INTENSITY-UPGRADE PLANS OF RIKEN RI-BEAM FACTORY

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Abstract

In 2008, the RIKEN RI-Beam Factory (RIBF) succeeded in providing heavy ion beams of ^{48}Ca and ^{238}U with 170 particle-nano-ampere and 0.4 particle-nano-ampere, respectively, at an energy of 345 MeV/u. The transmission efficiency through the accelerator chain has been significantly improved owing to the continuous efforts paid since the first beam in 2006. From the operational point of view, however, the intensity of the uranium beam should be much increased. We have, therefore, constructed a superconducting ECR ion source which is capable of the microwave power of 28 GHz. In order to reduce the space-charge effects, the ion source was installed on the high-voltage terminal of the Cockcroft-Walton pre-injector, where the beam from the source will be directly injected into the heavy-ion linac by skipping the RFQ pre-injector. The test of the ion source on the platform has started recently with an existing microwave source of 18 GHz. This pre-injector will be available in October 2009. We will show further upgrade plan of constructing an alternative injector for the RIBF, consisting of the superconducting ECR ion source, an RFQ, and three DTL tanks. An RFQ linac, which has been originally developed for the ion-implantation application will be reused for the new injector. Modification of the RFQ as well as the design study of the DTL are under progress. The new injector, which will be ready in FY2010, aims at independent operation of the RIBF experiments and super-heavy element synthesis.

INTRODUCTION

The accelerator complex of the RIKEN RI-Beam Factory (RIBF)[1] is schematically shown in Fig. 1. It consists of a heavy-ion linac (RILAC)[2], which is used as an injector, and four booster cyclotrons (RRC[3], fRC[4], IRC[5] and SRC[6]) in a cascade. The fRC is exclusively used for very heavy ions such as uranium and xenon, where the rf frequency of the RILAC is fixed to 18.25 MHz and the beam energy at the exit of the SRC is 345 MeV/u. For medium-mass ions such as calcium and krypton, the fRC is skipped; it is possible to tune the final energy in this variable-frequency mode. There is another acceleration mode in the RIBF, where the light ions such as deuteron and carbon are injected through the AVF cyclotron (K70 MeV)[7] and boosted by the RRC and SRC.

The RILAC plays another important role of providing intense beams for the synthesis of super-heavy elements (SHE) using the GARIS spectrometer[8]. Combined with the energy booster[9], medium-mass nuclei such as iron and zinc are accelerated to the maximum energy of 5.8 MeV/u.

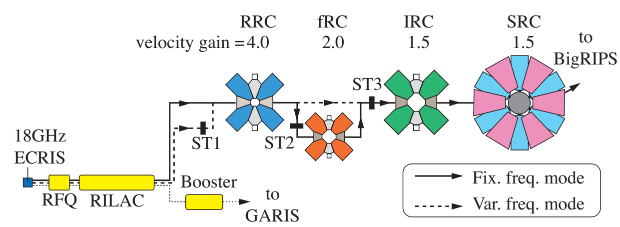

Figure 1: Conceptual layout of the accelerator chain of the RI-Beam Factory (RIBF). A linac injector (RILAC) is followed by the booster cyclotrons: RRC (RIKEN Ring Cyclotron, K540 MeV), fRC (fixed-frequency Ring Cyclotron, K570 MeV), IRC (Intermediate-stage Ring Cyclotron, K980 MeV), and SRC (Superconducting Ring Cyclotron, K2600 MeV). The charge strippers are indicated by ST1 - ST3.

As already reported[10], the intensities of the extracted beams from the SRC reached 170 particle-nano-ampere (pnA) and 0.4 pnA for ^{48}Ca and ^{238}U, respectively, at an energy of 345 MeV/u. The transmission efficiency through the accelerator chain has been significantly improved so far: the efficiency from the exit of the RILAC to the exit of of the SRC has exceeded 60 % in the calcium acceleration. Using the uranium beam in the BigRIPS spectrometer[11], more than twenty candidates of new radioactive isotopes were discovered within a week in November 2008. Thus the exploration into the nuclear extremes was started.

The intensity of the calcium beam is coming closer to our final goal of 1000 pnA, as mentioned above. It is clear that, however, we need more beams from the ion source for the very heavy ions such as uranium. In order to meet the demand, a new superconducting ECR ion source has been constructed, which is capable of the microwave power of 28 GHz. We are planning to upgrade the intensity in two steps with different injection schemes as shown below.

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NEW PRE-INJECTOR FOR RILAC

Superconducting ECR ion source[12, 13]

The main features of the ion source are as follows. First, the size of ECR surface is large. It has as large plasma volume as 1100 cm^3. Second, the field gradient and surface size at ECR zone can be changed independently to study these effects on the ECR plasma.

Six sets of solenoid coils and hexapole coil are used for making the magnetic field. The inner solenoid coils are used for introducing a flat magnetic field region between the mirrors. The maximum magnetic field of RF injection side, that of beam extraction side, and radial magnetic field at the surface of the plasma chamber are 3.8, 2.4 and 2.1T, respectively.

A photograph of the coil system is shown in Fig. 2. The coils use a NbTi-copper conductor and are bath-cooled in liquid helium. The hexapole field in the central region is increased by using iron poles, which is same structure as the VENUS ion source at LBNL[14]. The excitation test of the coil system was successfully performed in October 2008. After assembling the cryostat, the ion source was brought to RIKEN in December 2008. The source has been installed on the high-voltage platform as illustrated below.

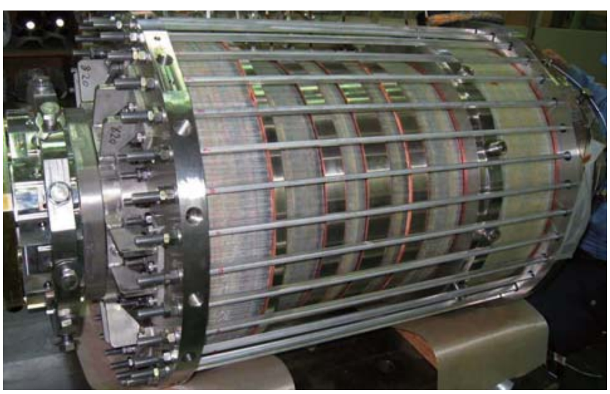

Figure 2: Superconducting coil of the ECR ion source.

Beam Line

In the fixed-frequency operation of the RIBF shown in Fig. 1, the uranium beam starts with 35+ from the ion source. Low frequency operation of the RFQ pre-injector[15] at 18.25 MHz requires, however, such low extraction voltage as 5.7 kV for the uranium beam. High power beams of 5.7 kV surely grow up due to their space charge forces in the low-energy beam-transport (LEBT) line. On the other hand, the RILAC requires such low injection energy as 127 kV for this beam. Therefore, we decided to put the superconducting ECR ion source on the high-voltage terminal of the original Cockcroft-Walton pre-injector so that extracted beam from the source can be directly injected to the RILAC, skipping the RFQ, as shown in Fig. 3. We expect that the emittance growth can be suppressed in the beam transport system. In addition, the extraction voltage of the ion source can be set as high as 27 kV, which will help us to obtain higher beam currents.

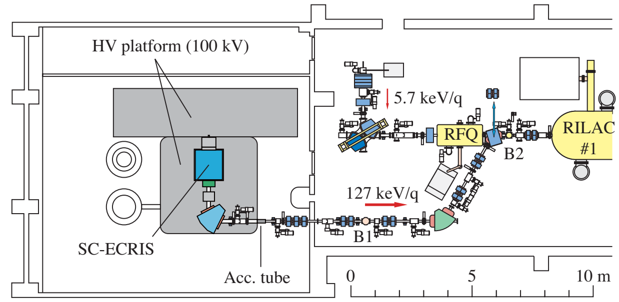

Figure 3: Configuration of the new pre-injector for the RILAC. B1 and B2 denote the bunchers operated at the fundamental frequency.

On the platform, an LEBT system including an analyzing magnet and beam monitors are settled. The analyzing magnet has been constructed according to the design of the LBNL[16]. The large pole gap of 180 mm leads to beam aberration due to fringing fields. Corrective measures have been taken by shaping the pole faces in such a manner as to introduce aberration countering sextupole moments to the beam. The original power generator of 50 kVA will be used for the devices on the platform as well as an additional power transformer of 50 kVA. At the end of the platform, an accelerating tube with ten gaps is placed, which was confirmed to withstand the high DC voltage of 120 kV.

The beam from the high-voltage terminal goes through a medium-energy beam-transport (MEBT) line consisting of two bending magnets of 60°, one quadrupole triplet, four quadrupole doublets, and a buncher system before joining the beam line from the RFQ. Existing devices will be reused for all these components: for example, the bending magnets used here are the ones that were once removed from the beam line from the Cockcroft-Walton in 2003. The base plate of the second bending magnet was designed so that dipole can be quickly replaced by a quadrupole doublet for the variable-frequency operation and the GARIS experiments where the RFQ pre-injector is used.

The MEBT line, which has a feature of achromatic transport, was designed mainly based on the TRANSPORT code[17]. Detailed simulations have also been performed using the TRACK code[18] including the space charge effects[19].

The vacuum is another key issue for the transport system. In order to keep the beam loss in the MEBT line below 5 %, it was estimated that the vacuum level should be lower than 2×10^{-6} Pa[20]. We will use four TMPs of 220 l/s and two cryogenic pumps of 750 l/s in the MEBT line to realize this vacuum level. In addition, surface treatment was applied to almost all the vacuum components: the beam pipes made of aluminum alloy and the vacuum chamber in the second dipole have been chemically polished, and the chamber in the first dipole adopted electric polishing.

Current Status

The ion source and the LEBT system have been fully assembled on the platform. Excitation test of the superconducting coils and vacuum test were successfully performed so far. We also confirmed that the devices on the terminal work perfectly with the high voltage being applied. The first plasma was ignited on May 11 with an existing microwave power source of 18 GHz. Since a small problem was found in the cooling channel of the plasma chamber, the rf power is limited to 50 W at present. A new plasma chamber will be ready in June and the generation of uranium ions will be started in this summer.

The installation and alignment of the MEBT line will be completed in June. The evacuation of the beam line will be started in June, and the beam will be acceptable in July. In October, the accelerator complex of the RIBF will have a configuration shown in Fig. 4: the expected beam current of uranium is 5 pnA after the SRC. The medium-mass ions are still to be delivered from the original 18-GHz ECR ion source. This injection scheme with two ion sources will make it possible to reduce the switching time of the beam which is necessary for changing the ion species.

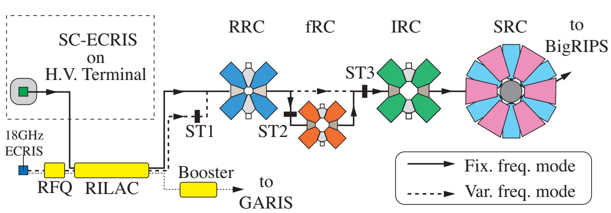

Figure 4: Expected configuration of RIBF at the middle of FY2009. Heavy ions such as uranium and xenon will be supplied from the superconducting ECR ion source on the high-voltage terminal of the Cockcroft-Walton generator.

NEW LINAC INJECTOR FOR RIBF

Outline

The recent success in the synthesis of SHE[8] using the GARIS spectrometer in the RILAC facility strongly encourages us to pursue the search for the heavier elements and to study the physical and chemical properties of SHEs more extensively. This compels us to provide a longer beam time for these experiments. However, the SHE research and RIBF conflict with each other, because both of them use the RILAC. Therefore, a new additional injector linac to the RRC has been proposed and designed[21], which will make it possible to conduct the SHE research and RIBF independently, as shown in Fig. 5. The new injector, which will be placed in the AVF-cyclotron room, will be used exclusively in the fixed-frequency operation of the RIBF.

The injector is designed to accelerate ions with a mass-to-charge ratio of 7, aiming at heavy ions such as $^{136}Xe^{20+}$

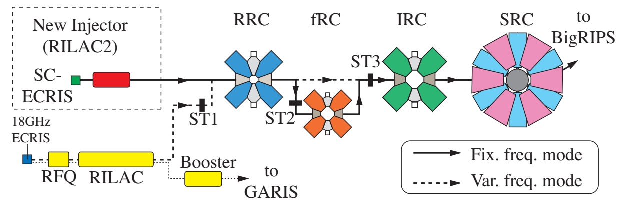

Figure 5: Expected configuration at the end of FY2010. Heavy ions such as uranium and xenon will be supplied by the new injector. Independent operation of RIBF and SHE research will be realized.

and $^{238}U^{35+}$, up to an energy of 680 keV/u in the cw mode. The output beam will be injected to the RRC without charge stripping. The injector consists of an ECR ion source, an LEBT system including a pre-buncher, an RFQ linac based on the four-rod structure, and three DTL tanks based on the quarter-wavelength resonator (QWR). There is a rebuncher resonator between the RFQ and the first tank of the DTL. The rf resonators excluding the pre-buncher are operated at a fixed rf frequency of 36.5 MHz, whereas the pre-buncher is operated at 18.25 MHz. Strong quadrupole magnets will be placed in the beam line between the rf resonators.

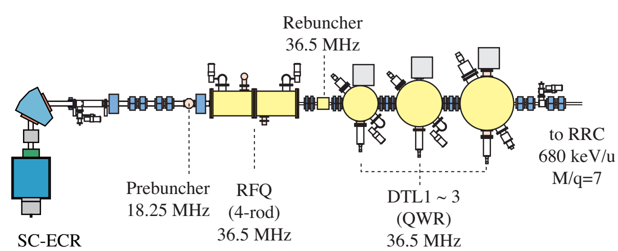

Figure 6: Schematic drawing of the new injector.

Construction of the new injector has started since the budget was fortunately approved at the end of FY2008. In order to save the cost, we decided to use the superconducting ECR ion source mentioned above for the injector: they will be moved to the AVF-cyclotron room in summer 2010. Moreover, we will reuse an RFQ linac which was constructed fifteen years ago, as shown below, and modify a decelerator resonator developed for Charge-State-Multiplier system[22] for the last tank of the DTL.

RFQ Linac

In November 2007, an RFQ system including two post accelerators and their rf amplifiers was transferred to RIKEN through the courtesy of Kyoto University. This RFQ system was originally developed by Nissin Electric Co., Ltd. in 1993[23]. Since the termination of its acceleration tests in the company, the system has been maintained in the Advanced Research Center for Beam Science, Kyoto University for several years.

The RFQ linac, based on a four-rod structure, accelerated heavy ions of m/q = 16 up to an energy of 84 keV/u in the cw mode with an rf frequency of 33.3 MHz. When the RFQ resonator is modified so as to have a resonant frequency of 36.5 MHz, it becomes possible to accelerate ions of m/q = 7 to 100 keV/u without changing the vane electrodes.

The main parameters of the RFQ after the modification is listed in Table 1, that were obtained by scaling the original parameters. The required rf power for the intervane voltage of 42.0 kV is 11 kW according to the original shunt impedance of 77.9 kΩ[24]. The RFQ has been reassembled in the RIBF building and high power tests was successfully performed in October 2008 using the original amplifier at 33.3 MHz. No significant problem was detected even at the input power of 14 kW.

Table 1: Main Parameters of RFQ

Frequency (MHz)	36.5
Duty	100 %
Mass-to-charge ratio (m/q)	7
Input energy (keV/u)	3.28
Output energy (keV/u)	100
Input emittance (mm·mrad)	200 π
Vane length (cm)	222
Intervane voltage (kV)	42.0
Mean aperture (r_0 : mm)	8.0
Max. modulation (m)	2.35
Focusing strength (B)	6.785
Final synchronous phase	$-29.6°$

In order to modify the resonant frequency, we are planning to put a block tuner into every gap between the posts supporting the vane electrodes. The size of the tuner was optimized by Microwave Studio, and the rf measurement using test pieces made of aluminum was started as shown in Fig. 7. High power tests at 36.5 MHz will be done in October.

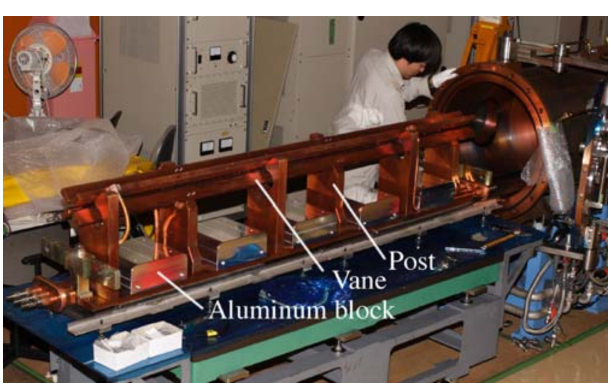

Figure 7: RFQ electrodes in preparation for the rf measurements with block tuners made of aluminum.

Drift Tube Linac

Initial parameters of the DTL were determined by optimizing the beam dynamics and rf characteristics of the resonators. A computer program, developed for the design of the RILAC booster[9], was used for the beam tracking simulation, whereas Microwave Studio was used to estimate of the rf-power consumption. The beam calculations have also been checked by the TRACK code.

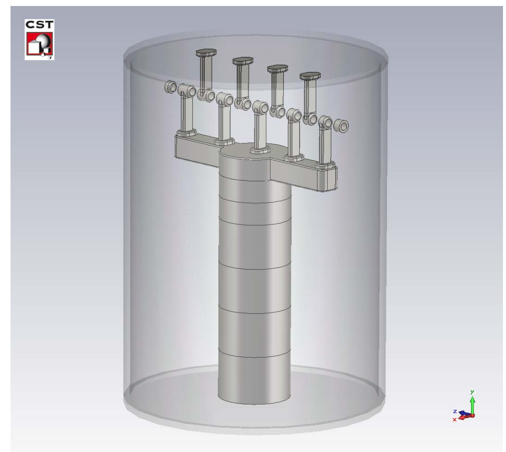

Figure 8: Schematic drawing of the DTL resonator.

The structure of the DTL tanks is designed based on the quarter-wavelength resonator, which is similar to that of the RILAC booster. The inner diameter of the resonators ranges from 0.8 to 1.3 m, depending on the beam energy. The maximum electric field on the drift tubes is kept below 1.2 Kilpatrick. Table 2 shows the main parameters of the DTL.

Table 2: Design parameters of DTL

Resonator	DTL1	DTL2	DTL3
Frequency (MHz)	36.5	36.5	36.5
Duty	100 %	100 %	100 %
Mass-to-charge ratio (m/q)	7	7	7
Input energy (keV/u)	100	220	450
Output energy (keV/u)	220	450	680
Length (= Diameter: m)	0.8	1.1	1.3
Height (m)	1.3	1.4	1.9
Gap number	10	10	8
Gap voltage (kV)	110	210	260
Gap length (mm)	20	50	65
Drift tube aperture (a: mm)	17.5	17.5	17.5
Peak surface field (MV/m)	8.2	9.4	9.7
Synchronous phase	$-25°$	$-25°$	$-25°$
Power (for 100% Q: kW)	5.1	13.4	15.4

The power losses estimated with Microwave Studio range from 5 to 15 kW. In order to save the construction cost and space for the equipments, direct coupling scheme has been adopted for the rf amplifier. Detailed design of the amplifier is under progress.

Beam Line

Design study of the LEBT section from the analyzing magnet to the RFQ is almost completed, as shown in Fig. 6, using TRANSPORT and TRACK. A quadrupole quartet has been introduced to help the beam matching with the solenoid coil placed before the RFQ. The position of the pre-buncher was optimized so that enough bunching effect could be obtained for the expected beam current of 200 eμA of $^{238}U^{35+}$.

The DTL requires compact quadrupole magnets with very high magnetic-field gradients (0.4 T/cm), to obtain sufficient transverse focusing as well as to prevent the phase width of the accelerated beam from spreading widely. Two types of quadrupole magnets have been designed: short quadrupoles (Q_s) with an effective length of 6 cm and long quadrupoles (Q_l) with an effective length of 10 cm. These quadrupole magnets will be used as quadrupole doublets ($Q_s + Q_s$) and quadrupole triplets ($Q_s + Q_l + Q_s$). The maximum beam width estimated with the optical calculations is 45 mm, as shown in Fig. 9, and the bore diameter was chosen to be 50mm. Therefore, the pole-tip field should be approximately 1 T, which is close to the limit of the conventional normal-conducting magnets. Another difficulty in the design is that the space allowed for the coils is as small as 4 cm on each side in the beam direction. It was finally confirmed using the TOSCA code that a field gradient of 0.41 T/cm is excited by 11900 ampere turns per pole for the long quadrupole magnet, which corresponds to an overall current density of 6 A/mm^2.

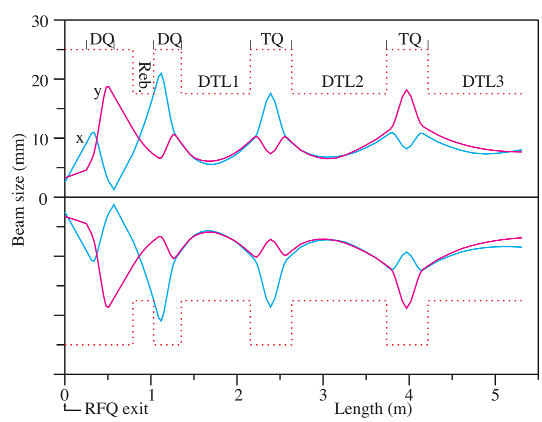

Figure 9: Calculated beam envelopes in the DTL. The emittance ellipses were assumed to be 0.6 π mm·mrad (normalized) in both of the transverse planes.

One of the post accelerators of the ion implantation system[24] will be reused for the rebuncher between the RFQ and the DTL. It is based on a spiral loaded resonator with three gaps. The drift tubes and the beam chamber are now under fabrication. Another post accelerator will also be modified and used for a rebuncher in the high-energy beam-transport (HEBT) section between the DTL and RRC.

Outlook

The RFQ and DTL including the MEBT line will be installed in the AVF-cyclotron room in March 2010. The superconducting ECR ion source will be moved to the new injector in summer 2010, and we hope to deliver the uranium beam of 50 - 100 pnA from the SRC by using this injector.

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