*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-4.033 (2004)*

Collisionless shocks driven by ultra-intense lasers

M. Marti[1], J.R. Davies[1], R.A. Fonseca[1], L.O. Silva[1]

J. Fahlen[2], M.A. Tzoufras[2], C. Ren[2], F.S. Tsung[2], W.B. Mori[2],

[1] *GoLP Centro de Física dos Plasmas, Instituto Superior Técnico, Portugal*

[2.] *Dep. Physics and Astronomy, University of California Los Angeles, California 90095, USA*

Abstract. The interaction of ultra-intense lasers with solid targets can lead to multi-MeV ions. The mechanisms responsible for the highest energy ions in recent experiments are still under strong debate, but our recent work shows that for intensities above to 10^{20} W/cm^2 collisionless shocks can be responsible for the highest energy protons in thin solid targets [1]. We have performed 1 dimensional (1D) and 2 dimensional (2D), fully explicit particle in cell (PIC) simulations of laser plasma interactions in an overdense regime under the framework OSIRIS [2]. A wide range of simulation parameters (density, target thickness, laser intensity) has been studied. When the laser interacts with a long-scale near-critical density plasma, we observe a Rayleigh-Taylor like instability [3], leading to bubble structures in the shock front. These instabilities can be successfully suppressed either by increasing the plasma density, or by suppressing the preplasma.

1. INTRODUCTION

High intensity (I ~ 10^{20}W/cm^2), high contrast (10^{10}:1) laser systems are opening new fields for the generation of high quality high-energy ion beams with many applications.

At ultra-high intensities, the laser can drive a nonlinear ion acoustic wave across the target [1], and for intensities in excess of 10^{21}W/cm^2, the launched shock wave has a high Mach number ($M \geq 2.6\, c_{s,}$ where c_s is the local sound speed), and can accelerate ions to energies higher than the other acceleration mechanisms i.e. acceleration in the front surface by the ponderomotive push of the laser or acceleration in the rear surface of the target due to the ambipolar explosion of the hot electron component.

To examine and to understand ion acceleration in solid targets we have conducted a detailed parametric study of intense laser-overdense plasma interactions. Our targets consist of a coplanar solid of hydrogen with homogeneous density. The laser propagates orthogonal to the target surfaces. After the impact of the laser on the front surface of the target, an electron beam is launched. Due to the ambipolar field building up in the front and in the rear surfaces of the target, the bulk of the fast electrons remain inside the target and move back and forth from surface to surface. The ambipolar field, in turn, accelerates the ions as well in the surface of the target into empty space.

As the laser impacts on the front surface of the target it pushes all the ions forward, much like a piston, accelerating them to a certain momentum. The piston driven ions evolve into a shock structure, propagating almost undisturbed across that target, while picking up other ions and reflecting them leading to energies corresponding to twice the shock speed.

2. SIMULATION PARAMETERS

All the simulations are performed under the OSIRIS framework [2]. For the simulation parameters in 1D (2D) we have used the following parameters: target thickness L_{target}: 0.1-40 (1-20)μm, size of vacuum chamber in front and rear of target: 40-80 (40)μm, transverse dimension of simulation box: (30)μm, plasma density: 10-90 (10-30)n_{cr}, where n_{cr} is the critical density according to the laser wavelength of 1μm, initial electron temperature (0-5) KeV, laser pulse length: 30-500 (100)fs FWHM, laser intensities a0 = 0.05-20 (4-16), spot size (5)μm FWHM or a plane wave, total simulation time 2.07 (1.04)ps, spatial resolution 1/10 (2≥/10) λ_{pe}, time resolution 2.23 10^{-2} - 0.74 10^{-2} (7 10^{-2}) λ_1^{-1} where λ_{pe} is the laser electron wavelength at n_{cr} and λ_1 is the laser circular frequency, particles per cell: 32 (4≥x≥4). The laser propagates in the x1 direction and it is linearly polarized along x3.

3. ELECTRON RECIRCULATION

In Figure 1, we see the p1x1 phase space of the recirculating electrons together with the corresponding E_1 field for two different times. The relatively large ambipolar field in the rear of the target (a) smoothes out as the protons move outside of the target thus reducing the space charge. The arrows in (c) and (d) indicate the

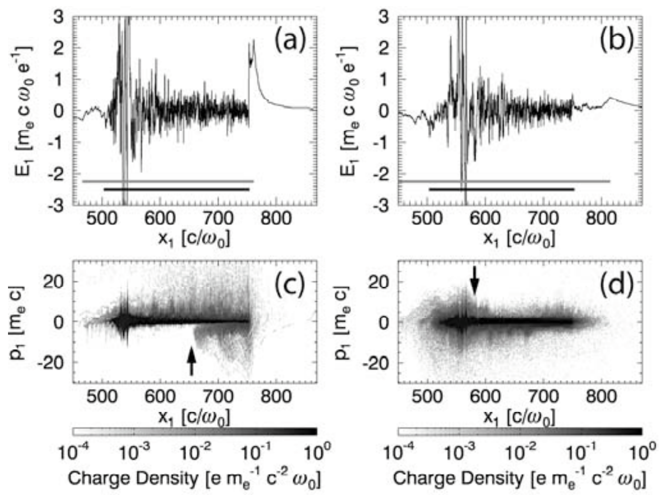

Figure 1: Evolution of the E1 field (a,b) and the electron phase space (c,d)

head of the electron beam. Electron recirculation plays an important roll in the shock formation by providing a uniform plasma temperature, guaranteeing a high sound speed c_s.

4. SHOCK ACCELERATION

In Figure 2, we can observe the p1x1 ion phase space along with the E_1 field for two

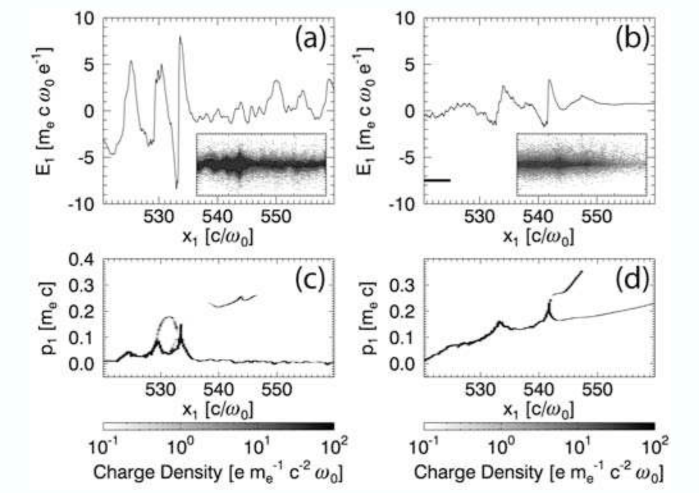

Figure 2: Evolution of the E1 field (a, b) and the ion phase space (c,d)

different scenarios. The insets show the corresponding p1x1 phase spaces of the electrons. Note that the shock structure consists of an electron trap - negative slopes in (a) and (b) - with a large potential barrier in front of it. This barrier is able to pick up ions and reflect them to twice the shock speed. With the right set of parameters it is even possible to combine the two acceleration mechanisms: If the shock formation time is longer than the time necessary for the nonlinear wave to cross the target, the shock builds up into the expanding plasma such that ions accelerated by the shock get further accelerated by the ambipolar field.

5. 2D SIMULATIONS

To benchmark our 1D simulations we carried out a set of 2D simulation and we have compared the results. The presence of the shock as well as the maximum energy achieved in 1D and 2D simulations are in good agreement. The finite spot size of the laser results in a non-planar shock front and it is subject to hole boring. In search of a planar shock front, we increased the finite spot size laser to a plane wave. We found evidence of a Rayleigh-Taylor like instability [3]. This instability affects the shock front in higher dimensions for very wide laser spot sizes and low target densities denoting the existence of bubble like structures in the ion density space. The laser envelope follows the bubbles. This instability is significantly suppressed for higher densities $\gamma_{pe}^{2}/(\gamma\gamma_{0}^{2}) > 1$, and it is not observed in our simulations when $n_{e0} \geq 10\ n_{cr}$.

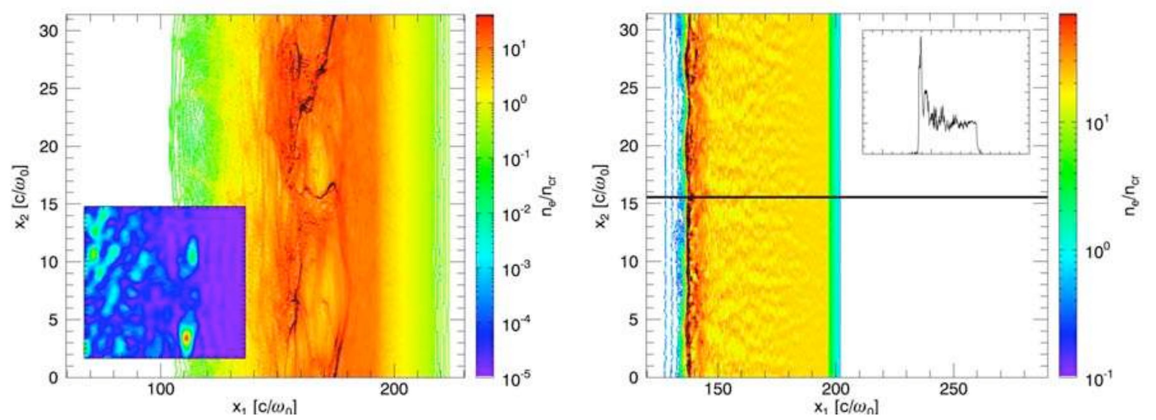

Figure 3: Electron density: low density target (left), and high density target (right). The inset shows the formation of photon bubbles (left), and the electron density along the axis (right)

I CONCLUSIONS.

We have given evidence for collision less laminar shocks with high mach-numbers. We have seen that there is a regime where shock acceleration can dominate. In account to future investigation, we have shown that the new laser systems currently under development will be able to launch plasma shock waves in laboratories opening way to new experiments important to problems in astrophysics and fast ignition. Furthermore we see a possibility to build better ion sources exploring this acceleration scheme.

Work partially supported by FCT (Portugal) and DoE.

[1] L. O. Silva, M. Marti, J. R. Davies, et al, Phys. Rev. Lett. **92**, 015002 (2004); M. Marti et al, submitted to Phys Rev. E (2004)
[2] R. A. Fonseca et al, LNCS **2331**, 342 (Springer, Heidelberg, 2002)
[3] E. J. Valeo and K. G. Estabrook, Phys. Rev. Lett. **34**, 1008 (1975)