HTc-SQUID BEAM CURRENT MONITOR AT THE RIBF*

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Abstract

For the purpose of measuring the DC current of heavy-ion beams non-destructively at high resolution, we have developed a high critical temperature (HTc) superconducting quantum interference device (SQUID) beam current monitor for use in the radioactive isotope beam factory (RIBF) at RIKEN in Japan. Because of its low vibration, a pulse-tube refrigerator cools the HTc fabrications that include the SQUID in such a way that the size and the operational costs of the system are reduced. Last year,we significantly reinforced the magnetic shielding system. The new strong magnetic shielding system can attenuate the external AC magnetic noise by 10^{-10}. With the aim of practical use in acceleration operation, we disassembled the prototype high-Tc SQUID current monitor (SQUID monitor), installed improved parts, and re-assembled it. Beginning this year, we have installed the SQUID monitor in the beam transport line in the RIBF. Here we describe the present details of the developed SQUID monitor system and the results of beam measurements.

INTRODUCTION

The reason for using a superconducting quantum interference device (SQUID) as a beam current monitor is that it has a very high magnetic sensitivity. For example, SQUIDs are used in studies of the neural activity inside brains and to diagnosis heart conditions in clinical environments. The magnetic fields induced by the brain and heart are very faint in the range of from 10^{-10} to 10^{-14} T. This extreme sensitivity allows a SQUID to measure a beam current nondestructively. Furthermore, we aim to downsize the system and reduce running costs by using high critical temperature (HTc) materials including the SQUIDs. Schematic drawings of the SQUID monitor and the cryostat inside the SQUID monitor are shown in Fig. 1. Both the HTc magnetic shield and the HTc current sensor were fabricated by dip-coating a thin Bi_2-Sr_2-Ca_2-Cu_3-O_x (Bi-2223) layer on a 99.7% MgO ceramic substrate [1]. The Bi-2223 layer is approximately 500 μm thick. When a charged particle (ion or electron) beam passes along the axis of the HTc current sensor, a shielding current produced by the Meissner effect flows in the opposite direction along the wall of the HTc current sensor. The shielding current acts so as to eliminate the magnetic field produced by the beam. Since the outer surface of the HTc current sensor is designed to have a bridge circuit [1], the current generated by the charged particle beam is concentrated in the bridge circuit and forms an azimuthal magnetic

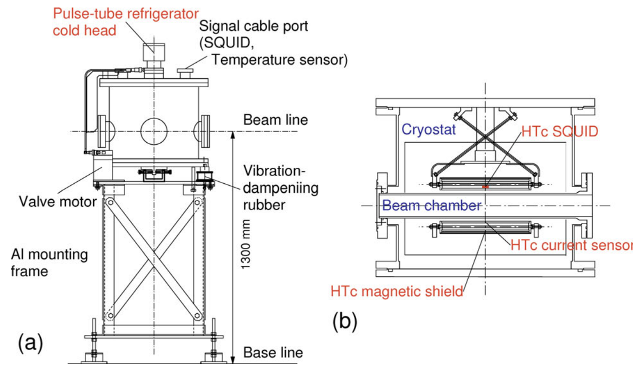

Figure 1: Schematic drawing of the (a) high-Tc SQUID current monitor (SQUID monitor) and (b) the cryostat inside the SQUID monitor.

field around it. The HTc SQUID is set close to the bridge circuit and can detect the azimuthal magnetic field with a high S/N ratio. The beam current can be precisely obtained by previously calibrating the HTc SQUID output voltage with a known reference current. As shown in Fig. 1-(b), the HTc SQUID monitor consists of two vacuum chambers completely separate from each other. One chamber contains a cryostat in which the HTc SQUID, HTc magnetic shield, and HTc current sensor are cooled. The other is the chamber through which the beam passes. All the fabricated HTc devices are cooled to around 70 K by a low-vibration pulse-tube refrigerator with a refrigeration power of 11 W at a temperature of 77 K. Eight vibration rubbers dampen the vibration caused by the pulse-tube refrigerator. Figure 2 shows a bird's-eye view schematic of the RIBF facility indicating the positions of the SQUID monitor. The research activities of the RIBF project make extensive use of the heavy-ion accelerator complex, which consists of two linacs and five ring cyclotrons, i.e., two RIKEN heavy-ion linacs (RILAC I, II), the AVF cyclotron, the RIKEN ring cyclotron (RRC), the fixed-frequency ring cyclotron (fRC), the intermediate-stage ring cyclotron (IRC), and the superconducting ring cyclotron (SRC). 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 by using the superconducting isotope separator BigRIPS.

Beginning this year, we have installed the SQUID monitor in the beam transport line in the RIBF (Fig. 2). We are presently using the SQUID monitor in practice for measurement of the current of beams of heavy-ions such as uranium.

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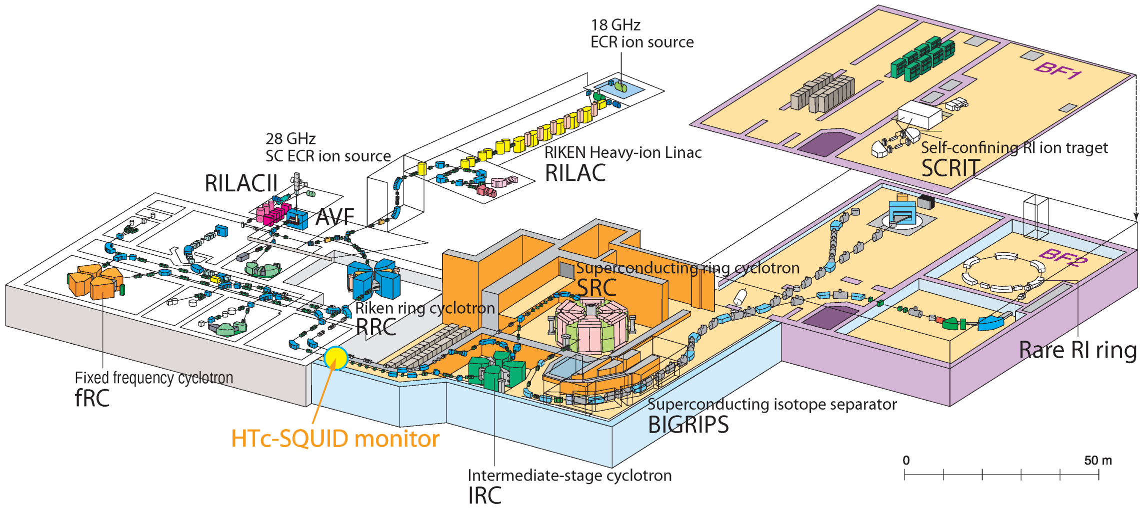

Figure 2: Bird's-eye view schematic of the RIBF facility showing the position of the HTc SQUID monitor.

PROTOTYPE DEVELOPMENT

HTc Current Sensor and SQUID

With the aim of increasing the beam current resolution of the SQUID monitor, we investigated improvement of the coupling efficiency between the magnetic field that is generated at the bridge circuit and the input coil of the HTc SQUID [1]. We developed a new HTc SQUID [2] with a high-permeability core that was installed in the two input coils of the HTc SQUID (Fig. 3). Furthermore, to increase the magnetic field produced by the bridge circuit, we successfully fabricated an HTc current sensor with two coils by using a newly developed spraying machine [3]. Although the conventional hand-coating method required professional skill to apply the Bi2223 layer onto the MgO substrate, the spray machine can perform the operation automatically and uniformly. As a result, the problem of Bi-2223 material peeling off during the sinter process was resolved and experience with coatings and the sinter process was gained.

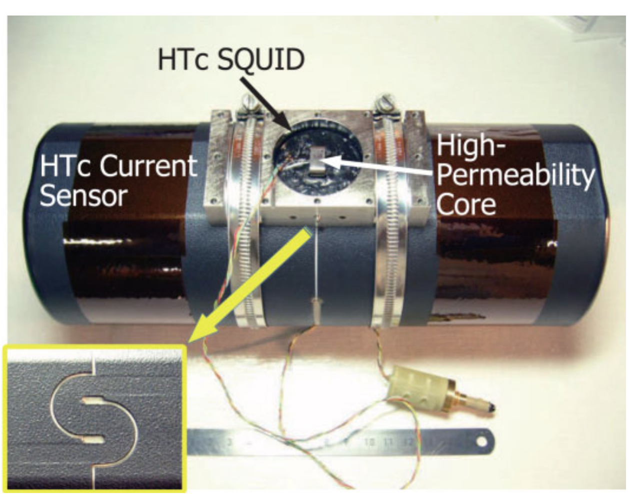

Figure 3: New HTc SQUID [2] with a high-permeability core that was installed in the two input coils of the HTc SQUID and HTc current sensor with two coils.

Prior to coating the MgO substrate with Bi-2223 material by using the spraying machine, we analyzed the critical temperature (Tc), critical current density (Jc), and X-ray diffraction patterns. Using three test pieces of MgO substrates (5 W ~ 50 D ~ 5 H [mm]) coated with Bi-2223 material, we confirmed the critical temperature of 105 K and critical current density of 3250 A/cm^2. From the X-ray diffraction patterns, it was clear that major peaks appear in the Bi-2223 phase.

Reinforcement of the Magnetic Shield

In general, the performance of monitors such as the SQUID monitor is determined by the S/N ratio. To improve the measurement resolution, it is important to attenuate external magnetic noise, which is mainly generated by distribution and transmission lines from the high current power supplies in the RIBF. Therefore, we developed a hybrid magnetic shielding method based on the properties of perfect diamagnetic materials (superconductors) and ferromagnetic materials [4]. The HTc current sensor also works as a superconducting shield by the Meissner effect (perfect diamagnetism). To design a hybrid magnetic shielding system, the attenuated magnetic field was calculated by using the electromagnetic field simulation program Opera-3d [5]. Since Opera-3d cannot deal with superconductivity, the value of 1×10^{-12} was used for the relative permeability of the HTc current sensor in the approximate calculation. The calculation shows that the hybrid magnetic shielding system can achieve a magnetic attenuation factor of 10^{-4}.

Since there exist 50 Hz and higher-order AC magnetic noises in the acceleration facility, that are much stronger than terrestrial magnetism, a noise canceller system (78200DAMC [6]) was designed and introduced to the SQUID monitor. This system is comprised of a magnetic field control unit, 3-axis AC/DC magnetic field sensors, and

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compensation coils. The compensation coils consist of three pairs of coils that are arranged perpendicular to each other. Each of these pairs forms a so-called Helmholtz-Coil-Pair, which is able to produce a homogenous magnetic field in between them. Each pair controls one direction (i.e., along the x-, y-, or z- axis).

To evaluate the performance of the hybrid magnetic shielding system and the noise canceller system, the output signals of the HTc SQUID were analyzed in the time- and frequency domains. Based on these findings, we consider that the combination of the hybrid magnetic shielding system and the noise canceller system can attenuate the external magnetic noise of the 50 Hz component by 10^{-10}.

INSTALLATION IN THE RIBF

Characteristic Frequency and Current Calibration

Because the prototype SQUID monitor was intend for practical use in accelerator operation, we disassemble it and installed improved parts, namely the HTc current sensor with two coils, the HTc SQUID with a high-permeability core, and the hybrid magnetic shield. During the reassembly operation, we improved the attainment temperature of the SQUID from 71 K to 67 K, by renewing the super insulation and applying Apiezon grease between the HTc SQUID and the SQUID holder. We then measured the characteristic frequency and calibrated the SQUID output voltage with a simulated beam current. The output voltage of the high-Tc SQUID controller as a function of the simulated beam current is plotted in Fig. 4. From these measurement results, we obtained the following calibration equation:

$$\begin{aligned} V_s &= S_{co} \times I_b \times G/500 \\ &= 49.28 \times I_b \times G/500, \end{aligned}$$

where S_{co}, I_b, V_s, and G are the coupling efficiency (mV/μA), beam current (μA), output voltage of the SQUID controller (mV), and gain of the SQUID controller, respectively. Furthermore, the characteristic frequency of the

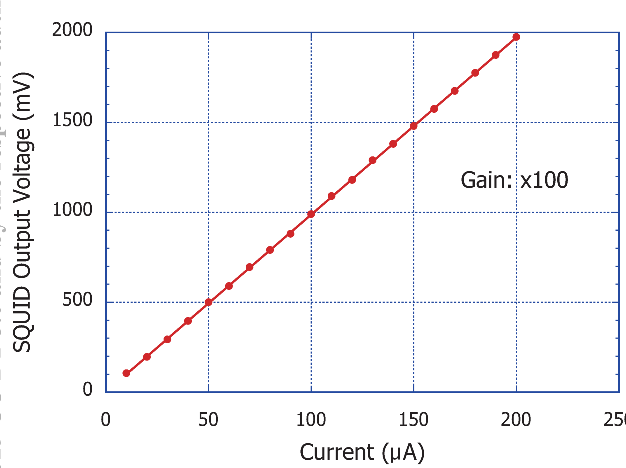

Figure 4: Output voltage of the HTc SQUID controller as a function of simulated beam current.

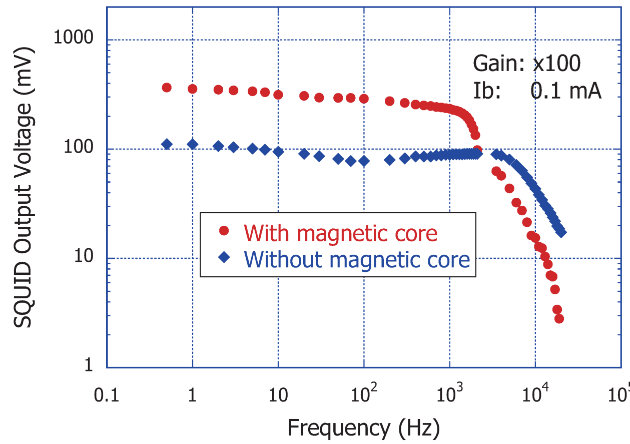

Figure 5: Characteristic frequency of the SQUID monitor measured by FFT in the frequency domain.

SQUID monitor was measured by performing a fast Fourier transform (FFT) in the frequency domain (Fig. 5). Although the frequency range with the magnetic core is several kHz narrower than without the core, the output voltage is higher with the core. Figure 6 shows the SQUID monitor equipped with the noise cancellation system, which was installed in the transport line between the fRC and IRC (Fig. 2).

Data Acquisition and Control System

A block diagram of the data acquisition and control system of the SQUID monitor is shown in Fig. 7. The PXI controller (NI PXI-8106 [7]) controls the HTc-SQUID controller (iMC-303 [8]), signal acquisition module (USB-4431 [7]), noise canceller controller and power supply (78200DAMC [6]), and temperature controller (Model 34 [9]). The analogue output signal from the HTc SQUID controller is acquired with the signal acquisition module and converted into a mea-

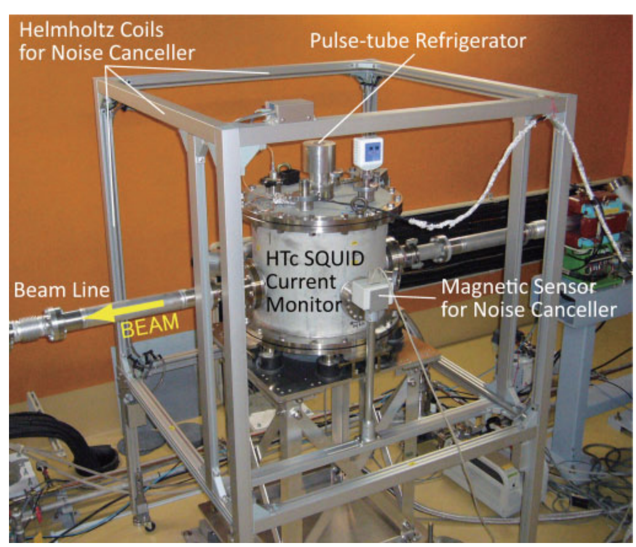

Figure 6: SQUID monitor equipped with the noise canceller system, which was installed in the transport line between the fRC and the IRC (Fig. 2).

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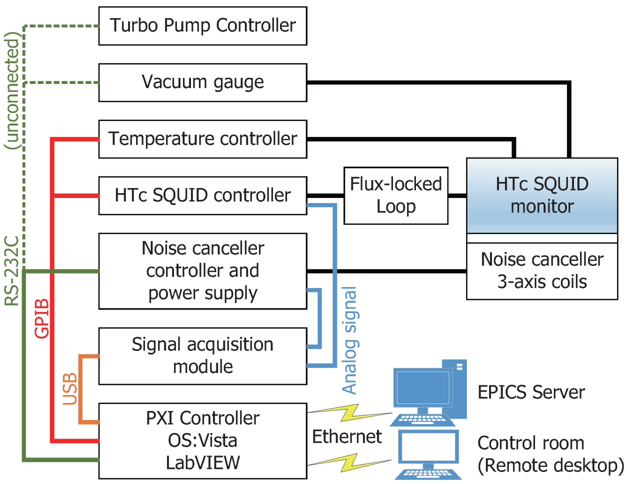

Figure 7: Block diagram of the data acquisition and control system of the SQUID monitor.

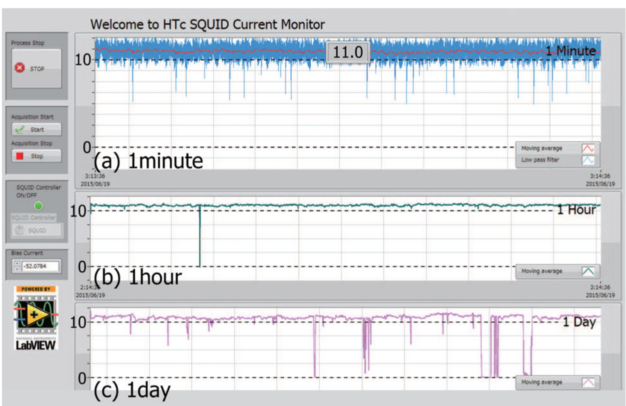

Figure 8: The 11 μA $^{78}Kr^{36+}$ intensity of the beam (50 MeV/u) was successfully measured with 500 nA resolution.

surement of the beam current. Similarly, the output signals of the 3-axis AC and DC magnetic fields measured with the noise canceller are also AD converted by the signal acquisition module. The feedback gains of the noise canceller are set via RS-232c and the bias current, modulation voltage, and skew voltage that concern the SQUID controller are set via GPIB. The programs for the data acquisition, control, and results display are written in LabVIEW [7]. The PXI controller is connected to a laptop in the main control room located 100 m from IRC hall via Ethernet and a remote desktop connection. The driving control and status monitoring of the beam chopper are controlled by the EPICS system.

MEASUREMENT OF BEAM CURRENT

Flux Trapping Removal

After we started to accelerate the heavy-ion beam and started the RIBF experiment, external magnetic flux passed through the HTc SQUID sensor and some unexpected flux was trapped inside it during its superconducting state. This flux trapping caused noise in the highly sensitive SQUID chip. The HTc SQUID is operated in a null detection mode where a flux-locked loop provides a negative feedback to maintain linear operation. The noise generated by the flux trapping gradually increased with time. Eventually, the flux-locked loop could no longer maintain the negative feedback because the noise level exceeded the amount of negative feedback. To purge any magnetic flux trapped in the sensor, a heater made of a small resister was mounted close to the SQUID chip in the sensor package. By raising the temperature of the HTc SQUID above its critical temperature Tc for 30 s, the SQUID noise was greatly reduced and the problem was resolved.

Experimental Results

We successfully measured the intensity of an 11 μA beam of $^{78}Kr^{36+}$ (50 MeV/u) with 500 nA resolution (Fig. 8), where the 11 μA beam produced a magnetic flux of 0.236 Φ_0 (a magnetic flux quantum phi zero of 2.07×10^{-15} weber) at the input coil of the high-Tc SQUID. Prolonged 1 min, 1 h, and 1 day recordings of the Kr beam current extracted from the fRC were achieved (Fig. 8). In these recordings, several dips in beam intensity due to ECR ion source discharge can be observed. The different beam current signals were analyzed by performing FFTs in the frequency domain (Fig. 9). The amplitude of the ripples in the modulated beam current increased with the beam current. The sampling time for data acquisition was 500 μs, and 2000 data points were averaged to improve the S/N ratio. Because the zero current point drifted due to temperature change, it was calibrated every hour by firing the beam chopper; this should be resolved in the near future.

CONCLUSIONS AND OUTLOOK

To measure the DC current of heavy-ion beams non-destructively at high resolution, we have developed a SQUID monitor for use in the RIBF at RIKEN in Japan. In the previous year, we strongly reinforced the magnetic shielding system. Since the prototype SQUID monitor was intended for practical use in acceleration operation, we disassembled

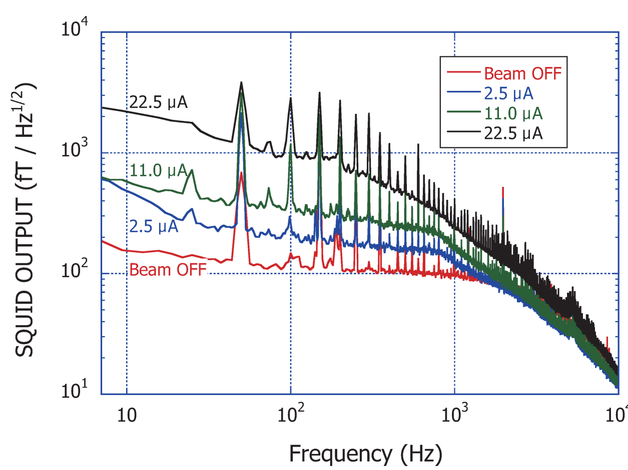

Figure 9: The results of analyses of different beam current signals by FFTs in the frequency domain.

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it, installed improved parts, and re-assembled it. At the Beginning of this year, we installed the SQUID monitor in the beam transport line in the RIBF and we have been using the SQUID monitor for current measurement of heavy-ions beams.

Although we can measure the intensity of a sub-μA beam, a minimum current resolution of more than two orders of magnitude lower is required at the RIBF. We can use MgO ceramic tubes for the substrates in the SQUID monitor, but it is difficult to make the required complex shape. Therefore, we are now investigating the possibility of coating a thin layer (70 μm) of Bi_2-Sr_2-Ca_1-Cu_2-O_x (Bi-2212) on a silver (Ag) substrate capable of corresponding to the complex shape. Although we tried to fabricate an HTc current sensor coated by Bi-2212 [10], it did not work as a superconductor because its critical temperature (Tc) was under 70 K. Figure 10 shows a comparison between the surfaces of Bi-2223 and Bi-2212 under a scanning electron microscope. It is clear that the surface of Bi-2212 is smoother than that of the Bi-2223. We coated both HTc materials on MgO substrates and confirmed that the Tc of each was higher than the temperature of liquid nitrogen.

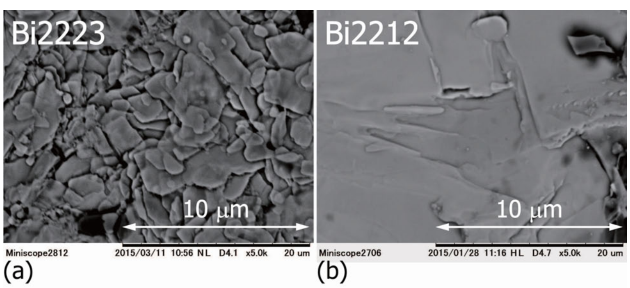

Figure 10: Comparison of the surfaces of (a) Bi-2223 and (b) Bi-2212 (b) as observed by a scanning electron microscope.

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