What is SQMS?

Superconducting Quantum Materials and Systems Center

A DOE National Quantum Information Science Research Center

20 Institutions
>275 Collaborators

Tasked to produce dramatic advancements in quantum technologies for computing and sensing and to build the first quantum computer at Fermilab
How Do We Realize a Quantum Computer?
Basics of Quantum Computing

Utilizes **qubits**: basic unit of quantum information $\rightarrow$ Two (energy) level system

**Superposition**

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Diagram showing the superposition state $|\psi\rangle$ on the Bloch sphere with angles $\theta$ and $\phi$. The state vector is represented as a vector on the surface of the sphere, with $|0\rangle$ and $|1\rangle$ at the poles.
Phenomena give a quantum computer the potential to provide computational capacity for dramatic speedups in several high impact areas:

- Simulating molecule dynamics & particle collisions, modelling financial markets
Promising Way of Realizing a Qubit: Superconducting Qubits

1. Resonators (cavities)

- 2D
- 3D

- Rigetti 8-qubit processor
- Fermilab SRF resonators

Promising Way of Realizing a Qubit: Superconducting Qubits

1. Resonators (cavities)

2D

3D

Rigetti 8-qubit processor

Fermilab SRF resonators


2. LC circuit with Josephson junction

“Transmon” qubits


Need long quantum coherence of superpositions for both resonator and JJ

→ Need a qubit that you can manipulate and not confuse with other states
Fermilab SRF Resonators in Quantum Regime for 3D: Highest Coherence Quantum Resonators Ever Demonstrated

- Technology originally developed for particle accelerators
- Demonstrated 2 s of coherence
- Excellent starting point for SQMS

SQMS Technology Thrust: How Do We Test and Improve Our Qubits?
Focus Area: Materials

• Decoherence comes from materials used to fabricate qubits/resonators
  – Loss tangent, adsorbates, TLS,…

• **Goal:** Understand and mitigate the key mechanisms of decoherence to improve coherence times

• Utilizing material science techniques to study possible origins of loss
  – TEM, SEM, SIMS, XPS, XRD, PPMS, APT, EELS, AFM, …
Test-Bed Devices for mK Characterization of Materials

• Developing new devices to test RF performance of materials in quantum regime
  – New geometries
  – Frequency tunable cavities

• Connecting RF performance to material differences will drive the optimization of qubit fab for longer coherence times
Focus Area: Devices

Goal: Develop methods for 2D and 3D superconducting device performance testing, benchmarking, integration, and quantum controls

- Incorporating Rigetti transmons into 3-D SRF cavities
- Initial results are record-breaking for the photon lifetimes
Enabling Testing at Ultra-Low Temperatures

• Quantum measurements require minimal thermal noise
  – Drives decoherence

• **Dilution refrigerator**
  – Cools to ~20 mK via conduction

• Complex RF equipment

• SQMS plans to make a record size DR at FNAL!
SQMS Science Thrust:
What Can we Do with These Cavities and Qubits in the Quantum Regime?
Focus Area: Algorithms, Simulations, and Benchmarking

Goal: Investigate and develop quantum algorithms and simulations enabled by the groundbreaking SQMS 3D and 2D prototypes through co-design principles.

Qubits considered for a D4 gauge field theory test simulation on Rigetti hardware.
Focus Area: Physics and Sensing

Goal: Exploit the center technological advancements for fundamental physics

DarkSRF experiment: A dark photon search

Orders of magnitude in sensitivity reach improvement via the SQMS advancements

Cavity and Nb$_3$Sn materials advancements for axion searches
DarkSRF: The Search for Dark Photons

- Looking for BSM physics: dark photons
- “Light shining through wall” experiment
- SRF cavities will offer many orders of magnitude improvement in sensitivity

Axion Detection with SRF Cavities

• Searching for cold dark matter candidates: axions
• Designing and manufacturing SRF resonators capable of allowing high-Q in multi-Tesla fields for axion detection.
  – Utilizing Nb$_3$Sn coated SRF cavities
• Currently setting up a proof-of-principle experiment at Fermilab and a second one in collaboration with INFN

New cavity shape optimized for low flux losses
Conclusion

- Exciting time to be a part of such a world-wide effort in the field of QIS
- SQMS has the potential of making dramatic advancements in many thrusts in the QIS field:
  - Superconducting qubits and sensors
  - Materials
  - Algorithms
  - Quantum communication
  - Hardware development
  - Cryogenics
  - RF design and engineering
- We look forward to bringing the first SRF quantum computer to life in the next few years!

*Thank you to Anna Grassellino for providing many of the slides in this talk*
Thank You for Your Attention