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Technical Note

Demagnetization of a Bi-2223 high-temperature superconducting coil in RT-1 through spontaneous temperature rise

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A B S T R A C T

The Ring Trap 1 (RT-1) device produces a magnetospheric configuration for the confinement of a high-β plasma with a Bi-2223 high-temperature superconducting magnet. Here we report the results of emergency demagnetization of the superconducting coil, where we could not connect current leads, temperature measurement connectors, and connectors for a persistent-current switch (PCS) heater to the coil. The spontaneous warming of the coil caused a rise in the flux-flow resistance of the superconducting coil, and the persistent current slowly decreased as coil resistance increased. Approximately 98% of the total stored magnetic energy was safely released before the quenching of the PCS, and there was no substantial damage to the superconducting coil.

1. Introduction

The Ring Trap 1 (RT-1) device [1–5] is a magnetospheric plasma experiment with a Bi-2223 [6] high-temperature superconducting coil magnet. The research goals of RT-1 are to realize ultra high-β plasma confinement (β is plasma pressure normalized by magnetic pressure) suitable for advanced thermonuclear fusion, and pure magnetic trap of antimatters such as electron–positron and antihydrogen plasmas. To minimize disturbance to the plasma, the superconducting coil of RT-1 is magnetically levitated inside the vacuum chamber, and an *artificial magnetosphere* is generated in a laboratory. In RT-1, we have succeeded to confine a plasma with the maximum local β values exceeding 30% [5]. Stable confinement of a non-neutral (electron) plasma is also realized, and the maximum confinement time exceeds 300 s. These research results have been achieved based on the recent technology progress of the levitated dipole-field coil made with Bi-2223 high-temperature superconducting wires [7].

After plasma experiment carried out on 7 September 2009, there was a temporal failure of a lift for the superconducting coil in RT-1, and we could not demagnetize the coil in the normal procedure. In this publication, we report the process of demagnetization of the coil due to the spontaneous temperature rise without external operations. The persistent current of the coil slowly decreased with increasing flux flow resistance due to the spontaneous warming of the coil. The coil current decayed to 13% of the rated value in 34 h before a built-in persistent-current switch (PCS) quenched. Rapid and excessive local heat input into the superconducting coil was thus avoided, and the coil was not substantially damaged in this accident.

2. Operation of superconducting coil in RT-1

Fig. 1a shows the r–z cross-section of the RT-1 device. The superconducting coil magnet of RT-1 is cooled, magnetized, and demagnetized at the bottom of the chamber. The coil is cooled down to 20 K using three GM refrigerators, and excited to 250 kA (116 A, 2160 turns) by using an external power source and the PCS made of YBOC thin-film [3] (Fig. 1b). The coil is then moved up to the equator of the device ($z = 0$ cm) using a coil lift. The superconducting coil is magnetically levitated by a levitation normal-conducting coil located at the top of the chamber. The vertical position of the superconducting coil is monitored by three-cord laser sensors, and the current of the levitation coil is feed-back controlled for realizing stable levitation. The use of Bi-2223 high-temperature superconducting wire has made possible more than 6 h of a continuous plasma experiment with the coil levitation. Prior to the plasma experiments, current leads, transfer tubes for cooling helium gas, connectors for thermocouple sensors and PCS control are detached from the coil inside the vacuum chamber. The coil is kept in a low temperature state without cooling due to the heat capacity of the coil wires [4] and operated in the persistent current mode. When the plasma experiment ends, the coil is moved back to the chamber bottom, and the electric connectors

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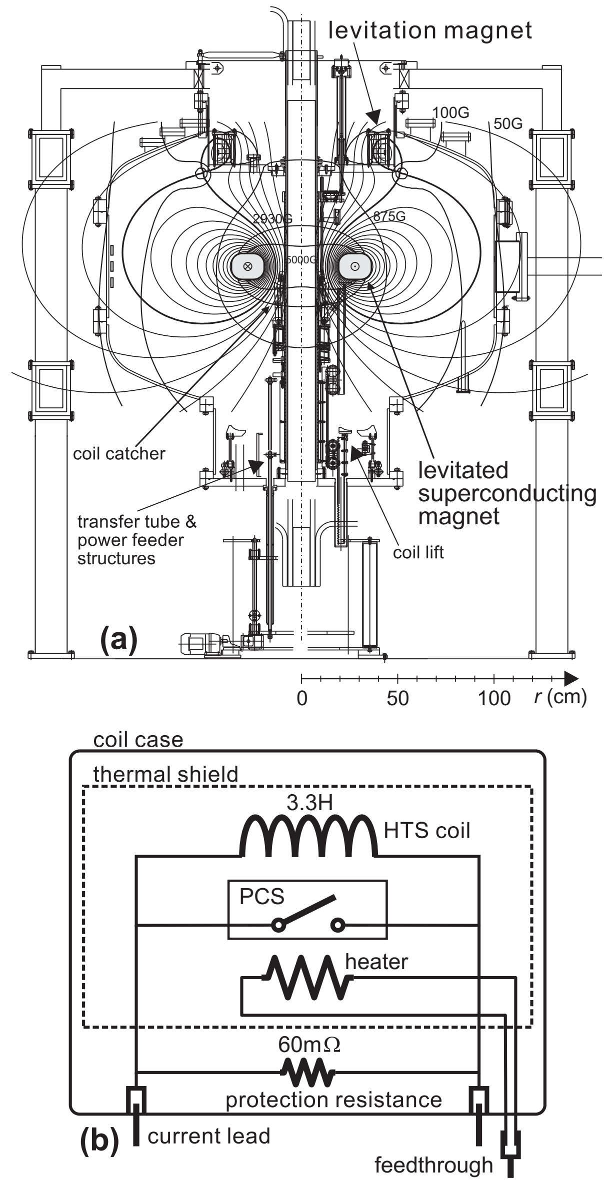

Fig. 1. (a) Cross-section of the RT-1 including the coil magnets, vacuum chamber, and magnetic surfaces. (b) Circuit diagram of the superconducting coil and PCS in the RT-1 device.

and the transfer tubes are attached. Then the coil is demagnetized and re-cooled in preparation for the next day experiment. The temperature rise of the coil from the detachment from and to the re-attachment to the refrigerators is less than 10 K. As shown in Fig. 2, the decay rate of the persistent-current in normal 8 h of operation (including 6 h of a plasma experiment) is 0.14 A/h, and the current decay rate from the magnetization to the demagnetization is less than 1%.

At the end of a plasma experiment conducted on 7 September 2009, the coil lift machine broke down inside the vacuum chamber of RT-1. Due to this trouble, we could not lift down the coil to the bottom of the chamber for demagnetization and re-cooling, while the superconducting coil was operated with the rated value of the persistent current.

In case of an emergency in the demagnetization phase, with troubles in a connection between the coil and the power source, the coil current is supposed to be demagnetized by PCS quenching [3,4]. As long as we can attach the connectors for the PCS control to

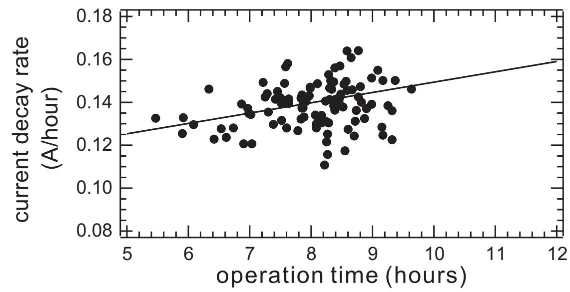

Fig. 2. Decay rate of the persistent current of the superconducting coil in the RT-1 device for various operating times without refrigeration.

the coil, we can use a heater for PCS quenching. As shown in Fig. 1b, a 60 mΩ protection resistance was put in the coil circuit of RT-1 outside the thermal shield. When the PCS quenches while the coil is operated with a persistent current, the stored magnetic energy is primarily released at the protection resistance and we can avoid excess heat input into the superconducting coil. In the case of this failure, we have experimentally confirmed that the manual PCS quenching at the rated value of the persistent current does not damage the superconducting wires, the PCS, or the protection resistance, and the coil can be safely demagnetized.

However, when the coil lift-down is impossible in the present situation, we cannot attach all of the connectors to the coil. Consequently, the PCS is out of control and the superconducting coil must be demagnetized even without monitoring its temperatures. Because the vacuum of the cooling tube in the superconducting coil and that of the vacuum chamber are common, we cannot vent the chamber to atmosphere for recovering the lift, in order to avoid thermal strain and destruction of the coil. In this case, we can do nothing but wait for the demagnetization of the coil by the spontaneous temperature rise. A numerical simulation [3] suggests the possibility of a "soft landing" scenario; The persistent coil current may slowly decrease with increasing flux flow resistance due to the spontaneous coil warming, without seriously damaging the coil. However, the demagnetization in this method was not tested in the real coil system, and experimentally, it was not clear whether the coil can be safely demagnetized from the rated value of the persistent current. In the following sections, we describe the process of the coil demagnetization in RT-1 due to the spontaneous temperature increase. The persistent coil current during the slow decay and quenching of the PCS was measured by a Hall magnetic probe and it is compared with the results of the numerical simulation carried out in Ref. [3].

3. Demagnetization of persistent current due to spontaneous temperature rise

The process of the coil operation and plasma experiment was as follows. At 10:00 am on 7 September, we excited the superconducting coil of RT-1 to the rated value of 116 A. After re-cooling the coil to 16.5 K, the electric connectors and the helium transfer tubes were removed from the coil at 12:20 pm. Then we moved up the coil to the equator of the chamber and conducted plasma experiment until 5:30 pm. When the plasma experiment ended and we tried to lift down the superconducting coil for demagnetization, we had a mechanical trouble on the coil lift inside the vacuum chamber. The coil was located between the equator and the bottom of the chamber when the coil lift broke down. At 10:00 pm, we gave up recovering the lift machine and decided to demagnetize the coil by spontaneous temperature increase. The persistent coil current I_{coil} was monitored by a Hall magnetic sensor. Measurements of the coil current started at this point were not straightforward, because the precise position of the coil was not clear and also the coil was tilted due to the increased backlash of the damaged lift gears. The current decay rate of the coil for 12 h of persistent-current operation obtained by an extrapolation in Fig. 2 is 0.16 A/h, and I_{coil} at 10:00 pm is estimated to be 114.1 A. We believe this value is credible, because it agreed within the margin of error with the measured I_c using the Hall sensor and estimated coil position. We note that the pressure inside the vacuum chamber was kept below 10^{-5} Pa by a mechanical booster pump and a turbomolecular pump during the spontaneous demagnetization.

Fig. 3 shows the temporal evolution of I_{coil} after 10:00 pm on 7 September. Comparison between the measured I_{coil} and numerical simulation of the soft landing scenario [3] is also shown in Fig. 4. Heat input into the coil caused by the flux flow resistance, radiation, and conduction are included in the calculation. When T_{coil} = 30 K, the total heat input is 0.9 W, including 0.21 W of radiation across multilayer thermal shield, 0.03 W of radiation at the current leads, 0.66 W of heat conduction through coil support structures inside the coil case, current leads, and measuring wires, and 0.004 W of heat caused by the flux flow resistance. We assumed that the coil case temperature is 300 K (close to the room temperature), and the effect of magnetic coil levitation on the heat input was negligible. We also assumed that the heat input caused by the radiation and conduction is 2 W and it was temporally constant in the calculation.

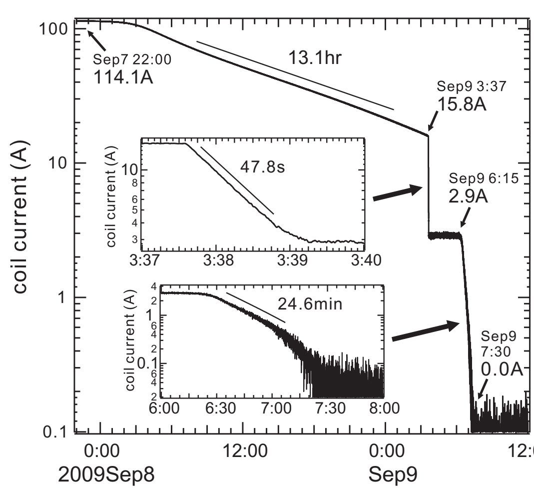

Fig. 3. Temporal evolution of the persistent coil current and the decay time constants measured using a Hall probe. Fitting curves are shifted vertically in order to avoid the overlapping of lines.

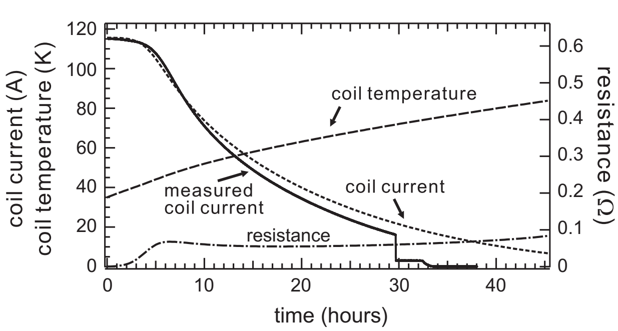

Fig. 4. Numerical simulation results [3] of the coil current, temperature, and flux-flow resistance of the superconducting coil without refrigeration. Measured coil current values are also plotted as a solid line.

We observed a pronounced decrease of I_{coil} from approximately 2:00 am on 8 September, due to the increasing flux flow resistance caused by the spontaneous temperature rise of the coil. The decay time constant of I_{coil} in this period was 13.1 h. After 26 h of steady current decay, there was a rapid decay of I_{coil} at 3:37 am on 9 September, where I_{coil} dropped from 15.8 A to 2.9 A with an exponential time constant of 47.8 s. The transition temperature of the YBCO thin-film PCS, T_{c-pcs} = 85 K, is lower than that of Bi-2223 coil (T_{c-coil} = 110 K). The PCS temperature at this point is then estimated to be close to T_{c-pcs}, and I_{coil} rapidly dropped as the PCS quenched. The current decay time constant of the coil circuit when the PCS is turned off (the off resistance is 1 Ω) is $\tau = L/R$ = 58 s, where L = 3.3 H is the self inductance of the superconducting coil, and R = 56.6 mΩ is a resistance of the parallel protection resistance and the off resistance of PCS. The observed decay time constant is below τ, and R component of the circuit is short by 12 mΩ. This is fairly reasonable when we consider that the temperature of the coil is higher than that of the usual cases and thereby the resistances of the current leads and the coil wires were above the normal values.

Before the PCS quenched at 3:37 am on 9 September, 98% of the initially stored magnetic energy of the coil had been slowly and safely released by the Joule heating due to the increased flux flow resistance. Because the PCS is designed not to be damaged even when it quenched while the coil is operated with the rated value of the persistent current, it is quite unlikely that the coil and the PCS were damaged in the present accident. In Fig. 4, fairly good agreement between the measured and simulated I_{coil} was observed, confirming that the increase of the flux flow resistance of the Bi-2223 coil was the main reason for the current decay. I_{coil} at t = 30 h is approximately 5 A below the simulated one. Also, the estimated coil temperature in the simulation at t = 30 h is below T_{c-pcs} = 85 K. This is possibly because the simulation was carried out using the above mentioned simplified model of the constant heat input due to the radiation and conduction.

After decayed to 2.9 A at 3:37 am on 9 September, I_{coil} was approximately constant until it decayed to zero with a time constant of 24.6 min at 6:15 am. We do not have a decisive explanation why I_{coil} decayed in such a two-stage way, especially because we could not measure the coil temperatures. One of possible explanations is that the transition temperature of the PCS rose at 3:37 am due to the decrease of the magnetic field strength at the first current decay, and the PCS was turned on again, realizing the persistent current mode. Another interpretation is the effects of residual magnetization of the Bi-2223 coil due to the difference between T_{c-pcs} and T_{c-coil}. Because the current decay time at 6:15 am is much longer than the time constant of the coil circuit, $\tau = L/R$ = 58 s, the increased flux flow resistance of the coil is the most probable cause for the second current decay.

4. Summary

We reported the process of the emergency demagnetization of the Bi-2223 superconducting magnet in RT-1. We lost the normal control of the coil due to the failure in the coil lift structure, when the coil was operated with the rated value of the persistent current. Safety demagnetization of the magnet was realized as the persistent current slowly decreased with the increasing coil resistance caused by the spontaneous temperature rise. Before the PCS quenched approximately 42 h after the excitation, 98% of the stored magnetic energy was gradually released due to the increasing flux flow resistance, and the rapid and local heat input into the coil was avoided. The superconducting coil was not substantially damaged, and we confirmed that the rates of current decay and temperature increase of the coil did not significantly change by the accident.

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