Toward a Predictive Capability on Laser-Plasma Instabilities in Inertial Confinement Fusion

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Lasers are primary drivers for high-energy-density (HED) experiments in laboratory. In the last 15 years, laser-driven HED experiments have brought many new discoveries in inertial confinement fusion (ICF), new extreme states of matter, particle acceleration, new radiation sources, and laboratory astrophysics. Understanding how laser energy couples to targets is a grand challenge in itself and is also a critical part in any laser-driven HED experiments. The physics of laser-plasma interactions is multi-scale, highly nonlinear and often kinetic. Advances in this field require interactive corporation between experiments, simulations, and theory.

The rich physics of laser-plasma interactions varies greatly depending on laser intensities and plasma conditions. *Here we focus on opportunities and challenges in ICF-related parametric instability study*. Recent ignition campaign on the National Ignition Facility (NIF) did not achieve ignition. The NIF designs represent our current best ideas to achieve ignition, and now we need to find new paths to ignition. Even after ignition, new ICF designs have to be discovered to make fusion a practical energy source. For this we need to redouble our efforts in understanding all aspects of ICF, including laser plasma instabilities (LPI).

However, the NIF ignition campaign and concurrent HED research did bring us new tools, data, and understanding of LPI. Today, a wealth of data exists on experiments with ignition-scale plasma sizes and laser energies. Fluid simulations are able to simulate laser propagation in mm-scale plasmas in 3D and the results in many cases agree with experiments. They are routinely used in hydro codes to predict the performance of target designs. Particle-in-Cell simulations are able to explore nonlinear kinetic physics in LPI with unprecedented realism and depth. We are on the verge of utilizing these new understandings to build a predictive capability of LPI in ICF.

The challenge of developing such a capability has its roots in the vast temporal and spatial scales in LPI's, from the hydrodynamic scales of *ns* and *mm* to the laser scales of sub-*fs* and sub-μm. It is necessary to build reduced description models that contain the relevant physics and can be computed efficiently. Here we want to identify two areas where significant progress can be made toward building such a capability. The first is *integrated comparison between simulations and experiments to identify key physics of LPI*. Significant progress has been made toward convergence between experiments and simulations on important LPI properties such as reflectivities, due to development of more direct experimental diagnostic and more

realistic simulations. However significant discrepancy exists regarding some important physics such as hot electron generation. Further convergence requires continues improvements on diagnostics and more faithful representation of experiments, including finding missing physics, in simulations. This can be for example full 3D geometry, inclusion of collisions in PIC codes, and more realistic representation of laser beams including speckles in simulations. A more subtle and interesting issue is how to couple simulations at different scales self-consistently. First-principle codes such as PIC are supposed to have all the necessary physics for LPI. But their predictions depend on the plasma temperature and density profile, which are taken as input and are from hydro simulations. However, those hydro simulations often use an overly simplified model for laser energy coupling and thus lead to incorrect plasma profiles. To make progress, we need to develop more direct measurements of the plasma conditions in experiments and iterative coupling of PIC and hydro codes. This way we can be certain to have the same conditions in the experiments and simulations. Only then can we use any found discrepancies to identify missing physics.

The second area is *how to incorporate all relevant LPI physics efficiently into a model for reliable target design.* State-of-the-art fluid codes such as pF3D have had considerable success in assessing beam scattering and reflection in mm-scale plasmas but still need improvements. Recent studies in direct-drive ICF show that all major parametric instabilities, i.e. stimulated Raman scattering (SRS), stimulated Brillouin Scattering (SBS), and two-plasmon decay (TPD) can couple through pump depletions and cross-beam energy transfer, especially in the high intensity regime of shock ignition. In particular, TPD is important both as a source for hot electrons and as a laser energy sink. Including TPD may mandate development of new fluid models. It is necessary to include fuller nonlinearities to obtain correct saturation level for the instabilities since TPD can be absolutely unstable. Kinetic physics such as hot electron generation has to be incorporated correctly. With many modes interacting, we may have to give up enveloping and solve the full wave equations instead. No doubt these will increase computation load and code complexity. However, with the constantly rapid increase of computer power, now may be a good time to develop new codes with physics that is proven to be relevant by experiments and first-principle codes.

Previous investments have brought us ever closer in achieving ignition in ICF. We should continue to invest in this area, increase our knowledge and utilize it to develop new design tools, and also train new generations of researchers, who will find novel ways to achieve fusion as a practical energy source.