Impact of Turbulent Transport on Macrodynamics via Plasma Current Modification

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Motivation

Transport due to microturbulence in a tokamak is known to impact the global stability of the plasma through density and temperature profile relaxation. Recently it is found that turbulent transport can also impact the macrodynamics of a tokamak plasma through direct modification of the global plasma current, both in net amount and in its spatial distribution, as opposed to the indirect route, i.e., modifying the neoclassical bootstrap current via changes in density and temperature gradients. This opens a new route for direct coupling between turbulent transport and the global dynamics of a tokamak plasma both in equilibrium and during transient events such as disruptions and ELMs. Calculations and simulations to date have indicated that the effect can be substantial but it is complicated depending on the plasma parameters. Developing a predictive capability for the turbulence-modified plasma current and validating it against existing tokamak experiments are essential steps toward plasma control and mitigation of tokamak transients to ensure the successful operation of ITER. In this white paper we will first discuss the various mechanisms through which turbulence can directly modify the mean plasma current and the consequences for the macrostability of the plasma, and then follow it with a high-level description of a specific research plan to further develop the predictive capability and its validation on current tokamaks.

Turbulent Current Drive Mechanisms

Recent research has uncovered a number of mechanisms through which microturbulence can influence the mean plasma current. Aside from an electron viscosity, which acts to redistribute the electron mean current, several collisionless mechanisms have been suggested for driving plasma current. One such mechanism relies on a close analogy with the familiar neoclassical bootstrap mechanism. Namely, within a toroidal plasma, the motion of trapped electrons in the presence of density or temperature gradients results in an asymmetry of co-moving versus counter-moving trapped electrons, the neoclassical diamagnetic effect. Within the conventional neoclassical bootstrap current calculation, this trapped electron asymmetry is subsequently translated into a passing electron current via the collisional detrapping of electrons. A collisionless analogue can be shown to result from the detrapping of electrons via wave-particle interactions with drift wave turbulence [1]. Here resonant interactions with the ambient drift wave fluctuations allows for an alternate means of establishing an equilibrium between trapped and passing electrons, and thus driving a mean electron current.

Alternatively, mechanisms familiar from the study of toroidal ion rotation have been suggested to possess analogues in the context of electron flow generation. Here, Ohm's law for the mean current is modified both by the addition of a turbulence induced electron-ion momentum exchange term as well as a turbulence driven electron momentum flux. In the case of the former, microturbulence acts as a means of facilitating the transfer of momentum between electrons and ions. In contrast to the collisional friction term (resistivity), this turbulent contribution does not have the form of a drag, and instead appears as an effective source or drive term. In addition, the turbulent electron momentum flux can be shown to contain an electron viscosity (hyper-resistivity), pinch as well as residual stress [2, 3]. This last contribution to the momentum flux does not depend on the electron flow or its gradient and hence appears as an effective source term in Ohm's law. Both of these current drive terms can be shown to require a non-vanishing average parallel wave number, and thus require a broken symmetry in the turbulence fluctuation spectrum. Analogous to ion momentum transport, ExB shear provides a robust symmetry breaking mechanism in the plasma edge due to the strong electric field gradient in this region.

Integrated Modeling and Validation of Turbulent Current Drive Mechanisms

An efficient, self-consistent model of turbulence driven current mechanisms in the presence of Coulomb collisions requires the development of a novel modeling tool. A first step toward the development of such a capability has been made by deriving a mean field equation that treats the resonant scattering by drift wave turbulence and Coulomb collisions on an equal footing [4]. Here, turbulence is modeled via a phase space quasilinear diffusion operator [5], whereas Coulomb collisions are included via the incorporation of a linearized Fokker-Planck collision operator. Such a modeling effort, however, requires making various assumptions with regard to characteristics of the background fluctuations. As a result, it will be necessary to verify this simple modeling framework against first principle gyrokinetic simulations. Initial work in this regard has been carried out by the global gyrokinetic code GTS [2]. Here, significant levels of turbulence driven current (of the same order as the neoclassical bootstrap current) were observed, although the strength of this current drive mechanism depended sensitively on both the equilibrium parameters as well as the characteristics of the underlying fluctuations. Resolving these subtleties requires multi-scale simulations treating neoclassical and turbulence physics self-consistently. This presents a great challenge and an excellent opportunity to apply HPC to solve an outstanding problem in fusion.

The model prediction of turbulence-induced global plasma current distribution provides both qualitative and quantitative bases for experimental validation on existing tokamaks where the bootstrap current comprises a significantly fraction of the overall plasma current. This combined experiment/theory/simulation study is needed to establish which of the above turbulent drive mechanisms are dominant under what plasma condition. The validated predictive capability of turbulence-induced plasma current will then become a key physics component in integrated modeling of tokamak equilibrium sustainment and transient events such as disruption and ELMs.

References

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