Adiabatic Demagnetization Refrigerators (ADR)

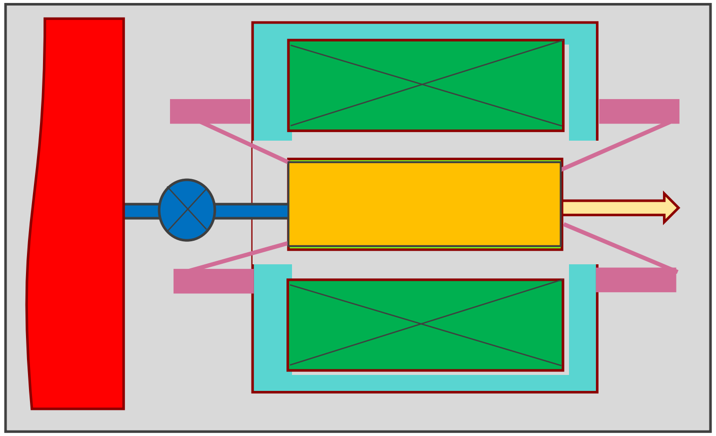
Introduction from the application side

Jean-Marc Duval

Lanef Demagnetization Day

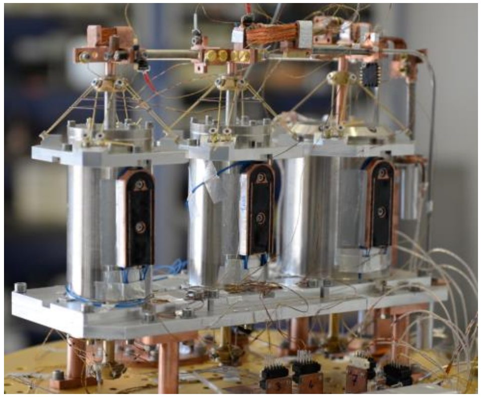
Grenoble, 20 Septembre 2021

1. **Description and operation**

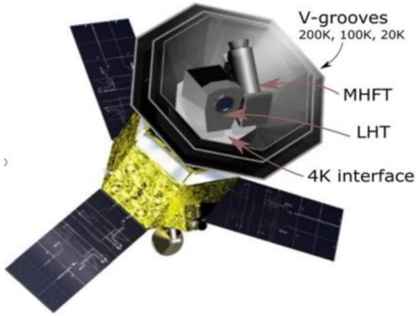


2. **Core components**
   - Magnetocaloric materials
   - Heat switches
   - Superconducting coils
   - Electronics
   - …

3. **Applications**
   - Laboratory work
   - Space applications



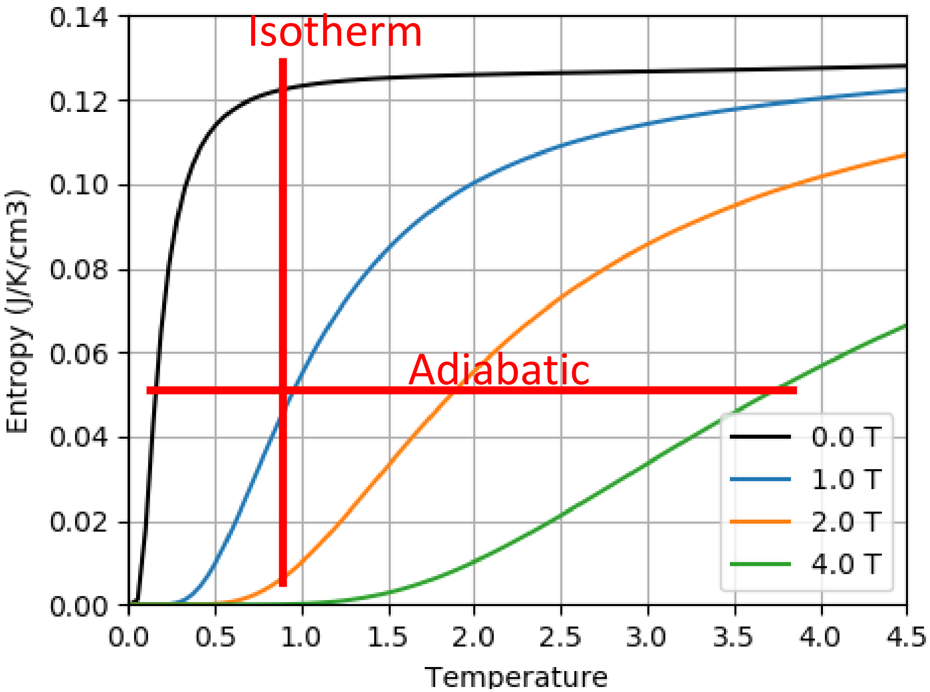
Paixao et al, 2018



Entropy, Temperature and Magnetic field

Magnetocaloric materials :

Temperature variations (or cooling /heating) with varying magnetic field



Convention for ADR diagrams :
diagram S versus T (and not T versus S)

Key diagram for applications :
S versus T (and B)

- Lowering B=> Cooling effect

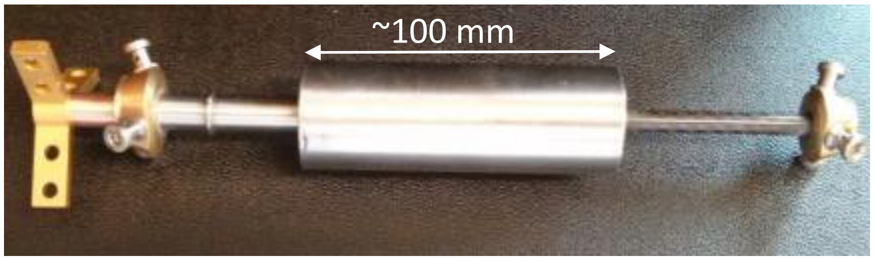
- **Reversible process**
  - Efficiency close to 100% !

- **Based on magnetic moment interactions with magnetic field => change of entropy**
  - Electronic moment =>ADR
  - Nuclear moment =>
  (Adiabatic) **Nuclear** Demagnetization Refrigerator

J. Tuoriniemi, A Casey and other presentations on nuclear demagnetization refrigerator

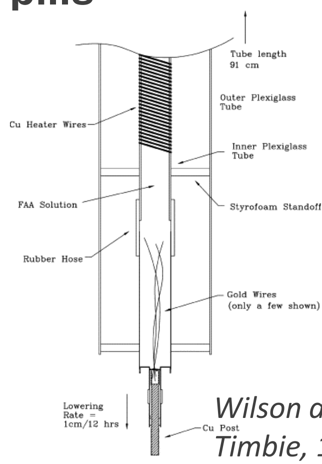
ADR materials

Examples of materials : alum and single crystal



"CPA" Chromic Potassium alum in its sealed pills

~20 mm



Wilson and Timbie, 1999

Pill obtained by crystalline growth in a solution around copper wires

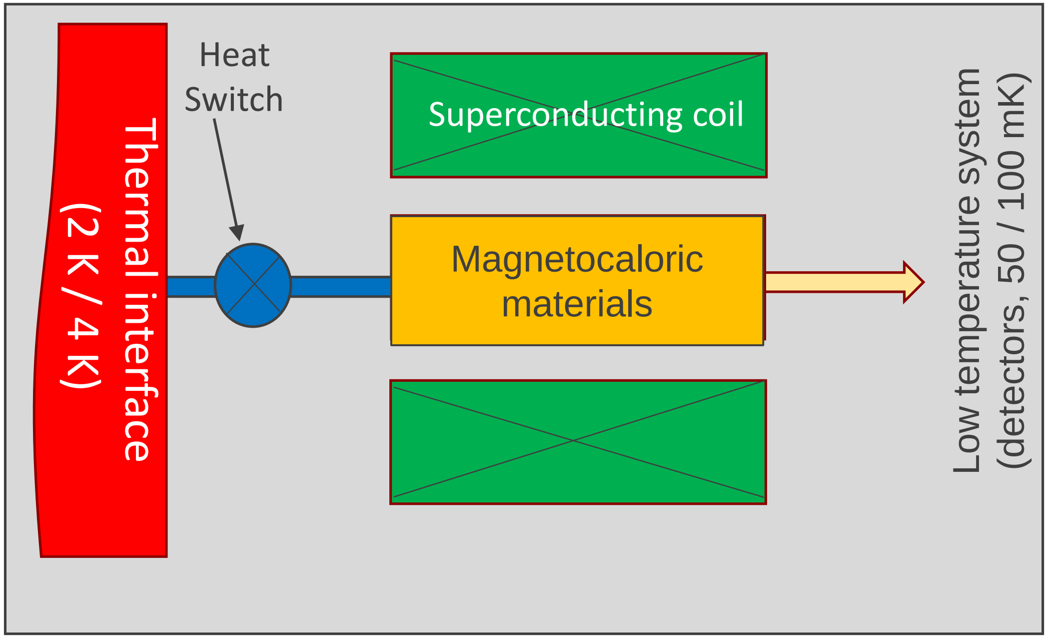
Other standard paramagnetic salt for T<1K : CMN, FAA …

"GGG" (Gadolinium Gallium Garnett) Single crystal and thermal bus

Crystal obtained by Czochralski method

GGG well adapted for 4K – 1 K cooling

Adiabatic Demagnetization Refrigerator

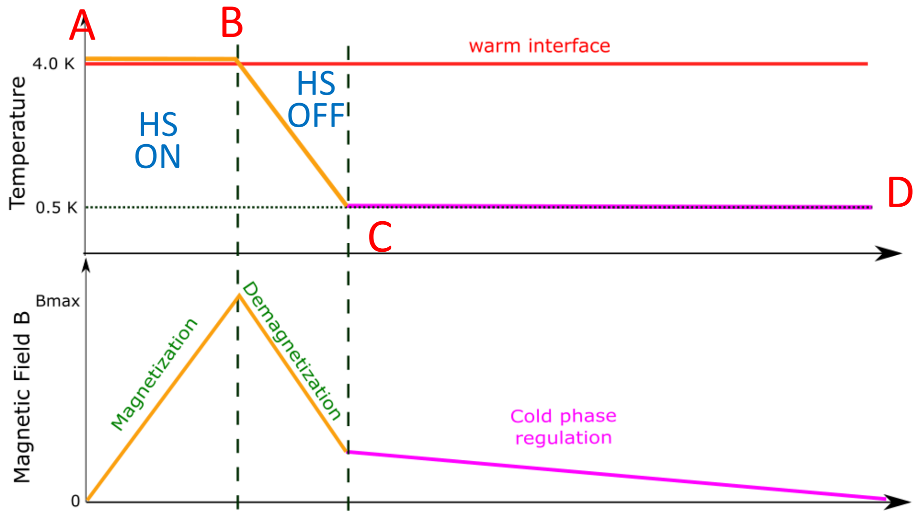


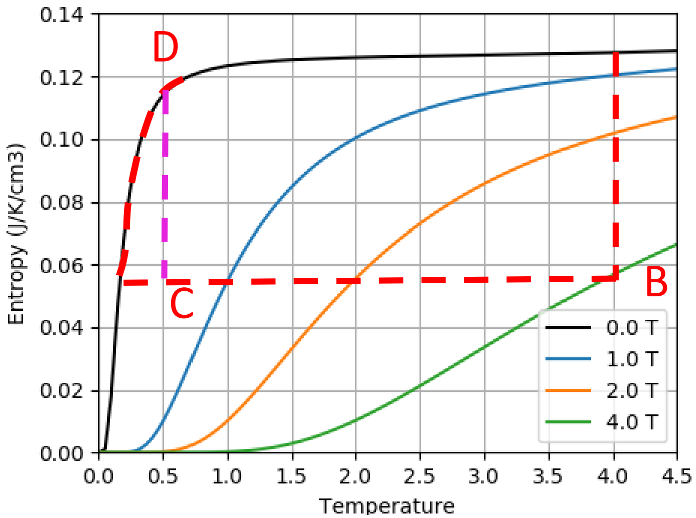
Heart of the system:
magnetocaloric materials
(typically paramagnetic)

Magnetic system (superconducting coil)

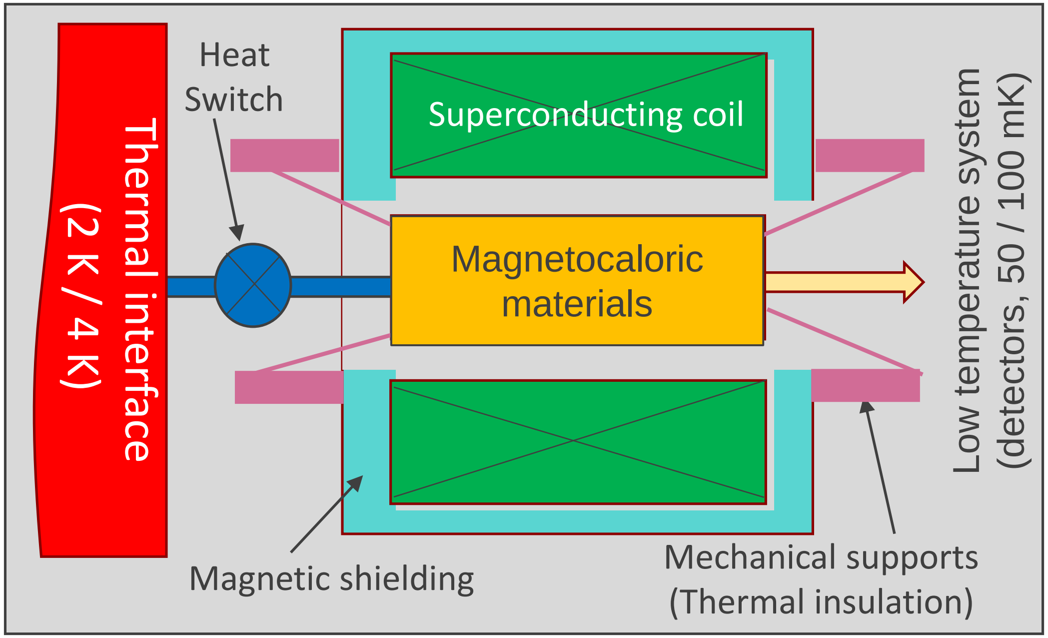
- Variation B => variation T

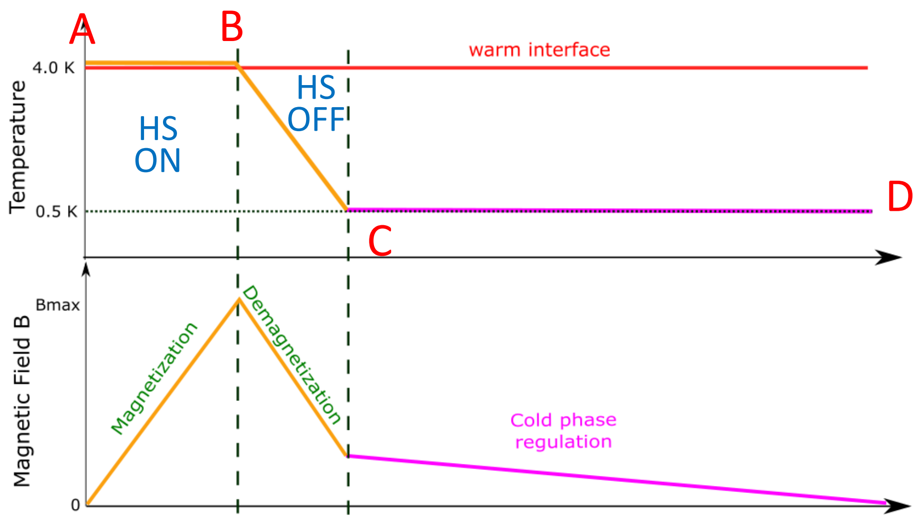
Heat switch + thermal interface





Adiabatic Demagnetization Refrigerator





Heart of the system:
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(typically paramagnetic)

Magnetic system (superconducting coil)

- Variation B => variation T

Heat switch + thermal interface

Magnetic shielding (ferromagnetic)

- => Reduces perturbations on detectors

Mechanical support

- Thermal insulation (e.g. Kevlar)

Large temperature ratio

4 K to 100 mK (factor 40) achievable

Excellent efficiency

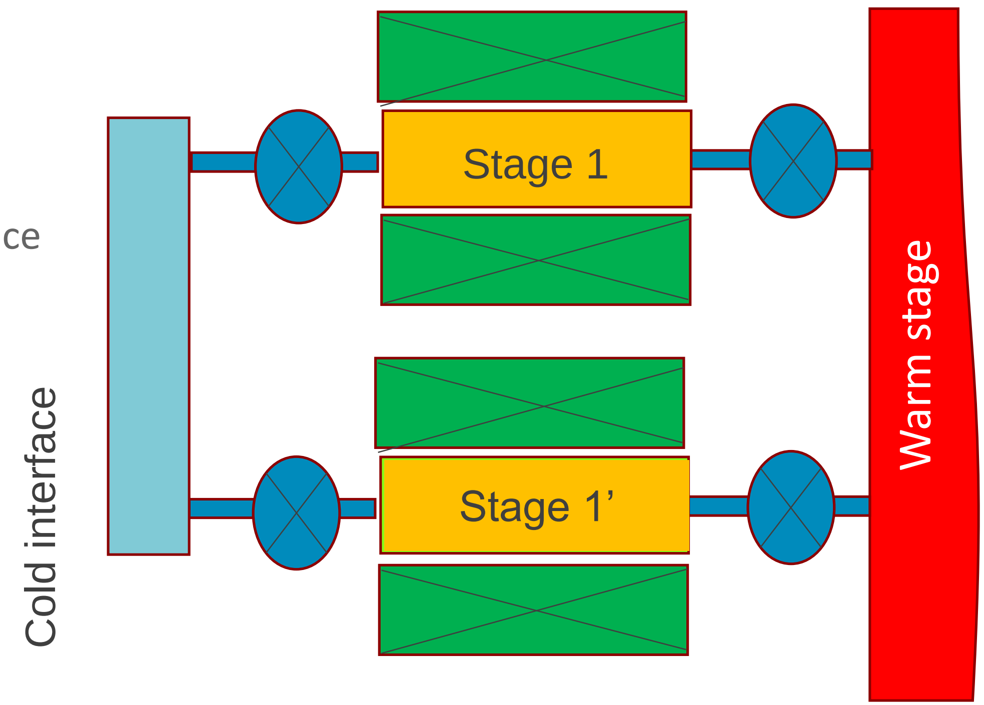
Limited by heat switch and support

Only true at very low temperature <~10 K

Continuous operation with 2 stages

Multi-stage operation : continuous cooling

- **Parallel configuration**
  - Stages are operating in opposing phase
  - Constant temperature on the cold interface



Advantage of continuous operation

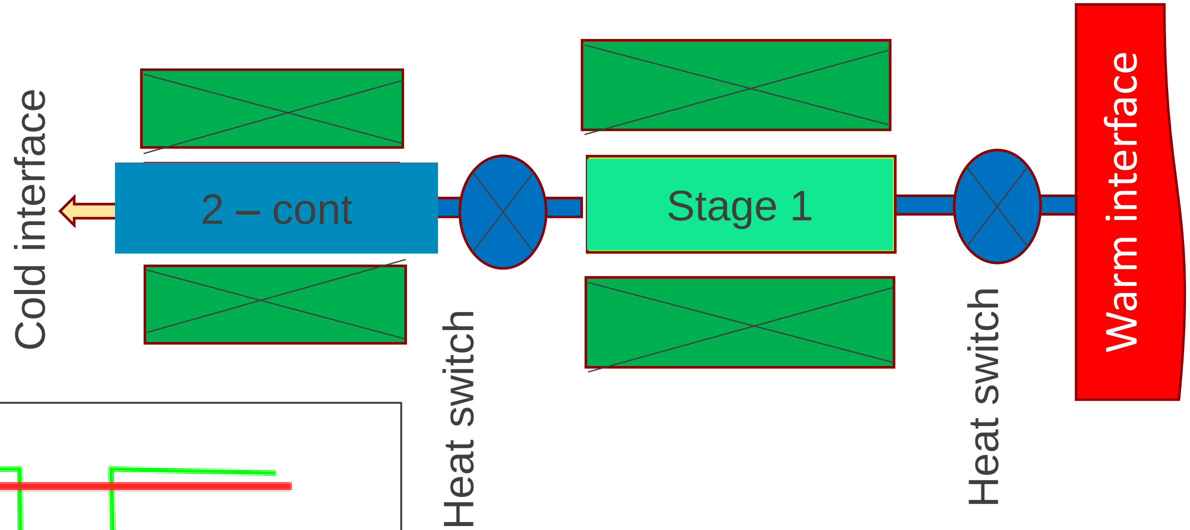
Smaller stages (each can be sized for ~1 hour), no need to design for >10 hours operation

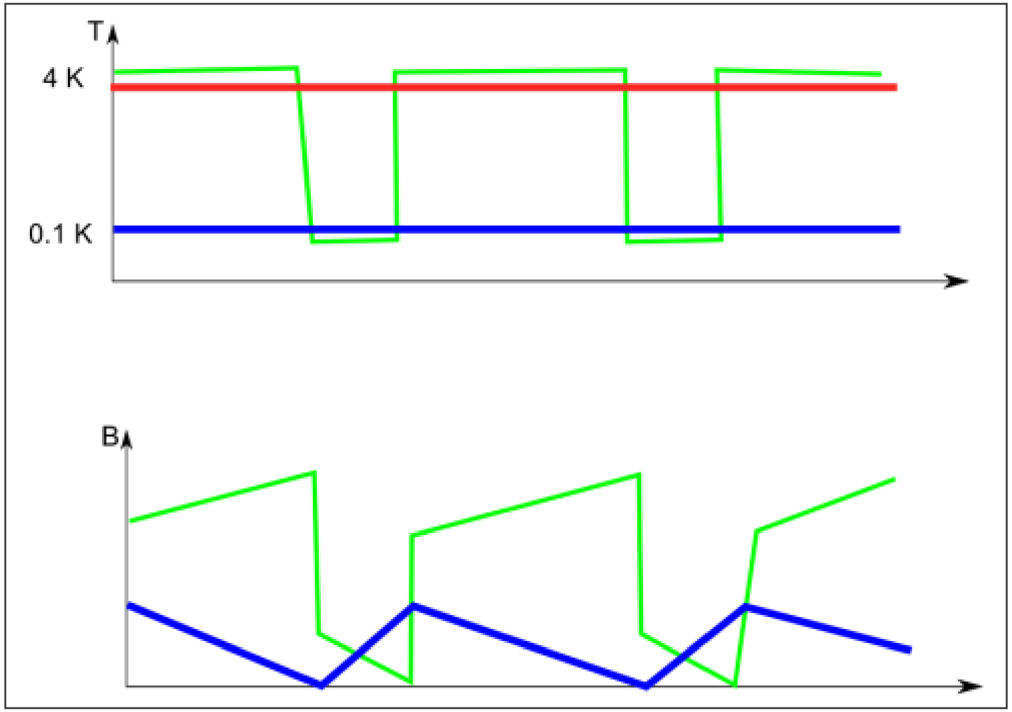
Parallel configuration is complex

4 Heat Switches required

Series configuration continuous cooling

- **Series configuration**
  - First stage goes from Tcold to Twarm
  - Last stage always at constant temperature





- Cold temperature regulated thanks to control of stage 2 magnetic field
- Heat rejected at warm temperature through first stage (like a bucket brigade)

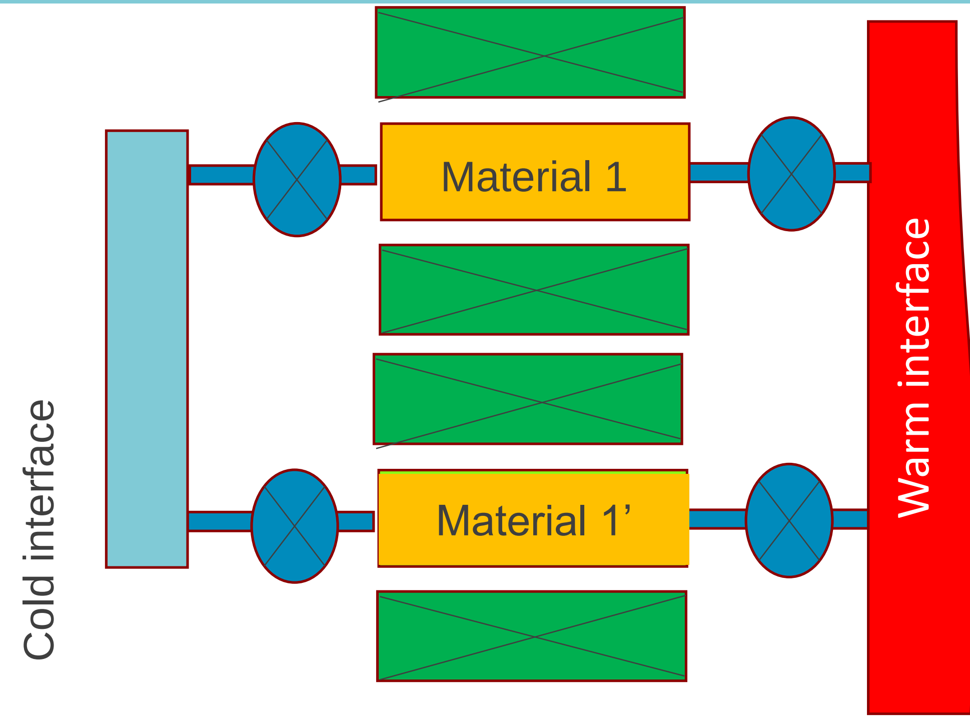
See work of P. Shirron et al (NASA/Goddard) on continuous operation

Continuous operation with 2 stages

Series configuration brings key advantages :

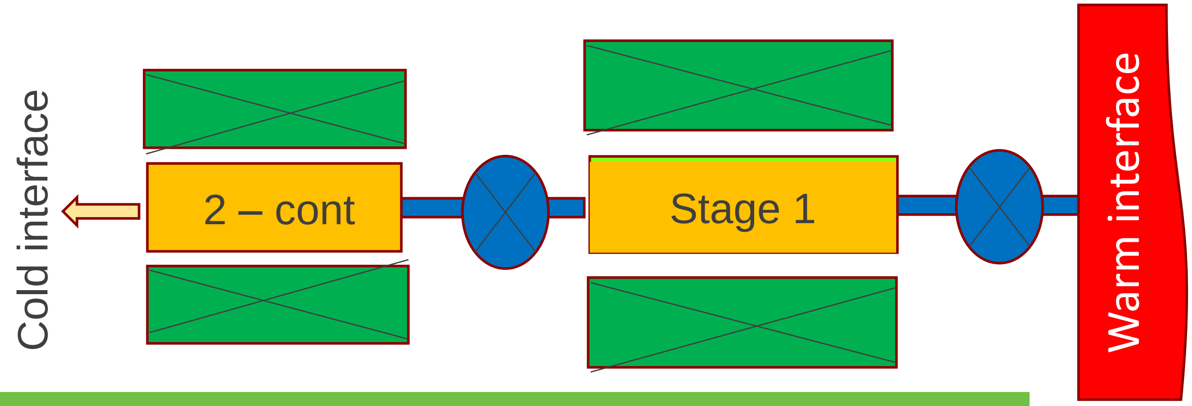
- Only 2 heat switches
- Lower mass of stage 2 (smaller magnetic field)

In most cases, series configuration leads to a more optimized design



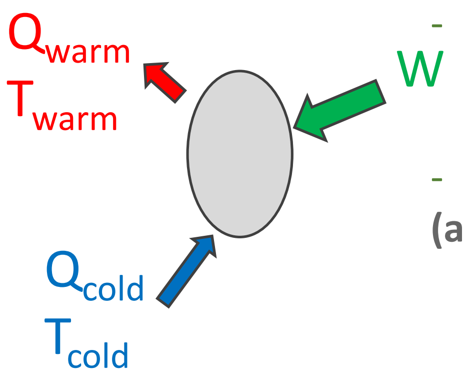
Continuous coolers design

Focus on optimization of mass and efficiency



D. Schmoranzer presentation on continuous nuclear demagnetization refrigerator

Factor of merit / Objectives



How to define thermodynamic efficiency?

- Standard cooler

$$COP = \frac{Q_{Cold}}{W} \qquad COP_{Carnot} = \frac{T_{Cold}}{(T_{warm} - T_{Cold})}$$

- ADR cooler (and subkelvin in general)

$$COP = \frac{Q_{Cold}}{Q_{warm}} \qquad COP_{Carnot} = \frac{T_{Cold}}{T_{warm}}$$

$$\eta_{Carnot} = \frac{COP}{COP_{Carnot}} < 1$$

ADR 'process' is reversible => η ~1

Design objectives for ADR

Targets :Temperature, Cooling power

- **One-shot ADR**
  - Maximize : hold time
  - Minimize: Mass, Volume
- **Lab Continuous ADR**
  - Maximize cooling power
  - Minimize volume (or cost)
- **Space Continuous ADR**
  - Maximize thermal efficiency
  - Minimize mass

Magnetocaloric material => Mass and Volume (Proportional to material and B)

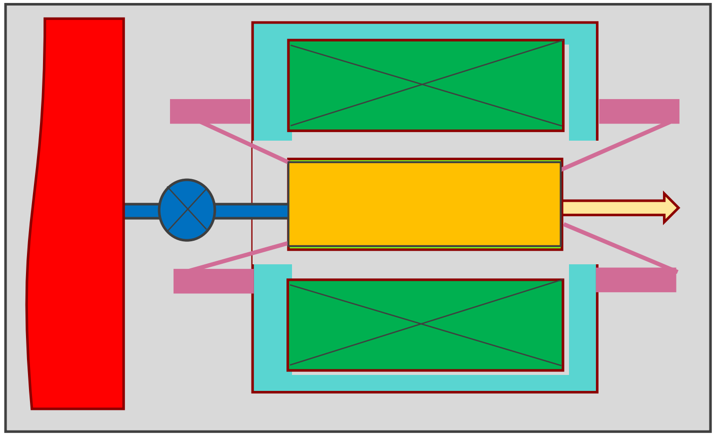
Heat switches, Support => Thermal efficiency

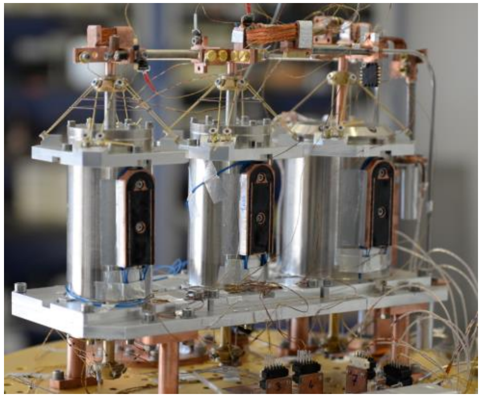
ADR Coolers

1. **Description and operation**

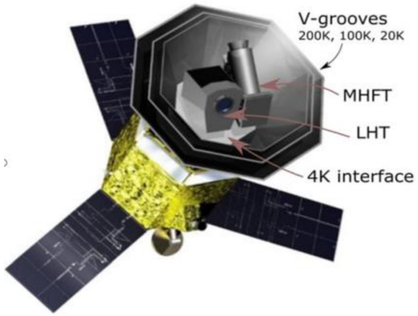
2. **Core components**
   - Magnetocaloric Materials
   - Heat switches
   - Superconducting coils
   - Electronics
   - …

3. **Applications**
   - Laboratory work
   - Space applications





Paixao et al, 2018

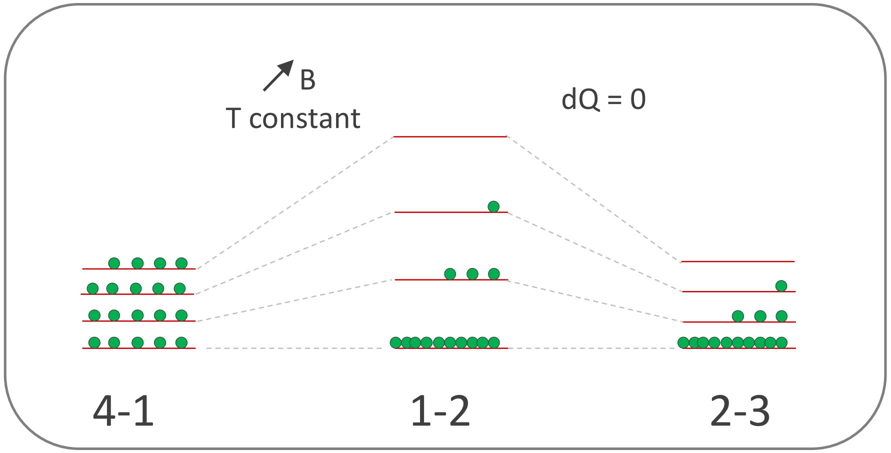


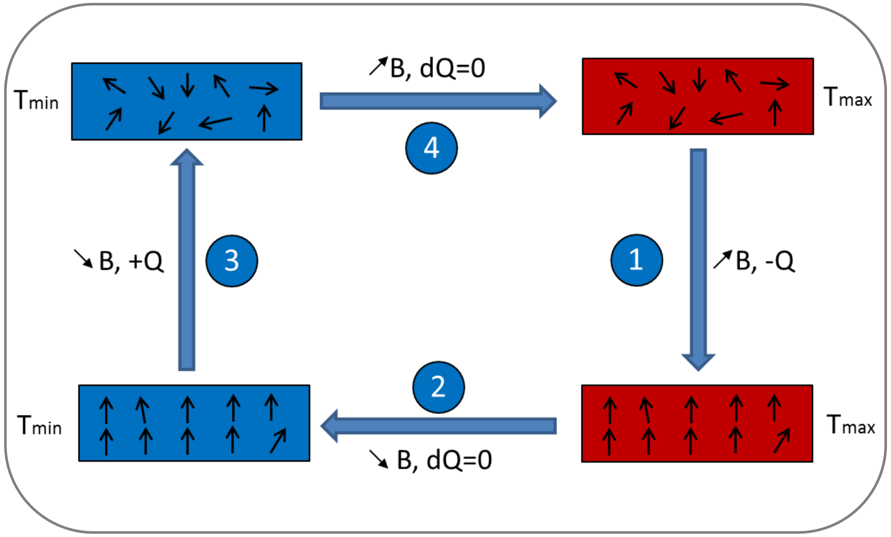
Principle

▶ Boltzmann distribution

$$P(E_m) \propto e^{-E_m/k_B T} \qquad P(E_m) \propto e^{-\frac{mg\mu_B}{k_B}.B/T}$$

$$E_m = mg\mu_B B, -J \leq m \leq J$$





Difficult to present a diagram => ST diagram are best!

▶ Standard model based on free ion approximation

$$Z = \left[\sum_{m=-l}^{l} \mathrm{P}(E_m)\right]^{n.N_0}$$

$$S = k_b \frac{d}{dT}(T\ln Z)$$

$$\frac{S(B,T)}{R} = \ln\left[\frac{\sinh(2J+1)\frac{x}{2}}{\sinh\frac{x}{2}}\right] + \frac{x}{2}\coth\left(\frac{x}{2}\right) - \frac{(2J+1)}{2}x\coth\left((2J+1)\frac{x}{2}\right)$$

$$x = \frac{g\mu_B}{k_B}\frac{B}{T}$$

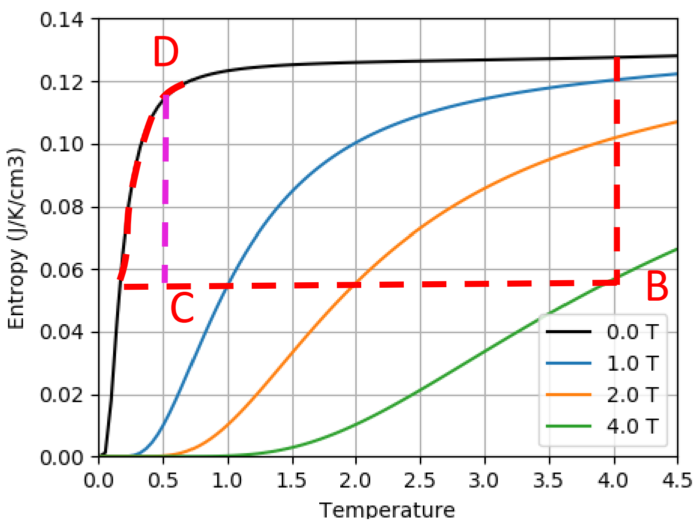
Principle

- **Boltzmann distribution**

$$P(E_m) \propto e^{-\frac{m g \mu_B}{k_B}.B/T}$$

$$S_{max} = nR\ln(2J+1)$$

$$\frac{S(B,T)}{R} = \ln\left[\frac{\sinh(2J+1)\frac{x}{2}}{\sinh\frac{x}{2}}\right] + \frac{x}{2}\coth\left(\frac{x}{2}\right) - \frac{(2J+1)}{2}x\coth\left((2J+1)\frac{x}{2}\right)$$



- **Constant B/T => Constant P(Em) => constant S => adiabatic cooling**

- **Free ion model can't represent low field behavior**
  - Interactions at low field
  - **Impact on design and prediction**

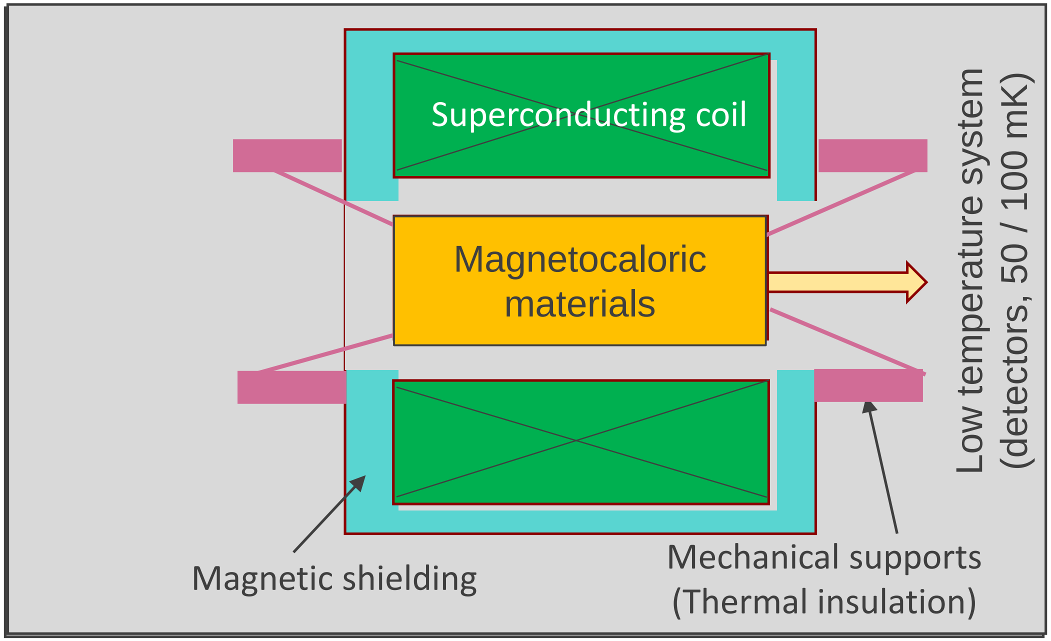
- **Optimum material is a compromise**
  - **Maximize Smax** and hence J and ions density
  - **Minimize Bmax** and hence g (Lande factor)
  - Minimize magnetic moment interactions (for low temperature operations)

- **Optimum material for each use and temperature range**
  - Need the full S versus T diagram (magnetization or DS plots are usually insufficient)

More on materials : see M. Zhitomirsky and E. Riordan presentations

Coil and Magnetic shielding

- **Superconducting coil**
  - Generates a magnetic field of several T
  - For space application, lowest current as possible (typically 2 amps)
  - Manufacturing : vacuum impregnation or « wet winding »



G. Donnier-Valentin on superconducting coil

- **Magnetic shielding**
  - Necessary to protect sensitive detectors and materials
  - Typical solution :
    - Ferromagnetic shield
    - For high field : active shielding (based on NMR design)
  - Innovative solution based on superconducting shielding

Magnetic shielding

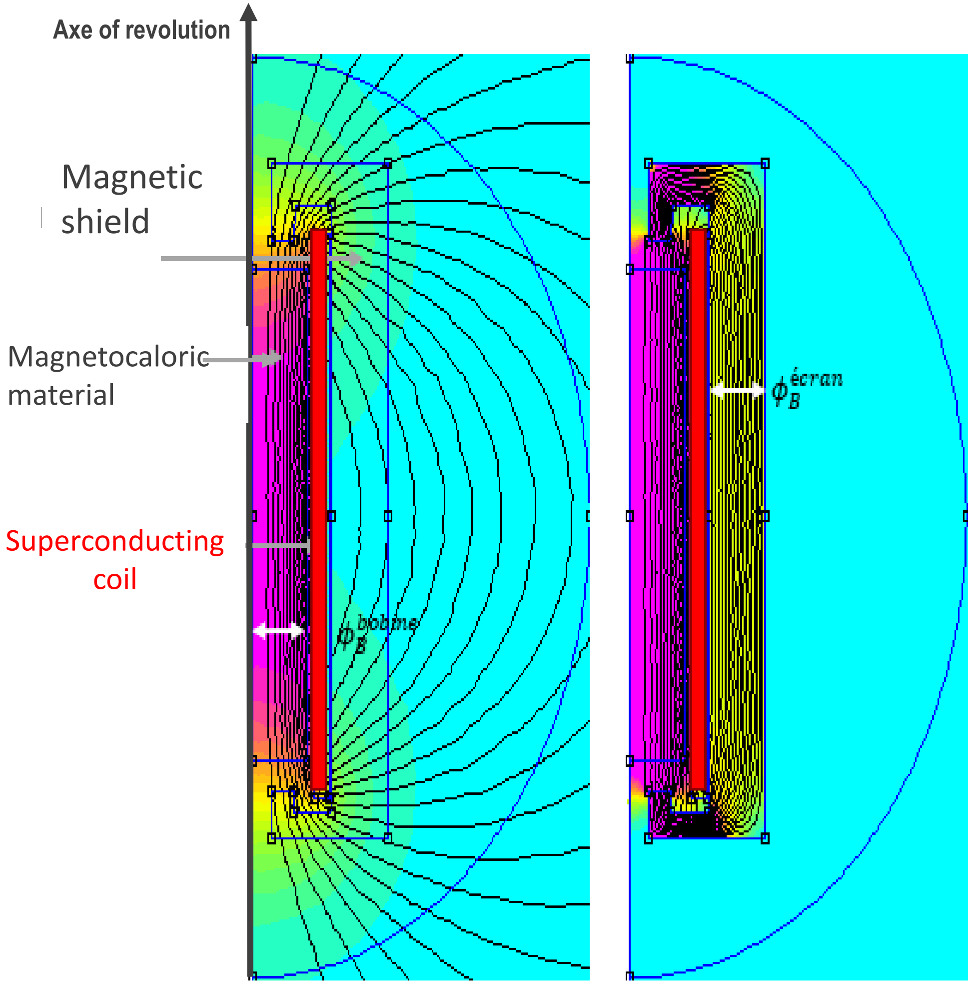
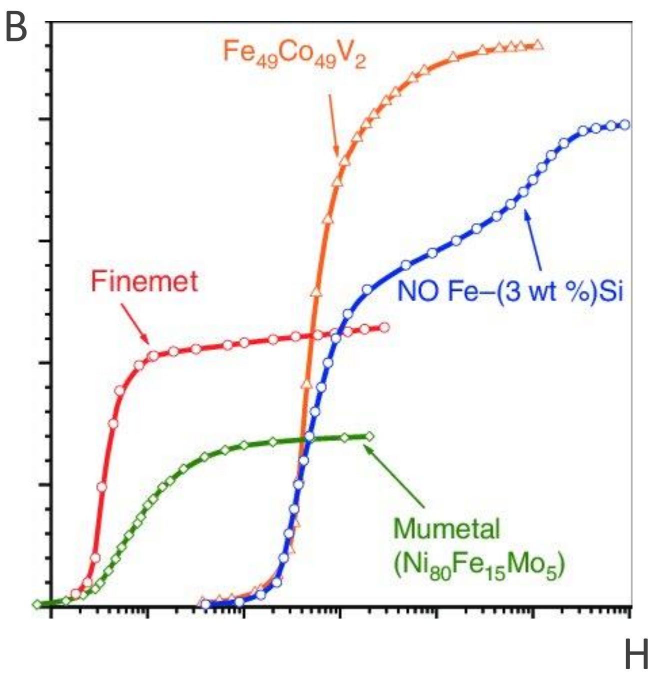


Illustration credit A. Leon, DSBT, 2020



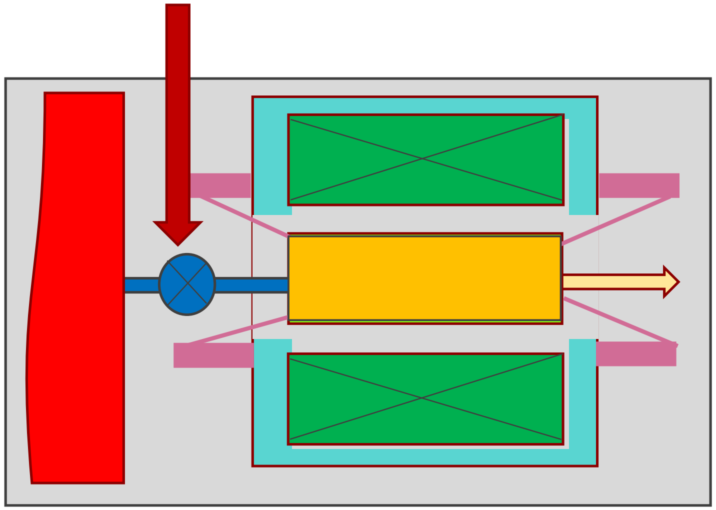
Choice of ferromagnetic materials depends on magnetic field

Characterization needed at low temperature!

Heat switches

Purpose : switching from thermally conductive to insulator

- **3 main technologies**
  - Mechanical heat switches
  - Gas-gap heat switches
  - Superconducting heat switches



Mechanical heat switches

Principle

- Mechanical contacts
- Activation by a motor

Characteristics

➕ No (or low) OFF conduction

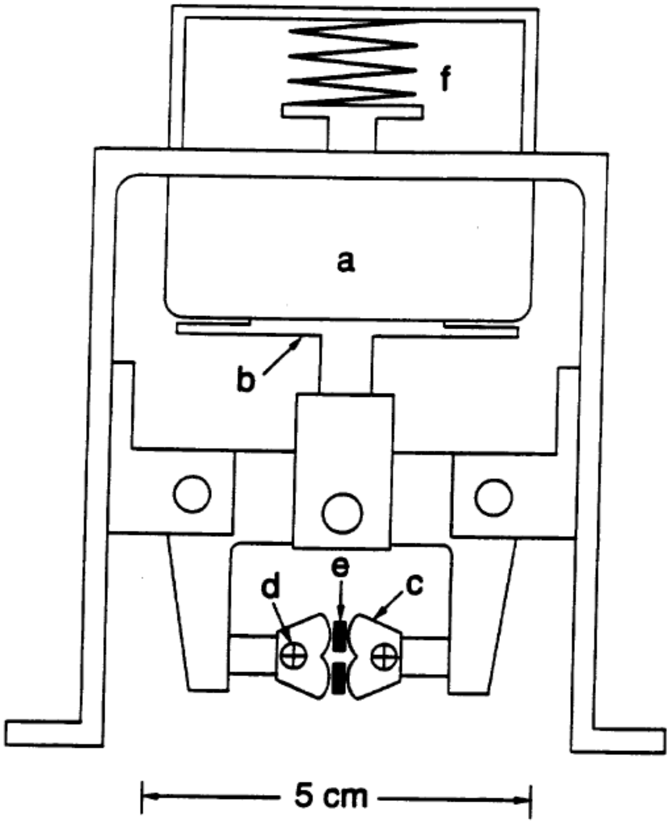
➖ Limited ON conduction (mechanical contact)

➖ Moving parts => risk of failure

Use

- Very efficient for long hold time experiment (no OFF conductance)
- Not suitable for continuous cooler (low ON conduction)
- Labs / Rocket/Balloon

Example



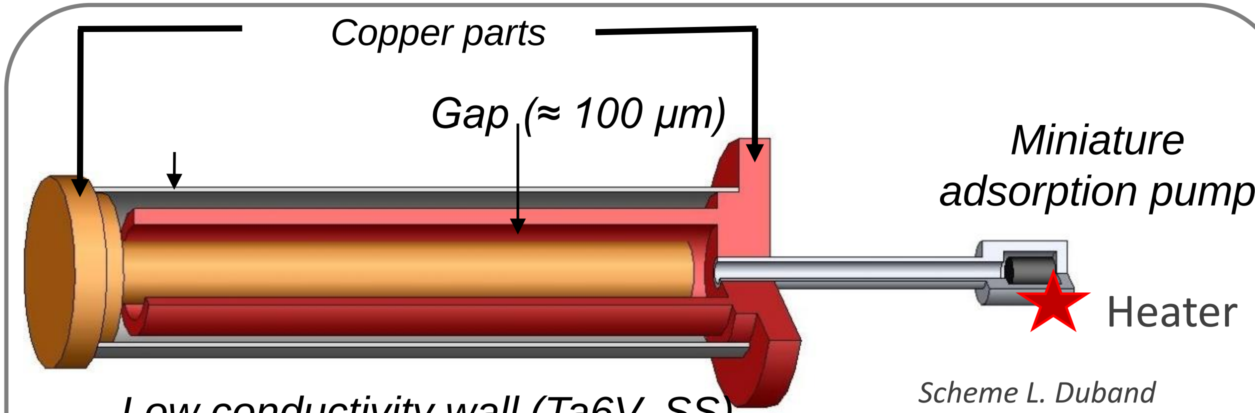
Hagmann et Richard, 1995

Large force required for good ON conductivity

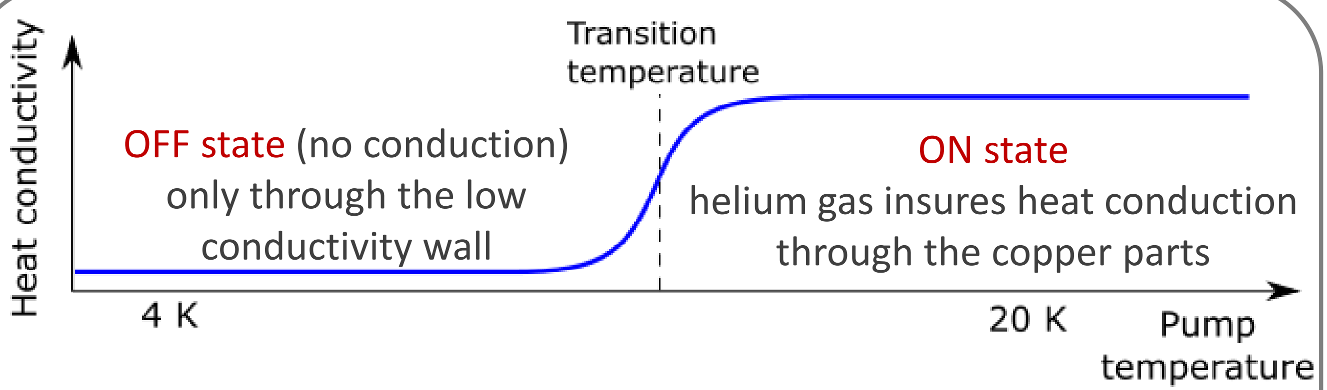
Gas gap heat switches

Design and principles

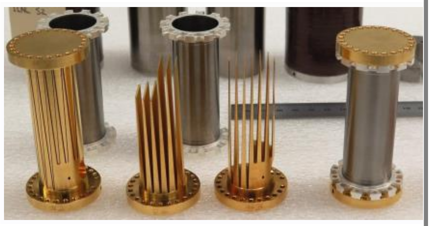
- Sealed device filled with helium gas
- Activation (ON or OFF) controlled by temperature of adsorption pump
- Heat flows through two main copper parts and a gas gap



Scheme L. Duband



Also in come shape



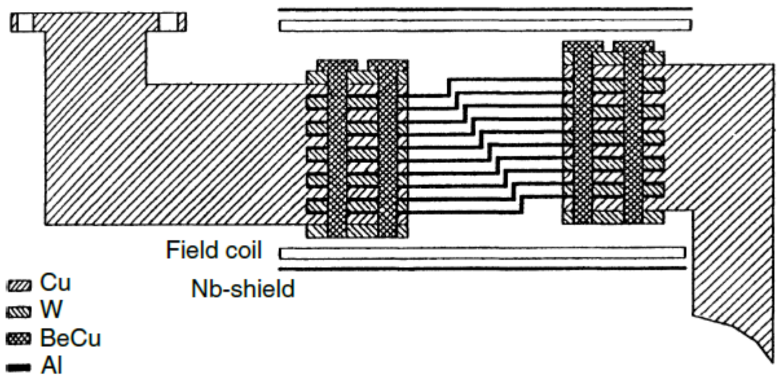
e.g. Shirron et al

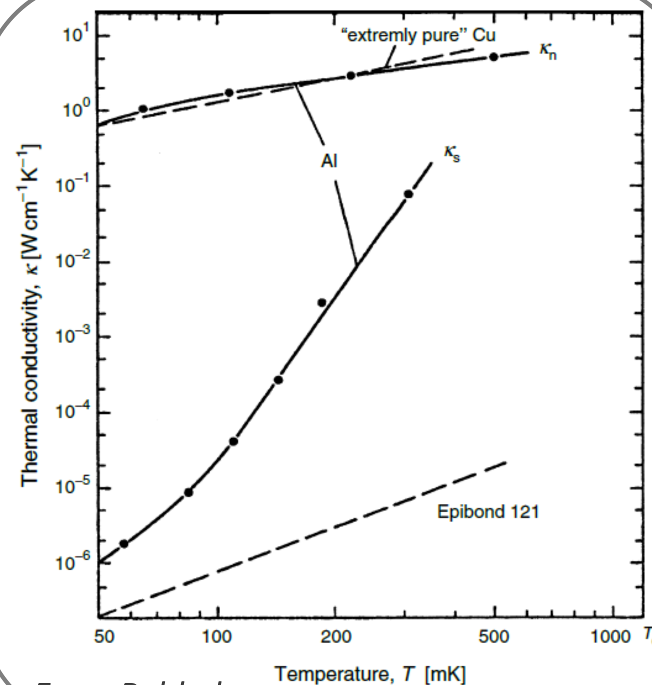
No moving parts, reliable, high ON/OFF ratio (>1000), good for T>0.3 K

Superconducting heat switches

Principle

- Low heat conductivity of superconducting material
- Transition from normal to SC thanks to applied magnetic field (~10s of mT)





From Pobbel

Material candidates

Aluminum, Lead, Indium, …

Critical points

Efficient only T<0.1 Tc
Contact heat conductivity
Magnetic system design
Aluminum, Lead, Indium, …

Only for T<<1.0 K

Main technology for T<0.2 K

CEA/CNRS

Shirron et al

S. Triqueneaux on nuclear adiabatic demagnetization

Key component : heat switches

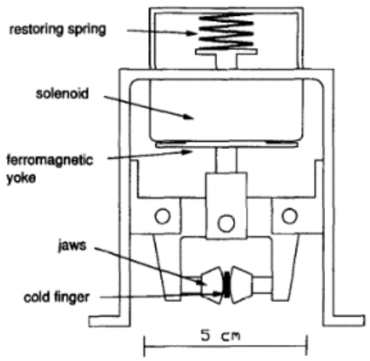
>3 heat switches technologies

+ Others (magnetoresistive …)

- **Mechanical heat switches**

Mechanically connect two parts

- Excelllent OFF position (~0)
- Low ON conductivity (contact resistance)



Hagmann et Richards, 1995

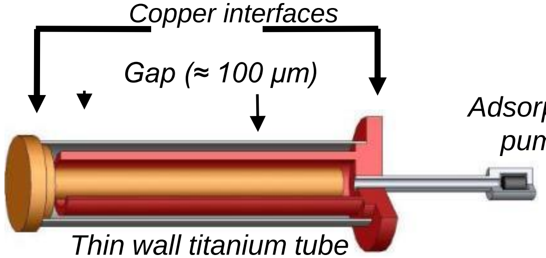
Excellent for one-shot ADR (except reliability)
Not adapted for continuous ADR

- **Gas Gap Heat switches**

Evacuate gas to pass OFF position

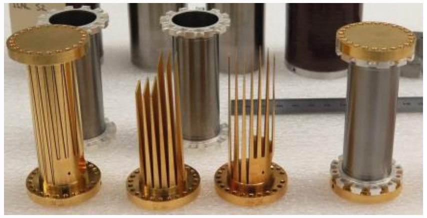
- Excellent ON position (T>0.5 K)
- Slow switching

Concentric shape



e.g. Duband et al

Come shape



e.g. Shirron et al

Reliability
Limited below ~300 mK

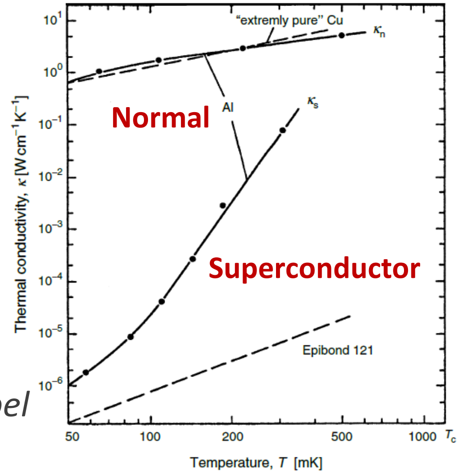
- **Superconducting heat switches**

« break » superconductivity with magnetic field

CEA /CNRS

Shirron et al

From Pobbel



Only technology for T_{ON}< 0.3 K (Continuous ADR)

Heat switches are crucial for continuous operation (thermal efficiency depends 90% of heat switches and thermal links)

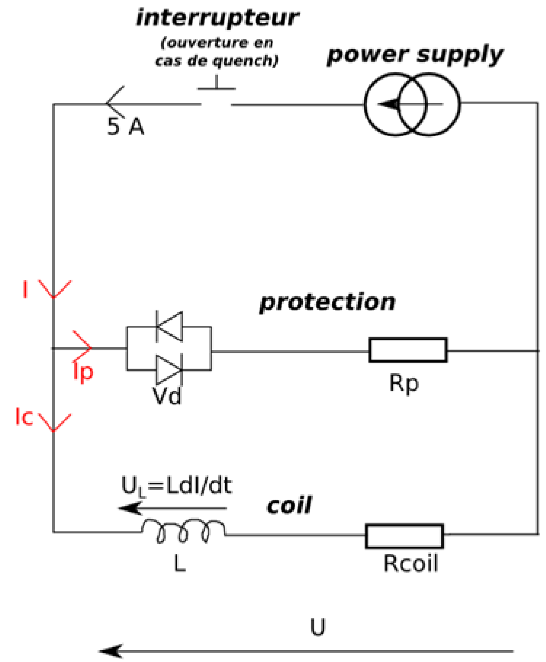
Other (also important) points

- **Temperature measurement**
- **Superconducting coil current control**

Commercial solutions : Lakeshore, AMI, …

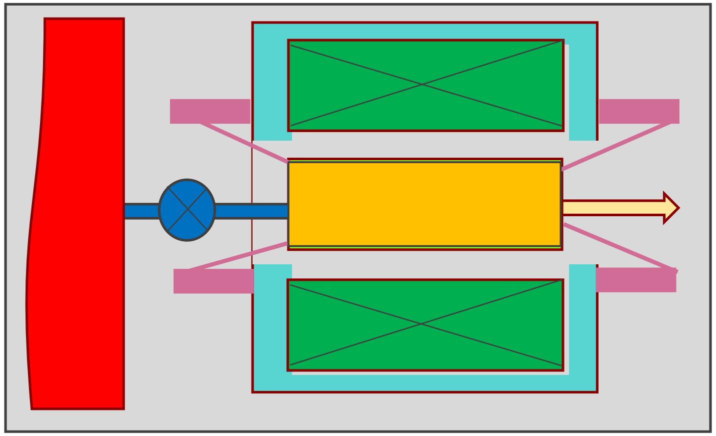
Specific developments at I. Neel (ex MMR3) and at DSBT and others

- **Quench protection**
  - Typical system based on diodes back to back in parallel with coil (dissipated energy in case of quench)



- **Current leads**
  - HTS superconducting wire commercially available for cryostat equipment
  - Specific development needed for space
- **Algorithm for continuous design**
  - Dedicated development for each experiments
- **Modelling and performance predictions**

ADR Coolers



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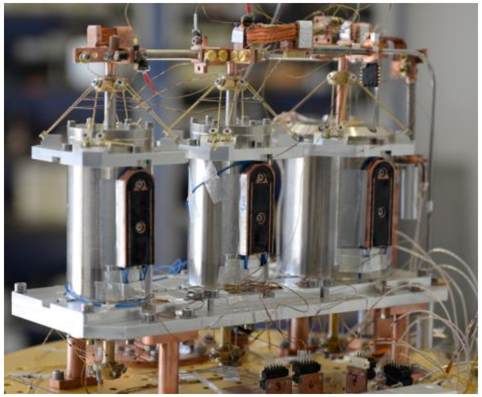
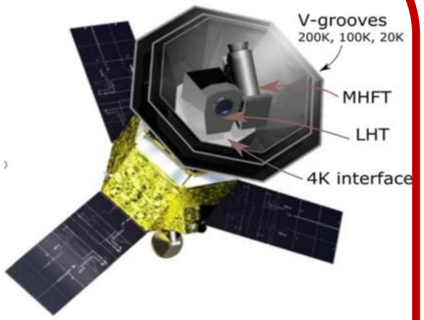




Paixao et al, 2018

First experimental demonstration

- **Predicted from the 1920s**
  - Giauque
  - Debye
- **First demonstration in 1933**
  - Giauque, 1933

Attainment of Temperatures Below 1° Absolute by Demagnetization of $Gd_2(SO_4)_3 \cdot 8H_2O$

We have recently carried out some preliminary experiments on the adiabatic demagnetization of $Gd_2(SO_4)_3 \cdot 8H_2O$ at the temperatures of liquid helium. As previously predicted by one of us, a large fractional lowering of the absolute temperature was obtained.

An iron-free solenoid producing a field of about 8000 gauss was used for all the measurements. The amount of $Gd_2(SO_4)_3 \cdot 8H_2O$ was 61 g. The observations were checked by many repetitions of the cooling. The temperatures were measured by means of the inductance of a coil surrounding the gadolinium sulfate. The coil was immersed in liquid helium and isolated from the gadolinium by means of an evacuated space. The thermometer was in excellent agreement with the temperature of liquid helium as indicated by its vapor pressure down to 1.5°K.

On March 19, starting at a temperature of about 3.4°K, the material cooled to 0.53°K. On April 8, starting at about 2°, a temperature of 0.34°K was reached. On April 9, starting at about 1.5°, a temperature of 0.25°K was attained.

It is apparent that it will be possible to obtain much lower temperatures, especially when successive demagnetizations are utilized.

W. F. Giauque
D. P. MacDougall

Department of Chemistry,
University of California,
Berkeley, California,
April 12, 1933.

Giauque, W. F., et D. P. MacDougall. « Attainment of Temperatures Below 1 ° Absolute by Demagnetization of Gd2(SO4)3·8H2O ». Physical Review 43, nº 9 (1 mai 1933): 768-768.

- **Applications and current status**
  - Main technology until the 1960's for low temperature physics
  - Mostly replaced by dilution fridge : more powerful, continuous cooling
  - Renewed interest for space application (including rockets or balloons) since the 1990s
  - Takes advantages of availability of superconducting coils

Laboratory applications

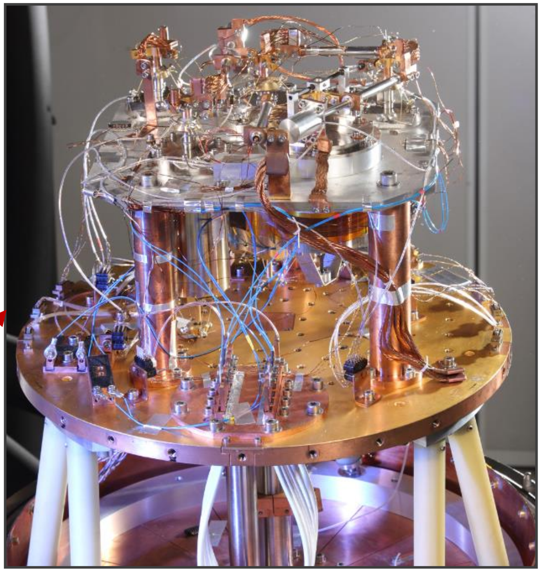
- **Mostly in competition with dilution for ground application**
  - Limited in energy (cooling power and experiment time) and mostly replaced by dilution

- **Advantages**
  - Easy control of temperature
  - Lower cost (than dilution coolers)
  - Reliability
  - No ^{3}He needed

- **Application for specific needs**
  - Commercial coolers (Entropy, HPD, …)
  - PPMS
    - Takes advantage of existing magnetic system

C. Marcenat presentation on PPMS

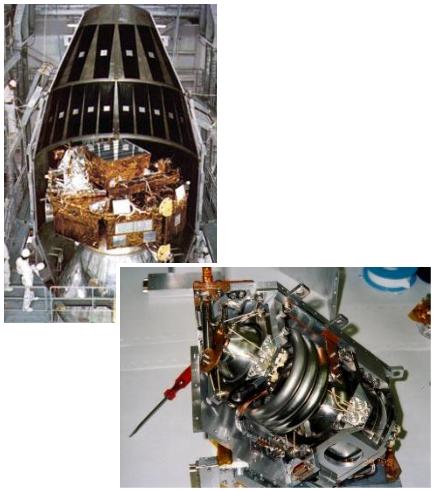
  - Laboratory demonstration of continuous cooling
  - Considered for high cooling power application
    - LHC studies in the 1980-90s
    - Looked again for e.g. FCC study



P. Camus presentation on Easycool

4 “Subkelvin” missions launched, 1 ADR

IRTS - SIRTF
1995

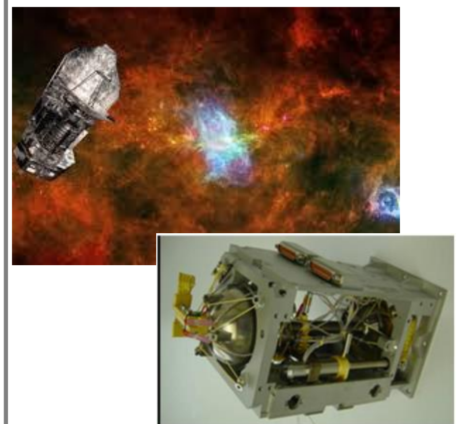


CMB

300 mK

Sorption cooler

Herschel
2009



Infrared
astronomy

300 mK

Sorption cooler

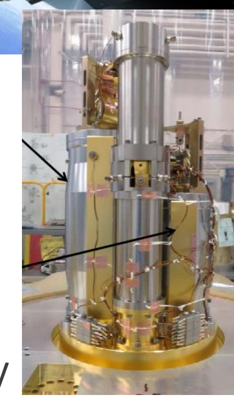
Planck
2009

CMB

100 mK

Dilution cooler

Astro-H, 2017
(and Astro-E2, 2012)



X-ray
Astronomy

50 mK

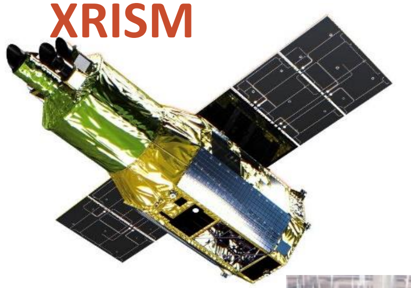
ADR

4 missions, 3 cryocoolers technologies: Sorption, Dilution, ADR

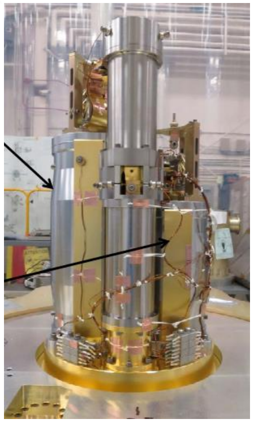
References : Matsubara (1996), Ade et al, A&A(2011), Kelley (2016), “Status Report on Astro-H.”

3 astrophysics missions in preparation

XRISM

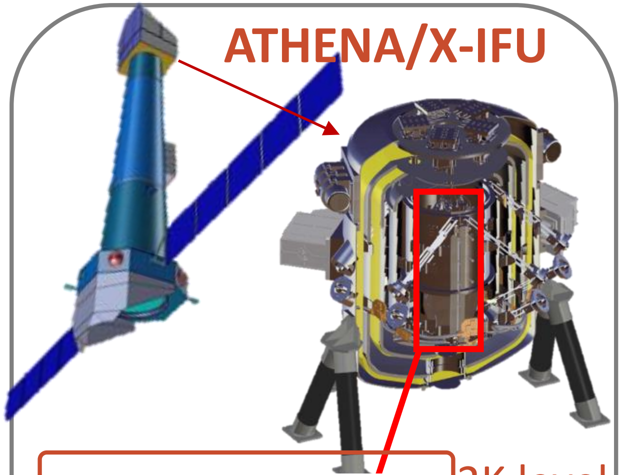


3-stage
ADR cooler

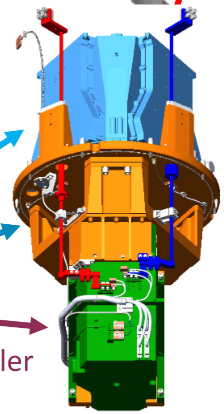


See innovative and extended work by P.Shirron et al at NASA Goddard on Space ADR

ATHENA/X-IFU



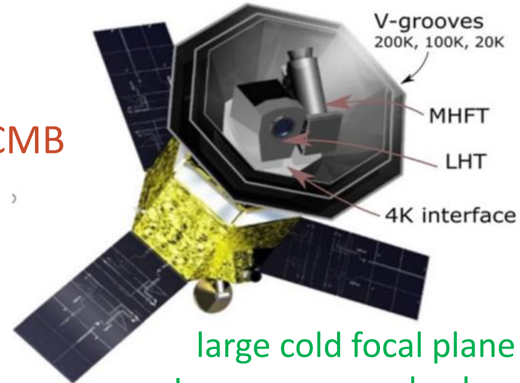
2K level
~25 kg



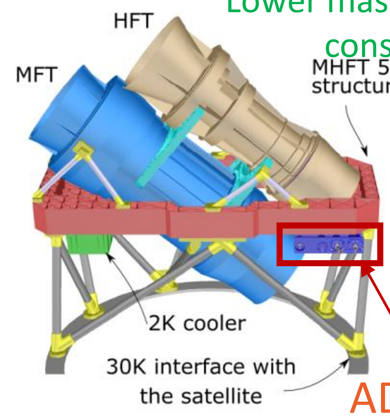
Courtesy F. Bancel, I. Charles

LiteBIRD

CMB



large cold focal plane
Lower mass and volume constraints



ADR cooler

3 + 4 stages ADR cooler

ADR coolers main space technology for T<250 mK
+ Dilution used on Planck and continuous development at I. Neel

L. Duband presentation

ADR considered for all current missions in advanced phase of development

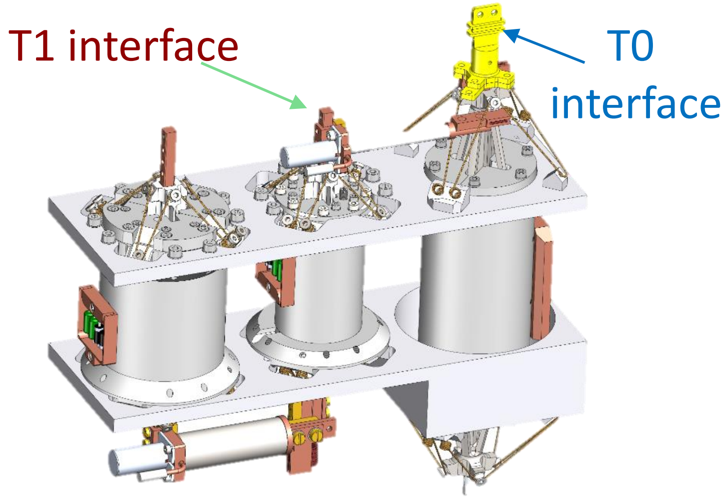
3-stage ADR for LiteBIRD

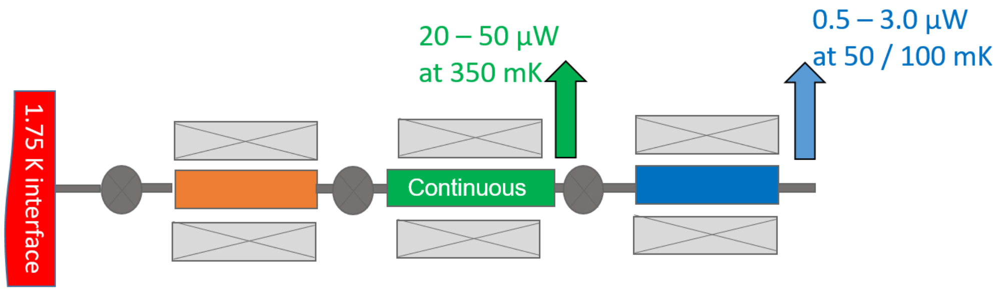
- **Interfaces:**
  - Low power dissipation on 2 K stage (<2 mW) and 4 K stage (<1 mW)
  - High cooling at intermediate stage 45 µW ~350 mK
  - Continuous (or high duty cycle) 100 mK cooling (2 µW)

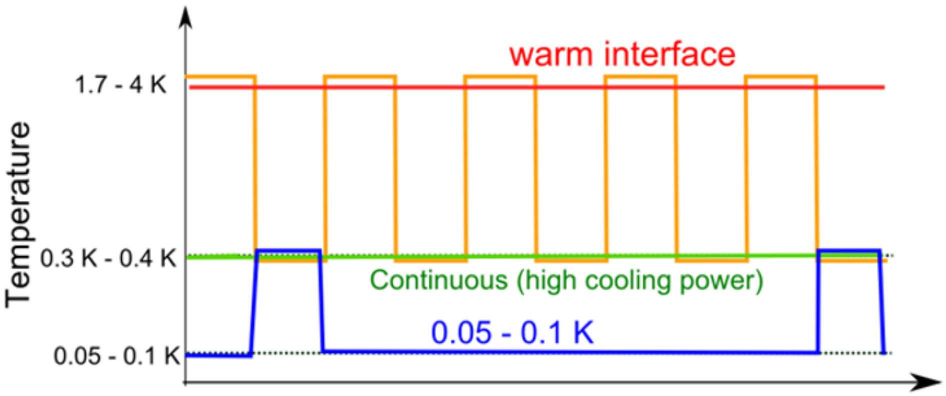
- **Take advantage of "new" material for a light 2K – 350 mK stage (YbGG)**

Material manufacturing work done with Pheliqs (C. Marin)

See E. Riordan presentation on detailed properties of YbGG







Conclusion

- **ADR technology developments mostly pushed by space applications**
  - Major technology for sub-kelvin cooling for space
  - Useful technology for specific laboratory experiments

- **Technological developments in various fields**
  - Cryogenics and Space cryogenics
  - Physics and theory
  - Material science engineering
  - Electronics
  - Magnetism
  - Mechanical and thermal engineering
  - …
- **Many communalities with nuclear demagnetization**

Key actors within Grenoble / Lanef community (and partners)

I'm looking forward to hearing all your talks today…

and to working together in the future