Low-background quantum sensing at Fermilab's underground facility

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Cross Frontier Sessions: Quantum Science & Technology (QST) Instrumentation (IF) & Underground Facilities (UF)
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Low-threshold quantum sensing R&D benefits from a purpose-built, low-background facility.

Talk outline:
1. Fermilab facility overview
2. Ongoing and planned R&D
3. “Community needs” assessment

This talk focuses on FNAL capabilities and community needs. Follow links for more info on individual R&D efforts.
MINOS underground experimental area currently hosts several active R&D efforts, and more are planned.

- 107-meter rock overburden (300 mwe)
- Groups hosted underground include:
  - NEXUS
  - SENSEI
  - MAGIS-100 (see Snowmass poster)
  - NQI Quantum Science Center (ORNL)
NEXUS: low-background He dilution fridge

- Developed by FNAL detector R&D, SuperCDMS, and Northwestern University
- 10 mK base temp. (CryoConcept HEXADRY)
- Internal lead shield protects RF and DC payload stages; External mu-metal shield
- 3.4 muons/cm²/day; O(100) DRU background rate w/ shield in place
- Planned DD generator gives 2.45 MeV n’s for recoil studies
- See below for experimental program summary
QUIET and LOUD: QSC facilities under development

- Quantum Science Center (ORNL-led NQI Center) building two companion facilities at Fermilab:
  - LOUD: high-throughput dilution refrigerator above-ground at Fermilab, for device characterization.
  - QUIET: same model fridge, but shielded and in an underground cleanroom, near NEXUS. Target here is 100 DRU for low-background studies of quantum sensors and other devices.

LOUD fridge received; commissioning begins soon.
Development of a pulsed, scanning laser for low energy calibration of cryogenic devices

Many science applications: understand phonon transfer in materials, quasiparticle poisoning, position-sensitivity of QIS devices to energy deposits, …

Device-agnostic design: qubits, MKIDs, (insert your favorite cryogenic device here)

Anticipated specs:

• ~1.5” x 1.5” scanning area
• <100μm spot size
• ~10μm position resolution
• O(100)Hz scanning speed
• O(μs) pulse width
• >10mK operating temperature

Nearing first 100mK demonstration (right)

Details: Snowmass Poster by K. Stifter
RFSoC for quantum device readout and control

- Xilinx RFSoC-based Quantum Instrument Control Kit (QICK)
- Eight ADC/DAC channels for direct pulse synthesis at GHz frequencies
- Open source software, firmware. Demo code is on GitHub.
Device R&D programs include:

- **Kinetic Inductance Detectors**
  - Lower thresholds \([100 \text{ eV} \rightarrow \sim 5(0.5) \text{ eV}]\)
  - Increase resolution \([\sigma_E = 40 \text{ eV rms} \rightarrow \sim 1-7(0.1) \text{ eV}]\)
  - Absolute energy calibration capability.  

- **Transition Edge Sensors**
  - [SuperCDMS HVeV detector R&D](https://link.springer.com/article/10.1007/s10909-022-02753-5): TES coupled to gram-scale Si absorber
  - Single e-h pair sensitivity with 3 eV energy resolution

- **Quantum Capacitance Detector**
  - Photon shot-noise-limited THz detectors based on Cooper Pair Box
  - NEP < 10-20 W/Sqrt Hz at 1.5 THz
  - [https://doi.org/10.1117/1.JATIS.7.1.011003](https://doi.org/10.1117/1.JATIS.7.1.011003) (P. Echternach, JPL/Caltech)

- **Superconducting qubits**
  - Studying the effect of ionizing radiation (cosmics, gammas) on qubit decoherence ([C. Wilen et al., Nature 594, pp 369–373 (2021).](https://doi.org/10.1117/1.JATIS.7.1.011003))
  - Ionizing backgrounds relevant for axion DM searches, but also QC error correction.
  - Four-qubit array from U. Wisconsin-Madison currently taking data.
SENSEI: Counting single electrons with a CCD

SENSEI: First Direct-Detection Constraints on Sub-GeV Dark Matter from a Surface Run

Michael Crisler,1,⁴ Rouven Essig,2,⁵ Juan Estrada,1,⁶ Guillermo Fernandez,1,⁷ Javier Tiffenberg,1,⁸ Miguel Sofo Haro,1,3,⁸ Tomer Volansky,4,5,8 and Tien-Tien Yu9,3,11

(SENSEI Collaboration)

Dark photon DM (A') absorbed by electron with coupling ε

SENSEI: Characterization of Single-Electron Events Using a Skipper Charge-Coupled Device

Liron Barak,1 Itay M. Bloch,1 Ana Botti,2,3 Mariano Cababiego2,3,4, Gustavo Cancelo,3

Breakthrough in understanding and quantifying e- “dark rates”
A note on community needs:

• A standard set of radiation calibrations would make it much easier for us all to directly compare backgrounds between facilities.

• We will be iterating between design, simulation, and testing a lot in the coming years. Healthy, multi-disciplinary collaborations will significantly shorten this cycle and make us all more productive.

• Who makes the qubits we spend months studying? Industrial partners may want the opportunity to provide devices for characterization in our facilities.
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