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In-flight RI beam separator BigRIPS at RIKEN and elsewhere in Japan

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Abstract

Presented are features of the in-flight radioactive isotope (RI) beam separators in Japan as well as of a next-generation separator BigRIPS being built at RIKEN for the RI-beam factory project. Characteristic features and present status of the existing separators are reviewed for the RIPS at RIKEN, the Secondary Beam Line at RCNP, the Secondary Beam Course at NIRS, the CRIB at CNS and the RMS at JAERI. Design features are outlined for the BigRIPS, which is characterized by two major features: large acceptances and a tandem (or two-stage) separator scheme. The large acceptances allow one to produce RI beams efficiently by using in-flight fission of uranium ions, being achieved by using superconducting quadrupoles with a large aperture. The tandem separator scheme allows one to deliver tagged RI beam. The integrated capability of the BigRIPS and the accelerators of the project can significantly enlarge the scope of future RI-beam experiments. A low-energy course following the BigRIPS can provide energy-degraded and -bunched RI beams to be applied for a gas catcher system with an RF ion guide, aiming at realizing a projectile fragmentation based ISOL system.

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Keywords: Radioactive isotope beams; In-flight RI-beam facilities in Japan; RIKEN-RIPS; RIKEN-BigRIPS; In-flight fission; Tandem fragment separator; Large acceptance; Superconducting quadrupoles

1. Introduction

Production of radioactive isotope (RI) beams by means of an in-flight separation scheme provides unique opportunities to study reactions and properties of unstable nuclei far from stability. RI beams, being produced by projectile fragmentation (PF) in heavy-ion collision at intermediate and high energies, are collected and separated by using an in-flight RI beam separator (projectile fragment separator). An achromatic magnetic spectrometer is usually employed as the separator, in which isotopes are separated in flight by the combination of magnetic analysis and energy loss, a technique called momentum-loss achromat [1,2]. At an intermediate focus of the separator, a wedge-shaped energy degrader (achromatic wedge) is inserted to generate the energy loss. The most important advantage of this in-flight separation scheme is that it can be applied to the production of all kinds of unstable nuclei independent of their chemical nature. Furthermore a short transit time of RI beams

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through the separator (the order of 100 ns) does not put any lower limit on the β-decay half-life of unstable nuclei to be studied. The high energies of projectiles allow one to use a thick production target and projectile fragments are emitted forward into a small cone due to the kinematic focussing at high energies. The cross-section of PF reactions is large, allowing one to produce RI beams very far from stability with meaningful intensities. These advantageous features of the scheme make it possible to efficiently produce a wide range of RI beams.

The RI-beam production based on this scheme was pioneered in the 1980s at LBNL [3] for the first time and then by the LISE separator at GANIL [4]. These facilities produced a wealth of new information on unstable nuclei, demonstrating the promising prospects of the scheme. In the 1990s, this led to the development of the second-generation separators worldwide, including the RIPS at RIKEN [5], the A1200 at NSCL/MSU [6], the FRS at GSI [7] and the LISE3 [8] and SISSI [9] at GANIL. These facilities were built with upgraded features, thus promoting a variety of RI-beam experiments, from which many important results were obtained. The development of accelerator technology, especially in ion-source technology, also played an important role in facilitating RI-beam experiments, allowing one to use intense primary heavy-ion beams.

In the mean time, small-size separators were also built, in which light-ion transfer reactions are employed in inverse kinematics to produce RI beams at low energies, including the MARS [10] at Texas A&M University and the CRIB [11] at Center for Nuclear Study (CNS). The kinematic focussing by inverse kinematics enables efficient production of some RI beams. These facilities aim at the production of specific RI beams close to stability to study the structure and reactions of unstable nuclei, especially of astrophysical interest.

In the 2000s, several new projects to build the next-generation facilities are going on or being planned worldwide, including the A1900 at NSCL/MSU [12], the BigRIPS at RIKEN, the Super-FRS at GSI [13] and the in-flight separator for the RIA project in USA [14]. The A1900 has been recently operational, while the BigRIPS is being built. The Super-FRS and the RIA separator are being planned. In these projects not only the capability of the separator but also the energies and intensities of primary beams will be greatly upgraded, allowing one to produce and study rare isotopes further from stability.

The most important features of the next-generation facilities are that (1) in-flight fission of uranium ions is used as a production reaction in addition to PF reactions and (2) the in-flight separation scheme may be combined with the ISOL scheme. The in-flight fission has large production cross-sections for medium-heavy neutron-rich isotopes, as demonstrated at GSI [15], further enlarging the accessible region of unstable nuclei. The gas catcher system with an RF-ion guide [16], which was originated by Wada et al., is being developed worldwide. This technique enables one to combine the in-flight scheme with the ISOL scheme, by which a PF based ISOL facility is made possible. High-quality accelerated RI beams may be obtained independently of the chemical nature of isotopes. The BigRIPS separator, designed for the RI-beam factory (RIBF) project at RIKEN, is one of the next-generation facilities, incorporating these upgraded features. The next-generation facilities will promote further development in nuclear science with RI beams.

In this paper, the in-flight RI beam separators in Japan are reviewed, emphasizing their characteristic features and present status and then outlined are the design features of the BigRIPS at RIKEN, which are characterized by large acceptances and a tandem (or two-stage) separator scheme.

2. In-flight RI beam separators in Japan (existing)

In Japan there are five in-flight RI-beam facilities. The facilities are classified into two types: intermediate-energy and low-energy RI-beam facilities. In the case of intermediate-energy facilities PF reactions in heavy-ion collision are used as a production reaction, while in the case of low-energy facilities light-ion induced transfer reactions, such as (p, n) and (^{3}He, n), are used in inverse kinematics at low energies. The intermediate-energy facilities in

Japan are the RIPS at RIKEN in Wako, Saitama [5], the Secondary Beam Line at Research Center for Nuclear Physics (RCNP), Osaka University in Osaka [17,18] and the Secondary Beam Course at National Institute of Radiological Science (NIRS) in Chiba [19]. The CRIB separator at CNS, University of Tokyo on RIKEN campus [11] and the RMS separator at Japan Atomic Energy Research Institute (JAERI) in Tokai, Ibaraki [20] are the low-energy facilities. The basic parameters of these existing separators are summarized in Table 1. The characteristic features and present status of the facilities are reviewed in this section.

2.1. RIPS separator at RIKEN

The RIPS at RIKEN [5] is both the pioneer and the largest facility in Japan, being commissioned in January of 1990. More than a half the beam time at RIKEN is given to RI-beam experiments using the RIPS. RI beams are produced by PF reactions with heavy ion beams provided by the RIKEN ring cyclotron (RRC) [21,22]. Having a K-value of 540 MeV, the RRC can accelerate heavy ions up to 135 MeV/nucleon (for ions with $A/q = 2$). The maximum beam intensity is as high as several hundred pnA in the case of light heavy ions. Fig. 1 shows a schematic layout of the RIPS. It forms a two-bend achromatic spectrometer, consisting of two 45° dipoles, 12 quadrupoles and 4 sextupoles. Isotopes are separated in flight by using the technique of momentum loss achromat. An achromatic wedge degrader, which preserves the achromaticity of the system, is placed at the intermediate focus F1 to generate the energy loss.

Table 1
In-flight RI-beam separators in Japan (existing)

Facilities	RIPS/RIKEN	RCNP	NIRS	CRIB/CNS	RMS/JAERI
Commissioning	January 1990	December 1993	1998	August 2001	1995
Energy region	Intermediate ~100 MeV/u	Intermediate ~70 MeV/u	Intermediate ~350 MeV/u	Low 1–10 MeV/u	Low 1–2 MeV/u
Production reaction	PF	PF	PF	Inverse kinematics	Inverse kinematics
Accelerator	Cyclotron $K = 540$ MeV	Cyclotron $K = 400$ MeV	Synchrotron (medical use)	Cyclotron $K = 70$ MeV	20 MV Tandem and booster linac
Type	Two-bend achromatic spectrometer	Two-bend achromatic spectrometer	Two-bend achromatic spectrometer	Two-bend achromatic + $E \times B$	Electromagnetic separator QQEDMDEDQQ
Energy degrader	Achromatic wedge	Homogeneous	Achromatic wedge	Homogeneous	None
Angular acc. (mrad)					
Horizontal	80	40	26	75	Not given
Vertical	80	28	26	75	Not given
Solid angle (msr)	5	0.45	Not given	5.6	Variable, maximum 15
Momentum acc. (%)	6	8	5	15	12
Maximum Bρ (Tm)	5.76	3.2	8.13	1.3	1.0, E$\rho = 20$ MV
Momentum resolution at F1 $(P/\Delta P)$[a]	1500	910	1940	5260	300[b]
(x/x) at F1[c]	−1.6	−1.9	−1.03	−0.3	
(x/δ) at F1[d] (m)	2.4	1.73	2.0	−1.58	
Total length (m)	27.5	14.8	29.9	12.8	9.4
Beam swinger	Yes	Yes	Yes	Rotatable[e]	Rotatable[e]
Main activities	Nuclear physics	Nuclear physics	Cancer therapy	Nuclear physics	Nuclear physics
References	[5]	[17,18]	[19]	[11]	[20]

[a] First-order momentum resolution at the intermediate focus (F1), for which object size is assumed to be 1 mm.

[b] Mass resolution.

[c] Magnification at the intermediate focus (F1) where the energy degrader is placed.

[d] Momentum dispersion at the intermediate focus (F1).

[e] The separator is rotatable.

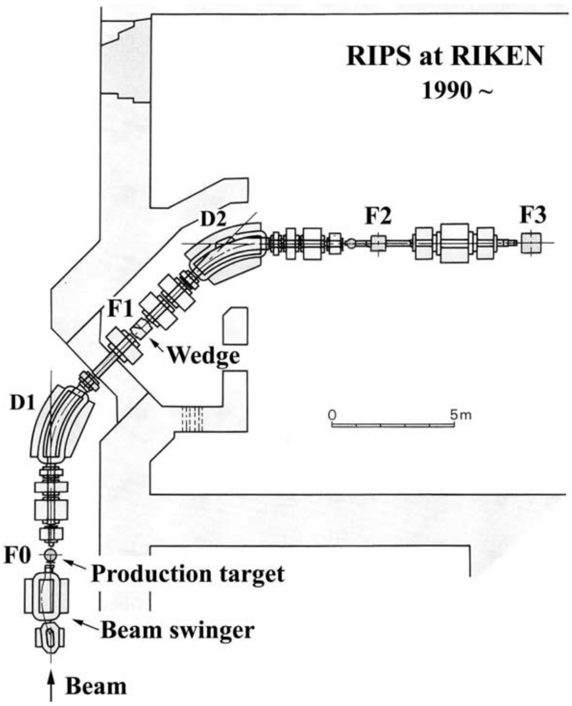

Fig. 1. A schematic layout of the RIPS separator at RIKEN.

One of the important features of the RIPS is the capability of producing high-intensity RI beams. This was achieved by adopting large magnetic rigidity as well as large acceptance in angle and momentum as listed in Table 1. High-intensity RI-beams facilitate secondary reaction studies of unstable nuclei far from stability. The large magnetic rigidity allows one to utilize primary beams with the highest possible energies even when producing very neutron-rich RI beams. The large acceptance permits efficient collection of projectile fragments even in the energy domain of 100 MeV/nucleon, where the fragments emitted are not very well focused kinematically. These features made it possible to produce high-intensity RI-beams, e.g. 10^4–10^5 pps even in the case of very neutron-rich nucleus ^{11}Li. This capability of RIPS significantly promoted secondary reaction studies of unstable nuclei. A variety of secondary reactions, such as elastic scattering [23], inelastic scattering [24], intermediate-energy Coulomb excitation [25], Coulomb and nuclear dissociation [26], transfer reactions [27], charge exchange reactions [28], RI-beam fragmentation [29] and fusion reactions [30], have been measured in inverse kinematics to study structure and reactions of various unstable nuclei. One of the important results is the recent findings of melting of the shell closure in neutron-rich $N = 8$ nuclei and a large deformation in neutron-rich $N = 22$ nuclei. The melting of shell closure and the large deformation were observed in ^{12}Be [31] and ^{34}Mg [29,32] nuclei, respectively, by measuring γ-rays from Coulomb and nuclear excitation as well as RI-beam fragmentation. The capability also facilitated and promoted RI-beam experiments of other kinds, such as a new isotope search [33], decay studies such as β-delayed proton [34] and neutron [35] decay measurements, studies on reactions of astrophysical interest (by direct [36] and indirect [37] measurements), nuclear moment measurement [38], and so on.

Another important feature of the RIPS is the capability of producing spin-polarized RI-beams, which was achieved by a beam swinger magnet installed right before the production target (see Fig. 1). The beam swinger magnet makes it possible to collect projectile fragments emitted at a finite angle other than 0°, hence allowing one to produce spin-polarized RI-beams through polarization phenomena in PF reactions. Spin-polarized RI-beams with a polarization of several percent were produced [39], being employed to measure magnetic dipole and electrical quadruple moments of various unstable nuclei by means of β-NMR method [38].

Recent upgrades of the injector linac RILAC significantly increased the intensities of primary beams, particularly of relatively heavy elements such as ^{48}Ca and ^{86}Kr [22]. The present intensity of ^{48}Ca is as high as 150 pnA, leading to the recent observation of new isotopes on and near the neutron drip-line: ^{34}Ne, ^{37}Na and ^{43}Si [40]. The scope of unstable nuclei to be studied at the RIPS is enlarged significantly. R&D studies of the gas catcher system are being performed with ^{8}Li ions at the RIPS [16]. An RF separator has been recently installed right before the F2 focus of the RIPS, aiming to improve the purity of proton-rich RI beams.

2.2. Secondary Beam Line at RCNP

The Secondary Beam Line at RCNP [17,18] was commissioned in 1993. RI beams are produced by PF reactions with light heavy ions at around 70 MeV/nucleon, which are provided by the RCNP ring cyclotron ($K = 400$ MeV) [41]. This separator is designed to be a two-bend achromatic spectrometer. Its unique feature is that a homogeneous energy degrader was used for the first time instead of an achromatic wedge degrader. The use of this degrader usually destroys achromaticity of the system. In the ion-optical design of this separator, the degrader was treated as a transfer matrix [17] and the ion optics were tuned so that the achromaticity could be restored. This feature is advantageous when a thin degrader needs to be fabricated. Another advantage is that the image magnification can be kept constant irrespective of the degrader thickness, resulting in a small dimension RI beam. Note that in the case of using an achromatic wedge, the magnification gets larger when so does the thickness, being inversely proportional to $1 - d/R$, where d and R represent the degrader thickness and the stopping range of the RI beam of interest, respectively. A drawback of using a homogeneous degrader is that the energy spread, measured relative to the central energy, gets larger, being inversely proportional to $1 - d/R$. Note that the energy spread remains the same if an achromatic wedge is used. Following the RIPS, a beam swinger magnet was installed. Main research activities are studies involving spin-polarized unstable nuclei.

2.3. Secondary Beam Course at NIRS

NIRS is an institute for radiation cancer therapy with heavy-ion beams. RI beams are produced by PF reactions with heavy ions provided by the medical synchrotron HIMAC [42]. The HIMAC is capable of accelerating relatively light heavy ions up to 800 MeV/nucleon. The Secondary Beam Course at NIRS [19] was built for the application of RI beams, especially positron-emitter beams such as ^{11}C, to cancer therapy. In cancer treatment with heavy ions, it is very important to verify the ion range in a patient's body to check if a tumor is properly irradiated. The use of a positron-emitter beam makes it possible to directly measure its stopping point by using a positron camera or a positron emission tomography system. This separator is designed be a two-bend achromatic spectrometer, in which an achromatic degrader is used for isotope separation. It is followed by an irradiation system [19], which consists of a scanning magnet system to scan the beam position, a range shifter to scan the ion range and a positron camera. Production and irradiation tests of the ^{11}C beam have been made using a ^{12}C beam at 430 MeV/nucleon. Some details are given in [19].

The separator is also used for physics experiments, such as structure studies using knockout reactions and measurements of nuclear moments. The separator is equipped with a beam swinger magnet.

2.4. CRIB separator at CNS

The CRIB separator [11] at CNS was built for the production of low-energy RI beams in the range of 1–10 MeV/nucleon, which are useful for spectroscopy of unstable nuclei and the study of nuclear reactions for nuclear astrophysics. Light-ion induced reactions, such as (p, n) and (^{3}He, n), are used in inverse kinematics. The CRIB was installed at the RIKEN facility under the CNS-RIKEN joint project, being commissioned in 2001. Heavy-ion beams provided from an AVF cyclotron [22], which is one of the two injectors to the RRC, are used to produce RI beams. Having a K-value of 70 MeV, the AVF cyclotron can provide relatively light heavy ions ($A < 40$) with energies up to about 10 MeV/nucleon and intensities as high as 1 pμA.

Fig. 2 shows a schematic layout of the CRIB. The CRIB consists of two stages: a two-bend achromatic spectrometer is followed by a Wien filter (E × B) system. Most of the magnets in the first stage were originally built for the polarization spectrograph DUMAS [43] at RCNP some 20 years ago. Although the design of CRIB is based on that of DUMAS, some modifications as well as the addition of the Wien filter were made. Similarly for the RCNP separator, a homogeneous degrader is employed for isotope separation. It is

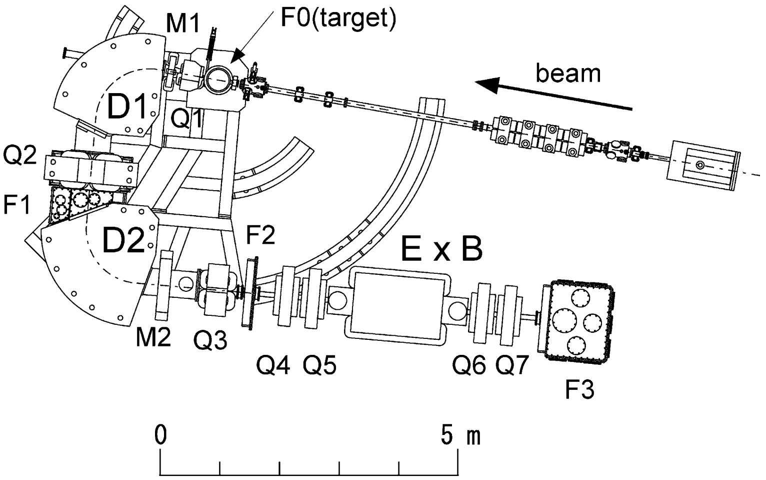

Fig. 2. A schematic layout of the CRIB separator at CNS, University of Tokyo. (Courtesy of T. Teranishi and Y. Yanagisawa, CNS, University of Tokyo.)

inserted at the intermediate focus (F1) of the first stage and the ion optics are adjusted so as to restore the achromaticity at the F2 focus. This feature is very important because the degrader used is rather thin (order of several mg/cm^2) in the energy range of CRIB. In fact it is difficult to precisely fabricate such a thin wedge-shaped degrader. The Wien filter system provides additional velocity separation, further improving the purity of RI beams.

Recently ^{12}N and ^{11}C beams have been produced by the ^{3}He(^{10}B, ^{12}N)n and ^{3}He(^{10}B, ^{11}C + p)n reactions at 7.8 MeV/nucleon, respectively. Elastic resonance scattering on protons was successfully measured for the ^{12}N and ^{11}C beams and proton resonance states in ^{13}O and ^{12}N were studied [44].

2.5. RMS separator at JAERI

The RMS separator [20] at the JAERI tandem booster facility [45] was built as a recoil mass separator to analyze fusion residues of heavy-ion reactions. It was designed to be an electromagnetic separator having a symmetric configuration of Q–Q–ED–MD–ED–Q–Q, where Q, ED and MD stand for a quadrupole, an electric dipole and an magnetic dipole, respectively. Recently a KEK group and their co-workers have begun to use the RMS as an in-flight RI beam separator [46], in which light-ion transfer reactions are used in inverse kinematics to produce RI beams in the energy range of 1–2 MeV/nucleon. They intend to directly measure reaction rates of astrophysical interest at these low energies. Recently a ^{16}N beam has been produced by the d(^{18}O, ^{16}N)α reaction and suppression of the primary beam was tested because it is crucial in their case [46]. They plan to measure the reaction rate of ^{16}N(α,n)^{19}F.

3. BigRIPS separator at RIKEN

The in-flight RI beam separator BigRIPS is being built at RIKEN for the RIBF project [47]. The BigRIPS is one of the next-generation separators, which aims at achieving RI beams of greater capability. In the case of BigRIPS, we have particularly tried to achieve the following aspects: (1) a drastic upgrade of RI-beam intensities, especially those of nuclei far from stability; (2) beam tagging to cope with poor purity of RI beams; and (3) the combination of the in-flight separation scheme with the ISOL scheme. For the first aspect, we are building a large-acceptance separator, particularly taking into account the use of in-flight fission. For the second aspect, we have adopted the tandem (or two-stage) fragment separator scheme, which allows one to tag RI-beam species in event-by-event mode. For the third one, we are building a dedicated beam course following the BigRIPS to provide energy-bunched and -degraded RI beams, where the gas catcher system being developed will be placed. The design features of the BigRIPS are outlined in this section.

3.1. RIKEN RIBF project

In the RIBF project, three new cyclotrons, called fRC, IRC and SRC, respectively, are being built as an extension of the existing RRC [47]. These four cyclotrons are operated in cascade mode, for which the upgraded linac is used as the injector. The SRC, the last one in the cascade, is a superconducting ring cyclotron with a K-value of 2500 MeV. Fig. 3 shows a schematic layout of the project, in which shown are the IRC, the SRC, the BigRIPS, RI-beam delivery lines and experimental halls and setups. The fRC is not shown in the figure, being placed in the existing facility. The RI-beam accumulator cooler ring and the electron–RI-beam colliding ring described in [47] are not shown, either. Part of the beam from the IRC can be transported back to the existing facility, which allows one to share the beam between the new and existing facilities (as shown in Fig. 3).

The cascade of the cyclotrons can provide a wide range of heavy ion beams, boosting their energies up to 400 MeV/nucleon in the case of relatively light elements ($A < 40$) and 350 MeV/nucleon in the case of heavier elements up to uranium. The maximum beam intensity is expected to be as high as 1 pμA, even for very heavy elements such as uranium. It is possible to provide intensities higher than 1 pμA in the case of relatively light heavy ions, although the radiation shielding being presently planned does not allow it. These features will lead to a significant increase in RI-beam intensity.

3.2. Production reactions

Not only the PF reactions with various heavy ions but also the in-flight fission of uranium ions

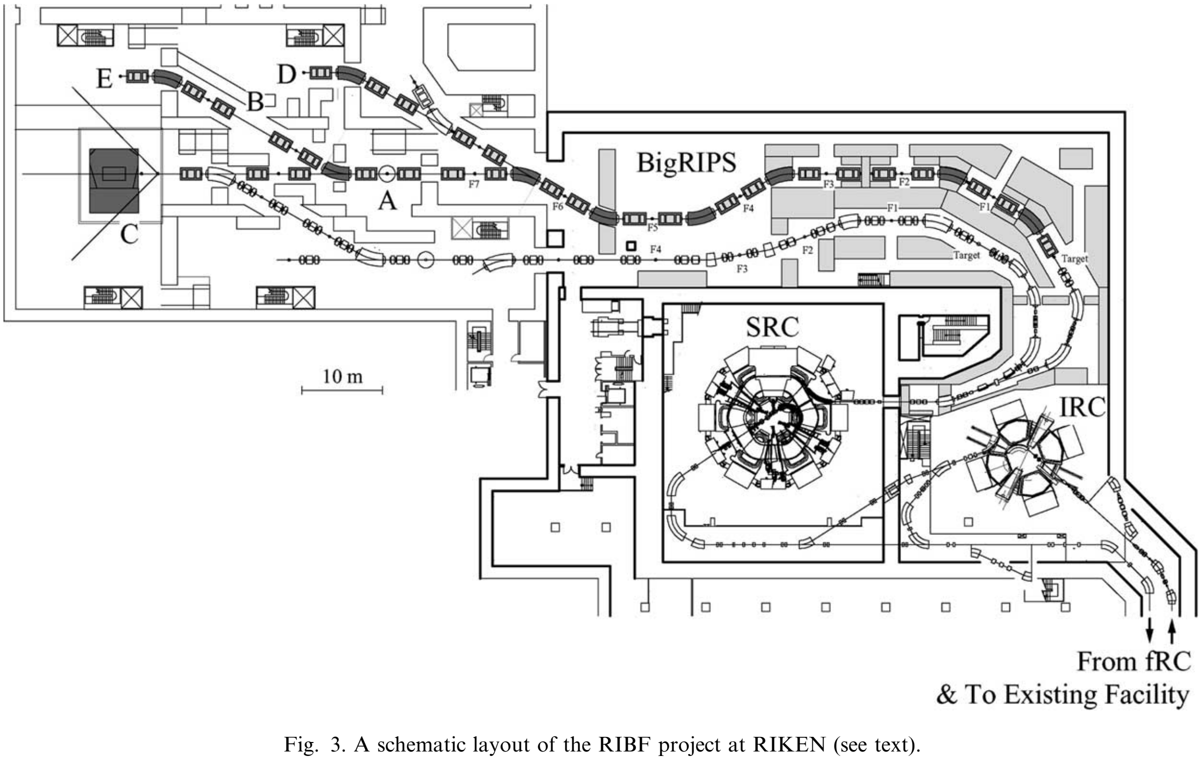

Fig. 3. A schematic layout of the RIBF project at RIKEN (see text).

will be used as the production reaction. The in-flight fission is very powerful for the production of neutron-rich RI beams with medium-heavy mass, significantly upgrading the intensities of RI beams in this region [15]. But the in-flight fission causes a much larger spread in both angle and momentum, as compared with the PF reactions. According to the reaction kinematics at 350 MeV/nucleon, the angular and momentum spreads of fission fragments are quite large, being estimated to be about 100 mr and 10%, respectively, when symmetric fission is assumed. These values are several times larger than those of medium-heavy fragments produced by the PF reactions. Hence a large-acceptance separator is needed to efficiently collect fission fragments. Even in the case of using the PF reactions, large acceptance helps to increase the RI-beam intensity significantly, particularly when RI beams are very far from the projectile or when the RI beams and the projectile are light isotopes.

3.3. Outline of the BigRIPS separator

Fig. 4 shows a schematic layout of the BigRIPS. The plan is to build two separators that are named BigRIPS-I and BigRIPS-II, respectively. The BigRIPS-I has been designed to be a large-acceptance separator in which superconducting quadrupoles with large apertures are used, while the BigRIPS-II will be a medium-acceptance separator. The use of in-flight fission was taken into account in designing the BigRIPS-I. Heavy-ion beams from the SRC are transported through a beam transport line to the production targets of the BigRIPSs. The two separators can share the beams by means of time sharing, which is achieved by placing a pulsing magnet in the transport line. This scheme lets one conduct two different RI-beam experiments simultaneously, enhancing productivity of the RIBF project. The construction budget of the BigRIPS-I has been funded and it is currently being fabricated. The RI-beam delivery lines that follow the BigRIPS-I will also be funded. However, it is still not clear when the BigRIPS-II will be funded.

Each BigRIPS has been designed to be a tandem fragment separator as shown in Fig. 4. The first stage of the BigRIPS-I forms a two-bend achromatic spectrometer, consisting of four superconducting quadrupole triplets (STQ) (STQ1 to STQ4) and two room-temperature dipoles (RTD) with a 30° bend (D1 and D2). An achromatic

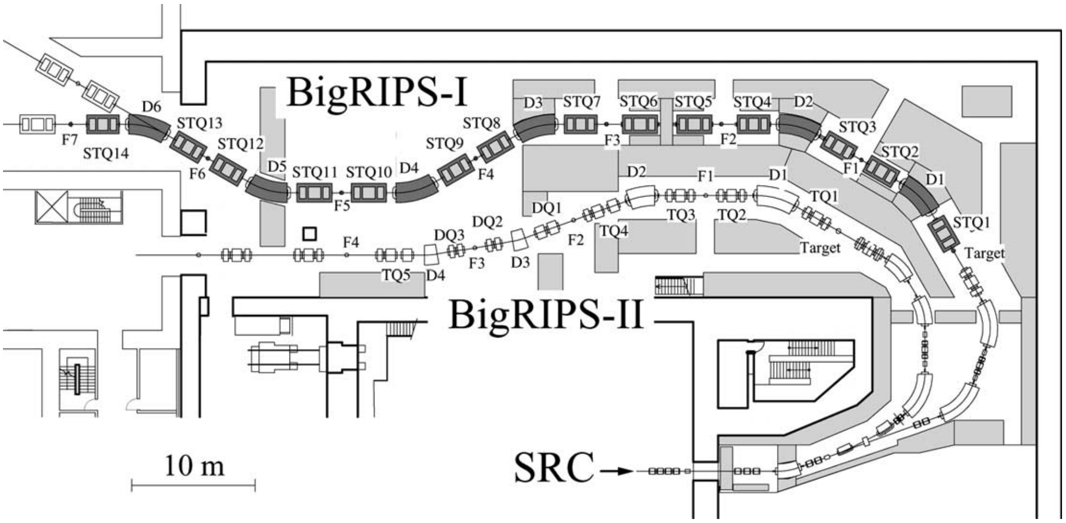

Fig. 4. A schematic layout of the BigRIPS separator at RIKEN. The BigRIPS-I is a large-acceptance separator, while the BigRIPS-II a medium-acceptance separator. STQn (triplet), TQn (triplet) and DQn (doublet) indicate quadrupole magnets. The STQn are superconducting quadrupoles, while the TQn and DQn are room-temperature quadrupoles. Dipole magnets (room temperature) are indicated by Dn. Fn denote focuses.

wedge degrader is inserted at the intermediate focus F1 for the isotope separation. A telescopic system consisting of two STQs (STQ5 and STQ6) is placed after the achromatic focus F2 to transport separated RI beams to the second stage. Thick concrete, which weighs about 10,000 tons in total, surrounds the first stage to shield neutron radiation. The second stage, starting from the F3 focus and ending at the F7 focus, forms a four-bend achromatic spectrometer, consisting of eight STQs (STQ7 to STQ14) and four RTDs with a 30° bend (D3 to D6). The intermediate focuses F4, F5 and F6 are momentum dispersive, while the final focus F7 is doubly achromatic. The four bends yield higher momentum resolution at this stage, where the RI-beam tagging is made. The BigRIPS-II has a relatively simple configuration as shown in Fig. 4 and all the magnets to be used are room-temperature magnets. Each stage of the BigRIPS-II has been designed to form a two-bend achromatic spectrometer. The bends in the first stage are not symmetric: 30° and 20°. The momentum resolution in the second stage is not so high because of the small bending angle (10°). In Figs. 5 and 6, respectively, the first-order optics of BigRIPS-I and BigRIPS-II are shown, which were calculated by using the code GIOS [48]. The main parameters of the BigRIPSs are listed in Table 2. The acceptances of the BigRIPS-I are large and comparable to the spread of fission fragments, allowing one to achieve high collection efficiency: almost half of the produced fission fragments may be accepted. The superconducting quadrupoles with large apertures and high fields and the RTD with a large gap yield these high acceptances. The acceptances of the BigRIPS-II were determined taking into account the use of PF reactions with medium-heavy projectiles only. Room-temperature quadrupole and dipole magnets having relatively small apertures and gap are used for the BigRIPS-II.

A Wien (E × B) filter system or an RF separator may be placed on the downstream side of BigRIPS-II and on the second stage of BigRIPS-I to cope with the expected bad purity of proton-rich RI beams. In the case of BigRIPS-I, the device may be

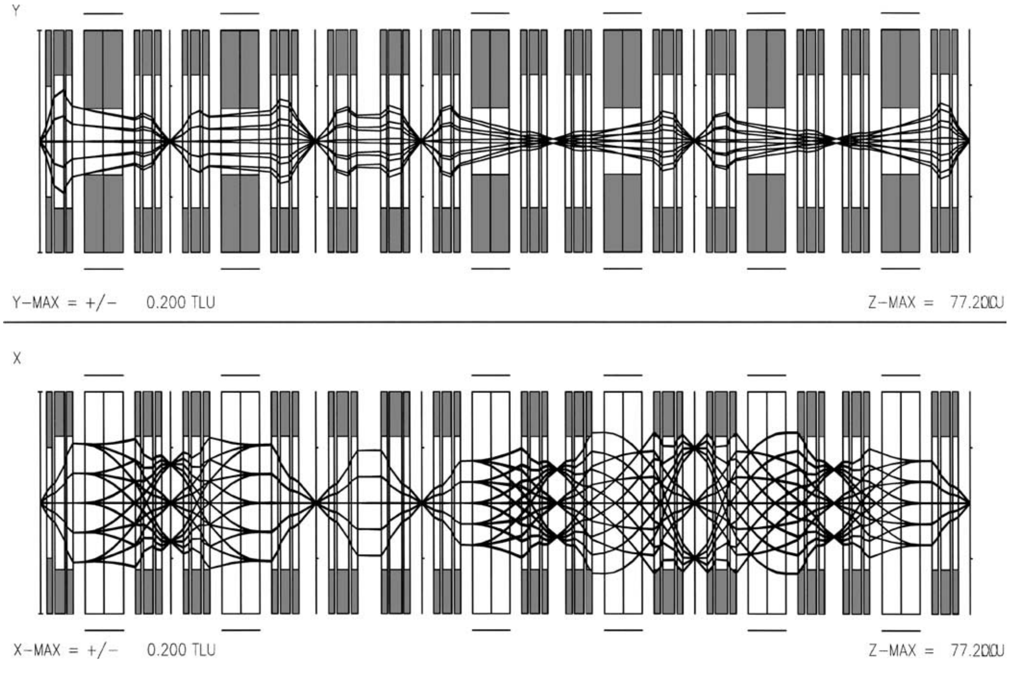

Fig. 5. The first-order beam optics of BigRIPS-I calculated by the code GIOS for the acceptances given in Table 2. The object size is taken to be 1 mm. The upper figure shows the vertical direction, while the lower one the horizontal direction.

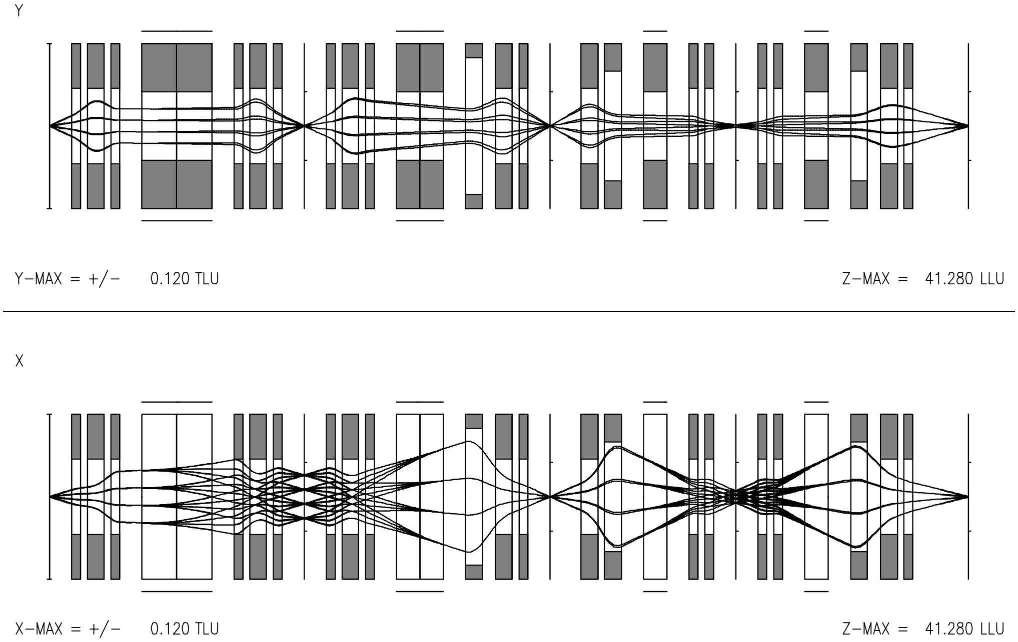

Fig. 6. The first-order beam optics of BigRIPS-II calculated by the code GIOS for the acceptances given in Table 2. The object size is taken to be 1 mm. The upper figure shows the vertical direction, while the lower one the horizontal direction.

Table 2
Basic specifications of the BigRIPS separator

	BigRIPS-I	BigRIPS-II
Configuration	Tandem separator	
First stage	Two bends	Two bends
Second stage	Four bends	Two bends
Energy degrader	Achromatic wedge	
Quadrupoles	Superconducting	Room temperature
Angular acceptance (mr)		
Horizontal	80	20
Vertical	100	30
Momentum acceptance (%)	6	3
Maximum magnetic rigidity (Tm)	9	9
Total length (m)	77	41
Momentum dispersion[a] (cm/%)		
First stage	−2.31	−2.1
Second stage	3.3	0.57
Momentum resolution[b]		
First stage	1290	2000
Second stage	3300	590

[a] At the mid focus of the stage.
[b] First-order momentum resolution at the mid focus, for which object size is assumed to be 1 mm.

installed in the straight section between the first and fourth dipoles of the second stage. A small beam winger magnet may also be installed right before the target to produce spin-polarized RI beams.

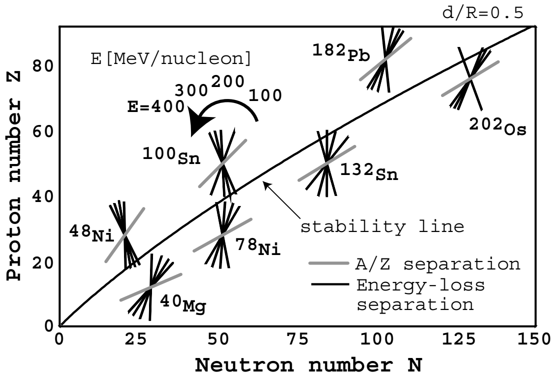

Fig. 7. Behavior of the energy-loss separation calculated for different energies and isotopes. The thickness of energy degrader is taken to be half of the ion range. The black solid lines, rotating as the energy increases, show the isotope line which has the same $B\rho$ value after passing through the degrader. (Courtesy of H. Sakurai, University of Tokyo.)

3.4. Tagging of RI beams

In the energy domain of RIBF, it is difficult to separate the isotones of an isotope of interest and their neighbors by means of the momentum-loss achromat, as illustrated in Fig. 7. Due to the nature of energy loss, they tend to have nearly the same $B\rho$ values as the isotope of interest even after passing through the energy degrader. Furthermore, the charge state is not fully stripped for medium-heavy and heavy elements. These situations result in poor purity: several isotopes are mixed in the RI beam, which is sometimes called ‘a cocktail beam’.

In designing the BigRIPS, we adopted the tandem separator scheme to cope with the poor purity. Fig. 8 depicts the concept of this scheme. The first stage of the BigRIPS serves to produce and separate RI beams, while the second stage serves to identify RI-beam species as well as to measure their momentum in an event-by-event mode. In the case of the BigRIPS-I, position-sensitive gas detectors such as PPAC [49] (at F3, F5 and F7), timing detectors such as thin plastic scintillation counters (at F3 and F7) and ΔE detectors such as MUSIC [50] (at F7) are placed at the focuses to measure the $B\rho$ value, the time-of-flight (TOF) and the energy loss. The particle-tracking method is employed to determine the $B\rho$ value and the TOF precisely. This scheme allows the event-by-event determination of the atomic number (Z), the ratio of mass number to charge number (A/q) and the momentum (P), which makes it possible to deliver tagged RI beams to experimental setups. Fig. 9 shows the relative difference of A/q for a given Z number as a function of A/q, which is calculated from the ion having an A/q value closest to that of

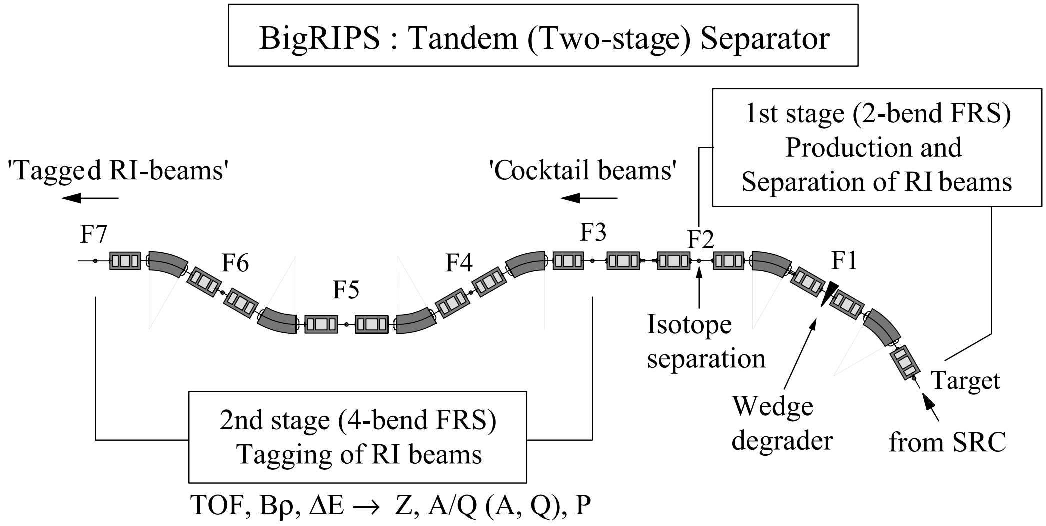

Fig. 8. A schematic diagram of the tandem separator scheme and RI-beam tagging.

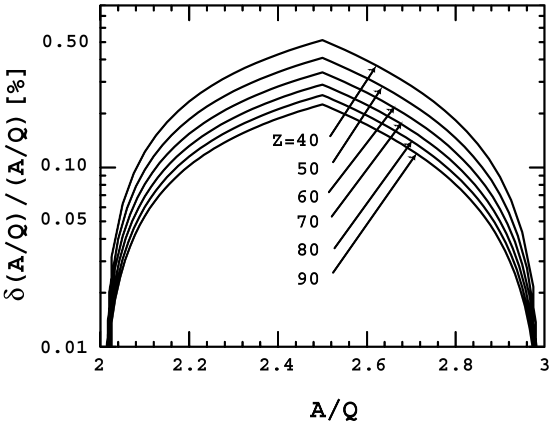

Fig. 9. Relative difference of A/q for a given Z number. The relative difference is calculated from the ion having an A/q value closest to that of the ion of interest, shown as a function of A/q. (Courtesy of H. Sakurai, University of Tokyo.)

the ion of interest. This difference gives the resolution of A/q needed to identify A and q of RI beams, hence giving the necessary resolution in the $B\rho$ and TOF measurements. The capability of the second stage of BigRIPS-I will be able to achieve the resolution, when A/q is not close to an integer number such as $A/q = 2$ and 3. As seen in the figure, very high resolution is needed when A/q is close to the integer numbers. The scheme works well in the most important cases of interest. Current detector technology allows one to tag RI beams with intensities up to 10^6 pps.

The tandem separator scheme will significantly facilitate RI-beam experiments, particularly those of secondary reaction studies. Furthermore, the tagged ‘cocktail beam’ allows one to measure reactions of several different nuclei simultaneously, enhancing the productivity of the facility. It is possible to place another degrader in the second stage for two-stage separation [13]. However large effects should not be expected because of the nature of energy loss at the RIBF energies.

3.5. RI-beam delivery lines and experimental setups

The BigRIPS separators are followed by the RI-beam delivery lines, which transport the tagged RI beams to different experimental setups placed downstream, as shown in Fig. 3. The same superconducting quadrupoles are used for the RI-beam delivery lines that follow the BigRIPS-I. The main setups to be built are a 0° spectrometer, a large-acceptance spectrometer and a low-energy RI-beam course.

Indicated as B in Fig. 3, a part of the RI-beam delivery lines has been designed as 0° spectrometer, of which target position is denoted as A, allowing one to analyze and identify projectile residues from RI-beam secondary reactions. The spectrometer forms an anti-mirror symmetric achromatic spectrometer with two intermediate focuses, consisting of two RTDs and six STQs. Surrounding the secondary target, a γ-ray array such as a germanium ball will be installed to detect γ-rays from secondary reactions, such as high-energy Coulomb excitation and RI-beam fragmentation, in coincidence with the projectile residues.

The large-acceptance spectrometer, indicated as C in Fig. 3, is a superconducting dipole magnet with a very large gap and high fields, allowing one to analyze projectile residues in coincidence with neutrons and protons emitted in the forward direction. A large-aperture superconducting quadrupole may be added in front of the dipole for vertical focusing. The momentum acceptance is large enough to accept decaying protons as well as the projectile residues at the same time and the magnet gap is large enough to efficiently detect neutrons emitted in the forward direction by using a neutron hodoscope placed downstream of the magnet. Secondary reactions, such as dissociation reactions and knockout reactions, will be measured to study structure and reactions of unstable nuclei.

The low-energy course, indicated as D in Fig. 3, is used for the PF-based ISOL system as well as the production of low-energy RI beams (5–10 MeV/nucleon). The optics of the course is so tuned that RI beams can be focused in a momentum-dispersive mode at the end. The use of a mono-energetic wedge degrader allows one to produce energy-bunched RI beams at low energies, which have a relatively small spread in energy and stopping range. The gas catcher system with an RF ion-guide [16] will be installed at the course, being followed by an ISOL system. Efficient stopping and extraction of RIs may be made possible independently of their chemical nature. This low-energy course will also be used for secondary reaction studies at low energies, such as the measurement of RI-beam induced fusion–evaporation reactions in which high-spin states can be studied by means of in-beam γ-ray spectroscopy.

3.6. Predicted RI-beam intensities

In the RIBF project, a much wider range of heavy-ion beams will be available with higher energies and higher intensities, compared with the existing RIKEN facility. The primary-beam energies should increase by about 3–5 times, while the intensities are expected to increase by about 3–1000 times, depending on atomic number of ions. Briefly, this should increase the RI-beam intensities by several tens of times in even the least cases.

The PF reactions are used to produce RI beams in all mass regions, while the in-flight fission is used when medium-heavy neutron-rich RI beams far from stability are requested with high intensities. In the case of using the in-flight fission of ^{238}U ions, for instance, the intensity of a doubly-magic neutron-rich nucleus ^{132}Sn is estimated to be on the order of 10^8 pps, which is almost 1000 times larger than the PF reaction of a ^{136}Xe beam. The intensity of another doubly-magic neutron-rich nucleus ^{78}Ni, located very far from stability, is estimated to be about 10 pps, which is large enough to conduct secondary reaction studies such as high-energy Coulomb excitation. This intensity is more than 10 times larger compared with the PF reaction of a ^{86}K beam. The doubly-magic proton-rich nucleus ^{100}Sn, which is also very far from stability, may be produced through the PF reaction with a ^{124}Xe beam. In this case, the intensity is estimated to be a few pps, which is large enough to make some secondary reaction studies as well as decay studies. The RI-beam intensity was estimated by using the cross-section data measured at GSI [51] for the in-flight fission and by using the EPAX2 formula [52] for the PF reactions.

The integrated capability of the BigRIPS and the RIBF cyclotrons will significantly enlarge the scope of unstable nuclei which can be studied. For instance, new isotopes will be observed further toward the drip line and a variety of secondary reaction studies will be applied for rare isotopes further from stability.

3.7. Superconducting quadrupoles and cryogenic system

The superconducting quadrupoles to be used for the BigRIPS-I are a quadrupole triplet, as mentioned in Section 3.3. Three quadrupoles connected rigidly to each other are installed in a helium vessel in a single cryostat, cooled in a bath of liquid helium.

Two types of superconducting quadrupoles will be used: an iron-dominated type and an air-core type. With a much smaller cold-mass weight, the latter type is adopted for the quadrupole triplet right after the production target (STQ1). The quadrupole triplet right after the first dipole (STQ2) may also be of this type. This is because they are exposed to high neutron radiation, which generates significant heat loads to the cold mass at 4.5 K in the cryostat. Smaller cold-mass weight reduces the heat loads. The rest of the quadrupole triplet (STQ3–STQ14 and those in the RI-beam delivery lines) are of the iron-dominated type.

All the iron-dominated quadrupoles have an identical cross-section. Their pole-tip radius and warm bore radius are 170 and 120 mm, respectively. Maximum pole-tip fields are 2.4 T, corresponding to a field gradient of 14.1 T/m. Nominal effective lengths of the three quadrupoles are 0.5 m, 0.8 or 1.0 and 0.5 m, respectively. Quadrupole coils are flat and of a racetrack shape, orderly wound with a NbTi superconducting wire having a diameter of 1.1 mm. The use of thin wire allows low-current operation and hence low liquid-helium consumption. The Ampere-turn of the coils is about 200 kA/pole. Correction coils, such as superconducting sextupole and octupole coils, are superimposed on some of the quadrupoles. A prototype of the quadrupole triplet has been built and successfully tested. Fig. 10 shows a photograph of the prototype. The design of the iron-dominated quadrupoles is based on those developed at NSCL/MSU [53], although the coils and some other details are significantly different. Details are given in [54].

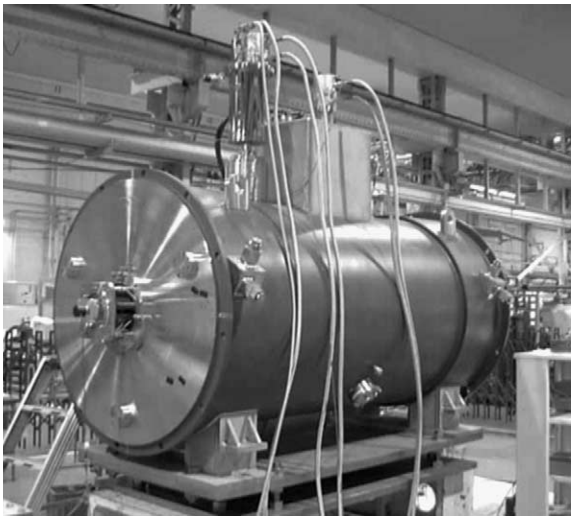

Fig. 10. A photograph of the prototype superconducting quadrupole triplet. A small refrigeration system is mounted on the cryostat. A field mapping device is installed in the inner bore of cryostat.

In the case of the air-core type, thicker superconducting wire will be used, because the absence of iron requires many more Ampere-turns. The quadrupole coils of this type are also flat and of a racetrack shape, orderly wound with a NbTi superconducting wire with a rectangular cross-section. The specification of STQ1 is as follows: the effective lengths are 0.5, 0.8 and 0.5 m, respectively; the warm bore radii are 90, 120 and 120 mm, respectively; the maximum field gradients are 24, 20 and 20 T/m, respectively. The specifications of STQ2 are the same as of the iron-dominated type. In designing the air-core type, it was important to adjust the cross-sectional shape as well as the position of the coils to achieve reasonable uniformity of the field gradient. The detailed design is in progress.

The five quadrupole triplets in the concrete shielding (STQ1 to STQ5) are cooled by an integrated cryogenic system with a large cooling capacity, in which a single refrigerator supplies liquid helium through a transfer line. Its cooling capacity is around 320 W at 4.5 K. This scheme has been adopted because these quadrupole triplets, particularly the first two triplets, are heated by the neutron radiation. The heat loads are estimated to be around 150 W at 4.5 K. On the other hand, the quadrupole triplets downstream (STQ6 to STQ14) are cooled by a small refrigeration system in which GM–JT refrigerators are employed. A small refrigeration system is mounted on the cryostat of each quadrupole triplet. We adopted this scheme because the neutron radiation should be very low in the second stage. This scheme reduces the fabrication cost significantly.

Possible radiation damages caused by the neutron radiation will be taken into account in the design of not only the magnets but also of other devices.

3.8. Production target and beam dump

The beam power expected in the RIBF is quite high, up to 100 kW: e.g. 45 kW for ^{136}Xe and 84 kW for ^{238}U at 350 MeV/nucleon and 1 pμA. The maximum beam power deposited in the production target is expected to be 20–30 kW, depending on target thickness. The power density in the target is also quite high, amounting to about 40 GW/m^2 for a beam size of 1 mm in diameter. In order for the production target to stand the heat load, a water-cooled rotating disk target [55] is being developed. Fig. 11 illustrates the rotating target system. The cooling water is fed through the rotating shaft to the cooling disk on which a disk target is fixed. The vacuum in the target chamber is maintained by using a magnetic-fluid feedthrough as shown in the figure. Simulation studies and beam testing have shown that the target is tolerant of the predicted heat load [55].

Primary beams will be stopped in a water-cooled beam dump inside the first dipole magnet of BigRIPS, the stopping place depending on the ratio of the $B\rho$ value of RI beams to that of primary beams. The beam dump, which is a copper plate, is installed inside and on both sides of the vacuum chamber of the first dipole. If the surface of the beam dump is perpendicular to the axis of beam, the power density is expected to be about 400 MW/m^2 in the worst case. Since this value is too high to cool, it is necessary to increase the area of beam spot where it stops. The beam dump is to be placed at a grazing angle, like 5–10°, with respect to the axis and moreover it has a saw-tooth shaped surface (vertically), so that the area can be

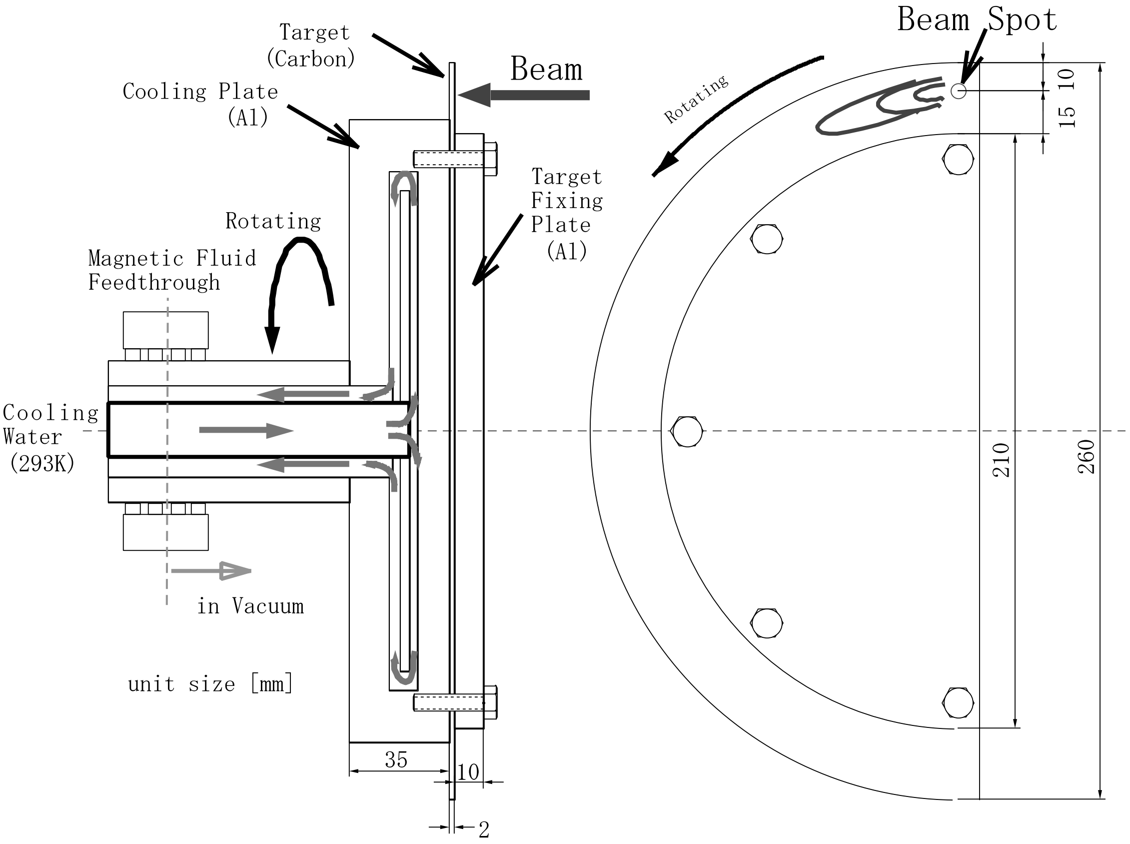

Fig. 11. A schematic diagram of the water-cooled rotating disk target. (Courtesy of A. Yoshida, RIKEN.)

enlarged. This way the power density can be reduced to the order of 10–20 MW/m^2. The grazing-angle stopping reduces the thickness of beam dump as well. The beam dump plate will be cooled using a turbulence flow of pressurized and sub-cooled boiling water [56]. Although the design study is still going on, according to the [56], it is possible to build a beam dump which can withstand the predicted power density.

4. Summary

In summary, the in-flight RI-beam separators existing in Japan, the RIPS at RIKEN, the Secondary Beam Line at RCNP, the Secondary Beam Course at NIRS, the CRIB at CNS and the RMS at JAERI, were reviewed emphasizing their characteristic features and present status. The RIPS and the separators at RCNP and NIRS are intermediate-energy facilities where PF reactions are used as the production reaction, while the CRIB and the RMS are low-energy facilities where transfer reactions are used in inverse kinematics at low energies. One of them, the RIPS at RIKEN, has been in operation for over 10 years, producing a wealth of new results on structure and reaction studies of rare isotopes far from stability and demonstrating the promising perspective of in-flight separation scheme.

Design features of the new in-flight separator BigRIPS at RIKEN, being built for the RIBF project, were outlined. The BigRIPS is one of the next-generation separators with upgraded features, characterized by large acceptances, a tandem separator scheme and production of energy-bunched low-energy RI beams. The large acceptances, achieved with superconducting quadrupoles with large apertures, allow one to efficiently produce RI beams by in-fight fission of uranium ions. The tandem separator scheme allows one to deliver tagged RI beams, by which secondary reaction studies will be greatly facilitated. The low-energy course following the BigRIPS allows one to deliver energy-bunched RI beams at low energies, which can be applied for the gas catcher system. This system should make it possible to combine the in-flight separation scheme with the ISOL system, realizing a PF-based ISOL facility. The RIBF cyclotrons have high performance in energy and intensity. The integrated capability of the cyclotrons and the BigRIPS will significantly enlarge the scope of future RI-beam experiments.

The detailed design and fabrication of the BigRIPS is in progress. The first RI-beam production is scheduled in 2006. The commissioning of the BigRIPS will open up a new era of in-flight RI beam facilities.

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