An Update on the Colossus mK Platform at Fermilab

Matthew Hollister, Ram Dhuley, Christopher James and Grzegorz Tatkowski
Fermi National Accelerator Laboratory
CEC/ICMC 2023
Presentation Outline

• Introduction to the Superconducting Quantum Materials and Systems Center at Fermilab and the goals of the Colossus 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 underlying phenomena that control the lifetime of the quantum states in the devices

• 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.
Colossus General Arrangement

- Key feature of the system is the 2-meter diameter cold plate at the 20-mK stage
- 20-mK cold volume is 5 cubic meters, enclosed by a copper thermal shield for stray light control in the experiment space
- Internal structure consists of 6 progressively colder plates with thermal shields
- Vacuum top plate now a flat head (replacing the dished head in the conceptual design) to allow more space for services and feed throughs.
Colossus Facility

- Conceptual design made use of an existing vacuum chamber (pictured)
- Now plan to replace with a new, larger vessel, although will still use the same work platform
Colossus Facility

An Update on the Colossus mK Platform at Fermilab
Colossus Facility
Overview of the Cryogenics System

- Thermal architecture consists of three distinct systems:
  - Liquid nitrogen supplied at 80 K to the first cold plate
  - Liquid helium supplied at 4.8 K, with some flow diverted inside the cryostat through an additional heat exchanger and JT valve to produce a superfluid stage
  - Sub-1 K stages provided by multiple Helium-3 dilution circuits

- Very high cooling power is available from the cryogenic plant, while multiple Helium-3 circuits operating in parallel overcomes the performance limitations in the operation of the individual heat exchanger stacks.
Mechanical Layout

- 80-K Plate (Liquid Nitrogen)
- 5-K Plate (Helium)
- 2-K Plate (Superfluid Helium)
- MC1 Plate (100 mK)
- MC2 Plate (20 mK)
- 1-K Plate (Still)
- 20-mK space (2m diameter, 1.5m tall)
- Vacuum chamber (3.4m diameter, 4.5m tall)

An Update on the Colossus mK Platform at Fermilab
Mechanical Layout

80-K Plate (Liquid Nitrogen)
5-K Plate (Helium)
2-K Plate (Superfluid Helium)
MC1 Plate (100 mK)
MC2 Plate (20 mK)
1-K Plate (Still)
Vacuum Top Plate
Thermal Staging

- Nominal temperatures and sizes of each thermal stage of the Colossus cryostat are tabulated below.

- Thermal shields are installed at all stages except the MC1 stage at 100 mK

<table>
<thead>
<tr>
<th>Stage</th>
<th>Nominal Temperature</th>
<th>Diameter / mm</th>
<th>Shield?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Vessel</td>
<td>300 K</td>
<td>3600</td>
<td>Yes</td>
</tr>
<tr>
<td>Thermal Shield</td>
<td>80 K</td>
<td>3000</td>
<td>Yes</td>
</tr>
<tr>
<td>Helium Stage</td>
<td>5 K</td>
<td>2800</td>
<td>Yes</td>
</tr>
<tr>
<td>Superfluid Helium Stage</td>
<td>2 K</td>
<td>2500</td>
<td>Yes</td>
</tr>
<tr>
<td>Still</td>
<td>1 K</td>
<td>2300</td>
<td>Yes</td>
</tr>
<tr>
<td>MC1</td>
<td>100 mK</td>
<td>2200</td>
<td>No</td>
</tr>
<tr>
<td>MC2</td>
<td>20 mK</td>
<td>2000</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Interstage Supports

- Each cold plate in the cryostat are suspended with a system of four fiber-reinforced bars.
- Attached with stainless brackets and rollers that allow rotation.
- Bars are arranged radially to compensate for shrinkage on cooling.
- Supports are designed to carry a load approaching 40,000 kg – allows later installation of cold high-density shielding.
Helium Cryoplant

• Platform will use an existing helium cryoplant, specified at 625 W @ 4.7 K

• Existing transfer line will be replaced to reduce losses and improve the helium quality delivered to Colossus

• Addition of a pumping skid adds 2-K operation to the plant

• More information in Tatkowski et al.
Helium-3 System

• Dilution cooling at the lower most plate will be provided by up to 10 dilution “cores” procured from a commercial vendor, each providing up to 20-50 μW @ 20 mK at the MC2 layer

• Discussions with vendors to procure these units is underway – this will be a competitive procurement

• Additional information in James et al.

Image: Janis Research Company
Helium-3 System

- Still pumping and condensing lines are designed to be modular, with assembly and leak checking on the bench before integration with the cryostat.

- Inlet capillaries wrap onto a common heat intercept plate at each of the upper thermal stages.
  - Precooling at 80 K and 5 K
  - Condensation at 2 K

- Bellows couplings for flexibility and thermal contraction between stages.
### 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>155 W</td>
<td>9 kW +</td>
</tr>
<tr>
<td>Helium Stage</td>
<td>5 K</td>
<td>50 W</td>
<td>200 W</td>
</tr>
<tr>
<td>Superfluid Stage</td>
<td>2 K</td>
<td>3.74 W</td>
<td>10 W</td>
</tr>
<tr>
<td>Still</td>
<td>1 K</td>
<td>1.2 mW</td>
<td>100 mW</td>
</tr>
<tr>
<td>Mixing Chamber MC1</td>
<td>100 mK</td>
<td>138 μW</td>
<td>3 mW</td>
</tr>
<tr>
<td>Mixing Chamber MC2</td>
<td>20 mK</td>
<td>1 μW</td>
<td>300 μW</td>
</tr>
</tbody>
</table>

* Excluding experimental wiring
Current Status and Timeline

• Detailed, final design is underway

• Procurement of long-lead items and fabrication expected to start towards the end of 2023

• Initial assembly and commissioning of the cryostat with limited mK capability expected in 2025

• Upgrade to full mK system in 2026-2027 depending on continued funding of the SQMS program
Acknowledgement

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.