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Design Studies of the Cylindrically Symmetric Magnetic Inflector

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Abstract

The spiral inflector steers the beam from the bore in the main magnet into the median plane to achieve the axial injection with an external ion source. In a conventional electrostatic infector, the injection beam energy is limited by the breakdown voltage on the electrodes. At the same time, the injection intensity is also limited by the small aperture in the electrostatic inflector. Magnetic inflector is a promising alternative to overcome these disadvantages. To demonstrate the technology, we use the TR100 main magnet model as a test bench to study the inflection conditions and optics of the passive magnetic inflector with a cylindrically symmetric structure. A mirror-like field with optimized mirror length and ratio provides a well-focused beam arriving at the median plane. The required magnetic field is produced by shimming a center plug in the injection hole. The space charge effect is also discussed with the simulation of a high-intensity injection beam.

Introduction

Recently, There are two types of magnetic inflector. One is the passive type which uses the iron in the injection hole to produce the required magnetic field. The other is the active one which uses a permanent magnet array. The passive type is more robust because there is no concern about the degaussing of the permanent magnet under the high beam loss in the injection hole. But it is only a concept, which has no existing design.

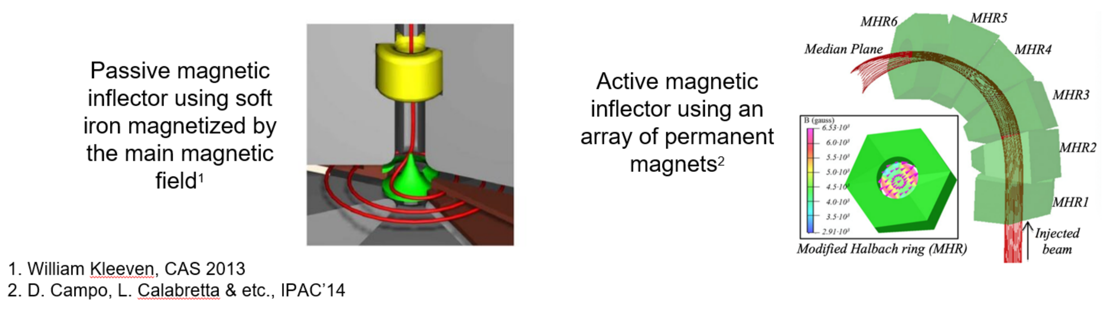

Figure 1: Two types of magnetic inflector.

Reference orbit

In a cylindrically symmetric system. The magnetic vector potential A only consists of the azimuthal component A_θ. Thus, the hamiltonian using cylindrical coordinates is written as

$$H=\sqrt{P_r^2c^2+P_z^2c^2+c^4m_0^2+\frac{c^2\left(P_\theta-qr\,\mathrm{A}_\theta\left(r,z\right)\right)^2}{r^2}} \quad (1)$$

Where the canonical momenta are

$$\begin{aligned} P_r&=p_r\\ P_\theta&=\gamma m_0\theta' r^2+qrA_\theta\\ P_z&=p_z \end{aligned} \quad (2)$$

A vector potential used to define the axial symmetric magnetic field is given as

$$A_\theta=\frac{A_1\beta r}{2}-A_2I_1(\beta r)\cos\beta z \quad (3)$$

Where π/β is the mirror length, $\beta(A_1+A_2)/(A_1-A_2)$ is the mirror ratio. The motion equation could be easily derived using the hamiltonian. We use the TR100 main magnet model as a test bench to study the injection, where the mirror length is around 15 cm and the mirror ratio is around 1.7.

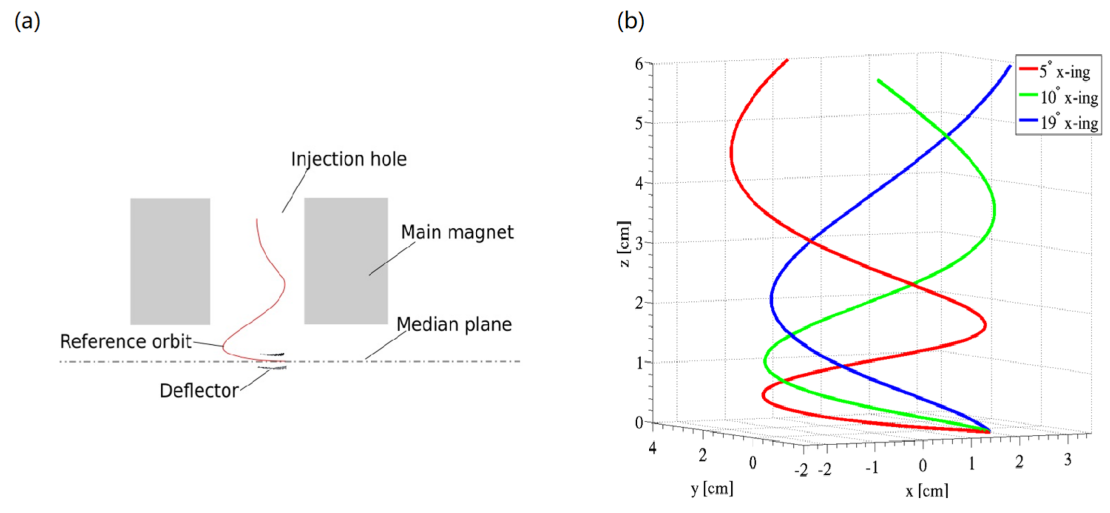

Figure 2: Reference orbit in the injection hole. (a) shows the conceptual model. By tracking the particle reversely from the median plane to the injection point with different Pitch angles, the different reference orbits are shown in (b).

Beam optics

In this paper, we use the coordinate (α,β,γ) in the optical coordinate system, which moves along the reference orbit as shown in figure 2, to study the beam optics. Transformation from (x,P_x,y,P_y,z,P_z) to $(\alpha,P_\alpha,\beta,P_\beta,\gamma,P_\gamma)$ is given by

$$\begin{bmatrix}\alpha\\P_\alpha\\\beta\\P_\beta\\\gamma\\P_\gamma\end{bmatrix}=\mathrm{M}^T\begin{bmatrix}x-x_c\\m_0v_0(x'-x_c')\\y-y_c\\m_0v_0(y'-y_c')\\z-z_c\\m_0v_0(z'-z_c')\end{bmatrix}+q\mathrm{M}^T\begin{bmatrix}0\\A_x-A_{x0}\\0\\A_y-A_{y0}\\0\\A_z-A_{z0}\end{bmatrix} \quad (4)$$

where the 6×6 matrix transformation matrix M is expanded from the coordinates transformation matrix.

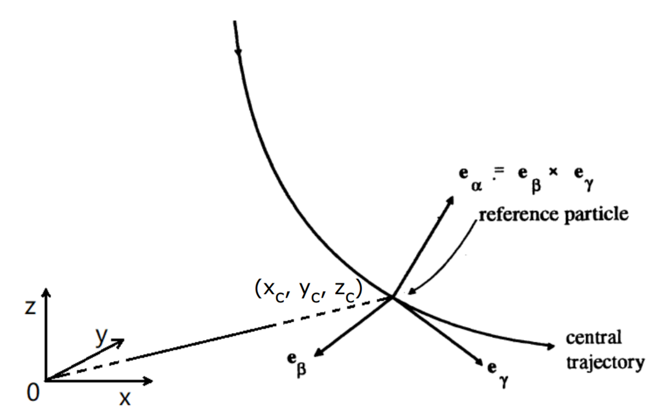

Figure 3: The moving optical coordinate system.

The transfer matrix is calculated by tracking 6 orthogonal particles

$$\mathrm{R}=\begin{bmatrix}1.99&0.15&-1.68&-0.02&0.38&0.13\\-5.02&0.19&-0.23&-0.18&3.87&0.21\\0.58&0.02&0.84&0.03&-0.55&-0.01\\-13.80&-0.37&-8.08&0.39&1.94&-0.64\\-0.03&0.04&-0.30&0.02&0.61&0.10\\5.32&0.22&-12.48&0.27&-5.43&0.86\end{bmatrix} \quad (5)$$

The beam envelope is studied in the $\alpha-\beta-\gamma$ moving frame. Figure 6 (a) shows the horizontal (β) and vertical (α) envelopes with optimal magnetic field parameters.

Magnet design

Figure 4 shows the structure of the central plug that we used to optimize the mirror field in the injection hole. Figure 5 shows the on-axis magnetic field.

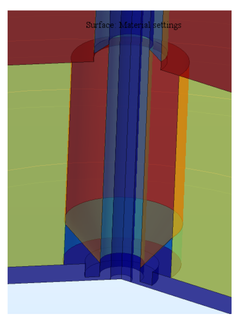

Figure 4: Steel plug in the injection hole. Blue colored structure is the vacuum region. Green is the sector pole. Red is the solid steel structure in the injection hole.

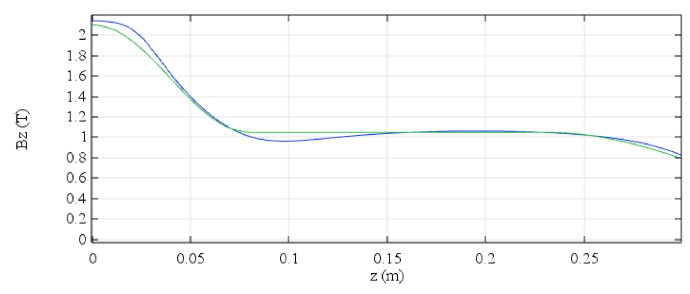

Figure 5: On-axis magnetic field in the injection hole after optimizing the shape of the center plug. The green line is the objective field that could properly focus the beam in the inflector. The blue line is the on-axis magnetic field produced by the designed main magnet with a properly shimmed central plug.

High intensity simulation

Figure 6 shows the Comsol simulation of the beam injection with considering space charge effect.

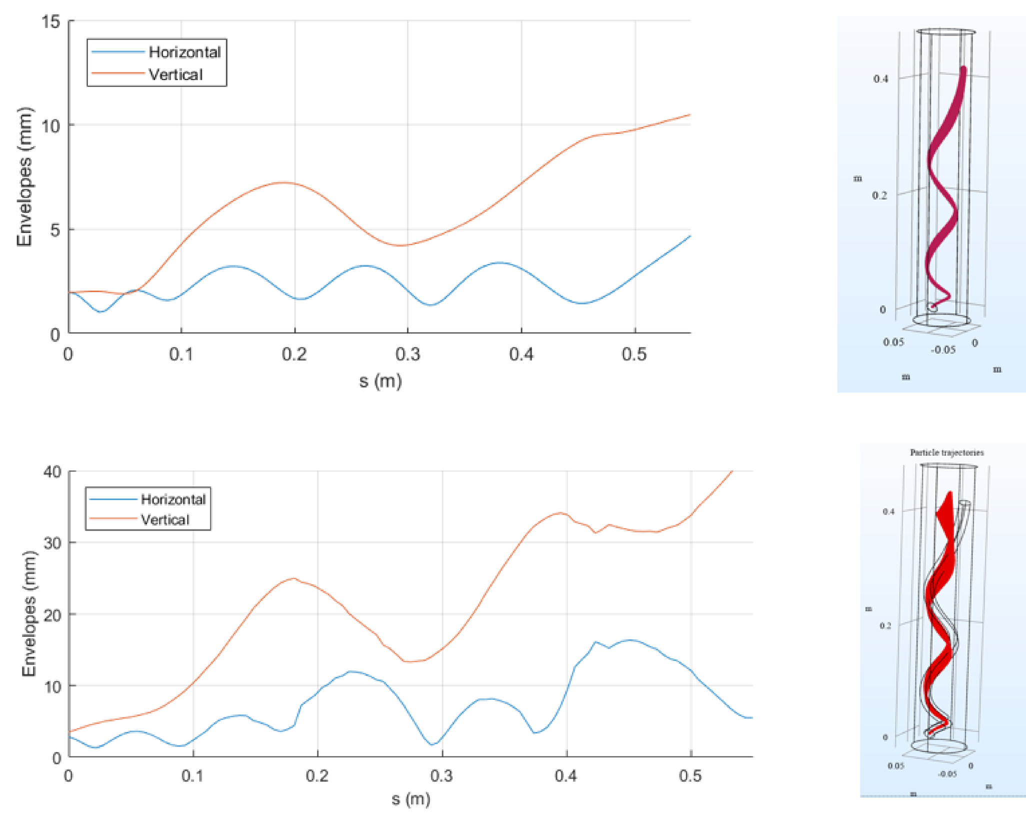

Figure 6: Envelope simulation considering space charge. The upper plot shows the simulation with 1 nA injection beam. The lower one shows that of the 10 mA injection beam. The frame of a spiral pipe in the lower 3D beam plot shows the reference beam path without considering the space charge effect. The reference orbit is changed by the space charge. A further design study of a shielding structure is needed to remove the repulsive force from different turns.

Conclusion

An electrostatic deflector should be placed at the end of the magnetic inflector, which will finally deflect the beam into the median plane with 0 vertical momenta. The required electric field strength in the electrostatic deflector is much lower than that in a conventional inflector. The envelope study suggests that the beam could be focused both horizontally and vertically in the moving frame with the optimized mirror ratio and mirror length of the field. A steel plug in the center region is designed to produce the required field in the injection hole. A preliminary simulation of the high-intensity DC beam injection is simulated using Comsol, the reference orbit is changed by the space charge. Thus, a further design study of a shielding structure is needed to remove the repulsive force from different turns.

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