PARTICLE-IN-CELL SIMULATIONS OF KINETIC EFFECTS IN HED PLASMAS

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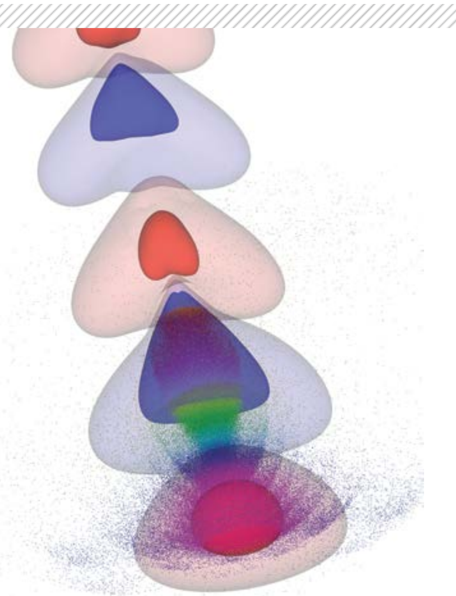

FIGURE 1: Streamlines and QuickPIC simulations of the two bunch experiment that appeared in Nature in November 2014. The figure shows the parallel electric fields and the two electron bunches. The bunch in the front is in a decelerating field and loses energy, and the trailing bunch in the back is in an accelerating field and gains energy. Using this setup, experimentalists at SLAC have both high accelerating gradient and high energy-transfer efficiency using the plasma wakefield accelerator (PWFA) concept.

EXECUTIVE SUMMARY:

Using a suite of particle-in-cell codes developed within the UCLA Plasma Simulation Group, we have been using Blue Waters to address important questions in high energy density (HED) plasmas, which are critical to the success of experiments at the SLAC National Accelerator Laboratory and the National Ignition Facility (NIF). Access to Blue Waters has allowed us to perform very large simulations in a timely manner and has provided key insights into ongoing experiments.

INTRODUCTION

The UCLA Simulation of Plasmas Group has been using particle-in-cell (PIC) simulations on parallel computers for nearly 30 years to study basic plasma science and to answer compelling science questions. This effort has involved unraveling complicated nonlinear plasma science, attempting to solve science problems of national importance, developing a robust suite of parallel PIC tools that run efficiently on a wide range of platforms, including the largest computers in the world, developing novel reduced PIC models, benchmarking these codes against theory and experiment, developing data visualization and analysis tools, and keeping abreast of relevant applied math and applied computer science research.

Currently, the research of the group and the OSIRIS consortium is focused on two key science areas, with clearly developed science questions; this research is funded by the Department of Energy (DOE) and the National Nuclear Security Administration (NNSA). The questions are:

1. Can laser plasma instabilities be controlled or even harnessed in inertial fusion plasmas?

2. 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?

Using Blue Water resources, we have made significant progress in these areas.

METHODS & RESULTS

Our research employs the particle-in-cell (PIC) method, where Maxwell's equations are solved on a grid using current and charged densities calculated by weighing particles onto the grid; each particle is pushed to a new position and momentum using relativistically correct equations of motion. The UCLA simulation group is a leader in the development of high-performance PIC codes and was awarded a Software Infrastructure for Sustained Innovation (SI2) grant by NSF.

Using our suite of locally developed codes on Blue Waters, we have published two papers in the journal *Nature* in the past 12 months. In one paper (published in November 2014), a plasma wake-field acceleration (PWFA) with two electron bunches demonstrated high efficiency (~30%) and high-quality electron beams (with energy spread as low as 0.7%) using plasma-based accelerators.

In the second paper (published in August 2015), physicists demonstrated the acceleration of positrons using plasmas and demonstrated 5GeV energy gain using only 1.3 meters of plasma. The ability to transfer energy makes the PWFA scheme very attractive as an energy booster to an electron-positron collider. Simulations performed on Blue Waters were critical in providing key insights in these experiments.

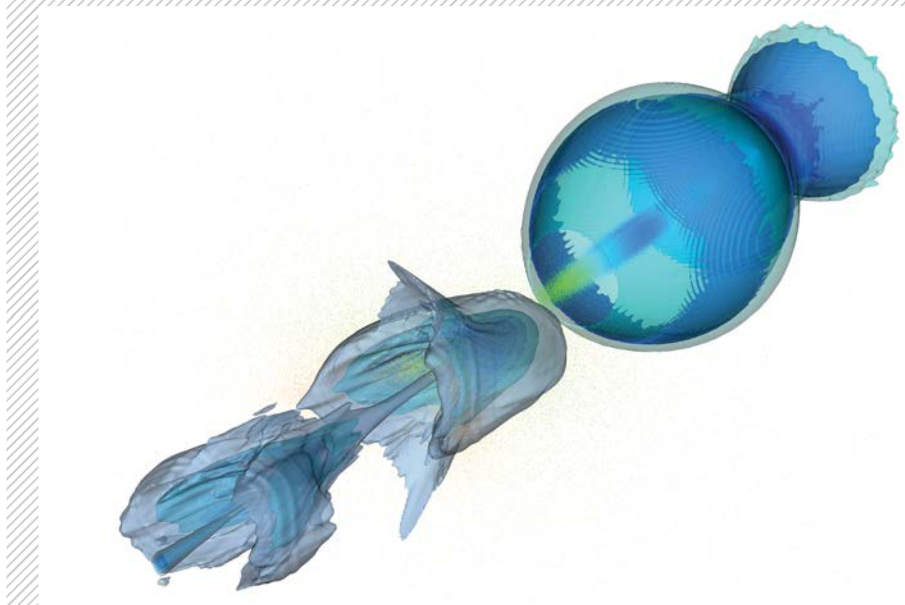

FIGURE 2: A future particle collider based on plasma wakes will need high-gradient, high-efficiency acceleration of both electrons and positrons, as seen in this computer simulation. Now positron acceleration by using wakes produced by a positron beam as it propagates through a plasma has been demonstrated. This figure shows wakefields generated by electrons (right) and positrons (left).

Blue Water is also invaluable in the study of laser plasma interactions in plasma-based accelerators and laser fusion. In a paper published in *Physical Review Letters* in July 2014 we have shown that, using a low-intensity pre-pulse to build up the plasma response in front of the main pulse, the leading edge of the main pulse does not diffract and facilitates the main pulse to reach a self-guided state that remains stable for more than 10 Rayleigh lengths. These simulations use more than 150 million grids and 300 million particles for close to 2cm of plasmas. Simulations of this scale can only be performed on a Track-1 supercomputer.

Lastly, using Blue Water we have performed 3D simulations that gave insights in understanding the formation of relativistic electron rings in laser-wakefield accelerators (LWFAs). 3D simulations on Blue Waters showed that electrons trapped in the second wave bucket become defocused when it moves into the decelerating region of the second bucket. As it becomes more defocused, it moves into a small stable region behind the first bucket, which traps these electrons and forms the rings observed in the Lawrence Livermore National Laboratory experiments. The process is highly nonlinear, and insights gained from the 3D simulations performed on Blue Waters were critical in the understanding of, and ultimately the control of, ring formations in future LWFA experiments.

WHY BLUE WATERS

Having Blue Waters access has allowed us to make quantitative comparisons between simulations and experiments (like those published in *Nature*) and allowed us to perform very large simulations that cannot be done elsewhere.

PUBLICATIONS

Litos, M., et al., High-efficiency acceleration of an electron beam in a plasma wakefield accelerator, *Nature* 515:92 (2014)

Tzoufras, M.; F.S. Tsung, W.B. Mori, A.A. Sahai, Improving the Self-Guiding of an Ultraintense Laser by Tailoring Its Longitudinal Profile, *Physical Review Letters* 113:245001 (2014).

Corde, S., et al, Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield, *Nature* 524:442 (2015)

Pollock, B.B., et al, Formation of Ultrarelativistic Electron Rings from a Laser-Wakefield Accelerator, *Physical Review Letters* Volume 115, Issue 5, Article Number: 055004 (2015) (OCI-1036224)