Improvements of a Beam Current Monitor by using a High Tc Current Sensor and SQUID at the RIBF

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Abstract. To measure a beam current non-destructively, a conventional DC current transformer (DCCT) has been used at accelerator facilities. However, the current resolution of the DCCT is worse than 1μA. This current resolution is sufficient for electron and proton accelerators in which the beam intensity is high, but it is not sufficient for lower intensity heavy-ion beams. Thus, superconducting technology has been applied to the precise measurement of the beam current. In particular, to measure the DC current of high-energy heavy-ion beams non-destructively at high resolution, a high critical temperature (HTc) superconducting quantum interference device (SQUID) beam current monitor (HTc SQUID monitor) has been developed for use in the radioactive isotope beam factory (RIBF) at RIKEN in Japan. Beginning this year, the magnetic shielding system has been greatly reinforced. The measurement resolution is determined by the signal to noise ratio, that is improved by attenuating the external magnetic noise and is mainly produced by the distribution and transmission lines from the high current power supplies. The new strong magnetic shielding system can attenuate the external magnetic noise to 10⁻¹⁰.

1. Introduction

The radioactive isotope beam factory (RIBF) project to accelerate all elements from hydrogen to uranium up to energies of 440 MeV/u for light ions and 350 MeV/u for heavy ions started in April 1997 [1]. The research activities in the RIBF project make extensive use of the heavy-ion accelerator complex, which consists of two linear accelerators and four ring cyclotrons including a 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 using a superconducting isotope separator, BigRIPS [2]. The combination of these accelerators and BigRIPS is greatly expanding our knowledge of the nuclear world into the previously inaccessible regions on the nuclear chart. For these facilities, since it is essential to measure the beam current non-destructively, an HTc SQUID monitor has been developed for the RIBF at RIKEN. As recently reported [3, 4], the high-Tc superconducting quantum interference device (SQUID) monitor allows us to measure the DC of high-energy heavy-ion beams nondestructively in such a way that the beams are diagnosed in real time and the beam current extracted from the cyclotron is recorded without interrupting beam user experiments. Unlike at other existing facilities, a low-vibration, pulse-tube refrigerator cools the HTc fabrications that includes the SQUID in...
such a way that the size of the system is reduced and the running costs are lowered, which is its largest advantage.

2. Reinforcement of the magnetic shielding

2.1. Fundamental principles of the HTc SQUID monitor

A schematic drawing of the HTc SQUID monitor system is shown in Fig. 1(a). Both the HTc magnetic shielding 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 99.6% MgO ceramic substrate. When a charged particle beam passes along the axis of the HTc tube, a shielding current produced by the Meissner effect flows in the opposite direction along the wall of the HTc tube so as to screen the magnetic field generated by the beam. Since the outer surface is designed to have a bridge circuit (Fig. 1(b)) [4], the current generated by the charged particle beam is concentrated there and forms an azimuthal magnetic field $\Phi$ around the bridge circuit. The HTc SQUID is set close to the bridge circuit and can detect the azimuthal magnetic field with a high S/N ratio. In particular, we adopt a SQUID gradiometer [5] to increase the S/N ratio.

2.2. Development of the hybrid magnetic shielding system

The performance of the current monitor is determined by the S/N ratio. To improve the measurement resolution, it is important to attenuate the external magnetic noise, that is mainly produced by the 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 and ferromagnetic materials. By applying this method to the HTc SQUID monitor, a high shielding effect could be obtained despite the compact system. This system consists of two shielding parts: one for the HTc current sensor and the other for ferromagnetic shielding materials. The HTc current sensor also works as the superconducting shield via the Meissner effect (perfect diamagnetism). The ferromagnetic shielding materials are made with high permeability alloys (Permalloy, Mu-metal, etc.) and consist of three parts: frame, cap, and band (Fig. 2). The HTc SQUID is installed inside the frame and onto the HTc current sensor, and the frame is covered by the cap. Consequently, the HTc SQUID is almost completely surrounded by the hybrid magnetic shielding system. As mentioned in the previous section, since the dip coated superconducting material of the HTc current sensor is peeled off except for the bridge circuit so as to concentrate the current induced by the beam passage, the external magnetic noise can penetrate through the peeled part. To prevent this penetration of external magnetic noise, the band plays an important role.

To design a hybrid magnetic shielding system, the attenuated magnetic field was calculated by using the electromagnetic field simulation program "Opera-3" [6]. This simulation assumes
there is a uniform magnetic field of $1 \times 10^{-5}$ T inside the boundary conditions and that the relative permeability of the ferromagnetic material is $1 \times 10^6$. Since Opera-3d cannot deal with superconductivity, the value of $1 \times 10^{-12}$ was substituted as the relative permeability of the HTc current sensor for the approximate calculation. The calculated result indicates that the magnetic field was attenuated from $1 \times 10^{-5}$ to $4 \times 10^{-10}$ T by applying the hybrid magnetic shielding system (Fig. 3(a)). Consequently, this calculation shows that the hybrid magnetic shielding system can achieve a magnetic attenuation factor of $10^{-4}$. A photograph of the completed hybrid magnetic system is shown in Fig. 3(b).

### 2.3. Active magnetic field canceller system

In the acceleration facility, since there exist 50 Hz and higher order AC magnetic noises that are much stronger than terrestrial magnetism, an active magnetic field canceller system [6] was designed and introduced to the HTc SQUID monitor. This system is comprised of a magnetic field control unit, combined AC/DC magnetic field sensors, and compensation coils. The compensation coils consist of three pairs of coils that are arranged perpendicular to each other. Each of these pairs form a so-called "Helmholtz-Coil-Pair", able to produce a homogenous magnetic field in between them, and each pair controls one direction (along x-, y-, or z-axis). Specifications of the active magnetic canceller system are listed in Table 1 and a photograph is shown in Fig. 3. Furthermore, by hooking up a terminal via RS-232C serial interface, access to the menu-driven interface of the system is achieved.

| Specification                  | Value                                      |
|-------------------------------|--------------------------------------------|
| Magnetic field attenuation    | Max. -40 dB                                |
| Bandwidth                     | DC - 1,000 Hz                              |
| Magnetic sensor(DC)           | 3 axes flux gate                            |
| DC Noise                      | $\leq 50 \text{ pT/}\sqrt{Hz}$             |
| Max. compensation             | 6 $\mu$T                                   |
| AD/DA converter               | 16 bit                                     |
| Magnetic sensor(AC)           | Search coil                                |
| AC Noise @1 Hz                | $\leq 150 \text{ pT/}\sqrt{Hz}$            |

**Figure 2.** 1: HTc current sensor with ferromagnetic shielding materials, 2: frame, 3: cap, and 4: band.

**Figure 3.** Calculated result by Opera-3d and a photograph of the completed hybrid magnetic system.
Figure 4. HTc SQUID monitor with active magnetic field canceller system.

Figure 5. Measured spectra in the frequency domain.

3. Measured spectra in the frequency domain
To evaluate the performance of the hybrid magnetic shielding system and the active magnetic canceller system, the output signals of the HTc SQUID were analyzed in the time- and frequency domains. Measured spectra in the frequency domain are shown in Fig. 5. Each of the three lines represents a measurement under a different condition as follows: 1. red line: before reinforcing the magnetic shielding, 2. blue line: after the reinforcing of the magnetic shielding, and 3. green line: perfectly shielded by a superconducting shield and threefold permalloy shields [8]. The same setting parameters of the HTc SQUID controller were used in these measurements. When the outputs of the HTc SQUID monitor were measured (lines 1 and 2), the RIBF experiment was performed: $^{238}\text{U}$ was being accelerated and the output powers of the high current power supplies was almost at maximum level. The signal was measured in the room next to where the power supplies were located, where the leakage magnetic field of the 50 Hz component was measured by a gauss meter as $4.5 \times 10^{-4}$ T. In contrast, the output signal of the 50 Hz component of the HTc SQUID monitor was $6 \times 10^{-14}$ T as shown in Fig. 5. Based on these findings, we consider that the combination of the hybrid magnetic shielding system and the active magnetic canceller system can attenuate the external magnetic noise to $10^{-10}$.

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