Title: Saturation of Instability-Driven Turbulence in Confined 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.**

In turbulence saturation, nonlinear energy transfer self organizes to moderate a balance between energy input and dissipation. For unbounded homogeneous fluids, where excitation is by external stirring, saturation as a self-organized process has been understood at some level since Kolmogorov [1]. In confined plasmas driven by collective instability, the situation is vastly different. Saturation is not generally understood even in qualitative terms. However, because it fixes excitation levels and transport, and its understanding is indispensible for predictive capability, saturation is a critical frontier of physics knowledge. Key differences between homogeneous fluids and confined plasmas illustrate the challenges. Firstly, in plasmas there are many collective modes, waves and instabilities affecting turbulent motions; they are described, not just with a single mathematical paradigm, like the Navier-Stokes equation, but with a hierarchy of nonlinear models. Secondly, because the turbulence is driven by instability, it is accompanied by generally hidden, large-scale dissipative structures that are accessible only in the turbulent state, but can be understood as a nonlinearly excited damped-mode roots of the instability dispersion relation [2]. Thirdly, because the plasma is confined there is inhomogeneity, symmetry breaking, and confining geometries and boundaries. Inhomogeneity is critical for instability. Symmetry breaking in turbulence leads to a global anisotropic structure expressing the anisotropy of the symmetry breaking [3]. Zonal flows are an example of this process. Add to these physics features differences in historical precedence and practice: the ability to study the large number of collective modes with linear analyses
means that far greater attention has been paid to instability than to saturation. Where nonlinear solutions are obtained, mostly numerically, a principal interest has been determination of the transport level, and understanding of saturation has lagged. These complications make saturation of instability-driven plasma turbulence a frontier problem that is far from solved.

Conventional approaches to understanding saturation typically envision a direct, one-step process. A nonlinearity, usually phase averaged via a renormalization procedure [4-5] or closure [6], directly modifies the instability energy input, either by removing energy to small scales where it is dissipated [7-9], flattening driving gradients [10-11], or by modifying instability eigenmode structure to enhance dissipation or diminish drive [12]. However, it is increasingly apparent that saturation is a self-organized system with multiple, mutually interacting nonlinear processes and feedbacks. All important elements may not even be fully identified, but at least involve the following:

**Multiple Instabilities of Confinement Geometries** – Bounded, inhomogeneous plasmas in geometries required for confinement give rise to numerous instabilities, with more than one active [13-15]. The instability with the largest growth rate is often assumed to characterize the fluctuations; in fact, any instability present can affect the fluctuation structure and transport, and nonlinear mode coupling can amplify the effect of instabilities with subdominant growth rates.

**Symmetry Breaking and Large Scale Anisotropy** – In magnetically confined plasmas the background magnetic field breaks symmetry to produce anisotropic waves and instabilities. Resulting drift waves have anisotropic propagation. Turbulent condensation on the zero-frequency wave creates a large-scale anisotropic structure in the form of a zonal flow or zonal field [3]. This turbulent structure has zero linear frequency, making it a highly efficient energy transfer channel for saturating instabilities [16-17].

**Large Scale Energy Sinks from Damped Modes** – Where there is instability there are damped modes from other roots of the dispersion relation [2]. Excited by the nonlinearity (see Fig. 1) these modes create an energy pathway to dissipation distinct from the pathway of the wavenumber cascade [16]. The energy branching between these two pathways, which is critical for fluctuation levels and transport rates, can only be understood by treating the linkage between pathways [18]. Zonal flows catalyze the energy pathway to damped modes by providing a highly efficient transfer channel [16,18].

**Interaction between the Turbulence and the Instability Drive though Turbulent Transport**

Turbulent transport feeds back on the instability drive in a highly nonlinear manner, which can drive the system toward or even below the marginal point for a linear instability. This combined with the multiple instabilities and large-scale anisotropies can modify the saturation level and transport characteristics.

**Magnetic fluctuations** – At finite plasma β turbulence acquires a magnetic component. The excitation of damped modes produces fluctuation structure with tearing parity and opens a magnetic-fluctuation induced transport channel [17]. The magnetic component can disable zonal flows, producing a nonzonal transition (NZT) to very high fluctuation levels [19]. When present, magnetic fluctuations are a key arbiter of the self-organized interaction.

Some key unanswered questions relating to saturation are:

• How do different instabilities and damped modes interact in the nonlinear state?
• How is the interaction modified when there is scale separation?
• What governs the energy branching ratio between the energy pathway to large-scale damped modes and the wavenumber cascade for instabilities active in magnetically confined plasmas?
• How does the branching ratio scale with collisionality, driving gradients, plasma beta, magnetic shear, curvature, etc., and what physics sets the scalings?
• Besides three-wave frequency mismatch [16, 20], what accounts for the observed dominance of the energy transfer channel between instability, zonal flow, and damped modes?
• What governs the differences in zonal flow drive across different instability regimes and for different beta values?
• Under what conditions do damped modes profoundly alter the character of the turbulence, e.g., making it magnetic instead of electrostatic?
• When are quasilinear transport approximations appropriate? What are the breakdown modalities?
• What is the role of magnetic fluctuations and their associated 3D effects in saturation?
• What aspects of saturation could be used for stellarator or tokamak optimization with respect to anomalous transport?

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

Analysis and understanding of saturation requires the full compass of interactive approaches between experiment, theory and numerical simulation. The importance of subdominant fluctuations necessitates the implementation of new measurement analysis techniques, both for experiment and simulation. These involve fluctuation decomposition techniques, like singular value decomposition (SVD) [21-22] and linear eigenmode decomposition, and their application to measures of energetics and energy transfer channels. Characterization of experimental fluctuation signals should no longer be based solely on the most unstable eigenmode, but on a reasonably complete mode decomposition. Implementation of eigenmode solvers [23-24] on gyrokinetic codes and mode decomposition analysis in simulation studies will accelerate understanding of saturation. Mode decomposition analyses represent a heretofore unexamined measure that occupies a unique rung in a primacy hierarchy [25] for validation. It is particularly potent and deep probing with regard to establishing the physics integrity of models pursuant to validated predictive capability. Energetics measures center around fluctuation-decomposed bispectral analysis, which probes energy transfer both in wavenumber space and in the potentially heavily populated space of damped modes [26]. Subject to measurement constraints, campaigns for both experiment and simulation should vary and control for instability drivers (gradients in ion and electron temperature and density), scale ranges both of instability and nonlinear energy transfer, and energy forms, including magnetic, electrostatic, and thermal and nonthermal particle distributions. Because it is difficult to achieve desired variations and control in any given experiment, it is critical that multiple experiments be studied, particularly across the range of magnetic geometries spanned by tokamaks, stellarators and the reversed field pinch (RFP), all of which host a similar set of instabilities and turbulence phenomenology.

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

The saturated turbulent state represents the set of plasma conditions that governs transport in fusion and energization processes in astrophysics such as particle acceleration and heating. As such, the impacts of thoroughly understanding saturation are enormous and include improved transport models, predictive capability, and strategies for reducing transport. Saturation as envisaged herein, while not expected to apply to every conceivable type of plasma turbulence, will arise broadly. Chief among applications is (gyroradius scale) microturbulence in magnetically confined fusion plasmas, specifically tokamaks, stellarators and RFPs. In astrophysical plasmas, damped modes are relevant to accretion disks, Kelvin-Helmholtz unstable systems, Rayleigh-Taylor unstable systems, and unstable current sheets. Symmetry breaking and large-scale anisotropy arise in situations with a strong guide field and/or rotation. This type of saturation has analogs in neutral fluid turbulence such as geostrophic turbulence [27-28].
Fig. 1. Linear eigenmode amplitudes at one perpendicular wavenumber $k_x, k_y$ (in the unstable range) for Cyclone base case ion temperature gradient driven turbulence in a tokamak as a function of growth rate gamma and frequency omega. A single eigenmode is unstable (right most point); the remaining are damped. From P.W. Terry et al., Phys. Plasmas 21, 122303 (2014).