**White Paper for Frontiers of Plasma Science Panel**

**Date of Submission:** June 22, 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.

<table>
<thead>
<tr>
<th>“P”, “S”</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Plasma Atomic physics and the interface with chemistry and biology</td>
</tr>
<tr>
<td>P</td>
<td>Turbulence and transport</td>
</tr>
<tr>
<td>P</td>
<td>Interactions of plasmas and waves</td>
</tr>
<tr>
<td>P</td>
<td>Plasma self-organization</td>
</tr>
<tr>
<td>P</td>
<td>Statistical mechanics of plasmas</td>
</tr>
</tbody>
</table>

Indicate type of presentation desired at Town Hall Meeting.

<table>
<thead>
<tr>
<th>“X”</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Oral</td>
<td>X</td>
</tr>
<tr>
<td>Poster</td>
<td></td>
</tr>
<tr>
<td>Either Oral or Poster</td>
<td></td>
</tr>
<tr>
<td>Will not attend</td>
<td></td>
</tr>
</tbody>
</table>

**Title:** Use of DIII-D to Address Frontier Science such as Unraveling the Nature and Impact of Quasi-2D Turbulence in Magnetized Plasmas

**Corresponding Author:** George McKee

- **Institution:** University of Wisconsin-Madison
- **email:** grmckee@wisc.edu

**Co-Authors:**

---

(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.**

Understanding fundamental turbulence is critical to development and optimization of plasmas for fusion energy and industrial purposes, as well as understanding behavior on astrophysical scales. The transport of energetic and thermal ions, impurities, electrons and neutrals through magnetized plasma is of central importance to the behavior, performance, dynamics, and stability of plasma systems. Individual particle orbits and collective instabilities interact strongly depending on the nature of the magnetic field. Density and temperature gradients, inherent to most plasma systems, provide a free energy source that can drive a range of ion and electron-scale instabilities [1]. The resulting turbulence grows and saturates through a range of mechanisms that include forward and inverse energy cascades, self-driven [2] and equilibrium sheared flows [3]. The impact of equilibrium quantities such as radial electric fields, ExB flows, and magnetic shear strongly impact turbulence in magnetized plasmas [4]. The fluctuating electric and magnetic fields associated with this turbulence transports particles and the energy, current and momentum they carry along and across magnetic field lines in a complex, self-organized equilibrium. In magnetically confined fusion plasmas, this particle and energy transport directly impacts the performance through confinement and stability. Turbulence is likewise inherent to solar plasmas, where pressure gradients, radiation pressure, flows, and gravitational forces form the driving and saturating mechanisms.
The magnetic field determines a direction with extremely rapid parallel transport, with collisional and/or turbulent (anomalous) transport occurring in the 2D orthogonal plane. While predominantly 2D, important 3D affects come into play and have recently been a topic of significant and growing interest. For example, altered magnetic field line curvature can significantly impact growth rates and saturated levels of turbulence [5, 6]. Relatively small magnetic perturbations to 2D systems can significantly impact turbulence and transport.

The major challenges confronting magnetized plasma turbulence research include understanding how pressure gradients and magnetic geometry drive instabilities, which instabilities dominate, how multiscale instabilities interact (a strongly complex and highly nonlinear process), how the resulting turbulence saturates, and the dynamics of the turbulent transport processes. A feedback loop ultimately causes the turbulence and transport to react back on the equilibrium gradients, creating a complex equilibrium. Plasma turbulence in a magnetized system can also undergo a remarkable and beneficial bifurcation, wherein increasing heat flux leads to increased turbulence, Reynolds Stress, zonal flow generation, and ultimately a transition in which turbulent energy transfer to zonal flows exceeds energy input, or shearing rates exceed growth rates, and the turbulence is then suppressed and particle and energy confinement increases dramatically [7]. This turbulence suppression is now relied upon as a crucial mechanism to achieve controlled fusion energy, and yet the critically important underlying turbulence processes are only now being unraveled. In addition, it’s instructive and essential to determine how various dimensionless parameters (e.g., ion gyroradius to system size [8], electron to ion temperature ratio, Mach number, collisionality, plasma kinetic to magnetic pressure, magnetic field safety factor, etc.) affect turbulence and associated transport.

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

We propose to engage with the plasma science community to pursue fundamental studies of plasma turbulence and resulting transport processes in a physically large, highly magnetized, relatively high-field and well-diagnosed magnetic plasmas available on the DIII-D tokamak experiment. Many diagnostics are currently available to pursue such research at DIII-D, along with multiple plasma heating systems (ohmic current, electron cyclotron heating and neutral beams), and the experiment has very flexible 2D with modest 3D toroidal magnetic geometry shaping capabilities. It may be possible, for example, to configure systems and plasma parameters to mimic solar plasmas conditions.

The DIII-D National Fusion Facility has strong collaborations with numerous universities in the US and abroad, and many students pursue thesis research on fundamental plasma physics topics at DIII-D. The research atmosphere is generally vibrant with strong interactions between national laboratory and General Atomics scientists with university professors, scientists, graduate students, and postdoctoral researchers. Major university collaborators include UC-San Diego, UC-Los Angeles, UC-Irvine, UC-Davis, Massachusetts Institute of Technology, University of Wisconsin-Madison, Columbia University, U. Texas-Austin, and numerous other US and international universities are welcomed to and do collaborate. This has afforded and facilitated a vibrant research atmosphere, fostered many excellent ideas that have advanced fusion plasma research in particular, and spawned related activities.

Universities have been key institutions for developing and implementing advanced fluctuation diagnostic systems for measuring turbulence and performing the relating scientific analysis. Examples include diagnostics that probe the behavior and dynamics of plasma turbulence and Alfvénic instabilities, such as Far Infrared Scattering, Phase Contrast Imaging, Reciprocating Langmuir Probe Arrays, Correlation and Doppler Reflectometry, Beam Emission Spectroscopy, Correlation Electron Cyclotron Emission (ECE), High-Resolution ECE, ECE-Imaging, Microwave Imaging Reflectometry, Cross-Polarization scattering, Ultra-Fast Charge Exchange Recombination Spectroscopy, CO2 interferometry, magnetics, etc. These can measure fluctuations in density, electron and ion temperature, and magnetic field, and can do so with
varying spatial and wavenumber sensitivities. Additional diagnostics can be added if required for specific research activities.

Like all members of the DIII-D program, university researchers propose, advocate, design and conduct experiments at the DIII-D National Fusion Facility, analyze data, publish papers, and present contributed and invited results at major national and international conferences and workshops. There are many excellent opportunities for focused and fundamental research at the DIII-D National Fusion Facility.

The development of the theory and modeling of plasma turbulence, and the commensurate activity of developing and validating fully nonlinear simulations of turbulent transport is also central to the research effort. The requirements of understanding the underlying mechanisms relies heavily on inferring behavior that cannot or is not typically measured.

The central mission of the DIII-D facility is to understand physics mechanisms and processes in tokamak plasmas in order to determine how to optimize and project high performance fusion plasmas for future reactors. A key aspect of this mission lies in understanding the basic processes, discovering the key principles and effects that govern behavior and testing how they can be manipulated, for example, to suppress turbulence. The facility is highly equipped with extensive ways to manipulate the plasma and its underlying parameters, and make perturbative tests, as well outstanding high-resolution diagnostics for multiple channels. It is therefore proposed to explore how to extend engagement of the facility with the broader community, which could provide a basis to more deeply understand the processes involved in plasma behavior through experiments on DIII-D and collaborative work with other community facilities as well as theoretical capabilities, and the deep expertise that lies in this community. The details and scope of this approach would of course need to be discussed with the community, DIII-D management and the funding agency, Fusion Energy Sciences in DOE, but a process to propose, review, prioritize and advocate for particular experiments would need to be considered. The DIII-D program is interested to engage with frontier plasma sciences community to understand how best to proceed, and identify areas of turbulence and transport, energetic particles and waves, as well as atomic physics, spectroscopy, materials science and others that could be advanced.

While this proposed activity has been geared towards potential research activities on the DIII-D National Fusion Facility (General Atomics), this conceptual framework could apply equally well at facilities such as the National Spherical Torus Experiment-Upgrade (Princeton Plasma Physics Laboratory) or C-MOD Tokamak (Massachusetts Institute of Technology) which, while topologically similar, offer different parameter ranges (e.g., aspect ratio, magnetic field, size), diagnostic and heating system capabilities.

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

Achieving a deeper and more complete understanding of plasma turbulence and resulting transport processes in plasmas can benefit a range of technical and scientific endeavors. A deeper understanding of solar energy transport phenomena, planetary magnetic systems (electrical system grid impacts), energy generation from fusion, plasma-processing systems for industrial applications (semiconductor and advanced material fabrication), lighting systems, etc. can be achieved through focused research. Another example is that of atmospheric systems: they exhibit significant commonality with turbulence in plasmas: both are largely 2D pressure gradient driven systems: Rossby waves in atmospheres are directly analogous to plasma drift waves, jet streams to zonal flows, and each with regionally localized energy and particle sources and sinks. Through the process of elucidating quasi-2D turbulence in magnetized plasmas, we can acquire a more thorough understanding of global atmospheric systems: how flows are generated, how they evolve over time, and how heat is transported from equatorial regions to poles in the presence of both driven turbulence and stabilizing flows.

[Prepared in consultation with Dr. Richard Buttery, DIII-D Director of Experimental Sciences]
References (Maximum 1 page)