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RIKEN RI BEAM FACTORY PROJECT

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1. Introduction

The RARF proposes "*RIKEN RI Beam Factory*" as a next facility-expanding project. The factory takes the aim at providing RI (Radioactive Isotope) beams of the whole 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 facility.

2. Accelerator Complex Proposed for RIKEN RI Beam Factory

The best means to generate such RI beams is the utilization of the so-called "projectile fragmentation." In general, the reaction cross section for this projectile fragmentation steeply enhances with increasing an energy of a primary beam up to 100 MeV/nucleon, and it saturates above around this energy. Thus, in order to efficiently generate RI beams of the whole mass range using this method, 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 performance that *a 100-MeV/nucleon uranium beam with the intensity over 1 pμA is obtainable.*

A new injector[1] composed of a frequency-tunable folded-coaxial RFQ linac (FCRFQ)[2] equipped with an 18-GHz ECR ion source (ECRIS-18)[3] is under construction in order to greatly upgrade the RILAC performance especially in the beam intensity. We use this machine as the initial-stage of the accelerator complex.

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.[4] 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 frequency-tunable IH linacs, whose operational radio-frequencies are twice that of the RILAC to double an acceleration gradient. In the present design a maximum gap voltage is set to be 350 kV, and total lengths of these linacs are 12.4 meters

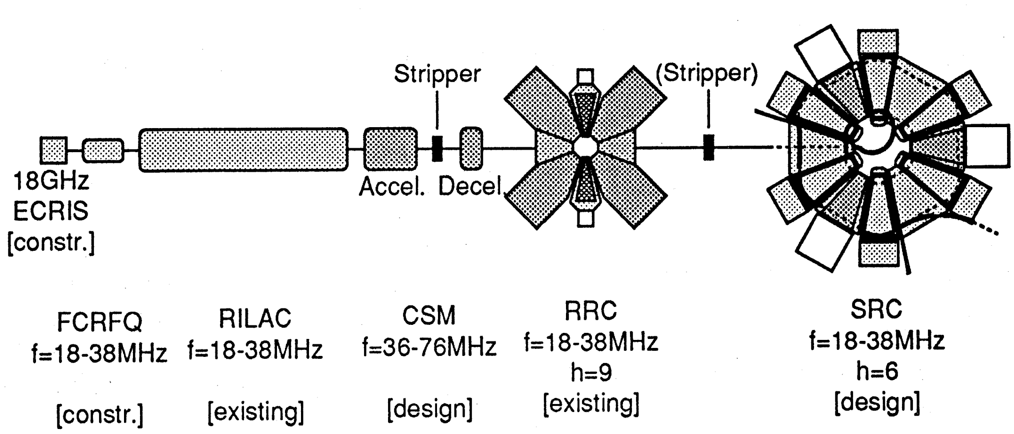

Fig. 1. Schematic diagram of the Heavy-ion Accelerator Complex proposed for the RIKEN RI Beam Factory.

(the partition into three or four units are 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.

Velocity of the RRC output beam is amplified by a factor of 2.26 with a six-sector superconducting ring cyclotron (SRC, under design)[6),7)], when the mean extraction radius (5.70 m) of the SRC is taken to be 2.26 times the mean injection radius (2.37 m). This mean injection radius is 2/3 times the mean extraction radius of the RRC. To meet a good matching condition, the harmonic number in the SRC is taken to be 6 as that in the RRC is 9. The preliminary calculation of betatron-frequency excursions implies that when we set the sector angle to be 23.5 degrees the maximum attainable energy is limited to be around 400 MeV/nucleon to avoid the crossing over ν_z=1.0 resonance.[6)]

Here, we illustrate the acceleration of a uranium-ion beam up to 100 MeV/nucleon. The rf frequency of the RILAC is 23.0 MHz. A $^{238}U^{16+}$ beam with an intensity (I^{ECR}) of 145 eμA from the ECRIS-18 (this intensity is extrapolated from the 10 GHz CAPRICE data) 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. The yield of 49^+ and the transmission efficiency of the FCRFQ are estimated to be 0.17 and 0.85, respectively, and thus a beam intensity of 1.3 pμA is to be obtained. This beam intensity (I^{SRC}) is preserved up to the final energy, 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). The RRC output energy (E^{RRC}) is 17.5 MeV/nucleon, and the SRC final energy (E^{SCR}) is 100 MeV/nucleon. The SRC sector field at the extraction (B^{SRC}) is needed to reach to 3.9 T. Similarly, the maximum beam intensities for typical gaseous elements are obtained as listed in Table 1, provided that the sector field (B^{SRC}) of 4T at the maximum can be achieved.

Quite high beam intensities can 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.*

Table 1. Prospects of primary-beam intensities of typical heavy ions.

Ion	RF frq MHz	q^{ECR}	I^{ECR} eμA	E^{RILAC} MeV/u	q^{CSM}	E^{RRC} MeV/u	E^{SRC} MeV/u	I^{SRC} pμA	B^{SRC} tesla
$^{16}O^{8}$	38.1	6	800	2.94	8	50.5	400	113	3.4
$^{40}Ar^{17}$	37.0	8	750	2..77	17	47.4	364	34	3.8
$^{84}Kr^{30}$	34.9	14	200	2.46	30	41.8	300	3.4	4.0
$^{129}Xe^{38}$	30.3	15	140	1.85	38	31.0	200	1.4	3.9
$^{238}U^{85}$	30.3	28	27	1.85	59	31.0	200	0.04*	3.2
$^{238}U^{58}$	27.2	22	80	1..49	58	24.7	150	0.22	4.0
$^{238}U^{49}$	23.0	16	145	1.07	49	17.5	100	1.3	3.9

* The charge-stripping is done in between the RRC and the SRC. The yield is assumed to be 30%.

3. Multi-Use Experimental Storage Rings (MUSES)

Figure 2 displays a quite preliminary lay out of the RI beam factory. The MUSES, installed downstream of an RI-beam generator (Big RIPS) for the SRC, consists of Double Storage Rings (DSR) and a small-sized Accumulator-Cooler Ring (ACR). 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 cooling electron beams. On the other hand, the ACR functions exclusively for the accumulation and cooling of RI beams by the multi-turn injection plus RF-stacking associated with the electron cooling as well as for the acceleration of electron beams from 0.5 GeV up to 2.5 GeV and their radiation damping: i.e., RI or electron beams are improved in quality by the ACR, and are injected into the DSR by one turn. With the ACR, the acceptance required for the DSR is significantly reduced. In the figure, the schematic drawing of the DSR is shown, but that of the ACR are not given.

In the DSR two rings of the same specifications as shown in Table 2 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 202.08 m, which is 6 times the extraction circumference of the SRC. The maximum $B\rho$–value becomes 12.76 Tm when a dipole field strength is 1.5 T at the maximum. If high-energy ion beams are demanded, the DSR serves as an ion synchrotron as well. The maximum energy is given, for example, to be 3.0 GeV for protons; 1.2 GeV/nucleon for light ions of q/A=0.5; and 0.82 GeV/nucleon for U^{92+} ions. For electrons the ACR boosts them up to the maximum energy of 2.5 GeV, and these electrons are stored in the DSR. In the present lattice structure, the betatron tune values are 6.335 (horizontal) and 5.763 (vertical). The operating ion-beam energy is kept to be under the transition energy, since the transition gamma is as high as 4.86. 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 16.7 m in length. These two long straight sections are dispersion-free in horizontal and vertical directions.

One of the key researches planned in 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. At 2.5 GeV, the de-Broglie wave-length of the electrons in the rest frame of the RI beam becomes 0.2 fm, which is sufficiently short to study the nuclear structure. To keep a sufficiently long Toushek lifetime, the RF voltage of 2.0 MV is applied to the electron beam. The number of stored electrons amounts up to 1.9×10^{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 $5.6\times10^{26}/\mathrm{cm}^2/\mathrm{s}$, provided that 1×10^7 particles of RI ions are stored and synchronously collided with electron bunches.

Other experiments such as ion-ion merging collisions at small angles are also envisaged. The luminosity is expected to be around $1\times10^{26}/\mathrm{cm}^2/\mathrm{s}$ 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.

For internal target experiments in the DSR, the stochastic cooling method is used. The band width is conservatively assumed at 500 MHz, and the feedback gain is 130 dB which is limited by an available wide-band RF power of 100kW.

Various aspects of beam-dynamic problems related to the detailed design of the DSR is being studied (one of them is given in Ref. 8), and the optimization of parameters of the ACR is under way.

Table 2. Parameters of the DSR.

Circumference C (m)	202.078
Max. $B\rho$ (Tm)	12.76
Average Radius R (m)	32.178
Radius of Curvature ρ (m)	8.506
Max. Beam Energy	
proton (GeV)	3.00
ion (q/A = 0.5) (GeV/nucleon)	1.20
ion (q/A = 0.387) (GeV/nucleon)	0.82
electron (GeV)	
Betatron Tune Values (Q_x/Q_y)	6.350/5.763
Momentum Compaction	0.0424
Transition γ	4.859
Max. Betatron Amplitude (β_x/β_y, m)	22.0/13.5
Max. Dispersion Function (D_x/D_y, m)	3.023/0.666
Betatron Amplitude at Interaction Point (β_x^*/β_y^*, m)	0.600/0.600
Length of Field-free Section at Colliding Section (m)	16.708

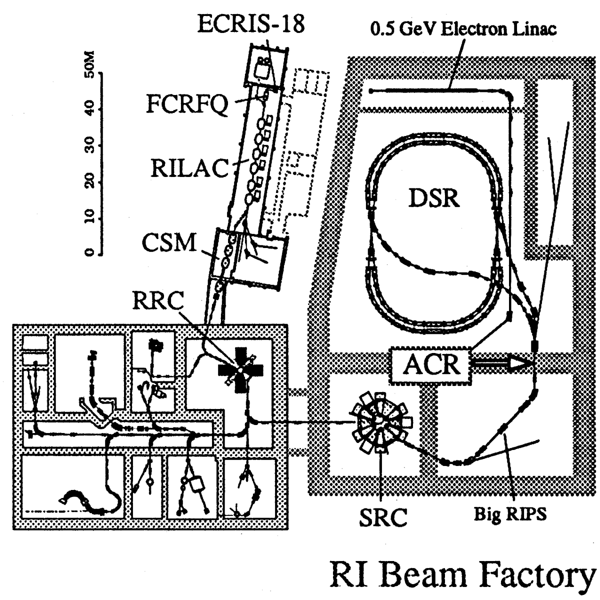

Fig. 2. Preliminary lay out of the RI beam factory.

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