S1: Solid-state Defect Engineering

S1.01: Programmable quantum matter with scalable entanglement for universal quantum information processing

Presenter: Pratyush Anand (MIT)
Authors: Pratyush Anand, Odiel Hooybergs, Louis Follet, Hamza Raniwala, Dirk Englund

We propose a theoretical path towards large-scale universal quantum information processing based on many-body spin combs realizing a quantum graph with programmable entanglement using our platform of color centers in diamond nanophotonic waveguides. The strained solid results in various position dependent electron spin resonance frequencies for the different color centers, effectively creating a spin comb. The spin comb is driven by a resonant AC strain field with a programmable periodic waveform that performs local qubit operations, like dynamical decoupling. The waveform is optimized using a new gradient ascent optimal control technique on concatenated composite pulses to correct for both off-resonance and amplitude errors simultaneously. In principle this enhances the coherence time T2* for all the qubits without consuming much power, as the entire system is resonant. To create non-local entanglement interactions between different qubits, we consider two types of bosonic links: a phononic bus and an optical bus for connecting qubits in the same and different waveguides respectively. Leveraging fabrication imperfections and corresponding differences in the fundamental modes of the waveguides ultimately allows all-to-all entanglement in our quantum graph.
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S1.02: Towards Integrated Control of Silicon Color Centers

Presenter: Alessandro Buzzi (MIT)
Authors: Alessandro Buzzi, Camille Papon, Odiel Hooybergs, Qiushi Gu, Hamza Raniwala, Carlos Errando-Herranz, Dirk Englund

Color centers in silicon have garnered significant attention as a promising platform for realizing scalable quantum memories. Their integration with silicon's well-established fabrication processes and their emission frequencies at telecom wavelengths make them attractive candidates for large-scale quantum systems. However, a deeper understanding of these emitters' physics and formation mechanisms is crucial for their extensive implementation. In this study, we present the characterization of G centers, a type of color center in silicon, within various photonic structures. Our results aim to better understand the emitters' optical properties and how these are affected by the surrounding environment. We further propose strategies and devices for achieving controllable strain and electrical tuning of the emitters, paving the way for integrated quantum architectures with enhanced control over quantum defects.
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S1.03: Digital Twin Enabled Error-free Imaging
Presenter: Yuqin Sophia Duan (MIT)
Authors: Hudson Loughlin, Vivishek Sudhir

Optical super-resolution imaging leveraging various methodologies surpasses the limitations imposed by the Abbe diffraction limit. A common approach involves reconstructing the fluorescence point spread function (PSF), a process inherently limited by photon shot noise. Solid-state emitters present a breakthrough with their shot-noise-unlimited fluorescence, which facilitates resolution beyond conventional spatial limits in the frequency domain. Yet, the exact boundaries of precision and especially accuracy at shot noise limit are not fully explored. In this study, we push the boundaries of super-resolution imaging to its fundamental limits by introducing a novel comprehensive digital-physical twin co-learning system, addressing critical considerations such as dipolar emission and setup imperfection. We validate our approach through experiments using silicon-vacancy (SiV) emitters at cryogenic temperature. Our results demonstrate a groundbreaking precision of 0.1~nm. This breakthrough makes a significant leap forward, bringing us into an atomic zone where the localization measurement errors become discretized, opening up a plethora of applications that leverage sub-atomic precision.
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S1.04: Pathway towards large-scale characterization of Er-doped state-of-the-art Si nanophotonic cavities
Presenter: Louis Follet (MIT) & Ian Berkman (MIT)
Authors: Louis Follet, Ian Berkman, Qiushi Gu, Christopher Panuski, Ian Christen, Dirk Englund

Spin qubits in silicon are promising material systems in the field of quantum information processing (QIP) due to their high manufacturability capabilities at the nanoscale. Within this domain, erbium-doped silicon (Er3+:Si) is gaining attention due to the <100 kHz homogeneous optical transitions with emission in the telecom C-band and millisecond electron spin coherence times. These properties enable a robust spin-photon interface for scalable quantum computing and long-distance quantum communication architectures. Nonetheless, due to the initial stage of the research on Er3+:Si for QIP applications, reports on the characteristics of Er3+ ions in Si photonic cavities remain limited. Here, we propose a pathway to characterize over one million Er3+ implanted state-of-the-art (Q/V~1e7) foundry-fabricated Si nanophotonics cavities using wide-field imaging in combination with automatized acquisition. This approach allows us to investigate the properties of Er3+ sites in Si nanophotonic cavities on a large scale and enables us to identify Er3+ ions coupled with high cooperativity to the cavities. Demonstrating the efficiency of this approach will significantly advance research on Er3+:Si for QIP applications and validates the applicability of this method to other emitters in Si.
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S1.06: Magnetic microwave pulse control schemes for non-identical tin-vacancy qubits

Presenter: Malick Sere (MIT)
Authors: Malick A. Sere, Isaac B. Harris, Dirk Englund

With the potential for high qubit densities, long coherence times, and relatively high temperature operation, diamond tin-vacancy centers are promising candidates for a scalable quantum processor platform. Magnetic microwave pulses can drive the resonances of these qubits, and can therefore be used to control them. However, unavoidable process variation and fabrication errors alter the properties of the defects. Variance in the qubits' resonance frequencies is expected, as is inhomogeneity in the applied magnetic field amplitudes experienced by the qubits. In this work, we devise methods of mitigating these effects through calibration and magnetic pulse design. Magnetic pulses can be shaped through amplitude and frequency modulation, a method used in NMR spectroscopy. The span of time over which a pulse is applied to specific qubits offers additional tunability. Through these means, pulse sequences and timings can be tailored to high fidelity operations for various ranges of qubit properties. Finally, a calibration step maps qubits to the appropriate pulse parameters. We demonstrate achievable fidelities and highlight system tradeoffs using simulation.
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S1.07: Electrical manipulation of G-centers in silicon

Presenter: Maddie Sutula (MIT)
Authors: Aaron Day, Jonathan Dietz, Alex Ruan, Denis Sukachev, Mihir Bhaskar, Evelyn Hu

Silicon color centers have recently emerged as promising candidates for commercial quantum information technologies, yet their interaction with electric fields is not well understood. In this talk, we will discuss electrical manipulation of G-centers in silicon -- quantum emitters that photoluminesce in the telecom O-band. We fabricated lateral electrical diodes with an integrated ensemble of G centers in a commercial silicon on insulator wafer. Under application of a reverse-biased DC electric field, the ensemble of G-centers redshifts by approximately 1.4 GHz/V above a threshold "turn-on voltage." The fluorescence intensity is modulated by increasing electric field, ultimately achieving 100% extinction. Finally, we use G center fluorescence to directly image the electric field distribution within the devices, obtaining insight into the spatial and voltage-dependent variation of the junction depletion region and the associated mediating effects on the ensemble. The emitter-field coupling is correlated to the photocurrent generated in the device. Our device architecture uniquely enables simultaneous optical and electrical manipulation of quantum emitters, and it is readily extensible to other emitters in silicon and other semiconductor platforms.
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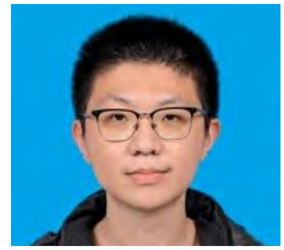
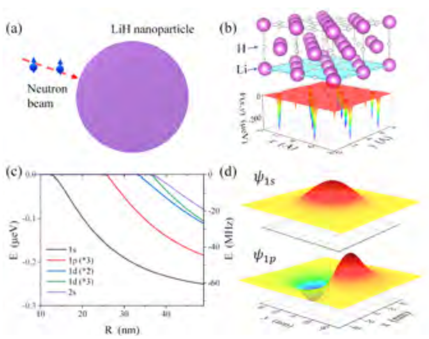
S1.08 μeV-deep neutron bound states in nanocrystals

Presenter: Hao Tang (MIT)
Authors: Hao Tang, Guoqing Wang, Paola Cappellaro, Ju Li





The nuclear strong force induces the widely studied neutron scattering states and MeV-energy nuclear bound states. Whether this same interaction could lead to low-energy bound states for a neutron in the nuclear force field of a cluster of nuclei is an open question. Here, we computationally demonstrate the existence of -μeV-level neutronic bound states originating from nuclear interaction in nanocrystals with a spatial extent of tens of nanometers. These negative-energy neutron wavefunctions depend on the size, dimension, and nuclear spin polarization of the nanoparticles, providing engineering degrees of freedom for the artificial neutronic “molecule”.

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S2: Atomic, Molecular, and Optical Physics

S2.01: Programmable quantum matter with scalable entanglement for universal quantum information processing

Presenter: Odiel Hooybergs (MIT)
Authors: Odiel Hooybergs, Pratyush Anand, Louis Follet, Hamza Raniwala, Dirk Englund

We propose a theoretical path towards large-scale universal quantum information processing based on many-body spin combs realizing a quantum graph with programmable entanglement using our platform of color centers in diamond nanophotonic waveguides. The strained solid results in various position dependent electron spin resonance frequencies for the different color centers, effectively creating a spin comb. The spin comb is driven by a resonant AC strain field with a programmable periodic waveform that performs local qubit operations, like dynamical decoupling. The waveform is optimized using a new gradient ascent optimal control technique on concatenated composite pulses to correct for both off-resonance and amplitude errors simultaneously. In principle this enhances the coherence time T2* for all the qubits without consuming much power, as the entire system is resonant. To create non-local entanglement interactions between different qubits, we consider two types of bosonic links: a phononic bus and an optical bus for connecting qubits in the same and different waveguides respectively. Leveraging fabrication imperfections and corresponding differences in the fundamental modes of the waveguides ultimately allows all-to-all entanglement in our quantum graph.
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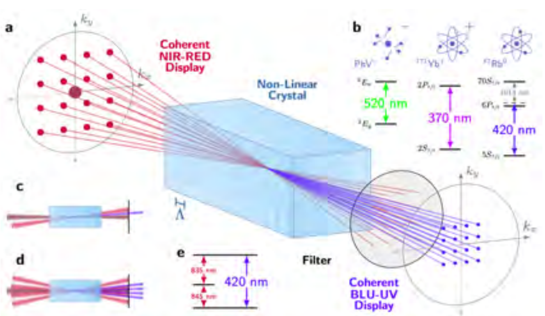
S2.02: Multi-Channel Short-Wavelength Optical Waveform Generation

Presenter: Thomas Propson (MIT)
Authors: Thomas Propson*, Ian Christen*, Hamed Sattari, Gregory Choong, Adrian J. Menssen, Amir H. Ghadimi, Franco N.C. Wong, Dirk Englund



Integrated photonic devices offer a path to perform site-addressable quantum gates on thousands of atomic systems, pushing beyond the limits of bulk optical modulators. Integrated photonic platforms with transparency in the blue and ultraviolet—wavelengths required for many quantum gate protocols—are less developed than platforms for the visible or telecom. Here, we propose and implement a strategy to convert light from arrays of thin-film-lithium-niobate integrated photonic modulators to blue and ultraviolet wavelengths via sum frequency generation with a strong pump beam. Using this strategy, we enable multi-channel, GHz modulation, from 300 nm to 900 nm with a single device. We discuss implications for Rydberg gates on neutral atom qubits.
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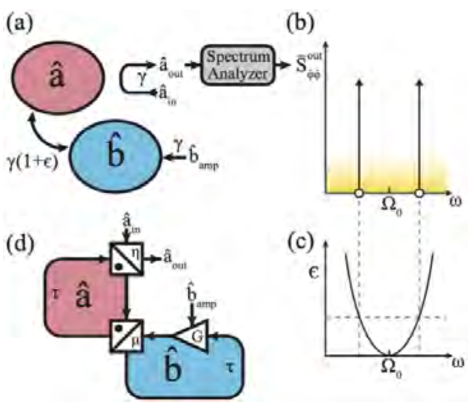
S2.03: Exceptional point systems offer no fundamental sensing enhancement

Presenter: Hudson Loughlin (MIT)
Authors: Hudson Loughlin, Vivishek Sudhir



Over the last decade, experimental and theoretical results generated considerable excitement about the prospects of precision metrology using exceptional point (EP) systems. These systems' eigenvalues diverge as they are slightly perturbed away from an EP, leading to a large signal even for small perturbations. However, there is an ongoing debate as to whether or not excess noise near the EP offsets these sensors' increased signal. We analyze the fundamental quantum and thermal noise properties of EP sensors and show that they have no fundamental sensing advantage compared with traditional sensors. However, EP sensors can be beneficial in practice compared to systems limited by technical, rather than fundamental, noise. The advantage of EP sensors is then restricted to the regime where sensing is limited by technical noises.

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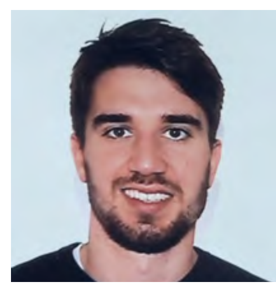
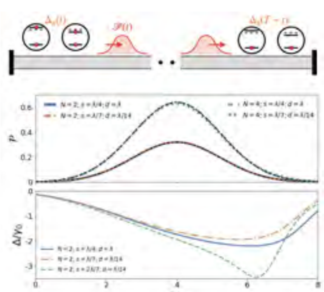
S2.04: Collective dark states as photon memories and sources of non-classial light

Presenter: Oriol Rubies Bigorda (MIT)
Authors: Oriol Rubies-Bigorda, Stuart J. Masson, Susanne F. Yelin, and Ana Asenjo-Garcia





The radiative properties of quantum emitters can differ drastically depending on the electromagnetic environment they are coupled to. When placed in the vicinity of a one-dimensional waveguide terminated by a mirror, distant emitters interact strongly through the virtual emission and reabsorption of waveguide photons. This gives rise to collective states of matter with enhanced and suppressed decay rates, which are typically referred to as super- and subradiant states. In this poster, we demonstrate that applying an optimal frequency shift to each emitter results in perfect single-excitation dark states (that is, strongly subradiant states with zero decay rate) and nearly perfect multiexcitation dark states for ensembles containing only a few emitters. We further show that these dark states can be readily used in quantum information protocols as few-photon memories and few-photon sources, as well as to generate highly entangled photon states for measurement-based quantum computing. Potential experimental implementations include neutral atoms or quantum dots coupled via a photonic crystal waveguide, and superconducting qubits coupled to coplanar waveguides.

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S2.05: Progress Towards Atom Arrays Coupled to a High-Cooperativity Bow-Tie Cavity

Presenter: Matthew Peters (MIT)
Authors: Matthew Peters, Guoqing Wang, David Spierings

We combine single atoms in optical tweezers with macroscopic optical cavities to study entanglement and quantum information. In contrast to generating entanglement with Rydberg-Rydberg interactions, we intend to do so with the enhanced atom-photon interaction of an optical cavity. This has the advantage of both generating long-range interactions between atoms and bypassing the finite lifetime of Rydberg states. It also allows the creation of different types of entanglement limited in fidelity only by the cooperativity of the optical cavity. Our experiment features a bow-tie cavity achieving high cooperativity ($\eta > 30$) and two degenerate traveling wave modes, which provide new opportunities to explore rich topics in cavity QED and quantum simulation. We are currently building our experimental apparatus and interfacing our strongly coupled bow-tie cavity with single-atom optical tweezers. Here we report the current progress in building the experimental setup and preliminary measurements of light-matter interactions in our system.
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S2.06: Real-time observation of light-assisted collisions with an optical cavity

Presenter: Edita Bytyqi (MIT)
Authors: Edita Bytyqi, Beili Hu, Michelle Chong, Gefen Baranes, Josiah Sinclair, and Vladan Vuletic

Efficiently loading single atoms into optical dipole traps is crucial for expediting the initialization stages of quantum information processing algorithms, often hindered by the rearrangement of a probabilistically loaded array to achieve a defect-free configuration of N atoms. Experiments have validated proposed theoretical models for the rates of one-body and two-body losses induced by light-assisted collisions in the presence of multiple atoms. However, existing studies primarily focus on the final single-atom loading probability and lack resolution in elucidating collision dynamics. In this work, we introduce a cavity-mediated approach enabling real-time observation of light-assisted collisions among Rb-87 atoms in a dipole trap at 808 nm with a 50 μs resolution. By selectively examining cases involving the loading of two atoms in the trap, we present quantitative findings on one-body and two-body loss rates, affirming earlier theoretical predictions. Our results reveal a stepwise signal that distinctly illustrates atom loss resulting from collisions. This work contributes to advancing our understanding of collision dynamics in the context of single-atom loading within optical dipole traps and paves the way toward deterministic loading of defect-free atom arrays.
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S2.07: Mitigating electric field noise from electrode surfaces in close proximity to trapped ions

Presenter: Matthew P Roychowdhury (MIT LL)
Authors: Matthew P Roychowdhury, David L Reens, Colin D Bruzewicz, Kyle Debry, May E Kim, Robert McConnell, John Chiaverini

Electrical noise from surfaces can be a challenge for quantum sensing and high-fidelity quantum information processing in atomic systems. In the trapped-ion context, the origin of this noise is unknown, but its characteristics appear dependent on the surface material. Previous work has demonstrated that the temperature dependence of the noise can be altered, and sometimes reduced, by energetic ion bombardment, or "ion milling" of trapping electrodes. The effectiveness of ex-situ ion milling in removing oxides and the subsequent effect on noise has been studied on Nb and Au. Here, we present studies of the effects of ex-situ milling on Al, Pt, NbN, and TiN. We also present temperature dependence of noise measurements using individual ions trapped near electrodes made from Al before and after repeated rounds of ion milling; we also present measurements of the material removal rate of the milling treatments. These results demonstrate both noise reduction and variation in the effect of milling across various materials, suggesting a need to investigate the effect of milling on a material-by-material basis.
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S2.08: Integrated Photonics for High-Fidelity Control of Large-Scale Rubidium Atom Array

Presenter: Hyo Sun Park (MIT)
Authors: Hyo Sun Park, Yin Min Goh, Thomas Propson, Adrian Menssen, Ian Christen, Chao Li, Avinash Kumar, Cole Brabec, Matt Zimmermann, Dirk Englund

Advances in laser technology have driven discoveries in atomic, molecular, and optical physics and emerging applications, from quantum computers with cold atoms or ions to quantum networks with solid-state color centers. Development of large-scale atom-based quantum technologies demands a new generation of “programmable optical control” systems that enable visible (VIS) and near-infrared (IR) wavelength operation, scalability beyond 1000s of individually addressable atoms, high-intensity modulation extinction and repeatability compatible with low gate errors, and fast switching times. To address these challenges, we have recently introduced an atom-control architecture based on VIS-IR photonic integrated circuit (PIC) technology, which meets those requirements. Here we present a scheme that integrates this atom-control PIC (APIC) technology as part of a rubidium (Rb) atom array quantum simulator. We anticipate that this scalable and reconfigurable architecture will offer a critical step toward realizing parallel individual programmability on neutral atom array platforms.
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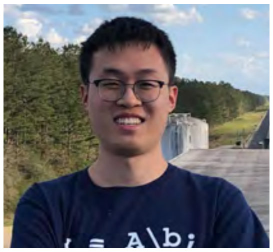
S2.09: LIGO as a quantum nondemolition detector

Presenter: Wenxuan Jia (MIT)
Authors: Wenxuan Jia



A quantum nondemolition (QND) detector allows for measurement of a quantum system without increasing the uncertainty of the measured observable during subsequent evolution of the system. LIGO, a gravitational-wave observatory, measures the position of a 40-kg test mass continuously to infer strain perturbation to the spacetime. However, a measurement on position introduces momentum backaction and increases the uncertainty of the subsequent position measurements, leading to the "Standard Quantum Limit" that limits the reduction of quantum noise. The recently upgraded LIGO A+ detector, which includes frequency-dependent squeezing with an input filter cavity, breaks the Standard Quantum Limit while optimally configured to observe gravitational waves, thereby converting LIGO into a quantum nondemolition interferometer.
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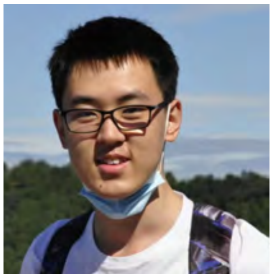
S2.10: Fast Preparation and Detection of a Rydberg Qubit using Atomic Ensembles

Presenter: Peiran Niu (MIT)
Authors: Wenchao X, Tamara Šumarac, Emily Qiu, Adrian Menssen, Shai Tsesses, Peiran Niu, Aditya V. Venkatramani, Sergio H. Cantú, Valentin Klüsener, Mikhail D. Lukin, Vladan Vuletić



Fast readout of qubits with high fidelity is essential for implementing a scalable quantum computation system. However, in the emerging individually controlled Rydberg atoms system, prior approaches for detecting qubits are either not fast enough or not reliable enough. The state-dependent ionization (~0.1 ms) offers only moderate fidelity, while state-dependent atom removal followed by relatively slow fluorescence imaging (~10 ms) achieves higher fidelity (>0.95). Although the Rydberg simulation and computation systems can work on millisecond timescales, achieving much faster detection will be substantially beneficial. Also, non-destructive fast high-fidelity detection could provide the possibility of quantum error correction. Here, we introduce a new approach harnessing Rydberg Electromagnetically Induced Transparency (EIT) for fast, nondestructive preparation, manipulation, and collective readout of a Rydberg qubit within an ensemble of N (~400) atoms. In this scheme, the preparation rate and signal-to-noise ratio are enhanced by a factor of N. The state readout is finished within 6 us with a single-shot fidelity of ~0.92. This method is 10^3 times faster than imaging a single atom with the same optical resolution.
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S2.11: Integrated Photonics for trapped-ion state detection and photon mediated entanglement generation

Presenter: Ethan Clements (MIT)
Authors: Ethan R. Clements, Felix Knollmann, Sabrina Corsetti, Ashton Hattori, Milica Notaros, Tal Sneh, Reuel Swint, Patrick T. Callahan, Dave Kharas, Gavin N. West, Thomas Mahony, Colin D. Bruzewicz, May E. Kim, Cheryl Sorace-Agaskar, Robert McConnell, Jelena Notaros, Isaac L. Chuang, John Chiaverini

Trapped-ion platforms are being developed for use in applications such as atomic clocks, quantum sensing, quantum networking and quantum information processing. For all these applications, entanglement generation between spatially separated ions is a resource that is either needed or beneficial for their functionality. While integrated hardware has been developed that allows precise control at a single particle level for trapped ions, integrated optical components have not yet been used for remote entanglement generation.
Previous demonstrations of photon mediated entanglement used free-space optics to collect and entangle photons emitted from the trapped ions. Here we detail recent work to characterize integrated photonic elements for light collection. We present tests of a trap-integrated collection grating which is used to collect ion fluorescence and perform state detection. Additionally, we discuss how additional integrated elements can be used with these collection gratings to perform photon mediated entanglement between spatially separated trapped ions. Integrated photonic circuits offer an avenue for scaling up the number of entangled ion nodes which can operate in parallel, potentially increasing the entanglement generation rate of trapped-ion quantum networks.
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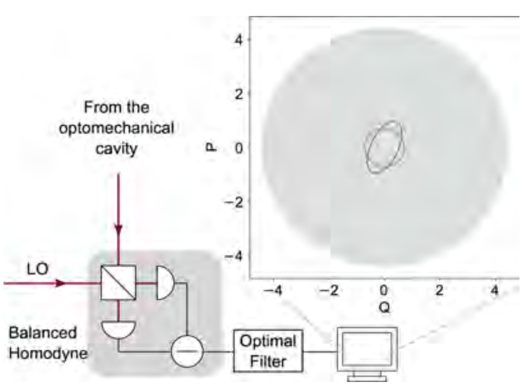
S2.12: Conditional State Preparation of a Micromechanical Oscillator in the Quantum Regime

Presenter: Benjamin Lane (MIT)
Authors: Benjamin Lane, Junxin Chen, Ron Pagano, Scott Aronson, Xinghui Yin, Thomas Corbitt, Nergis Mavalvala



Optomechanical systems in non-classical states are well-suited for studying macroscopic quantum mechanics and for use in future quantum technologies, such as force sensors and transducers. Preparing non-classical states of massive systems, however, is challenging. Utilizing fast continuous measurement to break the symmetry between position and momentum as well as causal, optimal estimators, we aim to prepare a conditionally squeezed mechanical state of a 100ng oscillator in the quantum regime. Our work would open a new door to explore decoherence

mechanisms on large quantum systems and could lead to more precise force sensing.
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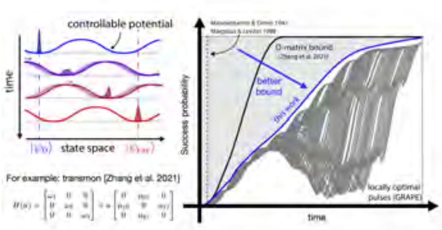
S3: Quantum Algorithms and Machine Learning

S3.01: Sum-of-Squares Bounds for Quantum Optimal Control
Presenter: Fleming Holtorf (MIT)
Authors: Flemming Holtorf, Frank Schäfer, Julian Arnold, Christopher Rackauckas and Alan Edelman



The practical utility of quantum devices is critically determined by the speed at which they can process and communicate information in a controlled manner. This speed is most frequently limited by technological constraints and the design of quantum control protocols. Here, we show how moment-sum-of-squares techniques can be used to put informative bounds on this processing speed and other performance metrics for quantum control. The bounds account for fine-grained system information and technological constraints. The proposed approach yields a hierarchy of convex optimization problems that furnish a convergent sequence of monotonically improving bounds on the attainable performance of a controlled quantum system. We demonstrate with several examples that these bounds outperform other techniques, in particular well-known quantum speed limits that only consider fundamental physical limitations but fail to account for technological limitations.
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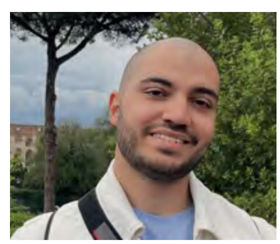
S3.03: Improved Quantum Algorithm for Nonlinear Ordinary Differential Equations
Presenter: Abtin Ameri (MIT)
Authors: Abtin Ameri



Quantum algorithms for nonlinear differential equations have recently become an active area of research. Carleman linearization has emerged as a suitable technique in the field, whereby a nonlinear system is embedded in a higher-dimensional, linear system (Liu et al. 2021). This embedding can be done efficiently when the parameter R, which quantifies the ratio of nonlinearity to linearity in the system, is small. This limits the potential applications of such quantum algorithms, since R for many nonlinear systems of practical interest can be large. In this work, we aim to extend the applicability of Carleman linearization by incorporating a more appropriate definition of the R parameter. We show specific examples of systems where the nonlinearity is large but Carleman linearization converges, and investigate the properties of such systems.
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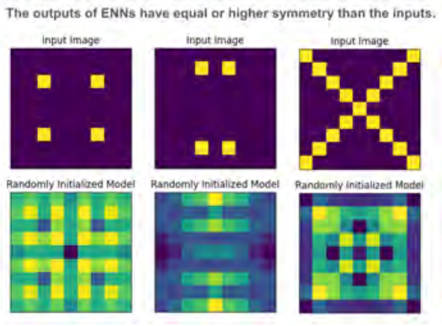
S3.04: Using Equivariant Neural Networks (ENNs) to Uncover Symmetry Implied Missing Information

Presenter: Elyssa Hofgard (MIT)
Authors: Elyssa Hofgard, Ray Wang, Tess Smidt



We demonstrate how Equivariant Neural Networks (ENNs) can identify sources of symmetry breaking in diverse physical data and uncover symmetry-implied missing information unbeknownst to the researcher. Symmetry and symmetry-breaking is crucial for understanding complex physical systems (e.g. phase transitions in materials and the discovery of the neutrino). Physical systems adhere to Curie's Principle–stating that when effects show certain asymmetry, this asymmetry must be found in the causes that give rise to them. ENNs are built to preserve symmetry and thus obey the same principles.
Recorded data can appear to deviate from strict symmetry constraints, thus recent studies emphasize the importance of relaxing equivariance to balance model bias with capturing complex patterns. Here, we present a complementary approach showing that fully equivariant models can be used for real-world problems where symmetry may be broken due to some noise, external forces, or other asymmetries in the environment. These methods can be applied to materials science, where approximate symmetry commonly arises due to structural defects, strain, or phase transitions. Understanding and characterizing these deviations from perfect symmetry are crucial for investigating material properties and behavior.
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S3.05: Tensor Network Assisted Variational Quantum Algorithm

Presenter: Wenhao He (MIT)
Authors: Junxiang Huang, Wenhao He, Yukun Zhang, Yusen Wu, Bujiao Wu, Xiao Yuan

Near-term quantum devices generally have shallow circuit depth and hence limited expressivity due to noise and decoherence. We propose a framework of tensor network-assisted variational quantum algorithms, allowing the solution of quantum many-body problems with shallower quantum circuits. We consider two examples of unitary matrix product operators and unitary tree tensor networks and demonstrate that they can be efficiently implemented. We numerically show that the expressivity is greatly enhanced with the assistance of tensor networks. We test our method for 2D Ising models and 1D time crystal Hamiltonian models with up to 16 qubits. The numerical results show that our method consistently outperforms the conventional approach with shallow quantum circuits.
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S3.06: Cross-entropy benchmarking and beyond in analog quantum devices: highly entangled states and noise verification

Presenter: Daniel K. Mark (MIT)
Authors: Daniel K. Mark, Adam L. Shaw, Zhuo Chen, Joonhee Choi, Pascal Scholl, Ran Finkelstein, Andreas Elben, Soonwon Choi, Manuel Endres

We discuss the use of sampling protocols in analog quantum simulators for fidelity estimation, mixed-state entanglement estimation, and noise verification. These protocols are enabled by universal fluctuations in natural quantum many-body states produced by generic Hamiltonian dynamics. These fluctuations were known to be present in the output of random unitary circuits, and we show that they are present in many-body Hamiltonian dynamics which can be easily realized in analog quantum simulators. Using such fluctuations, we design a sample-efficient protocol which estimates the fidelity between an experimentally prepared state and an ideal target state. We further develop this protocol to estimate the mixed state entanglement of the experimentally prepared state. We demonstrate these protocols in a 60-atom analog Rydberg quantum simulator, finding that our experiment is competitive with state-of-the-art digital quantum devices performing random circuit evolution. Finally, we demonstrate how such data can be used to learn about experimental noise.
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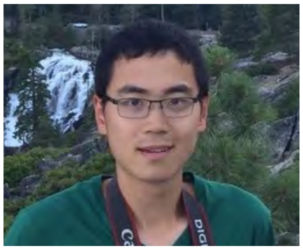
S3.07: Quantum Control Machine: The Limits of Control Flow in Quantum Programming

Presenter: Charles Yuan (MIT)
Authors: Charles Yuan, Agnes Villanyi, Michael Carbin



Quantum programming languages aim to reduce the burden of manipulating hardware-level logic gates in the implementation of a quantum algorithm. A hurdle to this goal is the difficulty of expressing control flow, such as branching and iteration, that depends on the value of data in quantum superposition. To implement algorithms for factorization, search, and simulation that contain control flow, quantum languages often require the use of bit-level logic gates as opposed to the high-level constructs provided by classical languages.

In this work, we identify a fundamental obstacle to control flow in quantum programming, which is that a quantum computer cannot correctly support the conventional conditional jump instruction in superposition, nor the β-reduction of λ-terms in superposition.
We formally prove that programming abstractions with non-injective state transition semantics, such as conventional conditional jumps and β-reduction, produce incorrect results in superposition. Thus, new abstractions are needed for quantum programming.
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S3.08: Efficient high-dimensional bell state measurement with linear optics and single photon emitters

Presenter: Niv Bharos (MIT)
Authors: Niv Bharos, Liubov Markovich, Johannes Borregaard

The use of higher-dimensional photonic encodings (qudits) instead of two-dimensional encodings (qubits) can improve the loss tolerance and reduce the computational resources of photonic-based quantum information processing. To harness this potential, efficient schemes for entangling operations such as the high-dimensional generalization of a linear optics Bell measurement will be required. We show how an efficient high-dimensional Bell state measurement can be implemented with linear optics and auxiliary photonic states. The Schmidt rank of the auxiliary state in our protocol scales only linearly with the dimensions of the input states instead of more than exponential as in previous proposals. In addition, we outline how the state can be generated deterministically from a single quantum emitter coupled to a small qubit processor. Our protocol thus outlines an experimentally feasible route for efficient, high-dimensional Bell measurements with linear optics.

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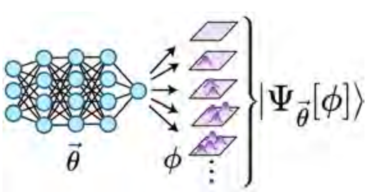
S3.10: Applying the Variational Principle to Quantum Field Theory with Neural Networks

Presenter: John Martyn (MIT)
Authors: Khadijeh Najafi, Di Luo



Physicists dating back to Feynman have lamented the difficulties of applying the variational principle to quantum field theories. In non-relativistic quantum field theories, the challenge is to parameterize and optimize over the infinitely many n-particle wave functions comprising the state's Fock space representation. Here we approach this problem by introducing neural-network quantum field states, a deep learning ansatz that enables application of the variational principle to non-relativistic quantum field theories in the continuum. Our ansatz uses the Deep Sets neural network architecture to simultaneously parameterize all of the n-particle wave functions comprising a quantum field state. We employ our ansatz to approximate ground states of various field theories, including an inhomogeneous system and a system with long-range interactions, thus demonstrating a powerful new tool for probing quantum field theories.

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S3.11: QuACK: Accelerating Gradient-Based Quantum Optimization with Koopman Operator Learning

Presenter: Di Luo (MIT)
Authors: Di Luo, Jiayu Shen, Rumen Dangovski, Marin Soljacic

Quantum optimization, a key application of quantum computing, has traditionally been stymied by the linearly increasing complexity of gradient calculations with an increasing number of parameters. This work bridges the gap between Koopman operator theory, which has found utility in applications because it allows for a linear representation of nonlinear dynamical systems, and natural gradient methods in quantum optimization, leading to a significant acceleration of gradient-based quantum optimization. We present Quantum-circuit Alternating Controlled Koopman learning (QuACK), a novel framework that leverages an alternating algorithm for efficient prediction of gradient dynamics on quantum computers. We demonstrate QuACK's remarkable ability to accelerate gradient-based optimization across a range of applications in quantum optimization and machine learning. In fact, our empirical studies, spanning quantum chemistry, quantum condensed matter, quantum machine learning, and noisy environments, have shown accelerations of more than 200x speedup in the overparameterized regime, 10x speedup in the smooth regime, and 3x speedup in the non-smooth regime. With QuACK, we offer a robust advancement that harnesses the advantage of gradient-based quantum optimization for practical benefits.

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S4: Low-dimensional Materials and Devices

S4.01: Kinetic Inductance Characterization of thin NbSe2 using microwave techniquesTraveling Wave Parametric Amplifiers

Presenter: Sameia Zaman (MIT)
Authors: Sameia Zaman, Joel I-J. Wang, Miuko Tanaka, Thomas Werkmeister, Max Hays, Daniel Rodan Legrain, Aranya Goswami, Thao Dinh, Michael Gingras, Bethany M. Niedzielski, Hannah Stickler, Mollie E. Schwartz, Jonilyn L. Yoder, Kenji Watanabe, Takashi Taniguchi, Terry P. Orlando, Jeffrey A. Grover, Simon Gustavsson, Kyle Serniak, Pablo Jarillo-Herrero, Philip Kim, William D. Oliver

We developed hybrid superconducting microwave resonators incorporating van der Waals (vdW) superconductors to explore the MW response of superconducting 2D materials in the GHz regime. We first developed a reliable technique to contact thin NbSe2, entirely encapsulated with hexagonal Boron Nitride (hBN), with a coplanar Al resonator. Then we fabricated a hybrid Al-NbSe2 resonator and measured the kinetic inductance of thin NbSe2. We report a kinetic inductance of 5 layers of NbSe2 of 0.3 nH/□. Crystalline 2D superconductors with high kinetic inductance can be used in superconducting quantum devices, photon detection, and other quantum sensors.
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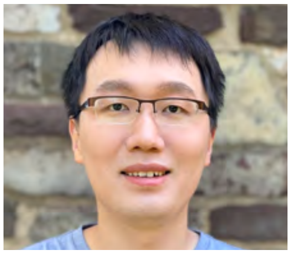

S4.02: Efficient Quantum Transduction Using Anti-Ferromagnetic Topological Insulators

Presenter: Haowei Xu (MIT)
Authors: Haowei Xu, Changhao Li, Guoqing Wang, Hao Tang, Paola Cappellaro, and Ju Li

Transduction of quantum information between distinct quantum systems is an essential step in various applications, including quantum networks and quantum computing. However, quantum transduction needs to mediate between photons with vastly different frequencies, making it challenging to design high-performance transducers, due to multifaceted and sometimes conflicting requirements. In this work, we first discuss some general principles for quantum transducer design, and then propose solid-state anti-ferromagnetic topological insulators to serve as highly effective transducers. First, topological insulators exhibit band-inversion, which can greatly enhance their optical responses. Coupled with their robust spin-orbit coupling and high spin density, this property leads to strong nonlinear interaction in topological insulators, thereby substantially improving transduction efficiency. Second, the anti-ferromagnetic order can minimize the detrimental influence on other neighboring quantum systems due to magnetic interactions. Using MnBi2Te4 as an example, we showcase that unit transduction fidelity can be achieved with modest experimental requirements, while the transduction bandwidth can reach the GHz range.
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S4.03: Precise patterning of graphene for voltage-tunable Josephson Junctions

Presenter: Pablo Mercader Perez (MIT)
Authors: Pablo Mercader-Pérez, Daniel Rodan-Legrain, Joel I. J. Wang, Réouven Assouly, Max Hays, Aranya Goswami, Sameia Zaman, Beatriz Yankelevich, Aziza Almanakly, Thomas Hazard, Michael Gingras, Bethany M. Niedzielski, Hannah Stickler, Mollie E. Schwartz, Jonilyn L. Yoder, Kenji Watanabe, Takashi Taniguchi, Terry P. Orlando, Simon Gustavsson, Jeffrey A. Grover, Kyle Serniak, Pablo Jarillo-Herrero, William D. Oliver

Gate-tunable Josephson junctions provide a promising platform to engineer novel elemental components of superconducting circuits. Particularly, graphene-based weak link Josephson Junctions offer the advantage that the critical current can be easily tuned by the gate voltage. Modifying the dimensions of the graphene can offer another control knob to achieve the desired critical currents This is important for applications such as gatemons (gate-tunable Josephson junction-based qubits), which have emerged as an alternative approach to mitigate some of the key challenges in superconducting qubits.

The ability to use an atomic force microscope to manipulate graphene via local anodic oxidation at a nanoscopic scale has been demonstrated before. Here we explore the use of this technique as part of a clean fabrication process of graphene based nanodevices with the goal to reliably make a Josephson Junction with a geometry controllable to the submicron scale.

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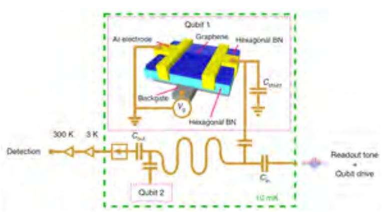
S4.04: Optimized Backgate Design for Enhancing Coherence Times in Graphene Gatemons

Presenter: Daniel Rodan Legrain (MIT)
Authors: Daniel Rodan-Legrain, Joel I. J. Wang, Pablo Mercader-Pérez, Réouven Assouly, Max Hays, Aranya Goswami, Sameia Zaman, Beatriz Yankelevich, Aziza Almanakly, Thomas Hazard, Michael Gingras, Bethany M. Niedzielski, Hannah Stickler, Mollie E. Schwartz, Jonilyn L. Yoder, Kenji Watanabe, Takashi Taniguchi, Terry P. Orlando, Simon Gustavsson, Jeffrey A. Grover, Kyle Serniak, Pablo Jarillo-Herrero, William D. Oliver



Gate-tunable Josephson junction-based qubits (gatemons) have emerged as a promising approach to mitigate some of the key challenges in standard, flux-tunable transmon superconducting qubits, such as qubit sensitivity to flux noise, crosstalk, and power dissipation. Unlike SQUIDs, gatemons do not rely on flux biases and can be controlled via an electrostatic gate. While gatemons have been realized in various systems, including semiconducting nanowires, two-dimensional electron gases, and graphene, their coherence times remain a limiting factor for achieving high-fidelity multi-qubit operations. Here, we present a graphene-based differential (floating) qubit design in which two capacitor pads are symmetrically coupled to the back gate line with equal strength. This geometry is expected to significantly inhibit energy decay through this channel, which is suspected to be the primary source of dissipation limiting prior work. We explore these improvements in the context of device design, fabrication, and microwave measurements. *drodan@mit.edu*

S5: Quantum Sensing & Imaging

S5.01: A Superconducting Bridge Rectifier Using the Asymmetric Surface Barrier Effect

Presenter: Matteo Castellani (MIT)
Authors: M. Castellani, O. Medeiros, A. Buzzi, R. A. Foster, M. Colangelo, K. K. Berggren

In large-scale systems based on niobium nitride (NbN) thin films, such as superconducting nanowire single-photon detector (SNSPD) arrays, a superconducting diode can be helpful for signal rectification. In particular, AC-to-DC converters based on bridge rectifiers might help decrease the number of cables exiting the cryostat by frequency multiplexing the bias levels of several superconducting devices on chip. Although the superconducting diode effect (SDE) has been demonstrated with several technologies, integrating them into NbN-based systems can be challenging due to platform incompatibility. The asymmetric Bean-Livingston surface barrier effect in thin-film micro-bridges under external magnetic fields provides a potential solution.
We fabricated reliable superconducting diodes by creating a lithographic triangular defect on one side of 1-μm wide and 14-nm thick NbN micro-bridges. By supplying a 4-mT magnetic field, we observed SDE with a maximum rectification factor of 42% at 4.2 K. We used such diodes to demonstrate bridge rectifiers for full-wave rectification of 3-MHz sinusoidal signals and AC-to-DC current conversion at 50 MHz. Finally, we simulated a bias distribution network for SNSPDs with frequency-multiplexed bias levels by exploiting the demonstrated devices.
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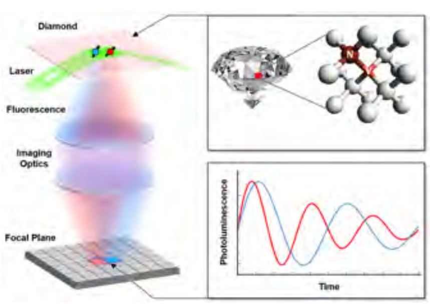
S5.03: Wide-Field Magnetic Imaging with NV Centers in Diamond

Presenter: Samuel Karlson (MIT)
Authors: Samuel Karlson, Jennifer Schloss, Andrew Maccabe, Paola Cappellaro, Guoqing Wang, David Phillips, Pauli Kehayis, Danielle Braje



Nitrogen vacancy centers in diamond are a leading high-sensitivity quantum sensor for magnetic fields. NV-based magnetometers offer micron-scale resolution and millimeter-scale field-of-view magnetic imaging capabilities under ambient conditions. Their applications range across various fields, including uses in biological systems, materials characterization, nuclear magnetic resonance, and circuit diagnostics. In this work, we demonstrate the capabilities of NV ensembles for magnetic imaging across a wide range of frequencies.
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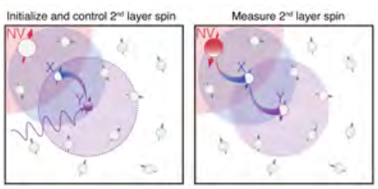
S5.04: Extending an electronic-spin quantum register via control of spin-chains in diamond

Presenter: Alexander Ungar (MIT)
Authors: Alexander Ungar, Won Kyu Calvin Sun, Alexandre Cooper, Paola Cappellaro



Dark electronic-spin defects in the environment of a Nitrogen-Vacancy (NV) center in diamond can be used to increase the size of solid-state quantum registers for applications in quantum sensing and communication. So far, these hybrid electronic-spin registers have only included 1st-layer spins which are directly coupled to the NV, resulting in register sizes that are limited by the NV coherence time. To address this problem, we present a scalable approach to extend control to spins beyond this NV coherence limit, and we experimentally demonstrate this for a 2nd-layer spin which is indirectly coupled to the NV. We exploit the 1st-layer spin as a probe to identify the 2nd-layer spin with spin-echo double resonance (SEDOR), and we initialize and demonstrate full single-qubit control of the 2nd-layer spin by performing concatenated polarization transfer across the spin-chain. We also show that our method of concatenated polarization transfer to sense spins in higher layers is more robust to decoherence as compared to correlated spectroscopy protocols. Together, our method and results pave the way for engineering larger quantum spin registers with the potential to advance nanoscale sensing of spin-labeled molecules and accelerate defect identification for quantum applications.
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S5.05: Frame Change Technique for Phase Transient Cancellation

Presenter: Andrew Stasiuk (MIT)
Authors: Andrew Stasiuk, Pai Peng, Garrett Heller, Paola Cappellaro

The precise control of complex quantum mechanical systems can unlock applications ranging from quantum simulation to quantum computation. Controlling strongly interacting many-body systems often relies on Floquet Hamiltonian engineering that is achieved by fast switching between Hamiltonian primitives via external control. For example, in our solid-state NMR system, we perform quantum simulation by modulating the natural Hamiltonian with control pulses. As the Floquet heating errors scale with the interpulse delay, δt, it is favorable to keep δt as short as possible, forcing our control pulses to be short duration and high power. Additionally, high-power pulses help to minimize undesirable evolution from occurring during the duration of the pulse. However, such pulses introduce an appreciable phase-transient control error, a form of unitary error. In this work, we detail our ability to diagnose the error, calibrate its magnitude, and correct it for $\pi/2$-pulses of arbitrary phase. We demonstrate the improvements gained by correcting for the phase transient error, using a method which we call the ``frame-change technique'', in a variety of experimental settings of interest.
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S5.06: Disordered Field Calculations for Local Observables in Solid-State NMR

Presenter: Garrett Heller (MIT)
Authors: Garrett Heller, Andrew Stasiuk, Paola Cappellaro

The disordered field model is a novel way to view Z-Z type interactions in solid-state magnetic resonance, enabling the disordered state technique for measuring local observables. We built an extensible codebase to compute the disordered field distribution in arbitrary solid-state crystals originating from heteronuclear dipolar spin Hamiltonians. Additionally, we estimated the spin diffusion rate for the disorder inducing spin species, determining the timescale under which the disordered field changes. We further estimated the noise correlations for arbitrary pairs of spins, which gives the minimum evolution time needed to prepare the locally disordered state. Preliminary experiments were conducted on a 7.1 T NMR spectrometer to verify these numerical predictions.
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S5.07: Characterizing Microwave Multiplexers for Cryogenic Particle Detectors

Presenter: Jiatong Yang (MIT)
Authors: Jiatong Yang, Wouter Van De Pontseele, Faith Reyes, Patrick M. Harrington, Steve Weber, Cyrus Hirjibehedin, William D. Oliver, Joseph Formaggio

Many modern particle physics experiments use large arrays of cryogenic sensors to obtain high energy sensitivity and high event statistics. Since these sensors are confined in sub-Kelvin cryostats with limited space, it is crucial to simplify cabling and reduce power dissipation with a multiplexed readout scheme. Compared to more traditional multiplexing techniques such as time and code division multiplexing, a frequency-division multiplexer made with high Q superconducting resonators allows for faster pulse response, higher multiplexing factor, and lower power dissipation, which makes it a promising component for future cryogenic particle experiments.
Together with Lincoln Laboratory, we designed, fabricated, and characterized microwave multiplexers in 6 and 18 channels configurations. The signals couple inductively into RF SQUIDs that modulate the resonant frequency of the superconducting resonators, which all connect to a common RF feedline for signal readout. In this poster, we present some characterization results of this device, including sensitivity measurements, circuit parameter extraction, and the power dependence of the device behavior.
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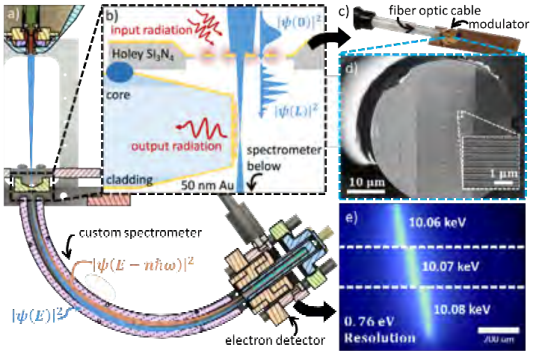
S5.08: Electron-Photon Interactions in a Scanning Electron Microscope

Presenter: John Simonaitis (MIT)
Authors: John W. Simonaitis, Maurice A. R. Krielaart, Stewart A. Koppell, Benjamin J. Slayton, Joseph Alongi, William P. Putnam, Karl K. Berggren, Phillip D. Keathley



Recently, there has been a surge in interest in the generation of heralded and quantum light sources by interacting free electrons with photonic nanostructures, and measuring the resulting output states. In this work, we describe our development of a testbed for studying such interactions in a 10-keV scanning electron microscope. This setup includes an ultrafast emitter, optical modulators for imparting structure onto the electron beam, a nanostructured interaction region, and electron and optical spectrometers with time-tagging electronics to characterize these interactions. Through this work we aim to better understand these interactions at energies orders-of-magnitude lower than previous work, and thus enable their application to heralded ion beam lithography and chip-scale technologies.

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S5.09: Vector magnetometry using cavity-enhanced microwave readout

Presenter: Reginald Wilcox (MIT)
Authors: Reginald Wilcox, David Phillips, Corey Hawkins, Erik Eisenach, Linh Pham, Jennifer Schloss, Dirk Englund, Danielle Braje

We demonstrate full vector magnetometry using nitrogen-vacancy (NV) defects in diamond with the recently developed cavity-enhanced microwave readout technique. The system relies on a very low frequency AC bias field which allows interrogation of multiple NV orientations. Selection of an appropriate bias field direction allows measurement of the projection of the magnetic field onto all four orientations of NV centers and thereby a reconstruction of the full vector magnetic field. Furthermore, since both positive and negative spin states are interrogated by the AC field, systematic drift due to temperature can be tracked and mitigated.

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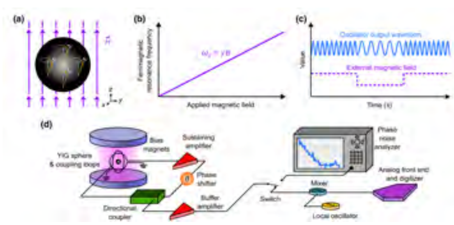
S5.10: Design Considerations for Ferrimagnetic Oscillator Magnetometer

Presenter: David Oliveira (MIT LL)
Authors: John F. Barry, Reed A. Irion, Matthew H. Steinecker, Daniel K. Freeman, Jessica J. Kedziora, Reginald G. Wilcox, Liam J. Fitzgerald, David J. Oliveira, and Danielle A. Braje



Quantum sensors offer unparalleled precision, accuracy, and sensitivity for a variety of measurement applications. We report a compact magnetometer based on a ferrimagnetic sensing element in an oscillator architecture that circumvents challenges common to other quantum sensing approaches such as limited dynamic range, limited bandwidth, and dependence on vacuum, cryogenic, or laser components. The device exhibits a fixed, calibration-free response governed by the electron gyromagnetic ratio. Exchange narrowing in the ferrimagnetic material produces submegahertz transition linewidths despite the high unpaired spin density (approximately 1022 cm−3). The magnetometer achieves a minimum sensitivity of 100 fT/ √Hz to ac magnetic fields of unknown phase and a sensitivity below 200 fT/ √Hz over a 1 MHz bandwidth. By encoding magnetic field in frequency rather than amplitude, the device provides a dynamic range in excess of 1 mT. The passive, thermal initialization of the sensor's quantum state requires only a magnetic bias field, greatly reducing power requirements compared to laser-initialized quantum sensors. With additional development, this device promises to be a leading candidate for high-performance magnetometry outside the laboratory, and the oscillator architecture is expected to provide advantages across a wide range of sensing platforms.
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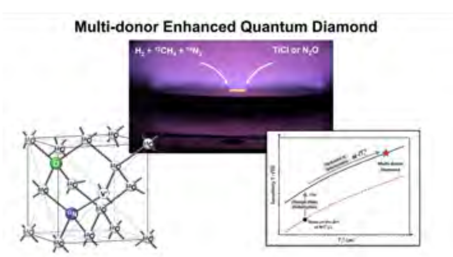
S5.11: Impact of Multiple Donors on NV- Centers in Quantum Diamond

Presenter: Eden Price (MIT LL)
Authors: Eden Price, Dane W. deQuilettes, Justin Mallek, Collin Muniz, Tom Osadchy, Linh Pham, Jennifer Schloss, Danielle Braje



Room-temperature quantum sensors based on nitrogen-vacancy (NV-) centers in diamond provide an exciting platform to achieved unparalleled performance in magnetic navigation, neuroimaging, and materials characterization. The formation of high-quality spin qubits requires impeccable control of diamond growth properties, such as nitrogen location and doping density, defect migration and formation, and charge state stability. Plasma-enhanced chemical vapor deposition (PE-CVD) is a promising technique to achieve controlled substitutional doping of N, but coherence times are often limited by N-N dipolar interactions, poor (< 10%) N to NV- conversion efficiencies, and charge state instability under high laser excitation. Here, we propose a method to overcome these challenges through a combination of PE-CVD paired with high energy implantation. Specifically, we grow and process diamond materials with controlled fractions of multiple donor species (group V, VI, and VII) that strongly impact the formation of NV- centers. We directly measure how these changes in the surrounding physical and chemical environment impact important quantum sensing properties such as the creation yield and charge state stability. These results invite questions about how diamond chemical composition directly impacts NV- performance. We expect this knowledge to be further leveraged to fabricate diamonds with unprecedented sensitivity for a range of quantum electronic and optoelectronic applications.
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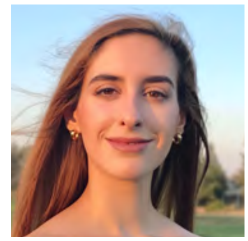
S6: Superconducting Systems

Part 1: Gates, Algorithms, Simulation, Infrastructure

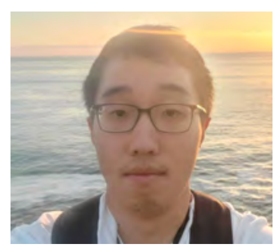
S6.01: Deterministic Bidirectional Remote Entanglement with Waveguide Quantum Electrodynamics



Presenter: Aziza Almanakly, Beatriz Yankelevich (MIT)
Authors: Aziza Almanakly, Beatriz Yankelevich, Bharath Kannan, Max Hays, Agustin Di Paolo, Alex Greene, Michael Gingras, Bethany M. Niedzielski, Hannah Stickler, Kyle Serniak, Mollie E. Schwartz, Jonilyn L. Yoder, Joel I-Jan Wang, Terry P. Orlando, Simon Gustavsson, Jeffrey A. Grover, William D. Oliver

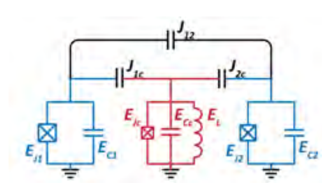
Routing quantum information between non-local computational nodes is a foundation for extensible networks of quantum processors. Quantum information transfer between arbitrary nodes is generally mediated either by photons that propagate between them or by resonant couplers. The utility is determined by the type of emitter, propagation channel, and receiver. Existing approaches involving propagating microwave photons have limited fidelity due to photon loss and are often unidirectional, whereas architectures that use direct resonant coupling are bidirectional in principle, but can generally accommodate only a few local nodes. In this work, we develop a quantum interconnect comprising an emitter, receiver, and propagation channel that circumvent these issues. We have demonstrated high-fidelity directional microwave photon emission using an artificial molecule comprising two superconducting qubits strongly coupled to a bidirectional waveguide. Quantum interference between the photon emission pathways from the molecule generates single photons that selectively propagate in a chosen direction. After emitting time-symmetric, directional photons from one module, we absorb those itinerant microwave photons with another identical module tiled along the same waveguide. *azizaalm@mit.edu, byankele@mit.edu*

S6.02: ZZ-Free Two-Qubit CZ Gate Based on Fluxonium Coupler



Presenter: Junyoung An (MIT)
Authors: Junyoung An, Leon Chen Ding, Youngkyu Sung, Roni Winik, Helin Zhang, Max Hays, Junghyun Kim, Ilan T. Rosen, David A. Rower, Kate Azar, Jeffrey Gertler, Michael Gingras, Thomas M. Hazard, Bethany M. Niedzielski, Mollie E. Schwartz, Hannah Stickler, Jonilyn L. Yoder, Joel I. J. Wang, Terry P. Orlando, Simon Gustavsson, Jeffrey A. Grover, Kyle Serniak, William D. Oliver

We propose an adiabatic, coupler-flux biased controlled-Z gate that is implemented between two transmon qubits coupled via a fluxonium, which we we call T-F-T architecture. The coupling mediated by fluxonium enables complete ZZ interaction cancellation when the gate is not operating. In addition, the two transmons are at the off-straddling regime, making the system less susceptible to microwave crosstalk and frequency crowding. We experimentally verified that complete ZZ cancellation is possible with two qubits in the off-straddling regime. In addition, we discuss the gate operation principle and optimization of the gate fidelity. *anjy@mit.edu*



S6.03: Non-Hermitian Dynamics without loss using Superconducting Circuits

Presenter: Reouven Assouly (MIT)
Authors: Reouven Assouly, Hanlim Kang, Michael Gingras, Bethany M. Niedzielski, Hannah Stickler, Jonilyn L. Yoder, Mollie E. Schwartz, Kyle Serniak, Jeffrey A. Grover, William D. Oliver

Non-Hermitian systems can exhibit interesting behaviors not seen in Hermitian systems, such as the presence of exceptional points where two (or more) eigenvectors collapse onto each other. Systems that exhibit these points typically involve loss and gain that considerably restricts the amount of quantum coherence.
In this poster, following a proposal by Wang and Clerk, we describe a closed, four-mode quantum system able to simulate the dynamics of a PT-dimer consisting of two coupled resonators, one with gain and the other with loss, ideally without any actual dissipation that could introduce noise. The four modes are implemented using four harmonics of a superconducting resonator. Arbitrary parametric coupling between the modes is achieved using a SNAIL coupler pumped by microwave drives.
Thanks to the versatility of these microwave-activated parametric interactions, all of the parameters of the system are tunable over a wide range of parameters. As predicted by the classical PT-dimer theory, we expect to observe the PT-symmetric and PT-broken phases separated by an exceptional point, as well as chiral mode switching. Due to the absence of dissipation, we also expect to observe a significant degree of entanglement.
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S6.04: Progress Toward Coherent Photon Arithmetic on a Superconducting Bosonic Mode

Presenter: William Banner & Christopher McNally (MIT)
Authors: William P. Banner, Christopher McNally, Max Hays, Alen Senanian, Andy Schang, Michael Gingras, Bethany M . Niedzielski, Hannah Stickler, Jonilyn L . Yoder, Mollie E. Schwartz, Kyle Serniak, Simon Gustavsson, Jeffrey A. Grover, Peter McMahon, and William D. Oliver

The rates of most primitive quantum logical operations on n-level systems are state-dependent. This makes arithmetic operations on n-level systems challenging as they require a-priori knowledge of the system state. A prior proposal has shown the theoretical implementation of coherent single-photon subtraction (SPS) from a bosonic mode to an auxiliary qubit via dissipation engineering. It uses two simultaneous drives. One drive irreversibly swaps an excitation from a bosonic mode to an auxiliary bit. The other drive makes the first coherent by irreversibly exciting the auxiliary bit. In this work, we make progress toward experimentally realizing the proposal on a superconducting processor. We support these experimental results with numerical simulations.
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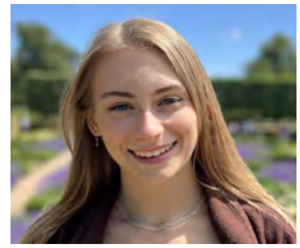
S6.05: Dynamically probing phase transitions on superconducting quantum processors



Presenter: Cora Barret (MIT)
Authors: Cora N. Barrett, Ceren B. Dag, Lauren H. Li, Amir H. Karamlou, Jeffrey A. Grover, William D. Oliver

Superconducting quantum processors are a promising architecture for analog quantum simulation of condensed matter systems, and therefore can be a great tool for studying criticality and other foundational condensed matter phenomena. We propose a series of experiments to dynamically probe quantum phase transitions in 1D spin chains on arrays of superconducting qubits with tunable couplings. We show how universal properties arise in the quench dynamics of the the transverse-field Ising, XY, and Su–Schrieffer–Heeger models. We also discuss how the Haldane phase can be simulated on a superconducting device, towards the goal of realizing topological edge modes with enhanced coherence properties for topological quantum computing.
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S6.06: Pulse Design of Baseband Flux Control for Adiabatic Controlled-Phase (CPHASE) Gates in Superconducting Circuits

Presenter: Qi (Andy) Ding (MIT)
Authors: Qi Ding, Alan V. Oppenheim, Petros T. Boufounos, Simon Gustavsson, Thomas A. Baran, William D. Oliver

Despite tremendous progress towards achieving low error rates with superconducting qubits, error-prone two-qubit gates remain a bottleneck in realizing large-scale quantum computers. Enhancing the fidelity of these gates to the highest feasible levels given limited coherence time is crucial. Therefore, the development of a systematic framework aimed at optimizing protocols for implementing such gates becomes imperative. One approach for implementing two-qubit gates in superconducting qubits is called the controlled phase (CPHASE) gates utilizing baseband flux control, where the interaction between $\ket{11}$ and $\ket{20}$ is leveraged. In this research, we study the adiabatic implementation of CPHASE gates, and formulate the design of the control trajectory for CPHASE gates into a pulse design problem. Our research indicates that the performance of the Chebyshev-based trajectory – the trajectory based on the Chebyshev pulse and weighted Chebyshev approximation – holds promise in surpassing that of the Slepian-based trajectory based on the Slepian pulse, which are currently widely used in quantum experiments.
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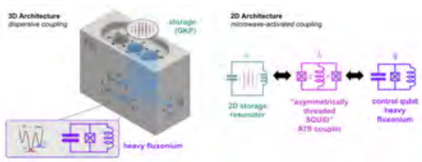
S6.07: Bosonic quantum error correction with heavy fluxonium

Presenter: Shantanu Jha (MIT)
Authors: Shantanu R. Jha, Shoumik Chowdhury, Max Hays, Miuko Tanaka, David Pahl, Junyoung An, Patrick M. Harrington, Michael Gingras, Jeff Knecht, Bethany M. Niedzielski, Hannah Stickler, Jonilyn Yoder, Mollie Schwartz, Kyle Serniak, Baptiste Royer, Jeffrey A. Grover, William D. Oliver



Bosonic quantum error correction (QEC) encodes information in the phase space of a quantum harmonic oscillator and offers a hardware-efficient path towards fault-tolerant quantum computing. In superconducting circuits, bosonic QEC using the Gottesman-Kiteav-Preskill (GKP) encoding has previously been achieved using the high-Q mode of a macroscopic 3D cavity controlled via fixed-frequency transmons. However, to date, previous demonstrations have been limited by bit-flips in this transmon control qubit (with T1 ~ 100us), resulting in logical lifetimes that are upper-bounded by approximately ~10T1. In this work, we dispersively couple a heavy fluxonium to a 3D cavity. Unlike the transmon, the fluxonium circuit exhibits a strong bit-flip protection when operated away from the sweet spot. Furthermore, we propose using the asymmetrically threaded SQUID as a microwave-activated coupler to yield faster GKP QEC rates while suppressing inherited nonlinearity in our bosonic mode. As compared to direct dispersive coupling, this parametric coupling enables us to use a heavier, and therefore more bit-flip-protected, fluxonium qubit. Finally, with faster error correction, we can use a lower-Q planar resonator to store logical quantum information in an extensible and fully 2D architecture.
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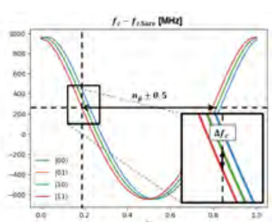
S6.08: Longitudinal two qubit gates between distant quantum dot qubits using a superconducting coupler

Presenter: Ilan Rosen (MIT)
Authors: Harry Hanlim Kang, Ilan T. Rosen, Max Hays, Kyle Serniak, Jeffrey A. Grover, William D. Oliver



The scalability of quantum dot qubits is constrained by the complex connectivity required for multi-qubit operations. A potential solution is a modular design, which utilizes entangling gates to connect distant qubits. Circuit QED techniques are pivotal for achieving this remote entanglement, leveraging the Coulomb interaction between the electrons in quantum dots and the photons in the superconducting element to create an effective spin-to-spin interaction between quantum dot qubits. Previous research has primarily focused on the transverse interaction between the charge in the quantum dots and the photons in either a resonator or transmon. Despite these efforts, there is a notable lack of experimental studies demonstrating successful two-qubit gates with sufficient fidelity for modular quantum computing. This work explores alternative strategies to address this challenge, specifically employing longitudinal coupling and adjusting the parameter regime of the transmon coupler. The analytic expressions and realistic fidelity estimations for various possible pulse sequences for the gate will be presented. *khanlim@mit.edu*

S6.09: Bosonic Quantum Simulation with a Superconducting Transmon Lattice

Presenter: Sarah Muschinske (MIT)
Authors: S. Muschinske, M. Moreira, K. Poulsen, I. T. Rosen, P. M. Harrington, R. Das, D. K. Kim, B. M. Niedzielski, J. L. Yoder, M. E. Schwartz, K. Serniak, J. A. Grover, W. D. Oliver

Quantum simulation with superconducting qubits has largely focused on models of two-level systems such as the hard-core Bose-Hubbard model. However, this choice massively truncates the size of the accessible Hilbert space – reducing the complexity of computation and preventing quantum information from being stored in the higher levels of the system. In this talk, we will discuss the feasibility of performing multi-level analog quantum simulation of the Bose-Hubbard model using superconducting transmon qudits. This approach offers several advantages, including efficient emulation of time evolution, reduced leakage from the computational subspace, and a wider range of Hamiltonian parameter values represented by the model. However, with these improvements comes increased complexity in readout and tomography protocols. We will give an overview of the design and control of transmon-based Bose-Hubbard emulators. We consider contributions to decoherence and decay of these higher excited states and discuss their impact on many-body behavior. Finally, we will give an outlook for future experiments as we move towards meaningful quantum advantage on noisy intermediate-scale quantum hardware.
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S6.10: Generating highly entangled many-body states on a superconducting processor

Presenter: Ilan Rosen (MIT)
Authors: Ilan T. Rosen, Amir Karamlou, Sarah Muschinske, Cora N. Barrett, Agustin Di Paolo, Leon Ding, Patrick M. Harrington, Max Hays, Simon Gustavsson, Jeffery A. Grover, William D. Oliver

Entanglement and its propagation are central to understanding quantum systems.
Notably, within closed interacting many-body systems, entanglement is believed to yield emergent thermodynamic behavior, yet a universal understanding remains challenging. Quantum hardware platforms provide a means to study the formation and scaling of entanglement. Here, we use a controllable 4-by-4 array of superconducting qubits to emulate a two-dimensional hard-core Bose-Hubbard lattice. Rather than preparing a definite state, we generate superposition states by simultaneously driving all lattice sites. We extract correlation lengths and entanglement energy for states prepared across the many-body energy spectrum of the lattice, observing volume-law entanglement scaling for states at the center of the spectrum and a crossover to the onset of area-law scaling near its edges. Lastly, we discuss extensions of this state preparation protocol that leverage the dynamic capability of superconducting processors by tracking the propagation of entanglement following a mid-experiment quantum quench.
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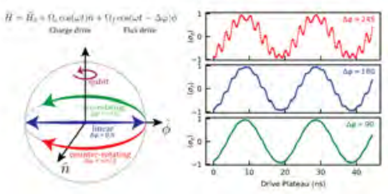
S6.11: Circularly Polarized Driving and Fast Gates with Fluxonium Qubits

Presenter: David Rower (MIT)
Authors: David Rower, Leon Ding, Max Hays, Ilan Rosen, Bethany Niedzielski, Mollie Schwartz, Jonilyn Yoder, Kyle Serniak, Jeffrey Grover, William Oliver



Fluxonium qubits are an attractive candidate for gate-based quantum computing due in part to their long coherence times. Two general features of a typical fluxonium are its low qubit frequency (less than 1 gigahertz) and its high anharmonicity (several gigahertz). One consequence, however, is related to the single-qubit gate speed: as the qubit drive power is increased, the rotating wave approximation breaks down before the leakage into non-computational states dominates the gate error. This is notably different with transmon qubits, which have a high qubit frequency but low anharmonicity.
In this work, we circumvent the aforementioned limitation by simultaneously performing linear charge and flux drives on a fluxonium superconducting qubit to create the circuit-quantum-electrodynamics analogue of circularly-polarized light. With this, we show both theoretically and experimentally that the rotating-wave approximation can be completely bypassed and use this technique to calibrate single-qubit gates as short as 10 ns with above 99.99% fidelity.
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S6.12: Addressing infrastructure requirements for the coherent control of large superconducting quantum systems

Presenter: Miguel S. Moreira (MIT)
Authors: M. S. Moreira, S. Muschinske, D. Zaidenberg, I. T. Rosen, C. N. Barrett, P. M. Harrington, R. Das, B. M. Niedzielski, J. L. Yoder, M. E. Schwartz, K. Serniak, J. A. Grover, W. D. Oliver

Superconducting-qubit systems are a promising platform for the implementation of error-corrected, fault-tolerant quantum computers, for which the surface code is a prominent approach. We consider an architecture where a repeatable tile of flux-tunable qubits, coupled through capacitive tunable couplers, is repeated to create lattices of qubits that can be controlled with minimal footprint and overhead, in a way amenable to the implementation of the surface code. Focusing on problems arising from the need to extend such platforms to relevant system sizes, while ensuring their coherent control, we propose various methods for the enhancement of control infrastructure required for 3D-integrated qubit designs. We do so at various levels of abstraction, from the qubit chip to the control software required for system calibration, including cryogenic package assemblies, signal delivery and room-temperature control electronics. Preliminary characterization of these will be presented.
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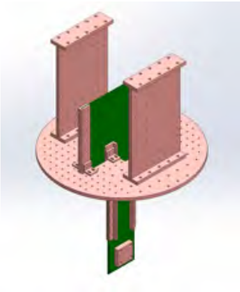
S6.13: Modular Cryogenic System for a Hybrid Superconducting and Quantum Dot Architecture

Presenter: Gabriel Cutter, Frederike Brockmeyer (MIT)
Authors: Gabriel Cutter, Frederike Brockmeyer, Harry Kang, Ilan Rosen, Jeffery Grover, Kyle Serniak, William Oliver



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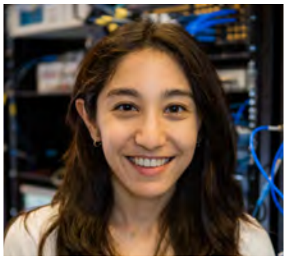
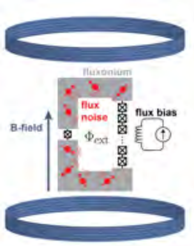
S6: Superconducting Systems

Part 2: Device design, Characterization, Packaging, Readout, Materials & fabrication, Noise



S6.14: Investigations of 1/f Magnetic Flux Noise in a Fluxonium Qubit with Weak Magnetic Fields

Presenter: Lamia Ateshian (MIT)
Authors: Lamia Ateshian, David A. Rower, Max Hays, Lauren H. Li, Leon Ding, David K. Kim, Bethany M. Niedzielski, Jonilyn L. Yoder, Mollie E. Schwartz, Terry P. Orlando, Joel I-Jan Wang, Simon Gustavsson, Jeffrey A. Grover, Kyle Serniak, Riccardo Comin, William D. Oliver



Low-frequency 1/f magnetic flux noise is known to limit the coherence of superconducting qubits, yet an understanding of its microscopic origins is still lacking. Although magnetically coupled surface defects are widely accepted to be the source, their identities and interaction mechanisms remain unknown. We showed in recent experiments on aluminum C-shunt flux qubits that the noise power spectrum responds anomalously to the application of weak in-plane magnetic fields. We report on the continuation of these studies with a fluxonium qubit. The fluxonium circuit, which consists of a single Josephson junction shunted by a capacitor and a linear inductor, can be made with transition frequencies as low as tens of MHz. It has sensitivity near half-flux to both charge and flux noise, potentially resulting in the relaxation time T1 having contributions from both dielectric loss and low-frequency magnetic flux noise. Here we present in-plane magnetic field characterizations of a fluxonium qubit with minimum frequency ~50 MHz, focusing on T1 spectroscopy and low-frequency flux noise spectroscopy. We observe new trends in the noise with magnetic field, which may provide further constraints for microscopic theories of flux noise and charge noise.
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S6.15: Statistical Analysis of Fluxonium Qubit Coherence Times

Presenter: Kate Azar (MIT Lincoln Laboratory)
Authors: Kate Azar, Thomas Hazard, Mallika Randeria, Jeffrey Gertler, Renee DePencier Pinero, Kunal Tiwari, Leon Ding, Max Hays, Junyoung An, Junghyun Kim, Ilan Rosen, Agustin Di Paolo, David Kim, Hannah Stickler, Bethany Niedzielski, Felipe Contipelli, Jeffrey Grover, Jonilyn Yoder, Mollie E. Schwartz, William D Oliver, Kyle Serniak

Superconducting qubits have demonstrated promise as a technology with which to build a quantum computer. A current roadblock to creating such a processor with these circuits is their finite coherence time, which limits gate fidelity. Fluxonium qubits have exhibited long coherence times and could be an avenue towards a high-coherence quantum processor. This work studies data on the circuit parameters, coherence, and single-qubit gate fidelities of planar aluminum-on-silicon fluxoniums. We consider data gathered for the purpose of collecting statistics on device performance, understanding how measured coherence times correlate with device parameters and achievable gate fidelities, and identifying the dominant loss mechanisms limiting device coherence.
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S6.16: Quasiparticle Dynamics in Offset-Charge-Sensitive Transmons

Presenter: Felipe Contipelli (MIT Lincoln Laboratory)
Authors: Felipe Contipelli, Patrick M. Harrington, Max Hays, Renée DePencier Piñero, Kate Azar, Greg Calusine, Thomas M. Hazard, David K. Kim, Bethany M. Niedzielski, Ali Sabbah, Hannah Stickler, Jonilyn L. Yoder, Mollie E. Schwartz, William D. Oliver, Kyle Serniak

Superconducting qubits are a promising platform to realize a large-scale quantum processor. The presence of nonequilibrium quasiparticles sets an inherent limit on the performance of transmons, a mature superconducting qubit architecture. Intentionally operating a transmon in an offset-charge-sensitive regime allows us to probe quasiparticle tunneling dynamics by detection of charge-parity jumps. Simultaneous parity jumps across multiple qubits can be indicative of quasiparticle-induced spatiotemporally-correlated errors, a significant challenge for quantum error correction protocols. In this work, we use a direct-dispersive charge-parity readout scheme to continuously monitor multiple qubits in an OCS transmon array. We implement filtering and shielding to maximally suppress contributions from photon-assisted tunneling. Further, we characterize the charge-parity lifetimes of devices with additional quasiparticle-tunneling mitigation strategies, such as a superconducting backplane.
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S6.17: Variable Frequency Emission from Fluxon Breathers in Josephson Transmission Lines

Presenter: Gregory Cunningham (MIT)
Authors: Gregory Cunningham, Kevin O'Brien

Single flux quantum (SFQ) technology, operating at the 4K stage of the dilution refrigerator and utilizing voltage pulses of area equal to the magnetic flux quantum, has proven to be a reliable framework for readout and control of superconducting quantum systems. However, scalability of such systems suffers from the requirement of room temperature electronics (RTE) to generate microwaves tones at specific frequencies. SFQ-based Josephson Arbitrary Waveform generation can synthesize tones from RTE up to 10 GHz with output powers of -68 dBm, but sizing and timing constraints from the SFQ hardware limit performance. Flux solitons (fluxons) in unbiased Josephson transmission lines (JTL) with resistive terminations can form breathers, union of fluxon and virtual fluxon of opposite polarity, that have decaying oscillations at frequencies set by junction critical current and capacitance. In this work, we show how the dynamics of breather formation from DC-centered fluxons can generate microwave tones over a range of GHz frequencies without room temperature synthesis or shunt / bias resistors. We detail metrics such as energy efficiency, bandwidth compression, output power, and sizing considerations.
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S6.18: Estimation of two-level systems in surface passivated superconducting microwave resonators

Presenter: Aranya Goswami
Authors: Aranya Goswami, Sameia Zaman, Andres E. Lombo, Pablo M. Perez, Kevin Grossklaus, Terry P. Orlando, Simon Gustavsson, Kyle Serniak, Joel I. J.Wang, Jeffrey A.Grover, Kevin. P. O'Brien, William D. Oliver

Surface amorphous oxides in superconducting films, commonly used to fabricate superconducting qubits, have been demonstrated to host two-level systems that can limit their coherence. Encapsulation with other materials can potentially reduce the formation of these lossy oxides and improve qubit performance. In this work, we study the effects of encapsulation of superconducting films with non-superconducting materials. For encapsulation, we explore both in-situ capping techniques, after the growth of superconducting films, as well as alternate methods, involving ex-situ etching and subsequent passivation. We first comprehensively study the surface morphology and crystallinity of these superconducting heterostructures using atomic force microscopy, electron microscopy, X-ray photoemission spectroscopy, and X-ray diffraction. Next, we characterize the critical temperature and residual resistivity ratio of these encapsulated films. Finally, we measure microwave resonator devices fabricated from encapsulated and non-encapsulated films in a dilution refrigerator operating at milliKelvin temperatures. Through this study, we aim to correlate the observed material properties with the DC and microwave behavior of superconducting microwave resonators encapsulated with normal metals.
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S6.19: Synchronous Detection of Cosmic Rays and Correlated Errors in Superconducting Qubits

Presenter: Patrick Harrington (MIT)
Authors: Patrick M. Harrington, Mingyu Li, Max Hays, Wouter van de Pontseele, Daniel Mayer, H. Douglas Pinckney, Felipe Contipelli, Michael Gingras, Bethany M. Niedzielski, Hannah Stickler, Jonilyn L. Yoder, Mollie E. Schwartz, Jeffrey A. Grover, Kyle Serniak, Joseph Formaggio, William D. Oliver

Quantum information processing at scale will require sufficiently long-lived logical qubits to perform sustained calculations. Quantum error correction promises to realize such qubits, but only if errors are sufficiently sparse in time and space. While superconducting circuits are poised to demonstrate robust logical qubits, recent experiments have suggested that ionizing radiation can cause many-qubit correlated errors at rates that would challenge conventional quantum error correction protocols. Here we provide evidence that correlated qubit errors are caused by cosmic rays. We used synchronous monitoring of scintillating radiation detectors and qubit energy-relaxation of up to 10 transmon qubits to show cosmic rays are a significant source of correlated qubit errors. Cosmic rays cause correlated error events at a rate of 1/(504 s). Moreover, our device is sensitive to all cosmic ray impacts within experimental uncertainty. This presents a challenge that must be addressed in future implementations of error correction with superconducting qubit processors, and more generally, in any solid-state quantum processors.
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S6.20: Effects of helium-ion exposure on superconducting-nanowire single photon detectors

Presenter: Francesca Incalza (MIT)
Authors: F. Incalza, M. Castellani, E. Batson, O. Medeiros, K. K. Berggren

High-temperature superconductors can allow for the development of superconducting-nanowire single-photon detectors (SNSPDs) that can operate at higher temperatures than standard superconductors, enhancing the efficiency and affordability of the device. Unfortunately, the fabrication of high-temperature superconducting nanowires damages the material and the realization of large and uniform detector arrays formed by thousands of detectors is fraught with complexities. As a result, the opportunity to modify the detector metrics through post-processing is attractive.
In this work, the effects of helium ion irradiation on superconductive nanowires single photon detectors are investigated. We exposed NbN single nanowires and SNSPDs to a range of irradiation doses from ~ 1014 to ~ 1020 ions/cm2 and thus demonstrated the impact of different doses on the target materials as well as improved the detector metrics. With an applied dose of 2.6·1017 ions/cm2, we were able to obtain an increase in the detector count rate of around a factor of 5. This capability suggests the potential to achieve uniform and consistent detector performance across an entire chip, offering a solution to the challenge of creating large, high-quality detector arrays.
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S6.21: Measurement of soft zero-pi qubit with parallel-plate capacitors

Presenter: Junghyun Kim (MIT)
Authors: Junghyun Kim, Ilan Rosen, Junyoung An, Max Hays, Agustin Di Paolo, Leon Ding, Kate Azar, Jeffrey Gertler, Thomas Hazard, Michael Gingras, Bethany Niedzielski, Hannah Stickler, Katrina Sliwa, Mollie E. Schwartz, Jonilyn L. Yoder, Terry P. Orlando, Jeffrey A. Grover, Kyle Serniak, William D. Oliver

Decoherence protection of zero-pi qubits requires maximizing the charge mode capacitance while simultaneously minimizing the flux mode capacitance. However, one major limiting factor of realizing zero-pi qubits is the stray capacitance caused by the large charge mode capacitors, which impedes decreasing the flux mode capacitance. Here, we show the soft zero-pi qubit implemented with small-area parallel-plate capacitors, achieving a large charge mode capacitance while reducing the stray capacitance. We discuss preliminary results on offset-charge calibration techniques using this qubit and on multi-tone spectroscopies.
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S6.23: Assessing the Impact of Fabrication Variations on Josephson Travelling Wave Parametric Amplifiers

Presenter: Andres Lombo (MIT)
Authors: Andres E. Lombo, Kaidong Peng, Eric Bui, Aranya Goswami, William D. Oliver, Kevin P. O'Brien

Josephson junction-based traveling wave parametric amplifiers (JTWPAs) are widely used in cQED experiments for high-fidelity readout of superconducting qubits over a large bandwidth. The bandwidth results from a transmission line configuration with thousands of Josephson junctions. However, achieving high gain in such a device necessitates multi-layer structures over a large footprint. As a result, the performance can be impacted by the non-uniformity inherent in the fabrication process.
In this work, we analyze the superconducting circuit performance in the presence of fabrication variations to predict the process constraints needed to enable the high reproducibility of nanostructured components in the JTWPA fabricated on an all-Aluminum qubit-compatible process. We show improvements in device performance from the refinement of Josephson junction fabrication treatments for yield and uniformity. Subsequently, we model cell-to-cell variations of circuit parameters and evaluate the impact of non-uniformity on the gain, quantum efficiency, return loss, and insertion loss. We correlate the effects of mismatched cell impedance and signal reflections between cells to the parameter spread in fabrication runs.
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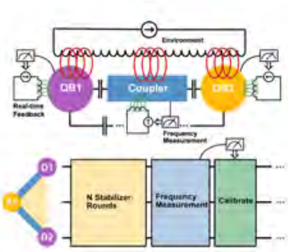
S6.24: Suppressing errors in quantum circuits using real-time, closed-loop feedback

Presenter: Lukas Pahl (MIT), Melvin Matthews (MIT)
Authors: Melvin Mathews, Lukas Pahl, David Pahl, Antti Vepsäläinen, Youngkyu Sung, Roni Winik, David K. Kim, Bethany M. Niedzielski, Jonilyn L. Yoder, Mollie E. Schwartz, Kyle Serniak, Simon Gustavsson, Jeffrey A. Grover, William D. Oliver



Realizing quantum circuits of practical relevance requires accurate, real-time control over all parameters of a large quantum processor, which fluctuate on short timescales due to coupling to environmental noise. Here, building on prior work with single qubits [1], we introduce a framework for using real-time, closed-loop feedback to stabilize frequency fluctuations in a grid of tunable transmons interacting via tunable couplers. We investigate different strategies for estimating frequency corrections and explore how feedback allows the system's tunability to be exploited for optimization without sacrificing device performance significantly. Combining these techniques, we study how our framework suppresses errors in multi-qubit quantum circuits that are vital for the realization of quantum error correction, including controlled-Z gates and parity check cycles.
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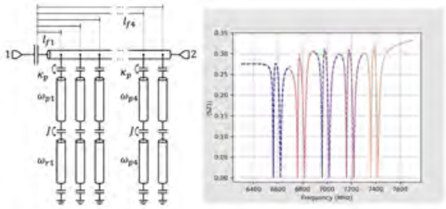
S6.25: Fast, optimal circuit design of multiplexed readout resonators with individual Purcell filters.

Presenter: David Pahl (MIT)
Authors: D. Pahl, L. Pahl, M. Hays, K. Serniak, J. A. Grover, W. D. Oliver



Multiplexed readout circuits with individual Purcell filters have emerged as a promising architecture satisfying the speed, fidelity, and scalability necessary for large-scale quantum error correction. At relevant system sizes, however, simultaneously designing for all target parameters quickly becomes intractable using typical Finite-Element-Method-based approaches. Instead, we present a circuit-based simulation approach together with a computationally efficient, closed-loop optimization of the entire readout circuit. We further study the hybridization dynamics of the readout and filter resonator and observe parameter regimes where the Purcell protection from the filter breaks down. Finally, we discuss the experimental realization of circuits in different parameter regimes as well as the readout performance of these systems.

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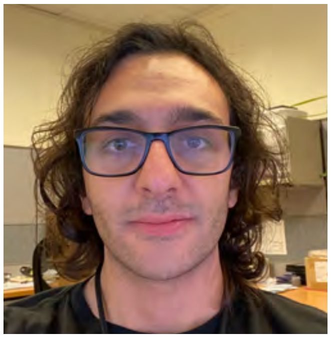

S6.26: Fluorine-based Selective Etching to Mitigate Material and Surface Losses in Transmon Qubits

Presenter: Ali Sabbah (MIT)
Authors: Ali Sabbah, Bethany M. Niedzielski, Michael Gingras, Felipe Contipelli, Kate Azar, Greg Calusine, Cyrus F. Hirjibehedin, David Kim, Jeff M. Knecht, Christopher O'Connell, Alexander Melville, Hannah Stickler, Jonilyn L. Yoder, Mollie Schwartz, William D. Oliver, Kyle Serniak

Superconducting transmon qubits offer a promising platform for the realization of scalable and fault-tolerant quantum computers. Although significant progress has been made, coherence for these qubits is still predominantly limited by material and interface losses, some of which arise due totx fabrication processing. We utilize a selective-etching technique to remove silicon oxides, which are a primary source of decoherence, from areas in proximity to critical circuit elements such as Josephson junctions. Devices that have undergone this fabrication process have shown improved qubit coherence, with little to no damage to the circuit elements.

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S6.27: Predicting Josephson Junction Critical Current from Room Temperature Data

Presenter: Hannah Stickler (MIT Lincoln Laboratory)
Authors: Hannah Stickler, Michael Gingras, Bethany M Niedzielski, David K Kim, Jeff Knecht, Kate Azar, Greg Calusine, Ali Sabbah, Felipe Contipelli, Duncan Miller, Arthur Kurlej, Jonilyn Yoder, Will Oliver, Mollie Schwartz, Kyle Serniak

Superconducting qubits are a promising technology to realize fault-tolerant quantum computers. To realize this promise at scale, it is essential to be able to predict the cryogenic performance of Josephson junctions from room temperature measurements of Josephson junctions. This can be accomplished by using the Ambegaokar-Baratoff relation to predict critical current of a junction from a series of room temperature junction resistances. These predictions taken at face value are not necessarily accurate. In this talk, we will discuss different data analysis techniques and mitigation strategies to use room temperature resistance data to more accurately predict cold junction critical current and qubit frequency.
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S6.28: High frequency microwave packaging for Josephson traveling wave parametric amplifiers

Presenter: Jennifer Wang (MIT)
Authors: Jennifer Wang, Alec Yen, Kaidong Peng, Wouter Van de Pontseele, Katrina Sliwa, Patrick Harrington, Yanjie Qiu, Kyle Serniak, Mollie E. Schwartz, Joseph A. Formaggio, William D. Oliver, Kevin P. O'Brien

The detection of single-photon microwave signals above 12 GHz is of significant interest for quantum sensing applications in neutrino mass measurement, dark matter searches, and quantum information processing. Below 12 GHz, quantum-limited amplification can be achieved with high-gain, broadband, and low-noise Josephson traveling wave parametric amplifiers (JTWPAs). However, standard microwave packaging for JTWPAs introduce package modes above 12 GHz, as well as impedance mismatches at the connectors and wirebond locations that hinder performance. Here we present an approach to high frequency microwave package design that optimizes package and connector modes, minimizes wirebonds on interposer chips, and employs signal-line compensation strategies for better impedance matching throughout. The package is modular, easily prototyped, and well-matched up to 27 GHz. This package will be deployed with a K band JTWPA tailored to the Project 8 neutrino mass measurement experiment, which will enable an SNR improvement of an order of magnitude compared to current HEMT amplifiers. Since this design features low reflection and minimal spurious modes over a broad frequency range, this package can also be be tailored to suit a wide range of superconducting quantum devices.
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S6.29: Readout of a Transmon Qubit Using a Directional Readout Resonator with Interference Purcell Suppression

Presenter: Alec Yen (MIT)
Authors: Alec Yen, Yufeng Ye, Kaidong Peng, Jennifer Wang, Gregory Cunningham, Michael Gingras, Bethany M. Niedzielski, Hannah Stickler, Kyle Serniak, Mollie Schwartz, Kevin O'Brien

Impedance mismatch in the readout bus is a leading cause of high variance in measurement rate κ in superconducting quantum processors. Moreover, the addition of bulky and high-magnetic field circulators and isolators is often needed for impedance matching. In this work, we demonstrate transmission-based readout of a transmon qubit using a directional readout resonator. Whereas a typical readout resonator would have a sharp dip in , S21, on resonance, our directional resonator demonstrates a dip of less than 1dB on resonance, thus closely preserving the 50-ohm readout bus. This both maximizes measurement efficiency and avoids needing a weakly-coupled port, a major source of impedance mismatch in many standard qubit readout schemes. To enable fast readout and reset, we propose a novel interference Purcell filter compatible with directional readout and demonstrate Purcell suppression by 2 orders of magnitude over a bandwidth of more than 600 MHz. This architecture is expected to facilitate more scalable and modular design of quantum processors.
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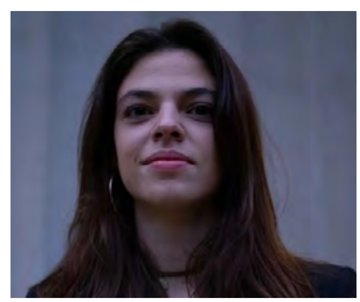
S6.30: Intermodulation Distortion and Quantum Efficiency in Josephson Parametric Amplifiers and Josephson Traveling Wave Parametric Amplifiers

Presenter: Daniela Zaidenberg (MIT)
Authors: Daniela Zaidenberg, Jessica Kedziora, Jennifer Wang, Kevin O'Brien



Josephson Traveling Wave Parametric Amplifiers (JTWPAs) enable near quantum limited broadband amplification of weak microwave signals for applications including frequency multiplexed superconducting qubit readout. Josephson Parametric Amplifiers (JPAs) are also high gain microwave amplifiers, but have much smaller bandwidths. As the input signal power is increased, JPAs and JTWPAs exhibit intermodulation distortion which degrades noise performance. This research simulates intermodulation distortion and the impact on noise performance for frequency multiplexed measurements. We demonstrate that operating JPAs and JTWPAs near the gain compression point results in a reduction in gain and significant reduction in quantum efficiency for a targeted weak microwave signal of interest. This study of intermodulation distortion aims to interpret experimental results in current devices and provide a foundation to design new amplifiers less sensitive to intermodulation distortion.
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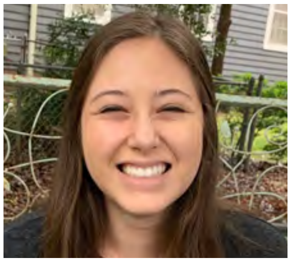
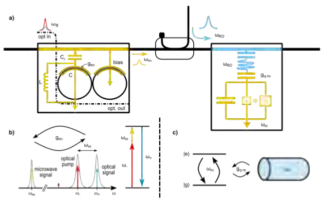
S7: Optics and Photonics



S7.01: Coherent optical control of a superconducting qubit

Presenter: Hana Warner (Harvard)

Authors: Hana K. Warner, Jeffrey Holzgrafe, Beatriz Yankelevich, David Barton, Stefano Poletto, C. J. Xin, Neil Sinclair, Di Zhu, Eyob Sete, Brandon Langley, Emma Batson, Marco

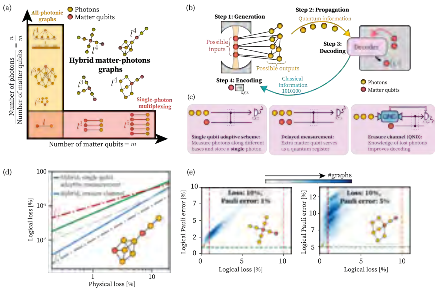


Superconducting qubits have emerged as a promising platform for quantum computing due to their strong Josephson nonlinearity and low loss. However, because they are typically accessed using microwave photons ~3-8 GHz range, the ultimate scale of these systems is constrained to a few thousand qubits due to the passive heat load and complexity of their cryogenic microwave electronics. We discuss an approach to instead interface with superconducting qubits using telecommunication frequency (~200 THz) optical signals that are cryogenically (~14 mK) converted to the microwave domain using a thin-film lithium niobate electro-optic transducer. We optically drive Rabi oscillations (2.27 MHz) without impacting qubit coherence times (800 ns). The high carrier frequency and large bandwidth of the optical signals can allow for wavelength-division multiplexing, resulting in 100-fold increase in the number of addressable physical qubits in a single fiber. Moreover, since silica optical fibers are weak carriers of thermal energy, they could be used to replace traditional microwave coaxial cables to provide a 1000x reduction in thermal load for signals routed in and out of a refrigerator. *hwarner@g.harvard.edu*

S7.02: Photon-Matter Hybrid Cluster States for Quantum Networks

Presenter: Gefen Baranes (MIT)

Authors: Gefen Baranes, Francisco Machado, Pieter-Jan C Stas, Aziza Suleymanzade, Vladan Vuletic, Susanne Yelin, Johannes Borregaard, Mikhail D Lukin



Future quantum networks will consist of both matter qubits for storage and processing of quantum information as well as photonic qubits for information transfer. This motivates us to study hybrid photon-matter cluster states and their abilities for quantum networking. We introduce a framework for building, analyzing, and optimizing hybrid states. Using this framework, our results are threefold. First, we demonstrate that hybrid cluster states exhibit better loss tolerance than single-photon multiplexing and all-photonic states, using fewer resources. Secondly, we show that varying experimental capabilities lead to distinct decoding mechanisms that directly affect transmission. Utilizing these insights, we demonstrate that by integrating a few additional matter qubits at the receiving node, we achieve an optimal logical loss scaling. Such scaling could be obtained with a perfect quantum non-demolition (QND) device, which, in theory, provides prior knowledge of photonic loss before arrival but remains an important experimental challenge. Finally, we confirm the robustness of our proposed hybrid cluster states against both photon loss and Pauli errors. *gbaranes@mit.edu*

S7.03: Thermodynamics of Light
Presenter: Tomi Baikie (MIT)
Authors: Tomi Baikie

Luminescent solar concentrators (LSCs) are theoretically able to concentrate both direct and diffuse solar radiation with extremely high efficiencies. Photon-multiplier luminescent solar concentrators (PM-LSCs) contain chromophores that exceed 100% photoluminescence quantum efficiency. PM-LSCs have recently been experimentally demonstrated and hold promise to outcompete traditional LSCs. However, we find that the thermodynamic limits of PM-LSCs are different and are more extreme. As might be expected, to achieve very high concentration factors, a PM-LSC design must also include a free energy change, analogous to the Stokes shift in traditional LSCs. Surprisingly, unlike LSCs, the maximum concentration ratio of a PM-LSC is dependent on the brightness of the incident photon field.
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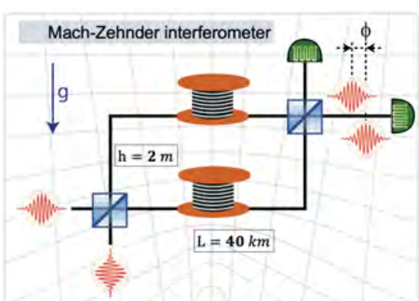
S7.04: Gravitational redshift measurement with entangled photons
Presenter: Elonora Polini (MIT)
Authors: Eleonora Polini



This experiment is designed to explore the intricate relationship between quantum mechanics and general relativity. Its primary objective is to examine the behavior of entangled quantum states in accordance with the predictions of general relativity. The experiment utilizes a large-scale optical fiber interferometer to measure the gravitational redshift-induced phase on single photons and pairs of entangled photons. This is achieved by vertically displacing one of the two arms of the Mach-Zehnder interferometer. Once established as a high-precision measurement tool, this versatile interferometer can be employed as a testbed for other experiments that explore the intersection of quantum field theory and general relativity. Additionally, it holds potential applications in the field of quantum key distribution.
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S7.05: Squeezing Experiment in Gravitational wave Physics
Presenter: Masaya Ono (MIT)
Authors: Hudson Loughlin, Jacques Ding, Xinghui Yin, Lisa Barsotti, Matthew Evans, Nergis Mavalvala

In order to detect gravitational waves, a laser interferometer is used. It is necessary to detect and control distances between mirrors that make up a laser interferometer to realize good sensitivity. There are various noises limiting the sensitivity of the detector. One of these noises is quantum noise. This noise exists in principle and is not removed completely. Squeezing is a way to reduce the quantum noise. By choosing one of the two noises (Shot noise and Radiation pressure noise) that are in the uncertainty principle, we can reduce the noise while the other noise increases. We are investigating how much squeezing level can be realized towards a higher squeezing level. We suppose that we can achieve a higher level of squeezing by preparing two squeezers that generate squeezed states and entangling the two squeezed states. In this poster, we show the theory regarding the higher level of squeezing, the experimental setup, and the latest result.
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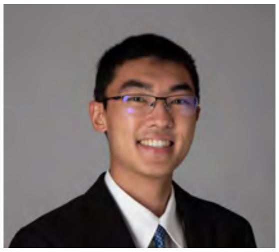
S7.06: Heisenberg limited interferometry using squeezed states of light
Presenter: Jacques Ding (MIT)
Authors: Jacques Ding, Hudson Loughlin, Masaya Ono



Precise phase shift estimation using a limited number of resources is pivotal in theoretical and experimental physics. For optical phases, classical states such as coherent laser fields exhibit a sensitivity scaling inversely with the square root of the mean photon number. Yet, the ultimate bound on the sensitivity of any measurement is set by the so-called Heisenberg limit, which, in the case of phase estimation, scales inversely with the mean number of photons. While this sets a theoretical lower bound, its attainability in an actual experiment remains an open question. In this work, we show that squeezed states of light, implemented in a Mach-Zehnder interferometer, hold quantum properties capable of achieving the Heisenberg limit. By producing squeezed vacuum at both inputs of the interferometer and performing homodyne detections at the outputs, the quantum Cramer-Rao bound is saturated. Furthermore, we offer insights into the ongoing realization of this pioneering experiment at the MIT LIGO lab, highlighting its potential to redefine precision measurements within the domain of quantum optics.
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S7.07: Model-based control of quantum systems for autonomous discovery

Presenter: Adyant Kamdar (MIT)
Authors: Adyant Kamdar, Dirk Englund

Control of quantum systems pose a multitude of challenges, often due to the large parameter space of unpredictable/uncontrollable variables. A possible solution would be leveraging the superior-inference power of an automated system when compared to the limited computational ability of an experimenter. Introducing a data-driven approach method, and creating a framework for Artificial Intelligence to interface seamlessly with all free parameters of a quantum system/experiment opens the door to a variety of potential optimizations at any end of the experiment stack.
For this end-to-end automated discovery framework to work, an agent - human or artificial - will need to interact with the experiment (physical twin) through a "controller", which has access to every free parameter of the experiment. Through the controller the agent will be able to vary all possible parameters, physical and digital (the ground truth/theory), and make conditional decisions (requiring the existence of a feedback loop from decision to result to next decision).

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S7.08: Large Scale Photonics Integrated Circuits for quantum information processing with artificial atoms

Presenter: Mustafa Yucel (MIT)
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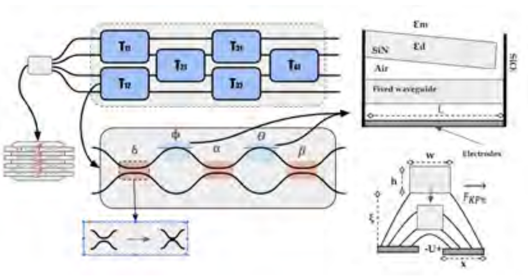

Photonics integrated circuits (PICs) are poised to revolutionize quantum and high-performance computing, shifting paradigms from traditional electronics. This study evaluates the compelling advantages of PICs, emphasizing performance boosts and quantum computing potential. PICs exhibit theoretical dominance in data handling, tapping into their inherent low-loss and expansive bandwidth to outpace electronic circuits. Their capacity for exact photon control is also critical for quantum information processing. We propose mesh PIC architectures that mitigate error rates, essential for dependable quantum computations. Theoretical frameworks and early simulations back PICs' functionality in cryogenic settings, suggesting compatibility with cryogenic MEMS for quantum computing infrastructures. While awaiting experimental corroboration, our research establishes a solid base for PICs' applications in cutting-edge computing scenarios.

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S7.09: Integrated Photonics for High-Fidelity Control of Large-Scale Rubidium Atom Array

Presenter: Yin Min Goh (MIT)
Authors: Yin Min Goh, Hyo Sun Park, T. Propson, A. J. Menssen, I. Christen, C. Li, A. Kumar, C. Brabec, M. Zimmermann, D. Englund.

Advances in laser technology have driven discoveries in atomic, molecular, and optical physics and emerging applications, from quantum computers with cold atoms or ions to quantum networks with solid-state color centers. Development of large-scale atom-based quantum technologies demands a new generation of “programmable optical control” systems that enable visible (VIS) and near-infrared (IR) wavelength operation, scalability beyond 1000s of individually addressable atoms, high-intensity modulation extinction and repeatability compatible with low gate errors, and fast switching times. To address these challenges, we have recently introduced an atom-control architecture based on VIS-IR photonic integrated circuit (PIC) technology, which meets those requirements. Here we present a scheme that integrates this atom-control PIC (APIC) technology as part of a rubidium (Rb) atom array quantum simulator. We anticipate that this scalable and reconfigurable architecture will offer a critical step toward realizing parallel individual programmability on neutral atom array platforms.
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S7.10: Integrated Photonics for Advanced Cooling of Trapped-Ion Quantum Systems

Presenter: Sabrina Corsetti (MIT)
Authors: Sabrina Corsetti*, Ashton Hattori*, Milica Notaros, Tal Sneh, Reuel Swint, Patrick T. Callahan, Felix Knollmann, Ethan R. Clements, Dave Kharas, Gavin N. West, Thomas Mahony, Colin D. Bruzewicz, Cheryl Sorace-Agaskar, Robert McConnell, John Chiaverini, and Jelena Notaros

Trapped-ion systems are a promising modality for quantum information processing due to their long coherence times and strong ion-ion interactions, which enable high-fidelity two-qubit gates. However, most current implementations are comprised of complex free-space optical systems, whose large size and susceptibility to vibration and drift can limit fidelity and addressability of ion arrays, hindering scaling. Integrated-photonics-based solutions offer a potential avenue to address many of these challenges.
Motional state cooling is a key optical function in trapped-ion systems. However, to date, integrated-photonics-based demonstrations have been limited to Doppler and resolved-sideband cooling. In this work, we develop and demonstrate integrated-photonics-based systems and associated devices for two advanced cooling schemes, polarization gradient and EIT. This has the potential to improve cooling performance for trapped ions, enabling scalable quantum systems.
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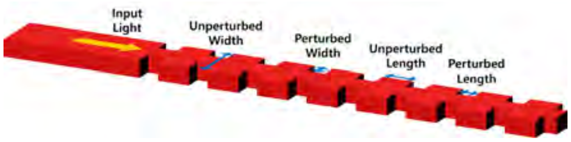
S7.11: Integrated Optical Grating-Based Antennas for Solid-State LiDAR Sensors

Presenter: Michael Torres (MIT)
Authors: M. R. Torres, S. Corsetti, D. M. DeSantis, A. G. Coleto, B. Mazur, M. Notaros, J. Notaros



Light detection and ranging (LiDAR) has emerged as a vital and widely-used sensing technology for autonomous systems, such as autonomous vehicles, since it enables 3D mapping with higher resolution than traditional RADAR. However, current commercial LiDAR systems utilize mechanical beam-steering mechanisms that decrease reliability, increase production cost, and limit detection range. To address these limitations, solid-state optical-phased-array-based (OPA-based) LiDAR, which enables low-cost, high-speed, and compact non-mechanical beam steering, has emerged as a promising solution for next-generation LiDAR sensors. In this poster, we develop integrated optical grating-based antennas, a critical device responsible for light emission in these solid-state LiDAR systems. We develop a device synthesis algorithm, design a suite of antennas with varying operating modalities, and discuss their design tradeoffs when applied to OPA subsystems.

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