# OBSERVATION OF E-FIELD STRUCTURES IN LASER PRODUCED PLASMAS BY PROTON IMAGING.

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#### Introduction

Until recently the interpretation of the dynamics and evolution of laser-produced plasmas was based on the measurement of hydrodynamic properties such as density and temperature of the plasma. Information on the electromagnetic fields present inside the plasma was obtained indirectly and the low temporal resolution of the measurements did not allow the fine structure of these fields to be resolved.

In the past few years the generation of multi-MeV proton beams from ultraintense laser interaction with solid targets has attracted great interest [1,2]. A new powerful and versatile probing technique has become available thanks to the high brilliance of the ion beams and the possibility of synchronising optically the proton beam generation with the main laser-plasma interaction[3]. A proton beam propagating through a plasma is affected by the presence of quasi-static e.m. fields that modify its internal structure. These modifications are imprinted on the cross section of the ion beam and are retained due to its quasi-neutrality.

Here we report on a series of experiments carried out on the VULCAN laser [4], where different plasma conditions of interest to Inertial Confinement Fusion were diagnosed using a proton beam as a probe.

#### **Experimental setup**

The plasma was formed by irradiating a 25um Al foil with a 527nm laser pulse. The pulse had a flat-top intensity profile and duration of 600ps. The pulse was focussed with an f/10 lens and the focal spot was modified from shot to shot in size and intensity profile by changing the focussing of the lens and by inserting Phase Zone Plates in the beam[5]. Typical irradiances on target were of the order of 10^14-10^15 W/cm^2.



Figure 1: top view of the setup for side-on probing

The proton probe beam was produced by a 1um wavelength CPA pulse focussed onto a 25um Al target at 5 10^19 W/cm^2. The pulse had a temporal Gaussian profile and duration of 1 ps.

The ion beam emerging from the rear surface of the Al foil was aligned with a detector made of several layers of radiochromic film (RCF)[6] stacked in the propagation direction of the beam. An aluminium foil in front of the RCF acted as an optical filter, stopping soft X-ray radiation and reflections from the vacuum chamber walls.

Face-on and side-on probing images were obtained by changing the orientation of the main target by 90 degrees (Figure 1).

Additional information on the plasma was obtained via transverse interferometry measurements using a 266nm laser beam with 1ps duration.

## **Proton images**

Figure 2 presents two RCF layers corresponding to a proton energy of 17.6 MeV.

Figure 2a shows a face-on image of a solid target with no plasma: the folding structures are due to the proton acceleration mechanism and to the internal dynamics of the ion beam. The presence of the target in the line of sight is not detected because the areal density of a 25um Al foil is too low to affect significantly the ion beam.

Figure 2b presents a face-on image taken at the peak of the plasma-forming laser pulse: in this case the protons going through the plasma are displaced, scattered or stopped by the e.m. fields generated during the laser interaction. The recorded image clearly shows the footprint of these processes on the proton cross section.



Figure 2: proton images with and without plasma

Comparison of these images with interferograms taken in similar conditions indicates that geometrical magnification holds for our imaging technique. The structures and modulations imprinted on the ion beam are likely to be due to electric and magnetic fields set up by the laser interaction and by electron transport inside the plasma.

## **Temporal evolution**

The temporal evolution of the observed structures was recorded by changing the delay between the plasma forming pulse and the CPA pulse. Images taken at the early stages of the laser interaction show the formation of these structures, which become fully developed towards the end of the pulse. Soon after the laser pulse is gone, the structures disappear and the image closely resembles the one when no plasma is present. This observation suggests that the e.m. fields in the plasma are set up and sustained by energy input coming from the laser. Side-on images (Figure 3) show that the detected structures extend from the solid density far out into the coronal region. It is clear that it is essential to take into account the whole range of processes that take place in the laser-plasma interaction when trying to interpret and understand the collected data.



Figure 3: side-on proton image; dashed lines indicate original position of the target; solid line marks electron density obtained from interferometry

#### **Focal spot variations**

When the irradiation conditions of the target were changed, distinct modifications on the recorded ion pattern were observed. This fact clearly indicates that the fields experienced by the protons are closely related to the interaction of the laser pulse with the plasma.

Face-on images show a fine structure made of cells, the size of which is changing with the properties of the focal spot. In our experiments, tight focus conditions lead to a uniform pattern of small cells about 60um in diameter. Larger focal spots correspond to a reduced number of bigger cells (~100um), apparently displaced in a pattern similar to that of convective cells.

The presence of a PZP introduces a finescale regular modulation on the laser profile, which is transferred to the e.m. fields structures inside the plasma, and subsequently detected by the ion beam. Side-on shots reveal a regular modulation in image intensity when PZPs are used.

## Simulations

3D PIC code simulations have shown in principle the possibility of storing information in a laser produced ion beam. By storing information we mean that modifications induced in the angular distribution of the ion beam by e.m. fields present inside a plasma are retained and carried by the ion beam itself. This information can be effectively recorded then on a detector that selects energy ranges and preserves the angular distribution of the particles.

Present day PIC codes model quite effectively the interaction of laser and plasma, particularly at high intensities. They serve as a powerful tool for investigating the generation of ion beams, and can resolve the dynamics of electric currents and self-generated magnetic fields inside the plasma [7,8]. Unfortunately such codes cannot follow the propagation of a proton beam on the centimetre scale of our experiments, due to computational constraints. Therefore we are presently developing a 3D ray-tracing code especially tailored on the parameters of our experiments. We intend to use this code to obtain the order of magnitude of the e.m. fields inside the plasma. Assuming different configurations for the fields, we can investigate the processes potentially accountable for the observed structures, and we could in principle discriminate the several processes that lead to the formation of the e.m. fields. Clearly the basic assumption is that protons propagate inside the plasma as testparticles. Interaction between the different parts of the ion beam is neglected: to

support this assumption, we point out that the number density of the proton beam is at least a factor 10^5 smaller than critical density of the plasma, when the protons interact with the target.

Preliminary simulations with a 2D version of the ray-tracing code were carried out assuming tubular E-field structures, like the ones that could be induced by density modulations caused by laser hot spots. We found that the E-field that could explain the experimentally observed pattern is of the order of 5 10^8 V/m.

## Conclusions

For the first time a laser-produced proton beam was used to diagnose a preformed plasma. Direct information about the e.m. fields inside the plasma was stored in the ion beam and subsequently recorded on a detector. Maps of the angular distribution of the beam were obtained at selected proton energy ranges. The temporal evolution of the observed structures and the modifications caused by different irradiation conditions were also investigated.

Many concurrent phenomena could lead to the observed ion patterns, and therefore an exhaustive set of simulations is needed to identify the fundamental processes that affect the propagation of the proton beam through the plasma.

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