Proton Radiography Measurements of Self-generated Magnetic Field Dynamics following the Irradiation of Solid Targets by a Long Pulse Laser

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The interaction between a nanosecond pulse laser and a planar solid target are subject to a multitude of mechanisms in which strong magnetic fields (of the order of Megagauss) are generated [i, ii, iii]. Stamper [i] showed that the major mechanisms responsible for the creation and development of azimutal self-generated magnetic fields are the non colinearity between the temperature and density gradient (cf fig.1). In such interactions, classical transport theory [iv] is usually used to describe the behavior of the plasma. Unfortunately, this theory becomes inadequate for electron temperatures found in ICF plasmas. Indeed, in high electron temperature ICF plasmas, the electron mean free path is long compared to the plasma characteristic gradient scale length. This implies that non local effects need to be accounted for. These will influence the heat flux [v] through modified transport coefficient given by [iv], and play a role in particular on the Nernst and Righi-Leduc effects. It is well known that there

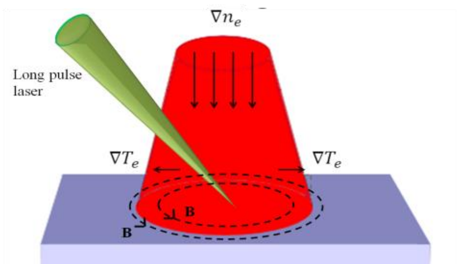

Figure 1 : Sketch of the major source term responsible for self-generated magnetic field

is a strong coupling between the magnetic field dynamics and the non local heat flow [vi] although this relation is still poorly understood. This work therefore aims to study experimentally self-generated magnetic field dynamics to test and validate the algorithms in the hydro-radiative code FCI2 to improve modeling electron heat transport relevant for ICF.

In past years, access to measure magnetic field in the dense parts of the plasma was difficult due to the limitation imposed by optical diagnostics which were used, e.g Faraday rotation [vii, viii, ix] or polarimetry measurements of self-generated laser harmonics [iii]. A new diagnostic based on proton radiography has demonstrated its interest in complementing these optical diagnostics and giving access to measurement in the dense plasmas [x]. It consists in irradiating a solid target by a CPA (Chirped Pulse Amplification) laser pulse to generate a beam of protons with a small divergence angle (~20°) through the TNSA mechanism (Target Normal Sheath Acceleration) [xi]. After passing through the interaction target and being deflected by the magnetic fields following Lorentz's force q(v×**B**), (see fig.2) protons are retrieved on a detector (typically a stack of radiochromic films RCF). The results presented here investigate self generated magnetic field dynamics using such proton probing diagnostic.
The experiment was carried out using the TITAN laser facility at the Lawrence Livermore National Laboratory (LLNL). One of the restricted conditions was the ability to, in the same time, used a nanosecond beam as the interaction beam, a CPA beam to drive the diagnostic for proton probing and an optical probe beam to measure through interferometry the plasma density. The main interaction beam was used in various configurations in energy and in pulse duration however the most common parameters were 2 ns duration with a rise time of ~100 ps and an energy of ~400 J at the fundamental wavelength of 1.053 µm. In order to be precise in term of absorbed energy by the plasma, we use a scattering reflectance target (Spectralon, see fig.2). The interaction beam was focused by a f/10 lens (focal length of 1m) using a Random Phase Plate (RPP). The spot size was chosen to be ~125 µm FWHM with ~50% of the total energy inside. The intensity on target was up to $4.5.10^{14}$ W/cm^2 as determined by simultaneous measurements of pulse duration, laser pulse energy and spot size.
The irradiation of a 50 µm Au target by an ultra-high intensity (CPA) laser produced the probing proton beam. The CPA laser had a pulse duration of ~1 ps and an energy of ~150 J and was focused by an f/3 off-axis parabola. This target was placed 4 mm behind the interaction target and protons were then collected by a stack of Radiochromic films (RCF). Since protons have different energies, they have different time of flight between the source foil and the interaction target. They will deposit then their dose in different layers of the stack according to their incident energy. So the dynamics of the magnetic fields can be seen in one shot over a time span of ~100 ps depending on the maximum proton energy. Notice however that, this time range is too short compared to the pulse duration of the interaction laser pulse (~2 ns) in order to be able to measure the dynamics of the self-generated magnetic field in a single shot. In order to do so, we thus changed the delay between the interaction beam and the

CPA laser producing the probing proton beam. This allowed to explore the dynamics of the magnetic field over the whole time of the interaction (~2 ns). The distance between the interaction target and the detector was approximately 3.7 cm giving a magnification on the detector plane around 10. An optical probe beam, frequency-doubled was also used in order to do Nomarski interferometry, and polarimetry giving information about plasma density and a quantitative information on magnetic field in the low density part of the plasma. This is of prime importance to be sure that we measure magnetic fields which actually are in the dense part of the plasma. The experimental set-up is shown in fig.2.

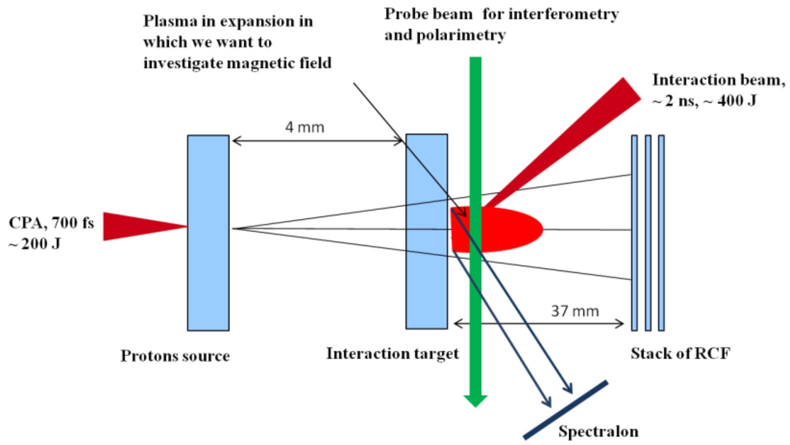

Figure 2: Experimental set-up

A typical example of data, using as interaction target a Mylar 23 µm thick foil is shown in Fig.3. t_0 is defined as the time when the interaction beam begin to interact with the target. As can be seen in Fig.3, there is a depletion of protons in the center of the RCF. This is due to the magnetic field which pushes out protons. We can also see structures in the zone of depletion of protons. This is probably related to turbulence and magnetic reconnection in the plasma due to the possible presence of many hot spots within the RPP-produced focal spot.

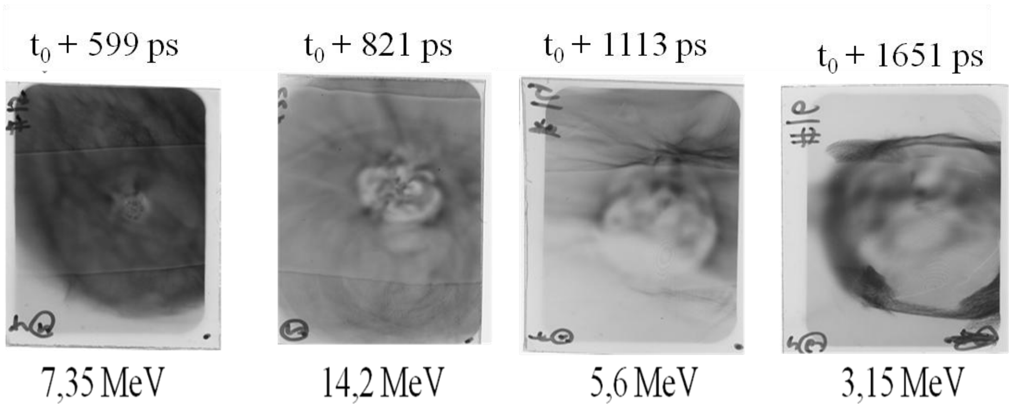

Figure 3: Protons radiographs at 4 different times. From left to right: 599 ps, 821 ps, 1.113 ns and 1.651 ns after the interaction beam irradiated the target. The energy below indicates the probing proton energy corresponding to the particular RCF layer in the stack

The evolution of the zone of proton depletion as a function of time for a Mylar target that is 23 µm thick and is irradiated by the interaction beam (2 ns, ~ 300 J) is shown in Fig.4.

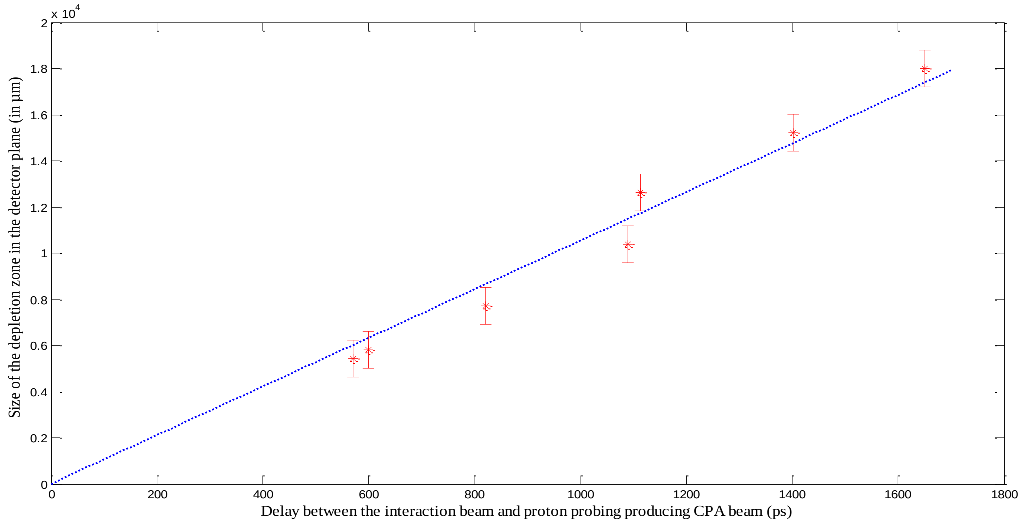

Figure 4 : Evolution of self-generated magnetic field during the interaction of a 2ns beam and a Mylar 23 µm thick foil. Here the absorbed energy was ~ 300 J.

It is found that the velocity of the edge of the self-generated magnetic field parallel to the target surface is approximately 1.10^6 $m.s^{-1}$ and stays constant in time during the irradiation of the laser. These observations will be compared to results observed in simulations in order to validate codes relevant for Inertial Confinement Fusion.

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