Present Status and Future Plan of RIKEN Accelerator Research Facility

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Abstract

The RARF heavy-ion accelerator complex has been satisfactorily upgraded. Beam currents of 135 MeV/nucleon light ions routinely exceed 200 pnA; the maximum record has reached 500 pnA. Use of a polarized deuteron beam of 270 MeV has been initiated for spin-related physics experiments. A new injector for the heavy-ion linac is under construction; it will enable a decided improvement in heavy-ion beam intensities. A conceptual design study of "*RIKEN RI beam factory*" is undertaken.

1. INTRODUCTION

The RARF (RIKEN Accelerator Research Facility) holds the intermediate-energy heavy-ion accelerator complex consisting of a K540 MeV ring cyclotron (RRC) and its two different injectors of a K70 MeV AVF cyclotron (AVF) and a frequency-tunable linac (RILAC). Since the facility was fully operational in 1990, extensive improvements have been made in the experimental apparatus and beam lines as well as the accelerators. Some of them are described in the following section.

So far 210 MeV protons, 270 MeV polarized deuterons and twenty-one kinds of heavy ions ranging up to erbium with energies of 7 - 135 MeV/nucleon have been delivered for a wide variety of experiments. Typical beam currents are, for example, 500 pnA for top-energy light-ions, and 60 pnA for 95 MeV/nucleon ^{40}Ar ions.

Very recently we have decided to propose "*RIKEN RI Beam Factory*" as a future project of the RARF. Nowadays nuclear physicists are vigorously pioneering a new realm of science exploiting RI (Radioactive Isotope) beams. This new boom has been brought about by the advent of powerful generators of RI beams attached to powerful heavy-ion accelerators. The RARF also houses such facility called RIPS (RIKEN Projectile fragment Separator) which provides high-intensity RI beams, e.g. a ^{11}Li beam of nearly 10^5 p.p.s. It should be noted that over 80% of nuclear physics research are now carried out by using RI beams. The aim of this new project is to foster such emerging trend into mega trend of next century. The present accelerator facility is extended into the factory where high-intensity RI beams of a wide mass range are available in a wide energy range up to several hundred MeV/nucleon. The conceptual design is presented in the last section.

2. UPGRADE RESULTS AND PROGRAM

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2.1. 10 GHz ECR ion source for the AVF

The AVF is equipped with a 10 GHz ECR ion source. A plasma cathode method has been applied to the first-stage structure of this ECR ion source in an attempt to efficiently supply electrons into the second-stage plasma [1]. As a result of this simple modification, beam currents of highly-charged gaseous ions have been greatly improved, e.g. 80 eμA of $^{40}Ar^{11+}$. The method is also very effective to produce highly-charged metallic ions from their oxide, because electron temperature in the plasma becomes sufficiently high to evaporate them. In addition, distinct characteristics of very long lifetime, quite small gas consumption and comfortable stability have been realized.

2.2. Polarized deuteron ion source for the AVF

The AVF is also equipped with a polarized deuteron ion source of the atomic beam type [2]. This ion source was commissioned in June 1992. Since then a lot of efforts have been devoted to improve the performance. As a result, the present level has reached to the extracted current of 140 μA with a polarization of 75 % of the ideal value. A 270 MeV polarized-deuteron beam of 100 nA with the same polarization has been used for the experiments. This current is, however, voluntarily limited from a radiation-safety point of view. Technically it can be increased to an order of μA.

2.3. Single-turn beam extraction from the AVF and the RRC

The single-turn beam extraction from the AVF is possible by utilizing the first harmonic field perturbation, which enables us to routinely obtain over 75% extraction efficiency. On the other hand, the off-centered acceleration technique to facilitate single-turn beam extraction has been established for the RRC. By means of this technique, a beam extraction efficiency of 100% is routinely obtained. In addition, very careful tuning gives us a nearly 100% transmission efficiency through the RRC.

These single-turn extraction techniques are very effective especially for spin-direction control of a polarized beam. Thanks to the realization of single-turn extraction in both the AVF and the RRC, a polarization is preserved from the ion-source exit to the RRC experimental target. Accordingly, the spin-direction of polarized deuterons accelerated by the AVF-RRC can be easily pointed in a wanted direction by using a very simple $E\times B$ spin rotator placed immediately downstream of the ion source.

2.4. New injector for the RILAC

Heavy ions are pre-accelerated by the RILAC, while light heavy ions by the AVF. Recently there has been growing demand for much higher intensity in RILAC-injected heavy-ion beams. In order to meet this requirement, a frequency-tunable RFQ linac equipped with an 18 GHz ECR ion source is under construction for a new injector of the RILAC. This injector will be installed in the summer of 1995 as an alternative to the existing 450 kV Cockcroft-Walton accelerator housing an 8 GHz ECR ion source (NEO-MAFIOS).

The resonator of the RFQ linac has a new type of a folded-coaxial (FC) structure, and the resonant frequency is tuned between 18 and 38 MHz by use of a movable shorting plate [3]. This FCRFQ is designed to accelerate ions with mass-to-charge ratios of 7 - 28 at up to 450 keV per charge, which is equivalent to the performance of the Cockcroft-Walton. As a result of a low-power test on a half-scaled model, the required rf power is found to be 6 kW at 17 MHz and it increases to 34 kW at 38 MHz in the cw operation. 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.

The 18 GHz ECR ion source (ECRIS-18) is of a single stage. The reason for adopting such configuration is that very high charge states are not necessary for the RILAC, and that this single-stage type is capable of producing high current beams for low charge states in contrast to the two-stage type. The characteristic of the ECRIS-18 is that both of the mirror field and the sextupole field are strong enough to confine the second-harmonic ECR zone. The plasma cathode method is also implemented.

3. FUTURE PLAN OF THE RARF

3.1. Proposed Accelerator Complex of RI Beam Factory

For efficiently producing a wide variety of RI beams, according to the calculated cross sections of projectile fragmentation reactions, energies of primary beams are required to exceed at least 100 MeV/nucleon for up to very heavy ions such as uranium. In order to realize such acceleration performance, we propose an accelerator complex as illustrated in Fig. 1 which exploits the existing machines as much as possible.

A high-intensity heavy-ion d.c. beam produced by the ECRIS-18 is bunched and accelerated by the FCRFQ with transmission efficiency of more than 90% even at 1 mA. This pre-accelerated beam is fully captured by the RILAC.

The output beam from the RILAC is passed through a charge-state multiplier (CSM, under design) to reduce its magnetic rigidity without velocity gain and injected into the RRC. The CSM consists of an accelerator, a charge stripper and a decelerator. The accelerator and decelerator are of frequency-tunable IH linacs, and their operational rf frequencies are twice that of the RILAC in order to double an acceleration gradient. In the present design a maximum gap voltage is set to be 340 kV, and total lengths are 8 meters (the partition into two or three units are necessary) and 3.7 meters, respectively. Transmission efficiency through the CSM depend only on charge state distributions after the charge stripper foil, because the 6-dimensional emittance of the RILAC beam is already adiabatically dumped enough to be fully captured by the acceptance of the CSM. We estimate this efficiency in terms of Shima's formula [4] which is quite reliable in the relevant energy region. This CSM is a decisive device in obtaining a higher-intensity or higher-energy very-heavy-ion beam in the proposed accelerator scheme, because magnetic rigidity of a most-probable charge-state beam can be decreased down to the acceptable value of the RRC in spite of increase of the injection velocity.

A velocity of the RRC output beam is amplified by a factor of 2.4 by a six-sector superconducting ring cyclotron (SRC, under design), when the mean extraction radius (5.70 m) is taken to be 2.4 times the mean injection radius (2.37 m). This mean injection radius is 2/3 times the mean extraction radius of the RRC. Consequently, the harmonic number is 6 as that of the RRC is 9. Based on the GANIL's study [5], the sector angle is set to be 20 degrees. This results in maximum attainable energy of 500 MeV/nucleon due to the limit of vertical focusing.

Let us exemplify uranium-ion acceleration up to 150 MeV/nucleon. The rf frequency is 25.5 MHz. The $^{238}U^{19+}$

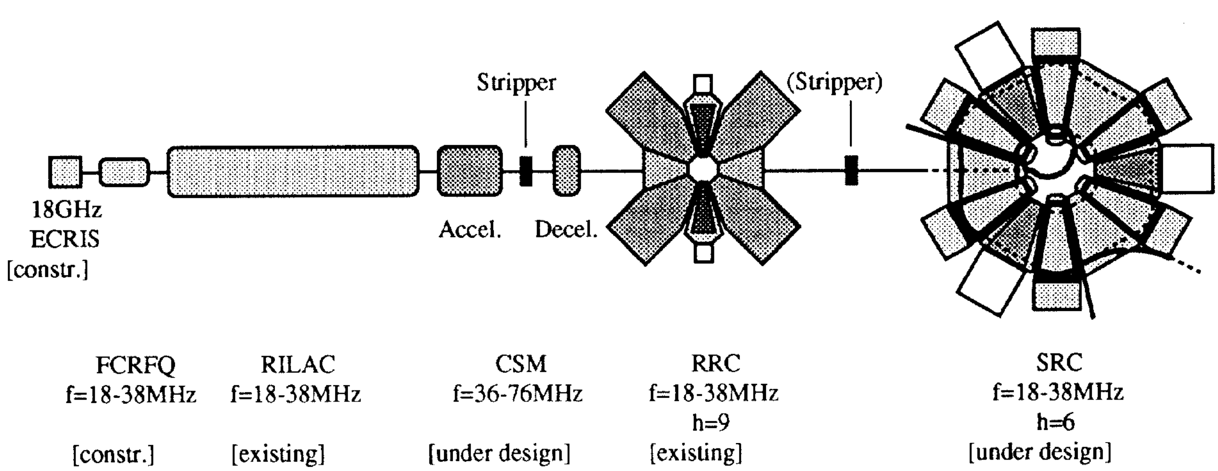

Fig. 1. Accelerator Complex of the Proposed "*RIKEN RI Beam Factory*".

beam with an intensity of 35 eμA (this value is taken from the 14.5 GHz CAPRICE data) is accelerated by the RILAC -CSM to 1.31 MeV/nucleon. The charge state is increased to 49+, but the intensity decreases to 0.9×0.17 times the initial intensity. This intensity of 280 pnA is preserved up to the final energy. The RRC energy is 21.7 MeV/nucleon, and the SRC final energy is 150 MeV/nucleon. The SRC sector field is needed to reach 5.48 T. If this field strength is too high to generate, we have to put another charge stripper before the SRC. Then the field strength is reduced to 3.33 T because of the further-stripped charge state of 83+, although the beam intensity is also decreased to 60 pnA.

Similarly the following beams are obtained:

$^{129}Xe^{35+}$	29MHz	210 MeV/nucleon	1.2 pμA	5.0 T
$^{84}Kr^{28+}$	32	280	7.5 pμA	4.8 T
$^{40}Ar^{16+}$	35	370	48.0 pμA	4.7 T
$^{16}O^{8+}$	38	500	180.0 pμA	4.4 T

Quite high-intensity primary beams are obtainable, but the radiation shielding problem also becomes serious.

3.2. Double Storage Ring (DSR)

Figure 2 displays a very preliminary layout of the factory. "Big RIPS" is a superconducting RI beam generator tolerant of a magnetic rigidity of 13.3 Tm (corresponding to that of 500 MeV/nucleon ^{11}Li). This factory features a state-of-the-art experimental facility of double storage ring (DSR): two storage rings are prepared following the SRC. They will be utilized for accumulating and cooling of RI and stable-nuclei beams, for boosting up their energies, for storage of electron beams to collide with RI beams, and for other scientific researches.

The outline of the DSR is given as follows: the two rings have the same specifications. The maximum $B\rho$ is 12.76 Tm (max. field strength is 1.5 T) and the ring circumference is 143.15 m, 4 times the extraction circumference of the SRC. The maximum beam energy is designed at 3.0 GeV for protons and 1.2 GeV/nucleon for q/A=0.5 light ions and 0.82 GeV/nucleon for U^{92+} beams. The lattice structure forms of a racetrack to accommodate two long straight sections for colliding experiments. The betatron tune values are calculated to be 6.364 (horizontal) and 5.940 (vertical). The operating beam energy is kept to be under the transition energy, as the transition gamma is as high as 4.784. The two long straight sections are dispersion-free. At the colliding points the beta-fuction amplitudes are 0.743 m (horizontal) and 0.629 m (vertical), respectively. The length of field free section near the colliding points is 5.016 m.

3. REFERENCES

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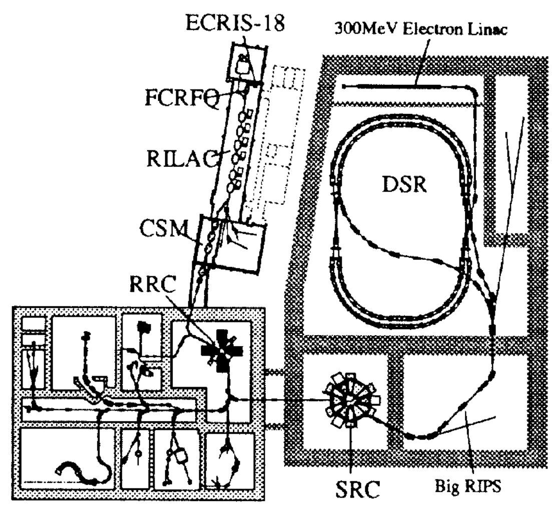

Fig. 2. Preliminary layout of "*RIKEN RI Beam Factory*".