PETASCALE SIMULATION OF HIGH-ENERGY-DENSITY (HED) PLASMAS

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EXECUTIVE SUMMARY

The UCLA Plasma Simulation Group has been using Blue Waters since its inception to apply our own suite of kinetic simulation tools, including the particle-in-cell (PIC) code OSIRIS and the Vlasov–Fokker–Planck (VFP) code OSHUN to probe fundamental physics relevant to current HED (high-energy-density) plasma experiments, including those at the Facility for Advanced Accelerator Experimental Tests at the U.S. Department of Energy's (DOE) SLAC National Accelerator Laboratory and the National Ignition Facility at Lawrence Livermore National Laboratory. In the past 12 months, the results of these petascale simulations have appeared in high-impact journals such as *Physics of Plasmas* and *Physical Review Accelerators and Beams*. Blue Waters has allowed the UCLA Simulation Group to perform petascale simulations in a timely manner and to train students in HED physics and high-performance computing.

RESEARCH CHALLENGE

The goals of the UCLA Plasma Simulation Group and its collaborators continue to be focused on three key areas funded by NSF and DOE. The key research questions are:

- Can plasma-based acceleration be the basis of new compact accelerators for use at the energy frontier, in medicine, in probing materials, and in novel light sources?
- Can laser–plasma interactions be controlled or even harnessed in inertial fusion energy-relevant plasmas?
- What are the collective processes responsible for the formation of shocks in collisionless plasmas? Are collisionless shocks in plasmas responsible for the most energetic particles in the universe?

METHODS & CODES

In the above problems, the systems are highly nonlinear and cannot be easily described by fluid models, and kinetic effects can play important roles. Therefore, particle-in-cell (PIC) models are ideally suited for their study, where Maxwell's equations are solved on a grid using current and charge densities, and the particles' orbits are calculated using Newton's laws. The UCLA Plasma Simulation Group and its collaborators at IST in Portugal maintain a large number of PIC codes, including OSIRIS, QuickPIC, and UPIC. These codes are all developed locally, share many of the same algorithms and data structures, and have been optimized for heterogeneous leadership-class supercomputers such as Blue Waters. All of these codes are open access, and both QuickPIC and UPIC are open source (on GitHub).

RESULTS & IMPACT

Using the tools described here, we continue to perform large-scale simulations to study the various issues facing current experiments in plasma-based accelerators and inertial confinement fusion. In the past 12 months, we have performed very large 3D and quasi-3D simulations of laser wakefield accelerators (LWFAs) in plasma down-ramps. Our simulations showed that the plasma down-ramp can decelerate the energetic electrons in the transverse direction, leading to a beam with very low emittance. Furthermore, the density down-ramp has a chirp in the accelerating gradient that compensates the energy chirp in the accelerated electrons, leading to an overall low energy spread. Our 3D simulations show that in a density down-ramp, electrons with ultra-high brightness ($> 10^{20} A^{-2} rad^{-2}$) and low overall energy spread (< 1MeV) can be generated using either an electron beam or a laser pulse driver, which makes this a promising candidate to drive X-ray free-electron lasers (FELs) with nanometer wavelengths [1].

Furthermore, 2D OSIRIS simulations with realistic laser beam optics [including beam smoothing techniques such as SSD (smoothing by spectral dispersion) or ISI (induced spatial incoherence)] have shown that, for sufficiently large temporal bandwidth (where the frequency bandwidth of the laser beam is comparable to the growth rate of the laser–plasma instability), laser–plasma instabilities (LPI) can be reduced under conditions relevant to current inertial fusion energy experiments [2]. These simulations are very relevant to ongoing experiments, yet at the same time, they explore fundamental kinetic effects in plasma physics, making them ideal for training students and postdocs.

WHY BLUE WATERS

The UCLA Plasma Simulation Group has been a user on Blue Waters since the very beginning. Blue Waters has continued to provide a very stable high-performance platform for the study of kinetic effects in high-energy-density plasmas. This stability has allowed us to perform a large number of petascale simulations that will help experimentalists produce brighter X-ray sources using X-FEL (using LWFAs) and produce higher-yield targets in inertial fusion experiments.

PUBLICATIONS & DATA SETS

Xu, X.L., et al., High quality electron bunch generation using a longitudinal density-tailored plasma-based accelerator in the three-dimensional blowout regime. *Phys. Rev. Accel. Beams*, 20 (2017), p. 111303.

Wen, H., F.S. Tsung, B.J. Winjum, A.S. Joglekar, and W.B. Mori, Kinetic Simulations of Reducing Stimulated Raman Scattering with Temporal Bandwidth in Inertial Confinement Fusion. In preparation (2018).

Wen, H., Petascale kinetic simulations of laser plasma interactions relevant to inertial fusion—controlling laser plasma interactions with laser bandwidth. *The 3rd International Conference on Matter and Radiation at Extremes*, Qingdao, China, May 2018.

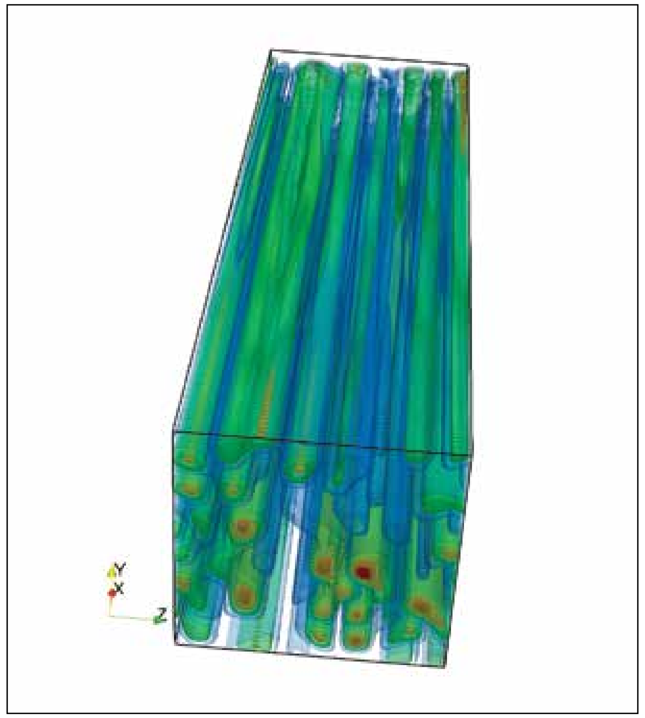

Figure 1: Spatial distribution of beam intensity from 3D OSIRIS simulation of laser–plasma interactions relevant to inertial confinement fusion. The pattern mimics the effects of optical elements that are present in current fusion experiments and is important for achieving quantitative agreement among simulations and experiments.