THEORY AND SIMULATIONS OF NEUTRALIZATION AND FOCUSING OF ICF ION BEAMS

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Introduction

Inertial Confinement Fusion (ICF) ion beams must be focused to a small spot during final propagation to the target. In general, both beam emittance and space charge limit the achievable spot size. Here we consider the latter and how its effect can be eliminated by injecting into the target chamber electrons which are comoving and coexstensive with the ions. Unlike focusing an ion beam through a neutralizing plasma channel, the present propagation mode requires a hard vacuum (10^{-4} to 10^{-5} Torr) target chamber into which both ions and electrons are injected, and thus avoids possibly deleterious beam plasma interactions.

We present two major results in this paper. First is a one dimensional model in which the ions focus self-similarly and the neutralizing electrons are an inertialess, isentropic gas which heats as the beam focuses. The model extends a previous one.[1] A solution of the model gives a simple formula (Eq. 8) relating an upper bound on the focal spot size to the beam perveance, initial radius, initial focal angle, and the initial temperature of the neutralizing electrons. The bound agrees with a series of one dimensional particle-in-cell (PIC) simulations of ion beams with both flat topped and parabolic radial profiles and underestimates the focusing by no more than 30%.

Second are two dimensional, azimuthally symmetric, PIC simulations of beam neutralization with field emitted electrons. These demonstrate that without a special grid to accelerate the electrons up to comoving speeds the latter are heated to temperatures on the order of or greater than their directed energy. According to the focusing model, such temperatures are too high for ICF applications. Sufficiently cool comoving electrons can be produced with the accelerating grid.

Focusing Model

We treat the ions as a cold fluid. In the beam frame the ion density n and radial velocity v are determined from the continuity and momentum equations:

$$\frac{\partial n}{\partial t}+\frac{1}{r}\frac{\partial nvr}{\partial r}=0 \tag{1}$$

and

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial r}=\frac{Ze}{M}E. \tag{2}$$

The electron density n_e is determined from electron force balance

$$n_e eE=-\frac{\partial P_e}{\partial r} \tag{3}$$

while the electron pressure P_e is determined from an isentropic equation of state. The latter is

$$\frac{P_e}{n_e^2}=4\pi e^2\lambda_D^2 \tag{4}$$

where the the right hand side is constant in space and time and has units of charge squared times length squared. We have defined it in terms of a global Debye length λ_D. We also make use of an electron temperature T_e defined to be P_e/n_e. Finally, Gauss's law closes the system

$$\frac{1}{r}\frac{\partial rE}{\partial r}=4\pi e(Zn-n_e). \tag{5}$$

A moment of an equation is produced by integrating the equation over the total configuration space volume. In the present geometry the volume element is rdr. For instance, if we first multiply Eq. (1) by n and integrate, we produce the n moment of ion continuity. The specific moments we need are: the r^2 and n moments of ion continuity, the nr^2 moment of ion momentum, the r moment of electron force balance, the 1 moment of the electron equation of state, and the rE and $Zn+n_e$ moments of Gauss's Law. If, furthermore, we require global charge neutrality, $Z\int drrn=\int drrn_e$, ion self-similarity, $v=H(t)r$, these moment equations constitute a set of nonlinear ordinary differential equations describing the time evolution of the fluid variables averaged over configuration space.

We close the set of moment equations by droping the n_e moment of $r^{-1}\partial(rE)/\partial r$. Since this term is negative definite, dropping it leads to a bound, specifically

$$M\ddot{R}\leq\frac{8\pi Z^2e^2\lambda_D^2<n>_iR^2}{R(R^2+4\lambda_D^2)}. \tag{6}$$

where the average ion density $<n>_i$ is defined as

$$<f>_i\equiv\frac{\int dr\, r\, n^2}{\int dr\, r\, n} \tag{7}$$

and likewise the ion beam rms radius is defined as $R^2=<r^2>_i$. The equality holds in the limits $R/\lambda_D\rightarrow 0$ and $R/\lambda_D\rightarrow\infty$. Details of this derivation will be published elsewhere.

The right hand side of Eq. (7) describes the force that resists focusing. It contains desired the physics. In the limit of hot electrons, $\lambda_D>>R$, the electrons should be ineffective in neutralizing the ion beam space charge. Indeed, the force function in this limit recovers the constant usual for space charge dominated beams. In the limit of cool but not absolutely cold electrons we expect the neutralized beam to act

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as a neutral fluid with a force function dominated by electron pressure. This is the case when $\lambda_D << R$. Finally, as expected there is no resistance to focusing when the electrons are absolutely cold, $\lambda_D=0$.

The first integral of Eq. (7) can be performed exactly. Specifically, if $R=R_o$ and $\dot{R}=\dot{R}_o$ define the initial conditions, the conditions at the focal point $R=R_f$ and $\dot{R}=\dot{R}_f=0$ are related to them by

$$(\frac{R_o}{R_f})^2 \geq e^{\alpha^2/k}+(\frac{R_o}{2\lambda_D})^2(e^{\alpha^2/k}-1). \tag{8}$$

where $k/\alpha^2 \equiv (2Z^2e^2\pi R_o^2 <n>_{io})/(M\dot{R}_o^2)$ and $\lambda_D^2 \equiv <T_e>_{eo}/(4\pi e^2 <n_e>_{eo})$. Given any initial ion and electron density profiles these parameters may be evaluated in terms of the beam line density N_L. This formula is a generalization of the usual spot size formula for space charge dominated beams. The latter is recovered in the $R_o/\lambda_D \rightarrow 0$ limit.

One Dimensional Simulations

The bound (8) agrees with one dimensional electrostatic PIC simulations of a focusing neutralized ion beam. In these simulations the ions were initialized cold but given a linear velocity profile, $v(r) \propto r$, which if undisturbed would eventually focus the ions to a point on the symmetry axis $r=0$. The electron were always initialized with exactly the same density profile as the ions, and given a Maxwellian velocity space distribution characterized by a uniform temperature $<T_e>_{eo}$ but no bulk velocity. Each simulation was run at least until the ions reached their focal point.

Among the dimensionless physical parameters, the ion to electron mass ratio is 40000, corresponding to Neon or Sodium ions, the initial dimensionless rms ion radius $R_o\omega_{peo}/v_{ro}$ is 141, and the initial density profiles are normalized so that the average initial density is the same in each of the cases. These parameters determine the theoretical quantity $\alpha^2/k=2$.

Altogether, sixteen simulations were performed: eight had initial flat profiles while eight had initial parabolic profiles. The only unmentioned relevant dimensionless physical parameter is the normalized initial electron temperature $<T_e>_{eo}/(m_e v_{ro}^2)$. The square root of this parameter is varied from 5 640 by factors of two in each of the two sets of eight simulations.

Results are displayed in Figure 1 which plots the focusing ratio R_o/R_f achieved in the simulation versus R_o/λ_D for both initially flat topped and parabolic initial radial beam profiles. The solid line is the theoretical bound (8). Note that the focusing ratio for flat topped and parabolic profiles is the same to within about 10% and that the bound underestimates the focusing by no more than about 30%. The model and the simulations both show that short Debye lengths or equivalently low initial electron temperatures are necessary for large focusing ratios.

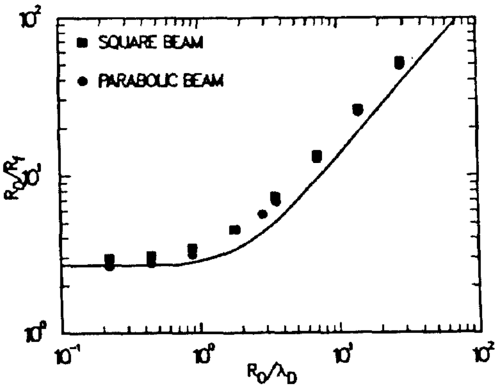

Fig. 1 Focusing ratio, R_o/R_f, achieved in sixteen one dimensional simulations with $\alpha^2/k=2.0$ and R_o/λ_D varying with the initial temperature of neutralizing electrons. Solid curve is theoretical bound (8).

Two Dimensional Simulations Of Beam Neutralization

It is easy to globally neutralize intense ion beams with electrons which have been field emitted from nearby surfaces, but is difficult to keep these electrons cool. Field emitted electrons typically pick up a random energy associated either with the radial potential well of the bare ion beam and or with a comoving speed. This heating can be avoided by placing a grid downstream of the emitting surface with a potential which accelerates the electrons up to an energy $m_e v_z^2/2$. Because of the large disparity in masses, the ion speed v_z changes a negligible amount in passing through this gap. For smooth acceleration the gap should be $.571(v_z/\omega_p)$ wide [2] where $\omega_p{}^2=4\pi e^2 n_i/m_e$.

Figures 2 and 3 contain results from PIC simulations of the field emission - beam neutralization process, respectively without and with the grid. The code used is ISIS, a fully electromagnetic two dimensional PIC simulation code[3]. In both cases a cold beam of 100 Mev Aluminum ions with 300 Amperes current was injected into the simulation region from the left axial boundary, electrons were emitted from the injection plane in numbers sufficient to zero out the normal electric field, and the simulation was run until both electrons and ions propagated across the region. Other physical parameters can be extracted from labels in the Figures, each one of which has one configuration space ($\tilde{r}$ vs $\tilde{z}$) and two phase space ($\gamma\beta_z$ vs z) and ($\gamma\beta_r$ vs z) particle plots showing both electrons and ions. By definition $\gamma^2 \equiv (1-v^2/c^2)^{-1}$, $\beta_z \equiv v_z/c$ and $\beta_r \equiv v_r/c$.

In Figure 2 electrons are pulled from all over the emitting surface and are energized on falling into the beam channel. In addition, they are accelerated axially by the beam space charge, overshoot the beam speed, and are reflected by the virtual cathodes which have formed. These processes result in electron radial and axial temperatures on the order of the energy of a comoving electron with $\beta_z=.088$.

In Figure 3 an accelerating grid has been placed one millimeter from the emitting surface. The grid reduces the radial field near the emitting plane and accelerates the electrons smoothly up to a comoving speed. Consequently, downstream electron temperatures are significantly smaller, specifically by about a factor of five.

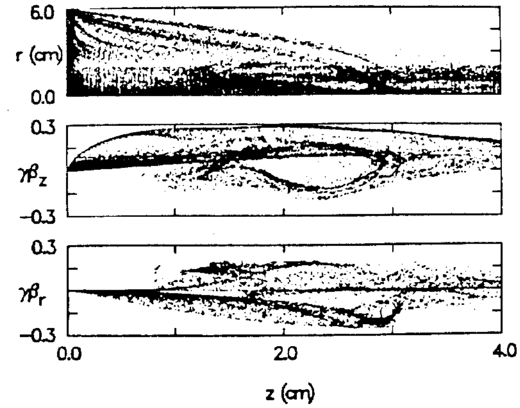

Fig. 2 Configuration, (r *vs* z), and phase space, ($\gamma\beta_z$ *vs* z) and ($\gamma\beta_r$ *vs* z), particle plots of injected ion beam and field emitted electrons.

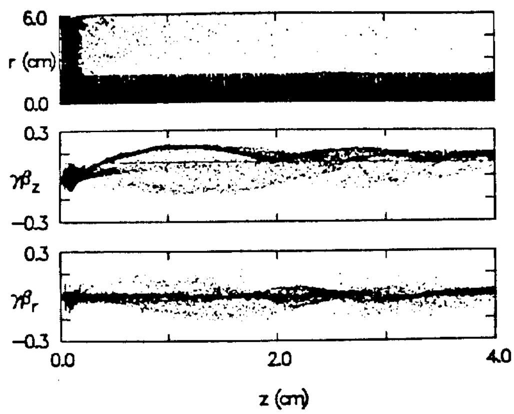

Fig. 3 Same as Fig. 2 except a grid which accelerates the electrons up to comoving speeds has been added 1 mm from the left boundary. Temperature of neutralizing electrons is substantially less than in Fig. 2.

Application To The High Temperature Experiment

In conclusion, we apply this focusing and neutralization model to the proposed High Temperature Experiment (HTE).[4] In this case we need to focus 16, 100 Mev, 300 Ampere, Aluminum ion beams on a disc target with a 2mm radius. The beams are initially 2.3 cm in radius and the focusing magnets will standoff about 1.78 meters from the target. Therefore, the required focusing ratio is $R_o/R_f=11.5$, the required focusing angle is $\alpha=.0129$, and the beam perveance is $k=2.66\ 10^{-4}$. The derived dimensionless parameters are $\alpha^2/k=.313$ and $(R_o/2\lambda_D)^2=1.33\ 10^4/T_{eo}^{1/2}$ where T_{eo} is the initial electron temperature in ev. Plugging all these numbers into the bound (8) we find that if $T_{eo}\leq 1.4$ kev the required focusing ratio will be achieved. A 1.4 kev electron corresponds to $\beta=.074$. Although it is difficult to estimate electron temperatures from Figures 2 and 3, we see that the downstream electrons produced without the accelerating grid in Figure 2 may very well be hotter than 1.4 kev while those produced with the accelerating grid in Figure 3 are definitely cooler than 1.4 kev.

References

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