

# High-power laser-plasma interaction in nanosecond regimes ‘at a glance’ using proton deflectometry

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**Abstract.** Recent experiments indicate that controlling the propagation of high-power laser beams through millimeter long and low-density plasmas still remains challenging. In such plasma conditions, it is equally important to consider the impact of the plasma on laser propagation and laser properties, and the impact of the laser on plasma conditions. These complex phenomena are still difficult to implement in fluid models owing to the highly non-linear physics at play. Yet, electromagnetic fields prove to be good signatures of most of these low frequency phenomena. In particular, local pressure gradients and electron transport can be inferred from the electric fields. Such in-depth plasma characterization can be achieved through proton deflectometry. For that purpose, we have developed a three-dimensional simulation capability in order to compute protons’ trajectories modified by the local electric fields.

## 1. Introduction

Detailed knowledge and understanding of the laser-plasma interaction is of fundamental interest in many high energy density (HED) configurations, and specifically in inertial confinement fusion (ICF). This is the case both in the indirect drive approach of ICF, where high-power laser beams have to propagate through several millimeters of plasma before reaching the hohlraum walls, and in the direct drive approach, where the reduction of the imprint on the fuel capsule could be achieved through plasma induced smoothing [1,2]. Recent experiments on the LIL [3,4], NIF (NEL) [5], LULI [6] and OMEGA EP [7] facilities brought to light the difficulty in modeling laser plasma propagation. Setting aside ionization that involves atomic physics, laser propagation in plasmas depends mainly on the local electron temperatures and densities that can trigger instabilities such as self-focusing and stimulated scattering off plasma waves. An interesting tool to investigate this interplay is to probe the electric fields driven by electron transport and ponderomotive effects inside the plasma through proton deflectometry [6]. In addition to the usual optical measurements, this diagnostic provides unique and novel characterization of the laser-plasma interaction by allowing to measure the electric fields within the plasma. In a joint effort, we explore this new tool both experimentally at the LULI 2000 facility and numerically, by using the transport code Diane [8] in order to compute the proton deflectometry due to the local electric fields calculated by our 3D paraxial code Hera [9]. In addition, we use the radiative-hydrodynamics code FCI2 to compute initial values for Hera.

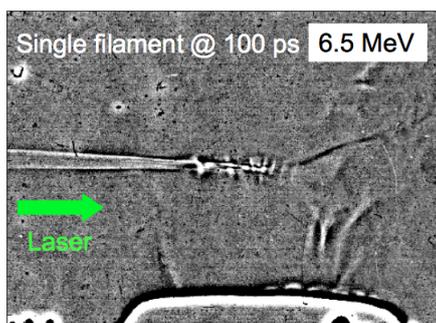


## 2. Proton deflectometry in underdense plasmas

Multi-MeV proton beams generated by high-power, typically greater than 100 TW, laser beams are commonly used on numerous facilities for radiography purposes, see reference [10] for a review. For underdense plasmas, that is plasmas whose electron densities are lower than the critical density  $n_c \sim 10^{21}/\lambda_0^2 \text{ cm}^{-3}$ , with  $\lambda_0$  the laser wavelength in  $\mu\text{m}$ , protons undergo mainly electromagnetic deflections. Proton deflectometry consists in recording proton's deflections after their propagation through a probed object, onto a pack of radiochromic films (RCF), as illustrated Fig. 1 for a typical image. The resulting patterns give an indication about the strength of the electromagnetic fields encountered, and indirectly about the physics under consideration. Due to the protons' high velocities, proton deflectometry probes the plasma on a picosecond time-scale, and temporally resolved, depending on the proton energy spectrum, the more energetic protons arriving first. The proton beam traverses a  $\text{mm}^3$  volume, and impinges onto a cm-size RCF with a few  $\mu\text{m}$  spatial resolution. Then, dose modulations recorded on each RCF allow to estimate an amplitude of the electric and magnetic fields generated during the laser-plasma interaction. In hot underdense plasmas, magnetic field amplitudes are too low for deflecting protons [6] and the electrostatic fields  $E$  mostly stem from the electron pressure gradient, first term in the right hand side (RHS) of the following equation, and the ponderomotive force, second term in the RHS,

$$eE \sim -\frac{1}{n_e} \nabla(n_e T_e) - \frac{1}{2cn_c} \nabla I, \quad (1)$$

where  $I$  is the laser intensity,  $n_e$  the electron density,  $T_e$  the electron temperature and  $e$  the electron charge. Plasma modifications due to those two forces lead to electron density modifications with a characteristic electrostatic signature. Thus, proton deflectometry is a unique tool for probing in depth ICF plasmas, giving quantitatively access to electrostatic field amplitude arising from the electron thermal and ponderomotive effects. In principle, such a diagnostic could discriminate between local or non local electron transport regimes when compared to hydrodynamic simulations [6].

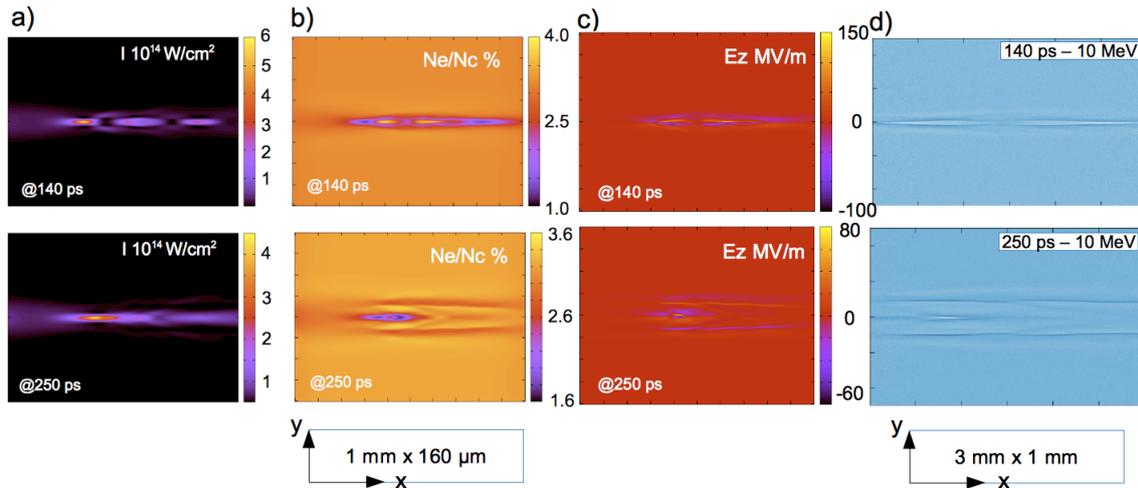


**Figure 1.** RCF pattern produced by 6.5 MeV protons from a recent LULI experiment. The laser beam propagates from the left to the right in a helium gas jet (we see clearly the 1 mm diameter nozzle at the bottom of the image), whose initial density is 1% of the critical density for a 1  $\mu\text{m}$  laser wavelength. The protons arrive 100 ps after the beginning of the pulse.

Although many experiments have demonstrated the interest of proton deflectometry, exhibiting specific patterns attributed to the existence of specific fields, it is still difficult to analyse quantitatively RCF without knowing *a priori* the field structures. This aspect arises from the two-dimensional (2D) representation of a three-dimensional (3D) interaction. The inversion problem points to the need of a simulation tool that calculates the 3D electric field structures resulting from the two forces, and then the proton's deviations into those structures. For this, we use our 3D massively parallel laser-plasma interaction code Hera to compute the electric fields, coupled to the 3D Monte-Carlo proton transport code Diane to simulate the dose received by the RCF. Hera includes a paraxial laser propagation solver, coupled to the mass and momentum conservation equations and taking into account Brillouin backscattering. Diane solves the multigroup Boltzmann-Fokker-Planck equation, including the Lorentz force in stationary regime. Our numerical tool was successfully compared to the analytical expressions detailed in Ref. [10].

### 3. Application to beam self-focusing

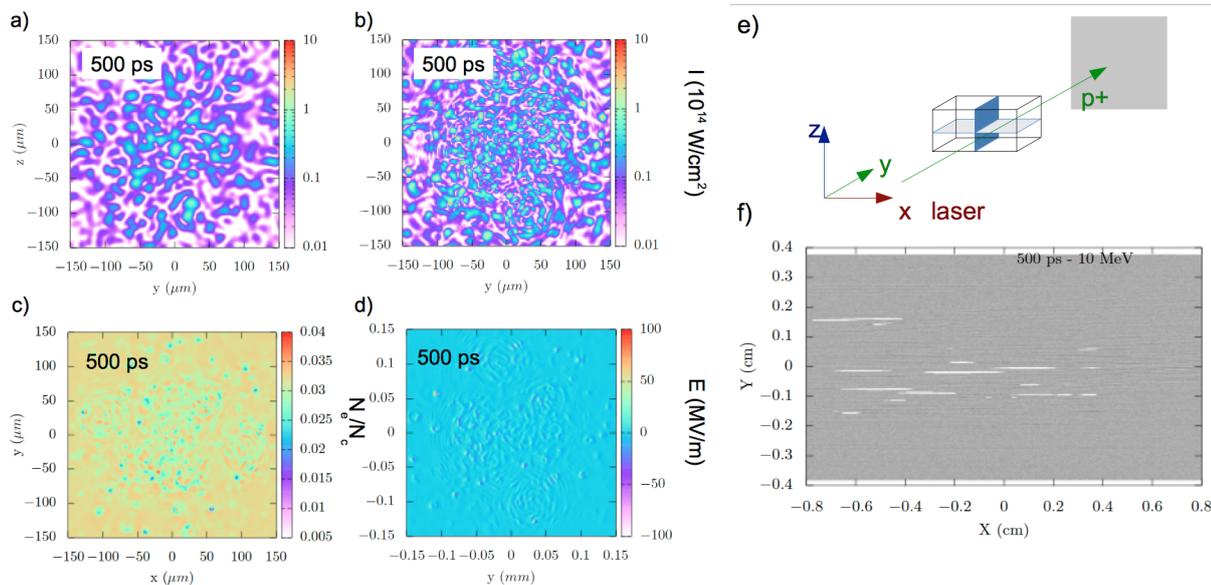
We use the Hera and Diane codes in two configurations. First, we consider a gaussian laser beam ( $\lambda_0 = 1 \mu\text{m}$ ,  $f_{\#} = 10$  and  $I = 10^{14} \text{W/cm}^2$ ) propagating in a 1-mm long,  $160\text{-}\mu\text{m}$  wide and  $3.2\%n_c$  He plasma. The electron temperature is around 180 eV. The laser beam has a constant power and propagates in the  $x$  direction and the proton beam in the  $y$  direction, see insert e) Fig. 3 for the geometry. We present, see Fig. 2, longitudinal maps of a) the laser intensity, b) electron density, c) electric field  $z$ -component and d) proton dose 140 ps and 250 ps after the beginning of the pulse.



**Figure 2.** Propagation of a single filament in a  $3.2\%n_c$  He plasma: a) laser intensity, b) electron density, c) electric field  $z$ -component and d) simulated proton dose. Hera simulation box is 1 mm long and  $160 \mu\text{m}$  wide. The magnification factor is 15 on Diane's simulated detector.

At 140 ps, the laser exhibits a strong self-focusing. The secular effect of the ponderomotive pressure digs plasma channels and results in high amplitude electric fields. Later, at 250 ps, the laser is less perturbed. The electron density map keeps the hydrodynamical history of the laser plasma interaction: transversal density bumps come from the successive self-focusing. The simulated proton dose matches this time history.

It is quite straightforward that proton deflectometry is useful for a single beam configuration. It is challenging to consider a more complex situation where the lasers are smoothed by a random phase plate (RPP), producing a speckle pattern in the focal plane. The second configuration corresponds to  $1 \mu\text{m}$  wavelength, 1.5 ns long and 20 J RPP beam propagating in a  $3.2\%n_c$  He plasma and focused over a  $200 \mu\text{m}$  FWHM focal spot (see Fig. 3 a). The plasma is 2-mm long and  $500\text{-}\mu\text{m}$  wide. We needed up to  $\sim 5.4 \times 10^8$  cells ( $512 \times 1024 \times 1024$ ) for the total domain discretization on 1024 cores. The focal spot in vacuum is shown top of Fig. 3 a), it can be compared to the focal spot in the transverse median ( $yz$ ) plane after 500 ps of propagation Fig. 3 b). In this simulation, the RPP beam undergoes a smoothing induced by the plasma response and becomes more and more spatially incoherent [1,2]. This is illustrated at the bottom of Fig. 3 c) and d) where, due to the ponderomotive pressure, strong density fluctuations appear, generating high amplitude electric fields, around 100 MV/m. We use the Diane code in order to simulate proton deviations through the probe volume. For this simulation, the proton beam is modeled by a 5 degrees half angle cone, positioned 7 mm off the plasma and aligned to the center of the simulation box. The detector is positioned 10 cm after the plasma, giving a  $\times 15$  magnification. Due to the cone aperture, we select a  $1 \times 0.5 \times 0.5 \text{mm}^3$  volume centered to the middle of the simulation box. For this simulation, the Diane code generated  $2.5 \times 10^8$  protons in 5h, using 32 parallel runs, each with 32 cores. The simulated proton dose on the detector is



**Figure 3.** Propagation of a laser beam with a speckle pattern in a  $3.2\%n_c$  He plasma. Maps a) of the laser intensity in vacuum, b) the laser intensity in the transverse median plane, c) electron density perturbations and d) the corresponding  $E_z$ . The geometry is shown in e) where the transverse median plane is colored in dark blue and the RCF in grey, and f) the simulated RCF for 10 MeV protons.

shown Fig. 3 f) for a 10 MeV proton beam, exhibiting in white strong density depletions. Such structures are linked to the speckles induced plasma modifications and their individual and dynamical self-focusing. It demonstrates that proton deflectometry applied to realistic laser-plasma interaction leads to discernable proton dose modulations, but a statistical approach (for example: measuring the characteristic filament's length) is necessary for a quantitative comparison to experiments. Probing plasmas by proton deflectometry provides a way to characterize the laser beam's properties during its propagation.

#### 4. Conclusion

Proton deflectometry is a promising tool for studying laser-plasma interaction in underdense plasmas. Complementary to the usual optical diagnostics, proton deflectometry, with multi-MeV beams, allows in situ characterization on mm-scale with very high temporal and spatial resolution from a single laser shot. Although evaluating an electric field amplitude is conceivable given an analytic form of the electric potential, this is not the case in general. For this reason, we have developed simulation capabilities using a laser-plasma interaction code coupled to a charged-particle transport code. Because intense speckles may lead to stronger local magnetization than anticipated, magnetic fields will be soon included in Hera simulations. Experiments on HED facilities such as LMJ with PETAL are envisioned.

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