2. Acceleration Scheme

Accelerators in the RIBF consist of three existing accelerators and three ring cyclotrons under construction. The existing accelerators are the RIKEN Linear Accelerator (RILAC), an AVF-type cyclotron (AVF) and the RIKEN Ring Cyclotron (RRC). These accelerators are energy-tunable machines. After the RILAC, a Charge State Multiplier (CSM) system [1] has been installed. The CSM consists of accelerator, decelerator and a charge stripper. Charge stripping after acceleration and deceleration to the RILAC energy increases charge-stripping yields of higher charge states. The CSM also works as an energy booster of the RILAC. Three ring cyclotrons under construction are a fixed-frequency Ring Cyclotron (fRC) [2], the frequency-tunable normal conducting ring cyclotrons, which is named as the Intermediate-stage Ring Cyclotron (IRC) [3], and the world's first separated-sector type Superconducting Ring Cyclotron (SRC) [4]. Specifications of five cyclotrons are summarized in Table 1. In addition to these six accelerators mentioned above, new injector linac is also proposed as an upgrade of the RIBF accelerator complex.

Table 1. Specifications of cyclotrons in the RIBF.

	K-number (MeV)	Number of Sectors	Velocity gain	RF system	Frequency range (MHz)	Harmonic number
AVF	70	4		2 with FT	12 - 24	2
RRC	540	4	4.0	2	18 - 38	5, 8 - 11
fRC	570	4	2.1	2 + FT	18 - 38	12
IRC	980	4	1.5	2 + FT	18 - 38	7
SRC	2500	6	1.51	4 + FT	18 - 38	5, 6

In the RIBF heavy-ion accelerator complex, three charge strippers are planned to use as shown in Fig. 1. The first stripper is located between the accelerator and decelerator of the CSM system preceded by the RILAC. The second stripper is located between the RRC and the fRC. The third stripper is located between the fRC and the IRC.

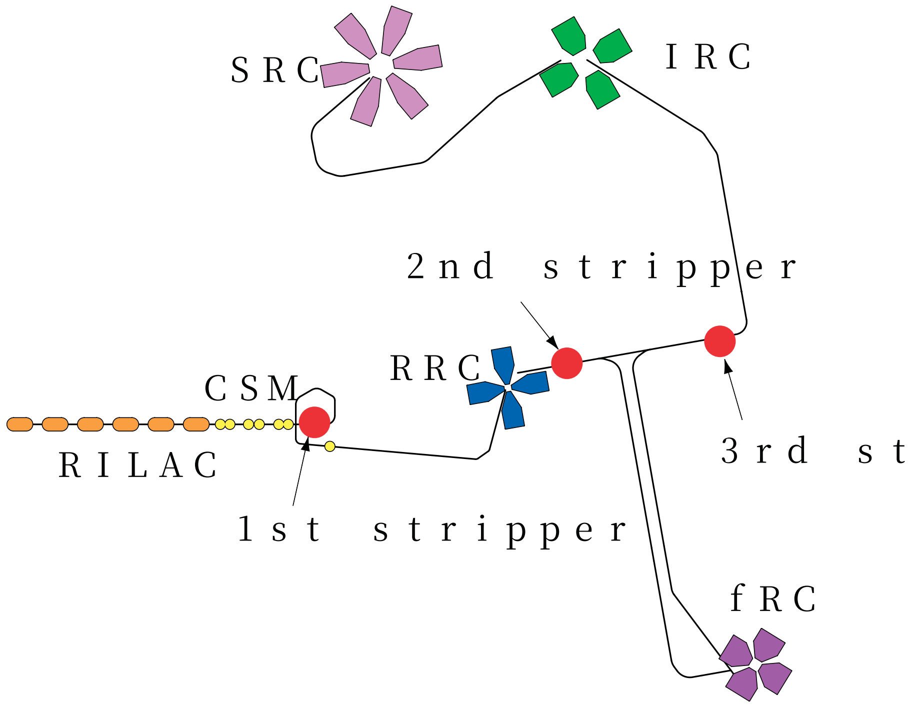

Figure 1. Schematic layout of the accelerators and charge strippers in the RIBF.

Using these six accelerators and three charge strippers, the following three acceleration modes will be available in the RIBF. The first one is the fixed-energy mode, the second one is variable-energy mode and the last is the polarized-deuteron mode. We will explain briefly these three modes.

Fixed-energy mode

Five accelerators (RILAC, RRC, fRC, IRC, SRC) will be used in series as illustrated in Fig. 2. The accelerators illustrated with dark colors will be used in this mode. All the elements from hydrogen to uranium will be accelerated up to 350 MeV/nucleon. However, the beam energy is fixed because the fRC is a fixed-frequency machine.

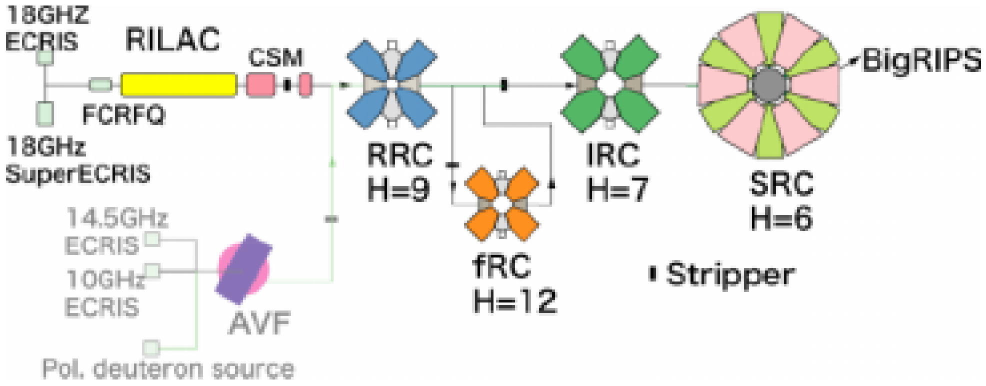

Figure 2. Fixed energy mode of the RIBF. Machines with dark colors are employed in the fixed energy mode. Machines with faint colors will not be used in this mode.

The acceleration energy after each accelerator is 0.7, 11, 51, 115 and 350 MeV/nucleon for RILAC, RRC, fRC, IRC and SRC, respectively. Two- or three-step charge stripping is necessary in the present mode. In the case of a low-beam-intensity (0.01 pμA, in the commissioning stage) 350-MeV/nucleon-^{238}U beam, three-step charge stripping will be performed. The first stripper is located between the accelerator and decelerator of the CSM system preceded by the RILAC. It should be mentioned that the beam energy at the first stripper will be raised up to 0.9 MeV/nucleon using the CSM. The second stripper is located between the RRC and the fRC. The third stripper is located between the fRC and the IRC. In the case of a 350-MeV/nucleon-^{136}Xe beam, the first charge stripper is unnecessary because the existing 18 GHz-ECR ion source is capable of providing ions with a highly-charged state sufficient for the acceleration in the RRC.

Variable energy mode

For ions lighter than ^{86}Kr, the beam energy higher than 350 MeV/nucleon will be realized without the fRC. The acceleration scheme is illustrated in Fig. 3. Typical examples of the variable-energy mode are a 350-MeV/nucleon-^{86}Kr beam and a 400-MeV/nucleon-^{48}Ca beam. In the case of the ^{86}Kr beam, a charge stripping after the RRC is necessary.

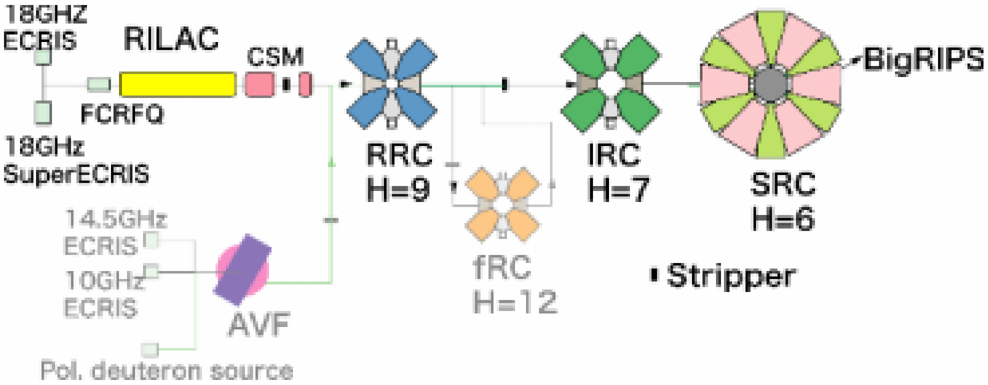

Figure 3. Variable-energy mode of the RIBF.

Polarized deuteron mode

The existing facility had been providing polarized deuteron beams for basic researches of nuclear physics. The polarized ion source placed in the upstream of the AVF cyclotron can provide polarized deuteron beams to the AVF. Two existing cyclotrons accelerated deuterons to 270 MeV without losing the polarity of the beam. The polarized deuteron mode in the RIBF aims to extend the energy region of polarized deuteron beams up to 880 MeV. The accelerators employed in this mode are the AVF, the RRC and the SRC as shown in Fig. 4. To realize this acceleration mode, the injection radius of the SRC was chosen to be the same as the extraction radius of the RRC.

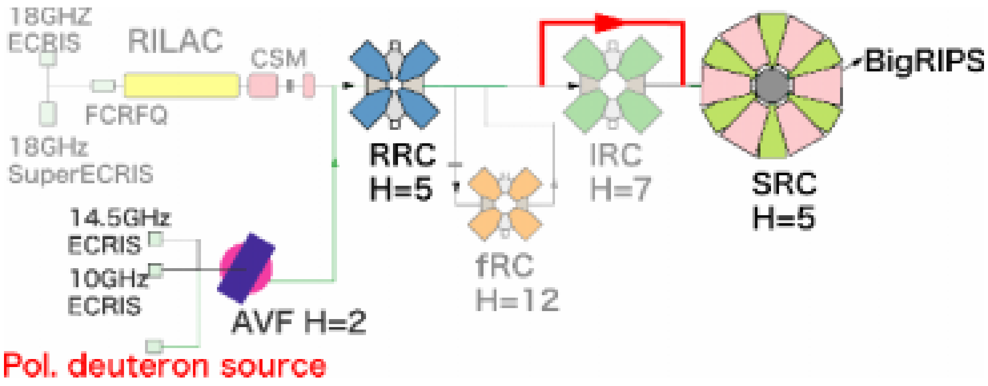

Figure 4. Polarized deuteron mode of the RIBF.

Charge stripping scheme

The charge-stripping scheme in the RIBF is summarized in Table 2 for 350-MeV/nucleon-^{238}U, ^{136}Xe and ^{86}Kr beams.

Table 2. Charge stripping scheme in the RIBF

Ion	^{238}U			^{136}Xe		^{86}Kr
Stripper section	1st	2nd	3rd	2nd	3rd	2nd
Energy (MeV/nucleon)	0.9	11	51	11	51	11
Required charge-state	35+	72+	88+	42+	51+	32+
Thickness (mg/cm^2)	0.025 [6]	0.5 [7]	14 [7]	0.15	14 [7]	0.15[8]
Expecting charge-state	36+	72+	88+	44+	52+	33+
Fraction	17% [5]	19% [7]	34% [7]	30%	48% [7]	38%[8]

The equilibrium charge state at the first stripper is calculated using the table in Ref. [5]. The estimated charge fraction requires that the incident beam intensity should be 0.9 pμA for a 0.01 pμA ^{238}U beam with the energy of 350 MeV/nucleon. There are some semi-empirical formulae for carbon foil lifetime made by fitting rather scattered experimental data [6, 9, 10]. When a 0.9 pμA uranium beam at 0.9 MeV/nucleon is focused on a carbon foil with 5-mm-diameter circular shape, using Livingston's formula [10], the lifetime of the carbon foil is predicted to be about 6 hours. To avoid this short lifetime problem of the carbon foil strippers for high-intensity uranium beams, a new injection system, which is capable of providing 0.7-MeV/nucleon-$^{238}U^{35+}$ beams, has been proposed.

After the second stripper, 3 pμA $^{238}U^{72+}$, 2 pμA $^{136}Xe^{44+}$, and 1 pμA $^{86}Kr^{33+}$ beam at 11 MeV/nucleon are required for the 1 pμA beam at 350 MeV/nucleon. In case of uranium, an experimental data [7] shows that the equilibrium charge state at 11.4 MeV/nucleon stripped by a 0.49 mg/cm^2 thick carbon foil is 73+ with a fraction of 19%. When a 15 pμA uranium beam is stripped by a 0.5 mg/cm^2 thick carbon foil, 1 kW power is deposited to the foil which easily evaporates the carbon foil. To solve the heat problem, a rotating carbon foil stripper is proposed for the second stripper.

After the third stripper section, 1 pμA beams are expected to be the same as the currents at the exit of the SRC. The GLOBAL calculation [7] predicts that fractions of $^{238}U^{88+}$ and $^{136}Xe^{52+}$ obtained by 14 mg/cm^2 thick carbon plates can be 34 % and 48 %, respectively. Such a thick stripper causes a serious energy loss of the ions. Hence, the acceleration energy of the fRC was chosen to be 51 MeV/nucleon, which is 10 % larger than the injection energy of the IRC (46 MeV/nucleon). A rotating carbon disk stripper will be used for the third stripper section.

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