White Paper for *Frontiers of Plasma Science Panel*

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

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	"X"
Oral	
Poster	
Either Oral or Poster	
Will not attend	X

Title:	Experiments on Plasma Shocks and Related Topics Enabled by Merging Supersonic Plasma Jets
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- ***Describe the research frontier*** **and importance of the scientific challenge.**

The research frontier addressed in this white paper is the experimental study of plasma shocks and the closely related topics of plasma equation of state (EOS), atomic physics, and interfacial instabilities. These problems are all significantly enriched by the presence of magnetic fields as well as multiple (mid-to-high Z) ion species in various, partially stripped ionization states.

Modern experimental capabilities to produce both lower-density (e.g., plasma guns or translated FRCs) and higher-density (e.g., wire-array Z pinch or laser facilities) plasma regimes have opened up new opportunities to diagnose in detail the structure and dynamics of plasma shocks and the closely related topics mentioned above. In the author's opinion, the situation today in plasma-shock experiments somewhat resembles that of magnetic-reconnection experiments 20 years ago (at the inception of the "modern era" of laboratory reconnection research), at which time any detailed space- and time-resolved diagnostic measurements of a magnetic-reconnection layer in the high-Lundquist-number regime was entirely new and novel.

Two-fluid (i.e., electrons and one ion species) collisional plasma-shock theory was formulated long ago [1] and predicts that two-fluid plasma shocks should exhibit interesting and fundamental differences from gasdynamic shocks. Yet, the detailed two-scale structure (arising fundamentally due to the different rates of ion and electron thermal transport near a shock layer) and ambipolar electric fields of two-fluid plasma

shocks (Fig. 1) have yet to be definitively characterized in well-controlled and well-diagnosed laboratory experiments. Experiments (e.g., Fig. 2) are on the cusp of being able to do so, e.g., [2–7]. Challenges stem from the need to simultaneously generate energetic- and fast-enough flows to produce shocks while simultaneously generating spatial and temporal scales amenable to detailed experimental measurements. The remarks in this paragraph apply to both magnetized and unmagnetized two-fluid collisional plasma shocks. Furthermore, multi-ion-species effects on collisional plasma shocks (more on this below) is a forefront area of research in high-energy-density (HED) and inertial-confinement-fusion (ICF) plasmas.

Collisionless-shock research [8,9] also has a long history in space satellite measurements [10,11] within the Earth's magnetosphere, backed up by extensive theoretical foundations [12]. Two key open questions in collisionless-shock research pertain to the detailed nature of the microphysics that provide the dissipation mechanism(s) and that can explain the acceleration of extremely energetic particles found throughout the universe. Laser-produced-plasma experiments are presently the best venue for studying both magnetized [13] and (initially) unmagnetized collisionless-shock physics [14–16]. I expect that there will be at least one other white paper discussing collisionless-shock experiments in detail, and thus will not do so here.

In a plasma, shock physics is strongly influenced by the EOS, i.e., ionization state and the relationships among specific internal energy, density, and pressure. Plasma EOS affects the degrees of freedom analogous to varying the ratio of specific heats γ in gasdynamic shocks. By simple inspection of shock jump conditions in gasdynamic theory, one sees that shock structure and jump conditions depend strongly on γ. For this reason, one can hardly undertake a serious and accurate experimental study of plasma shocks without also paying careful attention to the plasma EOS. In HED plasmas, EOS has been studied in great detail (even for mixtures of mid- and high-Z ions), motivated largely by ICF research [17], although uncertainties still exist [18]. At lower densities (e.g., 10^{13} to 10^{16} cm^{-3}), especially for mixtures of mid- and high-Z ions, plasma EOS has not received as much attention, is more complicated [i.e., local thermodynamic equilibrium (LTE) does not generally apply], and models are not as well validated against experiment. Lower-density plasma-shock experiments, by necessity, will also provide a simultaneous venue to produce data on plasma EOS in non-LTE regimes and in complex mixtures. This type of data, e.g., [7], will be uniquely valuable for validating EOS and ionization models.

To experimentally infer plasma EOS likely requires spectroscopy to infer electron temperature T_e, electron density n_e, and mean-charge state *Zbar*; this brings in the further research topic of plasma atomic spectroscopy. Again, in mixed-species mid-to-high Z plasmas, dynamic spectral data provides the opportunity to validate time-dependent collisional-radiative models. For example, spectroscopy data in one set of experiments [7] (Fig. 3) suggested a fast dynamical rise in the *Zbar* of interpenetrating, colliding plasmas (of an argon/impurity or hydrogen/impurity mixture). The rate of *Zbar* rise was not easily explained by straightforward one-step processes of electron-impact nor ion-impact ionization between the colliding plasma jets. Explanation of the data remains an open question.

Finally, to produce plasma shocks, one will also typically produce accelerating (or decelerating) interfaces between colliding plasmas (Fig. 4). There may or may not be magnetic fields present at the interface. Non-uniformities at the interface and different densities across the interface will lead to Richtmyer-Meshkov (RM) and/or Rayleigh-Taylor (RT) instabilities. While these topics are well studied, especially in the context of ICF, significant complications arising from self-generated or applied magnetic fields [19], as well as interspecies diffusion inherent in multi-ion-species plasmas [20–22], can lead to significantly different interfacial evolution [23] compared to the predictions of widely used average-ion radiation-hydrodynamic models. Obtaining detailed time- and space-resolved experimental data on RM and RT instabilities (especially in the presence of finite viscosity and magnetic fields) will pinpoint where standard models in common use (both for fusion experiments and in plasma astrophysics) are deficient and where model development is needed.

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

As mentioned above, plasma-gun, wire-array Z pinch, and laser-based facilities are all able to advance the frontier in these areas. I focus my discussion here on the plasma-gun-based approach.

The Plasma Liner Experiment (PLX) [24,25] at LANL (Fig. 5), originally constructed under FES/HEDLP sponsorship to study a novel approach to forming plasma liners (via merging supersonic plasma jets) as a magneto-inertial-fusion (MIF) compression driver [26], operated with two plasma railguns in the 2012–2014 time frame. Experiments were conducted on obliquely [3,6] and head-on [7, 27] merging plasma jets, both with and without an applied magnetic field in the jet-interaction region. A Helmholtz coil [25] can be placed in the middle of the vacuum chamber to magnetize the interaction region between merging jets. Over the past few years, PLX was validated as a platform to study all the topics discussed in this white paper, except for collisionless shocks. Our inability (thus far) to study the latter was due to the high level of impurities in railgun-driven plasma jets, resulting in a higher *Zbar* than originally anticipated. Due to the $Zbar^{-4}$ dependence of the counterstreaming ion-ion collisional mean free path, we were not able to achieve the collisionless regimes expected had *Zbar* remained near unity [28]. However, as discussed further below, we will soon be installing coaxial plasma guns that should largely eliminate the impurity issue and enable collisionless shock studies via merging supersonic plasma jets.

Because the plasmas on PLX are generated by colliding supersonic plasma jets somewhere within a large 9-ft.-diameter vacuum chamber, PLX plasmas have the unique attributes of being (a) relatively energetic (even with just two plasma jets, can likely transiently reach T_e~10 eV, T_i~50 eV, and $n_e > 10^{15}$ cm^{-3}), (b) macroscopic (few to tens of cm), (c) relatively long lived (tens of microseconds), and (d) free of any wall/boundary effects. Under ARPA-E support [29] to pursue the objective of forming plasma liners as an MIF driver, PLX will be upgraded (over the next few years) to have up to 60 innovative shaped coaxial guns [30], which have far lower levels of impurities and the capability to go to much higher-velocity plasma jets (compared to 50 km/s of the railguns). We expect to be able to access collisionless shock regimes and a much larger variety of geometries enabled by the much larger number of plasma guns. The ARPA-E support will also add new diagnostic capability, mainly focused on the ability to diagnose higher densities and temperatures expected in experiments using a much larger number of plasma guns.

Thus, for the plasma-gun-based platform, the experimental capabilities will soon largely be in place to address all the topics discussed in this white paper. Of course, more sophisticated diagnostics, e.g., Thomson scattering and quantitative imaging diagnostics, as well as well-coordinated theory/modeling, are always desired but subject to resource limitations. Modeling tools, e.g., the electromagnetic PIC code LSP [31], are available to support such experiments in both design and interpretation (including generating synthetic diagnostic signatures for direct comparisons to experimental data).

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

This research, based on studies of plasma shocks and related topics enabled by merging supersonic plasma jets, advances a new and exciting area of plasma science, with deep ties to both discovery science, (e.g., plasma astrophysics [32]), fusion energy sciences (e.g., inertial fusion or MIF implosions, and also applications such as high-velocity core refueling of tokamaks [33]), and even industrial plasma applications (e.g., pulsed-laser deposition or laser-induced breakdown spectroscopy [34–36]).

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Figures

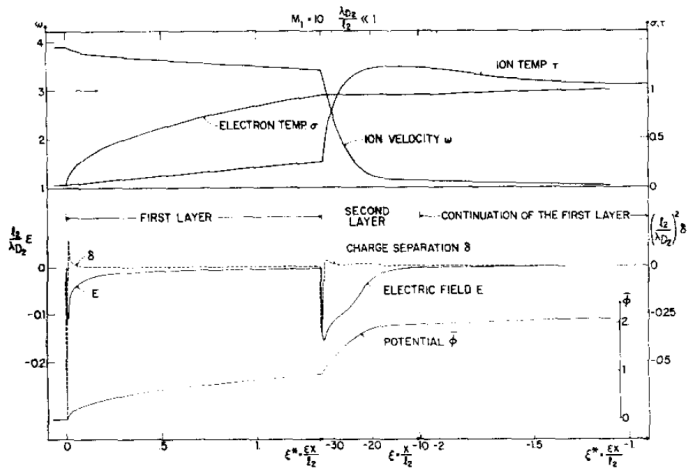

Figure 1. Distribution of flow and electrical variables through a 1D two-fluid plasma shock (*M*=10), from [1].

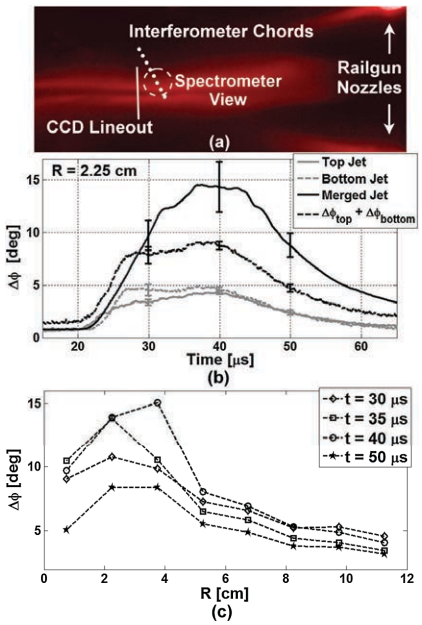

Figure 2. (a) CCD image of obliquely merging plasma jets (launched from top and bottom right) forming horizontal stagnation layer. Interferometer phase shifts show that (b) merged-jet density (second chord from bottom) exceeds the sum of that of individual jets and (c) density profile normal to the layer correlates with emission peak in CCD image. The double-peaked emission morphology in the CCD image is consistent with oblique plasma shocks [3]. Figure is from [3].

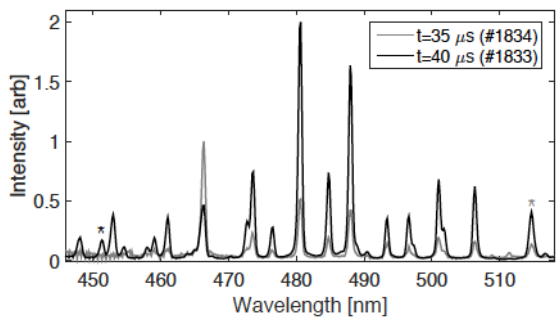

Figure 3. Spectroscopy data of the interaction region between head-on-merging argon/impurity plasma jets. The interaction begins as collisionless interpenetration followed by collisional stagnation. Changes in the spectra over 5 μs are used to infer changing conditions in n_e, T_e, and *Zbar* by comparing with detailed non-LTE atomic spectral modeling. Figure is from supplemental materials of [7].

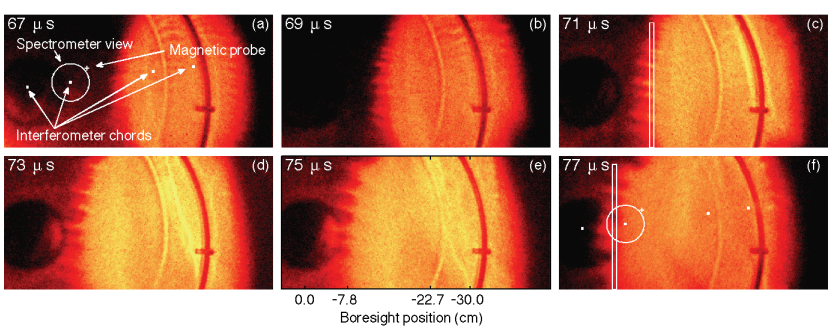

Figure 4. CCD images (from a single shot) capturing Rayleigh-Taylor-instability evolution between a high-velocity plasma (bright, coming in from right) decelerating against a stagnated magnetized plasma (dark, on left side of images). The instability wavelength is seen to evolve toward longer wavelengths; this is attributed to a combination of magnetic and viscous stabilization. Helmholtz coils generating an applied field into the page are visible in the images. Figure from [27].

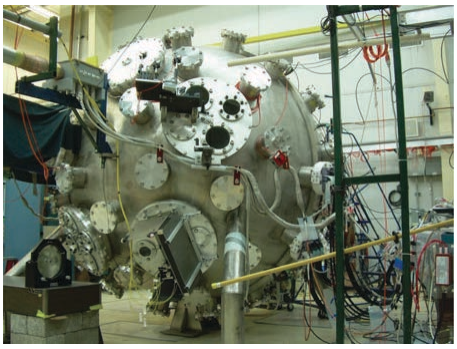

Figure 5. Photograph of the PLX vacuum chamber (2.74-m diameter), presently with two railguns installed. PLX will be upgraded to 60 coaxial guns under ARPA-E support. Photograph from [25].