1. Overview of the RIBF Project

Introduction

The advent of a radioactive isotope (RI) beam in the last half of 1980's has opened up a new fascinating discipline in the nuclear science and technology. To further develop this new promising field, the RIKEN Accelerator Research Facility (RARF) has undertaken construction of an "RI Beam Factory," or simply "RIBF" since April 1997 aiming to realize a next generation facility that is capable of providing the world's most intense RI beams at energies of several hundreds MeV/nucleon over the whole range of atomic masses.

Figure 1 shows a schematic layout of the existing facility and the RIBF under construction. At present, the RARF has the world-class heavy-ion accelerator complex consisting of a K540-MeV ring cyclotron (RRC) [1] and a couple of different types of the injectors: a variable-frequency heavy-ion linac (RILAC) [2] and a K70-MeV AVF cyclotron (AVF) [3]. Moreover, its projectile-fragment separator (RIPS) [4] provides the world's most intense light-atomic-mass (less than nearly 60) RI beams.

The RIBF will add new dimensions to the RARF's present capabilities: a new high-power heavy-ion booster system consisting of three ring cyclotrons with K=570 MeV (fixed frequency, fRC [5]), 980 MeV (intermediate stage, IRC [6]) and 2500 MeV (superconducting, SRC [7]), respectively, will boost energies of the output beams from 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. The goal of the available intensity is set to be 1 p μ A, which is limited due to presently planned radiation shielding power around a primary-beam dump. These energetic heavy-ion beams will be converted into intense RI beams via the projectile fragmentation of stable ions or the in-flight fission of uranium ions by the superconducting isotope separator, BigRIPS [8]. The combination of the SRC and the BigRIPS will expand our nuclear world on the nuclear chart into presently unreachable region.

Now (as of August, 2005) the assembling of the SRC, the IRC and the BigRIPS is under way at their respective sites in the RIBF accelerator building completed in April 2003. The assembling of the fRC has just started. The construction of the RIBF experimental building was complete in May 2005. The first beam (a 350 MeV/nucleon uranium beam with nearly ten pnA) is scheduled for late 2006. The routine operation for the users will begin in April 2007.

The RIBF project is divided into the phase I already approved and the phase II not yet approved. In the phase I, the booster ring cyclotrons, the BigRIPS and, in addition, a zerodegree forward spectrometer will be completed. Major experimental installations planned to be constructed in the phase II are under priority discussion. They are: a large acceptance superconducting spectrometer (SAMURAI), a gamma-ray detector array, a facility utilizing very slow RIBs provided via a gas-catcher and rf ion guide system (SLOWRI), a low-tomedium energy polarized RIB facility consisting of a gas catcher and a Stern-Gerlach separator at the RIPS (Polarized RI beams), a high-resolution RI-beam spectrometer (SHARAQ), a rare RI precision mass measurement apparatus consisting of an isochronous storage ring and an individual injection system (Rare RI ring), and an electron-scattering experimental apparatus consisting of a self-confining RI-ion target (SCRIT) in an electron storage ring and a uranium-photo-fission ISOL system. A new additional injector linac to the RRC to make it possible to concurrently conduct RIBF experiments and super-heavy-element experiments is also planned. It is our hope that the phase II will be approved and the construction will be undertaken in 2006.

In this chapter, the status of the RARF activities and the RIBF project will be described.

RARF

General description

As shown in Fig.1, the RARF has three kinds of accelerators: the RILAC, the RRC, and the AVF.

The RILAC, which was completed in 1981, is a heavy-ion linac having six variablefrequency resonators. The frequency range is 17 - 45 MHz. It was designed as the first injector to the RRC. It had been providing heavy-ion beams with almost the entire mass range with energies up to 2.5 MeV/nucleon. At the beginning, the pre-injector of the RILAC was a 500 kV Cockcroft-Walton high-voltage terminal equipped with a PIG heavy ion source. It was converted into the combination of a powerful ion source of 18 GHz ECR ion source [9] and a variable-frequency RFQ (FCRFQ) linac [10] in 1996. Heavy ion beams with high intensities more than 1 pµA became available. Six second-harmonic resonators were added as an energy booster after the RILAC in 2000. As a result, the maximum energy has been upgraded to 6 MeV/nucleon. These energy boosters were introduced as the acceleration part of the Charge-State Multiplier (CSM) [11], which was constructed in collaboration with the Center for Nuclear Study (CNS).

The RRC, which was completed in 1986 as the main accelerator, is a K540 ring cyclotron having four separated-sector magnets and two rf resonators. The first beam of 26 MeV/nucleon ⁴⁰Ar was successfully extracted from the RRC in December 1986 operated together with the RILAC as its injector. In the case of the RILAC-RRC mode, the operational frequencies of the two accelerators are the same, and the harmonic number of the RRC is 9, 10, 11, or 12 according to an injection energy. In 1987, the RRC began to deliver beams for

experiments and then the RARF officially started. The RRC reached to its full performance in 1989, when the AVF was completed. After the energy booster was installed in the RILAC, the operation of the RRC with the harmonic number of 8 has become available.

The AVF, which was designed as the second injector of the RRC, was completed in 1989. It is a K70 AVF cyclotron, having four spiral sectors and two rf dees with an angle of 85 degrees. The rf is tunable from 12 to 24 MHz. The AVF can accelerate ions having a mass-to-charge ratio smaller than 4, up to 3.8 MeV/nucleon (at 12 MHz) and to 14.5 MeV/nucleon (at 24 MHz). Its mean extraction radius of 71.4 cm is the four-fifth of the mean injection radius of the RRC. In the case of the AVF-RRC operation, the rf of the AVF is 1/2 sub-harmonic of that of the RRC, and the harmonic number of the RRC is five. Two types of ion sources, a 10 GHz ECR ion source and a polarized ion source are placed on the floor above the cyclotron vault. In the collaboration with the CNS, a new 14 GHz ECR ion source was installed in the injection line of the AVF and a flattop resonator [3] was added to the rf system of the AVF. Recently the K-value of the AVF was upgraded from 70 up to 78 by improving the magnet power supplies.

The beam lines of these three accelerators as of 2004 are shown in Fig.1. The RRC has six target rooms from E1 to E6. The RIPS, which aims at production of RI beams, has been in operation in E6. The magnetic spectrometer called SMART, which had been located in E4 since 1991, terminated its use in the spring of 2005. The fRC will be installed in this room. The GAs-filled Recoil Isotope Separator (GARIS), which had been initially installed in the E1 target room of the RRC, is now sitting in the target room of the RILAC. A low-energy RI-beam separator (CRIB) has been installed in the AVF beam line of E7, in collaboration collaboration with the CNS. There has been an irradiation facility for biological samples and dosimetry in E5 and an irradiation apparatus producing a large variety of RI's as multi-tracers in E3. The particle analyzer (PA) has been installed in E2 in collaboration with the CNS.

Operation

The RRC have been supplying a number of kinds of beams since 1986. They are plotted in a mass-energy plane as shown in Fig. 2. The accelerated beams cover the entire energymass range according to the initial design for both the RILAC-RRC and AVF-RRC schemes. The beams with the top energy of 135 MeV/nucleon for ions with a mass-to-charge ratio of 2 have been frequently used for the applications to biology and medicine in E5 and the RI production in E3. Especially these beams have been applied to an ion-beam breeding on plant business. The polarized deuteron beams with energies ranging 70 to 135 MeV/nucleon had been used at the SMART in E4. Because an orientation of spin at the SMART target is adjusted with a Wien filter in the injection beam line of the AVF, a single turn extraction should be realized in both the AVF and RRC, and it should be kept during the experiment. About 70% of the total beam time has been devoted into experiments using RI beams produced at the RIPS by the projectile fragmentation method. For the efficient production of the RI beams, the intense primary beams of neutron-rich isotopes are frequently required, such as 110 MeV/nucleon ¹⁸O, 100 MeV/nucleon ²²Ne, 70 MeV/nucleon ⁴⁸Ca, and 70 MeV/nucleon ⁸⁶Kr. These beams are marked in terms of emphasized-circles in Fig.2. The AVF-RRC scheme supplies enough beam intensities (>100 pnA) for ¹⁸O and ²²Ne, but poor intensities for beams heavier than ⁴⁸Ca (only several pnA).

The RRC had been designed to operate with a harmonics of 9 in the case of the RILAC-RRC scheme with the top energy of the RILAC. Using a part of energy booster of the CSM, the RRC operation with a harmonics of 8 was tried and successfully done in 2002. It gives an energy of 63 MeV/nucleon at the RRC with a frequency of 38 MHz. The beams of ⁴⁰Ar, ⁴⁸Ca, ⁵⁸Fe, and ⁸⁶Kr were accelerated in this scheme so far. In the most cases, the beam intensities are drastically increased, while their energies are somewhat lower (63 MeV/nucleon) compared with those in the AVF-RRC scheme. The beam intensities of these beams are compared in Table 1 for the AVF-RRC and RILAC-RRC operations. This increase in beam intensities is owing to that the performance of the ECR ion source and the beam transmission for the RILAC is much better than those for the AVF. As the beam intensity is sometimes more important than these energy-degrades for the RI beam production, this new scheme has recently been frequently used for RIPS experiments.

At the beginning, the RRC beams with a bottom energy were frequently used for superheavy element research at E1. Considering the acceleration efficiency, the GARIS was moved to a RILAC target room. The research experiments on a Z=113 element have been carried out at the GARIS since 2003. The high-intensity ⁷⁰Zr beam with an energy of 5 MeV/nucleon has been supplied on a rotating bismuth target of the GARIS in the e3 beam line of the RILAC more than 110 days from September 2003 to April 2005. Eventually two candidates of Z=113 element were detected so far. [12]

We measured the longitudinal emittance for various beams accelerated by the RRC using the SMART. [13] The energy spread and time spread measured for a 95-MeV/nucleon ⁴⁰Ar beam were 0.13 % (FWHM) and 700 ps (FWHM), respectively. We also estimated phase space distributions of beams of the RIBF at every stage of the acceleration scheme based on the measured emittance. We have thus confirmed that our accelerator complex will allow us to accelerate heavy-ion beams without any serious beam loss under their careful tunings.

Figure 3 shows the statistics of the RRC operation since 1987. A total of the operation hours per year had gradually but steadily increased, with reaching in 1990 to 6800 hr per year, which is considered to be a practical limit. After that, the operation time decreased slightly due to the RIBF construction work and slight reduction of the operation budget.

Schedule towards the RIBF

As the RIBF project is approaching to the commissioning, the RARF needs to start its preparations as follows. The production of uranium ions at the RILAC ion source began in June 2005, and its acceleration test will start in autumn 2005. To realize these, the ion source area was separated, in summer 2004, from the other accelerator areas into an independent room for the treatment of uranium material. In autumn 2004, we obtained the official permission by the government for the acceleration of uranium ion beam. The developments of charge-stripper for the uranium beams are in progress. [14]

The extraction beam lines of the fRC will appear in the D room, the RRC room and the E1 room as shown in Fig.1. The operation of the RRC will be interrupted due to the construction of these beam lines from April to June 2006. In autumn 2006, the RILAC and RRC will begin to provide beams into the RIBF accelerators (fRC, IRC and SRC.)

RIBF

Acceleration modes and performance

Figure 4 shows a schematic diagram of the RIBF heavy-ion accelerator system. In this diagram, a K-value and a velocity gain factor of each cyclotron are shown. Several acceleration modes will be available. Mode (1): RILAC+ RRC+ (stripper2) + fRC+ (stripper3)+ IRC+ SRC is used for the RI-beam generation at 350 MeV/nucleon (fixed energy). 115 MeV/nucleon output beams from the IRC can be transferred to the existing RIPS in the phase II. Mode (2): RILAC+ (stripper1) + RRC+ (stripper3)+ IRC+ SRC is used for variable energy experiments. Mode (3): AVF+ RRC+ SRC is used for polarized deuteron beam generation at 880 MeV in the phase II. The harmonic numbers for respective operation modes are also shown. Figure 5 summarizes the acceleration performance of the RIBF.

Expected primary beam intensities: estimation

At present, the beam transmission efficiency through the RILAC (between the exit of the mass-to-charge analyzing slit for the beam extracted from the 18 GHz ECRIS and the injection point to the RRC) and that through the RRC (between the injection point to the RRC and the extraction point from the RRC) are nearly 70% and also nearly 70%, respectively.

We conjecture that the former unsatisfactory efficiency is attributed mainly to: (1) the emittance broadening of the ECRIS beams caused by the strong space-charge effect and (2) the optical astigmatism due to the nonlinear aberration in the analyzer magnet section, and

that the latter one is attributed mainly to: (3) the insufficient longitudinal focusing power of the present rebuncher system between the RILAC and the RRC.

Nevertheless, assuming that the 100 % transmission efficiency can be realized for all of the fRC, the IRC and the SRC, 1 pµA beam will be achieved, for example, for ⁴⁸Ca, ⁸⁶Kr, ¹³⁶Xe beams at 350 MeV/nucleon, as shown in Table 2. And also nearly 10 pnA is expected for ²³⁸U beam at 350 MeV/nucleon without use of the first charge stripper (between the RILAC and the RRC) when 8 eµA of U³⁵⁺ beam estimated may be obtained from the present 18 GHz ECRIS [9].

In the near future, we plan to remedy the respective problems (1)-(3) listed above to improve the present unsatisfactory transmission efficiencies by taking the following measures: (1) We will raise the extraction voltage a few times higher to reduce the emittance growth and implement the neutralizing solenoid just after the exit of the ECRIS to reduce the space charge force; (2) We will modify the analyzing dipole magnet to have an appropriate sextupole field to compensate the non-linear optics; and (3) We will install a new double-rebuncher system between the RILAC and the RRC to produce an enough focusing power in the longitudinal direction and will modify the present sinusoidal rf system of the RRC into a flat-top acceleration system.

In order to realize the 1 p μ A uranium beam at 350 MeV/nucleon, in addition to these remedies, we will have to develop a new 28 GHz superconducting ECRIS [10].

fRC

Figure 6 shows a layout of the 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 fields, ion beams are accelerated with charge-to-mass ratios within a narrow band of their values.

The mean injection and extraction radii are 1.55 m and 3.30 m, respectively. Injection and extraction energies (10.5 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. [15] The K-value of the fRC is 570 MeV, which corresponds to the bending power of 50.7 MeV/nucleon $^{238}U^{71+}$. The frequency of the fRC is determined at 55 MHz, which is three times those of the RILAC and the RRC, so as to obtain high acceleration voltage in the main rf resonator with small mechanical size and low rf power. Acceleration voltage per one turn is expected to be 1 MV by use of two rf resonators to obtain large turn separation. Since the fRC is operated at the frequency three times that of the RRC, the fRC is also equipped with a flattop resonator to make the phase acceptance large ($\pm 10^{\circ}$).

The fRC will be placed in the E4 experimental room of the present building after evacuating the existing magnetic spectrometer. The beam is sent to the IRC after extracted through a hole in a yoke of the sector magnet.

IRC

Figure 7 shows a layout of the IRC. The IRC is a room temperature ring cyclotron with K-980 MeV, which 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. The IRC mainly consists of four sector magnets, beam injection and extraction elements, two acceleration resonators and one flattop rf resonator. The mean injection and extraction radii are 2.77 m and 4.15 m, respectively. 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.

SRC

A plan view of the SRC is shown in Fig. 8. The SRC mainly consists of six superconducting sector magnets, four main rf resonators, one flattop rf resonator, injection and extraction elements (among them the injection bending magnet (SBM) is superconducting). The valley regions are covered with magnetic shield irons in order to reduce the stray field. Some of the iron slabs of the magnetic shield are bridged on the top and bottom of the valley regions between the sector magnets, and the others are placed vertically between these top and bottom slabs. The total weight of these six falling-U-shaped structures is about 3,000 t; the total weight of the SRC amounts to 8,300 t. The K-value is 2,500 MeV. 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. A photograph of the SRC under assembling in the valut is shown in Fig. 9.

The sector magnet is 7.2 m in length and 6 m in height. The weight is about 800 t per each. The sector angle is 25 deg. 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, twenty-two pairs of normal conducting trim coils, warm-poles and a yoke.

This K2500-MeV SRC will be the world's first superconducting ring cyclotron with the ever largest K-value. In the course of design of the sector magnet, significant changes were made from the original design: (1) a pair of large active magnetic-shield coils have been

replaced with soft ion slabs that cover the valley regions, which results in the self radiation shielding and the self leakage-magnetic-flux shielding structure, and (2) the cold-pole scheme have been replaced with the warm pole scheme, which results in the shorter cooling time structure.

BigRIPS

The BigRIPS is designed to be of a two-stage RI beam separation scheme as shown in Fig. 10. The first stage from the production target 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. The in-flight fission of a uranium beam as well as the projectile fragmentation of various heavy ion beams are used to produce RI beams. A wedge-shaped degrader is inserted at the momentum-dispersive focus F1 to make achromatic isotopic separation based on the socalled dispersion matching technique. A high-power beam dump is placed inside of the gap of the first dipole to stop 100 kW primary beams. Thick concrete blocks of about 9,000 t surround the first stage to shield neutron radiation from the target and 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 difficulty, the second stage is employed to identify RI-beam species (the atomic number, the mass-to-charge ratio and the momentum) in an event-by-event mode, making 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 one 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 and room-temperature dipoles with large gaps.

The beam-line spectrometer called the zero-degree spectrometer will be constructed in the first phase. This spectrometer is specified for inclusive and semi-exclusive measurements equipped with gamma detectors around secondary targets.

Expansion of the nuclear world in the RIBF: estimation

The expected yields of RI beam have been estimated assuming the primary beam current and energy of 1 $p\mu A$ and 350 MeV/nucleon, respectively. The EPAX2 has been employed to obtain the production yields of unstable nuclei of interest, taking into account the BigRIPS angular- and momentum- acceptances.

The region on the nuclear chart where the production rate exceeding 1 particle/day, which will be enough to confirm the existence, can be obtained is indicated in Fig. 11 for the projectile fragmentation of appropriate stable nuclei and the in-flight fission of a uranium beam.

The expected intensity of doubly magic nuclei ⁷⁸Ni is found to be 10 particles/sec, which enables the detailed internal structure studies of this intriguing nucleus.

Experimental installations in the Phase II

Various experimental installations are planned as shown in Fig. 10, to exploit the potential of the RIBF facility.

The large-acceptance multi particle spectrometer (SAMURAI) is proposed to exclusively measure products with reactions as well as particle-decay, mainly for the invariant mass spectroscopy on particle-unbound states. The main part of the spectrometer system is a large-gap superconducting magnet with bending power of 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. The open geometry of SAMURAI gives us unique opportunities for studies of three-body forces and dynamical properties of isospin-asymmetry nuclear matters.

The high-resolution RI-beam spectrometer (SHARAQ) with momentum resolution of 15,000 is proposed. Based on this spectrometer, a new type of missing mass spectroscopy, where an RI beam is used as a probe, is utilized to investigate phenomena such as the double Gamow-Teller states, which have been hardly accessible with reactions induced by stable beams.

The slow RI-beam facility (SLOWRI) is proposed aiming to provide universal slow or trapped RI of high purity by combining the BigRIPS and a gas-catcher system utilizing the so-called rf ion-guide technique. This will allow a unique opportunity to perform precision atomic spectroscopy for a wide variety of RI's, not available in so far existing facilities worldwide.

The new system of electron scattering experiment for unstable nuclei using the SCRTI is proposed. The SCRIT (Self-Confining Radioactive Ion Target) is the trapped-ion cloud

formed at local position in an electron storage ring. Ions are three-dimensionally confined in the transverse potential well produced by the projectile electron beam itself and additionally applied longitudinal mirror potential. RI ions are injected into the potential well from outside. Therefore we need slow RI ion source like an ISOL. In our numerical calculation, the luminosity of e-RI collision is achievable to be more than 10²⁸ s⁻¹cm⁻², which is enough to determine the charge distribution of unstable nuclei.

The new precision mass measurement system (Rare RI ring) consisting of individual injection and a precisely tuned isochronous ring is proposed for energetic rare RI beams. In the scheme, we measure 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 RI particles event-by-event.

To return back the IRC primary beams to the RIPS at the present facility further enhances activities of spin-related subjects. The intermediate energy available at the IRC allows for a scheme to polarize spins of RI beams produced as well as stop them in a sample material of limited thickness. Thus, in addition to studies of nuclear structure through electromagnetic moments, beta-decay and beta-gamma spectroscopy, material science is promoted via several spin-related research techniques such as beta-NMR, gamma-PAD/PAC.

The recent great success of the discovery of the new super heavy element (SHE), ²⁷⁸113 using the RILAC, the CSM and the GARIS strongly encourages us to further pursue the heavier SHE search and to more extensively study nuclear physical and chemical properties of the SHEs. This compels us to provide a longer machine time for these experiments. However, this SHE research and the RIBF research are incompatible with each other, because both of these two researches use the RILAC. Thus, we propose to construct a new additional injector linac to the RRC which is planned to place in the RRC vault. The new injector will be used exclusively to produce the 350 MeV/nucleon primary beams (It is operated at the fixed frequency like the fRC.) This linac will make it possible to concurrently conduct the SHE and the RIBF researches.

Summary

The world-top-class radioactive-isotope-beam (RIB) facility, which is called "RI beam factory (RIBF)", is under construction at RIKEN. This facility is based on the so-called "in-flight RI beam separation" scheme. Commissioning of a new high-power heavy-ion booster system consisting of a cascade of three ring cyclotrons with K=570 MeV (fixed frequency,

fRC), 980 MeV (intermediate stage, IRC) and 2500 MeV (superconducting, SRC), respectively, is scheduled for late in 2006. This new ring-cyclotron cascade system boosts 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. These energetic heavy-ion beams are converted into intense RI beams via the projectile fragmentation of stable ions or in-flight fission of uranium ions by a superconducting isotope separator, BigRIPS. The combination of the SRC and the BigRIPS will expand our nuclear world into presently unreachable region. Major experimental installations are under priority discussion as the second-phase program of the RIBF project. Construction of the second phase is expected to start in 2006.

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	AVF => RRC					$RILAC \Rightarrow CSM \Rightarrow RRC$					
Ion	E _{RRC}	Stripping after AVF			I _{RRC}	E _{RRC}	Stripping after CSM			I _{RRC}	
	(h _{RRC})	$\mathbf{Q}_{\mathbf{i}}$	Q_{f}	E_{AVF}		(h _{RRC})	$\mathbf{Q}_{\mathbf{i}}$	Q_{f}	E _{CSM}		
	MeV/n			MeV/n	pnA	MeV/n			MeV/n	pnA	
⁴⁰ Ar	95 (5)	11	17	5.2	90	63 (8)	11	15	3.6	1000	
⁴⁸ Ca	70 (5)	11	18	4.0	7	63 (8)	11	17	3.6	150	
⁵⁸ Fe	90 (5)	13	24	5.0	4	63 (8)	13	21	3.6	80	
⁷⁰ Zn						63 (8)	16	25	3.6	120	
⁸⁶ Kr	70 (5)	20	31	4.0	4	63 (8)	16	30	3.6	90	

Table1. Upgrade of beam intensities with the CSM.

Table 2. Expected intensities (p μ A) of primary beams ⁴⁸Ca, ⁸⁶Kr, ¹³⁶Xe and ²³⁸U at the exits of the 18 GHz ECRIS, the RILAC, the RRC, the fRC, the IRC, the SRC when these beams are finally accelerated by the SRC to 350 MeV/nucleon. Both of the transmission efficiencies through the RILAC and through the RRC are assumed to be 70%. As for the fractions of the charge state after the charge strippers, see Ref. 16. The expected intensity of ²³⁸U beam from the 28 GHz ECRIS under the conceptual design is given in Ref. 10.

	18GHz	RILAC	RRC	Charge	fRC	Charge	IRC	SRC
	ECRIS			Stripper2		Stripper3		
⁴⁸ Ca	8+	8+	8+	19+	19+		19+	19+
(pµA)	10	7.0	4.9	2.0	2.0		2.0	2.0
⁸⁶ Kr	14+	14+	14+	33+	33+		33+	33+
	10	7.0	4.9	2.0	2.0		2.0	2.0
¹³⁶ Xe	20+	20+	20+	44+	44+	52+	52+	52+
	15	10.5	7.3	2.2	2.2	0.97	0.97	0.97
²³⁸ U	35+	35+	35+	72+	72+	88+	88+	88+
18GHz>	0.23	0.16	0.11	0.021	0.021	0.007	0.007	0.007
Super>	16	11.2	7.8	1.5	1.5	0.51	0.51	0.51



The arrows indicate major experimental installations planned in the second-phase program of the RIBF project. The experimental Figure 1. A schematic bird's-eye view of the existing facility (left-hand side) and the RIBF under construction (right-hand side). installations other than the zero-degree spectrometer have not been approved yet.



Figure 2. Performance of the RRC.



Figure 3. Statistics of the RRC operation since 1987.



Figure 4. Schematic diagram of the RIBF heavy-ion accelerator system. Acceleration mode (1): RILAC+RRC+fRC+IRC+SRC is used for the RI-beam generation at 350 MeV/nucleon (fixed energy). 115 MeV/nucleon output beams from the IRC can be transfered to the present RIPS in the Phase II. Mode (2): RILAC+RRC+IRC+SRC is used for variable energy experiments. Mode (3): AVF+RRC+SRC is used for polarized deuteron beam generation at 880 MeV in the Phase II.



Figure 5. A diagram of the RIBF acceleration performance (MeV/nucleon) for each atomic mass.



Figure 6. Layout of the fRC.



Figure 7. Layout of the IRC.



Figure 8. Layout of the SRC.



Figure 9. Photograph of the SRC under assembling in the vault. The control Dewar for the liquid He vessel can be seen on the top of the central region of the cyclotron.



Figure 10. Layout of the BigRIPS and the major experimental installations planned in the second phase



Figure 11. Great expansion of the nuclear world on the nuclear chart by the RIBF. The new region to be expanded will cover the hypothetical pathway to uranium synthesis in the supernova explosion.



The accelerator facility area of the RARF and the RIBF is indicated. (The RIBF building Aerial photograph of RIKEN Wako-city campus as of August, 2004. was completed in May, 2005.)

Close-up of the RARF building, which houses the RILAC (in the long building), the RRC, the AVF and the attached experimental installations (in the basement), and the RIBF building.

The RIBF building in foreground houses the IRC, the SRC and the BigRIPS. The building in background under construction as of August, 2004, when this photograph was taken, was completed in May, 2005 and will house experimental installations in the basement.

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