PARTICLE ACCELERATION IN LASER-DRIVEN MAGNETIC RECONNECTION

Samuel Totorica, Stanford University
2015-2016 Graduate Fellow

RESEARCH SUMMARY

Magnetic reconnection is a fundamental plasma process that converts magnetic field energy into plasma energy through the breaking and rearrangement of magnetic field lines [1]. The energy released as the magnetic field changes topology drives plasma flows, heats the plasma, and accelerates particles to high energies. Reconnection is ubiquitous in magnetized plasmas, occurring in systems in space physics, astrophysics, and the laboratory. It is believed to play a key role in frontier problems in physics including the origin of cosmic rays and has important implications for applications with a societal benefit such as space weather and nuclear fusion energy.

Observations of high-energy astrophysical sources such as pulsar wind nebulae, gamma-ray bursts, and jets from active galactic nuclei often indicate rapid energy dissipation and efficient particle acceleration, and the environment of these systems is commonly thought to be a magnetized plasma. As an efficient mechanism for dissipating magnetic energy in a plasma, reconnection is a promising candidate for producing the non-thermal particle distributions inferred to be present in these systems. However, the efficiency of reconnection in accelerating non-thermal particles and its dependency on plasma conditions remains poorly understood, and it is currently an active area of research to determine whether reconnection can account for the astrophysical observations.

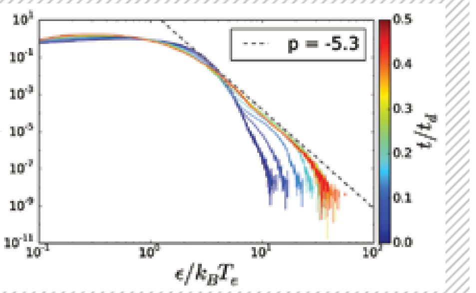

FIGURE 1: Temporal evolution of the electron energy spectrum for a simulation with typical laboratory conditions.

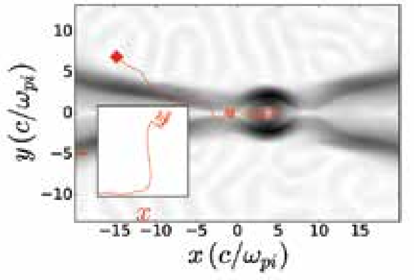

FIGURE 2: Example trajectory of an energetic electron over the magnitude of the magnetic field. Inset shows the energy of the electron as a function of position.

As a result of the national inertial confinement fusion program, high energy laser facilities have been developed that can ablate extremely hot and dense plasmas when focused onto solid targets. The conditions produced are in a regime where ohmic dissipation is negligible, enabling the use of scaling laws to study astrophysical phenomena. Experiments performed at these facilities study astrophysical processes, several of which have investigated magnetic reconnection. The expansion of two nearby ablated plasma bubbles can drive reconnection between self-generated or externally-imposed magnetic fields. Several features of reconnection have been observed in these experiments, however, none of these previous studies have addressed non-thermal particle acceleration, an important signature of reconnection for connecting to systems in astrophysics.

The goal of our research is to use first principles particle-in-cell (PIC) simulations to investigate particle acceleration from magnetic reconnection can be studied in laser-driven plasma experiments using the state-of-the-art PIC code OSIRIS [2]. The results of our simulations clearly indicate that laboratory experiments can play an important role in the study of particle acceleration by reconnection. For current experimental conditions, we show that non-thermal electrons can be accelerated to energies up to two orders of magnitude larger than the initial thermal energy (Fig. 1). The non-thermal electrons gain energy primarily by direct acceleration from the reconnection electric field near the X-points (Fig. 2), while particle injection into the reconnection layer and escape from the finite system establishes a distribution of energies that resembles a power-law spectrum. Energetic electrons can also become trapped inside the plasmoids (magnetic islands) that form in the current layer and gain additional energy from the electric field arising from the motion of the plasmoid. Based on our findings, we provide an analytical estimate of the maximum electron energy and threshold condition for observing suprathermal electron acceleration in terms of experimentally tunable parameters. These results pave the way for laser-driven plasmas as a new platform for the experimental study of particle acceleration induced by reconnection, which could help illuminate the role reconnection plays in explosive phenomena associated with space and astrophysical plasmas.

Also, we are developing a **novel** algorithm that holds potential for reducing noise and computational expense in PIC simulations. Interpreting the simulation particles as the vertices of an unstructured mesh that traces the evolution of the distribution function in phase space enables a discretization using deformable phase space volume elements rather than fixed-shape particles [3]. This new perspective retains fine-scale structure in the distribution function and may reduce the number of simulation particles required. We are currently using this method as a novel post-processing technique (Fig. 3), and future work will involve implementing it directly in PIC simulations to reduce noise and unphysical artifacts.

WHY BLUE WATERS

Simulations used for quantitative comparison with laser-driven plasma experiments must bridge the multiscale physics, from fluid dynamics to kinetic microscopic processes. These computationally demanding simulations can only be performed using the cores, memory, and communication performance of large-scale resources like Blue Waters. The fast response time of the NCSA staff to technical issues allowed for maximum productivity on the machine. I plan to continue to use high power computing systems to study problems in plasma physics and develop improved plasma simulation methods with an eye towards next generation machines.

PUBLICATIONS AND DATA SETS

Totorica, S. R., T. Abel, and F. Fiuza, Nonthermal electron energization from magnetic reconnection in laser-driven plasmas. Phys. Rev. Lett., 116 (2016), p. 095003.

Samuel Totorica is in his fourth year of the Physics Ph.D. program at Stanford University. He plans to graduate in spring 2018 with the goal of continuing research in computational plasma physics in a national research center.

“[In such a setting] I could have access to large-scale computer resources, contribute to projects with societal benefit, and interact closely with experimentalists,” says Totorica, “I hope to continue to develop novel plasma simulation methods, and apply them to support nuclear fusion efforts as well as explore astrophysical scenarios and how they can be tested in the laboratory. Access to Blue Waters has allowed me to gain experience and proficiency in performing large scale plasma simulations at an early stage in my career, and the high impact research it enabled me to perform has helped me to establish myself in the field of plasma physics.”

FIGURE 3: Charge density from a 2D simulation of the Weibel instability, rendered using standard CIC particles (left) and the new method (right).