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Development of a low-energy beam transport system at KBSI heavy-ion accelerator

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ABSTRACT

The Korea Basic Science Institute has developed a heavy ion accelerator for fast neutron radiography [1]. To meet the requirements for fast neutron generation, we have developed an accelerator system that consists of an electron cyclotron resonance ion source (ECR-IS), low-energy beam transport (LEBT) system, radio-frequency quadrupole (RFQ), medium-energy beam transport system, and drift tube linac. In this paper, we present the development of the LEBT system as a part of the heavy ion accelerator system, which operates from the ECR-IS to the RFQ entrance.

1. Introduction

Ion beam transports use two types of optical elements: magnetic and electric. For low-energy beams, electrostatic elements produce the stronger force; however, maintenance is easier for magnetic components. The magnetic elements are also dependent on the mass to charge ratio of the ions, which allows beam separation of various particle species. We have designed a low-energy beam transport (LEBT) system that utilizes magnetic elements, thereby simplifying both the manufacturing as well as maintenance. Fig. 1 shows the Korea Basic Science Institute (KBSI) accelerator system that consists of a 28 GHz electron cyclotron resonance ion source (ECR-IS), LEBT system, radio-frequency quadrupole (RFQ), and drift tube linear accelerator (DTL). The ion beams generated by the ECR-IS are separated, while the properties of the beam are estimated by the LEBT system. The beam is accelerated from 12 keV/u to 300 keV/u by the RFQ and then to 2.7 MeV/u by the DLT. Neutron imaging can be performed by the reaction of an accelerated lithium beam with a hydrogen target.

2. Optics design

The solenoid magnet provides horizontal and vertical isotropic focusing. It consists of coils wrapped rotationally around the beam tube and generates a longitudinal magnetic field. The focusing action is complex, but can be described assuming a thin lens [2]. The radial field at the entrance of the solenoid creates azimuthal motion given by

$$V_\theta = \frac{qBr_0}{2m} \tag{1}$$

where q is the charge number, m is the particle rest mass, B is the radial magnetic field strength inside solenoid, and r_0 is the radial coordinate of the particle when it enters solenoid. Inside the solenoid, the beam travels with a helical motion. The azimuthal motion v and magnetic field Bz cause the beam to converge towards the optical axis. At the solenoid exit, the initial azimuthal velocity is cancelled, but the beam maintains its radial velocity, which is expressed as

$$V_r = -\frac{r_0 q^2}{4m^2 v_z}\int B^2\,dz. \tag{2}$$

The focal length f of the thin solenoid is given by

$$\frac{1}{f} = \frac{q^2}{8mE}\int B^2\,dz \tag{3}$$

where f is the focal length, E is the kinetic energy, m is the mass, q is the charge number, and B is the magnetic field strength inside the solenoid. While the beam propagates inside the solenoid, the beam trajectory is determined by the rotation due to the azimuthal motion. Therefore, we have designed a LEBT system that contains a paired solenoid to prevent beam rotation caused by solenoid focusing. The matrix of the solenoid is determined by the

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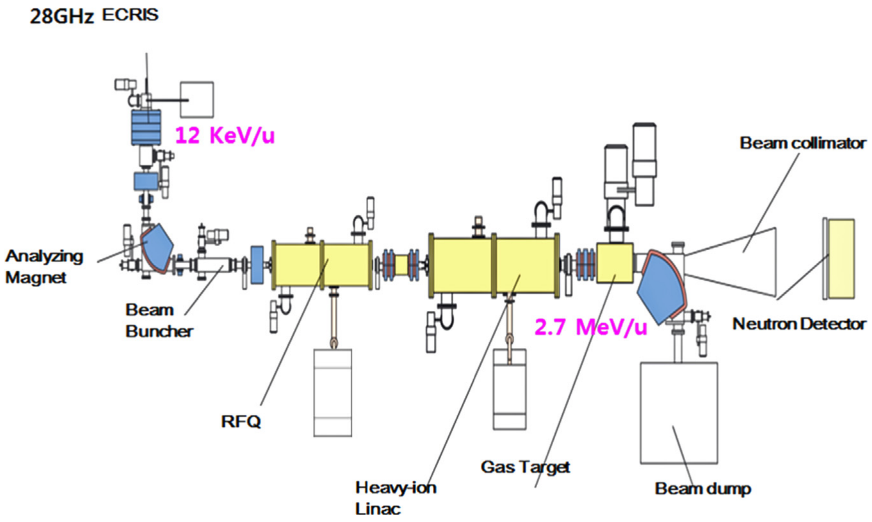

Fig. 1. The layout of the KBSI accelerator.

rotation product with focusing. The coupled solenoids cause ion beam rotation in opposite directions due to the flowing reverse current. Hence, this paired solenoid system effectively removes the beam rotation component of the solenoid magnet. This decoupling phenomenon was used in the muon-collider cooling channel [3–7] and in a heavy ion LEBT [8].

We designed the LEBT system, which satisfies the RFQ requirement, to operate all ion beams, from the heaviest uranium beam to the lightest proton beam. In the LEBT system design, we have assumed the initial parameters shown in Table 1 [9]. When ion beams are generated from an ECR ion source, various charged particles are produced simultaneously. Therefore, the beams must be separated and selected for beam transport through the LEBT system. After the beams pass through an analyzing dipole magnet, beam separation is determined by momentum dispersion. Specifically, the various beams are separated due to their momentum dispersion multiplied by the dispersion function inside the beam transport. Beam momentum is related to the charge state of the ion beam. Beams gain kinetic energy, which is related to their charge, through the voltage of the ECR extraction. The dispersion function is increased while the beam is travelling in a drift space after passing the analyzing dipole magnet. In order to successfully separate the beams, the multi-beam sizes, including the momentum dispersion, are designed to be as large as four times the beam size of a selected beam. The LEBT system is designed to meet both small and large dispersion at a slit.

The upper and lower halves in Fig. 2 show the vertical and horizontal beam envelopes, respectively. The left side shows the beam envelopes for the two solenoids and two quadrupoles, while the right side shows the beam envelopes for the four-quadrupoles. The effective length and bore diameter of the solenoid and quadrupole are identical. A comparison of these two envelopes indicates that the result for the solenoid is smaller than that of the quadrupole.

The optics and tracking codes (TRANSPORT [10] and TRACK [11], respectively) were primarily used in the design of the LEBT system. The LEBT simulation begins downstream from the yoke of the ECR ion source. The initial beam distribution used in the simulation is shown in Fig. 3. The normalized RMS transverse emittances of the lithium and uranium beam are 0.2 and 0.15 mm mrad, respectively. The initial particles generated in the 4-dimensional water-bag and longitudinal uniform models included an intrinsic energy spread of 0.05%. In Fig. 4, the blue curve indicates the horizontal beam envelope, while the red curve corresponds to the vertical envelope. Left side shows the uranium beam envelopes of 3.28 keV/u, and the right side shows the lithium beam with 12 keV/u, which were calculated using the TRANSPORT code. Here, 99.99% (4σ) beam distributions are used for the full-envelope simulation.

Table 1
Initial beam parameters.

Beam	Uranium	Lithium
Mass	238	7
Charge	35	3
Energy	3.28 keV/u	12 keV/u
Emittance$_{(n,r)}$	0.15 π mm-mrad	0.2 π mm-mrad
Emittance$_{(99.99\%)}$	220 π mm-mrad	160 π mm-mrad
Current	0.2 emA	1.0 emA

Beams are transported to the RFQ entrance through the LEBT system when it leaves the ECR-IS yoke. After passing the analyzing dipole magnet, a diagnostic box measures the beam profile, emittance, and current. As a requirement, the LEBT system is designed to transport various types of beams with matched Twiss parameters at the RFQ entrance. The maximum beam envelope is about 4 cm, and the maximum beam size is 3 mm at the RFQ entrance. The LEBT system is designed to transport the beams with 100% transmission. The LEBT system is also required to have good separation and satisfy the RFQ acceptance regardless of the beam species.

From the TRANSPORT simulation results, the designed layout of the LEBT system is shown in Fig. 5. The LEBT system consists of an analyzing dipole magnet, three solenoids, three quadrupole magnets, four steering magnets, and two diagnostic boxes. The bending radius of the dipole is 45 cm, and the bending angle is 90°. The dipole magnet has a pole-face angle of 28° at both the entrance and exit faces. Two diagnostic boxes were installed to measure the beam profile, emittance, and current downstream from the dipole magnet and upstream from the RFQ, respectively. The first diagnostic box consists of horizontal and vertical slits, screen monitor, wire scanner, and faraday-cup. The second diagnostic box consists of a pepper-pot, screen monitor, and faraday-cup. To avoid charge exchange, the residual gas pressure inside the LEBT system is designed to be on the order of 10^{-6} Pa.

The LEBT system was required to have a large acceptance for beam transport. Fig. 6 shows the Li^{3+} beam profiles, including the space charge (SC) effect from the TRANSPORT simulation. Inside the LEBT system, the SC effect causes beam loss through increasing beam size and emittance. From Fig. 6, it is obvious that the LEBT system is able to transport a lithium beam up to 1.6 emA.

30,000 macro-particles were used for the tracking simulation using the TRACK code. Multi-charge state beams with mass to