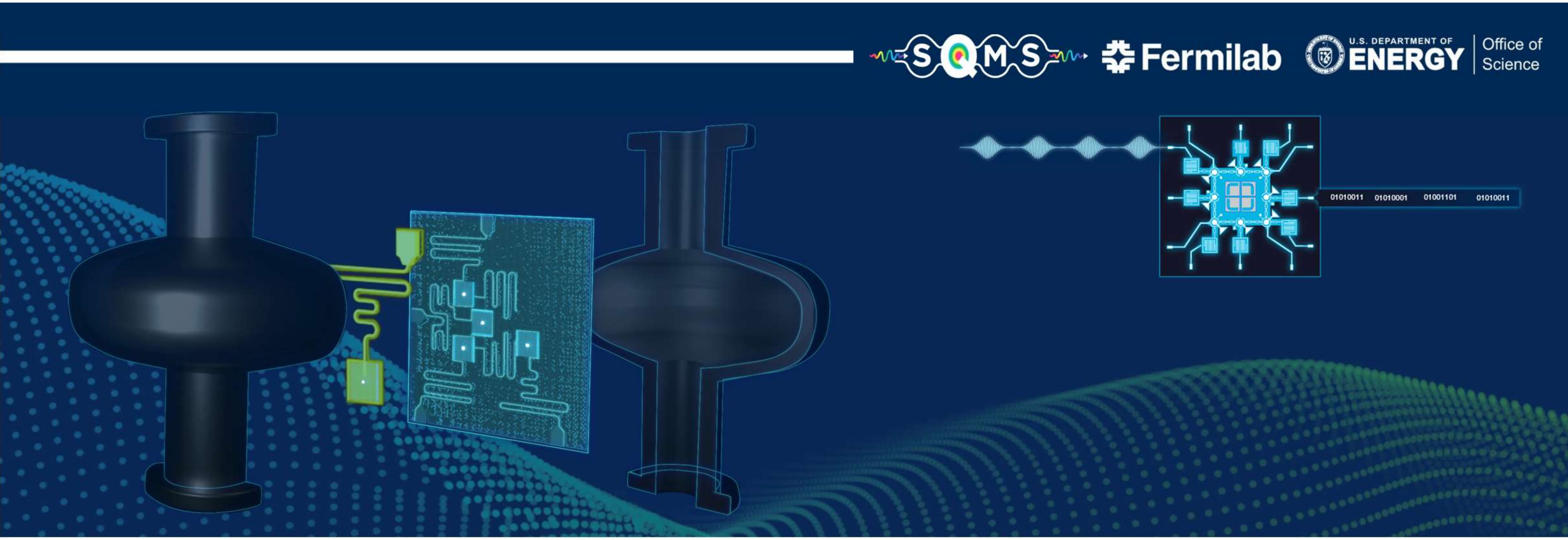

A large mK platform at Fermilab for quantum computing applications

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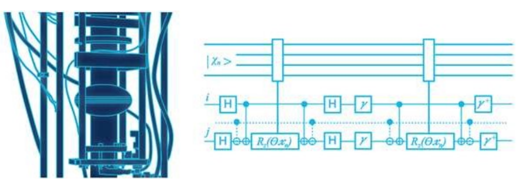
Presentation outline

- 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

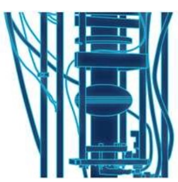


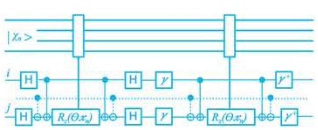
Introduction to SQMS

- 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**.

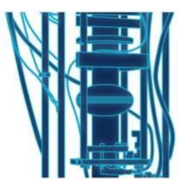
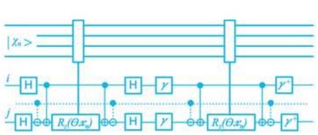
Dark photon experiment with SRF cavity at Fermilab

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**

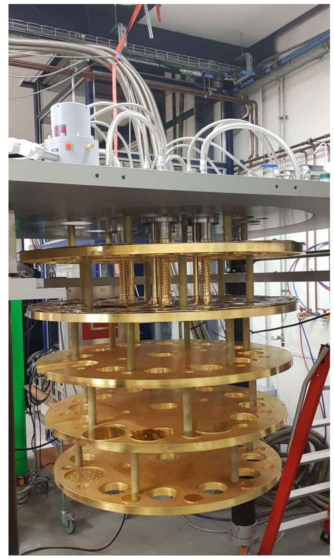
- Secondary goal of hosting dark photon experiments with a transmitter cavity at ~2 K and several receiver cavities at 20 mK. **Requires high cooling power at 2 K**

Larger dilution cryostats

20 mK
diameter
~300mm
(2008)

20 mK
diameter
~500mm
(2015)

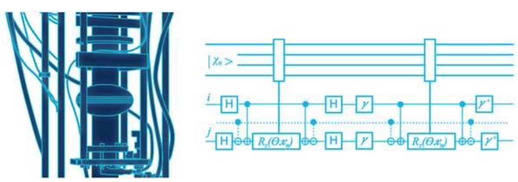


20 mK
diameter
~1000mm
(2022)

20 mK
diameter
~2000mm
(2025)

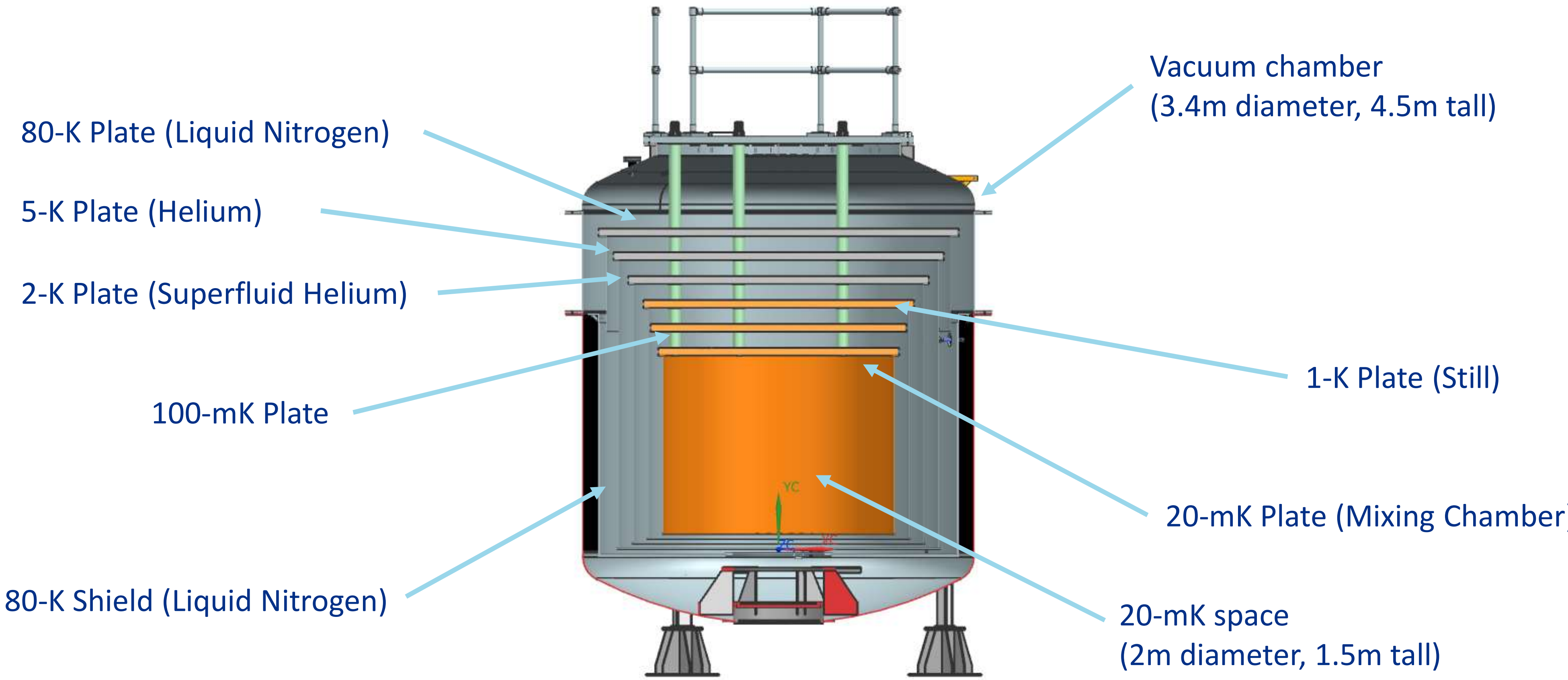
Overview of the cryogenics system

- 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

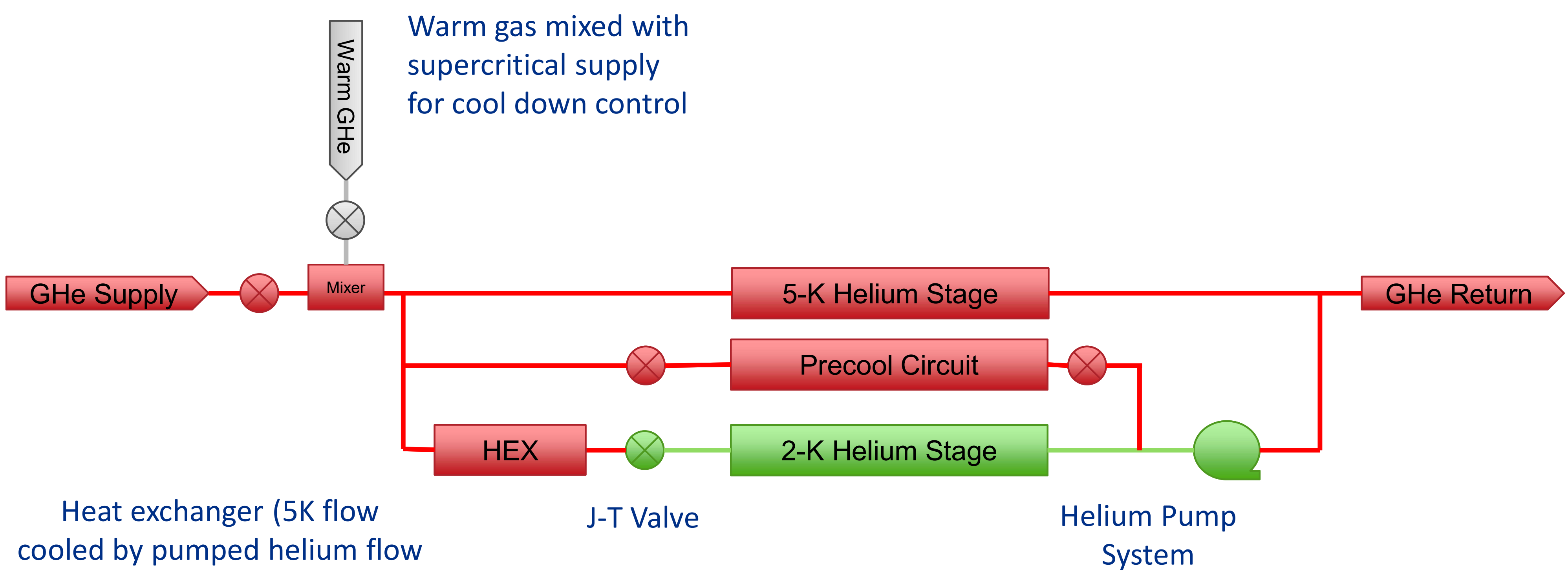


Platform facility – current arrangement

Thermal Staging and Mechanical Layout



Process diagram (5 K and 2 K stages)

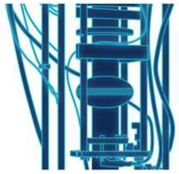
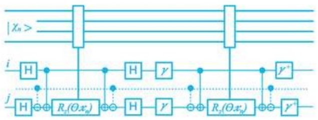


SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

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

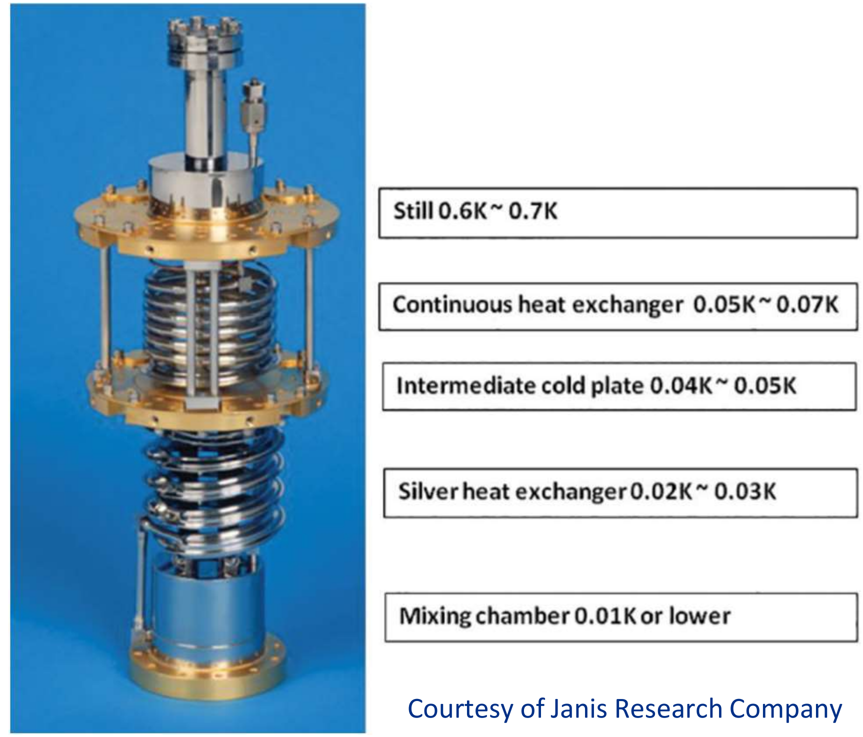
Superfluid helium system

- 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

Kinney vacuum booster and liquid ring pump skid

Helium-3 system

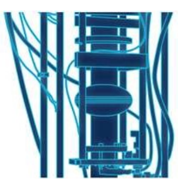
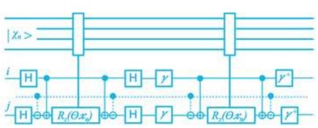
- Dilution cooling will be provided by up to **10 commercial dilution “cores”** procured from a commercial vendor, each providing up to **35 μW @ 20 mK**
- Pumping and condensation lines will be coupled to the commercial heat exchangers.
- Custom room temperature gas handling and pump system



Courtesy of Janis Research Company

Expected heat loads and performance

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

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

Acknowledgement

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