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Development of an experimental system for characterization of high-temperature superconductors cooled by liquid hydrogen under the external magnetic field

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Abstract. An experimental system has been developed to investigate electro-magnetic properties of high-Tc superconductors cooled by liquid hydrogen under the external magnetic field of up to 7 T. A LH₂ cryostat is concentrically mounted on the inside of a LHe cryostat to cool a NbTi superconducting magnet. The experimental system is installed in an explosion-proof room. Explosion proof electrical devices are used and current leads are covered with an enclosure filled with nitrogen gas. A remote control system has been developed. Furthermore, the effects of stray magnetic field on the existing and the new devices are investigated and electro-magnetic shielding panels and enclosure made of iron were designed. It is confirmed through the cryogenic test that the experimental system meets the design requirements.

1. Introduction

Liquid hydrogen (LH₂) is expected as a coolant of high-Tc superconductors because of the excellent cooling properties and the spectacular improvement of the electromagnetic characteristics when the temperature is decreased from 77 K to 20 K. However, there have been few experimental data for the cooling properties of LH₂ because of its explosive properties. For the first step, we have developed an experimental system to study cooling properties of liquid and supercritical hydrogen for wide ranges of pressures, temperature and flow rates [1]. Furthermore, over-current characteristics of MgB₂ immersed in LH₂ have been studied under no external magnetic field [2]. It is necessary to understand cooling stability of the superconductors cooled by LH₂ under some external magnetic field.

In this study, an experimental system has been developed to study electromagnetic characteristics of high-Tc superconductors cooled by liquid and supercritical hydrogen under magnetic field up to 7 T. The cryogenic test has been conducted so as to verify the performance.

2. Design of experimental system

2.1. Design details

Figure 1 shows a schematic of the developed experimental system, which has been designed based on the existing thermal-hydraulic one [1]. They are installed in an explosion-proof room. The design pressure of a LH₂ cryostat is 2.0 MPa. The hydrogen inventory is 61 L. There are three current leads (up to 500 A) in enclosures where nitrogen gas purges with a pressure of 5 kPaG, in order to set two



test pieces at a time. The liquid hydrogen can be pressurized to a desired value by a pure hydrogen gas (99.999%) that is adjusted by a dome-loaded gas regulator. The bath temperature is controlled by a sheathed heater with a capacity of 500 W. Five cernox temperature sensors are vertically located at the liquid levels of 13, 16, 20, 40 and 50 L. Hydrogen gas is temporarily supplied to the bottom so as to uniform the bath temperature.

A LHe bath, whose design pressure is 0.04 MPa, is concentrically mounted on the outside of the LH₂ bath through a vacuum layer. A Nb-Ti superconducting magnet (7 T) with a height of 406.4 mm, an inner diameter of 400.1 mm and an outer diameter of 558.8 mm is cooled. The superconducting magnet has an inductance of 112.4 H and a rated current of 175.27A. The current leads are also covered with the GN₂ enclosures, which are isolated from those for the LH₂ cryostat. It takes about an hour to achieve the excitation of 7 T due to the maximum current sweep of 0.09 A/s. The inventory of LHe is determined to 100 L above the top of the magnet. The allowable heat inleak need to be reduced below 18 W so as to get experimental duration of more than three hours. The heat inleak was estimated 12 W except for that the power lead. The cooling design for the power leads was carried out so as to reduce the heat inleak through them down to 2.5 W using the CFD code, STAR-CCM+.

When quench occurs, the stored energy of 1.71 MJ at the excitation of 7 T is used by the evaporation of LHe and the temperature rise of the magnet. The blow off rate is estimated to be 397 g/s based on the authors' data of the critical heat flux in a pool of saturated LHe ($5 \times 10^3 \text{ W/m}^2$) [3]. A flange insert valve whose size is 50A is installed not to exceed the allowable pressure in the LHe bath.

Two hydrogen gas detectors (RIKEN KEIKI, GD-A8-16), which are metal oxide and catalytic based sensor, are located on the ceiling with a height of 4 m. Explosion proof electrical devices are used such as a solenoid valve, a pressure transmitter and so on. The power leads are covered with the enclosure mentioned above. A remote operational system has been established and we maintain a safe distance from the apparatus during the experiment. If an off-normal event such as hydrogen leakage occurs, hydrogen is automatically released to the outside through the vent line and the power sources are shut off. However, the magnet is degaussed at the allowable speed because it is in helium atmosphere and the power leads are isolated by the GN₂ enclosure.

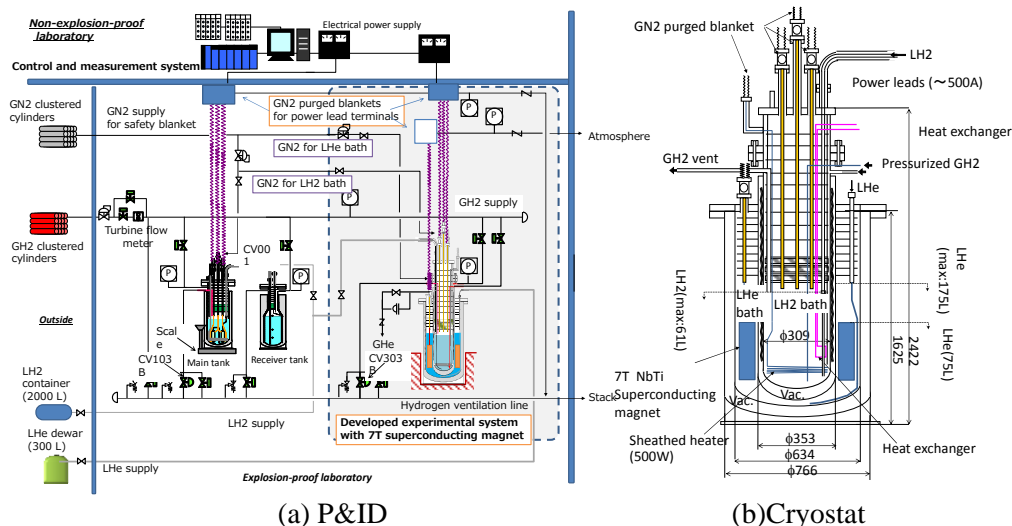


Figure 1. Schematic of an experimental system.

2.2. Countermeasure against stray magnetic field

The stray magnetic field is analyzed under the excitation of 7 T using ANSYS. The solenoid coil is located at the center of a cubic 14 m on a side in the analytical model. The current density of 1.08 A/m^2 is applied, which corresponds to the magnetic field of 7 T at the center of the coil. As shown in Fig.2, the analytical result indicates that the stray magnetic fields are estimated to be 30 G and 10 G at the horizontal distances of 3.2 m and 4 m away from the center of the magnet, respectively. It is

necessary to clarify the effect of the stray magnetic field on the existing and the newly-installed devices: the hydrogen gas detector, the explosion proof solenoid valve (ASCO, JE4) for on-off valves, that for pneumatic control valves (TOKO VALEX, T-8810), the hydrogen gas detector, pressure transmitter (NAGANO KEIKI, KH41-173), the scale corrected by electromagnetic force (Mettler Toledo, WMHC 300s) and an air-conditioning control panel located at the next control room. The effect of the magnetic field on the solenoid valves, pressure transmitter and the hydrogen gas detector were investigated in the magnetic field up to 300 G using a copper coil magnet with an inner diameter of 165 mm and a height of 30 mm. The solenoid valve functioned normally below 210 G because of the explosion-proof enclosure. The hydrogen detector and the pressure transmitter were not affected.

The solenoid valves were moved to 4-m away from the magnet where the magnet field is below 10 G. The magnetic field is less than 20 G at the location of the hydrogen detectors. The electro-magnetic shielding made of iron was designed for the control valves, the scale and the control panel. As shown in Figs.3 to 5, it is clarified that the stray magnetic field can be reduced below 25 G by using the shielding panel and enclosure with the thickness of 3.2mm and 7 mm, respectively.

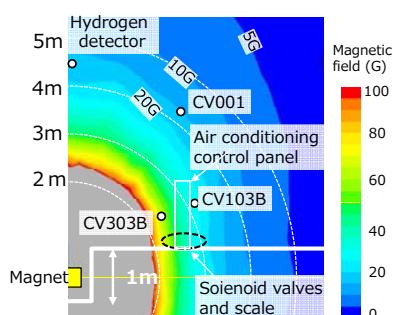


Figure 2. Stray magnetic field at 7 T.

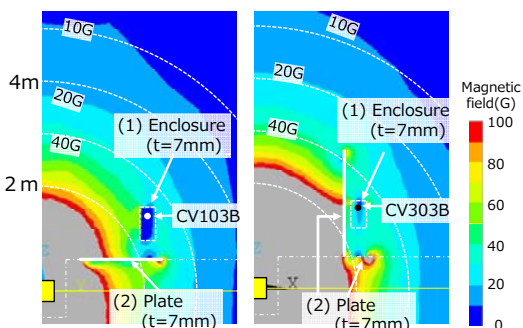


Figure 3. Countermeasures for CV103B and CV303B.

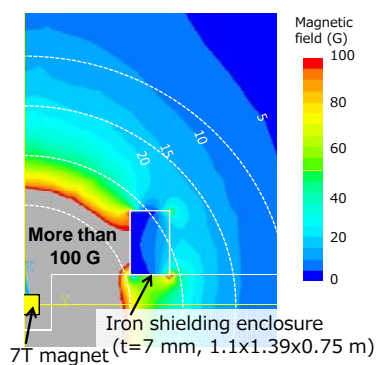


Figure 4. Countermeasures for scale.

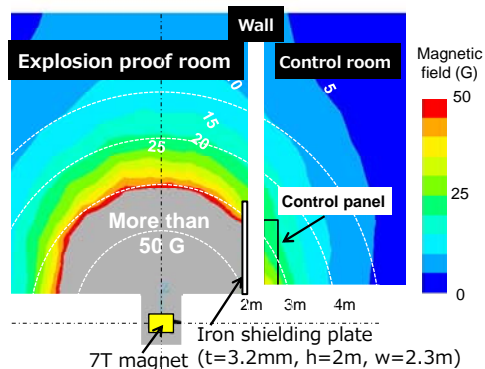


Figure 5. Countermeasures for air conditioning control

2.3. Commissioning

Figure 6 shows the first excitation test result. As shown in Fig.6, the heat leak into the LHe bath is 15.5 W given by the evaporation of LHe and agrees with the design value, when the evaporation gas flows only to the cooling channels for the power leads. When the evaporation gas flows not only to the power leads but also along the wall of the cryostat, the heat leak is decreased down to 5.3 W. The experimental duration of more than 3 hours can be achieved for the heat leak of 15.5 W. Figure 7 shows one of over current test results using a short MgB_2 wire with a diameter of 0.51 and a length of 130 mm (@HyperTech), which was immersed in subcooled LH_2 at the bath temperature of 21 K and the pressure of 1.1 MPa. The current was controlled to meet the exponential heat inputs $Q=Q_0 \exp(t/\tau)$ with the period τ of 5 s. As the transport current I increased, the wire resistivity R appeared at $I = 65$ A, which corresponds to a critical current, and the heat input Q to the wire also started to increase. It was

confirmed that the over current characteristic test was successfully carried out using the MgB_2 wire. Figure 8 shows the measured magnetic field distribution at the ground level for 6.4 T. The magnetic field at the devices can be mitigated below 20 G, which is lower than the allowable value. It is confirmed that the experimental system satisfies the design requirement.

3. Conclusion

An experimental system has been designed and fabricated to investigate electro-magnetic properties of high- T_c superconductors cooled by liquid and supercritical hydrogen under the external magnetic field up to 7T. The countermeasures against the explosion proof and the stray magnetic field have been conducted. It was confirmed through the commissioning that the developed experimental system satisfied the design requirements.

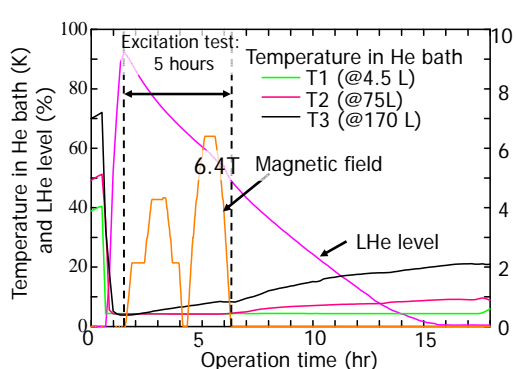


Figure 6. First excitation test result.

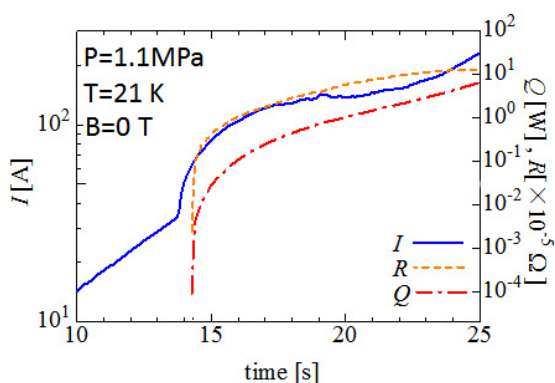


Figure 7. Over current test result.

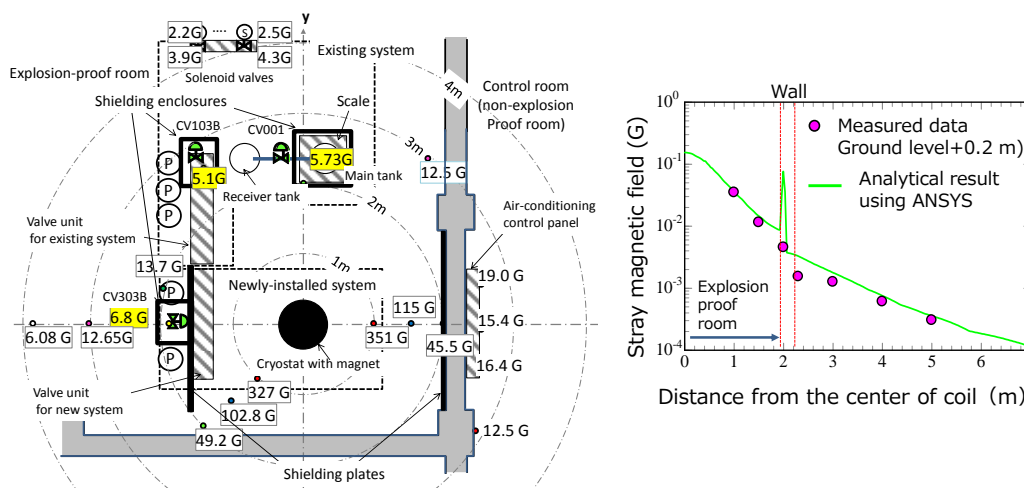


Figure 8. Measured stray magnetic field at the excitation of 6.4 T.

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