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	
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

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

Title:	**Highly Non-linear instability development in HED and Magnetized Plasmas**
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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.**

Hydrodynamic and magnetohydrodynamic (MHD) instabilities have been investigated for decades due to their ubiquitous nature throughout the cosmos and in the laboratory. Experimental studies have typically focused on the growth of isolated, seeded perturbations and are rarely able to drive the instabilities to a degree where secondary instabilities begin to develop and cascade to turbulence[1-4]. As an example of this phenomenon, the Rayleigh-Taylor (RT) instability is believed to reach a saturated state where small bubbles merge to form large ones, but by itself cannot initiate turbulence[5-8]. However, shear created as the bubbles rise through the heavier fluid and spikes fall through the lighter fluid gives rise to the Kelvin-Helmholtz (KH) instability, which can lead to turbulence[5-8].

Instabilities are often responsible for redistributing matter from one location to another and possibly on all scales. Shock-driven instabilities are believed responsible for transporting material from stellar cores to the outer envelopes of supernova remnants[8-10]. Due to our limited theoretical understanding and modeling capabilities, we have little insight into how this material is transported on the

observed time scales. Various models are used to describe this transport and attempt to reproduce observations, but only experiments will be able to advance our current understanding.

During Inertial Confinement Fusion (ICF) implosions, material from the imploding shell can be mixed into the core, significantly reducing nuclear yields[11-12]. Current modeling cannot predict exactly how such mechanisms happen. As a result, sub-grid turbulence models are invoked to reproduce results[5,12]. Three-dimensional modeling is able to better capture this physics and reproduce diagnostic results, but sub-grid turbulent mixing is still required[13]. The ability to predict, and hopefully mitigate, instability development and resulting mix is crucial to the success of ICF.

Additionally, hydro-instabilities are of importance due to their possible role in producing and amplifying cosmic magnetic fields. For example, RT spikes can generate magnetic fields when misaligned density and temperature gradients are present[14]. If the flows are highly magnetized and become turbulent, the so-called small-scale dynamo effect can amplify the small seed field by the stretching and folding action of the turbulent fluid[15-16]. Additionally, the RM instability has been suggested as an effective mechanism to amplify ambient magnetic fields by similar mechanisms[17]. Therefore, understanding the detailed non-linear evolution of these instabilities in high Reynolds and high magnetic Reynolds number systems can shed light on the basic question of magnetic field production in the universe.

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

Presently, a wide variety of instabilities are studied on pulsed power drivers, laser drivers, and shock-tube experiments. Shock tubes cannot access regimes relevant to ICF or cosmic phenomena. Laser drivers can reach relevant conditions, but only over very small spatial scales (~10's -100's μm) and short time scales (~10's ns). These short duration experiments cannot drive growth long enough to reach stages of highly developed, non-linear secondary structures, and therefore they cannot drive turbulence[18]. Additionally, the small spatial scales involved require extremely high magnetic fields to produce magnetized flows making dynamo effects extremely difficult to probe. Pulsed power drivers offer the distinct advantages of larger spatial and temporal scales. Though they have produced some relevant results these experiments generally lack the diagnostics and shot frequency to adequately probe secondary instability growth.

To truly understand the non-linear development of these instabilities and the growth of secondary instabilities, it is necessary not only to study isolated perturbations but also pseudo-random structures that are typically found as the seed for instability in nature. These experiments must be driven for long time scales and reach a wide variety of regimes, e.g. purely hydro-dynamic, ideal MHD, resistive MHD, and kinetic. Additionally, they must be diagnosed with a variety of techniques. Radiography is traditionally used to investigate mode evolution, but has limitations. Spatial resolution is the most important requirement, as secondary instabilities grow on smaller scales than the dominant primary structure. Secondary structures must be adequately resolved, lest they be mistaken for turbulent mixing.

To investigate the transport of material, new techniques must be employed that can identify the concentration and location of various materials. Radiography can't uniquely determine the distribution of material concentrations. X-ray fluorescence imaging is a well studied technique in condensed matter

physics[19] which is just now being applied to high energy density plasmas to probe the distribution of high-Z materials. Additionally, x-ray absorption spectroscopy can probe the distribution and ionization state of materials in a time- and space-resolved manner[20,21]. Both of these techniques require extremely powerful x-ray sources to make the relevant measurements. X-ray fluorescence can make use of a line source to pump the desired emission, while absorption spectroscopy requires a smooth and bright continuum source.

Despite their utility in investigating material transport, the above techniques cannot distinguish between bulk flows of material and turbulent mixing below the spatial resolution of the instrument. To truly make this distinction, the velocity distribution of the flows must be probed directly. This may be accomplished through various scattering and emission spectroscopy techniques, but will likely require significant theoretical and diagnostic development to be employed successfully. Only when diagnostics are capable of measuring self-similar and isotropic flows at many scales will one be able to distinguish turbulence from highly complex, three-dimensional flows. Additionally, proton deflectometry will likely be required to investigate field amplification [22,23]. This technique requires a powerful short-pulse laser to produce high-energy protons whose deflection due to electric and magnetic fields is measured. This technique is capable of measuring the line-averaged spatial distribution of the field.

Existing pulsed power facilities can reach much of the desired parameter space, but work must be done to increase the Reynolds numbers. The bulk of the work required to advance these experiments lies in the diagnostic capabilities. Time and space resolved measurements are required. Due to the low shot rate of existing facilities (~1/day) it is crucial that multiple images be obtained on a single shot. This likely requires a large number of independent laser beams, each capable of generating the necessary x-ray flux and/or a detector capable of acquiring many images along a single line of sight. Though they do not currently exist, facilities capable of reaching the necessary conditions over the required time-scales that can operate at higher shot rate (>3/day) while also possessing the necessary diagnostic infrastructure will enable unprecedented progress in this area.

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

The evolution of instabilities and the associated question of turbulence are at the heart of a wide variety of disciplines. As previously mentioned, the ejection of matter into the interstellar medium via supernovae is highly sensitive to late stage instability development. KH and associated turbulence are routinely invoked to explain some of the magnetic field permeating the cosmos. The degree to which this is accurate depends on the quality of the models used. Inertial confinement fusion shows promise as a route towards fusion energy, as well as a platform to study stellar fusion physics and nucleo-synthesis[24]. Instabilities and mix are likely the key factors limiting performance to date. Currently, our best models cannot explain this without resorting to empirical tuning of the simulations.

The need for validation of these models in appropriately scaled laboratory experiments is obvious. The technology exists to begin exploring the parameter space and demonstrating what scaled experiments are feasible. The diagnostics required to make real progress either don't exist in the same location as the requisite facility or do not exist at all. Significant work is also needed to connect experimental data in a quantitative way to the models that require validation. For this step, we must work closely with the astrophysics community to design appropriate experiments that are able to contribute quantitatively. Experimental, diagnostic and computational capabilities must all converge on this problem in order to make progress.

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Figures (maximum 1 page)