High intensity laser-plasma interactions
From laser amplification to the measure of magnetic fields in plasmas

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Two examples of noteworthy applications of high-intensity laser – matter interaction will be presented. Both these topics are characterized by a highly non - linear plasma response to the laser excitation. In a plasma-based laser amplifier the response of the plasma has been exploited to realize a unidirectional energy transfer from an electromagnetic wave to another one that is amplified. In Inertial Confinement Fusion, the way energy is delivered to the target is one of the main concerns. The non-linear and non-local response of the dense plasma target to the high power laser irradiation, leads to a particular topology of MegaGauss B-fields that self-generate following the irradiation, and that strongly affect heat deposition. The topology of these fields has been measured and characterized, leading to a correct modeling in numerical simulations.

1. A plasma based laser amplifier.

Plasma amplification [1] is part of the growing field of plasma optics [2], which aims at manipulating light (amplifying, focusing, diffracting etc.) using a fully-ionized plasma. The interest that this field has been lately receiving is due to the promising alternative that is offered to overcome the limits of solid-state based technologies when very high intensities are to be produced and manipulated. The damage threshold [3] and nonlinearities that occur in optical materials, and limit their use in laser amplifiers, do not affect a plasma, that being already ionized, can sustain high heat loads and power densities. It therefore becomes a good candidate amplifying medium.

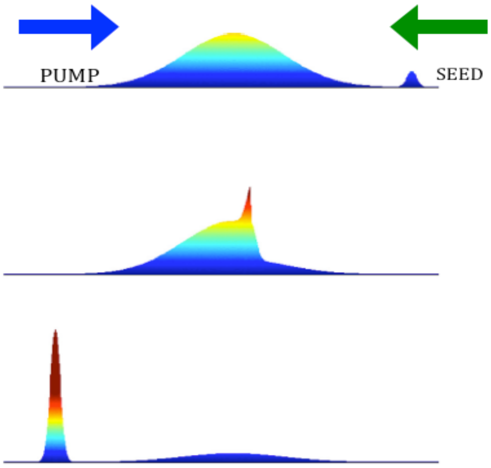

Figure 1 Principle of plasma amplification. The short, low energy seed (from the right) interacts with the longer, more energetic pump (coming from the left), in a preformed plasma. The seed is amplified and the pump is depleted

A laser plasma amplifier is thus a single-pass amplification process that features the interaction of two laser beams, a *pump* ($\boldsymbol{k}_p$, ω_p), delivering its energy, and a *seed* ($\boldsymbol{k}_s$, ω_s), to be amplified, within a preformed plasma (Fig.1). The mechanism relies on the response of the plasma to an intense laser excitation, in the form of an electrostatic (electronic or acoustic) plasma wave ($\boldsymbol{k}_{pl}$, ω_{pl}). This wave fulfills a 3-wave resonant coupling in terms of energy and momentum: $\omega_p = \omega_s + \omega_{pl}$ and $\boldsymbol{k}_p = \boldsymbol{k}_s + \boldsymbol{k}_{pl}$.

In particular, by using high pump beam intensities I (yet not relativistic), high plasma densities n_e (e.g. $n_e = 0.1\ n_c$) and low plasma temperatures T_e (e.g. $T_e = 100$ eV), a so-called *strongly coupled (sc)* regime of the laser-plasma interaction is attained [4]

In this regime of laser-plasma coupling, an intensity-driven, *nonlinear* ion acoustic oscillation develops ($\boldsymbol{k}_{sc}$, ω_{sc}). This ion wave (*Brillouin* mechanism), is a *forced* quasi-mode of the plasma, and is characterized by a complex frequency ω_{sc} [4].

The growth rate ($\Gamma_{sc} = Im\{\omega_{sc}\}$) of such an instability is proportional to the plasma density n_e and the instability, for typical parameters, can develop over timescales of the order of 100 fs: it is thus suited to set fast energy transfer, and hence to realize *amplification of short seed* pulses. Moreover, due to the low frequency ion modes ($\omega_{sc} << \omega_p$) no frequency downshift of one pulse with respect to the other is needed to fulfill the electromagnetic coupling: such a mechanism is realized with the interaction of *same wavelength* pump and seed pulses. These two reasons make this mechanism experimentally very interesting.

A proof-of-principle experiment was first performed at the 100TW installation at LULI (France), and we demonstrated the feasibility of using this scheme to realize the energy transfer from a few J, 10^{16}W.cm^{-2}, 6 ps pump pulse to a few mJ 400 fs, seed [5], both at the same wavelength λ_o=1058nm. Lately, we have designed and implemented an upgraded setup geometry in order to overcome the intrinsic limitations of the original scheme: namely (i) a limited overlapping region due to a crossing-beam geometry and (ii) a not-complete ionization of the plasma that caused refraction of the beams and consequent loss of energy available for transfer [6].

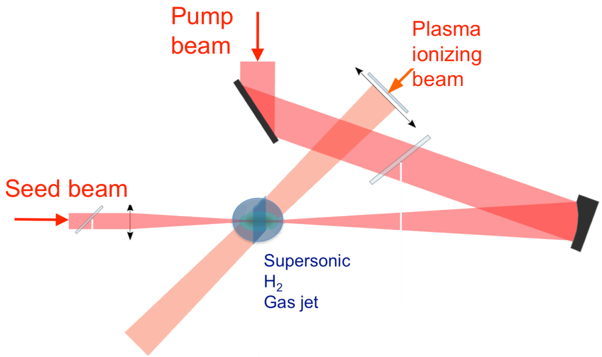

Figure 2 Scheme of the head-on interaction experiment at the ELFIE laser facility, LULI (France). A 6J, 6 ps, 10^{15}Wcm^{-2} pump was made to interact with a 5 mJ, 700 fs, 10^{13}Wcm^{-2} seed in a preformed plasma of density n_e=0.15n_c

By setting up a head-on geometry (Fig 2) to exploit a maximum overlapping of the beams within the plasma medium, using low Z gas (H_2) easier to fully ionize, we have recently obtained at the ELFIE facility (LULI, France) an absolute (i.e. with respect to the *incident* seed beam) amplification of a few mJ, sub-ps, 10^{13}W.cm^{-2} seed [6].

In Figure 3 the spectrum of the incident seed is compared to the one at the exit of the plasma without interaction (w/o pump), and to the one of the seed amplified after the interaction with the pump.

The seed signal, spatially and spectrally integrated, was recorded with a largest energy and intensity gain of a factor 5, which is a value proper of a typical amplification stage. This gain was associated with a 30 mJ of energy transfer [7].

An optimization of the beam coupling through improved beam profiles and plasma conditions, the use of longer interaction lengths and larger beam sizes, will lead to an energy transfer at the Joule level i.e., equivalent to what commercially available lasers can achieve. This will eventually provide a way to overcome present technological limits, and allow producing in the future ever-higher laser intensities, that will open the way to the exploration of new physical regimes.

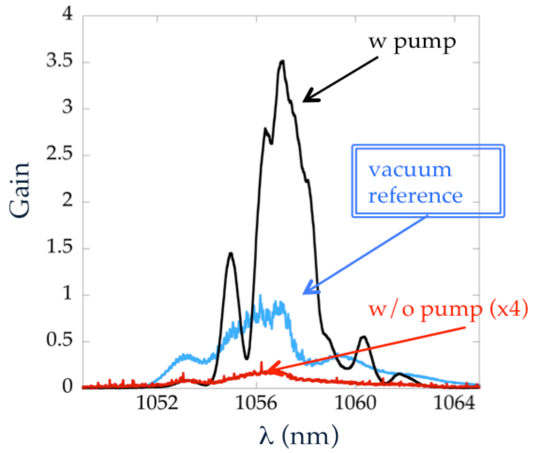

Figure 3 Spectrum of the vacuum seed compared to the one at the exit of the plasma and to the one obtained after interaction with the pump.

2. Topology of self-generated MegaGauss B fields

The study of heat transport in a dense plasma created by the illumination of a planar solid target by an intense (I~10^{13}-10^{14}Wcm^{-2}) nanosecond laser pulse, is significant from an Inertial Confinement Fusion point of view, in terms of geometry and conditions, since this interaction reproduces the one between heater beams and the internal walls of the Hohlraum in the ICF indirect drive scheme (Circled region n.2 in Fig.4).

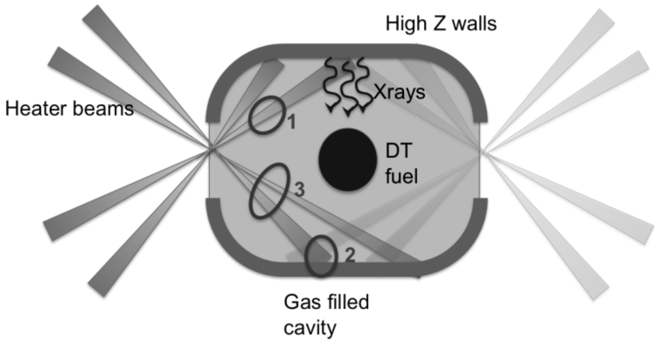

Figure 4 Scheme of the indirect rive scheme for Inertial Confinement Fusion. When the heater beam irradiates the walls of the cavity MegaGauss Magnetic fields develop .

It has long been known [8] that during this kind of interaction, MegaGauss magnetic fields, azimuthal with respect to the incident laser axis, self-generate at the edges of the focal spot on the target surface, due to the simultaneous presence of non-parallel temperature and density gradients. These fields affect the way heat is delivered to the target, and the consequent production of X-rays, by modifying the distribution function of heat carrying electrons. In particular, they are effective by trapping those long-range electrons that are responsible of non-local features of the heat transport. At the same time their evolution is highly affected by the electron currents themselves. That is the reason why these fields must accurately be taken into account within the hydrodynamic models that are used in simulations tools. We thus performed a simultaneous experimental study of heat transport through the target and of the self-generated B-fields. In order to produce such kind of interaction, a ~10^{14}W/cm^2, 2 ns laser pulse illuminated a solid (plastic, CH) target [9].

The B fields were measured by the innovative technique of proton radiography (shown in Fig.5). This technique exploits the deflections undergone by a laser-produced proton beam when crossing a field region. The global modifications of the proton pattern (measured by a plastic detector) allow retrieving two-dimensional imaging of the B-field extent in the regions of coronal plasma but also in denser regions.

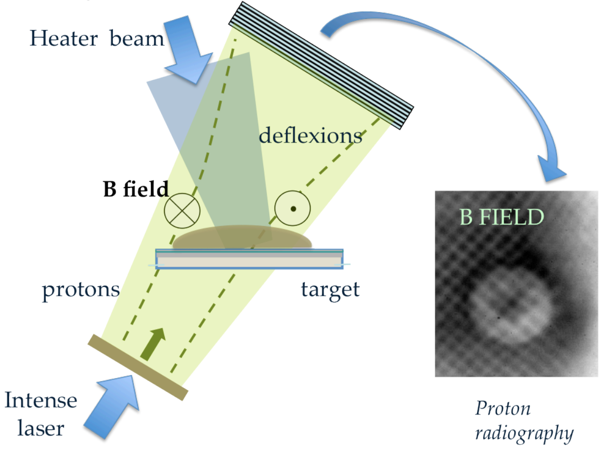

Figure 5 Principle of the proton radiography experiment A slightly divergent and laminar beam of spectrally broad protons (energies up to ~20MeV), is produced by an intense laser (~10^{19} Wcm^{-2}) illuminating a solid gold target. Protons undergo deflections proportional to the fields they cross. The global pattern, modified by these deflections, and recorded on a plastic detector, provides a 2D radiography of the azimuthal B-fields.

From the comparison between the experimental patterns of the radiography images with the calculated patterns, produced by the numerically modeled B-fields, we could observe how the measured fields extended over a larger region than the ones simulated by those numerical models [10]. This observation suggested that the fields might evolve faster away from their source region or that they are generated further away from the axis of the laser, as corroborated by other experimental studies [11]. A modeling effort was undertaken to properly describe by simulation the heat deposition and B-field generation and evolution.

We performed then a comparative study between more recent experiments, with new outcomes of the improved simulation code. This comparison has eventually shown for the first time a B field topology that was surprisingly different than what was obtained by previous models. This is shown in Fig.6.

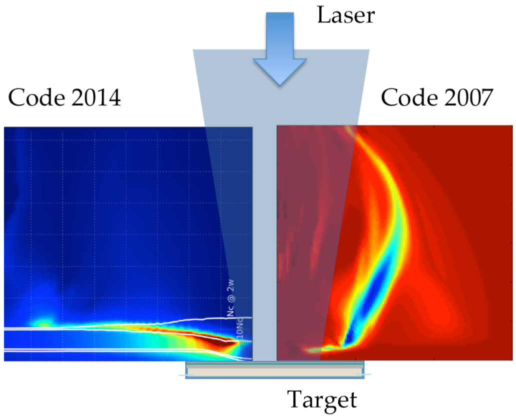

Figure 6. Comparison between the fields topologies as obtained by the improved model (left) and the previous ones. The toroidal B-field extends radially on the target surface, with respect to the laser axis, but is compressed in a region of high plasma density. This topology is strikingly different to the one previously accepted of B-Field plume that is projected both radially and outwards with a large component along the laser axis in low-density regions

This new vision, possible thanks to the proton radiography measurements, and reached thanks to a proper treatment of the heat transport in those terms governing the B-field evolution, has been presented in a recently published paper [13]. It will contribute to a better understanding of the physics governing the heat deposition in ICF schemes.

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