A large mK platform at Fermilab for quantum computing applications

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Presentation outline

• Introduction to the Superconducting Quantum Materials and Systems Center at Fermilab

• Goals of the mK platform project

• Cryogenic and mechanical layout

• Expected performance metrics

• Current status and expected timeline
Introduction to SQMS

• One of five centers set up under the National Quantum Initiative, hosted by Fermilab with partners at National Labs, universities and industry

• Overall goal is to “understand the physics and materials origin of coherence limiting factors” – in other words, to explore the physics and material science factors that control the lifetime of the quantum circuits

• A promising path to achieving long lifetime is to adopt a three-dimensional architecture coupling a superconducting qubit to a superconducting radiofrequency cavity
Quantum computing with 3-D structures

• One focus area for SQMS is the development of “qudit” devices, where a 2-D superconducting circuit couples to **multiple degrees of freedom** in a 3-D cavity

• Long cavity lifetimes have been previously demonstrated at mK temperatures (see Romanenko *et al.* 2020) – addresses the **coherence time** issue

• Results in a **physically large** object at mK temperatures

Niobium TESLA cavities of increasing frequency
Dark photon physics

• Experiments looking for “light shining through walls” effects to detect dark photons.

• SRF cavities offer extremely sensitive detectors of photons – one cavity is used as a transmitter, and the other is the receiver.

• Demonstrated at 1.4 K, would like to operate the receiver cavity (or cavities) at mK temperatures to increase sensitivity.
Goals of the mK platform project

• The primary intention of the large mK platform is to host a number of SRF qudit devices. **Requires a large volume at 20 mK**

• Quiescent power dissipation is relatively low, but active microwave components such as switches must be used. **Requires high cooling power at 20 mK**

• Secondary goal of hosting dark photon experiments with a transmitter cavity at ~2 K and several receiver cavities at 20 mK. **Requires high cooling power at 2 K**
Larger dilution cryostats

20 mK diameter
~300mm (2008)

20 mK diameter
~500mm (2015)

20 mK diameter
~1000mm (2022)

20 mK diameter
~2000mm (2025)

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Overview of the cryogenics system

• The mK Platform intends to construct a cryostat with a 20 mK volume of **2 meters in diameter by 1.5 meters in height**

• Cooling will be provided by several Helium-3 heat exchanger stacks below 1 K, with helium cooling above 2 K provided by a **helium cryoplant and liquid nitrogen supply**

• Platform will use an existing vacuum vessel and cryogenic infrastructure currently used for testing Mu2e solenoids at 4 K
Platform facility – current arrangement
Thermal Staging and Mechanical Layout

- **80-K Plate (Liquid Nitrogen)**
- **5-K Plate (Helium)**
- **2-K Plate (Superfluid Helium)**
- **100-mK Plate**
- **1-K Plate (Still)**
- **20-mK Plate (Mixing Chamber)**
- **20-mK space** (2m diameter, 1.5m tall)
- **Vacuum chamber** (3.4m diameter, 4.5m tall)
- **80-K Shield (Liquid Nitrogen)**

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Process diagram (5 K and 2 K stages)

Warm gas mixed with supercritical supply for cool down control

Heat exchanger (5K flow cooled by pumped helium flow)

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Helium Cryoplant

- Platform will use an existing helium cryoplant, specified at **600 W @ 4.5 K**

- Previously used as a liquefier, transfer line will be upgraded for supercritical helium with thermal shielding to minimize loses

- Fed by warm Kinney compressor system from low pressure storage tanks

Existing cryoplant, with expansion engines, valve box and 2000-liter storage dewar
Superfluid helium system

- Cooling at the 2 K stage is provided by a pumped helium system.

- Part of the supercritical helium is diverted to a plate heat exchanger (counterflow with 2 K gas) and expanded through a JT valve.

- Two phase mixture is pumped by a room temperature pump system.
Helium-3 system

- Dilution cooling will be provided by up to 10 commercial dilution “cores” procured from a commercial vendor, each providing up to 35 $\mu$W @ 20 mK

- Pumping and condensation lines will be coupled to the commercial heat exchangers.

- Custom room temperature gas handling and pump system
## Expected heat loads and performance

<table>
<thead>
<tr>
<th>Stage</th>
<th>Nominal Temperature</th>
<th>Expected Quiescent Load</th>
<th>Available Cooling Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Shield</td>
<td>80 K</td>
<td>250 W</td>
<td>1 kW +</td>
</tr>
<tr>
<td>Helium Stage</td>
<td>5 K</td>
<td>70 W</td>
<td>~200 W</td>
</tr>
<tr>
<td>Superfluid Stage</td>
<td>2 K</td>
<td>2.5 W</td>
<td>~25 W</td>
</tr>
<tr>
<td>Still</td>
<td>1 K</td>
<td>4 mW</td>
<td>~100 mW</td>
</tr>
<tr>
<td>Intermediate Cold Plate</td>
<td>100 mK</td>
<td>230 μW</td>
<td>1 mW</td>
</tr>
<tr>
<td>Mixing Chamber</td>
<td>20 mK</td>
<td>3 μW</td>
<td>300 μW</td>
</tr>
</tbody>
</table>

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Current status and timeline

- Detailed, final design is underway
- Procurement of long-lead items and fabrication expected to start in Fall 2021
- Assembly and commissioning of the 2-K system expected in Fall 2022
- Upgrade to full mK system expected in Summer 2023
- Integration of RF components and devices planned for the end of 2023
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