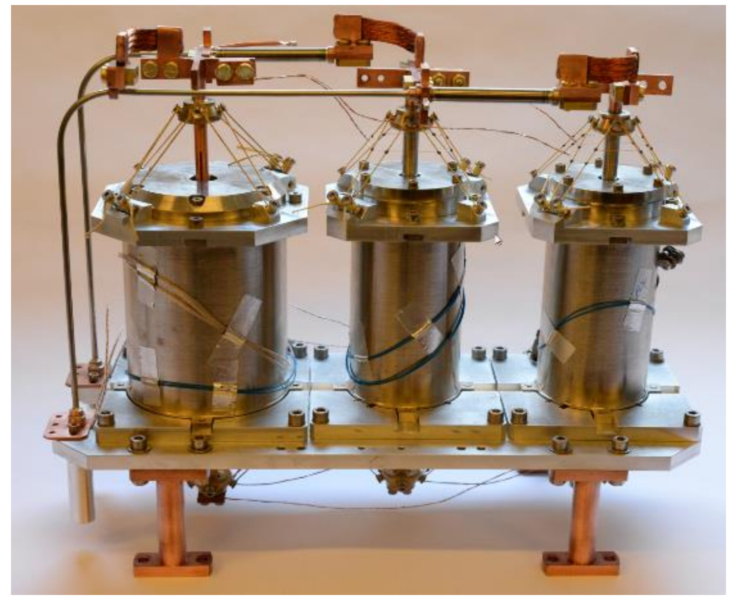
ADIABATIC DEMAGNETIZATION REFRIGERATORS

FROM RESEARCH TO INDUSTRY



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  - Efficiency

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- **Current developments and perspective**
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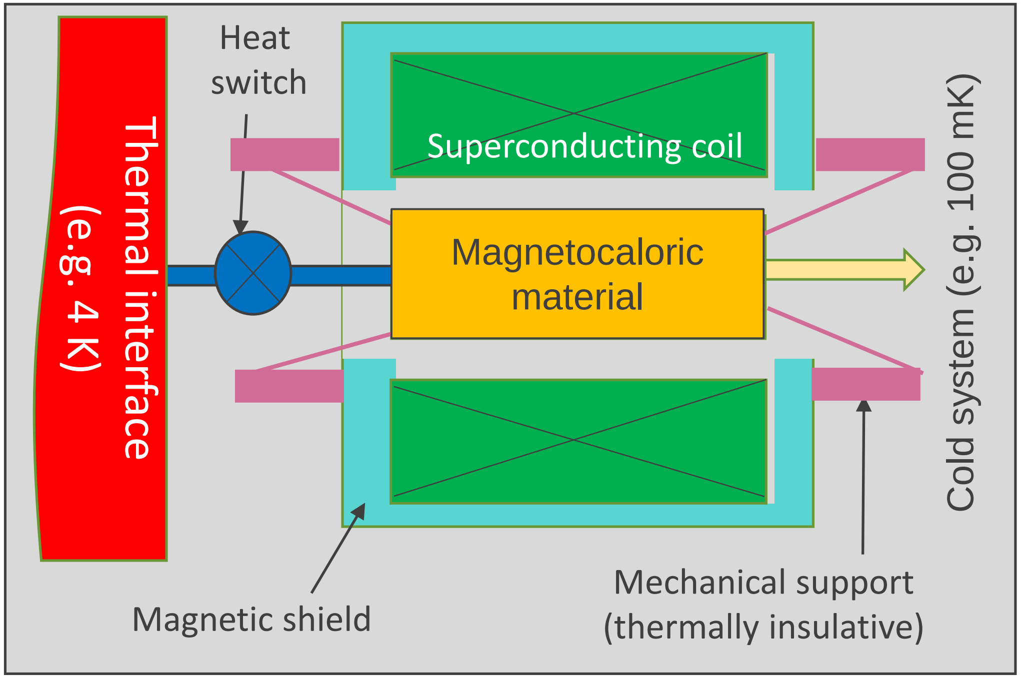
  - Space applications
  - Perspectives



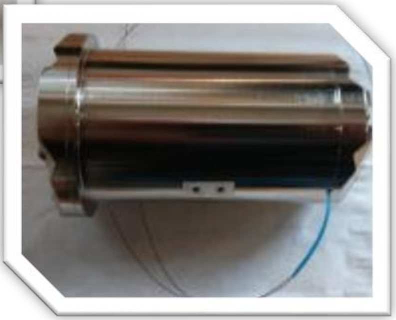
Heart of the system : magnetocaloric material

(typically paramagnetic material)

- **Magnetic system (e.g. superconductive coil)**
  - B variation => T variation
- **Heat switch + thermal interface**
  - => cryocooler
- **Ferromagnetic shield**
  - => reduces outside perturbations
- **Mechanical support**
  - Thermally insulative (e.g. Kevlar)

Details of components

Paramagnetic material "pill"
Here CPA (chromic-potassium alum)
and « thermal bus » (=thermal interface)



Superconducting coil and magnetic shield

Kevlar supports

ADR stage

Typical size
L ~150 mm

Context of adiabatic demagnetization refrigerators

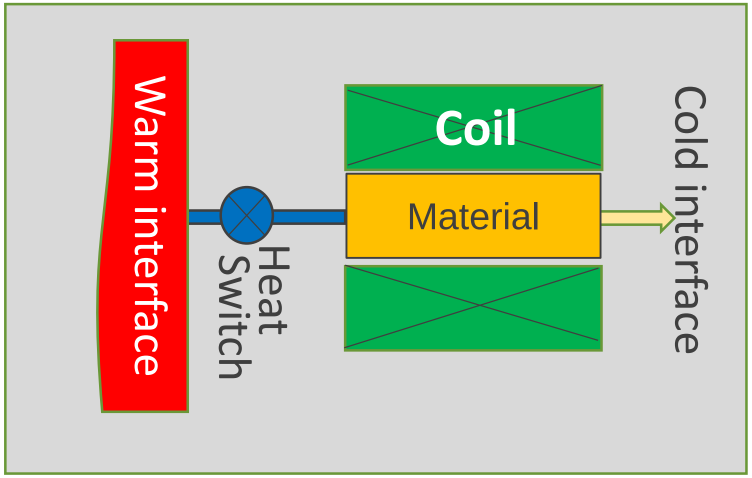
- **Historical context**
  - First technique to reach T<0.8 K
  - Demonstrated in 1933 (Giauque) to reach 0.53 then [De Haas et al] to reach 0.33 K
  - Widely used in cryogenics laboratory until being replaced by dilution refrigerator (continuous cooling, high cooling power…)

  - Other technique : nuclear demagnetization refrigerator : provides µK cooling, not discussed her

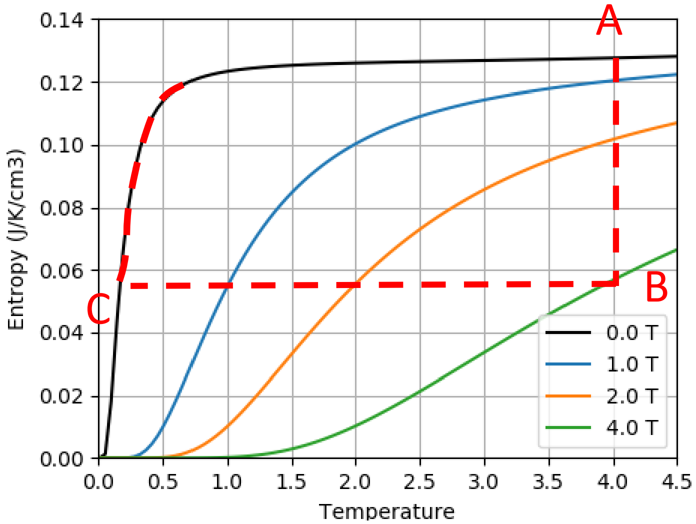
- **Today's use and research**
  - Technique for cooling down to 2 mK, starting at ~4 K
  - Renewed interest for space applications (and rockets)
  - Relatively easy to use, combined with pulse tube coolers for ground applications

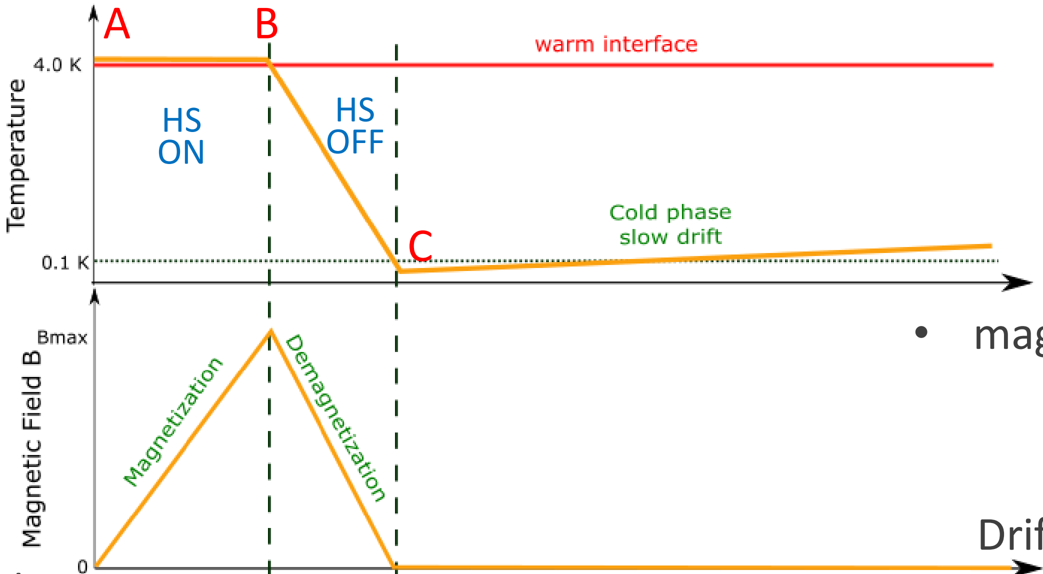
- **Focus of this class**
  - ADR, from a practical point of view

Typical operation



Properties : typical T-S diagram



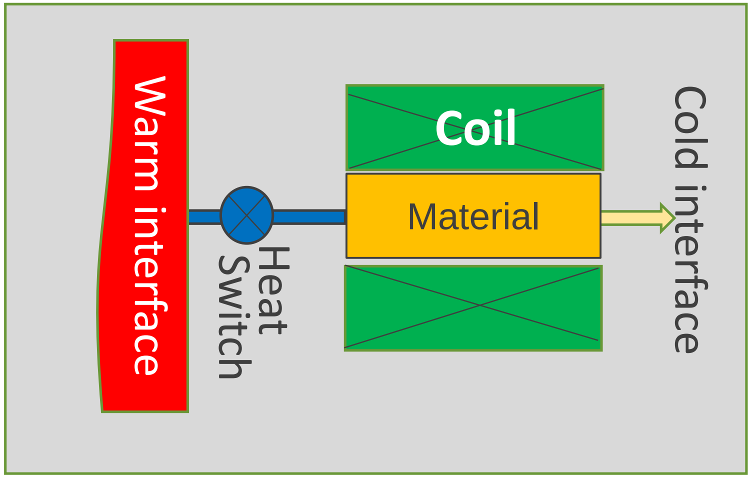


Non continuous operation:

- magnetization/demagnetization phase
  - cold « operating phase »

Drift once low temperature is reached

Simple demagnetization



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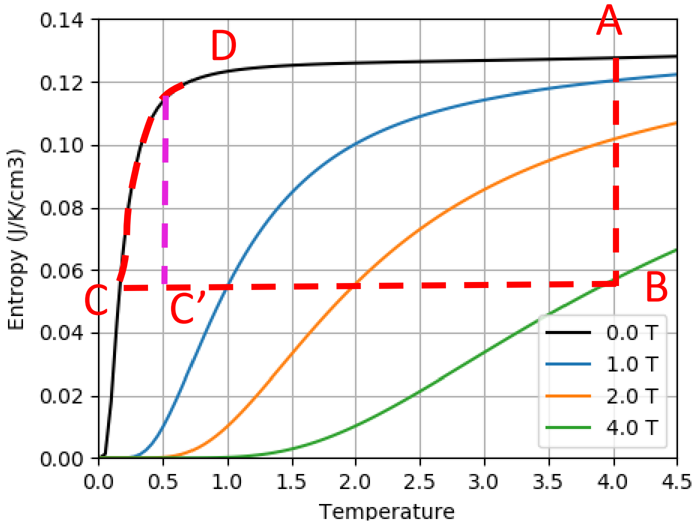
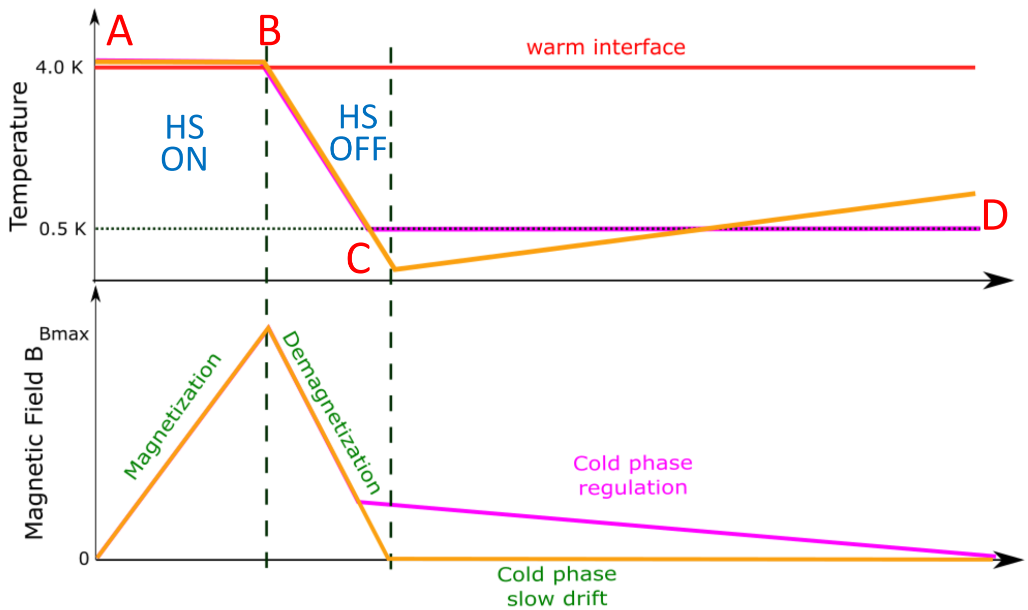
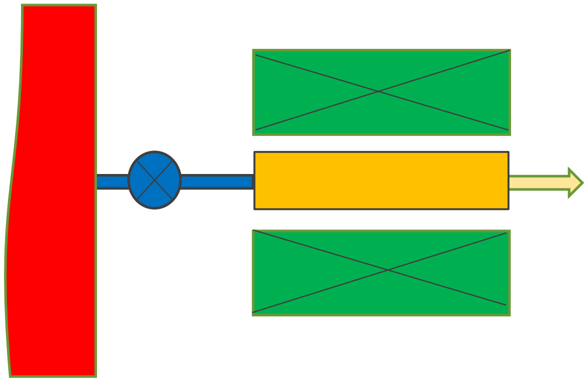


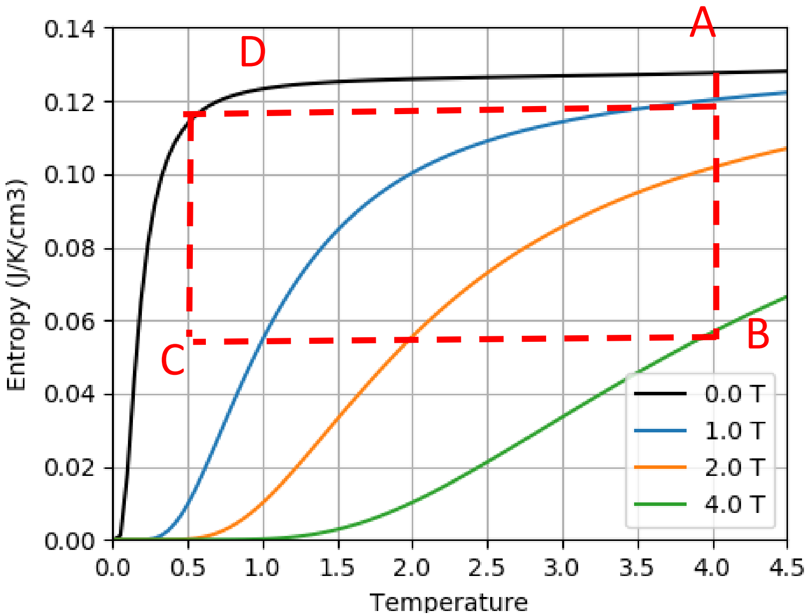
Simple demagnetization or cold phase regulation



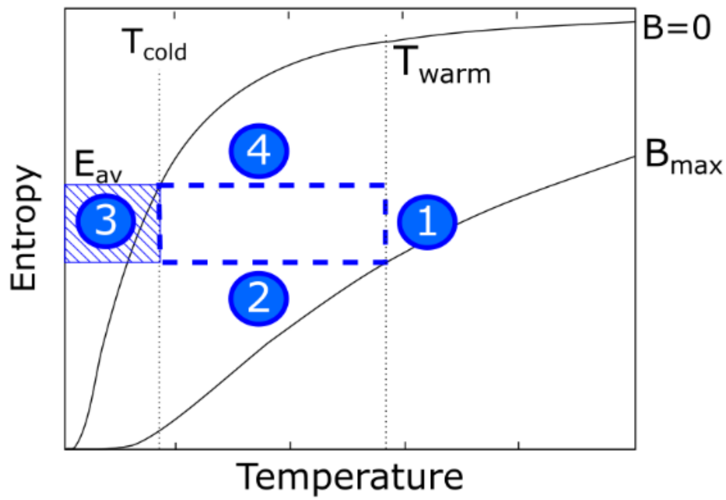
Regulation with no dissipation cost

More efficient than drift of temperature



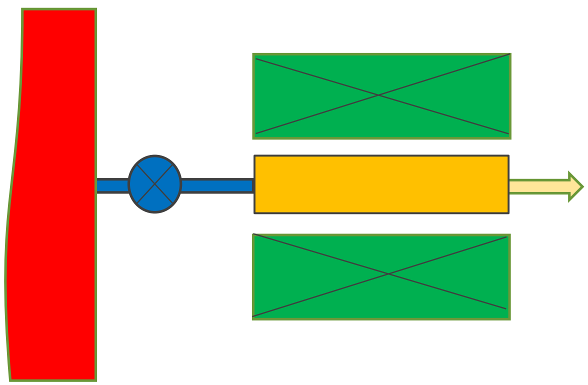


Magnetic Carnot Cycle

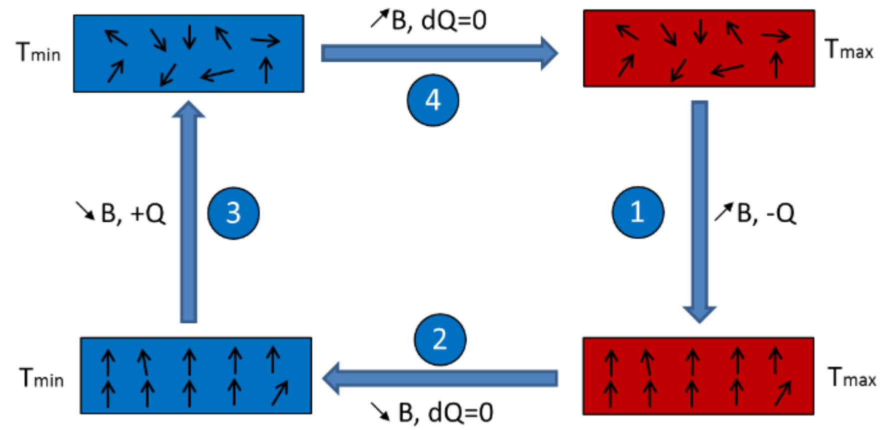


- Equivalent to Carnot cycle, with magnetic field variation instead of pressure
- Meaningful for several cycles in a row

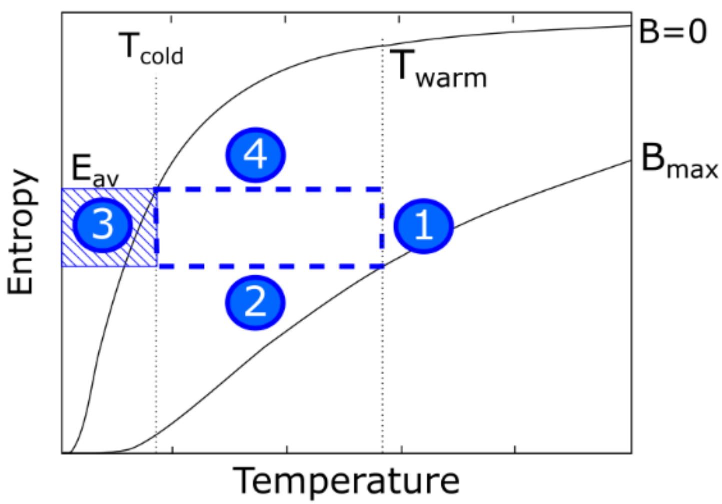
Magnetic Carnot cycle and schematic representation



Magnetic moment illustration



Courtesy D. Paixao Brasiliano



- Magnetocaloric effect due to variation in magnetic spin orientation and energy level
- Representation with spin direction for illustration

Simplified theoretical model to predict paramagnetic material performances

$$S = f(B/T)$$

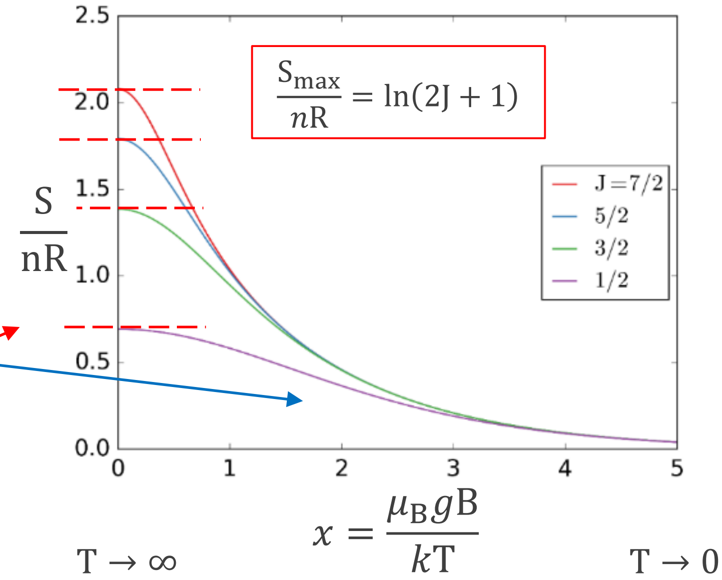
$$\frac{S}{nR} = \ln\left\{\frac{\sinh\left[(J+1/2)x\right]}{\sinh(x/2)}\right\} - x\,J\,B_J(x)$$

$$B_J(x) = \frac{1}{J}\left[(J+1/2)\coth\left[(J+1/2)\,x\right] - \frac{1}{2}\coth(x/2)\right]$$

$$x = \frac{g\mu_B B}{kT}$$

J : Total angular moment

g : Landé factor



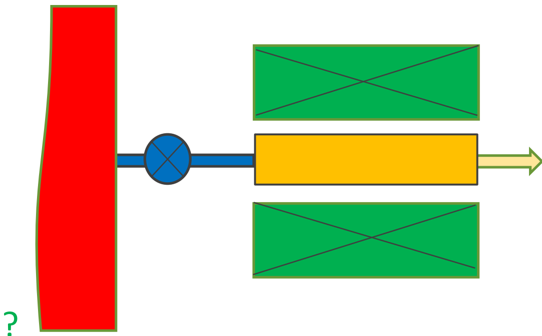
In general, materials with low interactions between magnetic moment

- **Aluns (T< 1 K) e.g. CMN, CPA, FPA : paramagnetic salts**
- **Garnets ([1K – 10 K]), ex GGG (GdGa2O5), DGG (DyGa2O5), …**

See Pobell, « Matter and Methods at low temperature » for more on this topic

Efficiency

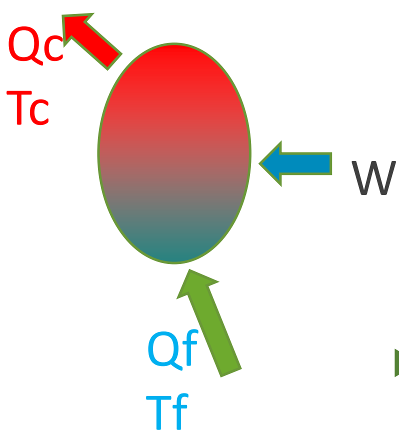
ADR is quasi reversible => follow Carnot ideal efficiency

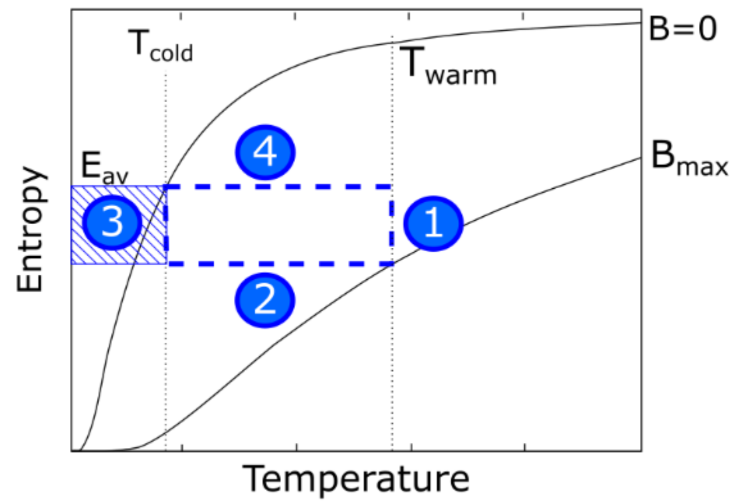


Question :

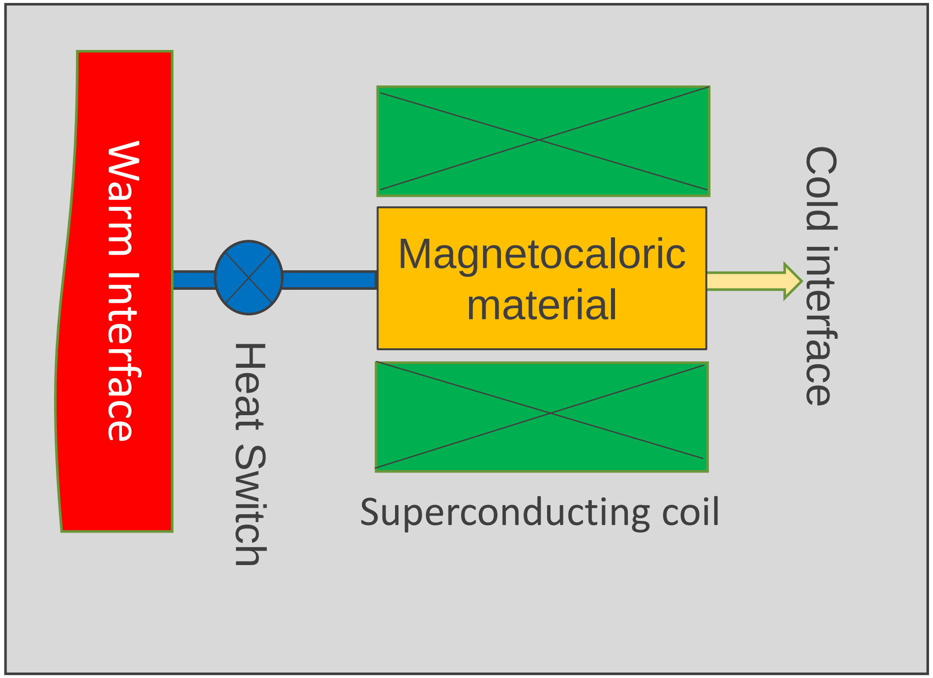
- ADR cooler provides 2 µW @ 100 mK during 12 hour
- Losses (mecanical support, heat switch = 0.2 µW.

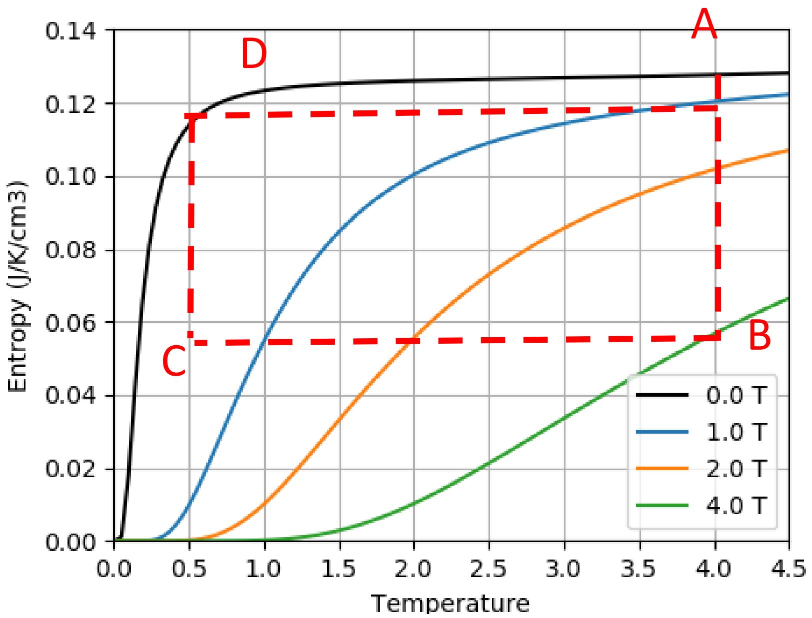
What is the energy deposited on the warm interface (4 K interface) during magnetization?





- In general, efficiency defined as : η = Qf / W
- For very low temperature coolers, W not critical but Qc is crucial
- Efficiency defined as Qc/Qf. Theoretical value : Tc/Tf





Superconducting coil
Magnetocaloric material
Heat switch

Electronic : temperature measurements and control of heat switch and magnetic field variations

Based on magnetocaloric effect

d

Part 2 – practical informations

- Key components : heat switch
- Operating modes : two stage, continuous …
- State of the art

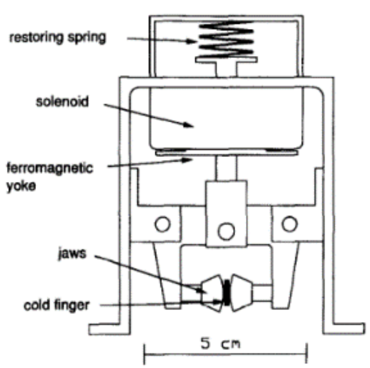
Key component : heat switches

More than 3 different kinds of heat switches

- **Mechanical heat switches**

Mechanically connect two parts

- Very good OFF position (virtually 0)
- Low ON position (depends on contact resistance)



Hagmann et Richards, 1995

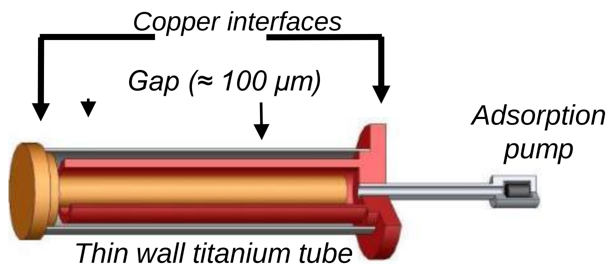
Large force required for good ON conductivity

- **Gas Gap Heat switches**

Evacuate gas to pass OFF position

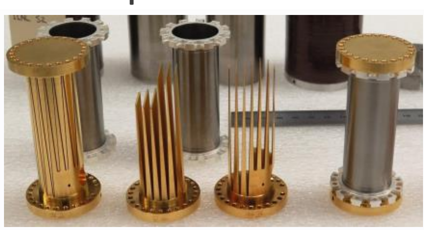
- Very good ON position (T>0.5 K)
- low OFF position

Concentric shape



e.g. Duband et al

Come shape



e.g. Shirron et al

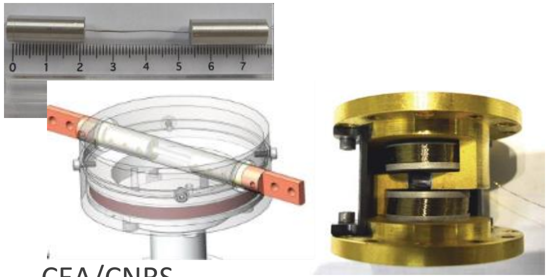
Very reliable

Low on conductivity below ~300 mK

- **Superconducting heat switches**

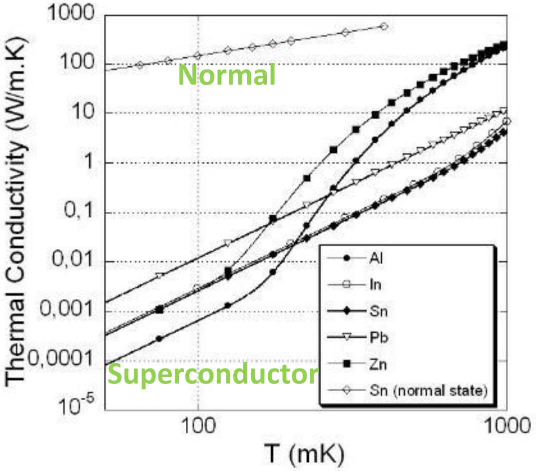
« break » superconductivity with magnetic field

- Used for TON < 0.5 K
- Care for low OFF position



CEA/CNRS

Shirron et al



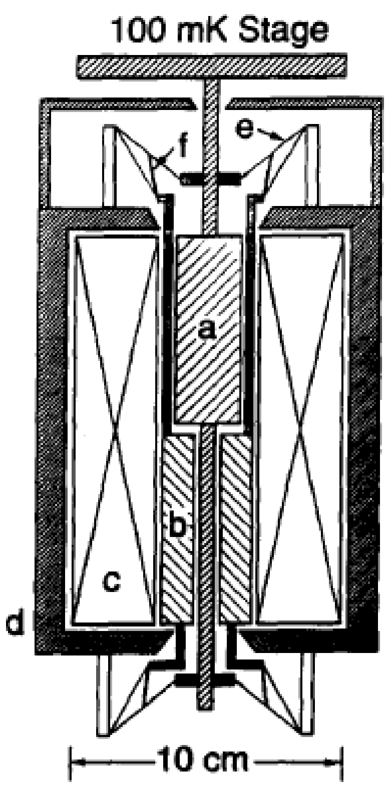
Only T<0.5 K

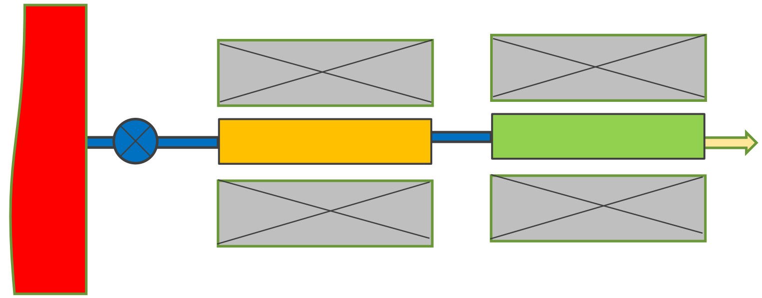
High OFF conduction

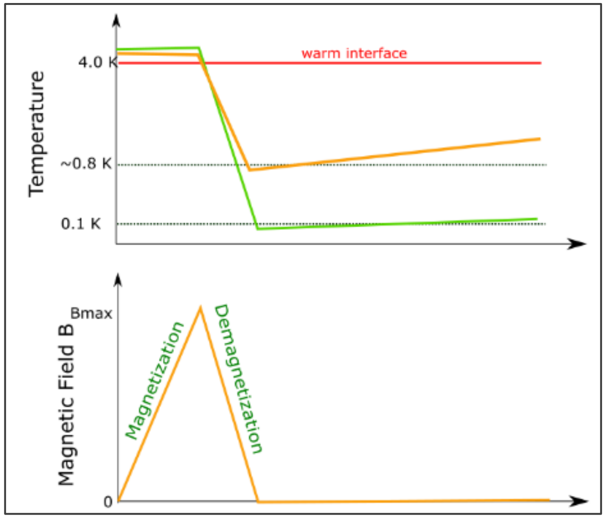
- **Other technologies possible (e.g. magnetoresistive)**

Two stage system

- **2 stage systems – 1 single magnet**



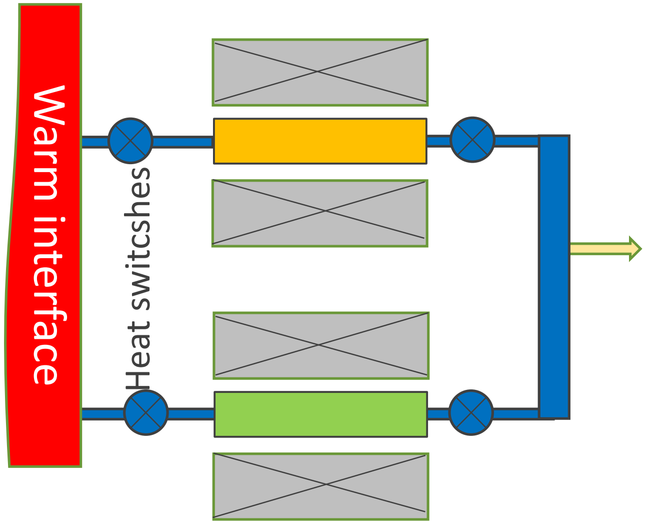


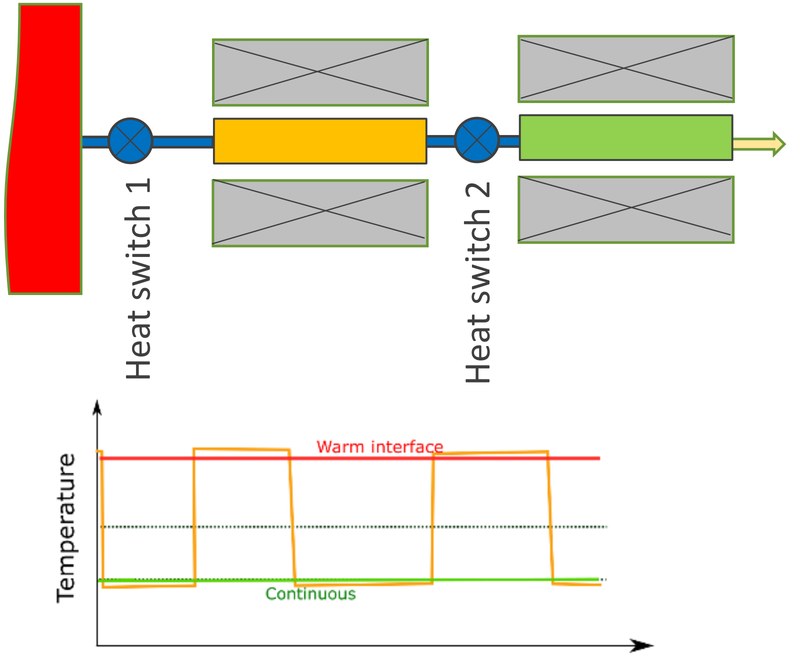


Stage 1 (b) acts as thermal screen
Stage 2 (a) provides 100 mK interface

Typical commercial solution. Active regulation (on one stage) is also possible

Parallel or series configuration?





Parallel configuration

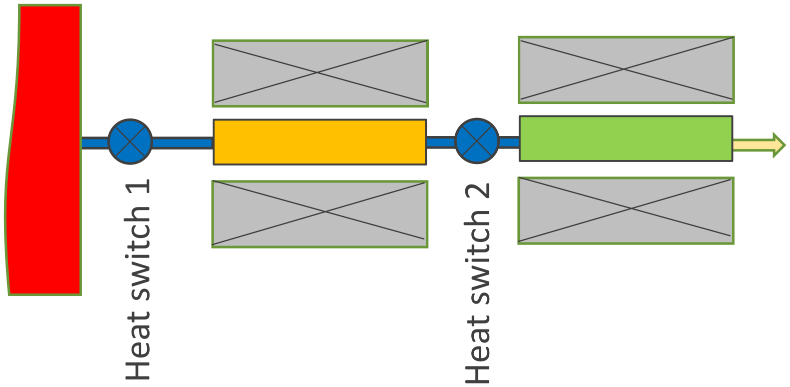
- Intuitive operation
- 4 heat switches required
- Better if limited power on warm interface

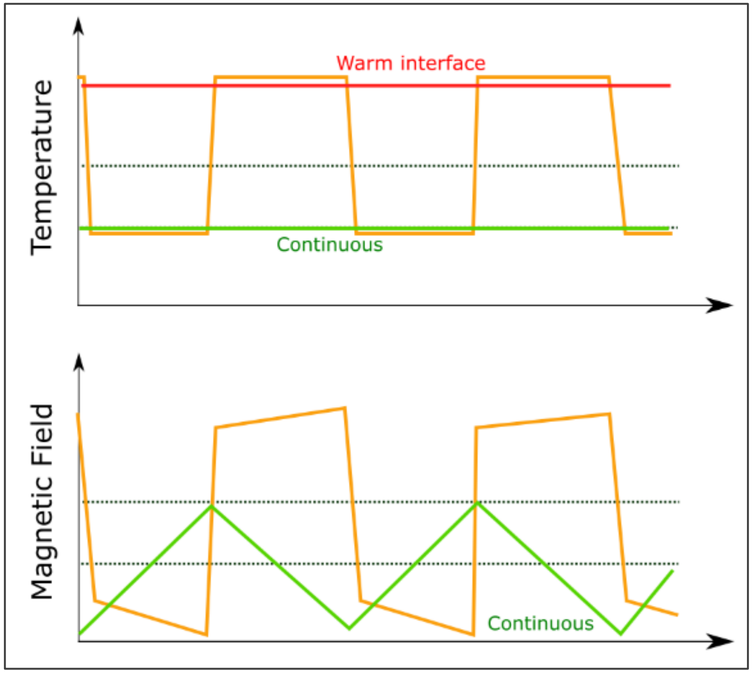
Series configuration

- Only 2 heat switches
- More stable last stage temperature
- Lower total mass

▶ **In general, continuous operation achieved with series configuration**

Series configuration





- Cold temperature regulated by control of magnetic field of second ADR stage
- Heat rejected to the warm stage through first stage

Question :

- An ADR cooler provides 1 µW @ 100 mK – continuous operation
- Efficiency is 60% of Carnot

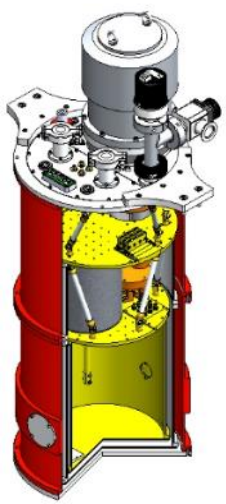
What is the average power deposited on the warm interface (2 K interface)?

Why only 60% efficiency?

Commercially available

'one shot' ADR
Typically 4 K – 100 mK
(ex: Janis, Entropy, …)

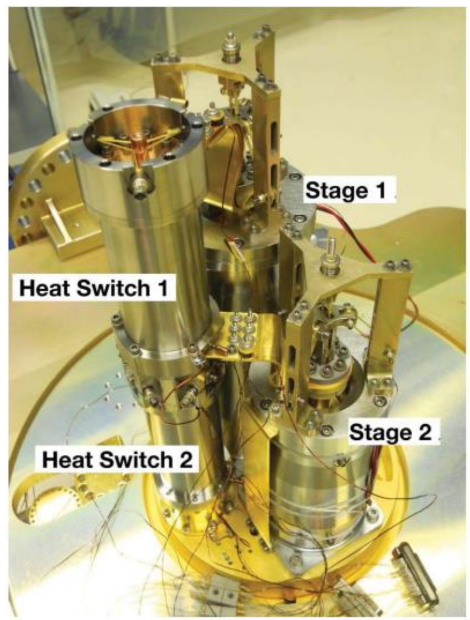
Entropy-cryogenics



Cooling power : ~µW @ 100 mK

Space model

Space application
(NASA/Goddard (P. Shirron) – USA



Example Hitomi satellite
50 mK measured in space
Only 2 missions flown so far

Common project CEA - CNRS

5 stages
2 continuous interfaces
100 mK continu

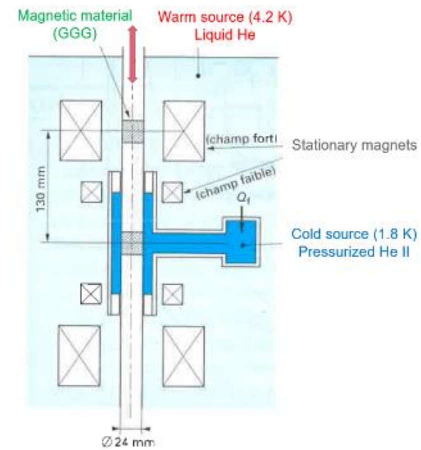
▶ d

Current research and perspectives : lower mass and materials quantities

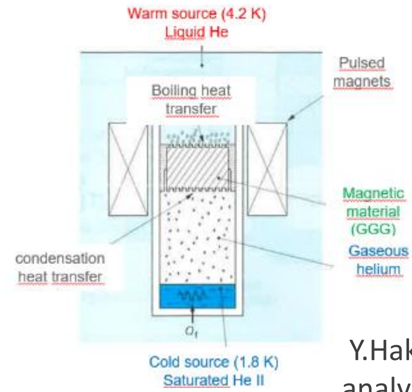
- Large scale refrigeration
- Space application
- Space : reduced size operation

ADR could be useful for much higher heat loads

- **Several studies made, starting before the 1980's**
  - SBT 1.35 W@1.8 K, 1984
  - Hitachi : 1.2 W @ 1.8 K, 1986
  - CERN design for up to 20 W cooling
  - Updated study (2017) by Tkaczub et a



A.Lacaze & al., Double acting reciprocating magnetic refrigerator : recent improvements, 1984



Y.Hakuraku & al., Thermodynamic analysis of a magnetic refrigerator with static heat switches, 1986

- **Main driving factor for large scale refrigeration**
  - Fast cycle operation (faster => lower size of paramagnetic material) and cost
  - Difficulty : heat flows and lower size => larger power per volume heat transfer
  - Use of liquid (helium, helium flow, …) heat transfer
  - Heat switches (as previously presented) not adapted

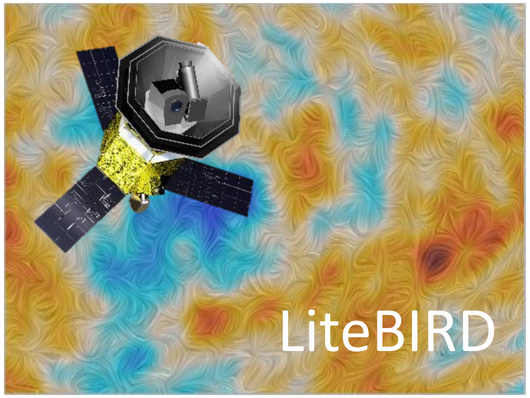
Large developments needed to propose realistic cooler

Future developments between 10 µW and Watts or kWatts?

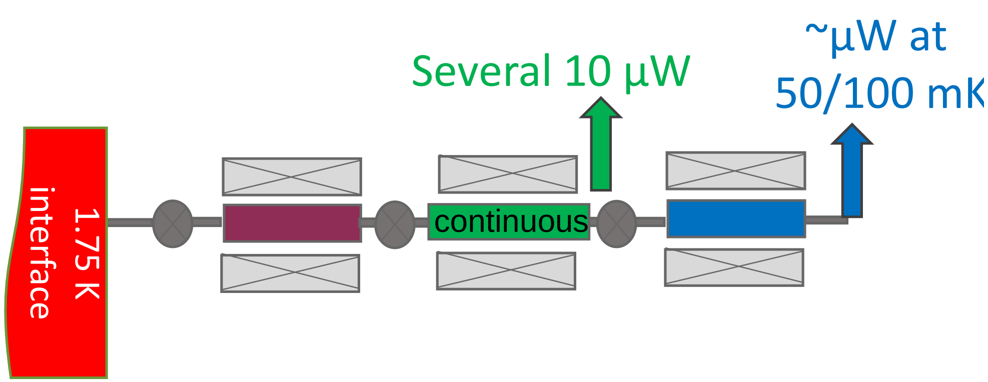
Application for space applications: 3 stages ADR

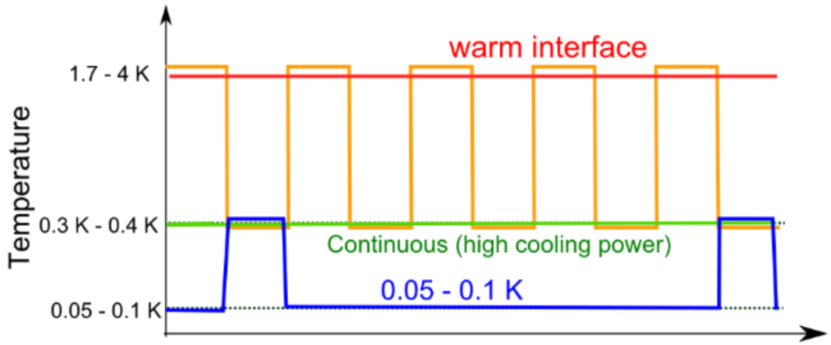
Some typical missions needs :

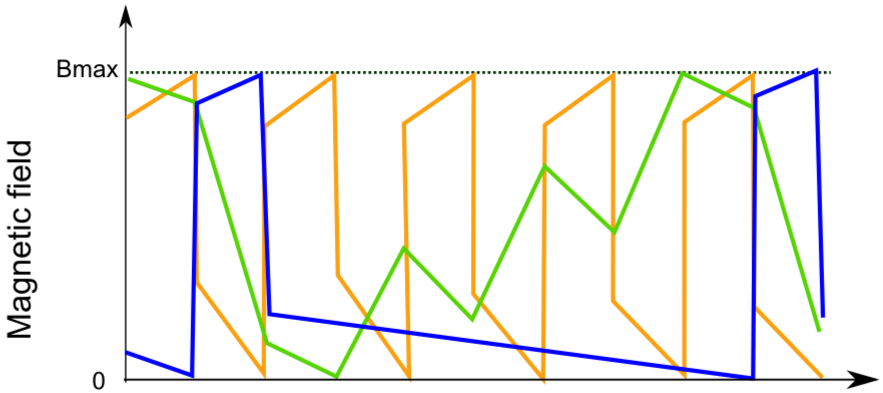
- **Several mission needs with :**
  - High cooling power requirements at 300 mK (20 – 50 µW)
  - Low power requirement at 50 / 100 mK (0.5 – 2 µW)
- **Interface temperature of 1.7 to 3.0 K**
  - Size dominated by 300 mK cooling



- **Proposed cooler with 300 mK continuous stage**

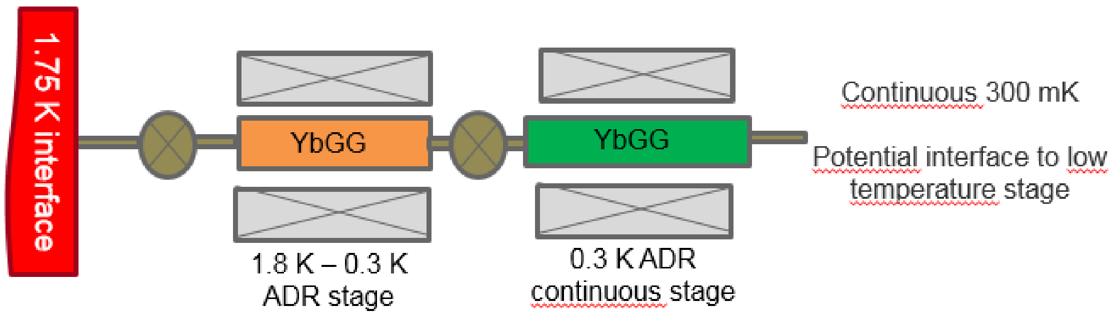


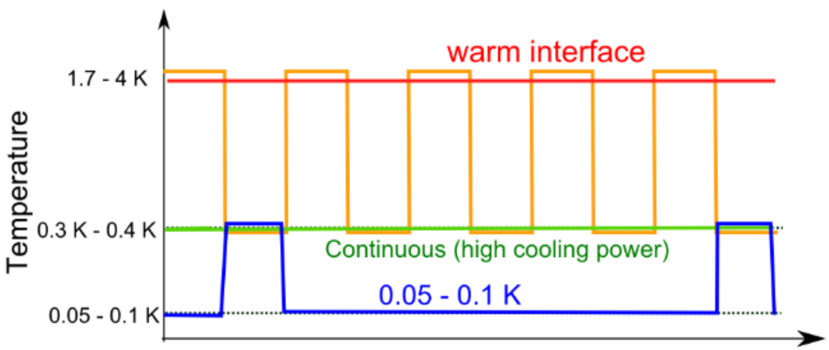


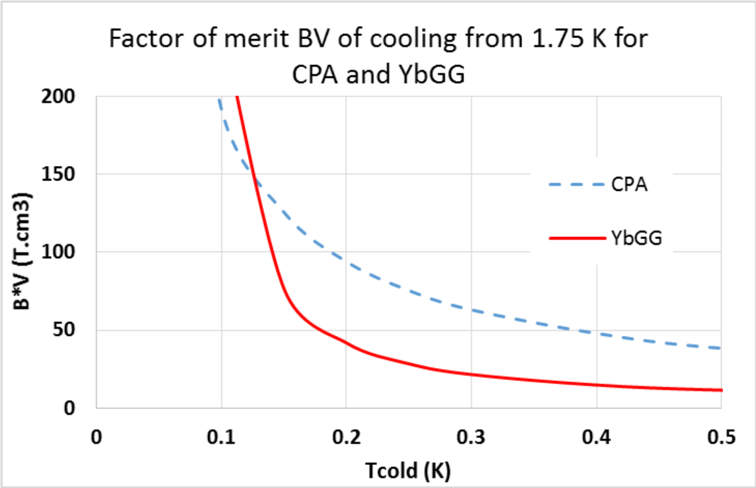


New material studied : YbGG cooler for 300 mK continuous operations

- Types of coolers with 1.75 K interface



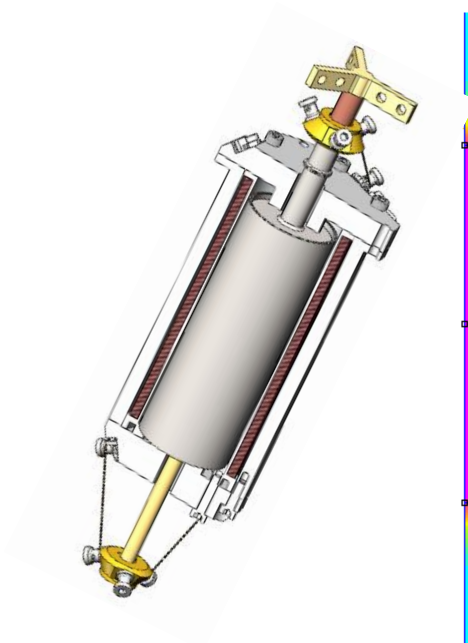


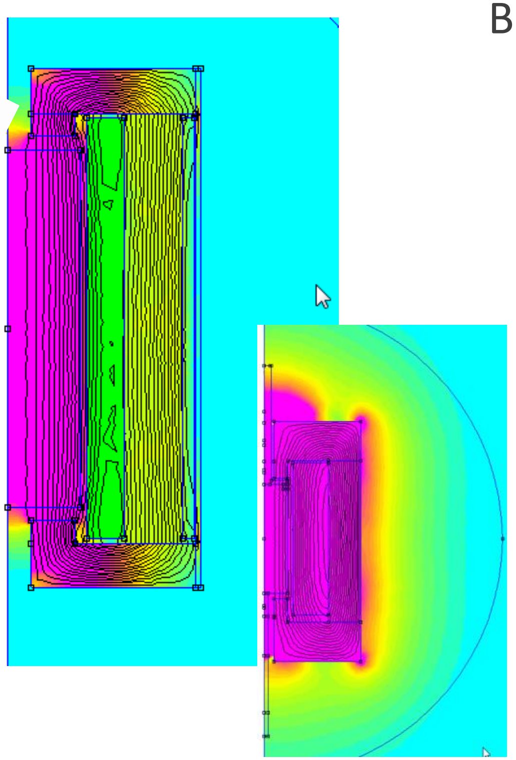


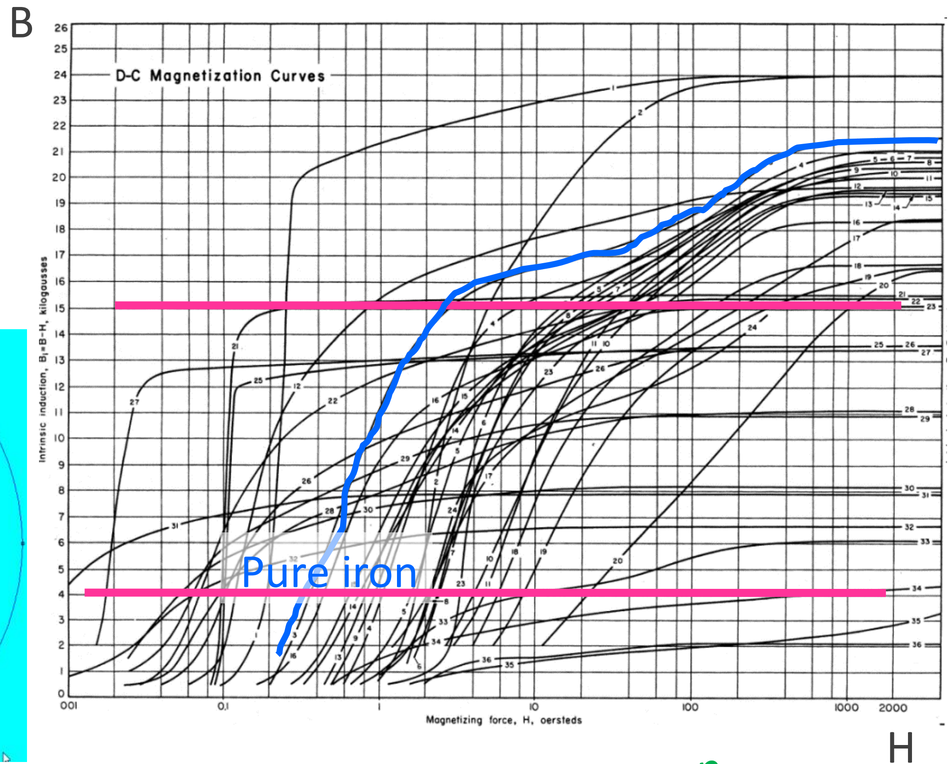
YbGG material 3 times lighter than equivalent CPA
Advantageous solutions for these requirements

Magnetic system optimization

Measurements and modelling







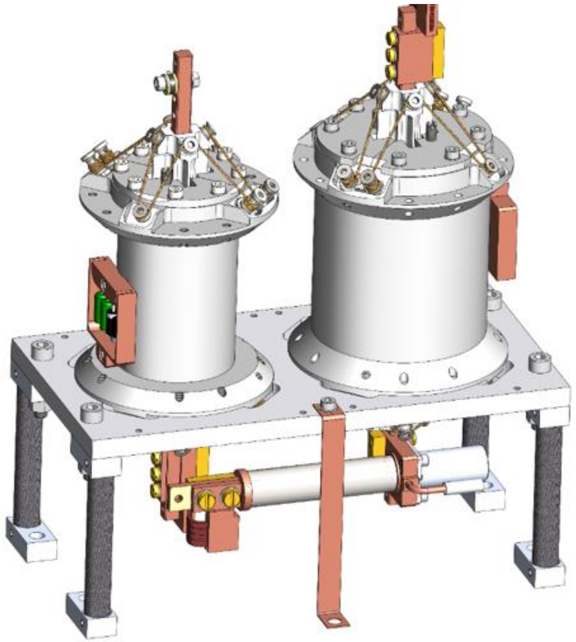
Only few data on properties at cold temperature

- **Mass minimization**
  - Lower parasitic magnetic field
  - Simple numerical simulation : Maxwell equations
  - Uncertainties on magnetic properties (at low temperature)
  - Knowledge / measurements of magnetizing curve required

conclusions

Magnetic refrigeration

- Interesting technique for low temperature operation (space, reliability, cost)
- Used for space and ground coolers
- Very interesting technology to work on (materials, magnetics, thermal, …)
- Challenges for improvements for demanding applications, especially reduced mass or higher cooling power (material, magnetic, thermal)



Next CEA/DSBT prototype for high power (40 µW) 300 mK cooling for space