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PIC mode simulation of solenoid collimation channel*

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Abstract A new SSC (Separated Sector Cyclotron)-Linac is being designed to serve as an injector for the SSC at the HIRFL (Heavy Ion Research Facility Lanzhou). The beam intensity at the LEBT (Low Energy Beam Transport) for the heavy ions after the selection is typically low and the space charge effects are inconspicuous. The space charge effects become obvious when the beam current increases to a few hundred microamperes. The emittance growth deriving from the space charge effects may be particularly troublesome for the following linac and cyclotron. An optical system containing three solenoids has been designed for the LEBT to limit the beam emittance and to avoid the unnecessary beam loss in the cyclotron, as well as for the purpose of immunizing the LEBT emittance growth due to the space charge effects. The results of the PIC (Particle-In-Cell) mode simulation illustrate that this channel could limit the beam emittance growth and increase the beam brightness.

Key words PIC, solenoid, LEBT, space charge effects, collimator

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1 Introduction

The utilization of collimators to remove unwanted particles is a well-known method that has been used to maintain beam quality since the 1970s. The new design of the LEBT in the SSC-Linac system of the IMP (Institute of Modern Physics) accelerator facility includes a three-solenoid collimation channel, which is behind the analysis dipole to cut the beam. A matching section is placed downstream of the collimation channel to match the beam with the following RFQ (Radio Frequency Quadrupole) linac. This concept has been tested during the commissioning process of the new SuSI [1] injection line at MSU, and the result appears to be successful.

The TRACE-3D code and the TRANSPORT code are available to study beam dynamics and to match the beam parameters between the ion source and the RFQ linac using linear approximation beam dynamics. There are a number of PIC codes that has been developed to simulate space charge dominated beam dynamics. BEAMPATH [2] is one of the codes that could be used to simulate unbunched continuous beam dynamics using the PIC method.

The parameters are shown in Table 1. This channel contains three solenoid magnets of the same strength separated by drifts spaces. The inner aperture of the collimation channel is selected to be 5 cm. Four circular apertures of the same radius are used for collimation. A beam profile monitor is placed at the exit of the channel to monitor the variations in beam emittance.

Table 1. The parameters of the three-solenoid collimation channel.

parameters	length/cm	strength/T
drift	10	
solenoid	60	0.35
drift	10	
solenoid	60	0.35
drift	10	
solenoid	60	0.35
drift	10	

2 The establishment of magnetic fields along the axis of the channel

A model of three solenoids has been developed using the OPERA-2D finite element program [3]. Fig. 1

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illustrates the longitudinal magnetic fields $B_z(z,0)$ along the axis of the channel with a maximum amplitude of 0.35 T, including the fringe region of the solenoid.

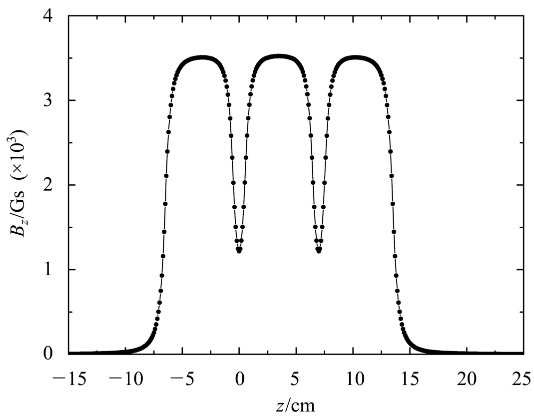

Fig. 1. The longitudinal magnetic fields along the z axis.

The axis fields distribution of the two-dimensional magnetic fields $B(z,r)$ in transverse and longitudinal directions can be calculated using the BEAMPATH code:

$$B_z(z,r) = B_z(z,0) - \frac{r^2}{4}\frac{\mathrm{d}^2 B_z(z,0)}{\mathrm{d}z^2}\ , \tag{1}$$

$$B_r(z,r) = -\frac{r}{2}\left[\frac{\mathrm{d}B_z(z,0)}{\mathrm{d}z} - \frac{\mathrm{d}^3 B_z(z,0)}{\mathrm{d}z^3}\right]. \tag{2}$$

3 The PIC mode simulation

3.1 The channel specifications and the initial beam parameters

The solenoid is an effective element for focusing the low-energy beam. It is selected in the collimation channel to eliminate the unwanted ions in both the horizontal and the vertical planes, and to further improve the beam brightness and transmission efficiency of the following linacs.

In this channel, three beam waists are formed in the center of the solenoids and four maximum envelopes appear in the center of the drift spaces. Four circular apertures of the same diameter are used as collimators at the place where the beam envelope is large and flat. Consider a 0 mA, 1.1 keV/u uranium beam. Suppose that it has a Gaussian distribution. Then, with the initial emittance $\varepsilon_{nx}=\varepsilon_{nyx}=$ 0.023 $\pi\cdot$cm$\cdot$mrad, the Twiss parameter $\alpha_x=\alpha_y=0$ and $\beta_x=\beta_y=100$ cm/rad, the beam transport can be calculated.

The results of multi-particle tracking are shown in Fig. 2(a), with the appearance of four maximum beam envelopes at the center of the spaces. The collimators have to be located at the place where the values of α are close to zero and the values of β are at their maximum. Fig. 2(b) illustrates the oscillation of the beam emittance in both horizontal and vertical directions along the channel. No significant beam emittance growth is observed in both directions during the process of the simulation with space charge effects off.

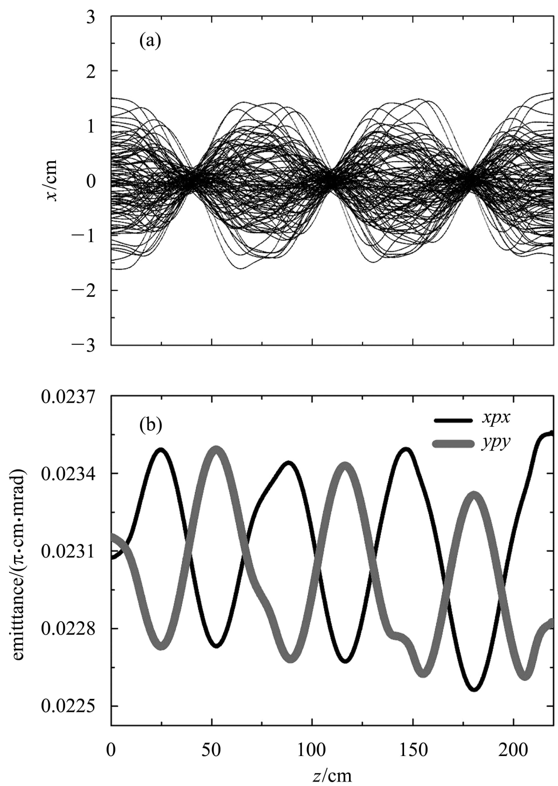

Fig. 2. (a) The multi-particle trajectories with space charge effects off; (b) the oscillation of beam emittance.

3.2 The emittance collimation

After performing a simulation using the linear approximation to beam dynamics, the four collimators are applied in the PIC mode to check the effect of beam collimation.

Figure 3(a) shows the final particle distributions in phase space and in real space, without and with the four successive collimators. During these simulations, the radii of four collimators of 1.2 cm are set to be the same. The transmission efficiency decreased from 100% to 83% and the brightness increased from $8.492\times10^5/\pi$·cm·mrad to $9.113\times10^5/\pi$·cm·mrad. The particle density in phase space increased to 7.5%.

Figure 3(b) illustrates the process of gradual beam emittance reduction from 0.023 $\pi\cdot$cm$\cdot$mrad to 0.0182 $\pi\cdot$cm$\cdot$mrad. The beam with a smaller emittance and higher brightness in phase space is a perfect fit for the subsequent acceleration in the linac.

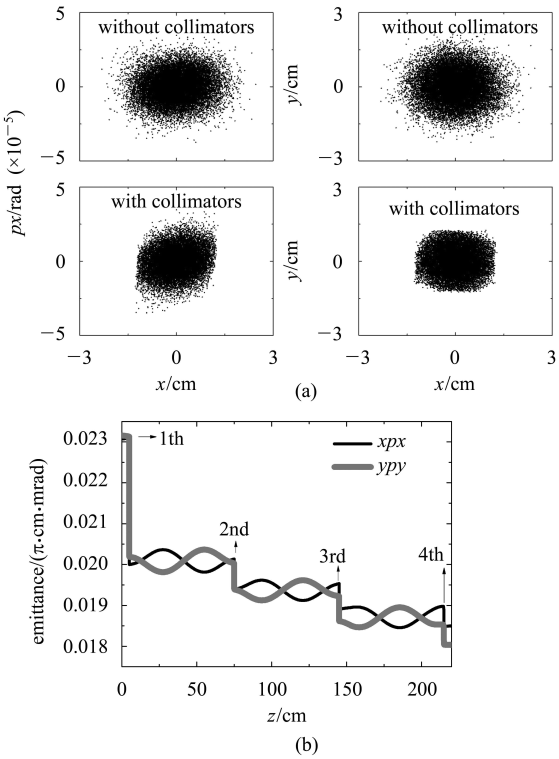

Fig. 3. (a) A comparison of the final particle distribution in phase space and in real space; (b) The process of emittance reduction by using collimators.

3.3 The simulation with space charge effects on

Particle motion in the collimation channel depends not only on the external solenoid fields but also on the fields from the Coulomb interaction of the particles. The space charge forces are directly proportional to the beam intensity [4]. The significance of the space charge fields reduces the effective focusing strength of the solenoid. The simulation results show that, in order to overcome the space charge forces of a 500 μA uranium beam at an energy of 1.1 keV/u, the solenoid field should be increased to 0.44 T.

Figure 4(a) shows the multi-particle trajectories of the beam in the presence of space charge effect forces. For an unbunched continuous beam, only transversal space charge forces are essential [5]. Electrostatic Coulomb repulsion forces pull particles away from the beam center, and the particle distribution in phase space becomes more sparse.

Figure 4(b) illustrates the electrostatic space charge field distribution along the channel. The strongest space charge electric fields appear to be at the beam waists. These effects become stronger with an increase in beam intensity.

Figure 4(c) demonstrates the process of space charge beam emittance growth in the horizontal plane and the vertical plane. The non-linear forces degrade the beam quality and obvious emittance growth (up to 3.5 times the original emittance) is observed according to the results of the simulation.

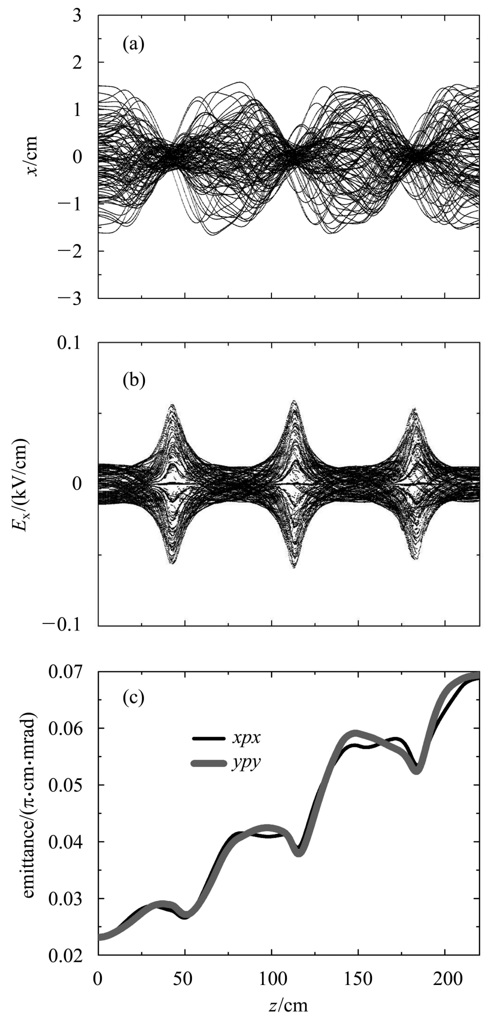

Fig. 4. (a) Particle trajectories with space charge effects on; (b) Space charge field distribution; (c) Beam emittance growth along the channel.

3.4 The immunity of beam emittance growth

Figure 5 illustrates the different final particle distributions in phase space by changing the aperture size. The emittance could be cut down uniformly to a different extent. The presence of nonlinear forces could produce a considerable departure from the elliptical trajectories in phase space, and could distort the phase space contours. If the phase space projections are described by effective phase space ellipses, such distortions cause an effective-emittance growth.

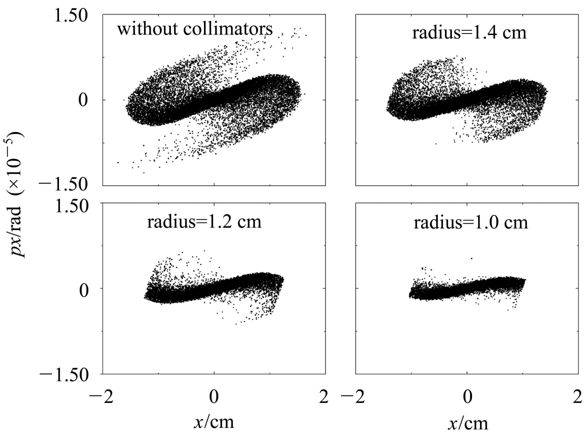

Fig. 5. The particle distributions in phase space due to the collimators of different radii.

The unwanted ions are dumped onto collimators, and the particles with better quality are still retained. The utilization of collimators could increase the beam brightness at the expense of decreasing the transmission efficiency.

Table 2 illustrates the final beam emittance, transmission efficiency and beam brightness due to collimators of different sizes. Using collimators of smaller radii could result in a smaller beam emittance and a higher beam brightness. If the radius of aperture were selected to be 1 cm, the beam brightness would be 2.3 times higher than that without collimators.

Table 2. The transmission efficiency (Eff), final beam emittance (ε_{nx}) and brightness (B) by changing the aperture size (R).

R/cm	Eff	$\varepsilon_{nx}/(\pi\cdot\mathrm{cm}\cdot\mathrm{mrad})$	$B/(\mu\mathrm{A}/\pi\cdot\mathrm{cm}\cdot\mathrm{mrad})$
5.0	1	0.069	7.246×10^3
1.4	0.833	0.051	8.167×10^3
1.2	0.576	0.025	1.152×10^4
1.0	0.396	0.012	1.650×10^4

4 Conclusion

The emittance of the ECR ion source is generally bigger than the cyclotron acceptance, and the space charge effects increase the beam emittance rapidly in the LEBT. The distribution of particles at the exit of the collimation channel is compact in the beam core, and gets sparse far away from the core when the space charge effects are strong. A three-solenoid collimation channel scheme is selected to control the beam emittance growth properly, and the future for the propose of increasing the beam brightness. The PIC simulation shows that this optical system can be used to control the beam quality by changing the aperture radius. The non-linear space charge effects in this case could be removed easily.

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