Self-organizing GeV nano-Coulomb collimated proton beam from laser foil interaction

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Circular Polarized (CP) laser pulses can accelerate ions very efficiently and produce sharply peaked spectra [1-3]. When normally incident on plane foils, the light pressure is quasi-stationary, following only the time dependence of the pulse envelope. Electrons are then smoothly pushed into the high-density material without strong heating and ions are taken along by means of the charge separation field. This is in contrast to linear polarization which triggers fast longitudinal electron oscillations and excessive heating.

For appropriate parameters, CP pulses may accelerate foils as a whole with most of the transferred energy carried by ions. The basic dynamics are well described by a one-dimensional (1D) model [3]. Acceleration terminates due to multi-dimensional effects such as transverse expansion of the accelerated ion bunch and transverse instabilities. In particular, instabilities grow in the wings of the indented foil, where light is obliquely incident and strong electron heating sets in. Eventually, this part of the foil is diluted and becomes transparent to the driving laser light. The central new observation in the present paper is that this process of foil dispersion may stop before reaching the centre of the focal spot and that a relatively stable ion clump forms near the laser axis which is efficiently accelerated. The dense clump is about 1 - 2 laser wavelengths in diameter. The stabilization is

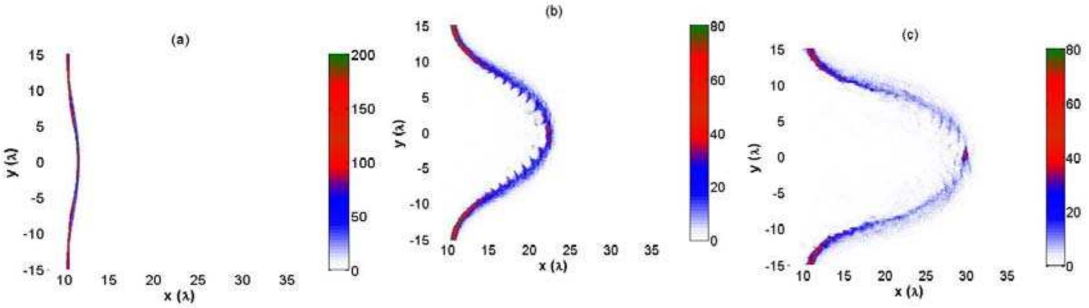

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Fig. 1 Electrons density evolution at times (a) $t = 16$, (b) $t = 36$, (c) $t = 46$, in units of laser period. The laser pulse is incident from the left and hits the plasma at $t = 10$.

related to the driving laser pulse that has passed the dispersed foil in the transparent wing region and starts to encompass the opaque clump, keeping it together. Acceleration is then similar to that studied for so-called ***reduced mass targets*** [4], where small droplets or clusters are used as targets. In what is described below, the new configuration is self-organizing with small pieces of matter punched out of a plane foil. In this Letter, we exhibit this new regime in terms of two-dimensional particle-in-cell (2D-PIC) simulations.

In the simulations, we have taken a CP laser pulse with wavelength $\lambda = 1\mu$m and maximum normalized vector potential $a = eA/mc^2 = 50$, corresponding to an intensity of $I = 1.37\times10^{18}$ W/cm$^2 \cdot 2a^2/\lambda^2$. The pulse has a Gaussian radial profile with 20λ full width at half maximum and a trapezoidal shape longitudinally with 20λ flat top and 1λ ramps on both sides. It is normally incident from the left on a uniform, fully ionized hydrogen foil of thickness $D = 0.5\lambda$ and normalized density $N = n_e / n_{crit} = 80$, where the electron density n_e is given in units of the critical density $n_{crit} = \pi m_e c^2 / \lambda^2$ and c is the velocity of light. Proton to electron mass ratio is $m_p / m_e = 1836$. The size of the simulation box is $60\lambda \times 40\lambda$ in (x,y) directions, respectively. We take 40 particles per cell per species and a cell size of $\lambda / 80$. The flat plasma foil is located at $x = 10\lambda$ initially. Periodic boundary conditions are used for particle and fields in transverse direction, and fields are absorbed at the boundaries in longitudinal direction.

The temporal evolution of the foil is shown in Fig. 1, separately for electron and ion density. One observes that electrons and ions move closely together. At $t = 16$ (in unit of laser period), about 6 laser cycles after the pulse front has reached the plasma, the foil is slightly curved, following the transverse Gaussian profile of the laser pulse. At $t = 36$, a periodic structure having approximately 1 λ scale is seen, very prominently in the electron distribution, but also already imprinted in the ion distribution. Such surface rippling has been identified before in a number of numerical studies [5-7] and has been described as a Rayleigh-Taylor-type instability (RTI) occurring in thin foils when driven by strong radiation pressure [8]. Here we depict it when the foil is already strongly deformed. At this time, the laser light is reflected from the indented walls and creates an intense standing-wave pattern at the bottom of the crater (see Fig. 2a).

We attribute the foil rippling to this λ-period seed pattern, at least in part. A second source is a fast current instability, setting in at early times when the foil is still plane. It has been described in [6]. Inspecting the longitudinal j_x current at time $t = 36$ in Fig. 2c, a periodic structure of current cells can be recognized, also with λ period. It indicates a pattern of forward and backward currents typical for Weibel instability, which is known to grow fast on the time-scale of the inverse plasma frequency ω_p^{-1}, which is shorter than the light period for solid density. These current patterns contribute to the unstable foil dynamics in the wing region.

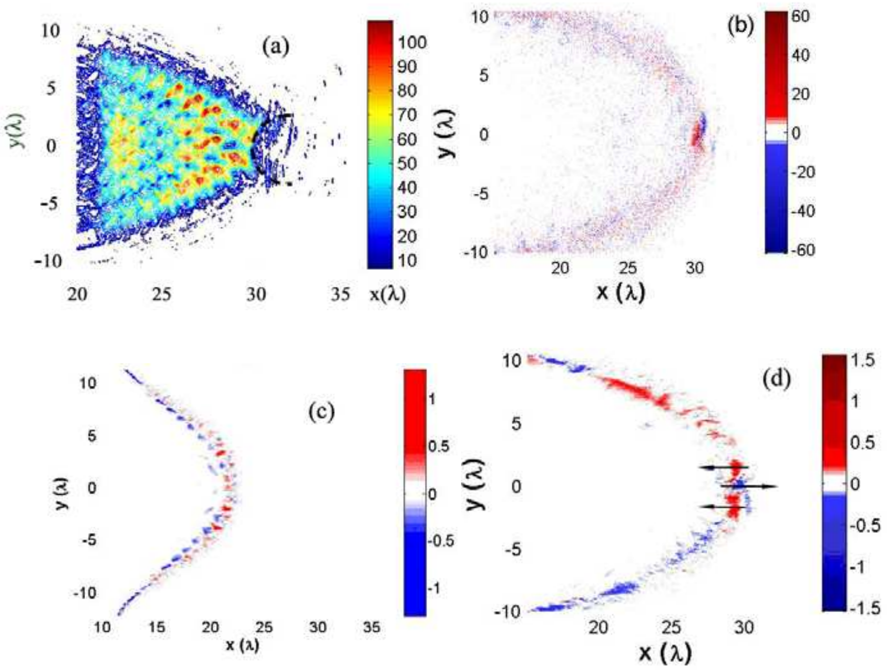

Fig.2 (a) laser field $\sqrt{E_y^2 + E_z^2}$ at $t = 46$, the dashed line marks the concave pulse front pushing the ion clump; (b) charge density distribution $(n_i - n_e)$ at $t = 46$; (c) current density at $t = 36$ (normalized by $en_e c$); (d) current density at $t = 46$. The black arrows in the clump region indicate the direction of electron motion.

The current cells, seen with λ-period at time $t = 36$ in Fig.2c, have almost been dissolved at time $t = 46$ in Fig.2d, except for the central cell on the laser axis which is stabilised by the local laser field. The black arrows in Fig.2d indicate the electron motion around the clump. Electrons move in laser direction on the axis and return on the side of the clump. This kind of current dipole may add to the stabilization of the clump by magnetic compression. Unfortunately, we did not succeed to show this B-field separately, because of the strong laser field superimposed.

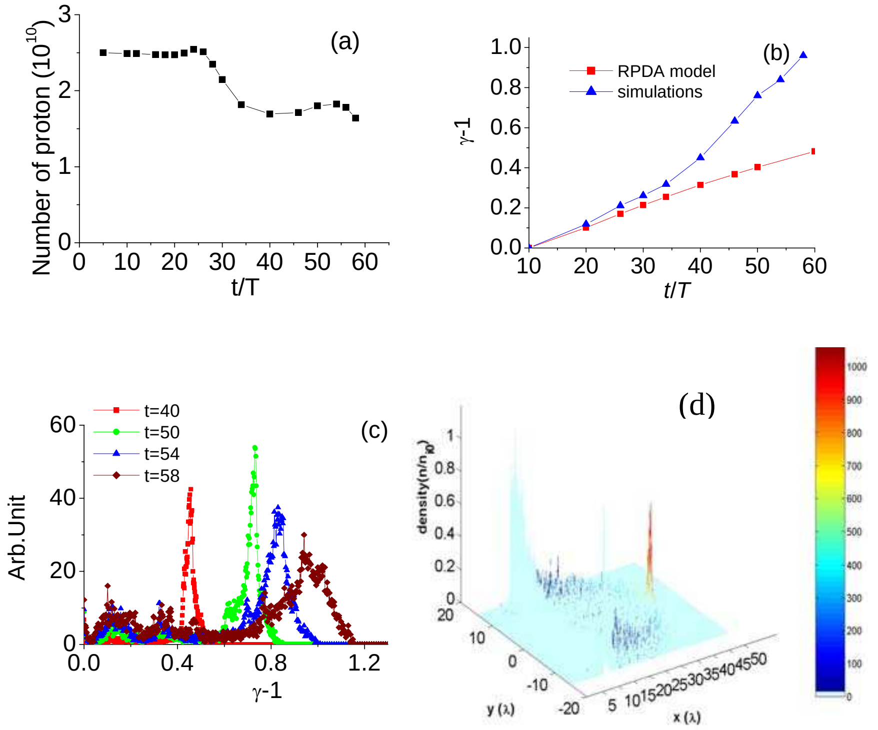

Fig.3 (a) Number of protons in the center of the foil ($r \le \lambda$) versus time in units of laser cycles; (b) proton energy; (c) evolution of energy spectrum for beam ions located inside the central clump ($r \le \lambda$); (d) energy distribution of protons at $t = 58$ (the colour bar gives ion energy in MeV).

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