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Design of the low energy beam transport section of the high current injector

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Abstract

A high current injector (HCI) is being designed as an alternate injector for the superconducting linear accelerator (LINAC) to provide relatively higher beam currents. Presently ion beam from 15 UD Pelletron is being injected into the LINAC installed in one of the seven beam lines of the Pelletron. The HCI will consist of a high temperature superconducting electron cyclotron resonance (ECR) ion source placed on a 400 kV high voltage platform that will provide the initial pre-acceleration. These ions will then be further accelerated to about 200 keV/u by a 48.5 MHz Radio Frequency Quadrupole (RFQ) accelerator. The RFQ will be followed by a Drift Tube Linac (DTL) section which will accelerate the beams to about 1.5 MeV/u for injection into the main superconducting linear accelerator. Due to the large axial magnetic fields of the ECR ion source at extraction, the emittance of the extracted beam is very high. The large emittance as well as space charge forces present in the multi-charged beam poses a severe challenge in the design of Low Energy Beam Transport System (LEBT). A large acceptance analysing magnet has been designed to analyse ions from the ECR source. This magnet will be placed on the high voltage platform to reduce beam loading of the high voltage power supply. The combined function magnet has been designed to incorporate higher order terms to reduce the higher order aberrations. Since the technical challenge of transporting low energy, high current ions lies mainly in the low energy section of the injector, utmost care has been taken in the design of the LEBT. The beam optics for tranporting the analysed beam from the ion source to the entrance of the RFQ has been performed using TRANSPORT , GIOS and COSY INFINITY codes.

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Keywords: HTS-ECRIS; Low energy beam transport; Analysing magnet

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1. Introduction

Inter University Accelerator centre (formerly known as Nuclear Science Centre) is an accelerator based research institute under University Grants Commission. It has a 15 UD Pelletron [1] which has been delivering beam to the user community since 1990 onwards. The major research activity is related with Nuclear Physics, Material Science, Atomic Physics and Radiation Biology. The beam energy delivered by the Pelletron is ~ 5 MeV/u for A < 30 and

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2.5 MeV/u for the higher masses which is below the Coulomb barrier for most of the medium mass ion-projectile combinations. To augment the beam energy, a superconducting LINAC [2] is being installed to provide beams of ~5MeV/u for the medium heavy ions. The input of LINAC demands high current, high charge state pulsed beam (150 ps). Since the pulsed beam available from the existing Pelletron is of low intensity (~ a few nA) and low charge state, an electron cyclotron resonance (ECR) ion source based high current injector (HCI) is being installed to provide relatively high current (a few pμA) heavy ion beams for the LINAC. A schematic of the entire facility showing the 15 UD Pelletron and associated planned accelerators is shown in Fig. 1. As a part of the HCI development programme, a high performance, high temperature superconducting (HTS) ECR ion-source [3] (HTS-ECRIS) has been developed in collaboration with M/s PANTECHNIK, France to deliver relatively high current (a few pμA) heavy ion beams.The ions from the ECR source are first extracted around 30 kV and mass analysed by a large acceptance analysing magnet. Typical beam currents of $^{20}\text{Ne}^{2+}$ and $^{40}\text{Ar}^{8+}$ are 2 mA and 732 μA respectively. This beam will be accelerated using deck voltage with a maximum allowable voltage of 400 kV. The energy of this beam will further be accelerated by a Radio Frequency Quadrupole accelerator (RFQ), Drift Tube Linac (DTL) and low β cavity resonators to match the existing LINAC beam-input energy requirements. A schematic of the proposed high current injector is shown in Fig. 2. A new beam hall is being constructed on the east side of the present beam hall I to house these facilities. A schematic layout of the building and tentative layout of beam line is shown in Fig. 3. Due to the large axial magnetic field (~ 1.5 T) at the extraction side of the ECR source, the emittance of the beam is very large (~ a few hundred π mm.mrad). The large emittance as well as the space charge forces present in the multicharged beam extracted from the ECR poses a severe challenge to the design of Low Energy Beam Transport System (LEBT). In the present paper we discuss the ion-optical design to transfer beam from the ECR source to the entrance of the RFQ.

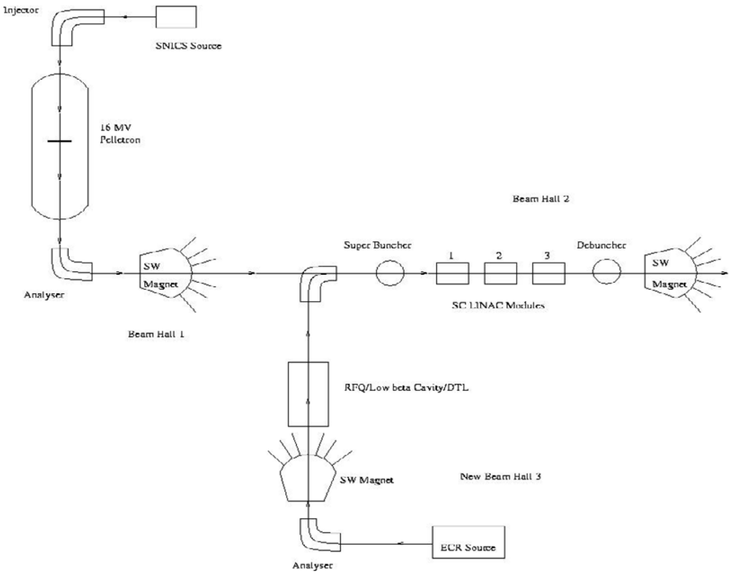

Fig. 1. Schematic layout of of the 15 UD Pelletron and associated accelerators.

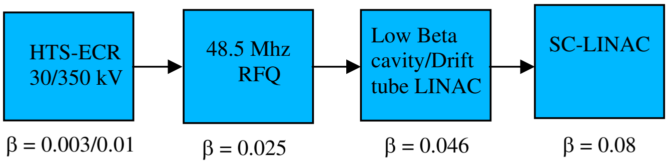

Fig. 2. Schematic of the proposed high current injector.

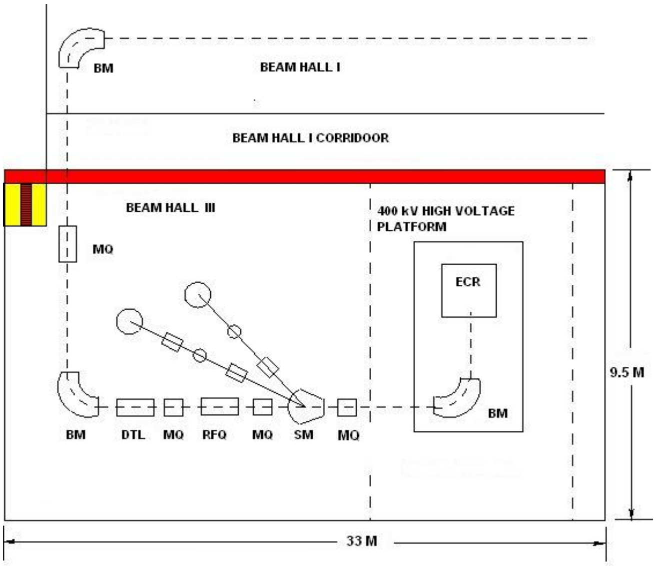

Fig. 3. Schematic layout of new beam hall III.

2. Ion optical design of LEBT

The LEBT consists of the high temperature superconducting ECR source, PKDELIS, multi-electrode extraction system, 90° analysing magnet, 400 kV high voltage accelerating column and a few focussing devices to transfer the beam from ECR to RFQ entrance. The ion optical design has been carried out considering the beam input parameters of maximum A/q = 7 and beam emittance of 200 π mm.mrad. The detail design of each section is described in the following sections.

2.1. Multi-electrode Extraction system

A typical beam extraction at 35 kV from the ECR ion source is shown in Fig. 4 assuming a total source current of 10 mA. The extraction system consists of a multi-electrode system comprising of three co-axial cylinders which can be independantly powered to achieve good focussing and resolution. A new type of high current, water cooled, movable extraction system is being developed so that the focussing properties of different A/q beams under the influence of a strong axial magnetic field can be optimised (Fig. 5.) to minimise the loss in beam intensity through the analysing magnet. The design of the new system is shown in Fig. 6.

2.2. Analysing Magnet

The extracted beam from the ECR is first mass analysed and then accelerated to an energy necessary to match the requirements of RFQ. The analysing magnet has been designed with the input parameters shown in Table 1. Since the analysing magnet is to be placed on a high voltage platform in order to reduce beam loading of high voltage deck power supply, the design aim is to have an air cooled, minimum weight, large acceptance, reasonable mass resolution magnet. The radius of the magnet, ρ, was chosen to be 0.3 m and optimized to minimize the weight. This gives a maximum field corresponding to 0.3 T for ME/q^2 = 0.4 a.m.u. MeV considering a 90° bend angle. The gap between the poles were optimised for different slit sizes so that good resolution is achieved without appreciable loss of beam intensity and the weight of the magnet is still not too large. The following examples shown below justifies the selection of the pole gap. For a slit size of 10 mm, y = 5 mm and y' = 40 mrad. The beam size at the entrance (0.6 m from the slit) turns out to be 29 mm and the mass resolution for 90° magnet, $\delta m/m$ is 1.7×10^{-2}. By taking smaller slit sizes, the resolution can be improved at the cost of beam intensity, otherwise the pole gap has to be increased further resulting in increase of weight of the magnet. The optimum gap of the magnet was found to be 80 mm for moderate resolutions and minimum loss of beam intensity. This resolution is good enough for mass region ~ 100 a.m.u. However, for higher masses it would be poor. The vertical focusing is due to the fringing field at the entrance and exit with particular entrance and exit angle.

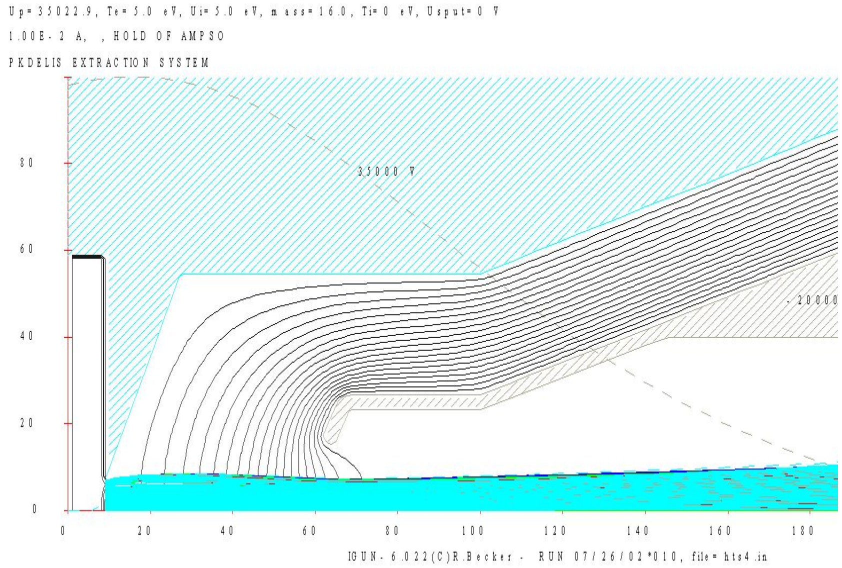

Fig. 4. Typical beam extraction at 35 kV assuming a total source current of 10 mA.

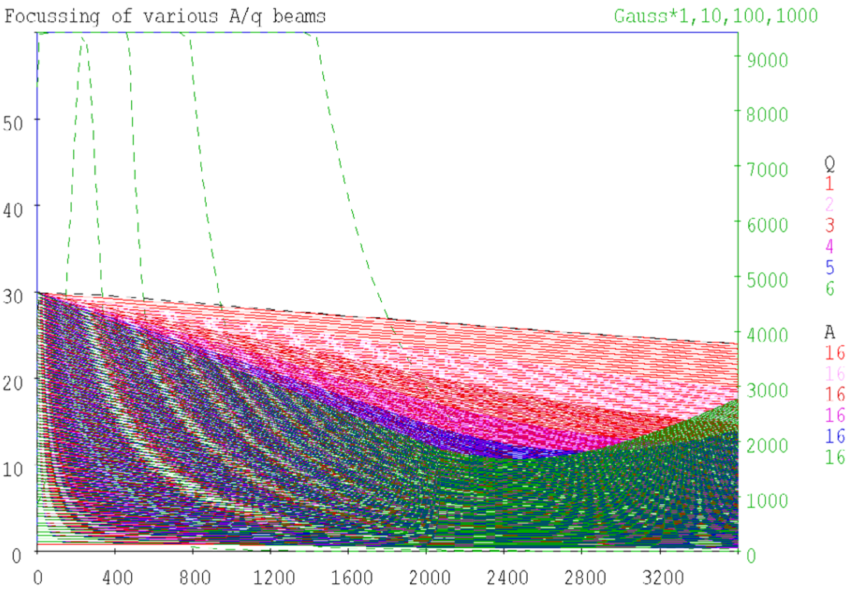

Fig. 5. Focusing of various A/q beams.

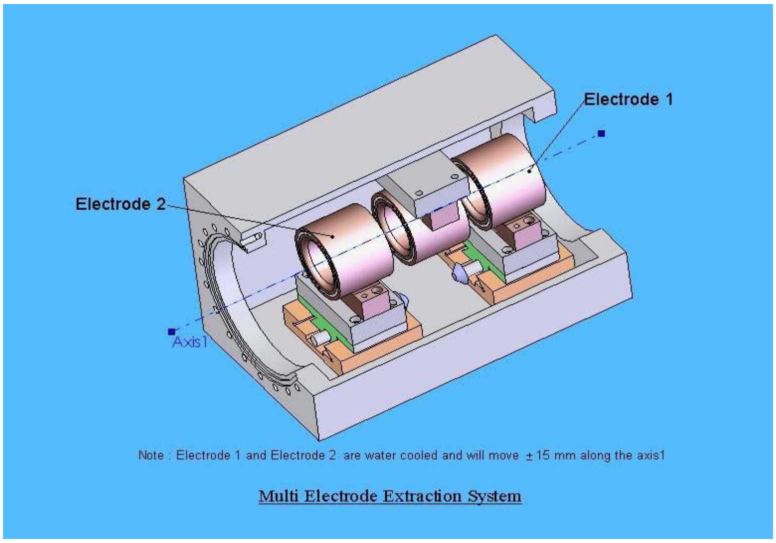

Fig. 6. Movable extraction system of HTS ECRIS.

Table 1
Beam parameters.

ME/q^2	Magnet rigidity ($B\rho$)	Emittance
0.4 a.m.u. MeV	0.09 T.m	200 π mm.mrad

For a 90° homogenous bending magnet, double focussing is normally achieved with entrance/exit angles ε = 26.6° and object/image distances $u = v = 2\rho$. The above mentioned values of entrance and exit angle give double focussing if the gap of the magnet is small compared to the length of the magnet. However, because of larger gap requirements, we need larger entrance and exit angles. We have optimised entrance and exit angles with gap effects using TRANSPORT [4], GIOS [5] and COSY INFINITY [6] codes. The optimised values are found to be: ε = 32.8° for $u = v = 0.80$ (instead of 0.6). The first order ion optics of the analysing magnet is shown in Fig. 7.

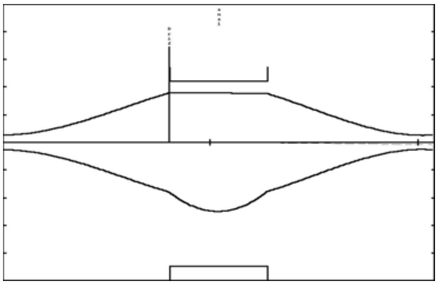

Fig. 7. First order ion optics of the analysing magnet (using TRANSPORT, upper: non-dispersive plane, lower: dispersive plane).

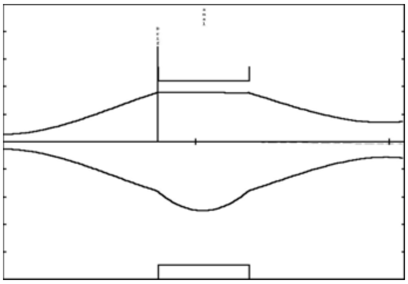

Fig. 8. Second order ion optics for analysing magnet without correction (using TRANSPORT, upper: non-dispersive plane, lower: dispersive plane).

In general, the image suffers from aberrations due to the higher order terms, particularly for the marginal beams especially in the case of beams having large emittances found typically from ECR ion sources [7] . The deterioration of the beam considering the second order effect is shown in Fig. 8. The most important contribution comes due to the terms containing x^2, y^2, x'^2, y'^2, xx', yy'. We have tried to minimise the geometrical aberrations due to the higher order terms by incorporating multipole field components in the magnet itself. Various options are available in literature to reduce higher order aberrations [8] . The vertical focussing is obtained by incorporating increasing sextupole field components at the entrance and exit. This has been achieved by considering cylindrical pole shape at entrance and exit with negative radius of curvature. Leitner [9] *et al.* have obtained the similar effect by introducing upward wings at the entrance and exit of the magnet. The horizontal focussing is achieved by introducing decreasing sextuple field components in the radial plane at the middle of the magnet. The magnetic field in the x-plane (radial plane) can be expressed as follows:

$$B = B_o(1+ n_1(x/\rho) +n_2 (x/\rho)^2 +n_3 (x/\rho)^3 +......)$$

where B_o is the field at the centre. For a homogeneous dipole magnet, $n_1 = 0$. We have minimized these aberrations up to third order by varying n_2 and n_3 using TRANSPORT and GIOS. In order to check the mass resolution, we have introduced 1.5 % mass dispersion which is shown in Fig. 9. As the beam current is relatively high, we had to consider the effect of space charge forces in the calculations. We found that the beam blows up significantly for a beam current of 1 mA. To accept large currents the gap of the magnet needs to be increased further which in turn will increase weight and cost of the magnet. We have compromised acceptance at the sacrifice of beam intensity to some extent which has been optimized for the system. The optimized magnet specifications are given in Table 2. The hardware design of the magnet was done using OPERA 3D/TOSCA [10]. The detailed hardware design of the analysing magnet is described elsewhere [11] . The magnet has been fabricated by Danfysik A/s, Denmark. The different parameters obtained from the field mapping data are compared with the specifications given in Table 3.

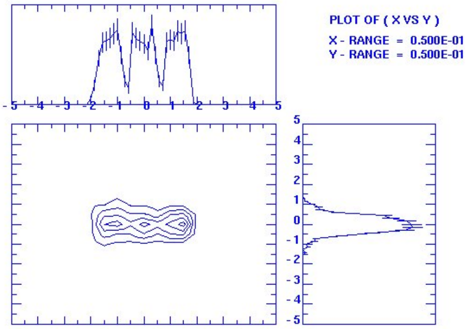

Fig. 9. Separation of masses around A=40 with mass dispersion of 1.5 % using GIOS with third order correction.

Table 2
Magnet specifications.

Maximum field	0.3 T
Bending radius	0.3 m
Bending angle	90°
Air cooled	Yes
Entrance, exit angle	32.8 ° ± 0.5
Entrance, exit pole shape	Cylindrical
Radius of curvature	–0.24 m ± 0.01
Pole profile	Approximate Rogowsky
Side pole profile	Champhered
Pole gap	80 mm
Homogeneity	$B = B_o(1+n_1(x/\rho)+n_2(x/\rho)^2+n_3(x/\rho)^3+..)$
n_1	0
n_2	-0.7 ± 0.07
n_3	0.9 ± 0.09

Table 3
Ion optical specification compared with model calculation and actual measured values at 0.3 T.

	Ion optical specifications	Model specifications	Measured value
Shim angle (°)	32.8 ± 0.5	32	31.7 ± 0.34
EFB radius (mm)	240 ± 10	250	255 ± 20
n_1	0	0	0
n_2	-0.7 ± 0.07	-0.694 ± 0.001	-0.67 ± 0.07
n_3	0.9 ± 0.09	0.873 ± 0.004	0.81 ± 0.15
n_4	0	-0.032 ± 0.046	-0.41 ± 2.49

2.3. Low Energy Accelerator Section

The mass analysed beam at the focal point of the magnet is then put into the low energy acceleration section through an electrostatic quadrupole triplet. The accelerator section consists of an accelerating column comprising of a number of co-axial disc type electrodes which can be polarised to achieve a maximum voltage of 400 kV. The RFQ is located at a distance of 4 m downstream. Another quadrupole triplet placed in between focuses the beam at the entrance of the RFQ. A 'three-port' switching magnet (0^o,10^o and 25^o) is planned in between quadrupole triplet and RFQ. The zero degree line is extended for HCI and the other two beam lines will be used for atomic physics and material science experiments. The position and aperture diameter of quadrupoles have been selected such that no beam is lost in transport. The simulation program TRANSPORT and GIOS has been used to optimise the parameters of the quadrupole lenses. Since the quadrupoles have large aperture, the effect of the fringing fields have been considered. The transverse beam optics simulation is shown in Fig. 10. From the simulation it is seen that the beam is transported without any appreciable loss in intensity.

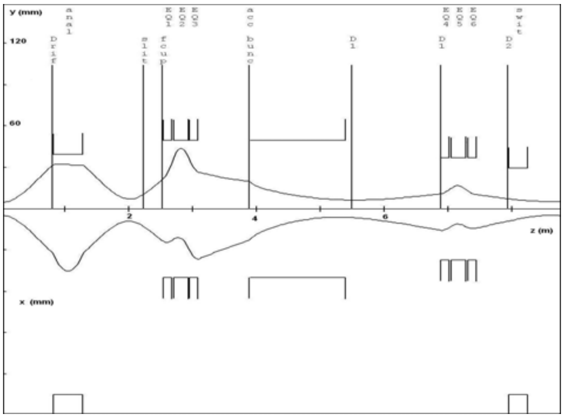

Fig. 10. Second order corrected beam envelope from ECR source up to RFQ entrance for E/q = 380 kV using TRANSPORT.

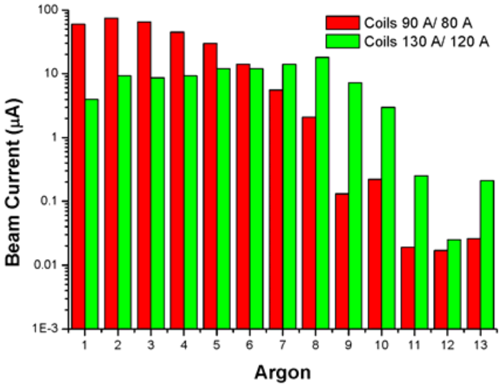

Fig. 11. A typical charge state distribution spectrum for argon at two different tuning conditions.

3. Discussion

The beam optics shown here is for Ar^{4+} using a deck voltage of 380 kV. It shows no beam is lost in transit from deck to RFQ. Final waist formed at the entrance of the RFQ is further shaped by radial matching section of the RFQ. Different codes have been used and compared to finalise the specifications of the different components. The analysing magnet is being used to analyse the ion beams from the ECR source. A typical spectrum for argon is shown in Fig. 11 for two different HTS coil current settings, both at 10 W of RF power.

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