Super-Intense Quasi-Neutral Proton Beams Interacting With Plasma: A Numerical Investigation

H. Ruhl, T.E. Cowan, and R.B. Stephens

General Atomics, P.O.Box 85608, San Diego, California 92186-5608 USA
Email: ruhl@fusion.gat.com

Abstract. Due to the unique properties of the recently discovered sheath laser-ion source the investigation of super-intense quasi-neutral ion beams interacting with plasma has become of substantial interest. Novel experiments in parameter regimes that bear relevance for future ion based Fast Ignition concepts can be envisioned. Simulations in two spatial dimensions of quasi-neutral proton beams interacting with a coronal plasma are presented. Beam-plasma instabilities are found. Ion beam instabilities, and ion beam energy loss in plasma will be discussed. The implications of the results for a proton based Fast Ignition concept are addressed.

1. Introduction

Intense laser radiation can generate high-brightness, energetic ion beams in the laboratory [1,2]. Given the unique properties of laser-accelerated ion beams novel experiments with ion beams interacting with plasma can be envisioned. Some of these may be relevant for a future Fast Ignition (FI) concept [3] based on ion beams which will require the deposition of a few kilojoules of energy stored in ions within a few ps on spatial scales of a few microns [4].

Recent experiments performed at LULI with a laser of 20 J pulse energy and 0.3 ps duration show that a few times 10^{12} ions per laser shot can be obtained from the rear surface of an irradiated solid. The source diameter of the emitted ions is less than 50 µm in these experiments depending on the energy of the ions. The laser generated ion beam is surrounded by hot electrons and has a wide energy spectrum with a slope of several million electron volts. Total ion currents of a few kA are obtained. Depending on the shape of the rear surface the ions can be focused. For ion drift lengths of about 1.0 mm which are close to scales discussed in the context of FI, and no ballistic focusing of the ions, the beam diverges to about 100.0 µm diameter. The achievable ion beam density after a drift of 1.0 mm is still about 10^{17} cm^{-3} while the current density is roughly 10^{11} A/m ^{2}. Taking the possibility of ballistic focusing of the ions into consideration, three to four orders of magnitude in beam and current density can be obtained. This represents a novel particle source.

Investigations of ion beam-plasma interaction frequently concentrate on single particle aspects of the beam-plasma interaction. However, collective beam-plasma effects may become dominant for the parameters of laser-generated ion beams. Numerical simulations in two (2-D) spatial dimensions taking full account of collective effects and the electro-magnetic nature of the beam-plasma interaction will be presented. Issues of beam stability in plasma and beam energy loss in plasma will be addressed. Beam stability and filamentation in reactor vessels has previously been studied by Lee et al. [5].

2. High Current Proton Beam-Plasma Interaction

Based on protons of about 10 MeV the concept of FI requires proton beam densities in the range of 10^{23} cm^{-3} and proton currents up to 10^{9} A, i.e., many times the Alfvén current of 4.5 MA for these protons. It is evident that currents of this magnitude require a high level of current neutralization by co-propagating electrons. A configuration consisting of electrons that co-propagate with protons is unstable and the proton beam might distort if the beam current is high enough. A simple consideration will help to understand when intrinsic beam forces start to become strong enough to distort the latter as the beam propagates into the target. Assuming a cylindrical beam, Ampére’s law relates the magnetic field B_{ϕ} with the current density j_z, where j_z is the effective net current density along z. We assume that j_z is constant along the radius r and the beam mono-energetic. After a few steps we find a relation of the form

$$\frac{\Delta v_r}{v_z} \approx \frac{2m_e}{m_i}\frac{\Delta z}{R}\frac{j_z}{I_A} \;, \quad I_A = 1.70\ \mathrm{KA}\beta_z\gamma_z \;, \quad \beta_z = \frac{v_z}{c} \;, \quad \gamma_z = \frac{1}{\sqrt{1-\beta_z^2}} \;, \tag{1}$$

which relates the radial beam velocity gain Δv_r to the longitudinal beam velocity v_z, the electron-ion mass ratio $m_e \backslash m_i$, the ratio of the effective net beam current I_z versus the electron Alfvén current I_A, and the beam propagation distance Δz versus the beam radius R. To prevent the beam from bending and eventually hosing, either large proton energies or short propagation distances at high net current or low net currents are required. In general it will not be possible to propagate a quasi-neutral beam whose constituent currents exceed the electron Alfvén current I_A significantly over a distance that is large compared to the beam diameter. This is particularly true in the vicinity of a steep plasma-vacuum interface. There, the co-propagating electrons will heat the plasma electrons, leading to enhanced thermal pressure and thermo-electric field generation

$$\mathbf{E} \approx -\frac{k_B T_e}{e}\frac{\nabla n_e}{n_e} \;, \tag{2}$$

where **E** is the thermo-electric field, T_e the hot electron temperature, and n_e the electron density. This field can decelerate protons at the front surface of the target and accelerate them at the rear surface. If the quasi-neutral beam deposits energy in the electron plasma of the absorber material the electro thermal field **E** will grow. Thus is can happen that the tip of the beam is accelerated when it exits the plasma. In that sense the absorber target can work as a proton beam accelerator.

An example of electron heating by beam electrons can be seen in Fig. 1. The background and beam densities given by n_{be}, n_e, n_{bi}, and n_i are 10^{16} cm^{-3}. The beam is almost mono-energetic as is inferred from plot (b) of the figure. The protons have an average energy of about 18.0 MeV while the co-propagating electrons are in the kilo-electron-volt range. Plot (a) of the figure shows the incident electron beam and the background plasma in the zp_z-

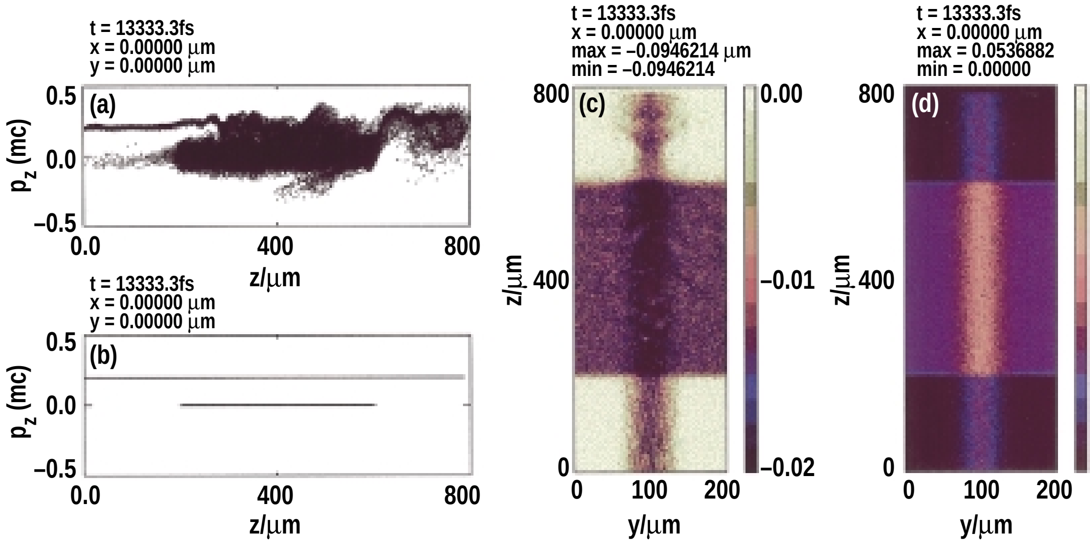

Fig. 1. 2-D simulation. A quasi-neutral proton beam impinges a plasma. The constituent beam currents are 0.4 kA. The beam envelope is Gaussian with a width of 25.0 μm. Plots (a,b) shows the electron and proton phase spaces at t = 13.3 ps. Plots (c,d) give the electron and proton densities. Plot (a) shows that the bulk of the electrons co-propagating with the protons gain energy when the beam exits the rear surface of the plasma. The protons in the beam suffer no distortion. Equation (1) reveals $\Delta v_r/v_z \approx 10^{-6}$ Δz/R which predicts no significant beam distortion.

plane of phase space. The electron momenta are normalized to $m_e c$. The quasi-neutral beam enters the plasma at z=200.0 µm and leaves it at z=600.0 µm. The majority of captured electrons as the proton beam leaves the plasma has gained energy. The beam deflection given by Eq. (1) is very small for the parameters of the simulation shown in Fig. 1. Consequently, the proton beam only weakly interacts with the background plasma and remains unperturbed as is seen from plot (d) of Fig. 1.

However, beam stability is significantly affected for large beam currents. The beam densities for the simulation shown in Fig. 2 are $n_{be} = n_{bi} = 10^{21}$ cm^{-3} . The injected protons are mono-energetic with $E_b \approx 18.0$ MeV and form a cylinder with a diameter of 10.0 µm at the injection point. The injected proton current is about 780.0 kA. The irradiated beam power is $P_b = 1.4 \times 10^{12}$ W. It is compensated by co-propagating electrons. The beam deflection criterion Eq. (1) predicts $\Delta v_r/v_z \approx 0.25\ \Delta z/R$ which means significant beam-plasma interaction. Indeed, as is inferred from plot (a) of Fig. 2, rapid electron heating takes place. In the process, the bulk electron distribution shifts upward along p_z since it absorbs part of the beam momentum. The beam decelerates slightly in the plasma and accelerates at the rear surface of the latter. Plots (c,d) of the figure show the proton density as the beam impinges the plasma and later as it interacts with it. From plot (d) we can see that the beam breaks up into filaments which hose.

Beam hosing is related to the fact that a configuration of electrons and protons propagating in the same direction is unstable. This instability is mild as long as the resulting forces on the beam are weak, which is the case for low current densities. Equation (1) summarizes details. As current densities grow, self-interaction of the beam with its own magnetic field can distort the latter. To release these forces current neutralization by co-moving electrons has to be violated. However, since the tip of the impinging beam heats electrons when it interacts with a plasma interface, electro-thermal fields emerge which are strong enough to remove part of the co-moving electrons from the beam. This seeds the growth of magnetic fields which drive the beam instability until the beam breaks up.

3. Summary

ICF related target heating with protons requires large currents. These currents do not propagate due to strong interaction with their self-generated magnetic field. To avoid this

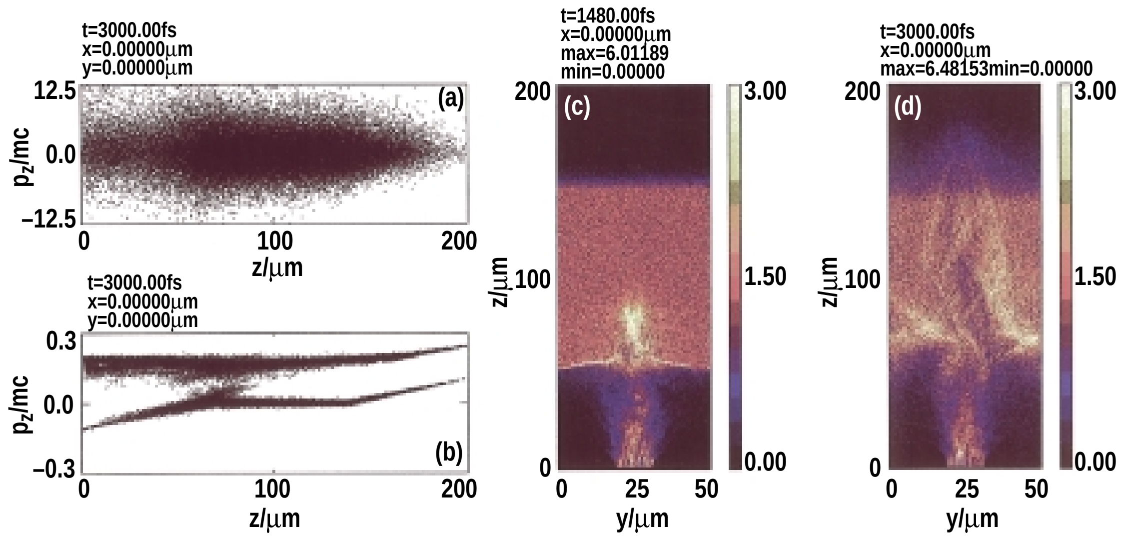

Fig. 2. 2-D simulation. A quasi-neutral proton beam impinges a plasma. The constituent beam currents are 780.0 kA. The beam envelope is a cylinder with a diameter of 10.0 µm. The irradiated beam power is $P_b = 1.4 \times 10^{12}$ W. Plots (a,b) shows the electron and proton phase spaces at t = 3.0 ps. It can be seen that the tip of the beam is accelerated by the energy it deposits in the plasma. Plots(c,d) give the proton densities at t = 1.4 ps and t = 3.0 ps. The protons in the beam suffer significant deflection. Equation (1) reveals $\Delta v_r/v_z \approx 0.25\ \Delta z/R$ which predicts significant beam distortion.

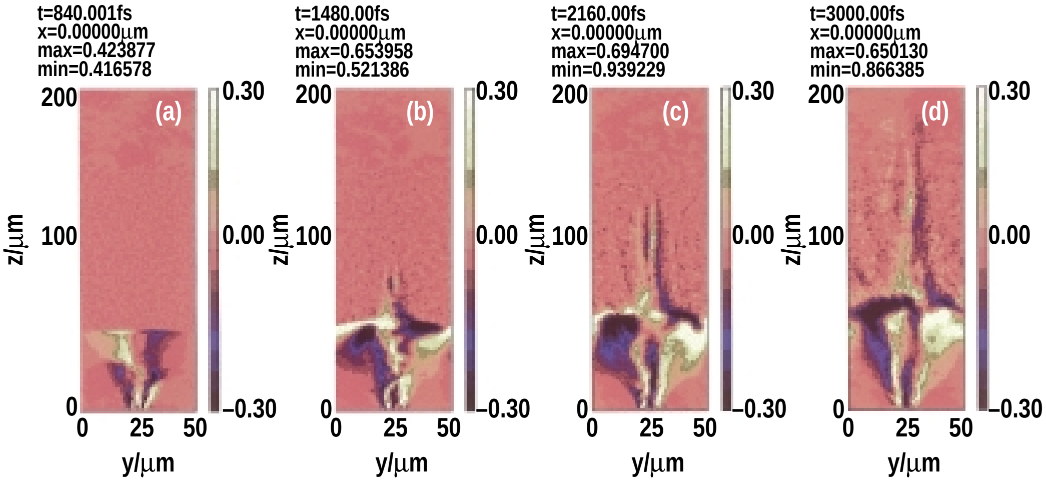

Fig. 3. 2-D simulation. A quasi-neutral proton beam impinges a plasma. The constituent beam currents are 780.0 kA. The beam envelope is a cylinder with a diameter of 100 μm. Plots (a,b) shows the electric field E_z surrounding the beam for various times and plots (c,d) the magnetic field B_x. The units are in $E_0 = 6.4\times10^{12}$ V/m and $B_0 = 2.2\times10^4$ Vs/m^2. The peak magnetic field strength is about 1.3×10^5 Vs/m^2.

effect current neutralization is required. However, such a configuration is still unstable. In order to have stable beam propagation low current densities are required. This means that one is supposed to place the focus of the beam in front of the irradiated target. As the irradiated target heats up due to the interaction with the beam, electro-thermal fields at the surface grow, which remove part of the beam electrons. This process triggers electromagnetic beam instabilities like beam filamentation and hosing. Our simulations reveal that high current quasi-neutral proton beams cannot penetrate plasma without significant distortion.

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References

[1] S.P. Hatchett et al., Phys. Plasmas **7**, 2076 (1999).
[2] R.A. Snavely et al., Phys. Rev. Lett. **85**, 2945 (2000).
[3] M. Roth et al., Rev. Lett. **86**, 436 (2001).
[4] S. Atzeni, Phys. Plasmas **6**, 3316 (1999).
[5] Edward P. Lee et al., Phys. Fluids **23**, 2095 (1980).