DESIGN OF NEW INJECTOR TO RIKEN RING CYCLOTRON

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Abstract

Design study of a new injector to the RIKEN ring cyclotron is presented. This injector will be exclusively used for the RI-beam factory (RIBF), providing intense beams of medium charge state of heavy ions such as $^{84}Kr^{13+}$, $^{136}Xe^{20+}$ and $^{238}U^{35+}$, while the present injector, RIKEN linear accelerator, is used for the research of the super heavy elements. Specifications of the main components of the new injector are shown, consisting of an ECR ion source, rf linacs and strong quadrupole magnets.

INTRODUCTION

The recent success in the synthesis of the super heavy element (SHE)[1] using the RILAC (RIKEN linear accelerator) - CSM (charge-state multiplier) - GARIS (gas-filled recoil ion separator) system strongly encourages us to further pursue the search for heavier SHEs and to more extensively study physical and chemical properties of SHEs. This compels us to provide a longer machine time for these experiments. However, the SHE research and RIBF (RI-beam factory) research conflict with each other, because both of them use the RILAC.

Therefore, a new additional injector linac to the RRC (RIKEN ring cyclotron) has been proposed, which will make it possible to concurrently conduct the SHE and RIBF research studies. The new injector, which will be placed in the RRC vault, will be used exclusively to produce primary beams of 350 MeV/u from the SRC.

OVERVIEW OF NEW INJECTOR

The injector is designed to accelerate ions with a mass-to-charge ratio of 7, aiming at heavy ions such as $^{84}Kr^{13+}$, $^{136}Xe^{20+}$ and $^{238}U^{35+}$, up to an energy of 680 keV/u in the cw mode. It consists of an ECR ion source of 18 GHz, a low-energy beam transport (LEBT) section including a prebuncher, an RFQ linac based on the four-rod structure, and three drift-tube linacs (DTL) based on the quarter-wavelength resonator (QWR), as shown in Fig. 1. The rf-resonators are operated at a fixed rf-frequency. Strong quadrupole magnets will be placed into the beam line between the rf-resonators. The output beam is injected to the RRC without charge stripping.

For the production of uranium ions, another ECR ion source, which will operate at 28 GHz, is under study. It will be installed in parallel with the 18 GHz ECR ion source in the new injector.

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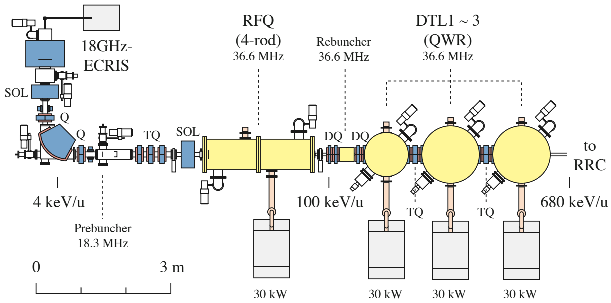

Figure 1: Schematic drawing of new injector.

INJECTOR COMPONENTS

Ion Source

Figure 2 shows the schematic drawing of the new 18 GHz ECR ion source. The new source has an additional solenoid coils between two solenoid coils as shown in Fig. 2. Using this coil arrangement, we can change the minimum magnetic field strength (B_{min}) of the mirror field without changing maximum magnetic field (B_{ext} and B_{inj}) independently to optimize the magnetic field gradient at the resonance zone, which will help to increase the plasma density and the electron temperature[2]. The maximum magnetic field strength of mirror field will be 1.4 T.

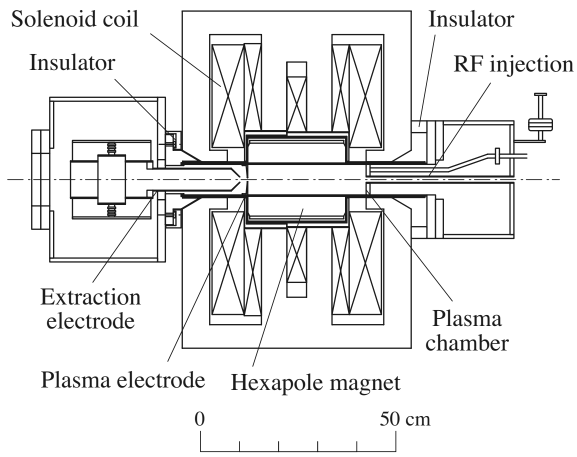

Figure 2: Schematic drawing of new 18 GHz ECR ion source.

To confine the plasma radially, we use the hexapole magnet which consists of 36 segments of permanent magnets. The inner diameter and length of plasma chamber is 78 and 300 mm, respectively. The magnetic field strength at the surface of the inner wall of the plasma chamber is 1.25 T. To protect the hexapole magnet form demagnetization by high temperature, the plasma chamber takes double wall structure to flow the cooling water. The inner wall of plasma chamber is covered by thin aluminum cylinder to supply the cold electrons to the plasma[3]. The movable negatively biased disc will be installed in the plasma chamber to tune the plasma potential[4]. These methods are very useful to increase the beam intensity of highly charged heavy ions from ECR ion source.

RFQ Linac

The parameters of the RFQ were determined using the PARMTEQ code. By compromising the RFQ length and defocusing force in the first DTL, the output energy of the RFQ was set to be 100 keV/u. The input emittance was assumed to be 200 π mm·mrad at 4 keV/u, which corresponds to a normalized value of 0.6 π mm·mrad. The main parameters are listed in Table 1.

The parameters in Table 1 are similar to those used in a four-rod RFQ constructed by NISSIN Electric Co., Ltd. in 1993[5]. The measured shunt impedance of this RFQ, which has a vane length of 222 cm and a resonant frequency of 33.3 MHz, is 47.6 kΩ. On the basis of this shunt impedance, the estimated power loss in our RFQ is about 20 kW.

Table 1: Design parameters of RFQ.

Frequency (MHz)	36.6
Duty	100 %
Mass-to-charge ratio (m/q)	7
Input energy (keV/u)	4
Output energy (keV/u)	100
Input emittance (mm·mrad)	200 π
Vane length (cm)	214
Intervane voltage (kV)	42.2
Mean aperture (r_0 : mm)	7.98
Min. aperture (a : mm)	4.55
Max. modulation (m)	2.41
Beam margin	1.35
Focusing strength (B)	6.8
Max. defocusing strength (Δ_{rf})	-0.225
Final synchronous phase	$-30°$

Prebuncher

The prebuncher in the LEBT section is one of the most important components in the injector. The PARMTEQ simulation shows that nearly 80% of the input beam is captured in the required rf-buckets of 18.3 MHz when the prebuncher is used, whereas the capture efficiency is less than 50% without it. It was also found that the phase width and energy width can be reduced significantly with the prebuncher, as shown in Fig. 3.

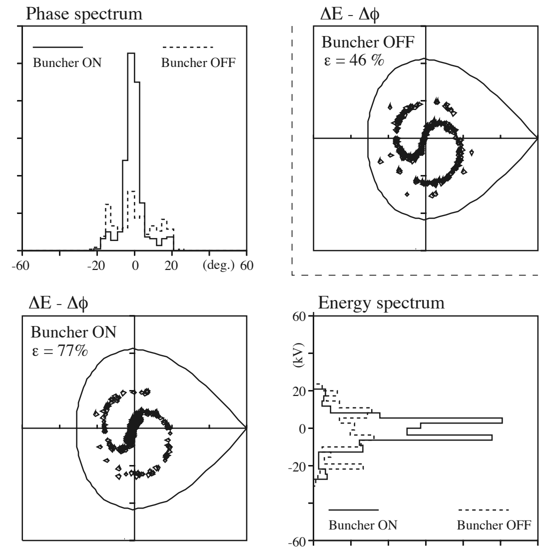

Figure 3: Longitudinal distribution of output beam of RFQ simulated using PAMTEQ code. A prebuncher of sinusoidal waveform in the LEBT section was included in the simulation, where the position of the prebuncher was assumed to be 2 m upstream of the RFQ entrance. The capture efficiencies (ϵ) are also indicated.

Drift Tube Linac

The DTL parameters are optimized by calculating the beam dynamics and rf-characteristics alternatively. A computer program, developed for the CSM design[6], is used for the beam tracking simulation, whereas the computer code MAFIA is used for the estimation of the rf-power consumption.

The designed structure of the DTLs based on the QWR, which is similar to that of the CSM resonators. The inner diameter of the resonators ranges from 0.8 to 1.1 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 DTLs. The power losses estimated with the MAFIA code ranges from 6 to 17 kW, as shown in the table.

Strong Quadrupole Magnets

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. The effective lengths are 6 and 10 cm for a short quadrupole magnet (Q_S) and a long quadrupole magnet (Q_l), respectively. 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 size estimated in ion optical calculations is 45 mm. Therefore, the pole-tip field should be approximately 1 T, which is close to the limit of the conventional normal conducting magnet. The space allowed for coils is 4 cm for each side in the beam direction.

Table 2: Design parameters of DTLs.

Resonator	DTL1	DTL2	DTL3
Frequency (MHz)	36.6	36.6	36.6
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	1.1
Height (m)	1.6	1.7	1.8
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 (100% Q: kW)	6	12	17

The magnets have been designed with the TOSCA code, while taking the design of the quadrupole magnets in the IH linac of the Institute for Nuclear Study[7] into account. The bore diameter was chosen to be 50mm for both short and long quadupoles. The excitation properties and effective length of the quadrupole magnets are shown in Figs. 4 and 5, respectively. For the long quadrupole magnet, a 0.41 T/cm field gradient is excited by 11900 ampere turns per pole, which corresponds to an overall current density of 6 A/mm^2. On the other hand, the field gradient of the short quadrupole remains 92 % of the requirement with an excitation current of 14900 ampere turns per pole (=7.5 A/mm^2). It will be possible to increase the field gradient further when reducing the bore diameter from 50 mm to 48 mm. In this case, it is preferable to adopt a lozenge-shaped beam duct. The cooling water conditions of the coil were also estimated. The maximum temperature rise of the cooling water is 26 °C with a pressure drop of 0.49 MPa, which is acceptable in our facility.

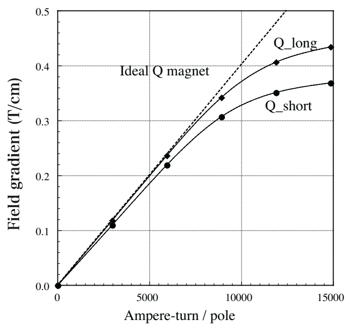

Figure 4: Excitation property of quadrupole magnets.

LEBT Section

Design study of the LEBT section is underway based on the present LEBT system of the RILAC[8], which simply

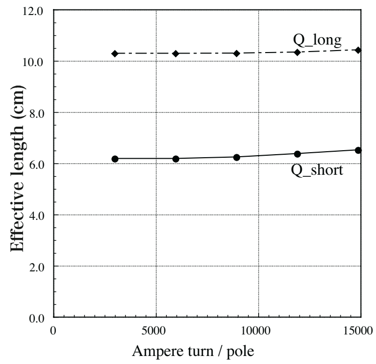

Figure 5: Effective length of quadrupole magnets.

consists of a dipole magnet and a solenoid coil. A solenoid coil after the ion source is added as shown in Fig. 1, since it has been found to be effective for beam focusing through a long experience on the present 18 GHz ECR ion source. In addition, a quadrupole magnet has been introduced on each side of the dipole magnet in order to manage the possible variation of the emittance of various kinds of ion beam. At the analyzing point near the prebuncher, the beam is focused only in the horizontal plane in order to reduce the defocusing force caused by the space charge. A quadrupole triplet has been introduced to help the beam matching with the solenoid coil placed before the RFQ; the RFQ has the same acceptance ellipse in the horizontal and vertical planes. The mass resolution of the LEBT system is about 100.

OUTLOOK

The new injector will be installed in the RRC vault. Further study of the following components is underway, which will be completed in FY2006.

- Rebuncher between the RFQ and DTL.
- High energy beam transport (HEBT) section from the DTL to the RRC.

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