonium qubit system

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Superconducting qubits are a subject of intense research as a platform for scalable quantum computing. While transmon qubits have received a lot of attention, the less ubiquitous Fluxonium qubit has been shown to have long lifetimes and gates unlimited by level anharmonicity [1]. Despite this, little research has been put into studying multi-Fluxonium devices. Here, one of the difficulties is understanding how their rich level structure can make them prone to measurement photons inducing transitions out of the qubit subspace [2]. We present a systematic study of a system comprising two capacitively coupled Fluxonium qubits sharing the same read-out cavity. By tracking the state dependent transmission of the read-out pulse, we determine the transition rates from state i to state j of the coupled system using a forward-backward analysis [3] to characterize these cavity induced transitions. By varying the flux bias of the system and the population of the cavity, we characterize the fidelity of this read-out.

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General-Purpose firmware for controlling quantum processors

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Field-programmable gate arrays (FPGAs) are ideally suited to the classical, digital control of quantum hardware. However their low-level programming is time consuming and system specific, making them inconvenient for laboratory exploration and development. We present a general-purpose firmware for the Xilinx Zynq UltraScale+ RFSoC platform which allows for flexible implementation of quantum readout and control sequences through a Python Application Programming Interface (API). Our approach allows for a wide variety of experiments with fine-tuning performed at runtime, without reloading large blocks of memory.

The classic approach to pulse sequencing requires uploading long blocks into the memory of an arbitrary-waveform generator. Even with high-speed data transfer this operation can take up a significant portion of an experiment runtime. As quantum processors scale up the number of qubits and control/readout lines, such data transfer quickly becomes a bottleneck. We solve this problem by parameterizing the signals, breaking them into smaller templates that can be concatenated, added, up or down converted, and stretched in time. This approach gives a high level of customization with only a few parameters uploaded to the device. Many different experiments can be programmed and executed without transferring data to or from the host computer.

Another challenge for scalable quantum control is synchronization between pulse generation and signal acquisition in multiple channels. Synchronizing multiple devices is not a trivial task, requiring tedious alignment of events and compensation for phase shifts. Our 'quantum event coordinator' leverages the stable clock for both logic (FPGA) and conversion (DAC, ADC) to precisely synchronize all signal generation, acquisition and analysis. Due to the high level of integration on the RFSOC chip, synchronization over 16 separate channels is achieved without any external hardware for clock recovery or distribution.

Tunable Valley Splitting in Bilayer Graphene Quantum Dots

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Quantum states in bi-layer graphene are four-fold degenerate: two-fold in spin, and two-fold in valley. Just like spin states, valley states split in energy in a perpendicular magnetic field, linear in the low field limit, with g-factor much larger than that of spin. Both degrees of freedom can be utilized for qubit preparations. For spin qubits, carbon-based system has the common advantage of expected long spin coherence time [1]. We demonstrate large and *in situ* gate tunable valley splitting in bi-layer graphene quantum dots, which is advantageous for valley qubit operations.

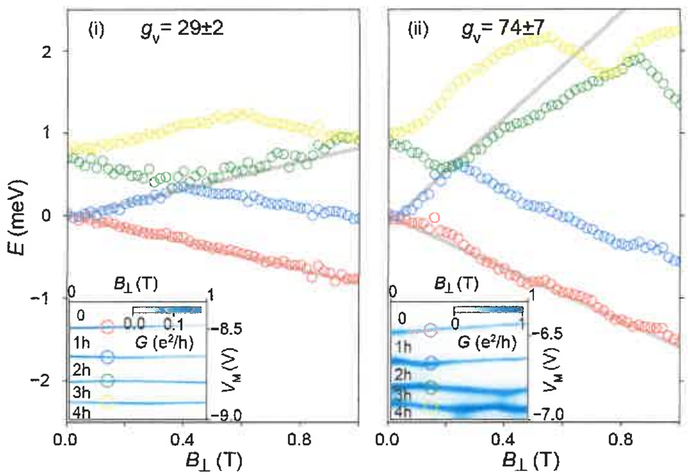

Figure 1 – Single particle energy level spectrum of a QD at two different voltage configurations in (i) and (ii) in perpendicular magnetic field, extracted from conductance maps shown accordingly as insets. Valley splitting is evidently much stronger in (ii) that

In bilayer graphene, a perpendicular electric field opens up a band-gap [2]. Exploiting this band-gap, with our two-layer gate geometry that is carefully designed and yet relatively straightforward, we form electrostatically tunable few-carrier quantum dots [3]. By varying gate voltages, the carrier occupancy and polarity, the dot-lead and dot-dot tunnel coupling, the dot size and geometry, and the strength of valley splitting can be tuned in situ at will. We find the valley g-factor to be tunable by over a factor of four from 20 to 90, where a larger splitting corresponds to a larger electronic dot size, tuned by barrier gates.

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Engineering of a semiconductor charge qubit coupled to a resonator – From coherence protection to ultrastrong coupling

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The prospect of using a superconducting resonator to couple distant spins in a semiconductor quantum dot-based quantum processor has received much attention. Recently, the strong-coupling limit between a single spin and a superconducting resonator has been realized [1,2,3]. Although interactions between distant spins have been observed, an exchange-like coupling between those remains elusive due to poor spin coherence. State of the art realization of spin-resonator coupling relies on hybridization between the electron spin and its charge degree of freedom. Hence, the spin acquires properties of a charge qubit, such as susceptibility to charge-noise. Thus, engineering of the charge qubit properties is crucial. Here, we investigate a depletion gate-defined double quantum dot charge qubit in GaAs, coupled to a SQUID-array resonator. We tune its decoherence, detuning noise, and qubit-resonator coupling strength in-situ, by changing its gate potential configuration. Using the dependence of these properties on the gate potential, we reproducibly achieve a qubit decoherence rate below 5 MHz. In a follow-up experiment, we investigate a charge qubit coupled to a Josephson-junction array resonator with an impedance of 4 kΩ. Using the previously identified dependence on the gate potential of the double quantum dot, we demonstrate a qubit-resonator coupling strength exceeding 10 percent of the uncoupled eigenfrequencies, realizing for the first time, the ultrastrong coupling regime [4] of a charge qubit coupled to a superconducting resonator. We anticipate that our findings will be crucial for resonator-based spin-spin coupling and enable the investigation of the ultrastrong coupling regime of charge qubits.

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Flip chip technique for hybrid quantum systems

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Despite their different strengths and shortcomings, all promising platforms in quantum information science have in common their unwanted coupling to motional degrees of freedom. Some examples of this are laser heating in trapped ions or phonon radiation in superconducting qubits. We are using these cross-platform interactions to our advantage by combining different systems using well controlled, high quality factor phonon modes in acoustic resonators. In particular, we are creating a hybrid device made of a bulk acoustic wave resonator coupled to a superconducting qubit to construct a quantum random access memory [1]. To simplify the fabrication process and to enable individual testing, we construct the phonon resonator and the qubit on separate chips. Here, we present the technique we use to combine the two chips using an epoxy-based photoresist both as spacers to set the separation between the chips and as glue to hold them together.

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Coherent superconducting qubits from a subtractive junction fabrication process

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Josephson tunnel junctions are the centerpiece of almost any superconducting electronic circuit, including qubits. Typically, the junctions for qubits are fabricated using shadow evaporation techniques to reduce dielectric loss contributions from the superconducting film interfaces. In recent years, however, sub-micrometer scale overlap junctions have started to attract attention. Compared to shadow mask techniques, neither an angle dependent deposition nor free-standing bridges or overlaps are needed, which are significant limitations for wafer-scale processing. This comes at the cost of breaking the vacuum during fabrication but simplifies integration in multi-layered circuits and implementation of vastly different junction sizes and enables fabrication on a larger scale in an industrially standardized process. In this work, we demonstrate the feasibility of a subtractive process for the fabrication of overlap junctions. In an array of test contacts, we find low aging of the average normal state resistance of only 1.6% over 6 months. We evaluate the coherence properties of the junctions by employing them in superconducting transmon qubits. In time domain experiments, we find that both, the qubit life- and coherence time of our best device, are, on average, greater than 20 µs. Finally, we discuss potential improvements to our technique. This work paves the way toward a more standardized process flow with advanced materials and growth processes, and constitutes an important step for the large scale fabrication of superconducting quantum circuits.

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Stehli *et al.*, Appl. Phys. Lett. **117**, 124005 (2020); https://doi.org/10.1063/5.0023533

Benchmarking the Variational Quantum Eigensolver for Quantum Chemistry on High-Performance Computers

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We use the Variational Quantum Eigensolver (VQE) as implemented in the Qiskit software package to compute the ground state energy of small molecules derived from water and hydrogen cyanide. The work aims to benchmark algorithms for calculating the electronic structure and energy surfaces of molecules of relevance to prebiotic chemistry and to run them on the available simulated and physical quantum hardware. The numerical calculations of the algorithms for small quantum processors will allow us to design more efficient protocols to be run in real hardware, as well as to analyze their performance. Future implementations on accessible quantum processing prototypes will benchmark quantum computers and provide tests of quantum advantage with heuristic quantum algorithms.

Optimal Control of Superconducting Qubits

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Reaching high speed, high fidelity qubit operations requires precise control over the shape of the underlying pulses. For weakly anharmonic systems, such as superconducting transmon qubits, short gates lead to leakage to states outside of the computational subspace. Control pulses designed with open-loop optimal control may reduce such leakage. However, model inaccuracies can severely limit the usability of such pulses. We implemented a closed-loop optimization that simultaneously adapts all control parameters based on measurements of a cost function built from Clifford gates. We directly optimize the amplitude and phase of each sample point of the digitized control pulse. We thereby fully exploit the capabilities of the pulse generation electronics and create a 4.16 ns single-qubit pulse with 99.76 % fidelity and 0.044 % leakage. This is a seven-fold reduction of the leakage rate and a three-fold reduction in standard errors of the best DRAG pulse we have calibrated at such short durations on the same system.

Components for scalable quantum logic with trapped ions

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Scalable quantum computing with trapped ions requires a real-time control system, featuring feedback functionality to enable conditional quantum logic. For this, an advanced radio-frequency pulse generator is integrated into the existing control infrastructure of the Mainz group. Additionally, robust and automated control software is mandatory. Methods from the emerging field of machine learning are a natural fit to quantum computing platforms, allowing for the implementation of robust, efficient, and automated calibration routines. Improved loading and verification of multi-qubit registers by using neural network-based image recognition is realized and the performance gain is analyzed. In addition, we present results of automated closed-loop optimization of methodological building blocks such as entangling gates and ground-state cooling.

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An integrated tool-set for Control, Calibration and Characterization of quantum devices applied to superconducting qubits

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Efforts to scale-up quantum computation have reached a point where the principal limiting factor is not the number of qubits, but the entangling gate infidelity.
However, a highly detailed system characterization required to understand the underlying errors is an arduous process and impractical with increasing chip size.
Open-loop optimal control techniques allow for the improvement of gates but are limited by the models they are based on.
To rectify the situation, we provide a new integrated open-source tool-set for Control, Calibration and Characterization (C^3), capable of open-loop pulse optimization, model-free calibration, model fitting and refinement.
We present a methodology to combine these tools to find a quantitatively accurate system model, high-fidelity gates and an approximate error budget, all based on a high-performance, feature-rich simulator.
We illustrate our methods using fixed-frequency superconducting qubits for which we learn model parameters to an accuracy of <1% and derive a coherence limited cross-resonance (CR) gate that achieves 99.6% fidelity without need for calibration.

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High-Impedance NbN Microwave Resonator as a Quantum Bus for Si Hole Spin Qubits

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Quantum computing is a major new frontier in technology promising computing power unattainable by classical computers. Among many different materials and approaches explored so far, silicon is emerging as a promising route to quantum computing with true potential in terms of scalability and manufacturability. With the recent development of spin-orbit qubit based on holes in silicon [1], it is nowadays conceivable to use a microwave photon as a « quantum bus » for long distance spin-orbit qubit interaction. The strong spin/photon coupling has been recently achieved using an engineered spin-orbit interaction with electron spins in silicon [2,3] or in carbon nanotubes [4]. Our goal here is to use the intrinsic spin-orbit term in the valence band of silicon to achieve this coherent spin/photon coupling.

Here we will present our co-integration project : a CMOS silicon spin qubit embedded in a high-impedance NbN superconducting microwave resonator. We will describe the result of the high impedance resonators in the coplanar waveguide geometry made of a 10 nm thick NbN film. In the single photon regime, the resonator exhibits an internal quality factor $Q_i > 2.10^4$ at zero field. While in the many photons regime, we measured $Q_i > 5.10^4$ in a 6 T in-plane magnetic field and $Q_i > 3.10^4$ in a 300 mT out-of-plane magnetic field. It is the first step towards long-range coupling of hole spin qubits in silicon.

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