Current and position beam monitor with HTS SQUIDs and HTS magnetic shield for the RIKEN Ring Cyclotron

T Watanabe¹, M Kase¹, Y Sasaki², S Watanabe³, T Ikeda¹, T Kawaguchi⁴ and Y Yano¹

¹ RIKEN (The Institute of Physical and Chemical Research), Wako-shi, Saitama 351-0198, Japan
² Matsushita Electric Industrial, Yagumonakamachi, Moriguchi-shi, Osaka 570-8501, Japan
³ Center for Nuclear Study (CNS), Graduate School of Science, Univ. of Tokyo, Wako-shi, Saitama 351-0198, Japan
⁴ KT Science Ltd., Fujie, Akashi-shi, Hyogo 673-0162, Japan

E-mail: wtamaki@riken.jp

Abstract. This year, a prototype of a highly sensitive beam current monitor with a High-Temperature Superconducting (HTS) SQUID and an HTS magnetic shield: HTS-SQUID monitor has been installed in the beam transport line of the RIKEN Ring Cyclotron (RRC). Unlike other existing facilities, the HTS-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 RRC can be recorded without interrupting the beam user’s experiments.

1. Introduction

The RIKEN heavy-ion accelerator facility consists of the main accelerator of the RRC and its injectors, which are a heavy-ion linac (RILAC) and an azimuthally varying field (AVF) cyclotron [1]. This system provides various beams from protons to bismuth ions in a wide range of energies for nuclear physics, nuclear chemistry and radiation biology studies. In this facility, to diagnose the beam, a variety of beam monitors have been developed. However, because most beam monitors are based on the interaction between the beam and the material, once the beam is stopped by a destructive monitor such as a Faraday cup, the beam can no longer be used. Generally, there will be a danger of activating and melting the cup, which can be caused by a mishandling operation. Thus, when some parameters such as RF cavities or many types of magnet are tuned, the beam intensity must be attenuated downward to approximately $10^{-3}$ of the full beam value by a series of attenuation screens so as to avoid activation as much as possible. After the tuning is completed and the attenuation screens are turned off, the property of the full beam is found to be different from that of the attenuated beam due to the spacial nonuniformity of the attenuation screens or a space-charge effect which makes the tuning difficult. To resolve this technical issue, a study of a cryogenic current comparator (CCC) was started in 2001 in RIKEN [2]. The first CCC was developed by Harvey in Australia in 1972 [3]. Thereafter, some applications of CCCs operating at liquid-helium temperature were reported
On the other hand, a prototype HTS CCC with an HTS gradiometer SQUID has been successfully demonstrated as a means of nondestructive sensing of argon beams by Hao et al. [6]. In this present study in RIKEN, the authors intended to develop an HTS-SQUID monitor system for practical use in accelerator facilities. Also, the application of this HTS-SQUID monitor to ion implantation for semiconductor production is currently being investigated, particularly the nondestructive and real-time dose measurements of drift and discharge caused by an ion source, with the aim of improving the yield of wafers significantly. In this paper, the present status of the HTS-SQUID monitor system, the results of successful beam measurements are described.

2. HTS-SQUID Monitor System

A schematic drawing of the HTS-SQUID monitor system is shown in Figure 1(a). This system consists of two vacuum chambers completely separated from each other: one for a cryostat in which the HTS SQUID, an HTS magnetic shield and an HTS current sensor are cooled, and the other for a beam chamber in which a beam passes through. In the present work, all these HTS fabrications are cooled by a low-vibration pulse-tube refrigerator which has a refrigeration power of 11 W at a temperature of 77 K. The operation temperature can be set in the range of 64 K to 90 K (the critical temperature of the HTS SQUID) using a heater, since the pulse-tube refrigerator is capable of cooling the system to temperatures lower than liquid-nitrogen temperature. Furthermore, it is possible to stabilize the temperature of the HTS SQUID with an accuracy of 5 mK using a PID feedback controller, which has four thermometers and a heater. The temperature of the cold head was measured as a function of time. Consequently, the deviation of the temperature over a period of 18 hours was controlled within 3.4 mK (1σ) [7]. Both the HTS magnetic shield and the HTS current sensor were fabricated by dip-coating a thin Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{x}$ (Bi-2223) layer on 99.9% MgO ceramic substrates. The HTS-SQUID system (Model BMS-G manufactured by Tristan Technologies) is composed of a low-noise HTS-SQUID gradiometer (Y-Ba$_2$Cu$_3$O$_{7-δ}$) [8].

In addition to current measurement, an important function that the beam position can be measured by dividing the thin-layer HTS current sensor into two parts and by setting a SQUID on each bridge has been performed [9]. It is our expectation that the HTS-SQUID monitor will be capable of measuring beam current and beam position simultaneously in real-time.

![Figure 1](image.png)

**Figure 1.** (a) Schematic drawing of HTS-SQUID monitor system. Aiming to put this monitor into practical use, the authors installed the HTS-SQUID monitor system in the beam transport line (b) in the RRC hall (c).
3. Experimental Results

Prior to the beam measurements in the RRC hall, preliminary measurements were successfully carried out as follows: (1) the first beam test of the HTS-SQUID monitor in the beam transport line for the electron cyclotron resonance (ECR) ion source in the CNS experimental hall and (2) the second beam measurement at the E1 experimental hall in RIKEN to measure the current of the high-energy heavy-ion beam [7]. This year, aiming at practical use for accelerator operations, the authors installed the HTS-SQUID monitor system in the beam transport line (Figure 1 (b)) in the RRC hall (Figure 1 (c)). However, the SQUID electric circuit, which has the dynamic range of 100 dB (from 1 μA to 0.1 A) and the frequency range from DC to 25 kHz, did not function normally due to the following reasons: (1) an RF background is caused by the high-power RF cavities of the RRC which can produce a total power of 0.6 MW; (2) a large stray magnetic field is induced by the main magnetic field of the RRC (max. 1.67 T); (3) there are a neutron radiation dose of 25.5 Sv and a gamma radiation dose of 3.0 Sv for a period of one year. The radiation doses of neutrons and gamma rays were measured using an ionization chamber and a 3He proportional counter, respectively. The actual radiation doses where the HTS-SQUID monitor is installed should be higher than the above values, because both dosimeters are located 4 m above the HTS-SQUID monitor. These dates gave tentative criteria for the judgment of safety for radiation damage. After overcoming these difficulties by reinforcing the RF shield and hiding the flux-locked loop (FLL) circuit with lead and concrete blocks, there were no more problems with the beam current measurement. As a result, a 10 μA 40Ar15+ beam intensity (63 MeV/u) was successfully measured with a 500 nA resolution, shown in Figure 2, where a 1 μA beam produced 6.5×10^{-6}Φ0 of magnetic flux at the input coil of the HTS-SQUID. Furthermore, a long recording of the extracted Ar beam current from the RRC without interruption of the beam user’s experiments lasting for approximately 4 hours was achieved, as is shown in Figure 3(a). In this recording, several dips in beam intensity due to ECR ion source discharge can be observed.
Figure 4. Results analyzed by fast Fourier transform (FFT), which were measured at 0 h (beam off) (a), 0.7 h (b) and 3.75 h (c) in Figure 3 (a).

at irregular intervals of 10 seconds to 60 minutes. Figure 3(b) shows a magnified image of Figure 3(a), which indicates that dips in current caused by ECR ion source discharge recovered within 400 ms. The current signals were analyzed by a fast Fourier transform (FFT) for a frequency domain and the results are shown in Figure 4. The amplitudes of ripples modulated on the beam current increased with beam current. All recording and control systems are connected to a PC-based data acquisition system. Through the Ethernet, these systems are linked to a laptop in the main control room located 200 m from the RRC hall. The sampling time for data acquisition is 500 μs and 100 data points are averaged to one data to improve the signal to noise ratio.

4. Conclusions and Outlook
In this present study, the authors intended to determine the possibility of measuring the DC of high-energy heavy-ion beams nondestructively and in real-time. Despite being performed in an environment with strong gamma ray and neutron flux radiations, RF background and large magnetic stray fields, measurements were successfully carried out. Although the intensity of a sub-microampere beam can be measured, a limit of minimum current higher than two orders of magnitude is required for fainter beam measurement. The possibility of fabricating the new HTS bridge circuit and introducing high-permeability cores into the SQUID through two holes has been investigated [9]. Figure 5 shows a picture of the new SQUID and the high-permeability cores. A test using a simulated beam current shows a 50-fold improvement in gain because the coupling efficiency of the transfer of magnetic field produced by the simulated beam current to the SQUID is improved.

The authors are grateful to R. L. Fagaly and M. Faley for valuable insights into the HTS-SQUID system and also thank S. Ono, B. Mizuno, H. Kanada S. Kojima and N. Koshio for their fruitful collaboration.

References
[1] Kase M et al 2004 Proc. 17th Int. Conf. on Cyclotrons and Their Applications (Tokyo: Particle Accelerator Society of Japan) p 160
[2] Watanabe T et al 2002 Proc. 8th European Particle Accelerator Conf. (Paris:EPS-IGA and CERN) p 1995
[3] Harvey I K 1972 Rev. Sci. Instrumen. 43 1626
[4] Peters A et al 1998 Proc. 8th Beam Instrumentation Workshop (AIP Conf. Proc. 451) (California: American Institute of Physics) p 163
[5] Tanabe T et al 1999 Nuclear Instruments and Methods in Phys. Research A 427 455
[6] Hao L et al 2001 IEEE Trans. on Appl. Supercond. 11 635
[7] Watanabe T et al 2004 Supercond. Sci. and Technol. 17 S450
[8] Faley M I et al 2001 IEEE Trans. on Appl. Supercond. 11 1383
[9] Watanabe T et al 2004 RIKEN Accelerator Progress Report 36 p 331