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Open boundary Vlasov simulations of the propagation of a localized proton beam in a plasma

F. Califano[1], F. Pegoraro[1], S.V. Bulanov[2]

[1]*Phys. Dept. and INFM, Pisa University, Italy;* [2]*General Phys. Inst., RAS, Moscow, Russia*

Abstract. With the help of “open boundary” 1-D 1-V Vlasov simulations, we investigate the collisionless dynamics of spatially and temporally localized high energy proton beams crossing a plasma foil and of the self-consistent electrostatic fields they generate. We consider both charge compensated and non compensated beams and study the neutralization of the beams, their density change when crossing the foil, their energy losses and their spreading in space and energy.

Highly collimated beams of energetic protons have been shown to be produced during the interaction of ultra-intense ultra-short laser pulses with overdense plasmas [1]. These proton beams are expected to have important applications ranging from ion fast ignition [2], to proton imaging [3], to localized energy deposition in biological tissues [4]. Depending on the specific process of ion acceleration [5] in the laser plasma interaction, the proton beams that are generated may be essentially neutral (charge compensated) or may be initially strongly charged. The beam properties are then effected depending on whether the beam propagates in an evacuated region, such as inside a plasma channel, or inside an electron cloud where the beam becomes charge neutralized. At the electron plasma relativistic energies and ultrafast time scales that are involved in these processes, both inductive electromagnetic fields and electrostatic fields due to charge separation are important in determining the dynamics of the proton beam.

Here we present a first simplified one dimensional numerical analysis of a model problem where a (non relativistic) high energy proton beam propagates in a one-dimensional plasma configuration. Only electrostatic effects are taken into account. The beam, which is initiated in vacuum and is either fully charged (no electrons) or fully compensated (as many electrons as protons), interacts with a plasma foil with density much larger than that of the beam. We consider plasma regimes where collisional (and ionization) effects are negligible. The simulations are performed with an "open boundary" Eulerian scheme for solving the Vlasov equation that has been explicitly developed in order to study plasmas with a transient influx of particles and/or energy. The main physics processes to be investigated in the case of a pure proton beam are the sweeping of a fraction of the plasma electrons by the moving electric potential of the proton beam, the dynamics of these electrons after they are extracted from the foil and propagate with the beam and the spreading of the proton beam in space and energy. Our numerical simulations indicate that, after crossing the foil, the proton beam charge is on average neutralized by a cloud of electrons which move with the proton beam and oscillate at the local beam plasma frequency. In the case of a neutralized beam the main physical mechanism at play is a beam plasma instability which involves the beam and plasma electrons.

We employ a numerical code that integrates the Vlasov-Poisson system of equations for a two component plasma in the 1D-1V phase space in the non relativistic limit:

$$\frac{\partial f_a(x,v,t)}{\partial t} + v\,\frac{\partial f_a(x,v,t)}{\partial x} - \Lambda_a \frac{\partial \phi}{\partial x}\frac{\partial f_a(x,v,t)}{\partial v} = 0; \quad a = e,\, i \tag{1}$$

$$\partial^2\phi/\partial x^2 = \int f_e(x,v,t)\,dv - \int f_i(x,v,t)\,dv; \quad E = -\partial\phi/\partial x \tag{2}$$

where all quantities are normalized with a characteristic density $\bar{n}$, the electron mass m_e, the Debye length λ_{De}, the inverse of the plasma frequency ω_{pe}^{-1} and a characteristic electric field $\bar{E} = m_e \omega_{pe} v_{th,e}/e$. Here $v_{th,e}$ is the electron thermal speed and $\Lambda_a = Z_a m_e/m_a$. We adopt the following boundary conditions: $f^>(v) = given$ for $v \geq 0$; $\phi = 0$; $at\ x = 0$ $f^<(v) = given$ for $v \leq 0$; $\frac{\partial \phi}{\partial x} = 0$; $at\ x = L_x$. The last condition, corresponds to $E = 0$ at $x = L_x$ and is valid until the fast particles reach the right boundary. At that moment the simulation is stopped. This condition implies that no electric field is generated by the proton beam in front of itself, as consistent with the causality requirement. In this model the proton beam is thought to originate from a neutral source outside the simulation box which is left negatively charged as the beam propagates. This negative charge outside the simulation box ensures that, in the 1D configuration considered here, the electric field due to the beam vanishes in front of the beam. The numerical algorithm adopted in these simulations, including the boundary conditions strategy, is described in Ref. [6]. We take $\Lambda_i = 1/1836$ and $L_x = 3000\,\lambda_{De}$. The initial conditions correspond to an electron-ion plasma slab with $T_e = T_i$ and centered at $x = 400$. The density of the slab in constant (and equal to 1) on an interval 270 Debye lengths wide with two ramps of 40 Debye lengths. The temperatures of the electrons and ions in the plasma slab are equal. From the left boundary we inject a Gaussian proton beam (together with an equally shaped electron beam in the charge neutralized case) 80 Debye lengths wide with mean velocity $u_0 = 5\,v_{th,e}$ maximum density $5 \cdot 10^{-2}$ and temperature half the plasma slab temperature. The transit time of the beam through the slab corresponds to approximately 10 Langmuir oscillation periods (calculated with the slab plasma density). The initial plasma configuration is not a Vlasov equilibrium and the electrons expand into the vacuum region creating a charge separation at the plasma vacuum interface which slows down the electrons leading to an ambipolar expansion of the plasma. However, due to the large beam velocity adopted in this model, the plasma expansion is slow compared to the beam propagation. Neglecting kinetic and thermal effects, the linearized response of the electrons in the slab to the non compensated beam is given by

$$\ddot{\xi} + \xi = -E_{beam}(x,t). \tag{3}$$

where $\xi(x,t)$ is the normalized displacement of the fluid element and $E_{beam}(x,t)$ the field carried by the beam. In the limit where the ramp up time of the electric field carried by the beam is longer than ω_{pe}^{-1} we have $\xi \approx -E_{beam}(x,t)$ i.e., the proton beam is neutralized as it enters the slab. This is shown in Fig. 1 (upper frames) where the electron and proton densities and electric field distribution are shown at $t = 90$. For the chosen parameters the proton beam is not strongly slowed down and it emerges from the slab propagating in vacuum with velocity $u \simeq 4.92$ at $t = 550$ together with the neutralizing electrons as shown in Fig. 1 (lower frames) at $t = 550$. The total number of protons in the beam is practically equal to that of the initial beam (before entering in the slab), $n_b^{t=550} = 0.997\,n_b^{t=45}$, and to the number of electrons travelling with the beam. The width and maximum density in the beam are close to their initial values and the beam temperature is nearly constant. The electron density in the beam is modulated by Langmuir oscillations (at the beam plasma frequency) that decay as the beam propagates due to phase space mixing, as shown in Fig. 2 at $t = 425$. Some protons are eventually reflected from the plasma slab to compensate for the lost electrons. In the case of the compensated beam the velocity difference between the beam and the plasma electrons inside the slab excites a fast growing electron beam instability that causes strong Langmuir oscillations (at the slab plasma frequency) as shown in Fig. 3 (upper frames) at $t = 136$. These oscillations slowly damp as the beam propagates out. The proton beam emerges from the slab and propagates in vacuum with nearly the initial velocity, $u_0 = 5$, together with the neutralizing electrons, as shown in Fig. 3 at $t = 540$ (lower frames). The proton beam spatial spreading is slightly smaller than in the non compensated case. The beam temperature is slightly decreased, $T_b^{fin} = 0.92\,T_b^{init}$. As in the previous case the electron density in the beam exhibits fluctuations at the beam plasma frequency. The total number of protons in the

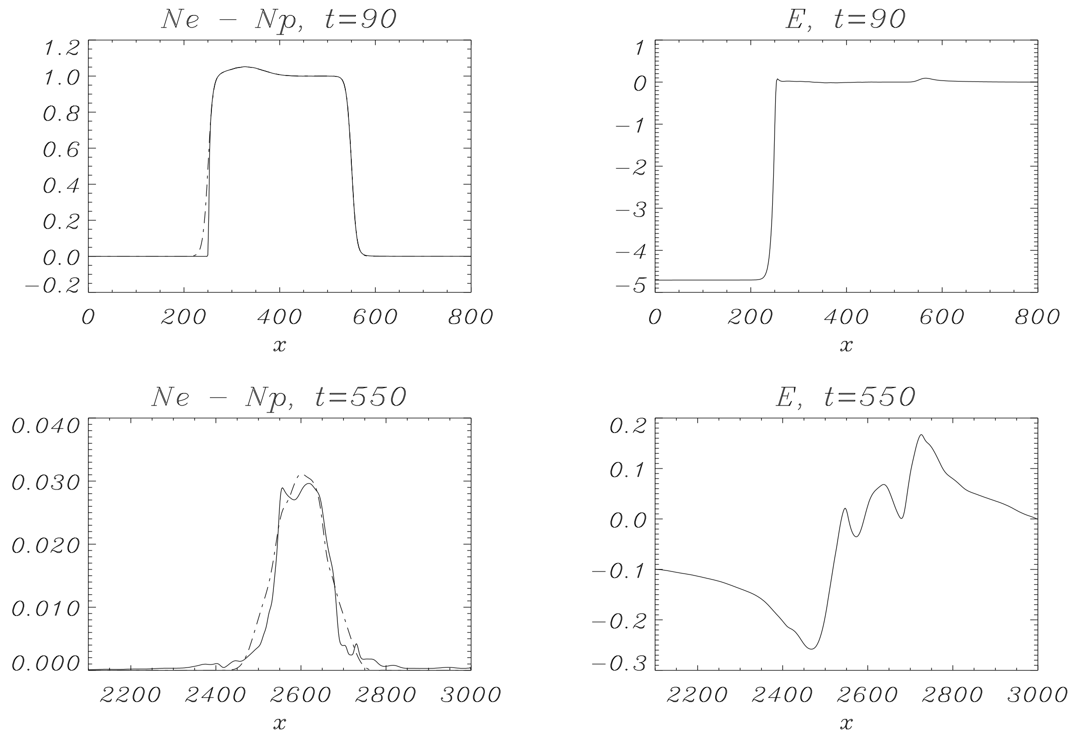

Figure 1: Interaction of a non compensated proton beam with a plasma foil. The electron and proton densities (continuous and dash-dotted lines) and the electric field at $t = 90$ for $0 < x < 800$ (upper frames) and at $t = 550$ for $2100 < x < 3000$ (lower frames).

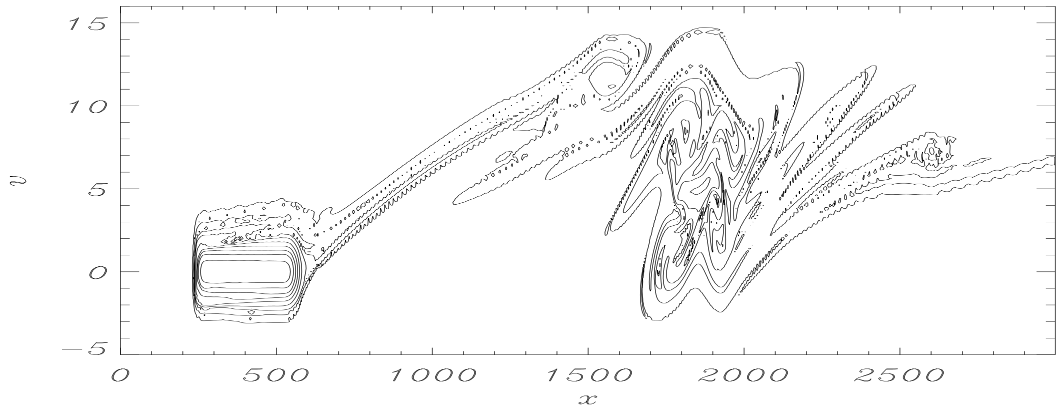

Figure 2: The electron distribution in phase space at $t = 425$ in the case of a non compensated proton beam interacting wih a plasma foil.

transmitted beam is equal to the total number of injected protons. The effect of the Langmuir oscillations on the electron distribution function in the slab and in the beam is shown in Fig. 4 at $t = 410$. These numerical experiments show that an open boundary Vlasov code can be conveniently employed in order to investigate the electrostatic interaction of a spatially and temporally localized particle beam with an inhomogeneous plasma, and to study the process of beam neutralization and beam propagation after leaving the plasma. The problem of the increase of the beam energy spread during the processes of propagation and neutralization is of particular importance for practical beam applications where good quality beams are required.
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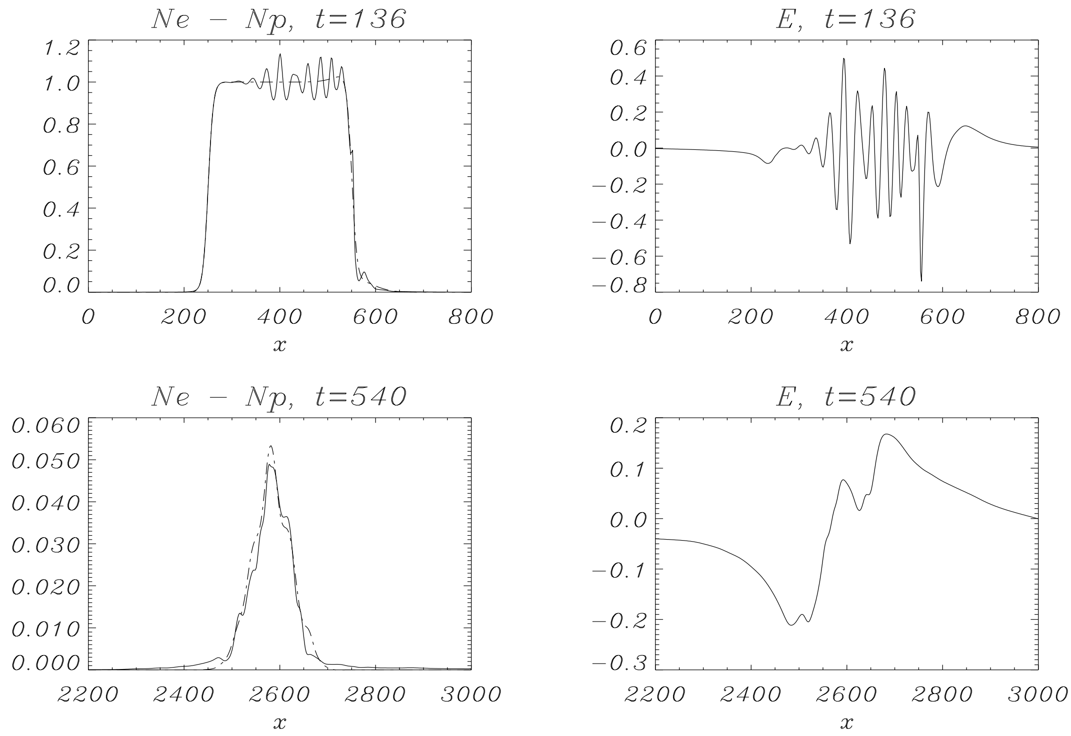

Figure 3: Interaction of a compensated proton beam with a plasma foil. The electron and proton densities (continuous and dash-dotted lines) and the electric field at $t = 136$ for $0 < x < 800$ (upper frames) and at $t = 540$ for $2100 < x < 3000$ (lower frames).

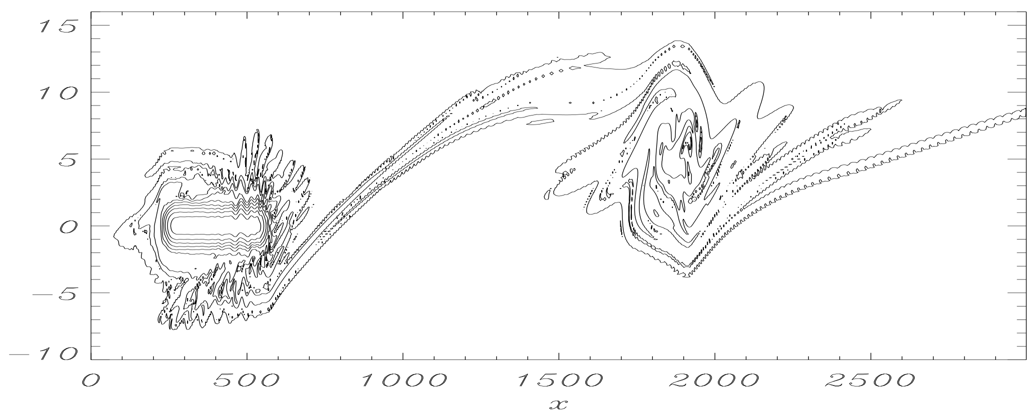

Figure 4: The electron distribution in phase space at $t = 425$ in the case of a compensated proton beam interacting wih a plasma foil.

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