HL 55: Superconducting Electronics: SQUIDs, Qubits, Circuit QED, Quantum Coherence and Quantum Information Systems 2 (jointly with MA, HL) (joint session TT/HL)

Time: Thursday 9:30–12:30 Location: HSZ 03

HL 55.1 Thu 9:30 HSZ 03

Waveguide Bandgap Engineering with an Array of Superconducting Qubits — •Jan David Brehm[1], Alexander N. Poddubny[2], Alexander Stehli[1], Tim Wolz[1], Hannes Rotzinger[1,3], and Alexey V. Ustinov[1,4,5] — [1]Physikalisches Institut, Karlsruher Institut für Technologie, Karlsruhe, Germany — [2]Ioffe Institute, St. Petersburg, Russia — [3]Institut für Festkörperphysik, Karlsruher Institut für Technologie, Karlsruhe, Germany — [4]National University of Science and Technology MISIS, Moscow, Russia — [5]Russian Quantum Center, Skolkovo, Moscow, Russia

In one dimension the interaction of qubits with free space instead of a cavity gives rise to an effective qubit-qubit coupling which is of infinite range and can be tuned by varying the qubit separation. In this work, we experimentally study an array of eight superconducting transmon qubits with local frequency control, which are all coupled to the mode continuum of a superconducting waveguide. The spacing between adjacent qubits is substantially smaller than the wavelength corresponding to their excitation frequency, eliminating almost completely the coherent exchange type interaction between qubits. By consecutively tuning the qubits to a common resonance frequency we observe the formation of super- and subradiant states as well as the emergence of a bandgap. Furthermore, we study the nonlinear saturation of the collective modes with increasing photon number and electromagnetically induce a transparency window in the bandgap region of the ensemble.

HL 55.2 Thu 9:45 HSZ 03

Employing a real-time processor for experiments with superconducting qubits — •Richard Gebauer[1], Nick Karcher[1], Alexey V. Ustinov[2,3], Martin Weides[2,4], Marc Weber[1], and Oliver Sander[1] — [1]Institute for Data Processing and Electronics, KIT, Karlsruhe, Germany — [2]Physikalisches Institut, KIT, Karlsruhe, Germany — [3]Russian Quantum Center, National University of Science and Technology MISIS, Moscow, Russia — [4]School of Engineering, University of Glasgow, Glasgow, United Kingdom

The control of superconducting quantum bits (qubits) relies on the ability to read out their state with high precision and apply custom pulses on the nanosecond timescale. As the field progresses, experiment schemes tend to get more complicated once the number of pulses increases, complex parameter changes are necessary and further data processing is needed. Conventional setups consisting of arbitrary waveform generators and digitizers connected to a measurement computer are not ideally suited to cope with this increased complexity.

A faster and more flexible solution is FPGA-based electronics. It not only dramatically reduces costs and space requirements but also simplifies measurements and enables customized control schemes like quantum feedback. Combined with a real-time processor, complex experiment flows and online data processing render possible.

We will present our platform to control and readout superconducting qubits with a focus on the real-time processing subsystem. Furthermore, we will show multiple experimental applications where the real-time processor is utilized, like evaluating correlation functions.

HL 55.3 Thu 10:00 HSZ 03

High power dispersive qubit readout and state preparation without parametric amplifier — •Martin Spiecker[1], Daria Gusenkova[1], Richard Gebauer[2], Lukas Grünhaupt[1], Patrick Winkel[1], Francesco Valenti[1,2], Ivan Takmakov[1,2,3], Dennis Rieger[1], Alexey V. Ustinov[1,4], Wolfgang Wernsdorfer[1,3,5], Oliver Sander[2], and Ioan M. Pop[1,3] — [1]Physikalisches Institut, KIT, Germany — [2]Institute for Data Processing and Electronics, KIT, Germany — [3]Institute of Nanotechnology, KIT, Germany — [4]Russian Quantum Center, MISIS, Moscow, Russia — [5]Institute Neel, CNRS, Grenoble, France

High-fidelity qubit readout is an essential requirement for fault-tolerant quantum algorithms. In theory, within the dispersive readout scheme, the state discrimination can be improved significantly if the resonator's photon population increases [1]. However, in practice the optimal photon number does usually not exceed 2.5 photons [2], and parametric amplifiers are needed to achieve a substantial signal-to-noise ratio.
In order to investigate the limitations of the readout fidelity we used a fluxonium qubit with a granular aluminum superinductance [3] having the advantage of reduced nonlinearity in comparison to previously used Josephson junction arrays. We demonstrate qubit measurements without a parametric amplifier at readout powers corresponding up to 200 photons in the resonator.

[1] A. Blais et al., PRA 69(6), 062320 (2004)
[2] T. Walter et al., PRA 7.5, 054020 (2017)
[3] L. Grünhaupt and M. Spiecker et al., Nat. Mater. 18, 816-819 (2019)

HL 55.4 Thu 10:15 HSZ 03

Experimental violation of the standard quantum limit for parametric amplification of broadband signals — •K. Fedorov[1,2], M. Renger[1,2], S. Pogorzalek[1,2], C. Scheuer[1,2], Q. Chen[1,2], Y. Nojiri[1,2], M. Partanen[1], A. Marx[1], F. Deppe[1,2,3], and R. Gross[1,2,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [2]Physik-Department, TU München, 85748 Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, 80799 Munich, Germany

Phase-preserving amplification is a crucial part of many protocols in microwave quantum information processing, such as quantum teleportation, remote state preparation [1], or dispersive qubit readout. Josephson parametric amplifiers (JPAs) allow amplification close to the standard quantum limit (SQL), implying a fundamental bound of 50 % for the maximal quantum efficiency η for amplification of narrowband input signals. We demonstrate that the SQL does not hold for broadband input signals and experimentally find $\eta = 70\,\%$ with an amplification chain consisting of a JPA and a cryogenic HEMT amplifier. We show that η can reach 100 % and experimentally is limited by the Poissonian fluctuations in the JPA pump line.
We acknowledge support by Germany's Excellence Strategy EXC-2111-390814868, Elite Network of Bavaria through the program ExQM, and the European Union via the Quantum Flagship project QMiCS (GrantNo.820505).
[1] S. Pogorzalek *et al.*, Nat. Commun. **10**, 2604 (2019).

HL 55.5 Thu 10:30 HSZ 03

Optimal control of a compact 3D quantum memory — Julia Lamprich[1,2], Stephan Trattnig[1,2], •Yuki Nojiri[1,2,3], Qiming Chen[1,2,3], Stephan Pogozarek[1,2], Michael Renger[1,2,3], Kirill Fedorov[1,2,3], Achim Marx[1,3], Matti Partanen[1,3], Frank Deppe[1,2,3], and Rudolf Gross[1,2,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Walther-Meißner-Strasse 8, D-85748 Garching, Germany — [2]Physik-Department, Technische Universität München, 85748 Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, 80799 Munich, Germany

Quantum memories are of high relevance in the context of quantum computing and communication. For building scalable architectures based on superconducting quantum circuits, 3D cavities are promising candidates for a quantum memory. Recently, a compact layout exploiting the multimode structure of a rectangular 3D cavity has been demonstrated [1]. In that work, the fidelity of the transfer process was also limited by state leakage. This can be overcome by pulse shaping using optimal control strategies [2]. Henceforth, we implement a search algorithm (CMA-ES) to find optimized pulses promising higher gate fidelities, and present first experimental results.
We acknowledge support by the Germany's Excellence Strategy EXC-2111-390814868, Elite Network of Bavaria through the program ExQM, and the European Union via the Quantum Flagship project QMiCS (Grant No. 820505).
[1] E. Xie et al., Appl. Phys. Lett. 112, 202601 (2018).
[2] Shai Machnes et al., Phys. Rev. Lett. 120, 150401 (2018)

HL 55.6 Thu 10:45 HSZ 03

Quasiclassical Green's Function Approach to Normal-Metal Quasiparticle Traps — •Raphael Schmit and Frank Wilhelm — Saarland University, Theoretical Physics Department

Superconducting qubits, such as the charge or the flux qubit, are thought to store the information needed for quantum information processing. However, unwanted interactions with the qubit's environment lead to decoherence of the qubit and thus information loss. In addition to these extrinsic sources for decoherence, there is also an intrinsic one: the coupling between the qubit and the non-equilibrium quasiparticle excitations in the superconductor the qubit is made of. Decoherence is due to quasiparticle tunneling through a Josephson junction, but there is also an inhomogeneous broadening caused by changes in the occupations of Andreev states in the junction. Both mechanisms are highly depending on the location of the quasiparticles: quasiparticles far away from junctions have much less contribution to decoherence than the ones close to it. While it is difficult to prevent the generation of quasiparticles, trapping them in less active regions of the device seems to provide a practicable way to improve the device performance.

We are aiming to establish a quantitative theory of normal-metal traps simply consisting of an island of normal metal which is in good metallic contact with the superconductor. To do so, we are applying a Green's function formalism - the Keldysh technique in the dirty limit with a quasiclassical approximation - to investigate the properties of non-equilibrium quasiparticles in mesoscopic devices.

HL 55.7 Thu 11:00 HSZ 03

Transmission spectra of an ultrastrongly coupled qubit-dissipative resonator system — •Luca Magazzù and Milena Grifoni — Institute for Theoretical Physics, University of Regensburg, 93040 Regensburg, Germany

We calculate the transmission spectra of a flux qubit coupled to a dissipative resonator in the ultrastrong coupling regime. Such a qubit-oscillator system constitutes the building block of superconducting circuit QED platforms. The calculated transmission of a weak probe field quantifies the response of the qubit, in frequency domain, under the sole influence of the oscillator and of its dissipative environment, an Ohmic heat bath. We find the distinctive features of the qubit-resonator system, namely two-dip structures in the calculated transmission, modified by the presence of the dissipative environment. The relative magnitude, positions, and broadening of the dips are determined by the interplay among qubit-oscillator detuning, the strength of their coupling, and the interaction with the heat bath.

[1] L. Magazzù and M. Grifoni, J. Stat. Mech. 104002 (2019).

15 min. break.

HL 55.8 Thu 11:30 HSZ 03

Diagrammatic Resummation Theory Approach to Few-Photon Scattering and Dynamics in Waveguide QED — •Kiryl Piasotski and Mikhail Pletyukhov — RWTH Aachen University, Germany

In the present talk, the diagrammatic resummation theory approach to the problems of multi-photon scattering and dynamics in the single-qubit waveguide QED is presented. It is shown that within the rotating wave approximation, irrespectively of the number of radiation channels, dispersion of the modes they are supporting, and the nature of the radiation-qubit coupling, the determination of both scattering and dynamical observables in the subspace of the fixed excitation number, is reducible to a solution of the closed finite system of linear integral equations. Further, the above described theoretical machinery is showcased on the number of problems regarding the systems with delayed coherent quantum feedback, namely it is shown how the formalism could be applied to determine the coherence functions of radiation within the scattering setup, as well as the determination of certain dynamical characteristics of non-Markovian waveguide QED systems.

HL 55.9 Thu 11:45 HSZ 03

Josephson-Photonics Devices as a Source of Entangled Microwave Photons — •Björn Kubala[1], Ambroise Peugeot[2], Simon Dambach[1,3], Juha Leppäkangas[4], Marc Westig[2], Gerbold Menard[2], Yuri Mukharsky[2], Carles Altimiras[2], Patrice Roche[2], Philippe Joyez[2], Denis Vion[2], Daniel Esteve[2], Fabien Portier[2], and Joachim Ankerhold[1] — [1]ICQ and IQST, Ulm University, Germany — [2]SPEC, CEA Paris-Saclay, France — [3]School of Physics and Astronomy, University of Nottingham, UK — [4]Physikalisches Institut, Karlsruhe Institute of Technology, Germany

The realization and characterization of efficient sources of entangled microwave photons is of paramount importance for many future applications of quantum technology. Josephson-photonics devices are very promising candidates for this task since they allow one to create a broad range of different entangled states in a surprisingly simple and robust way. Such devices consist of a dc-voltage-biased Josephson junction which is placed in series to several microwave cavities. Steady states with multifaceted entanglement properties then appear in steady state resulting from the interplay of multiphoton creation processes associated with the inelastic tunneling of Cooper pairs and subsequent individual photon leakage from the cavities. In this talk, we present a detailed theoretical study of the bipartite entanglement between photon pairs in the output transmission lines. Numerical simulations, taking into account low-frequency fluctuations of the bias voltage and the finite bandwidth of microwave signal detectors, show excellent agreement with recent experimental data.

HL 55.10 Thu 12:00 HSZ 03

Theory of injection locking for the Josephson laser — •Ciprian Padurariu, Lukas Danner, Björn Kubala, and Joachim Ankerhold — Institute for Complex Quantum Systems and IQST, Ulm University, 89069 Ulm, Germany

An intriguing recent experiment [1] has observed features of lasing in the microwave emission of a cavity driven by inelastic Cooper pair tunneling across a dc-voltage biased Josephson junction. A successful theory was developed explaining the emission in the lasing regime [2], however, the theory of injection locking remained unexplained.
Here, we provide the theory for injection locking in Josephson photonic devices. Specifically, we provide an analytical derivation of the phenomenological Adler equation for a large class of Josephson devices. We extract detailed guidelines for designing circuits capable of locking the phase against noises and estimate the rate of thermal and quantum phase slips that limit the locking precision.
The work aims at providing the missing ingredient, phase-stabilized Josephson oscillations, required to demonstrate the quantum entanglement of the emitted microwave light.

[1] M.C. Cassidy et al., Science 355, 939 (2017).
[2] S. Simon and N. Cooper, Phys. Rev. Lett. **121**, 027004 (2018).

HL 55.11 Thu 12:15 HSZ 03

Electron transport and spin qubit manipulation with surface acoustic waves — •Mikel Olano[1] and Geza Giedke[1,2] — [1]Donostia International Physics Center, Donostia, Spain — [2]Ikerbasque Foundation for Science, Bilbao, Spain

Spin qubits in quantum dots are among the most promising systems for the implementation of quantum computation. While coherence times and gate operation times have become very competitive, the realization of long-range interactions to enable more flexible quantum gates remains a challenge.

Here we investigate theoretically an approach to tackle this problem using a moving electrons trapped in the potential of a surface acoustic wave, that serves as an intermediary between distant stationary quantum dots.

We analyse the coherent transport and transfer of spin qubits between stationary and moving dots and quantum gates between two interacting spin qubits. Applications for the generation of multipartite entanglement and joint measurement of several qubits are discussed. The talk will highlight the parameters to be taken into account if these processes are to be optimized. The impact of the main sources of decoherence and non-adiabatic behaviour due to the time-dependence of the potential are discussed.