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.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	P
• Interactions of plasmas and waves	S
• Plasma self-organization	P
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	x
Poster	
Either Oral or Poster	

Title:	Study of astrophysical collisionless shocks and particle acceleration with lasers
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(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)

- ***Describe the research frontier* and importance of the scientific challenge.**

Collisionless shocks are ubiquitous in space and astrophysical environments, and are believed to play an important role in the acceleration of energetic particles throughout the Universe. Astrophysical shocks span a wide range of shock speed, Mach number, and magnetization, and can occur in plasmas of varying composition (i.e., electron-ion or electron-positron plasmas). Despite their diversity, collisionless shocks share common characteristics: they are believed to efficiently accelerate nonthermal particles, drive turbulence, generate and amplify magnetic fields [Medvedev & Loeb 1999; Kato & Takabe 2008], and also decelerate supersonic flows. The degree of shock formation and particle acceleration depend strongly on the plasma dynamics, and it is therefore critical to understand the microphysical processes that affect the overall macroscopic evolution [Ji2015]. Laboratory experiments associated with high-velocity laser-driven plasma flows have the potential to mimic some of the astrophysical plasma conditions, allowing for the *in situ* study of the interaction of collisionless plasmas and the physics that mediates shock formation and particle acceleration. Study of collisionless shock formation, magnetic field generation and cosmic ray acceleration in the universe and in the laboratory will certainly produce high impact results for the plasma physics and astrophysics communities.

One example of collisionless shock formation may be in supernova remnant (SNR) SN1006, shown in Fig. 1. In this system, the Coulomb mean free path length is much larger (~40 light years) than the system size (~30 light years) where a very sharp shock front (~0.1 light years) is formed. This suggests

that the shock must be collisionless [Takabe 2008]. In general, this is often the case in astrophysical plasmas, where the mean free path for Coulomb collisions is typically very large [Sagdeev & Kennel 1991; McKee & Draine 1991]. There are two major conditions where collionless shocks are formed: Weibel mediated collisionless shocks [Weibel 1959] where self-generated magnetic fields are the major players; and the case of preexisting magnetic fields where plasma reflects off of the compressed magnetic fields creating collisionless shocks [Spitkovsky 2009]. These collisionless shocks are believed to be responsible for cosmic ray accelerations known as diffusive shock acceleration (DSA) [Blanford & Ostriker 1978, Bell 1978, Caprioli & Spitkovsky 2014]. This research covers both categories as well as the key role of these collisionless shocks on cosmic ray acceleration.

This research will study the microphysics of collsionless shocks created by counter-streaming interpenetrating plasmas generated by lasers. By studying individual plasma parameters in a controlled fashion, one will be able to understand the physics underlying the creation of collisionless shocks and the shock dynamics and particle acceleration associated with collisionless shocks. The basic requirements for creating collisionless shocks in the laboratory are that $l^* << l_{\mathrm{int}} << l_{mfp}$: that is, the shock thickness, l^*, determined by the electrostatic or electromagnetic (Weibel) instabilities, needs to be smaller than the spatial scale of the interacting plasmas (the experimental scale), l_{int}, and these lengths should be much less than the Coulomb mean-free-path length, l_{mfp} [Ryutov 2012]. Laser experiments are ideal for creating these conditions and conducting these experiments. Despite recent experimental progress [Huntington 2015, Kugland 2012, Fox 2013, Niemann 2014], this field is still struggling to understand the details of what has been observed in the experiments. One of the effects that must be better understood is the localization of the filamentary Weibel structures near the midplane of the interpenetrating streams and interaction of the filaments with the flow shear and advection effects. Understanding these issues will allow us to find conditions where the collisionless shocks will be propagating upstream from the midplane, creating a hot stagnation zone between the shocks and thereby replicating a canonical picture of collisional shock formation in two colliding streams.

It is critical to continue these experiments at various laser facilities to develop the required diagnostics and computing capabilities for enhancing our understanding of astrophysical collisionless shock physics as well as related plasma physics phenomena.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

The approach for this project is to create high-Mach number plasma flows via high power lasers. We will irradiate the inner surfaces of CH, C, and Be planar targets with various separations using high power lasers at the laser facilities. This will create counter-streaming collisionless plasmas at >1000 km/s with ion-ion (Coulomb) collision mean-free path length >> 1 mm. We will diagnose the interacting plasma flows, collisionless shocks, and self-generated fields with Thomson scattering, proton deflectometry, optical interferometry, neutron diagnostics, B-dot probes, and Faraday rotation diagnostics.

We will build upon our achievements in imaging techniques to detect fine electromagnetic features in the interacting flows [Kugland 2012; Kugland 2013, Huntington 2015. Park 2015] as in Figure 2 and to deconvolve 3-D field structures from 2-D images by further developing the interpretive tools created by our group [Kugland 2012b, Levy 2015] and by using multiple projections.

While the existing facilities have some of the necessary diagnostic capabilities, many new capabilities are needed to better diagnose the experimental signatures. Strong magnetic Helmholz coils are needed for studying magnetized plasmas. Low-energy proton and neutron spectrometers are critical to moving forward on understanding the cosmic ray acceleration mechanism. Time resolving plasma magnetic field diagnostics such as pulsed polarimeter are needed to understand the magnetic field evolution from these experiments. 3-D computational tools that include PIC and MHD capability are needed to better interpret the experimental results.

In order to understand collisionless shock formation in the laboratory laser experiments, new experiments to study the transition regime from collisional shocks to collisionless shocks are essential.

This topic is important not only to the astrophysics but also to the fundamental plasma physics. A couple of approaches are: 1) one relatively simple method is to use mid-Z targets such as Al or Cu to decrease the flow velocity and increase the ion densities; 2) use smaller foil separation. Interpretation of collisional vs. collisionless will utilize various diagnostics and simulations.

In order to create reliable collisionless shocks reducing the collisionality, we will attempt to develop targets made of LiD, Li and, possibly, pure D (the latter with the use of cryogenic deuterium coatings). The smaller Z of these materials will reduce collisionality and create much cleaner conditions for isolating the collisionless effects. By studying the energy spectra of test particles passing through the turbulence region, we will be able to infer the dynamical characteristics of the micro-turbulence generated in the interpenetrating streams. The test particles (both protons and relativistic electrons) are produced either by an external source (short-pulse laser illumination of targets), or generated *in situ*, by the proton branch of the DD reaction.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit***.

This project will provide a controlled laboratory platform for studying the formation and evolution of astrophysically-relevant collisionless shocks created by counter-streaming plasmas. Our results will provide fundamental and quantitative understanding of the basic physics mechanisms by which a high-velocity flow environment contributes to the evolution of astrophysical objects and the generation of high-energy cosmic rays. Both of these phenomena have been unsolved problems in astrophysics for more than half a century. Through this research we will be able to: 1) create a new scientific technique for studying astrophysical phenomenon in the laboratory under controlled conditions; 2) foster new younger generation scientists by attracting them with very new and challenging subjects; 3) further develop the basic plasma physics theory used in both fusion studies and astrophysics; 4) develop new plasma magnetic field diagnostics for the HED and ICF applications; 5) solve the challenges in computational physics of 3-D modeling designed to encompass the details of the basic physics theory and develop new algorithms in a 3-D particle-in-cell code to understand the experimental signatures of magnetic field imaging.

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Figures (maximum 1 page)

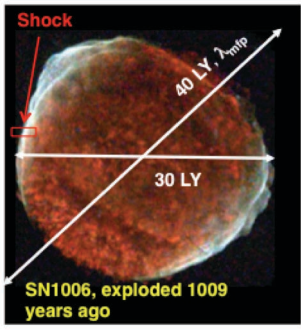

Fig. 1. Collisionless shocks are ubiquitous in space and in objects such as in this supernova remnant. In these systems, the Coulomb mean free path is much larger than the system and the shocks are generated by plasma instabilities.

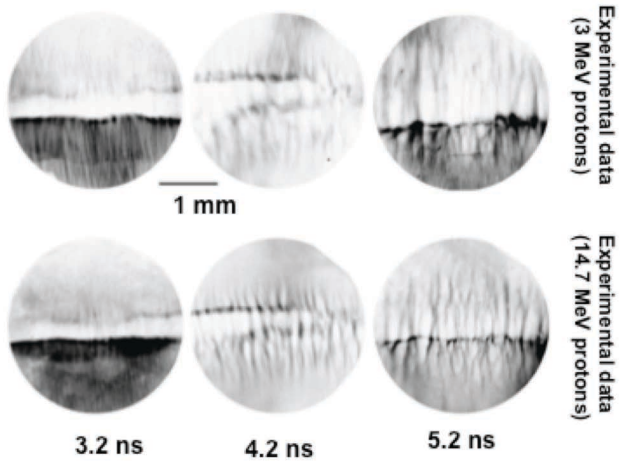

Fig. 2. Weibel instabilities observed in Omega experiments using D^3He imploding capsule generated protons (Huntington, Nature Physics, 2015)

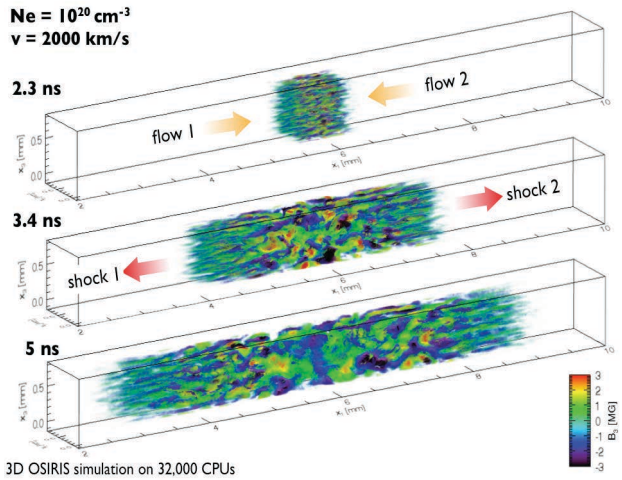

Fig. 3. Predicted Weibel evolution of NIF experiments by 3-D PIC simulation. Comprehensive simulation tools are essential to this research.