ADVANCED NUMERICAL MODELING OF COLLECTIVE FINAL FOCUS FOR INTENSE ION BEAMS*

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Abstract

This paper presents results of advanced numerical simulations demonstrating the feasibility of tight collective focusing of intense ion beams for the Neutralizing Drift Compression Experiment (NDCX-I). In the collective focusing scheme, a weak magnetic lens provides strong focusing of an intense ion beam carrying an equal amount of neutralizing electron background [S. Roberston, Phys. Rev. Lett. **48**, 149 (1982)]. For instance, a solenoidal magnetic field of several hundred gauss can focus an intense neutralized ion beam within a short distance of several centimeters. The enhanced focusing is provided by a strong self-electric field, which is produced by the collective electron dynamics. The numerical simulations are performed with the LSP particle-in-cell (PIC) code, and the results of the simulations are found to be in very good agreement with analytical predictions. Collective focusing limitations due to possible heating of the co-moving electrons during the transverse compression are also discussed.

INTRODUCTION

For applications to ion-beam-driven warm dense matter and high energy density physics, significant longitudinal and radial compression of a high-intensity ion beam pulse is required. One of the modern approaches to the compression process is to use dense background plasma, which charge neutralizes the ion charge bunch, and hence facilitates compression of the charge bunch against strong space-charge forces. In the conceptual design of an ion driver, a radially convergent beam with an imparted head-to-tail velocity tilt propagates through a long drift section filled with a neutralizing background plasma, where nearly ballistic (field-free) compression occurs. Typically, in order to provide additional transverse focusing, a strong (several Tesla) magnetic solenoid is placed downstream of the drift section. Due to the strong space-charge self-fields of an intense ion beam pulse, a neutralizing plasma is also required inside the magnetic solenoid. Note that apart from the challenge of using a several Tesla magnetic solenoid, filling it with a background plasma provides additional technical challenges [1]. However, the use of the collective focusing concept [2] can significantly simplify the technical realization of the beam final focus. Indeed, a neutralizing electron background can be dragged by the ion beam from the plasma that fills the drift section. The required magnetic field of the final focus solenoid can be lowered to the range of several hundred Gauss. Finally, a neutralizing plasma background is not required (should not be present) inside the final focus solenoid. As a practical example, here we present results of advanced numerical simulations demonstrating the feasibility of tight collective focusing of intense ion beams for the Neutralizing Drift Compression Experiment-I (NDCX-I) [3], which is a compact heavy ion driver for warm dense matter experiments.

COLLECTIVE FOCUSING LENS

The concept of a collective focusing lens [2] can be summarized as follows. First, let us review the principles of operation of a conventional magnetic lens for the case of a single-species charged particle beam. Moving from a region of a zero magnetic field into the magnetic lens, a beam particle acquires azimuthal angular momentum as the magnetic flux through its orbit increases. As a result, a radial focusing $V\times B$ force is acting on the beam particles inside the lens. For the case where the ion beam drags a neutralizing co-moving electron background into the magnetic lens, the neutralizing electrons entering the lens experience much stronger magnetic focusing than the beam ions and tend to build up a negative charge around the lens axis. As a result, an electrostatic ambipolar electric field develops that significantly increases the total focusing force acting on the beam ions. It can be shown for the case of quasi-neutral compression (provided by $\omega_{pe}>>\Omega_e$), and assuming small perturbations in the applied solenoidal field due to the beam self-fields (provided by $r_b<<c/\omega_{pe}$), that the produced radial self-electric field is given by [2]

$$E_r = -m_e \omega_{ce}^2(z) r / 4e . \tag{1}$$

Here, $\omega_{ce}(z)=eB_0(z)/m_e c$ is the electron cyclotron frequency, Ω_e denotes its maximum value inside the lens, $B_0(z)$ is the applied soelnoidal magnetic field, c is the speed of light, r_b is the beam radius, e and m_e are the electron charge and mass, respectively, and $\omega_{pe}=(4\pi e^2 n_{b0}/m_e)^{1/2}$ is the electron plasma frequency of the incident neutralized beam, where n_{b0} is the initial beam number density. Finally, r and z denote the radial and longitudinal coordinates, and the axis of the solenoidal lens is aligned along the z-axis. Note that due to conservation of canonical angular momentum, the azimuthal component of the electron velocity is given by $V_{e\theta}=\omega_{ce} r/2$, and the electric field in Eq. (1) provides the balance between the magnetic $V_{e\theta}\times B$ force, the centrifugal force, and the ambipolar electrostatic force acting on the neutralizing electrons inside the lens. The transverse ion beam dynamics is primarily determined by the radial

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electric field, and the focal length of the collective focusing lens is given in the thin-lens limit by [2]

$$L_f^{coll} = -4v_b^2 / (\Omega_e \Omega_i L_s), \quad (2)$$

where v_b is the axial beam velocity, L_s is the length of the magnetic solenoid, and Ω_i is the ion cyclotron frequency inside the lens. Note that that for a given focal length, the magnetic field required for a neutralized beam is smaller by a factor of $(m_i/m_e)^{½}$ compared to the field required for the lens to focus a single-species nonneutral ion beam [2].

It is important to point out that the neutralizing electrons should enter the lens from a region of a zero magnetic field in order to acquire the azimuthal angular momentum necessary for the radial $V \times B$ magnetic focusing to occur inside the lens. Therefore, the collective focusing will only occur if there is no background plasma or secondary electrons inside the lens. Otherwise, the rotating electrons co-moving with the ion beam will be rapidly replaced by the "non-rotating" background plasma electrons inside the lens, and the enhanced collective focusing will be suppressed [4].

A COLLECTIVE FOCUSING LENS FOR NDCX-I FINAL FOCUS

In the present configuration of NDCX-I, the radially and longitudinally convergent ion beam pulse passes through a final focus solenoid as it leaves the neutralized drift section (see Fig. 1). In the idealized simulations presented here, the upstream effects of the radial and longitudinal beam convergence are not taken into account, and the following initial beam parameters are considered: the injected beam density is $n_{b0}=10^{10}$ cm^{-3}; the directed energy of the beam ions is E_b=320 keV; the ion beam radius is r_{b0}=1 cm; the duration of the ion beam pulse is τ=40 ns; and the transverse and longitudinal beam temperatures are assumed to be T_b=0.2 eV. To model the short downstream part of the neutralizing drift section, a plasma layer is placed between z=-5 cm and z=15 cm. The plasma density is assumed to be uniform with $n_p=10^{11}$ cm^{-3}, and the electron and ion temperatures are taken to be $T_{e0}=T_{i0}$=3 eV. The ion beam pulse is allowed to drag the electrons when leaving the plasma layer should the forces on them induce such motion. Figure 2 presents the results of the numerical particle-in-cell simulations performed with the LSP code [5] and demonstrating the feasibility of a tight collective focus for the case where the magnetic field inside the final focus solenoid is B_0=700 G. The ion beam comes to a tight focus at $z_f \approx 30$ cm, with ~700 times increase in the number density, $n_f \approx 7\times10^{12}$ cm^{-3} [Fig. 2(a)]. The radial electric field inside the lens is shown in Fig. 2(b), and agrees well with the analytical predictions in Eq. (1).

It is of particular practical importance to discuss the physical limits of the collective focusing. Figure 3 shows the system parameters slightly upstream of the focal plane, including the ion beam density [Fig. 3(a)], the electron density [Fig. 3(b)], and the radial component of the electric field [Fig. 3(c)]. It is readily seen that near the focal plane, the total space-charge density is positive, and

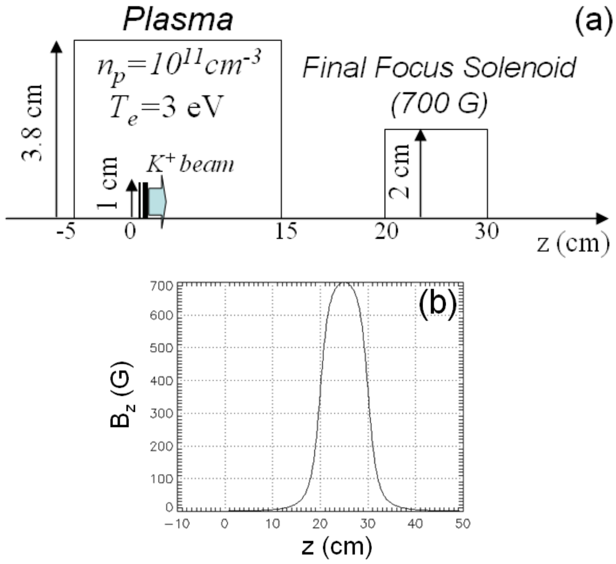

Figure 1: An idealized model of the NDCX-I final beam focus. (a) Schematic of the numerical LSP simulation. (b) The longitudinal profile of the applied axial magnetic field of the 700 G final focus solenoid.

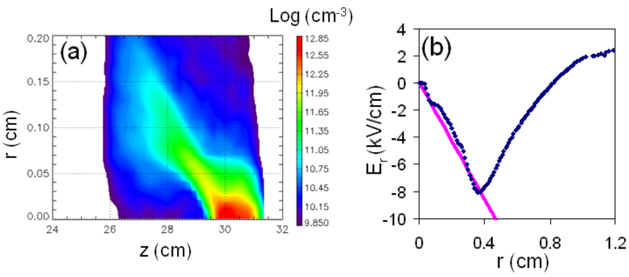

Figure 2: (Color) Results of the numerical simulations performed with the LSP code for the idealized model of the NDCX-I final beam focus. (a) Plot of the ion beam density at the focal plane corresponding to t=250 ns. (b) Radial dependence of the radial electric field inside the lens corresponding to z=25 cm and t=220 ns (blue dots). The analytical results in Eq. (1) are shown by the pink solid line in Frame (b).

the radial electric field is defocusing. This means that the compression of the co-moving electron beam comes to stagnation, whereas the ion beam still undergoes compression. This "final" ion beam compression is inertial, i.e., it occurs against the ion beam space-charge forces due to the ion beam radial convergence generated by the collective focusing. The plausible explanation of the electron transverse stagnation can be given by means of thermal effects [6]. Indeed, neglecting small electron inertia, the radial force balance equation for the electron fluid includes the focusing magnetic force, $-m_e\omega_{ce}^2 r/2$, the defocusing centrifugal force $m_e\omega_{ce}^2 r/4$, the defocusing electric force, eE_r, and the thermal pressure term, $\nabla p_e / n_e$. As the effective transverse electron temperature increases during compression, the electric field required to balance the magnetic electron focusing decreases. Finally, when the magnetic force is completely balanced by the thermal pressure, the electron compression comes to stagnation. A small additional compression of the co-moving electron beam, however, is still possible due to the positive radial electric field generated during the "inertial" ion beam compression. The parameters of the electron beam at the stagnation point can be estimated from

$$T_{es} \sim m_e \omega_{ce}^2 r_{es}^2 / 4\,, \qquad (3)$$

where, r_e and T_e are the electron beam radius and the effective transverse temperature. At the time corresponding to the plots in Fig. 3, the electron beam radius is r_e~0.1 cm, and it follows from Eq. (3) that T_e~215 eV. The corresponding normalized value of the effective radial thermal velocity, $\beta_{er} \sim c^{-1}(T_e/m_e)^{½}$ =0.02, is consistent with the results of the numerical simulations shown in Fig. 3(d). It is interesting to note that the value of the effective transverse temperature observed in the simulations is approximately consistent with the adiabatic compression of the electron beam, where $r_e T_e \approx$const.

Note that the radial ion beam density profile shown in Fig. 3(a) is hollow. This can be due to nonlinearities in radial profile of the focusing electric field near the axis [Fig. 2(b)]. However, it is important to point out that the ion beam profile is bell-shaped at the focus, as seen in Fig. 2(a). Furthermore, it has been observed in the numerical simulations that the radial profile of the electric field becomes nearly linear, when the magnetic solenoid is moved further downstream from the drift section in order to decrease the value of the fringe magnetic fields inside the plasma layer. It also should be noted that nonlinear aberrations can be produced due to the thermal

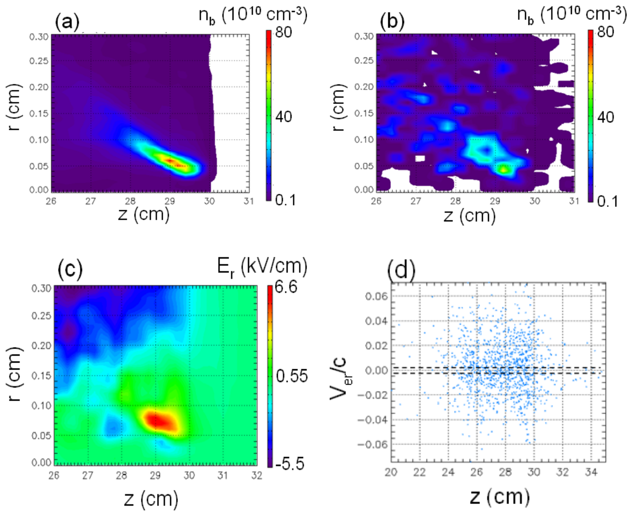

Figure 3: (Color) Effects of electron heating on collective beam focusing. Shown are plots of (a) ion beam density, (b) electron density, (c) radial electric field, and (d) electron phase-space (V_{er}/c,z). The results are obtained at time t=240 ns. The horizontal dashed lines in Frame (d) correspond to a characteristic initial electron thermal velocity specified by $(T_{e0}/m_e)^{½}$.

spreading in the transverse velocity distribution of a co-moving electron beam [7].

For the parameters of the illustrative example shown in Fig. 2, the focal plane lies near the downstream end of the final focus solenoid. For practical purposes, however, it can be important to have a gap between the final focus solenoid and the target plane (beam focal plane). The gap length can be controlled by variations in the final focus solenoid magnetic strength, and to investigate this phenomenon, the corresponding numerical simulations have been performed [8]. It has been observed that the focal plane can be moved downstream by lowering the magnetic field strength of the solenoid. However, the compressed beam density decreases with a decrease in the applied magnetic field. A plausible explanation for this includes the following. First, electron stagnation can occur earlier, in accordance with Eq. (3). Second, the "inertial" phase of the ion beam compression is more pronounced for a stronger magnetic field, because a steeper convergent angle is acquired during the collective compression inside the final focus solenoid.

CONCLUSIONS

The use of a collective focusing lens can significantly simplify the technical realization of the beam final focus in the Neutralized Drift Compression Experiment (NDCX-I). The required magnetic field of the final focus solenoid can be lowered from several Tesla to the range of several hundred Gauss. Also, a neutralizing plasma background is not required (should not be present) inside the final focus solenoid. The results of the idealized numerical simulations presented in this paper demonstrate the feasibility of tight collective focusing of intense ion beams for the Neutralizing Drift Compression Experiment (NDCX-I). The extended numerical simulations taking into account the effects of the radial and longitudinal convergence and ion beam pulse shaping will be the subject of future studies.

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