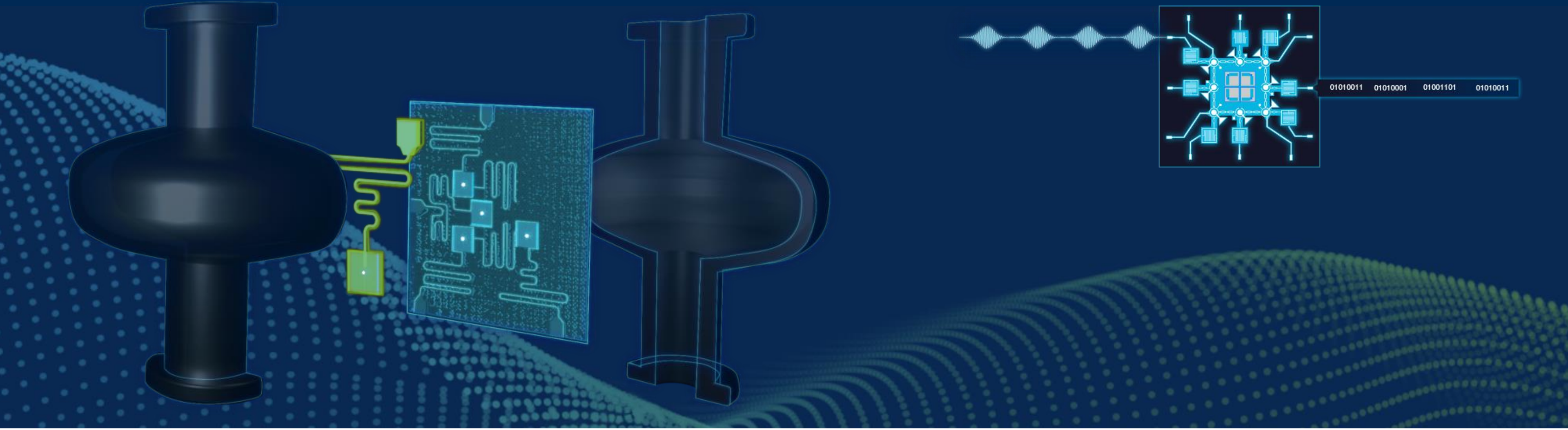


An Update on the Colossus mK Platform at Fermilab

Matthew Hollister, Ram Dhuley, Christopher James and Grzegorz Tatkowski
Fermi National Accelerator Laboratory

CEC/ICMC 2023

J4Or1A-02
FERMILAB-SLIDES-23-096-SQMS

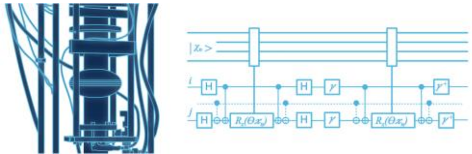
Presentation Outline

- 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

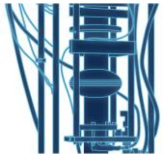


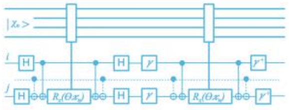
Introduction to SQMS

- 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

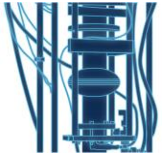


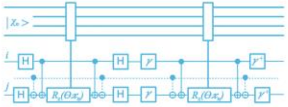


Quantum computing with 3-D structures

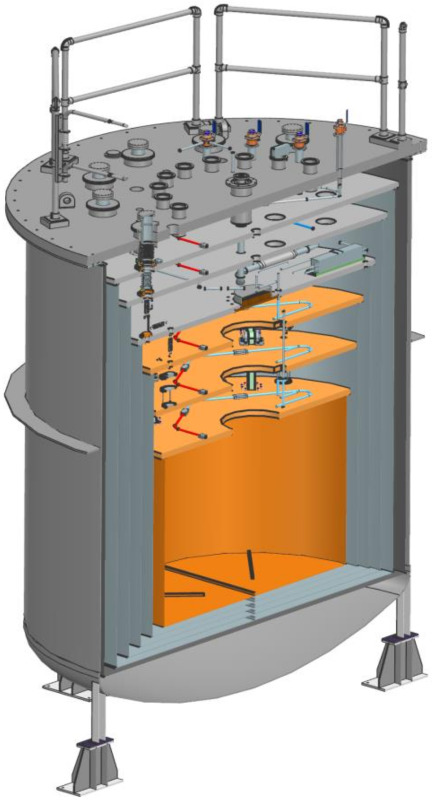
- One focus area for SQMS is the development of "qudit" devices, where a 2-D superconducting circuit couples to multiple degrees of freedom in a 3-D cavity
- Long cavity lifetimes have been previously demonstrated at mK temperatures (see Romanenko *et al.* 2020) – addresses the coherence time issue
- Results in a physically large object at mK temperatures

Niobium TESLA cavities of increasing frequency

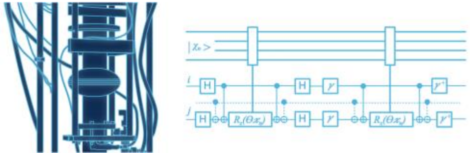




Colossus General Arrangement



- 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.

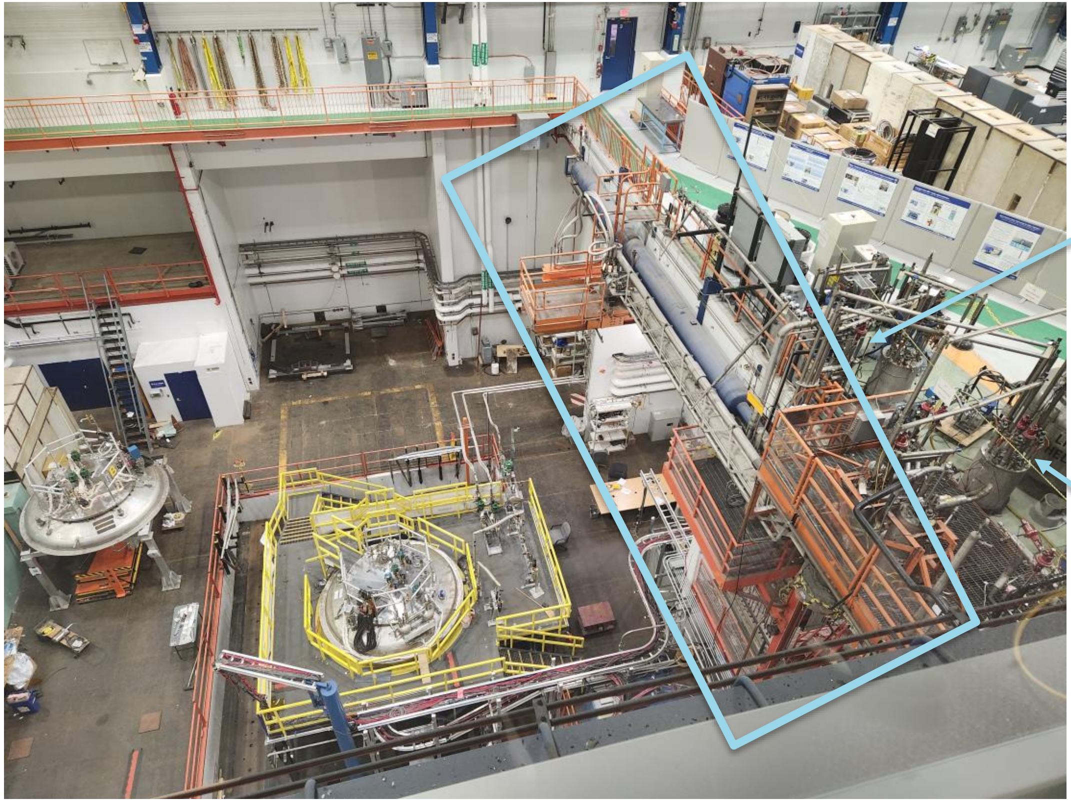


Colossus Facility

- 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

Colossus Facility



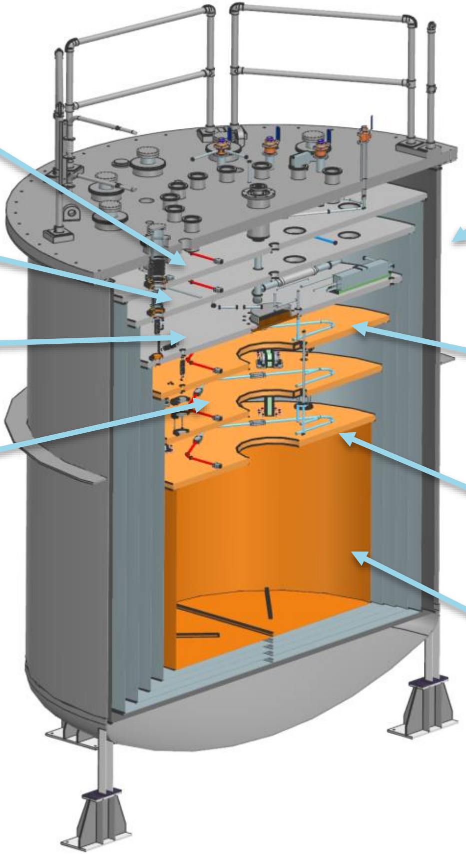
Transfer line assembly

Cryogenics Plant

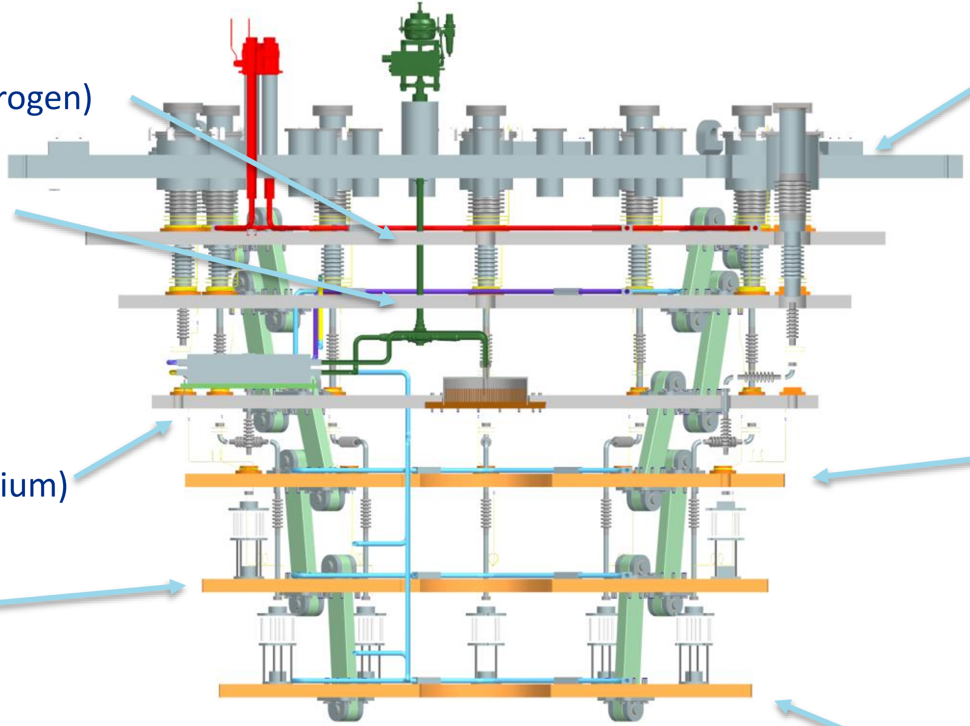
Overview of the Cryogenics System

- 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



Mechanical Layout

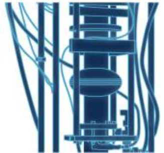


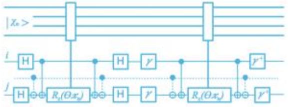
Thermal Staging

- 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

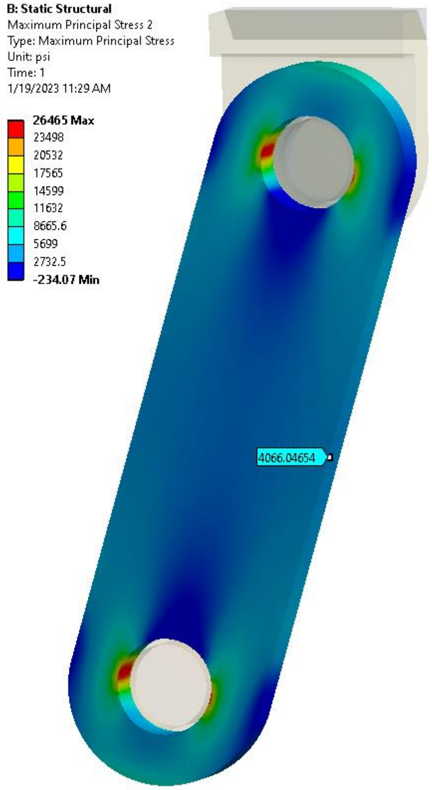
Stage	Nominal Temperature	Diameter / mm	Shield?
Vacuum Vessel	300 K	3600	Yes
Thermal Shield	80 K	3000	Yes
Helium Stage	5 K	2800	Yes
Superfluid Helium Stage	2 K	2500	Yes
Still	1 K	2300	Yes
MC1	100 mK	2200	No
MC2	20 mK	2000	Yes

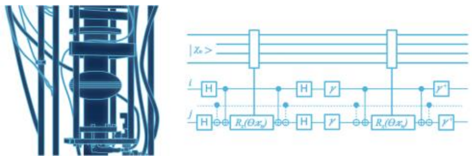




Interstage Supports

- 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.



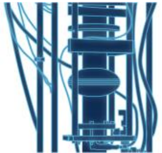


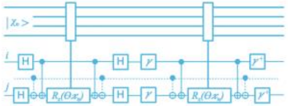
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

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.*

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





SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

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.*

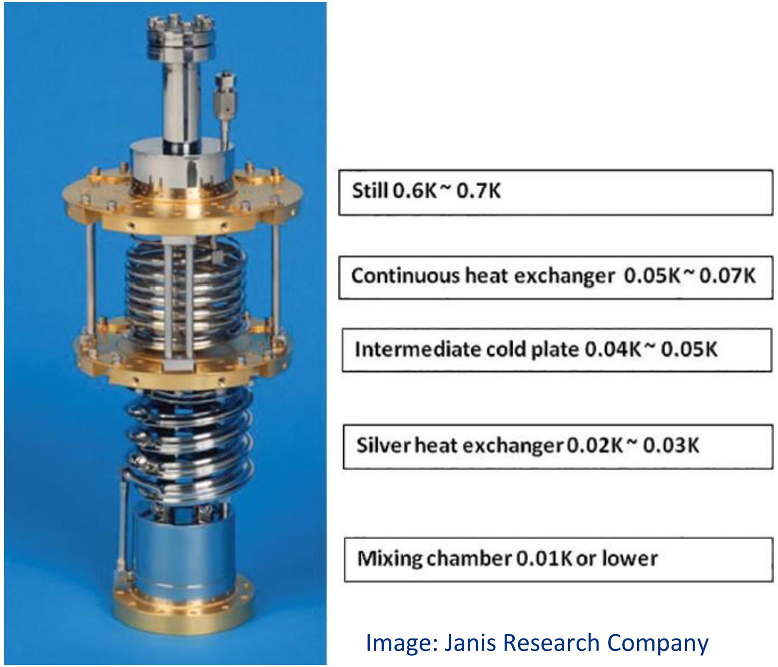


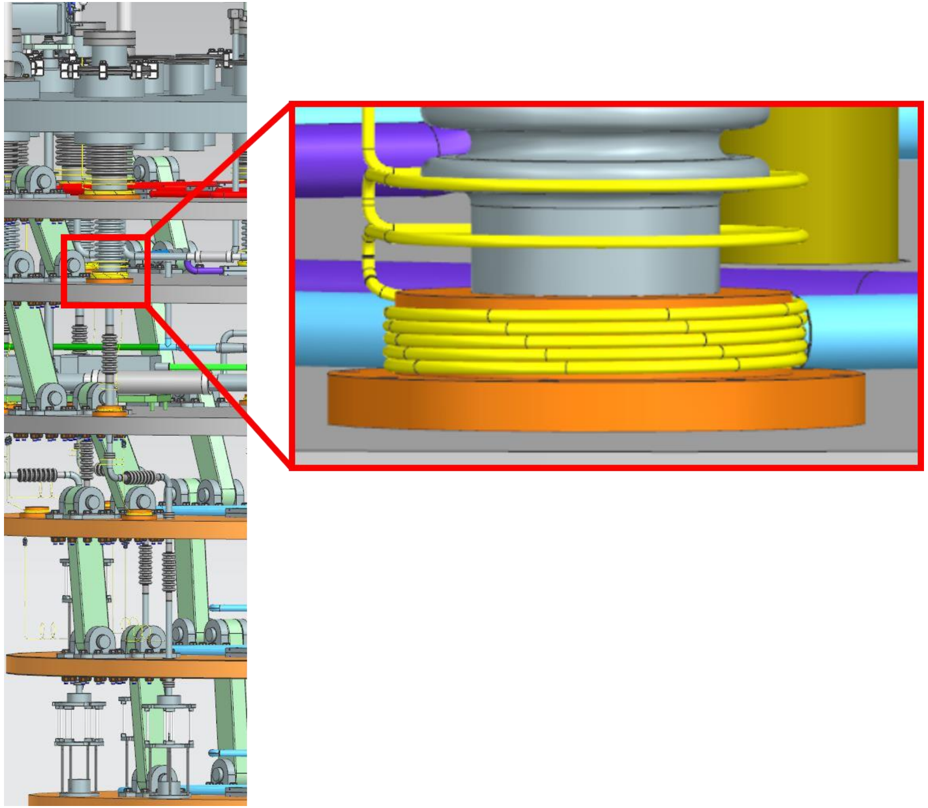
Image: Janis Research Company

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

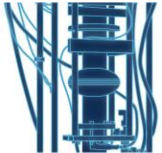
- Bellows couplings for flexibility and thermal contraction between stages.

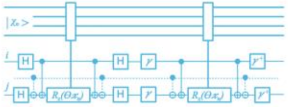


Expected Heat Loads and Performance

Stage	Nominal Temperature	Expected Quiescent Load *	Available Cooling Capacity
Thermal Shield	80 K	155 W	9 kW +
Helium Stage	5 K	50 W	200 W
Superfluid Stage	2 K	3.74 W	10 W
Still	1 K	1.2 mW	100 mW
Mixing Chamber MC1	100 mK	138 μW	3 mW
Mixing Chamber MC2	20 mK	1 μW	300 μW

* Excluding experimental wiring





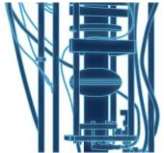
Current Status and Timeline

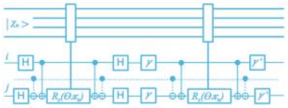
- Detailed, final design is underway

- 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.