DESIGN ASPECTS OF AN EXTERNAL INJECTION SYSTEM FOR VEC, CALCUTTA

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Variable Energy Cyclotron (VEC) is a K = 140 cyclotron which is at present accelerating light ions. It is proposed to instal a MICROMAFIOS ECR source[1] in order to obtain beams of light heavy ions like N,O,Ne, Ar etc. upto the energy of 35 MeV/A. Beam optical design of an external injection system to transport and axially inject the heavy ion beam into VEC has been developed. We propose to use an electrostatic mirror inflector at the machine centre. Phase space matching at the inflector exit, telescopic beam transport, minimization of aberrations have been the prime design criteria. Magnetic elements are preferred to take advantage of space charge neutralization.

Introduction

Advanced high charge state heavy ion sources working on the ECR principle are increasingly being installed or considered at many cyclotron laboratories[2-8]. These ion sources involve not too sophisticated technology and can deliver high charge state heavy ions in the medium mass range with appreciable intensities. Another advantage of ECR sources is that they run continuously without need for changing the eroded electrodes as is the case with PIG sources. They have 100% duty cycle. VEC design is similar to the 88 inch cyclotrons at LBL, Berkeley and Texas A&M University. It is very well suited for heavy ion acceleration over a large range of e/m values. It is single dee machine with a wide radiofrequency range. We plan to instal a room temperature source like MINIMAFIOS or MICROMAFIOS[9] which are considered to be very well suited for cyclotrons. Table 1 gives the performance of VEC + MINIMAFIOS combination for some representative ions. 5% efficiency from ion source exit to the cyclotron exit has been assumed.

Table 1

Ion	Energy (MeV/A)	Beam current (pnA)
^{12}C 6+	35.0	1
^{14}N 6+	25.7	12
^{16}O 7+	26.8	10
^{20}Ne 8+	22.4	5
^{40}Ar 11+	10.6	2

Design Criteria and Considerations

The ion source will be located in the high bay area above the cyclotron vault in a radiation free zone for easy accessibility. From the source the heavy ion beam must be transported over a distance of a few meters before it would be bent down to enter the axial hole through the upper part of the cyclotron magnet. The beam extracted from the ion source must be charge state analyzed by a suitable analysis system. The beam entering the axial hole is further transported down to enter the cyclotron magnetic field. From this point onwards upto the entry into the electrostatic mirror inflector, the ions experience very strong focussing due to the 'hole lens' effect[10]. This effect is accompanied by the emittance enlargement due to the presence of the longitudinal magnetic field component[11]. The beam inflected by the mirror should be matched as much as possible to the focussing conditions existing at the centre of the cyclotron, i.e.to the ν_r and ν_z values.

Telescopic beam transport systems have an advantage that they have waist to waist and point to point transfer properties[4]. The beam envelopes in such systems are, usually, varying periodically along the beam path. The number of focussing elements may be slightly larger than the conventional systems but the number of parameters is smaller because they are coupled. The point to point transfer properties offer advantages during the visual diagnostics of the beam. The telescopic systems having unitary (I) transformation properties introduce a modular character in the total system - a feature which makes the beam tuning simplified because each module can be tuned independently wherever applicable. We prefer to use such systems on our external injection lines - horizontal as well as vertical. In order to take advantage of the space charge neutralization we chose to use the magnetic element only.

An important aspect of the design is minimization of the emittance increase in the 'hole lens' region so that effective matching of the incoming beam to the cyclotron acceptance at the inflector exit can be accomplished. It is customary to assume the cyclotron acceptance ellipses as waists whose half widths are given by:

$$x_c = \left[\frac{\epsilon_h \cdot \rho}{\pi \cdot \nu_r}\right]^{1/2} \quad .. \quad (1)$$

$$z_c = \left[\frac{\epsilon_v \cdot \rho}{\pi \cdot \nu_z}\right]^{1/2} \quad .. \quad (2)$$

where ϵ_h and ϵ_v are the horizontal and vertical acceptances and ρ is the magnetic radius of the ions. We have assumed $\epsilon_h = \epsilon_v = \epsilon$ where ϵ is the beam emittance. The matching system should be able to take care of different $\nu_{r,z}$ values.

On-axis injection has only been considered. The injection voltage has hence been restricted to 10 kV in order to restrict the inflector size. The electric field between the high voltage electrode and the grounded grid has been assumed to be 45 kV/cm. The system was designed using the TRANSPORT code [12] for 10 keV deuteron beam with rigidity 20.432 kG-cm.

Horizontal Beam Handling System

A second order achromat[13] consisting of 4 identical unit cells should have a first order transfer matrix, R, such that:

$$R_{ij} = 1 \quad i = j \qquad .. \quad (3)$$
$$\quad\; = 0 \quad i \neq j$$

R corresponds to the TRANSPORT notation. A second

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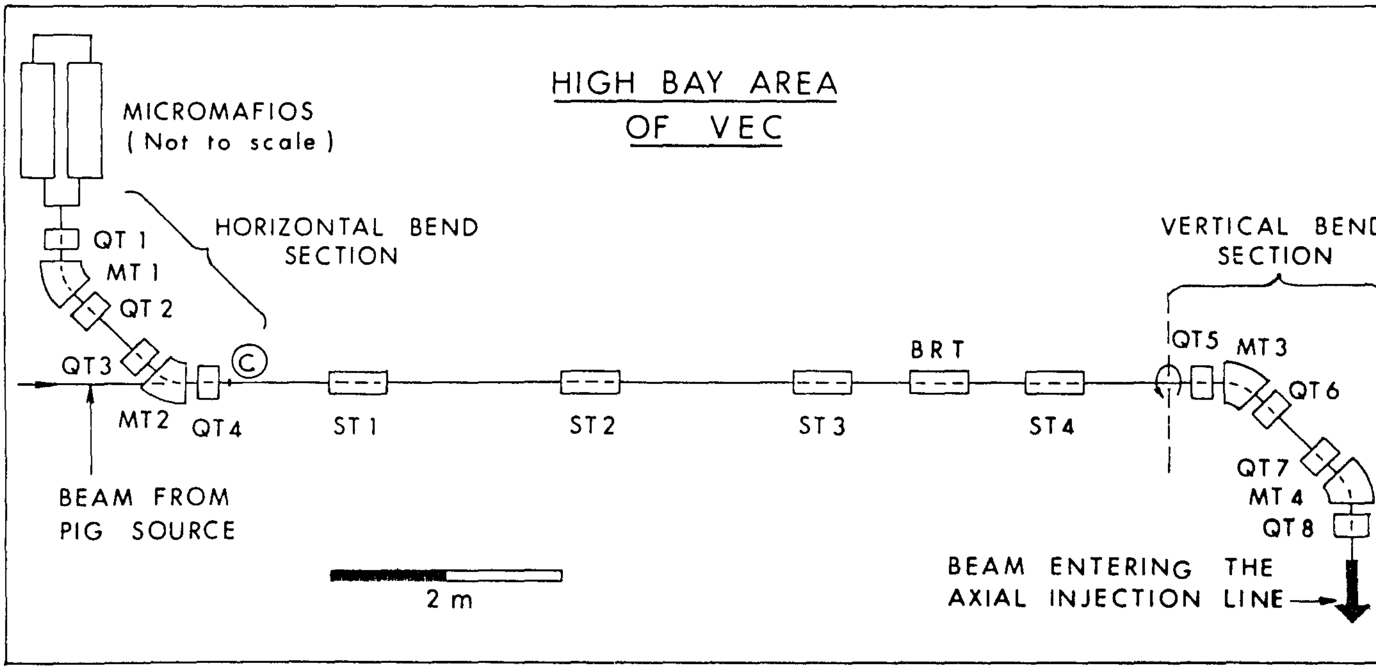

Fig.1: Horizontal beam handling and charge stage analysis system: QT - quadrupole magnets; MT - dipole magnets; ST - solenoid lenses; BRT - beam rotator solenoid. Charge state analysis is done at Ⓒ.

order achromat has vanishing second order aberrations in the transverse phase space and all the chromatic terms also vanish upto the second order when suitable sextupole component is introduced. Each unit cell consists of dipole and quadrupole components. At the end of the second unit cell the system is, however, dispersive where the momentum analysis can be performed. At this location the transverse part of R has a value-I. In our case each unit cell consists of a 45° uniform field dipole magnet (MT) with normal entry and exit and one quadrupole magnet (QT) on either side of the dipole for focussing. The dipoles have a ρ value of 37.5 cm and the quadrupoles have an effective length of 18.75 cm and half aperture 3.75 cm. The charge state resolution at the end of the second unit cell is given below:

$$\frac{dQ}{Q} = 2x \frac{\text{Image slit width } (s_i)}{\text{Dispersion Coefficient } (R_{16})} \quad .. \qquad (4)$$

For an object of 2 cm size with 0.5% momentum spread in the initial beam we have s_i = 2.25 cm. Our system has R_{16} = 101.43 cm which results in the charge state resolution of ~ 1 in 22.

Since, for VEC external injection system a vertical bend down is also needed, we have displaced the second half of the achromat about 8 meter downstream. Two conditions should now be generated in order to maintain the second order achromat properties. Firstly, a + I transformation beam transport system must be introduced between the two halves to cover 8 meter long path. Secondly, the beam must be rotated by 90° since the first bend is horizontal and the second vertical. The former condition was accomplished using solenoids(ST). Four unit cells each with a configuration: 0.75 m drift - 0.5 m solenoid (f=1 m) - 0.75 m drift: in succession form a +I system. The transfer matrix after every 2 unit cells is - I. The second condition was satisfied by providing an additional solenoid as beam rotator (BRT) between the third and fourth unit cells of solenoid transport system. The polarities of these 3 solenoids are so adjusted that the excitation of the beam rotator is minimum[4]. In

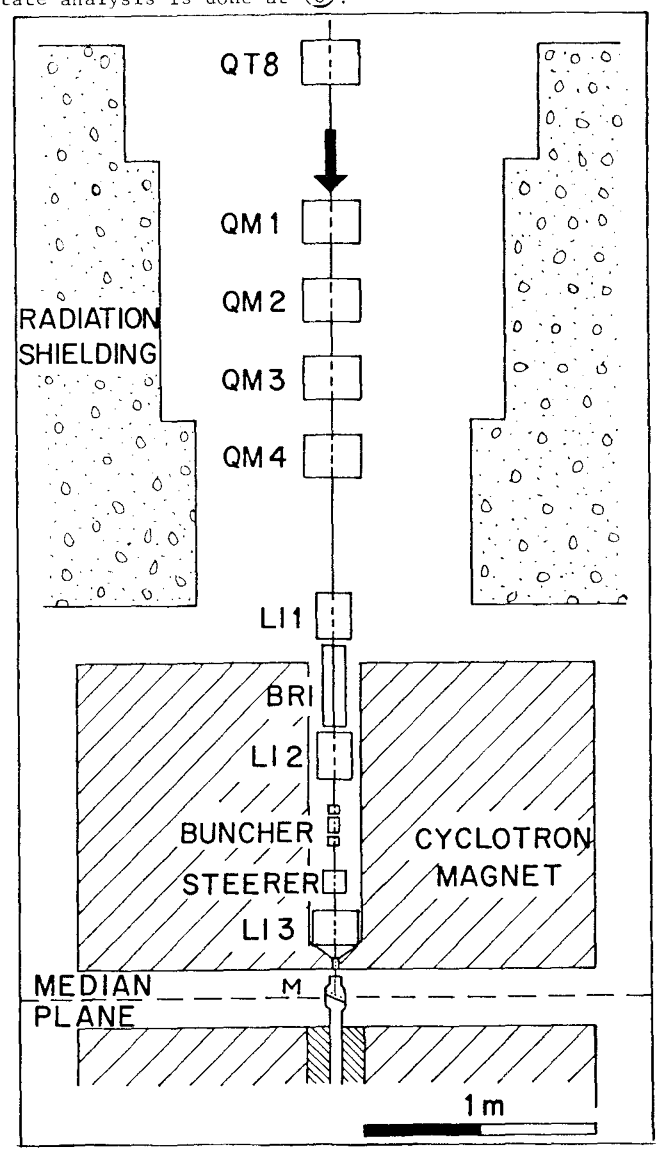

Fig. 2 : Vertical injection line : QM - matching quadrupole magnets, LI - magnetic lenses, M - inflector.

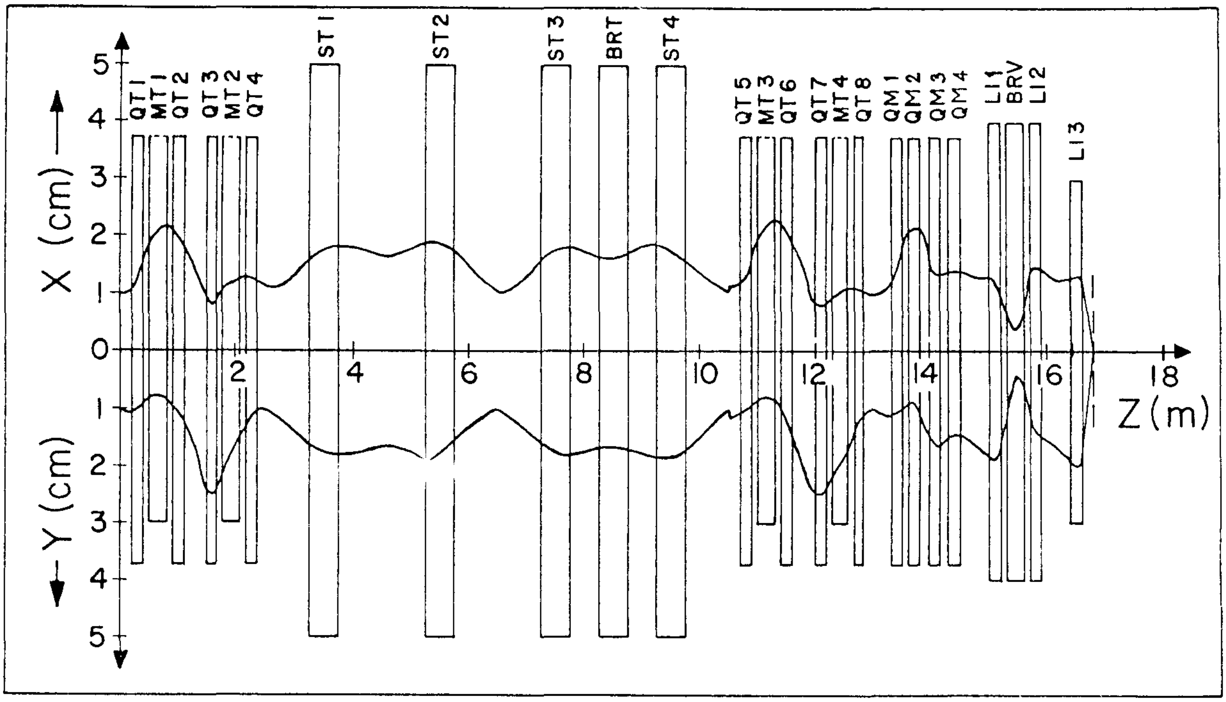

Fig.3 : Beam envelopes in the total injection system for the $\nu_r = 1$, $\nu_z = \frac{1}{2}$ case. Vertical bend starts at 10.5 m.

this configuration the total transfer matrix of this system is + I when the last drift space is reduced by f^2/f_r , where f_r is the focal length of the rotator.

The above arrangement of the split second order achromat and the solenoid transport system is shown in the fig.1.

Vertical Beam Line

Phase Space Matching System

Consists of 4 quadrupole magnets QM1 to QM4 all separated by 10 cm (Fig.2). Two parameters in each plane are matched assuming that the initial and final emittances are equal. These parameters are half beam size and orientation of the phase space ellipse. Quadrupole strengths are obtained using TRANSPORT by successive fitting. The importance of this system will be further discussed below.

Axial Beam Transport

Two magnetic lenses LI1 and LI2, shown in fig.2, form a - I transfer system, essentially for the beam transport. These are cylindrical magnetic lenses. Such lenses are suitable in the axial hole because the residual magnetic field is more or less cylindrical in nature. LI3 is a strong magnetic lens which focusses the beam sharply into the 'hole lens' + inflector system. The position and focal length of LI3 is optimized by tracing the beam back from the inflector exit through the 'hole lens.' The beam is further traced upstream through the LI2 - LI1 system in order to obtain the matching conditions for the phase space matching system.

Hole Lens

In our calculations the axial magnetic field was assumed to rise abruptly to its median plane value 10 cm upstream this plane and remaining constant upto the inflector. A case was also studied when the sharp field rise is situated at 11 cm upstream.

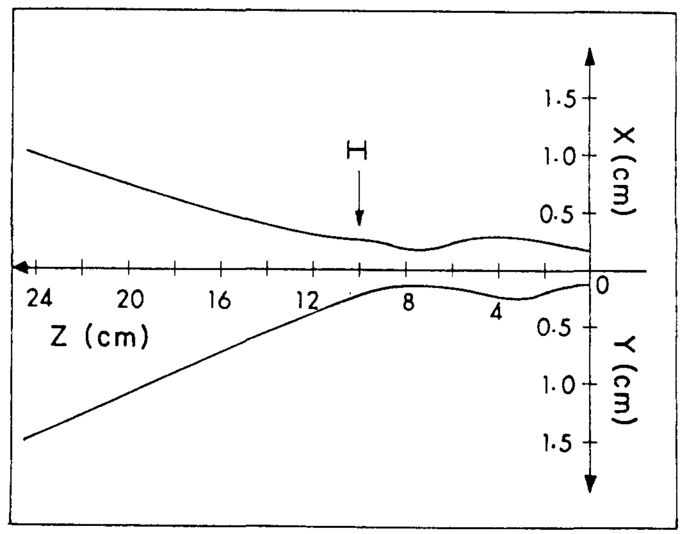

Fig.4. Beam envelopes in the last part of the injection system : 'hole lens' begins at 'H' position.

Electrostatic Mirror Inflector

The formalism developed by Bellomo et.al[11] has been followed to study the motion through the mirror. The forward and backward matrices derived in this reference were adapted to the TRANSPORT notation. 10 kV deutrons in a magnetic field of 17kG have a megnetic radius 12.061 mm. For a cyclotron acceptance of 500 mm-mrad in each plane the half waist sizes to be obtained at the mirror exit are as follows:

Horizontal,	$\nu_r = 1$	:	$x_0 =$	1.38 mm
Vertical,	$\nu_z = 1/3$	:	$z_0 =$	2.40 mm
	$= 1/2$	:	$=$	1.96 mm
	$= 2/3$	:	$=$	1.70 mm

The vertical injection line was designed assuming an incoming beam emittance of 500 mm-mrad for the $\nu_r = 1$, $\nu_z = \frac{1}{2}$ case for 'hole lens length' of 10 cm. In order to minimize the emittance enlargement a co-ordinate rotation was introduced by the solenoid (BRI)[4,11]. For this case, the emittance enlargement was less than 1% in each plane when BRI was excited to 'rotate' the beam by 22.2°. However, the horizontal and vertical waists which could be obtained at the inflector exit had half sizes 1.61 mm and 1.51 mm, respectively. The beam envelopes for entire system are shown in fig.3. The envelopes in the 'hole lens' and inflector region are shown in fig.4 on an expanded scale.

To accommodate changes in the ν_z values optimization was tried leaving QM1 to QM4 field strengths and beam rotation variable. Waists could be generated at the inflector exit with less than 1% emittance enlargement. The horizontal and vertical half waist sizes obtained were 1.75 mm and 1.65 mm, respectively, for ν_z=1/3 case, and 1.52 mm and 1.46 mm, respectively, for ν_z=2/3 case. Beam rotation for optimum solution was 19° for ν_z= 1/3 and 22.2° for ν_z= 2/3. Field strengths of QM1 also changed. Changes in these settings are larger for ν_z=1/3 as compared to ν_z=2/3 relative to the ν_z =1/2 solution.

When the 'hole lens length' is changed to 11 cm the emittance enlargement is about 14% in each plane. For an incoming beam of 400 mm-mrad, the horizontal and vertical half waist sizes obtained were 1.38 mm and 1.96 mm, respectively, for an enlarged emittance of 540 mm-mrad. The optimum beam rotation was -15.1°. Matching quadrupole settings were also changed. Fig.5 compares the obtained and the desired phase space ellipse at the inflector exit for the 4 cases discussed above.

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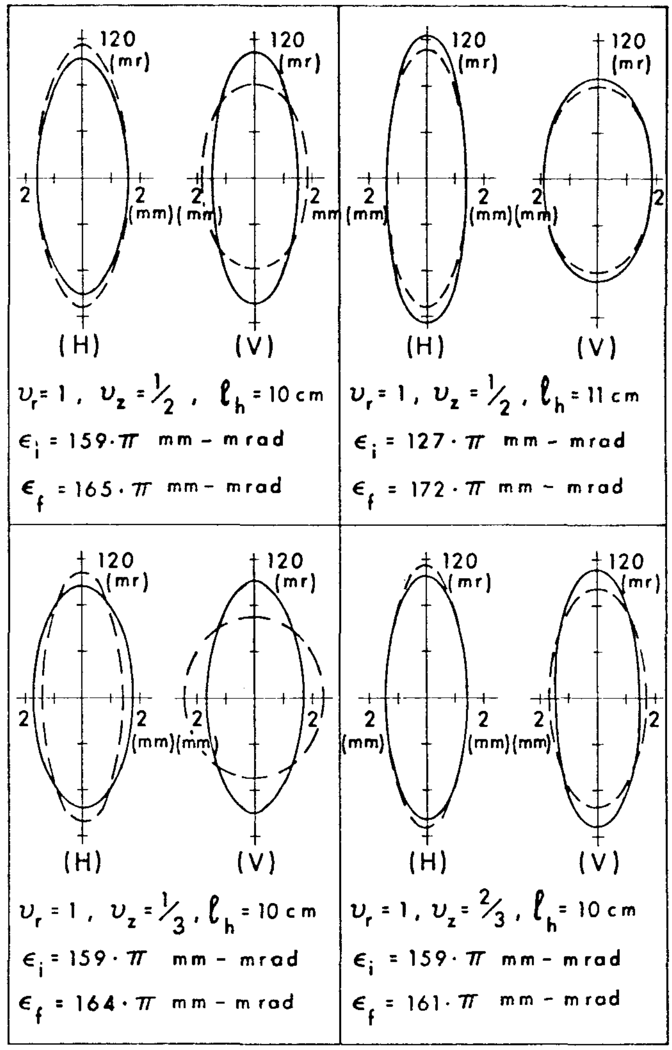

Fig.5 : Comparison of the desired (dotted) and obtained (line) phase space ellipses at the inflector exit for different cases.