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Plasma turbulence in complex magnetic field structures

ALEXANDER KENDL

Institute for Theoretical Physics, University of Innsbruck, Association Euratom-ÖAW, A-6020 Innsbruck, Austria

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Abstract. The influence of the shape of a confining magnetic field in closed toroidal flux surface geometry on drift wave turbulence is reviewed. In particular, the mechanisms of turbulent mode driving, damping and coupling are identified and implications for divertor tokamak and stellarator edge transport are discussed.

1. Introduction

The flux surface shape of a toroidal fusion plasma determines equilibrium, stability and transport properties in connection with gradients of plasma pressure and currents. Turbulent transport models for tokamaks are generally parametrized with respect to the magnetic field structure by vertical elongation and by triangularity. Further shaping is mainly introduced by the pressure shift, the presence of X-points on the separatrix and the breaking of axisymmetry. An important task for computational plasma physics is to determine the effects of the magnetic field structure on turbulent transport by first-principle numerical simulation.

In the following, recent computational results on instabilities, turbulence and transport in shaped magnetic fields are discussed and their implications on the L–H transition in tokamaks and on transport properties in stellarators are analysed.

2. Flux surface shape and turbulent transport

The structure of a confining magnetic field enters the gyrokinetic or fluid descriptions of plasmas via the curvilinear generalization of differentiation operators and via the non-uniformity of the magnetic field strength B. Different scales of plasma dynamics parallel and perpendicular to the magnetic field motivate the use of field-aligned flux coordinates. A typical choice is (Ψ, η, ξ) with the poloidal flux $2\pi\Psi$ as the generalized radial coordinate, η as the parallel coordinate, and ξ as the tangential field line label [1]. In this frame, field strength non-uniformity is expressed by normal and tangential (geodesic) components of the field line curvature $\kappa = \nabla \ln B$. The deviation in inclination of initially parallel, radially neighbouring field lines in the direction along $\mathbf{B}$ is described by the (local) magnetic shear $S = -\mathbf{B} \cdot \nabla(g^{\Psi\xi}/g^{\Psi\Psi})$.

The equilibrium flux surface shape of a toroidal plasma can be obtained by solving the Lüst–Schlüter/Grad–Shafranov equation or by minimizing an energy integral for given boundary conditions. Field line tracking on the flux surfaces then

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allows expression of Cartesian operators in terms of field aligned coordinates by use of metric coefficients. Simplified analytical parametrizations exist for some basic geometries, such as the 's-α' model for a torus with shifted circular flux surfaces.

Transport of energy and particles across flux surfaces in tokamaks and optimized stellarators is largely determined by drift wave turbulence. Coupled spatio-temporal fluctuations of the plasma pressure $\tilde{p}$ and the electric fields $\tilde{\mathbf{E}}$ lead to turbulent advection by the drift velocity $\mathbf{v}_E = (1/B^2)\tilde{\mathbf{E}} \times \mathbf{B}$ in the plane perpendicular to the magnetic field $\mathbf{B}$. Instability and evolution of the $E \times B$ vortices in the presence of a pressure gradient as a free energy source are determined by parallel electron response, and by the compressibility of fluid drifts in a non-uniform magnetic field. The influence of the former is strongest in the resistive drift-Alfvén (DALF) regime that dominates the L-mode edge plasma near the separatrix, whereas the latter mechanism is mainly responsible for instability in the regime driven by a large ion temperature gradient (ITG) in the plasma core and H-mode edge. In both cases, a population of trapped electrons can contribute to destabilization of (trapped electron (TEM)) modes. The magnetic field structure influences all of these primary instability mechanisms and the secondary formation of mesoscopic (zonal) flows.

While the instability of vortices in the DALF regime is considered to be largely nonlinear [2], some insight into the strength of driven scales in ITG turbulence may already be gained by linear analysis. Some literature can be found on the influence of flux surface shaping on linear ITG (and hyperfine-scale electron temperature gradient (ETG)) modes in tokamaks [3–5], stellarators [6,7] and model geometries [8–10]. Systematic studies in complex geometries have been carried out on fully developed ITG [3,11,12] and DALF [12–15] turbulence. (More work exists on computations in single specific realistic complex configurations, from which, however, it is difficult to extract generalizable conclusions.)

Reviewing these cited studies, several mechanisms of flux surface shaping effects acting on instabilities and turbulence can be identified. Elongation introduces enhanced local magnetic shear at the vertical tips of the torus, which limits the ballooning region and locally twists the mode structures. Local magnetic shear is further increased by shaping near an X-point. In the nonlinear regime, magnetic shearing decorrelates vortices and limits the growth of radial streamer structures. Local shear acts in addition to global magnetic shear, the latter being a result of radial variation of the rotational transform. Configurations with large global shear can be expected to show less dependence of growth rates and turbulence on small to moderate additional local shear, as reported in [6], whereas 'shearless' stellarators always show a strong influence of local shear [10].

Another nonlinear mechanism is the break-up of vortices by sheared zonal flows, which are enhanced by elongation due to a less effective geodesic transfer mechanism. This mechanism is facilitated by changing the coupling between zonal flows and the fluctuating turbulent spectrum, which limits the growth of zonal flows in toroidal geometry [16]. Reduction of geodesic curvature, such as by strong elongation, has been shown to reduce the coupling and to enhance zonal flows [17].

It is clear from all of these studies that elongation generically reduces both ITG growth rates [3–5] and turbulence [3,11,12], as well as DALF turbulent transport [12]. Triangularity has a much weaker influence. The local scaling of edge transport was found to behave approximately as κ^{-2}. Magnetic shear damping [15] has been identified as the main mechanism [12]. Zonal flow shear enhancement by elongation

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and X-point shaping is mainly effective for ITG turbulence [11,12], but is found to be of neglible importance for pure DALF turbulence [12].

3. Turbulence, flows and L–H transition in a divertor tokamak

The presence of an X-point due to a tokamak divertor introduces extreme local shaping of flux surfaces near the separatrix. In the vicinity of the X-point, local magnetic shear is strongly enhanced and geodesic curvature is reduced. The geodesic curvature term is sinusoidal, $\mathscr{K}^x \sim \sin\theta$, for circular flux surfaces. For a radial position $(V/V_0) = 0.95$, the reduction of $\mathscr{K}^x$ by X-point shaping is still moderate compared with the effect of elongation alone [12]. On the outermost closed flux surfaces close to the separatrix, $\mathscr{K}^x(\theta \approx \theta_X)$ can be reduced to near zero when the X-point is located, as usual, at the upper or lower poloidal position $\theta_X \approx \pm\pi/2$. Zonal flow enhancement in DALF turbulence by X-point reduction of the geodesic transfer mechanism can thus be expected only for around $(V/V_0) > 0.98$. For standard tokamak pedestal parameters, this corresponds to a region of only a few ion gyroradii inside the separatrix. It has been found, however, that the zonal shear flow enhancement by X-point shaping is much more efficient (approximately doubled for typical edge parameters in ASDEX Upgrade geometry) when ITG dynamics are becoming relevant in the edge [12]. The ion temperature T_i at the pedestal top and the T_i gradient over the pedestal increase when additional ion heating is applied in the tokamak core. The zonal flow amplitude and flow shearing in ITG edge turbulence, activated above a critical T_i gradient, rise accordingly. The ITG geodesic transfer mechanism is more sensitive to curvature modification and will also be affected across a broader radial region near the separatrix than for DALF turbulence.

In computations with non-local pressure profile evolution, diamagnetic effects on flow generation allow further radial spreading of initially localized seed flows. Hence, a significant local enhancement of zonal shear flow due to a transition from DALF to ITG turbulence in the outer edge of a tokamak shaped by an X-point can influence the flow amplitude in the overall pedestal region. This mechanism offers an explanation why the L–H confinement transition, which occurs for sufficiently high ion heating, is observed almost exclusively in divertor tokamaks. Moreover, the presence of two X-points in a 'double null' configuration further reduces geodesic curvature. Flow shear is consequently enhanced and will lower the H-mode threshold value of the heating power, which in our present model is related to the nonlinear (Dimits shifted) critical T_i gradient. However, current local computations have not yet produced a threshold transition. The effect appears to be gradual in simulations with realistic geometry but fixed pressure gradient. Computations with global profile evolution may be necessary to obtain the transition dynamics itself. Such global simulations with adequate resolution, including necessary mitigation procedures to counteract grid deformation, in a realistic representation of X-point geometry are challenging and, at the time of writing, still unavailable.

4. Turbulent transport in optimized stellarators

The strategy of minimizing geodesic curvature in advanced optimized stellarators is adopted in order to lower the fraction of trapped electrons and neoclassical transport. This can also be expected to directly reduce TEM instability and, by the mechanism discussed above, enhance sheared zonal flows.

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Computations of edge turbulence in a flux tube approximation to stellarator geometry, which introduced a gradual transition from circular flux surfaces to a three-dimensional helical advanced stellarator (Helias) geometry, have found a strong effect of local magnetic shear in these globally nearly shearless configurations [13]. In addition to elongation, the more pronounced (in comparison to a tokamak) shaping associated with triangular cross sections (alternating with elliptical shapes in each helical segment) of Helias configurations adds to the local magnetic shear. Zonal flows were found to contribute to lower transport levels twice as efficiently as in simple circular tokamak geometry [14], which may be attributed both to reduced geodesic curvature and to the higher aspect ratio of this stellarator. The presence of external magnetic islands also introduces X-points on the separatrix which are even more delicate to resolve computationally than those in a divertor tokamak.

A neoclassically optimized Helias stellarator can thus be expected to also have reduced turbulent transport. It is, however, difficult to generalize these results to other three-dimensional configuration concepts. For evaluating turbulence and zonal flow characteristics, it is necessary to perform individual computations for any specific new stellarator design. Moreover, the flux-tube approximation is not, in general, applicable for broken axial symmetry, and has to be replaced with an annular representation of the whole flux surface. This will enhance the computational expense by an order of magnitude compared to tokamak turbulence simulations.

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