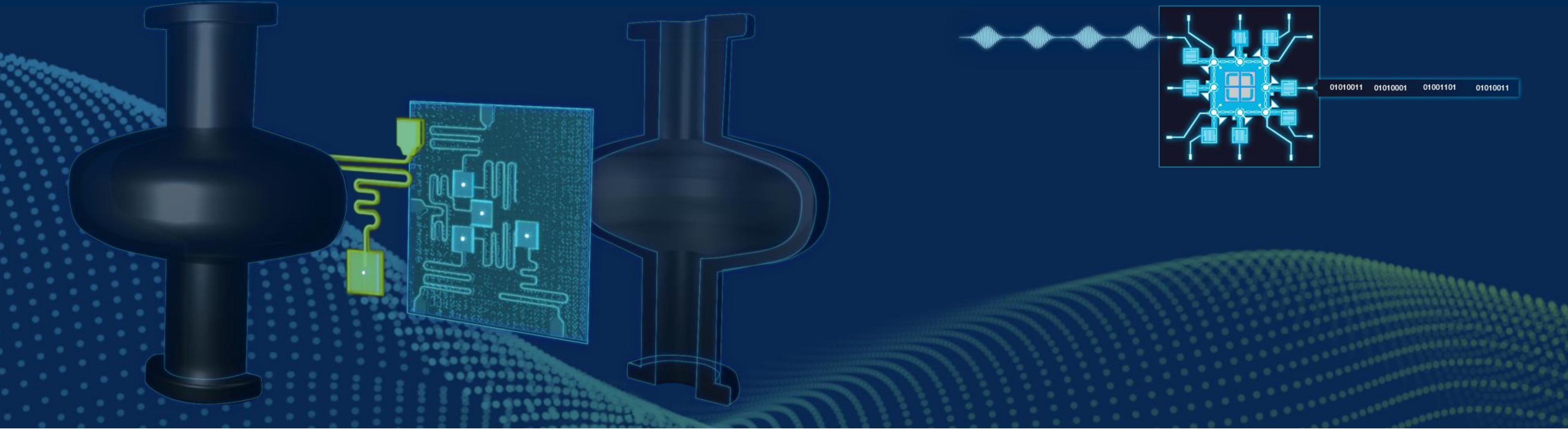

Cryogenics for Superconducting 3D Qubits and the Colossus Project in SQMS

Matthew Hollister

Fermi National Accelerator Laboratory

DESY Seminar, March 30 2022

Introduction to SQMS

- The Superconducting Quantum Materials and Systems Center is one of five centers set up under the National Quantum Initiative, hosted by Fermilab with partners at National Labs, universities and industry

SQMS Center is located in FNAL Technology Campus, in APS-TD buildings and the IARC building

SQMS Partners

Fermilab
rigetti
Northwestern University
AMES LABORATORY Creating Materials & Energy Solutions U.S. DEPARTMENT OF ENERGY
NASA Ames Research Center
NIST
INFN Istituto Nazionale di Fisica Nucleare
Stanford University
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
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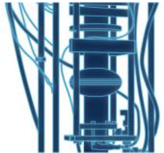
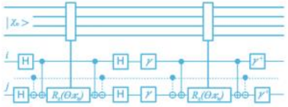
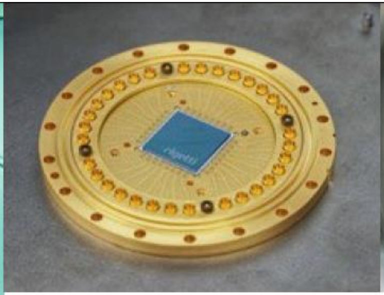
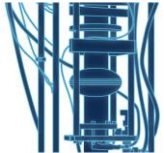
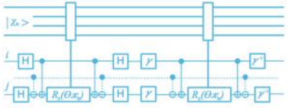



SQMS Mission



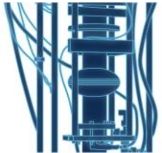
SQMS Mission Statement: “bring together the power of national labs, industry and academia to achieve transformational advances in the major cross-cutting challenge of understanding and eliminating the decoherence mechanisms in superconducting 2D and 3D devices, with the goal of enabling construction and deployment of superior quantum systems for computing and sensing."

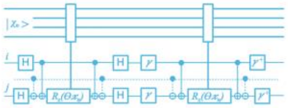




Presentation Outline

- SQMS at Fermilab
- Which quantum applications are we talking about?
- The needs of quantum science
- Cryogenics for SQMS and the Colossus refrigerator
- Concluding remarks





Quantum Science

- Covers an extremely broad set of applications.

- Probably the highest profile and visible area is that of quantum computing, but also encompasses quantum networking, cryptography, and many sensing applications that are directly applicable to our work in particle physics.

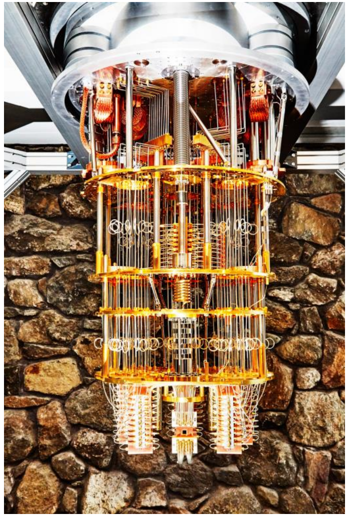


Image: IBM / Amy Lombard

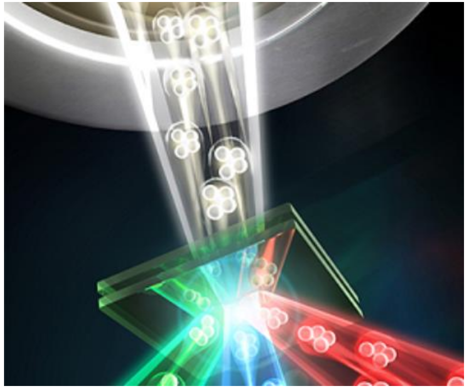
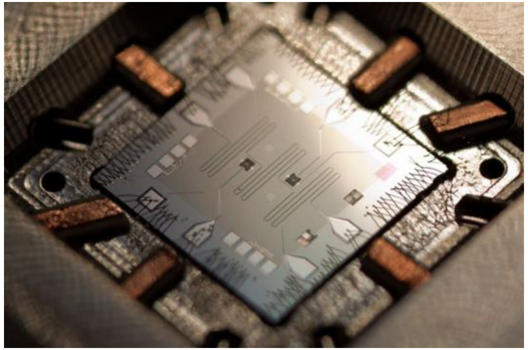


Image: University of Bristol



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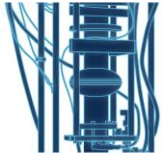
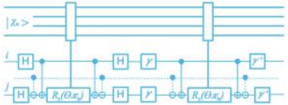




SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

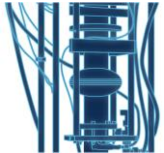
Quantum Science

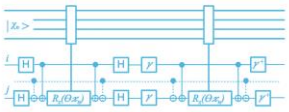
- The common theme of all these applications is that they rely on either quantum coherence (a wavelike superposition of states) or quantum entanglement mechanisms.

- In either case, these are inherently unstable systems that are extremely sensitive to external noise sources.

- In addition, many systems also rely on low temperature phenomena such as superconductivity.

- Quantum devices are frequently (although not exclusively) cryogenic devices.

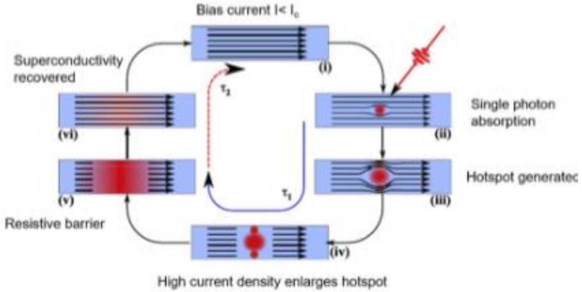




Quantum Sensors

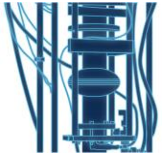
- Common example of a quantum sensor is a superconducting nanowire single photon detector, or SNSPD. Extremely sensitive devices capable, as the name implies, of detecting single photons.

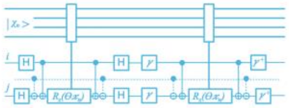
- Many different materials giving sensitivity to different wavelengths of light, typically operating at 1 K to 4 K.



SNSPD detection mechanism and integrated measurement system

(Credit: Single Quantum)



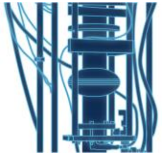
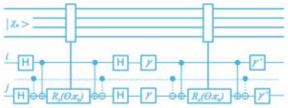


Quantum Computing

- The advantage of quantum computing over classical computing is not one of brute processing power, but rather one of addressing complexity.

- In complex problems involving, for example, large interconnected databases, a quantum algorithm can approach the problem in a multidimensional processing space that reveals connections between widely-separated data points.

- Many flavors of quantum processor are being explored, not all of them cryogenic (at least, not yet).

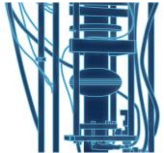
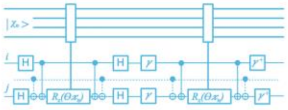



Qubits

- The fundamental unit of a quantum process is a referred to as a “qubit”, as opposed to a bit in classical computing.

- While a classical bit can only represent as single binary value (0 or 1), a qubit can represent any linear combination of the two values.

- Any system that can exist in a superposition of states can be used as qubit. These include resonators, trapped atoms, charge donors in silicon, among others.

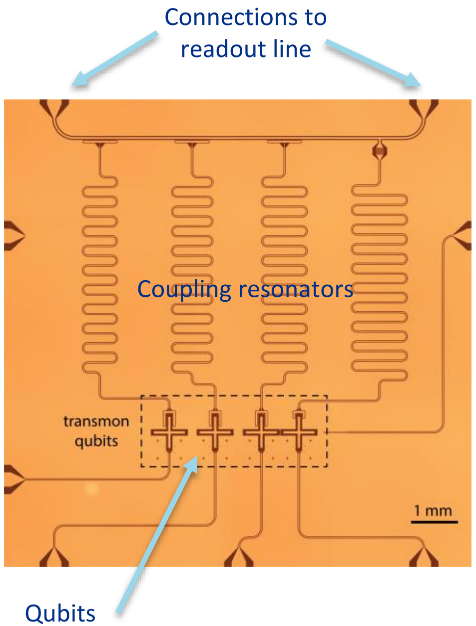



Superconducting Quantum Computing

- The designs that have seen the most development are generally based on superconducting circuits. There are many different implementations of these circuits, making use of phase, charge or flux quantization (or a hybrid or different types).

- The qubits are coupled to each other using an intermediate circuit such as a capacitor or a SQUID.

- Coupling to the readout circuits also uses an intermediate circuit such as a microwave resonator.



4 qubit quantum process (IBM)

Superconducting Quantum Computing

- Superconducting RF and similar qubits are intimately connected to dilution refrigerators – the continuous low temperature cooling is ideal for stable cryogenic devices.
- Cooling process based on heat of mixing of 3He into 3He/4He mixture.
- Operating temperatures between 10 and 50 mK are routinely achievable in such systems
- Current state of the art processors have ~50 qubits.

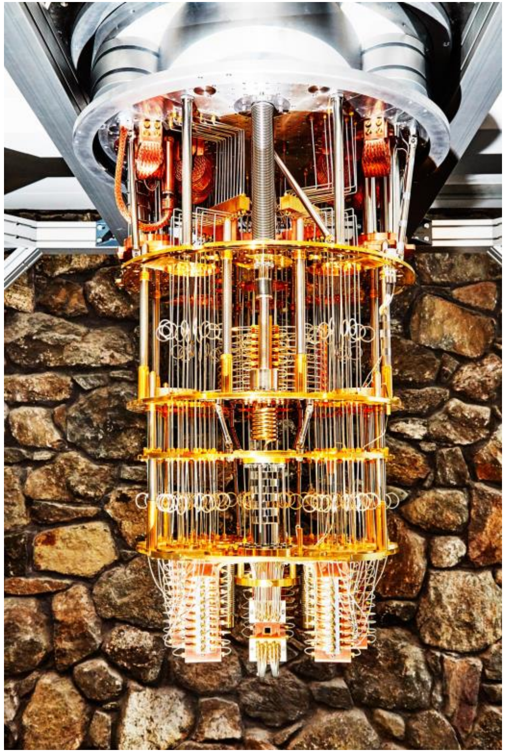
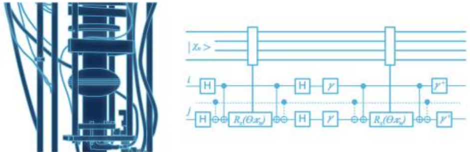


Image: IBM / Amy Lombard



Superconducting Quantum Computing

- The superconducting processors are microwave devices, making use of RF readout systems to connect the cryogenic processor to room temperature electronics for readout and control.

- Multiplexing factors are low. Multi-qubit processors need many readout lines and other components (isolators, amplifiers…) and a lot of room temperature electronics.

- Larger processors require larger refrigerators

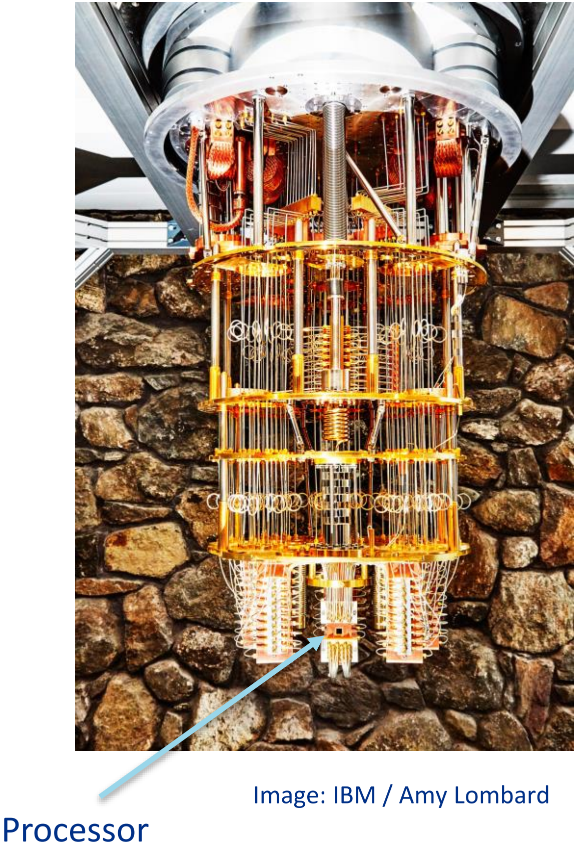
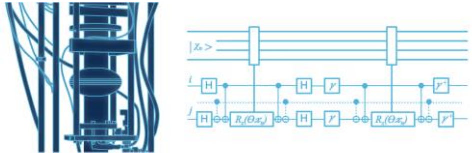


Image: IBM / Amy Lombard

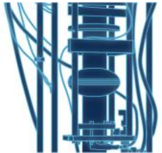


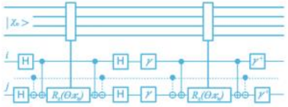
Some Issues with Scaling Up

- It is not feasible to arbitrarily scale up a mK cryogenic platform due to the nature of the dilution process.

- Capacity of mechanical coolers commonly used in fridge platforms is also a limiting factor in larger systems.

- Before we explore these two factors, we will very briefly discuss the design of a modern dilution refrigerator.





A Quick Tour of a Dilution Refrigerator

Precooling provided by 2-stage mechanical coolers (typically pulse tubes)

50 K

4 K

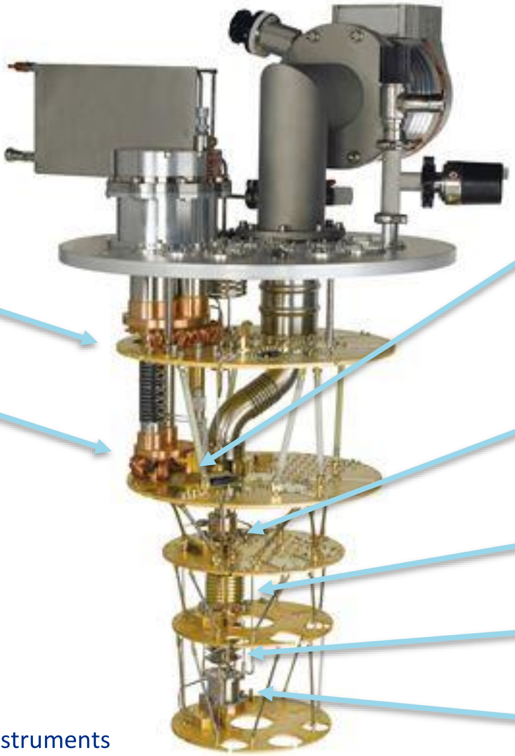
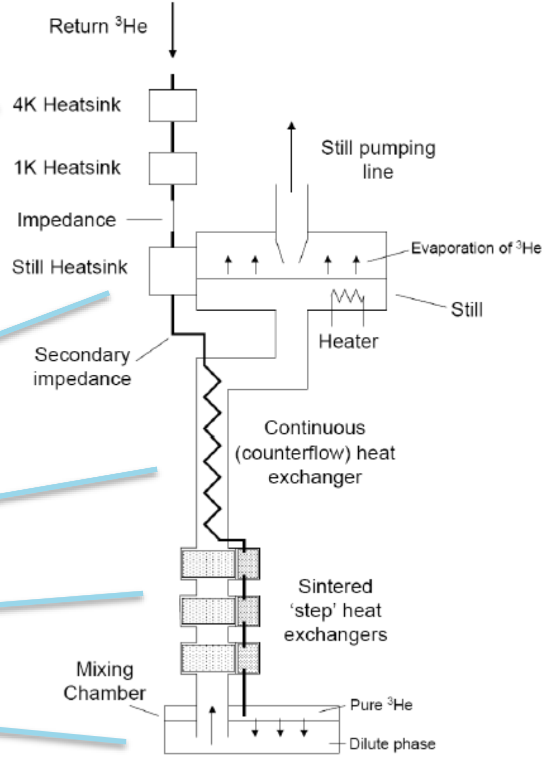


Image: Oxford Instruments



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Larger Dilution Cryostats

20 mK diameter ~250mm (2010)	20 mK diameter ~500mm (2015)	20 mK diameter ~1000mm (2022)	20 mK diameter ~1500mm (2025?)

Image: Oxford Instruments

Image: BlueFors

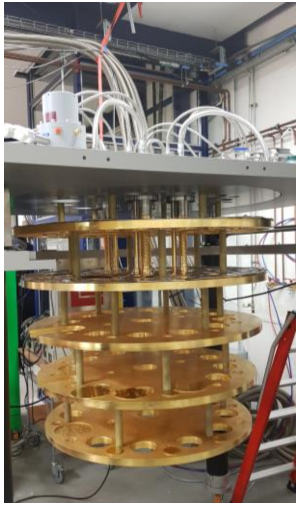
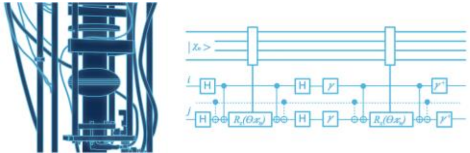


Image: Leiden Cryogenics

Image: BlueFors



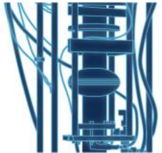
Circulation and Heat Exchange

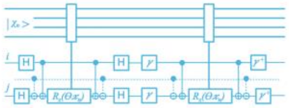
- The cooling power of a dilution refrigerator comes from the heat of mixing of pure 3He into a mixture of 3He and 4He.

- Cooling power of the dilution process is proportional to the 3He circulation rate, usually quoted as

$$Q_{MC} = 84 n_3 T_{MC}^2$$

where Q_{MC} is the cooling capacity, n_3 is the 3He circulation rate, and T_{MC} is the mixing chamber temperature





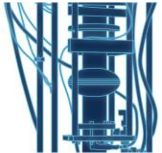
Limits on Heat Exchange

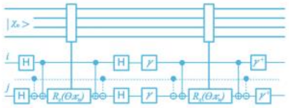
- The quoted equation is idealized, however. The full derivation yields a relationship that includes T_N, the temperature of the 3He as it enters the mixing chamber:

$$Q_{MC} = n_3(96T_{MC}^2 - 12T_N^2)$$

- From this, for practical purposes, the cooling power of the fridge is really a function of how effective the heat exchangers are. This applies to the heat exchangers higher up the system as much as down at the cold end of the process.

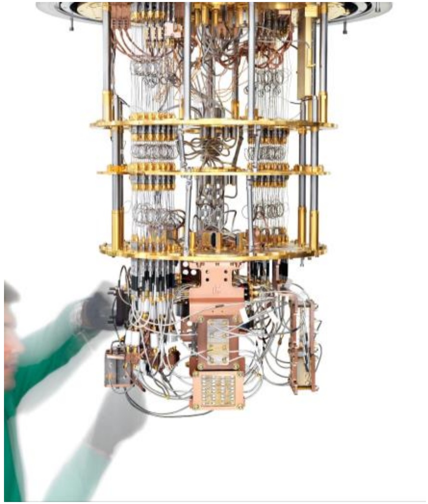
- Efficient heat exchange is challenging due to extremely large thermal resistance between solids and liquid helium at these low temperatures.



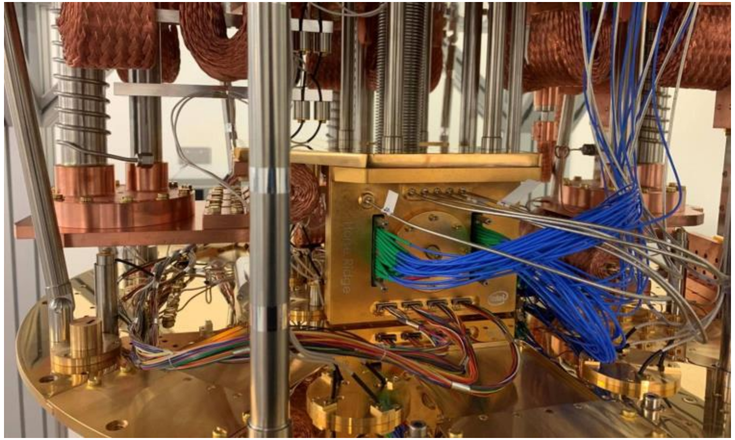


Precooling and Experimental Loads

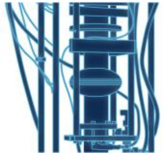
- In addition to the cold end of the dilution refrigerator, we must also consider the cooling of the 3He as it flows from room temperature, and the demands of experimental wiring.

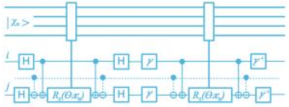


A typical quantum computer setup
Image: Rigetti Computing / Justin Fantl



Cryogenic control processor
Image: Intel





Large Platforms using Liquid Helium

- Another possibility for the construction of a large platform is to utilize a helium cryoplant rather than cryocoolers.

- For comparison, a Tevatron satellite refrigerator has 300 times more cooling power at 4 K than a cryocooler

- This is the approach taken in the design of a large mK platform under construction for SQMS.

Exterior of the large mK platform at Fermilab
Image: Fermilab

Larger Cryogenic Facilities – **a Concept for a “Quantum Data Center”**

- The most likely scheme for the deployment of quantum computers will be cloud-based, with “data centers” of many quantum processors (perhaps networked) located together in a way analogous to supercomputing centers.

- This is already being done on a small scale by the bigger industry players such as IBM and Rigetti.

- This leads to some interesting infrastructure possibilities

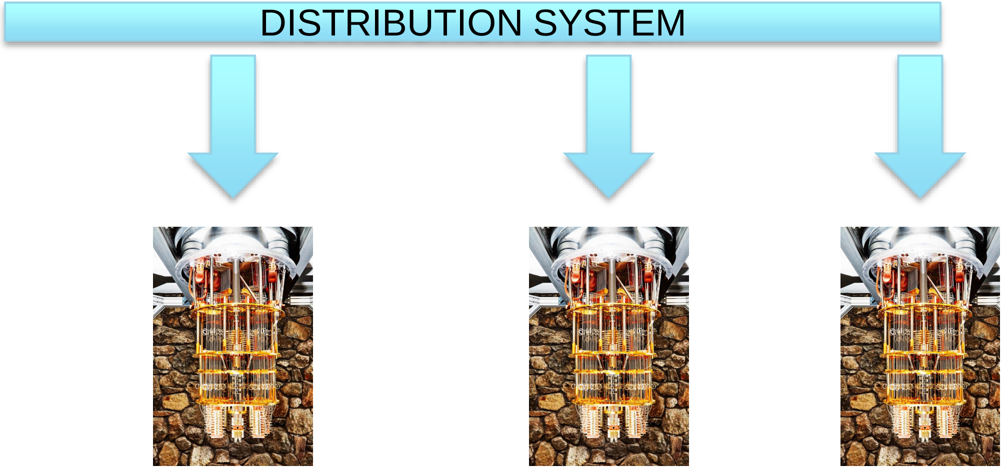
Image: IBM

Larger Cryogenic Facilities – **a Concept for a "Quantum Data Center"**

- As discussed previously, the use of liquid helium rather than mechanical coolers makes the construction of large individual platforms possible but can also support multiple small cryostats from a central plant.

Image: Fermilab

Central LHe plant



A Large Millikelvin Platform at Fermilab – the Colossus Project

- Aims to construct the largest and most powerful dilution refrigerator platform ever.
- Makes use of existing infrastructure as much as possible, including the workspace from the Mu2e solenoid test facility and the existing helium plant (originally from the Tevatron).
- Will have a 20 mK volume of 5 cubic meters (5-10x the current largest refrigerators) and up to 10x the cooling power.

Exterior of the existing Solenoid Test Facility at Fermilab (Image: Fermilab)

Quantum Computing with 3-D Structures

- One key focus area for SQMS is the development of so-called “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 – addresses the coherence time issue

- Results in a physically large object at mK temperatures

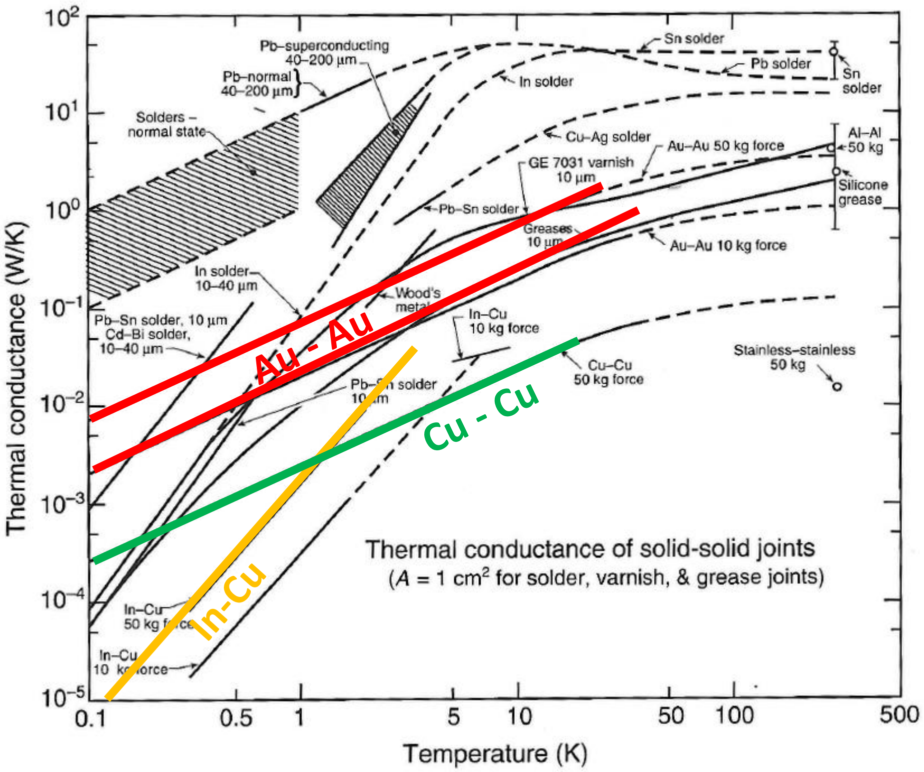
Niobium TESLA cavities of increasing frequency

Slide 25 Removed

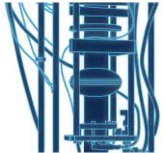
Contact Conductance

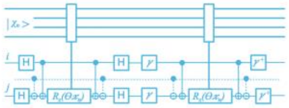
- Common joining techniques that work at “high” temperatures (>1 K) such as grease, solder or indium are much less useful at low temperatures.

- Simple metal-metal joints can also present problems at low temperatures.



Adapted from Eiken (2006)





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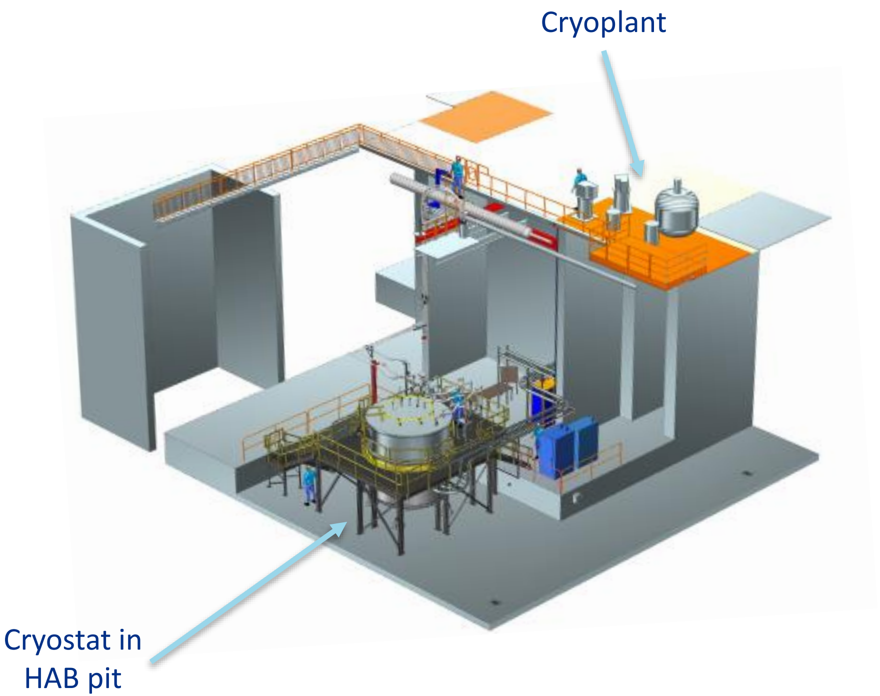
Colossus in HAB

- Colossus is located in the old assembly area of the CDF experiment.
- Subterranean space includes the platform cryostat, along with much of the cryogenic infrastructure and service facilities for the fridge.
- This is all in the same building as the SQMS offices, quantum labs and nanofabrication facilities.

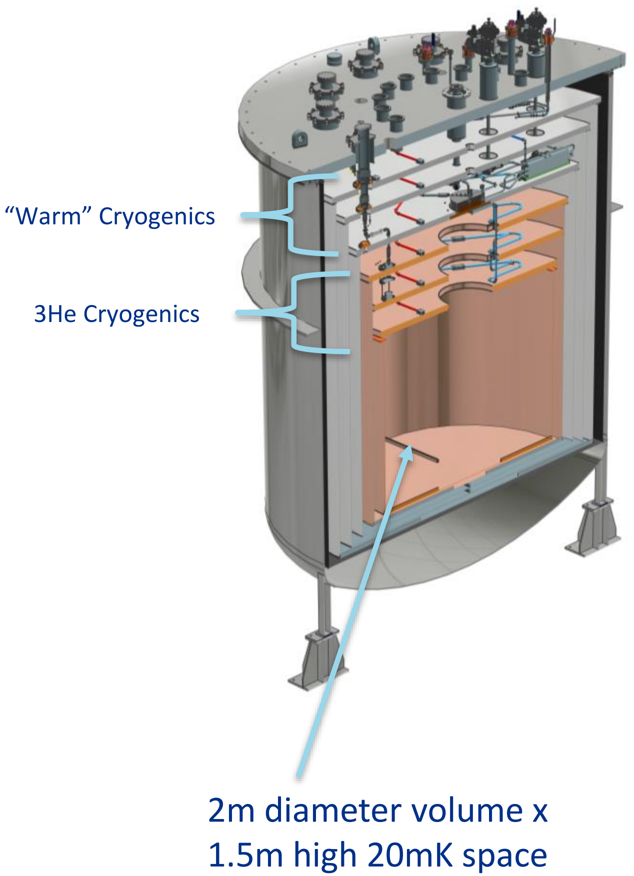


Colossus in HAB

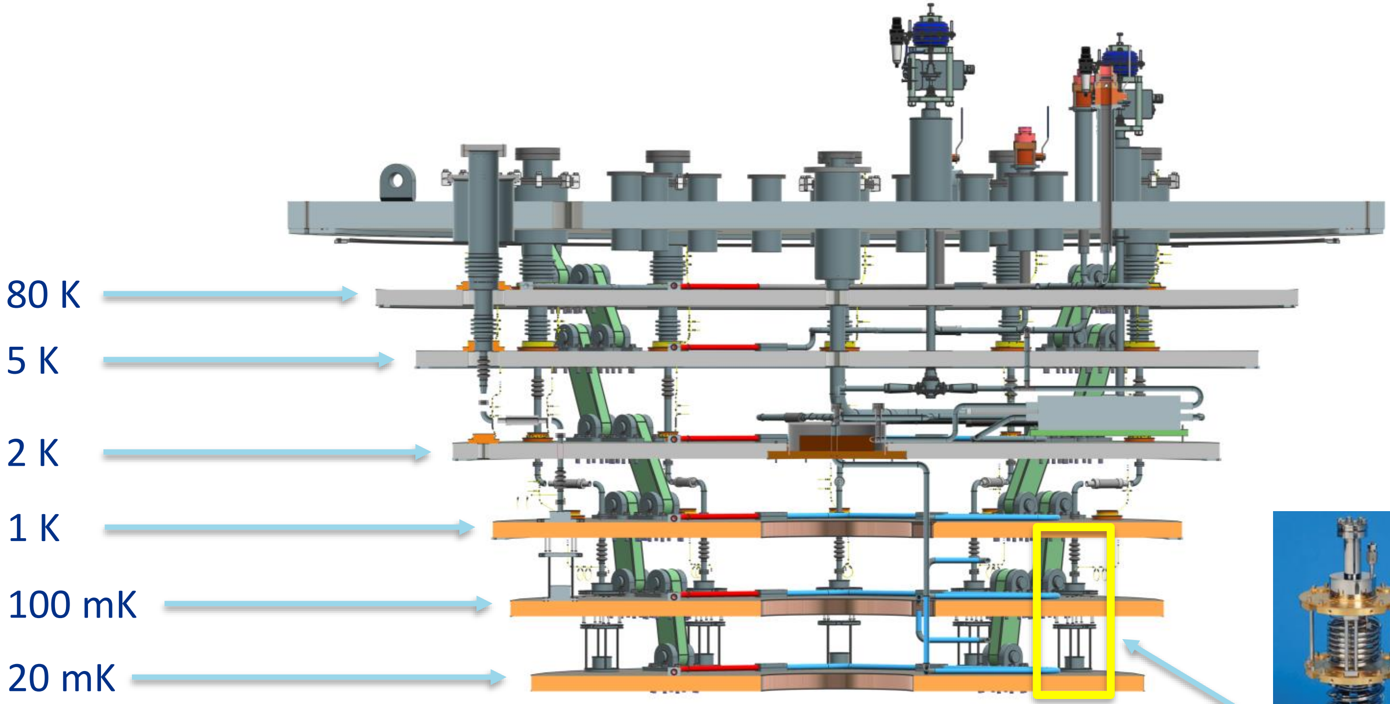
- Upper plates are cooled using liquid nitrogen and helium, with an upgraded helium plant adding a 2-K capability.

- The 2-K stage is something that doesn't appear in modern, cryogen-free refrigerators, but is useful as an intercept stage and for cooling cavities in Dark SRF experiments.

- mK cooling is provided by 10-12 parallel 3He circuits based on commercial heat exchanger stacks.



Temperature Stages



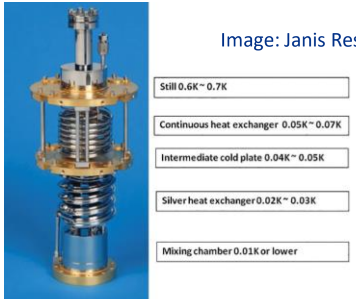
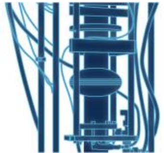
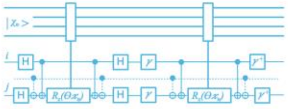


Image: Janis Research Company



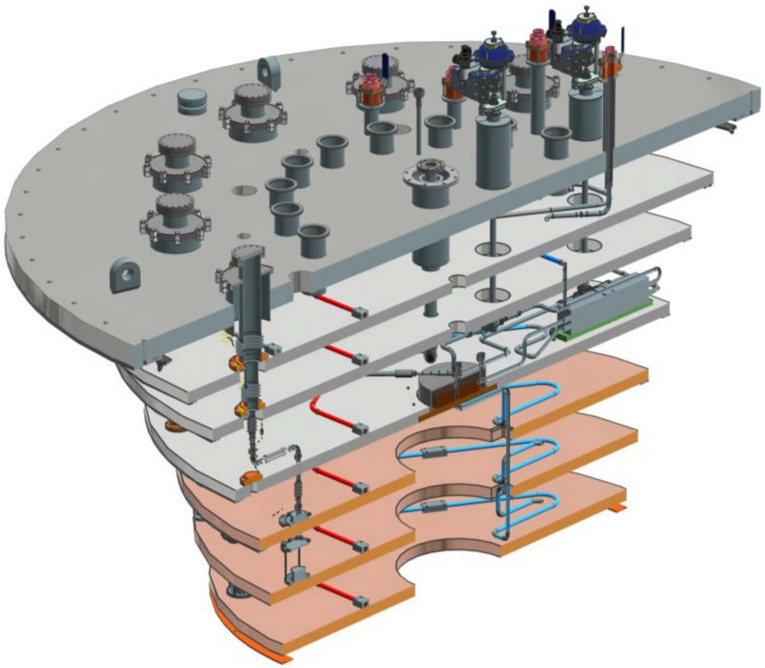


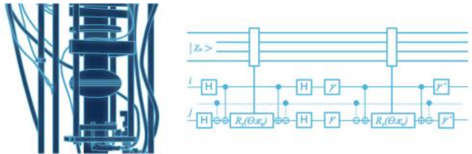
Expected performance

Stage	Nominal Temperature	Cooling Source	Available Power
Thermal Shield	80 K	Liquid Nitrogen	1 kW
Helium	5 K	Gaseous Helium	100 W
Superfluid	2 K	Pumped Liquid Helium	30 W
Still	1 K	Dilution fridge	100 mW
Mixing Chamber 1	100 mK	Dilution fridge	2 mW
Mixing Chamber 2	20 mK	Dilution fridge	300 μW

Design Challenges

- The size of the platform introduces some specific issues not seen in smaller fridges:
  - Distributed cooling. Can't rely on conduction in the plates at all temperatures
  - Thermal contraction and radial motion of the plates
  - Cooling the system down efficiently



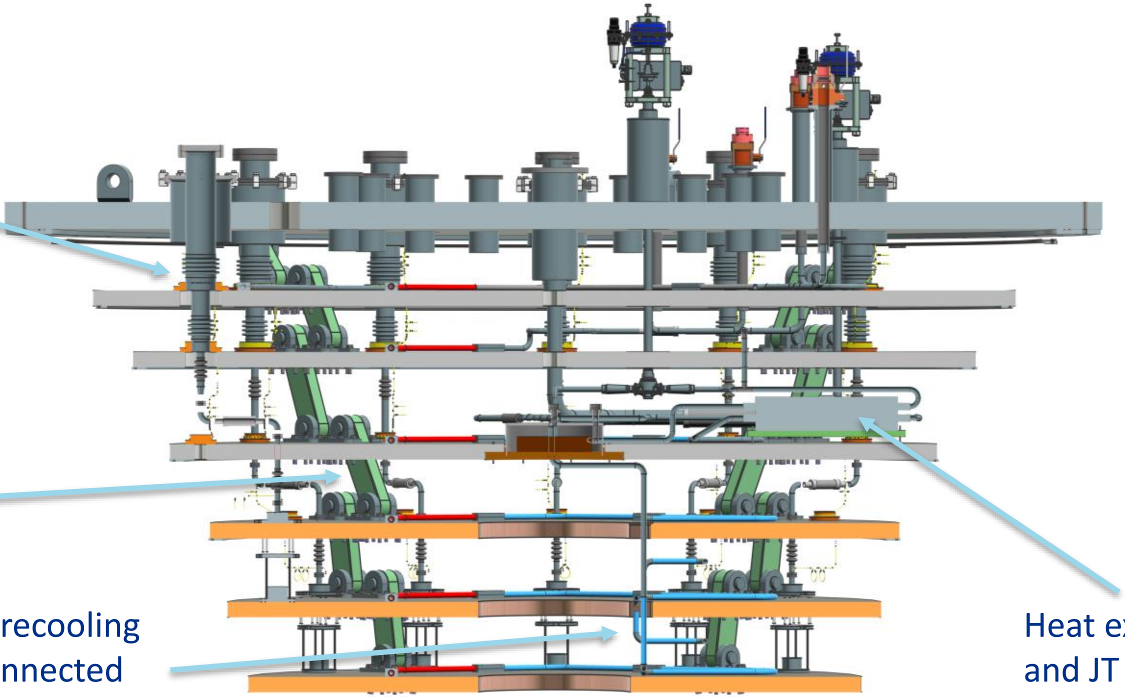


Colossus Internal Details

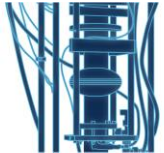
Careful analysis of lateral motion in pump lines, particularly the large-bore pump lines for the 3He circuit

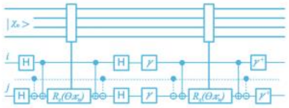
Hinged supports to allow radial motion from contraction

Helium precooling circuit connected to the lower plates

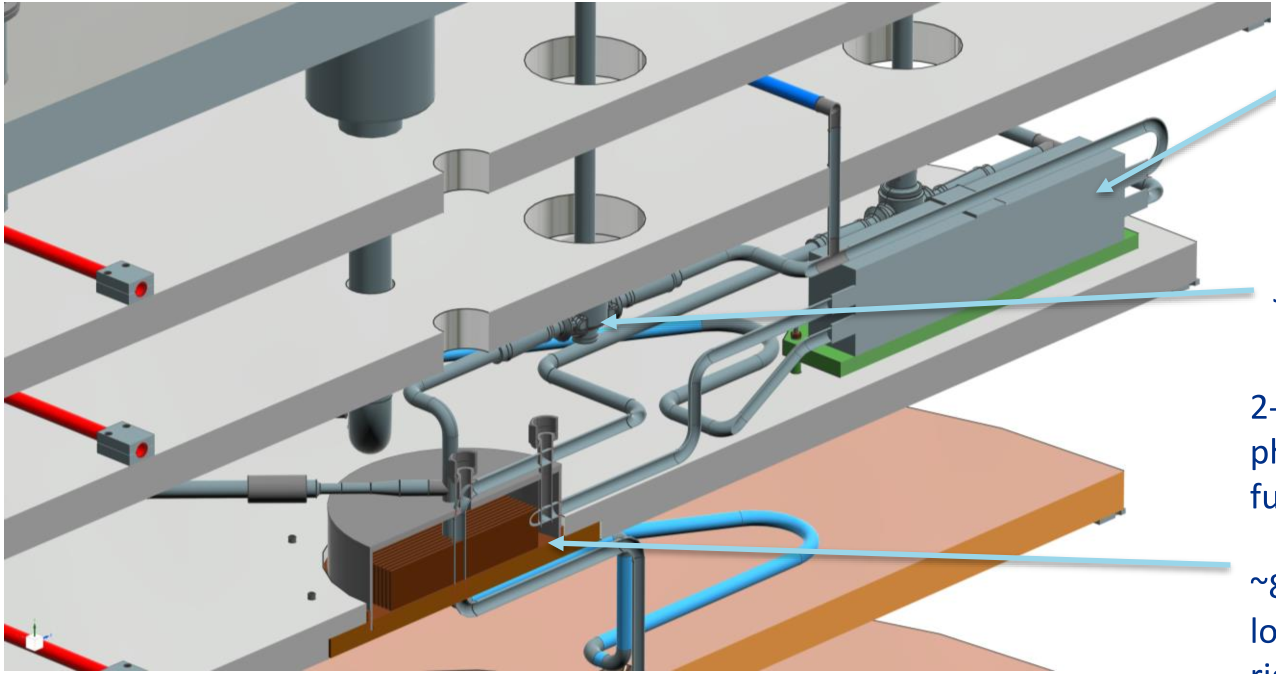


Heat exchanger and JT valve for the 2-K system





Colossus 2-K System



Precooling heat exchanger

J-T Valve

2-K Pot – essentially a phase separator ~50% full of liquid.

~80% of the expected load at 2-K comes right into the center of the plate

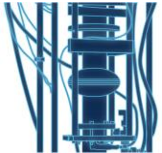
Concluding Remarks

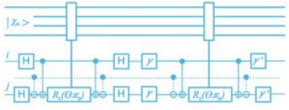
- Quantum science and cryogenics are two areas that are intimately connected.

- The state-of-the-art for millikelvin cooling has moved rapidly in the last 10-15 years, largely driven by the needs of commercial quantum computing development.

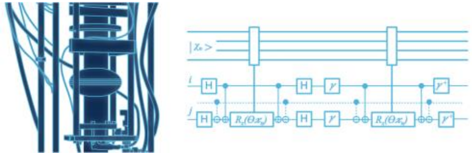
- The Colossus project is a key part of the SQMS mission, aiming to construct the largest and highest cooling power dilution refrigerator platform ever. The platform will be a core technology for the deployment of the 3D quantum processor architecture being developed.

- The major construction activities for Colossus are expected to start this summer, with the platform coming online in mid-2024.

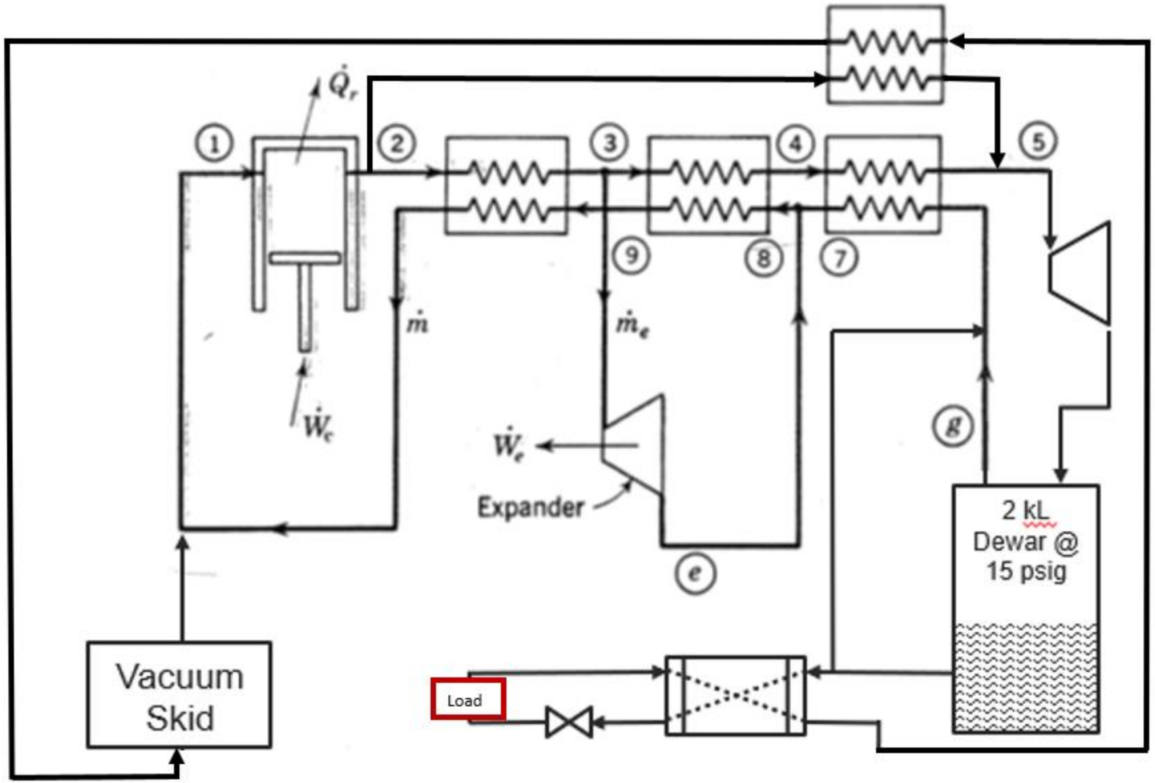




BACK UP SLIDES



Modified Tevatron Satellite Refrigerator Layout



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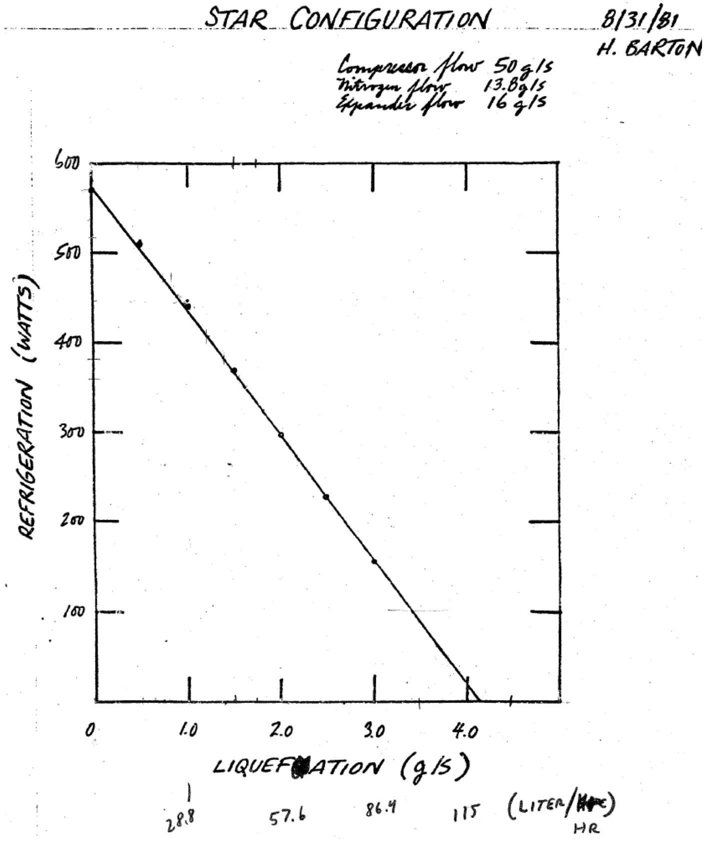
Tevatron Satellite Refrigerator Performance



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