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Conducting versus insulating walls in a heavy ion reaction chamber

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Abstract

We first pay attention to the inflight charge state distribution in a Pb ion beam propagating in a reactor-sized chamber delimited by metallic walls. We thus compare Livermore (code BIC) and Orsay (code BPIC) distributions in the presence of a residual Flibe gas pressure. Next, we replace the electron plasma due to Flibe ionization by a gliding plasma produced by the polarization of the incoming ion beam on insulating walls. Corresponding electrons, when attracted by the beam, are demonstrated to yield a very efficient current neutralization.

Keywords: Flibe gas pressure; Plasma; Ion beam; Insulating walls

1. INTRODUCTION

Among the crucial issues sustaining the heavy ion beam (HIB) fusion program, final HIB propagation in a reactor-sized chamber seems to have received the least attention (Barboza, 1996; Callahan, 1996; Vay & Deutsch, 1996, 1998; Olson, 2001).

Most of our fundamental understanding in this area is largely based on the definitive and analytic analysis (Olson, 1982, 2001) highlighting six different beam transport modes. However, the given beam electromagnetic patterns implicitly assume a constant projectile charge, an approximation mostly suited to intense and light ion beams. In the HIB case, we have to include beam dynamics effects arising from projectile ions ionization and recombination, as well.

Here we intend to stress first the modelization of the ion charge state distribution through particle in cell (PIC) codes out of accurate ionizing cross sections (Mabong, 1996) for HIB propagating in a reduced pressure of Flibe gas.

For this purpose, we have used two codes: a multienvelope one, BMENV and a PIC one, BPIC. Both have already been extensively benchmarked (Vay & Deutsch, 1996, 1998, 2001) with respect to former ones.

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Then we switch to exploring a novel approach to the neutralization of the HIB space charge which advocates the use of insulating chamber walls in lieu of metallic ones. Then one can capitalize (Kawata *et al*., 1996; Deutsch *et al*., 2001) on the HIB-induced wall polarization. The latter produces a gliding plasma which can emit some electrons to be captured by the beam, thus securing an efficient current neutralization.

2. BEAM STRIPPING

2.1. Multienvelope model: BMENV

To get a direct physical insight into the charge state dependence of ion beam focalizing, we consider a separate envelope equation for every ion beam charge state (at which is associated a comovins neutralizing electron beam). Thus, the entire ion beam appears as a superposition of several coaxial subbeams. The population N_i of the ith beam (charge state i) evolves in time according to (Vay & Deutsch, 2001)

$$\frac{dN_i}{dt} = [N_{i-1}\sigma_{st}(i-1 \to i) - N_i\sigma_{st}(i \to i+1)]n_g\beta c$$

in terms of Flibe gas density n_g, relative beam-gas velocity βc and cross sections σ_{st} $(i \to i+1)$ which account for the stripping of charge state i ions through collisions with residual gas. Then, a given beam charge state i may be given the envelope equation (in the beam frame)

$$\frac{d^2R_i}{dt^2} = \frac{\kappa_i}{R_i} + \frac{\beta^2c^2\varepsilon^2}{R_i^3}, \quad (1)$$

with

$$\kappa_i = \frac{ie^2\sum_{j=1}^{n}\left[N_j\begin{pmatrix}\left(\frac{R_i}{R_j}\right)^2, & R_i \le R_j\\ 1, & R_i \ge R_j\end{pmatrix} - N_{ej}\begin{pmatrix}\left(\frac{R_i}{R_{ej}}\right)^2, & R_i \le R_{ej}\\ 1, & R_i \ge R_{ej}\end{pmatrix}\right]}{2\pi\varepsilon_0\ell_b m_0} \quad (2)$$

sum of all electrostatic fields acting upon subbeam i. For each j there is an associated beam of ions of charge state j plus the electrons produced from beam stripping (first term in the squared bracket). Because these electrons are expected either to stay with the beam or to be replaced by electrons issued from gas ionization, they are taken into account directly into the first term, where we consider the total charge to be $(je)N_j$ (contribution from the ions stripped to the $+j$ charge state) $+(j-1)\times(-e)N_j$ (contribution from the electrons resulting from these stripping) $= eN_j$. Additionally, a subbeam of radius R_{ej} transporting N_{ej} neutralizing electrons (second term in the squared bracket) produced from the background gas ionization accompanies each ion subbeam j. Every subbeam is given the same length ℓ_b. For each j, the t-dependent neutralization factor reads as $f_j(t) = 1 - \exp(-n_g\sigma_{io}(j)\beta c[t-\tau])$ with $\tau = (1 - \exp[-\beta ct/\ell_b])\ell_b/\beta c$ and the corresponding number of neutralizing electrons N_{ej} for each subbeam j is then given by $N_{ej}(t) = N_j(t)f_j(t)$ with $\sigma_{io}(i)$, Flibe gas ionization cross section by beam ions with charge state i. We take $R_{ej} = \max(R_j, R_{emin})$ where R_{emin} is an arbitrary minimum radius accounting for the high mobility of electrons near minimum focusing.

2.2. Particle-in-cell modeling: BPIC

A full self-consistent and detailed description of the problem calls for PIC modeling, and we have used for that purpose the particle code BPIC (Vay & Deutsch, 1996). BPIC is an electromagnetic PIC code based on the Monte Carlo Collision algorithm to model the gas ionization by the beam ions and the beam stripping. It allows us to perform the calculations either in three dimensions (Cartesian XYZ), two dimensions (Cartesian XY, axisymmetric RZ), or one dimension (Cartesian X, axisymmetric R). In this article, we will present calculations performed with the RZ, XY, and R geometries. In the XY and R geometries, only a slice of the beam is modeled. In these slice modes, the treatment of beam neutralization requires a time-dependent estimation of the number of neutralizing electrons created in the simulated area at each time step. For this, we take the model developed previously (Vay & Deutsch, 1996, 1998) for the neutralization factor as applied in BMENV, giving the number of neutralizing electrons summed over all the beam ions charge states ($N_e(t) = \Sigma_j N_{ej}(t) = \Sigma_j N_j(t)f_j(t)$). The position of each new neutralizing electron created at each time step is randomly created inside the ion beam. BPIC calculations in slice mode (R or XY geometry) offer a reduced model compared to calculations in RZ (or XYZ) geometry, yet more detailed and self-consistent than with the BMENV model. The interest of the XY mode is to allow beam array modeling at a lower computational cost than a full three-dimensional calculation.

Table 1. *Mean energy transferred in PB^{n+}–BeF_2 ionizing collision (cf. Mabong, 1996)*

n	BeF_2 σ ion (in 0.889×10^{16} cm^2)	$\langle e\rangle$ (in 27.2 eV)
1	3.05	8.64
2	3.71	7.81
3	4.55	7
4	5.57	6.24
5	6.74	5.63
6	8.09	5.1
7	9.62	4.68
8	11.3	4.3
9	13.2	4.01
10	15.25	3.77

2.3. Benchmarking

Approximating the Flibe molecule by its more significant component BeF_2 and considering a lead heavy ion beam, one can see on Table 1 mean transferred energies through Pb^{n+}–BeF_2 ionizing collisions. These estimates (Mabong, 1996) decay slowly with increasing n.

To benchmark the code, we have run a case similar to one which has been run with the code BIC at Livermore (Callahan & Langdon, 1995). The parameters are given in Table 2. Before comparing the results, we have to describe some of the differences between the two codes.

Table 2. *Ion beam in reaction chamber (benchmarking)*

Ion charge	+1
Ion mass	210 a.m.u.
Ion energy	10 GeV
Bean current	3.125 kA, mean
	4.688 kA, peak
Pulse length	8 ns
Initial radius	5.2 cm
Focalization distance	2.84 m
Gas	Flibe
n_g	5×10^{13} cm^{-3}
mean free path (gas stripping)	0.4 m
mean free path (beam stripping)	1.2 m

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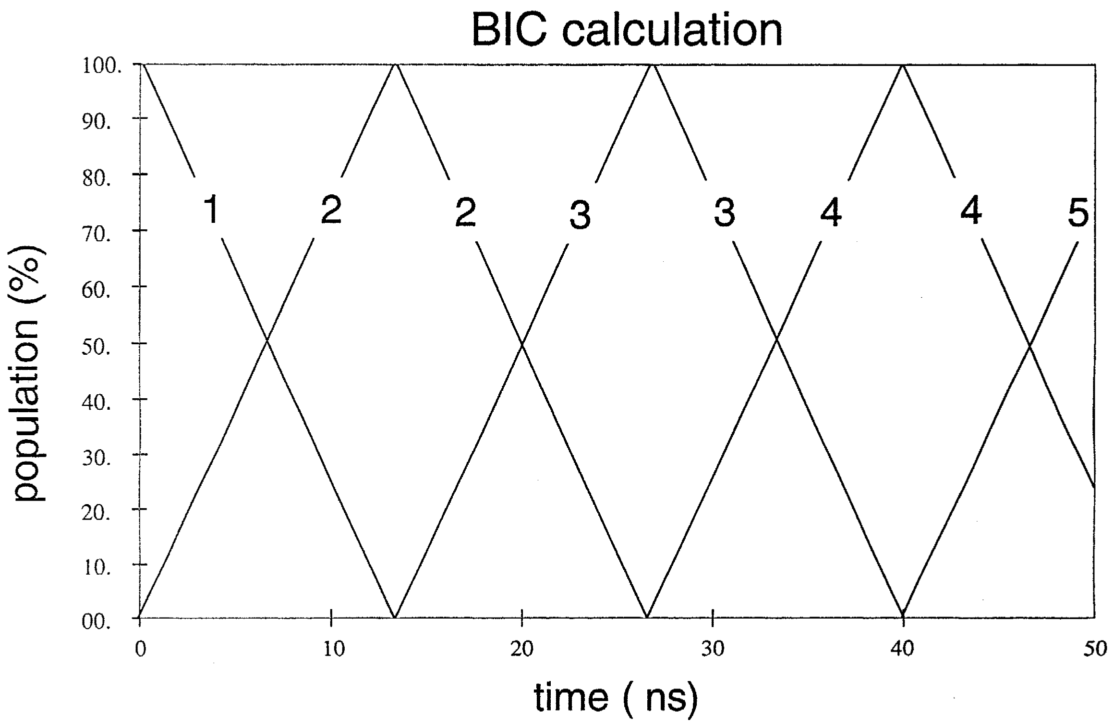

Fig. 1. Population time evolution for beam charge states. Integers label ionicity obtained from BIC code (Livermore).

The major difference concerns the treatment of beam stripping and gas ionization processes. In BIC, an ion stripping event or a gas molecule ionization event appends every l_{st} and l_{io} where l_{st} and l_{io} are the corresponding mean free paths. The evolution of the population of ion beam charge states as predicted by BIC is given in Figure 1 while the corresponding evolution as computed by BPIC is given in Figure 2. At $t = 31$ ns, we compare in Figure 3 the popula-

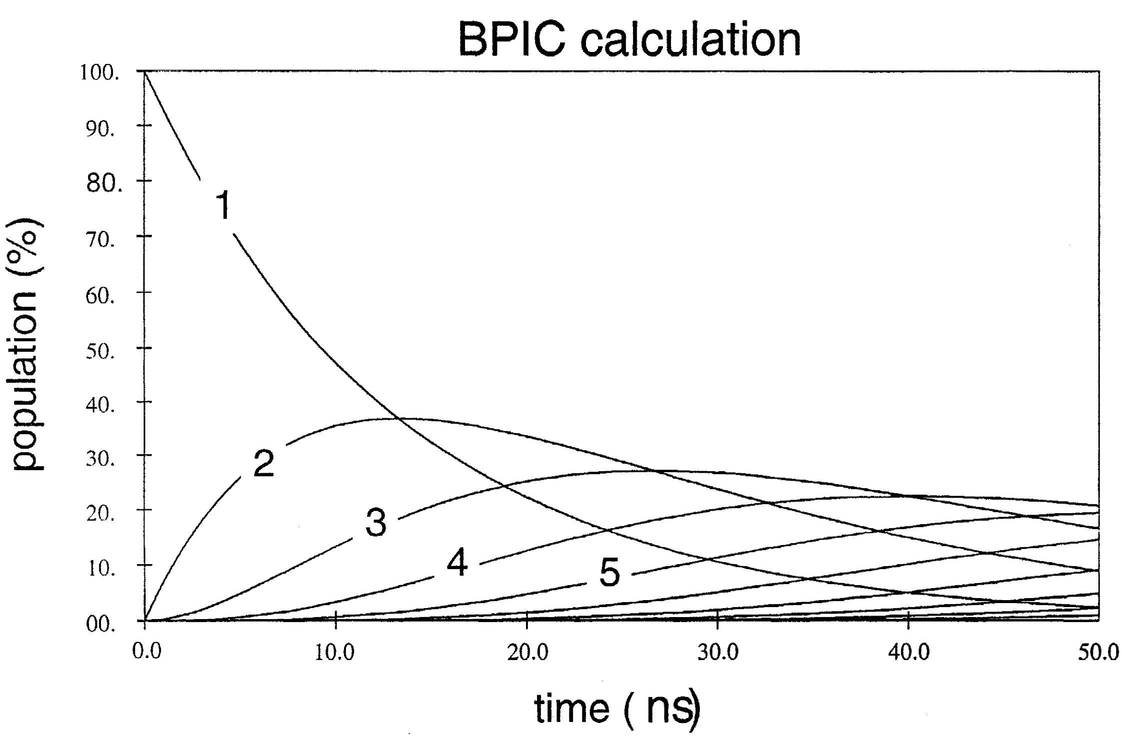

Fig. 2. Same as Figure 1 for BPIC code (Orsay).

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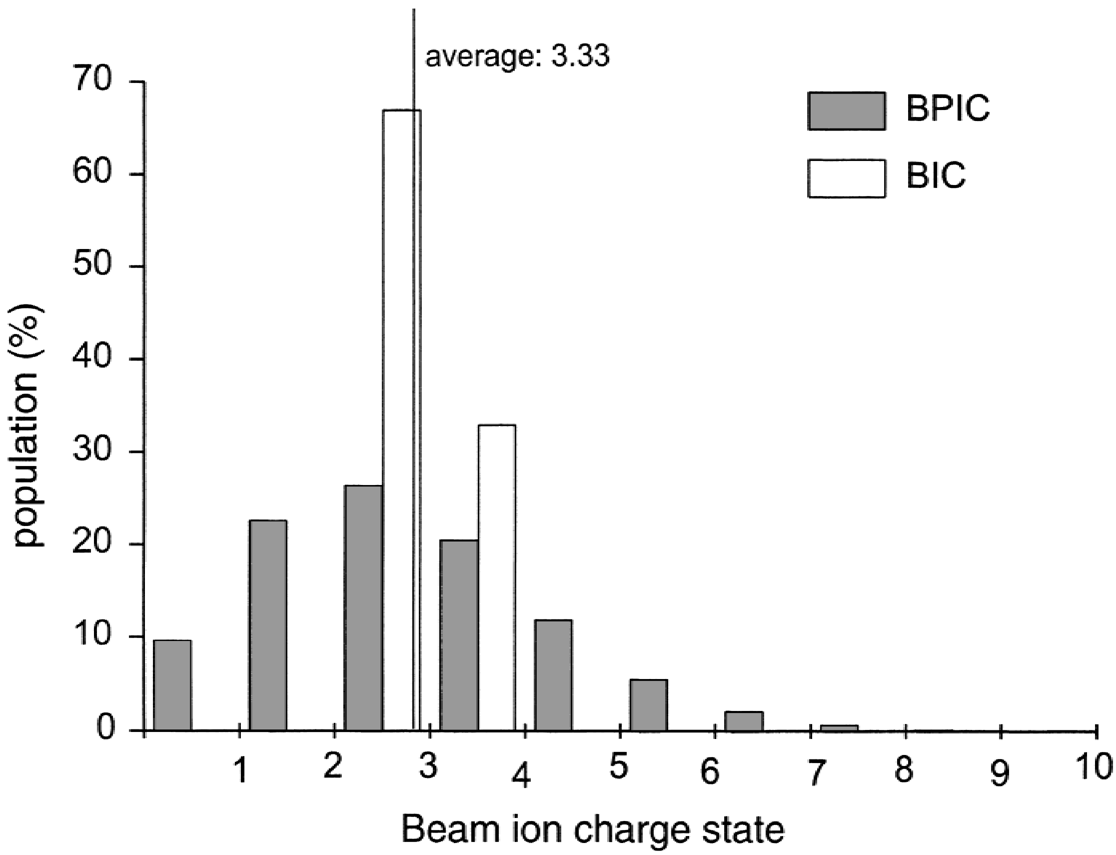

Fig. 3. Ion beam charge populations according to BIC code (Livermore).

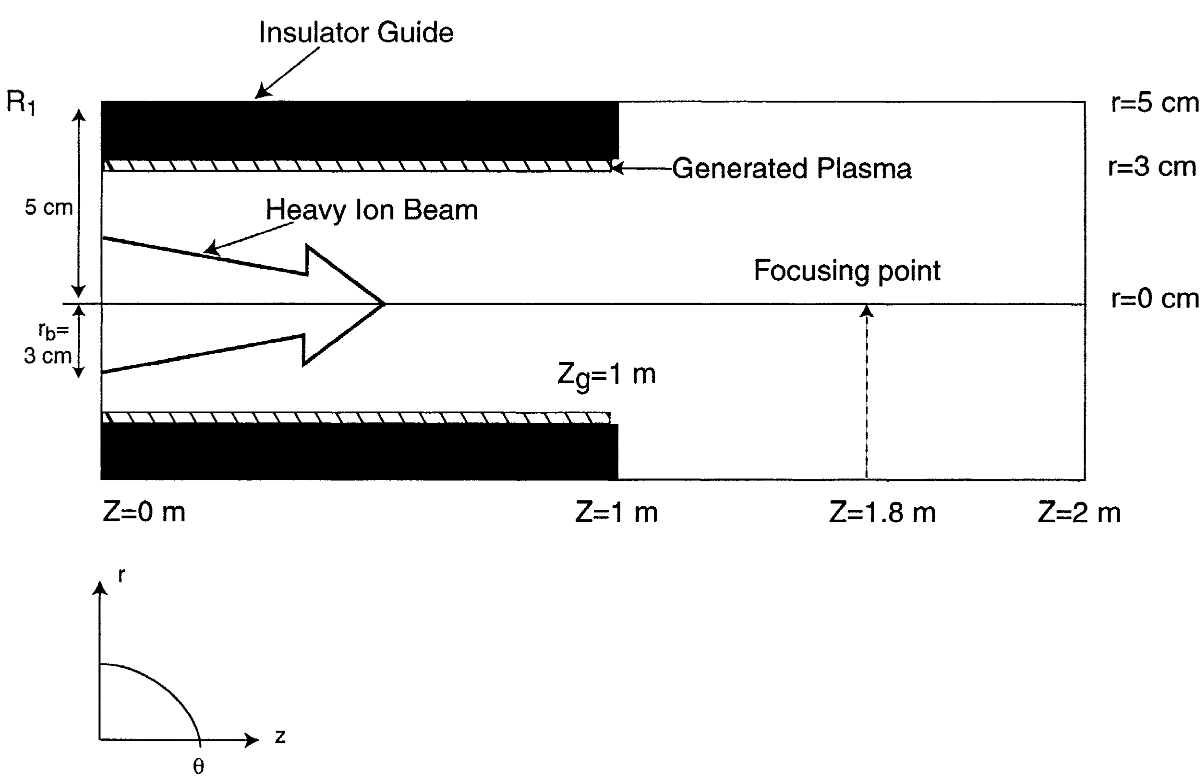

Fig. 4. Heavy ion beam guided by insulating walls.

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tion of charge states given by the two codes. Although giving the same averaged charge state for the entire beam (~3.33), BIC does not reproduce the actual distribution. To perform a fair comparison between the two codes, the algorithm used by BIC was also implemented in BPIC.

Another difference lies into the calculation of the focal spot containing 95% of the particles. In BIC, complete neutralization is assumed at the end of the propagation and the beam then propagates ballistically to the target. On the contrary, no similar assumption has been made in BPIC and the space charge forces are experienced by the beam during the full propagation. Here again, we have also implemented in BPIC the procedure used by BIC.

- Stripping (BIC method), focal spot (BIC method): R95% ~3.64 mm,
- Stripping (BIC method), focal spot (BPIC method): R95% ~3.71 mm,
- Stripping (BPIC method), focal spot (BIC method): R95% ~4.02 mm,
- Stripping (BPC method), focal spot (BPIC method): R95% ~4.70 mm.

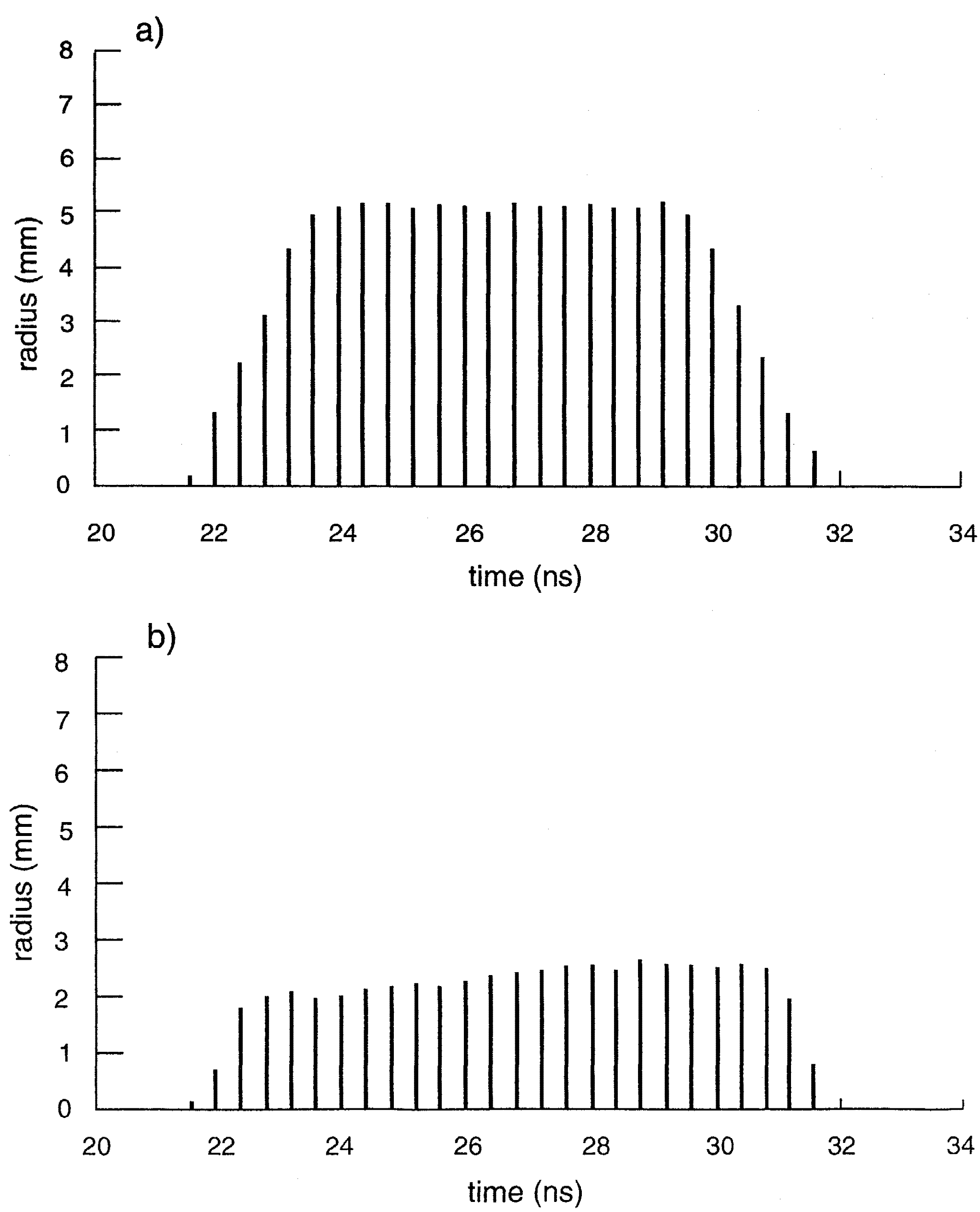

Fig. 5. Beam radius at focus point ($Z = 180$ cm). (a) without insulating guide; (b) with insulating guide.

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Using the same procedures as BIC, we have obtained a very close result. However, the last of the four results shows that using the Monte Carlo method for beam stripping and gas ionization, combined with maintaining the space charge force calculation during the full propagation process, produced a significantly larger spot size.

3. INSULATING BEAM GUIDING

Another recently advocated approach (Kawata *et al.*, 1996; Deutsch *et al.*, 2001) to the HIB space charge neutralization relies on propagation in front of insulating walls (Fig. 4).

Such a scheme makes use of a local electric field produced on the inner surface of the insulator beam guide by the incoming HIB itself. When this local electric field is above 1×10^7 V/m, it produces a local discharge resulting in a gliding plasma on the dielectric substrate. HIB can then extract some of these plasma electrons which will be securing a kind of dynamical sheath around it. Here we consider some results issued from 2.5-dimensional PIC simulations. The considered lead beam has a 5 kA maximum intensity and 8-GeV ion energy. The given pulse width is 10 ns with a 2-ns rise, and an initial radius of 3 cm.

Without the insulating wall, the beam radius at the focus point ($Z = 180$ cm) could expand up to 5 mm (cf. Fig. 5a). With an insulating wall (Fig. 5b), the largest radius is restricted to 2 mm. Those encouraging results highlight a significant reduction of the HIB space charge.

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