DESIGN OPTIMIZATION OF THE SPIRAL INFLECTOR FOR A HIGH CURRENT COMPACT CYCLOTRON

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Abstract

This paper describes the design of a spiral inflector in an environment where magnetic field is not constant in the region occupied by it and results of studies done on its optical properties in the presence of space charge. We have used the magnetic field data obtained from a 3D code and analytical electric field. We have also checked the orbit centering of the injected beam using a central region code. The effects of linear space charge have been evaluated and optimization of the input beam parameters has been done to minimize the coupling effects.

INTRODUCTION

At the Variable Energy Cyclotron Centre, we are developing a 10MeV, 5mA compact proton cyclotron [1]. A 2.45 GHz microwave ion source presently under testing for beam characterization, will produce ~20mA of proton beam at 80 keV. The extracted beam will be first collimated using slits, bunched using a sinusoidal buncher and will be injected axially in the central region of the cyclotron where a spiral inflector [2] will place the beam on the proper orbit. Two delta type resonators, each having ~ 45 degree angle located in the opposite valleys, will be used for providing acceleration to the beam.

Due to low average magnetic field and large ratio of hill/valley fields (~7), the computed magnetic field in the central region near the axis of the cyclotron is slightly lower than the resonance field (6.89 kG) and it also varies with radius. This makes the design of the spiral inflector more complicated and challenging.

We have developed a code to calculate the central ray in the spiral inflector using the 3D magnetic field data. Results were compared with CASINO [3]. The output of the program was used in code INFLECTOR [4] to find the shape of the electrodes. The electric field in the inflector was calculated using RELAX3D [5]. We have computed the paraxial ion trajectory in the presence of space charge effect and optimized the initial starting conditions of the beam to get minimum coupling effects in two transverse phase planes at the inflector exit.

SPIRAL INFLECTOR

Details of the spiral inflector have been described in classical reference [2] and in many other papers. Here we briefly outline the formulations used to design the spiral inflector. We have used the right handed Cartesian coordinate system x, *y*, *z* whose origin lies on the cyclotron axis. The *z* axis is vertically opposite in the direction of the incoming ion and major component of the magnetic field (B_z) is opposite to the z direction and initial electric field is along the *x* direction. The components of Lorentz force equation in the combined electric and magnet field can be written as:

$$x'' = \frac{q}{mv_0^2} E_x + \frac{q}{mv_0}\left(z'B_y - y'B_z\right) \quad (1a)$$

$$y'' = \frac{q}{mv_0^2} E_y + \frac{q}{mv_0}\left(x'B_z - z'B_x\right) \quad (1b)$$

$$z'' = \frac{q}{mv_0^2} E_z + \frac{q}{mv_0}\left(y'B_x - x'B_y\right) \quad (1c)$$

where v_0 is the velocity, *m* is mass and q is the charge of the ion. Here the electric and magnetic fields both are the functions of coordinates *x*, *y*, *z* and the prime denotes the differentiation with respect to path length $s = v_0 t$ .The electric fields for tapered electrodes of a spiral inflector can be written as

$$E_x = E_0\left(-\frac{x'z'}{\sqrt{x'^2+y'^2}} - \frac{y'}{\sqrt{x'^2+y'^2}}\tan\theta\right) \quad (2a)$$

$$E_y = E_0\left(-\frac{y'z'}{\sqrt{x'^2+y'^2}} + \frac{x'}{\sqrt{x'^2+y'^2}}\tan\theta\right) \quad (2b)$$

$$E_z = E_0\sqrt{x'^2+y'^2} \quad (2c)$$

Here θ is the local tilt angle and E_0 is the magnitude of the electric field which is always constant and perpendicular to the direction of motion of the ion and decides the height parameter *A* of the spiral inflector;

$$A = 2T/qE_0 \quad (3)$$

T is the kinetic energy of the ion. In fact *A* is the electric radius of the ion in the absence of the magnetic field.

In the case of a tilted inflector a component of the electric field is used to generate a force in the plane of the magnetic force to modify the beam centering. The spacing between electrodes is narrowed gradually to maintain the electric radius constant. The local tilt angle θ is given by

$$\tan\theta = k'\frac{A - z(s)}{A} \quad (4)$$

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where k' is a free parameter defines the maximum tilt angle $\theta_m = \tan^{-1} k'$ at the exit of the inflector (z = 0). Choosing a suitable value of A and k' one can easily solve the differential equations (1) to get the coordinates of central ion trajectory in a given magnetic field and hence the required shape of the spiral inflector.

We have written a computer code to analyze the central ion trajectory through the spiral inflector in the presence of 3D magnetic field and analytical electric field. We have performed all the calculations at injection energy of 80 keV. Important parameters of the inflector are listed in Table 1.

Table 1: Parameters of the inflector

Parameters	Values
Height (A)	8.6 cm
Tilt (k′)	0.65
Electric field	18.5 kV/cm
Off centering	4.1 cm
Electrode gap entrance/exit	1.4 cm/1.2cm
Position at exit (r,θ)	7.05 cm , 99.11°

The central trajectory data is used in the programme INFLECTOR to create the shape of the electrodes (shown in Figure 1) and mesh points for RELAX3D to calculate the electric field distributions in the spiral inflector.

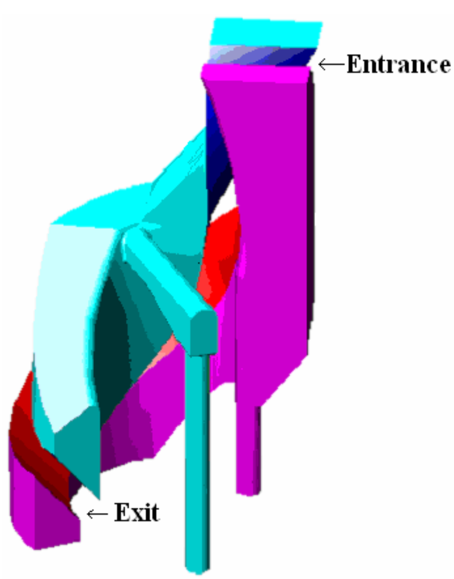

Figure 1: Optimized electrode geometry of the inflector.

Figure 2 shows the electric field calculated using RELAX3D on the axis along the central trajectories and compares with the analytical field (hard edge approximation). We can easily see that the effect of fringe field is very small due to the choice of comparatively large height A in the present design.

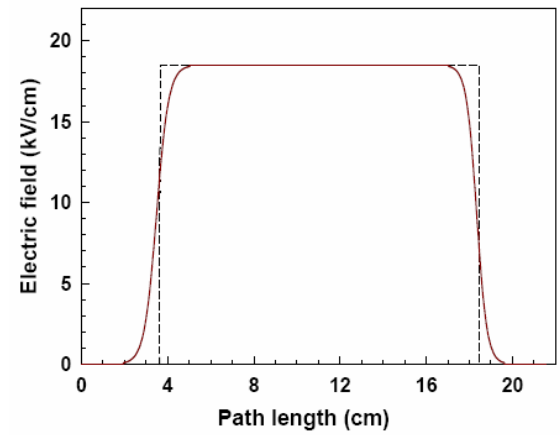

Figure 2: Comparison of analytic and computed electric field along the central trajectory inside the spiral inflector.

ORBIT CENTERING

The orbit centering of the injected beam to the central region of the cyclotron was checked using a central region code. The coordinates and velocity of the particle at the inflector exit are entered as an input to this programme. All calculations of the beam centering have been performed with following parameters: injection energy = 80keV, Dee Voltage = 125kV, gap width between dee and dummy dee = 2cm, dee height = 3cm and magnetic field obtained from 3D code. Figure 3 shows the position of the accelerating gaps in the median plane and accelerated orbits of protons.

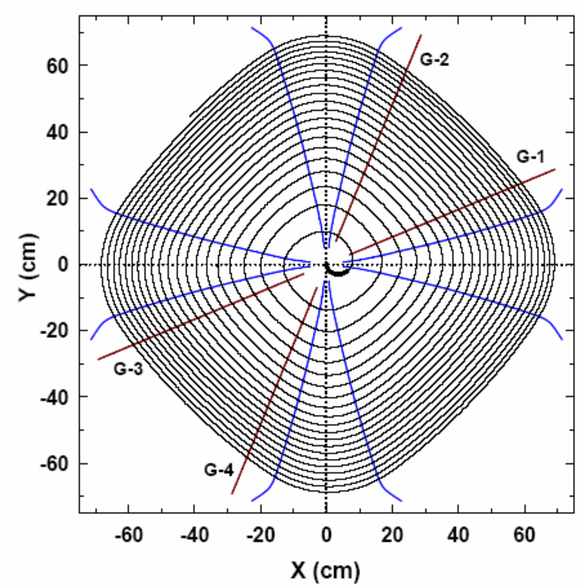

Figure 3: Position of the inflector, location of the accelerating gaps and optimized accelerated orbits for protons from 80 keV to 10 MeV.

INPUT BEAM OPTIMIZATION

Because of high intensity, it is necessary to study the effect of space charge on the beam transmission through the spiral inflector. In order to achieve the optimum performance, the input condition must be optimized to minimize the dilution of the beam emittance at the inflector exit. We have used the paraxial ray trajectory equations given in reference [6] with some modifications in the space charge term. Since these equations are valid only for a constant magnetic field, we have found out a constant field B_0=5.15 kG (resonance field 6.89 kG) which gives almost identical central ray trajectory for fixed *A* and *k'* as shown in Figure 4. In our calculations we have neglected the effect of fringe field at the entrance and exit of the spiral inflector which is very small.

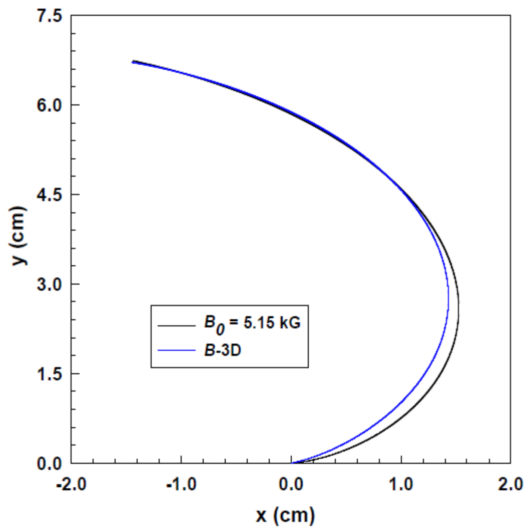

Figure 4: Central ray trajectories with 3D magnetic field and constant magnetic field of 5.15 kG.

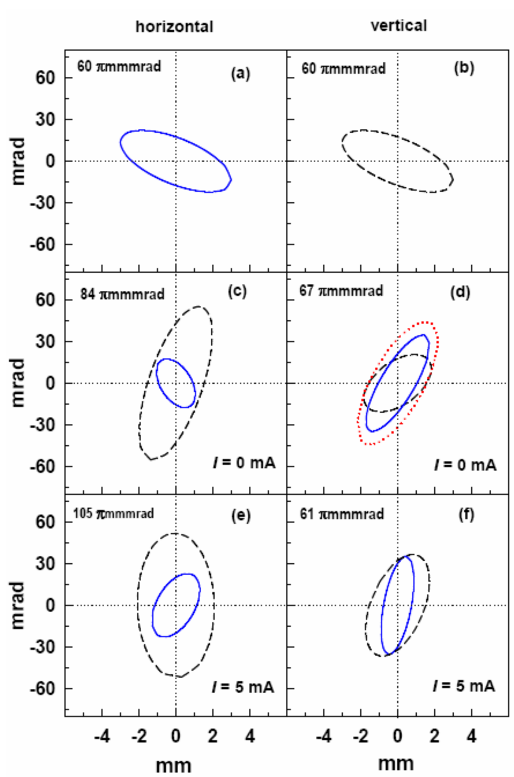

Figure 5: Phase space diagrams in horizontal and vertical planes: a) & b) at entrance; c) & d) at exit with I=0 mA, e) & f) at exit with I=5 mA (I_{peak} in the bunch~60mA)

The phase space ellipses, in the horizontal (h-plane) and vertical (u-plane) planes at the entrance and exit of inflector are presented in Figure 5 for two values of the beam current and of equal emittances 60 πmmmrad in both planes. We can clearly see the coupling effects between the horizontal and vertical motions. We have taken care that the effect of coupling on the emittance dilution should be minimum in the vertical plane because focusing forces are weak in this plane. The estimated effective emittances at the exit in the horizontal and vertical planes are indicated in Figure 5. The beam envelopes around the central ion trajectory obtained using twelve different initial conditions of the particles on entrance ellipse through the inflector is shown in Figure 6. The maximum beam size in both planes at the exit is within 5 mm, less than the gap between the electrodes at the exit (12 mm).

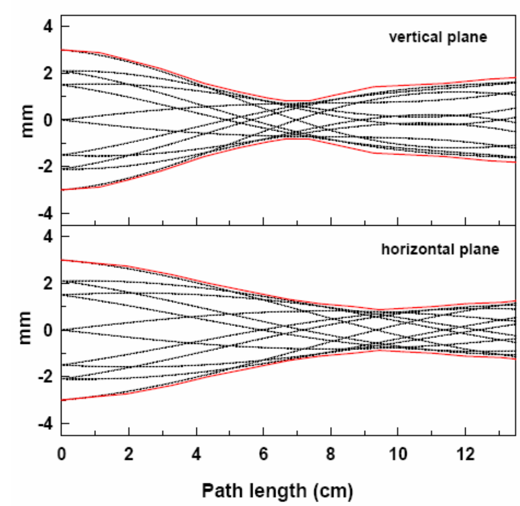

Figure 6: Beam envelop in the inflector.

CONCLUSION

We have presented the design of spiral inflector using 3D magnetic field data. The beam centering requirement forced us to chose tilt parameter *k'*= 0.65, making the fabrication a challenging job. Numerical simulations with linear space charge effects have been performed and input beam parameters have been optimised to have minimum coupling between the two transverse planes at the inflector exit.

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