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The RIKEN RI Beam Factory Project: A status report

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Abstract

In order to greatly upgrade the capability of its existing heavy-ion accelerator facility, RIKEN is constructing a new radioactive isotope (RI) beam facility, called "RI Beam Factory". This facility is of an in-flight RI beam separation scheme. Three new ring cyclotrons with *K*-values of 570 MeV, 980 MeV and 2500 MeV, respectively, boost energies of the output beams from the existing K540-MeV ring cyclotron up to 440 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions. The K2500-MeV ring cyclotron, SRC is the world's first superconducting ring cyclotron. These energetic heavy-ion beams are converted into intense RI beams via projectile fragmentation of stable isotopes or in-flight fission of uranium isotopes by a superconducting fragment separator, BigRIPS. The combination of the SRC and the BigRIPS will greatly expand our knowledge of nuclear world into presently inaccessible region on the nuclear chart. The new ring cyclotrons and the Big RIPS will be commissioned in late 2006. Construction of a part of major experimental installations planned is expected to start in 2007.
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1. Introduction and overview

The advent of a radioactive isotope (RI) beam in the last half of 1980s has opened up new fascinating disciplines of exotic nuclear physics [1] and RI implantation [2] in the nuclear science and technology. To further develop this new promising field, RIKEN has been constructing a next-generation RI beam facility called "RI Beam Factory," or simply "RIBF" since April 1997. The RIBF will be capable of providing RI beams of all elements, energies and intensities of which will reach several hundreds MeV/nucleon and will greatly exceed the current world standard.

Fig. 1 shows a schematic layout of the existing heavy-ion accelerator facility and the RIBF under construction. The existing facility commenced the regular operation for users in 1990. A K540-MeV ring cyclotron (RRC) [3] properly uses a couple of pre-accelerators: a 16-MV variable-frequency linac (RILAC) following an 8-MV fixed-frequency booster linac (CSM) [4], and a K70-MeV AVF cyclotron (AVF) recently modified as [5]. The RILAC has an injector of a variable-frequency RFQ linac (FCRFQ) [6] equipped with two 18 GHz ECR ion sources of normal conducting and superconducting (SCECR) types [7]. The AVF is equipped with two ECR ion sources of 10 GHz and 14.5 GHz (installed by the University of Tokyo), and a polarized deuteron source of an atomic-beam type (DPOL). Various experimental apparatus are installed not only for the application to nuclear physics, but also to nuclear chemistry, bio and medical science, and materials science. Among them, a projectile-fragment separator (RIPS) is well known to produce very intense light-atomic-mass (less than nearly 60) RI beams [8].

The RIBF will add new dimensions to the existing facility's capabilities: a new high-power heavy-ion booster system consisting of three ring cyclotrons with *K*-values of 570 MeV (fixed frequency, fRC), 980 MeV (Intermediate stage, IRC) and 2500 MeV (superconducting, SRC), respectively, will boost energies of the output beams from

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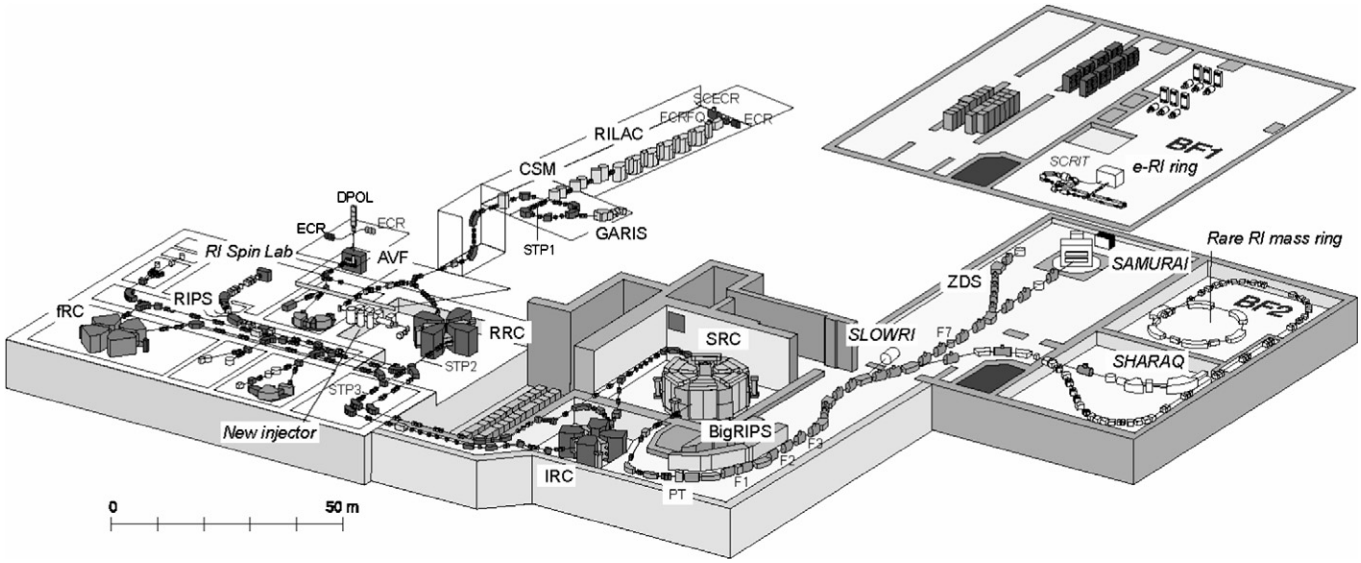

Fig. 1. Schematic bird's-eye view of the existing facility (left-hand side) and the RIBF under construction (right-hand side).

the RRC up to 440 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions. An 880 MeV polarized deuteron beam will also be available. These primary heavy-ion beams will be converted into intense RI beams via the projectile fragmentation of stable isotopes or the in-flight fission of uranium isotopes by a superconducting fragment separator, BigRIPS. The primary-beam intensity is targeted to be 1 particle micro amp. The combination of the SRC and the BigRIPS will greatly expand our knowledge of nuclear world into presently inaccessible region on the nuclear chart.

The RIBF building was completed in May 2005. The fRC and the IRC are now completed and ready for the commissioning. The magnetic field mapping of the SRC and the BigRIPS has been finished. Rf cavities, valley chambers and other components of the SRC are being installed. The assembling of beam transport lines and a zero-degree forward spectrometer (ZDS) arranged downstream of the BigRIPS is under way. The first RI beam is scheduled for late 2006. The regular operation for the users will commence in April 2007.

Major experimental installations planned to be constructed are: a large acceptance superconducting spectrometer (SAMURAI), a facility utilizing very slow RI beams (SLOWRI), a low-to-medium energy polarized RI beam facility at the RIPS (RI Spin Lab), a high-resolution RI beam spectrometer (SHARAQ) constructed by the University of Tokyo, a rare RI precision mass measurement apparatus (rare RI mass ring), and an electron-RI scattering experimental apparatus (e-RI ring). A new additional injector linac (New injector) to the RRC is also planned. A part of the construction will be undertaken in 2007.

2. Acceleration modes and performance of the RIBF

Several acceleration modes will be available. Mode (1): RILAC → (charge stripper1, STP1) [9] → RRC → (STP2) [9] → fRC → (STP3) [9] → IRC → SRC is used for the RI beam generation at 350 MeV/nucleon (fixed energy). In this mode, a part of 115 MeV/nucleon output beams from the IRC may be transferred back to the RI Spin Lab of the existing RIPS (time sharing). Mode (2): RILAC → (STP1) → RRC → (STP3) → IRC → SRC is used for variable energy experiments. Mode (3): AVF → RRC → SRC is used for providing an 880-MeV polarized deuteron beam. Fig. 2 summarizes the acceleration performance of the RIBF.

In order to achieve a 350 MeV/nucleon uranium ion beam with the intensity of 1 particle micro amp, the existing RILAC and the RRC will be upgraded. For the RILAC, a new 28 GHz superconducting ECR ion source [10] will be installed to generate a U^{35+} ion beam with the intensity higher than 16 particle micro amps (with this ECR ion source, we do not use the STP1). In order to enlarge longitudinal acceptance of the RRC, the present sinusoidal rf system will be modified into a flattop acceleration system [11].

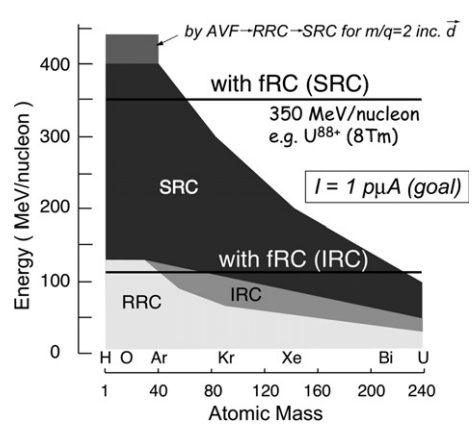

Fig. 2. Acceleration performance of the RIBF.

3. New ring cyclotrons

Specifications and basic parameters of new ring cyclotrons are briefly described below. More detailed descriptions of the fRC, the IRC and the SRC are given in [12–15], respectively.

3.1. fRC

The fRC is a four-sector room-temperature ring cyclotron, which is designed as a fixed-frequency machine unlike other cyclotrons in the RIBF, so as to minimize its construction cost. Moreover, in order to minimize magnetic field correction to form isochronous field, ion beams are accelerated with charge-to-mass ratios within a narrow band of their values.

Injection and extraction energies (11.0 and 50.7 MeV/nucleon) of the fRC are determined to compensate energy losses in the charge strippers in upstream and downstream of the fRC. The *K*-value of the fRC is 570 MeV, which corresponds to a bending power of 50.7 MeV/nucleon $^{238}U^{71+}$. Frequency of the fRC is determined at 55 MHz, which is three times of those of the RILAC and the RRC, so as to obtain high acceleration voltage in main RF cavity with small mechanical size and low rf power. Acceleration voltage per one turn is 1 MV by use of a couple of RF cavities to obtain large turn separation. Since the fRC is operated at the frequency 3 times of that of the RRC, a flattop cavity is also equipped with the fRC to make phase acceptance wider ($\pm 10°$).

The fRC is placed in the experimental room of the existing building after evacuating the magnetic spectrometer. We have successfully accelerated uranium ions up to the outermost radius corresponding to 50.7 MeV/nucleon in the fRC.

3.2. IRC

The K980-MeV IRC of a room-temperature ring cyclotron is placed upstream of the SRC. The injector of the IRC is the RRC (variable energy acceleration mode) or the fRC (350 MeV/nucleon mode). The maximum energy is 127 MeV/nucleon (e.g. $^{238}U^{88+}$). The IRC mainly consists of four-sector magnets, beam injection and extraction elements, two rf cavities and one flattop rf cavity. The average radii of the injection and the extraction are 2.77 m and 4.15 m, respectively (velocity gain of 1.5). Acceleration RF frequency is variable from 18.0 MHz to 38.2 MHz according to the energy of the accelerated ions. Maximum sector field is as high as 1.9 T, which is achieved with rather low power consumption of 0.5 MW.

3.3. SRC

The K2500-MeV SRC is the world's first superconducting ring cyclotron with the largest bending power than ever. It mainly consists of six superconducting sector magnets, four main rf cavities, one flattop rf cavity, injection and extraction elements (among them injection bending magnet, SBM is superconducting [14]). The valley regions between the neighbouring sector magnets are covered with about 1 m thick soft iron slabs in order to reduce the inverse-direction stray field, which causes the beam deflection power in the valleys. The top and bottom iron slabs bridge between the sector magnets, and the side slabs (double-leaf hinged doors open for maintenance) are placed vertically between these top and bottom slabs. The total weight of the shielding slabs is about 3000 tons; the total weight of the SRC amounts to 8300 tons. This self leakage-magnetic-flux shielding structure results in the self radiation-shield. The outer radius and height of the SRC are 9.2 m and 7.6 m, respectively. The mean injection and extraction radii are 3.56 m and 5.36 m, respectively. The SRC allows us to accelerate light heavy ions at 440 MeV/nucleon and very heavy ions at 350 MeV/nucleon.

The sector magnet is 7.2 m in length and 6 m in height. The weight is about 800 tons per each. The sector angle is 25°. The maximum sector field is 3.8 T, which is required to accelerate U^{88+} ions at 350 MeV/nucleon (8 Tm). Main components of the sector magnet are: a pair of superconducting main coils, four sets of superconducting trim coils, their cryostat, thermal insulation support links, 22 pairs of normal conducting trim coils, warm-poles and a yoke.

We have succeeded in the full excitation of both of the superconducting sector magnets and the SBM with no quench. It took three weeks to cool down the six superconducting sector magnets (140-ton cold mass) from room temperature to 4.5 K.

4. BigRIPS and ZDS

The BigRIPS is of a two-stage RI beam separation scheme. The first stage from the production target (PT) to the F2 focus comprises a two-bend achromatic spectrometer, consisting of four superconducting quadrupole triplets (STQs) and two room-temperature dipoles (RTDs). This first stage serves to produce and separate RI beams. A wedge-shaped degrader is inserted at the momentum-dispersive focus F1 to make achromatic isotopic separation based on the dispersion-matching technique. A high-power beam dump is placed inside of the gap of the first dipole to stop 80 kW primary beams. Thick concrete blocks of about 9000 tons surround the first stage to shield neutron radiation from the target and the beam dump. The second stage from the F3 focus to the F7 focus consists of eight STQs and four RTDs, comprising a four-bend achromatic spectrometer. Since our energy domain is not so high, the purity of RI beams is expected to be poor due to the nature of energy loss as well as the mixture of charge state. Several isotopes are mixed in an RI beam. To overcome this drawback, the second stage is employed so as to identify RI beam species (their atomic number, mass-to-charge ratio and momentum) in an event-by-event mode, and thereby

to make it possible to deliver tagged RI beams to experimental setups placed downstream of the BigRIPS.

The angular acceptances of the BigRIPS are designed to be 80 mrad horizontally and 100 mrad vertically, while the momentum acceptance to be 6%. The maximum bending power is 9 Tm. The total length is 77 m. The angular and momentum spreads of fission fragments at 350 MeV/nucleon uranium ions are estimated to be about 100 mrad and 10%, respectively. The acceptances of BigRIPS are comparable to those values, allowing us to achieve high collection efficiency for the in-flight fission fragments; almost half of the produced fission fragments may be accepted. These high acceptances are made possible by the use of superconducting quadrupoles with large apertures (14.1 T/m, 24 cm in the warm-bore diameter) and room-temperature dipoles with large gaps (1.6 T, 14 cm in the gap width). We have succeeded in the full excitation of all the STQ's.

The ZDS is the beam line spectrometer equipped with gamma-ray detector arrays around secondary targets, which is specified for inclusive and semi-exclusive measurements.

The expected yields of RI beams have been estimated by EPAX2 [16] with a primary beam with the intensity of 1 particle micro amp and the energy of 350 MeV/nucleon: the expected intensity of doubly magic nuclei ^{78}Ni, ^{132}Sn. and ^{100}Sn, for instance, may be 10, 10^7 and 1 particles/s, respectively, which will enable the detailed internal structure studies of these intriguing nuclei.

The detailed description of the BigRIPS and the ZDS is given in [17]

5. Major experimental installations planned

The SAMURAI spectrometer [18] is of a QQQ-D configuration, where the dipole D is a large gap (80 cm) superconducting H-type magnet with 6.7 Tm for momentum analysis of heavy projectile fragments and projectile-rapidity protons with large angular and momentum acceptance. The large gap also enables measurements of projectile-rapidity neutrons with large angular acceptance in coincidence with heavy projectile fragments (neutron detector walls are placed forward). This dipole rotates according to experimental requirements.

The SHARAQ spectrometer [19] is of a QQ-D-Q-D configuration, where the first doublet Q is superconducting. The spectrometer rotates around a target position to define scattering angles. In order to achieve momentum resolution of 15,000, dispersion-matching optics is indispensable on the beam transport line from the BigRIPS. This spectrometer is under construction and will be installed in the site in 2007.

The SLOWRI [20] aims to provide slow or trapped RIs of high purity by stopping various RI beams from the BigRIPS inside a gas-catcher system and ejecting them by means of the RF ion-guide technique. This will allow a unique opportunity to perform precision atomic spectroscopy for a wide variety of RIs, which has never been available in the existing facilities worldwide.

The e-RI ring is a novel system of electron scattering off unstable nuclei to precisely measure their charge distribution using the SCRIT (Self-Confining Radioactive Ion Target) [21]. The SCRIT is a trapped-ion cloud formed at a local straight section in an electron storage ring of a few hundreds MeV. RI Ions are three-dimensionally confined in the transverse potential well produced by the circulating electron beam itself and longitudinal mirror potential additionally applied. An intense slow RI ion source like an ISOL or the SLOWRI is needed, because RI ions are injected into the potential well from the outside. A proof-of-principal experiment is under way by means of the prototype.

The rare RI mass ring [22] is a new precision mass measurement system for energetic rare (1 particle per day in production rate) exotic nuclides. It consists of individual injection system and a precisely tuned isochronous ring. In this scheme, measurement is made of a time-of-flight of a particle in the ring and its velocity before injected into the ring (on the long transport line) by combining individual injection. The accuracy of the mass measurement can be achieved at the order of 10^{-6} for the momentum acceptance of the order of 10^{-2}. Individual injection also allows us to identify the mass-measured particles event-by-event.

The recent great success of the discovery of the new super heavy element (SHE), ^{278}113 [23] using the RILAC, the CSM and the GARIS strongly encourages us to further pursue the heavier SHE search. The new injector [24] will make it possible to concurrently conduct the SHE and the RIBF researches.

6. Summary

Commissioning of the powerful RI beam generator of the RIBF composed of the new booster ring cyclotrons and the new fragment separator is scheduled for late 2006. When the RIBF will bring its performance into full play, it will give us a fascinating opportunity to artificially produce and experimentally study almost all nuclides that have been created and now are being created in the universe. With the RIBF, we will be able to challenge to establish the unified model of nuclei and to elucidate the element genesis.

References

[1] I. Tanihata et al., Phys. Rev. Lett. 55 (1985) 2676.
[2] K. Asahi et al., Phys Lett. B 251 (1990) 488.
[3] M. Kase et al., in: Proc. of CYCLOTRON04, Tokyo, Japan, 2004, p. 160.
[4] O. Kamigaito et al., Rev. Sci. Instr. 76 (2005) 0133061-1.
[5] S. Kohara et al., Nucl. Instr. and Meth. A 526 (2004) 230.
[6] O. Kamigaito et al., Rev. Sci. Instr. 70 (1999) 4523.
[7] T. Nakagawa, Y. Yano, Nucl. Instr. and Meth. B 241 (2005) 935.
[8] T. Kubo et al., Nucl. Instr. and Meth. B 70 (1992) 309.
[9] H. Ryuyo et al., in: Proc. of PAC05, Tenessee, USA, 2005, p. 3751.
[10] T. Nakagawa et al., RIKEN Accel. Prog. Rep. 39 (2005) 233.
[11] L. Stingelin et al., RIKEN Accel. Prog. Rep. 39 (2005) 237.

[12] N. Inabe et al., in: Proc. of CYCLOTRON04, Tokyo, Japan, 2004, p. 200.
[13] J. Ohnishi et al., in: Proc. of CYCLOTRON04, Tokyo, Japan, 2004, p. 197.
[14] H. Okuno et al., in: Proc. of CYCLOTRON04, Tokyo, Japan, 2004, p. 373.
[15] N. Sakamoto et al., in: Proc. of CYCLOTRON04, Tokyo, Japan, 2004, p. 342.
[16] K. Suemmerer, B. Blank, Phys. Rev. C 61 (2000) 034607.
[17] T. Kubo et al., Nucl. Instr. and Meth. B 204 (2003) 97.
[18] Y. Sasamoto et al., CNS Annual Report 2004, 2005, p. 85.
[19] T. Uesaka et al., CNS Annual Report 2004, 2005, p. 42.
[20] M. Wada et al., Nucl. Instr. and Meth. A 532 (2004) 40.
[21] M. Wakasugi et al., Nucl. Instr. and Meth. A 532 (2004) 216.
[22] Y. Yamaguchi et al., CNS Annual Report 2004, 2005, p. 83.
[23] K. Morita et al., J. Phys. Soc. Jpn. 73 (2004) 2593.
[24] O. Kamigaito et al., RIKEN Accel. Prog. Rep. 39 (2005) 261.