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# Cooling Stability Test of MgB<sub>2</sub> Wire Immersed in Liquid Hydrogen under External Magnetic Field

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**Abstract.** Liquid hydrogen (LH<sub>2</sub>), which has large latent heat, low viscosity coefficient, is expected to be a candidate for a cryogen for superconducting wires, not only MgB<sub>2</sub> but also other HTC superconductors. LH<sub>2</sub> cooled superconducting wires are expected to have excellent electro-magnetic characteristics, which is necessary to be clear for cooling stability design of LH<sub>2</sub> cooled superconducting device, however, due to handling difficulties of LH<sub>2</sub>, there are only few papers on the properties of LH<sub>2</sub> cooled superconductors, especially under external magnetic field. We designed and made an experimental setup which can energize superconducting wires immersed in LH<sub>2</sub> with the current of up to 500A under the condition of external magnetic field up to 7 T and pressure up to 1.5 MPa. In order to confirm experimental method and safety operation of the setup, over current tests were carried out using MgB<sub>2</sub> superconducting wires under various external magnetic field conditions. Critical current of the test wire at the temperature 21, 24, 27, 29 K under external magnetic fields up to 1.2 T was successfully measured. The resistance of the wire also was measured, while the transport current exceeded the critical current of the wire.

## 1. Introduction

Generally, the high-T<sub>c</sub> superconductors, such as YBCO and BSCCO are cooled by liquid nitrogen (77K), however, it is considered that the excellent electro-magnetic properties of such materials are achieved with temperature of 20 – 40 K. Liquid hydrogen (LH<sub>2</sub>) has excellent properties as a coolant, such as large latent heat, low viscosity coefficient and so on [1]-[3]. The characteristics of J<sub>c</sub>-B (critical current density and critical magnetic flux density) of high-T<sub>c</sub> superconductors cooled by LH<sub>2</sub> are fairly good compared with those by LN<sub>2</sub>, while the heat capacity of the materials in LH<sub>2</sub> temperature is still large for better cooling stability. Especially, LH<sub>2</sub> is expected to be the coolant for MgB<sub>2</sub> superconductor whose critical temperature is 39 K.

Cooling stability in steady state and transient state of superconductors and their coils cooled by LH<sub>2</sub> in a certain magnetic field is important issue for design of LH<sub>2</sub> cooled superconducting power apparatus. We have developed a thermal-hydraulics experimental system for liquid hydrogen [4]-[6] in order to investigate heat transfer characteristics for wide ranges of subcoolings, pressures up to supercritical and flow velocities in forced flow cooling. The experimental set-up for investigating electrical properties of liquid hydrogen cooled superconductors under external magnetic field was designed and made [7]. In this paper, over-current test of an MgB<sub>2</sub> short sample (supplied by Hyper Tech) under magnetic field in order to evaluate the experimental set-up was described.



## 2. Experimental set-up[7]

Experimental set-up for investigating  $\text{LH}_2$  cooled superconductors under magnetic field was designed and made as shown in Fig.1 (cross-sectional view). The  $\text{LH}_2$  cryostat has 61 L volumetric capacity of  $\text{LH}_2$  with 309 mm inner diameter. The insert of  $\text{LH}_2$  cryostat has 3 current leads ( $\sim 500$  A), then two test sample can be set at once. A superconducting magnet which can produce up to 7 T in experimental space ( $\sim 300$  mm diameter and 400mm height) lower part of the  $\text{LH}_2$  cryostat is set in the liquid helium (LHe) cryostat. Major specification of the test facility is listed in Table 1.

Test superconductors, which are set immersed in  $\text{LH}_2$ , can be tested with excitation of various current patterns ( $\sim 500$  A) in a certain magnetic field ( $\sim 7$  T). Test pressure can be set up to 2.0 MPa. Test temperature can be set 20  $\sim$  32 K using sheath heater placed at the bottom part of the cryostat.

The  $\text{LH}_2$  cryostat is equipped though the bore area of the magnet. Maximum current sweep rate is 0.09 A/s. It takes about one hour to excite the magnet up to 7 T.

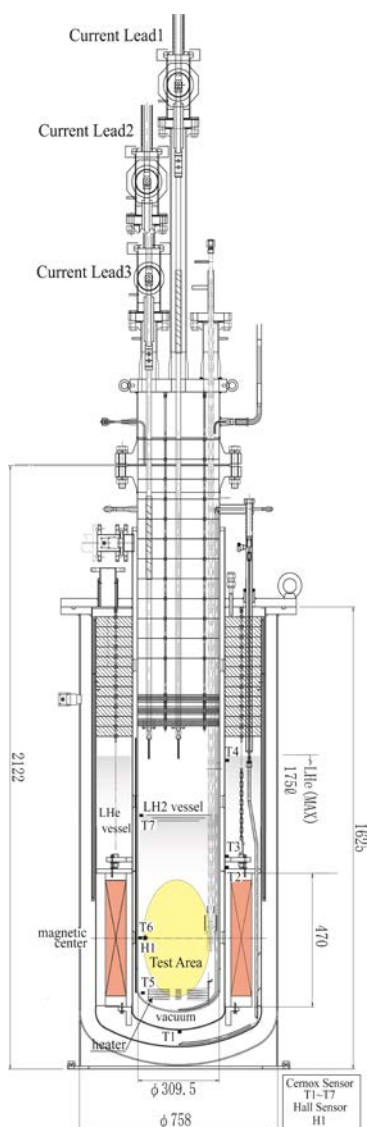


Fig. 1 Cross-sectional view of cryostats for electro-magnetic property tests of liquid hydrogen cooled superconductors.

TABLE 1

SPECIFICATION OF CRYOSTAT AND MAGNET

Liquid Hydrogen Cryostat	
Inner diameter	309.5 mm
Height (bottom to top flange)	2218 mm
Volumetric capacity for $\text{LH}_2$	61 L max
Liquid Helium Cryostat	
Inner diameter	350 mm
Outer diameter	630 mm
Height (bottom to top flange)	1625 mm
Volumetric capacity for LHe	175 L max
Superconducting Magnet	
Material	NbTi
Inductance	112.36 H
Rated current	175A
Max. magnetic field (center)	7 T

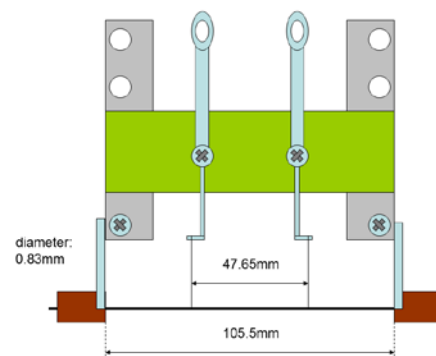


Fig. 2 Illustrated test sample of  $\text{MgB}_2$  short wire and set-up.

### 3. Test insert

Test section is inner-bottom area (309 mm diameter and 400 mm height) of the LH<sub>2</sub> cryostat where the external magnetic field is generated by the superconducting magnet immersed in LHe (see Fig. 1). The test sample, that is, short MgB<sub>2</sub> wire as illustrated in Fig. 2 was set orthogonal oriented to the field and at the center in height of the magnetic field profile.

The sample wire is monolith MgB<sub>2</sub> wire of 0.83 mm diameter, 160mm length. Configuration of the wire is 20 % MgB<sub>2</sub>, 41.8% Copper and 38.2 % Nb barrier.

### 4. Critical current and Electrical resistance of the wire

#### 4.1 Quasi steady state heat transfer experiment

The current through the MgB<sub>2</sub> short sample was controlled to meet the exponential heat inputs  $Q=Q_0 \exp(t/\tau)$  with various periods  $\tau$  in order to evaluate the heat transfer property from heated wire surface to LH<sub>2</sub>. The pressure of the main tank was set to 1.1 MPa. The bulk-liquid temperature (subcooling temperature) was set 21, 24 27 and 29 K by use of the sheath heater equipped at the bottom of the cryostat. The heat input was calculated by the current and the tap voltage of the test wire.

One of the experimental results with quasi-steady state heat input ( $\tau = 2.0$  s) is shown in Fig 3. The AC loss of the wire during current increasing was considered to be negligible. The bulk temperature of the liquid hydrogen was 21 K (subcooled by 11 K) and the pressure was 1.1 MPa. As the transport current  $I$  increased, at around 5.2 s, the wire resistance  $R$  appeared and the heat input  $Q$  to the wire started to increase. At about 8.0 s, as the nucleate boiling began, cooling property was improved. The current was successfully shut down preventing from burning out of the wire.

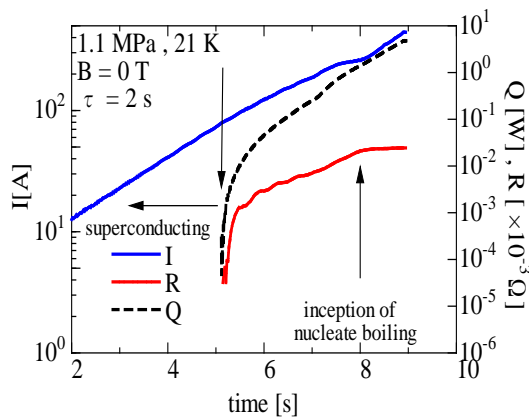


Fig. 3 Quasi-steady state heat input test ( $\tau = 2.0$  s,  $T_B = 21$  K, subcooled by 11 K, and the pressure was 1.1 MPa).

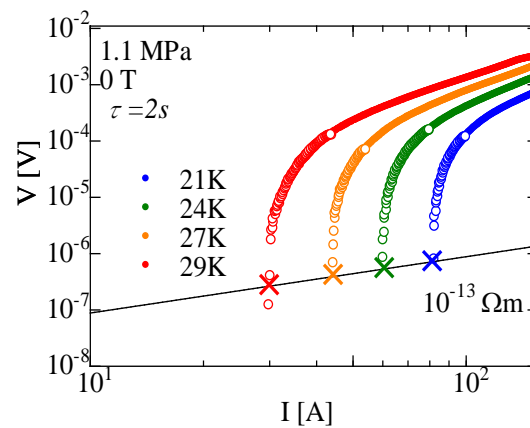


Fig. 4 Tap voltage versus transport current during quasi-steady heat input ( $\tau = 2.0$  s) under 21, 24, 27 and 29 K without magnetic field. The critical current was evaluated for each temperature.

#### 4.2 Critical Current of the test sample

Fig 4 shows an experimental data of the tap voltage versus transport current at the appearance of the resistance of the test wire with the quasi-steady state heat input ( $\tau = 2.0$  s) under the bulk liquid temperature of 21, 24, 27 and 29 K without magnetic field. The intersection point of each line with the constant resistivity line of  $10^{-13}$   $\Omega\text{m}$  is indicated the critical current. The critical current decreases as higher temperature. The gradient of the tangential line at the intersection point which is related to the  $n$ -value of the wire is evaluated to become smaller as the higher temperature.

### 4.3 Critical Current under magnetic field

The same experimental data of the tap voltage versus transport current with magnetic field of  $B=0.41$  T is shown in Fig. 5. The critical current was degraded with external magnetic field at each temperature, such as from 82 A to 27 A at 21K. It can be observed the  $n$ -value becomes smaller with higher magnetic field.

The same experiments were carried out with external magnetic field of 0.205, 0.41, 0.82 and 1.25 T. The characteristics of  $I_c(B)$  was evaluated as shown in Fig. 6 with temperature as a parameter.

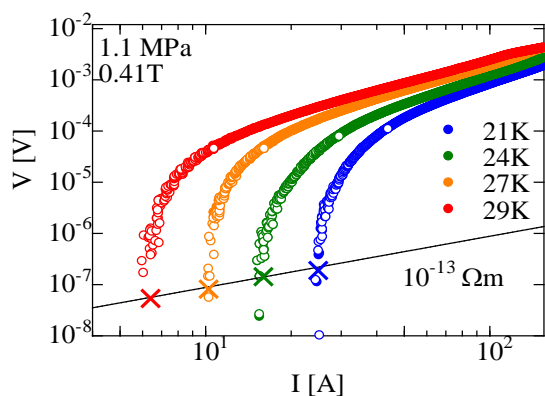


Fig. 5 Tap voltage versus transport current during quasi-steady heat input ( $\tau = 2.0$  s) under 21, 24, 27 and 29 K with external magnetic field of 0.41 T. The critical current was evaluated for each temperature.

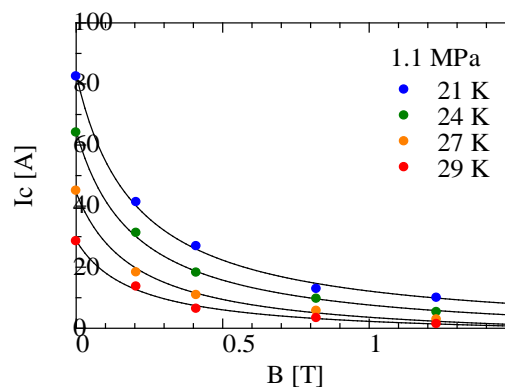


Fig. 6 Critical current of the test wire versus external magnetic field under 21, 24, 27 and 29 K.

## 5. Conclusion

We designed and made an experimental setup which can energize superconducting wires immersed in  $LH_2$  with the current of up to 500 A under the condition of external magnetic field up to 7 T and pressure up to 1.5 MPa. Using this experimental set-up, over-current tests were carried out using  $MgB_2$  superconducting short wire under various external magnetic field conditions. Critical currents of the test wire at the temperature 21, 24, 17, 29K under external magnetic field up to 1.25 T were measured. All the tests were performed with remote-operation system in a safe manner.

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