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Observation of an intermediate rotation regime on JET

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Error fields (EF) are responsible in tokamaks for the slowing down of plasmas and the onset of large locked modes which in turn may degrade considerably the confinement, trigger an H to L transition and sometimes create a disruption[1,4,5]. The braking mechanism is described qualitatively well by Fitzpatrick's model[2] in terms of balance between an electro-magnetic (EM) torque which tends to slow down the plasma and a viscous torque which tends to push it back to its natural rotation frequency. This model predicts the existence of a forbidden band of rotations[3] between half the natural rotation frequency and the inverse reconnection time of the resonant surface. This prediction is indeed confirmed by many experiments with moderate momentum input[4]. For higher momentum input, however, a new intermediate rotation state appears just in the middle of the forbidden band. The new rotation state corresponds to just a single discrete frequency which may be kept by the plasma even if the EM torque is increased. We report here of such observations and of a modified model which explains well this behaviour.

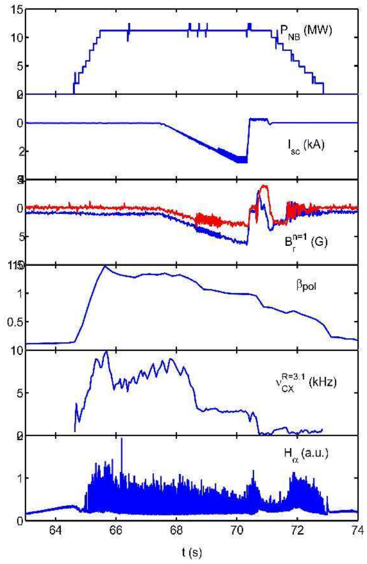

Figure 1Overview of JET pulse 53606

The target plasma used to obtain the intermediate rotation regime (IRR) is heated with up to 12 MW of NBI and has a very high β_p which leads to the development of a 3/2 neoclassical island. The error field is generated using either the old internal saddle coils or the new external Error Field Correction Coils (EFCC). The two systems generate a fairly different EF in terms of spatial harmonics but the EFCC system was designed in order to generate a similar 2/1 harmonic as that of the saddle coils. It is still difficult, however, to compare the penetration thresholds between the two systems as we still do not have a good model of the influence of sideband harmonics for JET. The rotation is measured both by CX spectroscopy of light impurities and by the rotation of the 3/2 island. The penetration process is shown in figure 1: the EF is ramped up slowly, the first transition occurs at 68.8 when the rotation drops by more than ½ its original value, then for more than one sec. the rotation frequency remains constant despite the constant ramp-up of the EF. During this period the confinement is slightly degraded but still remains in H-mode. Eventually the H-mode is terminated by the onset of a large locked-mode which may be triggered by the removal of the EF. During the IRR there is a transition from type I ELMs to type III ones. We would like to compare this behaviour

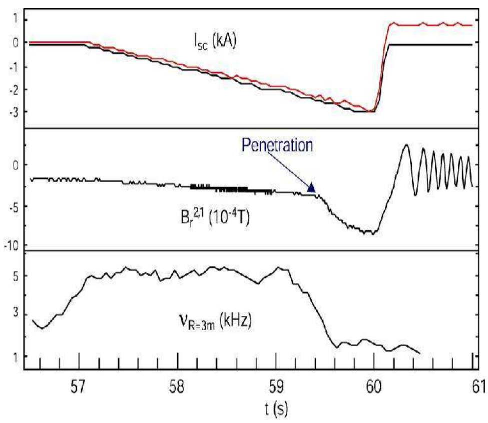

Figure 2 Overview of a conventional EF induced mode lock in JET

with the more conventional one during a discharge with just 1MW of NBI. In figure 2 we can see that the plasma braking occurs just in a single step, the braking is followed by the onset of the locked mode which can then spin-up when the EF is removed. In Fitzpatrick's model[2] two toroidal torques act on the rational surface: a viscous and an EM one. These must be balanced in order to obtain equilibrium. The EM torque is due to the interaction of the external EF with the induced field at the rational surface; the viscous torque is the one that tends to push the small island in the direction of its natural rotation be it induced by the NBI or by the diamagnetic drift.

$$T_v = -\mu k_v (\omega - \omega_0) \qquad (1$$

$$T_{EM} = -k_{EM} \frac{\omega \tau_R}{1+\omega^2 \tau_R^2} B_r^2 \qquad (2$$

In the formulae above ω is the rotation frequency at the rational surface, ω_0 is the unperturbed (i.e. without EF) rotation frequency, τ_R is the reconnection time at the rational surface, μ is the viscosity, B_r is the radial component of the resonant EF, and k_V and k_{EM} are constants which depend on the system geometry. In our modified model the EM torque has the same functional form but the viscous torque is modified so that the viscosity has a jump when the flow shear exceeds a given threshold v'_{cr}. We do not enter into the details about why the viscosity has this jump but we may assume that a threshold for the onset of some instability (the Kelvin-Helmholtz one for instance) has been exceeded. Of course other measurements could reinforce this model in particular if any saturation of the central rotation frequency for increasing NB power is found. The viscosity is given by:

$$\mu = \begin{cases} \mu_0 & v' < v'_{cr} \\ \mu_1 & v' > v'_{cr} \end{cases} \qquad (3$$

where we have that $\mu_0 < \mu_1$. In the simplified assumption that for all plasma between the resonant surface and the LCMS ($r_s<r<a$) the viscosity is always either μ_0 or μ_1, we have that the viscous torque becomes:

$$T_V = -k_V \begin{cases} \mu_1 (\omega - \omega_0) & \mu = \mu_1 \\ \mu_0 \omega - \mu_1 \omega_0 & \mu = \mu_0 \end{cases} \qquad (4$$

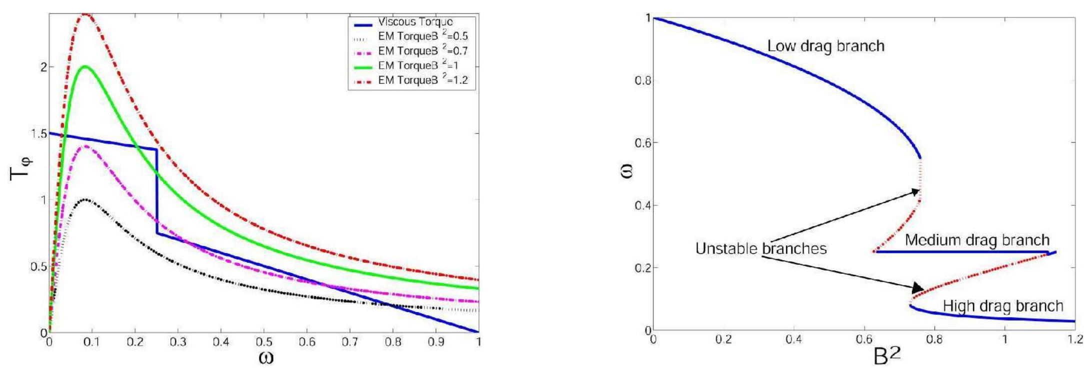

Figure 3. Torque balance for the modified Fitzpatrick's model: we have now three stable rotation branches and two unstable ones

we have then that the viscous torque is now made of two lines with a jump between them (see figure 3). The jump happens at a frequency ω_{IR} which depends on the total momentum input. The frequency ω_{IR} sits right in the middle of the forbidden region and corresponds to the IRR that we were looking for. In the modified model we have now three stable branches (including the IRR) and two unstable ones as can be seen from figure 3. At high momentum input we may then measure up to four thresholds:

1. From the low drag (high rotation) regime to the IRR: T_{HM}.
2. From the IRR to the high drag (low rotation) regime: T_{ML}.
3. From the high drag regime to the IRR: T_{LM}.
4. From the IRR to the low drag regime: T_{MH}.

On top of this we may also measure the intermediate rotation frequency. In the traditional Fitzpatrick's model we may measure just two thresholds: one for the locking and one for the unlocking.

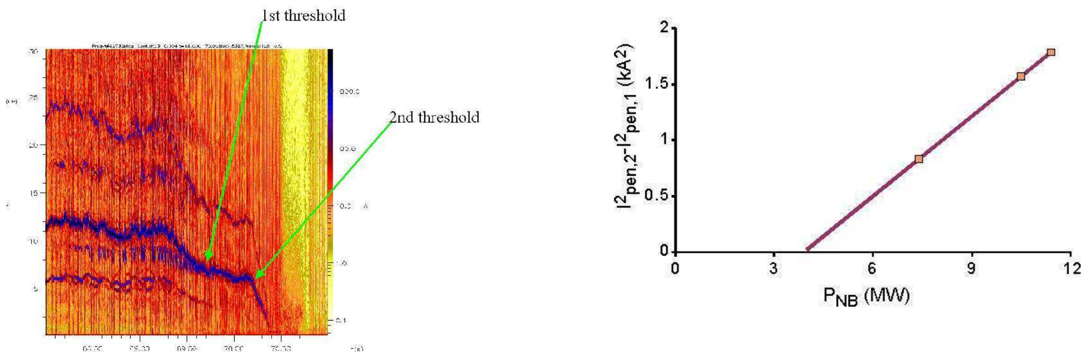

Figure 4 a) Measuring the 1st and 2nd thresholds using the rotation frequency of the 3/2 neo-classical tearing mode. b) Scaling of the threshold difference with NB power.

The length of the intermediate plateau of figure 4b is given by:

$$L_{plateau}=T_{ML}-T_{MH}\propto B^2_{r,ML}-B^2_{r,MH}\propto I^2_{EFCC,ML}-I^2_{EFCC,MH} \quad (5$$

In figure 4 we show how we have been able to measure in the same series of shots both the 1st and 2nd thresholds from the rotation frequency of the 3/2 neo-classical island. In order to measure the length of the intermediate plateau we should be able to measure both the 2nd and 3rd thresholds We assume however that we do not commit a too large error if we use the 1st threshold instead of the 3rd one. We show in figure 4b the scaling of the intermediate plateau with the total NB power (proportional to the momentum input). According to the modified Fitzpatrick's model it turns out that the intermediate plateau and the intermediate frequencies must scale as:

$$\Delta T=T_{ML}-T_{MH}\propto(\mu_1-\mu_0)\omega_{IR} \quad (6$$

$$\omega_{IR}=\omega_{0s}+r_s\log(\frac{a}{r_s})(\omega'_{cr}-|\omega'_{0s}|) \quad (7$$

Where ω_{0s} is the rotation frequency at the rational surface in the absence of EM torque and ω'_{0s} is its gradient. Both these quantities are proportional to the total momentum input and so both ΔT and ω_{IR} must scale as P_{NB}. From eq. 7 we see that the IRR appears when ω'_{0s} reaches the critical value and that the intermediate plateau starts with a finite length. We observe however that the first one (figure 4b) does indeed scale as P_{NB} but the second one is almost constant for all our discharges. This discrepancy may be due to the fact that we are not measuring the actual rotation frequency at the rational surface but rather the rotation of the 3/2 tearing mode. The mechanism of the self-similar braking[6] may also play a role.

Conclusions

- We have observed a new rotation regime which is forbidden in the standard mode locking/penetration framework.
- The new rotation regime is very resilient and has a large window of stability against EF penetration.
- In the IRR the confinement is only moderately degraded.
- The IRR is like a safety net against locked modes in the sense that we have some operating space left to try and stabilize any large mode and/or remove any residual EF. Of course it is not clear yet if this regime will be present in ITER.
- We can explain such observation with the assumption that the viscosity degrades above a certain critical toroidal shear flow.
- The new theory predicts the existence of 3 stable rotation regimes including the IRR.
- The theory predicts that the plateau length and the intermediate frequency scale linearly with the beam power but our preliminary findings show that only the former scales with P_{NB}.
- Future experiments should confirm that the IRR exists also at lower beta poloidal, that we can observe all 4 transitions between the 3 regimes and that at very high momentum transfer there may be even 2 intermediate plateaus.
- The mesurements of these thresholds will put further constraints on our models of EF penetration.

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