DESIGN OF THE LOW ENERGY BEAM TRANSPORT IN RIKEN NEW INJECTOR

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Abstract

The RI beam factory at RIKEN Nishina Center needs high intensity of uranium ion beams. We constructed a new injector, RILAC2, which would provide several hundred times higher intensity. As a part of the RILAC2, we designed the low energy beam transport, LEBT, from the ion source to the RFQ entrance. We present its requirements and problems, and show our design as the solutions to them. Especially we focus a technique of a pair of two solenoids to treat a rotational operation and a focusing operation independently. Based on this design, the LEBT has been constructed. The RILAC2 will be operational this winter.

INTRODUCTION

As a part of the RI beam factory project at RIKEN Nishina Center (RIBF), we are constructing a new injector, RILAC2, to provide several hundred times higher intensity of uranium ion beams [1]. The RILAC2 consists of an electron cyclotron resonance ion source (ECRIS), an analyzing bending magnet (BM), a buncher, a RFQ, a re-buncher, and 3 DTLs [2, 3] (Figure 1). The 28 GHz superconducting ECRIS [4] and the DTLs were newly developed [5, 6]. The ECRIS has been tested and has been operated for a year. The RFQ is an improved one that was originally operated

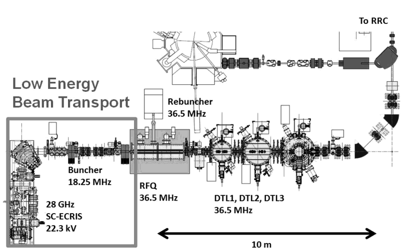

Figure 1: The layout of the RILAC2.

at Kyoto University. The buncher will be operated at the first harmonic, 18.25 MHz. The RFQ, the re-buncher and the 3 DTLs will be operated at the second harmonic, 36.5 MHz. The RILAC2 will be operational in winter 2010.

As a part of the RILAC2, we designed the low energy beam transport (LEBT) from the ECRIS to the RFQ entrance (Figure 2). We assumed the beam properties, since

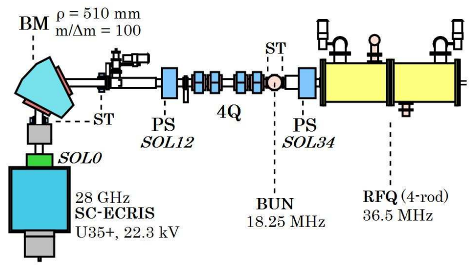

Figure 2: The RILAC2 LEBT design. The abbreviations BM, PS, ST, 4Q, BUN represent the analyzing bending magnet, a set of paired solenoids, a steering magnet, a series of four quadrupoles, and a buncher.

we had to design the LEBT before testing the newly developed ECRIS. In this paper we present its requirements and problems, and show our design as the solutions to them. Based on this design, the LEBT is now under construction.

REQUIREMENTS

The main requirements of the LEBT are summarized in Table 1.

Table 1: The Main Requirements of RILAC2 LEBT

Total length (ECRIS to RFQ)	6.8 m
Beam	$^{238}U^{35+}$
Acceleration voltage	22.3 kV
Estimated emittance	$\sim$ 150 π mm·mrad
$B\rho$	0.056 Tm
Energy per nucleon	3.28 keV
90 degree analyzing bending magnet	
Bending radius	510 mm
Resolution	100
RFQ Acceptance	
ϵ_x, ϵ_y	150 π mm·mrad
$x_{\max}, y_{\max}$	4.47 mm
$x'_{\max}, y'_{\max}$	49.0 mrad
r_{12}, r_{34}	-0.410

The emittance of U^{35+} after the analyzing bending magnet was estimated from the results of Versatile ECRIS for Nuclear Science (VENUS) at Lawrence Berkeley National Laboratory [7]. The design of the analyzing bending mag-

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net is the same as the VENUS system, which has sextupole compensation on its yoke.

The beam condition deeply depends on the level of space charge (SC) compensation. The expected U^{35+} current would be 0.5 emA at most. However, since oxygen is used as supporting gas at the ECRIS, the ECRIS produces not only U^{35+} but also U ions with other charge states and O ions. The total produced ion current may have over 10 emA. The SC effect of the ions increases the beam emittance and rules the beam properties of U^{35+} in the low energy region. To compensate the SC effect of the ions, we keep and use electrons inside of the LEBT. The electrons are originally produced by residual gas ionization or beam scratching on beam chamber. We set the double layered extraction system at ECRIS. This system produces mirror electric field to keep the electrons inside of the LEBT. As lens elements in the LEBT only magnetic lenses are used not to absorb the kept electrons, The compensation ratio was estimated from 80 percent to 99 percent [7] [8]. In the design, we divided the LEBT into 3 sections defined as follows. The section 1 is around the extraction electrode of the ECRIS. The section 2 is from the ECRIS to the analyzing bending magnet. The section 3 is downstream of the analyzing bending magnets. The adopted assumptions in the simulation for each section are listed in Table 2. In the section 1, we simulated multiple-ion beams cylindrically with IGUN. In the section 2, we compared two type simulations. One was the simulation of multiple-ion types with KOBRA, and the other was the simulation of single-ion type with TRANSPORT. Both simulations showed the similar figure of U^{35+} in phase space. However, the KOBRA simulation showed non-normalized emittance as $\sim$600 π mm·mrad, which was 4 times larger than the emittance estimated from VENUS. In the section3, with considering the RFQ acceptance, we adopt a initial condition having 200 π mm·mrad and the results at the end of the section 2 in phase space obtained with KOBRA.

Table 2: The Assumptions to Design RILAC2 LEBT

Section	SC ratio	Current	Ions
1	100%	10 emA	O and U ions with IGUN [9]
2	10%	0.1$\sim$1 emA	O and U ions with KOBRA [10]
2	10%	0.1$\sim$1 emA	U^{35+} upstream of the analyzing BM with TRANSPORT [11]
2	0$\sim$100%	0$\sim$0.5 emA	U^{35+} inside the analyzing BM with TRANSPORT
3	0$\sim$100%	0$\sim$0.5 emA	U^{35+} with TRANSPORT

The transverse real space distribution of ions is also an uncleared issue. Therefore in the simulations of the section 3, we adopted several initial conditions having different horizontal and vertical waist positions. The LEBT design was required to accept as many different beam conditions from the ECRIS as possible. We needed large acceptance of each lens element and accurate diagnostics system in the LEBT.

The RFQ is a 4-rod RFQ having 4 vanes of 45 degree inclined plane horizontally and vertically [12]. It will be operated with 36.5 MHz. It requires 22.3 kV to $^{238}U^{35+}$ and cylindrically strong focusing acceptance. We need at least 4 free degrees in the LEBT lens elements for good matching. A buncher of 18.25 MHz is needed upstream of the RFQ. The buncher has 2 gap system of 64.5 mm gaps, 150 mm total length and 40 mm inner diameter. The buncher needs to be located within 1 m from the RFQ for its voltage requirement. The beam diameter through the buncher needs to be less than 25 mm diameter for its electric field distribution. These requirements are necessary for over 75% transmission through the RFQ [13].

There are two diagnostics systems. The first diagnostics system locates downstream of the analyzing bending magnet. It includes an analyzing slit, a vertical slit, emittance slits, 2 profile monitors, a viewing target monitor, a Faraday cup, and vacuum pump. Its emittance monitor is expected to have 10% accuracy. The chamber length of the first diagnostics system is about 1 m. If we set a quadrupole lens right after the chamber, the beam diameter would be over 100 mm. The second diagnostics system locates upstream of the RFQ. It has an emittance monitor, 2 profile monitors, viewing target monitor, and vacuum pump. Its emittance monitor needs to measure 45 degree inclined emittances to operate skewed quadrupoles between the RFQ and the DTLs. In each diagnostics system, the 2 profile monitors will be used to adjust the beam axis with steerers.

DESIGN RESULTS

The result of the RILAC2 LEBT design is Fig. 2. Figure 3 is the U^{35+} beam profile simulated with TRANSPORT in the LEBT. The transverse lens elements are a

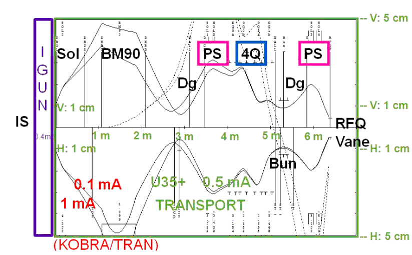

Figure 3: The beam profiles in the RILAC2 LEBT simulated with TRANSPORT. The abbreviations Sol and Dg represent a single solenoid and a diagnostics chamber. The upper half shows vertical beam envelopes and the lower half shows horizontal beam envelopes. The larger and smaller envelopes are for ions of 1 mA and 0.1 mA in the section 2. The ions in the section 3 are 0.5 mA.

single solenoid right after the ECRIS extraction, the 90 degree analyzing bending magnet, a pair of solenoids, 4 quadrupoles and another pair of solenoids. The bending magnet is between 2 steerers. The buncher is between 2 steerers. The quadrupoles have 100 mm diameter. The paired solenoids are identical, but will be operated to generate magnetic field in counter direction each other.This operation cancel the rotational function of a single solenoid, and the paired solenoids can be used as decoupled isotropic focusing elements. In front of each pair of solenoids there is a diagnostics chamber. The paired solenoids enabled us to reduce the beam size in the following lens elements, to decouple horizontal and vertical emittances, and to keep long drift space for diagnostics chambers. They also help us to adjust the lens elements from low to high intensity beams in space charge dominant region, as our LEBT.

PAIRED SOLENOIDS

The 6×6 transfer matrix of a solenoid lens is the product of a rotational matrix and a focusing matrix, which are interchangeable. A rotational matrix and a drift matrix are also interchangeable. Therefore, the matrix of a series of two solenoids can be expressed as the product of a rotational matrix and a complex of two focusing matrices holding a drift matrix between them. The matrix of a series of two identical solenoids, *pair solenoids*, has no rotational components, and decouples the horizontal and vertical directions, if the solenoids have the same current but in opposite directions.

Besides the decoupling feature for emittance, the pair solenoids have the merit of maintaining smaller beam radii in the magnets than do the quadrupoles. Figure 4 shows the beam envelopes between the case of pair solenoids and quadrupole magnets with the same initial conditions in RILAC2 LEBT design. The beam radii are reduced to half by using a pair of solenoids. Increasing only the number of quadrupoles cannot reduce the beam radii effectively.

CONCLUSIONS

As a part of RIKEN's new injector RILAC2, we designed its LEBT from the ECRIS to the RFQ entrance. We designed the LEBT through several assumptions and simulations taking account of space charge effects, before the tests of the newly developed ECRIS. The technique of paired solenoids was adopted to reduce beam envelopes without transverse coupling. Based on this design, RILAC2 LEBT is under construction.

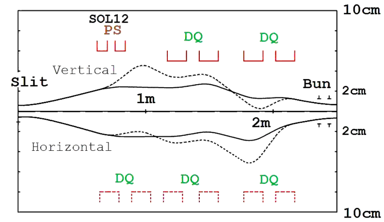

Figure 4: Beam envelopes from the analyzing slit to the buncher in RILAC2 LEBT. The upper half shows vertical beam envelopes and the lower half shows horizontal beam envelopes. The beam comprises U^{35+} ions with an acceleration voltage of 22.3 kV and 200π mm·mrad emittance horizontally and vertically. The solid lines are the beam envelopes of the case in which pair solenoids are placed right after the slit. The effective length and bore diameter of the lens elements are shown as the solid marks in the upper half. The dashed lines are the beam envelopes of the case in which 6 quadrupole magnets are placed right after the slit. The effective length and bore diameter of the lens elements are shown as the dashed marks in the lower half. Both have pair solenoids in front of the RFQ entrance. The beam envelopes of both cases are superposed.

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