ELECTRIC FIELD DISTRIBUTION IN A SPIRAL INFLECTOR FOR CYCLOTRON INJECTION APPLICATIONS

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Abstract

The results of numerical studies of the electric field distributions in a spiral inflector, designed for axial injection system of H^-, D^- and He^{++} beams into the Oak Ridge Isochronous Cyclotron (ORIC), are presented in this report. Discrepancies are found between the electric fields obtained from numerical computations and those derived from theoretical field distributions within the inflector. Fringe fields at the entrance to the inflector, in combination with the field discrepancies, lead to significant deviations in particle trajectories from those derived from analytical expressions for fields within such devices. A method is described for shaping the electrode surfaces of the spiral inflector that is effective in compensating for fringe fields at the entrance to the inflector and a simple solution is introduced that eliminates the seemingly unavoidable shift in the central beam path. As a consequence of these studies, we arrive at a design for a spiral inflector that operates at a low voltage with greatly improved optical properties in which the paths of injected particles are precisely known.

1 INTRODUCTION

In order to deliver higher intensity, H^+, D^+ and He^{++} beams for ISOL target production of radioactive species for post acceleration at the Holifield Radioactive Ion Beam Facility (HRIBF), an axial injection system for the ORIC has been proposed [1]. The injection system utilizes a spiral inflector to inject beams from an external ion source system into the gyration plane of the cyclotron [2]. For this application, the energy of the injected beam must be as high as practical in order to reduce space charge effects associated with the high-intensity beams required to meet future radioactive ion beam intensity needs at the HRIBF. However, maximum injection energies are limited by the voltage-holding capability of the device.

A spiral inflector must bend beams through 90 degrees into an orbit that, after first turn acceleration by the cyclotron *dees,* misses the device. Therefore, the physical size of the device must be small. Belmont and Pabot invented the first spiral inflector at Grenoble [3] to fit within the limited space available in the central region of their cyclotron. The device demonstrated a high injection efficiency (up to 100%), superior to that of an electrostatic mirror. Since this development, these devices have been widely used in axial injection systems [4-6]. However, it is well known that beam trajectories within a spiral inflector do not follow the theoretical path and are shifted by the action of fringe fields at the entrance to and exit from the inflector [7,8]. By modifying the electrodes at the entrance to the inflector, these shifts can be reduced but cannot be completely eliminated by this method. It is a common practice to design a spiral inflector with an electrode gap size nearly twice that of the beam dimension to guide the injected beam through the spiral electrode system. This design requires that higher voltages be applied to the device. The inflector, described in this paper, eliminates path shifts and operates at much lower voltages than prior art devices.

The results of numerical electric field studies for the inflector with the 3D finite-element code ANSYS [9] show that, aside from fringe-field effects at the entrance and exit of these devices, electric-field distributions inside inflectors do not agree with those derived from theoretical treatments of the problem due to the nature of the twisted electrode structures. These effects lead to significant deviations of particle trajectories through these devices that affect the accuracy of injection into the gyration planes of cyclotrons. By reshaping the electrodes at the entrance and exit of the spiral inflector, discrepancies of the electric fields within the inflector can be reduced and completely eliminated by re-centering the inflector electrode system.

2 DESIGN OF THE SPIRAL ELECTRODES

A spiral inflector with an electric bending radius, A = 4.06 cm, and magnetic gyration radius, R = 2.77 cm and K = 1.13 (K is defined in Refs. [2-6].) has been designed for injection of 50-keV proton beams into the ORIC. The central beam trajectory in the spiral inflector, derived analytically, serves as the starting point for the design [2]. Fig. 1 schematically represents the spiral inflector electrodes. Since the structure is twisted, electric-field distributions inside the inflector will deviate from those of the symmetrical structure resulting in combined forces from all the adjacent surfaces that alter the trajectories of particles through the system, as seen in Fig. 2.

Since the spiral inflector has an entrance to and exit from a gap between the twisted electrode pair, fringe fields exist at the entrance and exit of the inflector. Fig. 3 displays the computed and theoretical electric-field distributions at the mid-point of the spiral inflector. Although the fringe fields at the exit of the inflector are modified by the RF field of the cyclotron *dees*, the major component of the field accelerates beams toward the *dees*, and therefore, does not appreciably affect the trajectories of particles since they have already passed through the inflector. However, the same is not true for particles at entrance to the device, the field pushes the trajectories away from the desired path. The maximum shift of the central beam inside the original spiral inflector is approximately 1 mm, as simulated with a code especially written for calculating this effect [2].

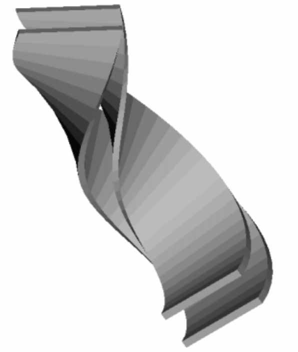
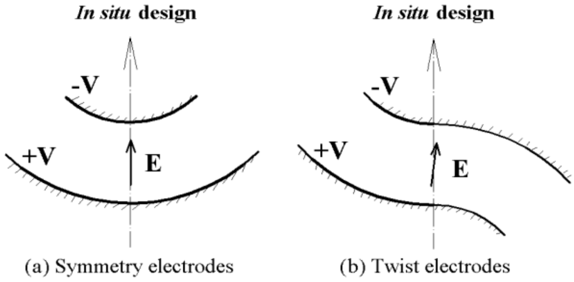


Fig. 1. Computed electrodes of a spiral inflector.



(a) Symmetry electrodes (b) Twist electrodes

Fig. 2. Actual direction of electric fields (solid arrow) and those of the *in situ* design (dashed arrow) in (a) symmetric electrode system and in (b) a twisted electrode system.

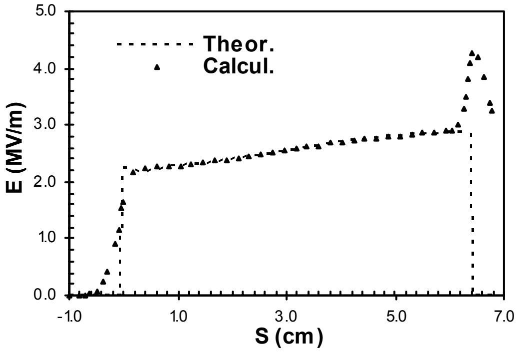


Fig. 3. Calculated and theoretical-field distributions of the original spiral inflector, fields at exit of the inflector are influenced by the cyclotron *RF* field.

By shortening the inflector electrodes at entrance to compensate for the fringe field, the shift in beam path can be reduced (e.g., shortening by 1.1 mm reduces the central ray shift to ~0.4 mm). Fig. 4 shows the electric-field distribution at the mid-plane of the spiral inflector with the electrodes shortened by 1.1 mm. However, the method cannot eliminate the beam path shift completely because electric field discrepancies inside the twisted electrode structure are unaffected by this operation. In fact, after shortening the electrodes, the position of the electric field curvature is changed, as noted in Fig. 4. The direction of the fringe field is rotated by ~3.5°, although not obvious in the figure.

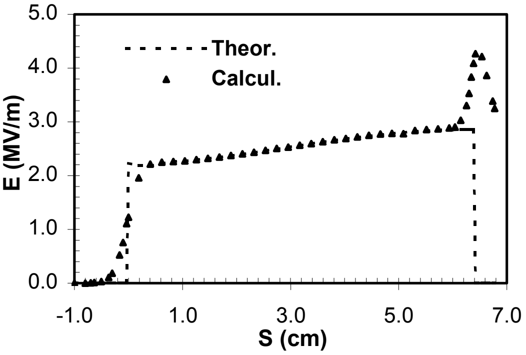


Fig. 4. Calculated and theoretical field distributions of the spiral inflector with the entrance electrodes shortened by 1.1 mm.

3 ROTATION OF THE ELECTRODES

Discrepancies between the calculated and theoretical electric-field distribution inside the spiral inflector can be seen by comparison of the three field components. Significant differences only occur for the perpendicular field components (x and y components). Fig. 5 shows the calculated and theoretical x and y components of the field inside the inflector. The calculated fields have magnitudes quite close to those of the theoretical forms but have slightly different peak locations. However, these seemingly very small differences lead to significant shifts in positions of beam trajectories in the device due to the twisted nature of the electrodes, and therefore, have significant influences on the accuracy to which beams can be injected into the central region of a cyclotron.

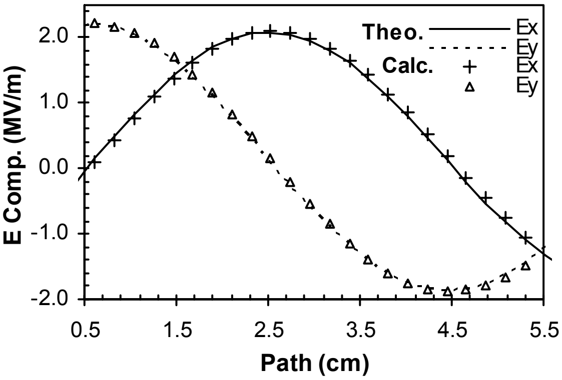


Fig. 5. Computed and theoretical perpendicular electric field components, *Ex* and *Ey* inside the spiral inflector.

By rotating the inflector electrodes horizontally, the field discrepancies within the twisted electrode structure can be reduced. The following term is used to determine the rotation of the electrodes [2],

$$\delta\phi = F \cdot [2Kb - \frac{(2Kb)^2}{K \cdot \pi}] \qquad (1)$$

where, F is constant and; b is the particle deflection angle from the axis of the magnetic field (0 to $\pi/2$). (For definitions of other parameters, see Ref. [2].)

Fig. 6 shows the perpendicular electric-field components of the theoretical distributions in the spiral inflector and those computed with the inflector electrodes rotated for $F = 0.027$. As noted, the discrepancies in electric-field distributions are reduced. After the shortening of the electrodes, the shift in the central beam path inside the inflector is reduced from 1 mm to ~0.7 mm.

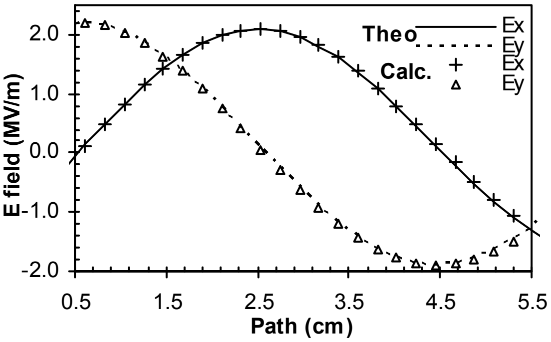


Fig. 6. Calculated and theoretical perpendicular electric-field components, *Ex* and *Ey* inside the spiral inflector with electrodes rotated at $F = 0.027$.

Rotation of the inflector electrodes can also be used to partially compensate for fringe fields at the entrance to the spiral inflector and thereby, reduce shifts in the beam path [2]. Shortening the electrodes at the entrance to the inflector reduces the effective length of the electric bend and therefore, the voltage across the inflector electrodes must be increased accordingly. However, rotating the entrance electrodes of the inflector does not affect the operational voltage of the device. Fig. 7 shows top views of the spiral electrodes of the design before and after rotating the electrodes at entrance by 15°. The beam path shift is reduced to approximately 0.6 mm after rotation.

(a) Original spiral inflector (b) Entrance electrodes rotate 15°

Fig. 7. Top view of the spiral inflector electrodes: (a) the original design; (b) entrance electrodes rotated by 15°.

4 RE-CENTERING THE INFLECTOR

Fringe fields effects at the entrance to the spiral inflector and discrepancies of the electric-field distributions inside the device displace the injected beam away from the intended path. In principle, the shift in path can be completely eliminated by shortening the entrance electrodes and by rotation of the electrodes appropriately. However, such iterations require many time consuming, tedious numerical computations because of the complicated electrode structure and the large effects on beam trajectories caused by small changes. Nevertheless, a spiral inflector with zero shift of the central trajectory is pursued that can operate at relatively low voltages for injection of 50 keV *p* and 59 keV *d* beams into the ORIC. A conventional large-gap spiral inflector is not commensurate with the available space and energies of beams required for an axial injector for the ORIC because of the high voltages required for operation and the incumbent high voltage breakdown and shorting problems that accompany this design.

A simple solution has been found that can be used to completely eliminate beam path shifts inside an inflector. The technique involves the re-centering of the spiral inflector according to the actual (or precisely calculated) central beam path. This re-centering technique is performed in two steps: (1) by calculating the central beam path in the original inflector, and then (2) by re-centering the inflector electrodes according to the shift in the calculated central trajectory. By use of these simple procedures, the shift in central trajectory can be reduced to less than 0.1 mm and the gap size and operational voltage can be reduced by ~40%.

5 CONCLUSIONS

Numerical electric-field analysis provides a powerful tool for the design of spiral inflector systems. Fringe-field effects at the entrance and field variations within the inflector cause deviations of the central trajectory from the desired path. By re-shaping the inflector to compensate for fringe-field effects and re-centering the electrodes of the inflector according to the actual beam trajectory, beam path shifts can be completely eliminated. A low voltage, high transmission efficiency, spiral inflector design for accurately injecting intense beams into the central magnetic field regions of cyclotrons can be realized.

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