IMPROVEMENT OF BEAM CURRENT MONITOR WITH HIGH Tc CURRENT SENSOR AND SQUID AT THE RIBF

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Abstract

We have developed a High Critical Temperature-Superconducting Quantum Interference Device (HTc-SQUID) monitor using a highly sensitive beam current (position) monitor with an HTc current sensor and a SQUID for the Radioactive Isotope Beam Factory (RIBF) at RIKEN in Japan. Our study aims to non-destructively measure the DC of high-energy heavy-ion beams such that the beams can be diagnosed in real time and the beam current extracted from the cyclotron can be recorded without interrupting the beam user's experiments. Both the HTc magnetic shield and current sensor were dip-coated with a thin layer of Bi-Sr-Ca-Cu-O (Bi-2223, Tc = 106 K) onto 99.9% MgO ceramic substrates. Since a low-vibration pulse-tube refrigerator cools the HTS fabrications, we are able to downsize the system. As a result, 1 μA Xe beam intensity (50 MeV/u) was successfully measured with 100 nA resolution. From 2010, we have started improving the HTc current sensor by using two-turn coils in order to achieve higher resolution. In this paper, we report the present status of the project and the measurement results of the HTc-SQUID monitor.

ACCELERATOR COMPLEX AND EXPERIMENTAL RESULTS OF RIBF

In April 1997, the Radioactive Isotope Beam Factory (RIBF) started a 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 heavy ions [1]. Figure 1 shows a schematic layout of the RIBF-facility. The research activities in the RIBF project make extensive use of the heavy-ion accelerator complex, which consists of one linac and four ring cyclotrons, i.e. a variable-frequency linac (RILAC), the RIKEN ring cyclotron (RRC), a fixed-frequency ring cyclotron (fRC), an intermediate-stage ring cyclotron (IRC) and a superconducting ring cyclotron (SRC). Energetic heavy-ion beams are converted into intense radioactive isotope (RI) beams by the projectile fragmentation of stable ions or the in-flight fission of uranium ions by using a superconducting isotope separator, BigRIPS [2]. The combination of these accelerators and the BigRIPS is expected to considerably 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 discovered new RIs, the neutron-rich palladium isotopes of $_{125}$Pd and $_{126}$Pd, by using the uranium beam [3, 4].

In 2008, the RIBF succeeded in providing heavy-ion beams of $_{48}$Ca and $_{238}$U with particle currents of 170 pnA and 0.4 pnA, respectively, at 345 MeV/u. We have been investigating new isotopes using the in-flight fission of the 345 MeV/u uranium beam. Consequently, fission fragments were analyzed and identified using the BigRIPS and in only four days, we discovered 45 new neutron-rich isotopes in a region of nuclear chart never explored before. From the operational point of view, however, the intensity of the uranium beam should be considerably increased. Furthermore, the RIBF research conflicts with the ongoing research on the synthesis of super-heavy elements using a gas-filled recoil separator (GARIS), because both of them use RILAC. To reconcile this conflict, an additional injector linac for the RIBF (RILAC2) was proposed and constructed. We now have a superconducting electron cyclotron resonance (ECR) ion source, a radio frequency quadrupole (RFQ) linac and three drift tube linacs (DTLs). The new injector, RILAC2, enables us to independently operate our RIBF experiments and conduct research on super-heavy element synthesis [5].

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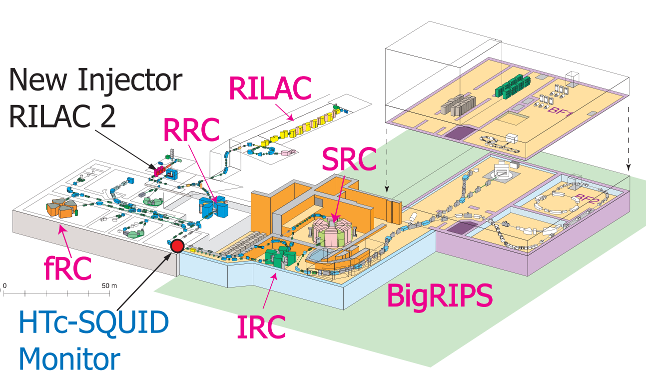

Figure 1: Schematic bird's-eye view of the RIBF facility.

PRACTICAL USE OF HTC-SQUID MONITOR FOR RIBF

We developed an HTc-SQUID monitor at RIKEN to non-destructively measure the DC of high-energy heavy-ion beams in real time [6]. Prior to practical use in the RIBF, preliminary test measurements were successfully carried out as follows: (1) first, a beam test of the HTc-SQUID monitoring system was conducted in the beam transport line of the ECR ion source in the CNS experimental hall: (2) second, a beam current measurement was

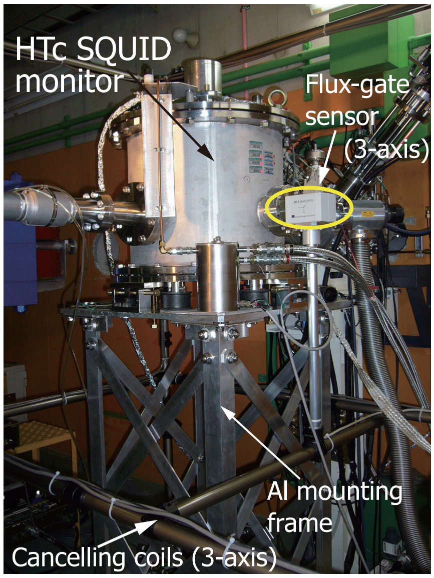

Figure 2: HTc-SQUID monitor equipped with Al mounting frame and noise cancellation system, which was installed in the transport line between fRC and IRC (Fig. 1).

performed in the E1 experimental hall in RIKEN and (3) finally, a beam analysis was conducted in the frequency domain in the RRC accelerator hall in RIKEN. For cancelling environmental magnetic noise, the previous iron mounting frame was replaced with one made of aluminium with relative permeability of 1. The design of the noise cancellation system is based on a three-axis Helmholtz cage and feedback control engineering. Three-axis flux-gate sensors are placed near the equipment. A signal is fed through the proprietary controller to a compensation coil, producing precisely calibrated electromagnetic fields. Figure 2 shows the HTc-SQUID monitor equipped with the Al mounting frame and the noise cancellation system, that was installed in the transport line between fRC and IRC (Fig. 1). As a result, in 2009, we were able to measure a 3.6 μA ^{132}Xe^{20+} (10.8 MeV/u) beam (Fig. 3) and 1 μA ^{132}Xe^{41+} (50.1 MeV/u) beam for use in the accelerator operations at the RIBF.

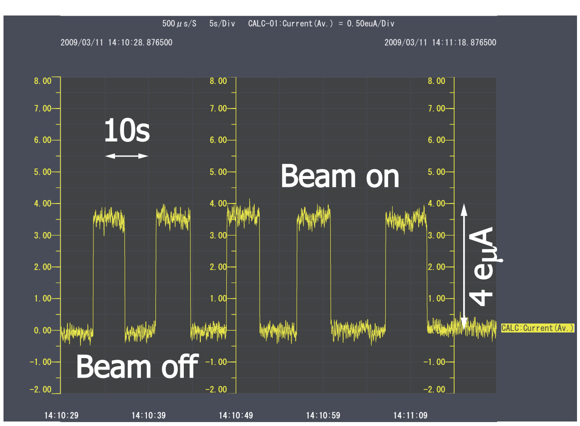

Figure 3: Measurement result for a 3.6 μA ^{132}Xe^{20+} (10.8 MeV/u) beam.

IMPROVEMENT OF HTC-SQUID MONITOR

After the HTc-SQUID monitor was installed in the transport line between fRC and IRC for practical use, magnetic flux jumps were gradually observed. The SQUID sensor is typically operated in a null detection mode where a flux-locked loop (FLL) provides a negative feedback to maintain a linear operation. If the HTc-SQUID captures a frozen flux on the superconducting thin films which can cause the magnetic flux jump, then the frozen flux can be removed by increasing the temperature of the film above Tc. Although the superconducting thin films were heated by a heater several times, the flux jumps could not be stopped. Since the flux jumps occurred frequently, the HTc-SQUID monitor was disassembled and diagnosed. An electrical test was performed and the characteristics of the device were found to be significantly different from the original ones. The modulation voltage used in the FLL decreased from 2.2 V to 0.5 V and the noise increased. Since some visible cracks were also found on the surface of the HTc-SQUID, we concluded that the HTc SQUID had clearly deteriorated. The deterioration can be attributed to the fact that the HTc-SQUID had already been used for five years and that it had experienced a minimum of 100 heat cycles. Thus, a new HTc SQUID [7, 8] was fabricated. Figure 4 shows a photograph of the new one with two holes to accommodate a high-permeability core. The core is made of Cryoperm10, a high nickel-content alloy that is specially processed for increased permeability under decreasing temperature. The core is composed of 80% Ni Fe and has three times higher permeability at 77 K than at the room temperature.

The HTc current sensor is fabricated by dip-coating a thin Bi_2-Sr_2-Ca_2-Cu_3-O_x (Bi-2223) layer onto a 99.9% MgO ceramic substrate. When a charged particle (ion or

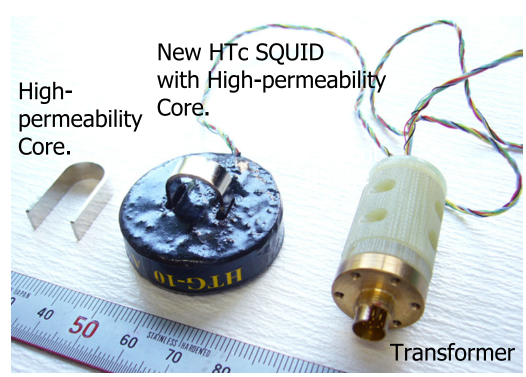

Figure 4: New HTc-SQUID with two holes containing high-permeability core.

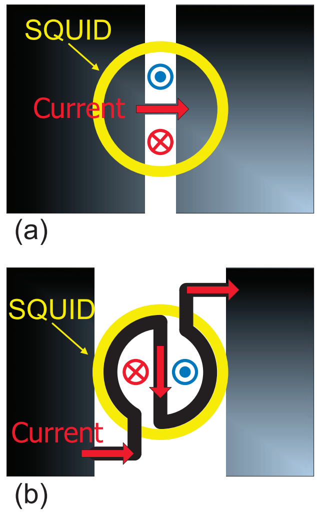

Figure 5: Schematic drawing of (a) conventional bridge circuit and (b) improved two-coil bridge circuit of the HTc current sensor.

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 to screen the magnetic field generated by the beam. Since the outer surface is designed to have a bridge circuit (Fig. 5(a)), the current generated by the charged particle beam is concentrated in the bridge circuit and forms an azimuthal magnetic field Φ 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. To further improve the sensitivity of the HTc-SQUID monitor, we designed an HTc current sensor with two coils (Fig. 5(b)). Since the two coils cover the input coils of the HTc-SQUID effectively, the coupling efficiency between the magnetic field produced by the beam current and the SQUID should be improved. The coil and the high permeability core were combined in the HTc-SQUID. We measured the sensitivity to be 21 times higher using a simulated beam current. Fig. 6 shows a coating machine which coats the Bi-2223 material onto the MgO ceramic substrate. A turntable rotates the substrate and a nozzle moves vertically to coat it. Fig. 7 shows the completed HTc current sensor with two coils.

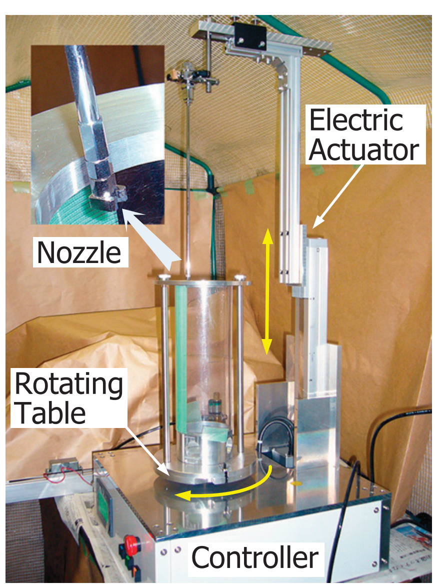

Figure 6: Coating machine which coats Bi-2223 onto the MgO ceramic substrate.

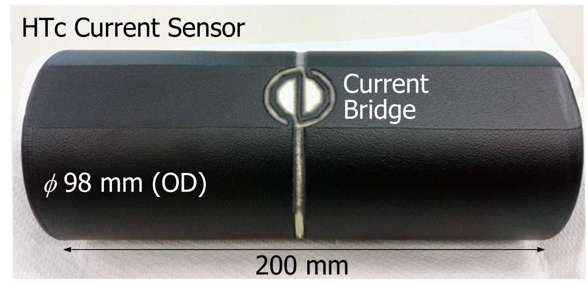

Figure 7: New HTc current sensor.

CONCLUSIONS AND OUTLOOK

We have developed the HTc-SQUID monitor with the HTc current sensor and the SQUID for the RIBF at RIKEN. In this study, we have started improving the HTc current sensor by using two-turn coils in order to achieve higher resolution. In the near future, we will install the HTc current sensor and the SQUID in the HTc SQUID monitor.

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