THU-PO3-802-09

Research of combined use of magnetic refrigeration technology for refrigerant circulation type high temperature superconducting coil cooling system

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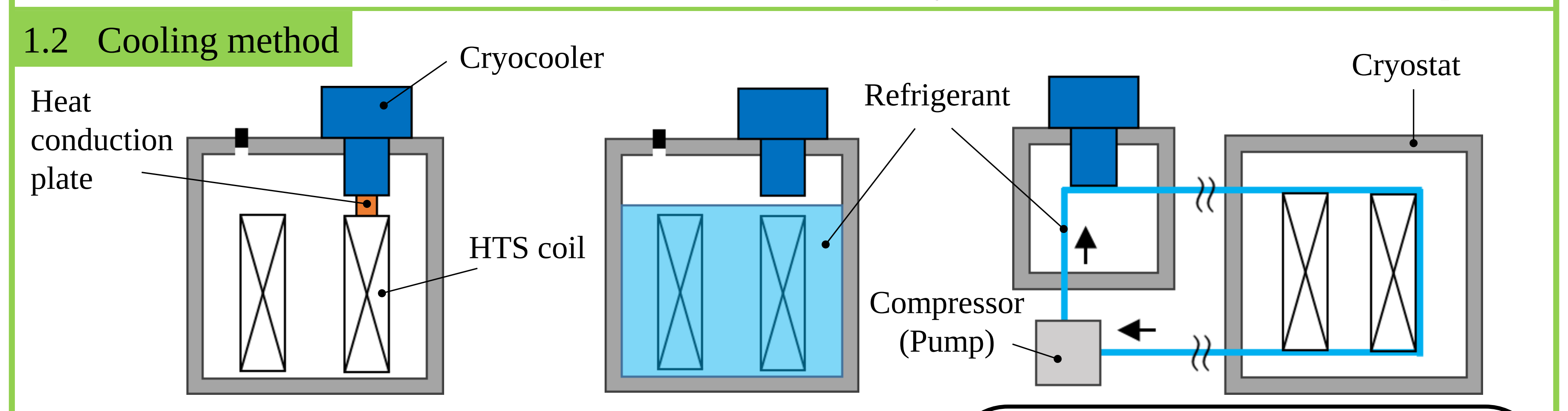
1. Introduction

1.1 Background

We aim to create a system for cooling a HTS (High Temperature Superconducting) coil for induction heating in metal processing plants. The requirements for the system are as follows.

(I) Cooling system can be kept cold at about 20 K for stable operation of the HTS coil.
(II) The amount of refrigerant used is small and the operating cost is low.
(III) The structure is flexible and can be cooled even if the cryocooler and the HTS coil is far apart.

1.2 Cooling method



	(i) Direct cooling	(ii) Recondensation cooling	(iii) Refrigerant circulation cooling
Pros	Using a small amount of refrigerant.	Easy to cool multiple coil.	Using a small amount of refrigerant. Can cool a coil away from cryocooler.
Cons	Cannot cool a coil away from cryocooler.	Cannot cool a coil away from cryocooler. Using a large amount of refrigerant.	Not very suitable for multiple coil colling.

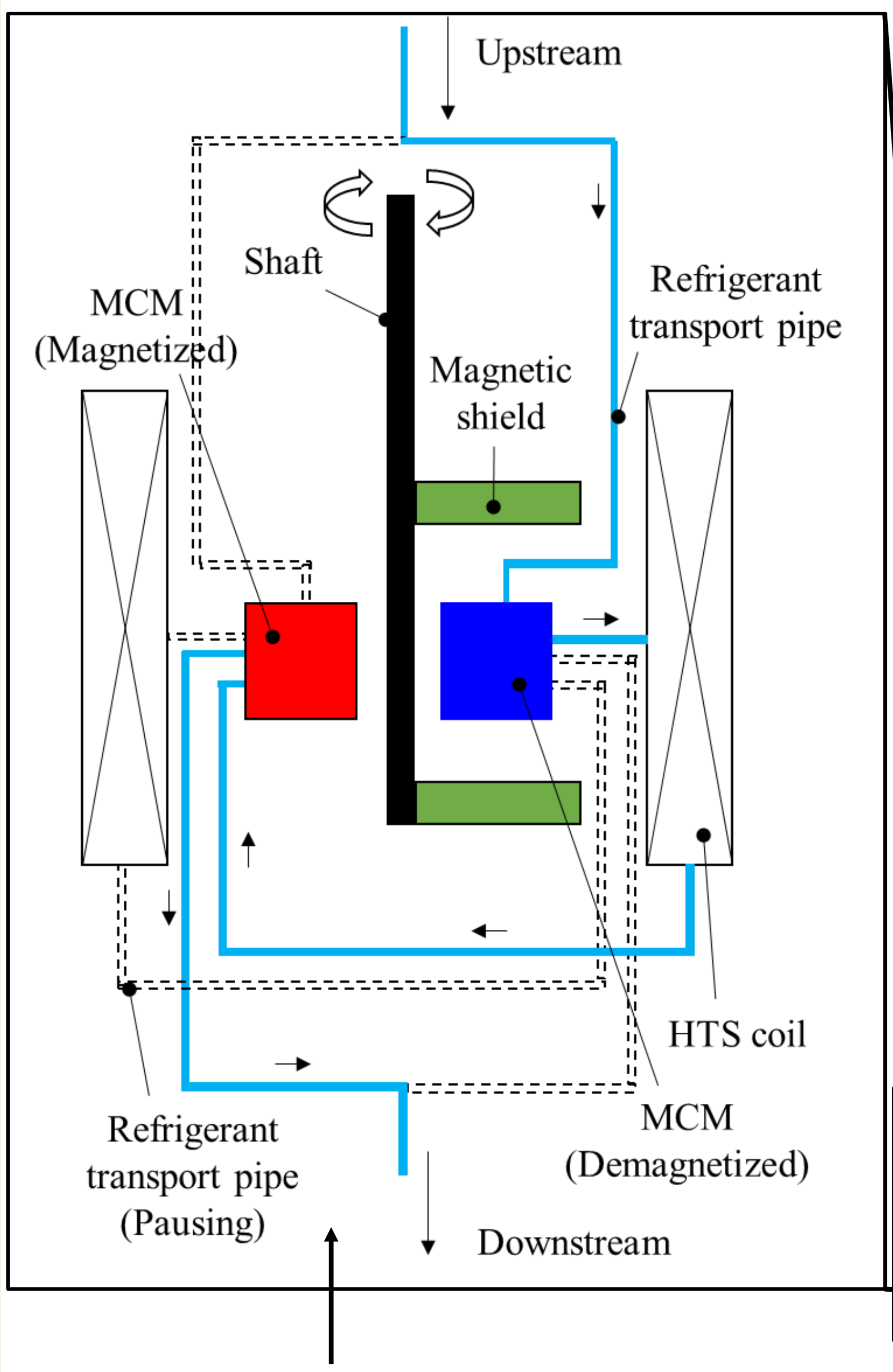
1.3 Object

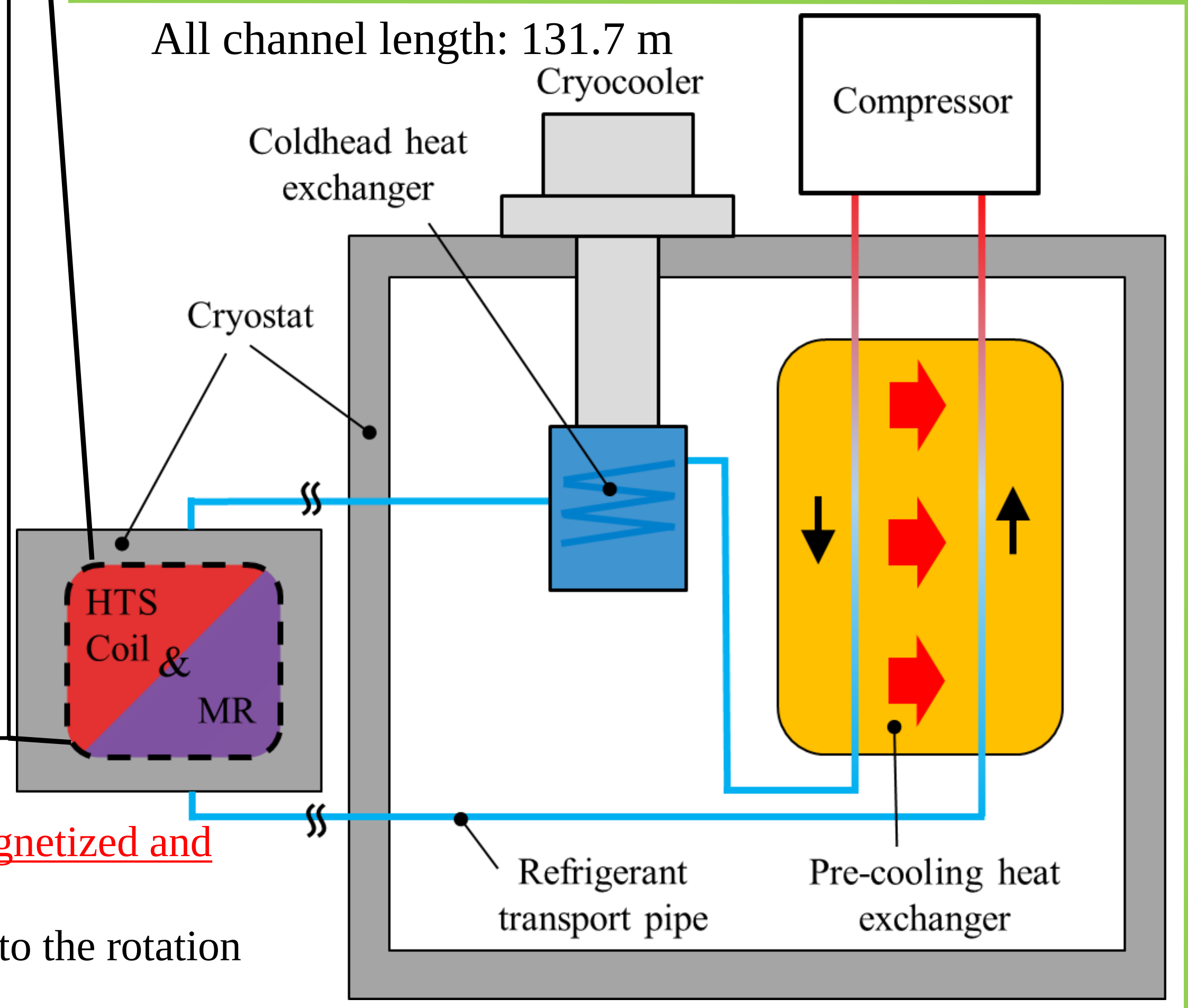
(iii) system is suitable for the purpose because it uses little refrigerant and has flexible structure.

The magnetic field in the cryostat that protects the HTS coil from heat cannot be used for induction heating. We aim to improve the performance of refrigerant circulation cooling system by using MR (Magnetic Refrigeration) technology that utilizes this unused magnetic field.

2. One dimensional numerical analysis of heat transfer of cooling system combined with MR technology

2.1 Overview of cooling system





Volumes surrounded by magnetic shields are demagnetized and not surrounded volumes are magnetized.
The refrigerant transfer pipe is switched according to the rotation of the shaft on which magnetic shields is attached.

2.2 Method of analysis

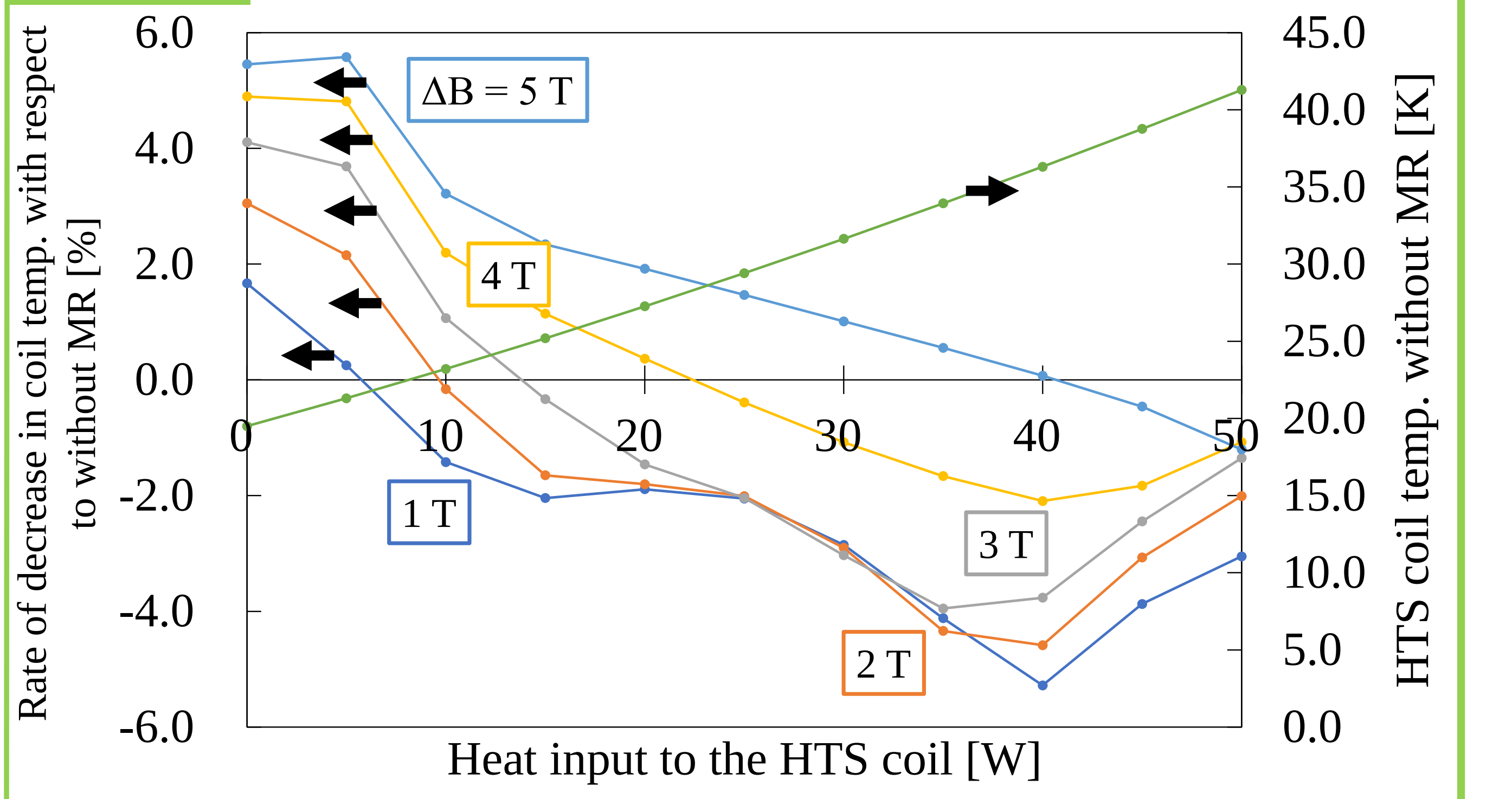
The following equation was solved under the conditions shown in the table on the right.

$$\rho c_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}\right)=-\frac{q_{rad}+q_{ex}}{S\mathrm{d}x}+k\frac{\partial^2 T}{\partial x^2}+\frac{4}{3}\eta\left(\frac{\partial u}{\partial x}\right)^2$$

ρ: Density [kg/m^3] c_p: Specific heat at constant pressure[J/(kg・K)]
k: Thermal conductivity [W/(m・K)] T: Temperature [K]
u: Flow velocity [m/s] q_{rad} : Radiation energy [W]
q_{ex} : Heat exchange amount at each mesh [W] η: Viscosity [Pa・s]
S: Cross sectional area of refrigerant transport pipe [m^2]
x: Position [m] t: Time [s]

Refrigerant [-]	He
Inner diameter of refrigerant transport pipe [mm]	6.4
Mass flow [g/s]	1.0
Discharge pressure [MPa]	2.0
Ambient temperature [K]	295
MCM (Magnetocaloric Material) [-]	$Dy_{0.8}La_{0.2}Ni_2$, $Er_{0.6}Dy_{0.4}Al_2$
Mass of MCM [kg]	8.0
Rotation speed of magnetic shields [Hz]	10
MCM filling length [m]	1.5
Change of magnetic field ΔB [T]	1, 2, 3, 4, 5

2.3 Result



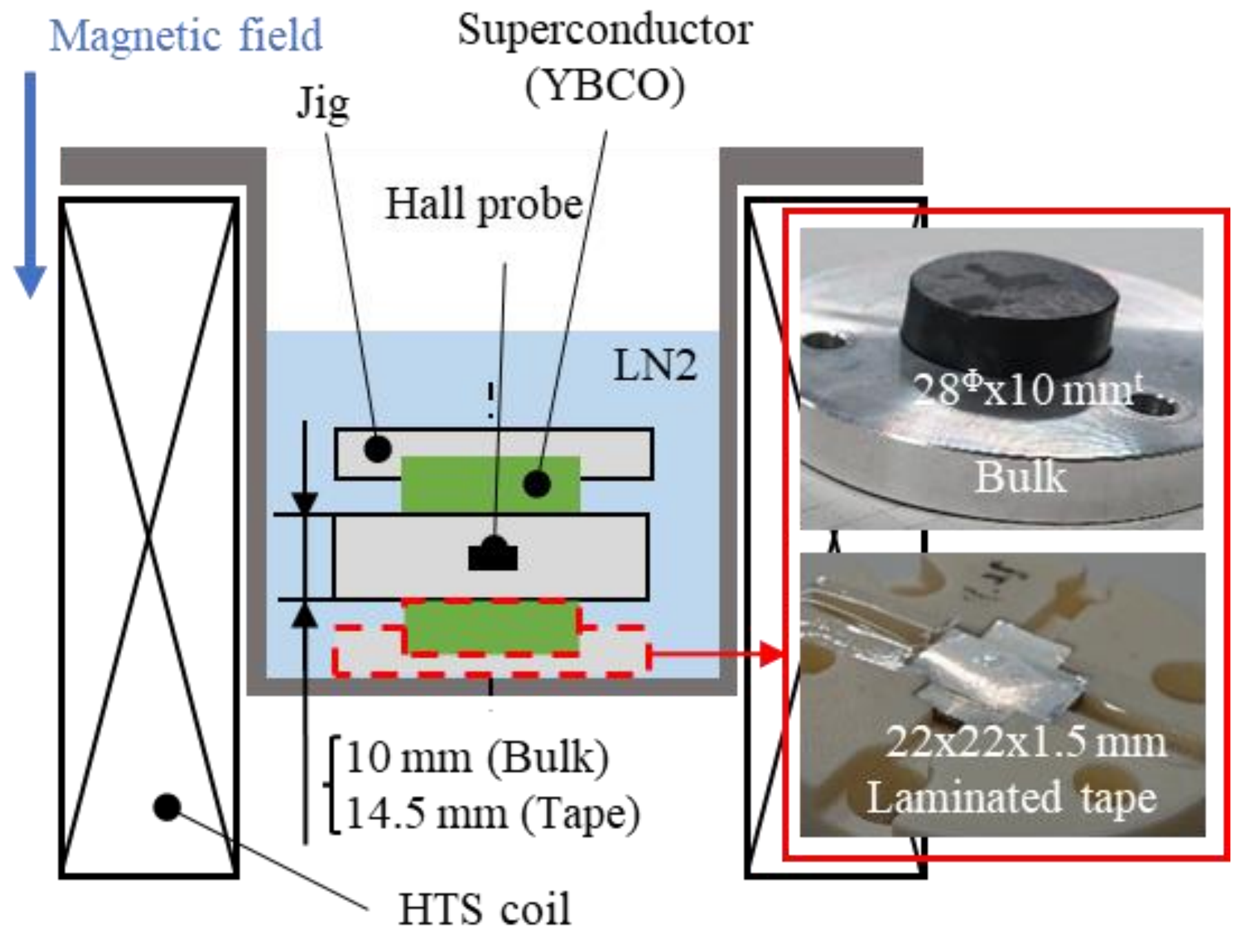
As the amount of change in the magnetic field increases, so does the temperature drop of the HTS coil. And the robustness is increased so that superiority can be secured regardless of the heat input to the HTS coil.

3. Magnetic shielding experiment and axisymmetric numerical analysis

3.1 Relationship between MR and magnetic shields

The change of the magnetic field is required for cooling assist by MR technology. Methods of change include changing the distance between the coil and MCM and using AC current, but both are not practical due to structural or thermal problems. Therefore, as shown in 2.1, we are studying changing field the magnetic shields of superconductor by moving them.

3.2 Method of experiment and analysis



Bulk: Made by CAN SUPECONDUCTORS s.r.o.
Laminated tape: Made by SuperOx JAPAN LLC, 30 tapes with a thickness of 50 μm are laminated in cross shape.

Magnetic field (~ 3 T) was applied to a pair of superconductor and the Hall probe sandwiched between them as shown in the lower left figure. Then, the difference between the applied field and the measured field by the probe was defined as the shielding magnetic field. We performed numerical analysis under the same dimensions and field condition (uniform field) as in the experiment. The equation used for the analysis is as follows.

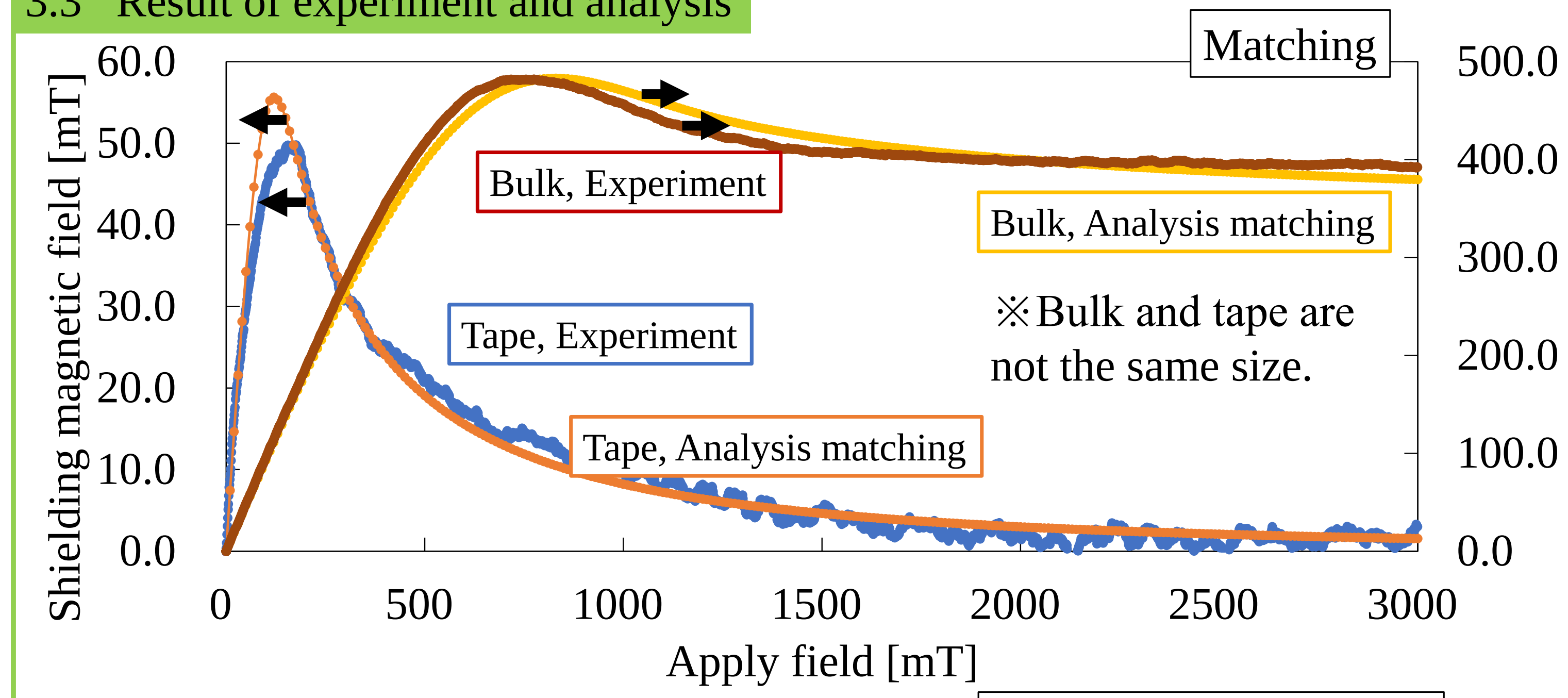
$$\boldsymbol{J}=rot\left(\frac{1}{\mu}rot\boldsymbol{A}\right)+\sigma\left(\frac{\partial\boldsymbol{A}}{\partial t}+gradV\right)$$

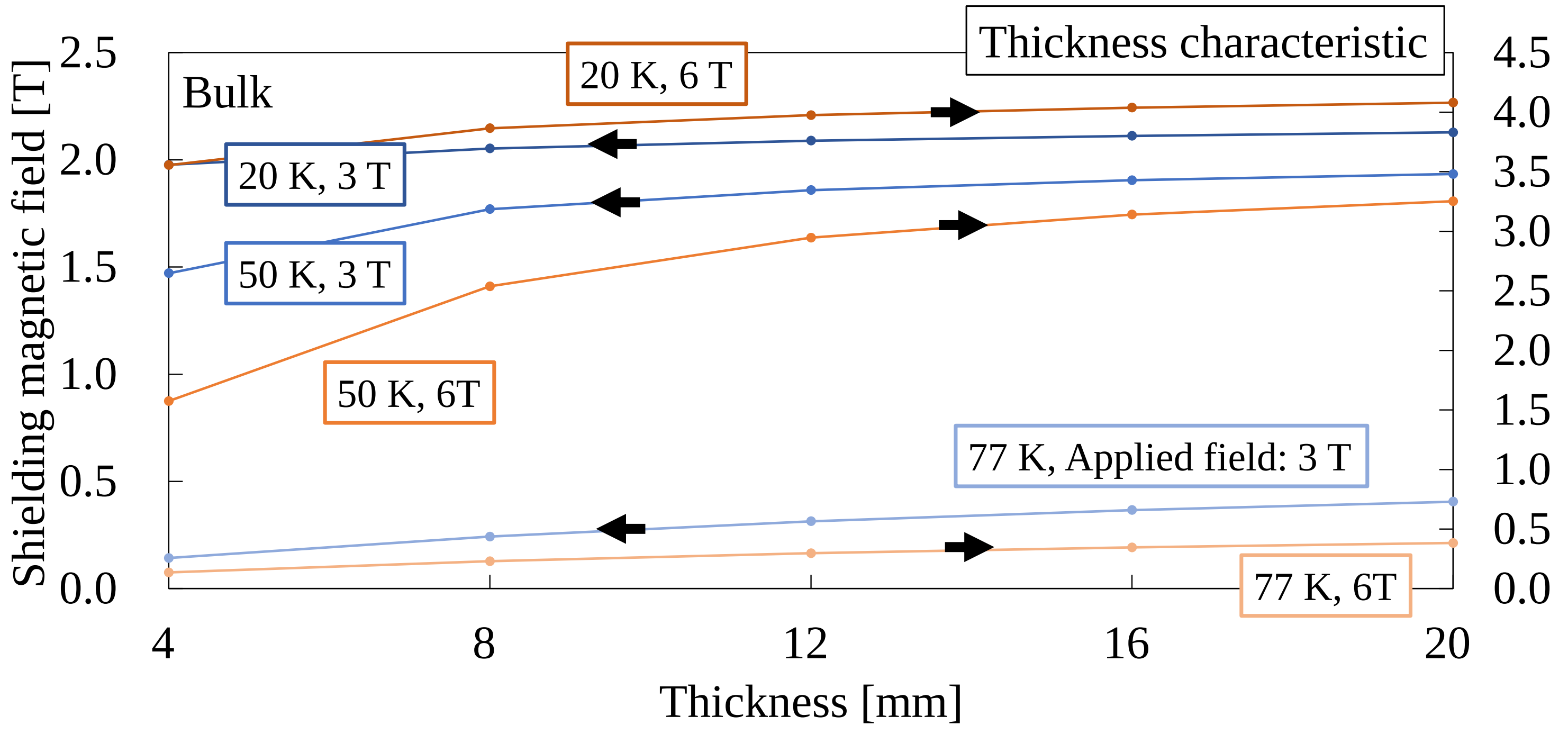
J: Current density [A/m^2] μ: magnetic permeability [H/m]
A: Vector potential [T・m] σ: electrical conductivity [S/m]
V: Voltage [V] t: Time [s]

We found a critical current density that matched the shielding magnetic field obtained in the experiment and that obtained in the analysis. As a result, it was found that the bulk's critical current density is more superior. The critical current density was appropriately changed with respect to temperature changes[1], and analysis was performed under the conditions shown in the table below to investigate the thickness characteristics of the bulk magnetic shields.

Diameter [mm]	50
Shield spacing [mm]	30
Temperature [K]	20, 50, 77
Applied field [T]	3, 6

3.3 Result of experiment and analysis





4. Discussion

By increasing the magnetic field change, robustness was obtained that could maintain the cooling assistance effect regardless of the heat input to the HTS coil. If the heat input becomes large and the temperature difference between the MCMs exceeds the adiabatic temperature change, the cold heat cannot be taken out at the timing when the MCM (Magnetized) is demagnetized. For this reason, the increasing adiabatic temperature change due to increase the magnetic field change is thought to have affected robustness. In magnetic shielding by superconductors, the shielding ability was significantly different between 77 K and others. If the maximum shielding magnetic field determined by the critical current density is exceeded, the magnetic field invades the shield and loses its shielding ability. It is considered that this result was obtained because a sufficient critical current density was obtained at 50 K or less. And it is considered that the shielding magnetic field became larger because the magnetic field became difficult to penetrate by increasing the thickness. The reason why bulk was superior to laminated tape was that the tape contained few superconductor.

5. Conclusion

One dimensional heat transfer analysis showed that the larger the change in the applied field to the MCM, the better the robustness of assistance effect. The characteristics of the magnetic shield that determines the magnetic field change were investigated by experiments and analysis, it was found that the bulk is suitable for the shield and can shield as much as 4 T magnetic field at 20 K. The affects of physical quantities other than magnetic field changes on the cooling system and the dimensional dependence of the magnetic shields will be investigated.

6. Reference

1) V. Antal et al., Relationship between local microstructure and superconducting properties of commercial $YBa_2Cu_3O_{7-\delta}$ bulk (2020), Supercond. Sci. Technol. 33