TT 5: Transport: Quantum Coherence and Quantum Information Systems - Experiment (Joint session of HL, MA and TT organized by TT)

Time: Monday 9:45–13:00 Location: H22

TT 5.1 Mon 9:45 H22

Tunable coupling between fixed-frequency superconducting transmon qubits — •Stefan Filipp[1], David C. McKay[2], Easwar Magesan[2], Antonio Mezzacapo[2], Jerry M. Chow[2], and Jay M. Gambetta[2] — [1]IBM Research - Zurich, 8803 Rueschlikon, Switzerland — [2]IBM TJ Watson Research Center, Yorktown Heights, NY, USA

The controlled realization of qubit-qubit interactions is essential for both the physical implementation of quantum error-correction codes and for reliable quantum simulations. Ideally, the fidelity and speed of corresponding two-qubit gate operations is comparable to those of single qubit operations. In particular, in a scalable superconducting qubit architecture coherence must not be compromised by the presence of additional coupling elements mediating the interaction between qubits. Here we present a coupling method between fixed-frequency transmon qubits based on the frequency modulation of an auxiliary circuit coupling to the individual transmons. Since the coupler remains in its ground state at all times, its coherence does not significantly influence the fidelity of consequent entangling operations. Moreover, with the possibility to create interactions along different directions, our method is suited to engineer Hamiltonians with adjustable coupling terms. This property can be utilized for quantum simulations of spins or fermions in transmon arrays, in which pairwise couplings between adjacent qubits can be activated on demand.

TT 5.2 Mon 10:00 H22

Concentric transmon qubit featuring fast tunability and an anisotropic magnetic dipole moment — •Jochen Braumüller[1], Martin Sandberg[2], Michael R. Vissers[2], Andre Schneider[1], Steffen Schlör[1], Lukas Grünhaupt[1], Hannes Rotzinger[1], Michael Marthaler[1], Alexander Lukashenko[1], Amadeus Dieter[1], Alexey V. Ustinov[1,3], Martin Weides[1,4], and David P. Pappas[2] — [1]Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany — [2]National Institute of Standards and Technology, Boulder, Colorado 80305, USA — [3]National University of Science and Technology MISIS, Moscow 119049, Russia — [4]Johannes Gutenberg University, Mainz, 55128 Mainz, Germany

We present a planar qubit design based on a superconducting circuit that we call concentric transmon. While employing a straightforward fabrication process using Al evaporation and lift-off lithography, we observe qubit lifetimes and coherence times in the order of $10\,\mu$s. We systematically characterize loss channels such as incoherent dielectric loss, Purcell decay and radiative losses. The implementation of a gradiometric SQUID loop allows for a fast tuning of the qubit transition frequency and therefore for full tomographic control of the quantum circuit. Due to the large loop size, the presented qubit architecture features a strongly increased magnetic dipole moment as compared to conventional transmon designs. This renders the concentric transmon a promising candidate to establish a site-selective passive direct $\hat{Z}$ coupling between neighboring qubits, being a pending quest in the field of quantum simulation.

TT 5.3 Mon 10:15 H22

Quasiparticle-Induced Decoherence of Microscopic Two-Level-Systems in Superconducting Qubits — •Alexander Bilmes[1], Jürgen Lisenfeld[1], Sebastian Zanker[1], Michael Marthaler[2], Gerd Schön[2], Georg Weiss[1], and Alexey V. Ustinov[1] — [1]PHI, KIT, 76131 Karlsruhe, Germany — [2]TFP, KIT, 76131 Karlsruhe, Germany

Parasitic Two-Level-Systems (TLS) are one of the main sources of decoherence in superconducting nano-scale devices such as SQUIDs, resonators and quantum bits (qubits), although the TLS' microscopic nature remains unclear. We use a superconducting phase qubit to detect TLS contained within the tunnel barrier of the qubit's Al/AlOx/Al Josephson junction. If the TLS transition frequency lies within the $6-10$ GHz range, we can coherently drive it by resonant microwave pulses and access its quantum state by utilizing the strong coupling to the qubit. Our previous measurements of TLS coherence in dependence of the temperature indicate that quasiparticles (QPs), which diffuse from the superconducting Al electrodes into the oxide layer, may give rise to TLS energy loss and dephasing [1]. Here, we probe the TLS-QP interaction using a reliable method of *in-situ* QP injection via an on-chip dc-SQUID that is pulse-biased beyond its switching current. The QP density is calibrated by measuring associated characteristic changes to the qubit's energy relaxation rate. We will present experimental data which show the QP-induced TLS decoherence in good agreement to theoretical predictions.

[1] J. Lisenfeld et al., PRL **105**, 230504 (2010)

TT 5.4 Mon 10:30 H22

Transmon qubits enter circuit nano-electromechanics — •Daniel Schwienbacher[1,2], Matthias Pernpeintner[1,2,3], Friedrich Wulschner[1,2], Philip Schmidt[1,2,3], Frank Deppe[1,2,3], Achim Marx[1], Rudolf Gross[1,2,3], and Hans Huebl[1,2,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [2]Physik-Department, TU München, 85748 Garching, Germany — [3]Nanosystems Initiative Munich (NIM), 80799 München, Germany

The field of cavity nano-electromechanics combines nano-scale mechanical elements with microwave circuits for the investigation of the light-matter interaction on a quantum level. In this context ground state cooling, electromechanically induced transparency effects, as wells as state transfer between the mechanical and photonic modes have been demonstrated. Recently, Abdi et al.[1] have proposed the integration of a nanomechanical beam into the capacitor of a transmon qubit, which is in turn coupled to a microwave resonator and predicted enhanced electro-mechanical coupling rates as well as the preparation of mechanical Fock states and the generation of three-partite entanglement. Here, we present an experimental study concerning the integration of a nanomechanical beam, a transmon qubit, and a microwave resonator on a single chip. We will discuss fabricational aspects and first spectroscopy data of the device.

We thankfully acknowledge financial support by the DFG via the collaborative research center SFB 631.

[1] Mehdi Abdi et al., PRL **114**, 173602 (2015)

TT 5.5 Mon 10:45 H22

Thermal microwave states acting on a superconducting qubit — •Jan Goetz[1,2], Miriam Müting[1,2], Max Haeberlein[1,2], Friedrich Wulschner[1,2], Edwar Xie[1,2,3], Peter Eder[1,2,3], Michael Fischer[1,2], Frank Deppe[1,2], Kirill Fedorov[1,2], Hans Hübl[1,2], Frank Deppe[1,2,3], Achim Marx[1], and Rudolf Gross[1,2,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [2]Physik-Department, TU München, 85748 Garching, Germany — [3]Nanosystems Initiative Munich (NIM), Schellingstraße 4, 80799 München, Germany

We analyze the influence of broadband thermal states in the microwave regime on the coherence properties of a superconducting (transmon) qubit coupled to a transmission line resonator. We generate the thermal states inside the resonator by heating a 30 dB attenuator to emit blackbody radiation into a transmission line. In the absence of thermal fluctuations, the qubit coherence time is limited by relaxation. We find that the relaxation rate is almost unaffected by the presence of a thermal field inside the resonator. However, such states induce significant dephasing which increases quadratically with the number of thermal photons, whereas for a coherent population of the resonator, the increase shows a linear behavior. These results confirm the different photon statistics, being Poissonian for a coherent population and super-Poissonian for a thermal population of the resonator.

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TT 5.6 Mon 11:00 H22

Displacement of squeezed propagating microwave states — •Kirill G. Fedorov[1], P. Yard[1,2], S. Pogorzalek[1,2], P. Eder[1,2,3], M. Fischer[1,2,3], J. Goetz[1,2], F. Wulschner[1,2], E. Xie[1,2,3], F. Deppe[1,2,3], A. Marx[1], and R. Gross[1,2,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [2]Physik-Department, Technische Universität München, 85748 Garching, Germany — [3]Nanosystems Initiative Munich (NIM), Schellingstraße 4, 80799 München, Germany

The displacement of propagating quantum states of light is a fundamental operation for quantum communication. It can be applied to fundamental studies of macroscopic quantum coherence and has an important role in quantum teleportation protocols with continuous variables. We study an experimental implementation of this operation for propagating squeezed microwave states. We generate these states using a Josephson parametric amplifier and implement the displacement operation using a specific cryogenic directional coupler. We demonstrate that even for strong displacement amplitudes we do not observe any degradation of the reconstructed quantum states. Furthermore, we confirm that path entanglement generated using displaced squeezed states, also stays constant over a wide range of the displacement power.

We acknowledge support by the German Research Foundation through SFB 631 and FE 1564/1-1, the EU project PROMISCE, and Elite Network of Bavaria through the program ExQM.

15 min. break

Invited Talk TT 5.7 Mon 11:30 H22

Coherent Suppression of Quasiparticle Dissipation in a Superconducting Artificial Atom — •Ioan Pop — Physikalisches Institut, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany — Department of Applied Physics, Yale University, New Haven, CT 06520, USA

We demonstrate immunity to quasiparticle dissipation in a Josephson junction. At the foundation of this protection rests a prediction by Brian Josephson from fifty years ago: the particle-hole interference of superconducting quasiparticles when tunneling across a Josephson junction [1]. The junction under study is the central element of a fluxonium artificial atom, which we place in an extremely low loss environment and measure using radio-frequency dispersive techniques [2]. Furthermore, by using a quantum limited amplifier (a Josephson Parametric Converter) we can observe quantum jumps between the 0 and 1 states of the qubit in thermal equilibrium with the environment. The distribution of the times in-between the quantum jumps reveals quantitative information about the population and dynamics of quasiparticles[3]. The data is entirely consistent with the hypothesis that our system is sensitive to single quasiparticle excitations, which opens new perspectives for quasiparticle monitoring in low temperature devices.

[1] B. D. Josephson, Physics Letters **1**, 251 (1962)
[2] I. M. Pop et al., Nature **508** (2014)
[3] U. Vool et al., PRL **113** (2014)

TT 5.8 Mon 12:00 H22

Tunable superconducting resonators with integrated trap structures for coupling with ultracold atomic gases — •Benedikt Ferdinand[1], Daniel Bothner[1,2], Dominik Wiedmaier[1], Dieter Koelle[1], and Reinhold Kleiner[1] — [1]Physikalisches Institut and Center for Quantum Science (CQ) in LISA$^+$, Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany — [2]Kavli Institute of Nanoscience, Delft University of Technology, PO Box 5046, 2600 GA, Delft, The Netherlands

We intend to investigate a hybrid quantum system where ultracold atomic gases play the role of a long-living quantum memory, coupled to a superconducting qubit via a coplanar waveguide transmission line resonator. As a first step we developed a resonator chip containing a Z-shaped trapping wire for the atom trap. In order to suppress parasitic resonances due to stray capacitances, and to achieve good ground connection we use hybrid superconductor - normal conductor chips. As an additional degree of freedom we add a ferroelectric capacitor making the resonators voltage-tunable. We furthermore show theoretical results on the expected coupling strength between resonator and atomic cloud.

TT 5.9 Mon 12:15 H22

Quantum correlations in microwave frequency combs — •Thomas Weissl[1], Erik Tholén[2], Daniel Forchheimer[1,2], and David B. Haviland[1] — [1]KTH- Royal Institute of Technology, 106 91 Stockholm, Sweden — [2]Intermodulation Products AB, 823 93 Segersta, Sweden

Non-linear superconducting resonators are used as parametric amplifiers in circuit quantum electrodynamics experiments [1]. When pumped below threshold the pump correlates vacuum fluctuations in the signal and idler bands giving rise to two-mode squeezed vacuum. When a non-linear oscillator is pumped with a frequency comb complex multipartite entangled states can be created as demonstrated in similar experiments in the optical domain [2]. We present a method to generate and measure microwave frequency combs by up- and down-conversion from intermediate frequencies. The comb is generated and analyzed using a multi-frequency lock-in amplifier. From transmission measurements we extract correlation- and quasi-probability functions.

[1] E. Tholén et al., APL **90**, 253509 (2007)
[2] M. Chen et al., PRL **112**, 120505 (2014)

TT 5.10 Mon 12:30 H22

Microwave experiments with quantum phase-slip in superconducting AlO_x nanowires — •Sebastian T. Skacel[1], Marco Pfirrmann[1], Jan N. Voss[1], Micha Wildermuth[1], Julian Münzberg[1], Lucas Radtke[1], Sebastian Probst[1], Martin Weides[1,2], J. E. Mooij[1,3], Hannes Rotzinger[1], and Alexey V. Ustinov[1] — [1]Physikalisches Institut, Karlsruher Institut für Technologie, D-76131 Karlsruhe, Germany — [2]Institute of Physics, Johannes Gutenberg University Mainz, D-55128 Mainz, Germany — [3]Kavli Institute of Nanoscience, Delft University of Technology, 2628 CJ Delft, The Netherlands

Superconducting nanowires in the quantum phase slip (QPS) regime allow to study the flux and phase dynamics in duality to Josephson junction systems. We experimentally study QPS effects of nanowires which are embedded in a resonant microwave circuit. The samples are probed at ultra-low microwave power and applied magnetic field at mK temperatures. The AlO_x nanowires, with a sheet resistance in the kΩ range, are fabricated by sputter deposition of aluminium in a controlled oxygen atmosphere. The wires are defined with conventional electron beam lithography into hydrogen silsesquioxane (HSQ) down to a width of 15-30 nm.

We present the single layer process fabrication and measurements of nanowires galvanically coupled to a superconducting lumped element microwave resonator.

TT 5.11 Mon 12:45 H22

Localized quantum phase slips in TiN nanowires — •Ina Schneider[1], Tatyana Baturina[1,2], and Christoph Strunk[1] — [1]Inst. f. Exp. und Angewandte Physik, Uni Regensburg — [2]Inst. f. Semiconductor Physics, RAS, Novosibirsk, Russia

We investigate TiN nanowires with 780 nm length and widths ranging from 50-780 nm close to the superconductor/insulator transition. In zero magnetic field the superconducting transition of wider wires resembles that of macroscopic films, while narrower wires develop a finite and T-independent resistance down to the lowest temperatures. In perpendicular magnetic field B a pronounced nonmontonic magnetoresistance occurs. The $R(T)$-curves at fixed B show a reentrant insulating behavior very similar to that of Coulomb-blockaded linear arrays of Josephson junctions [1].

The $I(V)$-characteristics display a characteristic cross-over from the dc-Josephson effect towards Coulomb blockade at very low voltages and temperatures within a globally superconductive-like $I(V)$. In the linear regime, the magnetoresistance displays strong fluctuations. We interpret our results in terms of disordered Josephson networks with a B-dependent Josephson coupling energy that favors coherent quantum phase slips at certain B.

[1] A. Ergül, et al., NJP **15**, 095014 (2014).