

## Laser acceleration of ion bunches by circularly polarized pulses

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Ion acceleration in the interaction of high-intensity, ultrashort laser pulses with solid targets is currently a major topic in laser-plasma physics. Much experimental and theoretical work has been devoted to mechanisms such as sheath acceleration in the expanding plasma at the back of the target [1] or shock wave acceleration at the interaction surface [2]. These mechanisms are driven by the high-energy “fast” electrons, which for normal incidence of linearly polarized pulses are accelerated by the oscillating component of the  $\mathbf{v} \times \mathbf{B}$  force. For circular polarization of the laser pulse, however, this driving force is switched off and no high-energy electrons are generated. We have investigated the acceleration of ions in this regime [3]. By using 1D and 2D particle-in-cell (PIC) simulations we find that high-density ion bunches moving into the plasma are promptly generated at the laser-plasma interaction surface.

Fig.1 shows results from a 1D PIC simulation where a circularly polarized laser pulse (dimensionless intensity  $a_0 = 2$ ) impinges on an overdense plasma slab (density  $n_e = 5n_c$ ). We identify three stages: a) a charged layer is formed due to the compression of the electrons by the ponderomotive pressure, and the ions are accelerated by the space-charge field and pile up forming a high-density spike; b) the ion density spike “breaks” producing a ion bunch which moves into the plasma; c) while the first ion bunch moves ballistically, secondary bunches may be produced if the laser pulse duration is long enough.

A simple analytical model has been used to explain the basic features of ion bunch production [3]. In the model, a linear profile of the ponderomotive force inside the plasma is assumed; as a consequence, all ions within the region of evanescence of the laser pulse reach the same point

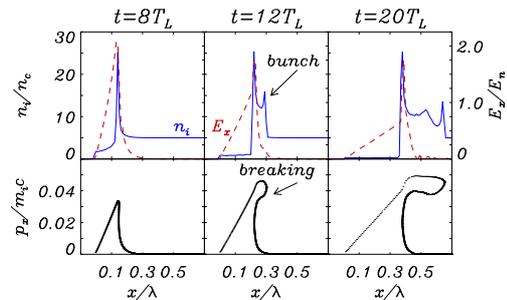


Figure 1: Acceleration of ion bunches (1D PIC simulations). Top: ion density (blue) and electric field (red, dashed); bottom: ion phase space  $(x, p_x)$ . Time is in laser cycle units

at the same time, leading to the “breaking” of the fluid description; qualitatively, this behavior is observed in the PIC simulations (see the phase space plots in the bottom row of Fig.1).

The simple model provides scaling laws for the maximum ion velocity in the bunch and the acceleration time as a function of pulse intensity  $a_L$  and plasma density  $n_e$ :

$$\frac{v_b}{c} \simeq 2 \sqrt{\frac{Z m_e n_c}{A m_p n_e}} a_L, \quad \tau_b \simeq \frac{1}{\omega_L a_L} \sqrt{\frac{A m_p}{Z m_e}}. \quad (1)$$

The maximum velocity  $v_b$  is twice the “hole boring” speed, i.e. the average velocity of the ion front. These estimates are in fair agreement with the results of PIC simulations, as shown by Fig.2 that shows the values of  $v_b$  obtained in simulations versus the theoretical scaling.

Ion bunch formation is also observed in 2D simulations, where it coexists with the bending of the plasma surface (hole boring). Fig.3 shows the density contours from a 2D simulation at three different times. The ions are accelerated almost perpendicularly to the target surface resulting in low divergence. The ion energy spectrum resembles the intensity distribution of the laser pulse. The overall features of the 2D simulations confirm the reliability of the 1D modeling.

It is worth to stress the differences between the present mechanism and shock acceleration (see e.g. Ref.[2]), where the laser pulse acting as a piston drives a shock wave into the plasma which reflects the ions thus accelerated up to velocities twice the shock speed. In the present case the fastest ions have twice the piston velocity, i.e. the velocity of the laser reflection front at the breaking time, and they come from *behind* the front. There are no fast electrons ahead of the shock; the ion bunch drags electrons during its motion through the plasma. It is also worth to notice that the present mechanism of ion bunch formation is of electrostatic and kinetic nature while a purely hydrodynamic description is not adequate.

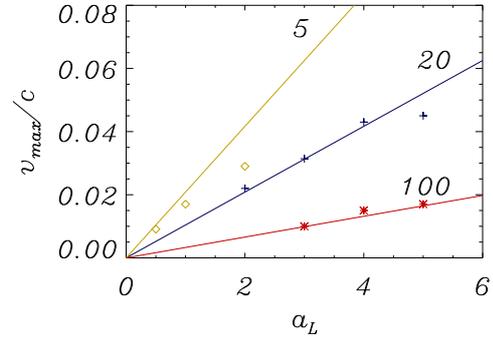


Figure 2: Scaling of bunch velocity vs. the laser pulse amplitude  $a_L$  and the density  $N = n_e/n_c$  (points: simulation data; lines: analytical formula).

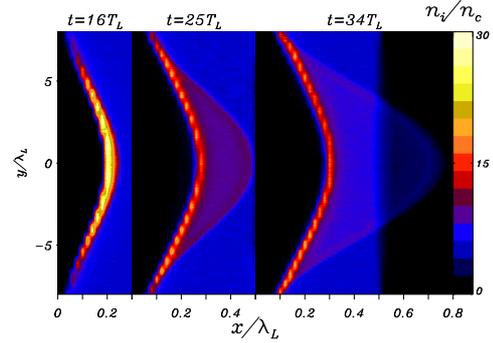


Figure 3: Contours of ion density  $n_i/n_c$  from 2D simulations at three different times. The laser pulse impinges from the left and has a transverse FWHM of  $4\lambda_L$ . Notice the different scales on the  $x$  and  $y$  axis.

The particular features of ion bunches (high density, energy of a few hundreds keV, short duration) make them attractive as a driver for the production of fusion neutrons pulses with ultrashort duration [4]. We have considered a symmetrical, double-sided irradiation of a thin foil deuterated target, where two colliding ion bunches are generated maximizing the energy in the center-of-mass system while minimizing the duration of neutron emission. This experimental geometry is similar to the one of Ref.[5], where a “laser-confined” thermonuclear fusion approach, based on long duration pulses, was proposed, but the laser pulse duration must be much shorter (a few cycles) than in Ref.[5]. Our approach is based on a *beam fusion* concept with emphasis on the ultrashort duration of the neutron emission, and without concerns of target stability. Fig.4 shows PIC simulation results for a two-side irradiation of a thin foil with density  $n_e = n_{i0} = 40n_c$  and thickness  $\ell = 0.05\lambda$ , using pulses with  $a_L = 2.5$  and duration  $\tau_L = 5T_L$  (FWHM). The ion density reaches a maximum value of  $\simeq 35n_{i0}$  with rise and fall times of  $\simeq 0.1T_L$ .

The resulting yield of fusion reactions and the history of neutron emission have been computed from the ion distribution function obtained at any time in the simulation. The results are shown in fig.5 for the two cases of a pure deuterium ( $n_{i0} = 40n_c$ ) and a deuterated plastic ( $CD_2$ ,  $n_{i0} = 250n_c$ ) target. The pulse intensity was  $a_L = 2.5$  and  $a_L = 8$ , respectively, roughly corresponding to the “optimal” values as estimated from analytical modeling [4]. In both cases, a neutron burst with an ultrashort duration of less than one cycle, corresponding to about 0.7 fs (FWHM) for a laser wavelength  $\lambda = 0.8 \mu\text{m}$ , is generated.

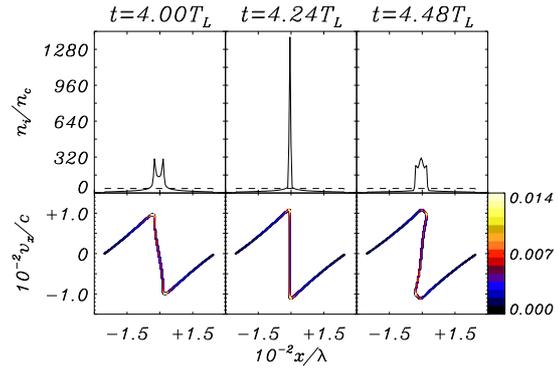


Figure 4: The ion density  $n_i$  (top row, solid line) and the phase space distribution  $f(x, v_x)$  (bottom row) at different times (labels) from an 1D PIC simulation of two-side irradiation of a thin foil. The initial density profile is also shown (dashed line).

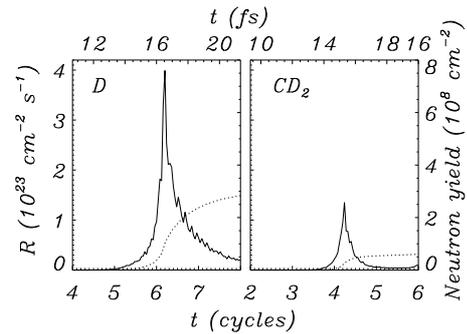


Figure 5: Numerical evaluation of the rate (solid line) and the total number (dotted line) of neutrons produced per unit surface for a “D” (Fig.4) and “CD<sub>2</sub>” targets.

The number of neutrons produced for Joule of the pulse energy is estimated to be  $\sim 10^3 \text{ J}^{-1}$ . This number is roughly one order of magnitude lower than those inferred from experiments with short pulses and various target types (see references in [4]), where, however, the expected duration is likely to be much longer (e.g. not shorter than the laser pulse duration) than in the present scheme.

A possibly simpler approach to a femtosecond neutron source may be based on a single short pulse impinging on a layered target with a thin surface layer of deuterium for ion acceleration and an inner tritium layer to produce neutrons at 14 MeV via the reaction  $\text{D} + \text{T} \rightarrow \alpha + \text{n}$ . If the tritium layer is not thicker than the ion bunch length  $l_b$ , the neutron burst duration might be limited to  $\sim l_b/v_m$ . We estimated that such a scheme might produce  $\sim 10^{10}$  neutrons with 14 MeV energy and a pulse duration of a very few femtoseconds [4].

## References

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