RIKEN RI BEAM FACTORY PROJECT: PROGRESS REPORT

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Abstract

The radioisotope (RI) beam facility is under construction at RIKEN. In the first phase, a new multi-stage acceleration system consisting of three ring cyclotrons with K=510 MeV, 980 MeV and 2500 MeV in each will be commissioned in 2005. It will boost the heavy-ion beams' energies obtained by the existing K540-MeV ring cyclotron up to 350 MeV/nucleon. Intense RI beams are produced mostly via the projectile fragmentation of these energetic heavy ions or partially via in-flight fission of uranium ions. In the second phase, various experimental installations for direct use of these RI beams, an accumulator cooler ring and an electron-RI beam collider, etc. will be built step by step.

1 INTRODUCTION

The RIKEN Accelerator Research Facility (RARF) is currently constructing the radioisotope (RI) beam factory (RIBF) which aims at a next generation facility capable of providing the world's most intense RI beams over the whole range of atomic masses.

Figure 1 shows the plan view of the RIBF. At present the RARF has the heavy-ion accelerator complex consisting of a K540-MeV ring cyclotron (RRC) and two different types of the injectors: a variable-frequency Wideröe linac (RILAC) and a K70-MeV AVF cyclotron (AVF). Moreover, its projectile-fragment separator (RIPS) has been providing the world's most intense light-atomic-mass RI beams. In the new factory, a cascade of a K510-MeV fixed-frequency ring cyclotron (fRC), a K980-MeV intermediate-stage ring cyclotron (IRC) and a K2500-MeV superconducting ring cyclotron (SRC) will be a post-accelerator for the existing RRC. This new cyclotron system will be able to boost the RRC beam's output energy up to 400 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions. The goal of the beam intensity is higher than 1pμA.

As in the existing RIPS, RI beams will be generated mostly by projectile fragmentation. In addition, in-flight fission of uranium ions will be used for the efficient production of very neutron-rich isotopes in the medium mass region. A BigRIPS will be installed to generate such RI beams with larger magnetic rigidity.

The RIBF will include an electron-RI beam collider (e-RI Collider) equipped wth an accumulator cooler ring (ACR) for conducting electron scattering experiments on unstable nuclei.

2 RILAC

Figure 2 illustrates the schematic diagram of the heavy-ion accelerator complex for the RIBF. The RILAC will be the initial-stage accelerator for the RIBF accelerator complex. In order to upgrade the RILAC performance in the beam intensity, the pre-injector system consisting of a frequency-tunable folded-coaxial RFQ linac (FC-RFQ) equipped with an 18-GHz ECR ion source (ECRIS-18) has been developed. The FC-RFQ has successfully covered heavy-ion beams in the energy-mass region required, and the beam transmission efficiency of about 90 % is routinely obtained. In addition, high-intensity highly-charged ion beams have been produced by the ECRIS-18.

Recently, the charge-state multiplier (CSM) has been partially completed. It consists of two variable-frequency accelerator linacs, four fixed-frequency accelerator linacs, and one variable-frequency decelerator linac. With this CSM, very intense heavy-ion beams with 5.85 MeV/nucleon at maximum will be available in the RILAC experimental hall especially for the super-heavy element search. In addition, the acceleration performance of the RILAC-RRC system will be greatly upgraded.

3 NEW CYCLOTRON CASCADE

As shown in Fig. 2, the velocity gains in the fRC, the IRC and the SRC are 2.0, 1.5 and 1.506, respectively. Figure 3 shows the energies at each acceleration stage for the ion mass. When bypassing the fRC, the combination of the IRC and the SRC accelerates light ions reaching around Ar up to 400 MeV/nucleon, Kr^{30+} up to 300 MeV/nucleon, U^{58+} up to 150 MeV/nucleon and U^{49+} up to 100 MeV/nucleon. The beam intensity is expected to be 1 pμA for light ions, but to be less than 1 pμA for very heavy ions. With the fRC, which is a fixed rf-frequency machine to minimize the construction cost, very heavy ions from Kr to U can be accelerated up to 350 MeV/nucleon with high intensities (the goal is 1 pμA), because the low-frequency operation of the RILAC allows us to take full advantage of high-intensity, low-charge-state ions from the ion source. As shown in Fig. 2, for example, U^{10+} ions are accelerated by the RILAC, then charge-stripped U^{35+} through the RRC, U^{72+} through the fRC, and U^{88+} through the IRC and the SRC. Only 1% of U^{10+} ions from the ECRIS are accelerated to the final energy due to the charge stripping loss. In order to skip over a nasty low-energy-stage charge stripping to realize a 350-MeV/nucleon uranium beam with 1 pμA, we have to develop a powerful ECRIS that is able to produce U^{35+} beam with 15 pμA. For Xe ions, our ECRIS-18 presently produces Xe^{20+} beam with 10 pμA to realize a 350 MeV/nucleon Xe beam with 1.8 pμA without the charge stripping at the low energy as shown in Fig. 2.

The IRC is a four-sector room-temperature ring cyclotron, which is designed so as to be imitative of the RRC to facilitate its fabrication. The maximum sector field is 1.9 T corresponding to a magnetic rigidity of 4.57 Tm. The mean extraction radius is 4.15 m and the harmonic number is 7. The rf frequency is ranged from 18 to 38 MHz. The IRC has been completed in the factory and the magnetic field is being mapped.

The SRC, the plan view of which is shown in Fig. 4, is a six-sector superconducting ring cyclotron. The maximum magnetic rigidity of extracted beams is 8 Tm

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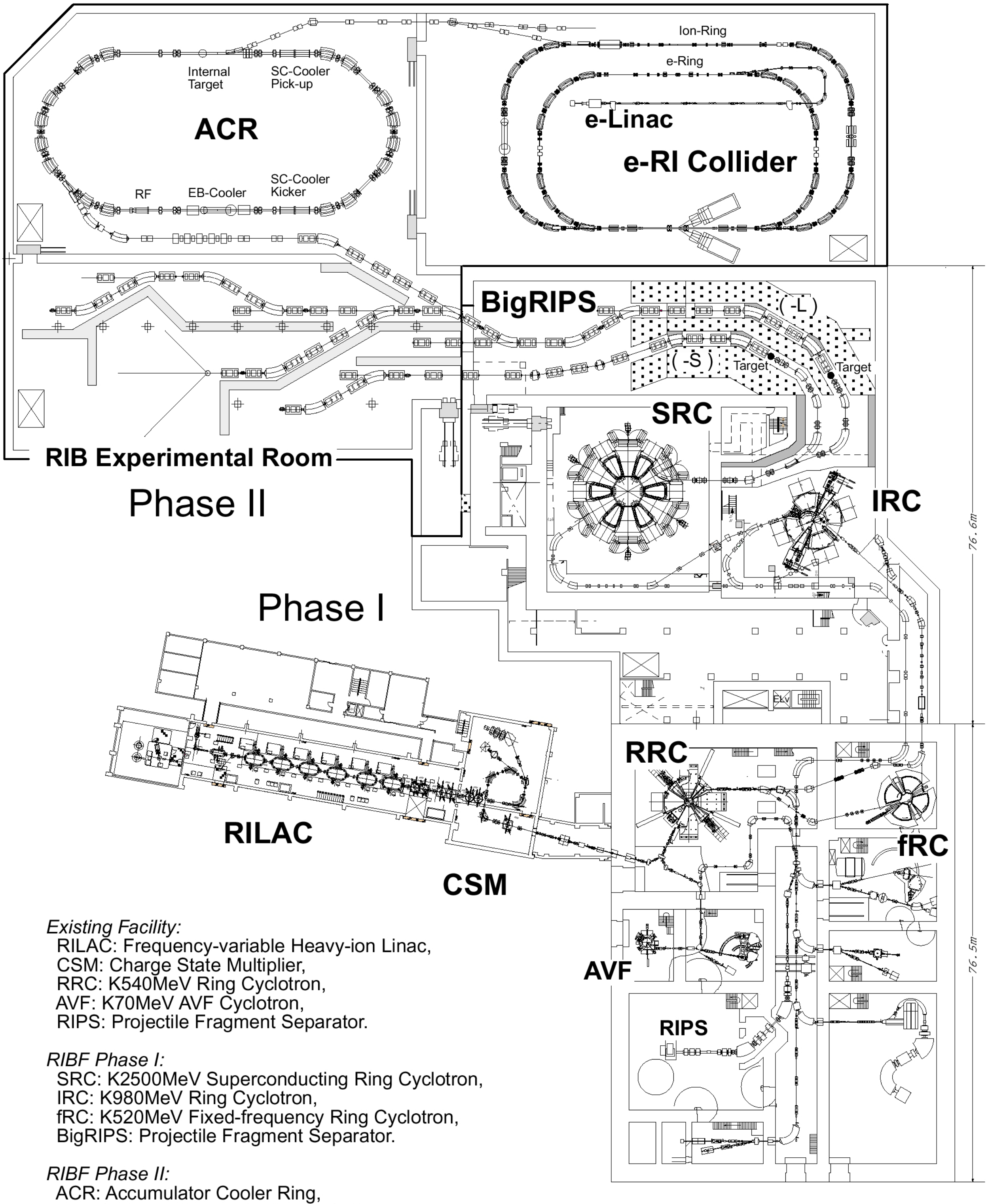

Existing Facility:
RILAC: Frequency-variable Heavy-ion Linac,
CSM: Charge State Multiplier,
RRC: K540MeV Ring Cyclotron,
AVF: K70MeV AVF Cyclotron,
RIPS: Projectile Fragment Separator.

RIBF Phase I:
SRC: K2500MeV Superconducting Ring Cyclotron,
IRC: K980MeV Ring Cyclotron,
fRC: K520MeV Fixed-frequency Ring Cyclotron,
BigRIPS: Projectile Fragment Separator.

RIBF Phase II:
ACR: Accumulator Cooler Ring,
e-RI Collider: Electron-RI Beam Collider.

Figure 1: The layout of the RI Beam Factory (RIBF). The first phase of the RIBF building is presently under construction and will be completed in 2003. The construction of the second-phase building, the layout of which is preliminarily depicted here, is planned to begin in 2002 and will be completed in 2005.

which exceeds that of 350 MeV/nucleon U^{88+} beam (7.94 Tm). The mean extraction radius is 5.36 m and the harmonic number is 6.

As shown in Fig. 4, the SRC is almost completely covered with soft-iron slabs about 0.8 m in thickness, except in the central region. A part of these iron slabs are bridged on the top and bottom of the valley regions

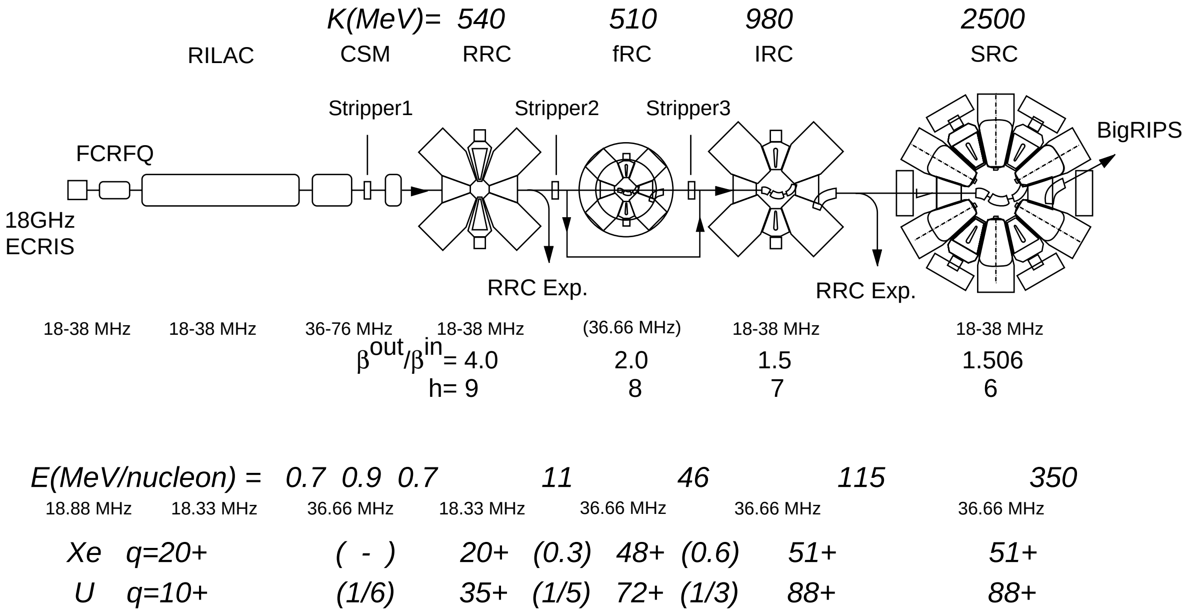

Figure 2: Schematic diagram of the RIBF accelerator complex, showing charge states and yields in each acceleration stage for obtaining a 350 MeV/nucleon Xe/U beam. The numbers in the parentheses give yield ratios for the repective charge states after each stripper..

between the sector magnets. The other part of them are placed vertically between these top and bottom slabs so as to cover the space between the back yokes of the neighboring sector magnets. The total weight of this falling-U-shaped iron-slab structure (referred to as the "iron cover") is about 4,000 tons (the total weight of the SRC amounts to 7,800 tons). The vertical outside slabs are assembled to form a double-leafed hinged door to be opened when the maintenance is carried out for the rf resonators, vacuum pumps, and so on in the valley region. This "iron cover" yields the following good results: (1) The SRC is self radiation-shielding. We need neither very thick concrete-shielding walls nor huge non-magnetic local shielding. (2) The SRC is self leakage-flux-shielding (the stray field even in the valley is as low as 0.1 T at maximum.) We need neither the active magnetic shielding which is difficult to fabricate nor the thick iron plates enclosing the huge SRC vault. The small stray field in the valley allows us to use cryopumps, motors, control devices, and so on in a safe situation. The stray field outside the SRC is about 200 gauss at the maximum near the yoke and the vertical outside shield-wall. We place the rf oscillators near the SRC as they are for the RRC and the IRC. The SRC vault is very safe for those working at the site even inside the cyclotron.

The sector field needed to bend, for example, U^{58+} 150 MeV/nucleon (7.52 Tm) is 3.7 T. According to relatively low flutter, the operating domain of the vertical betatron frequencies locate in the values between 0.5-1.0. The maximum magneto-motive force required and the maximum stored energy are about 4 MA/sector and 235 MJ, respectively. All the injection and extraction magnetic channels inside the sector magnets are normal with the moderate power consumption and their structures are very similar to those for the RRC and the IRC. The shift of the injection and extraction trajectory depending on the

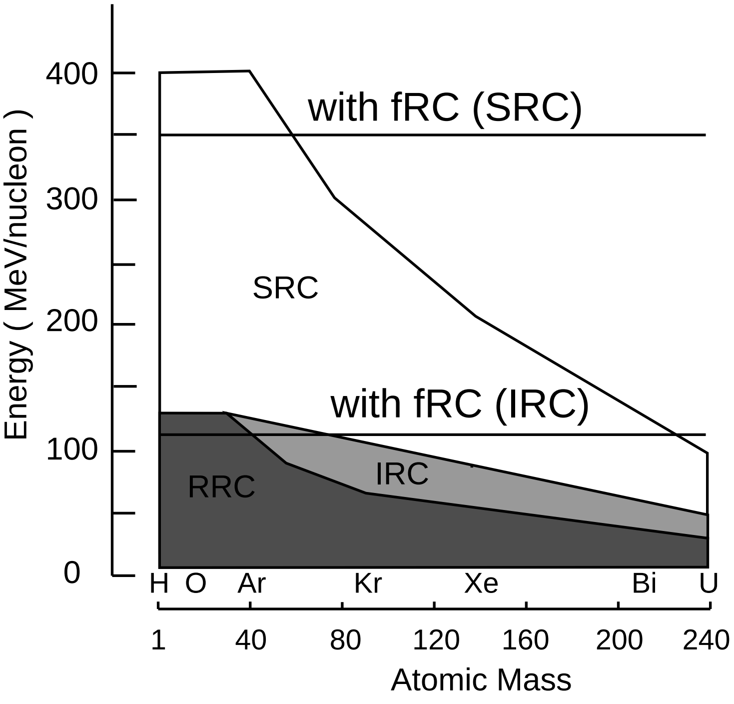

Figure 3: Energy vs. mass performance of RIBF accelerator complex.

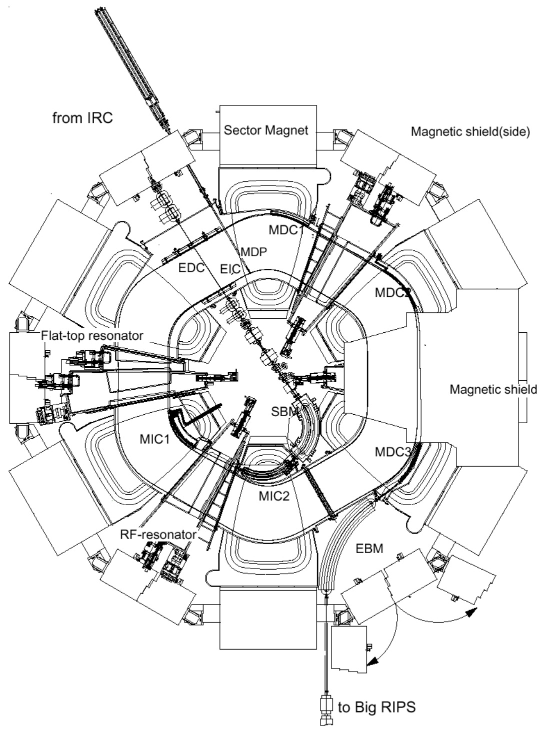

Figure 4: Plan view of the SRC.

negative stray field strength is very small (almost no shift).

The winding of the main coil is scheduled to start around September 2001. The completion of the SRC is scheduled for the spring of 2003.

The fRC is a four-sector room-temperature ring cyclotron. The maximum magnetic rigidity of extracted beams is 3.28 Tm. The mean extraction radius is 2.77 m and the harmonic number is 8. The rf frequency is fixed to be 36.7 MHz. The detailed design is being made.

4 BIG RIPS

We will install a couple of RI-beam generators as illustrated in Fig 1: the large-acceptance BigRIPS-L and the small-acceptance BigRIPS-S. Both of them are simultaneously utilized by time-sharing a primary beam.

The BigRIPS-L consists of a couple of achromatic spectrometers connected to each other in series. The first-stage spectrometer is used as a projectile fragment separator to produce RI beams, while the second one is used as a spectrometer to make particle identification of RI beams as well as to measure their momentum and angular dispersion. RI beams are tagged event by event with respect to momentum, angle and ion species. The reason why we adopt this tandem scheme is that purity of RI beams obtained by the first-stage is expected to be still poor due to the nature of energy loss in our energy domain. RI beams tagged are transported to various experimental set-ups placed downstream.

The BigRIPS-L is designed to have large acceptance, so that it can efficiently collect projectile fragments produced by in-flight fission of uranium beams. This in-flight fission has high capability of producing very neutron-rich medium-heavy RI beams, because it has large production cross-section for those isotopes. The acceptance of BigRIPS has been taken to be 80 ~ 100 mrad for angle and 6 % for momentum. Such large acceptance allows us to collect almost 50 % of fragments produced by the in-flight fission of uranium beams at 350 MeV/nucleon, when the symmetric fission fragments are selected. For producing RI beam species in other region of nuclear chart, such as proton-rich isotopes and lighter neutron-rich isotopes, projectile fragmentation of suitable heavy ions is to be used. In this case, the BigRIPS-L can collect almost 100 % of fragments produced.

The first-stage of BigRIPS-L is a mirror-symmetric system with two dipole magnets. A wedge-shaped energy degrader is placed at its intermediate focus to make isotopic separation. The second-stage is a mirror-symmetric achromatic system with four dipole magnets. The use of four dipole magnets allows us to obtain higher momentum resolution, which is required for the tagging of RI beams. The maximum bending power of BigRIPS-L is about 8 Tm, when its optics is tuned for the large acceptance mode to collect fission fragments. On the other hand, when the optics is tuned for smaller acceptance, which is nearly a half of the large acceptance, the bending power limit increases to 9.5 Tm, which corresponds to that of isotopes with A/Z=3 and E=400 MeV/nucleon. This mode is to be used for collecting relatively light neutron-rich RI beams produced by projectile fragmentation. The quadrupole magnets of BigRIPS-L are superconducting, so that the high acceptance and the large bending power such as 20 T/m with a warm bore of 24 cm in diameter can be achieved. Its prototype has been built recently and the design has been successfully confirmed by the test.

Huge normal concrete slabs of 5000 tons in total weight surrounds the production target area for safely shielding fast neutrons produced by 350 MeV/nucleon CW heavy-ion beams with 1pμA.

5 ACR

A RI beam produced is transported to the injection point of the ACR along the length of nearly 70 m. On the transport line, a debuncher system and a skew quadrupoles or solenoids system will be installed to enhance the injection efficiency of the RI beam into the ACR by improving the matching of the six-dimensional emittance of the RI beam produced to the six-dimensional acceptance of the ACR.

In Fig. 1 the plan view of the ACR is shown. The ACR has asymmetric lattice structure consisting of the achromatic arc (left) and the semi-isochronous arc (right) to efficiently cool the accumulated RI beams especially in the cooling time[1]. Its circumference is 146 m and the harmonic number is 30. In this configuration, the ACR accepts 227-MeV/nucleon RI beams which are most efficiently produced by 350-MeV/nucleon primary beams. The maximum magnetic rigidity is 8.0 Tm, the horizontal/vertical acceptances are 125π/40π mm•mrad and the momentum acceptance is ±1%. The isochronous-mode operation is also possible when the precision mass measurement is done.

RI-beam's micro-pulses coming from the BigRIPS are injected into the ACR by means of the multi-turn injection. Then, the rf-stacking is immediately performed. After repeating the injection and the rf-stacking by 4 times, the beam is pre-cooled by means of the stochastic cooling. One cycle of injection, rf-stacking and cooling is expected to take typically 100 ms. This cycle is repeated in the intrinsic lifetime of the RI or until the space charge limit is reached. Following this process the accumulated beam is finally cooled to less than 0.1% in momentum spread and 0.1π mm•mrad in transeverse emittance by combining the stochastic and the electron cooling techniques.

The number of RI ions stored in the ACR is determined by the balance of the supply rate and decay rate due to the intrinsic lifetime. This is limited by space charge effect rather than the lifetime for RI ions neighboring on the stability line, which has high production rate and long lifetime.

The accumulated RI beams in the ACR will be fast extracted and one-turn injected into the e-RI collider.

6 E-RI COLLIDER

The e-RI collider for electron-scattering experiments on unstable nuclei consists of an electron and an ion storage rings that intercept at one colliding point with each other.

The electron-beam's energy is 500~700 MeV which is obtained by an electron linac. This energy is determined by experimental requirement for the resolution of electron-scattering angles. The feasible stored-beam's current and the beam emittance are 500 mA and 30π nm•rad, respectively to get high luminosity within the tolerable beam-beam effect. The electron ring has a FODO structure in arcs to realize the required emittance. A 500-MHz rf cavity is installed to compensate radiation loss. Circumference of the electron ring is 114 m and the harmonics is 182.

The ion ring has maximum rigidity of 8 Tm, which is the same as that of the ACR. The lattice of the arc section has mirror symmetry to make dispersion suppression easy. An electron cooler is located in a short straight section to compensate the emittance growth by beam-beam effect. An RF cavity is also located to keep bunch length. The circumference of the ion ring is 146 m which is the same as that of the ACR and the harmonics is 30.

In the colliding section, where two rings intercept, a lattice of each ring is designed so as to get high luminosity. The β values are determined to be 2 m for the electron beam in both of horizontal and vertical directions and 2 m for the ion beam. These large β values are required by obtaining better angular resolution for the electron spectrometers rather than reducing the hour-glass effect. We adopt the head-on collision scheme to get higher luminosity. In order to realize this scheme, the ratio of the magnetic rigidity of the RI beam to that of electron beam is kept to be constant (2.9) by appropriately selecting the electron beam's energy.

The design mentioned above is preliminary. The luminosity required is higher than $10^{27}/\mathrm{cm}^2/\mathrm{s}$ in order to clearly measure charge distributions in unstable nuclei in some-ten-day experiments. This luminosity should be obtained by primary heavy-ion beams with peak currents of 1pμA. This limitation for the peak current is attributed mainly to the transient beam loading rather than the space-charge effect in the ring cyclotrons. The design goal is to obtain the above luminosity for unstable nuclei having their life time shorter than 1 minute. In the present design such level of the luminosity is attainable for life times longer than 100 seconds, assuming that the tolerable linear tune shift, ξ is to be 0.05.

7 SCHEDULE

The construction of the first-phase building, and the fabrication of the IRC, the SRC and the BigRIPS will be finished early in 2003. In 2003 and 2004, the overall installation and final tuning of these machines will be done. We will submit the budget for the fRC in FY2002, and we expect to install this cyclotron during the above final tuning. The first RI beam from the BigRIPS is scheduled for the late autumn of 2005.

The construction of the second-phase building will be started in 2002 and will be finished in 2005. After its completion, major experimental set-ups, e.g. a large acceptance spectrometer and a gamma-ray detector, etc., the ACR system, and e-RI collider will be constructed and installed step by step.

REFERENCES

[1] M. Wakasugi et al.: Proc. of EPAC 2000, p.1357 (2000).