



Fermilab's Underground Facilities for Quantum Sensing

Daniel Baxter

Coordinating Panel on Advanced Detectors (CPAD) Workshop 2026

21 October 2026

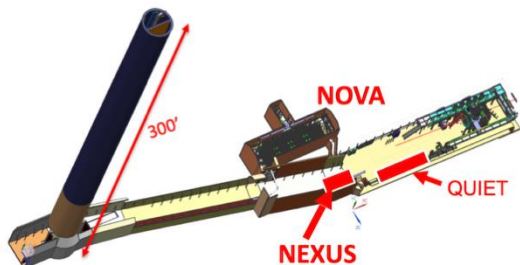


Northwestern
University



Unique Capability – NuMI/MINOS Underground

- The **NuMI** neutrino beamline at Fermilab includes a cavern 100m underground which shields 99.5% of cosmic ray muons (225 m.w.e.)
- **NOvA** near detector is still operational
- **MINOS & MINERvA** near detectors decommissioned
- Low-background detectors moved in!





Fermilab General-Use Quantum Testbeds

Three unique facilities that are being used to understand the energy-response of superconducting qubits:

1. **LOUD** – surface laboratory for rapid iteration
2. **QUIET** – underground laboratory identical to LOUD but with >99% fewer cosmic ray muons
3. **NEXUS** – underground laboratory equipped with a deuterium-deuterium neutron generator and a modular shielding environment, for ultra-low-background studies

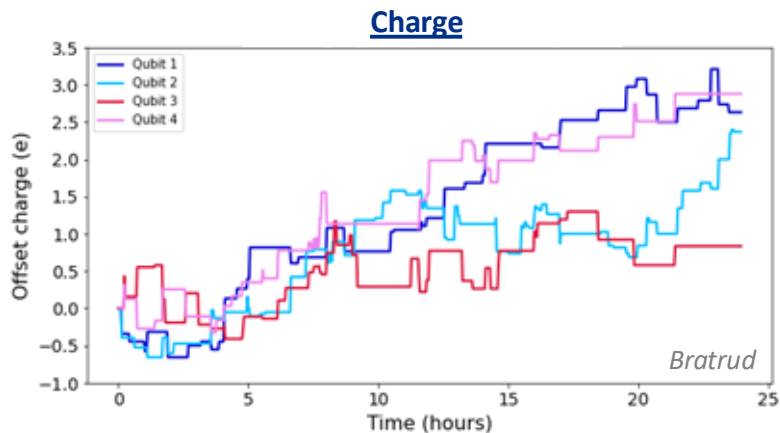




Superconducting Qubits as Sensors

Superconducting qubits offer a unique set of features that motivates them as low-energy sensors:

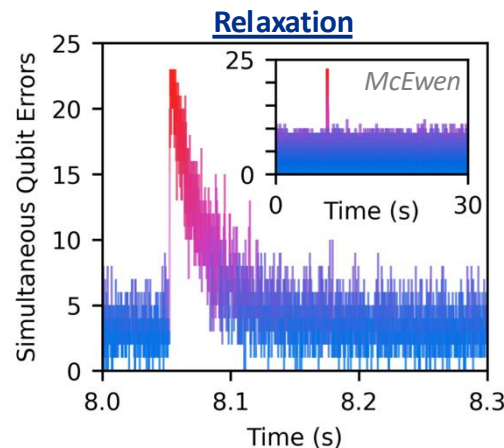
- The energy state gap from $|0\rangle$ to $|1\rangle$ is ~ 10 μeV , lower than the threshold set by Cooper pair breaking in standard superconductors
- As RF sensors, qubits are inherently multiplexable (although less-so than MKIDs)
- Qubits can be operated in different modalities simply by switching the gate sequence



Bratrud et al, Nat. Comm. **16**, 9906 (2025) [[arXiv:2405.04642](#)]

Wilén et al, Nature **594**, 369 (2021) [[arXiv:2012.06029](#)]

Christensen et al, PRB **100**, 140503 (2019) [[arXiv:1905.13712](#)]



Celi et al, (2026) [[arXiv:2604.13176](#)]

Linehan et al, PRD **111**, 063047 (2025) [[arXiv:2404.04423](#)]

Harrington et al Nat. Comm. **16**, 6428 (2025) [[arXiv:2402.03208](#)]

McEwen et al, Nat. Phys. **18**, 107 (2022) [[arXiv:2104.05219](#)]

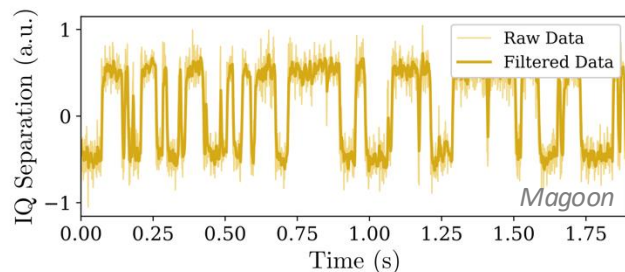


Superconducting Qubits as Sensors

Superconducting qubits offer a unique set of features that motivates them as low-energy sensors:

- The energy state gap from $|0\rangle$ to $|1\rangle$ is ~ 10 μeV , lower than the threshold set by Cooper pair breaking in standard superconductors
- As RF sensors, qubits are inherently multiplexable (although less-so than MKIDs)
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Quasiparticle Counting



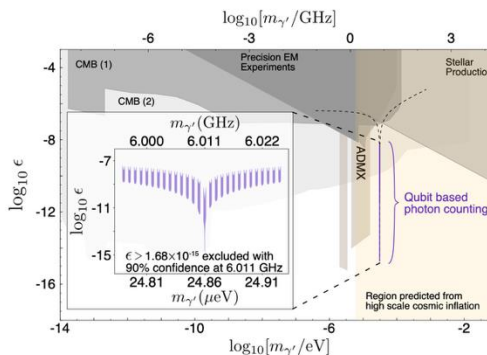
Magoon et al, (2026) [[arXiv:2601.16261](#)]

Ramanathan et al, APS Open Sci. **1**, 000013 (2026) [[arXiv:2405.17192](#)]

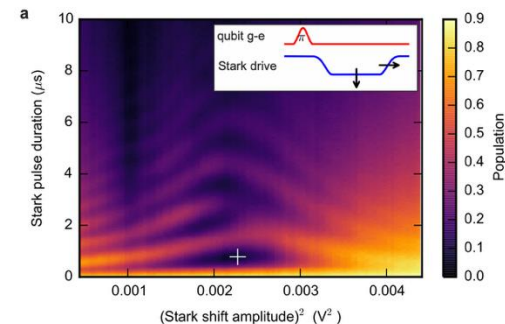
Fink et al, Phys. Rev. App. **22**, 054009 (2024)[[arXiv:2310.01345](#)]

Photon Counting

Dixit et al PRL **126**, 141302 (2021) [[arXiv:2008.12231](#)]



Phonon Counting



Omahen et al, PRL **136**, 180802 (2026) [[arXiv:2507.02653](#)]

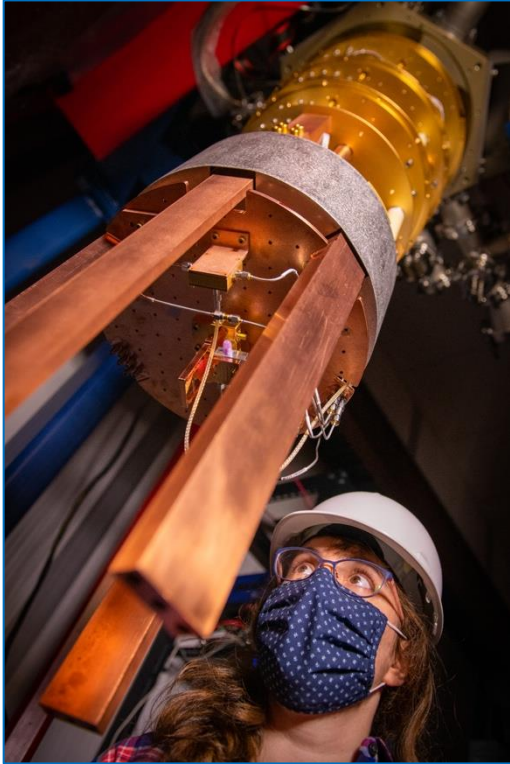
Linehan et al, PRD **112**, 115005 (2025) [[arXiv:2410.17308](#)]

Chu et al, Science **358**, 199 (2017) [[arXiv:1703.00342](#)]



Test Facilities – NEXUS @ FNAL

Northwestern EXperimental Underground Site

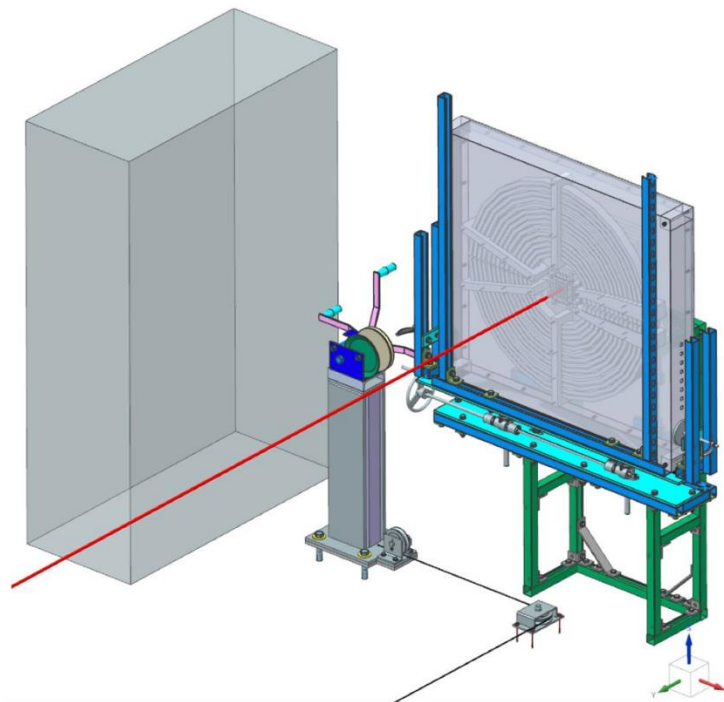


Test Facilities – NEXUS @ FNAL

Northwestern EXperimental Underground Site



2.5 MeV D-D neutron generator



Backing array (design)



Backing array (as built)

Test Facilities – NEXUS @ FNAL

Northwestern EXperimental Underground Site



Progress Towards sub-keV Nuclear Recoil Facility at MINOS, Fermilab

Oct 20, 2026, 2:40 PM

20m

Auditorium (Alder Hall)

Presentation

RDC 7 Low-Bac

Speaker

Pratyush Kumar Patel (Northwestern University)

Description

We present ongoing progress in developing a sub-keV nuclear recoil calibration facility at NEXUS (located underground in MINOS at Fermilab) for future calibration of cryogenic detectors in rare-event searches. Initially developed as a part of SuperCDMS operations, project development is centered on a segmented backing array and a 2.5-MeV Deuterium-Deuterium (DD) neutron generator. The backing array consists of plastic scintillator (EJ-200) detectors instrumented with a silicon photomultiplier (SiPM) readout, enabling scintillation-based detection of scattered neutrons. The facility provides a controlled platform for studying low-energy nuclear recoil detector response, ionization yield, and threshold behavior, ultimately enabling improved sensitivity for rare-event searches.



Design, Construction, and Characterization of a Highly Segmented Neutron Backing Array for Nuclear Recoil Calibration

Oct 20, 2026, 3:00 PM

20m

Auditorium (Alder Hall)

Presentation

R

Speaker

Isabella Foti (Northwestern University)

Description

I will present the design, construction, and commissioning of a highly segmented neutron backing array developed for low-energy nuclear recoil calibration measurements as a contingent of SuperCDMS operations. The array consists of plastic scintillator (EJ-200) detectors instrumented with silicon photomultiplier (SiPM) readout arranged in a highly segmented geometry to provide precise angular information for neutron-scattering measurements. This segmentation enables neutron scattering angles to be reconstructed and, through two-body elastic-scattering kinematics, provides a constraint on the corresponding nuclear recoil energy in a target detector. Commissioned in tandem as support for cryogenic detectors, this array will improve sensitivity, allowing for more precise study of low-energy detector response, ionization yield, and threshold behavior. I will describe the detector design, construction, readout and data acquisition system, scintillator response characterization, and calibration of the individual detector elements.



See excellent talks yesterday by Pratyush Patel & Isabella Foti

2.5 MeV D-D neutron generator

Backing array (design)

Backing array (as built)





Test Facilities – QUIET @ FNAL

Quantum Underground Instrumentation Experimental Testbed

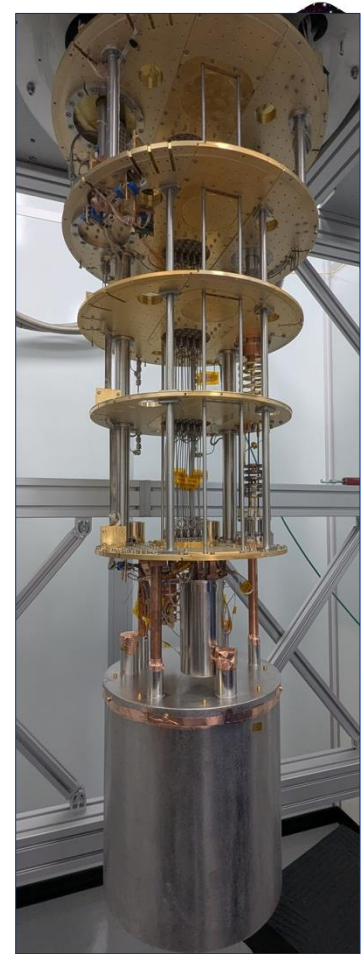
This QSC facility is the deepest low-background underground cryostat dedicated to superconducting qubit operation in the USA

- Oxford Proteox w/ up to 16(48) NbTi(SS) RF lines
- 250 ft² Class 10,000 clean room
- 50 ft² antechamber for gowning and material cleaning
- >99% reduced cosmic ray muon background
- Design of passive radiation shield is underway



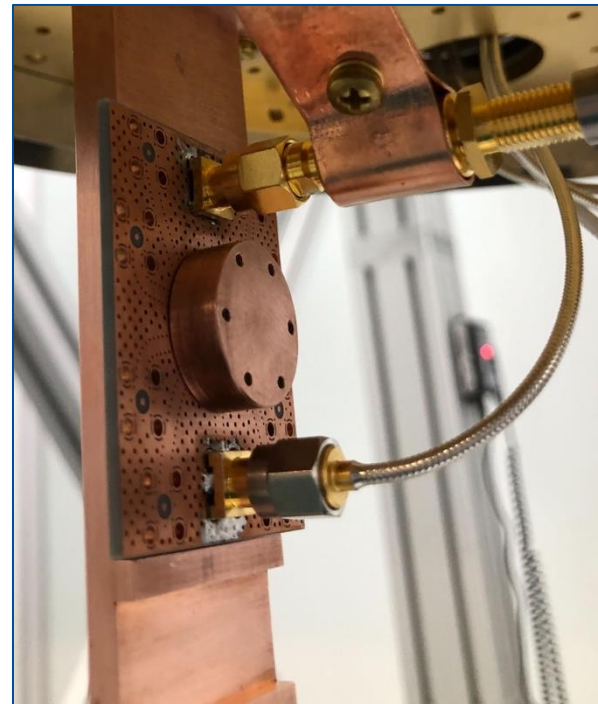
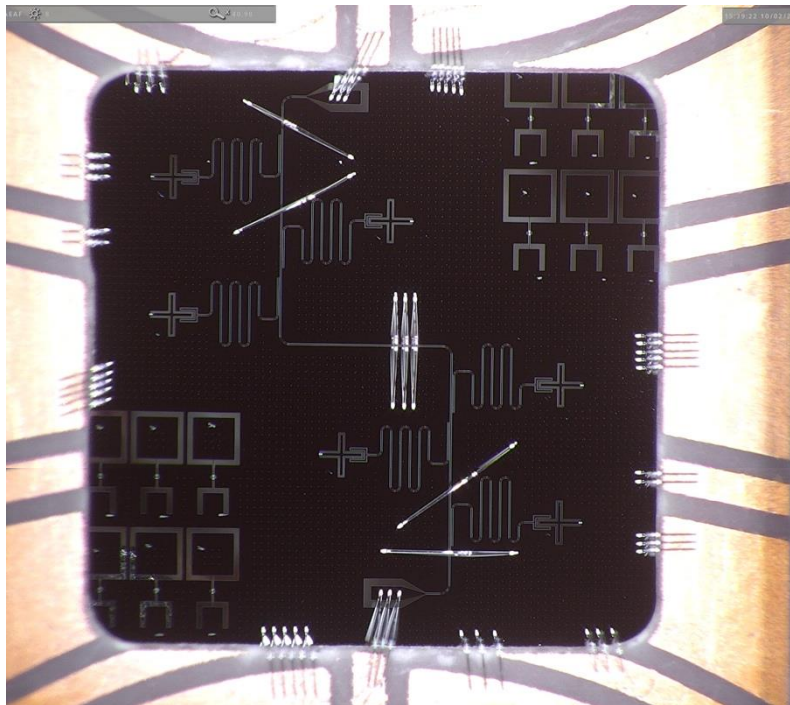
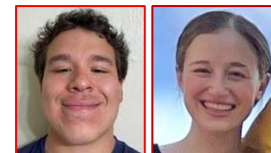
Test Facilities – QUIET @ FNAL

Quantum Underground Instrumentation Experimental Testbed



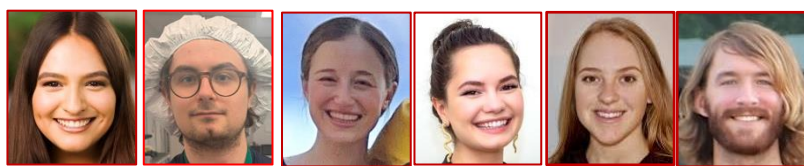
Fabrication of Devices

Devices made in-house taking data!

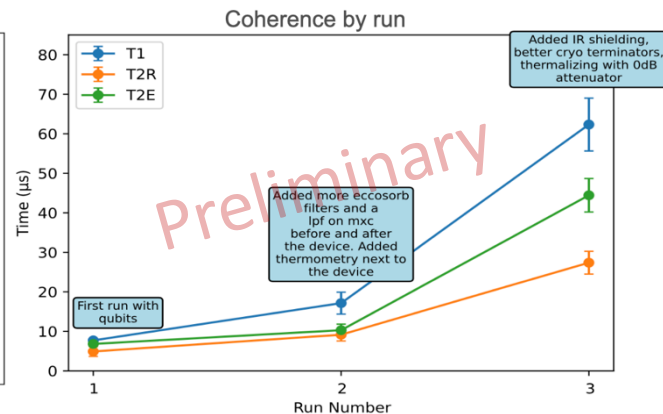
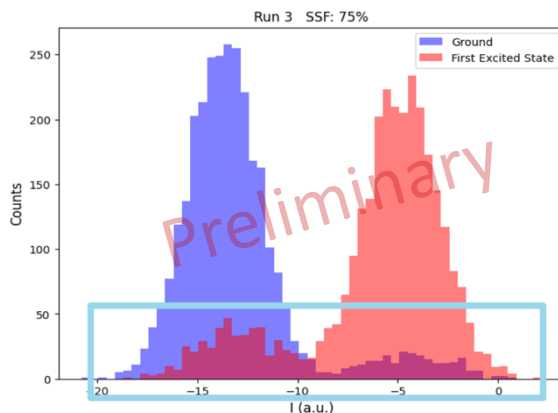
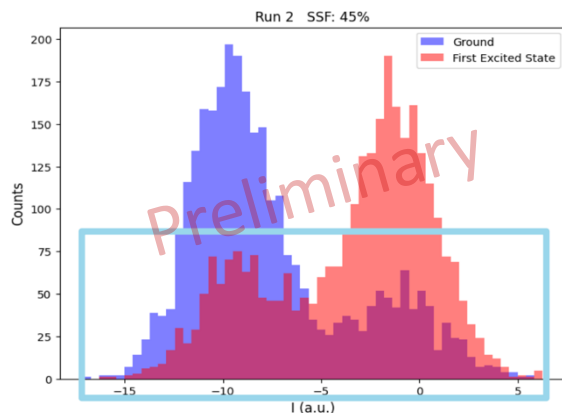


Chip design credit to Ziqian Li of SchusterLab

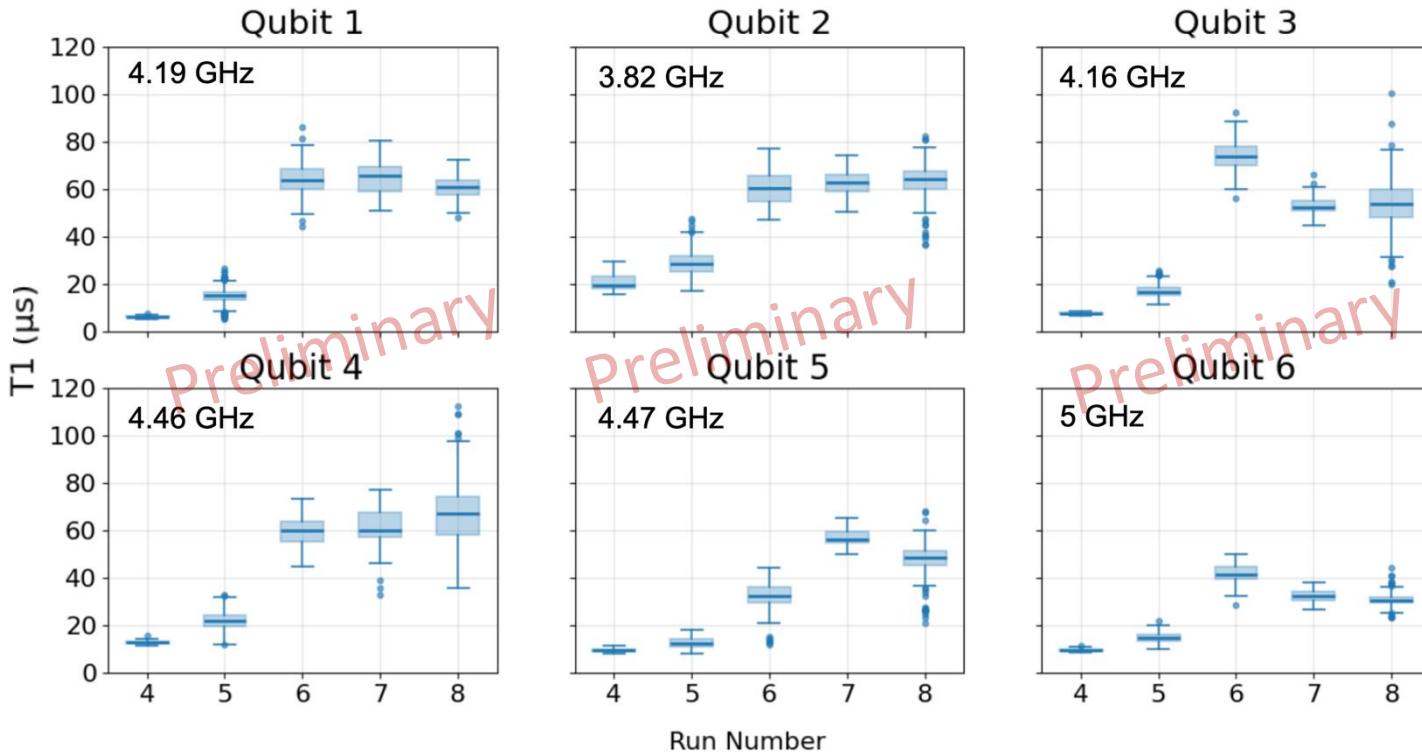
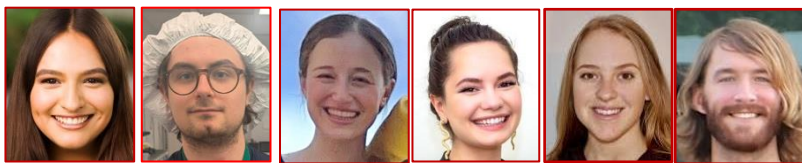
Optimization of qubits in QUIET



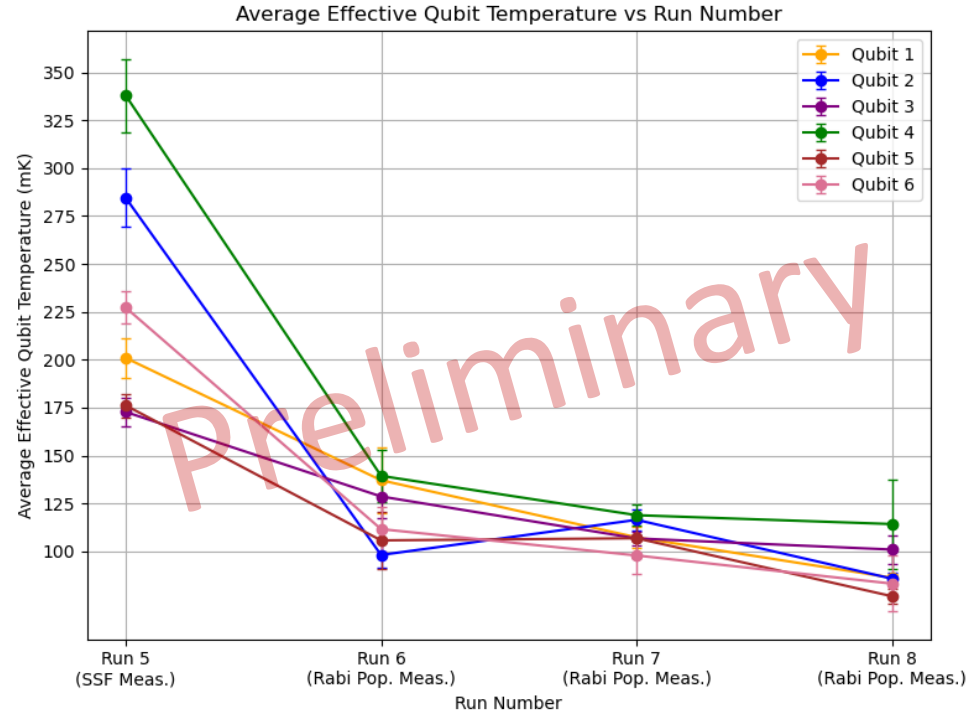
- Significant improvement over IR shielding of our qubits has improved qubit performance enough to begin external radiation studies
- Very interested in studying the dynamics of qubit performance with and without radiation present.



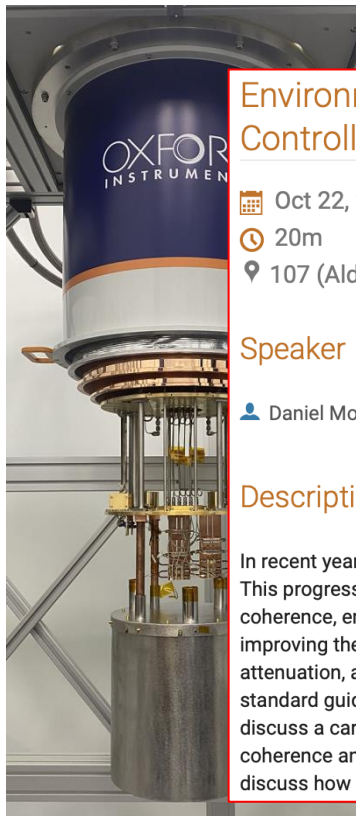
Optimization of qubits in QUIET



Optimization of qubits in QUIET



Optimization of qubits in QUIET



Environmental Dependence of Qubit Observables Under Controlled Tuning

Oct 22, 2026, 4:50 PM

20m

107 (Alder Hall)

Presentation

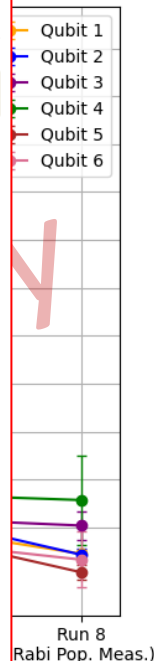
RDC 8 Quar

Speaker

 Daniel Molenaar (Illinois Institute of Technology)

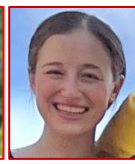
Description

In recent years, superconducting qubits have advanced significantly in both computing and sensing applications for HEP. This progress has brought increasingly intricate hardware configurations which strongly influence device performance. Qubit coherence, environmental backgrounds, and overall control fidelity together limit the capability of qubit-based sensors, improving these areas enables highly sensitive detection mechanisms. Environmental controls such as shielding, attenuation, and filtering therefore become increasingly important as devices scale up. While many best practices exist, no standard guide explains how individual components and their placement influence device performance. In this talk, we discuss a carefully constructed study spanning multiple runs and qubits, in which qubit performance metrics such as coherence and readout fidelity improved dramatically as we improved the shielding, attenuation, and filtering. We also discuss how far these results transfer across experiments and fridges

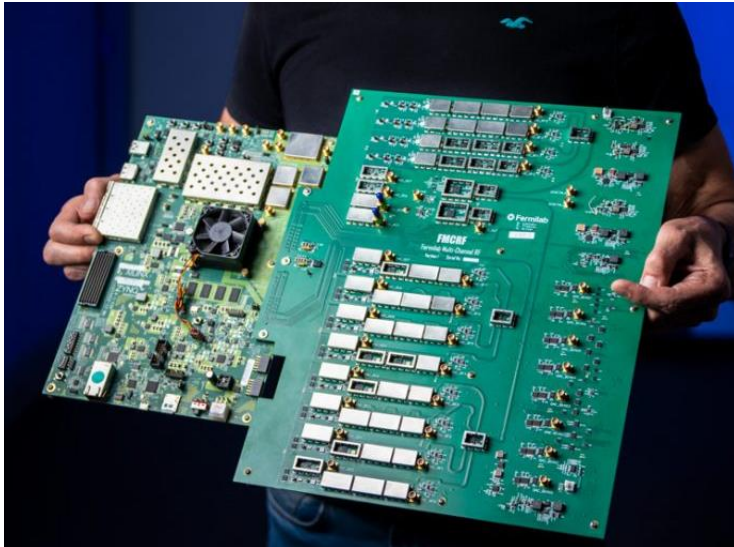


Qubit Control & Readout

- Fully integrated readout & control system for QIS, quantum networks, and superconducting detectors



QICK = “Quantum Instrumentation Control Kit”



Arnaldi et al, (2026) [arXiv:2610.03609]
Ding et al, Phys. Rev. Res. **6**, 013305 (2024) [arXiv:2311.17171]
Stefanazzi et al, Rev. Sci. Instrum. **93**, 044709 (2022) [arXiv:2110.00557]

Between 4-10 payloads/chips cold at a time



Quantum Acoustics

Device planned for next run of QUIET

Linehan et al, PRD **112**, 115005 (2025) [arXiv:2410.17308]

Charge Qubits & SQUATs

SQUAT device currently cold in QUIET (w/ SLAC)

Wilén/Bratrud chip still kicking in NEXUS (5 years running)

Magoon et al, (2026) [arXiv:2601.16261]

Bratrud et al, Nat. Comms. **16**, 9906 (2025) [arXiv:2405.04642]

MKIDs

MKID device currently cold in QUIET

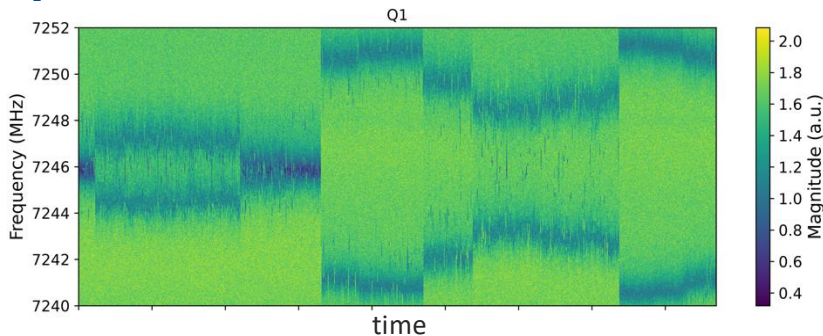
Temples et al, Phys. Rev. App. **22**, 044045 (2024) [arXiv:2402.04473]

Chip Design & Material Integration

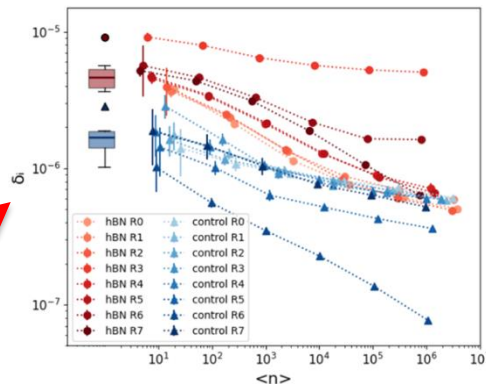
Further hBN studies planned for next run of QUIET (w/ Cornell)

Christiansen-Salameh et al, (2026) [arXiv:2610.12556]

Seidel et al, (2026) [2607.20795]



Grace Bratrud
(2025 GIRA)



Joyce Christiansen-Salameh
(2025 SCGSR)

Calibration

Alpha calibration underway in NEXUS

Poudel et al, (2026) [arXiv:2606.00473]

Tabassum et al, Rev. Sci. Inst. **96**, 103101 (2025) [arXiv:2504.06995]

Stifter et al, J. Opt. Microsyst. **5**, 024503 (2025) [arXiv:2405.02258]

Decoherence Studies

Further analysis of new data underway

Celi et al, (2026) [arXiv: 2604.13176]

Linehan et al, PRD **111**, 063047 (2025) [arXiv:2404.04423]



Other Talks By Our Group!

- Huge involvement in simulation (G4CMP) and AI-driven analysis/control

G4CMP Modeling of Athermal Phonon Transport in Quantum-Acoustic Detectors

Oct 21, 2026, 4:45 PM

15m

Auditorium (Alder Hall)

Presentation

RDC 8 Quant



Speaker

Mr Ziyu Cai (Illinois Institute of Technology)

Description

Phonon-mediated detectors have emerged as a promising technology for detecting low-energy particles, including neutrinos through coherent elastic neutrino-nucleus scattering (CEvNS) and dark matter. Coupling phonons with qubit technology, in addition to piezoelectric transducers, enables the realization of highly sensitive quantum acoustic detectors for such particle detection. An important consideration currently is to efficiently transport phonon energy deposited from the particle interaction to the quantum acoustic detector. In this talk, we present our work on the implementation of G4CMP to model phonon and quasiparticle transport and dynamics and investigate how superconducting geometry and relevant device parameters affect phonon transport and collection efficiency. We also specifically incorporated TeO_2 and LiNbO_3 for the first time in G4CMP. These studies will help us design highly sensitive quantum detectors for neutrino detection.

see also...

Hernandez et al, Nucl. Inst. Meth. A **1073**, 170172 (2025) [arXiv:2408.04732]

Learning Across Qubit Domains: Machine Learning Techniques for Superconducting Qubits

Oct 21, 2026, 6:15 PM

15m

Auditorium (Alder Hall)

Presentation

RDC 8 Quant



Speaker

Jehu Martinez (Illinois Institute of Technology)

Description

Superconducting qubits are highly sensitive to their local environment. This sensitivity enables their use in quantum sensing, but it also makes them more susceptible to environmental noise. Background noise, device defects such as two-level systems, and changes in the qubit operating environment can all influence device performance. As a result, models developed under one set of conditions may not directly generalize to another. This work investigates Normalizing Flows, a class of machine-learning models that learn the probability distribution of a dataset, and how well they can model distributions across different superconducting qubit measurements. In this talk, their application as an anomaly-detection tool is evaluated across multiple qubit measurement modalities, where the learned probability distributions are used to identify deviations from expected device behavior. Building on these results, the approach is being extended to study how models trained in one qubit domain can be adapted to different measurements and experimental conditions, including whether limited fine-tuning can improve adaptation without requiring complete retraining. More broadly, this work investigates how anomaly-detection models can remain useful across different qubit domains.

see also...

Gaytan-Villarreal et al, (2026) [arXiv:2607.14293]

We're Hiring!



RESEARCH SCIENTIST (DEVICE FABRICATION)

RESEARCH SCIENTIST, Device Fabrication: Located at Northwestern University, to join the group of Professor Enectali Figueroa-Feliciano and Dan Baxter. The successful applicant will join the Figueroa Group at Northwestern, and lead the qubit and detector fabrication effort. We are building various transmon-based qubit computation and sensor devices, as well as MKIDS and TES-based detectors for particle physics. Preference will be given to candidates with demonstrated leadership of research groups, supervision and mentoring of students, and familiarity with successful grant writing.

The Figueroa Group is currently involved in several projects involving device fabrication:

- We are currently designing transmon-based qubits to study TLS noise, quasiparticle poisoning, the quantum Zeno effect, correlated errors, cross-talk, and phonon interactions in qubits. We are also working on training AI to design qubits, and will be fabricating and validating AI qubit designs.
- We are part of the HARMONICA project, and DARPA-funded effort to design and build QIS-based neutrino detectors. As part of this project, we are designing and fabricating quantum acoustic detectors and quantum parity detectors; both using transmons for their readout.
- In addition to transmon-based devices, we are fabricating MKID and TES-based detectors for a variety of projects in QIS, dark matter, and neutrino physics.

REQUIREMENTS: A minimum of three years of experience working in a lithography fabrication environment. Applications will be evaluated on a rolling basis until the position is filled.

Please submit a letter of interest and curriculum vitae, and have three letters of recommendation sent to: figueroagroup-jobs@northwestern.edu

POSTDOCTORAL RESEARCHERS IN PARTICLE PHYSICS AND QUANTUM COMPUTING

Located at Northwestern University, to join the group of Professor Enectali Figueroa-Feliciano. The successful applicant will play a leading role in the CosmiQ quantum sensing and computing initiative with Fermilab.

The Figueroa Group is currently involved in several projects involving cryogenic detectors:

CosmiQ is an R&D effort to develop qubits and related technologies for both particle sensing and quantum computing with members from Fermilab, IIT, and Northwestern. Northwestern is an active partner working on qubit measurement, modeling, and fabrication. We are focusing on the interplay between radiation and qubits, understanding how to maximize/minimize qubit sensitivity for sensing/computing. We are designing and fabricating transmon-based qubits to study and manipulate these effects, and on strategies for enhancing robustness and adaptability of qubits for fault-tolerant quantum computing.

R&D at Fermilab: Our group, in collaboration with Fermilab, operates two sister facilities: the Northwestern EXperimental Underground Site (NEXUS), and the Quantum Integration and Experimental Testbed (QUIET). Both are 100 meters underground in Fermilab's MINOS tunnel.

REQUIREMENTS: A Ph.D. in physics. Candidates' background must be in experimental nuclear or particle physics, superconducting qubits and quantum computing, or experimental condensed matter physics. Applications will be evaluated on a rolling basis until the position is filled.

Please submit a letter of interest and curriculum vitae, and have at least two letters of recommendation sent to: figueroagroup-jobs@northwestern.edu

<https://figueroa.physics.northwestern.edu/jobs/index.html>

Acknowledgements – CosmiQuantum@FNAL



FNAL Group

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Rakshya Khatiwada

Kester Anyang
Ziyu Cai
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Jehu Martinez
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Joyce Christiansen-Salameh*
Pratyush Patel
Firas Abouzahr
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Isabella Foti
Lily Johnson
Kostas Papadopoulos
Giana Pérez
Alejandro Rodriguez
Iffat Zarif

PRESENTING AT CPAD

*group alumni