White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing "P" in right column.
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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	S
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• Plasma self-organization	S
• Statistical mechanics of plasmas	S

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	X
Poster	
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Title:	**Particle acceleration in shocks: from astrophysics to the laboratory *in silico***
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Research frontier and importance of the scientific challenge

The universe is filled with energetic particles, cosmic rays, with energies as much as 8 orders of magnitude higher than those produced in terrestrial/laboratory accelerators. The mechanisms behind these cosmic accelerators remain a mystery. It is known that collisionless shocks, which are closely associated with the propagation of intense streams of particles in plasmas, are a source of cosmic rays. However, how the particle acceleration mechanisms depend on the plasma conditions and on the physics of shock formation and magnetic field amplification is not yet fully understood. This requires a detailed understanding of the plasma microphysics of streaming instabilities and shocks for conditions that range from weakly to highly magnetized, from non-relativistic to highly relativistic. It also requires a critical understanding of the interplay between the physics at the small scales and the global dynamics of the systems.

The fast progress in laser technology is bringing the study of high-velocity collisionless shocks into the realm of laboratory plasmas, where the associated microphysics can be probed directly in a controllable manner and properly scaled to astrophysical environments. Large-scale particle-in-cell (PIC) simulations can capture the kinetic physics of laser-driven shocks from first principles, and thus play a critical role in such experimental studies by (i) characterizing the dominant plasma processes that lead to shock formation and particle acceleration, (ii) identifying the optimal laboratory configurations for the study of such processes, and (iii) modeling the experimental observations.

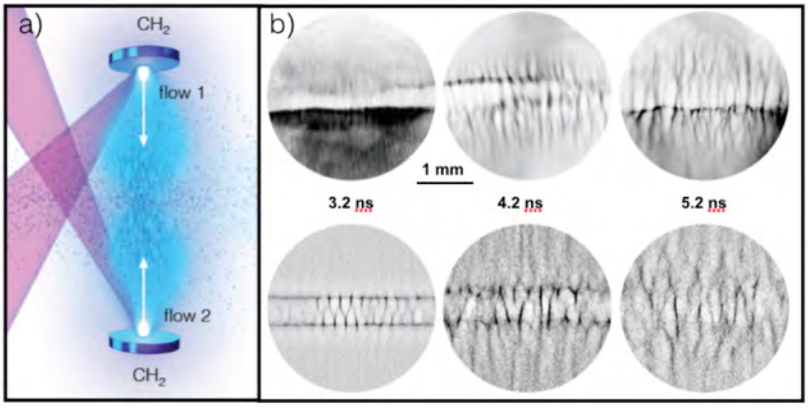

Figure 1. Study of magnetic field amplification through the ion Weibel instability in counter-streaming collisionless plasmas [2]. (a) Experimental configuration at the OMEGA laser facility. (b) Comparison of experimental (top) and PIC simulated (bottom) proton radiographs of the interaction showing generation and evolution of filamentary magnetic fields associated with the Weibel instability. The 3D OSIRIS PIC simulations model the interaction of the counter-streaming flows for measured plasma parameters as well as radiography process self-consistently requiring 128,000 computing cores.

The synergistic development of experimental and first principles simulation tools can offer groundbreaking insights into the physics of collisionless shocks and particle acceleration in plasmas, provide a test bed for models of cosmic ray acceleration, and lead to the development of efficient plasma-based acceleration schemes for terrestrial applications.

Approach and tools

The approach proposed to study the microphysics of collisionless shocks and particle acceleration is to develop well-diagnosed laser-driven plasma experiments and integrated fully kinetic simulations that can model realistic laboratory configurations. High Mach number plasma flows can be created in the laboratory from the interaction of intense lasers with matter [1]. The plasma conditions can be varied by using different targets and laser parameters. External magnetic fields can be applied to control the initial plasma magnetization.

On the numerical level, massively parallel fully kinetic PIC simulations have now developed to a stage where they can be used to model in 3D the interaction of these flows for appropriate laboratory conditions [2,3] and in some cases also model the self-consistent plasma generation for the relevant experimental time [4]. These simulations should be used to study counter-streaming plasmas for different conditions (flow velocity, plasma temperature, magnetization, ion species) and characterize (i) the plasma instabilities that lead to formation of collisionless shocks, (ii) the dominant particle acceleration mechanisms in these shocks, and (iii) magnetic field amplification by accelerated particles. Results will provide a clear understanding of the dominant plasma microphysics processes associated with particle acceleration in shocks and their signatures for different plasma conditions. This understanding can then guide the design of experimental configurations where laser-driven flows are used to study these processes. However, this requires important additional developments, namely (i) coupling the kinetic physics to the MHD evolution of the experimental system either using multiple codes or integrated massively parallel PIC simulations, (ii) including Coulomb collisions in the simulations to determine the conditions for which they do not affect the evolution of the microphysics of the system, and (iii) modeling experimental diagnostics for direct comparison with data (e.g. interferometry, proton radiography, angularly resolved particle spectra). Recently, this approach has been successfully used to characterize magnetic field amplification through the Weibel instability in laser-driven counter-streaming collisionless

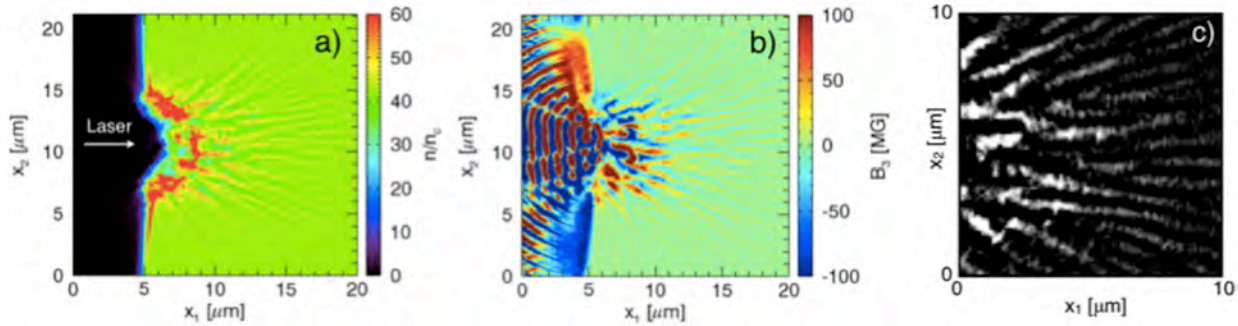

Figure 2. *Ab initio* PIC simulation of the Weibel/current filamentation instability driven by relativistic electrons produced in the interaction of the MEC/LCLS short pulse laser with a 20 μm hydrogen plasma. (a) Density and (b) magnetic field profiles are clearly correlated and show the development of regular filaments with density perturbations δn/n ~ 50% and magnetic field amplitudes up to 100 MG. (c) Reconstructed plasma density structure from simulated PCI diagnostic for LCLS x-ray parameters.

plasmas [2] (see Fig. 1). The same approach can be used with equal success to model different plasma conditions and processes associated with shock formation and particle acceleration.

On the experimental level, it is important to develop the required tools and diagnostics in the laser facilities that can have the strongest impact in the field. Experiments at NIF and OMEGA can benefit from the high laser energy to drive non-relativistic collisionless shocks for large dynamical time scales and capture particle acceleration processes. However, it is critical to develop good diagnostics to probe the plasma evolution in terms of density, velocity, and fields with high spatial (10 microns) and temporal (100 ps) resolution. The MEC end station of LCLS offers unique conditions to probe relativistic streaming plasmas and the associated shock formation and particle acceleration mechanisms. The short pulse high-intensity laser can drive the relativistic flow and the coherent x-rays from LCLS can probe the associated fast plasma dynamics with the required spatial (1 micron) and temporal resolution (10s fs) (see Fig. 2). However, in order to drive a fully formed collisionless shock and study particle acceleration the short pulse laser needs to be upgraded to higher power (PW) and energy (kJ).

Impact

The microphysics of collisionless shocks, particle acceleration, and magnetic field amplification is important to understand better the behavior of plasmas in both astrophysical and high energy density laboratory environments, and can ultimately lead to critical insights on the origin of cosmic rays. The coupling of laser-driven laboratory experiments with massively parallel fully kinetic simulations can provide this understanding. Moreover, by identifying efficient particle acceleration mechanisms in laser-driven plasmas one can envision the development of compact plasma-based accelerators for different applications with important societal impact, such as radiotherapy of deep-seated tumors [5,6].

References

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