Sub-Kelvin cooling systems for quantum computers

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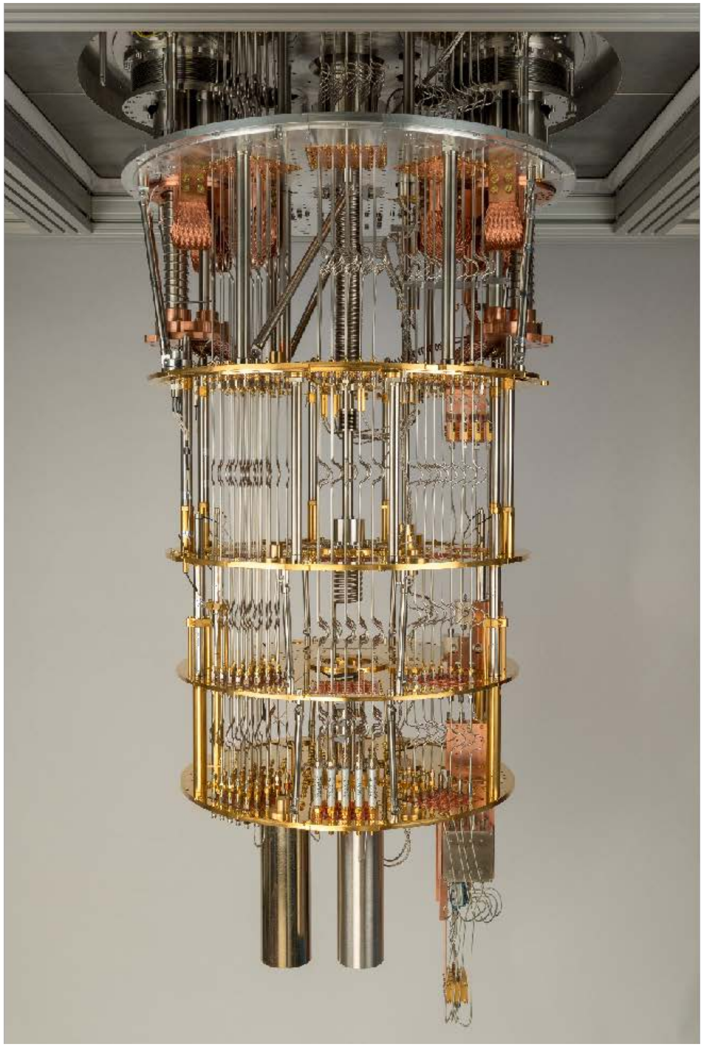
Architecture of cryogenic systems in quantum computing systems

a)



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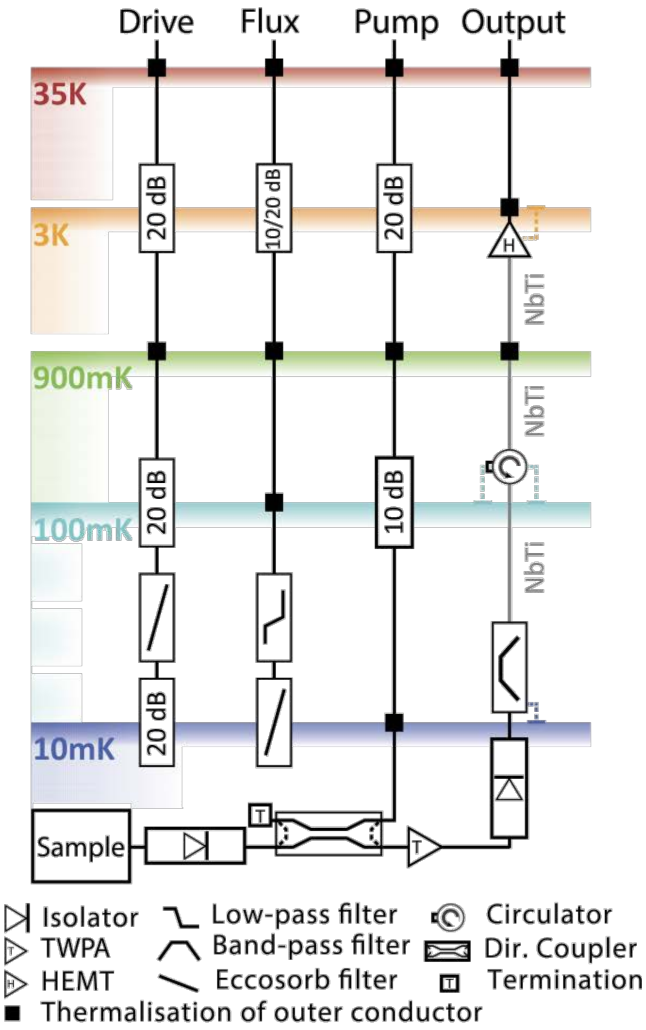


Figure from Engineering cryogenic setups for 100-qubit scale superconducting circuit systems , S. Krinner et. al.

Why the need for sub-Kelvin cooling in quantum computers?

- Quantum processors based on superconducting circuits or trapped ions will need to be cooled to sub-Kelvin temperatures
- Thermal energy can excite vibrational motion that disrupts the quantum processors and its operation
- For processors based on trapped ions the low temperature naturally cryopumps to prevent molecular/atomic collisions and subsequent excitation of the qubits
- The RF lines, drive lines, read-out lines, etc. all need to be thermally sunk at low temperatures carefully to prevent the qubits from being thermally excited
- Thermal radiation can drive undesirable internal RF transitions in trapped ions or can raise a superconducting circuit above its critical temperature
- Power fluctuations in laser sources as well as RF power source instabilities perturb the QC system

Methods of cooling below 1 Kevin

Dilution Refrigerators

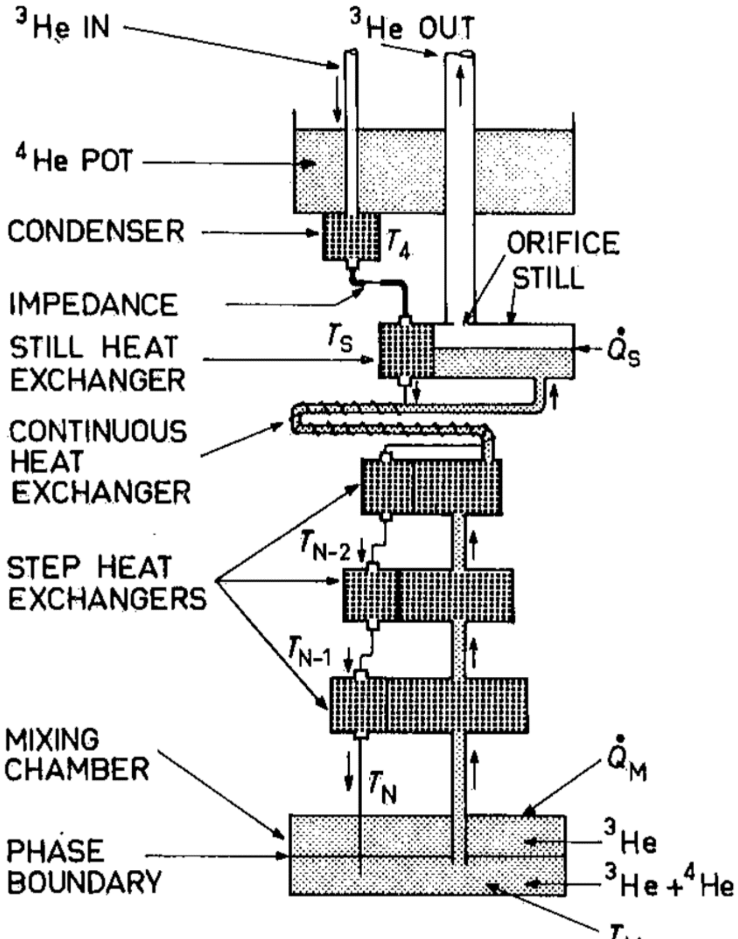
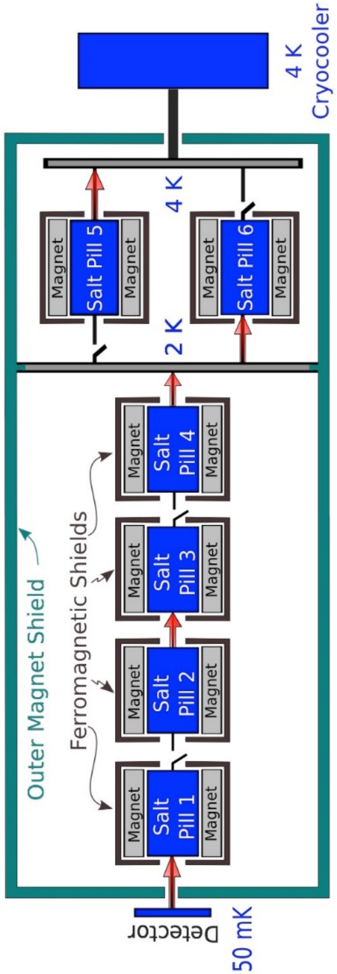


Figure from O.V. Lounasmaa, 1974

Continuous Adiabatic Demagnetization Refrigerator



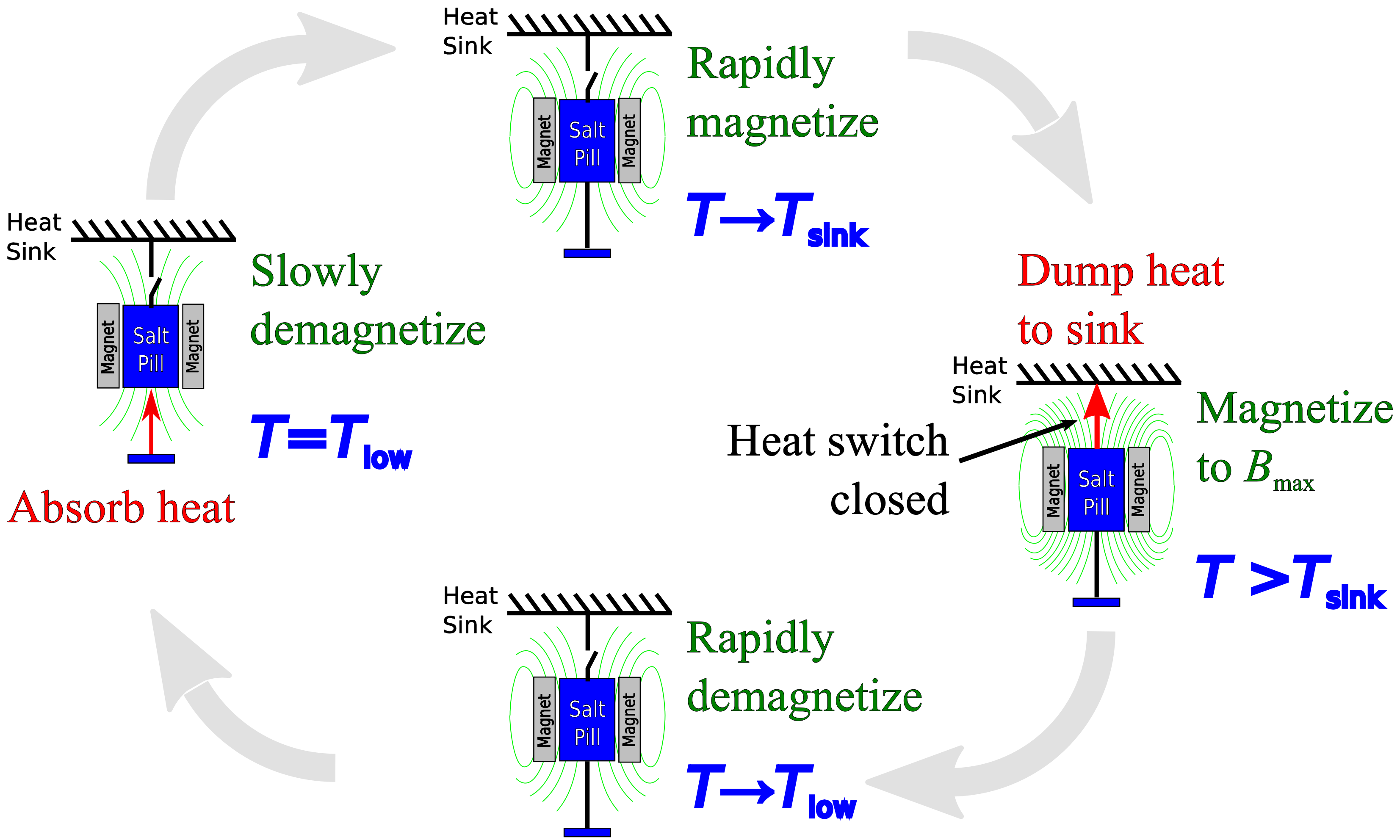
Challenges with current cooling technology

- In general quantum computing systems require:

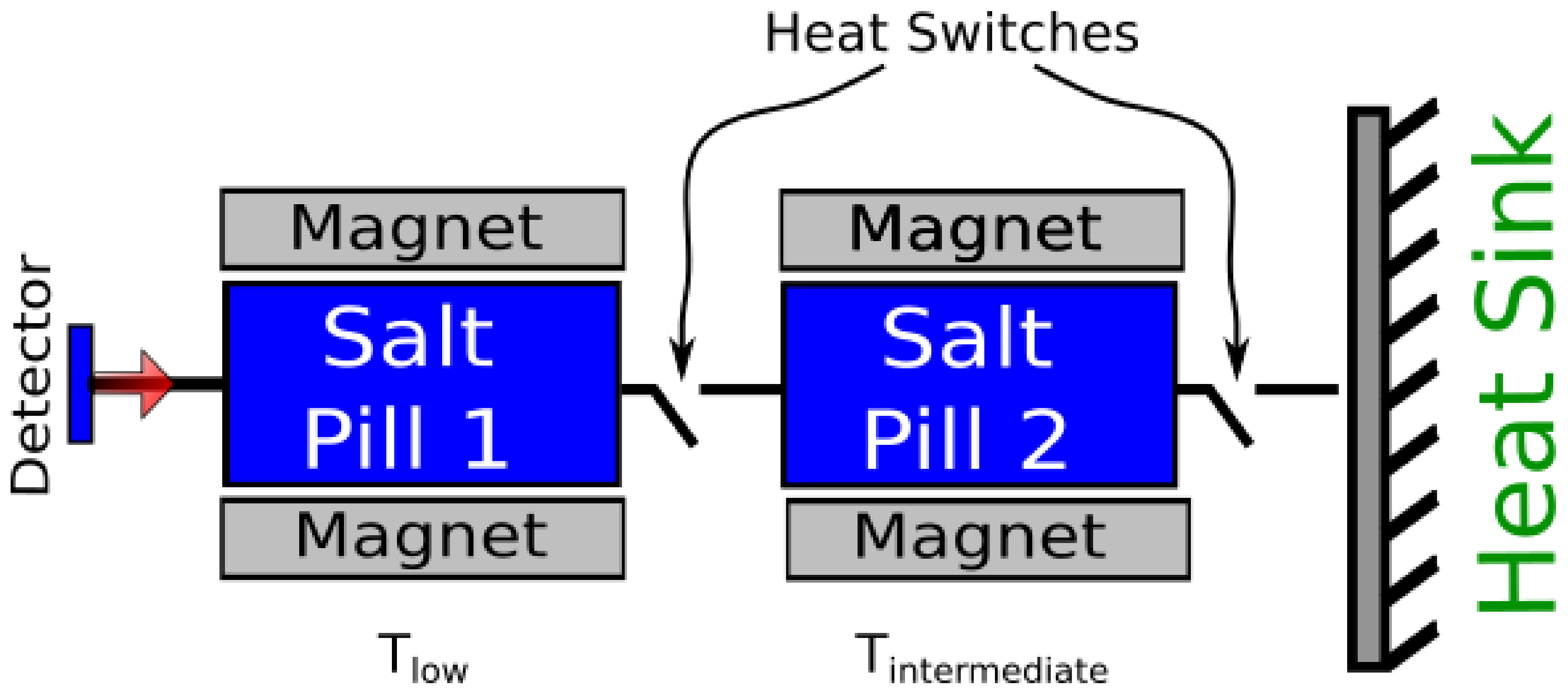
- Attaining very low temperatures
- High temperature stability
- No vibrations
- High cooling power at very low temperatures
- No external interference such as thermal radiation, magnetic field, etc.
- High level of vacuum – especially for trapped ion based quantum processors

- Careful integration and thermal sinking of:
  - ❖ Attenuators
  - ❖ Amplifiers
  - ❖ Circulators, and
  - ❖ Filters

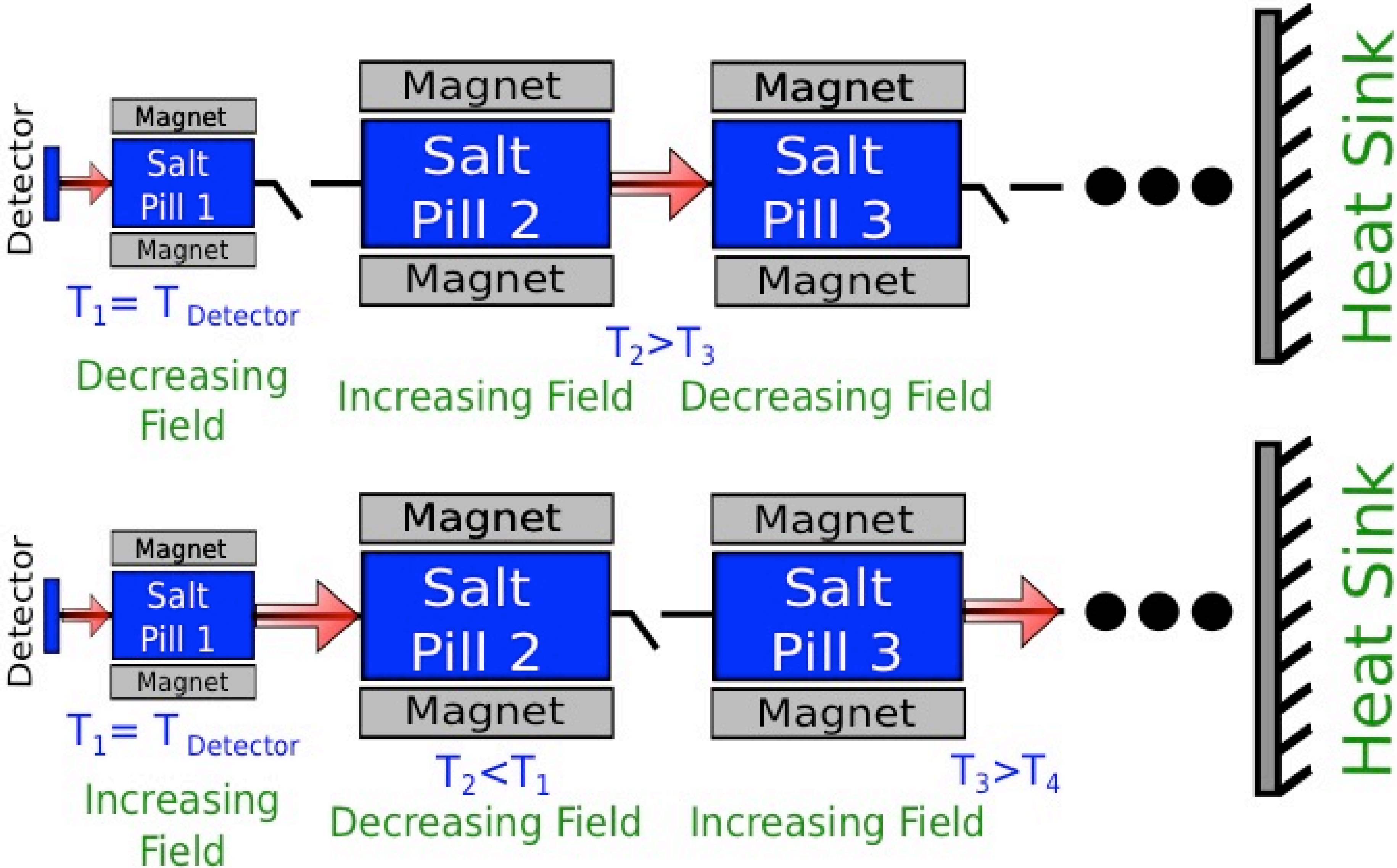
Adiabatic Demagnetization Refrigeration



Adiabatic Demagnetization Refrigeration



Continuous ADR



CADR built for External Lab

4 Stages

- ① 45 g CPA [0.050 K]
- ② 100 g CPA [0.325 -> 0.045 K]
- ③ 100 g CPA [1.4 -> 0.275 K]
- ④ 82 g GGG [3.3 -> 1.2 K]

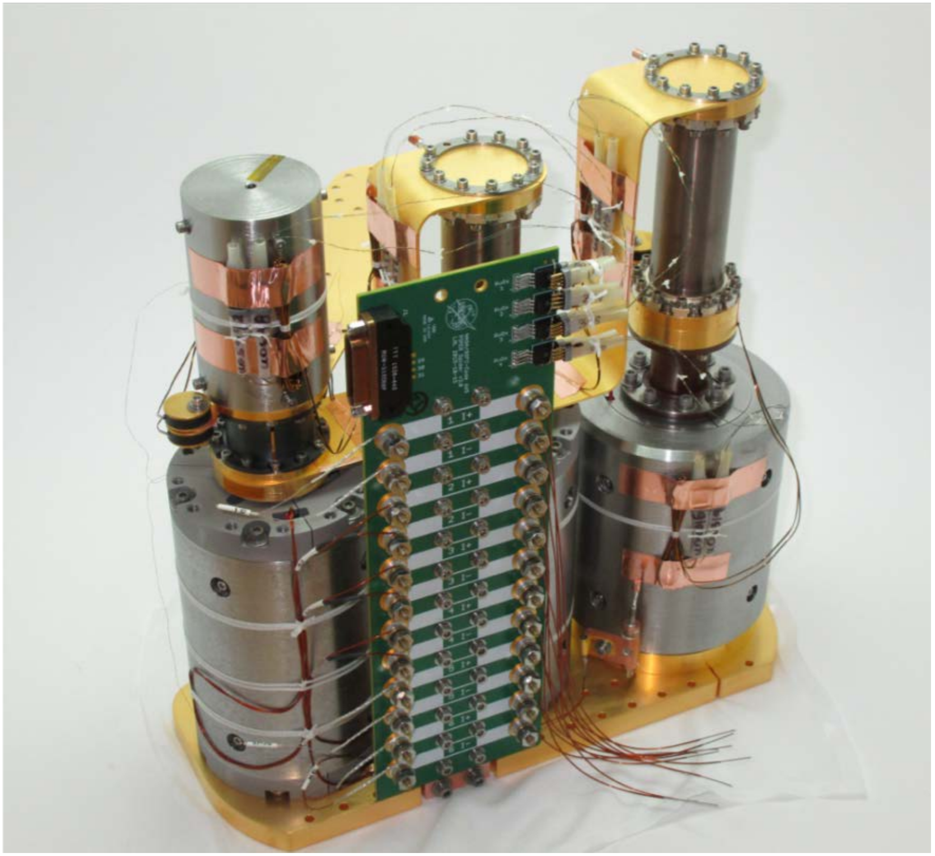
ADR Heat Sink

- GM Cooler at 3 K

Heat Switches

- ① Superconducting Switch (1 -> 2)
- ② Passive Gas-Gap (2 -> 3)
- ③ Passive Gas-Gap (3 -> 4)
- ④ Internal Passive Gas-Gap (4 -> H.S.)

CADR built for PIPER Mission



4 Stages

① 45 g CPA [0.100 K]

② 100 g CPA [0.375 -> 0.09 K]

③ 100 g CPA [1.4 -> 0.275 K]

④ 82 g GGG [4.5 -> 1.2 K]

ADR Heat Sink

4.2 K liquid helium

Heat Switches

① Superconducting Switch (1 -> 2)

② Passive Gas-Gap (2 -> 3)

③ Passive Gas-Gap (3 -> 4)

④ Internal Passive Gas-Gap (4 -> H.S.)

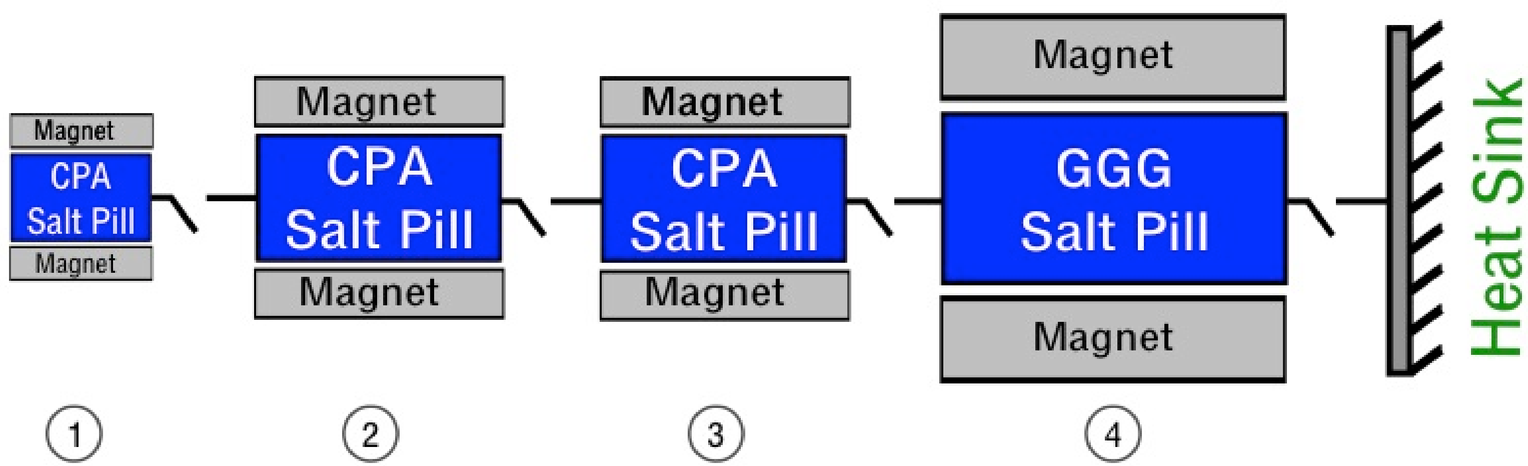
Same CADR; Different Configurations

4 Stages

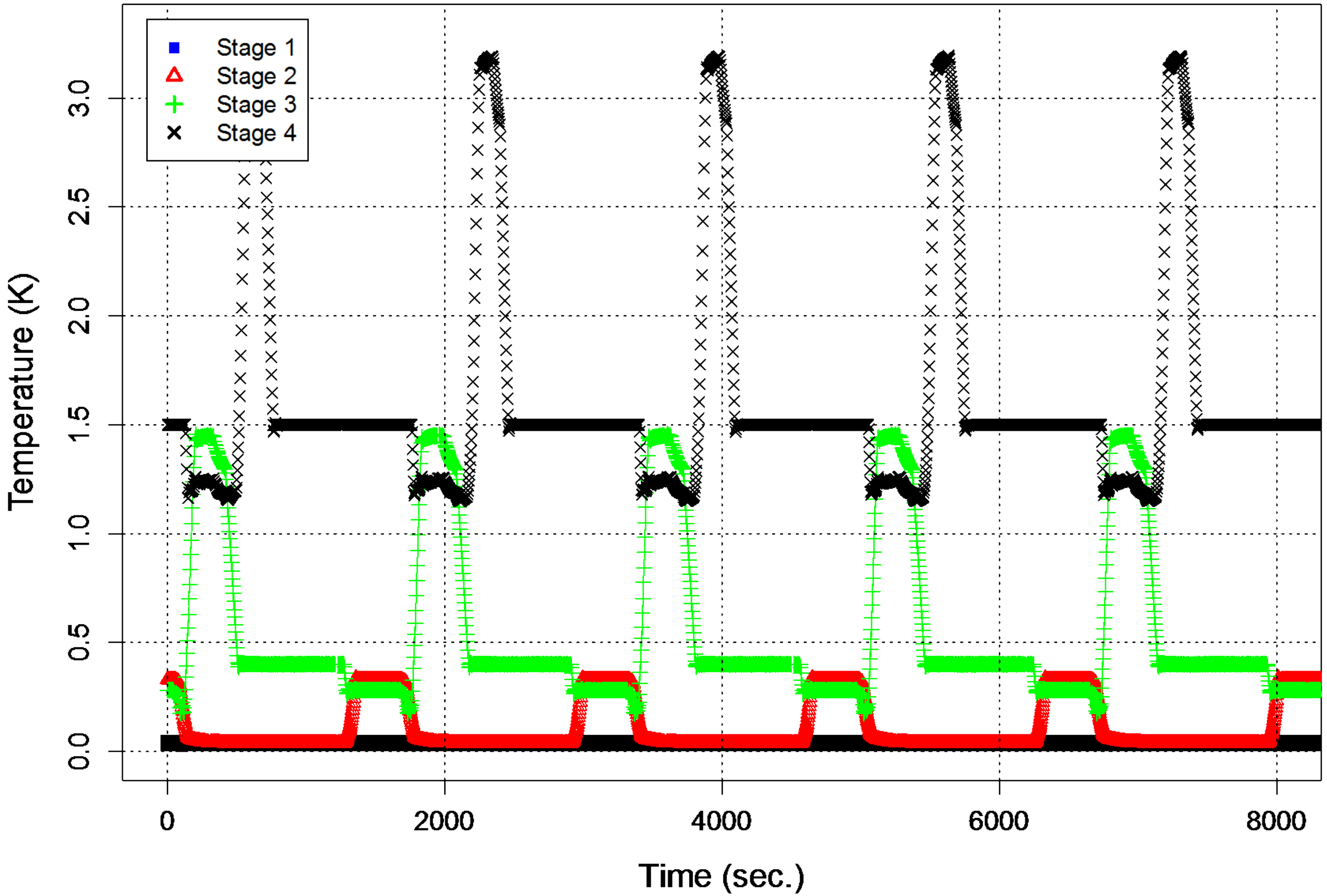
1. 45 g CPA [0.100 K]
2. 100 g CPA [0.375 -> 0.09 K]
3. 100 g CPA [1.4 -> 0.275 K]
4. 82 g GGG [3 -> 1.2 K]

Heat Switches

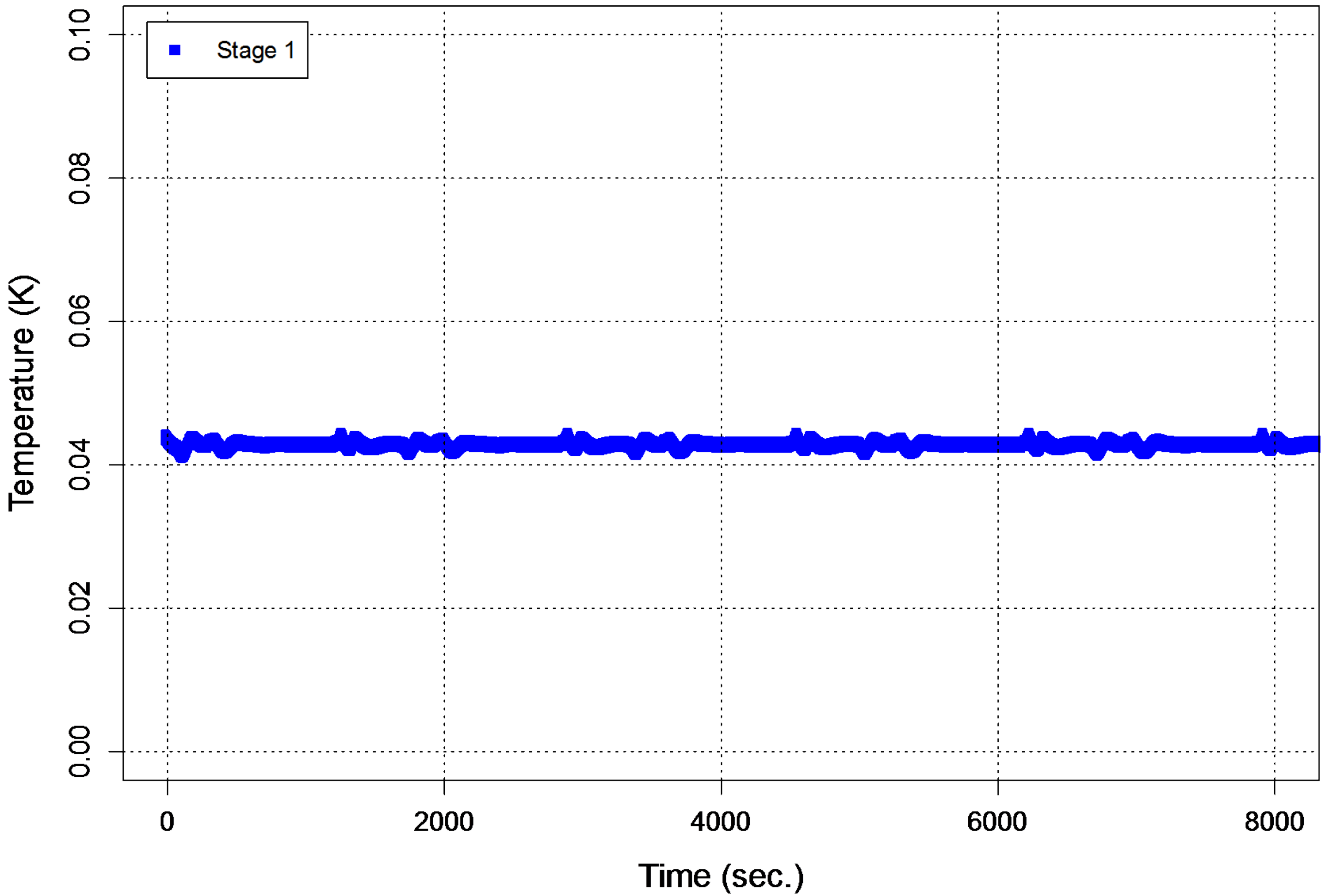
1. Superconducting Switch (1 -> 2)
2. Passive Gas-Gap (2 -> 3)
3. Passive Gas-Gap (3 -> 4)
4. Internal Passive Gas-Gap (4 -> H.S.)



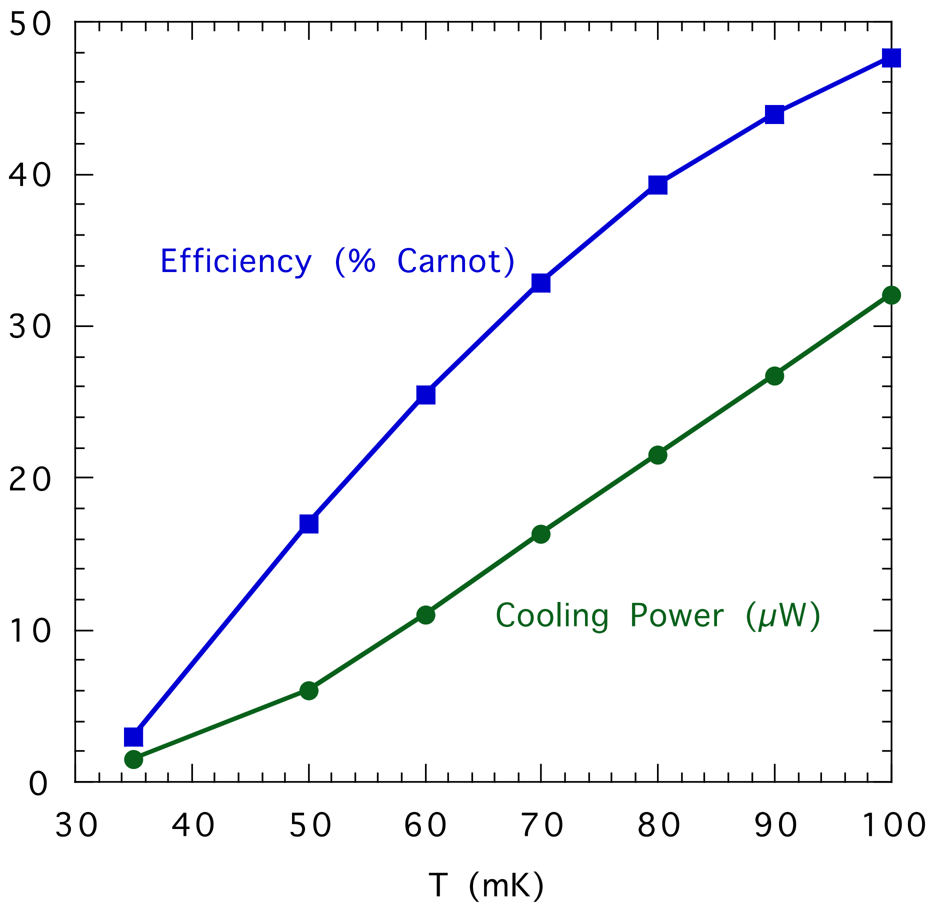
Continuous Operation at 43 mK



Continuous Operation at 43 mK



Heat Lift etc.



* Cooling power in addition to parasitic heat loads

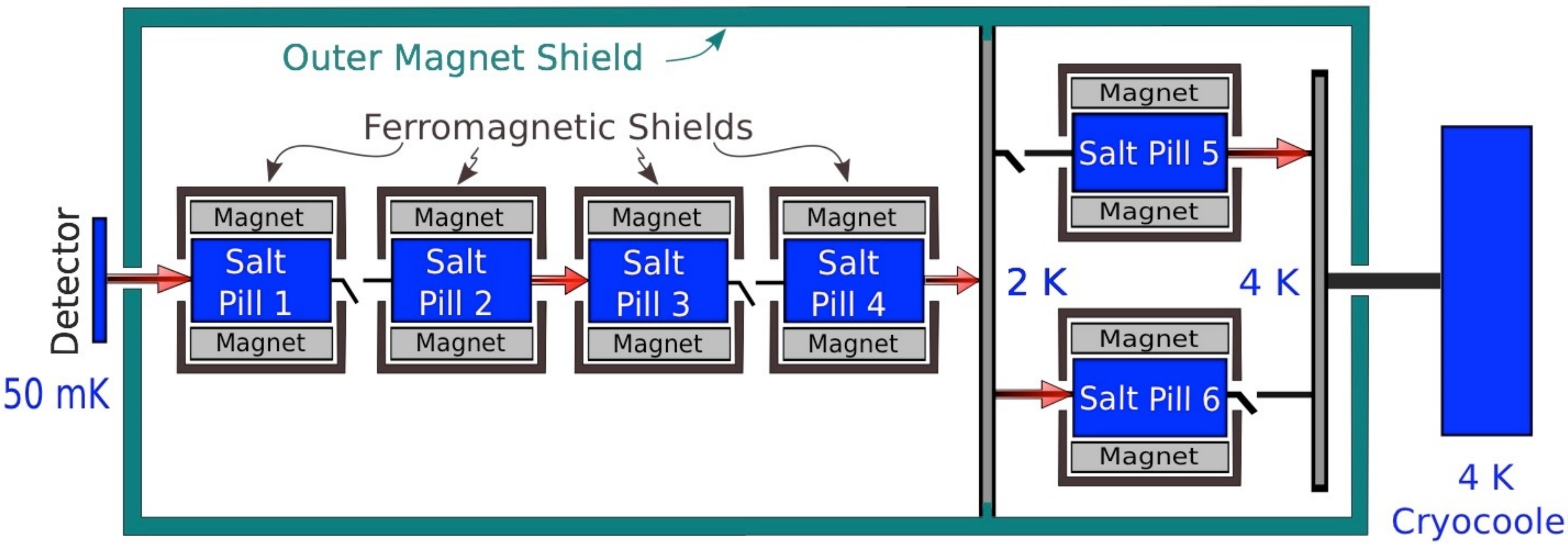
CADR was developed using research money provided by NASA/GSFC in the early 2000's (Shirron *et al.*)

- Measured cooling powers and overall efficiency measured for that system

Measurements show new system has lower available cooling power due to stronger Kevlar suspensions

- In the version that uses a GM cryocooler for a heat sink, additional vibrational heating in the Kevlar seen as well

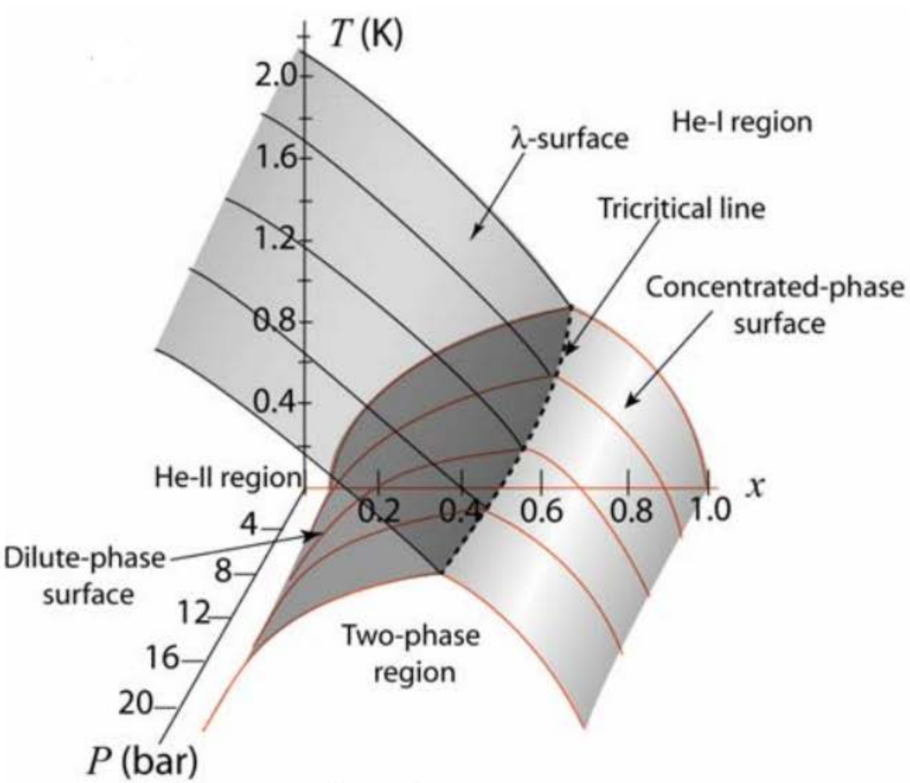
Many Possibilities

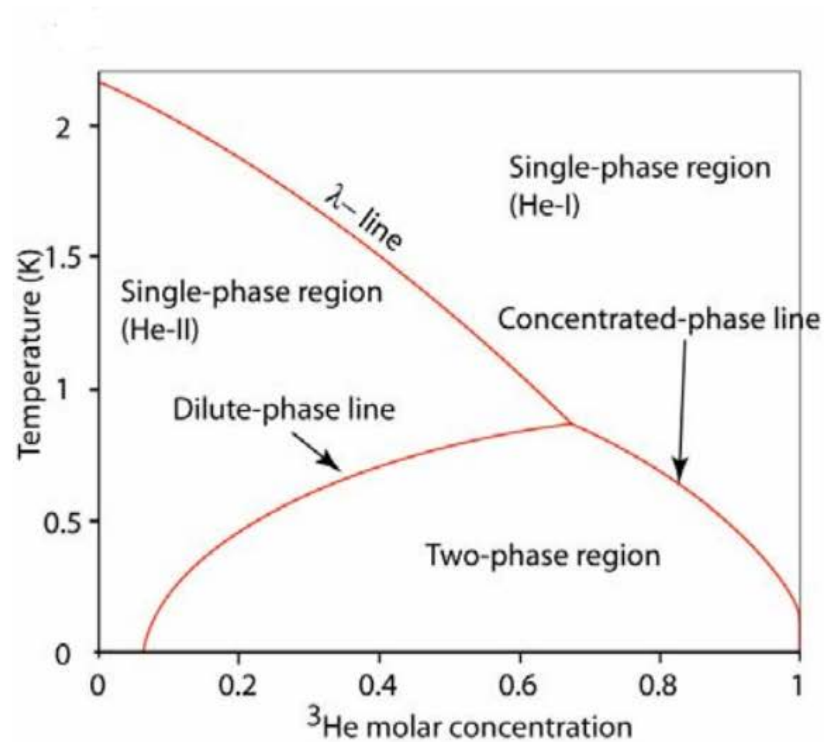


Two, or more, unique continuous temperatures possible

- Asynchronous CADRs
- In this example, one is a 2 K, the other 0.050 K

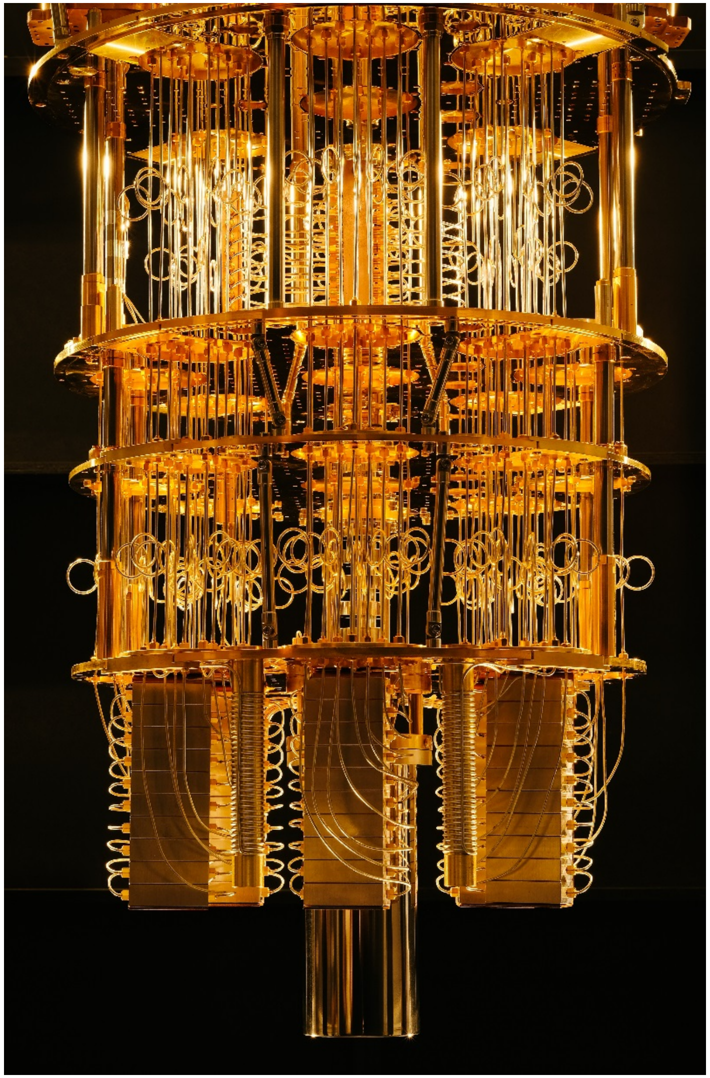
Dilution Refrigerators





Chaudhry, 2009

Dilution Refrigerators



IBM Q Dilution refrigerator

DR/CADR hybrid coolers

- Dilution refrigerators can be used in combination with Continuous ADRs.
- Dilution refrigerators can provide the low temperature background necessary for the quantum processor.
- A Continuous ADR can be used to provide the low temperature background for attenuators, amplifier, filters, and circulators.
- Traditionally the attenuators are tuned and optimized given the temperature of each stage in a dilution refrigerator to provide best possible combination of attenuation of signal and power minimization to the mixing chamber.
- This can be addressed by freeing one up from the pinned temperature stages and further optimize the sinking stages to that custom provided by pairs of CADRs with their heat rejected to a traditional cryocooler.
- Modularity of CADR units are highly desirable for this purpose.

Thermophysical properties measurements

- Quantum computer systems require use of parts that need to operate at cryogenic temperatures
- It is common to propose new candidate materials which have not been completely characterized at cryogenic temperatures for this purpose, especially in the advent of metal 3D printing of various elements
- Selection of these materials often rely on meeting specific criteria (e.g structural components may need to posses low thermal conductivity and high strength, or harnesses may need to have low electrical resistivity and low thermal conductivity, etc.)
- Property measurement at low temperature beneficial to future development could include:
  - ❖ Thermal conductivity
  - ❖ Electrical resistivity
  - ❖ Specific heat capacity
  - ❖ Emissivity
  - ❖ Absorptivity
  - ❖ CTE measurements

Summary

- There is a need for higher cooling powers and lower temperatures

- The future of quantum computing will also require changes and adjustments to the current architecture that would enable larger array processors

- Both DRs and CADRs are promising methods to providing large scale cooling for qubits

- Additionally DRs and CADRs can be used in a hybrid fashion to minimize the heat leak and maximize RF, drive, read-out lines for the quantum processor