BEAM DIAGNOSTICS FOR RIBF IN RIKEN

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Abstract

The Radioisotope Beam Factory (RIBF) at RIEKN started its operation in the end of 2006 with the aim of conducting systematic studies on the physics of radioactive isotopes. The simultaneous use of five accelerators in series necessitates precise measurement of beam properties such as beam intensities, beam energies, and bunch lengths. Hence, a beam diagnostic system plays an important role in the efficient and stable operation of RIBF. In this paper, we provide a brief summary of the conventional beam monitors used during the daily operations of RIBF. In addition, new non-destructive monitors that have been developed bearing in mind forthcoming intensity upgrades are described.

RI BEAM FACTORY

The RIBF project [1] aims to produce the world's most intense radioactive isotope beams using a four- or five-step accelerator complex. Our mission is to explore vast unknown fields of physics involving short-lived nuclei including r-process nuclei, which are required to gain an understanding of the process of nucleosynthesis in the universe. The two major acceleration schemes used in the RIBF project are illustrated in Fig. 1. The first scheme involves a variable-energy mode in which we use the RIKEN heavy-ion linear accelerator (RILAC) [2], RIKEN ring cyclotron (RRC) [3], intermediate-stage ring cyclotron (IRC) [4] and the world's first superconducting ring cyclotron (SRC) [5] in series. These accelerators are all of the variable frequency type and their beam energies can be changed. The variable-energy mode is used for ions lighter than those of krypton, and its maximum energy is 400 MeV/nucleon for ^{48}Ca and 345 MeV/nucleon for ^{86}Kr. However, an additional cyclotron, i.e. a fixed-frequency ring cyclotron (fRC) [6] should be used to accelerate ions heavier than those of xenon up to 345 MeV/nucleon, as shown in Fig. 1 (b).

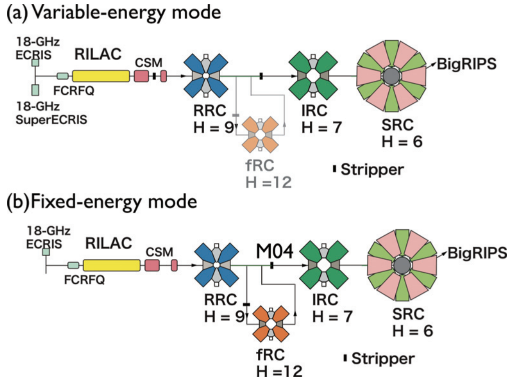

Figure 1: Acceleration schemes used in RIBF.

The beam intensities already achieved is 1 pμA, 0.23 pμA, and 1 pnA for 345-MeV/nucleon ^{18}O, 345-MeV/nucleon ^{48}Ca, and 345-MeV/nucleon ^{238}U, respectively. The total transmission efficiency of the three cyclotrons used in the variable-energy mode is nearly 85%. In contrast, the overall transmission efficiency of the four cyclotrons used in the fixed-energy mode is 40%.

CONVENTIONAL MONITORS

The beam intensities and transmission efficiency mentioned above are achieved by the use of the following conventional monitors (some of which are destructive).

Monitors Used in Beam Transport Lines

Monitors installed in beam transport lines and used in the fixed energy mode are summarized in Table 1. A Faraday cup is used to measure the beam intensity. Its design has been improved during the last three years to reduce uncertainties in the measurements. We originally adopted a compact design with a 1-kV ring suppressor and a relatively shallow cup structure. The original design allowed us to use only a single port of a beam chamber installed in beam lines. However, we found that this design overestimated beam intensities by a factor of 2 or 3 for uranium ions with energies more than 10 MeV/nucleon. The modified design employs a longer cup structure and a 72-mm suppression electrode, using which a uniform distribution of a suppression electric field can be achieved. The modified design still overestimates the beam intensity by a factor of 1.1 or 1.2, but the present overestimation is within acceptable limits for daily operations. The calibration of the beam intensity was carried out using a 40-cm long Faraday.

Table 1: Number of monitors used in beam transport lines. Abbreviations FC, PF, and PS represent a Faraday cup, beam profile monitor, and plastic scintillator, respectively.

Beam line	FC	PF	PS	Length (m)
RRC - fRC	9	12	3	81
fRC - IRC	10	25	4	119
IRC - SRC	6	13	3	64

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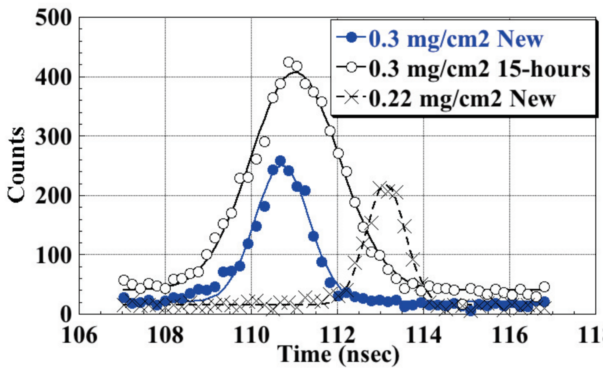

Figure 2: Longitudinal beam width measured by plastic scintillators.

We employ wire scanners as beam profile monitors. The profile monitors are used not only to check whether ions are transported according to our design but also to measure beam emittances based on the first-order ion optical theory. An example of emittance analysis can be found in Ref. [7].

Plastic scintillators are used in the time-of-flight (TOF) method to determine the beam energy. In the measurements, the beam intensity is greatly reduced (1000 cps) using beam attenuators. A mismatch in the beam energy being injected into a cyclotron causes a large-amplitude betatron oscillation of the beam centroid and results in beam loss during injection and extraction. In the case of uranium acceleration, a very thick carbon-foil is used to strip the electrons of the uranium beam, which is installed between fRC and IRC. Since a thickness error of the carbon-foil charge stripper causes the uranium beam to have the difference energy loss, the direct measurement of the beam energy is essentially important for the energy matching.

A longitudinal beam profile measured by using a plastic scintillator is also important to obtain good transmission efficiencies of the beam because the longitudinal emittance of the beams should be smaller than the longitudinal acceptance of RIBF accelerator complex. A striking example of the beam-width measurement is shown in Fig. 2. The time structure of a uranium beam were measured by using a plastic scintillator placed 38 m downstream of the charge stripper installed between RRC and fRC. When a new unused carbon-foil was used as a charge stripper, the longitudinal emittance was within the acceptance and resulted in more than 90% transmission efficiency in fRC. On the other hand, use of a charge stripper that had already been used for 15 h severely deteriorated beam quality, as shown in Fig. 2 and caused a beam loss of 50% in fRC.

Monitors Used in Cyclotrons

Phase pickup monitors and radial probes still play important roles in RIBF cyclotrons. Phase pickup electrodes are used to obtain good isochronous magnetic fields; 20, 14, 15, and 20 of these electrodes are used for RRC, fRC, IRC and SRC, respectively. In actual operation, a step-by-step optimization procedure is adopted. Starting with the values determined by magnetic-field measurements, the currents in the main and trim coils of the cyclotrons are updated to

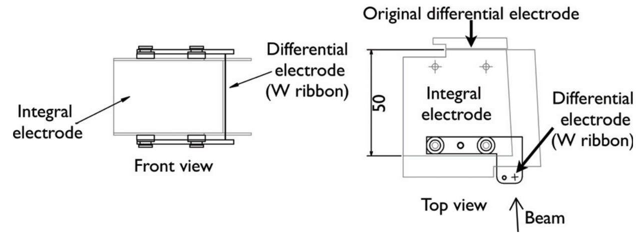

Figure 3: Modification of electrodes for SRC main radial probe. A tungsten ribbon (width : 0.3 mm) is introduced in front of the integral electrode instead of the original differential probe.

minimize a deviation from the idealistic isochronous condition by using the results of numerical simulations performed before the actual operation. Typically five rounds of updates are required to obtain the isochronous fields in which phase excursions of ions remain within a few RF degrees. In RRC, which started its operation in 1986 and is now used as an injector in RIBF, signals measured by phase pickup electrodes are pre-amplified and these signals can be monitored by using a digital oscilloscope because of a good signal-to-noise ratio. However, this is not the case with the three newly constructed cyclotrons (fRC, IRC, and SRC) because the operating acceleration voltages in these cyclotrons are twice as large as that in RRC and stray electric fields become signal-to-noise ratio worse. To overcome this problem, lock-in amplifiers and interference filters have been introduced.

A radial probe, which moves from the inner to the outer region or visa versa, measures the beam intensity and the turn pattern. The beam intensity is measured by the so-called integral electrode, whereas the turn pattern is measured by the so-called differential electrode. Both electrodes are insulated from each other. At the beam commissioning stage of RIBF, we employed similar designs as those used in RRC for the integral and the differential probes, but encountered several problems. The first problem is that a differential probe catches secondary electrons that are emitted by heavy-ion bombardment with the integral electrode The second problem is the electric noise due to stray electric fields, especially fields generated from flat-top resonators. The first problem is reduced by modifying the probe-head design, as shown in Fig. 3. To solve the second problem, the cylindrical covers of the radial probes are grounded by adding contact fingers to the upper half of the probes in addition to contact fingers already present in the lower half [8]. The differential probes are used during daily operations in order to select the optimum phases of the RF fields in the cyclotrons by comparing turn patterns. To avoid melting of the differential probes caused by the heat load, a beam chopping technique is used during the actual high-intensity operations.

NEWLY DEVELOPED MONITORS

Beam-phase and RF-phase Monitoring System

The destructive monitors described in the above section are useful for tuning a beam with a relatively low intensity

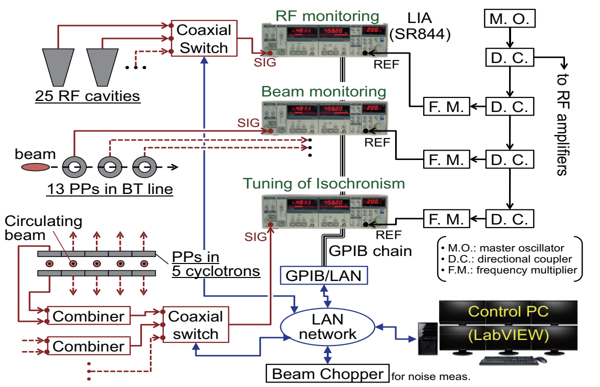

Figure 4: Block diagram of beam-phase and RF-phase monitoring system.

(less than few microamperes). However, non-destructive monitors that work continuously are required for the stable operation of RIBF. An integrated system that monitors the beam phases and RF fields of the accelerators has been developed [9]. The block diagram of this monitoring system is shown in Fig. 4. Signals induced by the passage of ions are detected by pickup electrodes. The signals are pre-amplified and continuously analyzed by a lock-in amplifier SR844 (Stanford Research Systems, Inc.). The resulting voltage and phase of the signal are displayed using a new software developed on the LabVIEW framework (National Instruments Corporation.). The target frequency of the lock-in amplifier is determined to obtain a better signal-to-noise ratio. The signals detected by the pickup electrodes installed in the RF cavities are also analyzed in a similar manner as described above. The merit of this integrated system is that we can easily understand the correlation between the fluctuations in the RF fields and the changes on the beam phases. An example of stability analysis can be found in Ref. [9]. By using the monitoring system, we found strong correlations between the measured fluctuations in the beam phase injected into RRC and the insufficient stability of the RF fields of the injector. Hence, old automatic voltage regulators were upgraded, and consequently, the stability of the beam improved.

Beam Intensity Monitor Using High-TC SQUID

A highly sensitive beam current monitor with a high-critical-temperature (high-Tc) superconducting quantum interference device (SQUID) and a high-Tc current sensor, that is, a high-Tc SQUID monitor, has been developed for use in RIBF at RIKEN [10]. In the present work, the high-Tc SQUID monitor allows us to measure the direct current (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 can be recorded without interrupting the experiments performed by beam users. Both the high-Tc magnetic shield and the high-Tc current sensor were fabricated by dip coating a thin layer of Bi_2-Sr_2-Ca_2-Cu_3-O_x (2223-phase, Tc = 106 K) on a 99.9% MgO ceramic substrate. Unlike in other existing facilities, all the high-Tc devices are cooled by a low-vibration pulse-tube refrigerator in our facility, enabling us to downsize the system. Last year, to enable its practical use, the high-Tc SQUID monitor was installed in RIBF. Using the monitor, a 1-μA Xe beam intensity (50 MeV/u) was successfully measured with a 100-nA resolution. Figure 5 shows the high-Tc SQUID monitor equipped with an Al mounting frame and a noise cancellation system, which was installed in the transport line between fRC and IRC.

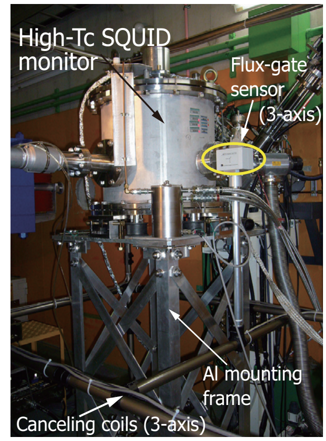

Figure 5: High-Tc SQUID monitor equipped with Al mounting frame and the noise cancellation system, which was installed in transport line between fRC and IRC.

SUMMARY

Beam commissioning was carried out in RIBF using conventional beam instrumentation, as described above. Satisfactory performance of the beam monitors was achieved in the commissioning stage but some limitations were found, especially with regard to their destructive nature for beams. Several non-destructive monitors were developed and their effectiveness was demonstrated by using them during RIBF operation. One of the major remaining problem is to measure the time structure of a beam without reducing its intensity in order to avoid losing the space-charge effect during the measurement.

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