

ENERGY AND ANGLE FEATURES OF THE ACCELERATED ELECTRONS AND IONS IN THE INTERACTION OF A ULTRA-INTENSE LASER PULSE WITH AN OVERDENSE PLASMA

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The development of short pulse ultra-intense lasers [1] over this decade has triggered a considerable interest in the effects which arise from the interaction of intense radiation with a plasma. Nowadays, more than 10 Joules in less than 1 picosecond at 1 μm wavelength can be focused to provide laser irradiances up to 10^{20} W/cm^2 . Even though many applications are already envisioned, the understanding of the processes underlying the laser-matter interaction is unmaturing. A solid target located at the laser focus is rapidly ionized, leading to a free electron density of order 10^{23} cm^{-3} , well above the critical density n_c (cm^{-3}) = $10^{21}/\lambda_0^2$ (with λ_0 the laser wavelength in μm) below which, according to classical dynamics, the plasma is transparent. The electron dynamics is actually relativistic, with transverse momentum (normalized to $m_e c$, where m_e is the electron mass and c the velocity of light in vacuum) $a_0 = 0.85 (I_{18} \lambda_0^2)^{1/2}$; I_{18} denotes the laser irradiance in 10^{18} W/cm^2 . The intricate motion of the electrons at the target surface causes efficient laser absorption into high density bursts of MeV electrons penetrating the solid target. These hot electron jets have been proposed as additional heating sources for inertial confinement fusion targets [2]: this so-called fast ignitor concept is a major potential application, which present studies try to validate by parts.

This paper reports on three specific studies from multi-dimensional numerical simulations: (i) electron acceleration, (ii) ion acceleration and the correlated neutron signature, and (iii) transport through a dense plasma, such as the plasma surrounding the inertially confined fuel. In part (ii), a deuterated target is assumed: the fast deuterons are energetic enough to inelastically collide with the immobile deuterons and produce fast neutrons, which can be used as an efficient diagnostic of MeV charged particles. Part (iii) pinpoints the competition between the diffusion induced by the electron/ion collisions and the pinch caused by the electron-current-driven magnetic field. The results reported herein complement previous studies on the self-induced transparency of a plasma, caused by the relativistic increase of the electron mass [3] and on electron heating for both infinite [4] and finite mass ions [5,6].

The strongly nonlinear behavior of the plasma imposes use of kinetic models. For parts (i-ii), the plasma is modeled by means of electron and ion momentum distributions, whose charges compose an electrically neutral medium, and which evolve according to the

relativistic Vlasov equation with self-consistent fields. The fields are computed from Maxwell equations, with the plasma charges and currents as sources. The plasma can be considered collisionless since the quiver motion along the laser electric field makes the electron-ion collision frequency much weaker than the electron plasma frequency. The Vlasov equation is solved with a particle-in-cell (PIC) method, using the two-dimensional planar-geometry code MANET, running on a parallel Cray T3E computer. For part (ii), the generation of neutrons has been studied with a post-processor of MANET, for the specific case of a deuterated target. Ion slowing down, and neutron production by the reaction $D + D \rightarrow n + He + 3.6 \text{ MeV}$ are modeled via tabulated experimental cross sections [7]. In part (iii), the transport of electrons in the dense target has been studied with a simplified 3D PIC model: we only considered the two-component transverse magnetic field, calculated from Maxwell-Ampère equation. No space-charge electric field is included, since the electron beam charge is neutralized by the plasma ions, whose density remains larger than the electron beam one. Elastic electron-ion collisions are modeled by a stochastic rotator; the inelastic collisions due to plasma electrons and ions are represented by a drag term.

Figure 1 displays the density map from MANET for a slightly overdense plasma ($4n_c$) with a linear density ramp, after 0.45 ps time of interaction. Electron cavitation and electron mass increase let the laser bore a $24 \lambda_0$ long channel into the plasma. The angular diagram of the average kinetic energies of the fast electrons accelerated in the channel peaks at 1 MeV in the forward direction. This energy is below the ponderomotive potential Φ_p (MeV) = $0.51 (\sqrt{1+a_0^2}-1)$ (i.e. 2.6 MeV for our conditions), contrasting with the first results [8]. Actually, we have observed that the larger the area where the interaction takes place, the more energetic the electrons, approaching Φ_p .

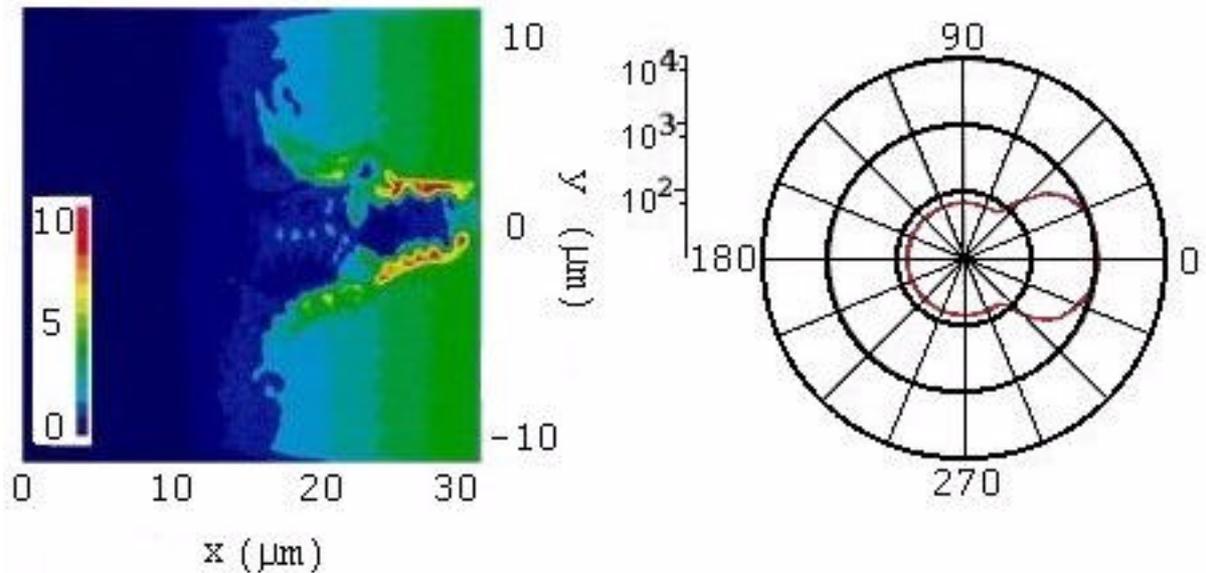


Figure 1. (left) electron density map and (right) polar diagram of the average kinetic energies of the fast electrons (kinetic energy in excess of 100 keV). $\lambda_0 = 1 \mu\text{m}$, $I_{18} = 51$, $n_e/n_c = 4$, ion mass $m_i/Zm_e = 3672$ (Z is the ion charge number). Gaussian focal spot with FWHM = $6 \mu\text{m}$. Bell-shaped time profile with FWHM = 0.25 ps. Display time = 0.45 ps.

The simulations have evidenced two kinds of accelerated ions: the ones which are radially expelled from the beam center by the lack of negative charges induced by the electron cavitation, and the ones which bounce on a collisionless propagative shock [9]. When thermal ions are passed by the shock front (characterized by a large electric potential jump Φ), those with kinetic energies (in the shock frame) below $e\Phi$ are reflected; initially immobile ions can then be accelerated to twice the shock front velocity, as if pushed by a piston. The behavior of this ion wave is crucially dependent on the effective electron temperature at the shock location.

If the target is deuterated, the accelerated D ions can collide with target ions and create neutrons. This could be the basis of a high-energy threshold diagnostic of laser-plasma interaction. In Fig. 2, the polar diagrams of the ion energies show two different shapes: for the conditions of Fig. 1 (top), ions have a very large energy, up to 4 MeV and 10^8 neutrons are produced with anisotropy 1:2 for 0:90 degrees. This is the signature of radially expanded ions. By contrast, when the density is $50 n_c$, for a slightly lower irradiance, the fast ions are

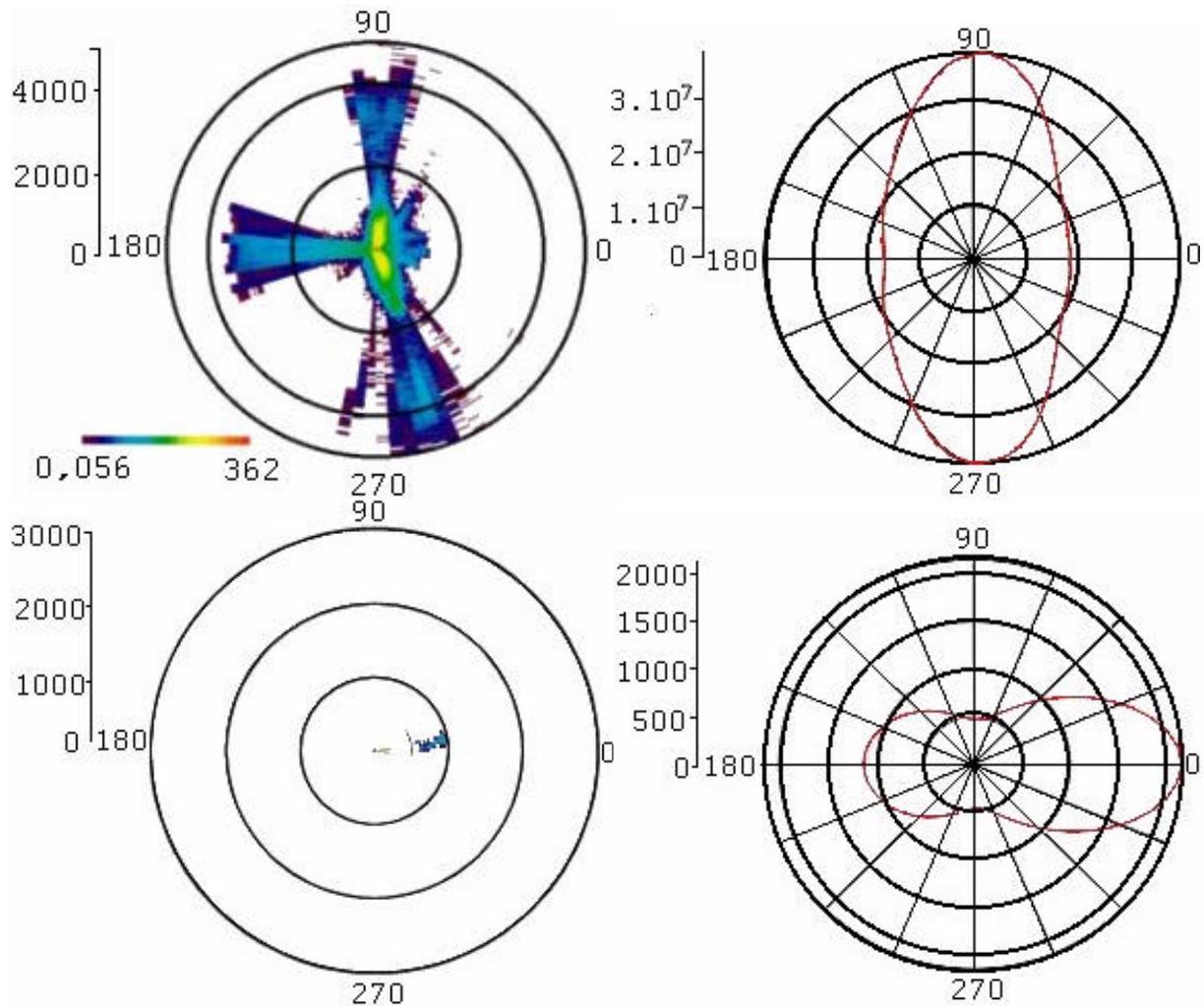


Figure 2. (Left) angular diagram of the ion energies from PIC simulations and (right) neutron production given by the post-processor. Top: conditions of Fig. 1. Bottom: $I_{18} = 35$, $\lambda_0 = 1 \mu\text{m}$, $n_e/n_c = 50$, $m_i/Zm_e = 3672$, $6 \mu\text{m}$ FWHM Gaussian focal spot. Flat time profile. Display time = 0.15 ps.

less energetic and more collimated; only 10^4 neutrons are observed with anisotropy 2-3:1, over 0.15 ps. For comparison, in recent experiments performed on the P102 laser at CEA/Limeil [10], 10^6 neutrons/sr along the laser axis were measured, with 2-3:1 anisotropy for 0:90 degrees, in the same range of irradiance with 0.35 ps FWHM pulse.

To model electron beam propagation, the relativistic Fokker-Planck equation is solved analytically via Langevin equations. The electrons appear to slow down and scatter on the same time scale. In Fig. 3 (left), analytical calculation show that 1 MeV electrons are transported over 120 μm in a density profile typical of a fusion target (the density increases exponentially from 10^{21} to 10^{25} cm^{-3}); inclusion of the pitch angle reduces this distance by 5 μm only. The right-hand picture illustrates the propagation of a 1 MeV electron beam, initially collimated in a 2 μm diameter disk. Typically, about 1 MA will flow inward into the target, but we assume that the current is rapidly neutralized by return electrons. The effective current inducing the azimuthal B-field is then much smaller. In Fig. 3, an effective current of 30 kA has been chosen. We observe that the self-consistent field increases the electron penetration. Only 10 % of the initial electron energy have been lost in the plasma due to inelastic collisions.

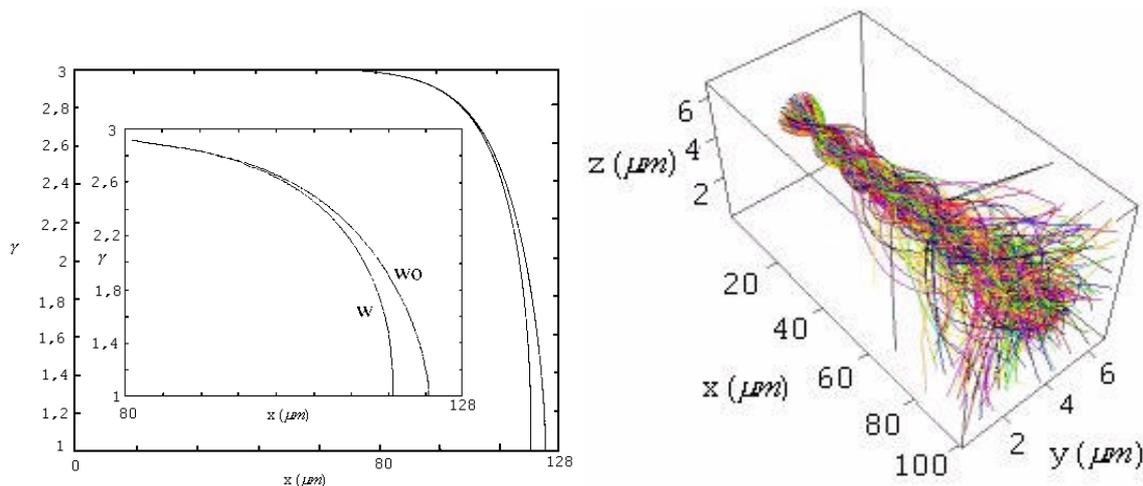


Figure 3. (left) slowing down with and without pitch angle. (Right) simulation of beam transport over 100 μm . The electron density increases exponentially from 10^{21} to 10^{25} cm^{-3} over 100 μm . Atomic number $Z = 1$. The plasma electron temperature is 3 keV.

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