Rare–RI Ring project at RIKEN RI Beam Factory

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Abstract

A new apparatus named "Rare–RI Ring", for precisely measuring the masses of short–lived rare nuclei including the r–process region is proposed. The Rare–RI Ring is one of the major experimental installations at the RIKEN RI Beam Factory. It consists of three main parts: a long injection beam line, a fast kicker system and a cyclotron–like storage ring. The combination of a long injection beam line and a fast kicker system enables us to inject short–lived rare nuclei into the ring one by one. The revolution time of each nucleus in the ring is measured with an accuracy of better than 10^{-6}. Overall, the masses of short–lived rare nuclei including the r–process region can be determined with an order of 10^{-6} precision.

Key words: Precision mass measurement; Cyclotron–like storage ring; Individual injection
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1. Introduction

The r–process nuculeosynthesis, which probably has some relation with supernova explosions, is one of the astronomical mysteries. Although it is thought that uranium and some elements heavier than iron are generated through r–process nuculeosynthesis, the r–process path has not yet been solved. The field of nuclear physics can contribute by measuring the mass and half–life of nucleus relevant to the r–process. Particularly the mass has played an important role in neutron captures and the β–decays that effect the r–process path. Thus, systematic mass measurements for neutron–rich unstable nuclei that locate far from the β–stability (*i.e.*, short–lived and rare nuclei) are indispensable. Since it is difficult to increase the statistics for these short–lived rare nuclei including the r–process region, a device that specializes in mass measurements is required.

We propose a new apparatus, named "Rare–RI Ring", which allows us to determine the mass with an order of 10^{-6} precision even for only one particle by measuring the revolution time of the particle in isochronous optics. In addition, since its measuring time would be less than 1 ms, this new apparatus is suitable for mass measurements of short–lived rare nuclei including the r–process region. It will be located at the RIKEN RI Beam Factory (RIBF) as one of the major experimental installations [1]. Short–lived rare nuclei including the r–process region will be generated with a production rate of about one particle per day by uranium in–flight fission with an intensity of 1 pμA at the RIBF.

From the historical point of view, the mass measurement in isochronous optics was originally designed for TOFI [2,3] at LAMPF. An isochronous optics was then applied to the storage ring ESR [4] at GSI to measure masses of short–lived nuclei (IMS: Isochronous Mass Spectrometry) [5–8]. The IMS is planned to be upgraded at the future FAIR project [9]. Both the ring systems at the RIBF and the FAIR will thus complementary work for precision mass measurements. Here, we report on the principle and the present status of our project.

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2. Principle

At first, an isochronous magnetic field inside our ring is adjusted to a reference m_0/q particle of well–known mass. In a first–order γ–factor correction, the isochronous magnetic field is formed by the edge–angle of each sector magnet. It is designed for a fixed energy of 200 MeV/nucleon (γ_t=1.214). More precise isochronous magnetic field is formed by using trim coils of each sector magnet. Reference particles for a wide range of momentum ($\delta P/P \sim \pm 1\%$) are injected onto their equilibrium orbits of the ring by dispersion matching. And the isochronous magnetic field is produced by measuring the phase difference in each orbit with high–resolution time–of–flight (TOF) counters.

Next, the revolution time (T_1) of an unknown mass m_1/q particle that has a slightly different mass–to–charge ratio (*i.e.*, m_1/q=m_0/q+ $\Delta(m_0/q)$) is measured in such a cyclotron–like storage ring. For an unknown mass particle, the isochronism is no longer fulfilled. In this case, m_1/q can be expressed as

$$\frac{m_1}{q} = \frac{m_0}{q}\frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \frac{m_0}{q}\frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-(\frac{T_1}{T_0}\beta_1)^2}}, \tag{1}$$

where $\gamma_{0,1}$ is a relativistic factor defined as $\gamma_{0,1} = 1/\sqrt{(1-\beta_{0,1}^2)}$ and $\beta_{0,1} = v_{0,1}/c$. The relative differential value of m_1/q is expressed as

$$\frac{\delta(m_1/q)}{m_1/q} = \frac{\delta(m_0/q)}{m_0/q} + \frac{\delta(T_1/T_0)}{T_1/T_0} + k\frac{\delta\beta_1}{\beta_1}, \tag{2}$$

where

$$\frac{\delta(m_0/q)}{m_0/q} = \frac{\delta B_0}{B_0} + \frac{\delta T_0}{T_0}, \tag{3}$$

$$k = -\frac{\beta_1^2}{1-\beta_1^2} + (\frac{T_1}{T_0})^2\frac{\beta_1^2}{1-(T_1/T_0)^2\beta_1^2}. \tag{4}$$

The coefficient k is on the order of 10^{-2} for $\Delta(m_0/q) \sim$ 1%. To evaluate the mass of a non–isochronous particle, a correction for the velocity β_1 is required.

The mass of a non–isochronous particle within a m/q difference of 1% can be determined with an order of 10^{-6} precision by measuring $T_{0,1}$ with an accuracy of better than 10^{-6} and β_1 with an accuracy of better than 10^{-4} independently, under the condition that the isochronous magnetic field (B_0) inside the ring is tuned with a precision of better than 10^{-6}.

3. Conceptual design

Our new apparatus for such a direct mass measurement consists of three main parts: a long injection beam line, a fast kicker system and a cyclotron–like storage ring.

A long injection beam line is necessary to measure β with the required accuracy, which will be connected with BigRIPS [10]. A start counter for the β measurements will be located at the F3 achromatic focus of BigRIPS, and a stop counter will be located upstream of the entrance of the ring. A thin plastic scintillator [11] or a microchannel plate [6,12], which has a timing resolution better than 100 ps, will be used for start and stop counters. The distance is about 180 m from the start counter, which gives more than 1 μs flight time for nuclei of 200 MeV/nucleon. Therefore, the long injection beam line allows us to measure β with an accuracy of better than 10^{-4}. The arrangement of the beam line elements has not yet been decided. The beam optics calculation is performed with GIOS and COSY INFINITY.

Concerning our injection method, it is based on an individual injection method [13]. The combination of a long injection beam line and a fast kicker system enables us to inject particles into the ring one by one. A certain particle will be selected using BigRIPS, and then a trigger signal will be generated with some counters at the F3 focus of BigRIPS. The trigger signal must be transmitted to the kicker system faster than the particle itself. Under the present conditions, it takes about 1350 ns flight time at a distance of about 230 m (from the trigger point at the F3 focus to the kicker magnets) in the case of 200 MeV/nucleon. On the other hand, the transmission time of the trigger signal is about 1300 ns from the signal start to the completion of injection preparation. Thus, the above conditions satisfy individual injection.

The ring, which is about 56 m in circumference, is a unique device having the features of both a cyclotron and a storage ring. To tune the isochronous magnetic field, the sector magnet of the ring will have trim coils. The selected particle of 200 MeV/nucleon will be brought onto the equilibrium orbit of the ring using the combination of a septum magnet and the kicker system. After it revolves about 3000 times on the equilibrium orbit, it will be ejected from the ring using a combination of the same kicker system and another septum magnet. The revolution time of the particle will be measured with an accuracy of better than 10^{-6} using thin plastic scintillators. The ejected particle will be identified using some counters ($B\rho$–TOF–ΔE–E method).

The floor arrangement of our apparatus under design is shown in Fig. 1. All dipole magnets and some quadrupole magnets for the long injection beam line are recycled TARNII [14].

4. Experimental devices

Rough specifications of the cyclotron–like storage ring, the kicker system and septum magnets were decided using the transfer matrix method in a hard–edge approximation without any imperfections (misalignment, field error, etc). In the following estimations, the beam Bρ is assumed to be 6.43 Tm, which corresponds to A/Z=3 in 200 MeV/nucleon.

The ring specifications are summarized in Table 1. The ring consists of six sector magnets and straight sections.

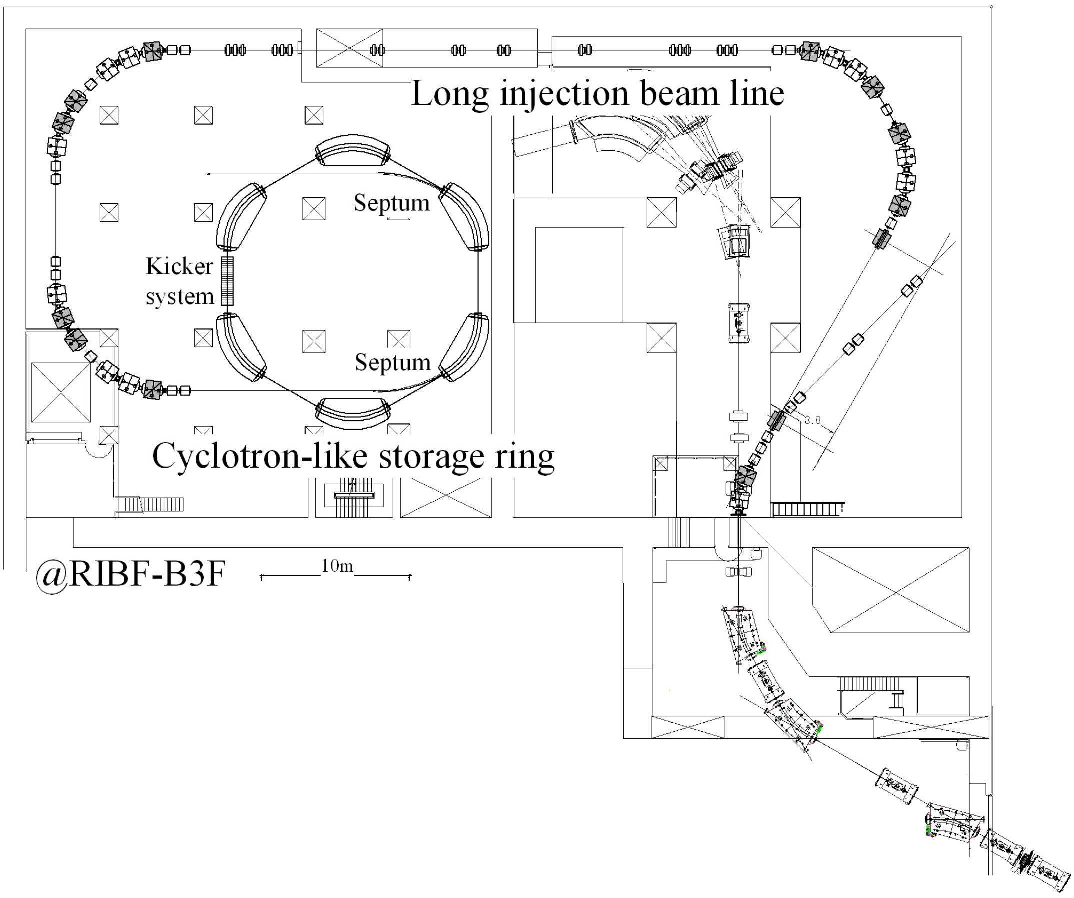

Fig. 1. Floor arrangement of our apparatus, presently under design.

Under the present conditions, we calculated the tune values and TWISS parameters using the MAD program. The horizontal and vertical tune values are 1.26 and 0.78, respectively. The phase advance between the septum magnets and the kicker system is about $3\pi/2$ (see Fig. 1). The isochronous magnetic field inside the ring must be tuned with a precision of better than 10^{-6} for the radial region corresponding to a large momentum acceptance ($\delta P/P \sim \pm 1\%$). To evaluate the magnetic field, we have developed a simulation code with a 4th–order Runge–Kutta algorithm. In a first–order γ–factor correction, we considered the edge–angle effects for each sector magnet. When the edge–angle was set about 0.155 radian, the isochronous magnetic field was formed with an accuracy of better than 3.5×10^{-5} in the simulation. Trim coils are used for further tuning with an accuracy of better than 10^{-6}.

Table 1
Specifications of the ring

—RING—	Sector number	6
	Circumference	56.13 m
—SECTOR MAGNET—	Bending angle	1.047 rad
	Edge angle	0.155 rad
	Magnetic pole length	4.5 m
	Radius of curvature	4.297 m
	Magnetic strength	∼1.5 T

The kicker system specifications are summarized in Table 2. A traveling–wave type would be used for this kicker system. In relation to the transmission time of the trigger signal, the response time of the power supply for the kicker system is a crucial issue, since the response time of the power supply is half of the transmission time of the trigger signal. A technical improvement is needed that decreases the response time of the power supply as much as possible. The kicker system must generate a high magnetic field strength with rapid rise and fall times, and a uniform flattop for efficient injection and ejection must be made. Since an injected particle passes the kicker system 330 ns after injection, the magnetic field strength should be completely adjusted to 0 T within that time. Furthermore, the injected particle should be ejected from the ring using the same kicker system about 1 ms (330 ns/turn × 3000 turns) later. We plan a feasibility study using a prototype kicker system.

The septum magnet specifications are given in Table 3.

Table 2
Specifications of the kicker system

Kick angle	$\sim$ 29 mrad
Total core length	2.4 m
Aperture	height; 0.05 m, width; 0.23 m
Rise time	140 ns
Magnetic strength	0.078 T
Characteristic impedance	12.5 Ω
Current	3090 A
PFN voltage	77 kV
Total number of unit kicker	12
Kick angle per unit kicker	2.417 mrad
Cell number per unit kicker	8
Inductance per unit cell	145 μH
Capacitance per unit cell	925 pF

The septum magnet will be operated as a DC magnet. The magnetomotive force is about 30000 AT.

Table 3
Specifications of the septum magnet

Bending angle	30 deg.
Radius of curvature	8.573 m
Magnetic strength	0.75 T

5. Outlook

The masses of short–lived rare nuclei including the r–process region will be measured with an order of 10^{-6} precision using our new apparatus. It consists of three main parts: a long injection beam line, a fast kicker system and a cyclotron–like storage ring. The long injection beam line and the fast kicker system are necessary to inject particles into the ring one by one. The beam optics calculation for the long injection beam line is performed with GIOS and COSY INFINITY. We have decided on rough specifications for the cyclotron–like storage ring, the kicker system and septum magnets using the transfer matrix method in a hard–edge approximation without any imperfections. Particularly the cyclotron–like storage ring is a key device for our project. Therefore, we have developed a simulation code with a 4th–order Runge–Kutta algorithm. To calculate the beam motion in the whole apparatus, including BigRIPS, we will be used the MOCADI program with our simulation code.

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