TT 37: Superconducting Electronics: SQUIDs, Qubits, Circuit QED

Time: Friday 9:30–13:15 Location: H22

TT 37.1 Fri 9:30 H22

Nb constriction Josephson junctions and nanoSQUIDs patterned by He and Ne focused ion beams — •Simon Pfander[1], Timur Griener[1], Julian Linek[1], Thomas Weimann[2], Ute Drechsler[3], Reinhold Kleiner[1], Armin Knoll[3], Oliver Kieler[2], and Dieter Koelle[1] — [1]Physikalisches Institut, Center for Quantum Science (CQ) and LISA$^+$, Universität Tübingen, 72076 Tübingen, Germany — [2]Department Quantum Electronics, Physikalisch-Technische Bundesanstalt (PTB), 38116 Braunschweig, Germany — [3]IBM Research Europe – Zürich, 8803 Rüschlikon, Switzerland

Nanopatterning of superconducting thin film structures with focused He or Ne ion beams (He/Ne-FIB) offers a flexible tool for creating constriction-type Josephson junctions (cJJs) and strongly miniaturized superconducting quantum interference devices (nanoSQUIDs) for magnetic sensing on the nanoscale. We present our attempts to use He/Ne-FIB for fabricating Nb cJJs and nanoSQUIDs which shall provide ultra-low noise and high spatial resolution for their application in scanning SQUID microscopy (SSM). The nanoSQUIDs are designed as sensors for magnetic flux and dissipation. They shall be integrated on custom-made Si cantilevers, which will provide the possibility of simultaneous conventional topographic imaging by atomic force microscopy (AFM). We will discuss the status of this project and challenges that have to be met on the way to combine SSM and AFM on the nanoscale.

We acknowledge the European Commission under H2020 FET Open grant FIBsuperProbes (number 892427).

TT 37.2 Fri 9:45 H22

Development of a three-wave-mixing Josephson traveling-wave parametric amplifier — •Victor Gaydamachenko[1], Christoph Kissling[1,2], Lukas Grünhaupt[1], Ralf Dolata[1], and Alexander B. Zorin[1] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Technische Universität Ilmenau, Germany

Modern quantum experiments profit from wideband amplification of small microwave signals with noise approaching the quantum-limit. A promising approach to design an amplifier having a bandwidth of several GHz, power gain of 20 dB, and quantum-limited noise are traveling-wave parametric amplifiers (TWPAs). We develop a Josephson traveling-wave parametric amplifier (JTWPA), based on a series array of 1500 rf-SQUIDs, and utilising the three-wave mixing regime. One of the main challenges of TWPAs is power leakage to unwanted processes like the generation of higher harmonics and mixing products, which significantly limit the gain. To solve this obstacle, we apply a dispersion engineering technique. Here, we present numerically optimised parameter sets for practical realisation of our concept. Simulations of the device operation show a signal gain of 20 dB in the frequency range from 3 GHz to 9 GHz.

TT 37.3 Fri 10:00 H22

Charge-mediated quantum phase slip interference — •Jan Nicolas Voss[1], Micha Wildermuth[1], Max Kristen[1,2], Hannes Rotzinger[1,2], and Alexey V. Ustinov[1,2] — [1]Physikalisches Institut, Karlsruher Institut für Technologie, Karlsruhe, Germany — [2]Institut für Quantenmaterialien und Technologien (IQMT), Karlrsruher Institut für Technologie, Karlsruhe, Germany

The duality between quantum phase slip junctions and Josephson junctions has triggered a variety of theoretical and experimental works and set the basis for a new type of quantum device based on coherent quantum phase slips. We present a realization of a quantum phase slip interferometer based on two strongly coupled superconducting nanowires. The interference is controlled by a gate voltage and visible as a periodic modulation of the critical Coulomb blockade voltage. The strength of the modulation strongly depends on the homogeneity of the wires, as the phase slip rates exponentially depend on the normal state resistances of the wires. We use the intrinsic electromigration technique ([1]) to adjust and homogenize the resistances of the wires in-situ and therefore are able to study a large range of wire impedances for single devices.

[1] J. N. Voss, Y. Schön, M. Wildermuth, D. Dorer, J. H. Cole, H. Rotzinger, A. V. Ustinov, ACS Nano 15, 4108 (2021)

TT 37.4 Fri 10:15 H22

RF superconducting arbitrary waveform generator for Qubit control — •Hao Tian, Oliver Kieler, Alexander Fernandez Scarioni, Silke Wolter, Rolf-Werner Gerdau, Johannes Kohlmann, and Mark Bieler — Physikalisch Technische Bundesanstalt

The Josephson Arbitrary Waveform Synthesizer (JAWS) allows for the quantum-accurate-generation of spectrally-pure, arbitrary waveforms. It consists of a series array of Josephson junctions and is driven by GHz bit sequences (current pulses). So far, JAWS circuits are mainly used at National Metrology Institutes for metrological purposes with output frequencies in the kHz to MHz frequency range. Within the scope of the national QuMIC project, PTB and other partners are currently further developing JAWS circuits with the aim to realize a compact and robust module, which is suitable for control and readout of superconducting qubits. In this talk, we will present the work, which is currently undertaken at PTB to reach this goal. Here, the main focus lies on the design and the fabrication of novel JAWS circuits and complex waveguide filters, capable of synthesizing arbitrary waveforms at GHz frequencies. This work was partly supported by German Federal Ministry of Education and Research (contract number: 13N15934).

TT 37.5 Fri 10:30 H22

Gate-tunable kinetic inductance in proximitized nanowires — •Lukas Johannes Splitthoff[1], Arno Bargerbos[1], Lukas Grünhaupt[1], Marta Pita-Vidal[1], Jaap Joachim Wesdorp[1], Yu Liu[2], Angela Kou[3], Christian Kraglund Andersen[1], and Bernard van Heck[4] — [1]Delft University of Technology, Delft University of Technology, Delft, The Netherlands — [2]Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark — [3]Department of Physics and Frederick Seitz Materials Research Laboratory, University of Illinois Urbana-Champaign, Urbana, USA — [4]Leiden Institute of Physics, Leiden University, Leiden, The Netherlands

Superconducting-semiconducting nanowires combine two frontiers of condensed matter in a hybrid state, which offers formidable possibilities for quantum computing and quantum sensing devices. In this talk, we study a quarter-wave coplanar waveguide resonator shunted by a hybrid InAs/Al nanowire. We show a gate voltage controllable resonance frequency and demonstrate a frequency shift of up to 8MHz. We relate the frequency shift to the change in kinetic inductance of the hybrid nanowire which arises from the gate-tunable hybridization of the superconductor to semiconductor interface. From our measurement results we extract the normal state conductivity and the superconducting gap of the hybrid nanowire. The measurement technique demonstrated in this work complements existing characterization methods for hybrid nanowires and forms a promising path towards gate-controlled superconducting electronics.

TT 37.6 Fri 10:45 H22

Microwave photonics in high kinetic inductance microstrip networks — •Niklas Gaiser[1], Samuel Goldstein[2], Guy Pardo[2], Naftali Kirsh[2], Ciprian Padurariu[1], Björn Kubala[1,3], Nadav Katz[2], and Joachim Ankerhold[1] — [1]ICQ and IQST, University of Ulm, Ulm, Germany — [2]The Racah Institute of Physics, The Hebrew University of Jerusalem, Israel — [3]Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany

Microwave photonics based on superconducting circuits is a promising candidate for many quantum-technological applications. Progress towards compact integrated photonics devices in the microwave regime, however, is constrained by their long wavelengths.

Here, we discuss a solution to these difficulties via compact networks of high-kinetic inductance microstrip waveguides with strongly reduced phase velocities experimentally realized in [1]. We describe, how the Kirchhoff equations of a periodic network map to a tight-binding model, which allows a description in term of Bloch waves and band structures, to explain experimental features. The ability to employ band-structure design techniques together with the unique properties of compactness, reduced speed of light, and strong non-linear features allows the design of highly versatile on-chip microwave networks. Furthermore utilizing this platform, we present first theoretical device proposals of linear and non-linear functional units, such as

beamsplitters, filters, resonators and diodes exploiting non-reciprocity.
[1] S. Goldstein, G. Pardo, N. Kirsh, N. Gaiser, C. Padurariu, B. Kubala, J. Ankerhold, and N. Katz, New J. Phys. 24 023022 (2022)

TT 37.7 Fri 11:00 H22

Emission of photon multiplets by a dc-biased superconducting circuit — •Björn Kubala[1,2], Gerbold Menard[3], Ambroise Peugeot[3], Ciprian Padurariu[2], Chloe Rolland[3], Yuri Mukharsky[3], Zubair Iftikhar[3], Carles Altimiras[3], Patrice Roche[3], Helene le Sueur[3], Philippe Joyez[3], Denis Vion[3], Daniel Esteve[3], Joachim Ankerhold[2], and Fabien Portier[3] — [1]Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany — [2]ICQ and IQST, Ulm University, Germany — [3]SPEC, CEA Paris-Saclay, France

We show experimentally that a dc-biased Josephson junction in series with a high-impedance microwave resonator can emit up to $k = 6$ photons simultaneously for each Cooper pair tunneling through the junction [1]. Our resonator is made of a simple micro-fabricated spiral coil that resonates at 4.4 GHz and reaches a 1.97 kΩ characteristic impedance, corresponding to an effective fine-structure constant, $\alpha \sim 1$. Measuring the second order correlation function of the emission from the resonator allows computing the Fano factor F of the emitted photons, found to coincide with the naive prediction $F = k$ in the weak driving regime. At larger Josephson coupling E_J, a more complex behavior is observed in quantitative agreement with numerical simulations. This simple scheme highlights the ability of superconducting devices operating in the microwave domain to reach strong-coupling regimes of matter-light coupling inaccessible to conventional quantum optics experiments in the visible domain.
[1] G. C. Menard, et al., Phys. Rev. X **12**, 021006 (2022).

TT 37.8 Fri 11:15 H22

Waveguide quantum electrodynamics in high impedance networks — •Miriam Resch[1], Ciprian Padurariu[1], Björn Kubala[1,2], and Joachim Ankerhold[1] — [1]ICQ and IQST, Ulm University, Ulm, Germany — [2]Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany

The emerging field of high impedance quantum circuits aims to exploit the extraordinary properties of high kinetic inductance materials, such as granular superconductors. The low propagation speed of electromagnetic excitations in such devices enables to strongly couple sub-units of quantum information devices, namely various types of qubits or resonators and waveguides. Theoretical description of such strongly coupled systems is challenging as the localized modes of the sub-unit typically couples to many waveguide modes simultaneously so that many common approximation schemes break down. While strong-coupling effects in closed systems have been widely investigated, showing, e.g. the breakdown of the Jaynes-Cummings model, our project aims at describing strongly coupled open quantum systems and photon emission. With experimental collaborators, we ultimately want to identify strong-coupling signatures in observables of the emitted radiation. Here, we present as preliminary steps towards the description of more complicated systems first investigations based on an ansatz, where the wave function of the complete system (unit + waveguide) is described by superposition of coherent states as proposed in [1], which allows to solve the system dynamics in a numerically efficient way.
[1] Nicolas Gheeraert et al., New J. Phys. 19 (2017) 023036

15 min. break

TT 37.9 Fri 11:45 H22

Fano interference in microwave resonator measurements — •Simon Günzler[1,2], Dennis Rieger[2], Martin Spiecker[1,2], Wolfgang Wernsdorfer[1,2], and Ioan Pop[1,2] — [1]IQMT, Karlsruhe Institute of Technology, Germany — [2]PHI, Karlsruhe Institute of Technology, Germany

Resonator measurements are a simple but powerful tool to characterize a material's microwave response. The losses of a resonant mode are quantified by its internal quality factor Q_i, which can be extracted from the scattering coefficient in a microwave reflection or transmission measurement. Here we show that a systematic error on Q_i arises from Fano interference of the signal with a background path. Limited knowledge of the interfering paths and their relative amplitudes in a given setup translates into a range of uncertainty for Q_i, which increases with the coupling coefficient. We experimentally illustrate the relevance of Fano interference in typical microwave resonator measurements and the associated pitfalls encountered in extracting Q_i. On the other hand, we show how to characterize and utilize the Fano interference to eliminate the systematic error.

TT 37.10 Fri 12:00 H22

Direct observation of microscopic tow-level systems in granular aluminum films — •Maximillian Kristen[1,2], Jan N. Voss[2], Micha Wildermuth[2], Andre Schneider[2], Hannes Rotzinger[1,2], and Alexey V. Ustinov[1,2] — [1]Institut für QuantenMaterialien und Technologien (IQMT), Karlsruher Institut für Technologie — [2]Physikalisches Institut, Karlsruher Institut für Technologie

Thin films of disordered superconductors are extensively studied due to their applicability in quantum circuits and detectors, where they can provide kinetic inductances orders of magnitude higher than their geometric inductance. While these films generally show very high quality factors in microwave measurements, their disordered microscopic structure favors the presence of numerous material defects behaving as two-level systems (TLS). TLS have been shown to be a major source of dielectric loss in microwave circuits and are limiting the coherence properties of modern superconducting qubits.

We present microwave spectroscopy measurements of resonators made from highly resistive granular aluminum films. By applying mechanical strain and electric fields, we observe several TLS strongly interacting with the resonator modes. We compare the measured data to an analytical model for the single-photon interaction with TLS and estimate relevant physical properties.

TT 37.11 Fri 12:15 H22

Magnetic 1/f noise in superconducting microstructures and the fluctuation-dissipation theorem — •M. Herbst, A. Fleischmann, L. Gastaldo, D. Hengstler, L. Münch, A. Reifenberger, C. Ständer, and C. Enss — Uni Heidelberg

The performance of superconducting devices like SQUIDs and qubits is often limited by 1/f-noise and finite coherence times. Various types of slow fluctuators in the Josephson-junctions and in the passive parts of these superconducting circuits can cause such noise, and devices most likely suffer from a combination of different noise sources, which are hard to disentangle and therefore hard to eliminate. Magnetic flux noise caused by fluctuating magnetic moments of magnetic impurities or dangling bonds in superconducting inductances, surface oxides, insulating oxide layers and adsorbates should be a very likely contribution in many cases. We present an experimental setup to measure at Millikelvin temperatures both, the complex impedance of superconducting micro-structures as well as the magnetic flux noise that is picked-up by these structures. This allows for very important sanity checks by connecting both quantities via the fluctuation-dissipation-theorem. In order to allow for state-of-the-art sensitivity in both experiments, the structures under investigation are part of a Wheatstone-like bridge, read-out by two cross-correlated independent dc-SQUID readout chains. We present measurements of the insulating SiO2 layers of our devices, the superconducting structures themselves, and magnetically doped noble-metal layers in the vicinity of the pickup coils at T = 20-800mK and f=100mHz-100kHz.

TT 37.12 Fri 12:30 H22

A quantum Szilard engine for two-level systems coupled to a qubit — •Martin Spiecker[1], Patrick Paluch[1], Niv Drucker[2], Shlomi Matityahu[1], Daria Gusenkova[1], Nicolas Gosling[1], Simon Günzler[1], Dennis Rieger[1], Ivan Takmakov[1], Francesco Valenti[1], Patrick Winkel[1], Richard Gebauer[1], Oliver Sander[1], Gianluigi Catelani[3], Alexander Shnirman[1], Alexey V. Ustinov[1], Wolfgang Wernsdorfer[1], Yonatan Cohen[2], and Ioan M. Pop[1] — [1]Karlsruher Institut für Technologie, Karlsruhe, Germany — [2]Quantum Machines, Tel Aviv-Yafo, Israel — [3]Forschungszentrum Jülich, Jülich, Germany

The innate complexity of solid state physics exposes superconducting quantum circuits to interactions with uncontrolled degrees of freedom degrading their coherence. By using a simple stabilization sequence we show that a superconducting fluxonium qubit is coupled to a two-level system (TLS) environment of unknown origin, with a relatively long energy relaxation time exceeding 50ms. Implementing a quantum Szilard engine with an active feedback control loop allows us to decide whether the qubit heats or cools its TLS environment. The TLSs can be cooled down resulting in a four times lower qubit population, or they can be heated to manifest themselves as a negative temperature environment corresponding to a qubit population of 80%. We show that the TLSs and the qubit are each other's dominant loss mechanism and that the qubit relaxation is independent of the TLS populations. Mitigating TLS environments is therefore not only crucial to improve qubit lifetimes but also to avoid non-Markovian qubit dynamics.

TT 37.13 Fri 12:45 H22

Green's function approach to modelling finite size systems for applications in superconducting waveguide QED — •Pradeepkumar Nandakumar[1], Andres Rosario Hamann[1,2], Rohit Navarathna[1], Maximilian Zanner[3], Mikhail Pletyukhov[4], and Arkady Fedorov[1] — [1]ARC Centre of Excellence for Engineered Quantum Systems, School of Mathematics and Physics, The University of Queensland, Saint Lucia, Queensland 4072, Australia — [2]Department of Physics, ETH Zurich, CH-8093 Zurich, Switzerland — [3]Center for Quantum Physics, and Institute for Experimental Physics, University of Innsbruck, A-6020 Innsbruck, Austria — [4]Institute for Theory of Statistical Physics, RWTH Aachen University, 52056 Aachen, Germany

In superconducting waveguide QED, artificial atoms are coupled to a 1D radiation channel that consists of continuum of electromagnetic modes. Waveguides are often modelled as infinite in size with open boundary conditions for the ease of understanding. However, while modelling waveguides employed in experiments, one should consider both the finite size of the waveguide as well as its coupling to measurement apparatus. To this end, we have developed a general method to realistically model any waveguide QED system using the Green's function methods that is often employed in studying electronic transport. We apply our formalism and experimentally study the formation of Atom-Photon Bound States (APBS) using two transmon qubits coupled to a 3D rectangular waveguide. Our results identify the prospects for using APBS for studying bosonic impurity models.

TT 37.14 Fri 13:00 H22

Dirac physics and charge localization due to quasiperiodic nonlinear capacitances — •Tobias Herrig[1], Jedediah Pixeley[2], Elio König[3], and Roman-Pascal Riwar[1] — [1]Forschungszentrum Jülich, Germany — [2]Rutgers University, Piscataway, New Jersey, USA — [3]Max-Planck Institute, Stuttgart, Germany

Superconducting circuits are an extremely versatile platform to realize quantum information hardware, and, as was recently realized, to emulate topological materials, such as Weyl semimetals or Chern insulators. We here show how a simple arrangement of capacitors and conventional SIS junctions can realize a nonlinear capacitive element with a suprising property: it can be quasiperiodic with respect to the quantized Cooper-pair charge. Integrating this element into a larger circuit opens the door towards the engineering of an even broader class of systems. First, we use it to simulate a protected Dirac material defined in the transport degrees of freedom. The presence of the Dirac point leads to a suppression of the classical part of the finite-frequency noise. Second, we are able to exploit the quasiperiodicity to implement the Aubry-André model, and therebey to emulate Anderson localization in charge space. Our setup implements a truly non-interacting version of the model, in which the macroscopic quantum mechanics of the circuit already incorporates microscopic interaction effects. This should be contrasted to conventional solid state and cold atomic realizations, where competition between interaction and localization are a common side effect. We predict that quantum charge fluctuations directly probe the localization effect.