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# Laser-plasma Interaction in Ignition Relevant Plasmas: benchmarking our 3D modelling capabilities versus recent experiments

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**Abstract.** We have developed a new target platform to study Laser Plasma Interaction in ignition-relevant condition at the Omega laser facility (LLE/Rochester)[1]. By shooting an interaction beam along the axis of a gas-filled hohlraum heated by up to 17 kJ of heater beam energy, we were able to create a millimeter-scale underdense uniform plasma at electron temperatures above 3 keV. Extensive Thomson scattering measurements allowed us to benchmark our hydrodynamic simulations performed with HYDRA [1]. As a result of this effort, we can use with much confidence these simulations as input parameters for our LPI simulation code pF3d [2]. In this paper, we show that by using accurate hydrodynamic profiles and full three-dimensional simulations including a realistic modeling of the laser intensity pattern generated by various smoothing options, fluid LPI theory reproduces the SBS thresholds and absolute reflectivity values and the absence of measurable SRS. This good agreement was made possible by the recent increase in computing power routinely available for such simulations.

## 1. Introduction

Modeling laser-plasma interaction (LPI) processes in real-size experiments has been recognized as a challenging task. One of the main difficulties is the vast parameter space in electron density, temperature and spatial scales that are typically spanned by an ignition relevant laser-plasma experiment on current laser facilities. This leads to a plethora of (usually coupled) LPI processes such as filamentation, parametric instabilities, nonlocal heat transport. Another issue is the description of the spatially smoothed laser beams used on all modern facilities, which exhibit intensity structures from the hundreds of microns down to the micron scale. There are two main branches to numerical modeling approaches for LPI. Particle-in-cell or Focker-Plank type codes solve consistently a set of Maxwell-Vlasov-like equations and are limited to short timescales (picoseconds), small plasma volumes (typically one laser speckle) or low dimensionality (1 or 2 dimensions). While 3-dimensional PIC simulations of diffraction limited short pulse experiments are becoming common thanks to increasingly powerful computers, long pulse (nanosecond) ignition scale (cubic millimeter) LPI experiments are still out of reach for such numerical tools. The second approach is to use a fluid-based description of LPI processes. This allows relaxing both spatial and temporal resolutions and no discretization in particle velocity space is required. The goal of this paper is to describe progress we have made following this path over the last five years.

In part 2, we will review recent progress in both target design which is providing plasma conditions closer to NIF hohlraums, and simulation capability which has evolved from mainly 2D simplified simulations to full 3D simulations of Stimulated Brillouin Scattering (SBS) over a millimeter-scale target and a realistic spatially smoothed laser beam. Part 3 details these latest results.

## 2. Recent progress with experimental and simulation platforms

One of the grand challenge of LPI studies is to provide guidance for the design of hohlraum targets on the next generation of laser facilities for ignition attempts (NIF, LMJ). As Fig. 1 shows, the laser

beams will have to propagate through multi-millimeter subcritical plasmas at electron temperatures up to 6 keV. Currently, the Omega laser (LLE) is best suited for such studies. It can typically deliver up to 30 kJ of heater beam energy on target to preheat the plasma before an interaction beam is used to probe the plasma. Experiments[3] that studied LPI at 0.527 nm in 2002 using open-geometry targets (gasbag) reached  $T_e = 2$  keV over  $L = 1$  mm. Using a closed-geometry (hohlraum) target[4], where the interaction beam is fired along the axis, allowed for better coupling, for which  $T_e > 3$  keV was reached over  $L = 1.6$  mm. In 2004, the first experiment[5] on NIF-early-light (NEL), using 4 of the 192 NIF beams with a total of 15 kJ of energy allowed for the first time to reach interaction lengths greater than 6 mm, but  $T_e$  was below 2 keV. Finally, in 2007, 5-mm-long hohlraums with equatorial holes (to allow coupling of an additional 15 beams) reached  $T_e = 3$  keV and  $L = 5$  mm at Omega. All these gas-filled targets were designed to obtain an electron density  $N_e$  around 6 percent of the critical density at  $0.351 \mu\text{m}$ , which corresponds to the initial density fill in NIF point design hohlraums. This series of targets thus provides a good platform for validating the LPI modeling capabilities that are being used to quantify the LPI risk of ignition hohlraums.

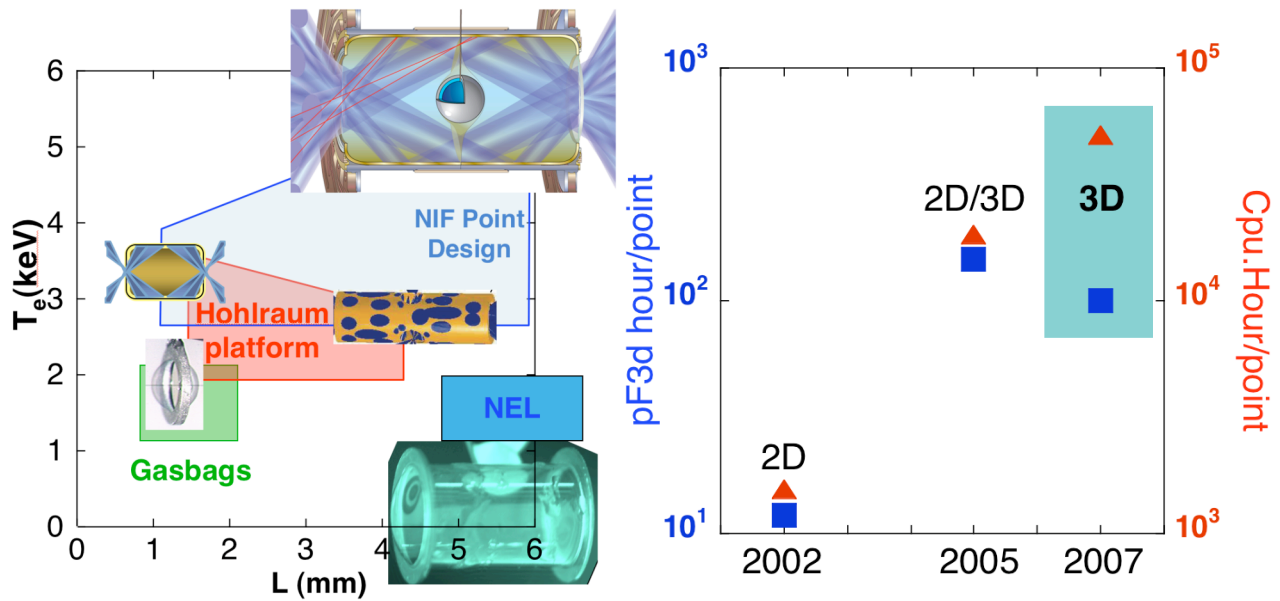


Figure 1. (left): our LPI target platform has evolved since 2002 in order to reach ignition relevant plasma conditions. Going from an open geometry (gasbag) to a closed geometry (hohlraum) allowed us to reach  $T_e > 3$  keV at Omega. Coupling more energy into the target increased the interaction length to 5 mm. (right): at the same time, progress in numerical algorithms and increasing computing power routinely available enables for the first time full three-dimensional simulations of LPI processes for Omega experiments in 2007.

Our modeling capability has also made significant progress since 2002. We use the fluid code pF3d [2], which includes a nonlinear hydrodynamics package coupled to a paraxial solver for the laser propagation. Stimulated Brillouin and Raman instabilities are modeled with enveloping in both time and space, using linear kinetic corrections to the fluid limit. Advanced beam smoothing schemes (double polarization, spectral dispersion) are accurately described. Pf3d is massively parallel and scales up to thousands of processors. Modeling a typical Omega LPI experiment requires simulating a plasma volume of  $500 \times 500 \times 2000 \mu\text{m}$ , which requires a few billion numerical cells. While this limited us to a two-dimensional (2D-planar) approach circa 2002, three-dimensional (3D) heat



of magnitude. While agreement for large reflectivity doesn't constraint much the modeling as it is dominated by whole beam pump depletion, one should note that using a simplified plasma profile (i.e. a uniform slab) or neglecting coupling between filamentation and SBS can lead to much larger simulated reflectivities. Also, the plasma is long enough so that a large reflectivity (15%) are seen

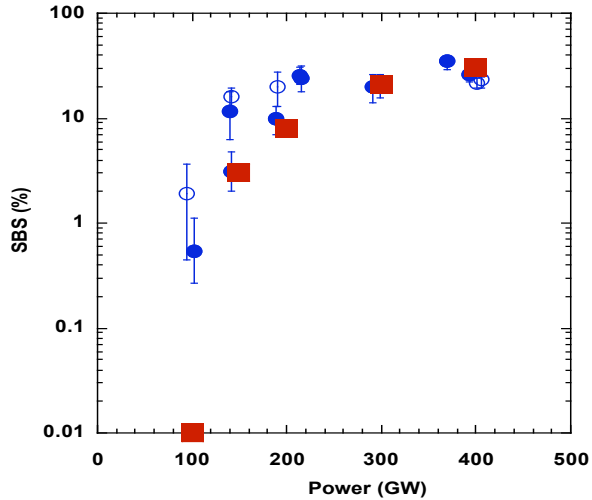


Figure 3: Measured (blue circles) and simulated (red squares) instantaneous SBS reflectivity at 700 ps as a function of laser power. Using 3 Å of SSD (open circles) had no measurable effect.

while the amplitude of driven acoustic waves remains modest ( $\delta n/n_e < 1\%$ ) and kinetic-type nonlinearities such as trapping or wave-breaking are unlikely to play a significant role. Simulations show that the SBS threshold around 150 GW is determined by an interplay between whole beam amplification enhanced by its large contrast and SBS seeding from a few self-focusing intense speckles. This threshold can be quite sensitive to plasma parameters and beam model, thus providing a strong validation of our modeling capabilities for SBS. Using 3 Å of SSD bandwidth has no measurable effect on SBS, both in the experiment and in simulations, as it is in a strongly damped regime and saturates before the speckle pattern can change. SRS was below measurement threshold for all powers and negligible in simulations too ( $< 10^{-4}$ ).

#### 4. Conclusion

While developing a predictive modeling capability for LPI remains a challenge, we have made a significant step towards that goal by using a detailed description of the plasma conditions and the laser beam intensity pattern as input to full 3D fluid-based LPI simulations done with our massively parallel code pF3d. This experimental validation is for now limited to stimulated Brillouin backscatter in a regime where kinetic effects are not expected to play a significant role (long hot plasma at moderate density and laser intensity). This is a regime of interest for forthcoming attempts at ignition on NIF and LMJ.

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