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Observation of Neo-classical Tearing Modes in JET

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ABSTRACT

Neo-classical tearing modes have been identified in JET ELMy H-mode discharges at medium to high beta. The n=2 modes as observed in both ECE and SXR data, have a clear island structure and a global character. The critical normalised beta at the onset of the modes is found to scale with the normalised Larmor radius. The scaling with collisionality is much weaker and has a negative power.

1. INTRODUCTION

Neo-classical tearing modes (NTM) are thought to be responsible for the beta limit in long pulse discharges which can be well below the limit set by ideal MHD instabilities [1,2]. They have been observed in TFTR [3], DIII-D[4], AUG [5], JT-60U [6] and COMPASS-D [7]. From the DIII-D data a scaling of the critical normalised beta with collisionality ($\beta_N \sim \nu_*^{+0.3}$) was obtained. Previously in JET, no collisionality dependence of the beta limit was found [8]. High beta discharges with β_N close to 4 have been sustained for up to 5 seconds, the length of the neutral beam (NB) heating phase. The modes observed at high beta were m/n=1/1 and m/n=2/2 modes and ELMs.

Recently, at medium to high β_N (between 2 to 3) and higher toroidal field (so that fast ECE data is available) modes with the characteristics of neo-classical tearing modes have been identified in JET long pulse ELMy H-mode discharges. The modes are mostly triggered by a large sawtooth crash after which the modes persist until the NB power is switched off. The toroidal mode number is predominantly n=2. (n=1 neo-classical tearing modes are also observed, mostly at higher β_N.) The reduction in confinement time caused by these modes is between 10 and 20%. After the appearance of the n=2 mode the sawteeth are in general suppressed and the electron temperature profile is locally flattened around the q=1.5 surface. These modes typically appear above a normalised plasma pressure β_N of about 2, but long pulse discharges without continuous n=2 modes exist up to β_N ~2.6. However, in low temperature, high density discharges the critical beta can be significantly below 2. Figure 1 shows the time traces of two ITER-like ELMy H-mode discharges, one with a NTM, triggered at β_N=2.6, and one without a NTM, at β_N=2.1. The reduction in confinement in this case due to the NTM is 13%. The NTM causes a flattening in the electron temperature profile of about 15 cm. Estimating the confinement loss using $\Delta\beta/\beta = 4\,(\rho_s/a)^4\, w_{sat}/\rho_s$ [9] (with ρ_s the radius of the island, w_{sat} the island width and a the minor radius) gives a reduction in the confinement time of 15% for an island width of 15cm.

In the recent JET DT campaign neo-classical tearing modes have been observed in ITER demonstration discharges, for β_N >2.5. At β_N=2.5 the ELMy H-mode DT discharge is sawtoothing without neo-classical tearing modes. However at higher normalised beta, a NTM is triggered by a sawtooth, after which the sawteeth are stabilised (although a continuous n/m=1/1 mode is present). With the NTM present at a β_N=2.9 the confinement factor H_{97E} is 0.92 (±10%) compared to H_{97E} = 0.96 at β_N = 2.5 without a NTM.

Modelling of the evolution of the magnetic perturbation (i.e. island size) as a function of time with the modified Rutherford equation yields good agreement with the measurements (see Fig. 2). This shows that the plasma pressure is the driving force of the n=2 mode which identifies the mode as a neo-classical tearing mode as opposed to a tearing mode driven by the gradient in the current density.

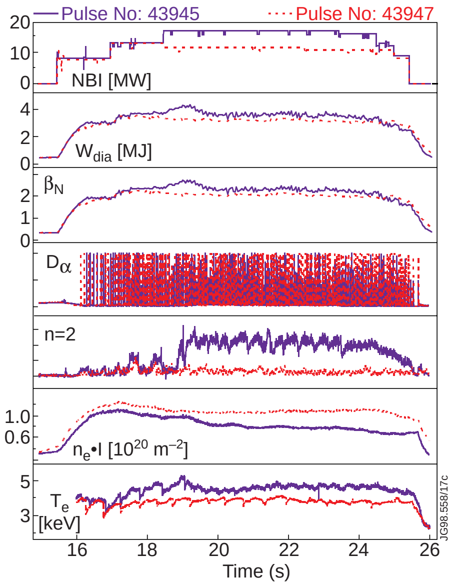

Fig. 1 Example of a long pulse ITER-like ELMy H-mode discharge (1.7T/1.7MA, q_{95}=3.4) with an n=2 mode present. The mode is triggered by a sawtooth after t=19.2 s at β_N = 2.65. Included is a similar discharge with lower heating power in which the n=2 mode is stable at β_N = 2.1.

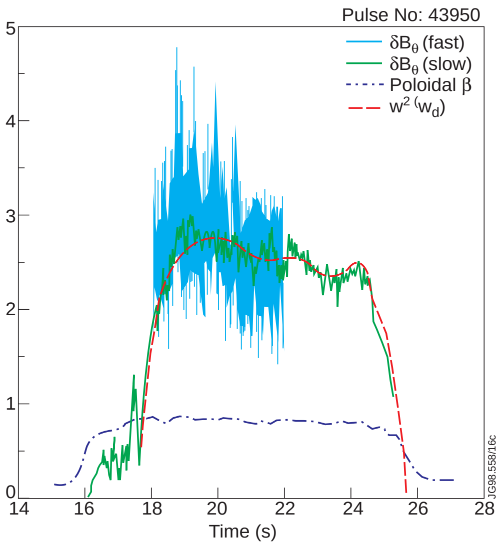

Fig. 2 The experimental and modelled evolution of the island width in discharge #43950. Shown is the fast and slow (filtered) magnetic data and the modelled values as a function of time (w^2). Included is the time trace of the poloidal beta. At t=24.5s the NB heating steps down.

2. MODE STRUCTURES

The n=2 modes have been observed in the fast 48 channel ECE diagnostic. The electron temperature perturbation shows the characteristics of an island structure, i.e. a minimum in the perturbation at the q=1.5 surface and a phase jump of 180 degrees at the minimum (see Fig.3). The modes have also been observed with the SXR cameras. The 178 viewing lines of the JET SXR diagnostic allow a detailed tomographic reconstruction of the perturbation of the SXR emission in the poloidal plane. Figure 4a shows the result of a tomographic inversion of the perturbation in the SXR emission due to an n=2 neo-classical tearing mode in discharge #40563. The tomographic reconstruction of the n=2 mode shows coupled m=2 and m=3 poloidal harmonics and a phase inversion at the same radius as the ECE data.

The amplitude of the mode is much larger on the low field side, where the m=2 and m=3 components add up, than on the high field side. A similar structure of the neo-classical tearing mode was found in AUG [2] and DIII-D [10]. Both diagnostics show the perturbation to be a relatively global mode. The mode is largest inside the q=1.5 surface and extends inward up to the magnetic axis. The component outside the q=1.5 is relatively small up to 30-40% of the amplitude inside the q=1.5 surface.

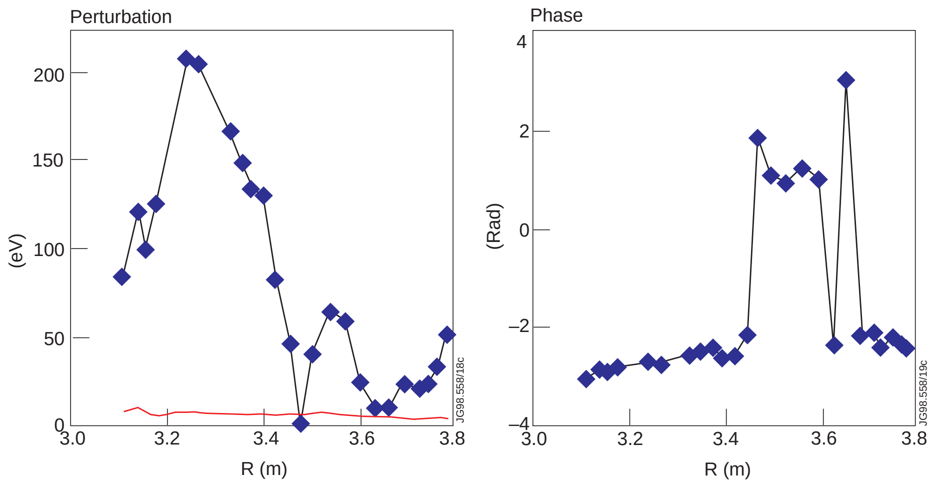

Fig.3 The amplitude and the phase of the perturbation in the electron temperature due to a neo-classical tearing mode as measured with the JET heterodyne ECE diagnostic. The frequency of the mode is 18kHz with an n=2 toroidal mode number.

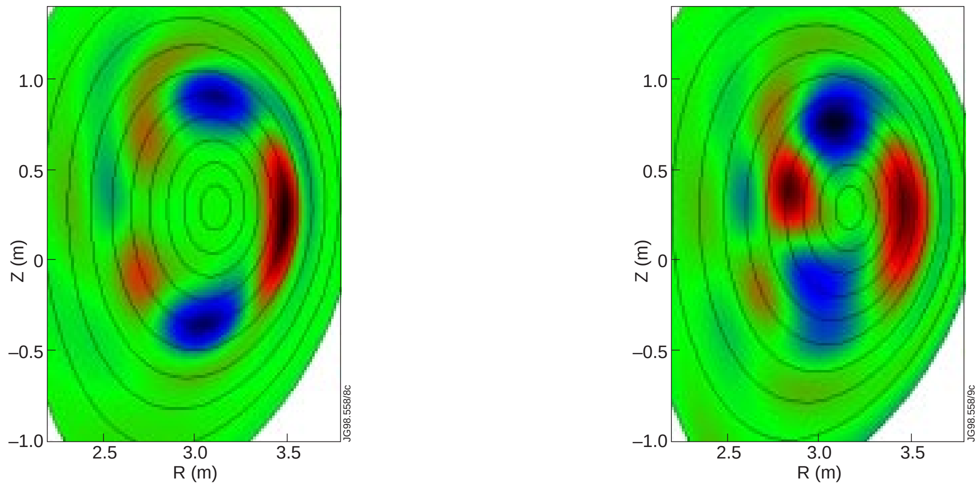

Fig.4 Tomographic reconstruction of the perturbation in the SXR emission in the poloidal plane for two cases. On the left (Fig. 4(a)) the perturbation at medium beta (β_N = 2.4) in discharge #40563 and on the right (Fig. 4(b)) at high beta (β_N = 3.0) in discharge #40564.

3. SCALING OF NORMALISED BETA AT THE MODE ONSET

A database has been collected containing 40 discharges from the Mark IIA experimental campaign in which a continuous n=2 mode is present. The parameters of the discharges are taken at the time the n=2 mode appears. All the discharges have a ITER relevant ellipticity (E~1.8), triangularity (δ ~ 0.25) and safety factor (q_{95} ~ 3.4). Some of the discharges are still ELM-free when the n=2 mode appears. Regression with the normalised collisionality and Larmor radius defined in global and local parameters yields :

$\beta_N \sim \nu^{*\,-0.1}\ \rho^{*\,+0.7}$ $\nu^* = 5.26\ 10^8\ a^4\ E\ n^3_{e,max}(10^{19}) / (W^2_{dia})$, $\rho^* = 2.23\ 10^9\ (W_{dia} / a^2\ n_{e,max}\ E\ I_p)^{1/2}$.

$\beta_N \sim \nu^{*\,-0.2}\ \rho^{*\,+0.6}$ $\nu^* = 6.23\ 10^{-4}\ n_e\ R\ q / (T_e^2\ \varepsilon^{3/2})$, $\rho^* = 4.57\ 10^{-3}\ (m_i/m_p)^{1/2}\ T_e^{1/2} / B$.

The value of β_N at the onset of the instability, for both the local and the global parameters, has a small negative dependence on the collisionality, ν* and stronger dependence on the normalised Larmor radius, ρ*. This scaling is very different from the scaling $\beta_N \sim 5.2\ \nu^{*0.3}$ derived from the DIII-D data. The difference may be due to the different regime in the parameter $\nu_i/\varepsilon\ \omega$ (ν_i is the ion collision frequency, ε the inverse aspect ratio and ω the mode frequency, taken to be the diamagnetic frequency) which influences the polarisation current contribution to the modified Rutherford equation. Thus, schematically we can write an expression for the onset of neoclassical tearing modes, within the framework of this model in the form [11]

$$\beta_N = C_1 (W_s/\rho_{bi})\ \rho_* / [1 - g(\rho_{bi}/W_s)^2]$$

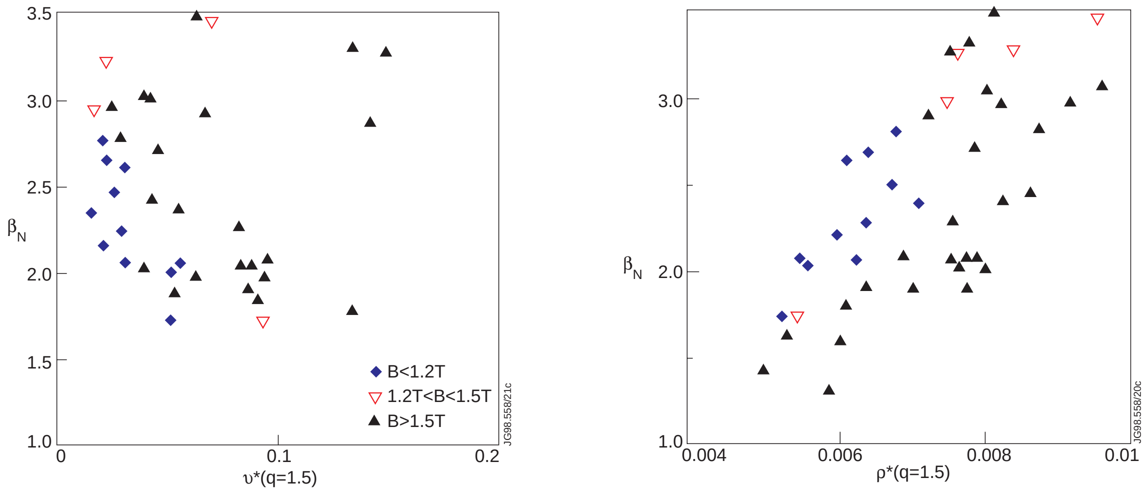

Fig.5 The value of the normalised beta at the onset of the neo-classical tearing mode as a function of the normalised collisionality n (left, Fig. 5a) and as a function of the normalised Larmor radius r* (right Fig. 5b).*

where g is approximately constant for $\nu_i/\varepsilon\ \omega$ <<1 (typical of JET), but increases at higher collisionality (typical of DIII-D). Here W_s is the seed island width, provided by the sawtoooth for example, and ρ_{bi} is the ion banana width. The denominator must be positive to trigger the NTM, and this introduces a threshold island width $W_s \sim \rho_{bi}$. Neglecting any residual scaling of W_s with plasma parameters (which can be important) we see that taking $W_s \sim \rho_{bi}$ in the above expression provides an interpretation for the different scalings for the onset observed on JET and DIII-D.

4. HIGH BETA DISCHARGES

At higher values of β_N, typically above 3, n=1 modes appear. These n=1 modes grow to such a large amplitude that a soft-stop is triggered by the JET control system, i.e. the plasma is slowly terminated by ramping down the heating power and plasma current, to avoid a disruption. The occurrence of the n=1 modes is not reproducible, in some discharges the mode appears immediately in the high beta phase, in others only at the end of the NB heating after 5 s or is completely absent. It is the n=1 mode which ultimately limits the maximum β_N, the n=2 modes alone lead to a degradation of the confinement but not a limitation in β_N. Long pulse high beta discharges with a β_N above 3, with an n=2 mode present, have been sustained for 4 s, the full duration of the NB heating phase.

The mode structure of the n=2 mode at high normalised beta is dominated by a global m=2 component. The m=3 component becomes more difficult to distinguish. Fig. 4b shows a tomographic reconstruction of the perturbation due to an NTM in high beta discharge #40564.

5. CONCLUSION

Neoclassical tearing modes have been identified in medium and high beta JET discharges. The n=2 modes show a phase jump of 180 degrees and a minimum in the perturbation at the q=1.5 surface (characteristic of an island) in both the ECE and the SXR data. The amplitude of the perturbation is much larger inside the q=1.5 surface than outside. The n=2 mode has both an m=2 and an m=3 component (similar to NTM modes in AUG and DIII-D). The m/n = 2/2 component becomes dominant at high beta. The calculated magnetic perturbation based on the modified Rutherford equation for neoclassical tearing modes is in good agreement with the measured evolution of the perturbation. A weak, negative, dependence of the critical β_N on ν^* ($\sim\nu^{-0.2}$) was found (unlike DIII-D). The critical β_N does scale with ρ^* ($\rho^{0.7}$). The difference in scaling could be due to the different regime in the parameter ($\nu_i/\varepsilon\omega$) which is much smaller for JET data. A similar scaling with ρ^* was also observed in AUG at low collisionality. At high beta (β_N>3.) m/n=2/1 modes become unstable which lead to a pre-programmed control system soft stop or a disruption.

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REFERENCES

[1] SAUTER O., Phys. Plasmas **4** (1997) 1654.

[2] ZOHM H., et al., Plasma Physics and Controlled Fusion, Vol. 39, p. B237, (1997).

[3] CHANG Z., et al. Phys. Rev. Lett 74, 4663 (1995).

[4] LA HAYE R., et al., Proc. 16th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion, Montreal, Canada (1996), IAEA-CN-64/AP1-21 (Vol.1 p. 747, Vienna 1997).

[5] ZOHM H., et al., Proc. 23rd EPS Conf. On Controlled Fusion and Plasma Physics Kiev (1996).

[6] KAMADA Y., et al., Proc. 16th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion, Montreal, Canada (1996), IAEA-CN-64/A1-6.

[7] GATES D.A., et al., Proceedings 16th International Conference on Plasma Physics and Controlled Nuclear Fusion, Montreal, Canada (1996), IAEA-CN-64/A1-6 (Vol.1 p.715 Vienna 1997).

[8] HUYSMANS G.T.A., CORDEY G., GORMEZANO C., SIPS A.C.C., TUBBING B.J.D., 24th EPS Conference on Controlled Fusion and Plasma Physics, Berchtesgaden, Vol. 21A, p.1857 (1997).

[9] CHANG Z. and CALLEN J.D., Nucl. Fus. 2 (1990) 219.

[10] REN C., et al, Bull. Am. Phys. Soc. 42 (1997) 1974.

[11] WILSON H., et al, Proc. 23rd EPS Conf. On Controlled Fusion and Plasma Physics Kiev (1996).