

**AP8-07 Magnet science and technology 2**

# **Study on a Stationary Metamagnetic AMR System Using AC Superconducting Magnet**

**\*Harumi Yamamoto<sup>1</sup>, Daiki Kobayashi<sup>1</sup>, Kyohei Natsume<sup>1</sup>, Koji Kamiya<sup>1</sup>  
1. National Institute for Materials Science (Japan)**

**38th International Symposium on Superconductivity (ISS2025)  
@DEJIMA MESSE NAGASAKI  
4 December 2025**



# Outline



- 1. What are “Magnetic Refrigeration” and “AMR”**
- 2. Concept of Stationary Metamagnetic AMR System**
- 3. Design and AC Loss on Superconducting Magnet**
- 4. Scalability of Stationary Metamagnetic AMR System**

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# 1. What are “Magnetic Refrigeration” and “AMR”

## What is Magnetic refrigeration?

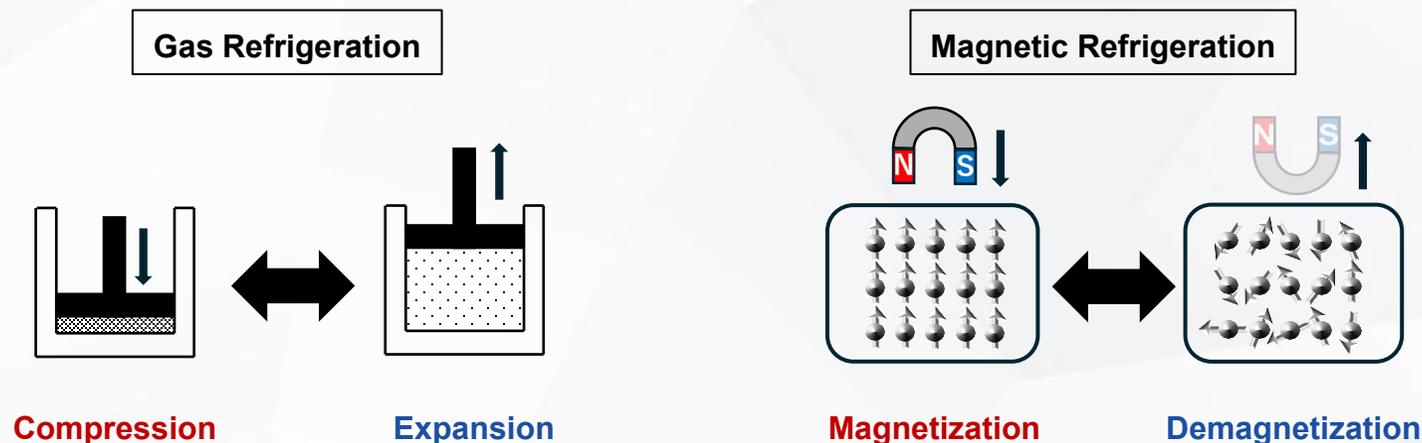
Magnetocaloric effect (MCE): Magnetic entropy changes by applying magnetic field

Magnetic refrigeration utilizes MCE combined with heat exchange

## Advantages of Magnetic refrigeration (In comparison with gas refrigeration)

Reversible cooling cycle: Magnetic Carnot cycle satisfied theoretical efficiency

Environmental safety: No use of Freon or any other refrigerants to produce CO<sub>2</sub>



$$\text{Gas: } dU = TdS - pdV$$

(Work with compression and expansion)

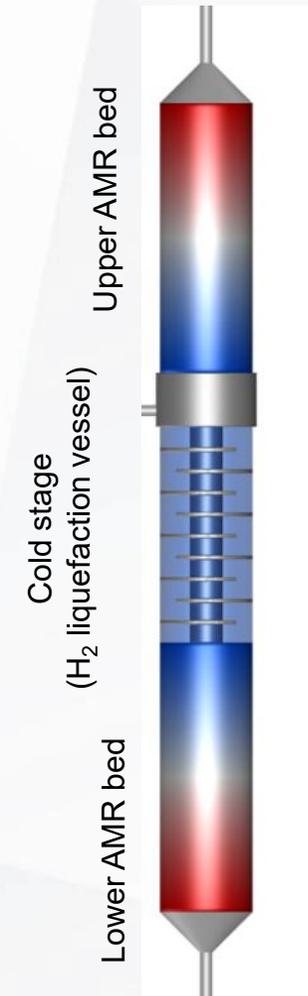
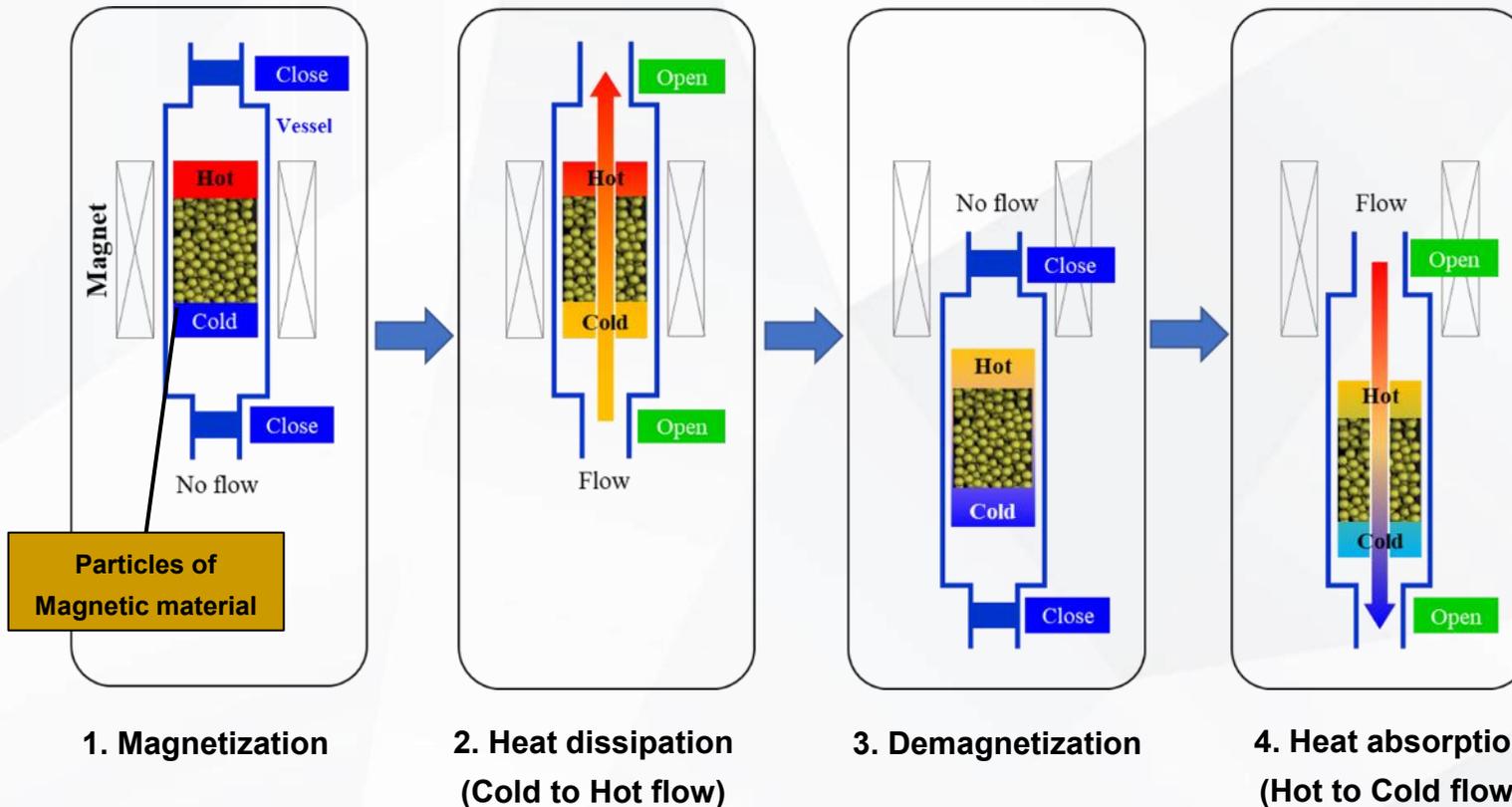
$$\text{Magnetic material: } dU = TdS + \mu_0 HdM$$

(Work with magnetization and demagnetization)

# 1. What are “Magnetic Refrigeration” and “AMR”

## Active Magnetic Regenerative Refrigeration (AMR) System

Magnetic material functions as regenerator in addition to refrigerant.  
It can extend operating temperature range.



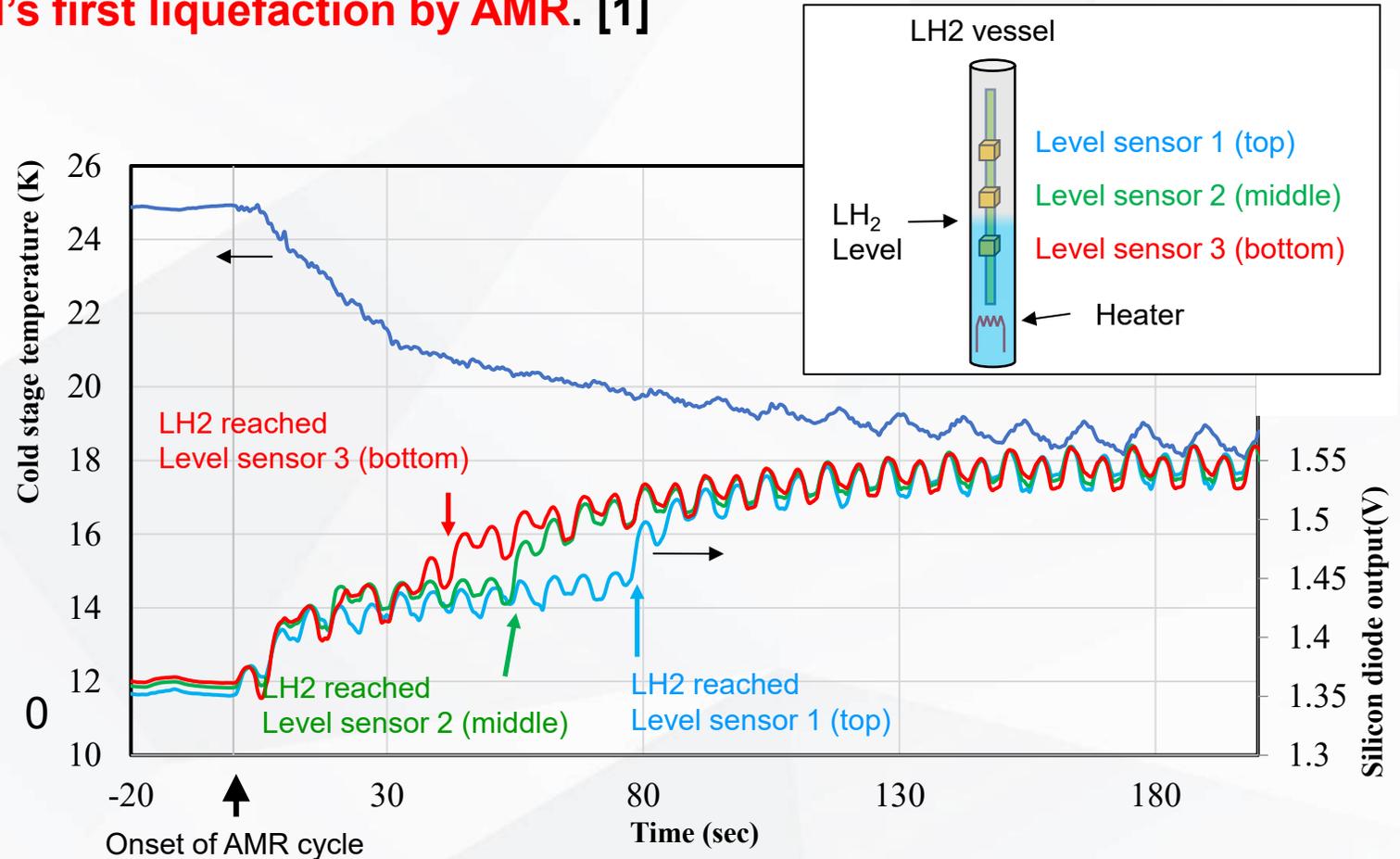
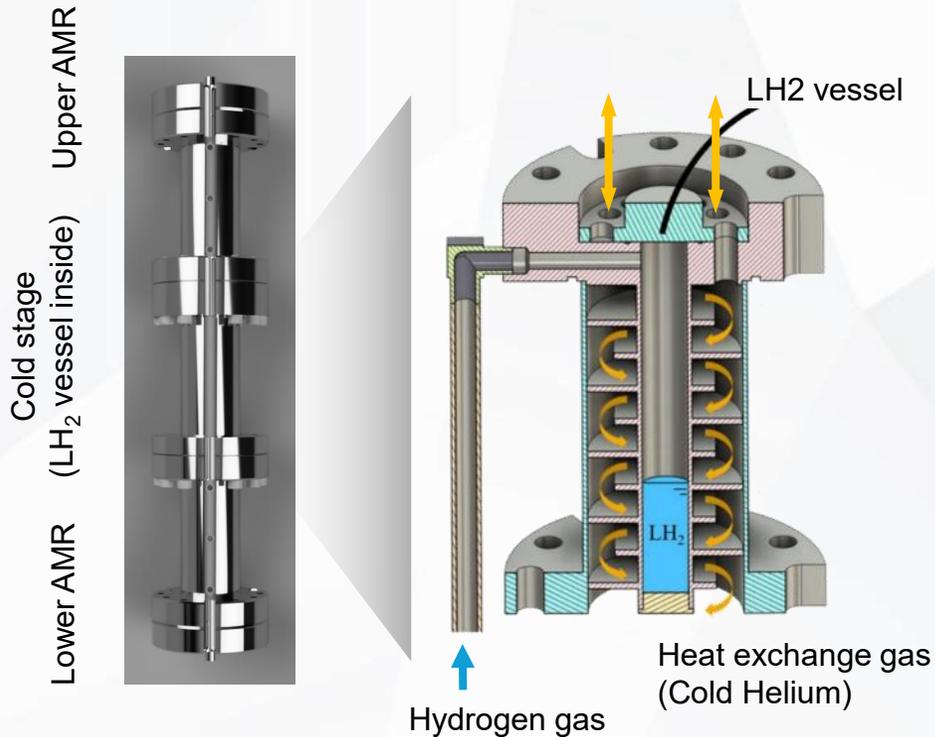
Tandem AMR and H<sub>2</sub> Liquefaction vessel

# 1. What are “Magnetic Refrigeration” and “AMR”

## Recent progress on AMR system for Hydrogen liquefaction

NIMS successfully demonstrated **world’s first liquefaction by AMR**. [1]

Achieved % Carnot 60% (FOM 0.6). [2]



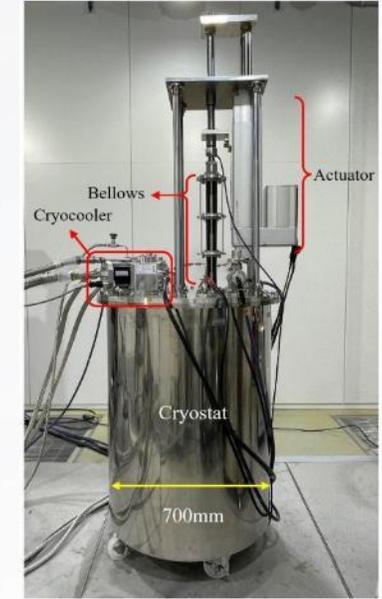
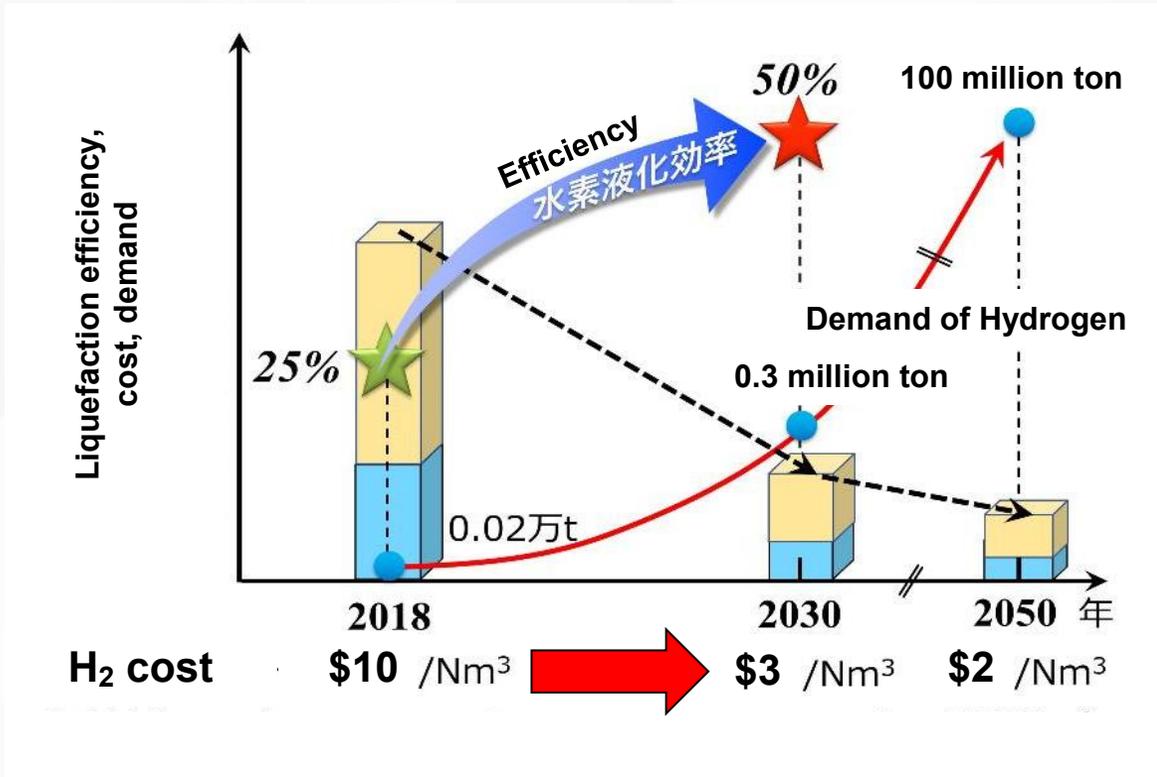
# 1. What are “Magnetic Refrigeration” and “AMR”

## Expected Applications of AMR

Highly efficient liquefaction for coming hydrogen society  
Hydrogen liquefaction for utilization of water on the Moon etc.

## Issues of AMR system

High magnetic field (~5 T) is necessary.  
It requires a mechanical drive.



5 T Nb-Ti DC Superconducting Solenoid for AMR  
(Field variation is generated by moving magnetic materials inside the magnet)

# Outline



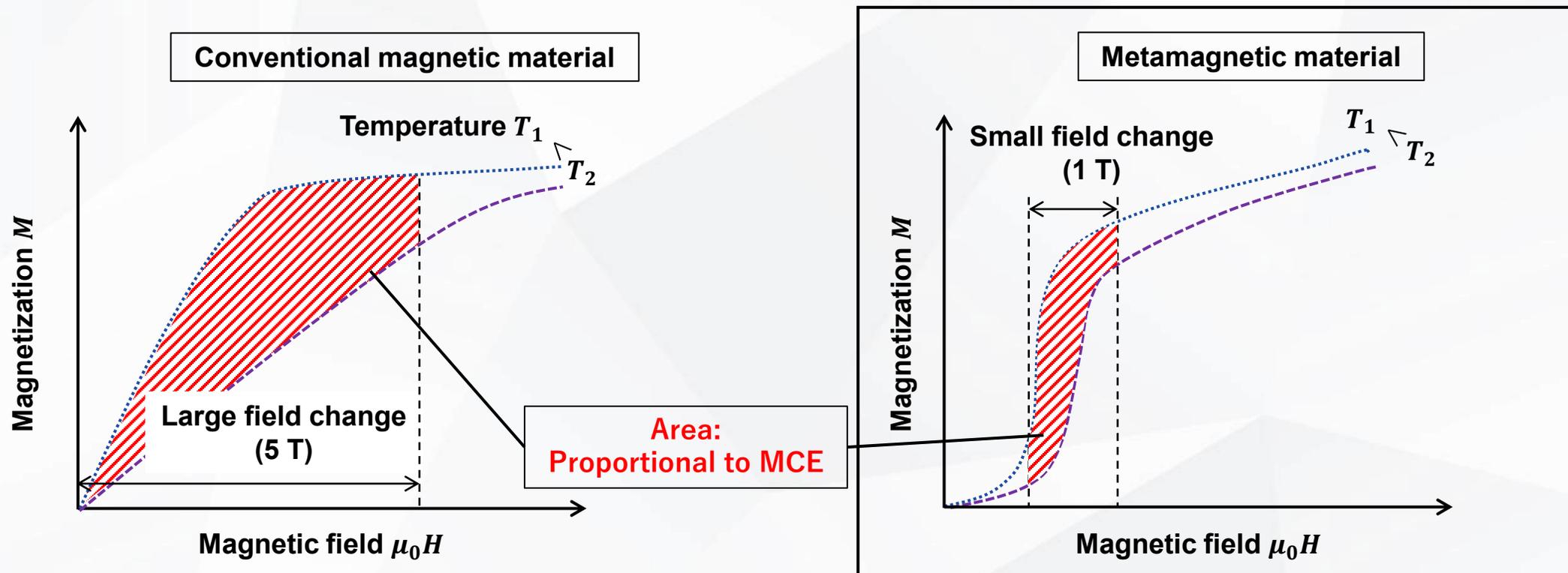
1. What are “Magnetic Refrigeration” and “AMR”
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# 2. Concept of Stationary Metamagnetic AMR System

## Property of Metamagnetic material

Conventional magnetic material: Large MCE with large magnetic field fluctuation

Metamagnetic material: Abrupt magnetic transition, Large MCE with small magnetic field change



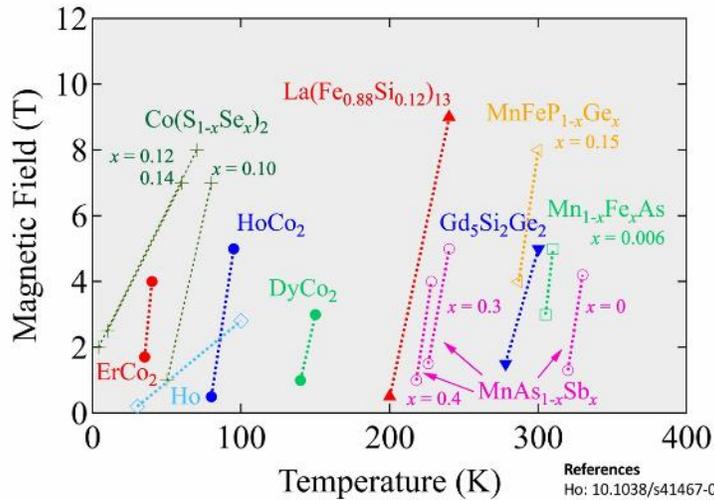
# 2. Concept of Stationary Metamagnetic AMR System

## Existing Metamagnetic materials

Many metamagnetic materials are found in wide temperature range and magnetic field range.

Holmium for wide temperature range and low magnetic field suitable for Hydrogen liquefaction

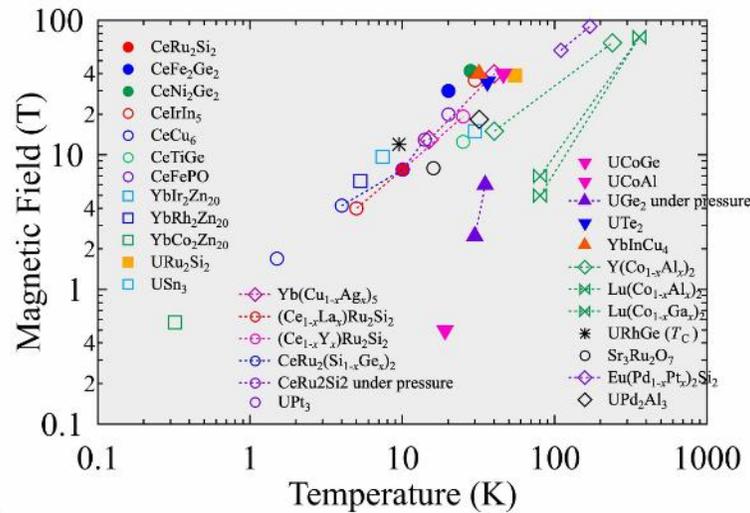
磁気冷凍材料のメタ磁性



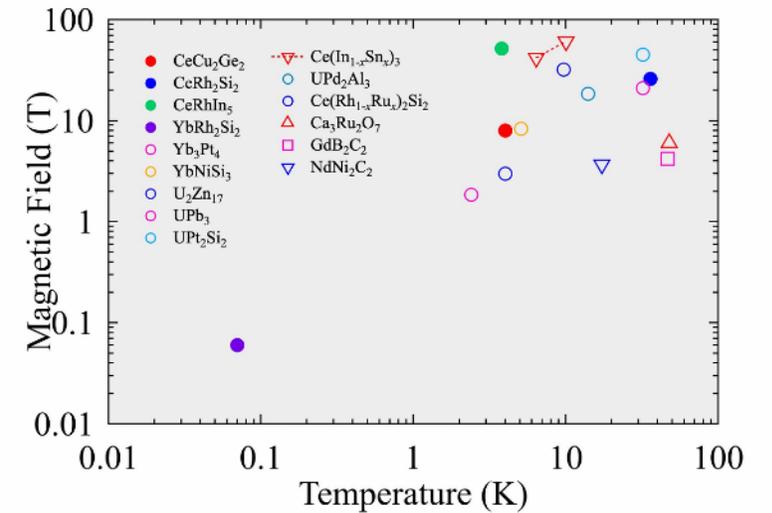
References  
 Ho: 10.1038/s41467-021-21234-z  
 ErCo<sub>2</sub>: 10.1016/S0925-8388(00)01305-0  
 HoCo<sub>2</sub>, DyCo<sub>2</sub>: 10.1016/S0921-4526(02)01099-2  
 La(Fe<sub>0.88</sub>Si<sub>0.12</sub>)<sub>13</sub>: 10.1063/1.370471  
 MnAs<sub>1-x</sub>Sb<sub>x</sub>: 10.2320/matertrans.43.73  
 MnFeP<sub>1-x</sub>Ge<sub>x</sub>: 10.1143/JPSJ.75.113707  
 Mn<sub>1-x</sub>Fe<sub>x</sub>As: 10.1038/nmat1732  
 Gd<sub>5</sub>Si<sub>2</sub>Ge<sub>2</sub>: 10.1103/PhysRevLett.78.4494  
 Co(S<sub>1-x</sub>Se<sub>x</sub>)<sub>2</sub>: 10.1109/TMAG.2014.2303818

June 61

重い電子系物質のメタ磁性 I (パラ磁性)



重い電子系物質のメタ磁性 II (反強磁性)



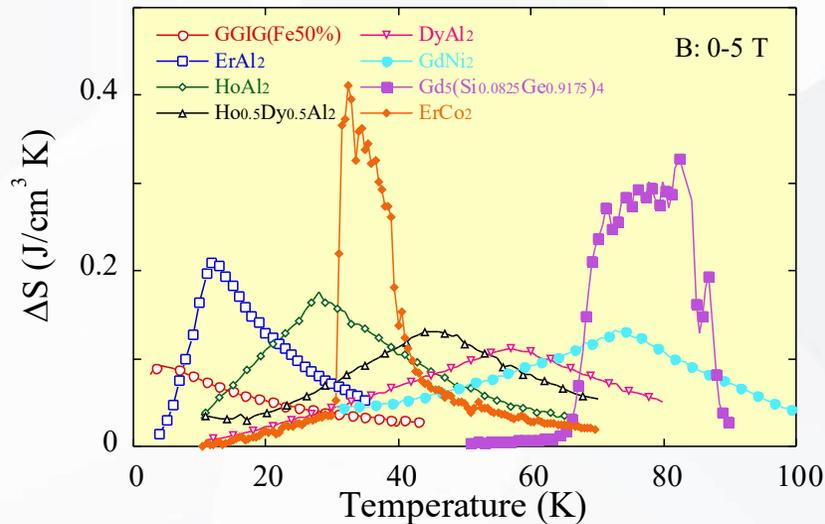
# 2. Concept of Stationary Metamagnetic AMR System

## Estimation of MCE on Metamagnetic Holmium

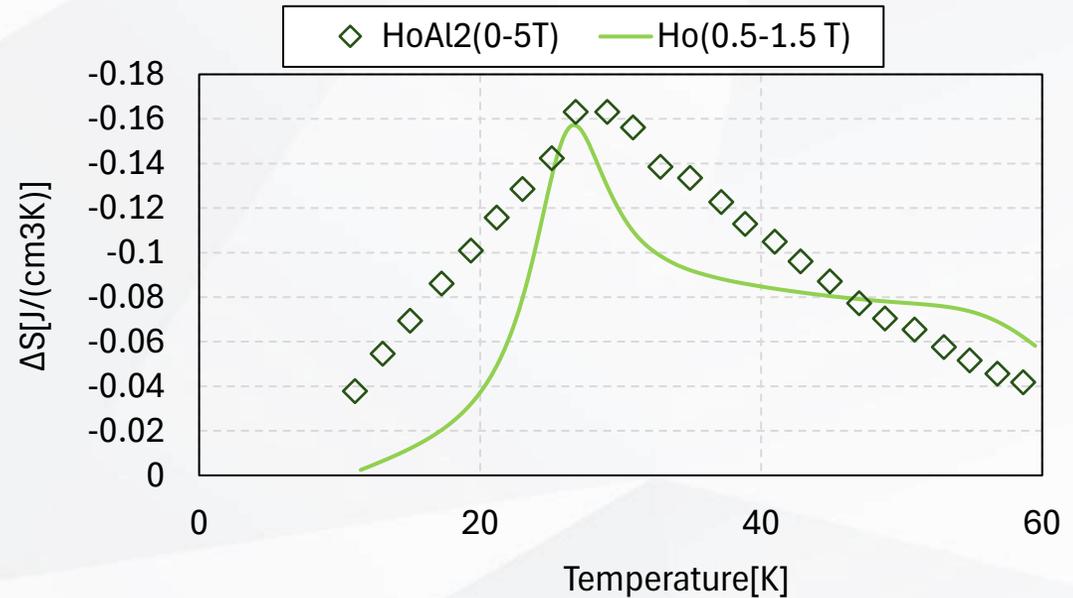
Magnetic entropy change:  $\Delta S = \int_{\mu_0 H_1}^{\mu_0 H_2} \frac{\partial M}{\partial T} d(\mu_0 H)$

Metamagnetic Ho with 0.5 to 1.5 T (1 T) exhibits almost same MCE as HoAl<sub>2</sub> with 0 to 5 T (5 T)

**Required field variation reduced to 1/5.**



Magnetocaloric effect of conventional magnetic refrigeration materials ( $\mu_0 H = 0-5$  T)



Magnetocaloric effect of metamagnetic Ho [10 $\bar{1}$ 0] ( $\Delta\mu_0 H = 1$  T)

## 2. Concept of Stationary Metamagnetic AMR System

### Controllability of temperature range

Peak of  $\Delta S$  changes following the “Offset” field.

0.2-1.2 T (“0.2 T offset”): Suitable for 20 K range

1.2-2.2 T (“1.2 T offset”): Suitable for 50 K range

### Estimation of cooling capacity of Holmium

Cooling capacity:

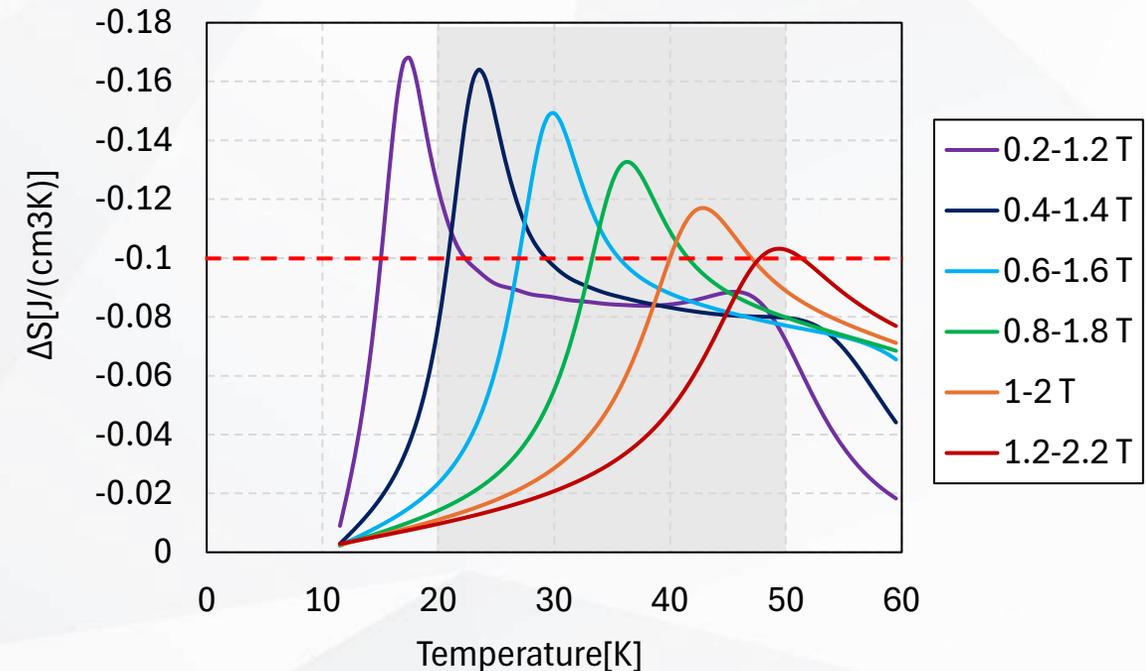
$$Q_{theory} [W] = |\Delta S [J/(cc \cdot K)]| \cdot T_{cold} [K] \cdot \frac{Volume [cc]}{T_{cycle} [s]}$$

Ho can cover 20-50 K range with

$$|\Delta S| \geq 0.1 \text{ J}/(cc \cdot K)$$

Required volume:

$$Volume = \frac{Q_{target} \cdot T_{cycle}}{|\Delta S| \cdot T_{cold}} = \frac{Q_{target} \cdot T_{cycle}}{0.1 \text{ J}/(cc \cdot K) \cdot 20 \text{ K}}$$



# 2. Concept of Stationary Metamagnetic AMR System

## Concept of Stationary Metamagnetic AMR System (Meta-AMR)

Metamagnetic material can reduce required magnetic field variation.

-> Making stationary design (field sweep) more realistic

Temperature range of MCE can be controlled by magnetic field offset.

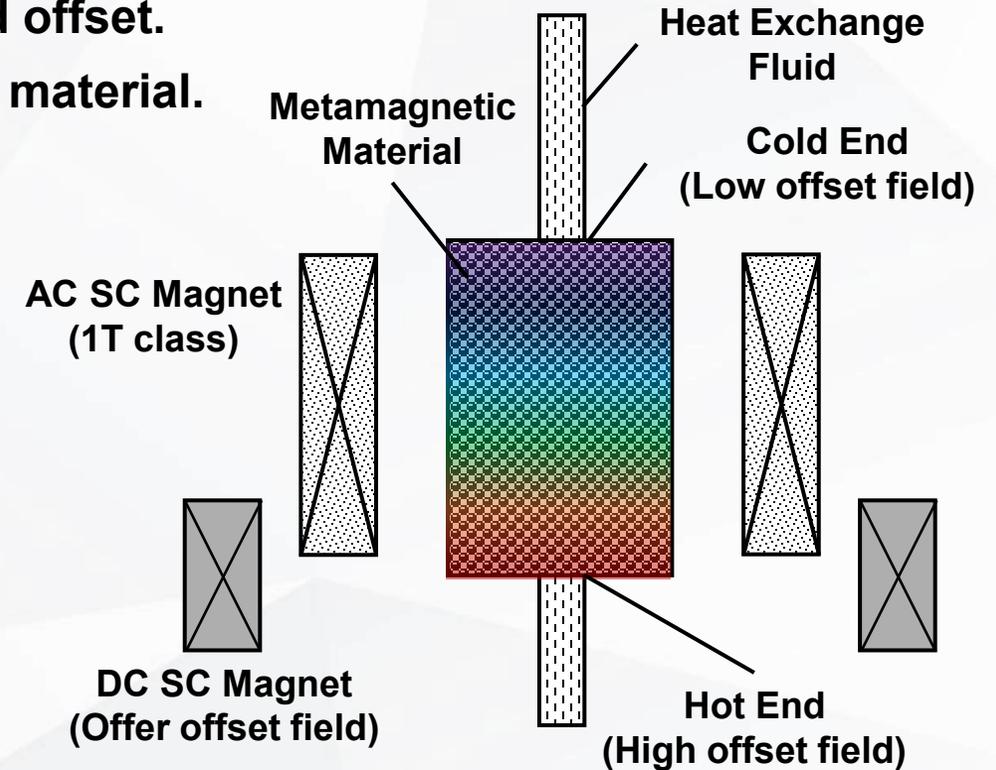
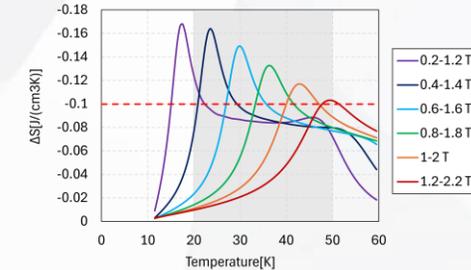
-> Wide operating temperature range is achievable with single material.

## Magnetic Field Generation for Meta-AMR

AC superconducting magnet: Control of AMR cycle

DC superconducting magnet: Control of temperature range

- ✓ **Lightweight superconducting magnet**
- ✓ **No need for heavy actuators, improved reliability**
- ✓ **High frequency, Downsizing**
- ✗ **AC loss, AC Magnet power supply**



## 2. Concept of Stationary Metamagnetic AMR System

### Target value for Meta-AMR design

Capacity: 200 W@20 K

(Equivalent to ~25 kg/day hydrogen liquefaction)

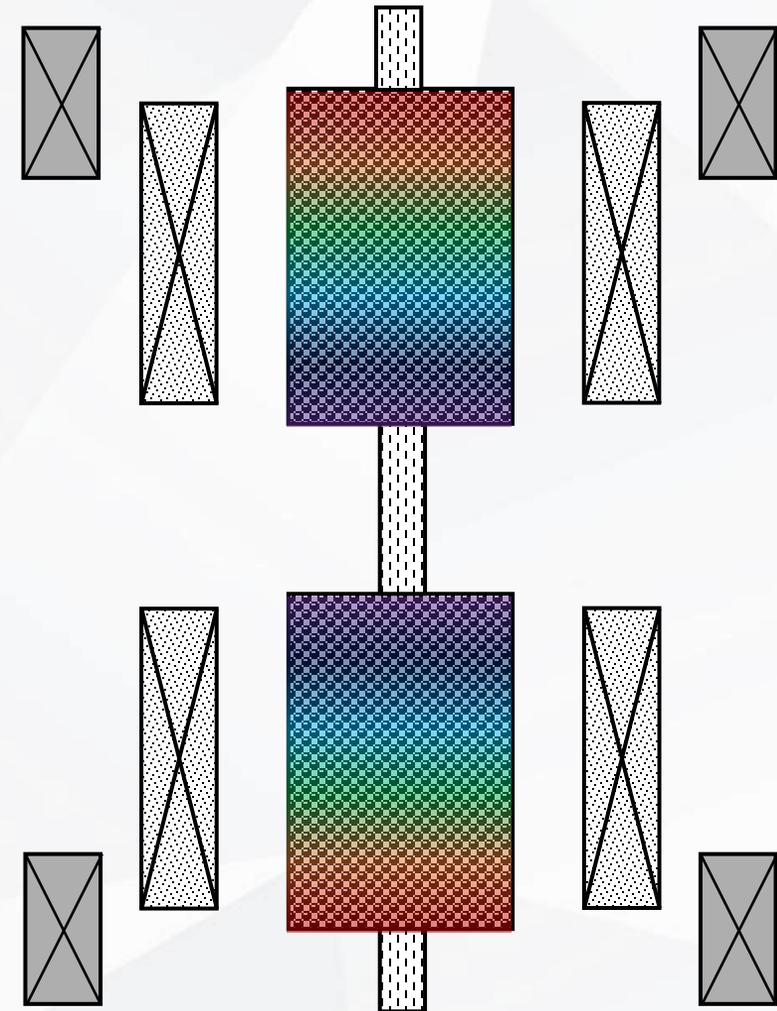
Temperature range: 20 K(Cold end)-50 K(Hot end)

Cycle time: 10 s/cycle (0.1 Hz)

Required volume:

$$Volume = \frac{Q_{target} \cdot T_{cycle}}{0.1 \text{ J}/(\text{cc} \cdot \text{K}) \cdot 20 \text{ K}} = \frac{200 \text{ W} \cdot 10 \text{ s}}{0.1 \text{ J}/(\text{cc} \cdot \text{K}) \cdot 20 \text{ K}} = 1000 \text{ cc}$$

Tandem metamagnetic material bed of  
~1500 cc ( $\phi 8 \times 30 \text{ cm}$ ) $\times 2$  is employed.



Tandem Meta-AMR System

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4. Scalability of Stationary Metamagnetic AMR System

# 3. Design and AC Loss on SC Magnet

## AC Superconducting Magnet

A time-varying magnetic field of  $0 \leftrightarrow 1$  T is applied to the entire magnetic material (0.1 Hz).

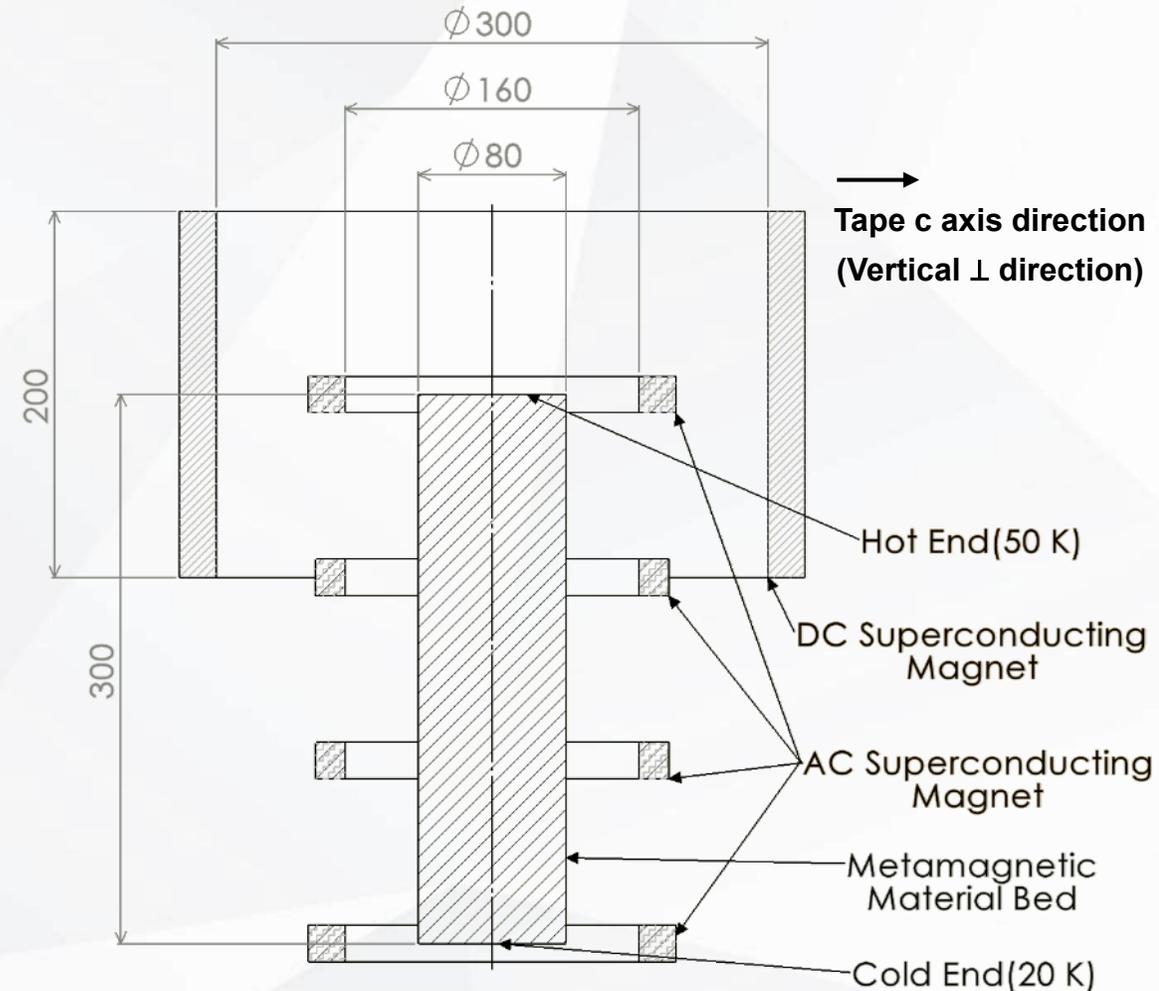
## DC Superconducting Magnet

Applying a DC offset magnetic field 0.2 T (Cold end, 20 K) ~ 1.2 T (Hot end, 50 K)

## Magnet design parameters of 200 W Meta-AMR

Wire: 4 mm-w REBCO tape @20 K ( $J_e > 1.4 \times 10^5$  A/cm<sup>2</sup>)

	AC Magnet	DC Magnet
Operating current	$0 \leftrightarrow 100$ A	100 A
Number of turns	$(1000+800+800+1000) \times 2$	$3200 \times 2$
Inductance	$1.1$ H $\times 2$	$2.8$ H $\times 2$



Electromagnet design of one side of 200 W class Meta-AMR

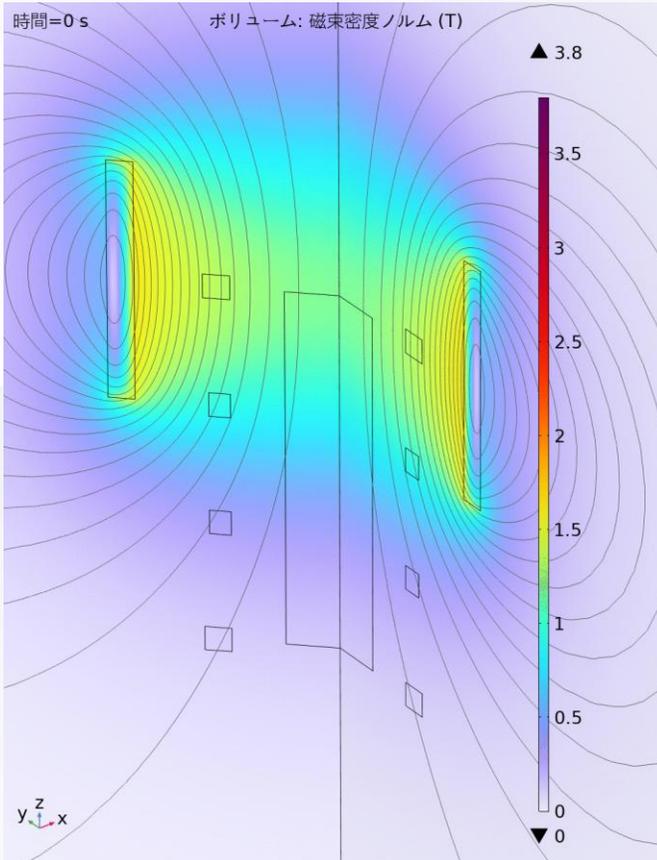
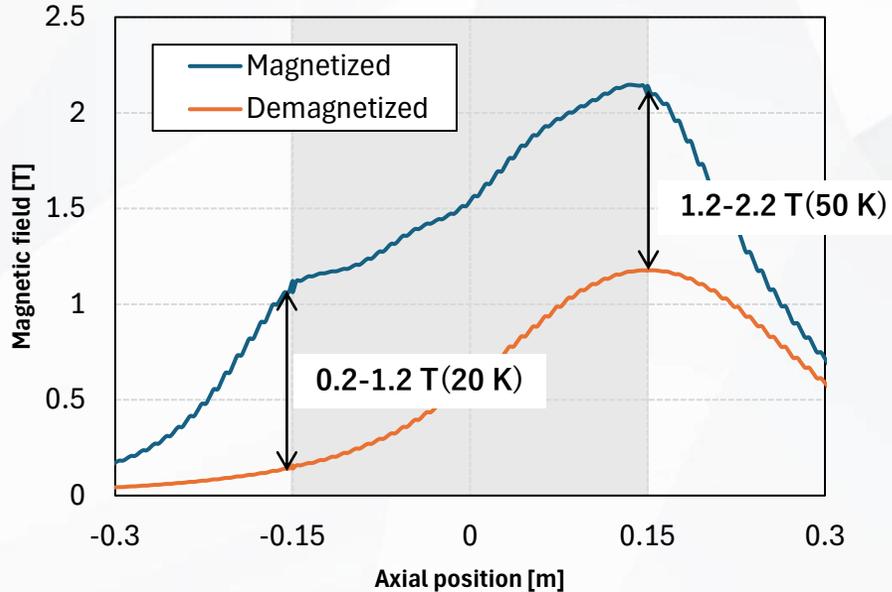
# 3. Design and AC Loss on SC Magnet

## Magnetic field calculation with FEM

$$\mu_0 H_{\max} = 3.7 \text{ T} \quad (\mu_0 H_{\perp \max} = 1.9 \text{ T})$$

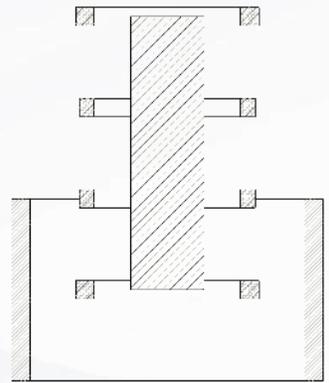
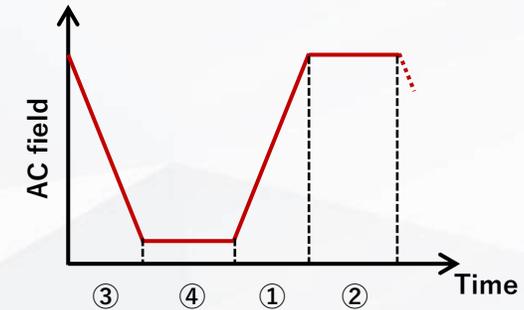
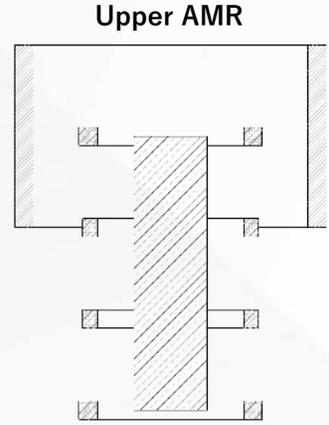
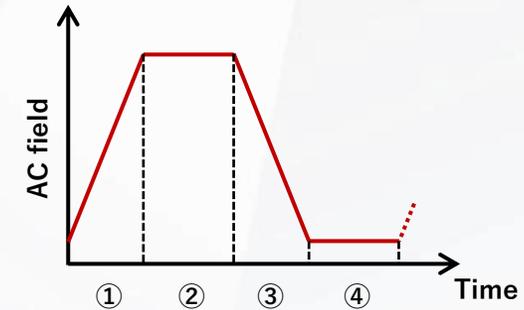
$$I_{e \min} \sim 700 \text{ A (20 K) (4 mm-w)}$$

Change in magnetic field strength along the central axis



Waveform of one cycle

- ①: Mag. (1.5 s)
- ②: C to H Flow (3.5 s)
- ③: Demag. (1.5 s)
- ④: H to C Flow (3.5 s)



# 3. Design and AC Loss on SC Magnet

## AC Loss calculation method

Hysteresis loss density [W/m<sup>2</sup>] based on Brandt and Indenbom[3]

$$p_h = \mu_0 w J_e H_{\perp m} g\left(\frac{H_{\perp m}}{H_c}\right) f, \quad g(x) = (2/x) \ln \cosh x - \tanh x, \quad H_c = J_c d / \pi$$

H calculated by FEM was used.

## Assumptions about Variables of REBCO

$$J_e = \lambda J_c \quad (\lambda: \text{Occupancy rate}), \quad H_{\perp m}(r, z) = (H_{\perp \max} - H_{\perp \min}) / 2,$$

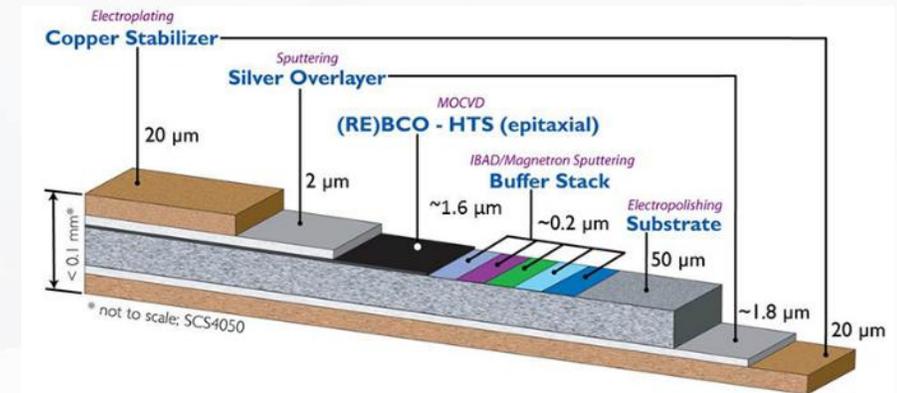
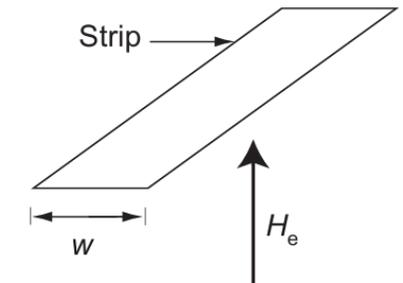
$$w = 4/n \text{ mm} \quad (n: \text{Number of divisions}),$$

$$d = 1.5 \text{ }\mu\text{m}, \quad J_c = \text{const.} = 5 \times 10^{10} \text{ A/m}^2$$

$$\text{Critical length: } l_{PC} \sim 2 \sqrt{\frac{2\rho w J_c}{\mu_0 \dot{H}}} \sim 2 \sqrt{\frac{2 \cdot \rho \cdot 4/n \times 10^{-3} \cdot 5 \times 10^{10}}{1}} \sim 4 \times 10^4 \sqrt{\frac{\rho}{n}} \text{ m}$$

-> Assume that coupling loss  $p_c$  is negligible

Tape c axis direction  
(Vertical  $\perp$  direction)



REBCO Superconducting Tape[4]

[3] E H Brandt et al Phys. Rev. B 48 (1993)12893

[4] Superpower-inc. HP

# 3. Design and AC Loss on SC Magnet



## Integration of AC loss density

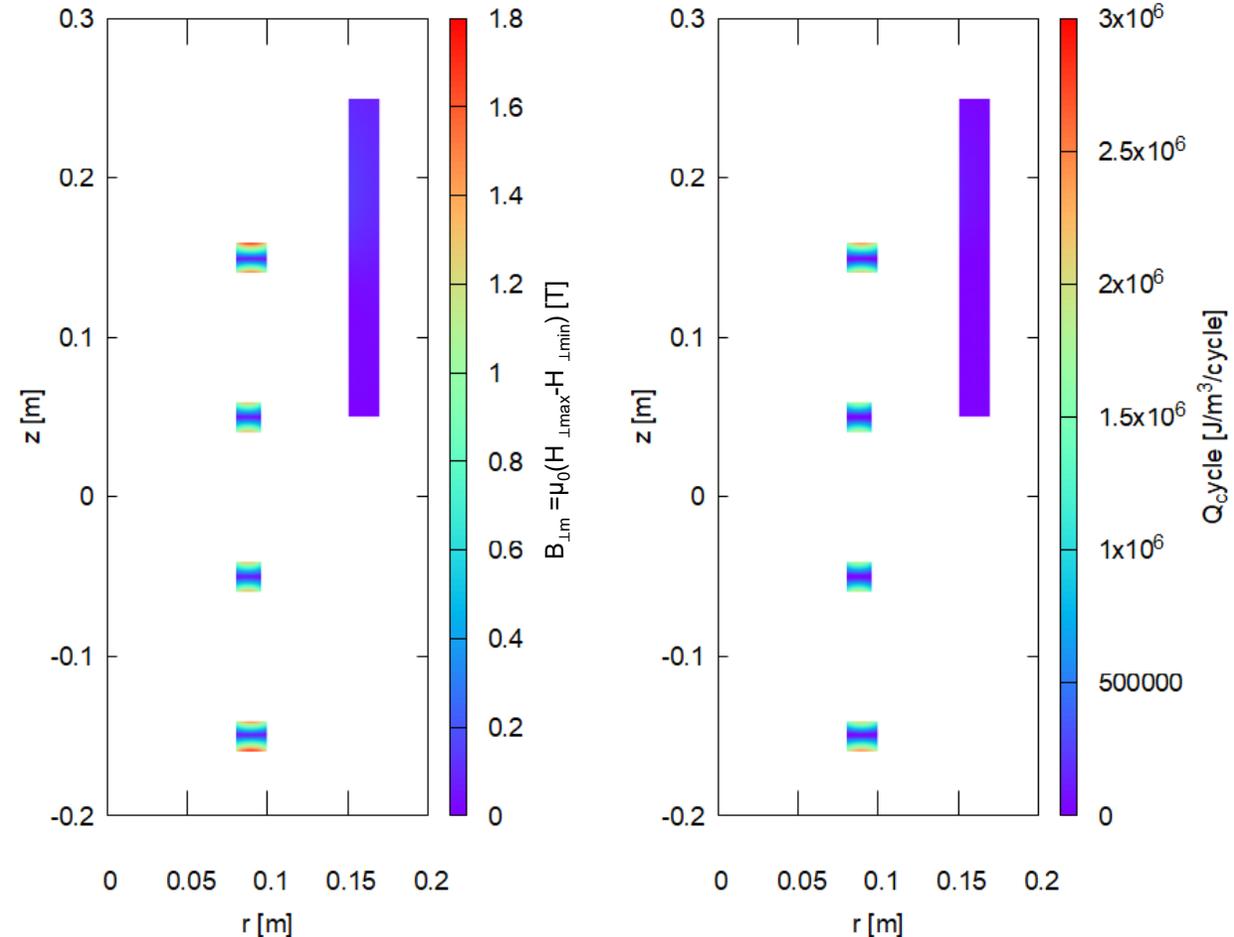
$$E_{\text{total}} [\text{J/cycle}] = E_{\text{hysteresis}} + E_{\text{coupling}} = P_{\text{total}} [\text{W}] \cdot f$$
$$= \int (p_h + p_c) dV = \iiint (p_h + p_c) r dr d\theta dz$$

## AC Loss of Magnet with 4 mm-w tapes

$$E_{\text{total}} = 1.0 \times 10^4 \text{ J/cycle}$$

$$P_{\text{total}} = 1.0 \times 10^3 \text{ W}$$

**High hysteresis loss due to wide width**  
**Losses occur only in AC magnets**  
**subject to strong magnetic field fluctuations**



# 3. Design and AC Loss on SC Magnet

## AC Loss of Magnet with 4/100 mm-w tapes

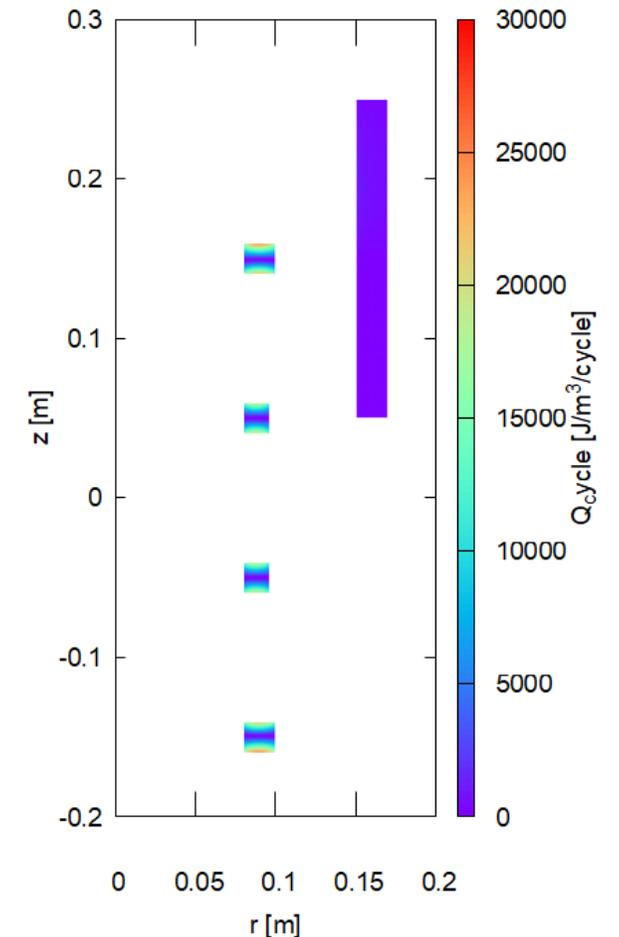
$$E_{\text{total}} = 1.0 \times 10^2 \text{ J/cycle}$$

$$P_{\text{total}} = 10 \text{ W}$$

**AC loss is reduced to 1/100 of the original value.**

**It is small enough compared to the refrigeration capacity and is acceptable as heat generation.**

**Striation can avoid AC loss problems.**



# Outline



1. What are “Magnetic Refrigeration” and “AMR”
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3. Design and AC Loss on Superconducting Magnet
4. **Scalability of Stationary Metamagnetic AMR System**

# 3. Scalability of Stationary Meta-AMR System

## Scalability of 200 W Class Meta-AMR

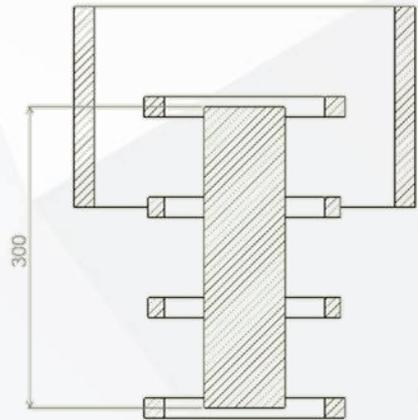
Assuming that the product of magnetic material volume and frequency is proportional to the capacity,

$$f_1 \cdot \pi r_1^2 l_1 = f_2 \cdot \pi r_2^2 l_2, \quad r: \text{radius}, \quad l: \text{length}$$

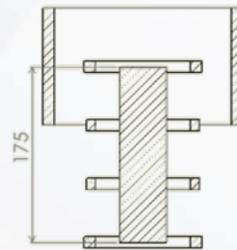
Assuming  $r_1/l_1 = r_2/l_2$ ,

$$r_2/r_1 = l_2/l_1 = 1/\sqrt[3]{f_2/f_1} = (1/\sqrt[3]{f_2})/(1/\sqrt[3]{f_1})$$

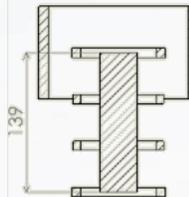
Frequency [Hz] $f$	Dimension of magnetic material $\propto 1/\sqrt[3]{f}$
0.1	$\phi 80 \times 300 \text{ mm}$
0.5	$\phi 47 \times 175 \text{ mm}$
1	$\phi 37 \times 139 \text{ mm}$



0.1 Hz Design ( $\times 1$ )



0.5 Hz Design ( $\times 0.58$ )



1 Hz Design ( $\times 0.46$ )

If the frequency can be increased, the magnetic material can be made smaller.

If the magnetic material is made smaller, the magnet can also be made smaller.

# 3. Scalability of Stationary Meta-AMR System



## Scalability calculation of 200 W Class Meta-AMR

Frequency [Hz] $f$	Magnet Weight [a.u.] $\propto 1/f$	AC loss $\propto f \times 1/f = 1$ (independent of $f$ )	AC Operating Current [A] $\propto \sqrt[3]{f}$	AC Voltage[V] $\propto (1/\sqrt[3]{f})^6 \times \sqrt[3]{f} \times f$ $= 1/\sqrt[3]{f}$	AC Input Power* [W] $\propto \sqrt[3]{f} \times 1/\sqrt[3]{f} = 1$ (independent of $f$ )
0.1	1	10 W (100 J/cycle)	100 ( $2.5 \times 10^4$ A/cm <sup>2</sup> )	76	7.6 k
0.5	1/5	10 W (20 J/cycle)	171 ( $4.3 \times 10^4$ A/cm <sup>2</sup> )	44	7.6 k
1	1/10	10 W (10 J/cycle)	215 (5.4 A/cm <sup>2</sup> )	35	7.6 k

**AC loss does not change even if frequency is changed.**

**Smaller (High freq.) design has advantage in system weight and AC voltage.**

**Smaller design requires high current (density).**

**-> Even smaller design seems to be feasible.**

**\*If regeneration is used, the net input power will be smaller.**

# Conclusion



**We propose “Meta-AMR,” a stationary AMR system that replaces conventional ferromagnetic refrigerants with metamagnetic materials.**

**Using metamagnetic Ho, we achieved a magnetic entropy change comparable to HoAl<sub>2</sub> driven by a 5 T field change, while reducing the required field swing to 1 T.**

**With a DC offset field, Ho provides more than 0.1 J/cc·K of  $\Delta S_m$  over a broad 20–50 K range.**

**Two REBCO SC magnets were designed to generate suitable fields for a 200 W-class Meta-AMR.**

**The estimated AC loss is about 10 W, within an acceptable heat budget.**

**Further AC-loss reduction will require improved filamentarization of REBCO tapes.**

**Higher-frequency operation could further downsize the system, though optimized power-supply design and magnetic-energy recovery schemes remain key issues.**

# Appendix

# Benchmark gas refrigerator



## Creare TB Refrigerator (Hydrogen)

Refrigeration capacity: 150W @ 20K,  
Mass: 660 kg, Power: 9 kW

## Creare TB Refrigerator (Oxygen)

Refrigeration capacity: 350W @ 90K,  
Mass: 140 kg, Power: 2.8 kW

## Creare TB Refrigerator for HST (20 years ago)

Refrigeration capacity: 7W @ 70K,  
Mass: 18.5 kg (2.64 kg/W), Power: 350 W (50 W/W)

