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Topology-Controlled Dissipation and Magnetic Stabilization in Niobium Transmon Qubits

Bektur Abdisatarov, Tanay Roy, Daniel Bafia, Akshay Murthy, David van Zanten, Grigory Eremeev, Hani Elsayed-Ali, Akshay Murthy, Alexander Romanenko, Anna Grassellino, Rohan Kapur, Sergey Tolpygo

Fermilab

Magnetic fields are generally considered harmful to superconducting qubits because trapped vortices cause microwave loss. Here we show that controlled magnetic environments can instead stabilize transmon qubits while revealing a sharp topology-driven transition to dissipation. Tantalum-capped niobium transmons were cooled in calibrated perpendicular fields to trap defined flux levels. For trapped fields up to 600 mG, relaxation times exceeded 100 μs and T_1 fluctuations were reduced by more than a factor of two. Above 600 mG, T_1 collapsed abruptly to the few-microsecond regime. Wide-field NV-diamond magnetometry reveals that this transition coincides with the emergence of percolating vortex-channel networks across capacitor pads. We define a vortex-connectivity order parameter from NV images and show that the relaxation-rate increase follows a threshold law $\Delta\Gamma_1 = A \max(0, D - Dc)^p$ with a transferable morphology threshold $Dc \approx 0.02$. These results establish vortex topology, rather than density, as the key variable governing dissipation onset.

Chip-Integrated Vortex Manipulation

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The positions of Abrikosov vortices have long been considered as means to encode classical information[1,2]. Although it is possible to move individual vortices using local probes[3,4], the challenge of scalable on-chip vortex-control remains outstanding, especially when considering the demands of controlling multiple vortices. Realization of vortex logic requires means to shuttle vortices reliably between engineered pinning potentials, while concomitantly keeping all other vortices fixed. We demonstrate such capabilities using Nb loops patterned below a $NbSe_2$ layer. SQUID-on-Tip (SOT) microscopy[5,6] reveals that the loops localize vortices in designated sites to a precision better than 100 nm; they realize “push” and “pull” operations of vortices as far as 3 μm. Successive application of such operations shuttles a vortex between adjacent loops[7]. Our results may be used as means to integrate vortices in future quantum circuitry[8,9]. Strikingly, we demonstrate a winding operation, paving the way for future topological quantum computing and simulations.

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Nonlinear Microwave Dynamics of Pinned and Semi-Loop Vortices

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Trapped vortices in superconductors disrupt the operation of superconducting quantum and digital electronic circuits and introduce residual resistance in superconducting radio-frequency (SRF) cavities. Understanding the detailed dynamics of trapped vortices under oscillating magnetic fields is essential for advancing these technologies. We have developed a near-field magnetic microwave microscope to study the dynamics of a limited number of trapped vortices under the probe when stimulated by a localized rf magnetic field. [1]. By measuring the local second-harmonic response (P_{2f}) at sub-femto-Watt levels, we isolate signals exclusively arising from trapped vortices, excluding contributions from surface defects and Meissner screening currents. Toy models of Niobium superconductor hosting vortex pinning sites are introduced and studied with Time-Dependent Ginzburg-Landau (TDGL) simulations [2] of probe/sample interaction to better understand the measured second-harmonic response. The simulation results demonstrate that the second-harmonic response of trapped vortex motion under a localized rf magnetic field shares key features with the experimental data. This measurement technique provides access to vortex dynamics at the micron scale, such as depinning events and spatially-resolved pinning properties, as demonstrated in measurements on a Niobium film with an antidot flux pinning array. If time permits, we will also discuss third-harmonic generation from probe-induced RF vortex semi-loops created at surface defects in Nb [3] and Nb_3Sn [4].

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Magnetic-Field-Driven Dissipation in Superconducting Quantum Circuits: From 3-D Cavities to 2-D Qubits

Daniel Bafia

Fermilab

Magnetic flux is a known limitation in superconducting quantum devices, yet its quantitative contribution to dissipation in the quantum regime remains poorly understood. In this talk, I present a systematic effort to quantify magnetic-field-driven losses from simplified 3-D cavity systems to 2-D qubit architectures. In 3-D niobium cavities, we provide the first direct quantification of trapped vortex dissipation at millikelvin temperatures, establishing flux as a measurable decoherence channel and developing a validated quantum-regime vortex electrodynamics model. Extending this framework to planar transmon qubits, we examine both applied and ambient-field cooldown conditions. We find that qubits are robust in T1 up to hundreds of milligauss and observe a reduction in T1 fluctuations under applied fields, suggesting that controlled magnetic biasing may enhance device stability. By connecting RF measurements with materials science insights, these results establish a quantitative, cross-platform understanding of magnetic-field-driven dissipation and point toward strategies to suppress loss and improve coherence stability.

Vortex structures and dynamics in patterned superconducting films

O. Leonard, **Simon J. Bending**, S.E. Pate, Z-L Xiao, L. Cadorim, M.V. Milošević

University of Bath

In addition to active junction elements, large passive 'moats' are routinely introduced into digital superconducting circuits to trap unwanted vortices that would otherwise seriously impact circuit operation. Here we use scanning Hall microscopy to study the effectiveness of flux trapping by arrays of square moats patterned in a sputtered Nb film. The vortex trapping efficiency of moats is often inadequate and new approaches appear to be needed to address this problem. One possible new direction is the introduction of spatially asymmetric 'ratchet' potentials into films which allow vortices to be driven to desired locations (e.g., moats). We have extended our imaging studies to vortex structures in a Nb film patterned with a sawtooth 'ratchet' topography. We study the effective pinning potential for this geometry as well as commensurability effects that arise at high fields. Finally, we present preliminary investigations of the dynamics of vortices actively driven through the ratchet potential.

Flux removal from multilayer superconducting structures using a ratchet layer

Leonardo Cadorim

University of Antwerp, Belgium

Superconducting microelectronics offer a promising alternative to CMOS technology, as they are theoretically capable of dissipation-free operation. Over the past decade, continued industrial and academic research has advanced superconducting digital technologies, though their maturity and scalability still lag behind conventional semiconductor platforms. One of the most challenging problems in superconducting devices is the unwanted magnetic flux trapping. During device operation, superconducting vortices can become pinned in the complex geometry of the circuit, disturbing its operation. Here, we propose that the trapped flux can be removed from the device through the inclusion of an extra superconducting layer with an asymmetric thickness profile. By applying an AC current through this layer, one can achieve directional vortex motion, with the vortex line able to move along the slope of the thickness profile but not in the opposite direction, a phenomenon known as the ratchet effect. We then show that the directional motion can be used to depin vortices in the circuit layers due to the magnetic coupling of the vortex lines. Through the numerical solution of the time-dependent Ginzburg-Landau (TDGL) equations, we have optimized the ratchet profile, investigating how the period, asymmetry and height of the ratchet pattern influence the conditions for the emergence of directional motion. We validate the simulations by comparing their predictions with experimental results. Finally, we numerically test the method of flux remotion in multilayer superconducting systems, determining optimal values of AC current and amplitude.

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Co-authors: Samuel Pate, Robert Dawson, Zitong Zhao, Andreas Glatz, Zhili Xiao, Alexei Koshelev, Boldizsar Janko, Milorad V. Milosevic

The Effect of Vortex Core Shape in Molecular Dynamics Simulations of Abrikosov Vortices in Ratchet Modulated Superconducting Films

Robert Dawson

University of Notre Dame

Molecular dynamics simulations is widely used to model vortex motion in superconducting films by treating them as point-like objects subject to their overdamped equation of motion. However, for simulations focusing on flux trapping in height modulated films, the full shape of the vortex can play a critical role. To account for the vortex shape, we begin with the Ginzburg-Landau free energy of a vortex with a Clem profile in a film with an arbitrary height modulation. By calculating the force from this free energy, the simulation is able to treat the vortex as a point-like object while applying an effective pinning force that accounts for its core shape. To study the accuracy of this technique, we apply it to a ratchet modulated film in the presence of an AC drive force. We compare our results with analogous Time-Dependent Ginzburg-Landau simulations, and find good agreement for both the critical currents and the average vortex velocity.

Co-authors: Leonardo Cadorim, Milorad V. Milosevic, Alexei Koshelev, Boldizsar Janko

Power-efficient chip-scale hybrid superconductor–semiconductor electronics enabling cryogenic logic and quantum technologies

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Hybrid superconductor–semiconductor (S–Sm) electronics are emerging as a powerful platform for cryogenic computing and quantum technologies. By combining the electrostatic tunability and scalability of semiconductor devices with the phase coherence and ultra-low dissipation of superconducting circuits, these hybrid architectures enable a new class of energy-efficient cryogenic logic and quantum-compatible hardware. Within this framework, Josephson-junction–based devices, including Josephson junction field-effect transistors (JJFETs or JoFETs) and superconducting Josephson diodes, provide versatile building blocks for non-dissipative switching, non-reciprocal transport, and voltage-controlled modulation of supercurrent through gate-tunable semiconductor channels.

In this talk, I present recent advances in hybrid S–Sm integrated circuits based on Nb and NbN superconducting platforms coupled to gate-defined semiconductor systems such as InGaAs, Si/SiGe, and graphene. We demonstrate the fabrication and experimental realisation of gate-tunable superconducting switches, Josephson diode devices, and hybrid superconducting circuits. Microwave spectroscopy and low-temperature transport measurements reveal their switching dynamics, non-reciprocal behaviour, coherence characteristics, and operational stability. These results highlight the potential of hybrid S–Sm electronics as scalable building blocks for cryogenic logic, low-loss signal processing, and quantum-technology hardware operating at millikelvin to kelvin temperatures.

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Abrikosov Vortices Switching Josephson Current in Magic Angle Graphene

Vadim Geshkenbein

ETH, Zurich

Planar Josephson junctions made from atomically thin films exhibit poor transverse screening, causing the magnetic-field dependence of the Josephson current Ic(B) to deviate from the standard Fraunhofer pattern of conventional junctions. Given the weak screening, the junction is highly sensitive to Pearl vortices in the leads. Vortices alter the phase pattern and affect the Josephson current. Thermal and quantum fluctuations can cause vortices to jump in and out of the leads, leading to shifts in the Fraunhofer-like pattern, as observed in recent experiment [1, 2]. Our model quantitatively explains these jumps, whose timescale depends on magnetic field, current, temperature, and superfluid stiffness. At elevated temperatures, fast vortex jumps may wash out the Fraunhofer pattern well below Tc. By analyzing the timescale of these jumps, we can determine the superfluid stiffness and the Berezinskii-Kosterlitz-Thouless transition temperature of magic-angle twisted four-layer graphene. These values are in agreement with recent kinetic inductance measurements [2,3]

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Dissipation of trapped vortices in high-Q superconducting resonators and thin film structures.

Alex Gurevich

Old Dominion University, Norfolk VA

This talk gives an overview of recent theoretical and computational developments in the understanding of losses caused by trapped vortices in high-Q resonators and thin film structures with the emphasis on superconducting cavities for particle accelerators, microcavities for quantum computing and single photon detectors. Features of extreme dynamics of single vortices driven by currents close to the depairing limit and the role of pinning in nonlinear vortex dissipation in thin films are addressed. Ways of manipulating density of trapped vortices and reducing vortex losses in superconducting thin film structures are discussed.

Development of Cryogen-Free SQUID on Tip Fabrication process and Scanning SQUID Microscope platform for Imaging from Near-Zero to 1-Tesla Fields

Martin Huber

University of Colorado, Denver

We present the development of a cryogen-free SQUID-on-Tip (SOT) fabrication process [Denver] and the associated cryogen-free scanning SOT microscope platform [Boulder] designed for nanoscale magnetic imaging across a broad magnetic field range and a temperature range of 300 mK to 9 K. The SOT substrate, a 1 mm O.D. quartz glass capillary, is drawn down to diameters ranging from 50 to 300 nm using a commercial pipette puller. A wide variety of pipette geometries and superconducting (SC) materials can be accommodated to achieve multi-junction SOTs and others with unique geometries, which enable the wide range of field operation. Normal-metal electrical contacts are deposited on the 1 mm O.D. region of the pipette via self-aligned thermal vacuum deposition; the pipette is then rotated 90º and masked such that a 250 µm long shunt resistor is deposited to bridge the future SC leads. The unique feature of this fabrication process is the use of a cryogen-free UHV chamber cooled to 8 K to deposit the self-aligned SC features at the very tip of the pipette. Low-pressure He gas is introduced between depositions to facilitate additional thermal coupling of the pipette to the cooling system. The scanning SOT microscope incorporates an ultra-low-vibration closed-cycle cryostat with a 300 mK base temperature, enabling extended, stable operation without the use of liquid cryogens. The microscope also supports exchange-gas environments for controlled thermal studies of samples. With its high spatial and magnetic sensitivity across both low- and high-field regimes, this platform provides a versatile tool for investigating a wide range of superconducting, magnetic, and quantum materials.

Vortex Structure and Core Spectroscopy in Superconducting Materials for Qubit Applications

Maria Iavarone

Temple University

Understanding vortex behavior in superconducting materials is important for improving coherence in superconducting qubit platforms. We use scanning tunneling microscopy and spectroscopy (STM/STS) to investigate vortices and vortex-core electronic structure in Nb films, Nb–Au-, and Nb–Re-based bilayers relevant to quantum device applications. Films prepared using different deposition techniques and exhibiting varied morphologies are systematically studied. I will discuss how film morphology and proximity influence vortex arrangement and core spectroscopy. The results provide insight into materials platforms relevant for superconducting qubits.

A Gibbs Energy Framework for Analyzing Interacting Vortices in Multilayer Superconducting Structures

Kyle Jackman

SUN Magnetics

We present a Gibbs free energy-based framework for analyzing vortex trapping in thin film and multilayer superconducting circuits. By formulating vortex self-energy, field interaction energy, and vortex-vortex interaction terms within a unified Gibbs free energy landscape, we determine stability conditions, forces, and threshold fields for sequential vortex trapping. The approach extends naturally from single-vortex models to multiple interacting vortices in complex geometries. Implemented in the InductEx engine, the method enables efficient analysis of vortex configurations in large-scale, multilayer superconducting circuits and arbitrary three-dimensional structures. This methodology provides a practical design tool for mitigating flux trapping in superconducting electronics, including quantum circuits and SFQ technologies, and offers a scalable framework for studying interacting vortices in advanced superconducting systems.

Co-author: Coenrad Fourie

Finite-Thickness Effects on Transport in Superconducting Thin Films

Dorcas Joseph

Northern Illinois University

We report on 3D time-dependent Ginzburg–Landau simulations of vortex dynamics in ratchet-patterned Nb thin films, motivated by improving superconducting logic devices through reliable removal of trapped flux. For a ratchet-to-film thickness ratio of 33% at T=0.5Tc, the simulated voltage–current characteristics agrees well with analytical predictions and prior 2D studies at low and intermediate currents. However, unlike the analytical model, and 2D models (MD or TDGL), our 3D results show a sustained ratchet effect even in the nominal free-flux-flow regime, indicating persistent directional vortex motion enabled by finite-thickness geometry. This highlights the importance of full 3D modeling for realistic superconducting microelectronics. Ongoing work investigates how thinner films (larger ratchet-to-thickness ratios) and higher temperatures modify ratchet efficiency, phase-slip activity, and velocity decay, with the goal of optimizing vortex-control strategies for superconducting microelectronics.

Co-authors: Andreas Glatz, Zitong Zhao, Daniel Foster

Widefield NV diamond microscopy for characterization of flux trapping in superconducting electronics

Michele Kelley

MIT – Lincoln Laboratory

In order for superconducting electronics (SCE) to fulfill its promise as an energy efficient CMOS alternative, significant improvements in reliability and scalability are required. Achieving this goal requires understanding and mitigating magnetic flux trapping, which adversely affects the superconducting circuits. The interplay between magnetic flux vortices, circuit elements, moats intended to sequester flux, ground planes, and material defects creates a complex landscape which is too ambiguous for electrical testing alone to disentangle, even when specialized characterization techniques like bit-by-bit analysis for shift registers are employed.

Here we present a cryogenic quantum diamond microscope for imaging flux in SCE. We use nitrogen-vacancy (NV) centers, which are magnetically sensitive atomic scale defects in diamond that are robust across a wide range of temperatures and magnetic fields. The microscope works by bringing a diamond with a layer of nitrogen-vacancy centers into close proximity with an SCE circuit and imaging the magnetic field dependent fluorescence from the NV centers in a camera. The exceptional magnetic field sensitivity of NV centers enables rapid, simultaneous visualization of flux vortices in SCE circuits over a millimeter-scale field of view.

In this talk, we present our R&D 100 Award-winning cryogenic quantum diamond microscope and highlight recent progress in studying how material defects and circuit design contribute to flux pinning.

Dynamics of vortex-based memory cells

A. Skog, R. A. Hovhannisyan, T. Golod, and **V. M. Krasnov**
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The lack of dense random-access memory is one of the main obstacles to the development of digital superconducting computers. It has been suggested that AVRAM cells [1,2], based on the storage of a single Abrikosov vortex—the smallest quantized object in superconductors—can enable drastic miniaturization to the nanometer scale.

In this work, we present the numerical modeling of such cells using time-dependent Ginzburg–Landau equations. The cell represents a fluxonic quantum dot containing a small superconducting island, an asymmetric notch for the vortex entrance, a guiding track, and a vortex trap. We determine the optimal geometrical parameters for operation at zero magnetic field and the conditions for controllable vortex manipulation by short current pulses. We report ultrafast vortex motion with velocities more than an order of magnitude faster than those expected for macroscopic superconductors. This phenomenon is attributed to strong interactions with the edges of a mesoscopic island, combined with the nonlinear reduction of flux-flow viscosity due to the nonequilibrium effects in the track.

Our results show that AVRAM cells can be scaled down to sizes comparable to the London penetration depth, ∼100 nm, and can enable ultrafast switching on the picosecond scale with ultralow energy per operation, ∼0.1 aJ. For details see Ref. [3].

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Vortex Dynamics in Patterned Niobium Thin Films

Oscar Leonard, Simon Bending

University of Bath

Vortex nucleation, confinement, and transport in patterned Niobium thin films were investigated using scanning Hall probe microscopy, enabling high-resolution Bz imaging via Hall voltage detection. Moat-array structures were characterised under applied fields from –11 to 9 G. Effective flux trapping was observed within ±1.25 G, with vortex population scaling approximately linearly with field. The temperature dependence of individual vortex scans indicated a quenching temperature between 8.75 K and 9 K, suggesting structural formation is dominated by long-range vortex–vortex interactions very close to Tc. Samples with a 'ratchet' topography were examined to probe the effective pinning potential and commensurability effects. At high fields, vortices formed chain-like configurations along ratchet channels. In-plane screening currents induced bidirectional vortex motion across multiple ratchet periods. Peaks in B–H loops near 9 G revealed commensurate ordering of the Abrikosov lattice over integer multiples of the ratchet spacing, demonstrating geometry-mediated control.

Active management of trapped magnetic flux in a superconducting device

Brenna Petrelli, Joshua Bedard, Jacob Franklin, Jonah Britton, Ryan Laing, Sage Hanlon, Kyle Jackman, Lieze Schindler, Johannes A. Delport, Tessa Hall, Paul Rossouw, Coenrad Fourie, Daniel T. Yohannes, Ilya Sochnikov, **Oleg Mukhanov**

SeeQC, Inc.

Trapped magnetic flux has been a persistent problem for more than 40 years impacting superconducting digital and quantum Integrated circuit operation preventing widespread insertion into practical applications. Although there are many mitigation techniques including magnetic shielding, moats in the layouts, defluxing warmup cycles, cooldown temperature profiles, these passive approaches do not lead to deterministic flux-free state. In this talk, we will review our active flux management approach to deterministically move magnetic vortices out of active circuit areas with directional control using on-chip network of pulsed electric drivelines. We will review new simulation and experimental results.

Magnetic imaging of superconducting devices

Katja Nowack

Cornell University

Magnetic imaging provides a direct way to probe the behavior of superconducting structures. In this talk, I present several examples of how scanning SQUID microscopy can be used as a local magnetic probe to study vortices and proximity effects in superconducting materials and devices. First, we visualize vortex configurations in NbTiN thin-film structures to investigate flux trapping. Imaging of strips with varying width and arrays of antidots with different size and spacing reveals how geometry and pinning sites influence vortex distributions. Second, we study superconducting devices where proximity effects at interfaces between superconductors and normal metals modify electronic transport. By mapping the local superfluid stiffness in transition-edge sensors (TESs), we probe the spatial structure of these proximity effects extending across the device. Finally, if time permits, I will show imaging of vortex lattices in two-dimensional Josephson junction arrays. When the magnetic flux per plaquette is rational, vortices form ordered configurations commensurate with the lattice. While some of these states appear in transport measurements, scanning SQUID imaging reveals additional ordered vortex configurations that are not detected in transport.

Co-authors:

Rishi Mishra, Ruiheng Bai, Aliakbar Sepehri, Blake Hodges, Seifallah Ibrahim, Benjamin Huet, Gilles Delie, Daan Buseyne, Kristiaan Temst, Nagananda Krishnamurthy, Nandini Trivedi, Margriet Van Bael, Anne-Marie Valente-Feliciano, Peter Koufalis, Yen Lee Loh, Cequn Li, Austin R. Kaczmarek, Maciej W. Olszewski, Daniel C. Ralph, Valla Fatemi, S. Walker, J. Austermann, D. Bennett, W. B. Doriese, S. M. Duff, J. Hubmayr, K. Morgan, M. D. Niemack, D. Schmidt, D. Swetz, J. Ullom, J. Weber

Distinguishing Different Types of Plastic Flow in Vortices and Skyrmions with Machine Learning

Cynthia Olson Reichhardt

Los Alamos National Laboratory

Principal component analysis (PCA) is a powerful method that can identify patterns in large, complex data sets by constructing low-dimensional order parameters from higher-dimensional feature vectors. There are increasing efforts to use space-andtime- dependent PCA to detect transitions in nonequilibrium systems that are difficult to characterize with equilibrium methods. Here, we demonstrate that feature vectors incorporating the position and velocity information of driven vortices and skyrmions moving through random disorder permit PCA to resolve different types of disordered motion as a function of driving force and the ratio of the Magnus force to the dissipation. Since the Magnus force creates gyroscopic motion and a finite Hall angle, skyrmions can exhibit a greater range of flow phases than what is observed in overdamped driven vortex systems with quenched disorder. We show that in addition to identifying previously known skyrmion flow phases, PCA detects several additional phases, including different types of channel flow, moving fluids, and partially ordered states. Guided by the PCA analysis, we further characterize the disordered flow phases to elucidate the different microscopic dynamics and show that the changes in the PCA-derived order parameters can be connected to features in bulk transport measures, including the transverse and longitudinal velocity-force curves, differential conductivity, topological defect density, and changes in the skyrmion Hall angle as a function of drive. We discuss how asymmetric feature vectors can be used to improve the resolution of the PCA analysis, and how this technique can be extended to find disordered phases in other nonequilibrium systems with time-dependent dynamics.

Controlling vortex dynamics to avoid flux acalnches in superconduting thin films

Wilson Ortiz

Universidade Federal de Sao Carlos, Brazil

Inspired by the goals of the workshop, I will present a summary of what we have learned - during a quarter of a century - about vortex motion in superconducting thin films: smooth versus abrupt penetration, guidance, inherent and engineered factors that trigger flux avalanches, and how to avoid them. Noteworthy, flux avalanches in thin films can be sparked by perpendicular ac-fields as low as 10-4 Tesla (1 Oe).

The broad set of results on which this presentation is based was obtained through fruitful and long-lasting collaborations among my group and several laboratories around the world.

Vortex ratchet effect in thickness modulated asymmetric niobium gratings

Samuel Pate

Northern Illinois University

Flux trapping in niobium is a major obstacle to the advancement of superconducting devices, and efficient techniques for eliminating trapped flux are required to improve device performance. We investigate vortex removal by fabricating asymmetric pinning potentials to realize the vortex ratchet effect [1]. Asymmetric thickness-modulated pinning potentials are fabricated in niobium films using grayscale electron-beam lithography. The patterned films are subsequently etched by reactive ion etching, which transfers the periodic thickness modulation into the niobium layer. Transport measurements reveal an asymmetric enhancement of the critical current arising from the thickness-modulated pinning potential. When an AC current is applied, a DC rectified voltage is observed, demonstrating the vortex ratchet effect and the resulting asymmetric vortex motion in the grating. We explore the optimization of thickness-modulated pinning potentials and their potential application for vortex removal in superconducting devices.

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Co-authors: Leonardo Cadorim, Robert Dawson, Milorad V. Milosevic, Andreas Glatz, Boldizsar Janko, Ralu Divan, and Zhili Xiao

Correlation between meso- and macro-scopic vortex behavior and quality factors of superconducting qubits

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We investigate correlations between vortex-lattice behavior and the performance of superconducting transmon qubits using a broad set of magnetic and transport measurements, including magneto-optical visualization of flux structure, magnetization, resistivity, critical fields, and London and Campbell penetration depths. Our study focuses on niobium and tantalum thin films grown on various substrates and fabricated under different sputtering conditions, annealing protocols, and capping layers. It is concluded that vortex pinning is not always detrimental to the performance. I will discuss our results in the context of the current understanding of quantum decoherence of superconducting qubits.

Skyrmions and Wigner Crystals on Periodic Substrates

Charles Reichhardt

Los Alamos National Laboratory

We numerically examine the depinning, sliding, and melting of commensurate and incommensurate skyrmions and Wigner crystals on periodic substrates and compare the dynamics to those of superconducting vortices. We show that sliding skyrmion molecular crystal states can form for multi-skyrmion occupancy of periodic substrates. In the Wigner crystal system for commensurate fillings, we find a strongly pinned state that depins into a sliding crystal, while at incommensurate fillings, the depinning threshold is strongly reduced. For fillings below $1/2$, the depinning occurs in a two-step process. Above the first depinning threshold, there is an extended range of drives where the conduction occurs via the sliding of antikinks along the charge stripes, followed by a second threshold where all of the charges begin to slide. At finite temperatures, the external driving reduces the effective melting temperature at commensurate fillings and enhances creep at incommensurate fillings. We show that depinning into different sliding states, such as moving fluids or moving crystals, produces nonlinear features in the transport curves. We also show that transport is asymmetric on either side of a commensurate filling due to the different dynamics for interstitials versus holes in the commensurate structure. A variety of sliding states should be accessible for generalized Wigner crystals at finite temperatures even for low drives.

Microscopic structure of the vortex cores in granular niobium: A coherent quantum puzzle

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In homogeneous type-II superconductors, each Abrikosov vortex has a tiny core where the superconducting gap $\Delta(r)$ is known to smoothly vanish towards the 2π-phase singularity on the scale of the coherence length ξ. The cores host quantized quasiparticle energy levels known as Caroli-de Gennes-Matricon (CdGM) bound states [Caroli et al., Phys. Lett. v. 9, 307 (1964)]. In pure materials, the spectrum of the low-lying CdGM states has the characteristic level spacing $\sim (\Delta_0^2)/E_F$, where E_F is the Fermi energy and Δ_0 is the bulk superconducting gap. In disordered superconductors, the CdGM states shift and broaden due to scattering. Here, we show [1], both experimentally and theoretically, that the situation is completely different in granular Nb films, which are commonly used in superconducting electronics. In these films, in which the grains are smaller than ξ, the gap $\Delta(r)$ in the quasiparticle spectrum reduces towards the vortex core centres by discrete jumps at the grain boundaries and, for some vortices, does not vanish (Fig.1). The bound states adapt to the local environment and appear at unexpectedly high energies. Both $\Delta(r)$ and bound states form a puzzle-like spatial structure, elements of which are whole grains.

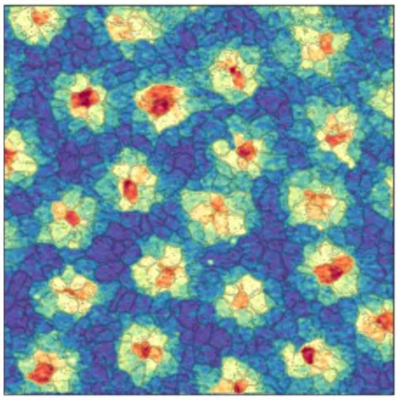

Fig.1. Spatial distribution of the gap in local quasiparticle spectra measured in Nb film at 0.5 T by low-temperature STM/STS.

We also discovered a very slow regime of vortex motion that we were able to track with the sub-nanometer precision over hours after the initial perturbation of the vortex lattice. This regime, related to the granular structure of the system, resembles the viscous motion of glass.

Our discovery shakes up the established understanding of the quantum vortex and encourages a reconsideration of the vortex motion and pinning mechanisms in granular superconductors.

[1] https://arxiv.org/abs/2601.20486

Advanced Microscopy Techniques at the Notre Dame Integrated Imaging Facility

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University of Notre Dame

The Notre Dame Integrated Imaging Facility (NDIIF) provides a comprehensive suite of advanced microscopy and microanalysis capabilities supporting interdisciplinary research across materials science, engineering, physics, chemistry, and the life sciences. This poster highlights key techniques available at NDIIF, including high-resolution transmission electron microscopy (TEM), aberration-corrected scanning TEM (STEM), focused ion beam (FIB) sample preparation, in-situ experimentation, and analytical methods such as EDS, EELS, and tomography. We illustrate how these approaches enable atomic-scale structural, chemical, and functional characterization of complex materials, interfaces, and devices.

Magnetic landscape of superconducting resonators under radio-frequency excitation

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Superconducting resonators are essential components in quantum circuits and highly sensitive sensors. However, their performance is often compromised by magnetic flux penetration, as the interaction of flux quanta and the induced radio-frequency (RF) currents in the superconducting thin film leads to significant energy dissipation. At low operating temperatures, this issue is aggravated as thermomagnetic instabilities can trigger the sudden propagation of magnetic flux avalanches. An important open question is whether the RF excitation itself stimulates the nucleation and propagation of magnetic flux avalanches in the superconducting thin film. The literature remains inconclusive on this point, partly due to the lack of compelling evidence for this phenomenon. In this presentation, we address this challenge by directly visualizing magnetic flux penetration through Faraday rotation imaging under simultaneous RF excitation. We demonstrate that the avalanche activity exhibits a weak dependence on the RF intensity. However, magnetic flux bursts clearly influence the RF transmission properties of the device. Furthermore, we can unambiguously associate a particular avalanche event with a jump in resonance frequency. This enables us to identify the loci of most deleterious events and understand the distinct origins of upward and downward frequency shifts. These observations are supported by electromagnetic simulations in which local changes of the kinetic inductance mimic flux avalanches and confirm the invasive character of the MOI technique. The insights gained from this study aim to contribute to the broader understanding of the magnetic resilience of superconducting resonators and to improve their efficiency and stability.

Co-authors: Julia Baumgarten, Nicolas Lejeune, Lukas Nulens, and Joris Van de Vondel

Anomalous Peak Effects in Superconductors with Columnar Defects

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When heavy-ions with sufficient energy are introduced in superconductors, columnar defects (CDs) are created, which enhance the critical current density (Jc) significantly. CDs offer additional control through their orientations relative to the crystal axis or external magnetic field. Jc – H characteristics in superconductors with CDs often exhibits an anomalous peak, known as the anomalous peak effect (APE), at around ~1/3Bφ (Bφ: matching field), which was first recognized in $(Ba,K)Fe_2As_2$ when two sets of CDs were introduced symmetrically about the c-axis. It is suppressed when asymmetries are introduced—either in the configuration or density of the two CD species. A similar APE was later reported in $NbSe_2$ when tilted CDs were introduced. We have confirmed that APE can appear in $(Ba,K)Fe_2As_2$ with tilted CDs and in $NbSe_2$ with splayed CDs. In this talk, we summarize the present status of APE in $(Ba,K)Fe_2As_2$ and $NbSe_2$ with various configurations and densities of CDs.

Co-authors: W. J. Li, K. Kato, A. Takahashi, Y. Kobayashi, S. Pyon, R. Sakagami, T. Kambara, A. Yoshida, S. Okayasu, and A. Ichinose

Magnetic Flux Imaging in a 3D Superconductor Integrated Circuit

Ren Tong

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We report on imaging magnetic flux distributions in a multilayered superconductor integrated circuit which emerge during magnetization and after field cooling of the circuit in the DC magnetic field. The obtained complicated field maps expose the flux propagation across the patterned superconducting ground planes sandwiching layers with Josephson junction-based logic cells, fine wire grid around the functional units, and multiple superconducting fill structures located in different inner layers. The observed intricate flux distributions are explained by specific patterns of Meissner screening currents and superconducting critical currents in different mutually interacting parts of the integrated circuit. Our results provide important insights into possible ways of improving the protection of superconductor integrated circuits from magnetic fields and their resilience against flux trapping.

Magnetic Flux Trapping in Superconductor Integrated Circuits: Detection, Imaging, and Moat Mitigation

Sergey Tolpygo

MIT – Lincoln Laboratory

Superconductor integrated circuits (SICs) consist of Josephson junctions (JJs) interconnected by superconducting thin-film layers (Nb, NbN, NbTiN) forming inductors, ground planes, transmission lines, etc. Logic data are encoded by single flux quanta (SFQ) or direction of circulating currents in superconducting loops. SICs cooled through the critical temperature Tc in nonzero magnetic field Br, mostly expel magnetic flux, but some number of vortices may be trapped in superconducting films. Trapped flux may affect JJs, interfere with data, thereby compromising performance of SICs. Although SICs operate in shielded environments and use protective structures (moats and antidots) to sequester flux away from logic/memory cells, flux trapping is viewed as a serious obstacle to very large-scale integration of superconducting circuits. I review flux trapping phenomena in superconducting films and VLSI circuits, and methods of detecting, localizing, and imaging trapped flux developed and implemented recently at MIT Lincoln Laboratory. I discuss electrical methods based on studying individual cells in very large scale SFQ shift registers and optical imaging of vortices using large-field-of-view magnetic microscopy based on optically detected magnetic resonance on nitrogen-vacancy (NV) complexes in diamond. The developed NV-diamond magnetic microscope is a fast, high-resolution tool for imaging magnetic fields above the surface of superconducting samples in a few-millimeter field of view, using a digital camera. Moats -- etched regions in circuit layers placed in ground planes and around critical circuitry -- are a simple passive approach to sequester flux. We systematically examined the effectiveness of moat arrays to sequester flux in superconducting niobium films typical for ground planes in integrated circuits as a function of moat array geometry (size, shape, and density) and background magnetic field. By measuring the vortex expulsion field, we estimated the flux saturation number and flux trapping temperature for a range of geometries. We have found that many moat designs effectively sequester flux in magnetically shielded environments (B < 1 uT), with high-aspect-ratio rectangular “slit" moats providing the strongest mitigation at minimal area cost. However, our measurements show that moats alone do not eliminate flux trapping in non-ideal films, as vortices can preferentially pin at material defects. The obtained results provide design guidance for flux mitigation in superconducting integrated circuits and highlight the need for combined optimization of circuit geometries and materials.

DC-operated Josephson junction arrays as a cryogenic on-chip microwave measurement platform

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The control and readout of superconducting qubits conventionally relies on signals within the 4-8 GHz frequency range [1]. However, existing systems face challenges, as the high-frequency signal is typically generated at room temperature and transmitted through multiple attenuation stages to the cryogenic environment, inducing noise and lacking scalability [2]. Addressing these issues, it is more beneficial to situate the control circuits near the qubit devices. As a step towards this goal, we leverage arrays of weak link Josephson junctions as on-chip signal generators capable of converting DC voltage into AC current, emitting voltage-tunable radiation, according to the Josephson relations [3]. We successfully fabricated such arrays, utilizing superconducting MoGe and NbTiN islands with dimensions of 500 x 500 nm^2, that are placed on a 5 nm-thick Au film, as the weak link material [4]. Fig. 1 shows the detected RF signal emitted by the arrays when biased with a DC voltage, with high power regions, in red, following the Josephson relation. The emitted radiation can be further tuned using temperature, magnetic fields, applied currents and device design. Furthermore, a clone of the SNS junction arrays can also serve as a fully DC-operated microwave radiation detector, leading us to propose a high-frequency measurement platform entirely based on DC instrumentation and wiring.

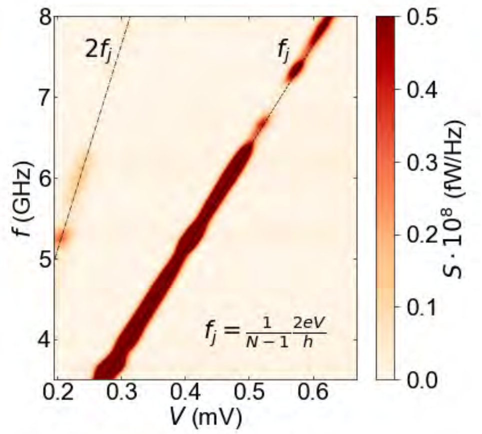

Figure 1: Emitted radiation (frequency and power) as a function of DC voltage over the junction array. Dashed lines show the Josephson relation, with N the number of junctions.

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