Simulations of the NTM threshold with the neoclassical viscous stress tensor in XTOR-2F

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1. Introduction

Simulation of Neoclassical Tearing Modes (NTM) are carried out with the non linear MHD code XTOR-2F [1]. Modelling of those non linear instabilities are of great importance as it is strongly expected that they will limit the operational conditions for future experiments and reactors. Recently, a new model has been implemented in the code. It consists in the generalization of the pressure through the parallel viscous stress tensor and provides a consistent treatment of the neoclassical physics. In this framework, non linear (2,1) modes that are unstable above a certain threshold have been obtained. They have been characterized to be NTMs. The critical island width is found to be larger with the new model than with the previous implementation that evolved as a function of the pressure gradient.

2. Physical model

The viscous stress tensor has been implemented in a Chew-Goldberger-Low (CGL) form [4]:

$$\Pi_{\|s} = \frac{3}{2}\pi_{\|s}\left[\mathbf{bb} - \frac{1}{3}\mathbf{I}\right], \qquad \pi_{\|s} = \frac{2}{3}(p_{\|s} - p_{\perp s}) \tag{1}$$

with the pressure anisotropy given by:

$$\frac{3}{2}\pi_{\|s} = -n_s m_s \mu_s \frac{\mathbf{B}^2}{\langle(\mathbf{b}\cdot\nabla B)^2\rangle}\left[\left(\mathbf{V_s} + k_s\frac{2\mathbf{q_{\perp s}}}{5p_s}\right)\cdot\nabla\ln B + \mathbf{b}\cdot\nabla\times(\mathbf{V_s}\times\mathbf{B})/B + \frac{2}{3}\nabla\cdot\mathbf{V_s}\right]. \tag{2}$$

where $s = i, e$ corresponds to the ions and electrons, respectively. The neoclassical coefficients μ_s and $k_s = \mu_{s,2}/\mu_{s,1}$ are calculated according to [5]. In the present paper, only the perpendicular component of the heat flux has been taken into account. The parallel viscous stress tensor appears both in the momentum equation and Ohm's law in the normalized framework of XTOR:

$$\rho\partial_t\mathbf{V} = -\rho\left(\mathbf{V}\cdot\nabla\mathbf{V} + \mathbf{V_i^*}\cdot\nabla\mathbf{V}_\perp\right) + \mathbf{J}\times\mathbf{B} - \nabla p - f_{\mu_i}\nabla\cdot\Pi_{\|i} + \nu\nabla^2\left(\mathbf{V} + \mathbf{V}_i^*\right) \tag{3}$$

$$\mathbf{E} + \mathbf{V}\times\mathbf{B} = \eta\left(\mathbf{J}_\| - f_{bs}\mathbf{J_{bs}} - \mathbf{J_{CD}}\right) - \alpha\frac{\nabla_\| p_e}{\rho} \quad \text{with} \quad \mathbf{J_{bs}} = \frac{\mu_e}{\mu_e + \nu_{ei}}\left[\mathbf{J}_\| + \frac{m_i}{m_e}\frac{1}{\alpha}\frac{\left(\nabla\cdot\Pi_{\|e}\right)_\|}{\mu_e}\right] \tag{4}$$

where the neoclassical resistivity is given by $\eta \approx \eta_{SP}(\nu_{ei} + \mu_e)/\nu_{ei}$ with η_{SP} the Spitzer resistivity. $\alpha = 1/(\omega_{ci}\tau_A)$ scales to the diamagnetic contribution, τ_A the Alfvén time and ω_{ci} the ion cyclotron frequency. $\nabla \cdot \Pi_{\parallel i}$ in the momentum equation drives ion poloidal velocity while $\nabla \cdot \Pi_{\parallel e}$ generates the bootstrap current. The ad-hoc coefficients f_{μ_i} and f_{bs} have been introduced in order to scan neoclassical friction and bootstrap current amplitudes.

3. NTM threshold simulations

For NTM simulations purpose, a circular cross-section plasma with $\beta_N = 1.59$ is considered. Other important parameters are $q_{min} = 1.15$ and $\alpha = 0.03$. In this configuration, the (2,1) mode is linearly stable and the bootstrap current is sufficiently large to enable non linear destabilization.

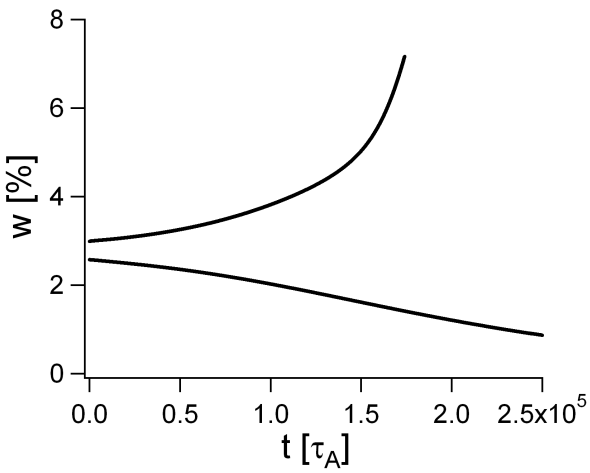

Figure 1: *Evolution of the magnetic island width for a stable and an unstable case for a circular cross-section case.*

Figure 1 shows a stable and an unstable case. It points out the presence of a non linear threshold above which the seed islands become unstable at a size corresponding to about 2.95% of the small radius.

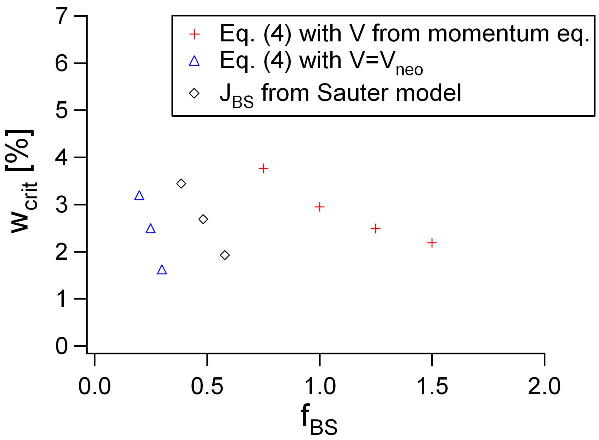

Figure 2: *Critical island size as a function of the parameter f_{BS} for three different models for the bootstrap current ($f_{\mu_i} = 1$).*

A way to determine if the mode observed is a NTM is to verify that its drive is due to the bootstrap current perturbation. For this purpose, a scan of the coefficient f_{bs} is performed. When it is increased, the bootstrap current fraction and thus its perturbation for a given seed island is larger. In this case, the threshold above which the mode is unstable should be reduced if we are in presence of NTMs. This is exactly the behaviour that is obtained with the model where $\nabla \cdot \Pi_i$ and $\nabla \cdot \Pi_e$ are given by Eqs. (1)-(2) and that is shown in Figure 2 (crosses). The non linear mode is thus confirmed to be a NTM.

Two other models are displayed on the same figure. All of them take into account the ion viscous stress tensor in the momentum equation. The first one uses also the bootstrap current form (4) but the fluid velocity is replaced by the neoclassical velocity ($\langle \nabla \cdot \Pi_{\parallel i} \rangle = 0 \Rightarrow \mathbf{V}_{neo} = -\mathbf{V}_i^* - k_i \mathbf{V}_{Ti}^*$) in the electron viscous stress tensor. The second one corresponds to an expression of the bootstrap current that varies as a function of the pressure gradient ($\mathbf{J}_{BS} = J_{BS,0}(\nabla p / p_0')\mathbf{b}$

where $J_{BS,0}$ is given by Sauter model [2, 3]).

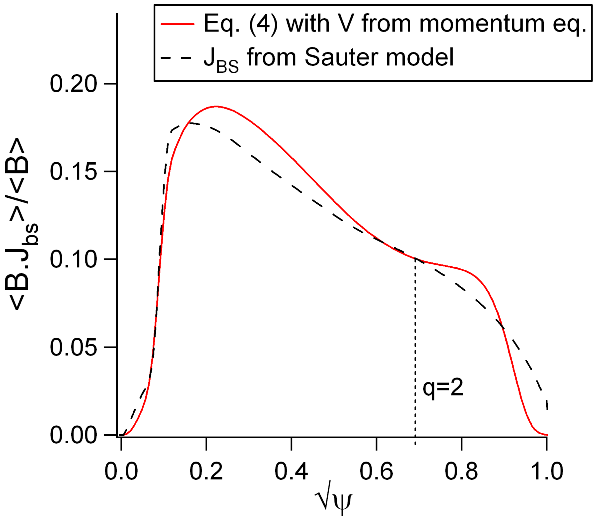

Figure 3: *Flux averaged bootstrap current for two different models for* $f_{BS} = 1$.

The points have been placed so that, for a given f_{BS}, the local bootstrap current at the $q = 2$ surface is the same. An example is displayed in Figure 3. The difference between both profiles is mainly due to the fact that the parallel heat flow is not retained presently in the model described by Eqs. (1)-(4). The radial derivative is for example not the same at $q = 2$ surface. The main observation from Figure 2 is that the complete neoclassical model gives the highest critical island width.

Part of the difference between critical island widths comes from the linear growth rate itself. The farther it is from the stable-unstable limit, the larger will be the critical seed island required to destabilize the NTM. In all the models presented here, the bootstrap current increases the linear growth rate. The discrepancy between the two formulations that use Eq. (4) is caused by other terms of the momentum equation that are at the origin of the difference between fluid and neoclassical velocities. By increasing f_{μ_i}, the influence of the ion viscous stress tensor is raised so that the velocity approaches its neoclassical value. Figure 4 (left) shows that in that case, the difference between their growth rate is also reduced. We can also deduce from it that the discrepancy between fluid and neoclassical velocity has a stabilizing effect.

Finally the structure of the perturbed bootstrap current is investigated. In the case of the bootstrap current form that varies with the pressure gradient, the reduction of the average bootstrap current at the magnetic island position and the presence of the $m = 2$ mode make appear holes at the O-points, which are the driving source of NTMs. Such a direct observation is no more possible with the complete neoclassical model (Fig. 4 (right)). In this case the perturbation is composed of a large quantity of modes that appears inside or close to the magnetic island. It is due to the poloidal variation of the bootstrap current. Anyway, even if they are not clearly visible, the terms necessary to the development of NTMs are present.

5. Conclusions

Studies of NTM driving mechanisms have been undertaken with the newly implemented model based on the parallel component of viscous stress tensor. The (2,1) mode that has been obtained is unstable above a critical island width. It has been shown to be a NTM as the non

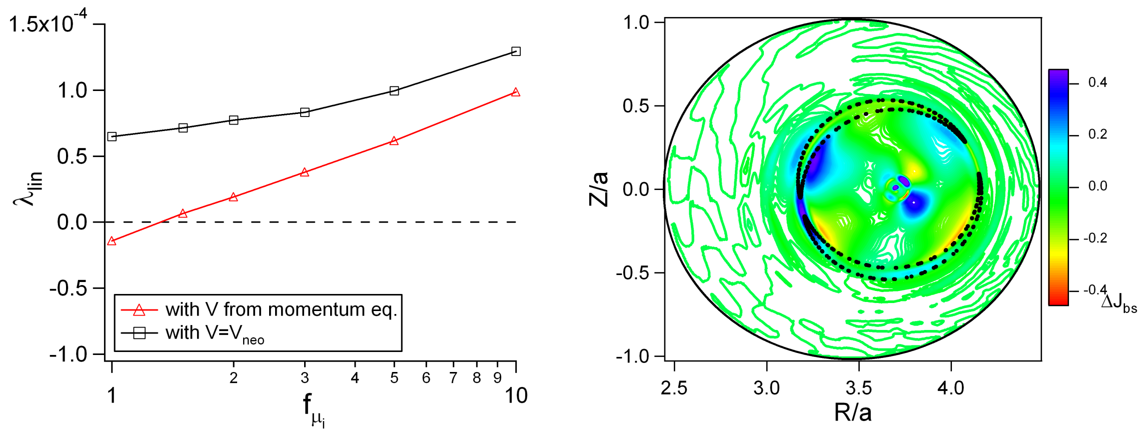

Figure 4: *Left: Linear growth rate as a function the parameter f_{μ_i} for the two models with the electron viscous stress tensor in the bootstrap current ($f_{BS} = 1$). Right: Perturbation of the bootstrap current in an unstable case with the complete neoclassical model.*

linear threshold is reduced by the increase of the bootstrap current fraction. The complete neoclassical model has been compared with two other formulations in order to better understand its effect on the NTM threshold. The fact that ion velocity does not follow exactly the neoclassical drive provided by the ion viscous stress tensor increases the critical island size. Finally the drive for NTM, i.e. a lack of bootstrap current at the O-point, is only a small part of the perturbed bootstrap current structure that is obtained with the complete neoclassical model.

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