White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***June 15, 2015***

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	S
• Turbulence and transport	S
• Interactions of plasmas and waves	
• Plasma self-organization	
• Statistical mechanics of plasmas	P

Indicate type of presentation desired at Town Hall Meeting.

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

Title:	**Nonequilibrium approaches to averaged properties**
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- ***Describe the research frontier*** **and importance of the scientific challenge.**

Research Frontier: Develop and test approaches to the theoretical and computational treatment of the averaged properties of nonequilibrium plasma systems.

Plasmas can rarely be said to be in thermodynamic equilibrium. Most often, the closest they come is to approach some steady state. Yet we typically analyze their behavior using averaged properties based on equilibrium statistical mechanics. Examples of such properties include specific internal energy, specific entropy, specific heat, and opacity. This may suffice for ideal plasmas, at least when they have simple constituents. In non-ideal plasmas, strongly radiative plasmas, or relativistic plasmas, however, the evaluation of these properties is not trivial and can be very sensitive to non-equilibrium behavior. In some cases, the value of some properties may be multivalued or may exhibit complex hysteresis behavior. One example of this is a plasma created from a porous foam, for which the relation of internal energy to pressure can have both these properties.

Yet to model complex systems involving such plasmas, one needs methods with which to address such issues. To date, there has been some progress using multiscale computational models,[1] of which much more is needed. But there has been only a little progress[2,3] in finding clever ways to understand the behavior that do not require vast computations. And progress toward experiments that can probe the underlying details, such as for example the nature of the internal motions in a plasma from foam or the evolution in time and space of the ionization state distribution, has been quite limited.

One example of the type of problem that is relevant here is the interaction of shock waves with plasmas containing velocity perturbations. Such perturbations, often described specifically as a vorticity field, would not be present in equilibrium. But they often arise, may even be turbulent, and can persist for relatively long times. And they affect the plasma properties and the behavior of shock waves. The Figure shows an example from one of the few works to consider this issue.[3]

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

Continuing advances in theory and computations are clearly needed, and need to be supported. There is enormous scope for innovation in both areas; it is very likely that the best approaches to these issues remain to be defined.

In experiments, the evident need is for plasmas changing in time, but at rates that can be diagnosed. The values and gradients in time and space need to be accurately measured. A central limitation for this topic will be diagnostics. Likely diagnostics include Thomson scattering, interferometry, and absorption spectroscopy. The facilities will need enough beamlines to provide plasma creation, perhaps perturbations of the plasma, and the diagnostics.

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

One of many ways in which 21st-Century plasma physics differs from mid-20th-Century plasma physics is in the creation and study of systems that cannot sensibly be described as small perturbations from some thermodynamic equilibrium state.

Work at this research frontier will impact a wide range of plasma research and applications. Any research with rapidly evolving plasmas may be affected, especially in the relativistic, radiative, and strongly coupled regimes. The applications that will benefit include ultrafast plasma systems, laboratory astrophysics at high energy density, the design of precise material preparation using plasmas, and inertial confinement fusion.

References (Maximum 1 page)

[1] N. R. Barton, J. V. Bernier, R. Becker, A. Arsenlis, R. Cavallo, J. Marian, M. Rhee, H. S. Park, B. A. Remington, and R. T. Olson, A multiscale strength model for extreme loading conditions, Journal of Applied Physics 109 (2011).

[2] G. Hazak, A. L. Velikovich, J. H. Gardner, and J. P. Dahlburg, Shock propagation in a low-density foam filled with fluid, Physics Of Plasmas 5, 4357 (1998).

[3] J. G. Wouchuk, C. H. R. de Lira, and A. L. Velikovich, Analytical linear theory for the interaction of a planar shock wave with an isotropic turbulent vorticity field, Physical Review E 79 (2009).

Figures (maximum 1 page)

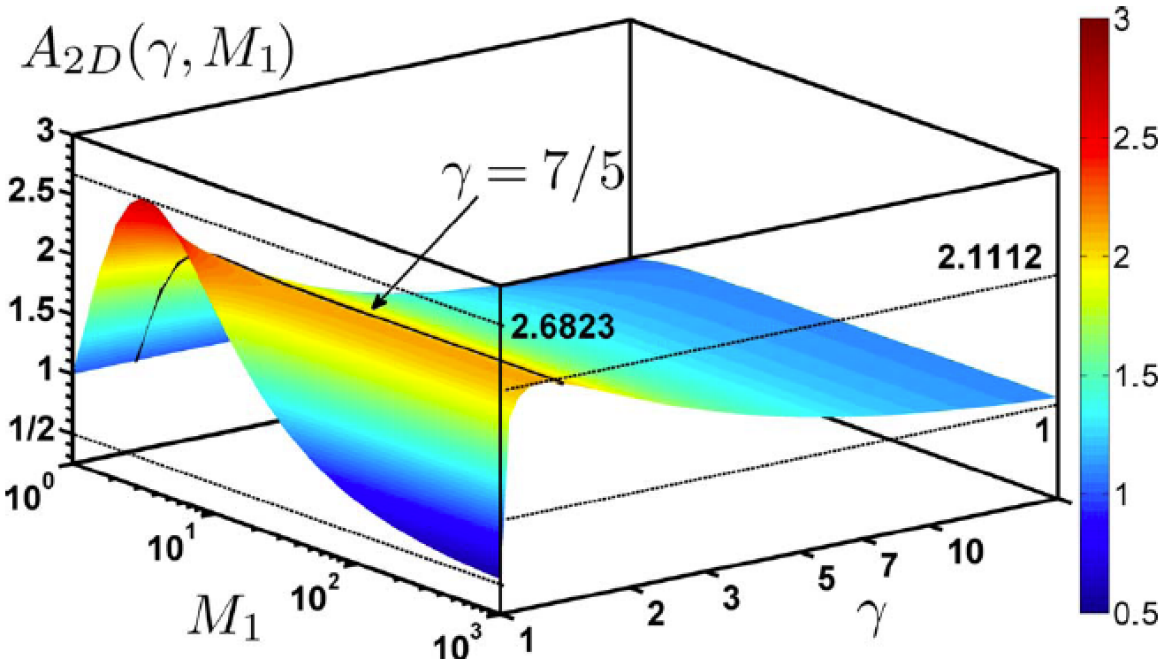

FIG. 30. (Color online) Kinetic-energy amplification factor for a shock interacting with a random 2D vorticity field, as a function of γ and M_1 [Eq. (184)].

Figure 1. Kinetic-energy amplification factor for a shock interacting with a random 2D vorticity field, as a function of adiabatic index γ and shock wave Mach number M_1. From Wouchuk et al. (2009).