STORI'24: Present and future of the Rare-RI Ring Facility at RIBF*

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Abstract: The storage ring facility called Rare-RI Ring (R3) at the RI Beam Factory (RIBF), RIKEN is overviewed herein. The primary objective is obtaining precision atomic masses to understand astrophysical nucleosynthesis. R3 is located downstream of the fragment separator BigRIPS in the OEDO-SHARAQ branch. Randomly produced radioactive ions are individually identified using auxiliary detectors at BigRIPS. Only a single ion of interest is injected into R3 using the dedicated fast kicker system and ejected after thousands of revolutions in an event-by-event scheme. Revolution times under the isochronous ion-optical condition provide the mass-to-charge ratios of stored ions. A series of commissioning, physics programs, and technical upgrades are summarized. In addition to mass measurements of exotic nuclei, future perspectives of new experimental opportunities are addressed.

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I. INTRODUCTION

Storage rings have historically been built to accumulate ions of interest and increase their phase space densities for various high-energy physics experiments. Today, they have also been proven to be useful as experimental devices for radioactive ion beams [1]. The revolution frequencies of stored ions in a well-cooled or isochronous condition are proportional to their mass-to-charge ratios, enabling direct mass measurements of exotic nuclei [2, 3, 4]. The fast technique can address even very short-lived species down to microseconds [5]. Owing to the characteristics of high energy beams, fully stripped or few-electron ions are available for an extended period where novel in-flight β- and γ-decay modes have been achieved, that cannot be observed at standard decay spectroscopies in the laboratory [6, 7, 8]. With a very thin gas target and beam recycling, low-energy astrophysical reaction studies have been performed at inverse kinemtaics [9, 10], which are still a challenge at normal kinematics with conventional setups. These unique features have extended traditional nuclear physics experiments and provided new knowledge of nuclear properties and dynamics. The strong points of storage rings for radioactive beams are addressed:

- Mass resolving power,
- Highly charged, or selected charge-state ions,
- Cooling techniques: electron, stochastic, and laser,
- Revolution for multiple use of (rare) ions,
- Long-time storage under ultra high vacuum (UHV),
- Accumulation to increase stored ion number,
- Many or single stored ions, bunched or coasting beams,
- Deceleration; fine beam control with RF,
- Higher-order tunable ion optics: standard and isochronous modes,
- Internal targets: gases and electrons,
- Dedicated detector setups: non-destructive Schottky pickup, thin foil time-of-flight detector, UHV-compatible silicon detector telescope, etc.

Currently, the operational storage rings for radioactive beams are the pioneering Experimental Storage Ring (ESR) at GSI/FAIR in Darmstadt [13], the Cooler Storage Ring for Experiment (CSRe) at IMP in Lanzhou [14],

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and the Rare-RI Ring (R3) at RIBF, RIKEN [15, 16]. Note that ESR and CSRe are built at the synchrotron facilities but R3 at the cyclotron facility. Table 1 shows a comparison of three storage rings in the isochronous mode which is employed to the mass measurements of short-lived nuclei, called Isochronous Mass Spectrometry (IMS). In constrast, cooling techniques are applied to the mass measurements of long-lived nuclei at ESR, called Schottky Mass Spectrometry (SMS) [17].

Recently, the low-energy storage ring CRYRING (Swedish in-kind contribution to FAIR) has been commissioned at GSI/FAIR and is in operation as ESR@CRYRING for atomic and nuclear physics experiments [18]. CRYRING is also designed to store decelerated RI beams prepared at the fragment separator FRS [19]–the ESR facility [20]. A dedicated reaction telescope setup has been installed [21].

II. CONCEPT AND UNIQUENESS OF R3

The Rare-RI Ring, as shown in Fig. 1, is directly connected to the fragment separator BigRIPS [22] in the OEDO-SHARAQ spectrometer branch [23]. The primary objective of R3 is the isochronous mass spectrometry (IMS) of exotic nuclei to contribute to the understanding of astrophysical nucleosynthesis. A relative mass value precision is required to be higher than 10^{-6}. Owing to the highest RI beam intensities at RIBF, extremely neutron-rich nuclei along the *r*-process pathway are the target species to be measured. They are short-lived and their production rates are very small, which means that cooling, long-time storage, and accumulation are no longer available. Therefore, the R3 concept involves selecting a single exotic ion among a large amount of fission fragments and injecting and storing it in the ring through the fragment separator. Three unique points are addressed below. See also Table 1.

• Individual injection:

For injecting an ion each time to be achieved, a fast kicker system has been invented and routinely been operated. Usually a kicker response time ranges in microseconds at the synchrotron facilities, whereas that at R3 is faster by an order of magnitude. The kicker repetition rate can be changed up to 100 Hz at a maximum. This individual injection scheme has the additional advantage that the event-by-event based information from auxiliary detectors at the fragment separator is available. This is in contrast to the synchrotron-based facilities in which a beam is fast-extracted and is stored as a bunch.

• Lattice design:

As shown in Figure 1, R3 has the cyclotron-like lattice structure to have a wide momentum acceptance. The twenty-four dipole magnets are recycled from the cooler synchrotron TARN-II facility [24] and are arranged such that R3 has the six-fold symmetry with a sector forming four dipoles. No focusing magnet but edge focusing is implemented in R3. For the isochronous condition to be tuned precisely, ten trim coils are embedded in the two dipoles outside in each sector; thus a total of ten adjustable parameters exist [16]. An isochronicity of $\delta T/T = 2.8\times10^{-6}$ (σ) has been currently achieved, where T denotes revolution time [11]. In contrast, ESR and CSRe have the higher-order correction magnets for isochronous tuning such as sextupole and octupole magnets.

• Velocity and magnetic rigidity corrections:

Under the isochronous condition, revolution times of stored ions are proportional to their mass-to-charge ratios. However, this is true only for a reference ion with a particular m_0/Q. An ion of interest generally has a slightly different m/Q and does not exactly satisfy the isochronous condition. Therefore, velocity or magnetic rigidity $B\rho$ measurements are required to correct for the revolution

Table 1. Comparison of three storage rings in the isochronous mode.

	R3	ESR	CSRe
Circumference (m)	60.4	108.4	128.8
Max. rigidity (Tm)	6.5	10	8.4
Transition energy γ_t	1.2	1.4	1.4
Momentum acceptance (%)	±0.5	±0.3	±0.33
Injected beam form	Individual	Bunched	Bunched
Particle identification	Separator/Revolution	Revolution	Revolution
Mass measurement mode	IMS	IMS(+SMS)	IMS
Mass correction method	Velocity/$B\rho$	$B\rho$ tagging	Double TOF
IMS mass resolution (ppm)	~ 2.8 (σ)[11]	~ 1.1 (FWHM)[8]	~ 0.5 (σ)[4]
Lattice design	Weak focus	Strong focus	Strong focus
Cooling	–	Stochastic/Electron	Electron

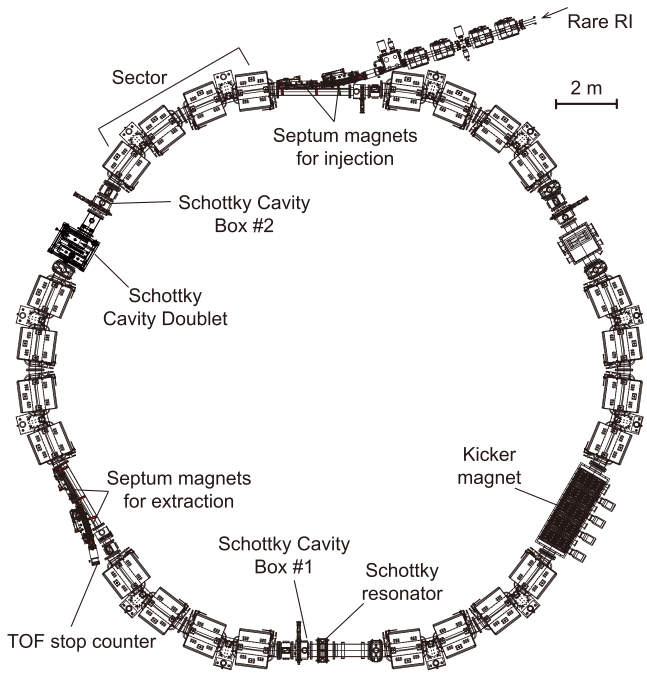

Fig. 1. Overview of the Rare-RI Ring.

times of ions of interest. Such corrections are straightforward at R3, because the event-by-event based scheme naturally provides information of transverse and longitudinal emittances from auxiliary detectors installed at each focal plane of the beam line. As an alternative method, the $B\rho$-tagging method was applied at ESR, where a narrow slit at the dispersive focus of the fragment separator FRS properly defined the $B\rho$ values of stored ions, despite loss of statistics [25].

Recently, CSRe has achieved the $B\rho$-defined IMS technique, which exploits two identical time-of-flight detectors set up at a straight section to precisely determine the velocities of stored ions [26]. The mass precision has been significantly improved to an order of 10^{-7} or even better, which is now comparable to that of Penning trap experiments.

III. HISTORY AND ACHIEVEMENTS OF R3

The development history of the Rare-RI Ring is summarized in Table 2. The details of technical developments can be available in a series of reports published in the RIKEN Accelerator Progress Report [27] and in STORI international conferences [28].

• Design study (~2011)

From approximately ten years before the construction phase, dedicated discussions and technical developments have begun [29–32]. One of the main discussions was the beam energy of R3, which was 200 MeV/nucleon corresponding to γ_t = 1.214. For the individual injection scheme to be achieved, the kicker excitation should be synchronized with the particle arrival at the kicker position. This is why the injection beam energy is limited and a long injection beam line is required. Several concepts of beam line configuration and ring structure have been proposed [33]. For the ring magnets, the decision was made to recycle the TARN II magnets because of cost saving [24, 34]. Consequently, the weak-focusing cyclotron-like lattice structure was adopted, as shown in Fig. 1. The old magnets were carefully checked and restarted, in which the stability and uniformity of the magnetic field were the challenges to achieving a mass precision of 10^{-6} [35, 36]. The invention of the fast kicker system for individual injection was crucial [37] where the new hybrid charging system was developed [38]. Based on the detailed simulations on the precise isochronous field and particle trajectories [39, 40], the final design of the facility was fixed in 2011 [41].

Table 2. Summary of the R3 development history. MS indicates a machine study beam time.

Year	
~2011	Design study (lattice design, kicker development)
2012–13	Construction period
2014	Offline tests with α source
2015	MS01 (^{78}Kr primary beam), MS02 (^{48}Ca fragments)
2016	MS03 (^{238}U fragments)
2017	MS04 (OEDO installed)
2018	Ni, Pd regions (1st run)
2020	MS05 (Kicker upgrade)
2021	Ni, Pd regions (2nd run)
2024	MS06 (Steering magnets installed)

• Construction (2012–2013)

The construction started in April, 2012 [42] and was completed in March, 2013 [43, 44]. The dedicated infrastructures of the platform, crane system [45], power supply system [46], and magnet control system [47] have been developed. The dipole magnets were upgraded to implement trim coils to generate the precise isochronous field [48]. The quadrupole magnets after SHARAQ to R3 were provided from the 12 GeV KEK proton synchrotron. In parallel, the developments of thin time-of-flight (TOF) detectors [49–61], Schottky detector [62–65] and other unique detectors [66–72] have begun.

• Offline tests (2014)

Before beam commissioning, we confirmed the isochronous field using an α-source ^{241}Am [73]. A set of thin TOF and plastic scintillation detectors with the α-source in between was installed at a straight section. The one-turn TOF between two detectors was measured as a function of field gradient produced by the trim coils, where the measured TOF width represents the degree of isochronism. The field gradient for the minimum width was consistent with that of the calculated isochronous field. The waveform of kicker magnetic field was optimized to suppress disturbing reflected fields due to small impedance mismatch [74]. The flat-top field for injection was obtained in 465 ns after trigger signal input. The facility status just before commissioning was reported at the ARIS [75] and STORI'14 conference [76−79].

• Commissioning, MS01 and MS02 (2015)

In 2015, we commenced two commissioning experiments [80]. First (MS01), we used a ^{78}Kr primary beam of 168 MeV/nucleon to confirm injection, circulation, and extraction using the developed kicker system [81− 84]. The first-order isochronous field of ~10 ppm was successfully achieved and confirmed by the TOF and Schottky measurements [85, 86], where the TOF was measured between the focal plane upstream of R3 (SHARAQ target point) and the R3 exit. The revolution time of ^{78}Kr was obtained from the measured TOF (total storage time) divided by the turn number. The degree of isochronism from the analysis of TOF spectra was 1.9×10^{-5}. With the Schottky detector, a single ion of ^{78}Kr was clearly observed in a time frame of 32 ms, and the frequency resolution was 1.3×10^{-6} at FWHM [87, 88]. The beam line optics was also confirmed [89, 90].

Second (MS02), we used ^{48}Ca projectile fragments. The secondary beams of ^{36}Ar and ^{35}Cl were in-flight identified and injected in the ring in the same manner as the commissioning with ^{78}Kr, where the revolution times were successfully obtained for the fragments [80]. The storage of secondary beams was also confirmed using the in-ring TOF detector [91].

• Commissioning, MS03 (2016)

In 2016, the first mass measurement on ^{238}U fission fragments was conducted [92, 93]. Five isotones of ^{79}As, ^{78}Ge, ^{77}Ge, ^{76}Zn, and ^{75}Cu were used [94], the masses of which were precisely known. The isochronous reference nucleus was ^{78}Ge of 175 MeV/nucleon, and the isochronism of 5 ppm was achieved [16, 95]. A new TOF gate system has been developed to inject neutron-rich nuclei more efficiently [96]. The secondary beam production is synchronized with the cyclotron RF timing. The injection of abundantly produced nuclei close to stability can be suppressed by adjusting the RF signal timing as veto for the trigger logic. As an alternative to the in-ring TOF detector, a monitor detector based on the δ-ray electron detection technique was developed to confirm particle storage [97, 98]. The mass determination procedure has been established with these data [99, 100, 12].

• Commissioning, MS04 (2017)

The OEDO system was installed in the injection beam line [101]. The injection beam optics was then recalculated, and the fourth commissioning beam time (MS04) was conducted in 2017 to optimize the transmission efficiency [102]. The emittance matching at the kicker position was considered to increase the transmission efficiency [103], resulting in an order of magnitude improvement of approximately 2%. The degree of isochronism was further investigated and improved to 3.7 ppm [104]. The Schottky detector was also proven to be an appropriate monitor for tuning the isochronous condition [105].

• The first mass measurement campaign (2018)

In 2018, the mass measurements at the neutron-rich Ni region [106] and the south-west region of ^{132}Sn [107, 108, 109] were performed. For the former case, two $B\rho$ settings aiming at ^{74,76}Ni were employed. The results of Ni data will be published soon. For the latter case, two settings aiming at ^{123,124}Pd were employed. The isomeric state in ^{128}Sn was clearly observed [110]. The analysis of the dataset including ^{127}Sn, ^{126}In, ^{125}Cd, ^{124}Ag, and ^{123}Pd has been completed [111, 112], where ^{124}Ag was used for the mass reference. In this campaign, the particle selection technique with the TOF gate system was upgraded to include the ΔE gate system to further purify heavy ions of interest [113].

• Commissioning, MS05 (2020)

In the fifth commissioning (MS05) in 2020, the kicker system was further upgraded to make the magnetic waveform flat-top for extraction [114]. The output timing of the kicker subunits was properly adjusted such that the flat-top region covered one revolution time corresponding to approximately 400 ns. This is essential to efficiently extract the stored ion in a coasting mode after a 0.7 ms storage.

• The second mass measurement campaign (2021)

In 2021, the second mass measurement campaign at the neutron-rich Ni region [115] and south-west region of ^{132}Sn [116] were performed with this upgrade to complement the data measured at the first campaign. However, owing to higher voltages applied to the kicker system, several capacitors in the pulse forming network were severely damaged [117]. During the COVID-19 pandemic, we repaired them to obtain a stable operation of the kicker system for a long term [118].

• Commissioning, MS06 (2024)

In the sixth commissioning (MS06) in 2024, the new kicker system operation was successfully confirmed using a ^{124}Xe primary beam with 155 MeV/nucleon [119]. In addition, new vertical steering magnets installed in the injection beam line improved the transmission efficiency by 7 times. Note that the new Schottky detector system, the transverse Schottky cavity doublet from GSI and compact box-type cavities from Saitama, is now ready for operation. See Figure 1.

IV. NEW EXPERIMENTAL OPPORTUNITIES

As of January 2025, three proposals have recently been approved by the RIBF program advisory committee, which involve technical developments and will create new opportunities of storage-ring nuclear physics experiments. The uniqueness of these proposals are addressed:

• Charge state separation using a thin foil for heavy neutron-rich nuclei:

The original concept of the experiment (NP2312-RI-RING08 [120]) was proposed from the international collaboration with GSI [121] based on the experiences of atomic charge exchange processes at the FRS–ESR facility.

Because the RI beam energies at RIBF are intermediate at approximately 250 MeV/nucleon, the charge states of heavy RI beams are widely distributed around the most probable one depending on the velocity and atomic number of the ions. The problem is that different charge states of the primary beam ^{238}U evolve after it passes through a production target. The magnetic rigidity of one of the distributed charge states of ^{238}U becomes very close to those of heavy neutron-rich nuclei to be measured, for example neutron-rich lead isotopes. Subsequently, the intense background from the primary beam falls into the BigRIPS acceptance, preventing from any experiment thus far.

The novel concept proposed here is to use a charge stripper foil that is so thin that the charge state of an ion does not reach the equilibrium after passing through the foil. In such a case, a particular charge state can resonantly be transferred to others, which probability depends on the thickness of foil material. The effect has been demonstrated through theoretical calculations with relativistic electron wave functions [122, 123]. The proposed technique will efficiently reduce the intensities of the large background from primary uranium, meaning that any species over the nuclear chart can be delivered as a secondary beam. Consequently, the present foil technique will be beneficial to many other applications as well as mass measurements at R3.

• Transverse Schottky detector for stored single ions:

The resonant cavity-type Schottky detector for heavy ions was originally developed at GSI [124]. Compared with the existing capacitive-type pickups at ESR, the resonant Schottky detector has increased the signal-to-noise ratio by an order of magnitude, enabling fast measurements within a millisecond range [125].

Thus far, the resonant Schottky detectors, often in a pill-box shape, have been used to measure the revolution frequencies of stored ions. Furthermore, position-sensitive Schottky detectors have already been developed in circular accelerators, where the dipole excitation of electromagnetic fields in the cavity could be utilized for a large number of stored electrons [126]. However, because the signal from dipole mode is too small for single radioactive ions to detect with a desired precision, a new concept has been proposed: an elliptical shape of cavity can provide a larger position-sensitive signal from the monopole mode for single ions. The elliptical cavity has a dedicated R_s/Q_0 map whose strength has a linear correlation to position, where R_s is the shunt impedance and Q_0 is the quality factor of the cavity. Therefore, the Schottky signal amplitude is proportional to the position where the ions pass through. The details of the transverse Schottky at R3 are described in Refs. [127, 128] and the references therein. The test beam time of the transverse Schottky detector has been approved (NP2412-RIRING10 [129]).

With the present technique, magnetic rigidity $B\rho$ measurements in R3 will be possible because the horizontal positions of stored ions linearly correlate to their magnetic rigidities through the dispersion function. A measurement of the revolution times and orbits of stored ions clarifies the dynamics of ion motion in the ring, improving the injection efficiency. This detector will enable direct $B\rho$ corrections for each stored ion, reducing reliance on BigRIPS data and potentially improving mass precision further, while also facilitating in-flight decay studies by tracking orbit shifts.

• In-flight isomer identification and filtering:

Isomeric states of radioactive nuclei have been studied using conventional γ-ray spectroscopy in the stopped beam setups [130]. Because storage rings have an excellent mass resolving power, the isomeric states produced in secondary beams are in-flight identified event-by-event through their mass-to-charge ratios [110]. This will create a new opportunity for isomer reaction studies. Because R3 is coupled with the BigRIPS fragment separator and SHARAQ spectrometer, the event-by-event analysis using all the detectors in the beam line can be performed for the isomeric and ground states separately. R3 can even selectively extract the ion of interest from the ring after an appropriate storage to perform further applications, which will be useful for a new isomer filter system [119, 131]. Possible examples with isomeric beams will be measurements of reaction cross sections (NP2412-RIRING09) [132], proton elastic scattering, and other direct reactions.

V. SUMMARY

The novel storage ring facility called Rare-RI Ring, R3, has been constructed at RIBF. The features of the R3 are the single-ion event-by-event scheme at the cyclotron facility, where the fast kicker system for individual injection plays a major role. The weak focusing lattice structure with only dipole magnets provides a wide range of isochronicity. Over the past ten years, a series of commissioning and physics runs have successfully been performed. The mass determination procedure has been confirmed using nuclei with known masses [12]. The mass precision of ^{123}Pd has been improved and, consequently, the solar *r*-process abundance has been updated to be more consistent with observations [112]. Several technical upgrades have been completed [119] and new developments are being undertaken. New mass and lifetime measurement campaign will begin soon.

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