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Study on using high injection voltage and spiral inflector in the central region of VEC

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Abstract. A feasibility study of using high injection voltage and spiral inflector in the present heavy ion central region of VEC is described. Conditions necessary for waist-to-waist transfer of the ion beam in the hole lens of main magnet have been obtained. The results of orbit studies of a variety of heavy ions indicate that a spiral inflector can be used in the central region.

Keywords. Accelerator; cyclotron; spiral inflector; central region; beam dynamics.

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1. Introduction

At present the variable energy cyclotron (VEC) with $K = 130$ at Kolkata is accelerating various kinds of light heavy ions using an indigenously developed 6.4 GHz electron cyclotron resonance (ECR) ion source. The heavy ion beams coming from the ECR ion source (maximum extraction voltage ∼8–10 kV at present) are injected into the cyclotron axially from the top. Before entering the central region the beam is subjected to a rising magnetic field in the axial hole of the magnet (hole lens) where it is focused strongly. It is then introduced into the median plane using a gridded electrostatic mirror inflector. The acceleration then takes place by special accelerating electrode structures known as dee and dummy dee inserts. The necessary conditions for waist-to-waist transfer of the heavy ion beam in the hole lens of the main magnet and optimization of various central region parameters for proper centering of ion orbits using electrostatic mirror inflector have been described in detail in our earlier work [1].

Although the mirror inflector is easy to construct, it requires voltage on the electrode nearly equal to the beam voltage (∼10 kV), which some times becomes difficult to hold and thus limits the use of high injection voltage. Due to the presence of grid wires in the inflector, there is a loss of transmission and deterioration in the quality of the beam also. Nowadays, the electrostatic spiral inflector [2–4] which has large admittance and requires relatively low voltage on the electrode has become widely used inflecting device in many modern variable energy multi-particle cyclotrons as well as in compact cyclotrons. In the present work, we have carried out a feasibility study of using a spiral inflector at the place of mirror inflector in the central region as an inflecting device. We have tried to find out a suitable geometry of a spiral inflector which in combination with the present central region will produce a well centered beam without any modification of the existing accelerating electrodes in the central region. We have used code CASINO [5] to find out the trajectory of the reference particle in the spiral inflector, code RELAX3D [6] to compute electric field in the central region and a modified version of code PINWHEEL to simulate the orbits in the central region. We have studied the orbits of a variety of heavy ions.

2. Geometry of spiral inflector

The role of spiral inflector is to bend the axially injected ion beam into the horizontal median plane of the cyclotron. It consists of a pair of biased electrodes housed into a ground shielding. In an untilted spiral inflector the central trajectory is mainly governed by two parameters; the electric radius of curvature R in the absence of magnetic field (which in fact is the height of the inflector) and the magnetic radius of curvature ρ in the absence of electric field which are given by

$$R = \frac{2T}{QE_0} \tag{1}$$

$$\rho = \frac{\sqrt{2mT}}{QB_0} \tag{2}$$

where T is the initial kinetic energy, B_0 the magnetic field, Q the electric charge on the ion, m its mass, and E_0 the magnitude of the electric field. These two parameters are used to adjust either the inflector height or relative position of its entrance and exit. We also need two more parameters defined by

$$K = \frac{R}{2\rho}, \quad \tau_D = \pi K$$

where K is related to the amount of spiral and τ_D is the transit time of the ion through the inflector. These two parameters along with R and ρ, define the central trajectory of the ion beam through the spiral inflector [2].

The whole operating region of a cyclotron can be described by the well-known parameter $p = qB_0^2/A$ where q is the charge state and A the mass number of the ion. For VEC, for a range of q/A from 0.25 to 0.5, p varies from 5 to 150 respectively and it includes the acceleration of a variety of heavy ions. It is not possible to design a single spiral inflector which can cover the entire operating region and also fits into the space available in the central region without disturbing the configuration of the existing accelerating electrodes. Therefore, we have chosen the operating region from $p = 40$ to 90, which covers the acceleration of lightest heavy ions such as $O^{5+,6+}$, $Ne^{6+,7+,8+}$, Ar^{9+} etc. Keeping in mind the available space in the central region, we have selected the spiral inflector with $R = 1.5$ cm, $\rho = 1.7$ cm which gives $K = 0.44$ and $\tau_D = 1.385$. After having chosen the parameters of the inflector following the above procedure, we have used both analytical approach as well as code CASINO [5] to find out the central trajectory of the reference particle. Results are shown in figure 1. We get the following values of the output coordinates of the central trajectory in the median plane (x–y plane):

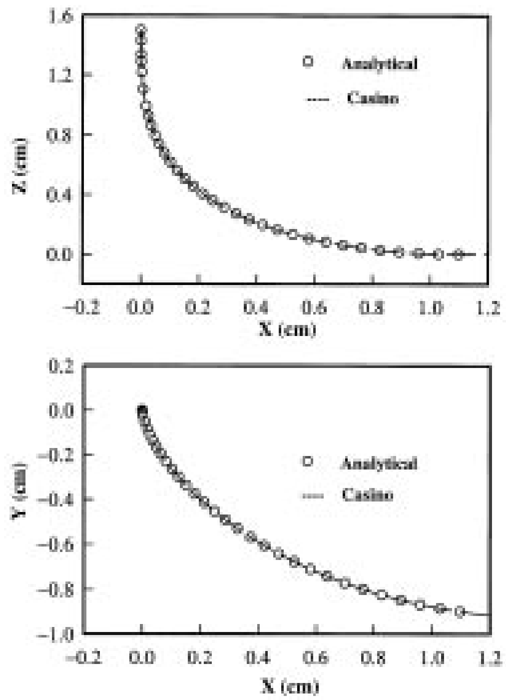

Figure 1. Central ray trajectories inside the inflector projection of vertical motion (top), and projection of motion in the median plane (bottom).

$$x_{\text{out}} = 1.098\,\text{cm}, \quad y_{\text{out}} = -0.899\,\text{cm}, \quad \phi = 100.65^\circ$$

where ϕ is the angle the trajectory makes with y-axis at the exit of inflector. These parameters define the cross-section of the inflector and are also required as an input for the orbit tracing code. Normally the aspect ratio between the width and the spacing of the electrodes is taken more than 2 to avoid the fringe field effect, but due to space constraints we have taken spacing and width equal to 5 mm and 7 mm respectively. Since the spiral inflector operates in scaling mode which demands that the radius of curvature ρ of the ion in the magnetic field must be constant, the scaling of injection voltage for different ions is governed by

$$V_{\text{inj}}(\text{kV}) = \frac{1}{20.88} \cdot \frac{q}{A} \cdot \left(B_0(\text{kG}) \cdot \rho(\text{cm})\right)^2. \tag{3}$$

The operating injection voltage and the required inflector voltage vary from 5.5 kV to 12.5 kV and 1.6 kV to 3.6 kV respectively.

3. Beam matching in the axial hole

Before entering the inflector, the heavy ion beam is subjected to a strong rising magnetic field in the axial hole of the magnet. The size of the inflector which bends the beam into the

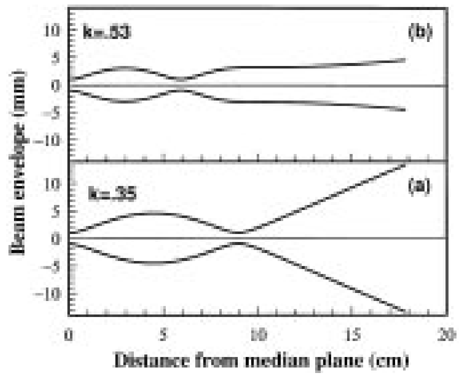

Figure 2. Beam envelope in the hole lens for two different modes of transmission for a 2 mm waist size at the median plane and an emittance of 500 mm·mrad. Here (**a**) λ oscillation, (**b**) $3\lambda/2$ oscillations. In each case the initial waist position is $\sim$10 cm away from the median plane.

median plane is very small and so it is necessary that the beam forms a waist there. This requirement puts restrictions on the distance of the object waist from the median plane and also on the initial beam size for a given emittance. A detailed treatment of the beam dynamics through the axial hole has been described in ref. [7] and here we point out only the relevant results. In figure 2, the envelopes of the beam are shown for a waist size of 2 mm at the median plane for different values of parameter k. In all the cases the position of the initial waist is chosen to be $\sim$10 cm from the median plane. The beam emittance is taken to be 500 mm·mrad. As the value of parameter k increases the number of oscillations increases and we see a change of envelope from one mode to another mode. This helps us to find out the position of the initial waist to be formed by the upstream transport optics for a given injection energy of the ion. In actual practice one chooses a suitable injection voltage and then finds the value of parameter k from the equation given below.

$$V_{\text{inj}}(\text{kV}) = 0.01197 \times \frac{p}{k^2} \tag{4}$$

where the parameter p, defined already, represents the operating region of the cyclotron and varies from 5 to 150 for VEC. Generally a high value of the injection voltage V_{inj} (8–12 kV) is chosen to avoid the space charge defocusing effects and the charge exchange losses in the transport line. Thus the choice of a proper mode is entirely dependent on the parameter p. It is clear from eq. (4) that for a high value of p, the parameter k should be high and the suitable mode of transmission may fall in $3\lambda/2$ mode or 2λ mode (not shown in figure). It should be pointed out here that the best zone for the initial waist to be formed by the upstream transport elements lies around 10–12 cm away from the median plane, otherwise the beam bust between the two waists becomes very large. We have also observed that once the final spot size of the beam is fixed, the position of the initial waist from the median plane is more or less independent of the beam emittance.

In the case of spiral inflector the radius of curvature ρ of the ion in the magnetic field is kept constant and injection voltage V_{inj} is scaled according to the value of the parameter p. This fact makes the parameter k also to be a constant for a given spiral inflector. The

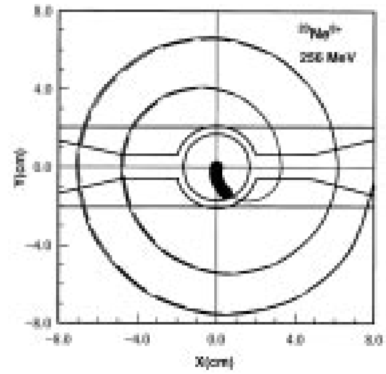

Figure 3. Simulated orbits of Ne^{8+} (256 MeV) in the central region optimized for a phase acceptance of $\pm 10^\circ$ using spiral inflector.

relation between k and ρ are given by $k\rho = 0.5$. For the present spiral inflector the value of k turns out to be 0.294 and predicts the λ-mode of transmission in the axial hole.

4. Orbit studies

The beam exiting from the inflector is immediately accelerated by special electrode structures called dee and dummy dee inserts. These are connected with dee and dummy dee respectively and are used to provide narrow accelerating gaps for efficient acceleration during the first few turns. During the initial phase of optimization, the electric field in the accelerating gaps was calculated analytically using a Gaussian function as

$$E_y = \frac{V_0}{\sigma\sqrt{2\pi}} \exp\left(-\frac{y^2}{2\sigma^2}\right) \tag{5}$$

with $\sigma = 0.4W + 0.2H$ where $W =$ gap width and $H =$ gap height of the electrodes. W and H were kept constant (11 mm) up to a radius of 5.4 cm and then slowly increased. This was chosen to satisfy the condition that all the ions (with high as well as low rigidity) must pass through this constant gap at least once to get sufficient acceleration. We tried various combinations of W and H in the process of optimization. Advantage of using the analytical approach is that the gap width and the height can be changed very quickly during the process of optimization of the geometry. Finally, electric field in the optimized geometry was calculated using the code RELAX3D from TRIUMF [6]. Calculations have covered the area 270 mm$\times$204 mm around the center in the x–y plane (median plane) and 140 mm in the z direction. The whole central region was divided by cubes with the mesh spacing equal in all the three directions, i.e., $h_x = h_y = h_z = 2$ mm.

The orbits of the accelerated particles were simulated using a modified version of the code PINWHEEL where the equations of motion in combined electric and magnetic fields are integrated using Runge–Kutta method. We have added few subroutines to the code to supply the analytical electric field data and the coordinates of the central trajectory at the exit of the inflector. We have optimized and checked the centering of a variety of ions such as O^{6+} (156 MeV and 200 MeV), $Ne^{6+,7+,8+}$ (200 MeV and 256 MeV) etc. We have minimized the centering error to less than 2 mm after three revolutions. In figure 3 the simulated orbits of $^{20}Ne^{8+}$ (256 MeV), optimized for a phase acceptance of $\pm 10^\circ$ are shown.

Our orbit studies indicate that a spiral inflector is feasible in the central region. One can use injection voltage up to 12 kV without any modifications in the existing accelerating electrodes. However, for higher injection voltage a new spiral inflector and some modifications in the central region are necessary.

References

[1] V S Pandit, P R Sarma and R K Bhandari, *Indian J. Pure Appl. Phys.* **39**, 58 (2001)
[2] L Belmont and J L Pabot, *IEEE Trans. Nucl. Sci.* **NS-13**, 191 (1966)
[3] D Toprek, J Sura, J Choinski and T Czosnyka, *Nucl. Instrum. Methods* **A469**, 24 (2001)
[4] P Belicev and D V Altiparmakov, *Nucl. Instrum. Methods* **A456**, 177 (2001)
[5] B F Milton and J B Pearson, CASINO User's Guide and Reference Manual, TRI-DN-89-19, Vancouver (1989)
[6] C J Cost and F W Jones, RELAX3D User's Guide and Reference Manual, TRI-CD-88-01, Vancouver (1989)
[7] V S Pandit, P R Sarma and R K Bhandari, *Indian J. Phys.* **72S**, (2), 49 (1999)