# CONSTRUCTION OF THE RARE RI RING AT THE RIKEN RI BEAM FACTORY

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*Abstract*

The Rare RI Ring (R3) heavy-ion storage ring is now under construction at the RIKEN RI Beam Factory. The aim of this ring is high-precision mass measurement of extremely short-lived and rarely produced unstable nuclei (rare RIs). Our target performance for mass determination is accuracy on the order of $10^{-6}$ ($\sim$ 100 keV), even for a single event. We use isochronous mass spectrometry to reduce measurement times to less than 1 ms. The R3 structure is based on cyclotron motion to achieve the target accuracy. Since an isochronism in R3 is established over a wide momentum range, rare RIs with a large momentum spread, $\Delta p/p = \pm 0.5\%$, are acceptable. Another significant feature of the R3 system is an individual injection scheme in which a produced rare RI itself triggers the injection kicker. This allows efficient use of unpredictably produced rare RIs. Ultra-fast response is required of the kicker system to establish the individual injection scheme. Technical challenges are forming a precision isochronous magnetic field and development of a fast response kicker system. This paper describes the R3 and its construction status.

## INTRODUCTION

Mass measurement is one of the most important contributions to research on nuclear properties, especially for short-lived unstable nuclei far from the $\beta$-stability line. In particular, high-precision mass measurements of nuclei located around the r-process pass (rare RI) are required for nucleosynthesis. The r-process is a promising candidate for solving the mystery of nucleosynthesis for elements heavier than iron. Supernovae and neutron star collisions are proposed as sites of r-process nucleosynthesis. A precision in mass determination on the order of $10^{-6}$ ($\Delta m/m$) is required to constrain environmental conditions such as temperature and neutron flux in these sites. The RIKEN RI Beam Factory is the world's most powerful RI production facility, and has allowed access to rare RIs [1, 2, 3]. Nuclei around the r-process pass have extremely short lifetimes (on the order of ms) and rare production rates, making precise mass measurement difficult. Our motivation in constructing the R3 is to establish a method that allows determination of nuclear masses with precision on the order of $10^{-6}$ and measurement times of less than 1 ms.

Some experimental methods for precise mass measurement have been established. An ion-trapping-based method using a slow RI beam [4] achieves excellent mass resolutions of better than $10^{-7}$. Schottky mass spectrometry conducted in a storage ring is also an elegant method that can achieve mass resolutions of $10^{-6}$, as demonstrated at ESR/GSI [5]. But measurement times in these methods exceed 1 s, making them unsuited to rare RIs. Another candidate for fast mass measurement is isochronous mass spectrometry (IMS) conducted in a storage ring; measurements for nuclei with lifetimes of 50 ms were demonstrated at ESR/GSI using this method [6]. However, the mass resolution achieved in IMS has so far been on the order of $10^{-5}$, which is insufficient for our purposes. The reason for this is that the isochronous mode of ESR provides relatively small acceptance, in momentum space in particular, because the lattice was originally designed as a strong focusing storage ring. Since the lattice design of R3 is based on cyclotron motion, it can provide isochronism in a wide range of momentum. Acceptances in momentum and $m/q$ value were designed to be much larger than that of the isochronous mode of ESR. We expect significant improvement in IMS mass resolution as long as the isochronous field is precisely formed in R3. Therefore, IMS using R3 will be capable of both high precision and fast measurement.

Another desired feature for R3 is to efficiently take advantage of opportunities for measurement of unpredictably produced rare RIs. We adopted an individual injection scheme in which the produced rare RI itself triggers the injection kicker magnets. To achieve this, full activation of the kicker magnetic field must be completed within the flight time of the rare RI from the originating point of the trigger signal to the kicker position. Development of an ultra-fast response kicker system is therefore a key issue for establishing the individual injection scheme.

The R3 design study has continued for over a decade, and construction began in 2012. Construction of the infrastructure and fabrication of major R3 hardware have been generally completed. We are now setting up and testing all equipment, including power supplies, the control system, and the vacuum system. Commissioning is planned for 2014.

## R3 IMS PRINCIPLES

Since design of the R3 beam orbit is based on cyclotron motion, its circulation frequency is described by the cyclotron frequency $f_c$,

$$f_c = \frac{1}{2\pi}\frac{q}{m}B, \tag{1}$$

where $q/m$ is the charge-to-mass ratio and $B$ is the magnetic field. The frequency is independent of beam momentum so long as the R3 isochronism is secure. Since the mass and magnetic field are relativistically given by $m = m_0\gamma$



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and $B = B_0\gamma$, respectively, the charge-to-rest-mass ratio is expressed by

$$\frac{m_0}{q} = \frac{1}{2\pi} T_0 B_0, \tag{2}$$

where $T_0$ is the revolution time $1/f_c$. Measurements of $B_0$ and $T_0$ are essential for determining the absolute value of the mass $m_0$. However, measuring $B_0$ with an accuracy of $10^{-6}$ is very difficult. We therefore measure mass of the rare RI $m_1/q_1$ as a value relative to that of a reference nucleus whose mass $m_0/q_0$ is precisely known. In the case where momentum of both the rare RI and the reference nucleus are identical, the flight pass length is also identical:

$$\frac{m_0}{q_0}\gamma_0\beta_0 = \frac{m_1}{q_1}\gamma_1\beta_1, \tag{3}$$

$$\beta_0 T_0 = \beta_1 T_1. \tag{4}$$

From these relations, the unknown mass $m_1/q_1$ is expressed as

$$\frac{m_1}{q_1} = \frac{m_0}{q_0}\frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-(\frac{T_1}{T_0}\beta_1)^2}}. \tag{5}$$

The relative uncertainty for $(m_1/q_1)$ is given as

$$\frac{\delta(m_1/q_1)}{(m_1/q_1)} = \frac{\delta(m_0/q_0)}{(m_0/q_0)} + \gamma_0^2\frac{\delta(T_1/T_0)}{(T_1/T_0)} + k\frac{\delta\beta_1}{\beta_1}, \tag{6}$$

where

$$k = -\frac{\beta_1^2}{1-\beta_1^2} + \left(\frac{T_1}{T_0}\right)^2 \frac{\beta_1^2}{1-(T_1/T_0)^2\beta_1^2}. \tag{7}$$

The first term of Eq. 6 is uncertainty in the reference nuclear mass, and should be on the order of $10^{-6}$ or less. The second term is uncertainty coming from an imperfect R3 isochronism and the time resolution of the time-of-flight (TOF) detector. Even when the R3 isochronism is perfectly tuned to the reference nucleus, isochronisms for rare RIs will be slightly broken. The third term of Eq. 6 corrects this effect. The value of $k$ is on the order of $10^{-2}$ even if $m/q$ differs from the reference nucleus by $\pm 1\%$. The third term is on the order of $10^{-6}$ as long as $\beta_1$ is measured with an uncertainty of $10^{-4}$. Therefore, precise measurements of the $T_1/T_0$ ratio and $\beta_1$ are essential in R3 IMS.

Figure 1 is a schematic diagram of our mass measurement using R3. R3 is located downstream from BigRIPS, and connected to the super-conducting ring cyclotron (SRC). Rare RIs produced at the F0 target section in Big-RIPS are separated and roughly identified at the F3 focal point. The rare RIs of interest and reference nuclei arrive at F3, where they produce trigger signals for the kicker system. The beam pass length from F3 to the kicker in R3 is 161 m, and the flight time of rare RIs is 950 ns with energy of 200 MeV/u. Trigger-signal transmission to the kicker power supplies and activation of the kicker magnetic field has to be completed within the flight time. We have succeeded in developing a fast-response kicker system that makes individual injection possible. The velocity of a rare RI $\beta_1$ is derived from measurement of TOF from F3 to the entrance of R3. Uncertainty of $\beta_1$ can be $\sim 10^{-4}$ in this measurement.

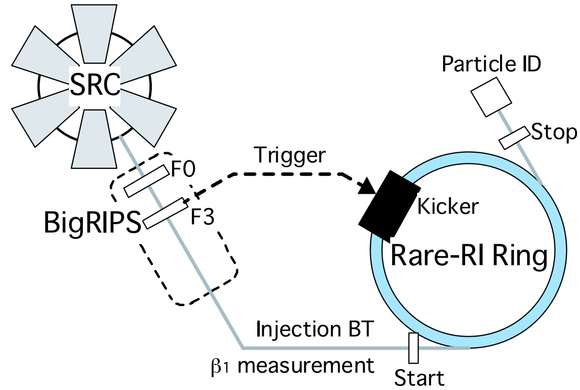


Figure 1: Concept of mass measurement at R3.

Rare RIs pass through a thin plastic scintillator at the R3 entrance, thus triggering TOF measurement. RIs are then transported along the injection orbit until the kicker position and put into the accumulation orbit by the kickers. After 2000 orbits ($\sim$ 0.7 ms), they are extracted by again activating the kicker magnetic field. Extracted rare RIs hit another thin plastic scintillator for stop signal generation, and are exactly identified using E and $\Delta$E detectors. R3 accepts not only rare RIs of interest but also the reference nucleus. As long as the difference between their $m/q$ values is less than $\pm 1\%$, neither particle will lag by a full lap within 2000 orbits. Therefore, the obtained TOF value $T_1$ can be precisely compared with $T_0$ as a reference. Since it is easy to make the time resolution of the TOF detectors smaller than 100 ps, the ratio of $T_1/T_0$ is surely obtained with an accuracy on the order of $10^{-6}$. If the isochronism in R3 and its stability are established with a precision of $10^{-6}$, the mass of rare RI can be determined with uncertainty on the order of $10^{-6}$, even when measuring only one event.

## THE RARE-RI RING

Figure 2 shows a schematic view of the R3 structure. All R3 devices were designed under the assumption that an incoming beam has an energy of 200 MeV/u and a charge-to-mass ratio $m/q$ of less than 3. The ring structure was designed with a similar separate-sector ring cyclotron concept. It consists of six sectors and 4.02 m straight sections, and each sector consists of four rectangular bending magnets. These magnets were first used in TARN-II [7], which was constructed at INS Tokyo University more than 20 years ago. The bending angle and the radius are 15 degrees and 4.045 m, respectively. A radially homogeneous magnetic field is produced in the magnet, and magnetic rigidity is 6.5 T·m at maximum. Main coils of all the bending magnets are connected in series, and a cur-

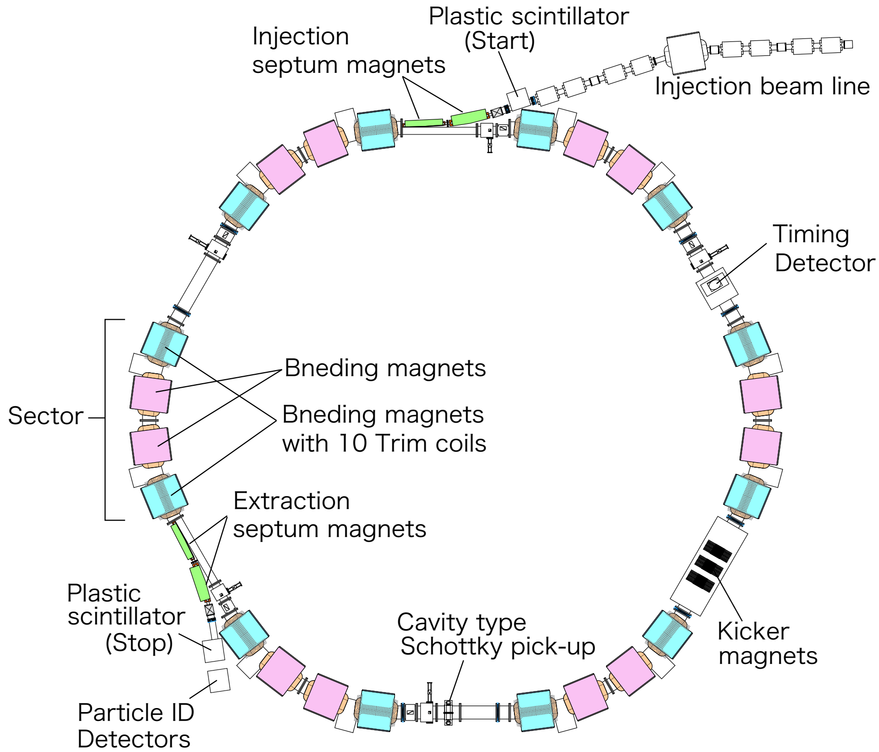


Figure 2: Mechanical structure of Rare-RI Ring.

rent of 3000 A is required for rare RIs, for example $^{78}$Ni with a magnetic rigidity of 5.96 T·m. Small variations in $B \cdot L$ product due to individual characteristics of the magnets are corrected by applying small currents to accompanying correction coils. Two magnets at both ends of each sector are additionally equipped with 10 trim coils to form an isochronous magnetic field. For $\Delta p = 0$ particles, the circumference is 60.35 m and the betatron tunes are $\nu_x = 1.21$ and $\nu_y = 0.84$ in the horizontal and vertical directions, respectively. The momentum acceptance is $\Delta p/p = \pm 0.5\%$, and the transverse acceptances are $20\pi$ mm·mrad and $10\pi$ mm·mrad in the horizontal and vertical directions, respectively. Although the transverse acceptances of the R3 itself are actually larger than these values, they are limited by that of the injection beam line. Of special note is that the isochronism is precisely fulfilled in a wide range of momentum (full width 1%), due to the cyclotron-motion based lattice design.

A rare RI transported through the injection beam line is inserted into the R3 injection orbit by septum magnets. A thin plastic scintillator is placed at the entrance of the septum magnets for start signal generation. We provided two septum magnets with bending angles of 12.7° and 5.3°. The injection orbit at the exit of the septum magnets is off-centered by 90 mm and parallel to an accumulation orbit. The septum magnetic fields are always activated to accept unpredictably produced rare RIs. Magnetic field leak at the accumulation orbit is negligibly small due to magnetic shielding using high-$\mu$ materials. Distributed-constant-type kicker magnets are placed at a position where the horizontal betatron phase advance is $3\pi/2$ from the injection septum. Momentum dispersion of the injection orbit is matched to that of the accumulation orbit at the kicker position. The kicker magnetic field triggered by the injected rare RI is already fully activated at the moment of beam arrival. The rare RI is kicked by an angle of 12 mrad and put into the accumulation orbit. The kicker magnetic field falls quickly; the remaining field after one revolution (355 ns) is less than 1%. After 2000 orbits the rare RI is kicked out through the extraction septum magnets. A thin plastic scintillator, a $\Delta E$ detector, and a total energy detector are placed on the extraction line.

We use ordinary beam diagnostic devices such as a screen monitor and a beam position monitor based on triangle pickup electrodes. Five sets of these monitors are distributed along the R3 orbit, and are useful in the machine tuning process using a high-intensity primary beam. They however are not practical for use with rare RIs due to their poor sensitivity. We therefore inserted highly sensitive monitors, which can be applied even to a single particle circulation. One of these monitors is a cavity-type Schottky pick-up. The resonance frequency is designed to be 186 MHz, which corresponds to the harmonic number 66. The expected quality factor is over 5000. Another is a timing monitor, which detects secondary electrons emitted from a carbon foil of thickness 50 $\mu$g/cm$^2$ placed on the accumulation orbit. Rare RI with energy 200 MeV/u survive only for the first 1000 orbits due to energy loss at the foil. Since this monitor has a position sensitivity with an accuracy of less than 10 mm, a correlation between hori-


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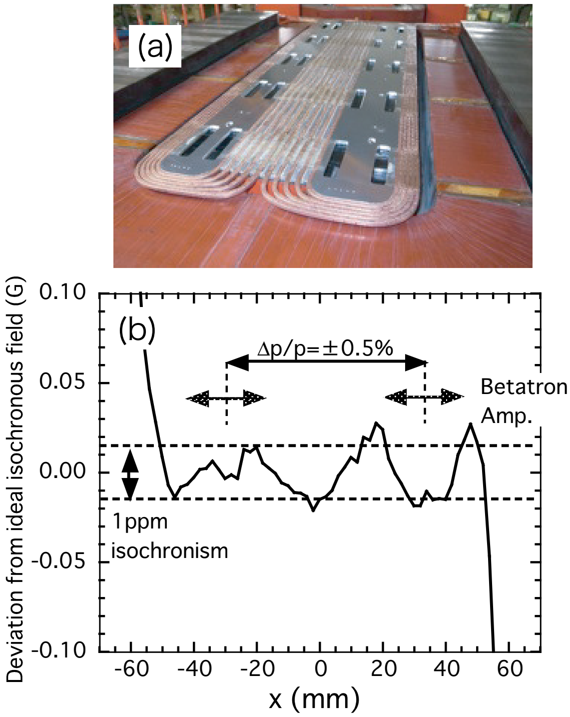


Figure 3: Photograph of 10 trim coils equipped to a bending magnet (a) and the deviation of the calculated magnetic field from an ideal isochronous field (b).

zontal beam position and revolution time will be obtained. Details concerning these monitors are described in Refs. [8, 9]. These devices play an active role in precise tuning of the isochronism.

### *Isochronism of R3*

The isochronous magnetic field is formed using 10 trim coils equipped to 12 bending magnets. Figure 3 (a) is a photograph of trim coils set on the bending magnet pole. Every trim coil is a one-turn coil made of a $6 \times 6$ mm$^2$ hollow conductor. Required current is 300 A at maximum. We calculated the isochronous field using the 3D computer software TOSCA by adjusting the currents applied to the 10 trim coils. Fig 3 (b) shows deviations from the ideal isochronous field. The amplitude of the deviation is within $2 \times 10^{-6}$ in a radial region of $\pm 50$ mm. This shows that a precise isochronism within the requirements of R3 is achievable using the 10 trim coils.

Stability of the magnetic field is another important issue. Stability of the power supply's output current for the main coils is guaranteed to be less than $10^{-5}$. The other power supplies for the trim coils and the correction coils are also stabilized to better than $10^{-4}$. Our preliminary measurements confirmed that stability in the magnetic field was better than $2 \times 10^{-6}$. The magnetic field is always monitored using high-precision NMR detectors. It is also important to monitor the temperatures of the iron yolk, the cooling water, and air in the room. We will investigate the effect of these temperatures on response of the magnetic field, and how the isochronous condition breaks in such environments. The resulting data will enable us to correct measured revolution times ($T_0, T_1$). Isochronism tuning will be performed by measuring TOF against a reference nucleus with an $m/q$ value similar to that of the rare RI of interest. This measurement will be repeated while varying the momentum to obtain a correlation between TOF value and momentum. The trim coil currents will be adjusted to make TOF unchanged independent of the momentum. These processes will be iterated until high precision in the isochronism is achieved.

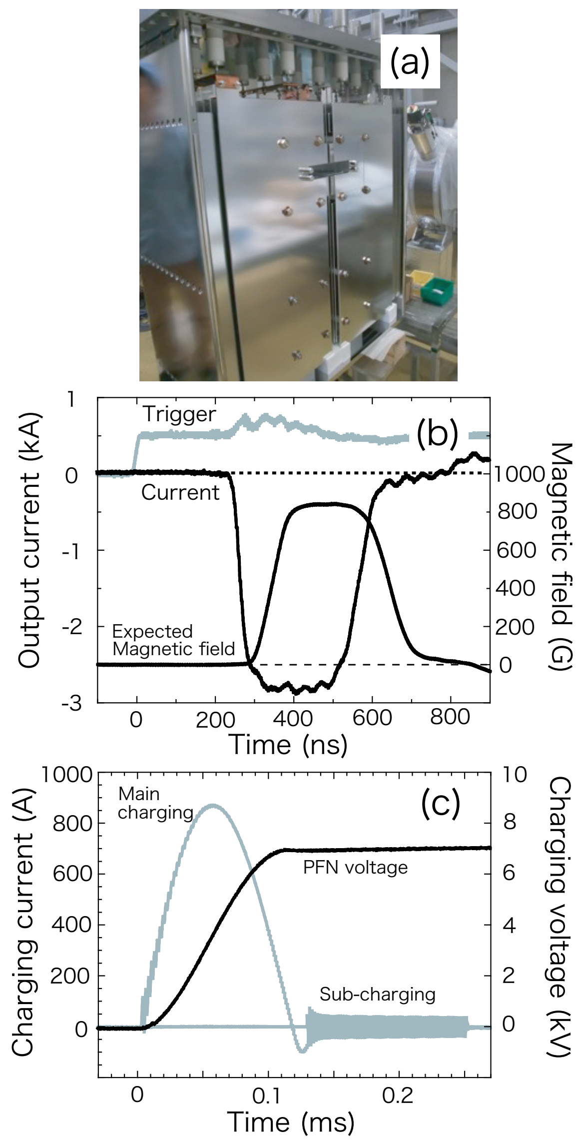


Figure 4: Performances of the fast-response kicker system. (a) is a photo of a pair of distributed constant-type kicker magnets. Wave forms of the output current form the kicker power supply, and expected magnetic fields are plotted together with the input trigger signal (b). Fast charging using a hybrid charging system is shown in (c).

### *Fast Response Kicker System*

Figure 4 (a) shows a photo of a pair of distributed-constant type kicker magnets. Each magnet consists of 13 cells with characteristic impedance 12.5 Ω. The aperture size is 180 mm and 40 mm in the horizontal and vertical directions, respectively. The kicker magnetic field is activated in a trapezoidal shape. Maximum magnetic field at the flat-top is 0.094 T at a current of 3000 A with 35 kV applied voltage. Performance features required for the kicker system are ultra-fast response, fast charging, and full-time charging. Specifically, fast response is for establishing the individual injection scheme, fast charging is for extraction of the rare RI after 2000 orbits (0.7 ms), and full-time charging is needed to efficiently accept rare RIs produced unpredictably.

The rare RI travels along the 161 m transport line from F3 in BigRIPS to the kicker position, with a travel time of 950 ns. The trigger signal generated at F3 by the rare RI itself is transmitted through an air-insulation coaxial tube to the kicker power supply, and takes about 430 ns. Output current of the kicker power supply is transmitted through four-parallel 50-Ω coaxial cables to the kicker magnet, and takes about 30 ns. The rise time of the trapezoidal shape of the magnetic field is 100 ns, the flattop duration is 200 ns, and the fall time is 100 ns. Response time of the kicker power supply is thus required to be shorter than 290 ns to kick the rare RI at the center of the flat top. A thyratron (e2V-CX1171) used as a switching device in the power supply has a typical rise time of 170 ns. We developed a four-way parallel amplifier circuit using MOS-FETs and fast pulse trances to drive the thyratron grid. The signal propagation time in this circuit was 105 ns, and the total power supply response time was 275 ns. Figure 4 (b) shows a response feature of our kicker system. Output current of the power supply rises at 250 ns from the trigger input. The center of the flat-top of the magnetic field is smaller than 500 ns, as shown by the expected wave form of the magnetic field. The individual injection scheme has thus been established by this success.

Since typical recovery time of the thyratron is 0.5 ms, the time required for re-charging the pulse forming network (PFN) in the power supply must be shorter than 0.2 ms. Furthermore, variation in charging voltage has to be controlled within 1% accuracy, although some charges remain in the PFN circuit after the discharge for injection. We therefore adopted a hybrid charging system. As shown in Fig 4(c), a main charger using a double forward converter composed of insulated-gate bipolar transistors (IGBT) charges PFN up to 90% of full charge. Subsequently, a sub-charger using a 500 kHz resonance circuit and pulse transformers feeds the remaining 10%. Since the sub-charger works to keep the charging voltage at a required level with an accuracy of ±1%, the kicker is always ready for the next discharge. This charging process is completed within 0.2 ms, and an accurate magnetic field is ensured for both injection and extraction.

Figure 5: Photograph of R3.

## SUMMARY

Construction of R3 started in 2012, aiming at precise mass measurement for rare RIs by the IMS method. This is a mass-measurement-dedicated storage ring, and its unique aspect is a cyclotron-based lattice structure. This lattice structure enables us to drastically extend momentum acceptance and to improve accuracy in mass determination with the IMS method. One major technical challenge is forming a precise isochronous magnetic field using 10 trim coils equipped on half the R3 bending magnets. We succeeded in development of a fast response kicker system, and the individual injection scheme is well established. Major R3 components have already been fabricated, and the ring components are precisely arranged (Fig. 5). The power supply control system and beam monitoring system are still under construction. We are now setting up and testing each device individually, and continue our preparations toward commissioning, which is planned for 2014.

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