

Ponderomotive ion acceleration in underdense and overdense plasmas

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Ponderomotive ion acceleration (PIA) in laser-plasma interactions occurs when the ions are accelerated by an electrostatic (ES) force which balances the secular ponderomotive force (PF) on electrons, $e\mathbf{E} \simeq \mathbf{F}_p = -m_e c^2 \nabla \sqrt{1 + |\mathbf{a}|^2}$, being $\mathbf{a} = e\mathbf{A}/m_e c$ the dimensionless amplitude of the laser pulse. In this sense it has to be distinguished by the cases of sheath acceleration driven by hot electrons or of the “Coulomb explosion” driven by the space-charge field of the ions themselves, which also occur in various interaction regimes.

We have investigated PIA and the related electric field dynamics following the self-channeling of an intense laser pulse in an underdense plasma. Fig.1 shows a two-dimensional (2D), electromagnetic (EM) particle-in-cell (PIC) simulation of the interaction of a laser pulse with wavelength $\lambda_L = 1 \mu\text{m}$, duration $\tau_L = 450 \text{ fs}$, intensity $I_L = 5 \times 10^{18} \text{ W cm}^{-2}$ with a

preformed, underdense He ($Z = 2$, $A = 4$) plasma with peak electron density $n_e = 0.1n_c$, being $n_c = 1.1 \times 10^{21} \text{ cm}^{-3}$ the cut-off density. The pulse propagates from the left side and is linearly polarized along z , i.e. perpendicularly to the simulation plane. We observe the formation of a charged channel due to the PF-driven displacement of electrons from the axis. The electrostatic field (E_y) changes qualitatively around the pulse peak: two narrow ambipolar fronts are observed. This field pattern is found to agree with time-resolved experimental measurements of the electric field dynamics, obtained with the proton imaging technique [1].

We found that the experimental measurements are well reproduced by a simple 1D, electrostatic (ES) PIC simulation in cylindrical geometry (r, p_r) where the laser pulse action is included solely by the PF corresponding to a pulse profile $a(r, t) = a_0 e^{-r^2/r_0^2} f(t)$, being $f(t)$ the pulse en-

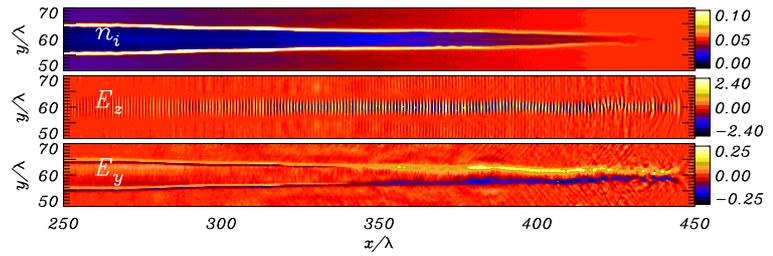


Figure 1: Electromagnetic 2D PIC simulation of laser interaction with an underdense plasma. The contours of ion density n_i (top), laser electric field E_z (middle) and electrostatic field E_y (bottom) are shown.

velope [1]. This model has then been used for a wider range of parameters to investigate radial PIA in underdense plasmas.

Fig.2 shows snapshots of a typical simulation. The parameters are $\lambda_L = 1 \mu\text{m}$, $r_0 = 3\lambda_L$, $a_0 = 4.5$ i.e. $I_L = 2.8 \times 10^{19} \text{ W cm}^{-2}$, $\tau_L = 1 \text{ ps}$ and $n_e = 10^{20} \text{ cm}^{-3}$. The dynamics can be described as follows. In the first stage, the radial PF instantaneously pushes part of the electrons outwards, creating a positively charged channel along the axis and a radial ES field which holds the electrons back. At this stage, in the simulation shown, the ES force balances almost exactly the PF. At a later stage, the radial electric field accelerates the ions in the channel. For $r > r_{max}$, being r_{max} the position at which the PF force has a

maximum, the ions feel a force which decreases with the radius, and thus they tend to pile up in the outer region of the focal spot, i.e. where the PF vanishes, producing a sharp peak of the ion density and finally leading to hydrodynamical breaking. At breaking, the fastest ions (with typical energies of a few MeV in the investigate range $a_0 = 1 - 3$) overturn the slowest ones and form a well-localized bunch which moves ballistically in the region outside the channel. These fast ions may correspond to the high-energy tail in the ion distribution which has been inferred in experiments for similar parameters [3, 4]. After breaking, we also observe a local inversion of the ES field, that produces a characteristic feature in the proton imaging data [1], and the return of a few ions along the axis channel producing a local density maximum there, that also agrees with experimental observations [5] and 2D EM simulations.

For high pulse intensities, complete depletion of electrons in a region around the axis can occur. This acts as a saturation mechanism for PIA, since the electric field cannot grow beyond the value of the field generated by the ions alone, without screening by the electrons. This can also be described as a transition from PIA to the Coulomb explosion regime: ions in the depleted region will be accelerated by their own space-charge field.

The dynamics of ion acceleration and bunch formation in the underdense plasma is indeed very similar to the case of ‘‘longitudinal’’ ponderomotive acceleration described in Ref.[2]. In this case, a laser pulse with circular polarization impinges at normal incidence on an over-

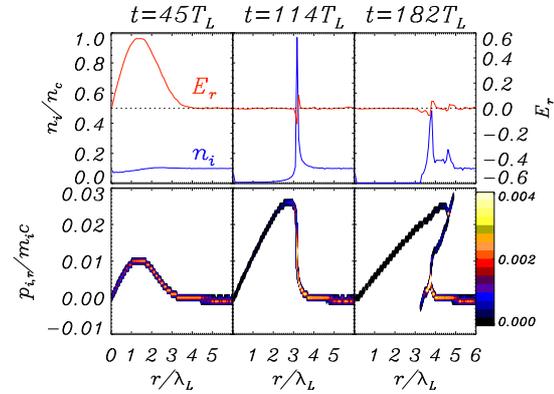


Figure 2: Electrostatic 1D PIC simulation of radial PIA. Top row: ion density. Bottom row: ion phase space. T_L is the laser period.

dense plasma and produces a short, dense bunch of fast ions. The use of circular polarization inhibits fast electron generation [2] and thus cuts sheath acceleration off, leading to a pure PIA.

Fig.3 shows results from a 1D EM simulation where a circularly polarized pulse with peak amplitude $a_0 = 2.0$ and 6 cycle duration, corresponding to $5.5 \times 10^{18} \text{ W cm}^{-2}$ and 20 fs for $\lambda_L = 1 \mu\text{m}$, impinges on a plasma slab of protons ($Z/A = 1$) with initial electron density $n_e = 5n_c$. The electron longitudinal momenta are nearly two orders of magnitude lower than the vacuum “quiver” momentum, i.e. the typical value of the “fast” electron momenta observed for linear polarization. An ultrashort, dense bunch of ions with energy up to 0.45 MeV is generated. Present-day or at least near-term laser systems yielding ultrashort (few cycles) pulses at $I \sim 10^{20} \text{ W cm}^{-2}$ may allow the production of femtosecond, solid-density ion bunches which may be useful for specific applications, such as the development of sources of fusion neutrons with similar or even shorter duration [6].

We evaluate the absorption efficiency and the ion spectrum obtained using circular polarization (CP) with those obtained for the linear polarization (LP) case with same plasma parameters, same pulse duration and same pulse energy (thus, the peak field amplitude is lower by a factor $\sqrt{2}$ in the CP case). The simulated case ($\lambda = 1 \mu\text{m}$, $I_L = 3.5 \times 10^{20} \text{ W cm}^{-2}$, $\tau_L = 86 \text{ fs}$, $n_e = 10^{22} \text{ cm}^{-3}$, $Z = A = 1$) is identical to that investigated in Ref.[7] to address ion “shock” acceleration. We find that the energy conversion efficiency into bunch ions is 13.7% for CP and it is considerably higher than the conversion value for the “shock” accelerated ions observed for LP. The comparison of the two spectra

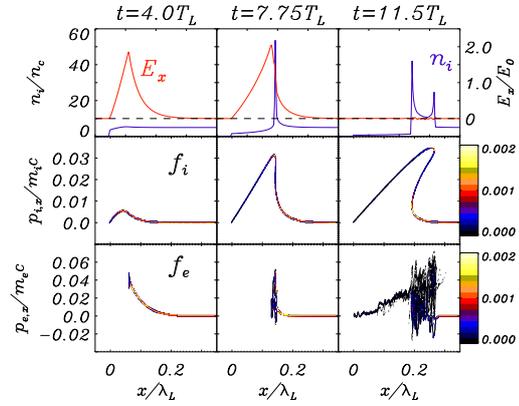


Figure 3: Electromagnetic 1D PIC simulation of longitudinal ion acceleration by a circularly polarized pulse. Top row: ion density; middle row: ion (x, p_x) distribution; bottom: electron (x, p_x) distribution. The laser pulse impinges from the left side.

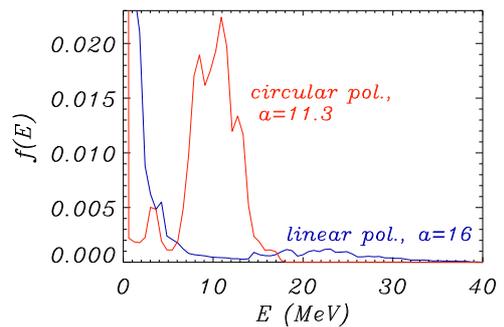


Figure 4: Comparison of ion energy spectra from 1D PIC simulations of ion acceleration with LP or CP pulses for the same plasma and laser parameters.

are given in Fig.4. We find that the CP spectrum is quite narrow and peaked around 10 MeV, while already in 1D geometry (i.e., without a spatial inhomogeneity of the pulse intensity) the LP spectrum is nearly thermal as the result of sheath acceleration by fast electrons at the plasma boundaries. Moreover, 2D PIC simulations show that for CP the divergence of the ion “beam” is low and that 2D effects, such as pulse focusing, as well as the presence of an inhomogeneous preplasma do not compromise ion bunch generation. It has to be stressed that the PIA mechanism based on CP, as described in Ref.[2], is physically different from the “shock” acceleration mechanism of Ref.[7].

We conclude by noting that, to our knowledge, preliminary results of ion acceleration with circular polarization have been reported just in one publication so far [8]. On the basis of our theoretical investigations we believe that ion acceleration using circularly polarized pulses is worth of experimental investigation and may find specific applications.

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