Development of new HTS-SQUID and HTS current sensor for HTS-SQUID beam current monitor

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Abstract. Two years ago, a prototype of a highly sensitive beam current monitor with a high-temperature superconducting (HTS) SQUID, an HTS current sensor and an HTS magnetic shield, that is, an HTS-SQUID monitor, was installed in the beam transport line of the RIKEN ring cyclotron (RRC). As a result, the beam intensity of a sub-µA beam was successfully measured by the prototype HTS-SQUID monitor. In fact, the intensity of a sub-µA \(^{40}\text{Ar}^{15+}\) (63 MeV/u) beam was successfully measured with a 500 nA resolution. However, the current resolution of the prototype HTS-SQUID monitor is not sufficient to measure the current of a uranium beam, which is accelerated in a new radioactive isotope (RI) beam facility called “RI Beam Factory” (RIBF). A minimum current resolution of 1 nA is required for the measurement of the uranium beam. Therefore, we are developing a new HTS-SQUID monitor so as to improve the current resolution. This new monitor consists of three parts, the HTS SQUID, an HTS current sensor and an HTS magnetic shield, and these parts have been separately developed this year. The high-permeability core that is installed in the two input coils of the HTS-SQUID is an extremely important part in this new HTS-SQUID monitor. A 50-fold improvement in gain was successfully realized using the high-permeability core compared with that obtained without the high-permeability core. Another key factor is the substrate of the HTS current sensor. A MgO ceramic tube was used for the substrate of the HTS current sensor in the prototype HTS-SQUID monitor. However, it was difficult to form the bridge circuit using the MgO ceramic substrate in the new HTS-SQUID monitor, because the bridge circuit that magnetically connects the HTS current sensor and the HTS-SQUID has to be three-dimensional. To solve this problem, silver (Ag) of 99.9% purity was adopted for the substrates of the HTS current sensor in the new HTS-SQUID monitor. Then the surfaces of the substrates were coated by a thin layer (70 \(\mu\)m) of Bi\(_2\)Sr\(_2\)-Ca\(_1\)-Cu\(_2\)-O\(_x\) (Bi 2212), which is an HTS material. We report the results of this development.

1. Introduction
The RIBF project to accelerate all elements from hydrogen to uranium up to an energy of 440 MeV/u for light ions and 350 MeV/u for very heavy ions started in April 1997 [1]. Figure 1 shows a schematic layout of the RIBF facility. The research activities in the RIBF project are based on the heavy-ion accelerator complex, which consists of one linac and four...
Figure 1. Schematic bird’s-eye view of the RIBF facility. The research activities in the RIBF project are based on the heavy-ion accelerator complex, which consists of one linac and four ring cyclotrons. Energetic heavy-ion beams are converted into intense RI beams via the projectile fragmentation of stable ions or the in-flight fission of uranium ions using a superconducting isotope separator, BigRIPS [2]. The combination of these accelerators and BigRIPS will greatly expand our knowledge of the nuclear world into the presently inaccessible region on the nuclear chart. We succeeded in accelerating a uranium beam to 345 MeV/u in March 2007, and $^{125}$Pd, a new RI, was discovered in July 2007.

During the beam commissioning, it is essential to keep the beam transmission efficiency as high as possible, because the production of the RI beam requires an intense primary beam, and activation produced by beam loss should be avoided. In this facility, to evaluate the beam transmission efficiency, Faraday cups are used. When an accelerated particle hits the surface of a Faraday cup, secondary electrons are always generated. If these electrons leave the insulated cup area, the reading of the beam current will be wrong by the number of lost electrons. Thus, preventing the escape of secondary electrons from the cup is very important for measuring the beam on/off signal.

Figure 2. A beam intensity of $10 \mu$A $^{40}$Ar$^{15+}$ (63 MeV/u) was successfully measured in real-time with a 500 nA resolution by the prototype HTS-SQUID monitor, where a 1 $\mu$A beam produced a magnetic flux of $6.5 \times 10^{-6}$ $\Phi_0$ at the input coil of the HTS-SQUID.
beam current precisely. Usually, this can be done by applying a high voltage close to the entrance of the cup. However, since the electrical field on the beam axis is lower than that on the edge, it is impossible to completely prevent the escape of the high-energy secondary electrons that are produced by high-energy heavy-ion beams such as uranium beams. To resolve this technical issue, we have developed an HTS-SQUID monitor at RIKEN [3, 4, 5]. As a result, a beam intensity of $10 \mu A$ $^{40}$Ar$^{15+}$ (63 MeV/u) was successfully measured with a 500 nA resolution by the prototype HTS-SQUID monitor, shown in Figure 2, where a 1 µA beam produced a magnetic flux of $6.5 \times 10^{-6} \Phi_0$ of at the input coil of the HTS-SQUID [6]. Because a minimum current resolution of more than two orders of magnitude higher (1 nA) is required for the measurement of the fainter heavy-ion beams generated in the RIBF project, we have developed new devices to improve the sensitivity.

2. New HTS current sensor and HTS magnetic shields

This year, both a new HTS current sensor and new HTS magnetic shields have been developed. Their schematic drawing is shown in Figure 3, and a photograph of the Ag substrates used in the new HTS-SQUID monitor is shown in Figure 4. A MgO ceramic tube was used for the substrate of the HTS current sensor in the prototype HTS-SQUID monitor. However, it was difficult to form the bridge circuit using the MgO ceramic substrate in the new HTS-SQUID monitor, because the bridge circuit that magnetically connects the HTS current sensor and the HTS-SQUID has to be three-dimensional. To solve this problem, silver (Ag) of 99.9% purity was adopted for the substrates of the HTS current sensor in the new HTS-SQUID monitor. Before fabricating the HTS current sensor and HTS magnetic shields, to compare the characteristics of the HTS material between Bi 2223 coated on the MgO substrate and Bi 2212 coated on an Ag substrate, small samples were produced. Using an electron probe (x-ray) microanalyzer (EPMA) at RIKEN, it was clearly observed that the surface of the HTS material Bi 2212 was smooth and that it adhered more strongly to the Ag substrate than Bi 2223.

The Ag tube used as the current sensor was coated with a thin layer of Bi 2212 on both the inner and outer walls of the tube. While a beam passes through the tube, a shielding current produced by the Meissner effect flows in the opposite direction along the wall, so as to screen the magnetic field generated by the beam (Figure 5(a)). Because the outer surface is designed to have a bridge circuit, the current is concentrated in the bridge circuit and forms an azimuthal magnetic field $\Phi$. The HTS-SQUID is located close to the bridge circuit and can detect the

![Figure 3. Schematic drawing of the new HTS current sensor and HTS magnetic shields used for the new HTS-SQUID monitor.](image-url)
azimuthal magnetic field. Figure 5(b) shows a close-up view of the improved bridge circuit. The high-permeability material is placed in the hole in the bridge (c) and an HTS-SQUID with a high-permeability core is placed on the bridge circuit (d). Finally, both materials are fixed using a high-permeability cylinder (e). The magnetic field generated by the beam is completely surrounded by the high-permeability materials. The HTS magnetic shields that operate on the basis of the Meissner effect consist of coaxial magnetic shields, a cylindrical magnetic shield and also the current sensor. The current sensor plays an important role not only as a current detector but also as magnetic shielding. Thus, the SQUID is almost completely surrounded by the HTS magnetic shields, which strongly shield it from environmental magnetic noise. In the fabrication process, we fabricated the following parts: (1) two inner cylinders, two outer cylinders and two disks for the substrates of the two coaxial magnetic shields, and (2) another cylinder and the bridge circuit for the substrate of the current sensor. After the fabrication, we welded both the inner and outer cylinders to the disks, and the bridge circuit to the other cylinder by electron-beam welding. The measured accuracy of the parts after the electron-beam welding was within $\pm 100 \mu m$.

All substrates were coated with a thin layer of Bi 2212. Figure 6(a) shows the Ag substrate and the HTS cylindrical and coaxial magnetic shields.

Figure 4. Photograph of Ag substrates used in the new HTS current sensor, and the HTS cylindrical and coaxial magnetic shields.

Figure 5. Schematic drawing of the improved bridge circuit of the current sensor. While a beam passes through the tube, a shielding current produced by the Meissner effect flows in the opposite direction along the wall, so as to screen the magnetic field generated by the beam. Using this improved current sensor, the magnetic field generated by the beam is completely surrounded by the high-permeability materials.
used for the current sensor and (b) the substrate coated with the thin layer of Bi 2212. The current sensor and cylindrical magnetic shield were fabricated without any difficulties. However, some pinholes of 0.5 mm diameter were formed after coating the HTS material on the substrates of the coaxial magnetic shields. Also, Ag crystals were discovered in the center of the pinholes using an optical microscope. To prevent the formation of pinholes, we attempted several methods such as grinding the surface of the Ag substrates, and changing the baking temperature and thickness of Bi 2212. Even though coating and etching processes were repeated 7 times using the same Ag substrates under various conditions, we could not prevent the formation of pinholes. The reason why the pinholes were formed is thought to be that the disks for the substrates of the coaxial magnetic shields were fabricated using a rolling mill. Thus, the substrates were then refabricated by casting the silver. By adopting this method, we could successfully coat Bi 2212 on the substrates of the coaxial magnetic shields without forming pinholes.

3. Improvement of sensitivity using new HTS-SQUID and high-permeability core
We developed a new HTS-SQUID and a high-permeability core that is installed in the two input coils of the HTS-SQUID to improve sensitivity. The core is composed of 80% Ni and Mo, Re and Fe. The measured inductance of the core using 20 turns of coil was 128 $\mu$H at the temperature of liquid nitrogen and 202 $\mu$H at room temperature. From these values, the calculated relative permeability is 2529 at the temperature of liquid nitrogen and 3991 at room temperature. The core is a very important part in the new current sensor of the HTS-SQUID monitor. A test in which a current wire was used to simulate a beam current showed a 50-fold improvement in gain, because the newly installed high-permeability core and the HTS-SQUID improved the transfer coupling efficiency of the magnetic field induced by the beam current.

![Figure 6](image1.png)

**Figure 6.** (a) Ag substrate used for the current sensor. (b) HTS current sensor coated with the thin layer of Bi 2212.

![Figure 7](image2.png)

**Figure 7.** Measured signal of the new HTS-SQUID with a high-permeability core. The sensitivity obtained was 1 V/1 $\mu$A, which was 50-fold higher than that obtained without the high-permeability core (0.02 V/1 $\mu$A).
Figure 7 shows the measured signal of the new HTS-SQUID with the high-permeability core and the sensitivity obtained was 1 V/1 µA, which was 50-fold higher than that obtained without the high-permeability core (0.02 V/1 µA).

4. Conclusions and outlook
In this study, we have developed a new HTS-SQUID and a high-permeability core that is installed in the two input coils of the HTS-SQUID to improve the sensitivity. These are extremely important parts in the new current sensor of the HTS-SQUID monitor. A test using a current wire to simulate a beam current showed a 50-fold improvement in gain. Furthermore, both a new HTS current sensor and new HTS magnetic shields have been developed. A MgO ceramic tube was used for the substrate of the HTS current sensor in the prototype HTS-SQUID monitor. However, it was difficult to form the bridge circuit using the MgO ceramic substrate in the new HTS-SQUID monitor, because the bridge circuit that magnetically connects the HTS current sensor and the HTS-SQUID has to be three-dimensional. To solve this problem, silver (Ag) of 99.9% purity was adopted for the substrates of the HTS current sensor in the new HTS-SQUID monitor. Then the surfaces of the substrates were coated by a thin layer (70 µm) of Bi$_2$Sr$_2$Ca$_1$Cu$_2$O$_x$ (Bi 2212). We plan to design a cryostat for the new HTS-SQUID monitor with higher sensitivity to measure the fainter heavy-ion beams generated in the RIBF project.

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