## White Paper for Frontiers of Plasma Science Panel

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**Title:** Center for Laboratory Study of Multiscale Turbulence: Understanding Cascades, Transport and Self-Organization in a Large, Adaptable, Steady State Plasma Torus

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Center for Laboratory Study of Multiscale Turbulence: Understanding Cascades, Transport and Self-Organization in a Large, Adaptable, Steady State Plasma Torus

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New Frontier in Magnetized Plasma Science

Progress in laboratory measurements [1], satellite observations [2-5], and scientific computing [6-12] has opened the possibility of achieving one of the most important challenges of plasma physics: predictive understanding magnetized plasma turbulence across an extreme range of scales. Turbulence in magnetized plasma involves anisotropic fluctuations, which interact nonlinearly and couple energy, momentum, and particle number through spectral cascades spanning four length scales: the global plasma size, \( L \), the injection scale, \( L_i \), the ion inertial length, \( \lambda_i \), and the particle gyroradius, \( \rho \). In astrophysical plasma, like the solar wind and interstellar medium, the ion inertial length and gyroradius are both very much smaller than both the plasma and injection scales. Energy cascades to small scale by way of a turbulent cascade of Alfvén waves [10-12]. In contrast, most laboratory plasmas, including low-\( \beta \) tokamaks, the inertial length is larger than the injection scale, and turbulence creates an inverse cascade [13-14] of modes (like drift-waves and flute-like interchange instabilities, and entropy modes) from smaller to larger scales, and self-organization results through the turbulent pinch [15-19]. For both the forward (3D) and inverse (2D) cascades in magnetized plasma, understanding turbulence requires understanding both mode-mode coupling and the kinetic effects that couple fluctuations to particle phase-space flows, usually at scales near the gyroradius. Nonlinear simulation, based on gyrokinetic theory, has become a promising approach to understand astrophysical turbulence, magnetospheric turbulence, and fusion devices. However, when these models of turbulence are quantitatively compared to observational [3] and experimental measurements [7], at multiple scales and under various physical conditions, uncertainties and questions arise often involving complex nonlinear plasma processes. To answer these questions systematically and to make further scientific progress, we require combined observational and computational efforts that benefit from a dedicated center for well-diagnosed and controlled laboratory study of multiscale turbulence across the range of dynamical processes that occur in magnetized plasma.

This White Paper presents an opportunity to meet this research need. We suggest the creation of a Center for Laboratory Study of Multiscale Turbulence by combining the full capabilities of an existing laboratory facility with state-of-the-art high-resolution fluctuation diagnostics and gyrokinetic and gyrofluid simulation efforts. This Center would give the broad plasma science community access to a steady state facility for controlled investigations of Alfvénic and interchange-like turbulence, cascades, transport, and self-organization under conditions relevant to both terrestrial and astrophysical plasmas.

Approach to Advancing the Frontier

Five years ago, a breakthrough in our capability to create and study steady-state turbulence in magnetized plasma was achieved using two superconducting dipole experiments: the LDX located at MIT [17] and the RT-1 at the University of Tokyo [20, 21]. When high-field superconducting current rings were levitated, a new state of plasma global self-organization resulted when interchange and entropy modes created and sustained profiles near a state of minimum entropy production [16, 22]. Particle distributions became isotropic on field lines, and plasma profiles evolved due to cross-field turbulent transport. Central plasma heating drove a strong up-gradient turbulent pinch, and global self-organization occurred at a rate in agreement with measured levels of turbulence. Bounced-average quasilinear theory [16] and nonlinear gyrokinetic simulations [15] reproduced the drive towards the
final self-organized state. Nonlinear mode-mode coupling and two-dimensional inverse cascades determined the evolution of the turbulent spectrum [14]. In contrast to magnetic self-organization where helical instabilities, excited in a current-carrying toroidal pinch, drive magnetic self-organization during resistive plasma relaxation [23], this state of global plasma self-organization does not change magnetic field topology, does not require helicity, and can be sustained indefinitely. In the laboratory magnetosphere, interchange turbulent mixing drive plasma pressure and density profiles to a state of minimum entropy production [16, 22], where local gradients of particle number and plasma pressure are comparable to gradients of magnetic flux tube volume throughout the plasma. This type of turbulent self-organization is a powerful concept to understand the physics of strongly magnetized plasma with applications to fusion devices, convective space weather, and non-neutral and exotic plasma [24]. Although global self-organization is strictly achievable only when the magnetic geometry provides global plasma confinement near the threshold of interchange instability, the up-gradient turbulent pinch and the inverse cascade of turbulent fluctuations have also been observed in tokamaks.

While the magnetic geometry and wave-particle drift-resonances of a levitated current ring resemble those in planetary magnetospheres, the turbulence, so far studied in the lab, is not Alfvénic. The low power levels and the heating method (ECH) applied to these experiments limit achievable plasma density. As a consequence, the inertial lengths in laboratory magnetospheres have, so far, been relatively large, $\lambda_i/L \sim 0.1$; interchange and entropy modes dominate turbulence; and electrostatic drift-kinetic resonances and nonlinear processes mediate turbulent energy exchange. By comparison, turbulence in planetary magnetospheres couples interchange and MHD Alfvén wave dynamics [2,4]. Internal mass loading, rapid plasma rotation, and interchange motion drive MHD turbulence [5] within the Jovian and Saturnian magnetospheres, while, in the Mercurian and Terrestrial magnetospheres, heliospheric fluctuations drive Alfvén wave turbulence at the polar cusp and magnetospheric boundaries and internal sources drive interchange turbulence at plasmaspheric boundaries.

We believe a full range of magnetized plasma turbulence, including both interchange and MHD Alfvén wave dynamics, can be studied in a single, steady-state plasma torus simply by decreasing the ion inertial length with higher power heating. At the world’s largest laboratory magnetosphere, located at MIT, a high-power RF (wide band, 4 to 26 MHz) transmitter is now available to increase the steady-state heating power 40-fold. Increased heating power results in proportionally higher density. When higher power heating is switched-on, magnetized plasma turbulence can be studied in steady-state through out a range of plasma beta, $0.1 < \beta < 1$, and plasma density, $0.013 < \rho_i/L < 0.1$ ($2 \text{ cm} < \lambda_i < 16 \text{ cm}$). At 5 m in diameter, the MIT experiment offers univalled access for multipoint fluctuation diagnostics. Linear calculations of externally driven Alfvén modes in realistic laboratory conditions show excitation of a wide spectrum of Alfvén waves with frequencies that (i) are the basis for Alfvén wave spectroscopy in the magnetosphere and (ii) should nonlinearly couple to interchange and entropy modes as thought to be the drive of turbulence in the Jovian and Saturnian magnetospheres. Higher heating power will also allow systematic tests of finite ion temperature modifications to bounce-averaged gyro-kinetics and turbulent self-organization, the possibility of zonal flow generation at high levels of turbulent power flux, steady and filamentary transport at boundary layers, and the temporal evolution of magnetized plasma turbulence.

**Impact**

We believe the field is at the threshold of achieving one of the most important challenges of plasma physics: predictive understanding magnetized plasma turbulence across an extreme range of scales. The large, axisymmetric, steady state plasma torus, confined by the magnetic field from a superconducting current ring, may very well be the simplest laboratory plasma torus that can operate over sufficiently wide range parameters to study turbulence relevant from astrophysical conditions to fusion science. By combining the capabilities from an existing laboratory facility with new high-resolution fluctuation diagnostics adapted from fusion studies, both Alfvénic and interchange mode turbulence, cascades, transport, and self-organization can be studied in large a steady state magnetized plasma for the first time. Recent laboratory and computational studies demonstrate a readiness to conduct a larger research program based on higher power heating of the laboratory magnetosphere and give confidence of continued progress advancing this important frontier.
References