

Quench and Recovery Characteristics of MgB₂ Coil with Various Protection Schemes

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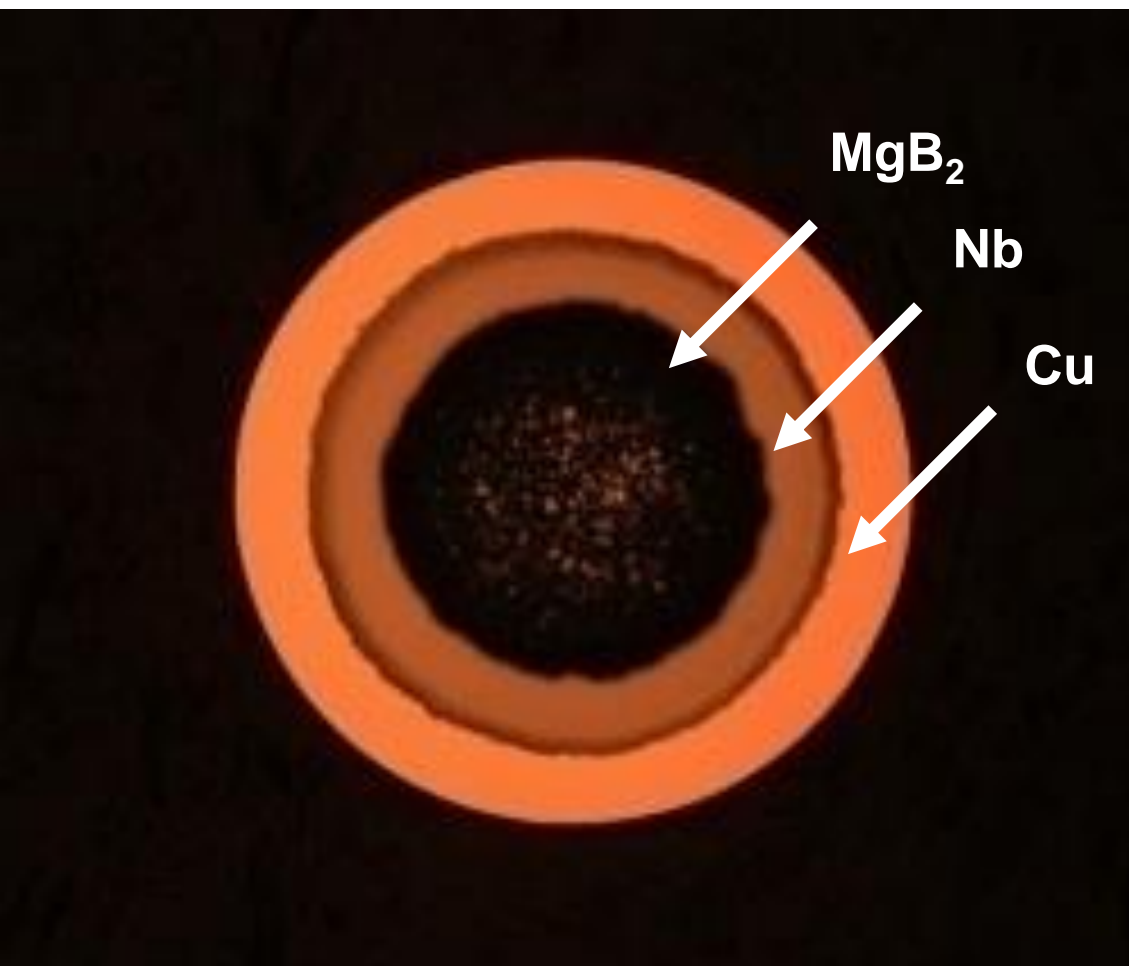
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Abstract

In recent years, magnesium diboride (MgB₂) has been regarded as one of the promising candidates for the development of MRI magnets owing to its critical temperature of 39 K, which allows magnets to be operated without the use of liquid helium (LHe), unlike their low-temperature superconductor counterparts. Prior to the development of the LHe-free MgB₂ MRI magnet, it is essential to investigate the appropriate protection scheme for the magnets. Therefore, this study examined passive and active protections for a proto-type MgB₂ coil using the MgB₂ wires manufactured by Kiswire Advanced Technology Co. Ltd. The quench and recovery characteristics of the MgB₂ coil with various protection schemes were evaluated in terms of the maximum hotspot temperature, maximum induced voltage, and recovery time.

Background

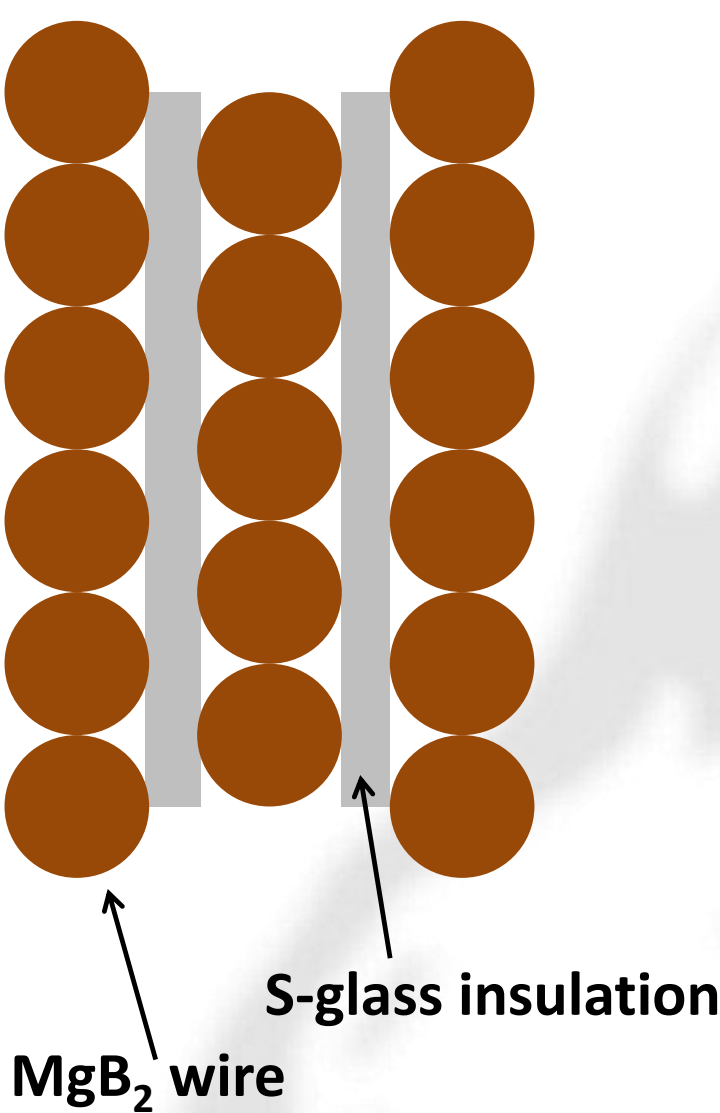
★ MgB₂ wires



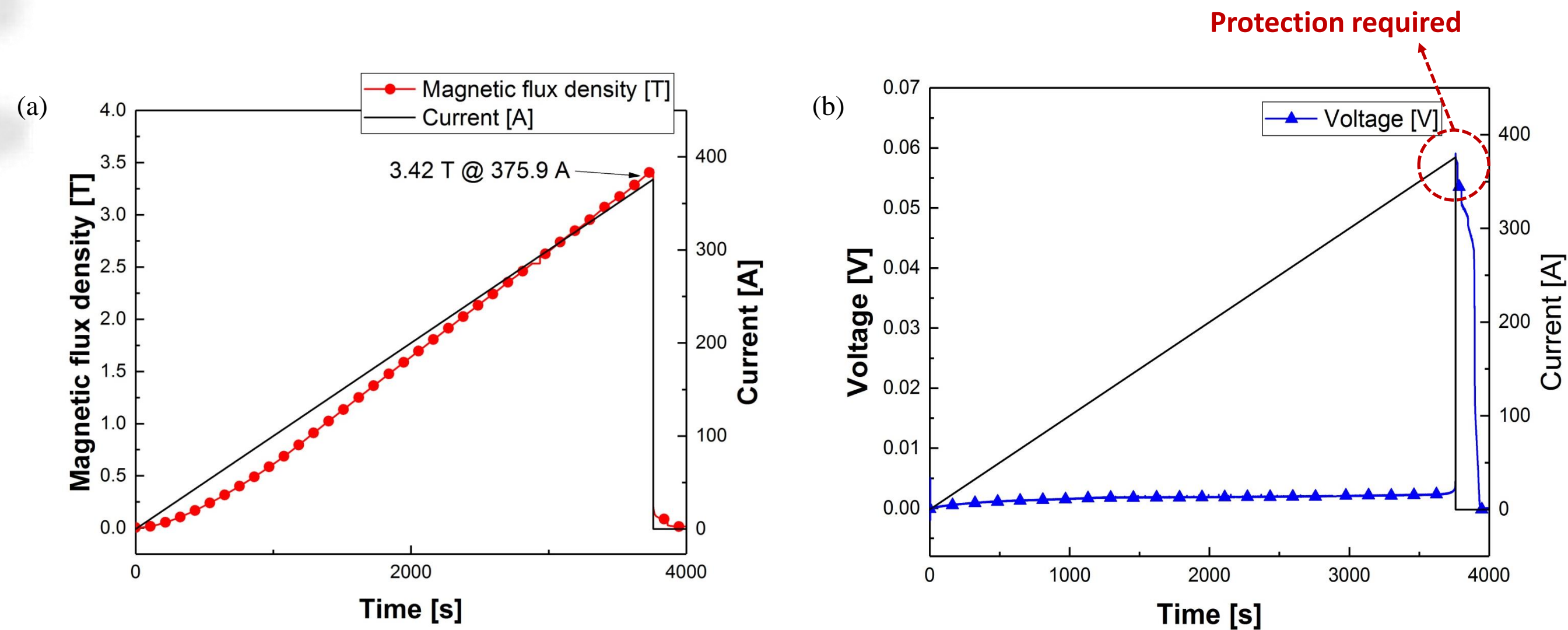
<Optical microscope image of the MgB₂ wire fabricated by KAT Ltd.>

<Specifications of the MgB ₂ wire>		
Parameters		Values
Company		Kiswire Advanced Technology
Packing density	[g/cm ²]	0.31
Diffusion barrier		Niobium
Stabilizer		Copper
Filament type		Monofilament
Diameter	[mm]	0.98
Condition		Un-reacted
Non-Sc/Sc		2.09
Heat treatment temperature	[°C]	675
Heat treatment time	[hr]	1

★ Partial insulated magnet



<Fabrication details for the prototype PI MgB₂ magnet>



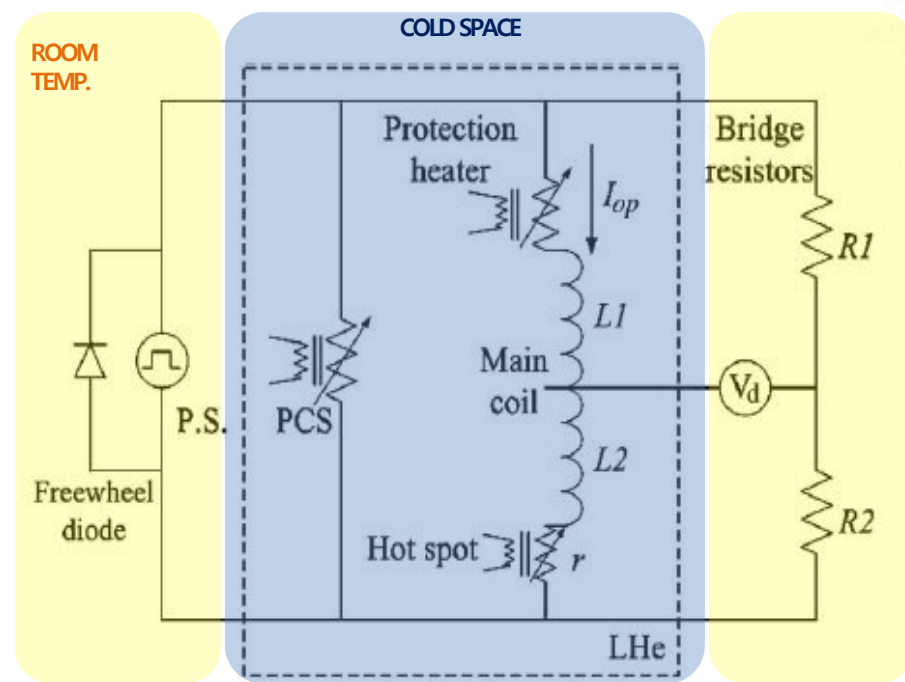
<Magnetic flux density (a) and voltage (b) for the PI MgB₂ magnet measured during the over-current test>

Result & Discussion

★ Specification of PI MgB₂ coil

<Specifications of the PI MgB ₂ coil>		
Parameters		Values
Conductor		
Material		MgB ₂
Diameter	[mm]	0.98
Manufacturer		K.A.T
Magnet		
Inner diameter	[mm]	52.74
Outer diameter	[mm]	71.24
Total height	[mm]	100.17
Turns; Layers		97; 8
Total conductor length	[m]	166.3
Operating temperature	[K]	4.2
Operating current	[A]	122.5
Coil constant	[mT/A]	8.16
Target center field	[T]	1.0
Inductance	[mH]	15.55

<Detect and activate heater>



<Circuit diagram of detect-and-activate-heater protection>

★ Stored magnetic energy

$$E_m = \frac{1}{2} L I^2 = \frac{1}{2} \times 15.55 [\text{mH}] \times (122.5 [\text{A}])^2 = 116.67 [\text{J}]$$

$$V_m = \frac{E_m}{U_{\text{copper}, 100\text{K}}} = \frac{116.67 [\text{J}]}{94.3 [\text{J}/\text{cm}^3]} = 1237.22 [\text{mm}^3]$$

$$l_m = \frac{V_m}{A_{\text{wire}}} = \frac{1237.22 [\text{mm}^3]}{\pi \times 0.49^2 [\text{mm}^2]} = 1640.23 [\text{mm}]$$

E_m : stored magnetic energy [J]
 L : inductance [mH]
 I : operation current [A]
 V_m : volume for dissipating energy [cm³]
 $U_{\text{copper}, 100\text{K}}$: enthalpy density of copper at 100 K [J/cm³]
 l_m : length for dissipating energy [cm]
 A_{wire} : cross-section area of MgB₂ wire [mm²]

★ Energy requirement of protection heater

$$E_p = V_m \times U_{\text{copper}, 30\text{K}} = 1237.22 [\text{mm}^3] \times 1.74 [\text{J}/\text{cm}^3] = 2.15 [\text{J}]$$

$$P_p = \frac{E_p}{\tau} = \frac{2.15 [\text{J}]}{0.2 [\text{s}]} = 10.75 [\text{W}]$$

$$Z(T_f, T_i) = \left(\frac{A_m}{A_{cd}} \right) J^2 \tau$$

E_p : heat input for protection [J]
 V_m : required volume for dissipating energy [mm³]
 $U_{\text{copper}, 30\text{K}}$: enthalpy density of copper at 30 K [J/cm³]
 P_p : power requirement [W]
 τ : required detection time [s]

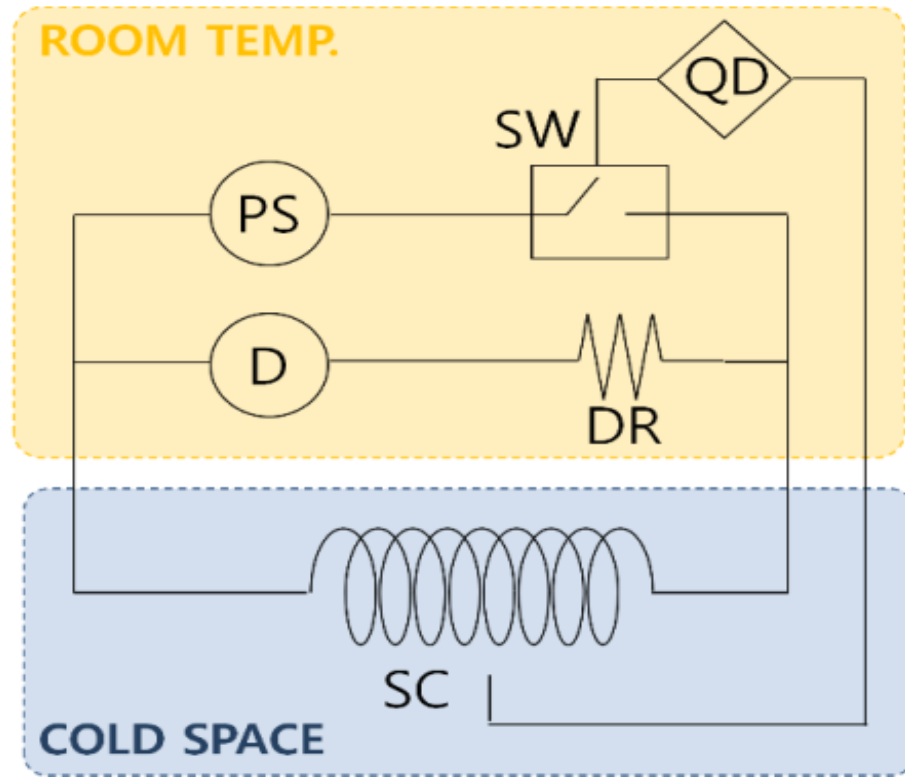
★ Hot spot size

$$l_q = \sqrt{\frac{3k(T_c - T_{op})}{\rho J}}$$

l_q : required length for quench [mm]
 k : thermal conduction [W/cmK]
 T_c : temperature of the conductor [K]
 T_{op} : operation temperature [K]
 ρ : resistivity of the conductor at 30 K [Ωcm]
 J : current density of the conductor [A/mm²]

$$l_q = \sqrt{\frac{3 \times 10 [\text{W}/\text{cmK}] \times (30 [\text{K}] - 10 [\text{K}])}{0.017 [\mu\Omega\text{cm}] \times (341.82 [\text{A}/\text{mm}^2])^2}} = 54.96 [\text{mm}]$$

<Detect and dump>



<Circuit diagram of detect-and-dump protection>

★ Resistance of dump resistor

$$Z(T_f, T_i) = \left(\frac{A_m}{A_{cd}} \right) J^2 \left(\frac{L}{2R_D} \right)$$

$$R_D = \left(\frac{A_m}{A_{cd}} \right) J^2 \frac{L}{2Z(T_f, T_i)}$$

$$R_D = \frac{0.3584 [\text{mm}^2]}{0.3959 [\text{mm}^2]} \times 341.82^2 [\text{A}^2/\text{mm}^4] \times \frac{15.55 [\text{mH}]}{2 \times 8.8 \times 10^6 [\text{A}^2/\text{m}^4]} = 0.00935 [\Omega]$$

E_m : stored magnetic energy [J]
 L : inductance [mH]
 I : operation current [A]
 A_m : cross-section area of matrix [mm²]
 A_{cd} : cross-section area of conductor [mm²]
 R_D : resistance of dump resistor [Ω]

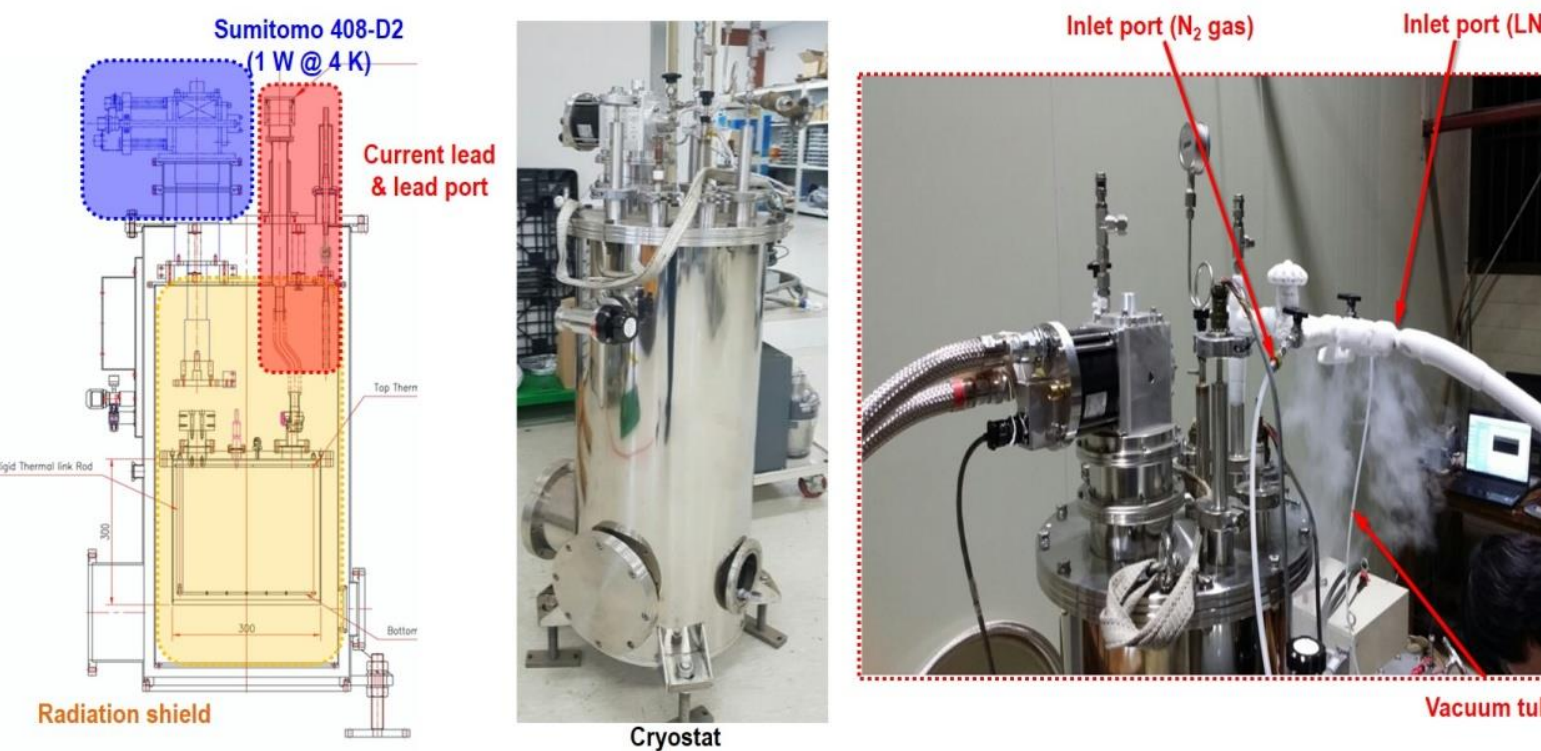
★ Total length of dump resistor

$$l_d = \sqrt{\frac{E_m R_D}{\rho_d C_p \Delta T}}$$

$$l_d = \sqrt{\frac{(116.67 [\text{J}]) \times (0.00935 [\Omega])}{(72 [\mu\Omega\text{cm}]) \times (25000 [\text{J}/\text{m}^3\text{K}]) \times (30 - 10 [\text{K}])}} = 1.74 [\text{m}]$$

l : total length of dump resistor [Ω]
 E_m : stored magnetic energy [J]
 R_D : resistance of dump resistor [Ω]
 ρ_d : resistivity of dump resistor [μΩcm]
 C_p : heat capacity of copper [J/K]
 ΔT : allowance temperature [K]

★ Future work



<Drawing and photographs of the conductive cooling system for the PI MgB₂ coil>

The quench and recovery characteristics of the PI MgB₂ coil will be examined in terms of the maximum hotspot temperature, induced voltage, and recovery time.