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Study of a magnetic refrigeration stage

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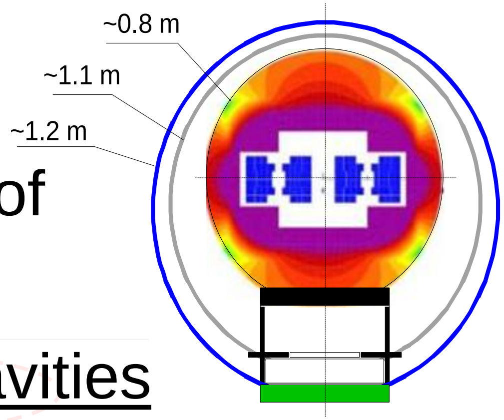
Contents

- ✓ **Motivations**
- ✓ **Magnetic refrigeration principles**
- ✓ **Review of the state-of-the-art**
- ✓ **Preliminary design study**
- ✓ **Conclusions**

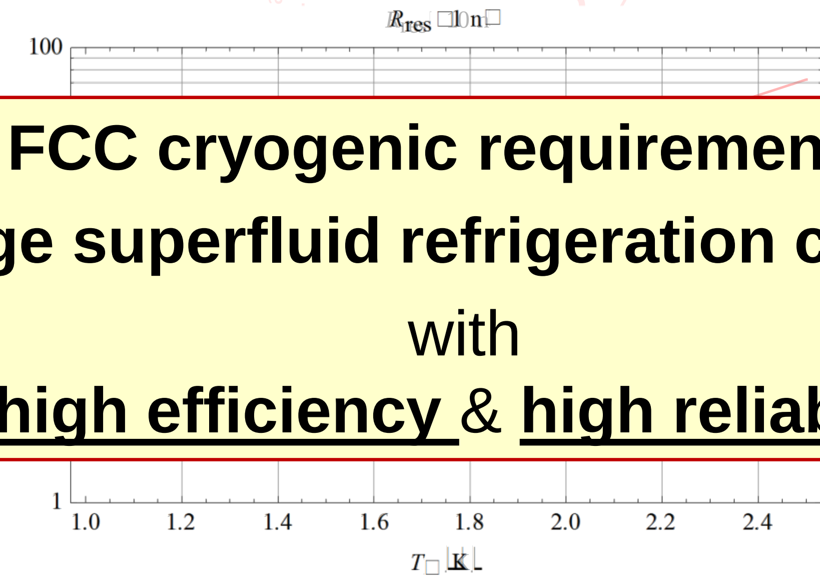
E.Palmieri / INFN

Superfluid Helium cooling for :

- High-field superconducting magnets of FCC-hh ***(10 kW range at 1.8 K)***
- High-gradient superconducting RF cavities of FCC-ee ***(5 kW range down to 1.6 K)***



L. Tavian / CERN



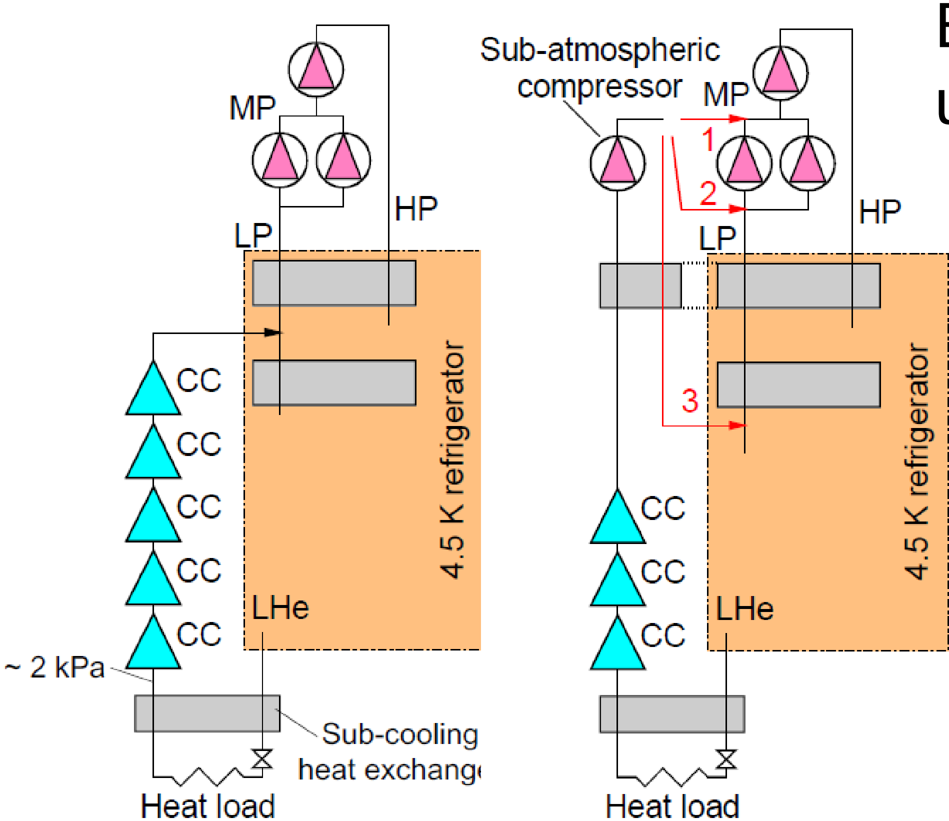
E.Jensen / CERN

FCC cryogenic requirements :

Large superfluid refrigeration capacity

with

high efficiency & **high reliability**



"Integral cold" cycle

CEBAF - SNS

"Mixed" cycle"

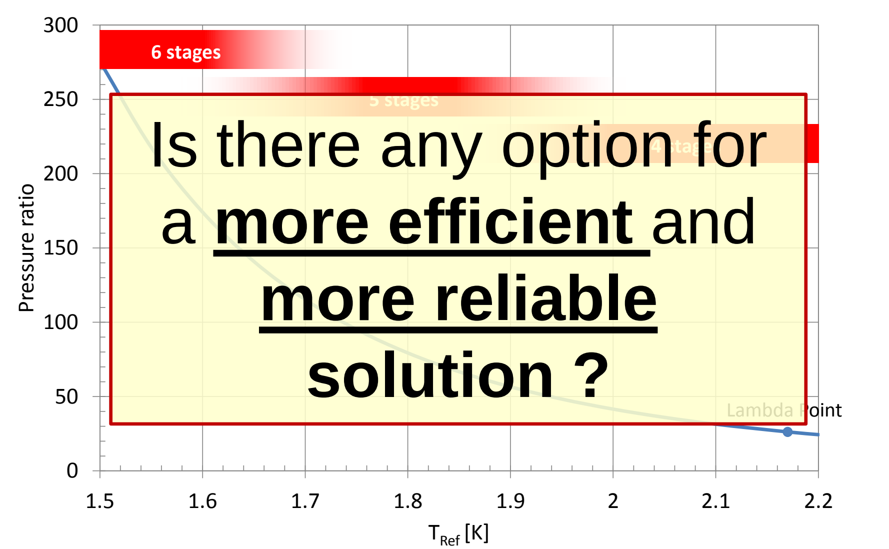
LHC

Generic scheme of < 2 K refrigeration cycles

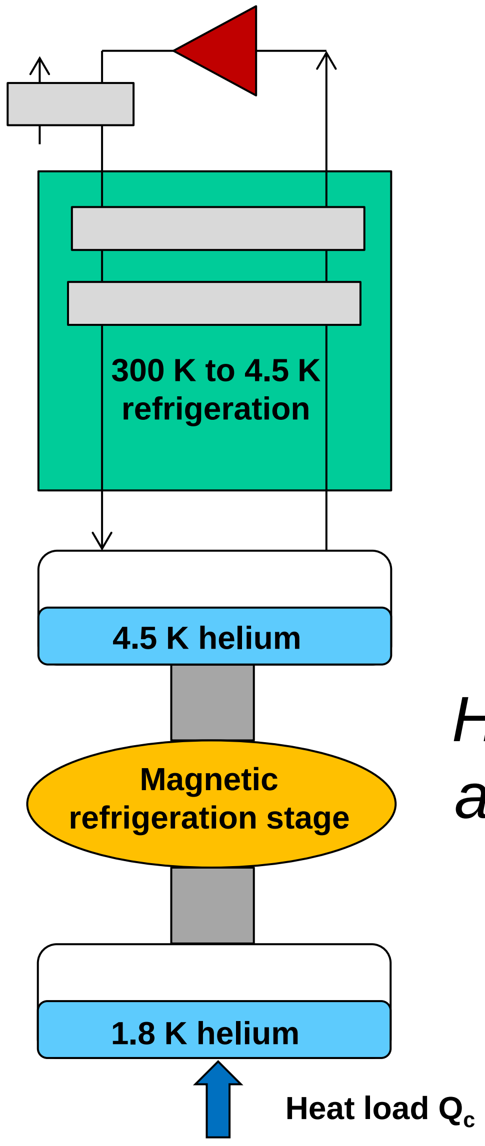
L.Tavian/ CERN

Existing large HeII refrigeration use **cold compressor in series**

- ❑ Complex control strategy
- ❑ Long downtime after stops
- ❑ Limited Carnot efficiency *< 20 %*



Is there any option for a **more efficient** and **more reliable solution ?**



- **More reliable** ?

Cold compressors could be totally or partially replaced by a Magnetic Refrigeration stage

- **More efficient ?**

High Carnot efficiency (> 50%) already measured at low cooling capacity for Magnetic Refrigeration stage between 1.8 K and 4.2 K

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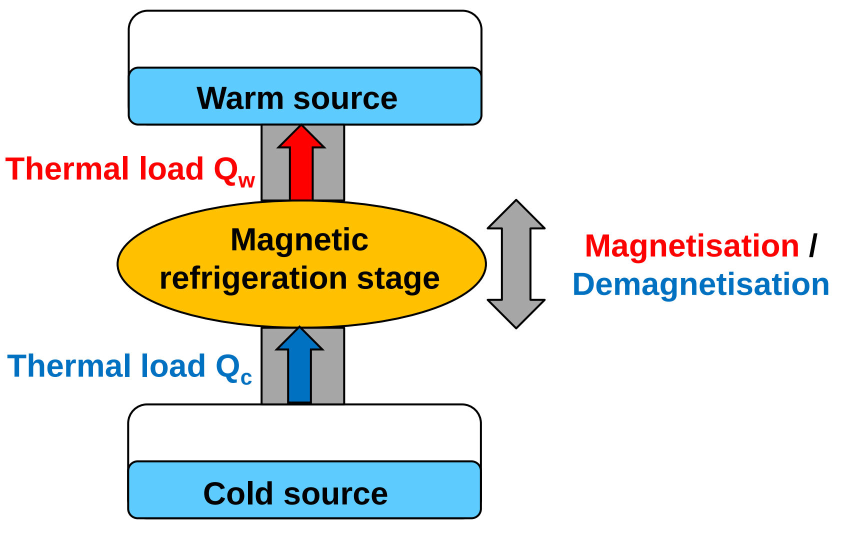
Magnetic Refrigeration or **Adiabatic Demagnetization Refrigeration (ADR)** is a **cyclic cooling system** which alternates between two states :

1. **Operating state :** Cool-down and heat removal from the cold source (Q_c)
2. **Recycling state :** Warm-up and heat rejection to the warm source (Q_w)

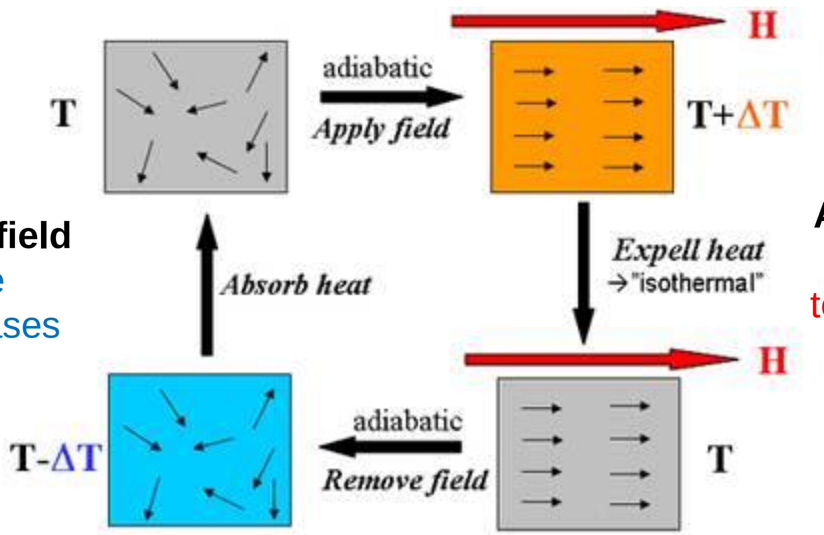


Magneto Caloric Effect

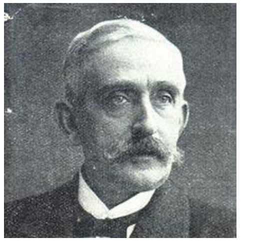
- Magnetic refrigeration is based on the **Magneto-Caloric Effect (MCE)** *(reversible variation of internal energy when applied magnetic field in a suitable material)*

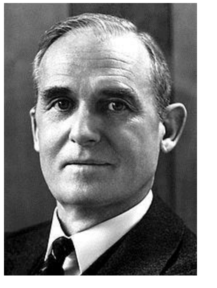
$$MCE = \left(\frac{\partial T}{\partial B}\right)_S$$

Remove magnetic field
spins randomize
temperature decreases



Apply magnetic field
spins align
temperature increases





- *Magneto Caloric Effect was discovered in pure iron in 1881 by Emil Warburg*
- *The cooling technology was first demonstrated experimentally in 1933 by William F. Giauque & D.P. MacDougall (< 1 K)*

IFW Dresden

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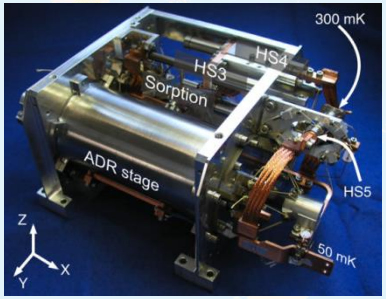
Worldwide works in magnetic refrigeration

- ❑ Sub-kelvin application (space detectors & laboratory cooling)
  Efficient & reliable products (space-qualified)

- ❑ 1 to 4.5 K cooling (LTS magnets & space detectors)
  Laboratory prototypes with achieved high efficiency

- ❑ 20-77 K range (Hydrogen liquefaction)
  On-going R&D

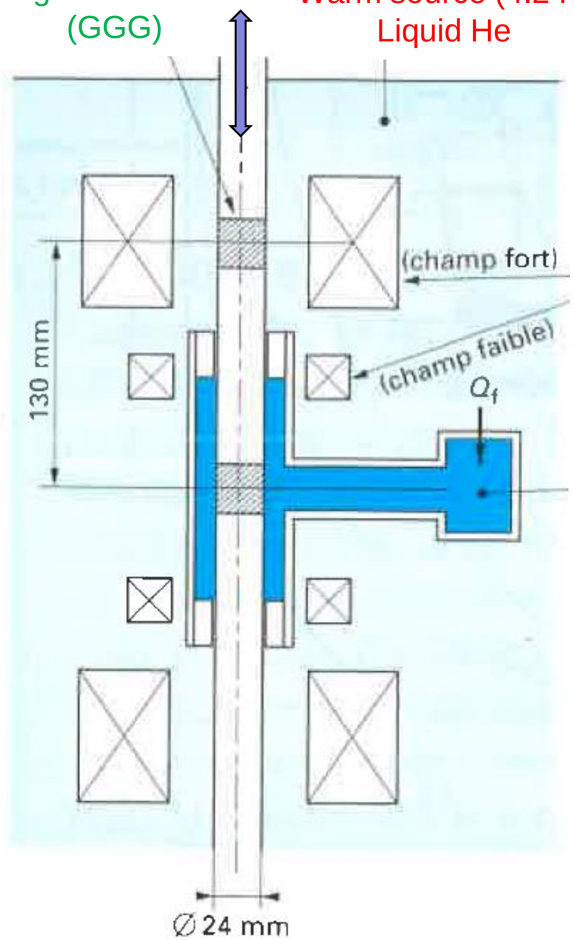
- ❑ Room temperature application
  On-going R&D



Space-qualified 50 mK cooler (CEA/SBT)

Reciprocating magnetic refrigeration between 1.8 K and 4.2 K

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



Cold source	**1.8 K**	**2.1 K**
Useful power Qc	1.35 W	2.2 W
FOM	53%	79,3%
Frequency	0.8 Hz	0.6 Hz
Magnetic field	4 T *(stationary)*	
Magnetic material	GGG *(moving)* *0.1 kg*	
Heat transfer	Alternatively in HeI & Pressurised HeII	
Warm source	**4.2 K**	

=> Carnot efficiency > 50 %

Magnetic refrigeration between 1.8 K and 4.2 K

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

(Y.Hakuraku & al., A Rotary Magnetic Refrigerator for Superfluid Helium Production, 1986)

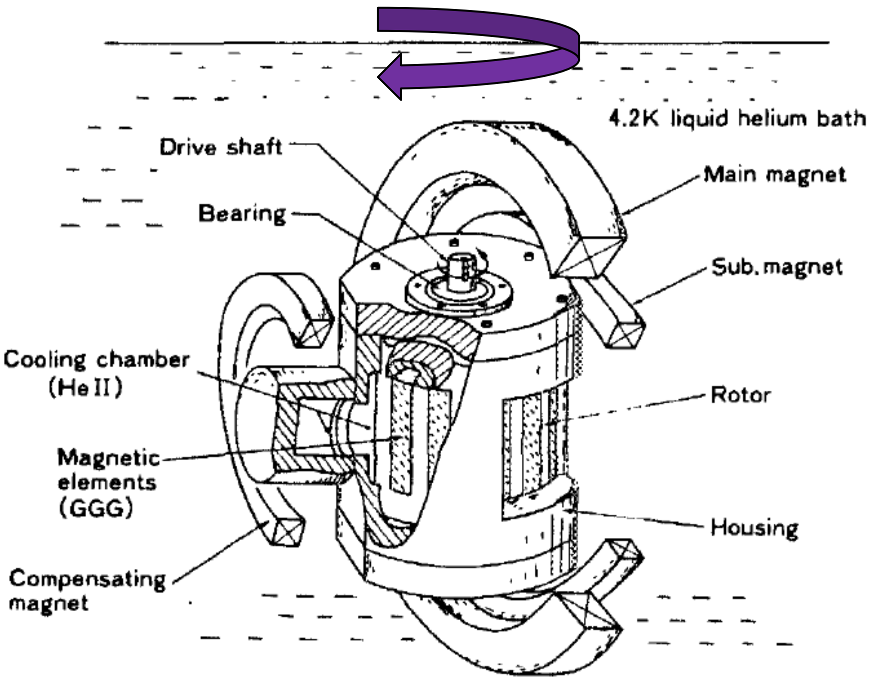


FIG. 1. Rotary-magnetic refrigerator for superfluid helium production.

Hakuraku / Hitachi

Static design / Rotating design

Cold source	**1.8 K**	**1.8 K**
Useful power	1.5 W	1.8 W
FOM	20%	34%
Frequency	0.2 Hz	0.4 Hz
Magnetic field	3 T (pulsed)	3 T (station.)
Mag. material	GGG (static)	GGG (rota.) 1.1 kg
Heat transfer	Permanent in HeI & HeII	Alternatively in HeI or HeII
Warm source	**4.2 K**	**4.2 K**

=> Innovative solutions for heat transfer

Magnetic Refrigeration between 1.8 K and 4.2 K

(A.Bezaguet & al., Design and construction of a static magnetic refrigeration between 1.8 K and 4.5 K, 1994)

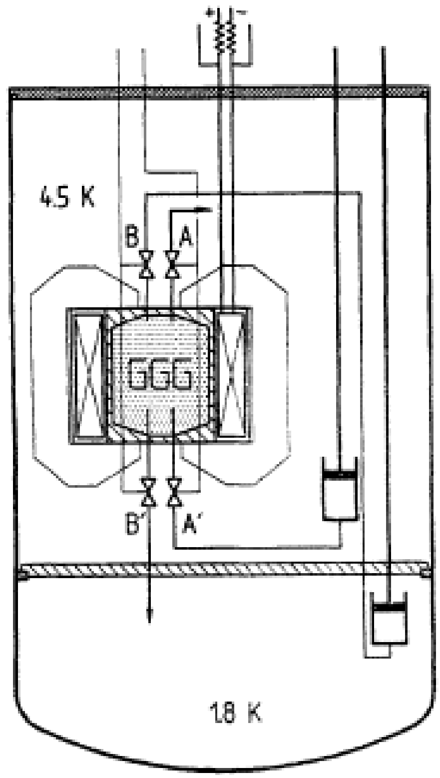


Figure 1 Schematic diagram of the static magnetic refrigerator

M.Schmidt / CERN

Cold source	**1.8 K**
Useful power	*10 W (first tests)*
FOM	*~10% (estimate)*
Frequency	0.2 to 1 Hz
Magnetic field	3,5 T *(pulsed)*
Magnetic material	GGG *(static)* *10 kg*
Heat transfer	Alternatively He I or He II flow circulation
Warm source	**4.2 K**

Works performed during the LHC preparatory phase but stopped just after first tests !

Tandem Magnetic Regenerative Refrigeration between 1.8K-4.2K

(S.Jeong & al., Experimental investigation of the regenerative magnetic refrigerator for 1.8 K, 1994)

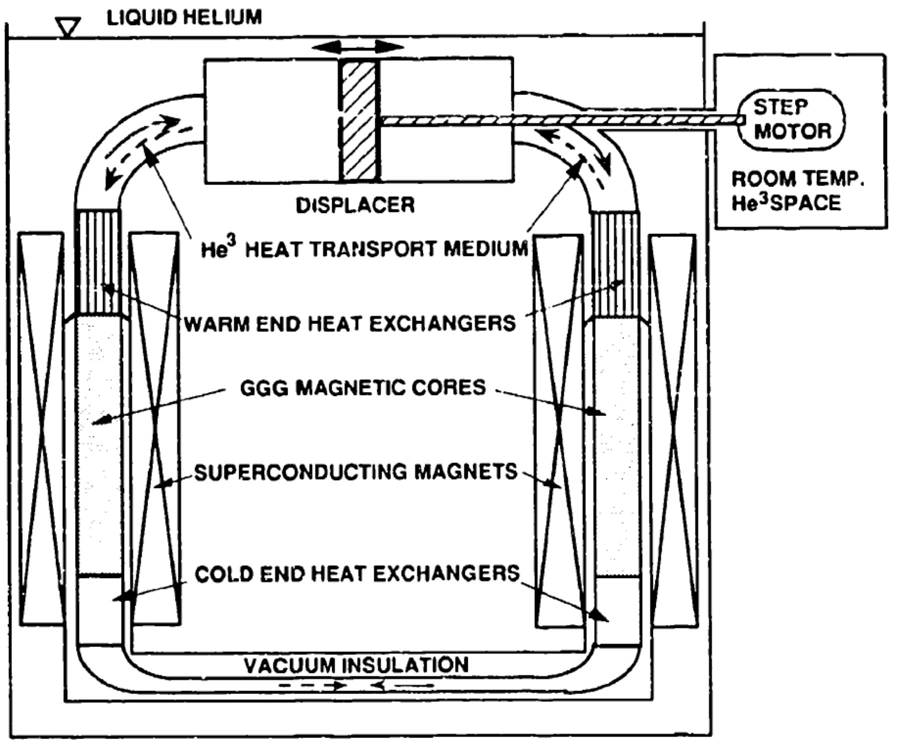


Fig. 1. Schematic diagram of the tandem regenerative magnetic refrigerator.

S.Jeong / MIT

Cold source	**1.8 K**
Useful power	*19 mW*
FOM	*~10% (estimate)*
Frequency	0.07 Hz
Magnetic field	2.8 T *(pulsed)*
Magnetic material	GGG *(static)* *0.135 kg*
Heat transfer	Oscillating He^3 *(60 mbar)*
Warm source	**4.2 K**

=> Tandem operation with He^3 oscillating flow

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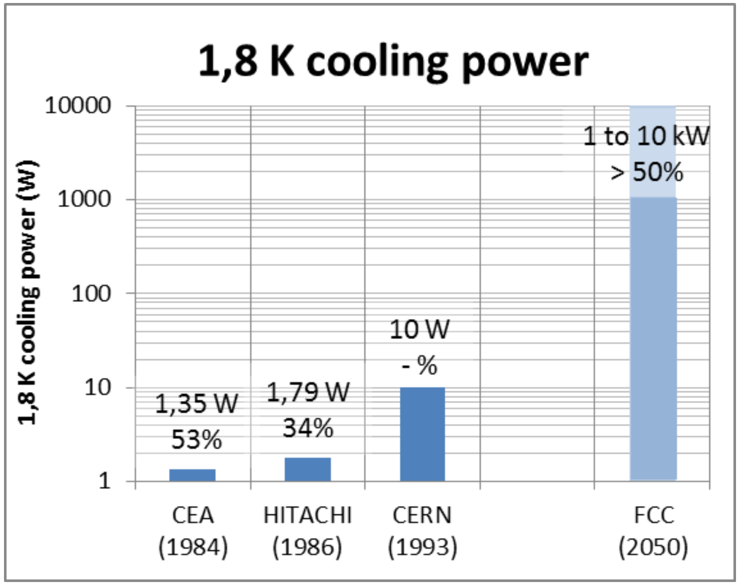
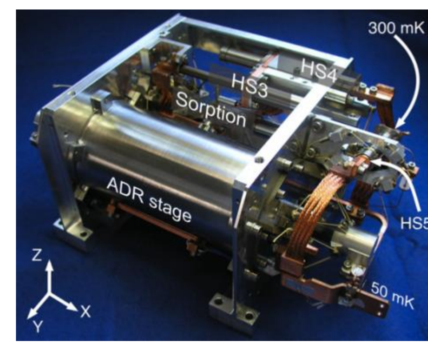


- **Favorable operating temperature** range
  - *< 5 K with high efficiency MCE*
- **High achieved efficiency**
  - *> 50% at 1.8 K*
- **Various design options**
  - *stationnary or pulsed magnet field,*
  - *conduction or convection heat transfer*

=> Need to select a design option and to scale up *towards 1 to 10 kW at 1.8 K or 5 kW down to 1.6 K*

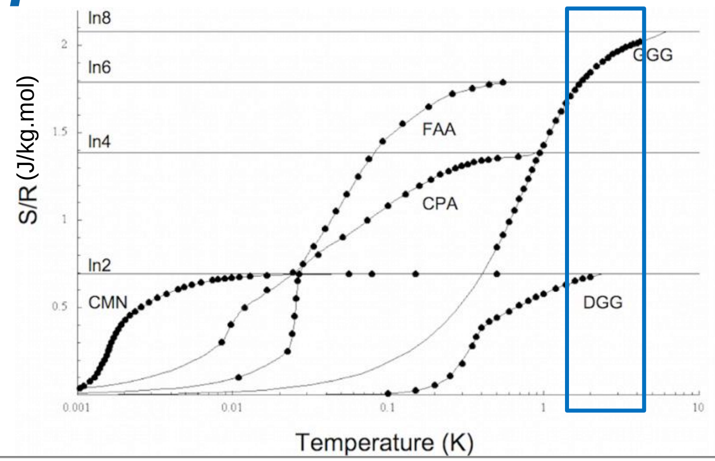
Strong CEA experience in magnetic refrigeration at subkelvin temperature for space cooling (heat switch, heat transfer, paramagnetic material development)



Space-qualified 50 mK cooler

Key parameters selection

Objectives FCC-ee : up to 5 kW down to 1.6 K

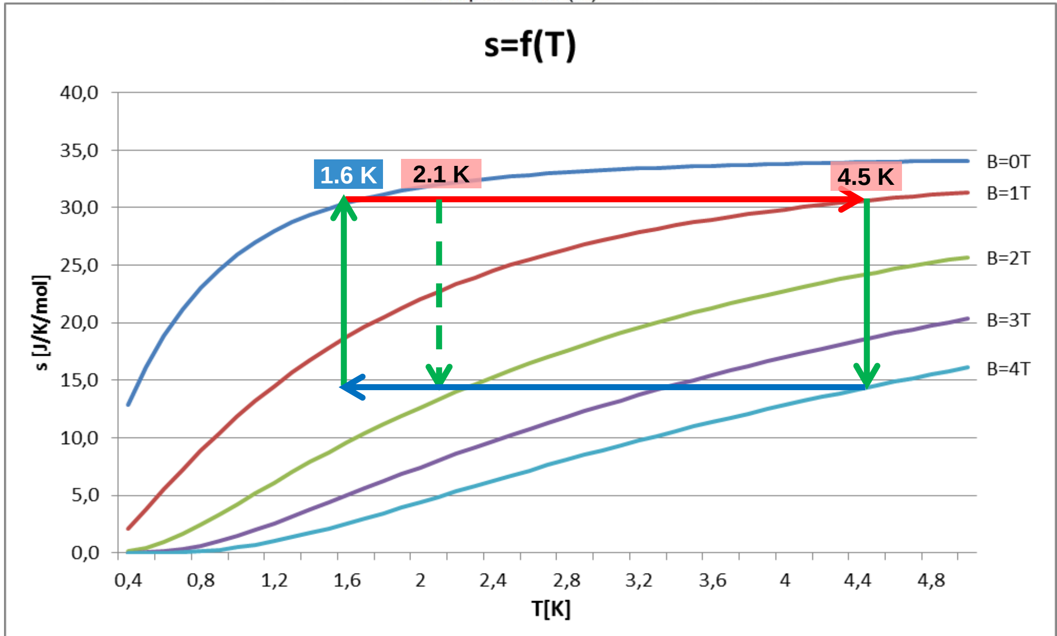


Magnetic Material ?

Selection of GGG for first iteration
Gadolinium Gallium Garnet $Gd_3Ga_5O_{12}$

Thermodynamic cycle & Magnetic Field ?

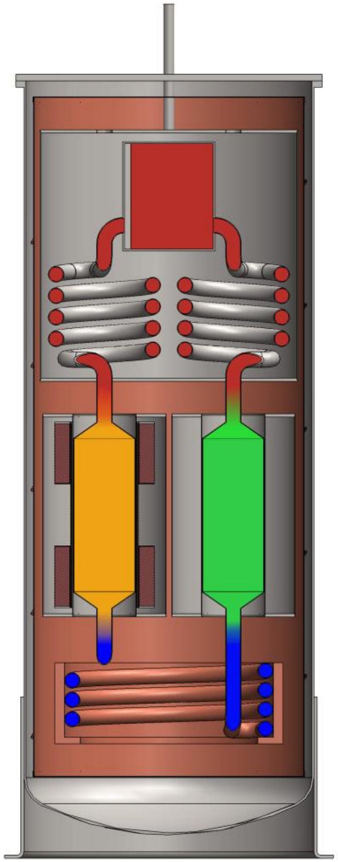
Selection of Magnetic Carnot cycle
4 T at 4.5 K or 2 T at 2.1 K
Up to 55 dm³ per kW at 1.6 K / 0,1 Hz



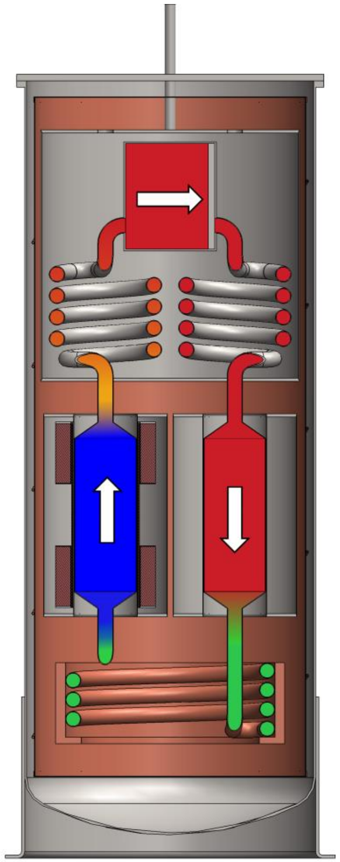
Heat exchange ?

Helium flow circulation

First iteration on design and simulations



Adiabatic
Magnetization & Demagnetization



Flow
Magnetization & Demagnetization

Cold source	**1.6 K**
Useful power	*Objectives : up to 5 kW*
FOM	*Objectives : > 50%*
Frequency	*0.1 Hz*
Magnetic field	*4 T*
Magnetic material	*GGG*
Heat transfer	*Oscillating He*
Warm source	***4.2 K***

Work started in the framework of FCC collaboration

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Conclusions

- **Large superfluid helium refrigeration capacity** is required for the FCC project
  - *10 kW range at 1.8 K for FCC-hh & 5 kW-range down to 1.6 K for FCC-ee*

- **Magnetic refrigeration as alternative option** to conventional gas cycles in terms of efficiency and reliability
  - *no or few cold compressors for helium bath pumping*
  - *> 50% Carnot efficiency expected according to prototypes results*

- **Key parameters for a magnetic refrigeration stage** have been selected and a preliminary design is on-going
  - *Challenging design study started at CEA in 2015*

Thanks you for your attention

Any question ?