Simulation results of a spiral inflector by CASINO program

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1. Introduction

An injection system used at a cyclotron is designed to deflect the negative hydrogen ions effectively from the vertical beam line of an external ion source into the horizontal direction at the median plane in order to accelerate them inside the cyclotron. An electrostatic mirror [1] consisted of a pair of planar electrodes at an angle of 45 degree to the incoming beam was considered as an injection system for the first time. The front grid electrode allows the beam to enter the electric field and the back electrode bends them by applying the required voltage higher than the energy of incoming ions. Although the mirror system has a simple structure, the grid reduces the transmission and increases the effective emittance of the beam at the exit. Such a mirror had the transmission efficiency as low as 3.5 % from the source to accelerated beam without a bunching system [1] because the simple mirror system excludes the motion of ions in a strong magnetic field. Although the mirror can be designed in small dimensions, it requires a very high voltage to deflect the ions. For instance, an electrostatic mirror with higher than 25 keV is able to inject 30 keV proton beams into the mid plane of a cyclotron, while a properly designed spiral inflector is required only ~10 keV. The reduced voltage on the electrodes will prevent sparking problems associated with high-voltage breakdown.

2. Methods and Results

The shape of the spiral inflector is simulated in order to have flexibility with two adjustable parameters, such as an inflector height and a tilt angle. Due to its flexibility and low voltage requirement, the spiral inflector has replaced the mirror system. To design a inflector, the direction of the beam at the inflector exit will be properly positioned and matched to the center region acceptances for optimal injection into the cyclotron. Therefore the optical properties of inflectors have been studied extensively theoretically [3-5] and experimentally [6]. In this work, the optimization of the inflector shape is carried numerically by simulating the ions trajectories using CASINO program [7]. CAlculation of Spiral Inflector Orbits (CASINO) is used to calculate ion orbits in a spiral inflector with an analytical electric and a uniform magnetic field configurations, which can be either analytically defined or be specified using a potential map from RELAX3D [8].

2.1 Two coordinate systems used for ion trajectories

To study the beam trajectory in a spiral inflector, two coordinate systems are defined (see figure 1). The first coordinate system (x,y,z) is fixed in space where the origin of this coordinate system will be the center of the inflector entrance aperture and where the three unit vectors of $\hat{i}$, $\hat{j}$, and $\hat{k}$ point along the x-, y-, and z-axis, respectively. The magnetic field is fixed along the *z*-direction in (*x*,*y*,*z*) frame so that the direction of the magnetic field (B) is parallel with $\hat{k}$. The z-axis is vertically opposite to the direction of the incoming ion beam.

The second coordinate system (referred to an optical coordinate system) is a moving coordinate system, which travels in space as the ions travel in the inflector. The origin of the optical coordinate system will be the position of the ions on the central trajectory at a time *t*. The orientation of these coordinate axes can be described in terms of three unit vectors $\hat{h}$, $\hat{u}$, and $\hat{v}$, which have the following properties: (a) a vector $\hat{v}$ is along the velocity vector of the ion on central trajectory, (b) a vector $\hat{u}$ is a unit vector perpendicular to $\hat{v}$ and lying in a vertical plane with a positive *z* component, (c) a vector $\hat{h}$ is a horizontal vector parallel to the median plane of the cyclotron, defined by the vector cross product as $\hat{h} = \hat{v} \times \hat{u}$.

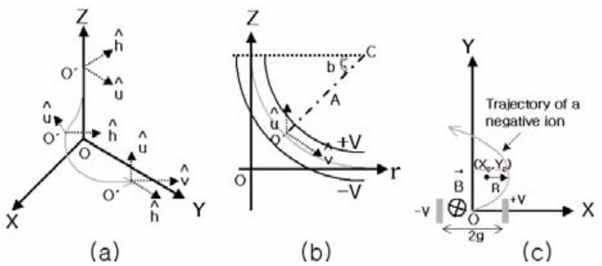

Fig. 1. (a) Schematic diagram for the central ion trajectory at inflector in two coordinate systems: a fixed (x,y,z) and an optical (u,v,h) coordinate systems. The gray solid line represents the path of a negative ion in two cylindrical capacitors where the projection of design orbit in spiral inflector has the shape like this path. (b) The negative charge particle goes through the design orbit when an upper electrode is applied with positive voltage (+V) and lower electrode applied with negative voltage (-V). The ions follow the equipotential lines, which are corresponding with electrode surfaces. (c) Trajectory of a negative ion projected in x-y plane. The magnetic field point out of plane and the electric field directs into a negative x direction.

2.2 Parameters for the shape of electrode of spiral inflector

Two parameters of A and R of the spiral inflector can be adjusted in order to position ions into the entrance of the spiral inflector on the magnet axis and to orient them properly to the exit of the spiral inflector for injection of the ions on the median plane of cyclotron. The value of A is the corresponding to the bending radius for an ion in a radial electric field E_u (see fig. 1), inversely proportional to the potential difference of the electrodes. We can recognize that in r-z projection in fig. 1(b) of design orbits, only E_o affect the motion of particle in 1/4 circle and the same as that in two cylindrical capacitors. From the assumption of the central ion trajectory following an equipotential surface, biased electrodes surface line should follow the design orbit. Schematic shape of biased electrode surface of spiral inflector is similar with the trajectories where the beam can be injected along the center of the entrance and easily positioned in the central region with slanted exit electrodes.

Table 1 Parameters of the spiral inflector used for CASINO calculation.

Parameter	Value
Injection Energy (E_o)	30 (KeV)
Height (A)	2.50 (cm)
Magnetic radius (R)	1.90 (cm)
Shape Parameter (K)	1.06
Central E-field (E)	24.0 (KV/cm)
Nominal Electrode Voltage (V_{nom})	$\pm$9.60 (KV)
Tilt Parameter (k')	0.80
Electrode Gap (d)	0.40 (cm)
Off Centering at exit (ρ_C)	0.75 (cm)
Position at Exit (r, θ)	(1.82 (cm), 125.38 (deg))

2.3 Simulation Results

The analysis of the ion trajectory through the spiral inflector is carried by the computer code of CASINO program [9]. Fig. 2 (a) shows the central orbit of the three-dimensional shape simulated in an analytic electric field distribution in the case of A=2.5 cm and k'=0.8 with a uniform magnetic field of B_o=13.2 Kgauss. The gap distance between two biased electrodes is d=0.8 cm and width of each the electrode is S=1.6 cm. The kinetic energy of injected H^- particles is 30 keV and other parameters of the spiral inflector used in CASINO are presented in Table 1. The orbits in r-z projection (b) and x-y projection (c) of design orbit are depicted in figure 2. Using the CASINO output, INFLECTOR program is executed to display the electrode shape.

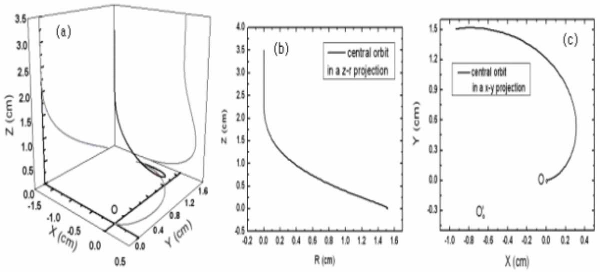

Fig. 2. Central orbit in (a) three-dimensional shape (b) a r-z projection (c) a x-y projection simulated in analytic electric field distribution and a uniform magnetic field. The point marked by letter O' is the center of the curvature of the ion trajectory at the inflector axis (or at the central region entrance of the cyclotron). The distance between O and O' is called off-center. The point marked by letter O is the position of the ion entrance in the spiral inflector (this point represents also the center of some cyclotron).

3. Conclusion

CASINO is used to get the ion-optical properties of the spiral inflector with various forms of the electrodes and to study approximately the effect of the edge of the electrodes. The beam of ions entering vertically along the center axis of the magnet from the top of the machine is deflected through an angle of 90 degrees by a spiral inflector. From the result of simulation a spiral inflector with a height of A=2.5 cm and a tilt parameter of k' =0.8 is optimized to make beam centering at the exit of spiral inflector. Fringe electric fields estimated by running RELAX3D are also considered to design the proper inflector closed to designed orbit satisfying p_z=0 condition by applying a reduced voltage at the electrode. Using the tilted electrodes more flexibility is achievable for matching the central orbit to the cyclotron indicating better optical properties.

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