Global electromagnetic gyrokinetic simulations of Energetic Particle driven instabilities in ITER

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Abstract

The effect of Neutral Beam Injection on the stability of Alfvén eigenmodes (AEs) in a Pre-Fusion-Power-Operation ITER plasma is considered using global gyrokinetic simulations using the code ORB5. While nominal energetic particle density is not found to drive the AEs unstable with an isotropic distribution function, the modes are found to be marginally stable, and excitable with double the nominal EP density.

In the case of higher mode numbers, Alfvénic Ion Temperature Gradient (AITG) modes are found to be unstable in the core of the plasma, close to a local maximum of the safety factor profile.

Introduction

Energetic Particles (EPs), such as those from Neutral Beam Injection (NBI) heating or the fusion products alpha particles, will be present in any burning plasma such as ITER. The confinement of such energetic particles is important for their effective heating of the background plasma. Electromagnetic Alfvénic perturbations can be driven unstable by EPs, and are able to redistribute the EP distributions, causing their transport. Previous work [1] considered the alpha driven toroidal Alfvén eigenmodes (TAEs) in an ITER 15MA fusion scenario. In this work, we consider a hydrogen pre-fusion ITER scenario, considering the NBI and its interaction with Alfvénic instabilities.

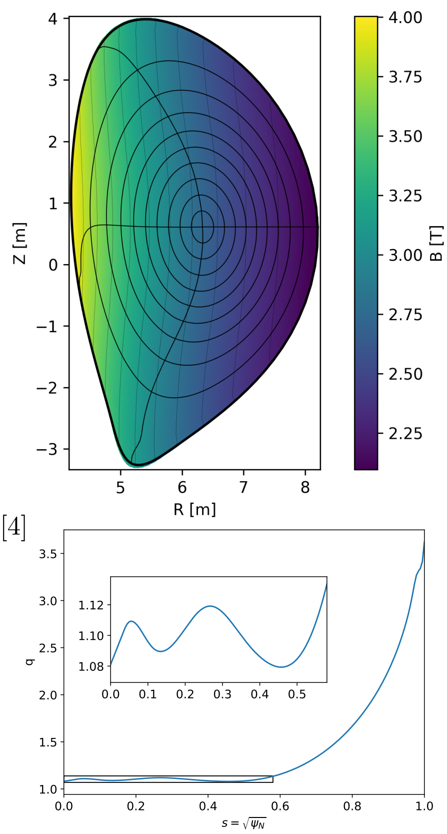

Figure 1: (a) ITER 15MA scenario equilibrium. The colour scale indicates $|B|$. (b) the safety factor profile.

ITER Pre-Fusion-Power-Operation-2 (PFPO-2) scenario (#101006)

The scenario [2] considered in this paper is a PFPO-2 hydrogen scenario with half-current and half-field, and was calculated by ASTRA [3]. It is defined in the IMAS/IDS [4] system as shot 101006, run 50, with the equilibrium data used for this work being construction from the IDS representation, with the equilibrium being reprocessed using CHEASE [5]. The density and temperature profiles are showing in 3. The electron temperature is peaked, with an axis value $T_{\mathrm{e},s=0} \approx 8\,\mathrm{keV}$, and a value at the top of the pedestal $T_{\mathrm{e,ped.\ top}} \approx 3\,\mathrm{keV}$. The main ion (hydrogen) temperature has similar core and pedestal top values, but the peaking is different, with the strong gradient region at smaller radius than that of the electron temperature. The electron and ions density profiles (linked via quasineutrality and the impurity density profiles) are only weakly peaked, with $n_{\mathrm{e},s=0} \approx 4 \times 10^{19}\,\mathrm{m}^{-3}$. Impurity species (Neon and Beryllium) are considered, and have temperature profiles matching the main ion profile.

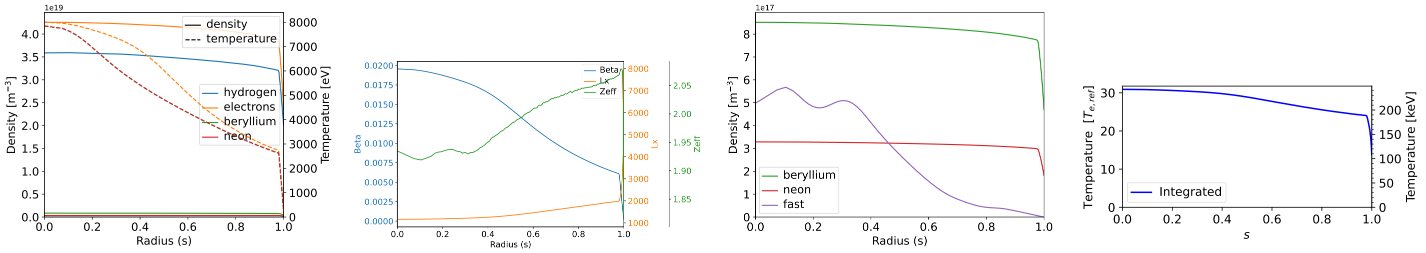

Figure 3: (a) Density (solid) and temperature (dashed) profiles for the bulk species in the scenario; (b) profiles of dimensionless quantities: electron $\beta(s)$, $L_\mathrm{x}(s) = 2/\rho^*(s) = 2a/\rho_s(s)$, $Z_\mathrm{eff}(s)$; (c) Energetic particle and impurity density profiles; (d) Equivalent pressure temperature of the energetic particles (assuming a 1 MeV slowing down).

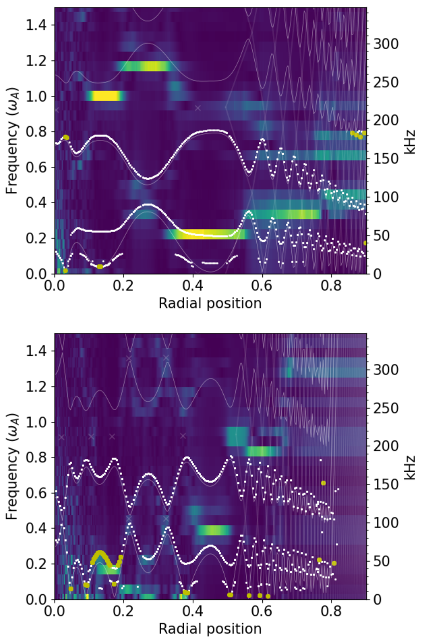

Figure 2: Radial spectrograms of (a) n=12 and (b) n=32 simulations without EPs. Overplot is the Alfvén continuum calculated from LIGKA (thin: MHD, thick: gyrokinetic).

The safety factor (q) profile is highly non-monotonic, and is shown in Figure 1(b) (note that the q profile obtained from CHEASE is not identical to the q-profile of the IDS, as written by ASTRA). ITER has 2 negative NBI beams capable of injecting particles with birth energies of 1 MeV (Deuterium) or 870 keV (hydrogen) [6]. In this work, we consider hydrogen beams, but treat the injection energy as 1 MeV, and the distribution function as an isotropic slowing down. A more realistic treatment of the NBI distribution function will be considered in future work, following similar treatment as was performed for ASDEX Upgrade in [7, 8].

Numerical Model: ORB5

In this work, the numerical results presented are obtained using the ORB5 code [9]. ORB5 is a global electromagnetic gyrokinetic particle-in-cell (PIC) code which uses markers to sample the 5D phase space ($\vec{R}$, $v_\parallel$, μ), with the equations independent of the gyrophase, and the magnetic moment (μ) of a marker constant in the absence of collisions. The code uses the mixed-variable representation of electromagnetic gyrokinetics [10], solving the linearized gyrokinetic quasineutrality equation, and the parallel Ampère's law, setting $\delta B_\parallel = 0$. A set of straight field line coordinates are used, with radial coordinate $s = \sqrt{\psi/\psi_\mathrm{edge}}$ (where ψ is the poloidal flux), toroidal angle φ, and poloidal angle $\theta^* = \frac{1}{q(s)} \int_0^\theta \frac{\vec{B}\cdot\nabla\varphi}{\vec{B}\cdot\nabla\theta'} \mathrm{d}\theta'$ (where θ is the geometric poloidal angle, and q(s) the safety factor). The field equations are solved on a basis of cubic finite elements and using Fourier methods in the two angular directions. This allows the use of Fourier filtering, which helps to reduce noise by excluding non-physical modes which are far from being field aligned [11, 12]. The local poloidal Fourier filter will retain modes with poloidal mode numbers $m_n(s) = \lfloor nq(s) \rceil \pm \Delta m$ at each radial point for each toroidal mode n, where a typical values of Δm is 5.

Alfvén Eigenmodes

Neglecting energetic particles, we perform a series of simulations with different n, initializing a radially broad $n = n_\mathrm{ref}$ field-aligned density perturbation. As this initial pertubation decays away, we can see the weakly damped eigenmodes of the system.

We observe stable Toroidal, Elliptical, Reversed Shear and/or Beta-induced AEs (TAEs, EAEs, RSAEs, BAEs) for various mode numbers, with examples for $n = 12$ and $n = 32$ frequency plots shown in figure 2. In the case of $n = 18$, we measure $\omega/\omega_\mathrm{A} = 0.342$, $\gamma/\omega_\mathrm{A} = -4 \cdot 10^{-3}$ (since this is close to the numerical uncertainty, for only this case, we reduced the timestep from $10/\omega_\mathrm{ci}$ to $2.5/\omega_\mathrm{ci}$ to improve our estimate of the damping rate).

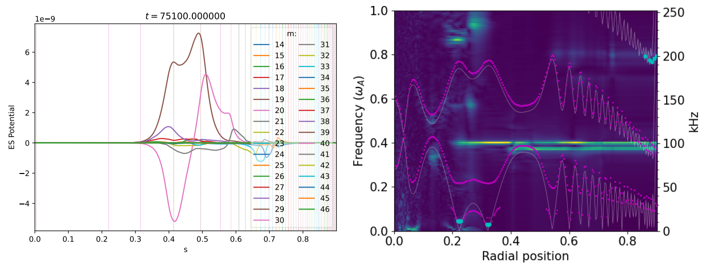

Figure 4: (a) Radial poloidal mode structure of the n=18 mode; (b) Radial spectrogram of the same simulation.

Effect of EPs

Adding the nominal EP density, as shown in figure 3, we find that the AEs are still marginally stable, with $n = 18$ exhibiting a net damping of $\gamma/\omega \approx -1\%$, and $\omega = 0.328\ \omega_A = 83\,\text{kHz}$.

Increasing the EP density to $2\times$ the nominal density, we find that many n are now linearly unstable. Taking again the example of $n = 18$, we see a pair of TAE-like modes with similar frequency, nothing that either side of the $q_{\min}$ surface, we have $q = (19 + 1/2)/18$ surfaces (present at $s = [0.0037, 0.414, 0.495]$). The poloidal mode structure and the split frequency are shown in figure 4. We note that due to the beating modes, measuring the growth rate is difficult, but we estimate $0.004 < \gamma/\omega_A < 0.008$, with frequency peaks at 95 kHz and 101 kHz (0.375 and 0.400 ω_A respectively), with the higher frequency component associated with the anti-ballooning Φ structure.

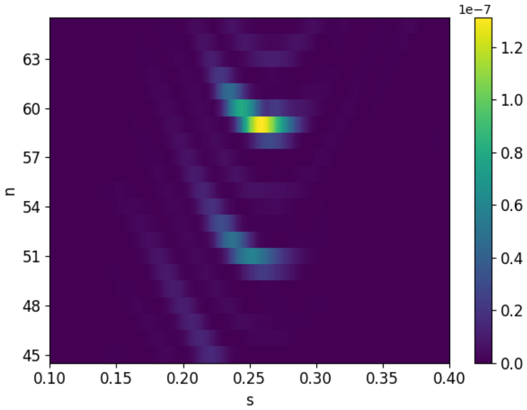

Figure 5: Electrostatic potential plotted against radius and mode number for 21 single-toroidal-mode-number simulations.

Alfvénic Ion Temperature Gradient instabilities

In this section, we again neglect the effect of the energetic particles, and we perform simulations with higher mode number $45 \leq n \leq 65$, focusing on the core of the plasma, since preliminary scans found core instabilities which required identification. In figure 5, we plot the electrostatic potential on the outboard midplane as a function of toroidal mode number, collected from 21 single n simulations after a constant amount of time ($t\omega_{ci} = 40000$). We see instabilities, e.g. $n = 50$: 37 kHz with $\gamma/\omega = 5.5\%$, with an apparent periodicity in mode number of ≈ 9. This periodicity is identified to correspond to rational approximations of the local $q_{\max}$ value of the safety factor. Comparing to the linear gyrokinetic eigenvalue solver LIGKA [13], we find that in this range of mode numbers, the imaginary part of the Alfvén continuum turns positive. We therefore identify these modes with BAE/RSAE like mode structures as AITGs [14, 15]. These instabilities are found to be almost unaffected by the addition of a simplified EP population.

Conclusions

Alfvénic instabilities are investigated for an ITER Pre-fusion-power-operation (PFPO) plasma, and two different scales are identified. "Conventional" Alfvén eigenmodes in the range 10–30 are found to be marginally stable or weakly damped in the presence of the nominal EP density, although this study needs to be extended to consider the effect of anisotropy. In addition, higher mode number instabilities are found, unstable independent of the EPs, driven by the bulk plasma gradient.

Acknowledgements

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References

[1] T. Hayward-Schneider, Ph. Lauber, A. Bottino, and Z.X. Lu. Global linear and nonlinear gyrokinetic modelling of Alfvén eigenmodes in ITER. *Nuclear Fusion*, 61:036045, 2021.

[2] A.R. Polevoi, A. Loarte, R. Bilato, N. Gorelenkov, Ye.O. Kazakov, E. Polunovskiy, A. Tchistiakov, E. Fable, V. Kiptily, A.V. Krasilnikov, A.Y. Kuyanov, R. Nazikian, S.D. Pinches, and M. Schneider. Impact of suprathermal ions on neutron yield in the pre-DT phase of ITER operation. *Nuclear Fusion*, 61(7):076008, 2021.

[3] G.V. Pereverzev and P.N.Yushmanov. ASTRA automated system for transport analysis in a tokamak. *Max-Planck IPP Report*, 5(98), 1991.

[4] F. Imbeaux, S.D. Pinches, J.B. Lister, Y. Buravand, T. Casper, B. Duval, B. Guillerminet, M. Hosokawa, W. Houlberg, P. Huynh, S.H. Kim, G. Manduchi, M. Owsiak, B. Palak, M. Plociennik, G. Rouault, O. Sauter, and P. Strand. Design and first applications of the ITER integrated modelling & analysis suite. *Nuclear Fusion*, 55(12):123006, 2015.

[5] H. Lütjens, A. Bondeson, and O. Sauter. The CHEASE code for toroidal MHD equilibria. *Computer Physics Communications*, 97, 1996.

[6] S.D. Pinches, T. Hayward-Schneider, O. Hoenen, S.H. Kim, Ph. Lauber, A. Loarte, A.R. Polevoi, V.-A. Popa, M. Salewski, M. Schneider, S.E. Sharapov, and S.H. Ward. Role of energetic ions in the iter research plan. EPS 2022.

[7] B. Rettino, T. Hayward-Schneider, A. Biancalani, A. Bottino, Ph. Lauber, I. Chavdarovski, F. Vannini, and F. Jenko. Gyrokinetic modelling of anisotropic energetic particle driven instabilities in tokamak plasmas. *Nuclear Fusion*, 2022.

[8] B. Rettino, T. Hayward-Schneider, A. Biancalani, A. Bottino, Ph. Lauber, I Chavdorovki, M. Weiland, F. Vannini, and F. Jenko. Gyrokinetic modelling of anisotropic energetic particle driven instabilities in tokamak plasmas. EPS 2022.

[9] E. Lanti, N. Ohana, N. Tronko, T. Hayward-Schneider, A. Bottino, B. F. McMillan, A. Mishchenko, A. Scheinberg, A. Biancalani, P. Angelino, S. Brunner, J. Dominski, P. Donnel, C. Gheller, R. Hatzky, A. Jocksch, S. Jolliet, Z. X. Lu, J. P. Martin Collar, I. Novikau, E. Sonnendrücker, T. Vernay, and L. Villard. ORB5: a global electromagnetic gyrokinetic code using the PIC approach in toroidal geometry. *Computer Physics Communications*, 251, 2020.

[10] A. Mishchenko, A. Bottino, A. Biancalani, R. Hatzky, T. Hayward-Schneider, N. Ohana, E. Lanti, S. Brunner, L. Villard, M. Borchardt, R. Kleiber, and A. Könies. Pullback scheme implementation in ORB5. *Computer Physics Communications*, 238, 2019.

[11] B.F. McMillan, S. Jolliet, A. Bottino, P. Angelino, T.M. Tran, and L. Villard. Rapid Fourier space solution of linear partial integro-differential equations in toroidal magnetic confinement geometries. *Computer Physics Communications*, 181, 2010.

[12] R. Hatzky, R. Kleiber, A. Könies, A. Mishchenko, M. Borchardt, A. Bottino, and E. Sonnendrücker. Reduction of the statistical error in electromagnetic gyrokinetic particle-in-cell simulations. *Journal of Plasma Physics*, 85(1), 2019.

[13] Ph. Lauber, S. Günter, A. Könies, and S.D. Pinches. LIGKA: A linear gyrokinetic code for the description of background kinetic and fast particle effects on the MHD stability in tokamaks. *Journal of Computational Physics*, 226(1), 2007.

[14] Fulvio Zonca, Liu Chen, and Robert A Santoro. Kinetic theory of low-frequency Alfvén modes in tokamaks. *Plasma Physics and Controlled Fusion*, 38(11), 1996.

[15] Fulvio Zonca, Liu Chen, Robert A Santoro, and J Q Dong. Existence of discrete modes in an unstable shear alfvén continuous spectrum. *Plasma Physics and Controlled Fusion*, 40(12), 1998.