

Effect of fast electrons on the stability of resistive interchange modes

L. García¹, M.A. Ochando², B.A. Carreras³, D. Carralero⁴, C. Hidalgo², B.Ph. van Milligen²

¹ *Departamento de Física, Universidad Carlos III de Madrid, 28911 Leganés, Madrid, Spain*

² *CIEMAT - Laboratorio Nacional de Fusión, Avda. Complutense 40, 28040 Madrid, Spain*

³ *BACV Solutions, 110 Mohawk Road, Oak Ridge, Tennessee 37830, USA*

⁴ *Max-Planck-Institute for Plasma Physics, Boltzmannstr. 2, Garching, Germany*

Introduction

In stellarators, populations of fast electrons are usually generated in plasmas of relatively low density heated by ECR [1, 2]. In a series of dedicated experiments to characterize the transport of suprathreshold electrons in the TJ-II stellarator, plasmas were initially heated by ECRH, and after ECRH switch-off, heating was taken over by neutral beam injection (NBI) with an overlap between the two heating phases of less than 10 ms. In this study, a vorticity probe was used to determine the magnetic fluctuations in three coordinate directions, together with an electrostatic probe array. The most outstanding and somewhat surprising finding is the substantial reduction, by a factor of 3.5, of the magnetic fluctuations in the NBI phase as compared with the ECRH phase.

Experimental results in high β plasmas show an increase of magnetic fluctuations with beta. Resistive MHD models using reduced MHD equations have been successful in explaining MHD activity in stellarators. The reduction of magnetic fluctuations described above cannot be explained by a pure resistive MHD model. It is pertinent to investigate whether the presence of fast electrons can modify the behavior of plasma instabilities substantially. Therefore, in the following we study the effect of adding a fast electron component to an MHD model in order to try to understand the experimental results qualitatively.

MHD Model

The role of fast electrons has already been studied in the context of MHD models. These models have been used mostly to study runaway electrons. Here, we introduce a simple modification of the resistive MHD equations, similar to the one used in Ref. [3], to investigate the potential impact of fast electrons on turbulence. In this model, both thermal and fast electrons contribute to the total current. However, the resistive term in the Ohm's law only contains the current carried by thermal electrons. The equation for the current density of the fast electrons is derived from the drift kinetic equation in the zero-gyroradius limit [3]. The geometry is a periodic cylinder. The dimensionless equations are [4]:

$$\begin{aligned}
\frac{\partial \tilde{\psi}}{\partial t} &= -\nabla_{\parallel} \phi - S \bar{\omega}_{*e} \left(\frac{T_{\text{eq}}}{n_{\text{eq}}} \nabla_{\parallel} n \right) + \eta (\tilde{J}_{\zeta} - \tilde{J}_f) \\
\frac{\partial \tilde{U}}{\partial t} &= -\mathbf{v}_{\perp} \cdot \nabla U - S^2 \nabla_{\parallel} J_{\zeta} + S^2 \frac{\beta_0}{2\epsilon^2} \frac{d\Omega}{dr} \left(\frac{T_{\text{eq}}}{n_{\text{eq}}} \frac{1}{r} \frac{\partial \tilde{n}}{\partial \theta} \right) + \mu \nabla_{\perp}^2 \tilde{U} \\
\frac{\partial \tilde{n}}{\partial t} &= -\mathbf{v}_{\perp} \cdot \nabla n + \frac{S}{\bar{\omega}_{ci}} \nabla_{\parallel} J_{\zeta} + D_{\perp} \nabla_{\perp}^2 \tilde{n} \\
\frac{\partial \tilde{J}_f}{\partial t} &= -\mathbf{v}_{\perp} \cdot \nabla J_f - S \bar{v}_{\parallel} \nabla_{\parallel} J_f + \bar{\chi}_{\perp} \nabla_{\perp}^2 \tilde{J}_f
\end{aligned} \tag{1}$$

Here, ψ is the poloidal magnetic flux, $U = \zeta \cdot \nabla \times \mathbf{v}_{\perp} / B$ is the toroidal component of the vorticity, \mathbf{v}_{\perp} is the perpendicular component of the velocity, n is the density, $J_{\zeta} = \nabla_{\perp}^2 \psi$ is the total current, and J_f is the current of the fast electrons. The parameters in the equations are defined in Ref. [4]; $\bar{v}_{\parallel} = \tau_A v_{\parallel} / R_0$, where v_{\parallel} is the velocity of fast electrons along the field line, and τ_A is the Alfvén time.

To model TJ-II plasmas, we have used the q -profile corresponding to the so-called (standard) magnetic configuration 100_44_64 [5], the same as those used in the experiments, and the corresponding curvature of the vacuum configuration. Furthermore, we have used equilibrium electron temperature and density profiles similar in shape to the experimental ones. These are shown in Fig. 1, normalized to the values at the magnetic axis. In the same figure, we show the fast electron equilibrium profile used in the calculations. Here we assume the existence of a source of fast electrons. It is expressed as fast electron current profile. Since one of the sources of the instability is the gradient of the equilibrium current density, for single helicity simulations we choose a current profile peaked at the magnetic axis and with slope different from zero only in a region close to the rational surface of the dominant component of the fluctuations. The value of the fast electron current density at the magnetic axis is J_0 , we will use J_0 as a parameter to characterize the variation of the population of the fast electrons.

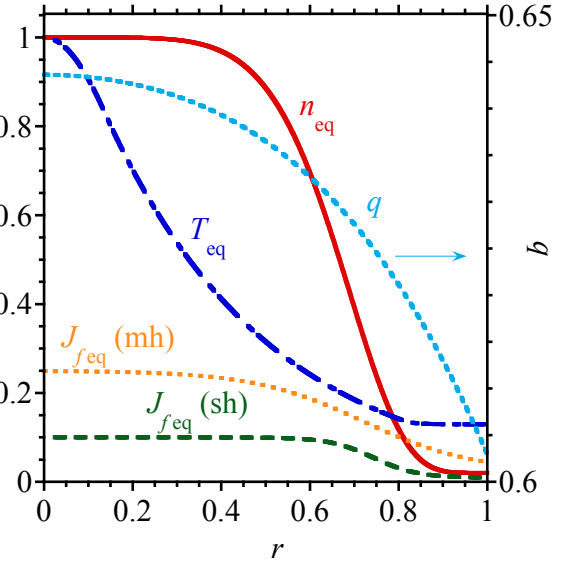


Figure 1: Equilibrium profiles used in single (sh) and multiple helicity (mh) simulations.

The effect of fast electrons on the linear growth rate is weak, but the poloidal flux function of the fastest growing mode changes parity with respect to the rational surface for relatively small values of the the fast electron current. When $J_0 = 0$, the eigenfunction corresponds to an interchange mode driven by the gradient of density, and the poloidal flux profile has almost an odd structure with respect to the rational surface. When we include the effect of fast electrons, there is a second drive for the instability, namely the gradient of the current of fast electrons. Fig. 2 shows the total current density J_ζ for $J_0 = 0.02$ together with the current of the fast electrons J_f and the current carried by thermal electrons $J_{res} = J_\zeta - J_f$. They correspond to the linear eigenfunction of the $(m = 5, n = 8)$ mode. The current carried by thermal electrons has almost an odd structure with respect to the rational surface, while the current of the fast electrons has almost an even structure. The reason is that the latter is mainly driven by the gradient of the equilibrium current of fast electrons. As J_0 increases, the fraction of the total current due to fast electrons increases, and there is a continuous change in the structure of the mode from interchange to tearing-like.

Nonlinear calculations

We have carried out first $q = 5/8$ single helicity nonlinear calculations, as this is the helicity with lowest poloidal mode number m in this magnetic configuration. The rational surface is relatively close to the plasma boundary. The experimental measurements suggest that this is the dominant component of the fluctuations.

The impact of fast electrons on the nonlinear saturation levels is stronger than the impact on the linear growth rates. The nonlinear calculations show an enhancement of all fluctuations. The main effect of the trapping of fast electron by magnetic islands induced by MHD turbulence is to increase the magnetic component of the fluctuations. The trapped electrons also modify the rotation of the islands. The rotation of the magnetic islands changes in direction and magnitude from the case without fast electrons. The increase in fluctuations also causes an increase of

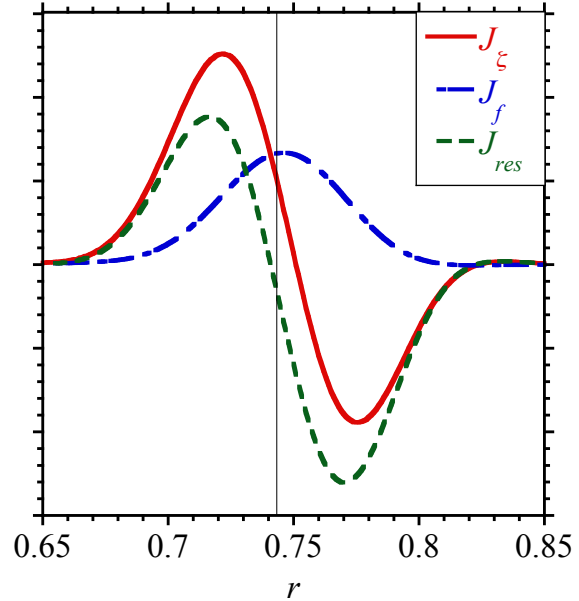


Figure 2: Total current density J_ζ , the current of the fast electrons J_f , and the current carried by thermal electrons J_{res} for $J_0 = 0.02$. The vertical line indicates the position of the rational surface.

the averaged quantities through nonlinear couplings. Such is the case of the average poloidal velocity, i.e., the zonal flow associated with the magnetic island. However, their increase is small compared with the change of the magnetic island rotation velocity. All these effects seem to explain some of the experimental observations well.

We have also considered the effect of the energy of fast electrons. For TJ-II, the energy corresponds to $\bar{v}_{\parallel} = 8$, while the case in which v_{\parallel} approaches the speed of light corresponds to $\bar{v}_{\parallel} = 20$. The parallel velocity narrows the eigenfunctions and decreases significantly the saturation level. The results for $\bar{v}_{\parallel} = 8$ and $\bar{v}_{\parallel} = 20$ are very similar.

We have started nonlinear multiple helicity calculations for TJ-II. The equilibrium current profile is different from the case of single helicity. The slope is different from zero over the whole radius. Fig. 3 shows the profile of the time-averaged mean square perturbation for a multiple helicity (mh) and a single helicity (sh) case. \bar{v}_{\parallel} is 8 for both simulations. The values of J_0 are chosen to have the same current gradient at the $q = 5/8$ rational surface. As can be seen from the figure, the fluctuation level increases strongly in the multiple helicity case. This is because the lower- m resonant modes in the different regions are nonlinearly coupled through modes resonant at higher-order rational surfaces located in between. Due to the low magnetic shear, the modes are spatially separated, but they are also broad. The calculation includes a large number of Fourier components (and helicities n/m), allowing for effective nonlinear coupling.

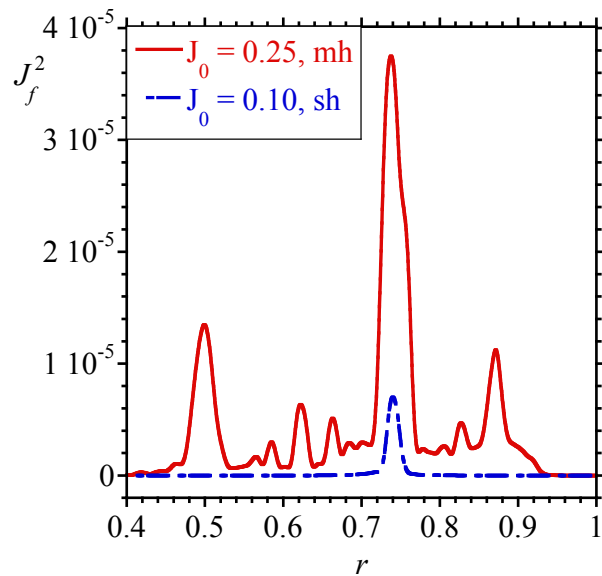


Figure 3: Profiles of the time-averaged mean squared perturbations of the current of fast electrons for a multiple helicity and a single helicity case.

References

- [1] M. Romé, et al, *Plasma Phys. Control. Fusion* **39**, 117 (1997)
- [2] M.A. Ochando, F. Medina, and the TJ-II Team, *Plasma Phys. Control. Fusion* **45**, 221 (2003)
- [3] P. Helander, D. Grasso, R.J. Hastie, and A. Perona, *Phys. Plasmas* **14**, 122102 (2007)
- [4] L. García, B.A. Carreras, V.E. Lynch, M.A. Pedrosa, and C. Hidalgo, *Phys. Plasmas* **8**, 4111 (2001)
- [5] C. Alejaldre, et al., *Plasma Phys. Control. Fusion* **41**, A539 (1999)