Fermilab U.S. DEPARTMENT OF ENERGY | Office of Science

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Quantum Computing Capabilities and Interests

Quantum Testbed Stakeholder Workshop

Hosted by the

Advanced Scientific Computing Research Program

Fermilab Capabilities and Interests Summary

Primary Expertise & Interest Areas

- Facilities for design, engineering, and operation of superconducting systems on all scales
- Leading experts on superconducting cavities and materials
- Quantum sensor development for HEP
- Shovel-ready use cases for moderate size quantum computers

Most Differentiating Factor

Fermilab has produced world-record ultra-low noise ultra-high efficiency superconducting microwave cavity systems, implemented on large scales and transferred to industry

Main Contribution/Role

- Host fully-integrated scalable superconducting qubit architectures provided by university and industry partners
- Lead superconducting cavity R&D for dramatic improvements in quantum coherence times
- Host cross-cutting quantum sensor development for fundamental science experiments
- Enable a large diverse user community to engage with many immediately applicable use cases for near-term quantum computers

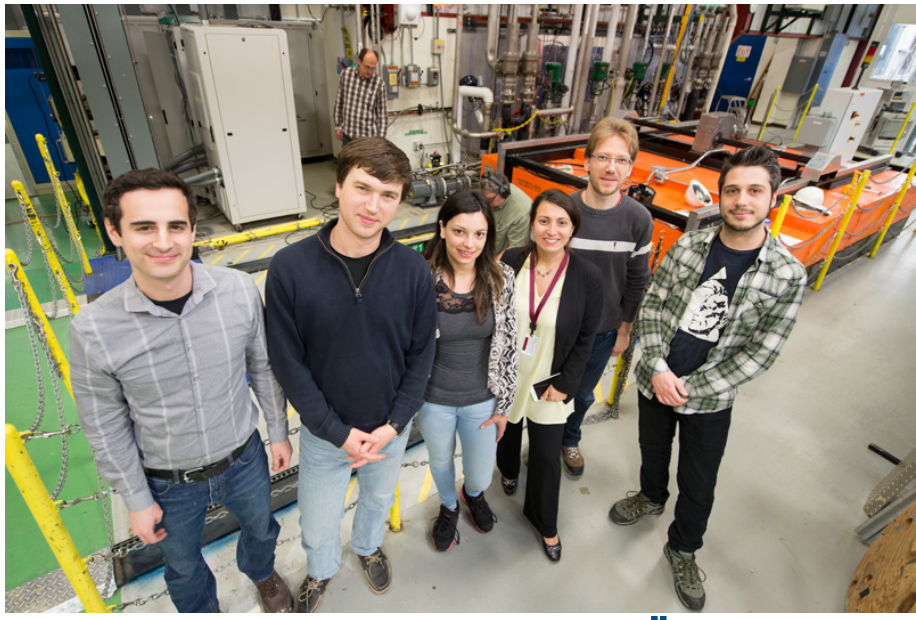
Quantum Computing Hardware Capabilities

- Fermilab has produced world-record ultra-low noise ultra-high efficiency superconducting microwave cavity systems, implemented on large scales and transferred to industry
- In collaboration with the Univ. of Chicago and supported by the Heising-Simons Foundation, currently building and operating transmon qubits coupled to superconducting cavities storing and reading single microwave photons
- Large existing facilities and expert teams for state-of-the-art design, production, surface processing, testing, scanning, and characterization of superconducting cavities and materials
- Dedicating a large clean lab space with vibration and magnetic isolation, cryogenics and other infrastructure suitable to test and operate ~50 qubit scale superconducting quantum computers

Fabrication and Characterization Capabilities

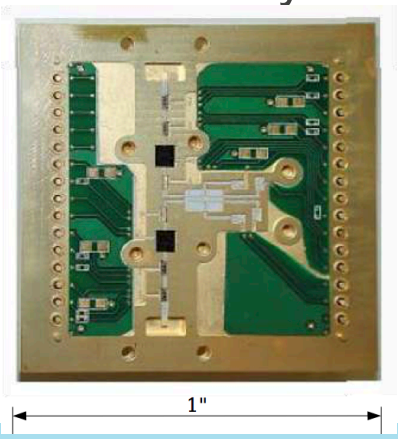
- Leading facilities for design, engineering, and operation of ultra-low noise ultra-high efficiency superconducting systems on small, large, and very large scales
- Leading experts on surface engineering, optimizing, and characterizing superconducting materials (niobium, copper, aluminum)
- Characterization using eddy current scanning, electron microscopy, electron backscatter diffraction, X-ray spectroscopy, laser confocal microscopy, and more

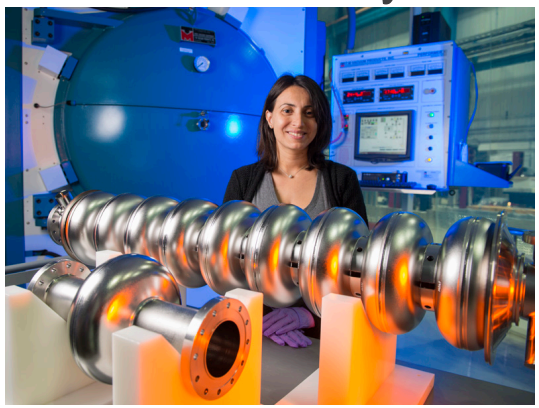
Photo of Fermilab SRF team includes 3 Early Career Awardees and a 2017 Presidential Early Career Awardee

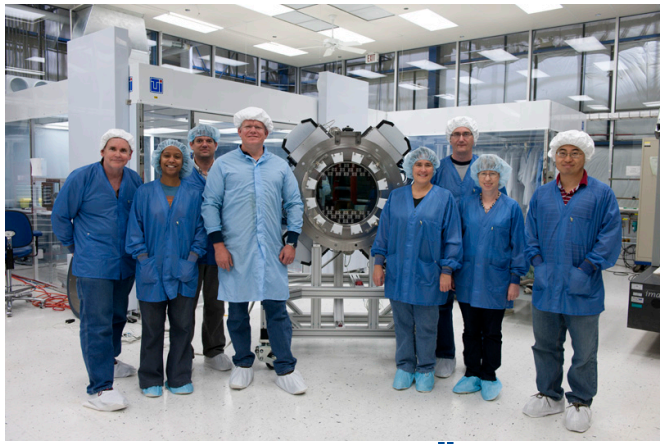


Capabilities in Engineering and Supporting Technology

- Systems engineering and large scale integration, e.g. world's largest CCD camera for Dark Energy Survey, South Pole Telescope 3G
- Deep and wide cryogenics expertise, including more than a decade of operating sub-kelvin cryogenic devices: CDMS and solid xenon for dark matter, MKIDS for dark energy, STJ's for neutrinos, TES bolometers for cosmic microwave background
- Extensive experience in ultra-low noise microwave electronics: design, assembly, QA, testing, integration
- Exabyte scale active archival facility securely serves thousands of active international users, Fermilab provides software systems and big data analytics to same community

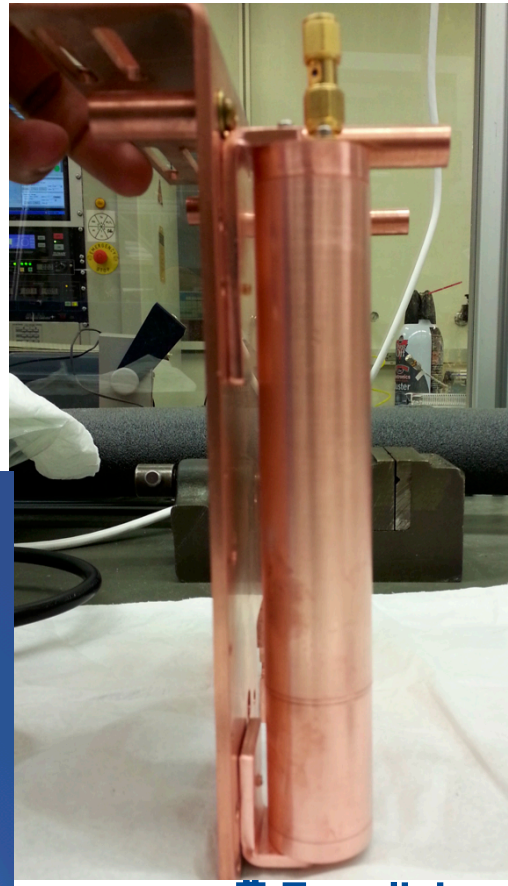






Applications to Domain Science

- Almost any device developed for quantum computing is also a quantum sensor with potential applications to HEP, e.g. detection of dark matter (or dark sector) particles, precision measurements of electric dipole moments, etc.
- Fermilab is already building coupled qubit-cavity sensors for axion dark matter detection
- Longer term applications to HEP include lattice QCD, other post-Moore's law simulation and data analysis needs, Laplace's Demon
- More details in the DOE roundtable report



Quantum Sensors at the Intersections of Fundamental Science, Quantum Information Science & Computing

Co-Chairs: Swapan Chattopadhyay, Roger Falcone, and Ronald Walsworth

Report of the DOE Roundtable held February 25, 2016

Investments in Quantum Computing Technology

Fermilab priorities and investments defined by the needs of HEP, the opportunities provided by advances in the larger QIS community, and the special capabilities of the lab. Current investments:

LDRD for superconducting quantum engineering collaborations with Univ. of Chicago, Caltech, Northwestern

LDRD for qubit-cavity R&D for axion dark matter detection in collaboration with Univ. of Chicago

Technical Division: Dedicating a large clean lab space with vibration and magnetic isolation, cryogenics and other infrastructure suitable to test and operate ~50 qubit scale superconducting quantum computers, connected to our SRF cavity and materials development labs

SiDet: large cleanrooms with multiple dilution fridges and ADRs for quantum sensor development. Combines activities underway for HEP applications to e.g. dark matter detection. Can serve multiple partner collaborations at the same time with fast turnaround

Quantum Computer Science Capabilities

- Fermilab serves a diverse science community of 2300 on-site users and another 1000 who use our computing resources remotely
- A leading center for classical software and algorithm development and deployment for a variety of computationally hard problems, e.g. lattice QCD, perturbative QCD, LHC data analysis, liquid argon neutrino event reconstruction, accelerator modeling
- Shovel-ready use cases for moderate size quantum computers: hard problems that are either intrinsically quantum or recast as difficult optimizations, e.g.
  - collaborating with Caltech and USC on quantum machine learning: using quantum annealer-trained classifiers for Higgs boson reconstruction
- Large motivated user base for validation and verification of quantum computing results versus mature classical methodologies

Facility Management Experience

- Global services office helps our large international user community with safe on-site access and secure remote access
- Users Executive Committee helps optimize user experience
- Subsidized on-site housing in the Fermilab Village
- Most open site of any DOE lab; diverse academic atmosphere
- Vast experience and expertise from, e.g. LHC, with providing user software and hardware support emphasizing common solutions
- Research facilities, safety and work procedures designed to integrate external users
- IARC provides dedicated space and technical resources on site for industry partners
- Routinely provide safe, fast turnaround of R&D projects led by external users at SiDet and other detector facilities as well as accelerator test beams

External Partnerships

- Partnering with Univ. of Chicago on building scalable modular superconducting quantum computers with longer coherence times
- Northwestern University-Fermilab Center for Applied Physics and Superconducting Technologies (CAPST) leverages lab capabilities in superconducting materials science
- Partnerships with Caltech and USC on quantum machine learning
- Close ties with Northern Illinois Center for Accelerator and Detector Development
- New partnership with IBM on quantum algorithm development for HEP use cases
- Working through DOE HEP on interagency partnerships, e.g. NIST
- Experience working with industry, including IP protection and technology transition e.g. high-Q superconducting cavity technology quickly transferred to industry for construction of the LCLS-II XFEL