Interaction of Alfvénic modes and turbulence via the nonlinear modification of the equilibrium profiles

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Introduction and motivation

A key step towards the achievement of controlled nuclear fusion in magnetic confinement devices is the mitigation of turbulence. Turbulence is generated by the nonlinear interaction of micro-instabilities like ion-temperature-gradient (ITG) modes [1]. ITGs are dominantly electrostatic (ES) modes driven unstable by the gradients of plasma temperature. A population of energetic particles (EP) is present in tokamak plasmas due fusion reactions and external heating mechanisms. EPs can drive electromagnetic (EM) oscillations like Alfvén Modes (AM) [2, 3] unstable.

The study of the interaction of EPs, macroscopic AMs and microscopic ITG-turbulence is a numerically demanding problem due to its multi-scale character. Moreover, a kinetic treatment is necessary to properly include wave-particle interactions. As the dynamics of interest is slower than gyrofrequencies, the gyrokinetic (GK) ordering is valid. Interaction of EPs and turbulence has been observed in experiments [4, 5, 6, 7]; it has been investigated by means of analytical theory [8, 3, 9, 10]; it has been investigated by means of flux-tube numerical simulations [11, 12, 13, 14, 15, 16]; recently, a first investigation by means of global EM numerical simulations has been performed [17].

AMs nonlinearly modify the equilibrium profiles [3, 18, 19, 20, 17]. Can we isolate and study numerically how this affects ITG turbulence? In this work, we investigate this problem, by means of the following simplified test. First, we run global selfconsistent EM simulations of AMs and turbulence with ORB5 (similarly to Ref. [17]) to save the profiles modified by the AM. Secondly, we use the modified profiles, for ES simulations of ITG turbulence.

Model and equilibrium

The numerical tool used in this work is the multispieces EM GK particle-in-cell code ORB5 [21, 22]. ORB5 is global, i.e. it resolves modes with structure comparable with the minor radius. Thus, it is appropriate for studying AMs with low toroidal mode number. A Krook operator is used as source for the thermal species, slowly restoring the initial thermal plasma profiles (it is not applied to the EP species here).

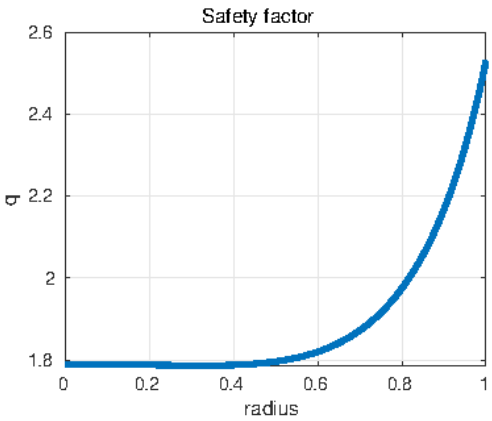

Figure 1: *Safety factor profile*

A magnetic equilibrium with circular concentric flux surfaces is considered. The geometry has a large aspect ratio and gradients peaked at mid-radius for simplicity. We use a monotonic safety factor profile here (see Fig. 1), instead of the profile with reversed shear used in Ref. [17]. The plasma density and temperature correspond to a value of normalized sound gyroradius of $\rho^* = \rho_s/a = \sqrt{T_e/m_i}/\Omega_i = 0.00571$, and $\beta = 8\pi n(T_i + T_e)/B^2 = 1 \cdot 10^{-3}$.

First part of the numerical experiment: study of the profiles modified by the AM

In the first part of this numerical experiment, we run selfconsistent nonlinear global EM simulations, with the goal of studying the modification of the equilibrium profiles. These simulations are similar to those described in Ref. [17].

In Fig. 2-left, the evolution of the radial electric field in time is depicted. In the first half of the simulation, no EPs are present, and ITG modes grow in amplitude and form a saturated turbulence state. Both zonal (i.e. flux-surface-averaged) and non-zonal (the remaining part) electric fields are shown. EPs are switched on at $t = 6 \cdot 10^4\,\Omega_i^{-1}$, driving AMs near the radius $\rho = 0.4$ (blue lines in Fig. 2-left). Note that $\Omega_i = 175.4\, c_s/a$, with $c_s = \sqrt{T_e/m_i}$.

The heat flux carried by the AM modifies the equilibrium profiles. As an example, one can

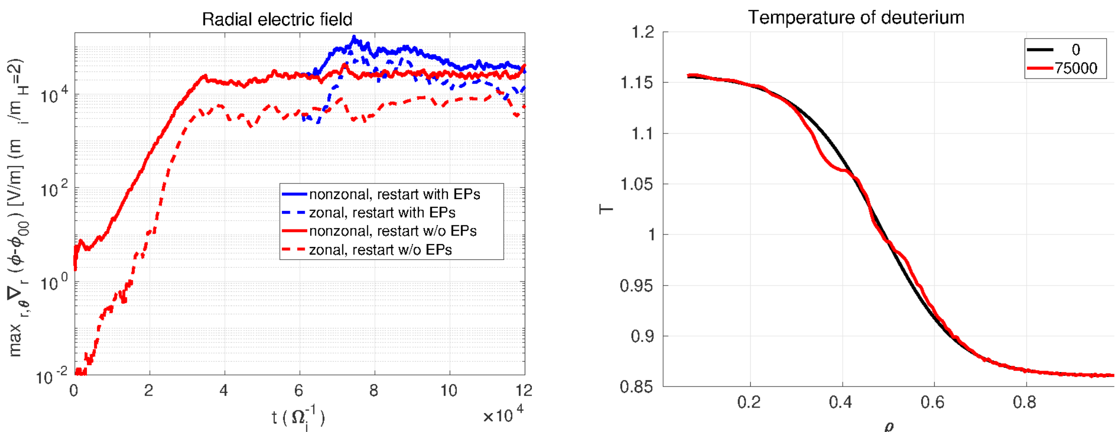

Figure 2: *On the left, radial electric field for a simulation with EPs (blue) and without EPs (red). On the right, modified ion temperature profile (red) compared with the unperturbed profile (black).*

see the thermal ion temperature profile at $t = 0$ and $t = 75000\,\Omega_i^{-1}$ (normalized with the value at $\rho = 0.5$). The modified profiles are saved, and used as input for ES ITG simulations.

Second part of the numerical experiment: effect of the modified profiles on turbulence

In the second part of this numerical experiment, we want to design a simple numerical test to isolate the indirect interaction of the AMs with turbulence, by means of the profile modification. We are not interested here in the wave-wave interaction of AMs and ITGs. To this aim, we take the saved profiles from the EM simulations, and we use them to perform nonlinear global electrostatic simulations. These simulations have no AMs. We also have only one kinetic species: thermal ions. No EPs are included here. Therefore, only ITG turbulence is present here (and zonal flows). The turbulence dynamics is measured with its heat fluxes. We find that the heat fluxes of the simulations with the modified profiles are about a factor 2 lower than the heat fluxes of the simulations with unperturbed profiles. This means that there is an effect of turbulence reduction due to the fact that AMs flatten the equilibrium profiles around $\rho = 0.4$.

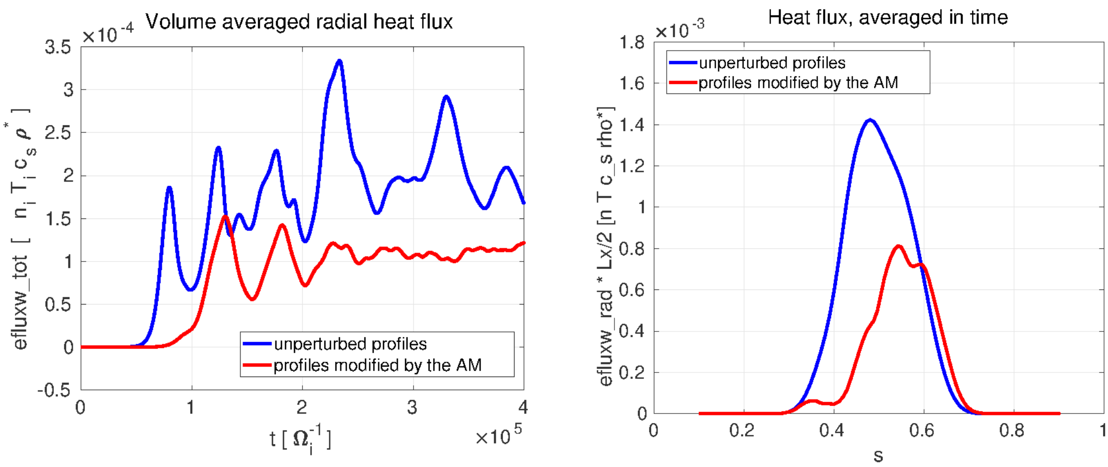

Figure 3: *Turbulence intensity (estimated by means of heat fluxes) in the ES simulation for the unperturbed (blue) and modified profiles (red). Time evolution (left) and radial structure (right).*

Conclusions and next steps

In this work, we have measured the modification of the equilibrium profiles due to AMs with EM simulations, and we have investigated the effect of the profile modification on ITG turbulence. The first part of the study is done by means of EM simulations (including AMs on top of ITG turbulence), whereas the second part is done by means of nonlinear ES ITG simulations. Turbulence is found to be reduced when the profiles modified by the AM are used, in comparison with simulations where the unperturbed profiles are used. This is a sign of an indirect reduction of turbulence by AMs.

As next steps, we would like to measure the phase-space zonal structures [18], to characterize the transport in simplified tests like this, and in selfconsistent simulations. Then, we will relax some simplifications on the configuration, to be closer to experiments, like in Refs. [23, 24, 25]. Finally, we want to study the effects on turbulence in self-consistent simulations, with linearly unstable AMs (like in Ref. [17]) or marginally stable AMs (like in Ref. [16]), with ORB5.

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References

[1] L. I. Rudakov, and R. Z. Sagdeev, *Sov. Phys. Dokl.* **6** 498 (1965)

[2] K. Appert, et al. *Plasma Phys* **24**, 1147 (1982)

[3] L. Chen, F. Zonca, Rev. Mod. Phys. **88**, 015008 (2016)

[4] G. Tardini, et al., *Nucl. Fusion* **47**, 280 (2007)

[5] W. W. Heidbrink, et al., *Phys. Rev. Lett.* **103**, 175001 (2009)

[6] M. Romanelli, A. Zocco, F. Crisanti, and JET Contributors, *Plasma Phys. Control. Fusion* **52**, 045007 (2010)

[7] A. Bock, et al., *Nucl. Fusion* **57** 126041 (2017)

[8] R. White, and H. Mynick, *Phys. Fluids B* **1**, 980 (1989)

[9] F. Zonca, et al., *Plasma Phys. Control. Fusion* **57** 014024 (2015)

[10] Z. Qiu, L. Chen, and F. Zonca, *Nucl. Fusion* **56**, 106013 (2016)

[11] C. Angioni, et al., *Nucl. Fusion* **49**, 055013 (2009)

[12] E. M. Bass and R. E. Waltz, *Phys. Plasmas* **17**, 112319 (2010)

[13] W. Zhang, V. Decyk, I. Holod, Y. Xiao, Z. Lin, and L. Chen *Phys. Plasmas* **17**, 055902 (2010)

[14] J. Citrin, et al, *Phys. Rev. Lett.* **111**, 155001 (2013)

[15] J. Garcia, et al., *Nucl. Fusion* **55** 053007 (2015)

[16] A. Di Siena, et al., 2019 *Nucl. Fusion* **59**, 124001 (2019)

[17] A. Biancalani, et al., *Plasma Phys. Control. Fusion* **63**, 065009 (2021)

[18] M. V. Falessi, and F. Zonca, *Phys. Plasmas* **26**, 022305 (2019)

[19] F. Zonca, L. Chen, M. V. Falessi and Z. Qiu, *J. Phys. Conf. Ser.* **1785**, 012005 (2021)

[20] M. V. Falessi, F. Zonca, Z. Qiu, and L. Chen, P5b.106, this conference.

[21] A. Mishchenko, et al, *Comp. Phys. Commun.* **238**, 194 (2019)

[22] E. Lanti, et al, *Comp. Phys. Commun.* **251**, 107072 (2020)

[23] A. Mishchenko, et al., *Plasma Phys. Control. Fusion* **63**, 084007 (2021)

[24] T. Hayward-Schneider, et al, O4.111, this conference.

[25] B. Rettino, et al, P1a.112, this conference.