High Energy Physics
Quantum Information Science Awards Abstracts
Tools for QIST Research

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NECQST: Novel Electronics for Cryogenic Quantum Sensors Technology

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Superconducting nanowire single photon detectors (SNSPDs) are the highest performing detectors available for time-correlated single photon counting from the deep UV to the mid-infrared. SNSPDs have been widely adopted within the quantum information science (QIS) community to enable, among others, fundamental tests of quantum physics, long-distance quantum communication, and quantum computing with trapped ions.

It is only within the past year, however, that state-of-the-art low-noise cryogenic amplifier technology has been used to improve the timing resolution of SNSPDs. By incorporating a cryogenic amplifier designed for radio astronomy, researchers at JPL were able to successfully reduce the timing jitter in SNSPDs from 12 ps FWHM to a record 2.7 ps FWHM. By leveraging recent advances in cryogenic transistor technology and the expertise in high-speed detector readout circuits available in the high-energy physics community, there is significant potential to improve the timing jitter, maximum count rate, and scalability of SNSPDs to enable significant new advances in QIS technology.

NECQST is a two-year technology development effort that focuses on the development of low-noise cryogenic amplifiers specifically designed for use with SNSPDs, based on state-of-the-art, commercially available SiGe heterojunction bipolar transistors (HBTs), operating at a range of 1-4 Kelvin. When cooled, SiGe HBTs naturally exhibit improved frequency response, current gain, noise, bandwidth, and output conductance. They exist in a BiCMOS implementation (SiGe HBT + Si CMOS), which are fabricated on large wafers at high yield and low cost using conventional silicon processing techniques and silicon economy-of-scale.

In this collaboration, the ASIC Development Group at Fermi National Accelerator Laboratory (FNAL) will develop crucial device models to predict the shift of transistor design parameters at deep cryogenic temperatures, while Cressler Group at the Georgia Institute of Technology (GT) will design the readout circuits with input from the Superconducting Devices Group at the Jet Propulsion Laboratory (JPL) and FNAL. JPL will finally integrate the devices with state-of-the-art SNSPDs and benchmark their performance.

Expected major outcomes are a reduction of the timing jitter of SNSPDs from the current record of 2.7 ps toward 1 ps and below, by reducing the noise of the readout amplifier chain, and a drastic reduction in the power dissipation associated with the use of low-noise cryogenic amplifiers.

Improving the timing jitter, maximum count rate, and pixel count of SNSPDs by developing improved cryogenic readout circuits, will ultimately enable transformative new capabilities in ultra-high-rate quantum communication, such as the transfer of quantum information between remote quantum information processing systems, the secure transfer of classical data over fiber at multi-Gbps speeds, and free-space communication with space-based quantum assets. Such performance advances will directly benefit the Caltech Intelligent Quantum Networks & Technologies (INQNET) program, and specifically the Fermilab Quantum Network program (FQNET) which aims to demonstrate high-rate quantum communication at Fermilab.

Skipper-CCD: new single photon sensor for quantum imaging

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Quantum imaging addresses the possibility of beating the limits of classical imaging by exploiting the peculiar properties of quantum optical states, such as entanglement. In the past few years sub-shot-noise imaging was demonstrated and sub-diffraction-limited quantum imaging was realized. A typical experimental setup for quantum imaging is shown in Fig. 1, where a pixelated photon detector is used to image the fields of idle and signal entangled photons produced by a non-linear optical element (BBO). The requirements in quantum imaging experiments include counting individual photons and measuring their correlations. The work proposed here is focused on introducing the newly developed skipper-CCD into the field of quantum imaging as a way to significantly improve signal to noise ratio (SNR) in these applications. This new sensor has photon counting capabilities in a very wide dynamic range, as shown in Fig. 1.

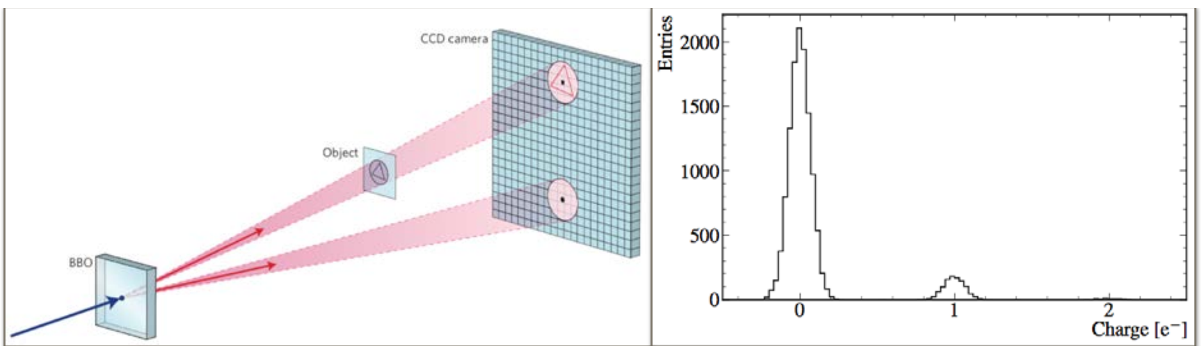

Figure 1. Left) The differential quantum imaging experiment. The β-barium borate (BBO) crystal produced an entangled pair which is then imaged with a CCD camera. Non-classical correlations are used for the improved differential imaging of a weakly absorbing object. [Figure from Nature Photonics] Right) Photon counting capabilities of the skipper-CCD, showing the signal for zero and 1 photo-electrons.

The project has three main thrusts. First, demonstrate sub-shot-noise quantum imaging with existing skipper-CCD. Second, design a new faster skipper-CCD optimized for quantum imaging applications. Finally, explore the potential of quantum imaging as a search for the entangled production of dark photons.

Ultra-High Q Superconducting Accelerator Cavities for Orders of Magnitude Improvement in Qubit Coherence Times and Dark Sector Searches

Lead PI: Dr. Alexander Romanenko (Fermilab)
Co-PI: Prof. Robert McDermott (Univ. of Wisconsin-Madison)
Co-PI: Dr. David Pappas (NIST/Univ. of Colorado-Boulder)

3D superconducting cavities are key elements of the superconducting quantum computing architectures. They can both serve as qubits in alternative logical state encodings such as "cat" states, or as a means to manipulate the transmon quantum states or as a quantum memory. The project combines complementary strengths of collaborating institutions – unique HEP SRF cavity technology and science (Fermilab) and QIS expertise (Univ. of Wisconsin-Madison and NIST) – for a potential thousand-fold increase in the coherence of the 3D superconducting qubits and memory. The same devices can be used as an enabling platform for the next generation of dark photon searches and exploring the proposed microwave communication concept, which is the secondary direction of the proposal.

Fermilab is the world leader in science and technology of superconducting radio frequency (SRF) cavities for accelerators and holds the capabilities to manufacture and surface-engineer niobium SRF cavities of record intrinsic quality factors $Q > 2 \times 10^{11}$ at $T \sim 1.4$ K [3], and recently has demonstrated the full quantum regime $Q \sim 2 \times 10^{10}$ corresponding to photon lifetimes up to **2 seconds**. In addition, Fermilab possesses broad expertise in successful large-scale integration of high Q cavities. The most recent example is manufacturing ~20 cryomodules for LCLS-II at SLAC each containing eight 9-cell 1.3 GHz cavities with $Q > 2.7 \times 10^{10}$ operating at 2 K.

In addition to the core SRF infrastructure, Fermilab has established a brand new ultralow temperature (down to < 10 mK) and quantum measurements SRF lab with a dilution refrigerator, magnetic shielding, and RF equipment for the full SRF cavity and qubit characterization.

University of Wisconsin, Madison is among the experienced QIS institutions with capabilities to design, manufacture, and characterize the transmon-type Josephson-junction-based qubits.

NIST has the unique strength in developing kinetic inductance traveling wave quantum limited amplifiers enabled by the extensive lithographic and surface characterization capabilities.

Combined, a high-quality transmon integrated into a high-quality-factor SRF cavity, and a quantum limited amplifier used for the state readout would allow to realize the potentially *record high coherence* (several orders of magnitude improvement) *superconducting 3D qubits and memory*. The same devices offer unique opportunities in experiments on quantum microwave communication, and in fundamental physics (dark photon searches).

FPGA-BASED QUANTUM CONTROL FOR HEP SIMULATIONS WITH QUTRITS

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Our objective is to develop a broadly applicable, portable tool set within the framework of superconducting-circuit-based quantum information systems that (i) leverages specialized technical expertise developed for accelerator controls and (ii) is optimized for executing quantum simulation experiments focused on HEP relevant phenomena requiring the use of ternary quantum logic. We propose to develop optically interconnected field programmable gate array (FPGA) modules for extensible control systems suitable for operating multiple quantum circuits with low latency and timing imprecision. Using this hardware, we will implement logical gate operations in ternary quantum logic and employ fast feedback routines to minimize fidelity losses due to stochastic noise processes.

The eight transmon ring quantum processors developed at UC Berkeley have demonstrated lifetimes that bring qutrit control within reach. We will use a high-bandwidth FPGA quantum control module to fully characterize the performance of an eight qutrit device, and implement novel computation and sensing protocols tailored for future HEP applications. Further, we will realize two, optically interconnected FPGA based interface modules with 14 bit resolution, < 3 ps timing jitter, single FGPA latency < 300 ns, and interconnect delays < 1 μs.

We will develop and publish a design repository of the complete system (hardware, firmware and software) used to drive, read out, and rapidly reset multi-qudit processors. Our work will also pave the way for the future development of dedicated Application Specific Integrated Circuit (ASIC) devices, possibly operating in a cryogenic environment.