# PROGRESS ON THE COMMISSIONING OF RADIOACTIVE ISOTOPE BEAM FACTORY AT RIKEN NISHINA CENTER

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*Abstract*

The Radioactive Isotope Beam Factory at RIKEN Nishina Center is a next generation facility which is capable of providing the world's most intense RI beams over the whole range of atomic masses. Three new ring cyclotrons have been constructed as post-accelerators for the existing facility in order to provide the intense heavy-ion beam for the RI beam production by using a in-flight separation method. The beam commissioning of RIBF was started in July 2006 and we succeeded in the first beam extraction from the final booster cyclotron, SRC, by using 345 MeV/A aluminum beam on December 28$^{th}$ 2006. The first uranium beam with energy of 345 MeV/A was extracted from the SRC on March 23$^{rd}$ 2007. Various modifications for equipments and many beam studies were performed in order to improve the transmission efficiency and to gain up the beam intensity. Consequently, the world's most intense 0.4 pnA $^{238}$U beam with energy of 345 MeV/A and 170 pnA $^{48}$Ca beam with energy of 345 MeV/A have been provided for experiments.

## OVERVIEW OF RI BEAM FACTORY

The Radioactive Isotope Beam Factory (RIBF) [1] at RIKEN Nishina Center was proposed in order to produce the world's most intense radioactive isotope (RI) beams over the whole range of atomic masses. The powerful RI beams allows us to expand our nuclear world on the nuclear chart into presently unreachable region and opens up new possibilities for the unified understanding of nuclear structure, for the elucidation of elemental synthesis, and for new scientific discoveries and applications. Figure 1 shows the entire layout of RIBF accelerator complex. The existing facility has a K540-MeV separate-sector cyclotron (RIKEN ring cyclotron, RRC) [2] and a couple of different types of the injectors: one is a linear accelerator complex that consists of a folded-coaxial radio-frequency quadrupole [3], a variable-frequency heavy-ion linac (RILAC) [4], and a energy-booster linac [5]; and the other is a K70-MeV AVF cyclotron (AVF) [6]. Three new ring cyclotrons with K=570 MeV (fixed-frequency ring cyclotron, fRC [7]), 980 MeV (intermediate-stage ring cyclotron, IRC [8]), and 2600 MeV (the world's first superconducting ring cyclotron, SRC [9]), respectively, have been constructed for the RIBF as post-accelerators, which can boost energies of beams up to 440 MeV/A for light ions and 345 MeV/A for very heavy ions extending to uranium. These 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 a superconducting in-flight fragment separator, BigRIPS [10]. The goal of the available beam intensity is set to be 1 p$\mu$A.

## FIRST BEAM AND INITIAL EXPERIMENT

The beam commissioning of RIBF was started in July 2006 in parallel with constructing the rest of equipments for latter-stage accelerator. At first, the beam acceleration test of fRC, which is the first booster among the new cyclotrons, was performed with uranium beam in the intervals of experiment at the existing facility. For the uranium beam acceleration, the beam from linac complex is fed to the cascade of RRC, fRC, IRC, and SRC, where the accelerators are used at fixed-energy mode with the rf frequency of 18.25 MHz and its harmonics. The first uranium beam with energy of 50 MeV/A was successfully extracted from the fRC on September 29$^{th}$ 2006. The beam study of fRC was performed at total seven times until November in order to improve the beam emittance and the transmission efficiency. After the completion of the beam line to IRC, beam commissioning of IRC began on November 21$^{st}$ by using $^{84}$Kr$^{31+}$ beam. For the ions not heavier than krypton can be accelerated by a variable-energy mode up to at least 345 MeV/A without using the fRC. The first beam was extracted from IRC on November 25$^{th}$, only 110 minutes were required from the injection to the extraction of IRC.

Because of the serious trouble on the heat insulating vacuum of helium cooling system, four acceleration resonators and one flat-top resonator were installed on the SRC at June 24$^{th}$ 2006 at last, which was five-months behind to initial plan. Installation of the power amplifiers and low-level controls was made from July to October 2006. After the resonators were carefully aligned, they were connected with the sector magnets to make a vacuum chamber for ion beams. The two vacuum chambers, which enclose the electrostatic channel or phase pickups, were installed in the two valley regions where no resonators fill the space. Evacuation pumps and beam diagnostics were also installed. Initial pumping of the beam chamber started from September

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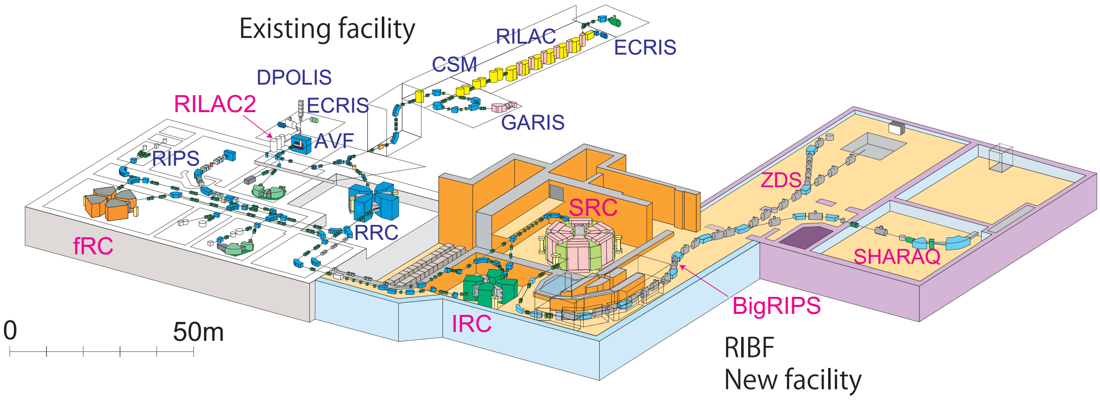


Figure 1: Bird's-eye view of RIBF at RIKEN Nishina Center.

$29^{th}$. After the leak hunt, cryopumps were turned on and the vacuum pressure reached to $5.0\times10^{-6}$ Pa at the end of October, which is the designed value. The power test of RF system was started on $13^{th}$ November. On $27^{th}$ November, the first resonator became operational in cw mode with a magnetic field of the sector magnets. The beam diagnostics were also installed to the SRC during this period. The superconducting coils were fully excited several times to check whether the installed components could work properly under stray fields from the sector magnets. Many local magnetic shields made of iron were put to the parts which did not work properly under the stray fields.

The beam commissioning of SRC started on December $17^{th}$ 2006 with using $^{27}Al^{10+}$ beam from the IRC. The beam tuning of SRC was hard work as compared with fRC and IRC. The first beam extraction was finally accomplished at 16:00 on December $28^{th}$ 2006. After the various modification of hardware and the conditioning of rf resonator, the first RI beam production at RIBF was achieved by the fragmentation of 345 MeV/A $^{86}Kr^{31+}$ beam on March $15^{th}$ 2007. Following the delightful event, the uranium beam acceleration of SRC was performed immediately because the uranium beam was the top priority for RIBF. The first $^{238}U^{86+}$ beam with energy of 345 MeV/A was successfully extracted from the SRC on March $23^{th}$ 2007. After passing the facility inspection, the beam became possible to utilize the experiment on April 2007. The initial experiment at the RIBF was carried out from mid-May to early in June by using the uranium beam, and a new isotopes $^{125}$Pd and $^{126}$Pd was successfully discovered [11]. A beam current of up to 30 pnA for 345 MeV/A $^{86}Kr^{34+}$ was attained on November $10^{th}$ 2007 at the exit of SRC.

## IMPROVEMENT OF PERFORMANCE

The total transmission efficiency of the accelerator complex for uranium beam was only 2 % in July 2007, where the charge stripping efficiency is not taken into account. The poor transmission efficiency was mainly caused by insufficient beam tuning due to the inappropriate beam diagnostics for uranium beam. For the uranium beam, huge number of secondary electrons disturbed the radial beam pattern on main differential probe (MDP) and boosted the apparent beam current on Faraday cups. In addition that, the stray field from the flat-top (FT) acceleration resonator overrode on the differential probe and the radial beam pattern was collapsed. The instability of rf voltage on four resonators in the RILAC, these resonators were controlled by old low-level gain controllers, complicated the adequate beam tuning during the commissioning. Another reason of low transmission for uranium beam was the emittance growth caused by the rough uniformity of the charge stripper carbon foils, which are required at the downstream of RRC and fRC for the uranium beam acceleration.

### *Modification of Beam Monitors*

In order to improve the transmission efficiency of cyclotrons, an accurate adjustment of rf voltage and phase is required, especially for the FT resonator. If the phase of FT resonator is shifted at only one degree, turn separation deteriorates drastically as shown in Fig. 2. It is desired to observe the proper information of radial beam pattern by using the MDP because the information gives a criterion for the adjustment of rf. The radial beam pattern is measured by a differential electrode mounted on behind an integral electrode with 0.5 mm overhang. Only the beam reached to the "0.5 mm" is counted at each radius. However, a lot of secondary electrons emitted from the sidewall of integral electrode due to hitting the uranium beam had a great influence on the detection of differential signal and the radial beam pattern could not be constructed properly. In order to overcome the problem, the differential electrodes were modified for fRC, IRC, and SRC to shift away from the integral electrode. In the case of SRC, new differential electrode of 0.3 mm$\times$3 mm tungsten ribbon was attached in front of the integral electrode at intervals of 10 mm. Another problem we had in the MDP was that the beam signal was disturbed by the electromagnetic radiation from the FT resonator: the rf frequency is high enough for the electromagnetic wave to travel through the vacuum chamber. A schematic drawing of the MDP in the chamber is shown in

Fig. 3. The driving shaft of the MDP is grounded by the metallic wheel on the chamber in the original configuration. Since the electromagnetic wave is TE01 mode, this asymmetric configuration allows the electric field to penetrate into the narrow gap between the shaft and the chamber, which induces the electric charge in the head of the probe. Therefore, we put an electric contact on the upper side of the shaft, as shown in Fig. 3, in order to suppress the electric field around the probe head. For the SRC, a pantograph structure was adopted for the contact because the chamber face was not seamless. An adjustment for balance of the vertically located movable shorts in the FT is required simultaneously in order to reduce the leakage of microwaves. These modifications enabled us to measure the radial beam pattern for entire region of the MDP with using the FT resonator as shown in Fig. 2.

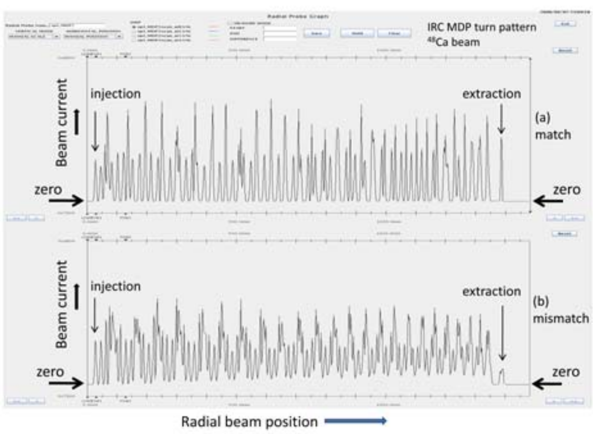


Figure 2: Radial beam pattern of $^{48}$Ca beam measured by MDP on IRC. FT resonator was activated. The rf phase of FT is matching in the upper panel, whereas the phase is shifted at only one degree in the lower panel.

Accurate measurement of beam current is essential for the elaborate tuning to reduce the beam loss in the injection and extraction channels of cyclotrons and in the beam transport lines. Newly designed Faraday cups and separated-type electron suppressor with 70 mm thickness were adopted to overcome the problem that the beam intensity was overestimated by a factor of two or three due to the insufficient suppression of secondary electrons. This new Faraday cup replaced the one mounted at the key point of accelerator complex. Faraday cup located at the exit of SRC is based on a special design, that consists of a fixed main-suppressor electrode, a fixed long-cylindrical electrode, and a cup bottom movable with respect to the beam axis. The beam stops on the cup bottom and the emitted secondary electrons are captured by the cylindrical electrode. Residual electrons are returned by the electrostatic field provided by the main-suppressor electrode. The sub-suppressor electrode is used to trap the electrons escaping from the aperture between the cup bottom and the cylindrical electrode. The cup bottom is made of oxygen-free copper with $\phi$62 mm inner diameter, and the bottom is 23 mm thick and cooled by water. This thickness is designed to fit beams from argon to uranium accelerated by the SRC.

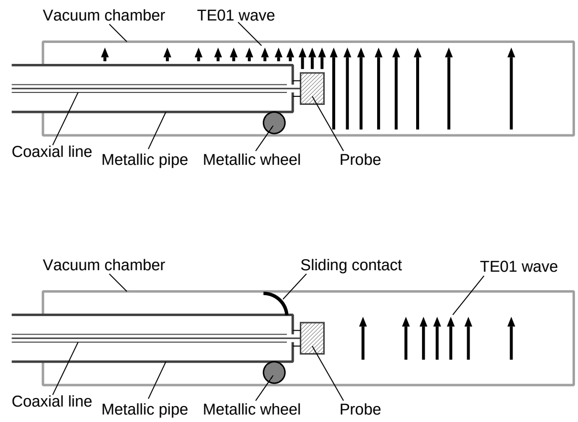


Figure 3: Effect to disturb the propagation of TE01 microwave.

## *Problem of Helium Cryogenic System*

Helium cryogenic system of SRC met the serious problem that the flow rate in the system had decreased gradually, the temperature of 80 K stage adsorbers had increased, and the inlet pressure of the first turbine had fallen. We had to stop the helium refrigerator every two months to warm it up to room temperature and transpire the impurity. By the long term investigation, the source of the problem was found that the lubricant oil of screw compressors had passed through the cascade of four-stage oil separators and polluted the first heat exchanger, 80 K adsorbers, first and second turbine, and their inlet filters in the refrigerator. This oil had frozen and degraded the flow rate of helium gas in the refrigerator. To rinse out the impurity, heat exchangers were taken out from the refrigerator and were washed away by using HCFC solvent. The charcoal in the adsorber was also replaced with the new one. Additional 1.5th and 5th oil separators were installed in parallel with the reconstruction of helium refrigerator to enhance the ability of oil elimination. This trouble delayed the steady operation of SRC from December 2007 until September 2008. The re-cooldown of SRC started at once and the superconducting coils were ready to operate in October 2008.

## *Present Performance*

A series of studies were performed without the SRC by using $^{48}$Ca and $^{238}$U beam during the reconditioning of helium cryogenic system. In this period, the monitoring system for the RF pick-up and beam phase pickup signal using lock-in amplifiers (SR844) was developed [12] and the long-term stabilities were clarified as described above. After solving the problem of helium cryogenic system, the acceleration of $^{238}$U was performed for the commissioning

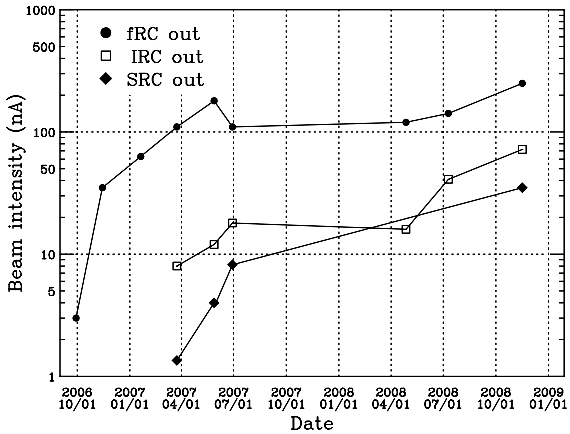


Figure 4: Evolution of maximum intensity for uranium beam during the commissioning.

of the Zero-Degree Spectrometer and following new isotope search experiment at BigRIPS in November 2008. The beam intensity from the SRC grew up to 0.4 pnA, which was ten times higher than the one in 2007. More than twenty candidates of new isotopes were discovered within a week.

Table 1: Transmission efficiencies from the ion source to the exit of each accelerator. Note that the observed currents include 20–30 % errors.

| | $^{86}$Kr | $^{238}$U | $^{48}$Ca |
|---|---|---|---|
| RILAC | 47 % | 40 % | 54 % |
| RRC | 28 % | 30 % | 50 % |
| fRC | Not used | 35 % | Not used |
| IRC | 20 % | 23 % | 48 % |
| SRC | 9 % | 16 % | 35 % |

Following that, the first acceleration of $^{48}$Ca on the SRC was carried out in December 2008 for a series of day-one experiment. The modifications performed in past two years and elaborate tuning of accelerators realized the world's most intense $^{48}$Ca beam that reached up to 170 pnA at the exit of SRC. Figure 4 indicates the evolution of the maximum intensity for uranium beam during the commissioning. The degradation of intensity on fRC in July 2007 corresponds to the adoption of new Faraday cups. The transmission efficiencies from the ion source to the exit of each accelerator are summarized in Table 1. The efficiency of 82 % for the SRC corresponds to about 500 W loss for 170 pnA $^{48}$Ca beam. In most cases, the major beam loss in cyclotron take place on the septum of electrostatic deflector (EDC). For the acceleration of kilowatt beams such as the $^{48}$Ca, large beam loss causes the serious thermal damage on the hardware and that restricts the maximum beam intensity effectively. For the protection during the $^{48}$Ca beam acceleration, type-E thermocouple gauges were mounted on the EDC septum to measure the temperature and switch off the beam if the maximum heat-up exceeded the criterion, which was set to 5 degrees in December 2008. The temperature clearly responded to the beam loss and that was available to improve the extraction efficiency via tuning as decreasing the temperature.

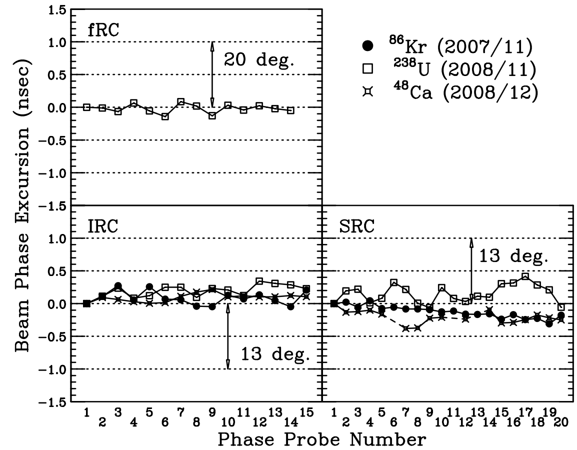


Figure 5: Isochronous condition of new cyclotrons. Data point of SRC phase probe no.6, 11, 13 in the case of $^{48}$Ca is not plotted because the probe was troubled by FT stray field.

The accurate isochronism is the significant condition for the cyclotron to make capable for providing the intense beam with high transmission efficiency. Figure 5 describes the excursion of periodic arrival time for revolving beam in each cyclotron as a function of phase pickups located along the radius vector. Signals were detected by the pairs of phase pickups which are radially mounted on the orbital region of cyclotron, and analyzed by the lock-in amplifier. The result of krypton beam indicates that the isochronous condition of the magnetic field is attained to the acceptable level for each cyclotron as the booster in the RIBF accelerator complex. The isochronous condition of uranium beam for the SRC is not as good as the others since the intensity of uranium beam in the SRC is not enough to obtain the data set with high signal to noise ratio.

In the case of $^{48}$Ca, the transverse emittance of beam at the entrance of SRC was evaluated to be $1.7\pi$·mm·mrad [13] in both the horizontal and vertical directions. This indicates no distinct emittance growth. However, it was found that the emittance grew by a factor of three from the RRC to the fRC for the uranium beam. That is caused by a emittance mismatch during the injection to fRC and by a dispersion mismatch at a rebuncher placed between the RRC and fRC.

## LIGHT ION ACCELERATION

The new acceleration mode using AVF-RRC-SRC combination can provide the extremely light ions such as deuteron and nitrogen with the energies of 250–440 MeV/A. For the acceleration mode, a new beam transport line bypassing the IRC was constructed in the fiscal

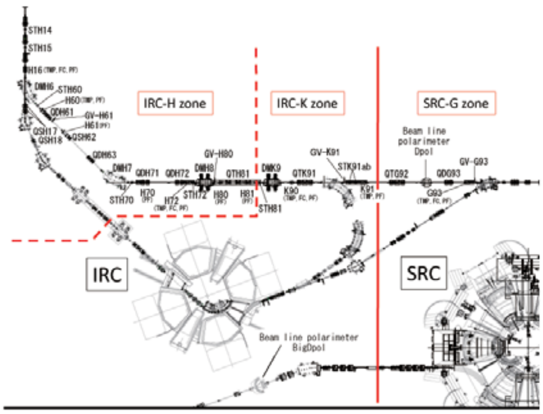


Figure 6: Schematic layout of IRC-bypass beam line used for relatively light-particle acceleration.

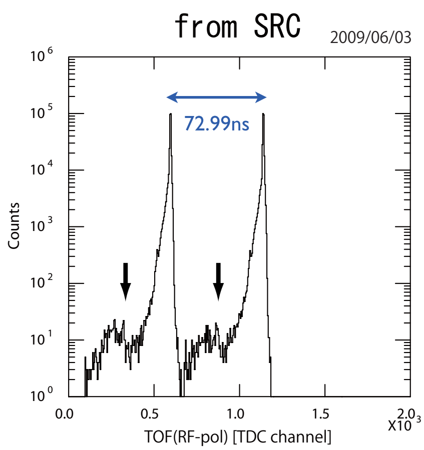


Figure 7: Longitudinal beam structure of polarized deuteron beam at the downstream of SRC. The down arrows indicate the mixture of different turn.

year 2008 [14]. The schematic layout of the beam line is described in Fig. 6. This acceleration mode was tested with a 250 MeV/A nitrogen beam in February 2009. New high-resolution spectrometer SHARAQ [15] was successfully commissioned by using the 250 MeV/A nitrogen beam in March 2009. This beam was also used for additional test experiment of SHARAQ and another experiment at BigRIPS in May 2009.

A 250 MeV/A polarized deuteron beam was accelerated to study the nuclear three-body force in April 2009. For the deuteron beam acceleration, special beam diagnostic devices were mounted on the SRC because the existing devices could not stop the deuteron beam in themselves. The elaborate beam tuning was performed because the single turn extraction was required for the polarized deuteron beam experiment. Figure 7 shows the longitudinal beam structure of the polarized deuteron beam downstream of SRC measured by a plastic scintillator. The time-of-flight spectrum indicates that the single turn extraction of SRC was remarkably actualized.

## OUTLOOK

Several modifications are organized in order to increase the beam intensity further more. New injector linac system [16] will be constructed in the fiscal year 2009. Combining with a new superconducting ECR ion source [17], we expect the uranium beam intensity to increase up to 100 times. The injector enables the independent and simultaneous operation between the RILAC and the RIBF accelerator complex. The old low-level circuits for RILAC will be replaced to the new stable ones. In order to reduce the disadvantage to the beam quality, thinner carbon foils will be employed for the stripper between the RRC and fRC. The power supplies of fRC magnet have to be modified since the charge state of uranium beam will be shifted from $71^+$ to $69^+$. The most difficult problem is regarding to the lifetime of stripper foil. Although various types of stripper are tested, excellent answer has not been obtained yet.

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