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Numerical study of drift wave turbulence in large magnetic islands

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Introduction

The interaction of turbulent dynamics and magnetic perturbation fields resonant at rational surfaces, i.e. magnetic islands is still a matter of discussion. The DED campain at TEXTOR [1] offers the interesting opportunity to induce deliberately large islands at the q=3-surface. In these experiments a strong signature of Alfvén dynamics has been observed by the use of reflectometry. Also imaging techniques allowed to study the spatial profile of turbulent density fluctuations in the island chains at q=3. Numerical studies on drift wave turbulence [2] and ballooning turbulence [3] in ergodized magnetic fields proved that the presence of a radial magnetic perturbation field can change the amplitude levels and the turbulent transport significantly. In this work we show that these effects also occur for a single perturbation mode (single island chain), thus without ergodization. The ATTEMPT code has been employed to simulate three-dimensional electromagnetic fluid drift turbulence in a realistic scenario reflecting TEXTOR-DED conditions. Besides the turbulent dynamics the ATTEMPT code also provides the selfconsistent modifications of the background plasma parameters, i.e. the static profiles of density, electric potential and radial magnetic field.

Turbulence model and computational details

The turbulent dynamics is represented by a four-field model describing the non-linear evolution of the electric potential ϕ, the density n, the parallel magnetic potential A and the parallel ion velocity u [4, 5].

$$\frac{\partial n}{\partial t} = -\mathrm{v}_E \cdot \nabla(n_b + n) - \mathscr{K}(\phi - n) + \nabla_{\|}(J - u)$$

$$\frac{\partial w}{\partial t} = -\mathrm{v}_E \cdot \nabla w + \mathscr{K}(n) + \nabla_{\|} J$$

$$\hat{\beta}\,\frac{\partial A}{\partial t} + \hat{\mu}\,\frac{\partial J}{\partial t} = -\hat{\mu}\,\mathrm{v}_E \cdot \nabla J + \nabla_{\|}(n_b + n - \phi) - \hat{C} J$$

$$\hat{\varepsilon}\,\frac{\partial u}{\partial t} = -\hat{\varepsilon}\,\mathrm{v}_E \cdot \nabla u - \nabla_{\|}(n_b + n)$$

These are the scaled equation of continuity, Ohm's law, the total momentum balance the quasineutrality condition, respectively, with vorticity w and current J defined by w=$-\nabla_\perp^2 \phi$ and J=$-\nabla_\perp^2 A$. The definitions of the operators $\mathrm{v}_E \cdot \nabla$, $\nabla_{\|}$, $\nabla_\perp^2$ and K for a field aligned slab-geometry used here, and the parameters $\hat{\beta}$, $\hat{\mu}$, $\hat{\varepsilon}$ and $\hat{C}$, can be found in [5]. The perturbations in the vector potential A, entering the parallel derivative $\nabla_{\|}$, consist of two parts. One is the self consistent intrinsic plasma response A_{int} arising from the parallel current. The other is a static contribution A_{ext} externally imposed by coil currents, so that $\nabla_\perp^2 A_{ext}$=0 within the computational domain, which is approximated in this work by

$$A_{ext} = -A_0\, e^{m_0 x} \cos(m_0\, \theta - n_0\, \varphi)$$

where m_0/n_0=12/4 and $A_0 = 10^{-5}\,\mathrm{T\,m}$ and $x = (r - r_0)/r_0$, with r_0 the radius of the $q = 3$-surface. This corresponds to perturbations of 12/4-symmetry with respect to standard toroidal coordinates (r, θ, φ).

Numerical results - static profiles

For the simulations the parameters $\omega_B = 0.046$, $\hat{s} = 1$, $\hat{C} = 7.65$, $\hat{\beta} = 1$, $\hat{\mu} = 5$ and $\hat{\varepsilon} = 17227$ have been chosen, corresponding roughly to and density of $n = 2.7 \cdot 10^{19}\,\mathrm{m}^{-3}$ and an electron temperature of $T_e = 42\,\mathrm{eV}$ at the $q = 3$-surface at $r_0 = 0.4\,\mathrm{m}$ in TEXTOR-geometry (minor radius $a = 0.5\,\mathrm{m}$, major radius $R_0 = 1.75\,\mathrm{m}$).

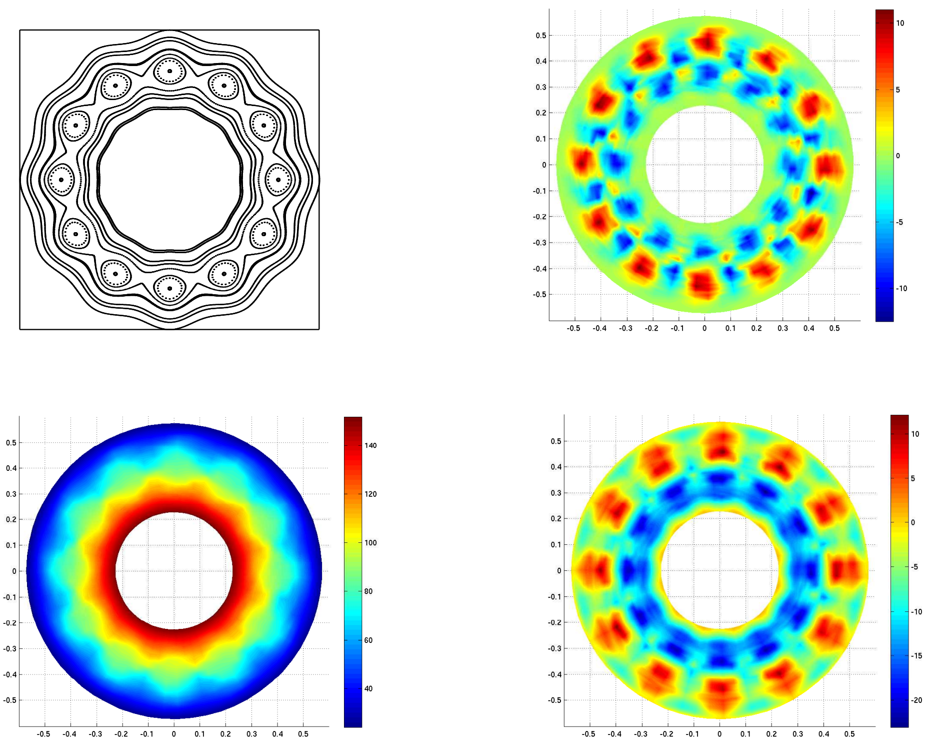

Figure 1: Poincaré-plot of the magnetic perturbation field (top left), poloidal profiles of the static density perturbation $\bar{n}$ (top right), the background density + static perturbation $n_b + \bar{n}$ (bottom left) and the difference $\bar{n} - \bar{\phi}$ of the static density and electric potential perturbations.

The simulation has been performed for $0 < t < 3000$ with time t in units of $c_s/L_\perp$ starting with a small random density perturbation. In the interval $2000 < t < 3000$ time averaged quantities have been computed. The Figs.1 show the time averaged density $\bar{n}$, the nonadiabatic part of the density $\bar{n} - \bar{\phi}$, and the “total” density profile $n_b + \bar{n}$, i.e. the sum of the (linear) background profile n_b and the static contribution $\bar{n}$, which is attributed to a new equilibrium. For comparison also the Poincaré-plot of the magnetic 12/4-perturbation field is shown and it is obvious that the static solutions reflect strongly the symmetry of the perturbation field. The total density profile exhibits clearly a flattening on the islands, whereas the difference $\bar{n} - \bar{\phi}$ is constant at the $q = 3$-surface and exhibits maxima and minima at the separatrix. A closer inspection of the profiles shows that the time average $\bar{n} - \bar{\phi}$ is qualitatively well described by a function of the form $f \sim x e^{-(2x/\sigma)^2} \chi^p$, where χ is a function which fulfils $\mathrm{B} \cdot \nabla \chi = 0$, with B the total magnetic field (equilibrium + perturbation). The width σ of the gaussian is the width of the islands. For an approximate (cylindrical) equilibrium field of the form $\mathrm{B}_0 = B_0/(qR)(\mathrm{e}_\theta + q\,\mathrm{e}_\varphi)$ with a linearized q-profile, $1/q = 1/q_0\,(1 - \hat{s}x)$, where $q_0 = q(r_0)$, an analytical form for the function χ can be found

$$\chi = (2x+3)x^2 + \frac{6\,q_0 A_0 R_0}{B_0\,\hat{s} r_0^2}\,(1 - e^{m_0 x}\cos(m_0\,\theta - n_0\,\varphi)) \qquad (1)$$

Using the above listed parameters and an exponent $p = 3$ one obtains the pattern shown in Fig. 2, which resembles quite well the result of Fig. 1 (bottom right).

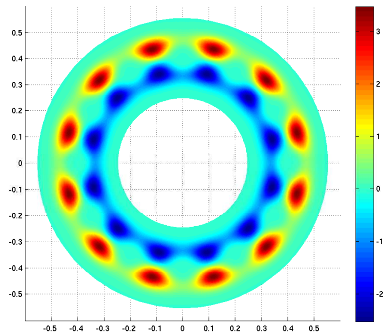

Figure 2: Plot of the function $x e^{-(2x/\sigma)^2} \chi^3$ (see text).

Even though the origin of this particular qualitative form of the nonadiabatic density $\bar{n} - \bar{\phi}$ is not clear at yet, the proposed functional form might give a useful hint for further (semi-) analytical studies on the static structures in the presence of a magnetic perturbation.

Numerical results - fluctuations

The Figs.3 show the radial profiles of the density and the radial $E \times B$-transport splitted into static and fluctuating contributions, as obtained by averaging over the unperturbed flux surfaces. Both quantities have a rather small staitc contribution in the case of the unperturbed magnetic field. In contrast the static perturbations are quite strong if the perturbation field is present. Despite of this the fluctuations in the density and the radial transport show also an increase of about 30 %.

Summary

The results demonstrate that the density and the electric potential exhibit a strong resonant behavior with respect to the perturbation mode. This is caused by the additional source for free

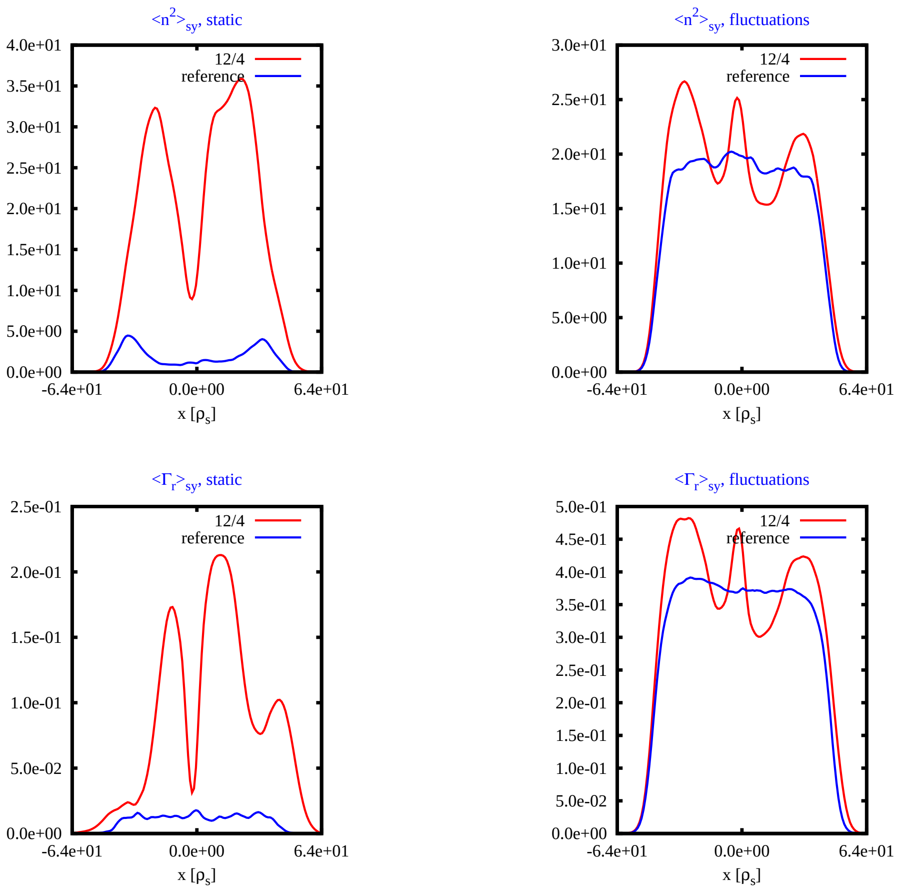

Figure 3: Radial profiles of the θ-φ-averaged static density perturbations (top left), density fluctuations (top right), static radial $E \times B$-transport (bottom left) and radial $E \times B$-transport due to fluctuations. The red curves show the profiles of the perturbed plasma, the blue curves show the unperturbed case.

energy of profile perturbations due to an additional access to the background density gradient in the presence of strong radial magnetic perturbation fields as discussed in [2]. The static perturbations in the density and the electric potential also reflect strongly the island chain structure and consequently the local turbulent transport exhibits a strong correlation with the O-point and X-point pattern of the perturbation field.

References

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