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.
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| • Plasma Atomic physics and the interface with chemistry and biology | “P”, “S” |
| • Turbulence and transport | S |
| • 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 | Prefer |
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Title: The Energetics of Self-Organized 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.

The visible universe is dominated by luminous plasmas that conspire through multiple processes to organize themselves by the generation and sustainment of magnetic fields. These self-generated magnetic fields serve as a source of free energy that can be released spontaneously to accelerate and heat ions and electrons, to modify flows, and to generate turbulence that impacts the distribution and transport of particles, heat, momentum, and magnetic flux. Laboratory plasmas exhibit many of these same features, creating a ripe opportunity to elucidate the general principles that govern self-organized plasmas. The combination of new and existing experiments, observational platforms, plus ever-increasing computational capabilities create a growing frontier with potential for rapid progress.

While the commonality of self-organizing processes in natural and laboratory plasmas is well recognized, key open questions define a grand challenge and clear basis for future research: What principles govern self-organization in two-fluid and kinetic regimes, i.e., those characteristics uniquely associated with the plasma state of matter? What triggers the sudden release of stored magnetic energy through explosive
instability and how is the magnetic field energy apportioned among thermal and fast particles, heating and accelerating both ions and electrons? How do self-generated flows, fields, and particle energization feed back on the global structure and dynamics? Are there robust, simplifying principles that capture the complexity of strong nonlinear interactions, like magnetic helicity conservation? What are the consequences of boundary conditions, inhomogeneity, and geometry (x-points, resonances, etc.)? Can we develop multi-scale computational models that encompass all essential processes, that are validated by experiments, and that have reliable extension to astrophysical systems?

While the wealth of data provided by satellite instruments has allowed detailed characterizations of the stellar corona, the solar wind, and Earth’s magnetosphere, observational data is constrained to the particular characteristics of these plasmas. Laboratory plasmas afford the unique ability to vary and control external constraints on the plasma like geometry and boundary conditions. Since dissipation in many astrophysical plasmas is facilitated by means other than collisions, it is necessary to develop and exploit hot, collisionless plasmas that can be probed by diagnostics designed for the particular challenges of self-organizing processes. A true understanding of the underlying principles can then be demonstrated through the prediction and control of self-organized plasma dynamics.

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

To advance research on collisionless processes in self-organizing plasmas requires facilities for creating and diagnosing sufficiently hot plasmas that collisional effects are subdued. Confinement requirements and the desire for multiple decades between the driving and dissipation scales in a turbulent cascade dictate the need for facilities of sufficient scale. Self-organization processes like collisionless magnetic reconnection take place on fast timescales and often involve very fine spatial scales. Measurements at the relevant temporal and spatial resolution in the environment of a hot plasma represents a diagnostic challenge. As such, there is a need for intermediate scale facilities and effort at larger scale facilities to enable:

• Dedicated experiments that exhibit the individual processes involved in self-organization
• Experiments that fully integrate multiple self-organization processes
• Diagnostic development that meets the temporal and spatial requirements of collisionless dynamics and provides measurements of magnetic and electric field fluctuations and particle temperatures, velocities, and distribution functions
• Models of experimental scenarios that fully incorporate multiple processes that work in combination to determine the temporal dynamics and spatial structure of the plasma.

The diagnostic and modeling challenges are similar to those faced in fusion research creating synergies that exploit related physics, methodologies, and facilities. For example, configurations like the Reversed Field Pinch (RFP) and the Spheromak display dynamics that are governed by self-organization constraints [1-3]. In particular, the RFP is one of the best terrestrial laboratories for observing ion energization (both heating and acceleration), magnetic flux conversion, momentum transport, and a turbulent cascade from magnetic reconnection in high-Lundquist-number plasmas. Figure 1 illustrates the prodigious ion heating observed during the nonlinear phase of multiple interacting tearing modes as they release free energy available from the magnetic field. Between 10-30% of the stored magnetic energy is released within a 100 µsec burst of rapid magnetic reconnection. The resulting ion heating depends both on ion mass [4] and on the charge-to-mass ratio [5]. The heating is anisotropic with respect to the magnetic field with $T_\perp > T_\parallel$ [6]
and relaxes on the ion-ion collision time. Figure 2 illustrates the concurrent formation of a non-Maxwellian ion tail [7], and while measurements of x-ray fluxes associated with reconnection suggest the formation of a similar electron tail (Figure 3), the bulk electron distribution is cooled. A disparity in the correlated fluctuations experienced by ions and electrons may drive different transport losses for the two species.

Physics that is uniquely related to the plasma state of matter is critical to understanding self-organization. For example, the decoupling of ions and electrons on timescales shorter than a collisional time results in dynamics beyond the MHD description [8]. The impact on self-organization is especially clear in the generation of a dynamo-like Hall emf that arises as an important ingredient in the relaxation of both current and flow gradients [9-13]. Study of these two-fluid dynamics helps test and extend our understanding of dynamical constraints developed in the MHD framework like helicity conservation.

The above discussion illustrates how capturing the interrelationship of the multiple processes involved in experimental plasmas requires good coordination of many diagnostics. We can approach this scientific frontier by supporting the development and operation of well-diagnosed experiments to extend our knowledge of self-organization processes beyond MHD, particularly to address the role of two-fluid and kinetic effects. Likewise, understanding this interrelationship among multiple processes requires the development of integrated modeling capability that captures the interaction between MHD instabilities, fast particles, microscale fluctuations, and Alfvén waves in realistic geometries. Answering the questions posed above to create a predictive model for the energization of self-organized plasmas requires modeling that extends from the global scale where instabilities drive the turbulent cascade down to scales where dissipation mechanisms dominate. The impact of boundary conditions and inhomogeneity is certainly important in laboratory plasmas and likely underappreciated in many natural plasma settings. Multi-scale modeling with sufficient spatial and temporal resolution and physics breadth is a grand challenge on its own. We must develop this integrated modeling capability so that we can test its predictive power against data from both laboratory experiments and astrophysical observations. The tools we develop to address self-organizing laboratory plasmas can inform efforts at modeling astrophysical plasmas like the accretion disks, jets, and radio lobes that develop around compact objects like black holes [14].

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

Research on the energetics of self-organization has broad impact on our understanding of laboratory, space, and astrophysical plasmas. The dimensionless parameters typical of astrophysical plasmas often preclude one-to-one matching in a laboratory-scale experiment. Demonstrating predictive capability and control is critical to gaining a general understanding of how the multiple processes of magnetic field generation, reconnection, particle energization, and turbulent transport interact to determine the temporal dynamics and spatial structure of these plasmas. Such demonstrations connect the work of the plasma physics community more broadly across the space and astrophysical sciences and help to build awareness of developments in our field.

Diagnostic innovation for measurements in hot plasmas is spurred by the temporal and spatial requirements of self-organization processes. These innovations can directly impact developments in fusion. Control of self-organization processes enables optimization of plasma confinement and heating. Finally, the complexity and structures that evolve as plasmas undergo self-organization are beautiful in their own right and compel us to explain them.
References (Maximum 1 page)

Figure 1: An example of the conversion of stored magnetic energy to ion thermal energy due to rapid reconnection events in the RFP.

Figure 2: Measurement of neutral particle flux following rapid reconnection using a neutral particle analyzer illustrating the generation of a non-thermal tail in the ion energy distribution. The blue line indicates an exponential fit to the thermal distribution while the red line indicates a power-law fit to the non-Maxwellian tail.

Figure 3: Measurement of the X-ray energy distribution before, during, and after a rapid reconnection event. Lines are fits to quantify non-thermal emission due to fast electrons.