Status and Outlook of Cryogenic Cooling for Compute

Dr. Yogendra Joshi, Program Manager, DARPA/MTO

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Is the Future of Supercomputing Frozen?

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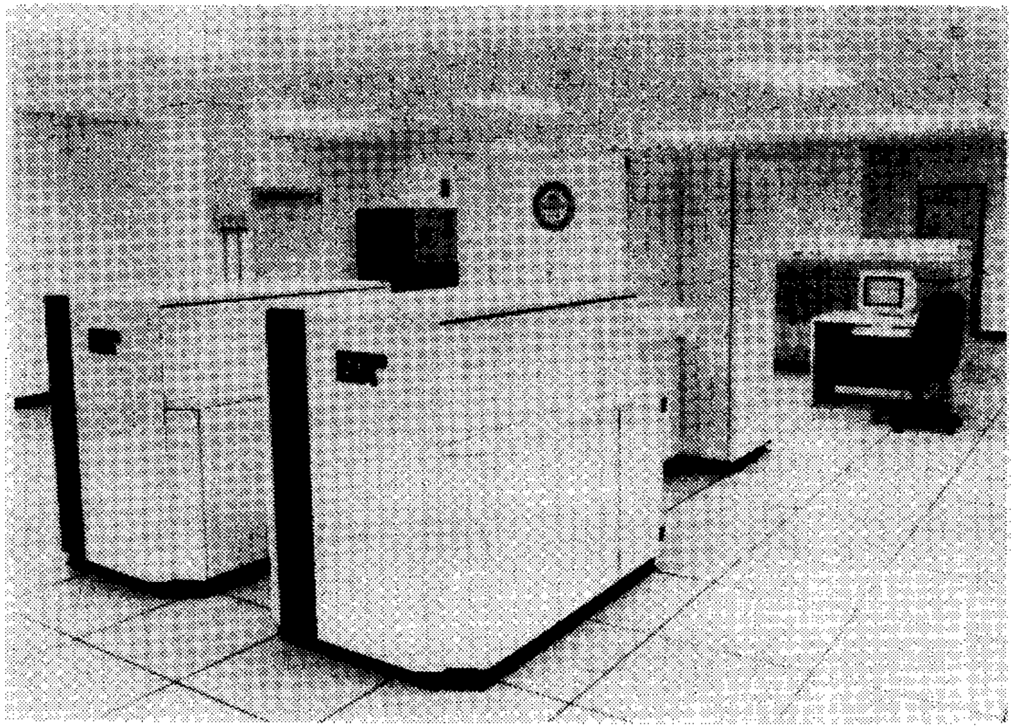

Fig. 1. ETA 10 liquid-nitrogen-cooled supercomputer. Configuration shown has four CPU's; system can go up to eight. The two foreground cabinets house two cryo processors each. The background cabinet houses the shared memory, interface logic, and fiber-optic I/O.

The ETA 10 Liquid-Nitrogen-Cooled Supercomputer System, D. M. Carlson, D. C. Sullivan, R. E. Bach, and D. R. Resnick, IEEE Trans. Electron Devices, 1989

Conventional Data Center Example: 5 MW

Hours per year = 8760

kWh per year = 44 x 10^6 kWh

Cost per year: \$0.1/kWh → \$4.4M

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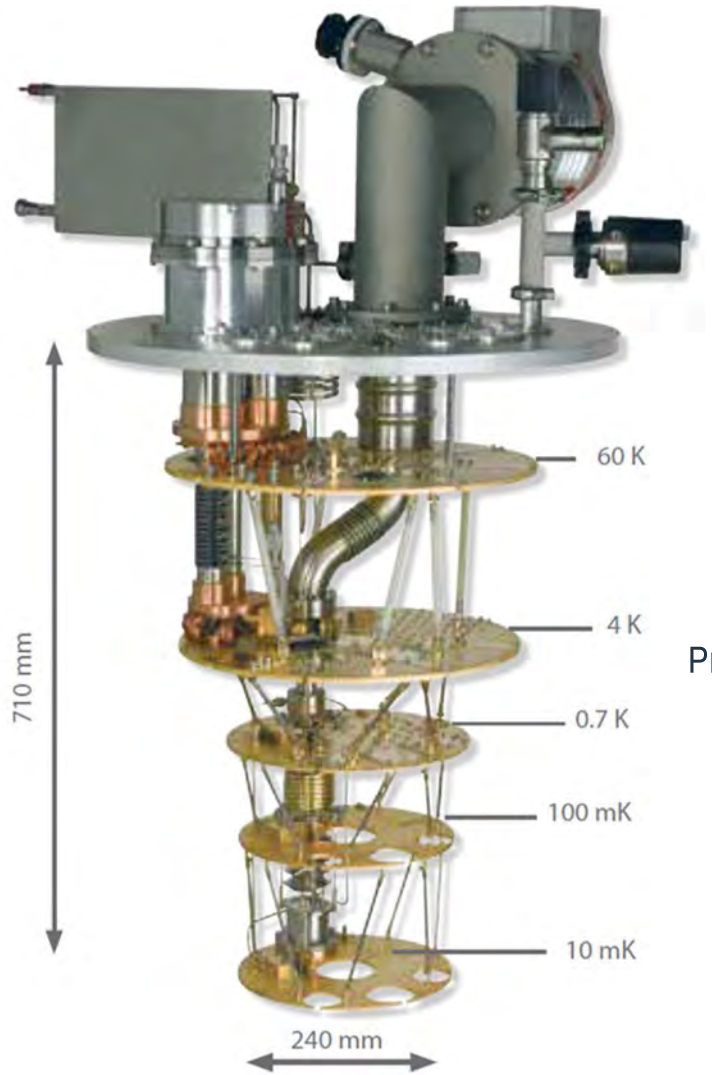
What About Quantum Computing?

- Millions of qubits will be needed to demonstrate quantum superiority (currently hundreds of qubits)
- Heat leaks across wide range of temperature are a significant challenge
- Packaging architectures and materials are key to minimize heat leaks
- Thermal packaging innovations, and/or cryogenic cooling equipment advances needed to realize practical quantum machines



Host and room temperature memory

Cryo-CMOS memory

Superconducting Processor and memory

~1,000 μW cooling power

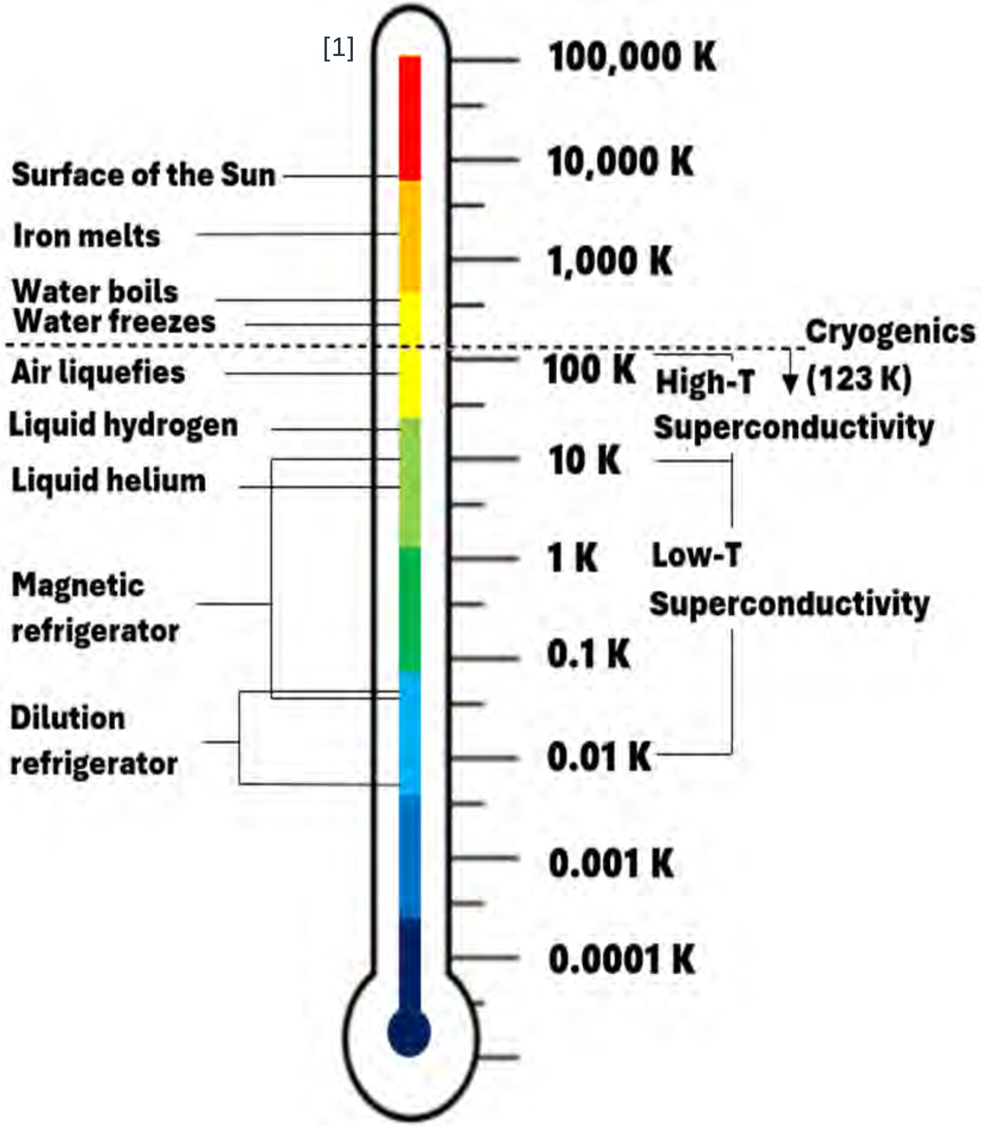
Superconducting Qubits

~30 μW cooling power

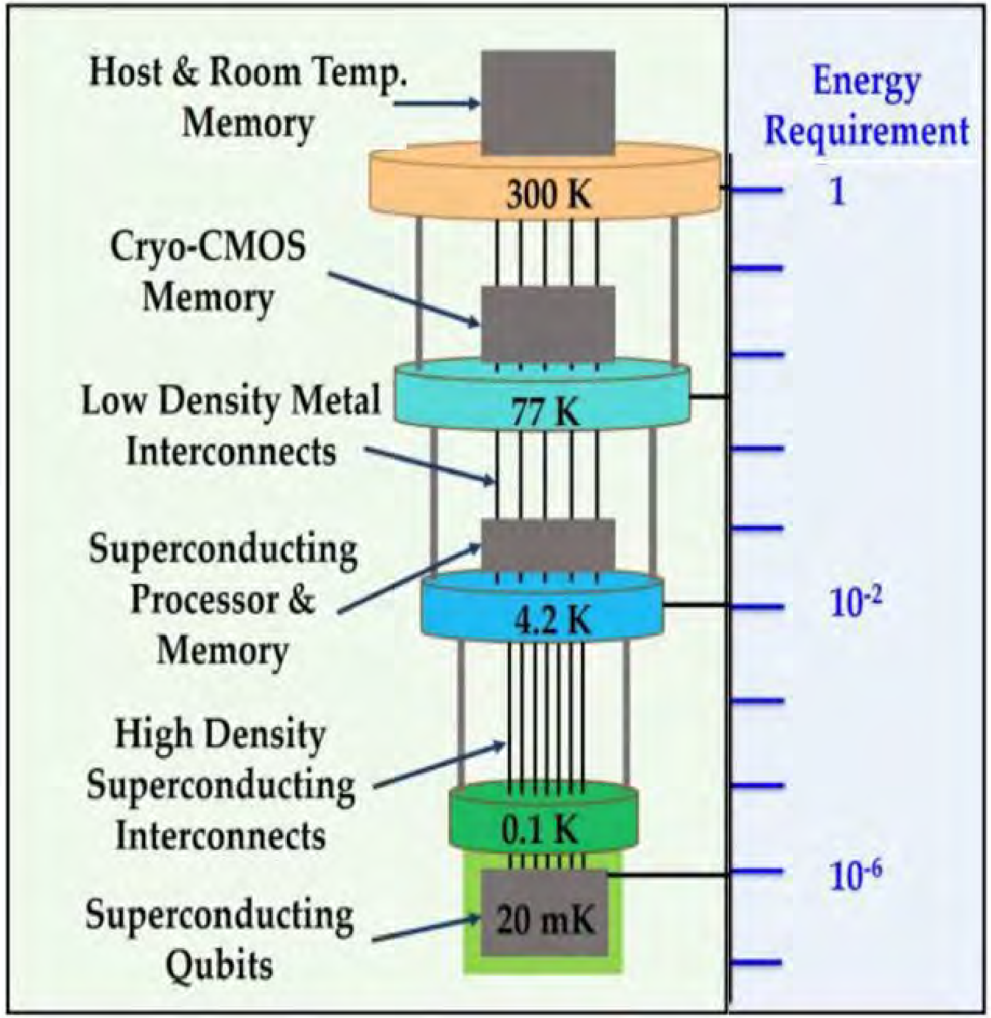
S. M. Ghiaasiaan and C. Kirkconnell, Cryogenics of Quantum Computing: Challenges and Opportunities, DARPA ERI Workshop on Cryogenic Computing Systems: Challenges and Opportunities, 2023

Temperature Ranges and Current Cooling Technologies

[1]

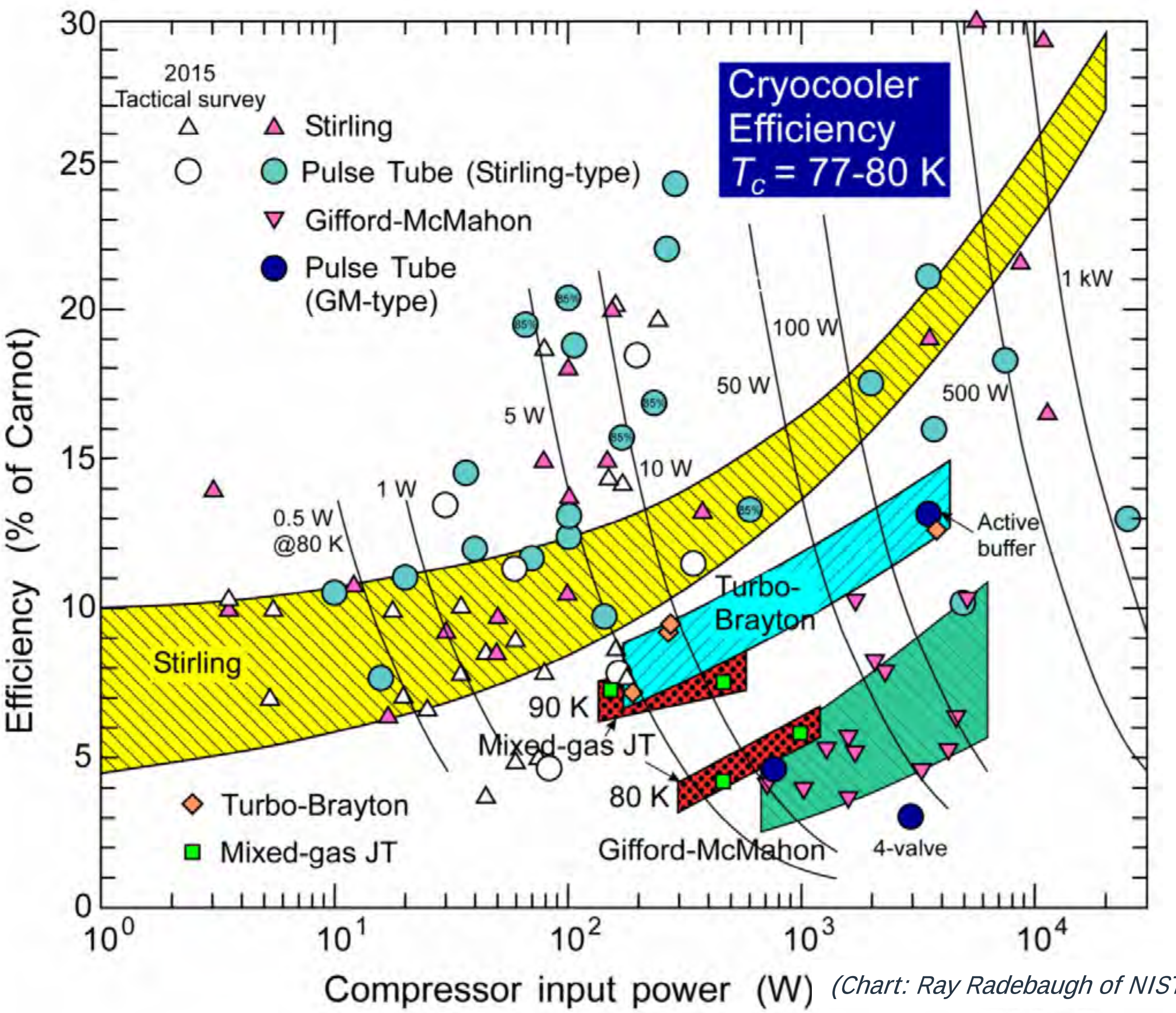


Proposed organization of a superconducting quantum computer[2]

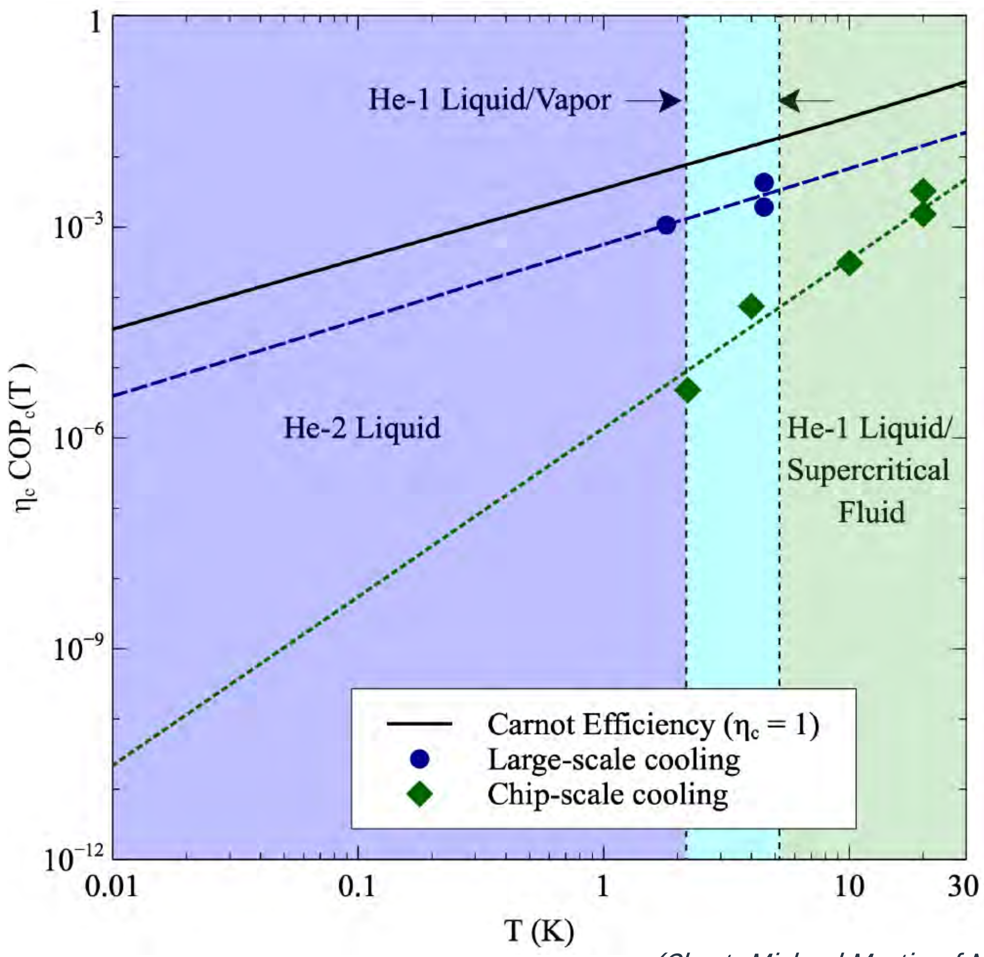


[1] Ghiaasiaan, S. M. and Kirkconnell, C., "Cryogenics of Quantum Computing: Challenges and Opportunities", DARPA ERI2.0 Summit, (2023)
[2] Alam, S., et al. "Cryogenic memory technologies." *Nature Electronics,* (2023)

Efficiencies of Various Types of Cryocoolers



(Chart: Ray Radebaugh of NIST)



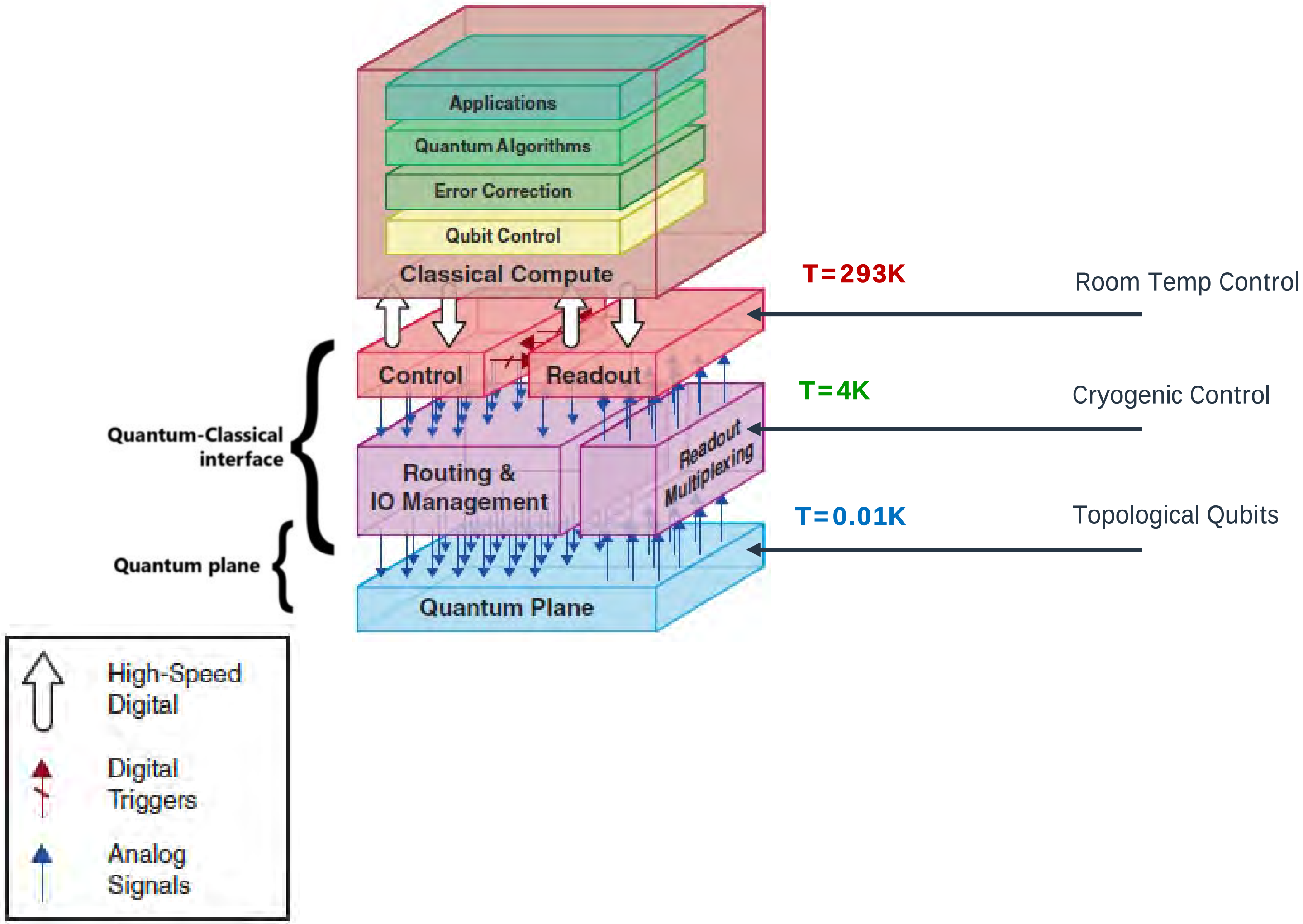
(Chart: Michael Martin of NREL)

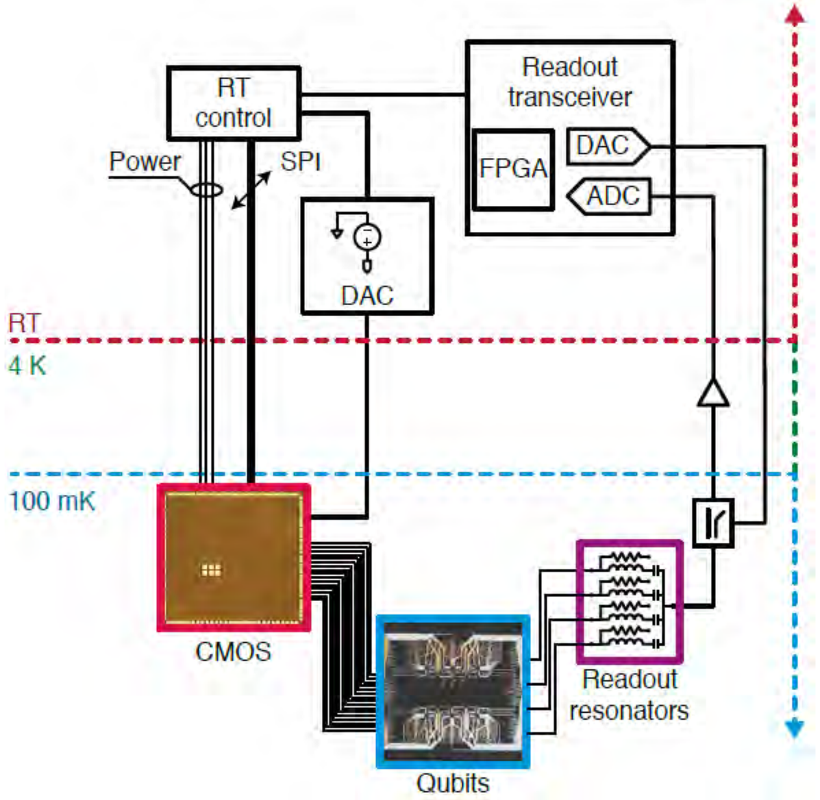
https://ieeexplore.ieee.org/abstract/document/9827605

https://trc.nist.gov/cryogenics/Papers/Review/2020-Review_of_Refrigeration_Methods.pdf

The Curse of Interconnects

Interconnect heat loss limits the available power for cryo-compute



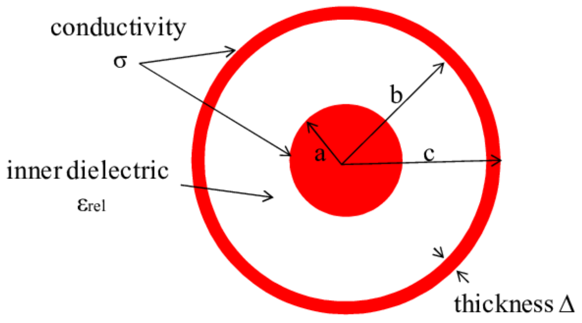


[1] Pauka, S. J., et al. "A cryogenic CMOS chip for generating control signals for multiple qubits." *Nature Electronics* 4.1 (2021): 64-70.

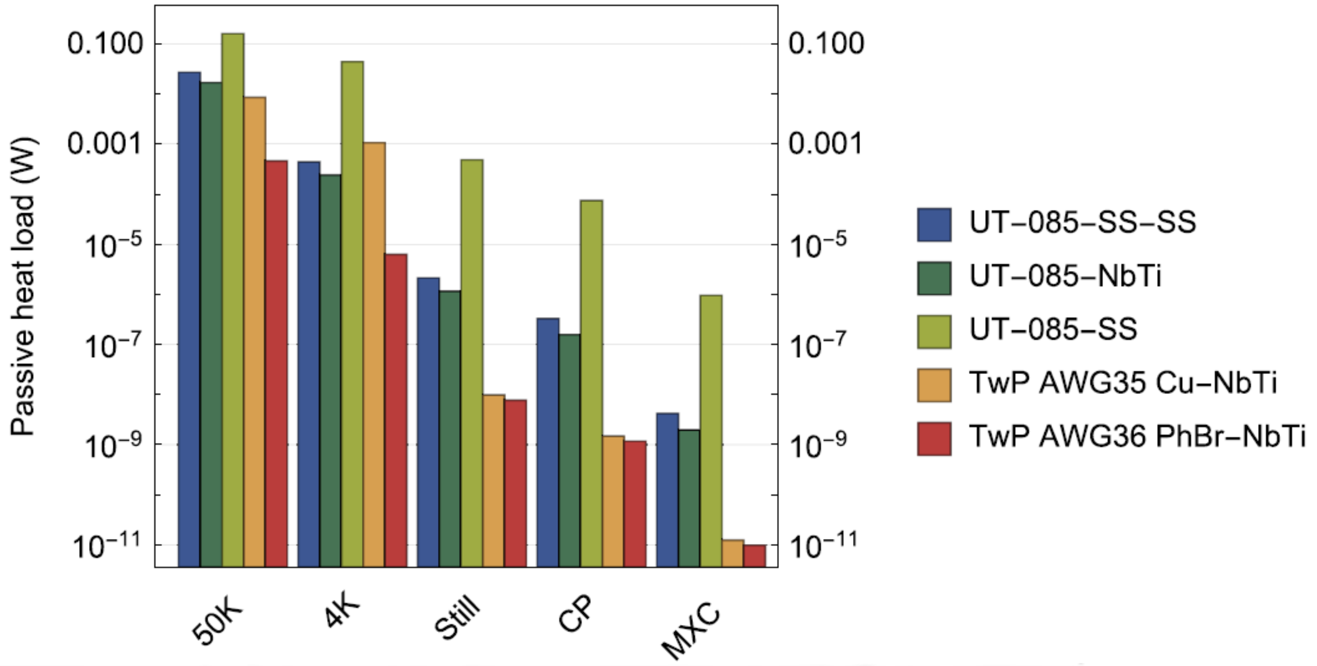
Passive Heat Losses

- Conducted heat through cabling due to temperature gradient between stages
- Leaked heat through system assembly

Co-axial cable



$$P_i = \int_{T_{i-1}}^{T_i} dT \, \frac{\rho_o(T)A_o + \rho_d(T)A_d + \rho_c(T)A_c}{L_i}$$



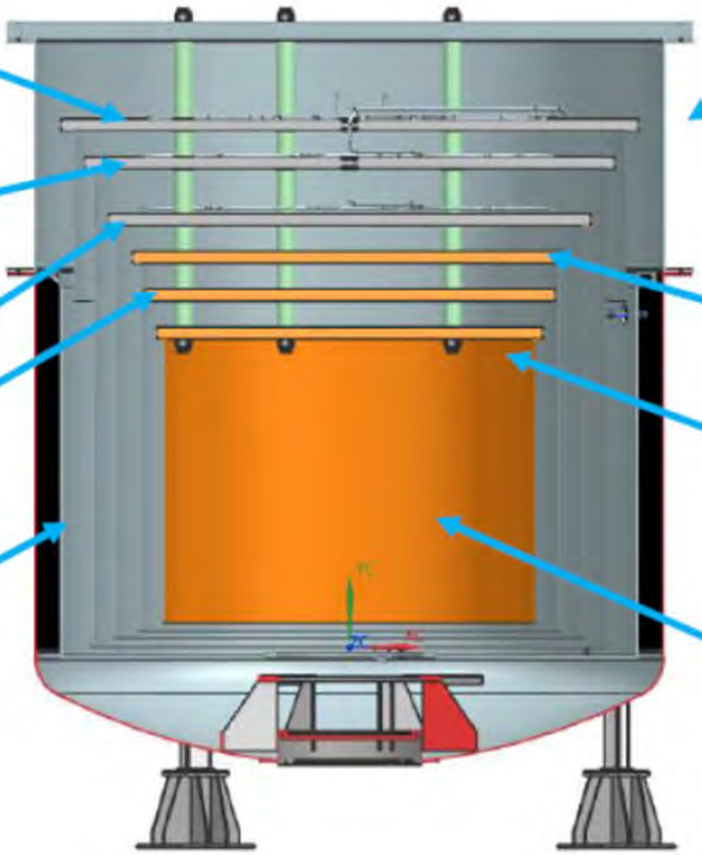
Stage name	Temperature (K)	Cooling power (W)	Cable length (mm)
50 K	35	30 (at 45 K)	200
4 K	2.85	1.5 (at 4.2 K)	290
Still	882×10^{-3}	40×10^{-3} (at 1.2 K)	250
CP	82×10^{-3}	200×10^{-6} (at 140 mK)	170
MXC	6×10^{-3}	19×10^{-6} (at 20 mK)	140

[1] Krinner, Sebastian, et al. "Engineering cryogenic setups for 100-qubit scale superconducting circuit systems." *EPJ Quantum Technology* 6.1 (2019): 2.

TwP: Twisted Pairs
CP: Cold Plate
MXC: Mixing Chamber

Innovations in Sub 4K Cryogenic Equipment

Fermilab (The *Colossus* Platform)

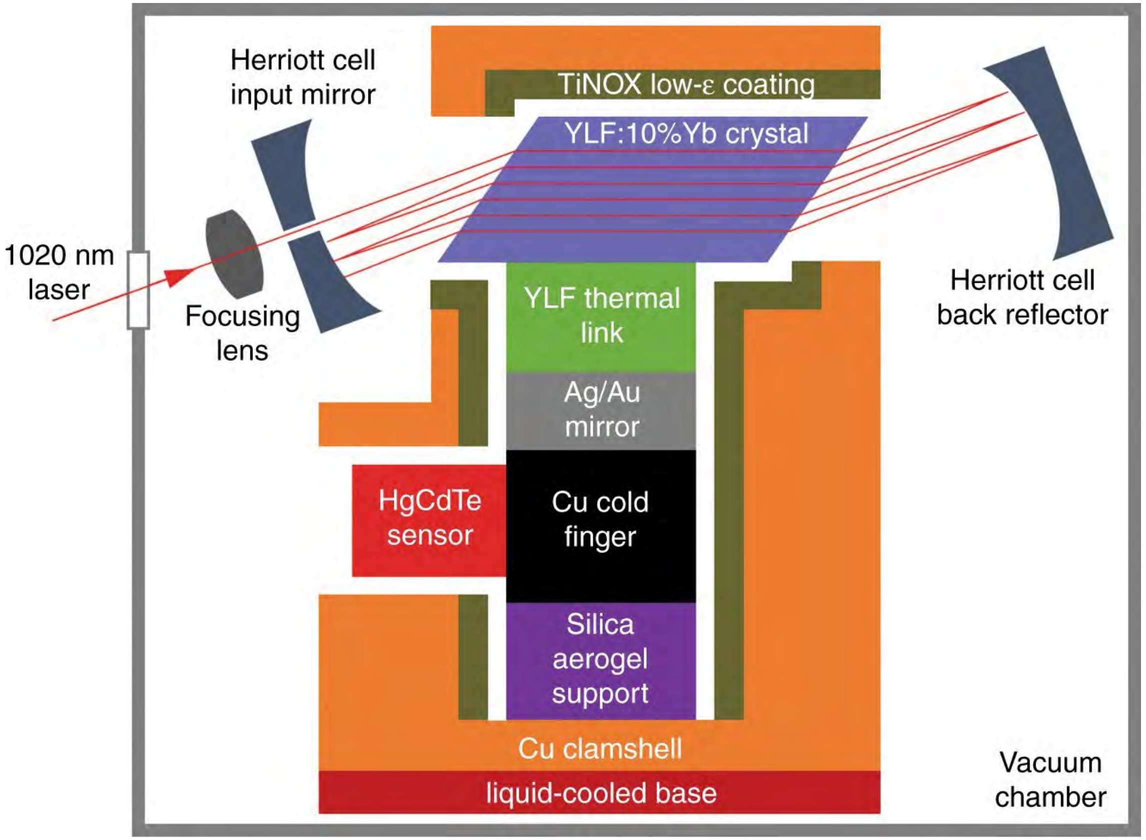


- 1,000 readout lines
- 5 m^3 of 20 mK space
- 10 commercial dilution cryocooler stacks, each disposing of 30-50 μW
- Is this a practical approach? Multiple dilution units per dilution refrigerator (DR)? How to connect multiple DRs?

Ghiaasiaan, S. M. and Kirkconnell, C., "Cryogenics of Quantum Computing: Challenges and Opportunities", DARPA ERI2.0 Summit, (2023)
Hollister, M. et al., "A large millikelvin platform at Fermilab for quantum computing applications", IOP Conf. Ser.: Mater. Sci. Eng., (2022)

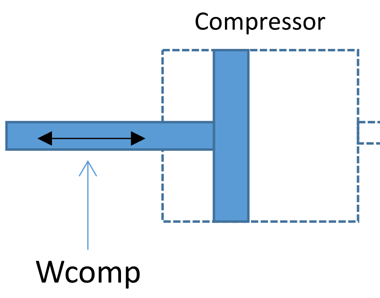
What Alternatives Exist within Cryogenic Refrigeration?

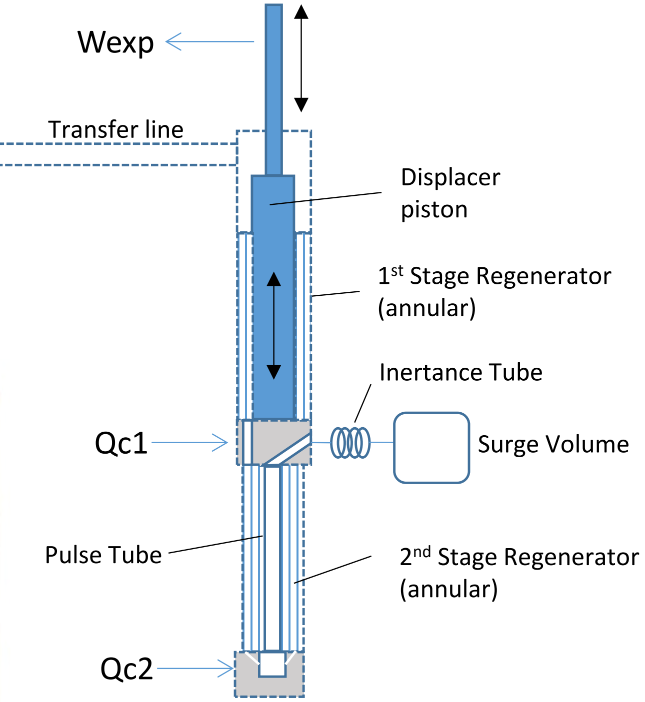
Solid-state optical/laser cooling[1]



Theoretically capable of mK temperatures, currently limited by low efficiency[2]

Mechanical cryocoolers[3]





Hybrid cryocooler uses Stirling as upper stage, pulse tube as lower stage[4]

[1] Hehlen, M. P. et al. "First demonstration of an all-solid-state optical cryocooler", *Light: Science & Applications*, 2018
[2] Martin, M. J. et al., "Energy Use in Quantum Data Centers: Scaling the Impact of Computer Architecture, Qubit Performance, Size, and Thermal Parameters", *IEEE Transactions on Sustainable Computing*, 2022
[3] Ghiaasiaan, S. M. and Kirkconnell, C., "Cryogenics of Quantum Computing: Challenges and Opportunities", DARPA ERI2.0 Summit, (2023)
[4] Schaefer, B. R. et al., "Raytheon's next generation compact inline cryocooler architecture", *AIP Conference Proceedings*, 2014

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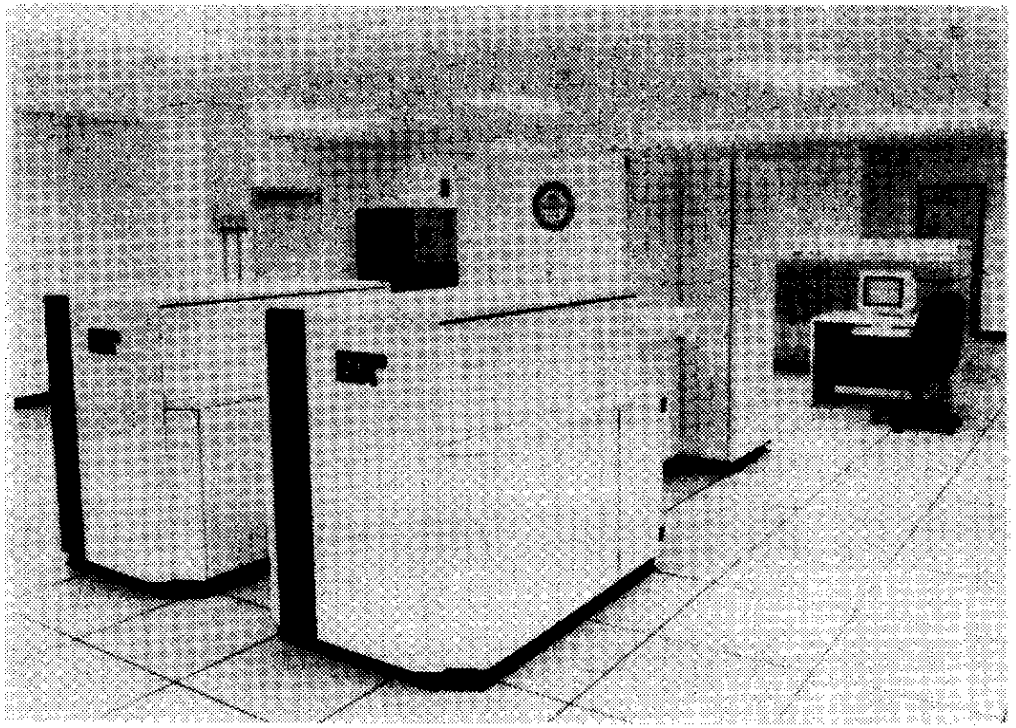

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