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Gyrofluid Simulation of the Ideal Ballooning Mode ELM Scenario

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Introduction. The physical mechanisms and scalings of cataclysmic outbursts in high confinement tokamak edge plasmas, which evolve from a macro-scale linear ballooning instability into a fully developed micro-scale turbulent phase during the burst, are analysed numerically. We present nonlinear gyrofluid computations of edge localised ideal ballooning mode events in the edge pedestal of toroidal magnetised plasmas. The range of scales reaches below the ion gyroradius, and the self-consistent evolution of the equilibrium is taken into account.

An electromagnetic 6-moment gyro-fluid model („GEMR") for both electrons and ions is used, including an energy-conserving treatment of finite ion Larmor radius effects, in global toroidal geometry with self-consistent plasma equilibrium, safety factor profile and Shafranov shift [1]. The necessity of resolution to the ion gyroradius scale is shown directly by consistency checks: converged cases are not otherwise obtained. Even with the finite beta well above the ideal MHD threshold, the results are outside of either the MHD or collisional Braginskii paradigms, on which other approaches are based.

Modelling of initial profiles. First-principles based local drift wave edge turbulence simulations are not yet able to obtain a realistic H-mode edge state with the known experimental characteristics: correct density and temperature pedestal profiles shapes or strength of flow shear are not obtained by self-constistent evolution by specifiying core sources only, nor has a threshold transition character been found in any verified edge turbulence simulation [2].

Therefore some kind „modelling" has to take place, when the IBM instability (as an H-mode phenomenon) and its subsequent nonlinear evolution is simulated with a nonlinear gyrofluid turbulence code: Although the realistic development of an edge transport barrier (and thus a full ELM cycle) can not be directly obtained, one still may prescribe the H-mode pedestal profile before the onset of an ELM, known from experimental data, as an initial state for the simulation. As a base case for the prescribed pedestal profiles the well diagnosed edge characteristics of ASDEX Upgrade H-mode shot #17151 is used here [3].

The complete set of nonlinear gyrofluid equations and energy-conserving computational methods, which are used in the present study, are presented in detail in Ref. [1]. The code uses a magnetic field aligned mesh, motivated by the quasi two-dimensional nature of $E \times B$

convection dominated fluid-like turbulence and by the parallel electron dynamics. GEMR does not use flute mode ordering on the derivatives however, since it uses global geometry and carries the entire flux surface. These cases use $n_y = 512$ perpendicular and $n_s = 16$ parallel mesh points. The radial domain ($n_x = 48$) spans the plasma edge region between the H-mode pedestal top, with plasma core parameters as inner boundary values, and the outer bounded scrape-off layer region ($r/a_0 = 1 \pm 0.06$). This represents a spatial range from the global scale to smaller than the ion gyroradius scale ($\delta = \rho_s/a_0 = 0.0025$).

The local parameters, taken as mid pedestal values, correspond to electron and ion temperatures $T_e = 300$ eV, $T_i = 360$ eV, densities $n_e = n_i = 2.5 \cdot 10^{19}$ m^{-3}, magnetic field strength $B = 2.0$ T, major torus radius $R = 1.65$ m, perpendicular temperature gradient length $L_T = L_\perp = 3.0$ cm, density gradient length $L_n = 6.0$ cm, safety factor $q = 5.0$ and magnetic shear $\hat{s} = 1.14$. The radial domain of the simulations cover a range equal to $L_\perp$ on either side of the last closed flux surface.

Profile pre-equilibration. The initial conditions are thus prescribed and are based on experimentally diagnosed radial temperature and density pedestal profiles $T(r)$ and $n(r)$ for each species (electrons and ions). A consistent electrostatic potential $\phi(r)$ is derived by numerically solving the neoclassical equilibration in a pre-processing step with a modified (zonally frozen) GEMR setup, resulting in a time-steady 2D dissipative solution. The parallel and perpendicular electron and ion temperatures, $T_{e\|}$, $T_{e\perp}$, $T_{i\|}$ and $T_{i\perp}$, may be directly adopted and fixed from experimentally derived values by filtering the zonal component out of the total time derivative. On the other hand, gyrocenter densities n_e and n_i have to be set to obey relaxation relations that allow the vorticity to freely evolve into equilibrium. This is achieved by freezing the zonal component of the sum (i.e., part of the pressure) during the equilibration phase, but allowing the difference (i.e, vorticity) to evolve freely. The numerical solution of the equilibration phase, starting directly from realistic steep pedestal profiles $T_0(x)$, into steady state is delayed by long, weakly damped global geodesic Alfvén oscillations. Convergence is expedited by ramping up all of the gradients gradually from zero to prescribed value over the first $50at/c_s$ of the run.

This pre-processing equilibration phase is run until convergence without ExB nonlinearities and with reduced perpendicular resolution (n_x, n_y, n_s)=($64 \times 4 \times 16$), which allows establishment of the 2D structure in a smooth manner. Then, the resolution is increased to the nominal values, and a random turbulent bath with relative amplitude $10^{-10}\rho_s/L_\perp$ is added to the background profiles.

Computation of the ELM blow-out. When this initialised pedestal pressure profile is ideal ballooning unstable, then the explosive IBM instability is in GEMR simulations observed to be

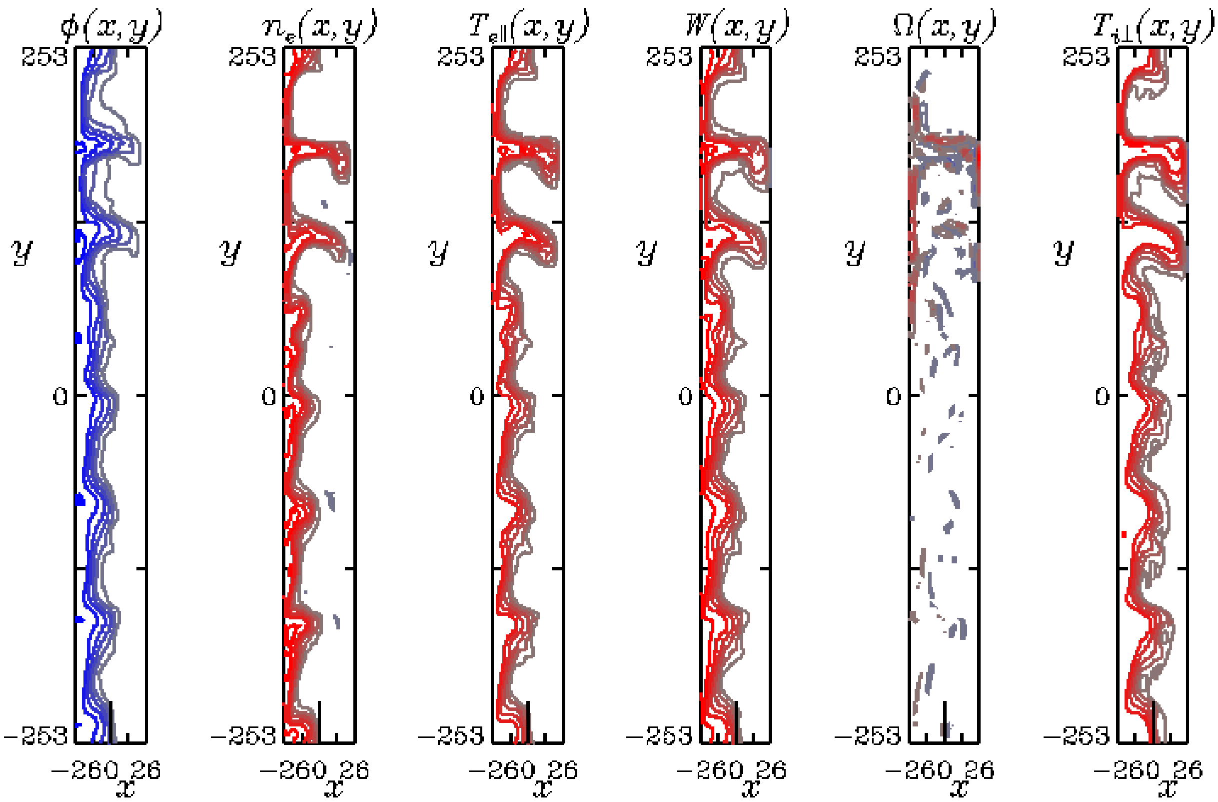

Figure 1: *Contour plots of electrostatic potential ϕ, electron density n_e, parallel electron temperature $T_{e\|}$, W_i, vorticity Ω and perpendicular ion temperature $T_{i\perp}$ in the perpendicular (x,y) domain of the simulation at $n_s = 8$ (outer midplane position) for the peak linear growth phase just before transition into turbulence.*

linearly growing in the pedestal region and further nonlinearly evolving during the following turbulent blow-out phase into the scrape-off layer. Previous nonlinear approaches on ELM ideal ballooning mode burst computations [4] have treated only the initial growth phase, focused on low-wavelength modes and were under-resolved, thus excluding saturation and a treatment of the turbulent phase. They also advance a scenario of nonlinear explosive growth which we examine.

The transition from initial (micro-)instabilities to generic edge turbulence was studied in detail in Ref. [5]. As the most unstable linear modes crystallise out of an initial random bath of small-amplitude perturbations, the linear growth rate rises and becomes steady. The maximum value of the instantaneous growth rate of total energy E given by $\Gamma(t) = (1/2)\partial_t \ln E$ may be taken as the maximal linear growth rate. The curve of $\Gamma(t)$ then falls very sharply to zero (over about $10L_\perp/c_s$) as saturation occurs. There is some structural adjustment over the next few $100L_\perp/c_s$ as the spectrum fills out, and then the turbulence is fully developed. But over the adjustment phase the value of Γ is well below its previous maximum.

The IBM ELM blow-out scenario is similar to this, initially, except that the instability is not a microinstability. Nevertheless, the scale differs by less than an order of magnitude: the resistive linear toroidal mode numbers are in the range of $n = 50 - 100$ while the main ideal ballooning mode is near mode number $n = 10$, on the entire flux surface, for these typical $\rho_s/L_\perp$ values.

The IBM instability is very violent, growing at a rate $\Gamma = 0.18 c_s/L_\perp$, just below the ideal interchange rate. The subsequent growth curve $\Gamma(t)$ appears qualitatively like the basic turbulence ones, however, except for several overshoot oscillations at saturation. At all time points in the nonlinear phase $\Gamma(t)$ is well below its previous maximum. At late times the initial blow-out no longer imprints the results: with a fixed source one merely finds bursty turbulence thereafter. Hence, there is no evidence for explosive instability.

The presence or absence of background current gradient terms ($\tilde{J}_\parallel \rightarrow \tilde{J}_\parallel + J_0$) everywhere the electron $\tilde{v}_{e\parallel}$ appears in the equations, with J_0 given by the q profile) was found to have no discernable effect on the result (since in physical units J_0 is well below $n_e e c_s q R/L_\perp$).

Conclusions. The main conclusion of this study is that the qualitative nature of the saturation and aftermath of the initial IBM blowout is the same as for generic edge turbulence given a small-amplutide start. Only the nature of the linear mode itself differs. The blowout saturates upon its own self generated drift-Alfvén turbulence, with a strong ion temperature component given the gradients. The vorticity spectrum reaches quickly to the ion gyroradius (ρ_i) scale, requiring the gyrofluid model and explaining why Braginskii models crash on entry to the nonlinear stage. Convergence in the aftermath requires resolving at least ρ_i. Unfortunately, due to the lack of a self consistent H-mode state in a well resolved computation, no threshold is found. At lower beta values one simply finds generic edge turbulence driven by the temperature gradients. It is not clear that this scenario really describes an actual ELM, but at least herein the MHD results lose validity upon initial saturation and no explosive instability is found.

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