White Paper for *Frontiers of Plasma Science Panel*

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• 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	

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Title:	Fundamental study of plasma turbulence
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1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)**

I. The grand challenge: Fundamental understanding of plasma turbulence

Exploration of the fundamental structure of turbulence in plasmas is a grand challenge for plasma physics, rich both in scientific content and in potential application, requiring the interaction of basic theory, computation, and experiment. Although plasma turbulence occurs in many different environments and parameter ranges in astrophysical, laboratory, and industrial plasmas, there is a common underlying structure (Krommes 2002). As in neutral fluid turbulence, quadratic nonlinearities redistribute conserved quantities across different scales, typically via an incompressible flow. Unlike in 2- or 3-D neutral fluid turbulence, the flow and its incompressibility are usually situated in a 5- or 6-dimensional phase space. Also, waves and instabilities typically contribute energy sources and sinks across all scales, precluding the existence of an inertial range and suggesting nonuniversality. As examples of promising directions in fundamental plasma turbulence research, let's consider three topics: i) the interaction of waves and instabilities with turbulence, ii) the interaction of turbulence with large-scale flows and fields, and iii) structure of the energy cascade in 5- or 6-D phase space.

i) The multiplicity of linear eigenmodes at all scales in a plasma has many implications for plasma turbulence. For example, the most direct energy pathway to dissipation may be via transfer from growing to damped eigenmodes at the same spatial scale rather than through a direct cascade to small scales, in

stark contrast to the standard direct cascade picture of 3-D Navier-Stokes turbulence (Terry 2006). Selective dissipation within the turbulent scales has also been proposed as a cause for "dynamical alignment" modifications to the energy spectrum in MHD turbulence (Boldyrev 2006). Contrarily, the interaction of non-normal linear operators with nonlinear energy redistribution can support steady-state plasma turbulence in the absence of unstable linear eigenmodes (Scott 2002). Measurements of turbulent fluctuations in laboratory plasmas such as LAPD may provide experimental data useful to benchmark theoretical models (Friedman 2013). Waves and their dispersion may also affect the turbulence in other ways, such as by modifying the typical phases between fluctuating quantities. This is reminiscent of the structure of geophysical and planetary turbulence (Holloway 1986), an analogy that has been and can be effectively exploited, with some care. Wave decorrelation also plays an important role in the "critical balance" hypothesis that has found much application in astrophysical turbulence (Goldreich 1995), while the interaction of velocity-space instabilities with turbulence appears to be a complex topic open for further investigation (Kunz 2014). At a fundamental level, statistical models of neutral fluid turbulence can lead to negative probability densities in systems with linear waves, requiring revision for reasonable application to plasma turbulence (Bowman 1997).

While the linear mode structure of various plasma systems has received extensive study, there is a lot of room for further development of models for the interaction of waves, instabilities, and turbulence, in particular in the difficult but often relevant limit of strong turbulence. Applications are manifold, varying from the prediction of wave-modified turbulent spectral indices in astrophysical plasmas to the calculation of heat fluxes in fusion plasmas when quasilinear formulas fail, as in the case of submarginal turbulence.

ii) Plasma turbulence is often characterized by the spontaneous generation of large-scale flows and fields, which in turn modify the statistics of the fluctuations that created them. In magnetized plasmas, the anisotropy due to **B** may cause an approximate enstrophy conservation resembling that of 2-D neutral fluid turbulence, which leads to inverse energy cascade and large-scale flows (Ottaviani 1992). Inhomogeneity in background plasmas, working through linear dispersion, can cause the formation of zonal flows resembling those in geophysics, possibly amenable to statistical modeling (Parker 2013) or description in terms of a modulational instability (Chen 2000). Some of the statistical methods used for flow generation have found further application in field generation, for example in modeling magnetic dynamos in astrophysical plasmas (Squire 2015). On the other hand, fusion plasmas have also been observed to rotate without the application of torque (deGrassie 2009) for physical reasons that may be quite different from inverse cascades or modulational instabilities (Park 2009, Stoltzfus-Dueck 2012).

Beyond the intrinsic scientific interest of the apparent generation of order out of disorder, the interaction of flows and turbulence in plasma are of practical importance for fusion systems: Turbulence-generated sheared flows are believed to regulate the amplitude of transport-causing turbulent fluctuations (Biglari 1990), in some cases suppressing the transport entirely (Dimits 2000). Rotation also helps to suppress the resistive wall mode (Strait 1995). Intrinsic rotation is important for any eventual fusion reactor, since (unlike neutral beams) alpha heating will not apply any torque.

iii) As in neutral fluids, the nonlinearities in plasma turbulence typically conserve a number of invariants including some quadratic fluctuation free energy. While plasmas may often be profitably described in fluid (3-D) terms, which sometimes allow description similar to that of neutral fluids, the energy is more fundamentally flowing through a 5- or 6-dimensional phase space. Although some promising studies have already been made, our understanding of the structure of this energy flow is still in its infancy. One could try to work out Kolmogorov-like models for kinetic turbulence in various parameter regimes (Schekochihin 2009, Kunz 2015). One could attempt to generalize subgrid models, similar to those used in large eddy simulations of neutral fluid turbulence, for application in a 5- or 6-D kinetic phase space (Bañón Navarro 2014). At this point, the topic remains wide open.

Fundamental models of phase-space turbulence could play a number of useful roles. For example, a basic understanding of the likeliest spectral indices could allow a more focused use of simulations to examine deviations (small or large) from that behavior. Subgrid models, although not a substitute for resolved direct numerical simulation, are often necessary for the computation of problems of practical interest, for which the range of spatial, velocity, and temporal scales exceeds the available computational resources.

II. Advancing the frontier: facilities and tools for fundamental understanding of plasma turbulence

Many tools are already in place for the fundamental study of plasma turbulence, both computational and experimental. Since plasma turbulence exists in almost any laboratory plasma device or nonlinear plasma simulation code, almost any existing code or device can be used for the fundamental study of plasma turbulence. It is more an issue of deciding which question to ask or which quantity to measure than it is an issue of which device or code to construct. Dedicated analytical theoretical work is invaluable here in helping to frame questions that may be productively addressed by the existing codes and experiments.

With that said, dedicated funding is necessary in order to make progress on basic understanding of plasma turbulence. Purely application-funded research leads to a focus on empirical or semi-empirical models, which require less time and effort for short-term progress on the application but lead to less fundamental understanding and cross-pollination between nearby fields, also potentially missing the scientific and applied breakthroughs that could come from first-principles scientific investigation of the plasma turbulence itself. Smaller experiments, such as LAPD at UCLA, the U Texas Helimak, Pegasus and MPDX at U Wisconsin, and LTX at PPPL, are valuable for dedicated studies of basic plasma turbulence, due to relatively low cost, good diagnostic access, and small size (which eases direct numerical modeling).

Most critically, dedicated funding needs to be made available for fundamental theoretical research in plasma turbulence, in particular at the analytical and lightweight numerical level. Insights gained from these low-cost investigations can be leveraged to focus and obtain greatly increased benefit from experimental and large-scale computational investments.

III. Impact and societal benefits of fundamental research in plasma turbulence

As in all basic science, it is very difficult to predict the eventual impact of the resulting new knowledge. Nevertheless, there are good reasons to believe that the relatively modest investment necessary for progress in this field will pay off. The similarity in the underlying structure of plasma turbulence in various environments and across wide ranges of parameter space suggests that any advances in fundamental understanding should have broad implications. Obviously, fusion scientists would like to exploit any available first-principles understanding of turbulence to reduce transport and improve performance of fusion devices. Fundamental plasma turbulence understanding could also have applications to astrophysical plasma applications such as space weather modeling. The approximate isomorphism to some geophysical models might allow cross-cutting application in weather and climate models, which must also cope with interactions of multiple scales, anisotropy, and wave-turbulence interaction. Again, since almost all plasmas support turbulence, and most applications desire to minimize or control turbulence to reduce its deleterious effects, virtually any plasma application might benefit from expanded understanding of fundamental behavior of plasma turbulence.

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