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P. Maget[1], H. Lütjens[2], B. Alper[3], M. Baruzzo[4], M. Brix[3], P. Buratti[4], R. Buttery[5],
C. Challis[3], R. Coelho[6], E. De la Luna[7], C. Giroud[3], N. Hawkes[3], G. Huysmans[1],
I. Jenkins[3], X. Litaudon[1], J. Mailloux[3], N. Mellet[1], D. Meshcheriakov[1],
M. Ottaviani[1] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Association EURATOM-CEA, IRMF, 13108 St Paul-lez-Durance, France
[2]Centre de Physique Théorique, Ecole Polytechnique, CNRS, France
[3]EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[4]ENEA Fusion, EURATOM Association, I-00040 Frascati, Italy.
[5]General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA
[6]Associação EURATOM/IST, Centro de Fusão Nuclear, Instituto Superior Técnico,
Av Rovisco Pais, 1049-001 Lisbon, Portugal
[7]Laboratorio Nacional de Fusion, Asociacion EURATOM-CIEMAT, Madrid, Spain
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ABSTRACT.

Neoclassical Tearing Modes (NTM) are part of the major MHD instability that should be avoided in a fusion reactor, for causing confinement degradation or disruption. It consists of a magnetic island that is metastable, i.e. it is linearly stable and grows to a large size when fed by a primary mode. This metastable nature explains why both the issue of the non linear threshold, and of the coupling to the primary mode that provides the seed, are crucial. In recent years, the threshold in performance for exciting a NTM has been shown to increase significantly with plasma rotation and flow shear, and the role of flow shear on the intrinsic stability rather than on the primary mode has been pointed out. On the other hand, theoretical works do not provide a clear explanation for this observation, and generally predict that flow shear has a weak effect or is destabilizing for magnetic islands in sub-Alfvénic flows. A stabilizing effect of flow shear has however been found using MHD models retaining perturbations parallel to the magnetic field ($\delta B_{||}$, $\delta V_{||} \neq 0$), either above a threshold in the magnetic Prandlt number $\mathrm{Prm} = \mu_0 \nu / \eta$ in cylindrical geometry, or without viscosity in toroidal geometry due to toroidal curvature and mode coupling. The general picture arising from experimental studies is that velocity shear acts in a similar way as magnetic shear on the Δ' stability parameter, thanks to a coupling between the plasma flow and the resistive layer at high Prm. In the present work, we investigate this issue, which is crucial for extrapolating to ITER, by computing the non linear threshold of the (2,1) NTM for a typical JET Advanced Tokamak discharge using the full MHD code XTOR, where, in addition to geometrical effects, anisotropic heat transport and bootstrap current perturbation are described.

1. CRITICAL ISLAND WIDTH FOR (2,1) NTM IN PLASMA WITH FLOW

The critical island width is calculated by inserting in a rotating plasma a seed island of increasing size. Here, the plasma is forced to rotate by a friction with a prescribed toroidal velocity source. Important parameters for this study are the magnetic Prandtl number $\mathrm{Prm} = \mu_0 \nu / \eta$, and the ratio of resistive to confinement times $\tau_R/\tau_E = \mu_0\, \chi_\perp / \eta$ (with $\chi_\perp$ the transverse heat diffusivity), which is about 150 in the experiment. In the toroidal direction, the Prm calculated from momentum balance by TRANSP is large ($\mathrm{Prm}_\varphi^{MB} \approx 100$), and it is generally considered to result from turbulence, resulting in $n_\varphi/\chi_\perp \sim O(1)$ [10]. In the perpendicular direction, viscosity is about 2 orders of magnitude lower with $\mathrm{Prm}_\perp^{coll} \sim Z^2 \sqrt{m_i/m_e}\, \beta$ (with Z the ion charge, $\beta = \mu_0 p_e/B^2$) (figure 1). The fact that 3D magnetic perturbations develop mainly in the perpendicular direction suggests that it is the small collisional viscosity that matters, but the role of parallel perturbations highlighted in reducedMHD simulations points towards an important role of the large toroidal viscosity. With the isotropic viscosity that we have at present in our model, we will vary Prm between these two values in order to determine if there exist conditions where rotation shear can have the stabilizing effect on (2,1) NTM that is observed experimentally.

The velocity shear length L_ω is defined as $a/L_\omega \equiv$ a $a/\omega_A d\ \omega/dR$ with $\omega = V_\varphi/R$, R the major radius at the equatorial plane, a the minor radius, $\omega_A = V_A/R_0$ with V_A the Alfvén velocity. In the experiment, $V/V_A \approx 4\%$ (i.e. largely sub-Alfvénic), $a/L_\omega \approx 0.06$ and the magnetic shear length is $L_s/a = (qR/s)/a \approx 7$ (with s the magnetic shear), all evaluated at $q = 2$. Refeering to the database of DIII-D (2,1) NTM threshold scan in flow shear [1], this corresponds to a situation where the critical β_N should be about 40% higher than in the non rotating case, which represents a significant improvement in the NTM stability.

In the absence of externally driven plasma flow, the modelled critical island width for the (2,1) NTM is determined by the balance between curvature stabilization and bootstrap drive, and was found to be around 5% of the minor radius [11].

A first series of simulations have been performed at $\tau_R/\tau_E = 600$, corresponding to a perpendicular heat diffusivity 4 times higher than in the experiment (but $\chi_{||}/\chi_\perp = 108$ for all cases). We find that rotation shear has a destabilizing effect in the low viscosity case (i.e. the critical island width decreases with a/L_ω), and that it has no significant effect onW_{crit} at Prm = 100 (figure 2). Flow shear has therefore a destabilizing effect on the (2,1) island at low Prm, in agreement with results from the standard reduced MHD model. High viscosity mitigates the destabilizing effect of flow shear, as found with reduced MHD models including parallel perturbations.

For $\mu_0\chi_\perp/\eta$ at the experimental level ($\tau_R/\tau_E \approx 150$), we find that the effect of flow shear on the (2,1) NTM is negligible at low Prm. This situation may be comparable with the one computed in toroidal geometry without transport nor viscosity in [8], where differential rotation was identified as stabilizing (due to mode coupling), but rotation shear at the resonance was strongly weakening this benefit. Here, the two effects may compensate to give this neutral effect of rotation. Higher Prm increases globally W_{crit}, and for Prm = 100, the NTM threshold is seen to increase slightly within the range of experimental rotation shear (figure 3).

The results of simulations are summarized in figure 4, where the effect of rotation shear on the W_{crit} is plotted in the (Prm, $\mu_0\chi_\perp/\eta$) domain. Situations with low viscosity are clearly incompatible with experimental observations, and a high plasma viscosity, Prm ≥ 100, is needed for producing the favourable effect of rotation on NTM threshold that is observed.

CONCLUSION AND PERSPECTIVES

We have addressed the question of the dependence of the (2,1) NTM critical island width on plasma rotation, and we have focussed in particular on the role of plasma viscosity, which is at the moment the explanation for the increasing NTM stability with rotation shear. Our simulations confirm that plasma viscosity plays an important role, and can compensate for the otherwise destabilizing effect of plasma rotation. We find that, at high Prm, the (2,1) NTM threshold can be (slightly) increased by plasma rotation, and its baseline value is increased. If expressed in the form of a Δ' effect in Rutherford equation, this leads to an increase of β_N threshold (and a decrease of saturated islands) with rotation shear, similar to what is seen experimentally for $q \leq 1$ discharges [3]. In ITER, lower resistivity is expected to induce larger Prm. However, it is not obvious that parallel perturbations would matter in a low rotation plasma, in which case the low Prm results would apply to low rotation (ITER) and high Prm results to high rotation, thus strengthening the critical island dependence on rotation. These uncertainties remain to be clarified in order to gain confidence on the extrapolation to ITER, and they motivate the implementation of a more advanced viscosity tensor (including anisotropy) in the MHD model.

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REFERENCES

[1]. R.J. Buttery et al., Physics of Plasmas **15** (2008) 056115.
[2]. S. Gerhardt et al., Nuclear Fusion **49** (2009) 032003.
[3]. R.J.L. Haye et al., Physics of Plasmas **17** (2010) 056110.
[4]. F.L. Waelbroeck, R. Fitzpatrick and D. Grasso, Physics of Plasmas **14** (2007) 022302.
[5]. G. Einaudi and F. Rubini, Physics of Fluids **29** (1986) 2563.
[6]. X.L. Chen and P.J. Morrison, Physics of Fluids **B2** (1990) 495.
[7]. R. Coelho and E. Lazzaro, Physics of Plasmas **14** (2007) 012101.
[8]. D. Chandra et al., Nuclear Fusion **45** (2005) 524.
[9]. H. Lütjens et al., Plasma Physics and Controlled Fusion 51 (2009) 124038.
[10]. A.G. Peeters, C. Angioni and D. Strintzi, Physical Review Letters **98** (2007) 265003.
[11]. P. Maget et al., Nuclear Fusion **50** (2010) 045004.

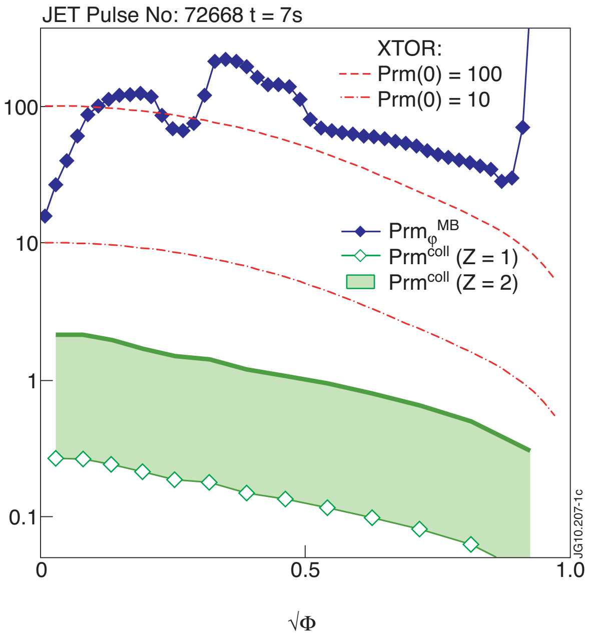

Figure 1: Prm from momentum balance (TRANSP), and collisional for different ion charges.

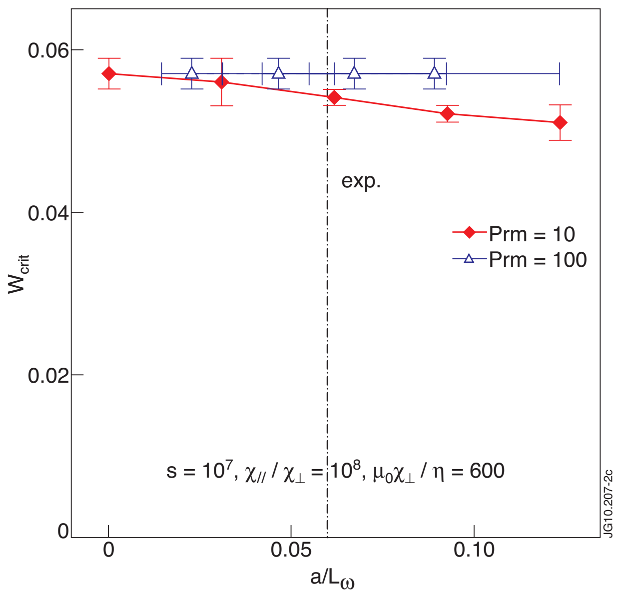

Figure 2: Critical island width versus velocity shear at $\mu_0\,\chi_\perp/\,\eta = 600$.

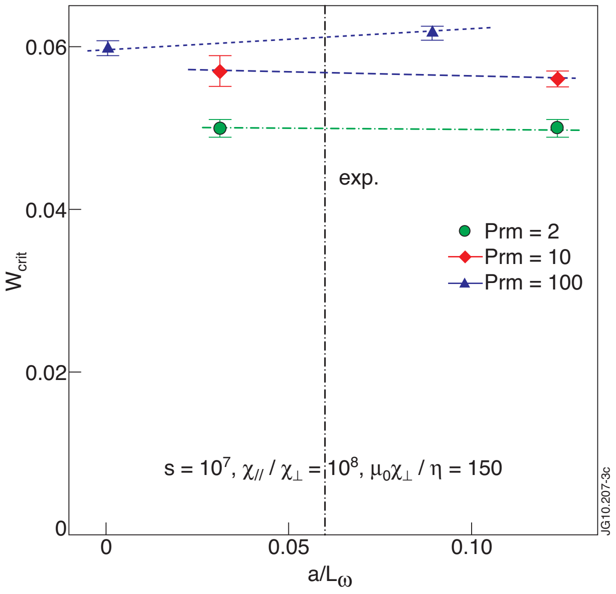

Figure 3: Critical island width versus velocity shear at $\mu_0\,\chi_\perp/\,\eta = 150$.

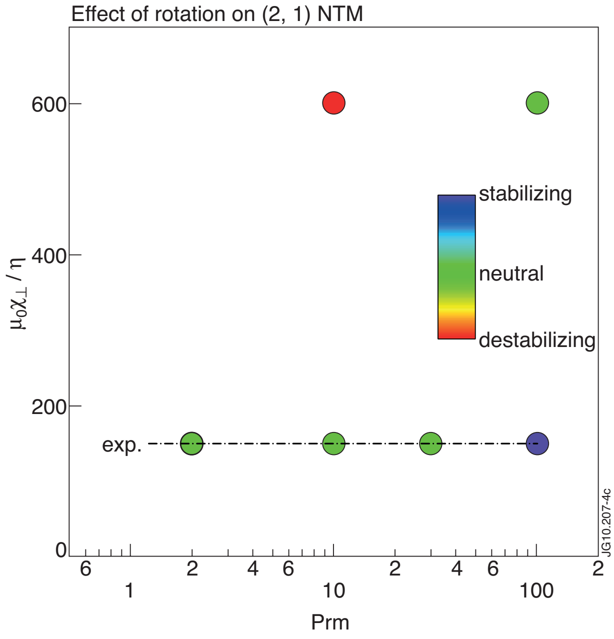

Figure 4: Summary of the effect of rotation on the (2,1) NTM threshold.