RIKEN RI BEAM FACTORY PROJECT

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Abstract

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.

OVERVIEW

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) and a couple of different types of the injectors: a variable-frequency heavy-ion linac (RILAC) and a K70-MeV AVF cyclotron (AVF). Moreover, its projectile-fragment separator (RIPS) 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), 980 MeV (Intermediate stage, IRC) and 2500 MeV (superconducting, SRC), 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 pμA, 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. The combination of the SRC and the BigRIPS will expand our nuclear world on the nuclear chart into presently unreachable region.

Now (as of May 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 fRC has been completed in the factory. The construction of the RIBF experimental building will be finished 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 and the BigRIPS as well as a zero-degree forward spectrometer will be completed. Major experimental installations planned to be constructed in the phase II (in FY 2006 - FY 2010) 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-to-medium energy polarized RIB facility consisting of a gas catcher and a Stern-Gerlach separator at the RIPS (Polarized RI beams), an high-resolution RI-beam spectrometer (SHARAQ), a rare RI precision mass measurement apparatus consisting 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 FY 2006.

The details of each planned experimental installation are described in Ref. [1].

ACCELERATION MODES AND PERFORMANCE

Figure 2 shows a schematic diagram of the RIBF heavy-ion accelerator system. In this diagram, a K-value and

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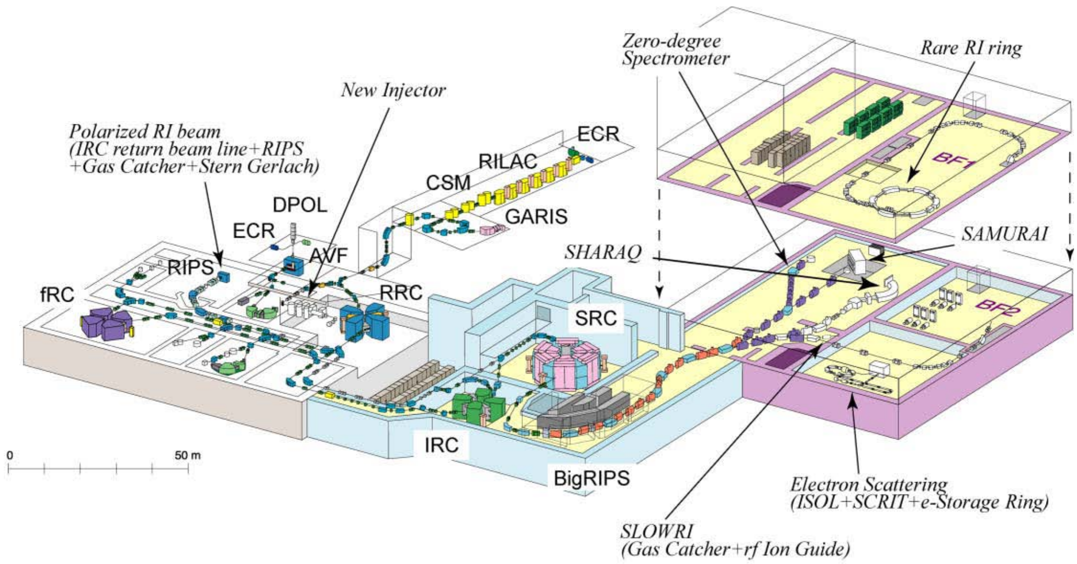

Figure 1: A schematic bird's-eye view of the existing facility (left-hand side) and the RIBF under construction (right-hand side). The arrows indicate major experimental installations planned in the second-phase program of the RIBF project. The experimental installations other than the zero-degree spectrometer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

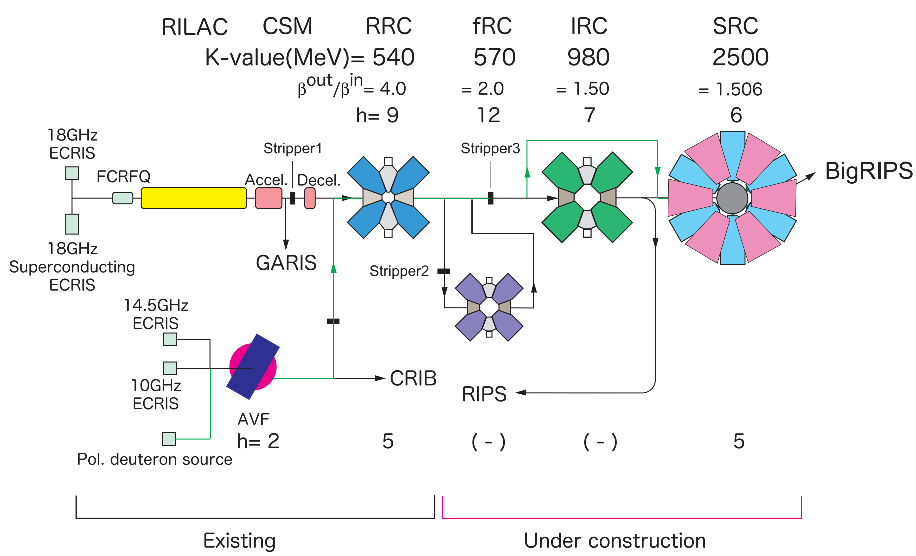

Figure 2: A schematic diagram of the RIBF heavy-ion accelerator system.

a velocity gain factor of each cyclotron are shown. The RILAC has an injector of a variable-frequency RFQ linac (FCRFQ) equipped with an 18 GHz ECRIS and an 18 GHz superconducting ECRIS and a booster linac (CSM). The AVF has a 14.5 GHz ECRIS, a 10 GHz ECRIS and a polarized deuteron source. Several acceleration modes will be available. Mode (1): RILAC+ RRC+ (stripper2) [2]+ fRC+ (stripper3)+ 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 existing RIPS in the phase II. Mode (2): RILAC+ (stripper1) [1] + 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 3 summarizes the acceleration performance of the RIBF.

NEW RING CYCLOTRONS

Specifications and basic parameters of new ring cyclotrons (fRC, IRC and SRC) under construction are briefly described below.

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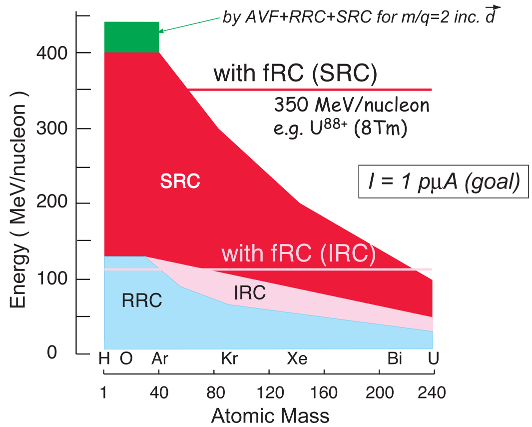

Figure 3: A diagram of the RIBF acceleration performance (MeV/nucleon) for each atomic mass.

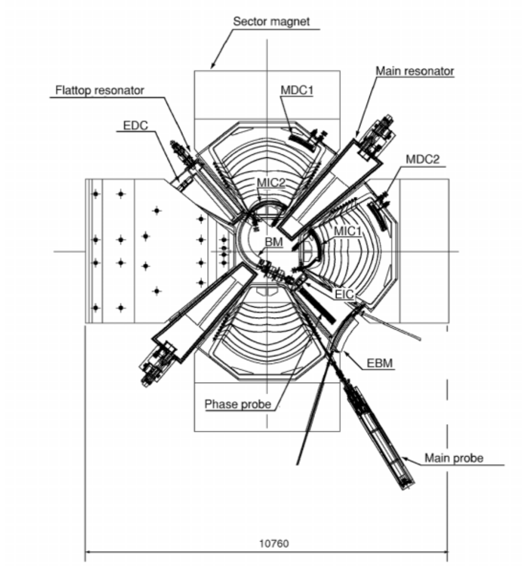

Figure 4: Layout of the fRC.

fRC

Figure 4 shows the 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 field, ion beams are accelerated with charge-to-mass ratios within a narrow band of their values.

Main specifications of the fRC are summarized in Table 1. 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. 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 3 times of the RILAC and the RRC, so as to obtain high acceleration voltage in main RF cavity with small

Table 1: Specifications of the fRC.

K Value (MeV)	570
Energy (MeV/nucleon)	
Injection	10.5
Extraction	50.7
RF Frequency (MHz)	
Main (2 sets)	55
Flattop (1 set)	165
Acceleration voltage (MV/turn)	1
Harmonics	12
Radius (m)	
Injection	1.55
Extraction	3.30
No. of sectors	4
Sector angle (degree)	58
Max. magnetic field (T)	1.68
Total weight of magnets (t)	1,320
Phase acceptance (degree)	±10

mechanical size and low rf power. Acceleration voltage per one turn is expected to be 1 MV by use of 2 RF cavities to obtain large turn separation. Since the fRC is operated at the frequency 3 times of the RRC, a flattop cavity is also equipped with the fRC to make phase acceptance large ($\pm10°$).

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

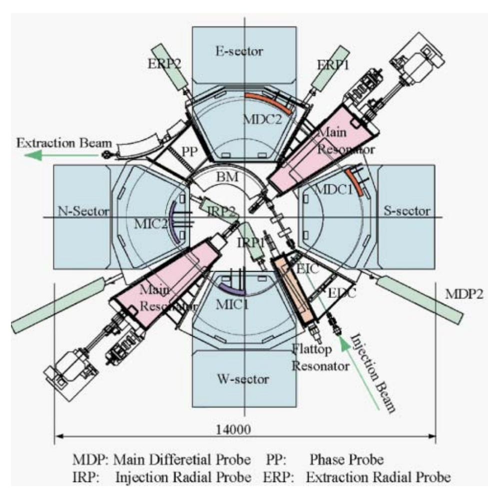

Figure 5: Layout of the IRC.

IRC

Figure 5 shows the layout of the IRC and Table 2 summarizes its specifications. The IRC is a room temperature ring cyclotron with K-980 MeV, which is placed upstream

Table 2: Specifications of the IRC.

K Value (MeV)	980
Energy (MeV/nucleon)	
Extraction (max.)	127
RF Frequency (MHz)	
Main (2 sets)	18.0-38.2
Flattop (1 set)	72.9-114.6
Acceleration voltage (MV/turn)	1.2
Harmonics	7
Radius (m)	
Injection	2.77
Extraction	4.15
No. of sectors	4
Sector angle (degree)	53
Max. magnetic field (T)	1.9
Total weight of magnets (t)	2,700

Table 3: Specifications of the SRC.

K Value (MeV)	2,500
Energy (MeV/nucleon)	
Extraction (max.)	440
RF Frequency (MHz)	
Main (4 sets)	18.0-38.2
Flattop (1 set)	72.9-114.6
Acceleration voltage (MV/turn)	2.4
Harmonics	6
Radius (m)	
Injection	3.56
(equal to the RRC extraction)	
Extraction	4.15
No. of sectors	6
Sector angle (degree)	25
Max. magnetic field (T)	3.8
Total weight (t)	8,300

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 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.

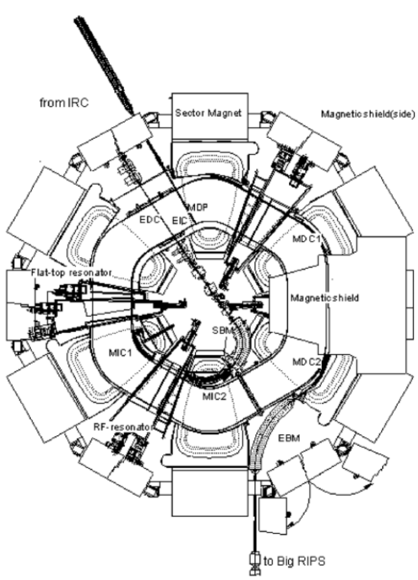

Figure 6: Plan view of the SRC.

SRC

A plan view of the SRC is shown in Fig. 6; its main parameters are given in Table 3. The SRC mainly consists of six superconducting sector magnets, four main rf (radio frequency) resonators, one flattop rf resonator, injection and extraction elements (among them 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 3000 t; the total weight of the SRC amounts to 8300 t. The K-value is 2500 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.

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

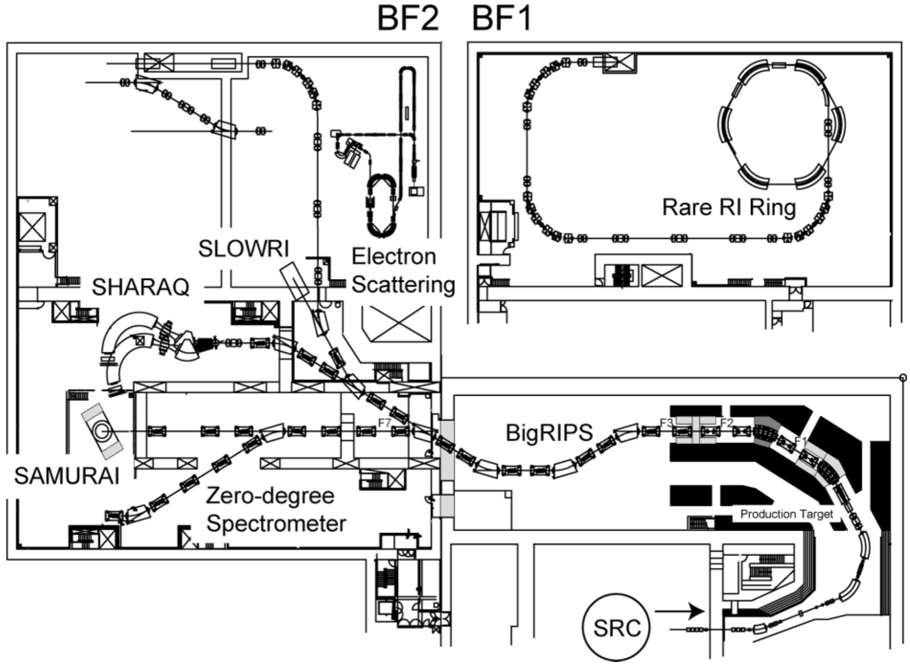

Figure 7: Layout of the BigRIPS and the major experimental installations planned in the second phase.

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. 7. 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 so-called 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 tons 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.

The expected yields of RI beam have been estimated: the expected intensity of doubly magic nuclei ^{78}Ni, for instance, is found to be 10 particles/sec, which enables the detailed internal structure studies of this intriguing nucleus.

REFERENCES

[1] Reports on RIKEN RI Beam Factory Project for RIBF International Advisory Committee 2004, to be published.

[2] H. Ryuto et al., in these proceedings.