Understanding the Nonlinear Physics of Laser-plasma Interaction through *"At-scale"* Plasma Kinetic Simulations on Roadrunner

Lin Yin, Brian J. Albright, Kevin J. Bowers[1] XCP-6; Ben Bergen, CCS-2
[1]Guest scientist currently with D.E. Shaw Research, LLC, New York, NY 10036

In 2010, inertial confinement fusion (ICF) experiments commence at the National Ignition Facility (NIF). In these, over a million Joules of laser energy are focused within a gas-filled hohlraum. The hohlraum walls absorb the laser energy and re-radiate it as X-rays, which absorb in a spherical capsule at the hohlraum center. This causes the capsule to compress, bringing the deuterium-tritium fuel to the high temperatures and pressures required for thermonuclear fusion.

To prevent the hohlraum walls from ablating during the ~10^{-8}s laser drive, a fill gas of hydrogen or helium is used. As the laser propagates through the fill gas, laser-plasma instabilities (LPI) may arise, which scatter laser light out of the hohlraum, degrade capsule implosion symmetry, and preheat the fuel with hot electrons, making compression harder to achieve.

Stimulated Raman scattering (SRS), the resonant amplification of electron density fluctuations by a laser, is one of the LPI concerns in ICF. In ICF experiments, a roughly uniform laser intensity is maintained across the beam with random phase plates that break the beam into an ensemble of laser speckles. For the success of fusion experiments on the NIF, we must first understand the physics of onset and saturation of SRS in the fundamental building block of a NIF laser beam, a single laser speckle. In a laser speckle, SRS manifests as the amplification of a forward-directed electron plasma wave (EPW) and the backward scattering of laser light. Unlike the linear growth of SRS, the nonlinear physics was not well understood

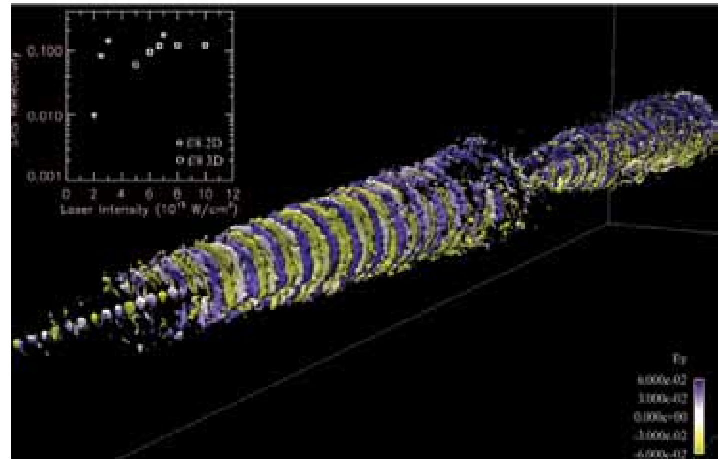

Fig. 1. Single-speckle LPI calculations using 16 CU of Roadrunner (11,520 ranks), nearly the full system; this calculation employed a record 0.4 trillion particles, >2 billion cells, and ran for nearly 58,160 time steps (~10^{19} floating point operations), long enough for two bursts of stimulated Raman scattering to grow from noise to significant amplitude at a laser intensity near the SRS onset. The inset shows the scaling of SRS reflectivity vs. laser intensity for 2D and 3D VPIC calculations; in 3D, the onset threshold is higher, owing to increased diffraction and side loss of hot electrons from laser speckles.

until recently [1,2]. Roadrunner has been used to assess the impact of the nonlinear SRS physics on laser penetration and energy deposition in fusion experiments. These fully kinetic plasma simulations employ the VPIC particle-in-cell code [3-6] and are performed in large plasma volumes in 3D at unprecedented range of time and space scales.

Until recently it has not been possible to simulate fully the comparatively large 3D plasma volumes of laser speckles. With VPIC on Roadrunner, simulations of the NIF holhraum plasma have been done using 4096 IBM Cell Broadband Engine (Cell BE) chips at a range of laser intensity values (see the inset in Fig. 1). These simulations [7] showed that SRS reflectivity within a solitary speckle exhibits nonlinear behavior: a sharp onset at a threshold intensity, whereby reflectivity increases abruptly to a level orders of magnitude higher than linear theory predicts over a small range of intensity, with a plateau in reflectivity at higher laser intensity in which SRS nonlinearly saturates; this generic behavior matches that measured in single speckle experiments at the LANL Trident Laser facility [8] with physics that cannot be captured by linear gain models of SRS growth within the speckle.

As a highlight of the unique simulations afforded by Roadrunner, the largest of these calculations was run on 16 connected units (CU) using 11,520 ranks, nearly the full Roadrunner system, and employed a record 0.4 trillion particles, over 2 billion computational cells, and ran for nearly 58,160 time steps (~10^{19} floating point operations), long enough for two bursts of stimulated Raman scattering to grow from noise to significant amplitude at a laser intensity near the SRS onset. Figure 1 shows isosurfaces of electrostatic field associated with these bursts; the wave fronts exhibit bending or bowing, arising from nonlinear electron trapping, as well as self-focusing, which breaks up the phase fronts.

The essential nonlinear physics governing SRS saturation has now been identified. The scattering manifests as a series of pulses, each of which passes through four distinct phases: 1) SRS grows linearly from density fluctuations, 2) electrons trapped by the EPW reduce the wave frequency and phase velocity by an amount that scales with EPW amplitude, 3) near the speckle center, where the amplitude is highest, the EPW phase velocity is lower than at the speckle's edge–EPW phase front bending ensues as shown by the top image in Fig. 2, and 4) the EPW wave amplitude exceeds the electron trapped particle modulation instability (TPMI) threshold [9,10]. TPMI generates waves off-axis from the laser direction and leads to EPW filamentation, self-focusing, and phase front breakup, shown by the bottom image in Fig. 2. Self-focusing increases transverse loss of trapped electrons and increases EPW damping.

From these basic science simulations, researchers are now able to better understand the essential nature of LPI nonlinear onset and saturation. Current research focuses on determining whether neighboring speckles can interact via exchange of hot electrons or waves to produce higher backscatter than they would individually, the kind of study only possible on Roadrunner, where at-scale kinetic simulations of laser-plasma interaction in 3D at realistic laser speckle and multispeckle scales can be prosecuted at unprecedented size, speed, and fidelity.

For more information contact Lin Yin at lyin@lanl.gov.

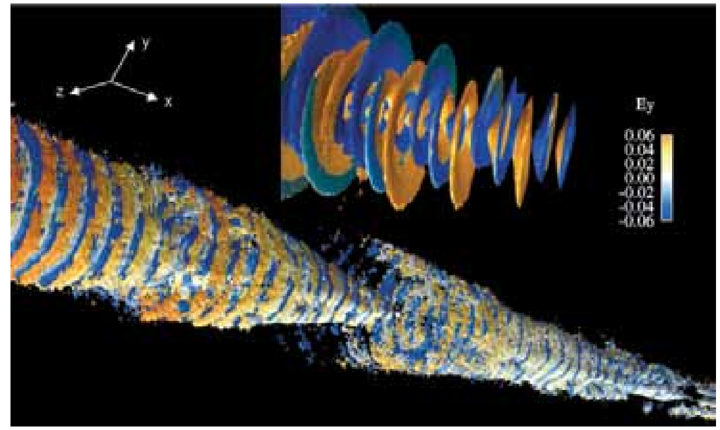

Fig. 2. (Top) A snapshot taken from a 3D VPIC LPI simulation at SRS pulse saturation of a f/4 laser beam, showing bending of iso-surfaces of EPW electric field across the speckle. The iso-surfaces are colored by the laser electric field intensity, graphically showing the source for SRS back-scatter has become incoherent. (Bottom) Self-focusing and filamentation in two bursts of SRS, a snapshot taken from a 3D VPIC LPI simulation of a f/8 laser beam. The speckle volume is 16x larger than the f/4 simulation, permitting more transverse self-focusing modes to develop. This leads to chaotic EPW phase variation across the speckle. This further reduces SRS source coherence and increases wave damping, quenching the SRS pulse.

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