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Heavy ion beam final transport through an insulator guide in heavy ion fusion

SHIGEO KAWATA, TETSUO SOMEYA, TAKASHI NAKAMURA, SHUJI MIYAZAKI, KOJI SHIMIZU, AND ALEKSANDAR I. OGOYSKI

Department of Energy and Environmental Science, Graduate School of Engineering, Utsunomiya University, Utsunomiya, Japan

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Abstract

Key issues of heavy ion beam (HIB) inertial confinement fusion (ICF) include an efficient stable beam transport, beam focusing, uniform fuel pellet implosion, and so on. To realize a HIB fine focus on a fuel pellet, space-charge neutralization of incident focusing HIB is required at the HIB final transport just after a final focusing element in an HIB accelerator. In this article, an insulator annular tube guide is proposed at the final transport part, through which a HIB is transported. The physical mechanism of HIB charge neutralization based on an insulator annular guide is as follows: A local electric field created by HIB induces local discharges, and plasma is produced on the insulator inner surface. Then electrons are extracted from the plasma by the HIB net space charge. The electrons emitted neutralize the HIB space charge well.

Keywords: Beam transport; Charge neutralization; Heavy ion beam; Inertial confinement fusion; Insulator guide

1. INTRODUCTION

In the heavy ion beam (HIB) final transport (Callahan *et al.*, 1995; Deutsch *et al.*, 2001), the key factors are as follows: final small focal radius (a few millimeters) (Tabak *et al.*, 1998*a*, 1998*b*), low emittance growth relating to the HIB particle energy and momentum divergences, HIB space charge and current neutralizations, HIB instabilities, and collision effects between the HIB and a background reactor gas. The HIB should be transported in a fusion reactor and focused on an approximately millimeter fuel pellet (Tabak *et al.*, 1998), which should be imploded in a spherically symmetrical manner (Emery *et al.*, 1982; Kawata & Niu, 1984; Sasaki *et al.*, 2001). In the long-distance transport of HIB, the HIB space charge and current should be neutralized, and electrostatic and electromagnetic instabilities should be suppressed (Qin *et al.*, 2000, 2001).

In this article, we study a HIB transport through an annular insulator beam guide (Hanamori *et al.*, 1998) by particle-in-cell (PIC) simulations in order to neutralize the beam space charge just after a final focusing element in an HIB accelerator. The results obtained in this study present that the HIB space charge is neutralized well by using an annular insulator guide located at the final transport in an HIB accelerator. Without a neutralization mechanism at the final transport part, the HIB final fine focus onto a fuel pellet cannot be realized.

2. HIB FINAL TRANSPORT THROUGH AN INSULATOR GUIDE

In a HIB inertial confinement fusion (ICF) reactor system (Hogan *et al.*, 1992; Lindl *et al.*, 1992), a HIB accelerator and final focusing elements should stand away from a reactor vessel so as not to be damaged by neutrons and fusion debris. Therefore the HIB space charge should be effectively neutralized after the final focusing element in an accelerator for a fine focus on a fuel pellet. To neutralize the HIB space charge and current, we propose a HIB transport system through an annular insulator beam guide. The insulator beam guide may be made of ceramics, for example, Al_2O_3. The physical mechanism of the insulator beam guide is as follows: A HIB creates a local electric field on the inner surface of the insulator beam guide. In our simulations, the magnitude of the electric field is monitored at the insulator guide surface. Then local plasma is generated at the insula-

Address correspondence and reprint requests to: Shigeo Kawata, Department of Energy and Environmental Science, Graduate School of Engineering, Utsunomiya University, Yohtoh 7-1-2, Utsunomiya 321-8585, Japan. E-mail: kwt@cc.utsunomiya-u.ac.jp

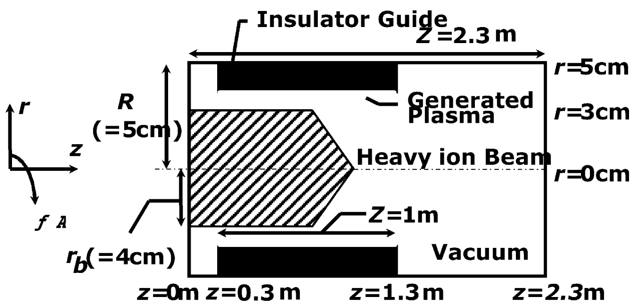

Fig. 1. HIB transport system using an annular insulator beam guide. The intense HIB creates a local electric field on the inner surface of the annular insulator guide. The local electric field induces the local discharges, and the plasma is produced on the insulator inner surface. Electrons are extracted from the plasma. The HIB space charge and current are effectively neutralized.

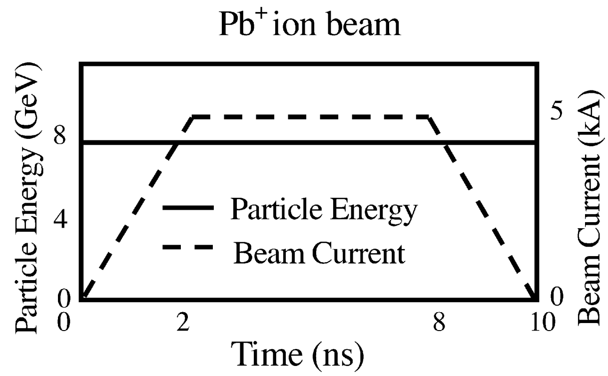

Fig. 3. Input Pb^+ ion beam waveform. The Pb^+ ion-beam-parameter values are as follows: The maximum current is 5 kA, the particle energy is 8 GeV, the pulse width is 10 ns, and the rise and fall times are 2.0 ns.

tor beam guide inner surface, when the magnitude of the electric field is beyond the threshold at the guide surface to induce the local discharges. We assume that the plasma consists of protons and electrons, and that the thickness of the plasma layer is infinitesimal. We also assume that a sufficient amount of plasma is generated at the insulator guide surface such that the charged particle emission from the insulator inner surface is limited by the space charge and the plasma temperature is 10 eV. Then, the electrons are extracted from the plasma generated on the inner surface of the insulator beam guide by the HIB net space charge. The emitted electrons follow the HIB, and the HIB space charge is effectively neutralized by the electrons. Therefore, the HIB can be transported efficiently and one may expect a fine focus through the insulator beam guide. In this article, we employ a Pb^+ ion beam to demonstrate the viability of the proposed insulator beam guide system. Our simulation model is shown in Figure 1. We assume that the phenomenon concerned is cylindrically symmetric (see Fig. 2). The PIC code used is a 2.5-dimensional electromagnetic one.

The Pb^+ ion-beam-parameter values are as follows: The maximum current is 5 kA, the particle energy is 8 GeV, the pulse width is 10 ns, and the rise and fall times are 2.0 ns (Fig. 3). The initial beam radius is 4 cm at $Z = 0$. The initial mean velocity of a focusing Pb^+ beam is given to focus at

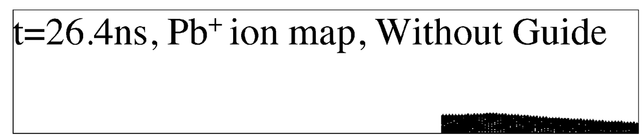

Fig. 4. Pb ion particle map in the case without an insulator guide. The mean velocity of Pb ions is given to focus at $Z = 2.1$ m. The focal radius is ~5.8 mm.

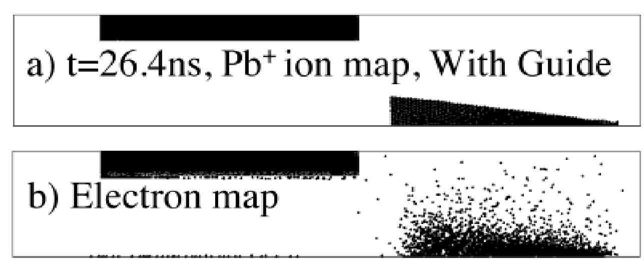

Fig. 5. Pb ion particle map and electron map in the case without an insulator guide. The focal radius is ~2.4 mm at $Z = 2.1$ m.

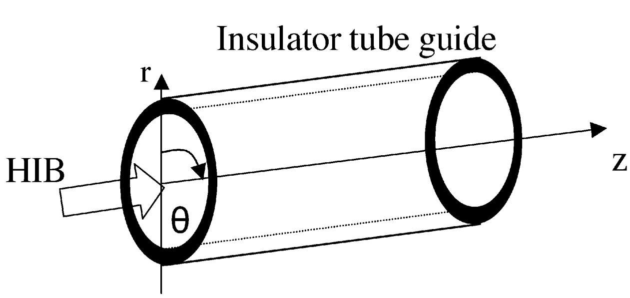

Fig. 2. The transport system in our simulation is cylindrically symmetric. HIB is a Pb^+ ion beam in this article.

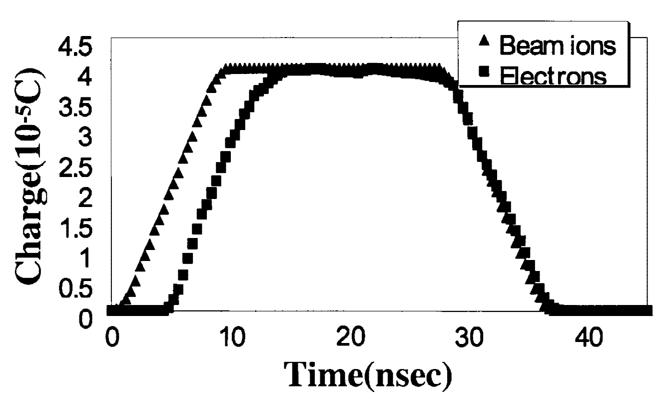

Fig. 6. History of the total space charges of HIB ions and electrons emitted in the transport area. The HIB charge is effectively neutralized.

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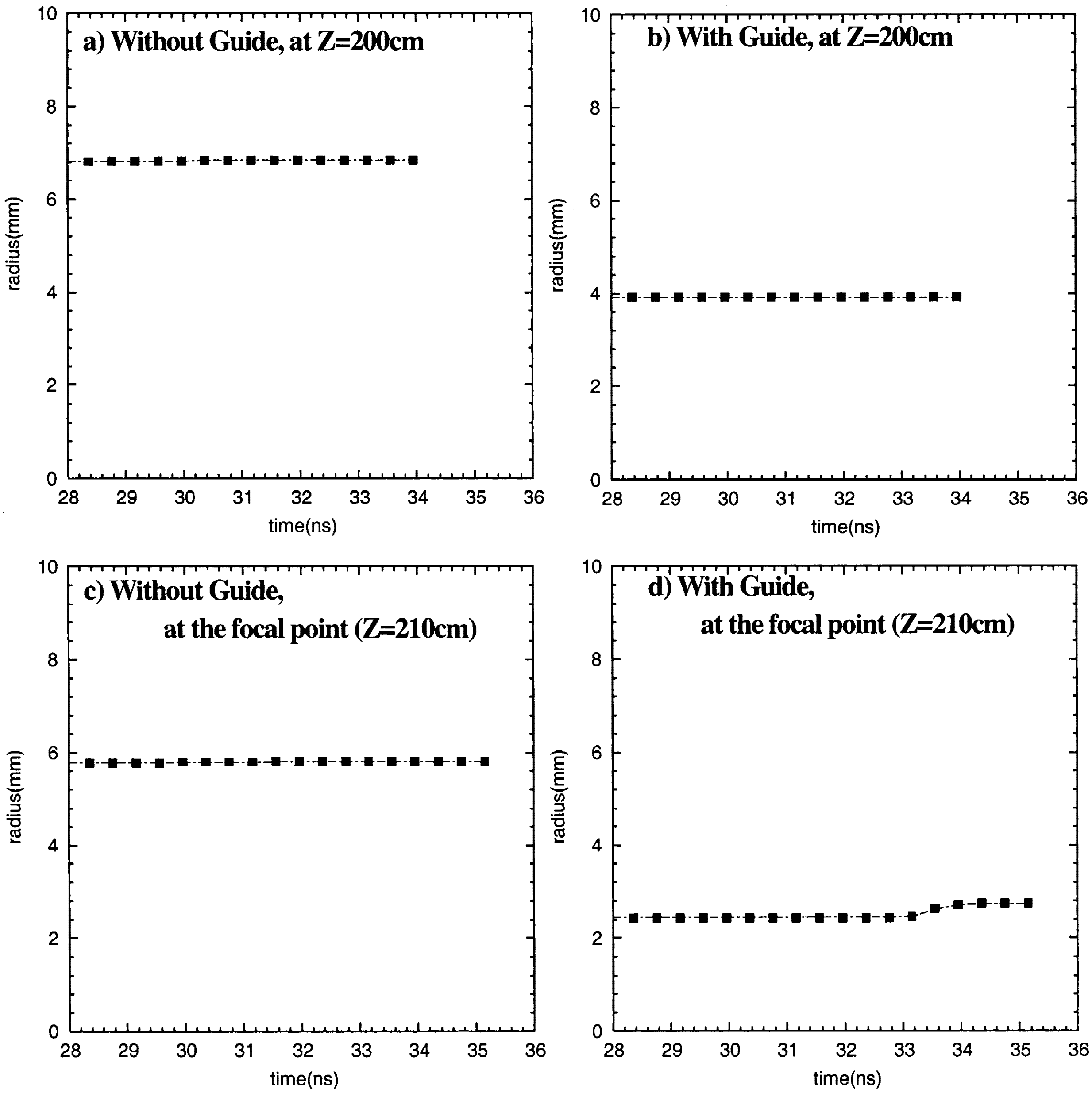

Fig. 7. Beam radius change in time at the $Z = 200$ cm (a) without the guide and (b) with the guide, and at the $Z = 210$ cm (c) without the guide and (d) with the guide. The HIB radial expansion is suppressed by the insulator beam guide.

$Z = 210$ cm, and the average speed of the HIB ions injected is determined by the waveform. The beam temperature is 10 eV and the beam ions enter uniformly at the beam entrance, that is, $Z = 0$. The maximum beam density is 1.3×10^{11} cm^{-3} at $Z = 0$. The transport area is in vacuum initially. In our simulation, local plasma is generated on the insulator guide surface, when the magnitude of the electric field exceeds the threshold for the local discharge. The threshold value employed in this work is 1.0×10^{7} V/m in this study. The most outer boundary of the simulation area is a conductor, and in actual situations or experiments (Kato *et al.*, 1995), the current flows through the conductor to the insulator surface. The origin of plasma generated on the ceramics insulator inner surface is gas or vapor absorbed into the insulator ceramics surface. Therefore the ceramics insulator itself can survive long enough (Kato *et al.*, 1995).

First, we simulate a Pb^{+} ion beam propagation in a vacuum without the insulator beam guide. The particle map of the Pb^{+} beam ions is shown in Figure 4. In this case, due to the beam space charge, the beam radius at $Z = 210$ cm (focal point) is about 5.8 mm (see Figs. 4 and 7c). Figure 5 presents the particle maps of the HIB ions and the electrons emitted from the insulator beam guide for the case with the proposed insulator guide system with the same initial conditions. The electrons extracted from the plasma move along with the Pb^{+} ion beam. The emitted

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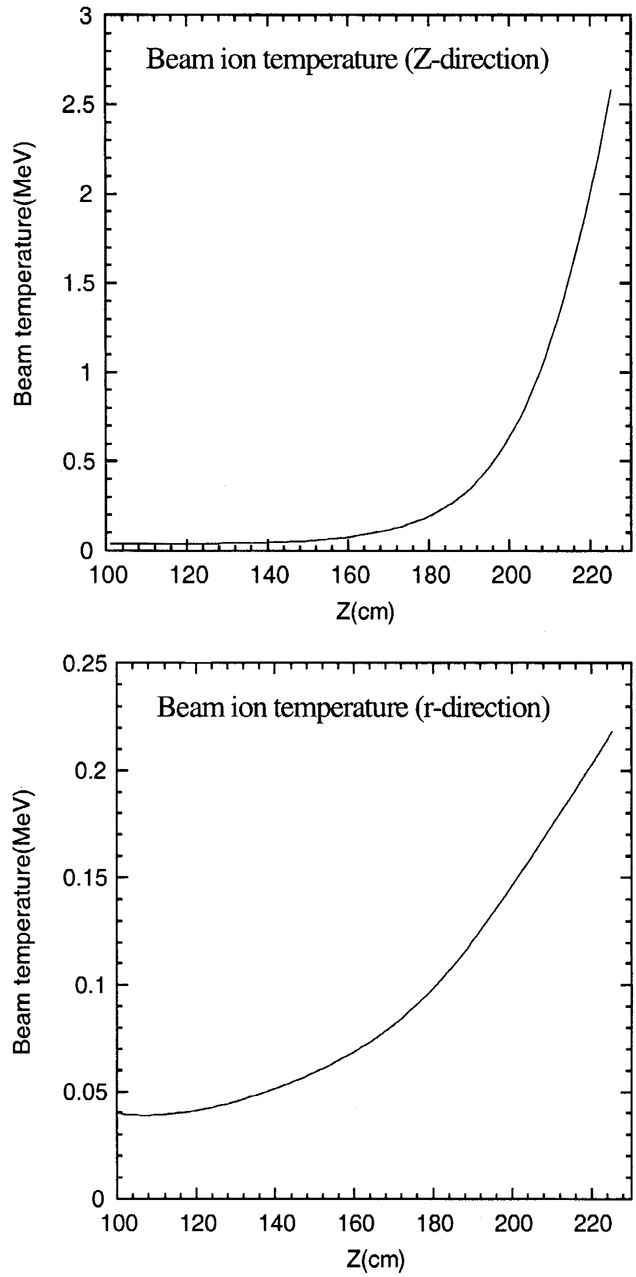

Fig. 8. HIB temperature in (a) Z direction and (b) r direction in the case with the guide.

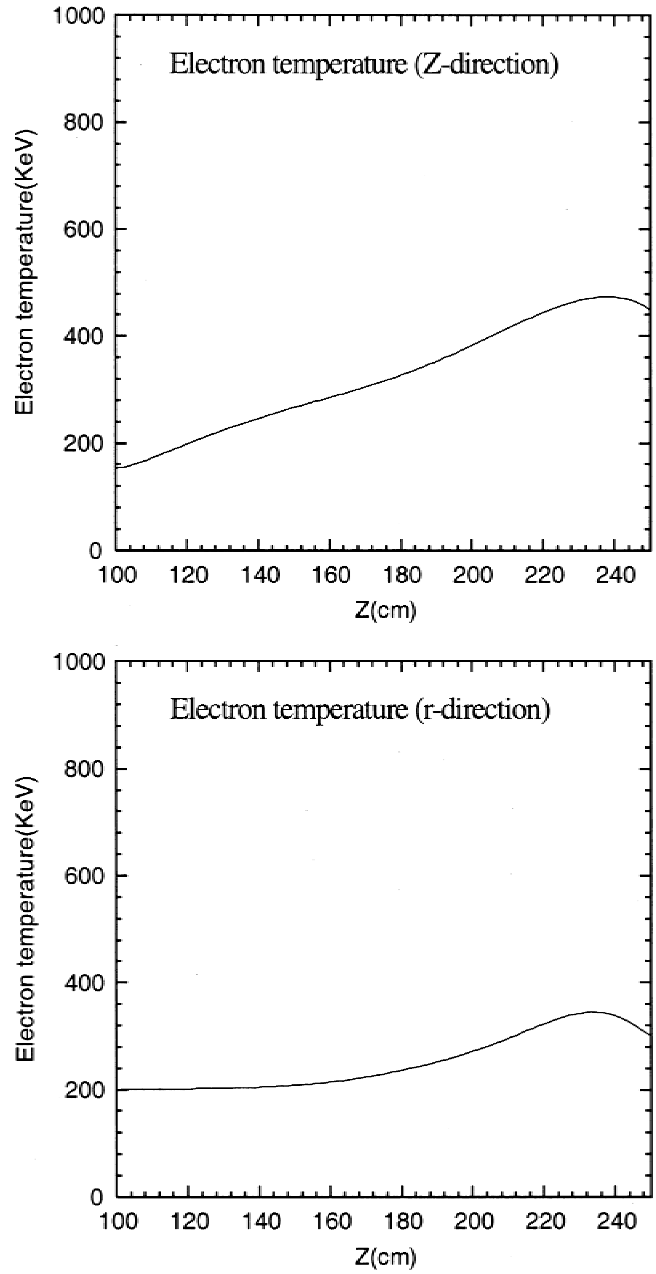

Fig. 9. Emitted electrons temperature in (a) Z direction and (b) r direction in the case with the guide.

electrons neutralize the space charge of the beam ions effectively, and suppress the radial expansion of the beam (Fig. 5a). Figure 6 shows the history of the total space charges of the beam ions and the electrons in the whole transport region. The beam space charge is neutralized rather well by the electrons emitted from the insulator beam guide. Figure 7b,d shows the beam radius at $Z = 200$ cm and at $Z = 210$ cm (focal point), respectively, in the case with the insulator beam guide. The final focal radius is about 2.4 mm in the case with the insulator guide. Figure 8 shows the HIB ion temperature in the Z direction and r direction for the case with the insulator guide, and Figure 9 presents the corresponding electron temperature in the Z and r directions. The HIB temperature becomes large as it approaches the focal point. Figures 10 and 11 show the HIB particle distribution in the phase space at $t = 20$, 24, and 28 ns for both the cases. To find the HIB quality, we evaluate the HIB emittance values in the all-transport region for both cases: The emittance is 0.113 π-mm-mrad at $t = 0$ ns, and 1.41 π-mm-mrad at $t = 24.3$ ns in the case with the insulator guide. On the other hand, the emittance is 2.07 π-mm-mrad at $t = 24.3$ in the case without the insulator guide.

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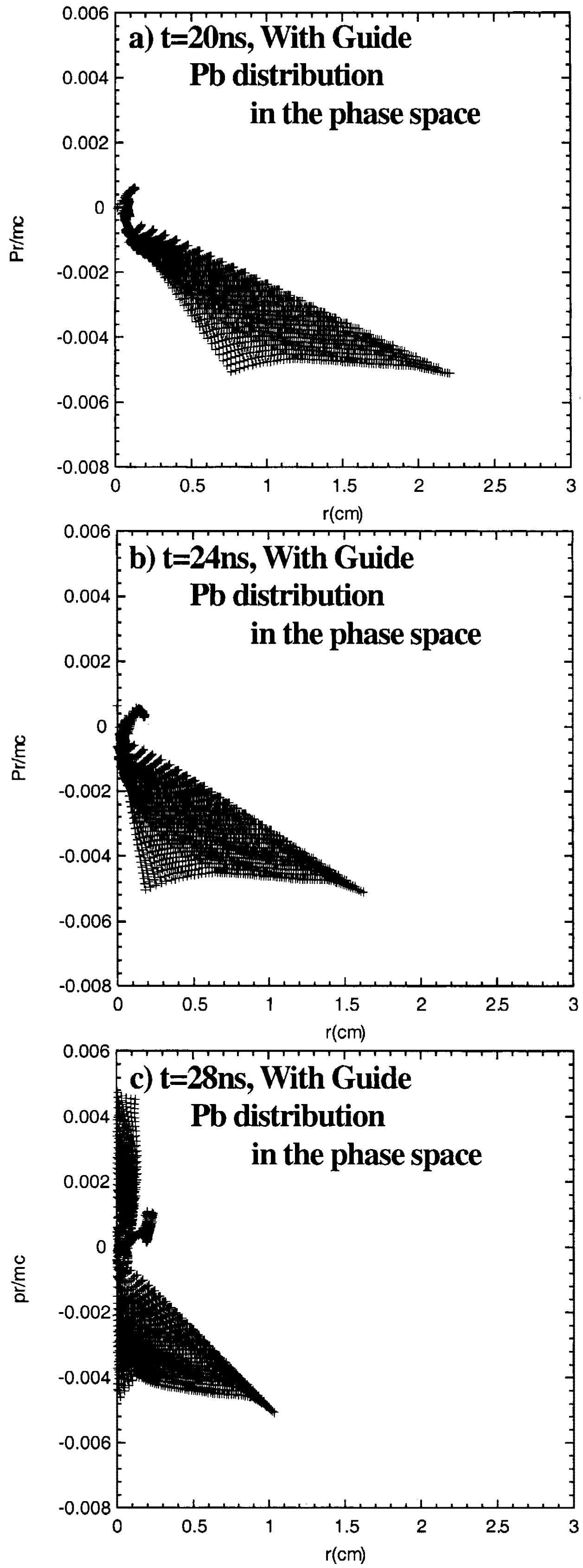

Fig. 10. Pb^+ ion beam distribution in the phase space without the guide. The particle distributions in $t = 20$ ns, $t = 24$ ns, and $t = 28$ ns are plotted in (a), (b), and (c), respectively.

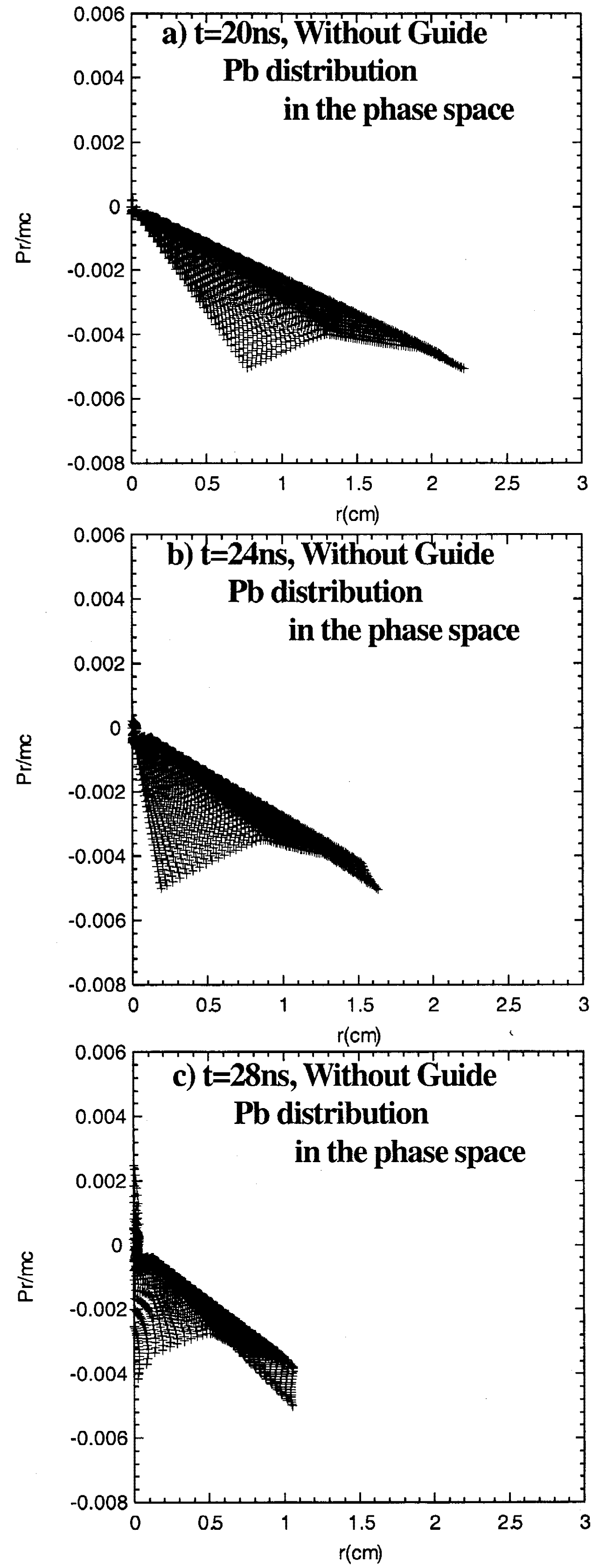

Fig. 11. Pb^+ ion beam distribution in the phase space with the guide. The particle distributions in $t = 20$ ns, $t = 24$ ns, and $t = 28$ ns are plotted in (a), (b), and (c), respectively.

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3. CONCLUSIONS AND DISCUSSIONS

In this work, we proposed an insulator beam guide for heavy ion beam neutralization. The insulator HIB guide system is simple, and an additional source plasma generation device is not required. Plasma electrons are emitted from the plasma generated on the insulator inner surface. The electrons move with the heavy ion beam, and the HIB space charge is effectively neutralized by the electrons. By the PIC simulation, it is confirmed that the heavy ion beam propagates well through the insulator beam guide. The insulator guide may be made of one kind of ceramics and may absorb a part of the reactor gas leaked from a beam port to the accelerator side, though this effect should be studied in another work in the future. The particle simulations also confirm that the heavy ion beam quality is kept high, and an emittance growth is suppressed through the insulator guide.

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