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	
• Plasma self-organization	S
• Statistical mechanics of plasmas	

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

Title:	Laboratory Astrophysics using Pulsed Power Machines
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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.**

In most subfields of physics, controlled experiments are at the forefront of progress, allowing theoretical predictions to be tested and new phenomena to be identified. In contrast, most of what we learn about the astrophysical universe comes from the passive collection of photons and high-energy particles. For most of the history of astronomy, laboratory astrophysics has consisted primarily of atomic and molecular physics associated with line emission, elemental abundances, and spectra.

But most astrophysical sources are composed of ionized magnetized plasmas in bulk motion that subsequently dissipates, energizing particles that subsequently radiate. In recent decades, there been increased recognition that magnetic confinement devices and high energy density inertial confinement facilities can probe previously inaccessible high energy density regimes relevant to astrophysics. Magnetic confinement devices create low plasma β (i.e. thermal pressure/magnetic pressure) conditions to gain insight into processes operating in astrophysical coronae, while inertial confinement facilities can be used to probe highly supersonic and hot dense regimes of astrophysics more akin to the high β interiors of astrophysical objects, explosions, shocks and jets. While no astrophysical object will ever be produced in the lab, controlled experiments can and have been designed to test particular physical processes that thought to be operating within astrophysics sources. The enterprise is still young, but the new laboratory tools for this enterprise may revolutionize avenues for progress in the nonlinear physics of astrophysics, presently limited to theory and simulations.

Among inertial confinement facilities, pulsed power machines have so far provided plasmas with the most relevant parameter regimes for supersonic plasma astrophysics in which magnetic fields play a dynamically important role. Many aspects of astrophysical flows in stars, protostars, molecular clouds, protostellar outflows and accretion disks can be characterized by the magnetohydrodynamic (MHD) approximation with typical dimensionless numbers such as Reynolds (Re), magnetic Reynolds (Re_m) and Peclet (Pe) all exceeding unity. When experiments can achieve these regimes, the insight gained from the time evolution of the experiment can be directly applied to the astrophysical system with numerically scaled temporal and spatial scales[1]. The hydrodynamic Reynolds numbers achieved in pulsed power machines are Re ~ 10^5 – 10^6, which are much higher than even simulations can accomplish but closer to astrophysical values. The typical values of Pe ~ 20-100 and plasma β ranging from ~ 10^{-1} - 10^3. Although such high Re and Pe can also be achieved in purely laser-driven plasmas, pulsed power experiments stand out for their ability to reach high Re_M ~ 10-500>>1 regimes. For stand-alone laser driven plasmas, only NIF can be expected to achieve the equivalent regimes. The high-end values are comparable to the limits of many numerical simulations. Pulsed power experiments produce magnetic Prandtl numbers $Pr_M = Re_M / Re \ll 1$, characteristic of denser phenomena of high energy density astrophysics, although many processes of large scales flows may not actually be so sensitive to this ratio. By changing the composition of wires in Z-pinch arrays, the ratio of cooling times t_{cool} to dynamical flow times t_{cool}/t_{hydro} can be adjusted to be much less than or comparable to unity. All of this provides tremendous versatility.

To exemplify the opportunity and potential of laboratory astrophysics with pulsed power machines, we highlight (1) previous jet experiments (2) the frontier of supersonic, magnetized, colliding, radiative flows (Fig 1) and (3) the potential to study MHD turbulence.

(1) MHD Jets- Pulsed power MHD jet experiments focusing on instabilities in the central body of an MHD driven jet/cavity ([2,2a,3,4,5]) have shown that, despite growth of kink instabilities, radiatively cooling magnetized jets remain collimated (Fig 2). This has provided compelling insight into the long-standing question of why astrophysical jets emanating from systems such as young stellar objects keep their collimation over large distances. The experiments and associated simulations also showed that the core of the jets remained thermal pressure dominated while the cavity surrounding the jets is a magnetically dominated tower, containing the collimating toroidal field. This structure, possibly ubiquitous in astrophysical MHD jets, was first demonstrated experimentally by these pulsed-power experiments. The experiments also revealed that these jets accelerate non-thermal protons up to ~1MeV, making direct contribution toward explaining the origin of magnetized energetic particles (ions and electrons) in corresponding jet cavities of active galactic nuclei.

(2) Interacting Supersonic Magnetized Flows and Flow-Obstacle Interactions- Prominent examples of colliding magnetized supersonic flows occur inside astrophysical jets where new flow collides with earlier flow that has slowed either by instability or because the jet turns off and on intermittently (Fig. 1). The resulting jet "internal shocks" are common in protostellar jets, fundamental to explanations of knots in active galactic nuclei, and widely used to explain prompt emission of cosmological gamma-ray bursts. Such interacting flows also occur at "accretion shocks" where plasma in-falling toward the accreting stellar or galactic engine transitions from being nearly in free fall to being angular momentum supported. Another example of interacting flows is the interaction between stellar winds and planetary magnetospheres the result of which can disrupt planetary atmospheres and destroy conditions for habitability. Yet another context for such interactions is so-called "triggered star formation" that arises from the interaction of supersonic winds and stationary gas leading to cooling instabilities that trigger subsequent cloud collapse.

Astrophysically relevant supersonic colliding, magnetized flows can be created via ablation from a radial foil Z-pinch and conical wire configurations [6,7,8,9,10,11,12]. Typical flows might incur magnetic fields whose strengths correspond to β ~ 3, and Mach number ~10. Counter streaming colliding plasma jets can be created with two Z-pinches driven by the same current (Fig 3). The electrical connection of the two Z-pinches can be varied in such a way that embedded toroidal magnetic fields can be oriented in the same direction in both outflows or oppositely directed. This allows comparison of configurations favorable and unfavorable to magnetic reconnection (Fig 4). The comparison of particle acceleration for these two cases would be of great interest for a range of astrophysical contexts. Use of different foils allows for different ratios of cooling to dynamical times and investigation of astrophysically relevant cooling instabilities.

By placing obstacles in the paths of single jets, the interaction of supersonic plasma flows with obstacles can be studied. Such obstacles can be spherical, cylindrical, or planar, and oriented normal to the flow or at some oblique angle. Different wire arrays can be used for such experiments [13,14,15] . Properties of the bow-shocks, their stability and role of radiative cooling can be compared for cases of unmagnetized and magnetized obstacles. A dipole obstacle would be particularly useful for modeling interactions between magnetized plasma winds and planetary magnetospheres.

(3) MHD Turbulence in Radiative Plasmas- Experiments seeking to explore the transition to turbulence have been long standing efforts in HEDP [16,17,18,19]. A comprehensive study of MHD turbulence in the laboratory (for all ranges of plasma β) comprising an exciting set of frontiers of broad applicability to astrophysics--from the solar wind to galaxy clusters--requires the high R_M conditions that pulsed-power machines are best suited to provide. In the high β regime of stars, galaxies, and galaxy cluster plasmas, MHD turbulence and turbulent dynamo action (=magnetic energy amplification from stochastic field line stretching) is expected. Outflows from inverse wire array Z-pinches [20] provide the opportunity to generate MHD turbulence by introduction of obstacles into initially high R_M magnetized supersonic laminar plasma flows. If $Re{\sim}10^5$ and Re_M ~100 can be achieved, then MHD turbulence in regimes where small-scale dynamo action is expected might be achievable. Obstacles of different geometries would correspond to different "forcing functions" of the turbulence. This can be compared against numerical simulations and would be very high profile laboratory astrophysics work.

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

Implementation of an adequate suite of plasma diagnostics is critical for all these studies. While astrophysical insights can be gained from the lessons learned in experiments, there is also feedback in the other direction, stimulating innovation of new diagnostic techniques.

Schlieren and shadowgraphy imaging are sensitive to the density gradients and allow measurements of the evolution of the spatial fluctuations of the electron densities, while interferometry can measure the line-averaged distributions of the electron density. Measurements of ion feature Thomson scattering spectra, performed in multiple positions along a probing laser (as in [20,21,22,23,24]), allows local measurements of temperature and flow velocity variations in the and possibly plasma turbulence. Line-averaged magnetic fields can be measured by Faraday rotation [24] to assess large scale self-organized magnetic fields. Proton radiography may be able to measure smaller scale magnetic structure as can miniature magnetic probes (Bdots).

But even with all of these promising techniques, obtaining a detailed characterization of velocity, density, and magnetic field strength and spectra in turbulent HEDP plasmas with a large dynamic range is a challenge. Combined interest from astrophysics and fusion communities will be helpful toward stimulating progress in the associated diagnostic development. Development of new techniques for measuring high energy ion and electron acceleration spectra from e.g. shocks and reconnection events is also of similarly broad cross disciplinary interest.

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

Laboratory experiments allow benchmarking of both fusion plasma and astrophysical plasma codes. Comparing their results to each other and to experiments is a highly valuable enterprise. Most astrophysical MHD codes are run without testing against real experimental systems, and HEDP experiments provide this opportunity. Ultimately, such experiments will reveal more about the plasma physics to astrophysicists than observations alone since parameters can more actively controlled in the laboratory. The models validated in the laboratory will also augment the repository of plasma models which researchers in other branches of physics can use to better understand fusion experiments.

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Figures (maximum 1 page)

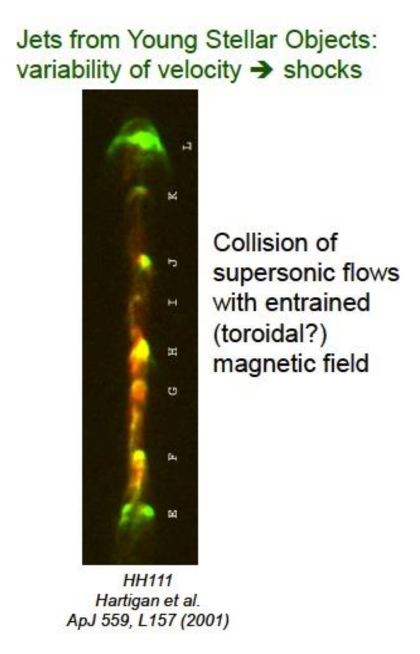

Figure 1. Colliding Flows in Young Stellar Jets. This hypersonic plasma flow is driven by a newly formed star at the base. Variations in ejection velocity produce the bright knots which represent colliding radiative magnetized flows in the frame of the jet's bulk motion.

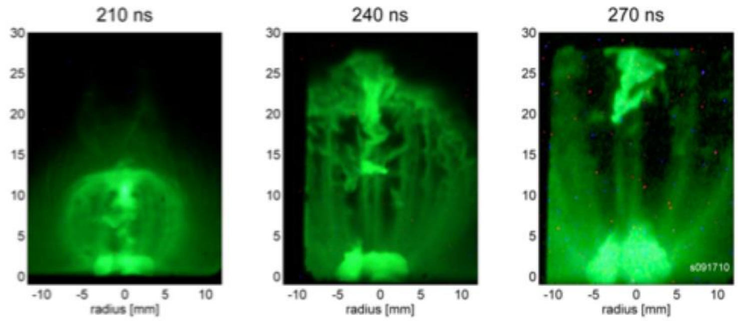

Figure 2. XUV images of evolution of MHD instabilities in the laboratory magnetic tower jet. (Lebedev et al 2005)

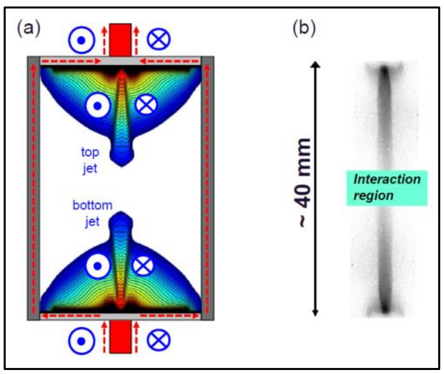

Figure 3. (Left) - Experimental configuration for counter-streaming magnetized plasma jets via two radial foil z-pinches driven by the same current; (Right) – XUV image illustrating high degree of collimation of the jets produced by radial foil z-pinches [Suzuki-Vidal et al, 2012].

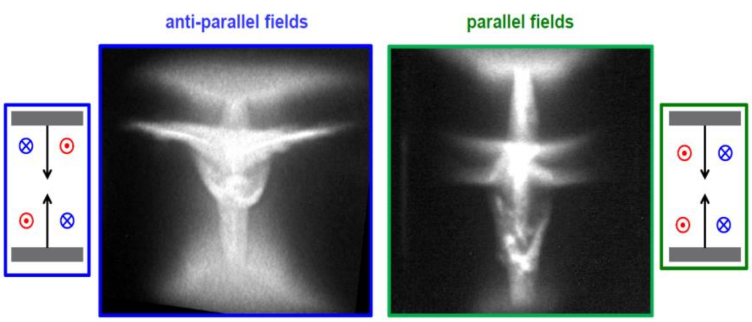

Figure 4. Gated optical images from preliminary experiments showing that orientation of the toroidal magnetic fields in the colliding flows has strong effect on the interaction. [Suzuki-Vidal et al, 2012].