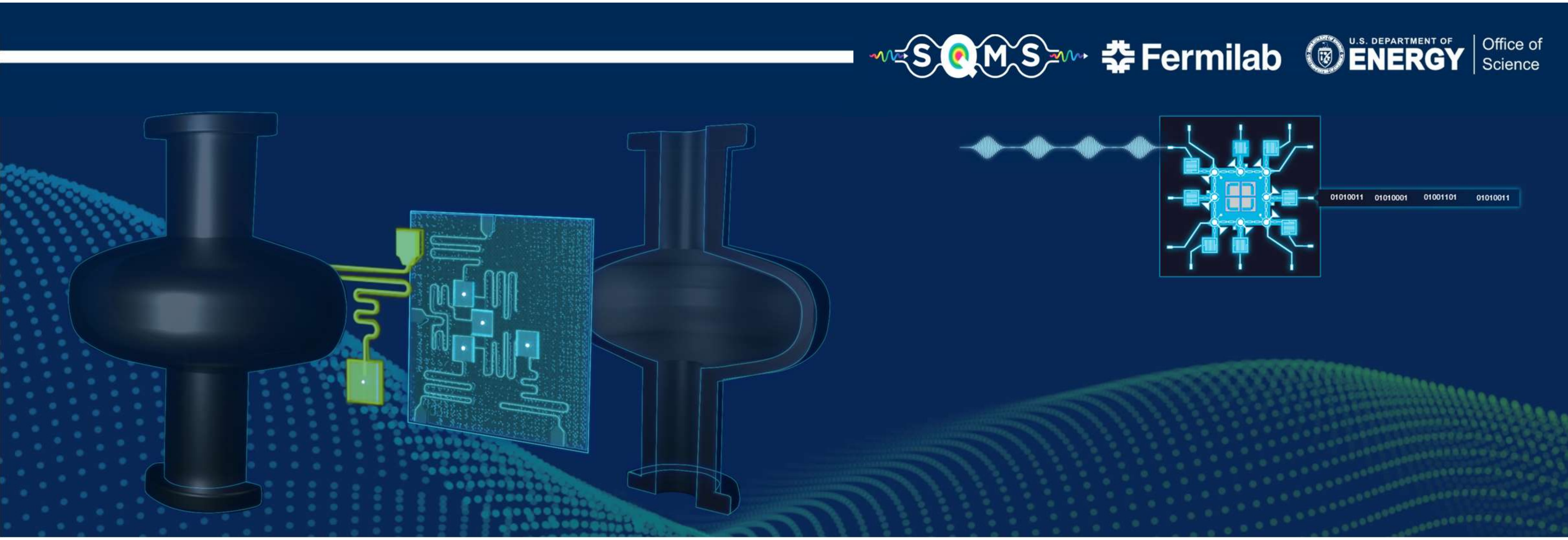

Cryogenic infrastructure for quantum computing

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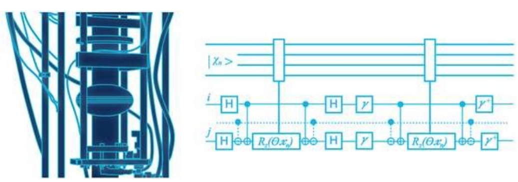
Presentation outline

- The needs of quantum computing
- Larger cryogenic platforms
- Larger cryogenic facilities
- Concluding remarks

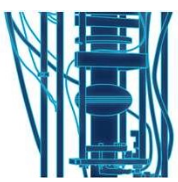


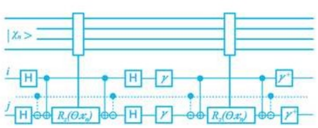
Cryogenics and quantum computing

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

- The designs that have seen the most development are generally based on superconducting RF resonators – for example “transmons”, but there are a number of other architectures.

- The common feature of these devices are that they either rely on a **cryogenic phenomenon** such as superconductivity, or they benefit from a **low thermal noise** environment.





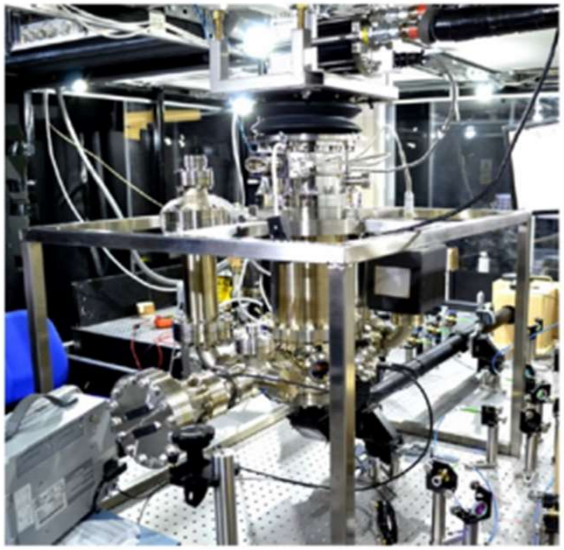
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Ion trap computers

- Another very promising approach is a **cryogenic ion trap**.

- The ion trap itself is an electromagnet device, but issues relating to **thermal noise** affecting the coherence of the trapped ions can be addressed by **combining the trap with a cryogenic system at ~10 K**

Cryogenic ion trap system at the University of Sussex. System combines a 4-K cryocooler with an ion trap (Image: University of Sussex)



Superconducting qubits

- Superconducting RF and similar qubits are intimately connected to **dilution refrigerators** – the continuous low temperature cooling is ideal for **stable cryogenic devices**.

- Current state of the art processors have ~100 qubits.

- Larger quantum processors need bigger cryogenic platforms with more cooling capacity.

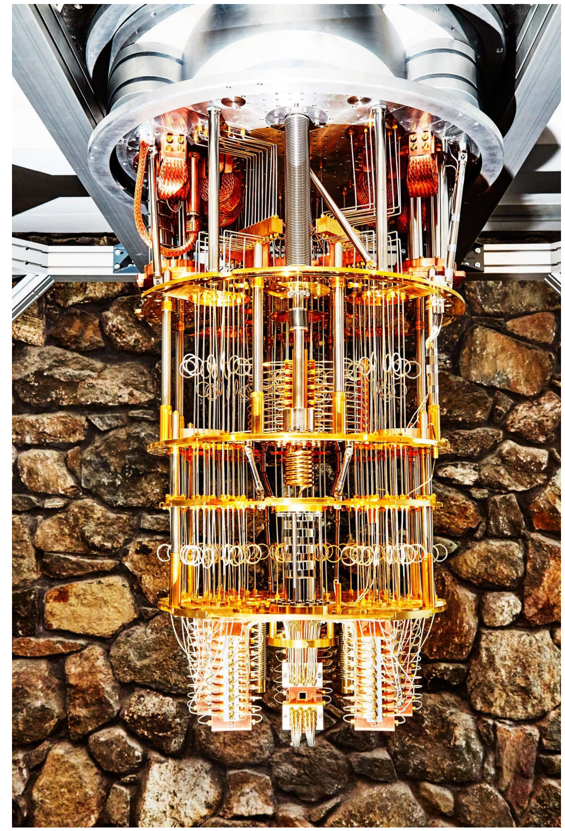


Image: IBM / Amy Lombard

Larger dilution cryostats

20 mK
diameter
~250mm
(2010)

Image: Oxford Instruments

20 mK
diameter
~500mm
(2015)

Image: BlueFors

20 mK
diameter
~1000mm
(2021)

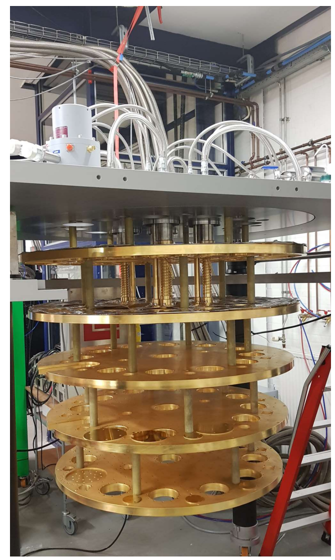


Image: Leiden Cryogenics

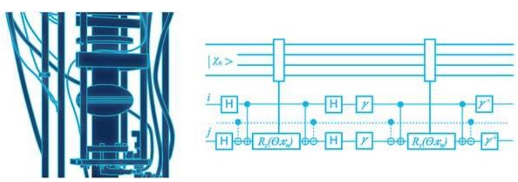
???

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 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

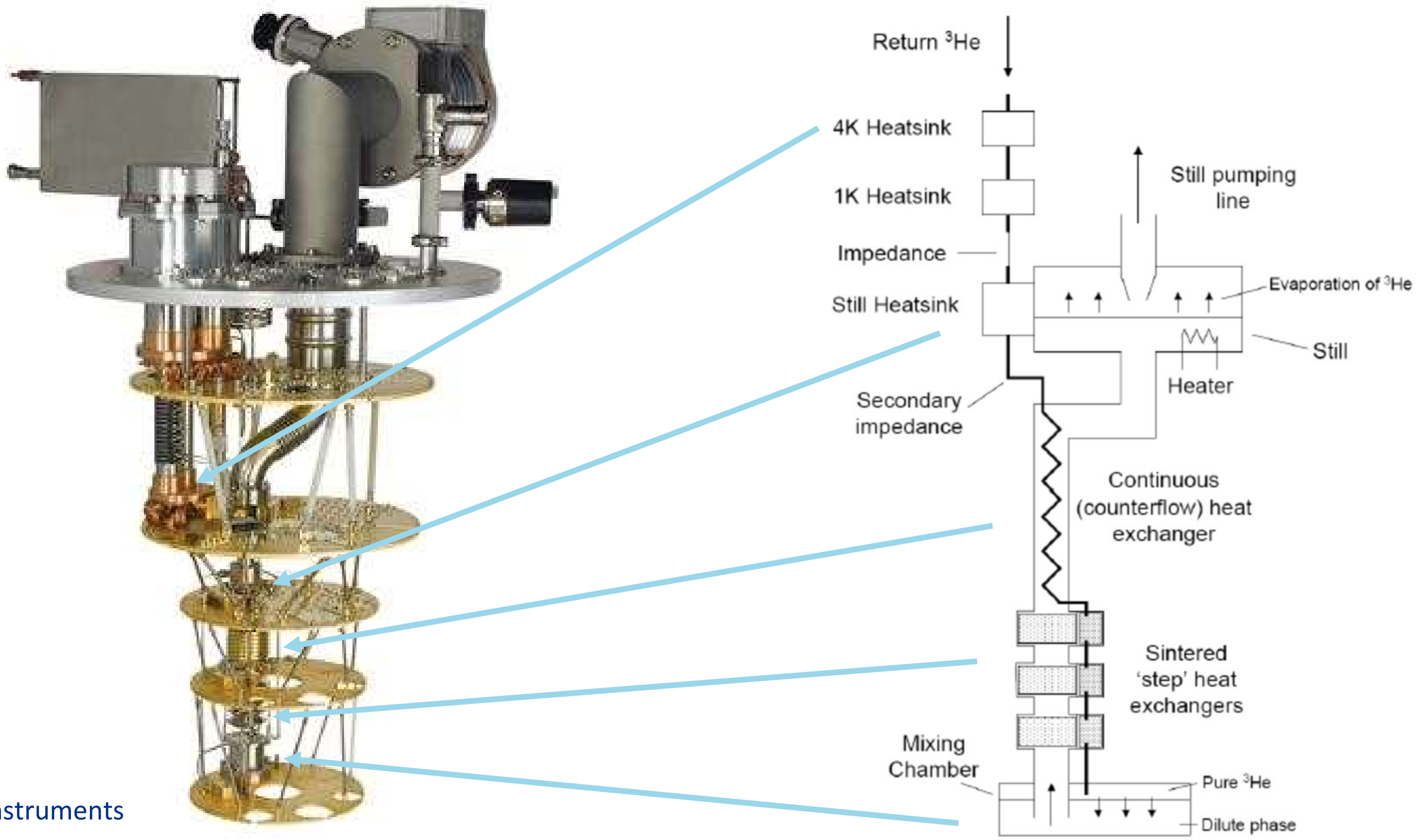


Image: Oxford Instruments

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

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

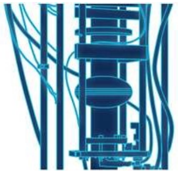
where Q_{MC} is the cooling capacity, n_3 is the 3He circulation rate, and T_{MC} is the mixing chamber temperature

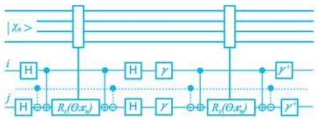
Circulation and heat exchange (2)

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

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

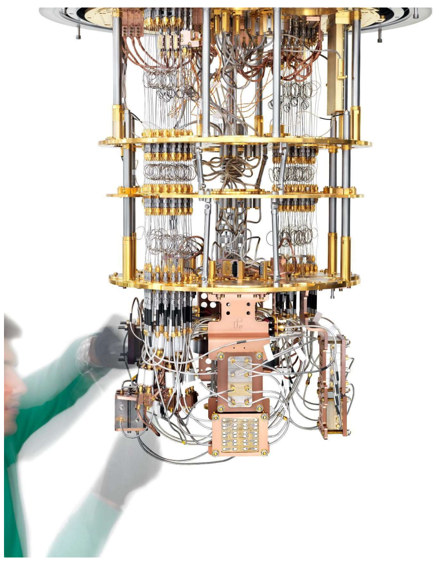
- From this, it can be seen that, for practical purposes, the cooling power of the fridge is really a function of how effective the heat exchangers are. This applies to the heat exchangers higher up the system as much as down at the cold end of the process.



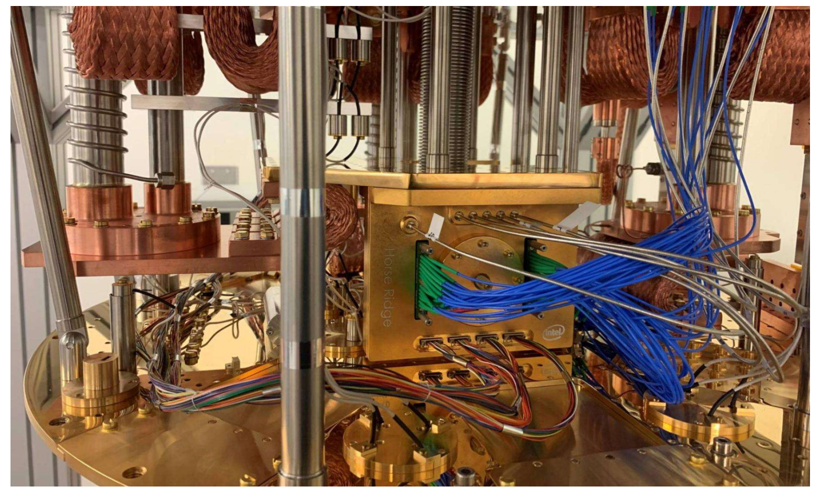


Precooling and experimental loads

- 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



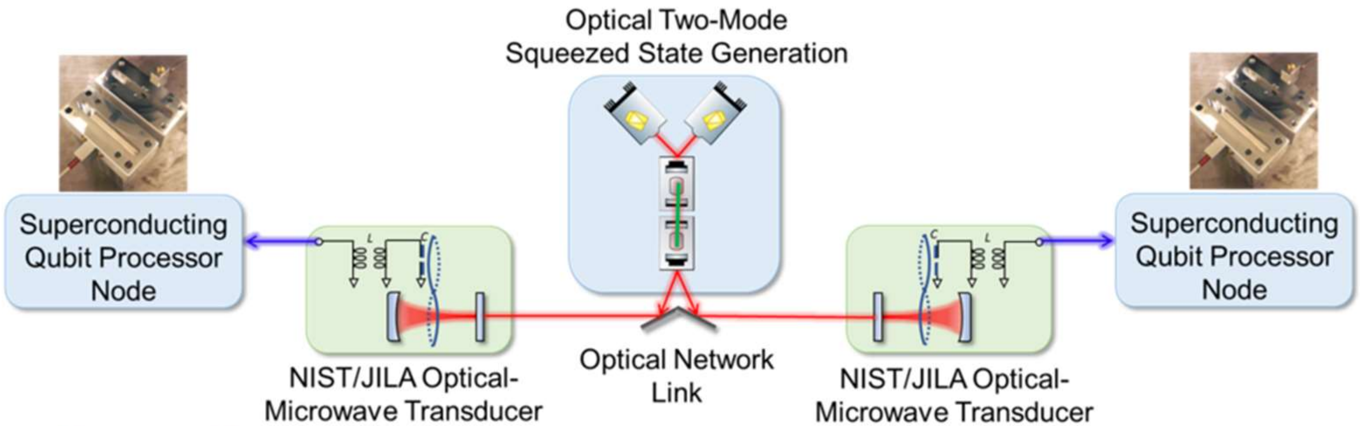
Cryogenic control processor
Image: Intel

Quantum networking

- Schemes to network quantum computers typically include some method of transduction to convert microwave photons to optical while maintaining coherence.

- **Advantageous if the transduction is cryogenic** to minimize noise sources.

- Photons can then be transmitted via optical link to another quantum processor.



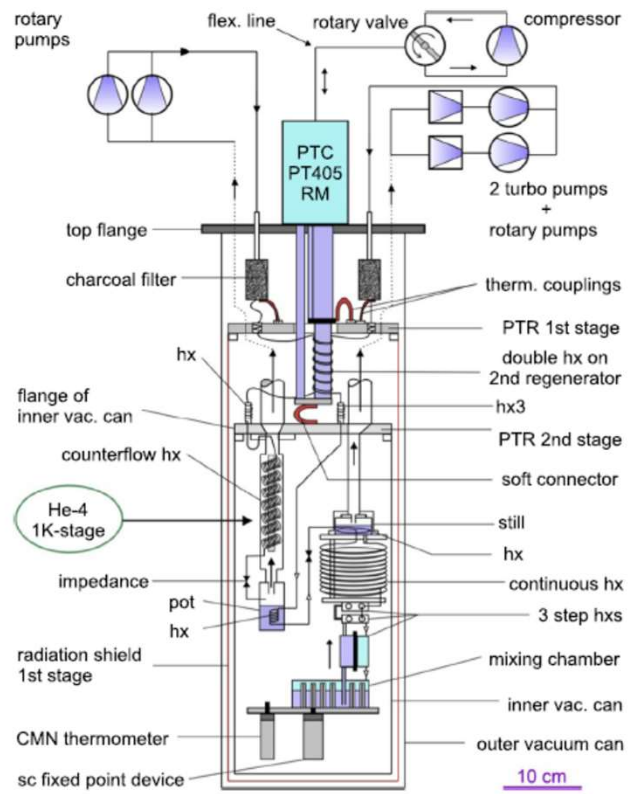
Quantum networking demonstration (image: NIST / Tasshi Dennis)

Large platforms with an extra thermal stage

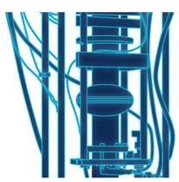
- A cryostat with a high Helium-3 circulation and/or a large load at intermediate temperatures can be realized using **a pumped 4He stage**.

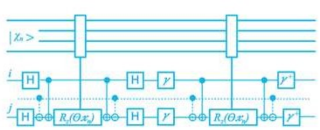
- Analogous to the “1-K Pot” on an older style dilution refrigerator.

- This configuration was described in the literature in 2009 (Hollister & Woodcraft, *Cryogenics*) and demonstrated in 2015 (Uhlig, *Cryogenics*).



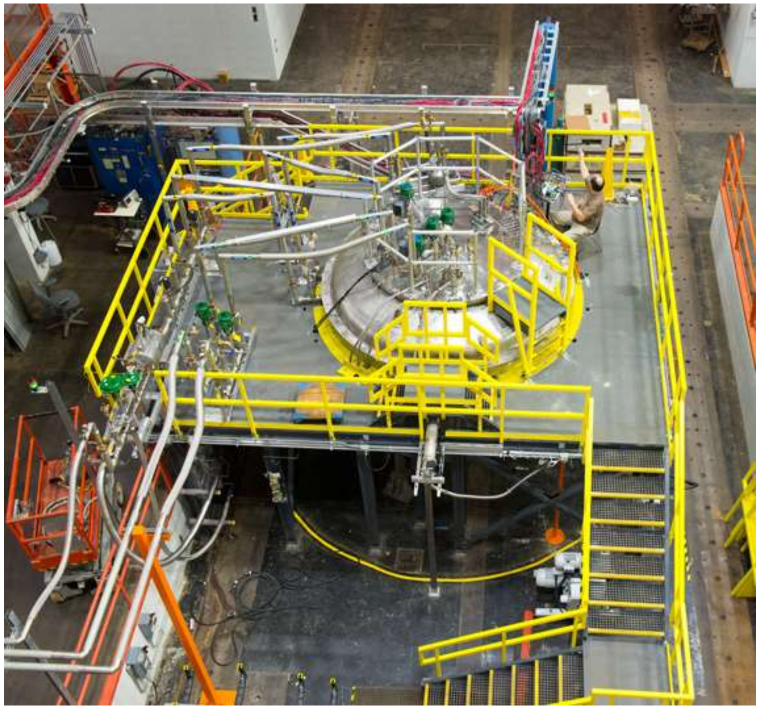
Dilution refrigerator with a 1-K condenser (Image: K. Uhlig)





Large platforms using liquid helium

- Another possibility for the construction of a large platform is to utilize liquid or supercritical helium rather than cryocoolers.
- This is the approach taken in the design of the large mK platform under construction at Fermilab – see my talk later today (M1OraA-03)
- The platform uses a 600W / 4.2 g/s cryoplant



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.

- This leads to some interesting infrastructure possibilities

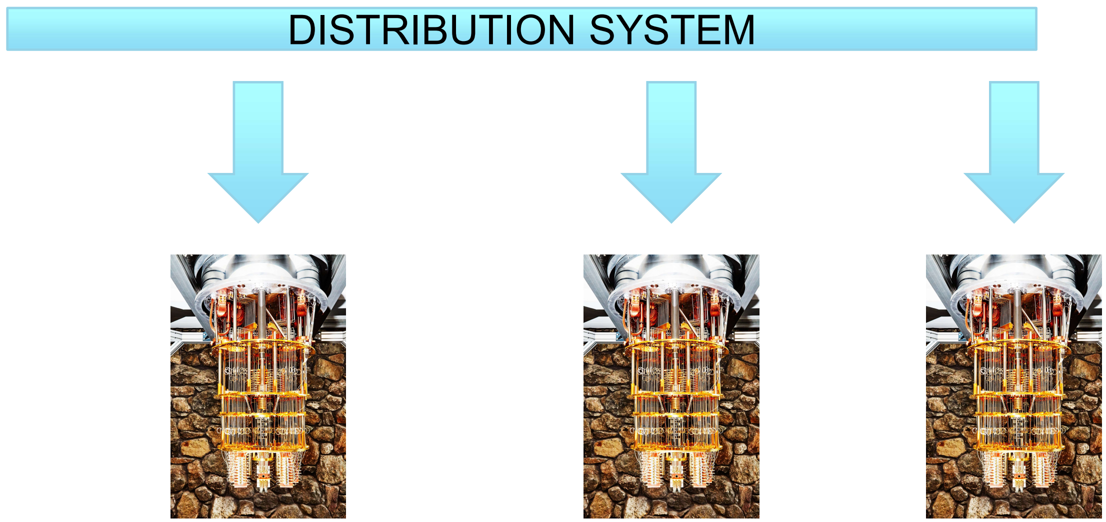
Image: IBM

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



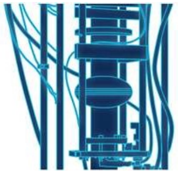
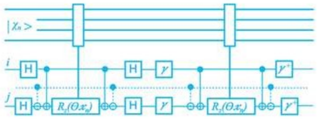
Concluding remarks

- Progress in the last decade on cryogenic technologies in the mK range has been extremely rapid, not doubt driven by commercial interests.

- Technology is still in infancy in many ways – the “scale up by brute force” approach has been successful so far, but this is not a sustainable path.

- There is a broad range of cryogenic expertise that has yet to be applied to the field of cryogenics for quantum.

- Likely to be some very exciting developments in the next five to ten years, both in the quantum computing field itself but also the cryogenic infrastructure.

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