*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, O-3.009 (2006)*

High-intensity laser-plasma interaction with underdense plasmas: channel evolution and late-time ion dynamics

S.Kar[1], M.Borghesi[1], C.A. Cecchetti[1], L.Romagnani[1], F.Ceccherini[2], T.Lyseikina[2], A.Macchi[2], F. Pegoraro[2], R.Jung[3], J.Osterholtz[3], O.Willi[3], M.Galimberti[4], L.A. Gizzi[4], R.Heathcote[5], A.Schiavi[6], S.V.Bulanov[7]

[1]*School of Mathematics and Physics, The Queen's University of Belfast, Belfast, Northern Ireland, UK*

[2]*Istituto Nazionale per la Fisica della Materia (INFM), Dipartimento di Fisica ``E. Fermi'', Universita di Pisa, Pisa, Italy*

[3]*Institut fur Laser-und Plasmaphysik, Heinrich-Heine-Universitat, Dusseldorf, Germany*

[4]*Intense Laser Irradiation Laboratory, IPCF-CNR, Pisa (Italy)*

[5]*Central Laser Facility, Rutherford Appleton Laboratory, Chilton (UK)*

[6]*Dipartimento di Energetica, Universita di Roma 1 ``La Sapienza'', Roma, Italy*

[7]*Advanced Photon Research Centre, JAEA, Kizu (Japan)*

INTRODUCTION

The study of the propagation of intense laser pulses in underdense plasmas is relevant to several highly advanced applications, including electron and ion acceleration development of X- and γ-ray sources and fusion neutron production. It is also of fundamental interest, due to the variety of relativistic and nonlinear phenomena, which arise in the laser-plasma interaction [1]. Among these, self-focusing and self-channeling of the laser pulse arise in this regime from the intensity dependence of the relativistic index of refraction and the ponderomotive expulsion of plasma from the propagation axis [2, 3]. For intense pulses, charge separation effects become important and the pulse can propagate self-guided in a charged channel [4]. Several experiments have investigated this regime, mostly providing indirect evidence of self-channeling via optical diagnostics [4, 5]. A related phenomenon is the later evolution of the charged channel determined by the acceleration of ions in the space-charge field (commonly known as Coulomb explosion). A phenomenon also frequently highlighted by multidimensional Particle-In Cell simulation is the formation of electromagnetic solitons in the wake of the pulse and their later evolution into larger post-soliton structures [1].

The development of the proton projection imaging technique [6] has provided a very powerful tool to explore the fast dynamics of plasma phenomena via the detection of the associated transient electromagnetic (EM) field structures. We will discuss here results of an experiment in which we used the proton imaging technique to study of the formation and subsequent evolution of a charge- displacement channel in an underdense plasma. The comparison of the experimental data with computational models allows to characterize in detail the dynamics of the channel at different stages of its evolution.

EXPERIMENTAL ARRANGEMENT

The experiment was carried out at the Rutherford Appleton Laboratory, employing the 100 TW Nd- GlassVulcan laser operating in the Chirp Pulse Amplification mode. The dual CPA configuration was employed, providing two CPA pulses with adjustable relative delays at ps precision. Each of the output beams delivered approximately 50 J in 1.2 ps (FWHM) duration. By using off-axis parabolas, the beams were focused down, on different targets, to spots of 10 µm FWHM, with peak intensity reaching about 1.5 10^{19} W/cm^{2}. One of the beams interacted with the He gas from a supersonic nozzle driven at 50 bar pressure. The other CPA beam was employed to generate the probe proton beams by irradiating it onto a 10 µm Au foil. The detector was a multilayered Radio- chromic film (RCF) detector, placed at a distance of 2- 3 cms from the gas jet. In the condition of the experiment, this provided a multi- frame temporal scan of the interaction for up to 50 ps in a single shot [1]. The time of arrival of the protons of a given energy at the interaction point was controlled by the relative time of arrival of the split CPA beams on their respective destination.

EXPERIMENTAL RESULTS

The evolution of the plasma following the high intensity short pulse laser propagation was observed over a time range of a few hundreds of picoseconds. The data presented in fig.1 refer to the early stage of the interaction of the laser with He gas at 50 bar pressure. The entry of the short pulse into the field of view and its propagation through the plasma were observed due to the generation of an instantaneous electron depleted ion channel under the action of the strong radial ponderomotive force of the laser. The radial electric field present in the positively charged ion channel deflected the probe protons outward from the laser axis, creating a 'negative' shadow of the channel over the RCF. Fig. 1 shows the proton images obtained at two early times of interaction, for two different laser intensities. The times are relative to the beam arrival at the centre of the field of view, which is taken as the time t=0. The proton projection images of the ion channel show three different characteristic features at different regions, corresponding to different stages of the interaction. They are: (I) a 'bullet' shaped channel (left end of frame (a)), (II) a 'white' channel (corresponding to lower probe proton flux than the background) with sharp black boundary (all frames), and (III) a white channel with a dark line on axis (left end of frames (b) and (c)).

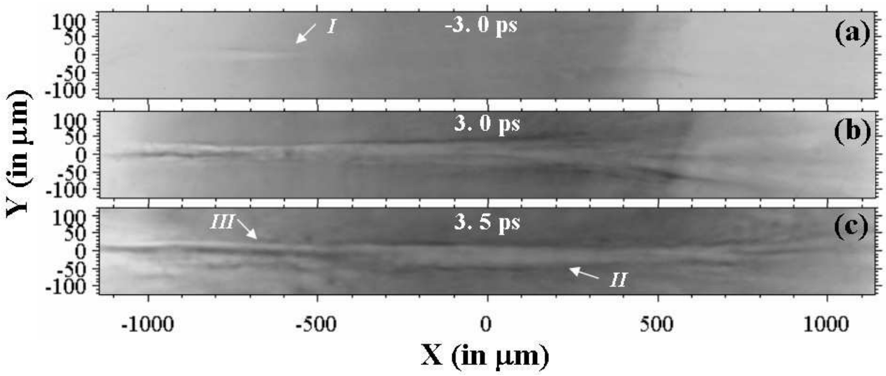

Fig. 1: *Proton projection images showing the different stages of the interaction of a laser pulse propagating through a 50 bar He gas jet. The peak vacuum intensity is 4 10^{18} W/cm ^{2} (frames (a) and (b)) and 1.5 10^{19} W/cm ^{2} (frame (c)). The arrows indicate features described in the text.*

The images shown are snapshots of the plasma taken during the propagation of the laser pulse through the gas preionized by the prepulse. The features mentioned above are imprinted in the proton probe cross section due to the effect of the radial fields surrounding the propagation axis at various stages of the plasma evolution during or immediately after the pulse propagation. As the pulse propagates, the radial ponderomotive force will expel electrons from the focal region, leaving the inner part of the channel positively charged and setting up a charge- separation electric field. Indeed, the 'white' channel (as well as the 'bullet' shaped leading part) feature indicates the presence of an electric field which points outwards, along the radial direction. On the other hand, the central dark line observed at later times in the channel, suggests that at a second stage the radial electric field must change its sign at some radial position (in other words, the radial field points inwards in the vicinity of the axis and outwards at larger distances from it), focusing the probe protons towards the axis.

At even later times, typically on the order of 6- 8 ps, the development of quasi- periodic modulations inside the channel was observed. These structures evolved into circular structures which were observed to decay on hydrodynamic time scales. A typical picture of the data showing this type of modulations is provided in fig. 2. These structures are tentatively being interpreted as related to the growth of solitons inside the channel. Solitons form in high- intensity interactions due to trapping of the redshifted electromagnetic radiation by the ambient plasma, which behaves as over- dense for them. Due to the ponderomotive force, they expel the electrons from the core producing a positively charged sphere, which deflects protons and are imprinted over the RCF as a “white” region, similar to that observed experimentally.

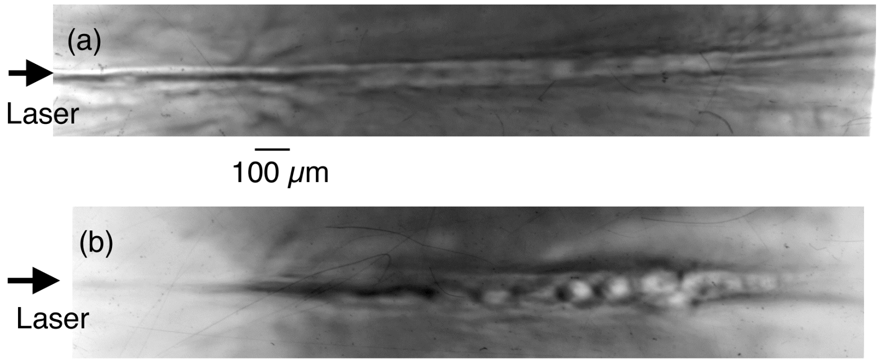

Fig.2 *– Proton projection images of the interaction region taken: (a) 9 ps and (b) 45 ps after the pulse propagation through the center of the frame.*

The main features of the observed channel in the experimental data are qualitatively reproduced by 2D EM PIC simulations in planar geometry, for a regime of parameters close to the experiment [7]. 1D PIC simulation in cylindrical geometry were also carried out, and coupled to particle tracing in the experimental conditions to support the interpretation of the proton imaging data. This work has been supported by an EPSRC grant, a Royal Society Joint Project grant, British- Council- MURST- CRUI and TR18 networks, and MIUR (Italy) via a PRIN project.

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