Superconducting Quantum Devices 2019 (SQD19)

James Watt School of Engineering

James Watt South Building

University of Glasgow

5-6 September 2019

Programme

5th Thursday September 2019

Talks: Stevenson Lecture Theatre, 3rd floor

Poster, industry exhibition, refreshments: Creativity Lab, 6th floor

12:00 pm onwards Lunch and Refreshments

2:00 pm Introduction

2:15 pm Talk 1
Tobias Lindstrom, National Physical Laboratory
Superconducting Quantum Computing in the UK – A brief overview

2:50 pm Talk 2
Shigehito Miki, National Institute of Information and Communications Technology
Toward realization of superconducting nanowire single photon imaging system

3:30 pm Coffee break and conference picture

4:00 pm Poster presentations

Each poster contribution will be accompanied by a **2 min presentation**
Please send a single .ppt slide to Martin.Weides@glasgow.ac.uk until **Wednesday 4th of September**

6:00 pm **Reception at Cloister**, Gilbert Scott Building

6th Thursday September 2019

9:00 am Talk 3
Ailsa Keyser, Imperial College London and National Physical Laboratory
Dispersive Readout of a Spin Ensemble: Developing On-chip Electron Spin Resonance

9:20 am Talk 4
Erik Jellyman, Lancaster University
Design and characterization of Josephson Travelling-Wave Parametric Amplifiers

9:40 am Talk 5
Ben Lang, University of Nottingham
Multi-photon resonances using a Josephson junction–cavity system

10:00 am Talk 6
Katie Elizabeth Porsch, University College London
Developing Capacitively Shunted Flux Qubits for Quantum Annealing

10:20am Talk 7
Peter Spring, University of Oxford
Spurious mode suppression using micromachined pillars in superconducting quantum devices

10:40am Talk 8
Ziad Melhem,Oxford Instruments nanoscience
Cryofree Technology for Quantum Applications

11:00 am Coffee break

11:20 am Talk 9
Kaveh Delfanazari, University of Cambridge
Artificially engineered quantum integrated circuits with array of Josephson field effect transistors

11:40 am Talk 10
Malcolm Connolly, Imperial College London
Topological insulator Majorana transmons

12:00 am Talk 11
Umberto Nasti, University of Glasgow
Emerging materials for superconducting nanowire photon counting arrays

12:20 pm Lunch and Refreshments, posters

2:00 pm Talk 12
Jon Collins, University of Glasgow
Superconducting nanobridge electronics for next generation quantum devices

2:20 pm Talk 13
Daniel Margineda, York Instruments
Controllable pi-junction in Hybrid Quantum Interference Devices

2:40 pm Talk 14
Rebecca Rodrigo, PGI-5 Forschungszentrum Jülich GmbH
NanoSQUIDs based on Nb nanobridges

3:00 pm Talk 15
Michael Faley, PGI-5 Forschungszentrum Jülich GmbH
MoRe/YBa2Cu3O7-x Josephson junctions, pi-loops and pi-SQUIDs

3:20 pm Talk 16
Connor Shelly, National Physical Laboratory
Shapiro steps as a probe of overheating in superconducting nanobridges

Up 4:00 pm Poster prize and closing remarks

Poster Presentations

Poster 1:
Aneirin John Baker, Heriot-Watt University
Many body operations with Super Conducting Circuits

Poster 2:
Paul Baity, University of Glasgow
Magnon spectroscopy of YIG films using superconducting resonators

Poster 3:
Giulio Campanaro, University of Oxford
Towards single-shot readout in double-sided coaxial circuit QED

Poster 4:
Max Cykiert, University of Surrey
Robust quantum optimal control with noise

Poster 5:
Sergey Danilin, University of Glasgow
Hybrid superconducting–ferromagnetic microwave circuits with on-chip control of coupling

Poster 6:
Sebastian de Graaf, National Physical Laboratory
Spectral and temporal mapping of surface two-level defects in superconducting resonators

Poster 7:
Tom Dixon, Royal Holloway, University of London
An Extension of the Coupled Mode Equations Describing Wave Mixing Processes

Poster 8:
Teresa Hoenigl-Decrinis, National Physical Laboratory
Absolute Power Quantum Sensor

Poster 9:
Koran Jackson, University of Glasgow
Microwave multiplexing of superconducting nanowire single-photon detector arrays

Poster 10:
Ciaran Lennon, University of Glasgow
Atomic Layer Deposition of NbN for SNSPDs

Poster 11:
Elena Lupo, University of Surrey
Superconducting quantum circuits with Majorana fermions

Poster 12:
Jharna Paul, University of Glasgow
Superconducting Nanowire Single-Photon Detectors on Waveguide-Circuits for Secure Quantum Communications

Poster 13:
Jamie Potter, University College London
Losses in NbN Nanowire-Embedded Coplanar Waveguide Resonators Exhibiting Incoherent Quantum Phase Slip

Poster 14:
Gavin Orchin, University of Glasgow
Niobium diselenide superconducting photodetectors

Poster 15:
Valentino Seferai, University of Glasgow
Cross-junctions for superconducting quantum technology

Poster 16:
Adam Stokes, University of Manchester
Gauge-relativity in QED: implications for ultrastrong and time-dependent couplings

Poster 17:
James Wills, University of Oxford
Utilising 2D/3D hybrid architectures for multi-mode superconducting quantum devices

Poster 18:
Taro Yamashita, Nagoya University
Superconducting flux qubit with NbN-based ferromagnetic pi junction

Poster 19:
Jonathan Pritchard, University of Strathclyde
Progress towards an atom-superconductor Hybrid Quantum Interface

Talk Abstracts

5th Thursday September 2019

[Talk 1]

Superconducting Quantum Computing in the UK – A brief overview

Tobias Lindstrom
National Physical Laboratory

Quantum computing has gone from being a somewhat esoteric area of science to a field which is attracting huge interest from government and industry. The field is becoming increasingly application driven and focus is shifting from basic science towards engineering; the goal being to build a quantum processor able to solve real-world problems in e.g. chemistry.
There are, however, still several challenges we will need to overcome in the next few years if we want to be able to build processors with even a moderate number (150-200) of qubits.
In this talk I will give a brief overview of the state of this field in the UK and worldwide. I will also discuss some of the identified challenges we will need to solve if we want to build a small-scale (NISQ) processor in the UK.
This presentation will be based on the report "*Opportunities for superconducting quantum technology in the UK*" [1] which was published by the National Physical Laboratory in November 2018.

[1] NPL Report TQE 13, available online http://eprintspublications.npl.co.uk/8260/

[Talk 2]

Toward realization of superconducting nanowire single photon imaging system

Shigehito Miki
National Institute of Information and Communications Technology

Two-dimensionally arranged superconducting nanowire single photon detector (SSPD) array would be a novel single photon imaging system, leading an innovation for various kinds of applications due to attractive features of SSPD. A critical issue in a development of SSPD array with large number of pixels is to reduce the number of readout lines which lead to a heat inflow from the room temperature. To reduce the number of readout cables, we have been developing SSPD array with superconducting logic circuit. Furthermore, SSPD array with row-column readout architecture can reduce the number of readout lines for the N x N pixel array to 2N from N2. In this work, we report our development of NbTiN-SSPD array with row-column readout architecture and superconducting logic circuit installed into a 0.1 W GM cryocooler system.

6th Thursday September 2019

[Talk 3]

Dispersive Readout of a Spin Ensemble: Developing On-chip Electron Spin Resonance

Ailsa Keyser
Imperial College London and National Physical Laboratory

We develop a ‘testbed’ system for experiments aiming to enhance the sensitivity of Electron Spin Resonance (ESR). Our device is a NbN fractal superconducting microresonator [1] with high-cooperativity coupling to an organic crystal containing $\sim$ 1011 spins [2] ($C \approx 23$). Inspired by qubit measurement protocols, we measure the spin decay rates dispersively with minimum disturbance to the spin ensemble. Unusually for an ESR experiment our microresonator is designed to have a high Q factor. We aim to benefit from both of these features by applying shaped pulses to the resonator, to suppress its long ringdown time and thereby enhance the ESR sensitivity (which scales with $\sqrt{Q}$) [3]. In the long term, this technique could accomplish pulsed interrogation of small numbers of arbitrary spins and so provide insights into the surface chemistry of, for example, superconducting qubit devices.

[1] S.E. de Graaf et al., *Appl. Phys. Lett.* 104, 052601 (2014).
[2] M.A. Christensen et al., *J. Mater. Chem.* C 2, 10428 (2014).
[3] T.W. Borneman & D.G. Cory, *J. Magn. Reson.* 225, 120 (2012).

[Talk 4]

Design and characterization of Josephson Travelling-Wave Parametric Amplifiers

Erik Jellyman
Lancaster University

The key element is a Josephson junction that can be viewed as a non-linear inductor. The junction inductance is determined by its critical current, which is defined in the fabrication and adjusted in the experiment

We are developing a Josephson traveling-wave parametric amplifier (JTWPA) using all-aluminium technology. The device is a superconducting coplanar transmission line with an array of 100-1000 non-hysteretic RF-SQUIDs. The Josephson inductance (LJ) exceed the geometric inductance and is in parallel to the latter; its modulation does not affect the device impedance. Modulation of LJ is achieved by the strong pump signal applied to the input port or by external magnetic flux. The SQUID array is analogous to a one-dimensional artificial medium with well-controlled quadratic and cubic non-linearities generating 2nd and 3rd harmonics of the signal. Device operation in the four- and three-wave mixing regimes is possible.

We are characterizing JTWPAs in a dilution refrigerator down to 8 mK. In the three-wave-mixing regime, the device can yield 20 dB gain for GHz range signals with large frequency separation between the signal and the pump, making it an ideal amplifier for weak signals.

[Talk 5]

Multi-photon resonances using a Josephson junction–cavity system

Ben Lang
University of Nottingham

Oscillators that are driven non-linearly at several times their natural frequency can exhibit a rich variety of interesting physics [1], including resonances where several photons are generated at once. A voltage-biased Josephson junction (JJ) in series with a microwave cavity [2] provides a novel way of exploring these kinds of effects. The Josephson frequency set by the dc voltage can be several times the cavity frequency, whilst a cavity engineered to have a high impedance leads to strong nonlinearities at the single-photon level [3]. Using a simple model of a JJ-cavity system we investigate the behaviour at resonances where 3 or more photons are generated by the tunnelling of each Cooper-pair. As the Josephson energy of the junction is increased, there is a transition from a regime where photons are produced in discrete bursts to more complex behaviour as the time between bursts is reduced. We also discuss the possibility of exploiting such systems to produce entangled states beyond single photon pairs.

[1] L. Guo, M. Marthaler and G. Schön, Phase Space Crystals: A New Way to Create a Quasienergy Band Structure, Phys. Rev. Lett. 111, 205303 (2013)
[2] A. D. Armour, M. P. Blencowe, E. Brahimi and A. J. Rimberg, Universal Quantum Fluctuations of a Cavity Mode Driven by a Josephson Junction, Phys. Rev. Lett. 111, 247001 (2013)
[3] C. Rolland, A. Peugeot, S. Dambach, M. Westig, B. Kubala, Y. Mukharsky, C. Altimiras, H. le Sueur, P. Joyez, D. Vion, P. Roche, D. Esteve, J. Ankerhold, and F. Portier, Antibunched Photons Emitted by a dc-Biased Josephson Junction, Phys. Rev. Lett. 122, 186804 (2019)

[Talk 6]

Developing Capacitively Shunted Flux Qubits for Quantum Annealing

Katie Elizabeth Porsch
University College London

Superconducting flux qubits are the fundamental building blocks of modern quantum annealers. A successful quantum anneal finds the solution to a problem Hamiltonian with a minimised time to solution and error rate, whilst avoiding non-adiabatic transitions. In practice, this requires a very high level of experimental control and an accurate knowledge of each qubit's energetics in the presence of fabrication and measurement errors. We demonstrate multiple methods for characterising a tuneable capacitively-shunted flux qubit (CSFQ) for the development of an aluminium Quantum Annealing machine. We present a method for determining all crucial qubit parameters with simple single-tone measurements of a resonator that is capacitively coupled to the tuneable CSFQ.

[Talk 7]

Spurious mode suppression using micromachined pillars in superconducting quantum devices

Peter Spring
University of Oxford

As superconducting quantum circuits scale up in size, the enclosures used to house them will contain spurious resonant electromagnetic modes detrimental to the circuits unless preventative steps are taken. A standard solution in conventional microwave circuits is the use of through-chip vias. Here we present an alternative that moves the through-chip electrical connection off the substrate and to the enclosure, which suppresses substrate and enclosure modes simultaneously. We achieve this by placing a substrate in a rectangular cavity incorporating an array of micromachined pillars, such that the minimum mode frequency is set by the pillar radius and spacing and not the enclosure dimensions. To accommodate the pillars the substrate is machined. We present an analytical model for the behaviour of these vias, and compare with simulations of enclosures for devices up to the 100 qubit-scale. Finally, we present proof of principle experiments on an enclosure incorporating a single pillar.

[Talk 8]

CryofreeB® Technology for Quantum Applications

Ziad Melhem
Oxford Instruments nanoscience

Recent developments of cryogenics and sample management are enabling new class of a variety of Quantum Devices. Next generation of quantum and nanotechnology applications will be dependent on platforms that can probe and manipulate matter at low temperatures. This contribution presents an overview of a new class of cold environments for quantum technologies and materials research with particular emphasis on quantum information processing (QIP), 2D materials characterisations and sensitive measurements for quantum applications. The new systems are compact in size and realized by exploiting the recent advances in cryogenic technologies integrated with advanced measurement systems. These new systems together with CryofreeB® technology facilitating a new class of Quantum Devices, nanotechnology applications, and 2D materials R&D.

[Talk 9]

Artificially engineered quantum integrated circuits with array of Josephson field effect transistors

Kaveh Delfanazari
University of Cambridge

Artificially engineered hybrid superconducting-semiconducting (S-Sm) quantum integrated circuits (QIC) on a chip of semiconducting InGaAs that contains one-dimensional arrays of Josephson Field Effect Transistors (JoFETs) will be demonstrated. All JoFETs embedded into the QICs are addressed and controlled by only two universal split-gates. The device advantages include: switching between individual devices and studying the statistics, quantum yields and reproducibility of many devices (S-Sm contacts, S-Sm-S JJs, and JoFETs) in one fridge cooldown. We discuss the device design, fabrication, characterization and measurements in sub-Kelvin temperature ranges. Our systematic studies could be very important for the optimisation of hybrid qubits and the realisation of the scalable topological quantum processors.

[Talk 10]

Topological insulator Majorana transmons

Malcolm Connolly
Imperial College London

A Majorana transmon is a conventional transmon with Majorana zero modes (MZMs) coupled across the Josephson junction. By enabling coherent single-particle transport, MZMs are predicted to mix charge parity states, leading to signatures in the excitation spectrum and enhanced relaxation times. I will describe recent progress towards building a Majorana transmon and plans to detect MZMs in junctions made from V-VI topological insulators (TIs) [1]. Initial results demonstrate that gate-tuneable TI-based superconducting circuits can be fabricated on Silicon in a scalable way via selective area molecular beam epitaxy, and should yield gatemons with longer relaxation times than III-V materials [2].

[1] K. Yavilberg, E. Ginossar, E. Grosfeld, arXiv:1902.07229v1 (2019)
[2] L. Casparis et al., Nature Nanotechnology 13, 915-919 (2018)

[Talk 11]

Emerging materials for superconducting nanowire photon counting arrays

Umberto Nasti
University of Glasgow

Superconducting nanowire single-photon detectors (SNSPDs) are the leading technology for low noise, high efficiency infrared single-photon detection. The excellent performance of SNSPDs at near infrared and telecommunications wavelengths has led to their adoption in important applications such as quantum secure communications, single photon spectroscopy and single-photon LIDAR. A clear challenge for the SNSPD community is to extend the spectral range of SNSPDs into the mid infrared, and to improve material uniformity to enable the realization of large area arrays for multimode or free space coupling. An important task is to evaluate potential materials for next generation mid-infrared SNSPD arrays. The standard SNSPD material, NbN, offers high performance operation up to 4 K, but has limited uniformity over large areas and a roll off in absorption and hence efficiency beyond telecom wavelengths. Our team have studied MoSi and TiN as alternative materials for SNSPDs. Our research group have produced high-quality 9.5nm thick NbN and 8nm thick MoSi via magnetron sputtering on high resistivity Si achieving respectively a transition temperature of 8.5 K and of 5.5 K. These films have been used to realize a configuration of 8-pixels array. Each pixels is patterned in a meander of active area 10x10 µm and wide 100 nm. The 8nm MoSi has demonstrated a single-photon regime at 1550nm and 1310nm wavelength, while the 9.5nm NbN has demonstrated high uniformity in terms of transport properties. In this work, we will present a detailed comparison of thin film and device properties for SNSPD arrays based via MoSi and NbN.

[Talk 12]

Superconducting nanobridge electronics for next generation quantum devices

Jon Collins
University of Glasgow

Quantum technologies exploit unique aspects of quantum mechanics to obtain unprecedented performance in applications including quantum computing and photonics. The transition from proof-of-principle demonstrators to practical large-scale system implementations is still at an early stage. Single Flux Quantum(SFQ)[1][2] electronics is an ideal candidate to develop control and readout schemes to efficiently scale multiplex large arrays of superconducting nanowire single photon detectors (SNSPD)[3][4]) and to provide a new way to control large-scale systems of high fidelity superconducting qubits with low leakage errors[5].
We present preliminary results on Nb nanobridge Josephson junctions for on-chip SFQ circuit elements for integrated control and readout of SNSPDs and qubits. We investigated the Josephson behaviour of the nanobridges and the consistency of parameters including critical current over a range of temperatures. Characteristics from nanobridge devices of different geometries were also measured.

[1] K. K. Likharev and V. K. Semenov RSFQ logic/memory family: a new Josephson-junction technology for sub-terahertz-clock-frequency digital systems, IEEE Trans. Appl. Supercond. 1, 3 (1991).
[2] C. D. Shelly et al, 2017 Weak link nanobridges as single flux quantum elements, Supercond. Sci. Technol. 30, 095013
[3] C. M. Natarajan et al, 2012 Superconducting nanowire single-photon detectors: physics and applications, Superconductor Science and Technology, vol. 25, no. 6, p. 063001
[4] H. Terai et al, 2009 Readout electronics using single-flux-quantum circuit technology for superconducting single-photon detector array, IEEE Trans. Appl. Supercond., vol. 19, pp. 350-353
[5] R McDermott et al 2018 Quantum-classical interface based on single flux quantum digital logic, Quantum Sci. Technol. 3 024004

[Talk 13]

Controllable pi-junction in Hybrid Quantum Interference Devices

Daniel Margineda
York Instruments

In this work we present Hybrid Quantum Interference Devices (HyQUIDs), a quantum flux sensitive magnetic sensor based on a superconductor-normal-superconductor single junction. We demonstrate that the supercurrent and the voltage to flux response can be controlled and reversed by modifying the occupation probability of the supercurrent-carrying density of states leading to a pi -junction behaviour that survives above 5 K.
The resistance of a metallic wire positioned in the centre of the junction in a symmetrical configuration can be used to investigate the supercurrent across the junction and the device sensitivity. The conductance oscillates periodically with the phase difference of the superconductor electrodes. The "giant" amplitude of the oscillation has been used to fabricate voltage-to-flux sensors. The dependence of the critical current with the voltage control was used to optimise the transfer function to a non-sinusoidal response when the critical current drops to zero.
pi -junction behaviour in these Josephson junctions has normally been reported, at millikelvin temperatures, when a mesoscopic wire is linked to the centre of the junction. By applying a voltage, the distribution function of the supercurrent-carrying states can be controlled. If the wire is short enough to neglect the electron-electron interactions, then an out-of-equilibrium distribution function exists. This double step function, formed by the superposition of the distribution functions of the two reservoirs in equilibrium, leads to the reversing of the supercurrent at a critical voltage. This effect can be described as a pi -junction, because the normal sinusoidal dependence of the supercurrent is shifted with respect to the superconductors phase difference δ to $I=I_c \sin(\delta+\pi)$. Pi-junction behaviour tends to disappear when the wire reaches local equilibrium due to electron-electron scattering, or by raising the temperature which smears out the double-step distribution function. Measuring the SNS junction critical current as a function of the voltage control and the differential resistance of the control wire as a function of the current across the junction, we demonstrate that pi -junction can survive to temperatures above 5 K. We were able to directly observe the evolution of the current-phase relation in the behaviour of the HyQUIDs

[Talk 14]

NanoSQUIDs based on Nb nanobridges

Rebecca Rodrigo
PGI-5 Forschungszentrum Jülich GmbH

We develop a novel direct current nanoscale superconducting quantum interference device (nanoSQUID) to be used for the construction of a highly sensitive scanning nanoSQUID microscope (SSM). Therefore, we have developed nanoSQUIDs with Josephson junctions in the form of Nb nanobridges, whose thickness, width and length are in the order of the superconducting coherence length in Nb thin films, which is approximately 15 nm at 4.2 K. Less than 30-nm-thick Nb films were deposited using dc magnetron sputtering on 300-µm-thick Si substrates with a 300-nm-thick buffer layer of SiO_2. A 40-nm-thick mask of PMMA resist was formed by electron beam lithography using a dose of 25 mC/cm2, at which PMMA operates as a high resolution negative resist. Compared to HSQ resist, PMMA has a much better availability, lower health risk, a longer shelf life and a simpler development procedure, while maintaining sufficient resolution. Next, another mask of UV6-0.6 resist, structured by deep-UV photo lithography, is applied to the Nb film for the structuring of the contacts and interconnects. Both, Nb nanobridges with widths down to 10 nm and nanoSQUIDs with the incorporated nanobridges, were then fabricated using reactive ion etching of Nb with pure SF6 gas through the combo-masks of PMMA and UV6-0.6 resists. The I(V) curve of a 20-nm-wide Dayem bridge has shown a non-hysteretic behavior at 4.2 K. The kinetic inductance of the SQUID loops is found to be far higher than the geometrical inductance. The microstructural and superconducting properties of the nanobridges and nanoSQUIDs will be presented.

[Talk 15]

MoRe/YBa2Cu3O7-x Josephson junctions, pi-loops and pi-SQUIDs

Michael Faley
PGI-5 Forschungszentrum Jülich GmbH

We have developed Josephson junctions (ds-JJs) between the d-wave superconductor YBa2Cu3O7 (YBCO) and the s-wave superconductor MoRe-alloy, using a gold film as a normal conducting barrier and a barrier for oxygen diffusion. MoRe-alloy has a superconducting transition temperature Tc of up to 15 K and is corrosion-resistant. I(V)-characteristics of the ds-JJs demonstrate a twice larger critical current along the [100] axis of the YBCO film compared to similarly-oriented ds-JJs made with a Nb top electrode. The characteristic voltage IcRn of the YBCO-Au-MoRe ds-JJs is 750 BμV at 4.2 K. YBCO-Au-MoRe ds-JJs that are oriented along the [100] axis of the YBCO film exhibit a 200-times higher critical current than similar ds-JJs oriented along the [110] axis of the same YBCO film. We observed ordering of spontaneously generated half integer magnetic flux quanta in the pi-loops correlated with minute spurious background magnetic fields, as well as with configurations and mutual coupling of the pi-loops. Different layouts of pi-loops based on the novel ds-JJs were arranged in various mutual coupling configurations and the spontaneously-induced currents were investigated using scanning SQUID microscope. We manipulated the magnetic states of the pi-loops by the local application of magnetic fields using nearby planar coils. The pi-shifts in phase of superconductor wave function can be used for the self-biasing of flux qubits and nanoSQUIDs. Conditions for different values of spontaneously induced magnetic fluxes are derived. Our work paves the way for the use of pi-loops for nanoscale magnetometry and in computations that are based on annealing processes.

[Talk 16]

Shapiro steps as a probe of overheating in superconducting nanobridges

Connor Shelly
National Physical Laboratory

We present measurements of superconducting nanobridge weak links made using a single-lithography nanofabrication procedure. Nanobridges typically exhibit hysteresis in their current-voltage characteristics as a result of hot-spot Joule heating. The spatial extent of the overheated region has been suggested to extend many microns into the electrodes. We present measurements of microwave-induced Shapiro steps in the dissipative branch of a hysteretic current-voltage characteristic. We use the Shapiro steps and the RSJ model to infer a reduced critical current and associated effective local temperature. The Shapiro steps provide evidence that a finite Josephson coupling exists in the dissipative state and is used to put an upper limit on the size of the region that can be heated above the critical temperature. Indeed, our inferred local temperature, and our thermal modelling suggest that the nanobridge remains below Tc and thus exists in the SS'S configuration in our work. This work provides evidence that Josephson behaviour can exist in thermally-hysteretic nanobridges and allows extension of the temperature ranges that nanobridge based SFQ circuits, nanoSQUIDs and Josephson voltage standards can be used.

Poster Abstracts

[Poster 1]

Many body operations with Super Conducting Circuits

Aneirin John Baker
Heriot-Watt University

Three Qubit gates have previously been broken down into a series of two and one Qubit operations. Here We propose a system which can perform three Qubit operations in a single step. Our approach can thus significantly reduce the gate's errors and execution time. Importantly, single shot Toffoli gates are not affected by multiplying gate fidelities.
We use a microwave drive frequency to activate coupled Qubits to perform the gate operation. The drive can be chosen to generate any gate which can be broken down into a series of Pauli operations (another such example is a CNOT gate).
Current implementations of Toffoli gates (IBMqx2) have fidelities of around 40%. We here report on a gate with potential fidelity upwards of 70%.

[Poster 2]

Magnon spectroscopy of YIG films using superconducting resonators

Paul Baity
University of Glasgow

Hybrid superconducting-ferromagnetic devices are promising components for future information processing technologies for storing, manipulating, or converting data in both classical and quantum regimes. For example, the interchange between superconducting microwave lines and ferromagnetic resonance dynamics in yttrium iron garnet ($Y_3Fe_5O_{12}$, YIG) films leads to new resonance spectra features from induced single domains and anisotropies [1]. However, at low temperatures, where superconducting quantum circuits operate, the gadolinium gallium garnet ($Gd_3Ga_5O_{12}$, GGG) substrate on which YIG is typically grown leads to an enhanced magnon linewidth and decreased magnon-photon cooperativity [2]. To ensure magnon linewidths remain low within the quantum regime, YIG films can be removed from their GGG substrates through methods such as mechanical polishing. We have studied superconducting-ferromagnetic hybrid systems comprised of substrate-free YIG films and on-chip superconducting resonators and will report on the low-temperature properties of these systems including the magnon linewidth and effective magnon-photon coupling strength.

[1] I. A. Golovchanskiy et al., Interplay of magnetization dynamics with microwave waveguide at cryogenic temperatures, arXiv: 1902.07566 (2019).
[2] S. Kosen et al., Microwave magnon damping in YIG films at millikelvin temperatures, arXiv: 1903.02527 (2019).
This work is supported by the European Research Council (ERC) under grant No. 648011 “QuantumMagnonics”.

[Poster 3]

Towards single-shot readout in double-sided coaxial circuit QED

Giulio Campanaro
University of Oxford

[Poster 4]

Robust quantum optimal control with noise

Max Cykiert
University of Surrey

In order to get useful output out of quantum algorithms we need to be able to perform operations on individual qubits. Despite these operations not being achieved perfectly there exists an error rate for which quantum computation will be feasible using some error correcting scheme, with an amount of redundancy in the qubits. This repetition of information can increase the number of qubits by a factor greater than a thousand! By obtaining extremely high fidelity, a measure of the reliability of the execution of said operations, this overhead can be reduced.
The way these reliable operations are achieved is by using microwave pulses. However, in the presence of fluctuations in the parameters of the qubit or when there is noise, the value for the fidelity drops significantly. Gradient based optimisation methods are suited for improving the fidelity, one such strategy, sequential convex programming [2], is used to fight these undesirable effects. SCP finds control pulses that are robust to fluctuations and noise in the parameters of the qubit and control. Due to the sensitivity to the initial condition of the optimisation a large number of starting points are often needed to be used to explore the fidelity landscape this requires code that can be run on multiple computers at once.

[1] B. Russell, Journal of Physics A: Mathematical and Theoretical, 50, 205302, (2017).
[2] J. Allen, Phys. Rev. A, 95, 042325, (2017).

[Poster 5]

Hybrid superconducting–ferromagnetic microwave circuits with on-chip control of coupling

Sergey Danilin
University of Glasgow

Hybrid quantum systems composed of components of different nature can harness advantages of constituting subsystems and as a result provide multifunctionality of the device. Quantum hybrid structures where superconducting circuits are combined with magnetic systems can employ magnon physics phenomena and offer means for studies of properties of magnetic elements for future applications in (quantum) spintronics and quantum information processing.

We report on the design, fabrication, and characterization of hybrid quantum systems comprising superconducting microwave circuits and ferromagnetic elements. We realize a fully planar geometry of the structure which provides an easy scalability. We study coupling between microwave coplanar waveguide resonators and um-sized ferromagnetic elements. The structures include on-chip bias lines which are novel additional control elements. These are used for quick in-situ tuning of resonance frequency of magnetic subsystems. Moreover, they make possible to tune the frequencies separately when several magnetic elements are present in the structure.

[Poster 6]

Spectral and temporal mapping of surface two-level defects in superconducting resonators

Sebastian de Graaf
National Physical Laboratory

Parameter fluctuations in superconducting qubits is becoming the Achilles heel in engineering large-scale superconducting quantum processors [1]. The parameter fluctuations can temporarily (for hours) degrade qubit performance, and the origin of the fluctuations is undoubtedly from surface two-level material defects. The presence of such defects has been well known for decades as they can be attributed to 1/f type charge and flux noise, but the exact chemical origin of these defects has only recently started to become unraveled using superconducting resonators [2].
Using frequency tuneable superconducting resonators, we demonstrate that they can detect the presence of individual, strongly coupled, surface TLS and track their energy drift over time, revealing a plethora of different TLS dynamics. We demonstrate that this platform provides a means to study the physics of surface TLS and parameter fluctuations relevant for superconducting qubits, although across a broader range of materials, temperatures and magnetic fields.

[1] P. V. Klimov et al., PRL 121, 090502 (2018); J. Burnett et al., arXiv 1901.04417; S. Schlor et al., arXiv: 1901.05352
[2] S. E. de Graaf et al., Nature comms 9, 1143 (2018)

[Poster 7]

An Extension of the Coupled Mode Equations Describing Wave Mixing Processes

Tom Dixon
Royal Holloway University of London

Small signal amplification is currently of paramount importance in the technological race for quantum accurate information processing. Amplification of single microwave photons has been achieved with parametric amplifiers, reliant on wave mixing. Parametric amplifiers utilise non-linear circuit elements to provide the wave-mixing medium. Typically, parametric amplification is achieved via difference frequency generation whereby two input tones - pump and signal – combine, and an idler is generated at the difference of their frequencies. These systems are eventually described by a corresponding non-linear differential equation where an analytical solution requires a number of approximations.

Motivated by the results of simulation software (WRspice) in modelling a travelling wave parametric amplifier (TWPA), we have extended the usual coupled mode equations (CME's). Focusing on a three wave mixing (3WM) scheme and allowing for pump harmonic creation up to third order, as well as sum frequency generation between pump, signal and idler tones.
We show quantitatively the effect second harmonic generation has in suppressing signal amplification. We also motivate further discussion on the detrimental effects of sum frequency generation at tones between pump and its second harmonic which may also lie outside the bandwidth of current experiments.

[Poster 8]

Absolute Power Quantum Sensor

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National Physical Laboratory

A two-level quantum system can absorb or emit not more than one photon at a time. Using this fundamental property, we demonstrate how a superconducting quantum system strongly coupled to a transmission line can be used as a sensor of the photon flux. We propose four methods and analyse them for the absolute calibration of power by measuring spectra of scattered radiation from the two-level system. Our results suggest that the absolute power calibration is independent of dephasing as long as its non-radiative relaxation is negligible. Our approach can be used for practical applications for example in calibration of transmission lines within dilution refrigerators.

[Poster 9]

Microwave multiplexing of superconducting nanowire single-photon detector arrays

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Superconducting nanowire single-photon detectors (SNPSDs) are a key enabling technology in advanced applications such as photonic quantum computing advanced imaging, dosimetry for laser medicine and space-to-ground communication. Single-pixel SNSPDs offer excellent performance in terms of infrared single photon detection efficiency, timing jitter, minimal dark count rate and high repetition rate. Scale up to large arrays of SNSPDs remains a significant challenge. The detection area of a single SNSPD is restricted by the intrinsically large inductance associated with superconducting thin films, a typical pixel has dimensions 10µmx10µm. Frustratingly, increasing the number of such detectors to cover larger areas by operating several of them in a traditional manner is not possible. Typically, a bias tee is used to provide a path for bias and readout of the detector simultaneously, each detector then requires a cable between room temperature and low temperature. These cables carry significant amount of undesirable heat into the low temperature setup and hence the requirement for a low temperature readout scheme.
Here, we present preliminary results on an innovative design to scale up SNSPDs from single pixels to large arrays whilst preserving excellent performance. The proposed design is based on a modified microwave bias and readout scheme to allow frequency domain multiplexing of a large number of detectors in the same bandwidth of operation with improved spatial and temporal resolution. Fabrication of the proposed readout scheme requires the same number of processes as a single-pixel SNSPD and is patterned on the same film.

[Poster 10]

Atomic Layer Deposition of NbN for SNSPDs

Ciaran Lennon
University of Glasgow

Superconducting nanowire single-photon defectors (SNSPDs) are the premier technology for high-efficiency infrared single-photon detection. One of the main challenges in the field of SNSPDs is in producing high quality, uniform thin films of superconducting material for patterning into devices. Atomic layer deposition (ALD), a form physical vapour deposition, is a technique that promises to drive forward efforts in the field of SNSPDs by enabling the production of thin films of superconducting materials with superior uniformity and superconducting properties than conventional techniques such as sputtering. This work will present a detailed comparison of the thin film properties of NbN produced by both ALD and sputtering, confirming uniformity by nano-optical mapping as well as investigating the effect of substrate on superconducting properties.

[Poster 11]

Superconducting quantum circuits with Majorana fermions

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University of Surrey

In the recent decades different setups of hybrid solid state systems have been proposed for quantum computing. Among them, hybrid topological-superconducting qubit, where we can encode quantum information in specific topological states called Majorana zero modes [1], by coupling them to superconducting systems [2]. In this work we show the theoretical study of controlling the quantum system consisting in a charge qubit with high Josephson energy (Transmon) hybridised with two coupled Majorana zero modes [3,4]. The use of a Transmon qubit leads to high anharmonicity in the system [5] and to peculiar features when combined with the parity mixing. Here we focus on the study of the system dynamics using time-dependent parameters, which is relevant in the context of quantum control. This is done in the view of future proposals of gate implementation.

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[Poster 12]

Superconducting Nanowire Single-Photon Detectors on Waveguide-Circuits for Secure Quantum Communications

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Superconducting Nanowire Single Photon Detectors (SNSPDs) set the Gold Standard for high speed, low noise infrared photon counting [1]. SNSPDs on waveguides [2-4] offer enhanced absorption efficiency due to the long interaction lengths with photons travelling along the waveguide. We have developed a complete fabrication process for SNSPD devices relies on silicon-on-insulator waveguides with integrated photonic components using NbTiN and MoSi4 superconducting thin-films. On-chip fibre coupling is achieved through optimised grating couplers at 1550 nm peak wavelength with minimum 5 dB loss per coupler. SNSPDs on waveguide circuits are a key component for scalable on-chip quantum photonics. A promising near-term application is in secure quantum communication networks based on the measurement-device independent quantum key distribution protocol [5-7].

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[Poster 13]

Losses in NbN Nanowire-Embedded Coplanar Waveguide Resonators Exhibiting Incoherent Quantum Phase Slip

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Quantum phase slip (QPS) — the particular manifestation of quantum fluctuation of the superconducting order parameter in superconducting nanowires — is the exact mathematical dual to the Josephson effect, which suggests the possibility of exploiting QPS for a large range of applications in quantum electronics. Our work focuses on fabricating superconducting nanowires that undergo QPS, and measuring their interaction with coplanar waveguide resonators, with the ultimate aim of demonstrating dispersive readout of a coherent QPS qubit embedded in a sufficiently low-loss circuit to be useful for quantum information processing applications. We have successfully fabricated nanowire-embedded resonators by two different methods — electron-beam lithography and neon focused-ion-beam — and these show flux-periodic frequency-tuning consistent with incoherent quantum phase slips. However, while we have previously shown that NbN nanowires can be embedded in resonators while maintaining high Q ~10^5, we find that those nanowire-embedded resonators which exhibit flux-periodic behaviour have a lower internal quality factor of a few thousand. In order to better understand the effects of dissipation associated with incoherent QPS, we have modelled a nanowire undergoing phase slips as a dissipative element coupled to a superconducting resonator. We show by circuit simulation how the quality factor of a resonator embedded with an incoherent QPS nanowire is limited, and assess how our experimental results compare with this limit.

[Poster 14]

Niobium diselenide superconducting photodetectors

Gavin Orchin
University of Glasgow

We report the photoresponse of niobium diselenide (NbSe2), a layered transition metal dichalcogenide (TMD) [1]. NbSe2 is a superconductor with a bulk superconducting transition temperature (Tc) ~7.2K [2]. Crystals can be exfoliated to produce flakes down to one molecular layer thick and maintain superconductivity with a reduced Tc ~2 K [3]. In this work, NbSe2 detectors were fabricated with micro-mechanically cleaved crystals 2 to 10 layers thick and tested under current bias in the 350 mK - 5 K range, where they are found to be superconducting and photosensitive. The superconducting state is perturbed by absorption of light, resulting in a voltage signal when the devices are current biased. The response is found to be energy dependent, making the devices useful for applications requiring energy resolution, such as bolometry, spectroscopy and infrared imaging.

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[Poster 15]

Cross-junctions for superconducting quantum technology

Valentino Seferai
University of Glasgow

Josephson tunnel junctions form the non-linear element in superconducting quantum circuits. Their long coherence and good scalability are key requirements for quantum technologies based on superconductors. Classically, the Josephson junctions for qubits are fabricated using evaporation and lift-off techniques with limitations in cross-wafer homogeneity and reproducibility. Here, we present superconducting cross-junctions formed at the cost of breaking the vacuum during fabrication, but a simplified integration in multi-layered circuits, and on larger substrates. Before the controlled oxidation (to form the tunnel junction) and deposition of the second electrode an Argon milling removes the native surface oxide on the bottom electrode. Cross-junctions allow the integration of different superconducting metals in the same barrier, opening hereby an avenue to interface and bandgap engineered circuits. The absence of resist during deposition and oxide formation permits higher temperature processing, and in-situ surface treatments, with the goal of reducing the overall loss density in the junction.

[Poster 16]

Gauge-relativity in QED: implications for ultrastrong and time-dependent couplings

Adam Stokes
University of Manchester

In quantum electrodynamics (QED) each choice of gauge provides different physical definitions of light and matter as quantum subsystems. This gauge-relativity is most evident in the ultrastrong light-matter coupling regime where it can have important implications for effective models that are in common use. In particular, we show that when truncating the material system to two levels, each gauge gives a different description whose predictions vary significantly for ultrastrong-coupling. Quantum Rabi models (QRMs) are obtained through specific gauge choices, but so too is a Jaynes-Cummings model (JCM) without needing the rotating-wave approximation. Analysing a circuit QED setup, we find that this JCM provides more accurate predictions than the QRM for the ground state, and often for the first excited state as well. Thus, Jaynes-Cummings physics is not restricted to light-matter coupling below the ultrastrong limit. Next, we consider time-dependent couplings as required for numerous applications. We show that in the absence of an argument to choose a particular gauge when promoting the coupling parameter to a time-dependent function, the description that results is essentially ambiguous. For sufficiently strong and non-adiabatic interactions, the qualitative physical predictions of final subsystem properties, such as entanglement and photon number, depend on the gauge chosen. This occurs even when the coupling vanishes at the preparation and measurement stages of the protocol, at which times the subsystems are unique and experimentally addressable. These findings are important for all applications which seek to prepare specific local properties such as entanglement or a certain number of photons.

[Poster 17]

Utilising 2D/3D hybrid architectures for multi-mode superconducting quantum devices

James Wills
University of Oxford

[Poster 18]

Superconducting flux qubit with NbN-based ferromagnetic pi junction

Taro Yamashita
Nagoya University

A superconducting flux quantum bit (qubit) is an attractive candidate to realize the large-scale superconducting quantum circuit because of its high anharmonicity. Recently, its coherence time and device-to-device reproducibility have been improved. A remaining issue of the conventional flux qubit is that an external flux bias (corresponding to the half flux quantum in the superconducting loop) is required to operate the qubit at its flux-insensitive point with the longest coherence time. Especially in the large-scale quantum circuit with many qubits, it is extremely challenging to tune all qubits to the optimal point simultaneously by a single magnetic field source. In this work, we develop a novel flux qubit which realizes the flux-bias-free operation by integrating a ferromagnetic pi junction. The pi junction provides the spontaneous pi phase shift in the superconducting loop, and thus the qubit reaches flux-insensitive point without the external flux bias. The qubit consists of a superconducting loop with three Al-based Josephson junctions and an NbN-based pi junction (NbN/CuNi/NbN junction) on a silicon substrate working as the phase shifter coupled to a TiN-based coplanar waveguide resonator. Our results show that the fabricated flux qubits are indeed at its flux-insensitive point without external flux biasing. We will show the detail of the NbN-Al hybrid fabrication process and the results of the spectroscopy and time-domain measurements in the session.

[Poster 19]

Progress towards an atom-superconductor Hybrid Quantum Interface

Jonathan Pritchard
University of Strathclyde

Neutral atoms provide an excellent resource for quantum information processing, combining the long atomic coherence times of the hyperfine ground-states with the strong dipole-dipole interactions of highly excited Rydberg states for generating deterministic entanglement between qubits separated by < 10 μm [1]. Scalable long-range interactions can be obtained by coupling the atomic array to a superconducting microwave cavity enabling hybrid quantum information processing where the cavity-mediated entanglement allows atoms to be coupled over cm length scales. This platform additional offers applications in optical to microwave frequency conversion and atomic quantum memories for superconducting circuits.
We present the first steps towards such an experiment demonstrating high fidelity control and entanglement of single atomic qubits, as well as development of new NbN coplanar waveguide resonators optimised for operation at 4K to allow strong coupling to Rydberg atom qubtis.

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