Proceedings of the 14th International Conference on Cyclotrons and their Applications, Cape Town, South Africa

RIKEN RI BEAM FACTORY PROJECT

Y. Yano, A. Goto, Y. Miyazawa, M. Hemmi, T. Chiba, T. Kageyama, K. Ikegami, M. Takanaka, T. Kawaguchi, S. Kohara, M. Kase, T. Tominaka, Y. Batygin, T. Kubo, T. Nakagawa, Y. Tanaka, E. Ikezawa, M. Wakasugi, T. Mitsumoto, N. Inabe, O. Kamigaito, H. Okuno, S. Fujishima, A. Ohtomo, and T. Ohkawa

The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-01, Japan

T. Katayama, S. Watanabe, and M. Tomizawa

Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan

J. Xia, Y. Rao, and Y. Yuan

Institute of Modern Physics, Chinese Academic of Sciences, Nanchang Road 253, P.O. 31, 730000, Lanzhou, P. R. China

The RARF (RIKEN Accelerator Research Facility) proposes "*RIKEN RI Beam Factory*" as a next facility-expanding project. In 1995 funding year, the budget for the three-year R&D has been partially approved. The factory is aimed at providing RI (Radioactive Isotope) beams over the whole atomic mass range with the world-highest level of intensities in a wide energy range up to several hundreds MeV/nucleon. We adopt the "projectile fragmentation" approach for realizing the factory. At present a superconducting ring cyclotron for an energy booster of the existing K540-MeV ring cyclotron is being investigated to provide primary heavy-ions, up to uranium ions, with the energies exceeding 100 MeV/nucleon. Multi-use experimental storage rings (MUSES) are also being studied as a new type of experimental installation. It consists of an accumulator-cooler ring, booster synchrotron ring and double storage rings. With the MUSES, various types of unique colliding experiments become possible: ion-ion merging or head-on collisions; collisions of either electrons or X-rays with ion (stable or RI) beams; internal target experiments; and atomic and molecular physics with cooler electron beams.

1 Introduction

The RARF (RIKEN Accelerator Research Facility) houses a heavy-ion accelerator complex consisting of a K540-MeV ring cyclotron (RRC) as a main accelerator and two different types of the injectors: a variable-frequency heavy-ion linac (RILAC) and a K70-MeV AVF cyclotron (AVF). The facility provides not only nuclear physicists but also researchers of atomic physics, nuclear chemistry, material science, radiobiology and others with various kinds of heavy-ion beams of a wide energy range of 1 MeV/nucleon to 100 MeV/nucleon. One of remarkable features of this facility is capability of supplying light-atomic-mass RI (radioactive isotope) beams with the world-highest level of intensities by the projectile-fragment separator, RIPS.[1] In these several years nuclear physicists have opened up a quite new and fascinating heavy-ion science exploiting such RI beams. In order to further promote this new science, the RARF proposes "*RIKEN RI Beam Factory*" as a next facility-expanding project. The factory takes the aim at providing RI beams covering over the whole atomic-mass range with the world-highest intensities in a wide energy range up to several hundreds MeV/nucleon.

This paper describes a conceptual design of an accelerator complex most suitable for realizing the factory, and briefly presents Multi-USe Experimental Storage rings (MUSES) proposed as a new type of experimental installation. In addition the RILAC-upgrade program currently running relevantly to the project is reported.

2 Accelerator Complex Proposed for RIKEN RI Beam Factory

The best means to generate RI beams of an intermediate energy is the utilization of the so-called "projectile fragmentation." In general, the reaction cross section for this fragmentation steeply enhances with increasing projectile's energy up to 100 MeV/nucleon until it saturates above around this energy. Thus, in order to efficiently generate RI beams over the whole mass range using this approach, firstly, primary-beam energies are required to exceed at least 100 MeV/nucleon even for very heavy ions such as uranium. Due to this condition, the availability of RI beams at the present RARF is restricted to their mass less than around 60. Secondly, needless to say, intensities of primary beams must be as high as possible. Thirdly, from the cost-effectiveness point of view, the existing machines should be exploited and utilized as much as possible. Based upon these considerations, we propose an accelerator complex as illustrated in Fig. 1 which possesses such acceleration

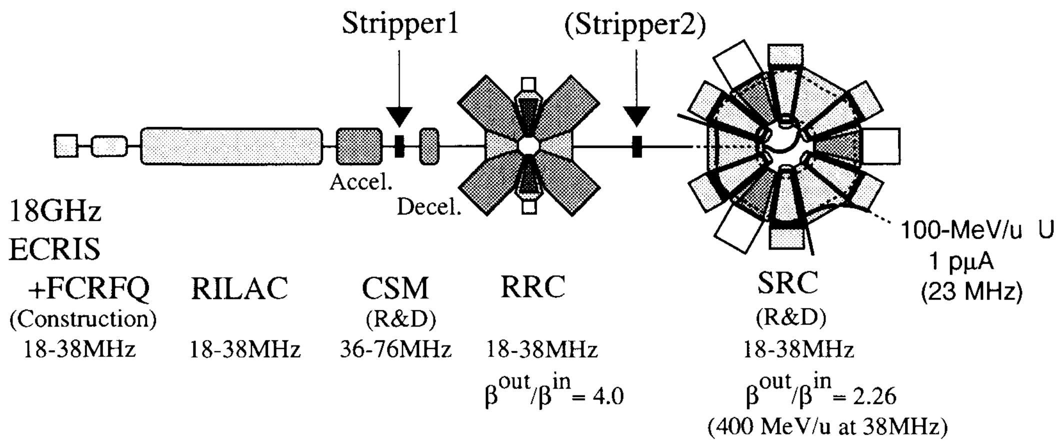

Fig. 1 Concept of the heavy-ion accelerator complex for the RI beam factory.

performance that *a 100-MeV/nucleon uranium beam with the intensity over 1 pμA is obtainable.* We build a superconducting ring cyclotron for an energy booster of the existing RRC, and upgrade the RILAC by introducing a new pre-injector system and a charge-state multiplier (CSM).

2.1 New Pre-injector System for the RILAC

The RILAC is capable of accelerating heavy-ions of wide mass-to-charge ratios covering from 1 to 28, changing the rf frequency between 18 MHz and 38 MHz. In this frequency region this linac works quite stably. We use this machine as the initial-stage accelerator. Presently the RILAC is equipped with an 8 GHz ECR ion source, but the performance of this source is not high enough for the "*Factory*." In order to upgrade the RILAC performance in the beam intensity by one or two orders of magnitude, a frequency-tunable RFQ linac equipped with an 18-GHz ECR ion source (ECRIS-18) has been developed for a new pre-injector of the RILAC.[2]

The fabrication of the whole system was completed in the spring of 1995. We have made performance test of the ECRIS-18 and the RFQ linac as well as beam acceleration test of the system. This pre-injector will be installed in the summer of 1996 as an alternative to the existing 450-kV Cockcroft-Walton accelerator.

2.1.1 FC-RFQ linac

The resonator of the RFQ linac has a new type of a folded-coaxial (FC) structure, and the resonant frequency is tuned by use of a movable shorting plate. The distinctive feature of this FCRFQ is the capability of the low frequency operation and the wide frequency-tunability in spite of its compact size: 700mm (W) × 1700mm (L) × 1150mm (H). This FCRFQ allows us to accelerate ions with mass-to-charge ratios of 6 - 27 at up to 450 keV per charge, which is equivalent to the performance of the existing Cockcroft-Walton accelerator.

The resonant frequency was measured to vary from 17.7 MHz to 39.2 MHz. From the shunt impedance measurement, the required maximum RF power was found to be 26 kW (cw) at the maximum inter-vane voltage of 33.6 kV. The beam transmission efficiency of 85 % at the maximum through the FC-RFQ linac was obtained in the first tests. The beam quality has not yet been measured.

2.1.2 ECRIS-18

The ECRIS-18 is of a single-stage type and operates at 18 GHz. The axial mirror field has peaks of 1.4 T (mirror ratio is 3.0) and the radial hexapole field is 1.4 T at the pole surface of 80 mm in diameter, both of which are high enough for the double-frequency operation. The axial mirror field is produced by a pair of solenoids enclosed with an iron yoke that are excited by two power supplies of 800 A. The power consumption of the solenoids is 140 kW. The radial field is produced with 36 segments of permanent magnets made of Nd-Fe-B. RF power of 18 GHz is fed by a klystron with the maximum output power of 1.5 kW. This RF power source is designed to operate in both cw and pulse modes.

Ion beam intensities from the ECRIS-18 were measured for gaseous elements such as oxygen, argon and krypton with an extraction voltage of up to 15 kV (though a required maximum voltage is about 10 kV for delivering a beam to the FC-RFQ linac). Obtained beam intensities of Ar^{11+} and O^{7+} ions, for example, were 160 and 130 eμA, respectively, with an RF power of about 600 W and an extraction voltage of 15 kV. Fig. 2 shows comparison of the performance of the ECRIS-18 and those of other ECR ion sources such as CAPRICE. It was found that at the same RF power the beam intensity increases with increasing the frequency of microwave and magnetic field strength.

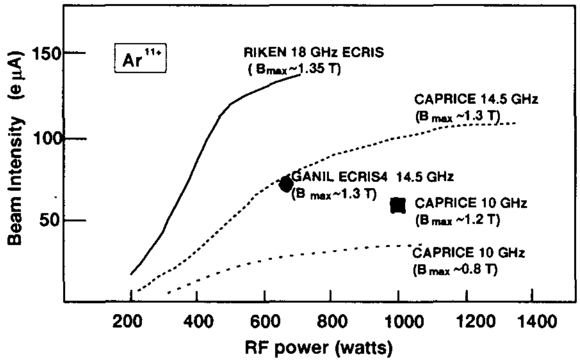

Fig. 2 Comparison between the ECRIS-18 (at the extr. vol. of 13kV) and other ECR ion sources (at 20kV).

2.2 Charge-State Multiplier (CSM)

A high-intensity heavy-ion d.c. beam produced by the ECRIS-18 is bunched and accelerated by the FCRFQ with the transmission efficiency of as high as 85% even at 1 mA. The value of the efficiency was calculated by the computer code BEAMPATH.[3] This pre-accelerated beam is fully accepted and accelerated by the existing RILAC.

The output beam from the RILAC is passed through a charge-state multiplier (CSM, under design) to reduce its magnetic rigidity with the velocity unchanged, and injected into the existing RRC. The CSM consists of an accelerator, a charge stripper and a decelerator. The accelerator and decelerator are of a type of frequency-tunable IH linacs, whose operational radio-frequencies are twice as that of the RILAC to double an acceleration gradient. In the present design maximum gap voltages are set to be 350 kV for 62 cells of the accelerator and for 28 cells in the decelerator, and total lengths of each are 12.4 meters (partition into three or four units is necessary) and 5.5 meters, respectively. Transmission efficiency through the CSM depends only on charge state distributions behind the charge stripper foil because the 6-dimensional emittance of the RILAC beam is already adiabatically damped so as to be fully captured by the acceptance of the CSM linacs. We estimate the yield of a given charge state in terms of Shima's formula[4] which is reliable in the relevant energy region. The CSM is a decisive device to obtain a higher-intensity or higher-energy very-heavy-ion beam in the proposed accelerator scheme; with this device the magnetic rigidity of a most-probable charge-state beam can be decreased down to the acceptable value of the RRC even when the injection velocity into the RRC is increased.

2.3 Superconducting Ring Cyclotron (SRC)

When we set the maximum beam energy of the SRC to be 400 MeV/nucleon and this energy to be achieved at 38 MHz of the maximum rf frequency of the RILAC, velocity of the RRC output beam is to be amplified by a factor of 2.26 by the SRC. To this end, the mean extraction radius of the SRC is taken to be 2.26 times the mean injection radius. We set this mean injection radius to be 2/3 times the mean extraction radius of the RRC; accordingly mean injection and extraction radii of the SRC are 2.37m and 5.36m, respectively. Then, to meet a good matching condition, the harmonic number in the SRC becomes 6 as that in the RRC

Table 1 Parameters of the accelerator complex (Sector angle = 23 deg.; with the second stripper).

Ion	f^{RILAC} MHz	q^{ECR}	E^{RILAC} MeV/u	E^{STRP1} MeV/u	q^{CSM}	E^{RRC} MeV/u	STRP2 yes/no	E^{SRC} MeV/u	B^{SRC} tesla
$^{16}O^{8}$	38.1	6	2.94	6.80	8	50.5	no	400	3.4
$^{40}Ar^{18}$	36.0	7	2.62	6.07	17	44.7	yes	330	3.4
$^{84}Kr^{36}$	34.9	14	2.46	5.71	30	41.8	yes	300	3.4
$^{129}Xe^{53}$	30.3	15	1.85	4.30	38	31.0	yes	200	2.8
$^{238}U^{85}$	30.3	28	1.85	4.30	59	31.0	yes	200	3.2
$^{238}U^{80}$	27.2	22	1.49	3.47	55	24.7	yes	150	2.9
$^{238}U^{78}$	23.0	16	1.07	2.48	49	17.5	yes	100	2.4

Table 2 Beam parameters for typical-ion acceleration (Sector angle = 23 deg.; with the second stripper).

Ion	E^{SRC} MeV/u	q^{ECR}	RFQ Effic.	STRP1 Effic.	q^{CSM}	E^{RRC} MeV/u	STRP2 Effic.	I^{SRC} pμA	I^{ECR} eμA
$^{16}O^{8}$	400	6	0.85	1.0	8	50.5	no	100	700
$^{40}Ar^{18}$	330	7	0.85	0.4	17	44.7	1.0	20	410
$^{84}Kr^{36}$	300	14	0.85	0.28	30	41.8	0.8	2	150
$^{129}Xe^{53}$	200	15	0.85	0.18	38	31.0	0.4	1	250
$^{238}U^{85}$	200	28	0.85	0.14	59	31.0	0.3	0.02	16
$^{238}U^{80}$	150	22	0.85	0.15	55	24.7	0.27	0.2	130
$^{238}U^{78}$	100	16	0.85	0.17	49	17.5	0.25	1	440

Table 3 Beam parameters (Sector angle =25 deg.; without the second stripper)

Ion	E^{SRC} MeV/u	q^{ECR}	STRP2 Effic.	I^{SRC} pμA	I^{ECR} eμA	B^{SRC} tesla	B^{SRC}(23 deg.) tesla
$^{16}O^{8}$	400	6	no	100	700	3.2	3.4
$^{16}O^{7}$	400	7	no	100	820(1)	3.9	
$^{40}Ar^{17}$	330	7	no	20	410	3.9	4.3
$^{84}Kr^{30}$	300	14	no	2	120	4.1	4.6
$^{129}Xe^{38}$	200	15	no	1	100	4.0	4.5
$^{238}U^{85}$	200	28	0.3	0.02	16	3.0	3.2
$^{238}U^{58}$	150	22	no	0.2	75(2)	4.1	4.6
$^{238}U^{49}$	100	16	no	1	110	4.0	4.5

(1): without STRP1
(2): STRP1-Effic. for 58+ = 0.07 while that for 55+ (most probable) = 0.15

is 9. The rf frequency range of the SRC is from 18 MHz to 38 MHz, which is the same as the RRC.

The 6-sector SRC with the sector angle of 23 deg. was, first, investigated. The design details are described in ref. 5.

Here, referring to Tables 1 and 2, we illustrate the acceleration of a uranium-ion beam up to 100 MeV/nucleon. The rf frequency of the RILAC (f^{RILAC}) is 23.0 MHz. A $^{238}U^{16+}$ beam with an intensity I^{ECR} from the ECRIS-18 is accelerated by the RILAC-CSM to 1.07 MeV/nucleon (E^{RILAC}). In the CSM the charge state is increased from 16^+ (q^{ECR}) to 49^+ (q^{CSM}) by the stripping at 2.48 MeV/nucleon (E^{STRP1}). The transmission efficiency of the FCRFQ and the yield of 49^+ are estimated to be 0.85 (RFQ Effic.) and 0.17 (STRP1 Effic.), respectively. The RRC output energy (E^{RRC}) is 17.5 MeV/nucleon, and the SRC final energy (E^{SRC}) is 100 MeV/nucleon. Provided that the transmission efficiency of both of the RRC and the SRC is 100% (this can be achieved by the *off-centering acceleration technique* which is routinely used for the RRC) and that the second stripper between the RRC and the SRC is not used, the beam intensity after the CSM is preserved up to the final energy. When the second stripper is used, the charge state is increased to 78+, but the beam intensity decreased with the efficiency (STRP2 Effic.) of 0.25. This STRP2 Effic. is estimated on the basis of the GANIL and the GSI data. If we demand 1 pμA (I^{SRC}), we need 440 eμA (I^{ECR}) from the ECRIS-18, while the magnetic field strength (B^{SRC}) in the extraction radius of the SRC becomes quite low at 2.4T. Similar estimation is shown for typical gaseous elements, provided that the sector field (B^{SRC}) of 3.4T is the maximum.

With the second stripper, B^{SRC} becomes moderate, but 440 eμA of U^{16+} is considerably hard to generate by the ECRIS-18. On the other hand, without the second stripper, B^{SRC} is required to reach to 4.5T (see Table 3). To reduce this difficulty, secondly, we investigated the case of the sector angle of 25 deg. as shown in Table 3. In this case the maximum B^{SRC} is decreased down to 4.1T, but 400 MeV/nucleon-$^{16}O^{8+}$ beam crosses ν_z=1.0 resonance, as shown in Fig. 3 where the tune values for the sector angle of

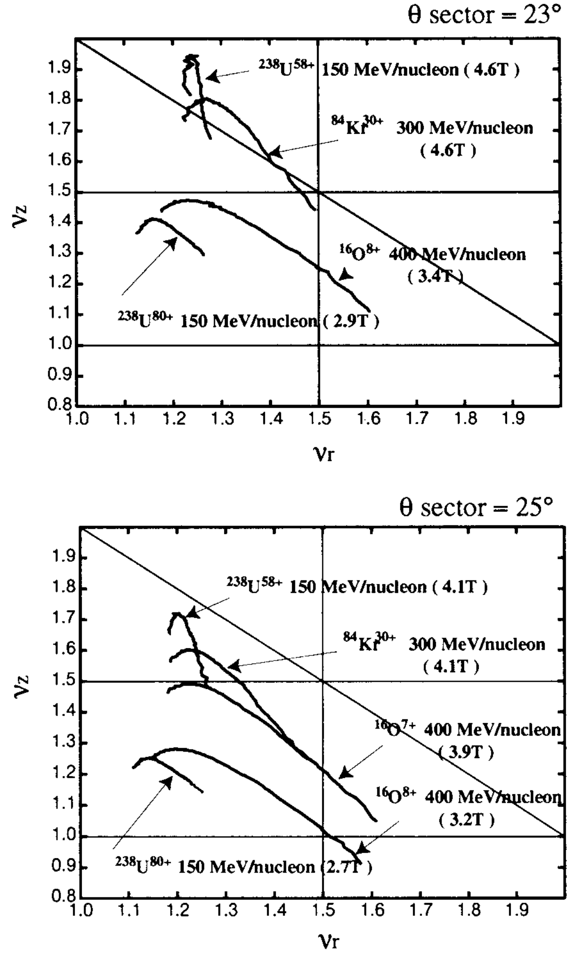

Fig. 3 Typical tune values in the cases of (top) 23-deg. sector angle and (bottom) 25-deg. sector angle.

23 deg. are also displayed. When $^{16}O^{7+}$ beam is accelerated up to the final energy without the first and second strippers, the situation is significantly improved, while high current of 820 eμA of O^{7+} is required from the ECRIS-18 if we demand 100 pμA from the SRC.

Based on these considerations, we made the design study of 4.1T sector magnet. Further details are described in ref. 5. Plan view of the sector magnet arrangement and the vertical cross section are shown in Figs. 4 and 5. Principal parameters of the magnet are listed in Table 4.

In table 5 comparison of the required I^{ECR} to the present performance of the ECRIS-18 and 14.5 GHz CAPRICE is given. Quite high beam intensities are expected to be provided especially for light ions, but use of such primary beams is not realistic from a viewpoint of the radiation-shielding-problem. We consider that a primary-beam intensity of 1pμA is sufficient to generate RI beams with desirable intensities in the whole mass region: *These primary beams will give us possibility to create and identify as many as one thousand kinds of new isotopes.* High current beams are used with a low duty factor of nearly 0.01% for the MUSES.

3 Multi-Use Experimental Storage Rings (MUSES)

3.1 Double Storage Rings (DSR)

Figure 6 shows a very preliminary layout of the "*Factory.*" "Big RIPS" is a superconducting RI beam generator with a magnetic rigidity of 11.6 Tm (corresponding to that of 400-MeV/nucleon ^{11}Li).

A new type of experimental facility, MUSES (Multi-Use Experimental Storage rings) is proposed for RIKEN RI beam factory. It consists of an Accumulator-Cooler Ring (ACR), Booster Synchrotron Ring (BSR) and Double Storage Rings(DSR). This MUSES is installed downstream from the Big RIPS. The DSR permits various types of unique colliding experiments: ion-ion merging or head-on collisions; collisions of electron and ion (stable or RI) beams; internal target experiments; and atomic and molecular physics with cooler electron beams. On the other hand, the ACR functions exclusively for the accumulation and cooling of RI beams and the BSR works solely for the acceleration of ion and electron beams: i.e., RI or electron beams are improved in quality by the ACR, are accelerated in the BSR and are injected into the DSR.

This section outlines the DSR, and the following section describes the BSR and ACR.

Table 4 Principal parameters of the sector magnet.

Sector magnet (1 sector : sector angle 25 deg.)	
Weight	900 ton
Pole gap distance	440 mm
Maximum field	4.1 T
Stored energy	100 MJ
Main coil	
Ampere turn	5 MA
Maximum current	5000 A
Maximum current density	40 A/mm^2
Trim coil	
Maximum current	500 A
Maximum current density	50 A/mm^2

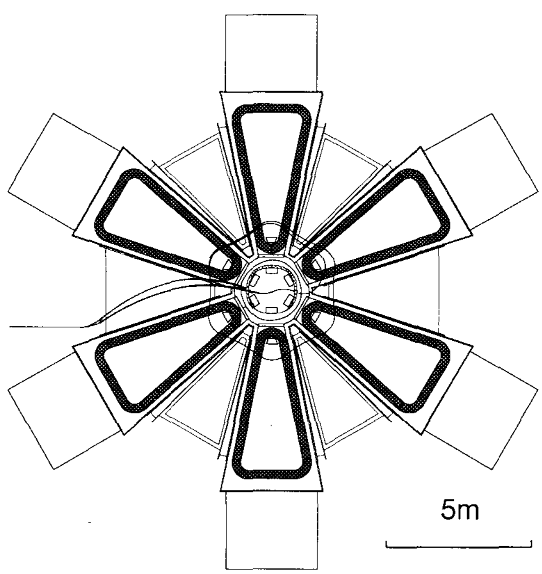

Fig.4 Schematic layout of the SRC together with the injection orbits.

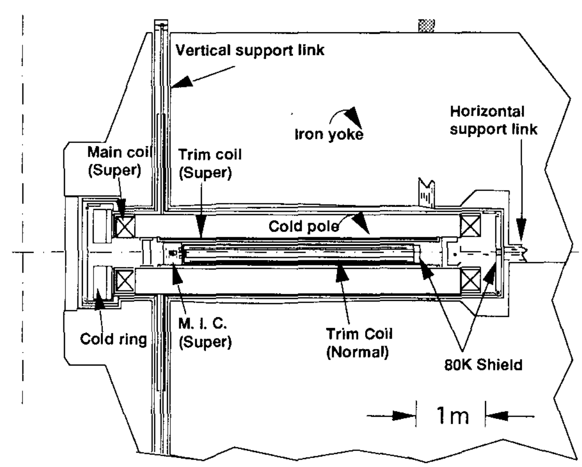

Fig. 5 Cross sectional view of the sector magnet.

Table 5 Comparison of the required beam intensity to the performance of the ECRIS-18 and the 14.5 GHz CAPRICE.

Ion	E^{SRC} MeV/u	I^{SRC} pμA	q^{ECR}	I^{ECR} eμA	$I^{ECRIS18}$ eμA extrac. voltage 10 kV	15kV	$I^{CAPRICE14.5}$ eμA extrac. voltage 20kV
$^{16}O^{8}$	400	100	6	700	550	610	800
$^{16}O^{7}$	400	100	7	820	110		100
$^{40}Ar^{17}$	330	20	7	410			
			8	470	330	410	500
$^{84}Kr^{30}$	300	2	14	120	90	110	120
$^{129}Xe^{38}$	200	1	15	100			80
$^{238}U^{85}$	200	0.02	28	16			20
$^{238}U^{58}$	150	0.2	22	75			25(*)
$^{238}U^{49}$	100	1	16	110			

(*): CAPRICE 10GHz

The two rings of the same specifications as shown in Table 6 are vertically stacked. Each lattice structure takes the form of a racetrack to accommodate two long straight sections. These straight sections of one ring vertically intersect those of the other ring at two colliding points. The ring circumference is 258.336 m, which is 46/6 times the extraction circumference of the SRC, 5.363m. It means that the harmonic of DSR is 46 while those of SRC is 6. The maximum $B\rho$–value becomes 14.6 Tm when a dipole field strength is 1.5 T at the maximum. The maximum energy is then, for example, to be 3.5 GeV for protons; 1.4 GeV/nucleon for light ions of q/A=0.5; and 1.0 GeV/nucleon for U^{92+} ions. For electrons the BSR boosts them up to the maximum energy of 2.5 GeV from 300 MeV injector linac, and are stored in the DSR. In the present lattice structure, the betatron tune values are 14.653 (horizontal) and 16.283 (vertical). The operating ion-beam energy is kept to be under the transition energy, since the transition gamma is as high as 24.44. At the colliding points the beta-function amplitudes are 0.6 m for both directions. The field-free section near the colliding points where experimental detector systems are installed, is 5.0 m in length. These two long straight sections are dispersion-free in horizontal and vertical directions.

One of the key researches planned at the DSR is the colliding experiment of an electron beam with an RI beam: 2.5 GeV electrons accumulated in one ring of the DSR are collided with an RI beam stored in the other ring. The scientific aim of this experiment is to determine the charge and current distribution in the neutron- or proton-rich radioactive nuclei. To keep a sufficiently long Touchek lifetime, the RF voltage of 2.0 MV is applied to the electron beam. The detailed specifications of stored electron beams in the DSR are given in Table 7. The number of stored electrons amounts up to 2.7×10^{12} particles which is limited due to the longitudinal coupled bunch instability. The typical colliding luminosity for the electrons and RI ions is estimated to be 5.6×10^{26} cm^2/s, provided that 1×10^7 particles of RI ions are stored and synchronously collided with electron bunches. In order to further improve the luminosity, the installation of a powerful pulsed heavy-ion source, e.g. a laser ion source or a metal-vapor ion source should be considered.

Another envisaged experiment is the isotope shift of X-ray absorption by the Li-like or H-like unstable nuclei. To produce the short wavelength X-ray from 20-1000 eV energy, the undulator will be inserted in an electron ring. In Table 8, the main parameters of undulator are given as well as the characteristics of the expected photon spectrum. To obtain the high flux mono-energetic X-ray, the emittance of stored electron beam should be as small as around 10 nano m.rad. The lattice structure of DSR is designed so as to give such a low emittance electron beam.

Other experiments such as ion-ion merging collisions at small angles are also envisaged. The luminosity is expected to be around 1×10^{26} cm^2/s when the number of stored ions are assumed at the space charge limit of 4×10^{12} particles and the colliding angle is 10 degrees.

3.2 Accumulator-Cooler Ring (ACR) and Booster Synchrotron Ring (BSR)

The ACR functions exclusively for the accumulation and cooling of RI beams : i.e., RI beams are improved in quality by the ACR, and are injected into the DSR. With the ACR, the acceptance required for the DSR is significantly reduced.

Taking the accumulation and cooling of an extremely neutron-rich $^{132}Sn^{50+}$ (a double-magic nucleus of 40 s in half-life) beam of 200 MeV/nucleon as an example, we give some specifications of the ACR. This RI beam is produced via the projectile fragmentation of a primary beam of ^{136}Xe ions with a peak current of 2 pμA (see Table 1). Typical beam characteristics are estimated as follows: The production rate is nearly 1×10^7 particles per second; the momentum spread is $\pm0.1\%$; the phase width relative to RF frequency is ±10 degrees; and the transverse emittances are 4.5 π mm·mrad in both horizontal and vertical directions.

Table 6 Parameters of the DSR.

Circumference C (m)	258.336
Max. $B\rho$ (Tm)	14.60
Average Radius R (m)	41.12
Radius of Curvature ρ (m)	9.733
Max. Stored Beam Energy	
proton (GeV)	3.55
ion (q/A = 0.5) (GeV/nucleon)	1.45
ion (q/A = 0.387) (GeV/nucleon)	1.00
electron (GeV)	2.50
Betatron Tune Values (Q_x/Q_y)	14.653/16.283
Momentum Compaction	0.00167
Transition γ	24.444
Max. Betatron Amplitude (β_x/β_y, m)	22.0/13.5
Max. Dispersion Function (D_x/D_y, m)	0.727/0.569
Betatron Amplitude at Interaction Point ($\beta_x{}^*/\beta_y{}^*$, m)	0.600/0.600
Length of Field-free Section at Colliding Section (m)	5.016

Table 7 Parameters of the Stored Electron Beam.

Max. Stored Beam Energy E_{max} (GeV)	2.5
Max. Stored Beam Current I (A)	0.5
Max. Stored No. of Electrons N	2.7×10^{12}
Injection Energy E_i (GeV)	2.5
Beam Emittance at 2.5 GeV ($\varepsilon_x/\varepsilon_y$) (nm·rad)	24.6/28.3
Energy Spread $\Delta E/E$	6.8×10^{-4}
Bunch Length σ (cm)	0.50
RF Voltage V_{RF} (MV)	2.0
Revolution Frequency f_{rev} (MHz)	1.161
RF Frequency f_{RF} (MHz)	499.0
Harmonic No. h	430
Number of Bunch (typical)	23
Touschek Lifetime at 2.5 GeV (s)	6.3×10^4
Synchrotron Radiation Loss at 2.5 GeV (keV/turn)	371.8

Table 8 Parameters of the Undulator and Photon flux.

Length L (m)	5.0
Length of One Period λ (cm)	4.0
Number of Period N	125
K Value	0.3 - 2.0
Beam Emittance at 2.5 GeV ($\varepsilon_x/\varepsilon_y$) (nm·rad)	24.6/28.3
Photon Flux at E_e=2.5 GeV, K=1.0 (photons/sec/mrad^2/0.1%BW)	1.3×10^{17}
Photon Energy at E_e=2.5 GeV, K=1.0 (eV)	982.5

Firstly, the above RI beam is stored in the ACR with the conventional multi-turn injection method. About 1×10^1 particles are injected for each one turn revolution, because the orbit frequency is nearly 1 MHz. Provided that the acceptance of horizontal phase space of the ACR is designed to be 125 π mm·mrad, and that the dilution factor is 1.25, after 22-turn injection, the emittance of the stored beam becomes as large as the full acceptance. At this moment, the number of stored particles increases up to 2×10^2 particles. Secondly, the stored particles are RF-stacked: The RF voltage of 24 kV is applied, and the frequency is swept from 30.30 MHz (corresponding to 200 MeV/nucleon) to 30.62 MHz. This frequency sweep brings about changes in the beam momentum and average radius by 1.8 % and 17 mm, respectively. This multi-turn-injection plus RF-stacking process is repeated at 10 Hz ($1/\tau_{cool}$) where τ_{cool} is a longitudinal stochastic cooling time. During this process the RF-stacked beam continuously undergoes the stochastic and electron cooling at the stacked top energy. Typical parameters of the stochastic cooling and electron cooler are tabulated in Tables 9 and 10. The longitudinal cooling time by the stochastic method is estimated to be as short as 0.1 s while the cooling time of electron cooler is several seconds. After a sufficiently longer period than the intrinsic half-life, the number of coasting particles accumulated in the ACR amounts up to the equilibrium value of 1×10^5. The momentum spread and emittances become less than 0.15 % and nearly 1 π mm·mrad, respectively. This high-quality stored beam is fast extracted, and is injected into the BSR by one turn.

The BSR serves as a synchrotron to accumulate and accelerate electrons from a 0.3 GeV linac to 2.5 GeV. At the initial energy of 0.3 GeV the damping times are estimated to be 0.5 s for the transverse direction, and 0.26 s for the longitudinal direction, which are short enough for the accumulation of electrons. The acceleration up to 2.5 GeV is done within 1 s. This top-energy electron beam is fast extracted and injected into the DSR by one turn. The BSR will also be used for the acceleration of ion beams transferred from the ACR. The maximum $B\rho$ of the BSR is designed at 14.6 Tm which is matched with the DSR. The accelerated ion beams will be fast extracted and one turn injected into the DSR, and also slowly extracted for the experiments.

Table 9 Parameters of the Stochastic Cooler.

Longitudinal Cooling Time (Number of Ions 1×10^8) (sec)	
U^{92+}(150 MeV/u)	0.06
C^{6+} (400 MeV/u)	0.01
Band Width W (MHz)	2000
Ambient Temperature T_n(K)	18
Atmospheric Temperature T(K)	80
Total Microwave Power P (kW)	10
Pickup Sensitivity Z_p (Ohm)	300

Table 10 Parameters of the Electron Cooler.

Maximum Electron Energy (keV)	300
Maximum Cooled Ion Energy (MeV/nucleon)	500
Maximum Electron Current (A)	10
Cathode Diameter (mm)	5.81
Electron Diameter at Cooling Section (mm)	50
Length of Cooling Section (m)	3.0
Cooling Time (s) for 200-MeV/nucleon $^{132}Sn^{50+}$, initial Δp/p=0.5% and emittance ε=125π mm·mrad	5.4

References

1. T. Kubo et al., "The RIKEN radioactive beam facility", NIM, B70 (1992) 309.
2. A. Goto et al., "Construction of a new pre-injector system for the RILAC", this proceedings.
3. Y. Batygin et al., "Effect of Field Variation on Beam Parameters in RIKEN RFQ Linac," 10th Symp. on Accel. Sci. Tech., Hitachinaka, Japan, Oct. (1995).
4. K. Shima et al.: *Atomic Data and Nuclear Data Tables*, **51,** (1992) 174.
5. T. Mitsumoto et al., "Design Study of Sector Magnets of Superconducting Ring Cyclotron for the RIKEN RI Beam Factory," this proceedings.

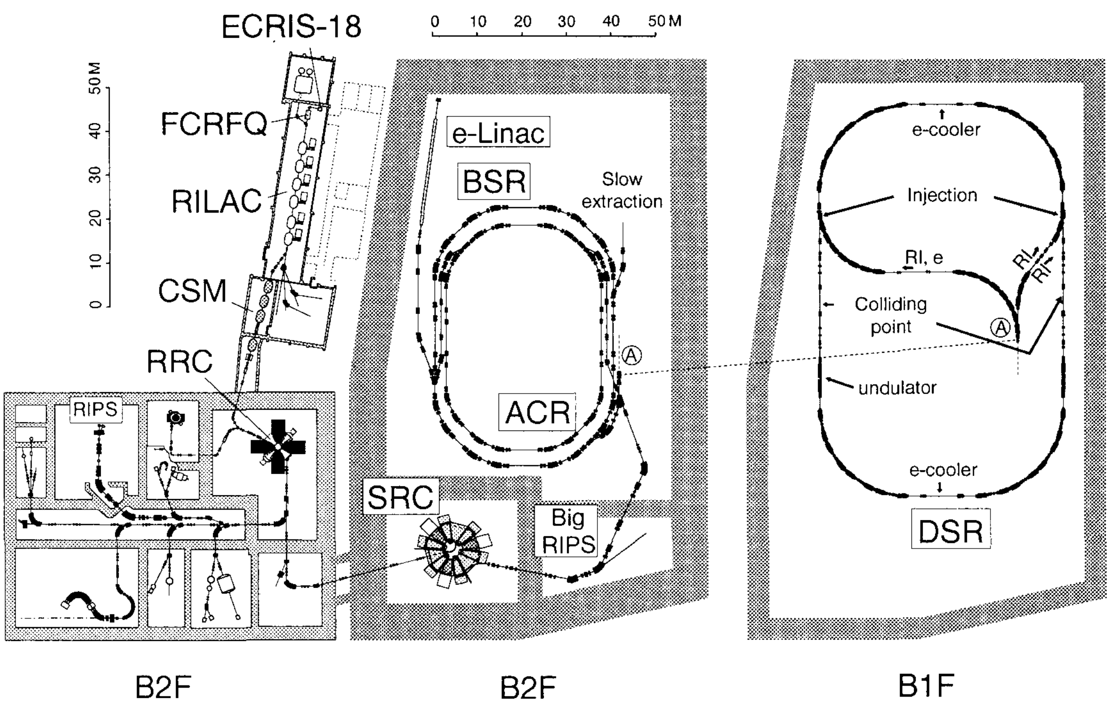

Fig. 6 Preliminary layout of the RIKEN RI beam factory. The accelerators are housed in the 2-story building.