Ions acceleration driven by prompt electrons emission in ns-laser generated plasma at moderate intensity I=10^{12} W/cm^2

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Abstract - Prompt electrons, plume fragmentation in a multi-layers structure and the existence of a double electron temperature inside the plasma bulk surviving to the plume expansion phase were observed from the data of a recent experiment in which a laser beam was focalized on a pure Aluminum target at power density of the order of 10^{12} W/cm^2.
These simultaneous observations, new in this range of intensity, clearly show the existence of ions bunch accelerated by the direct prompt electrons emission.

1. Introduction - When any material is heated to a sufficient degree, its constituent atoms separate into negative electrons and positive ions. This state of matter is called plasma and has unique properties that make it an attractive medium for particle acceleration. Conventional accelerator cavities can only sustain accelerating field gradients of the order of 10^6 V/m, as they are limited by the electric breakdown of the accelerator materials. Plasmas are already broken down and so the accelerating fields are not limited by this effect. Plasmas exhibit quasineutrality, i.e. the negative charge density of the electrons is equal to the positive charge density of the ions. Any significant separation of positive and negative charge is accompanied by strong electrostatic restoring fields. These transient fields are of interest as compact ultrahigh-gradient accelerating structures. Cutting edge laser technology is capable of producing pulses of light focusable to intensities of 10^{21}-10^{22} W/cm^2. At these intensities the laser's electric field rips electrons from their atomic orbitals and accelerates them to highly relativistic energies. These extremely energetic electrons propagate through the surrounding material, causing further plasma formation. Recent studies have indicated that ions can be efficiently accelerated during such interactions via several mechanisms [1-6], the most studied acceleration mechanism is known as Target Normal Sheath Acceleration [7].

Recently, new experimental data [8,9] at laser power density of the order of 10^{12} W/cm^2, have shown the existence of prompt electrons componet and plume fragmentation in a multi-layers structure. In figure 1-left are reported the Time Of Fligth (TOF) signalas measure by a not biased Lamgmuir probe, when the probe was located from 2.5 mm up to 14.5 mm from the target surface. The negative part, labeled as "*ph-e*", do not depend on the probe position: it exhibits the same temporal width of the laser pulse, that was fixed as zero time of the TOF spectra, and it is due to the photo-excitation of the probe tip. Figure 1 reveals that an additional negative excess of current at d=2.5 mm has been detected. This signal is due to a very fast prompt electrons bunch. In figure 1a we note also a "fragmentation" of the plasma signal: measurements feature primarily a series of positive ion bunches with decreasing amplitudes, characterized by an uncoupled dynamics with respect to the remaining part of the plasma, and then what we called the "plasma core". Plasma core expands at much lower velocity than bumps, as confirmed by the second part of the experiment, and its behavior is reproduced by hydro-dynamical simulations [8]. The estimated energy of electrons and ion bunches is reported in fig. 2.

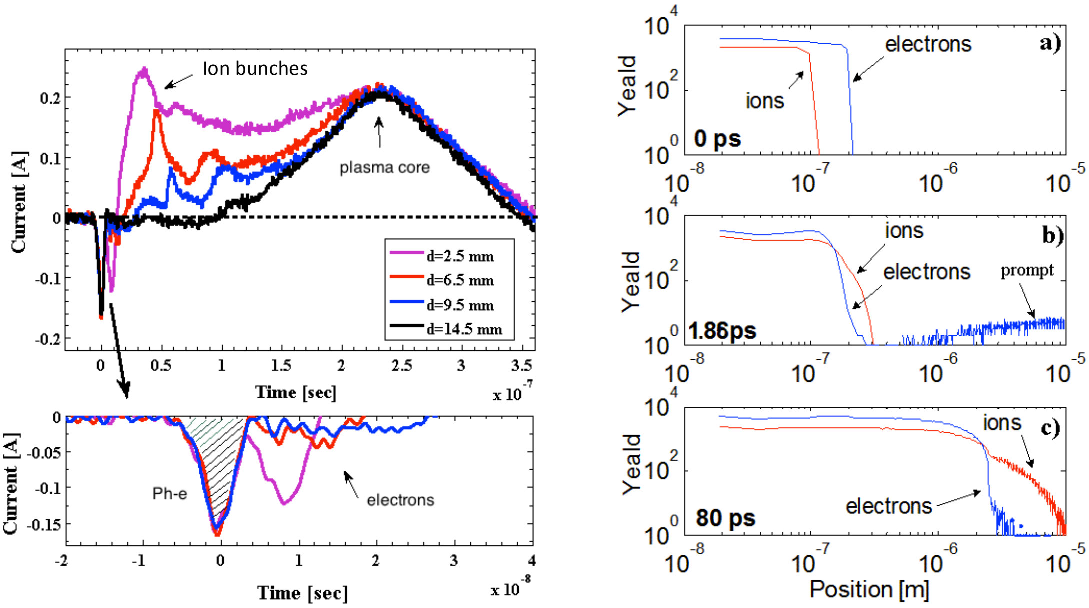

Figure 1. **Left** - a) Time of Flight signals obtained when the probe was located from 2.5 mm up to 14.5 mm far from the target surface. b) Prompt electrons signal. **Right** - PIC simulations on 1D lattice for our plasma with an initial spatial ions-electrons displacement. Ions and electrons density at different time steps a) t=0, b) t=1.86 ps; c) 80 ps.

All these simultaneous observations, new in this range of intensity, point out the existence of ions bunch accelerated by the direct prompt electrons emission. In order to understand the fundamental mechanisms responsible for such observations a series of numerical simulations were performed by using the so-called particle-in-cell (PIC) method [10] over a 1D lattice.

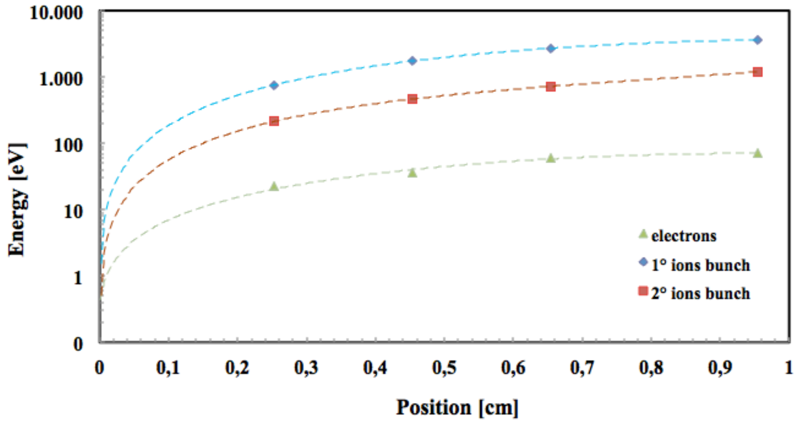

Figure 2. Energy of Ion bunches and electrons as function of detector position.

2. PIC Simulation - This method, based on mean field approximation, neglects individual close collisions between particles, while is able to estimate the influence of the Coulomb interaction in the expanding plasma cloud. The plasma flow was treated as having basically 1D behaviour and an idealised model of thermal evaporation from the target surface at constant temperature was inferred. In particular a constant evaporation flux approximation was adopted and the evaporated particles were assumed to be instantaneously ionised.

The evaporation follows a preformed plasma sheet extending on the lattice for several Debye lengths ($x_L=10\div20\ \lambda_D$). A spatial displacement between electrons (prompt) and ions was used as initial condition to simulate the time difference in their emission. In particular, initial ions and electrons density distributions were given by two Fermi distributions:

$$F_e(x) = N_e[e^{\frac{x-x_L}{d_e}} + 1]^{-1} \ , \ F_i(x) = N_i[e^{\frac{x-x_L}{d_i}} + 1]^{-1}$$

where N_e and N_i are the initial number of electrons and ions in the plasma sheet ($N_e = z_i N_i$, where z_i is the ion i-th charge state), while the parameters d_e and d_i regulate the electrons-ions spatial displacement (if $d_e = d_i$ there is no displacement). Ions at different charge states have been included in the simulation, following a gaussian-like distribution peaked on the value $<Z>=4+$. During the simulation, the initial quasi-neutrality is maintained only globally and not locally, by introducing the same amount of negative and positive charge into the 1D lattice. Finally, the initial velocity distributions of both electrons and ions in plasma sheet and plasma flow were assumed to be shifted-Gaussians, corresponding to a single initial temperature extracted from experimental data (of the order of 10^2 eV). The mean velocity of the adiabatic expansion was estimated through the following relation: $v=(\gamma KT_e/M_i)^{1/2}$ [8].

In Figure 1-Right we present the numerical results for the plasma's initial time evolution.

Fig. 1-r a) illustrates the initial electrons-ions displacement (t=0ps), with the non-neutral layer of prompt electrons in the plasma front. Fig.1-r b) shows the plasma evolution after 0.1 ps, featuring a tail of fast escaping electrons whose dynamics are decoupled from the rest of the plasma plume. Finally, in fig.1-r c) (at t = 80ps), it is evident that the expulsion of the prompt electrons has produced a non-neutral positive layer in the plasma front.

The structure of the non-neutral positive layer moving on the plasma front evidence the acceleration of the high charge states. The latter are characterized by higher velocity and placed ahead with respect with the lower charge states. Simulations feature that the acceleration of ions is not driven by the prompt electrons, but it is more the result of the reciprocal repulsion among the layers of different charge states. According to this picture, the fragmentation is driven by directly fast laser expelled electrons from the target surface, and proceeds because of reciprocal ion repulsion, similarly to the physical mechanism of TNSA [7].

In conclusion, the ion acceleration and plume fragmentation evolve following different stages which can be summarized in the following way: *i)* prompt electrons escape from the target quite soon, but not before they have repelled the electrons which populate the rest of the plasma; *ii)* the ions behave like a background layer: since they are extremely massive; *iii)* the compression of the electrons of the bulk creates the non neutral, positive layer in the plasma front (the ions are not ready to react to the abrupt quasi-neutrality violation); *iv)* the prompt electrons flow at much larger velocity than the bulk plasma, so that they disappear from the simulation lattice; *v)* ions can react to the charge separation in a time of the order of 100 ps, so that they remain substantially not affected by the prompt electrons escaping; *vi)* a non-classical double layer is thereby formed: ions stay in the plasma front, while electrons follow. The reciprocal repulsion inside the positive layer produces the fast expulsion of the positive front, which non-linearly fragments in a plurality of positive bunches populated by the highest charge states.

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