Superconducting Quantum Devices 2018 (SQD18)

National Physical Laboratory
Hampton Road
Teddington
Middlesex
TW11 0LW

18th July 2018

SQD2018 organised by Connor Shelly and Jonathan Williams (NPL)

The SQD meeting series is sponsored by Royal Holloway University of London

Programme at a glance

10:30 Refreshments available

10:50 Introduction

11:00 Talk 1
Martin Weides, University of Glasgow
Sensing and simulation applications with superconducting quantum circuits

11:23 Talk 2
Jonathan Burnett, Chalmers
Fluctuations in qubit lifetimes for long-lived T1 limited superconducting qubits

11:46 Talk 3
Sebastian de Graaf, National Physical Laboratory
Reducing 1/f noise in quantum devices by surface spin desorption

12:09 Talk 4
Matthias Mergenthaler, University of Oxford
A voltage-tunable superconducting qubit based on a carbon nanotube

12:32 Talk 5
Michael Hartmann, Heriot-Watt University
Simulating Quantum Magnets in Superconducting Circuits

12:55 Talk 6
Takahiro Tsunoda, University of Oxford
Implementing the Variational Quantum Eigensolver with error mitigation in a 2-qubit superconducting circuit

---

13:20 Lunch and Exhibition (Reception Area); Posters (F16-CS6/7)

14:40 Talk 7
Matthias Eschrig, Royal Holloway University of London
Towards a Superconducting Spintronics Device Concept

15:03 Talk 8
Niladri Banerjee, Loughborough University
Spin-orbit coupled triplet spin valve and dynamics of triplet Josephson junctions

15:26 Talk 9
Sergey Danilin, Karlsruhe Institute of Technology
Magnetic flux sensor based on a transmon qubit enhanced by phase estimation algorithms

15:49 Talk 10
Oscar Kennedy, University College London
SQUID tunable resonators - losses at half a flux quantum

16:12 Talk 11
Tianyi Li, University College London/National Physical Laboratory
Scalable, Tunable Josephson junctions and SQUIDs based on CVD graphene

16:35 Talk 12
Vivek Chidambaram, Cambridge University
Probing Andreev bound states in a proximitized two-dimensional electron gas using DC transport and light-matter interactions

---

17:00 Closing Remarks

Poster Presentations

P1: Laura Stuffins, Loughborough University
X-ray magnetic circular dichroism studies of heavy-metal/ferromagnetic/heavy-metal heterostructures

P2: Jamie Potter, LCN
Nanowire embedded superconducting coplanar resonators for study of Quantum Phase Slips

P3: Jon Fenton, UCL
Coherent quantum phase slips in DC transport in NbN superconducting nanowires: emergence and gate effect

P4: Elena Lupo, University of Surrey
Superconducting quantum circuits with Majorana fermions

P5: Gioele Consani, UCL
Numerical investigation of a circuit design for three-body interactions in quantum annealing

P6: Shaun Geaney, NPL
The Design of a Near-Field Scanning Microwave Microscope Operating in the Quantum Regime

P7: Gavin Dold, LCN/NPL
High-cooperativity spin coupling using rare-earth doped yttrium orthosilicate as a substrate

P8: Elias Polychroniou, Imperial College London/NPL
Investigation of Dayem Bridge NanoSQUIDs Made by Focused Ion Beam

P9: Tom Godfrey, UCL/NPL
Development of inductive microwave nanoSQUIDs for Quantum Technology Applications

P10: Jon Collins, University of Glasgow/NPL
Single Flux Quantum readout for Single Photon Detector Arrays

P11: Thomas Dixon, RHUL/NPL
Demonstration of parametric amplification in superconducting circuit simulation software

P12: Connor Shelly, NPL
Existence of Shapiro Steps in the Dissipative Regime in Superconducting Weak Links

P13: Kitti Ratter, University of Oxford
Multilayer Coaxial Superconducting Circuits for Quantum Computing

P14: Michael Thompson, Lancaster University
Coupled graphene junction SQUIDs

P15: Jelena Trbovic, Zurich Instruments
Multi-channel superconducting qubit measurements and control

P16: Kaveh Delfanazari, University of Cambridge
2DEG-based integrated superconducting-semiconducting hybrid quantum circuit

Quantum technology with artificial quantum spin circuits 11:00

Martin Weides
University of Glasgow

Quantum technology receives considerable attention from the academic and commercial sector, as well as from the media. Realizing this second quantum revolution appears feasible, with superconducting quantum circuits being a leading candidate to implement quantum coherent devices ranging from quantum simulators, quantum sensing to quantum information processing. We report on such a superconducting anharmonic multi-level circuits coupled to a harmonic readout resonator. The concentric qubit is a promising candidate to establish a site-selective passive direct z-coupling between neighboring qubits, being a pending quest in the field of quantum processing. The planar qubit design is based on a concentric outer electrode, yielding qubit lifetimes and coherence times on the order of 15s [1]. Due to the large loop size, the qubit architecture features a strongly increased magnetic dipole moment. It facilitates the emulation of the one-dimensional Fermi-Hubbard model by a double chain of concentric qubits [2]. The quantum Rabi model, describing the fundamental mechanism of light-matter interaction, is simulated by a driven qubit coupled to a quantized harmonic mode. In the ultra-strong coupling (USC) regime, where the effective coupling strength g is comparable to the energy of the bosonic mode, remarkable features in the system dynamics are revealed [3]. For sensing applications, analyzing weak microwave signals in the GHz regime is a challenging task if the signal level is very low and the photon energy widely undefined. A multi-level quantum system (qudit) allows to deduce the unknown photon frequency and amplitude from the higher level AC Stark shifts [4].

[1] J. Braumueller, M. Sandberg, M. R. Vissers, A. Schneider, S. Schloer, L. Gruenhaupt, H. Rotzinger, M. Marthaler, A. Lukashenko, A. Dieter, A. V. Ustinov, M. Weides, and D. P. Pappas, *Appl. Phys. Lett.* **108**, 032601 (2016).
[2] J.-M. Reiner, M. Marthaler, J. Braumller, M. Weides, and G. Schn, *Phys. Rev. A* **94**, 032338 (2016).
[3] J. Braumueller, M. Marthaler, A. Schneider, A. Stehli, H. Rotzinger, M. Weides, and A. V. Ustinov, *Nature Communications* **8**, 779 (2017).
[4] A. Schneider, J. Braumller, L. Guo, P. Stehle, H. Rotzinger, M. Marthaler, A. V. Ustinov and M. Weides, arXiv:1801.05144.

Fluctuations in qubit lifetimes for long-lived T_1 limited superconducting qubits 11:23

Jonathan Burnett
Chalmers

Long-lived superconducting qubits became possible after a decade of studying and mitigating numerous sources of decoherence. Generally, superconducting qubits have demonstrated high-levels of dephasing (frequency instability), which arises from various low frequency noise sources. We examine long-lived (T_1 of 50-80 microseconds) superconducting qubits, which show a T_1-limited T_2^* approximately 50% of the time. Therefore, the pure-dephasing of these qubits is almost non-existent. Despite this, when investigating how reproducible these coherence metrics are, we find significant drifts and periodic reductions in all qubit lifetime parameters.

Reducing 1/f noise in quantum devices by surface spin desorption

11:46

Sebastian de Graaf
National Physical Laboratory

Reducing noise and decoherence in solid state quantum devices will enable enhanced performance of a wide range of sensors and circuits, however, such efforts have been largely inhibited by the lack of knowledge about the origin of this noise and decoherence. We correlate measurements of frequency (dielectric) noise and loss in superconducting resonators made from NbN on Al_2O_3 with ultrasensitive in-situ electron spin resonance (ESR) measurements on the same devices [1]. We find that after removing a large fraction of surface spins by a simple heat treatment, the magnitude of the dielectric noise is reduced by almost 10 times [2]. Our data is in excellent agreement with a model for strongly interacting two-level systems [3,4], allowing us to attribute the origin of the dielectric noise to ESR-active slow two-level charge fluctuators on the surface of our devices. Here we show that surface spins directly affect the performance of high-Q superconducting resonators, but the chemical fingerprint of the ESR spectrum together with noise and loss data enables a whole new route to identifying the origin of noise in quantum circuits.

[1] S.E. de Graaf et al., *Phys. Rev. Lett.* **118**, 057703 (2017).
[2] S.E. de Graaf et al., *Nature Communications* **9**, 1143 (2018).
[3] L. Faoro et al., *Phys. Rev. B* **91**, 014201 (2015).
[4] J. Burnett et al., *Nature Communications* **5**, 4119 (2014).

A voltage-tunable superconducting qubit based on a carbon nanotube

12:09

Matthias Mergenthaler
Oxford University

Conventional Al/AlOx Josephson junctions are extensively used in research on superconducting circuits for quantum information processing. Recently superconducting qubit alternatives based on semiconductor-superconductor hybrids have been realized with InAs nanowires and a 2-dimensional electron gas [1-3]. As the qubit frequency control relies on voltage rather than magnetic flux, these devices are well suited to fast local control and are promising for applications requiring operation in magnetic fields. Further, studying the coherence of different types of superconducting qubits could enable a deeper understanding of decoherence mechanisms, and novel coupling mechanisms based on voltage controlled superconducting qubits have been proposed [4].

Here we present a first implementation of a superconducting qubit based on a carbon nanotube. We realize semiconductor-superconductor hybrid Josephson junctions based on carbon nanotubes by contacting them with a Pd/Al bi-layer, and implement voltage tunability using a local electrostatic gate. Strong coupling (g 100 MHz) to a coplanar waveguide resonator is demonstrated via observation of a resonator frequency shift dependent on applied gate voltage. Qubit parameters are extracted from spectroscopy and correspond well to DC measurements of similarly-fabricated carbon nanotube Josephson junctions. Qubit relaxation and coherence times in the range 10-100 ns are observed.

[1] T. W. Larsen, et al., *Phys. Rev. Lett.* **115**, (2015).
[2] G. de Lange, et al., *Phys. Rev. Lett.* **115**, (2015).
[3] L. Casparis, et al., arXiv:1711.07665v3.
[4] Z. Qi, et al., arXiv:1801.04291.

Simulating Quantum Magnets in Superconducting Circuits 12:32

Michael Hartmann
Heriot-Watt University

In this talk I will discuss our recent approach for implementing spin lattice Hamiltonians and the Hamiltonian of the Toric Code, in lattices of superconducting circuits. The spin-spin interactions and stabilizer interactions are in our concept realised via Superconducting Quantum Interference Devices (SQUIDs) driven by a suitably oscillating flux bias. All physical qubits can be individually controlled and strings of operators acting on them, including the stabilizers, can be read out via a capacitive coupling to common transmission line resonators. The architecture we propose thus provides a versatile quantum simulator for quantum magnetism, topological order and lattice gauge theories.

Implementing the Variational Quantum Eigensolver with error mitigation in a 2-qubit superconducting circuit 12:55

Takahiro Tsunoda
Oxford University

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

In this presentation, we report a quantum chemistry simulation using the VQE on a 2-qubit device based on a circuit architecture that employs coaxial qubit designs and out-of-plane wiring for future scalability to larger 2D qubit arrays. We use fixed frequency qubits and build the algorithm using a native 2-qubit interaction by static capacitive coupling. We investigate the use of error mitigation to improve the performance of the VQE.

Towards a Superconducting Spintronics Device Concept 14:40

Matthias Eschrig
Royal Holloway University of London

The past two decades have seen a paradigm shift in how ferromagnetism interacts with superconductivity in hybrid structures. With the utilisation of equal-spin pairs induced by a spatially or momentum dependent spin order interacting with proximity induced pairing correlations, the original competition between the two types of order is turned into a synergy. The Superspin Programme, run buy University of Cambridge, RHUL, UCL, and Imperial College, aims to combine key features of superconducting and spin electronics to demonstrate the potential for the field of superspintronics to emerge as a future device technology. In recent experiments [1] we have produced a pure spin current carried by equal spin Cooper pairs, utilising a ferromagnetic resonance technique in the ferromagnetic F layer of an N-S-F-S-N structure. We develop a theory which explains this effect in terms of a combination of intrinsic spin-orbit interaction and Landau mean fields present in the outer, normal layers.

[1] K. R. Jeon, C. Ciccarelli, A. J. Ferguson, H. Kurebayashi, L. F. Cohen, X. Montiel, M. Eschrig, J. W. A. Robinson, M. G. Blamire, *Nature Materials*, **17**, 499-503 (2018).

Spin-orbit coupled triplet spin valve and dynamics of triplet Josephson junctions

15:03

Niladri Banerjee

Loughborough University

The existence of unconventional triplet superconductivity in artificial superconductor/ferromagnet interfaces has been demonstrated recently in several experiments [1]. These equal-spin triplet Cooper pairs are immune to the pair breaking exchange field in a ferromagnet and can propagate over length scales which are significantly longer than the singlet pair coherence lengths. These dissipationless triplet currents carry a net spin creating a bridge between superconductivity and conventional spintronics. In the first part of the talk, I will focus on an entirely new connection between triplet superconductivity and spin-orbit coupling [2]. This manifests itself in a non-monotonic dependence of the superconducting transition temperature with applied magnetic fields in heterostructures of Pt/Co/Pt proximity coupled to a conventional spin-singlet superconductor (Nb). The results are explained on the basis of spin-orbit coupling actively controlling the generation of triplet Cooper pairs in the system. In the second part of the talk, I will present our results on the electrodynamics of triplet Josephson junctions [3]. Multilayer ferromagnetic Josephson junctions show a distinctly different moderately damped phase dynamics which is only present when the supercurrent transport is dominated by triplets. I will discuss some possible connections with the triplets and the unconventional phase dynamics.

[1] J. Linder and J. W. A. Robinson, *Nature Physics* **11**, 307315 (2015).
[2] N. Banerjee et al., *Phys. Rev. B* **97**, 184521 (2018).
[3] D. Massarotti et al., (submitted to *Phys. Rev. B*, 2018).

Magnetic flux sensor based on a transmon qubit enhanced by phase estimation algorithms.

15:26

Sergey Danilin

Karlsruhe Institute of Technology

Quantum phase estimation algorithms allow for a fast extraction of information stored in a quantum state of a system. These algorithms are used not only in quantum computing and quantum information processing but also for the tasks of quantum metrology. In the latter case the unknown parameter determining the energy spectrum of the system is evaluated. Phase estimation algorithms potentially allow to attain the Heisenberg limited scaling of precision 1/t, whereas in a standard classical measurement the precision is restricted by a short noise limit 1/t. In my talk, I will explain how a single transmon type qubit coupled capacitively to a quarter wavelength resonator can be used as a magnetic flux sensor. I also will describe the operation of one of the two metrological procedures based on phase estimation algorithms realized in the work. I will present the experimental results demonstrating the superiority in the magnetic flux precision of these procedures over a standard classical measurement. The ways to improve the achieved time scaling of the magnetic flux precision will be discussed.

SQUID tunable resonators - losses at half a flux quantum 15:49

Oscar Kennedy

University College London

Circuit quantum electrodynamics is ubiquitous in a new generation of quantum computer and novel quantum optical and optomechanical experiments which are performed in the solid state. In cQED experiments superconducting resonators act as cavities which couple to quantum objects allowing the quantum objects to be measured or manipulated by microwave light on or close to resonance with the cavity resonance. Several proposed cQED quantum optics experiments and promising quantum information architectures (coupling spin-impurity-qubits to read-out superconducting architectures) require tunable superconducting resonators. One particularly successful strategy to fabricate these devices has been to embed SQUIDs (i.e. flux-tunable inductors) within resonators. These resonators have been shown to tune substantially (routinely $> 100\,\mathrm{MHz}$). Rapid tuning of cavities by on-chip flux lines has also been demonstrated. However, as SQUID embedded resonators are tuned away from their zero-flux resonant frequency the quality factor of these resonators drops, with a minimum quality factor when the resonator is maximally detuned at half a flux quantum. This is not desirable for most applications and is also poorly understood. We perform systematic power- and temperature-dependent measurements on quarter wave coplanar waveguide resonators made tunable by the embedding of a nanoSQUID by neon-FIB at the current antinode. We study the power and temperature dependence of resonator losses as a function of tuning and propose models based on thermal noise in SQUIDs which may limit the quality factor when resonators are tuned.

Scalable, Tunable Josephson junctions and SQUIDs based on CVD graphene 16:12

Tianyi Li

University College London / National Physical Laboratory

Since the carrier density and resistivity of graphene are heavily dependent on the Fermi level, Josephson junctions with graphene as the weak link (SGS junctions) can have their I-V properties easily tuned by the gate voltage. Most of the previous works on SGS junctions and SQUIDs were based on mechanically exfoliated graphene, which is not compatible with large scale production. Here we show that SGS junctions and dc SQUIDs can be easily fabricated on CVD graphene and exhibit good electronic properties. Such scalable and tunable SGS junctions are especially useful for applications involving arrays of Josephson junctions, such as single flux quantum devices and superconducting qubits, where the properties of the junctions can be tuned to be identical. The SGS junctions and SQUIDs were fabricated on CVD graphene transferred to silicon substrates. The Nb electrodes were deposited by conventional EBL, sputtering and lift-off processes. The devices were measured in a ^{3}He cryostat with a base temperature of 300 mK. To reduce the normal state resistance and to increase the critical current, the SGS junctions we fabricated were relatively short ($50-450\,\mathrm{nm}$) and wide ($10-80\,\mu\mathrm{m}$). The junctions show good I-V properties and could work in wide temperature range from 0.3 K to 1.5 K without hysteresis. The junctions show obvious self-interference pattern under a perpendicular magnetic field, indicating that the distribution of the supercurrent is quite uniform. The critical current can be effectively tuned by the gate voltage up to an order of magnitude. As a result, the dc SQUIDs made up of those junctions can have their critical current tuned by both the magnetic field and the gate voltage. We have fabricated and measured SGS junctions with different lengths, and we found that the shortest junction (50 nm long) worked in the ballistic regime. We had evidence from both the $I_c - T$ relation and the $R_n - V_g$ relation. Operating devices with clean junctions in the ballistic regime could lead to performance improvements such as lower intrinsic noise.

Probing Andreev bound states in a proximitized two-dimensional electron gas using DC transport and light-matter interactions

16:35

Vivek Chidambaram

Cambridge University

The energy spectrum of Andreev bound states (ABS) is responsible for the nonlinear current-phase relationship of Josephson junctions (JJs), and consequently plays a key role in the behaviour of microwave photons in a wide range of superconducting quantum circuits. The ABS spectrum of a JJ made from a proximitized two-dimensional electron gas (2DEG) can be tuned using electrostatically-coupled gates, paving the way towards highly integrated circuits required for quantum information processing [1,2]. Understanding how the dynamics of ABS affect coherence in these new materials is an important concern for realising their full potential. One unique offering of the 2DEG is the capability to fabricate large networks of JJs, serving both as tuneable inductors and digital switches that can reconfigure the network in-situ. We showcase this by correlating DC transport with light-matter interactions of a few mode 2DEG superconducting quantum interference device (SQUID) coupled to a microwave cavity. We identify light-matter interactions as the cavity and ABS states in the SQUID hybridise with the cavity in the weak coupling limit and compare this with critical currents measured as a function of flux and gate voltage.

[1] J. Shabani, et al. *Phys. Rev. B* **93**, 155402 (2016).
[2] L. Casparis, M. R. Connolly, et al. arXiv:1711.07665 (2017).

Exhibitors

Cryogenic Ltd

ICE Oxford Ltd

Oxford Instruments NanoScience

Rohde & Schwarz UK Ltd