EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(01)02-81

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**See appendix of the paper by J.Pamela "Overview of recent JET results",*
Proceedings of the IAEA conference on Fusion Energy, Sorrento 2000

Preprint of Paper to be submitted for publication in Proceedings of the
EPS Conference,
(Madeira, Portugal 18-22 June 2001)

ABSTRACT

The destabilisation of Neoclassical Tearing Modes (NTM) requires a finite size seed island which is often provided by sawtooth activity. It is shown that the beta value at the onset of NTMs can be significantly modified by altering the sawtooth period using ICRH in JET. Sawtooth stabilisation, leading to long sawtooth periods, enables NTMs to be triggered at low beta value, consistent with larger induced seed islands. By destabilising sawteeth, that is with a shorter sawtooth period, larger beta values are required to trigger NTMs. This is the first clear direct demonstration of the relation between sawteeth and NTMs and opens the possibility of increasing the beta threshold by sawtooth destabilisation. Adding a slow power ramp-down, after the mode onset, shows that NTMs are metastable as long as the discharge is in H-mode in JET, emphasising the role of seed island control to avoid NTMs.

INTRODUCTION

Neoclassical Tearing Modes (NTMs) are known to limit tokamak performance to normalized beta values, β_N, well below the theoretical ideal-MHD β-limit (β is the ratio of the total pressure p to the confining magnetic pressure $B_0{}^2/2\eta_0$, and $\beta_N=\beta[\%]/(I_p/aB_0)$, with I_p[MA] the plasma current, B_0[T] the magnetic field and a[m] the plasma minor radius). The destabilisation of NTMs requires the formation of a seed island of a finite size, larger than a critical island width [1]. This island can be triggered by sawtooth precursor or crash, edge localised modes (ELMs), fishbones or other perturbations like pellets [2]. Once the island is formed, the pressure profile flattens and the resulting perturbed bootstrap current drives the island to a usually much larger saturated width. Different methods have been applied to stabilise the mode once it is formed, by local current drive with ECCD or by global current drive with LHCD [3], for example. Here a new method is proposed consisting of preventing the mode formation by reducing the perturbations such that the islands triggered are smaller than the critical island width. The main source of perturbations in most tokamaks is the sawtooth activity. Avoiding sawtooth altogether has been shown to increase the beta limit for NTMs [4]. However this is difficult to keep in steady-state for standard type scenarios and one loses the beneficial particle control provided by regular sawteeth. The idea developed in these experiments is to destabilise the sawteeth such as to have short and regular sawtooth periods, assuming that it will lead to smaller perturbations and seed island sizes. It is wellknown that sawtooth periods can be changed using ICRH [5] or ECCD [6] for example. Therefore the main scenarios of Refs. [5] have been used, that is changing the antenna phasing or the resonance location [7]. First we show the relation between long sawtooth periods and NTMs destabilisation at low beta. Sawtooth stabilisation is obtained mainly by increasing the fast particle population in the centre. In this way, NTMs can be destabilised at any field in JET, even at β_N as low as 0.5-1. We shall also show that on the contrary, by destabilising sawteeth (in the sense that shorter sawtooth periods are obtained) enables to increase significantly the β_N and neutron rate at the NTM onset.

RESULTS

We show in Fig. 1 the usual global plasma parameter domain, β_N versus ρ_*, at the m=3/n=2 NTM onset in JET. The blue symbols are NBI only discharges, red/pink those with ICRH. It shows that the cases with dominantly ICRH have much lower beta onset. The simplest explanation is that sawteeth are more strongly stabilised by the fast particles induced by ICRH than by NBI heating [8]. The solid blue circles are NBI only discharges which have a low beta onset. We have checked these cases and they all occur either after a sawtooth period of ~800ms or at the first measurable sawtooth crash out of the ohmic part, which is why they are marked differently. To directly test the effect of sawtooth, we compare discharges with 5MW of fundamental H minority ICRH and a power ramp-up of NBI power in order to trigger NTMs. The magnetic field is changed from shot to shot to span the resonance position from outside the inversion radius towards the centre of the plasma. The antennas have a +90º phasing such as to increase the fast particles pressure in the centre. With the resonance position moving inwards, the fast particle population inside q=1 increases [5b, 7] and so does the sawtooth stabilisation [9]. As can be seen on Fig. 2, small changes of 0.08T, leading to a 9cm shift of the resonance position, can change the sawtooth period from 440ms to 630ms. In these scenarios, all the discharges with sawtooth periods longer than approximately 600ms and $\beta_N \geq 0.8$-1 have triggered 3/2 NTMs at the sawtooth crash. On the contrary, as illustrated by the shot 51790 and 51792 in Fig. 2, discharges with sawtooth periods smaller than ~600ms have not triggered NTMs, even with more than 20MW of total power coupled to the plasma and β_N up to 2. It should be noted that the effect does not seem to be linear with sawtooth periods.

A further test is to change only the antenna phasing. The -90º phasing induces a drift of the trapped orbits outwards, reducing the stabilising term which results in much shorter sawtooth periods [5b]. Repeating the discharge 51794 at 2.49T with –90º phasing and otherwise similar parameters leads to regular sawtooth periods of about 200ms and no NTM are triggered even with 21MW total power coupled and $\beta_N \sim 2$. On the other hand, previously JET was unable to trigger NTMs with NBI alone at larger magnetic field ($B_0 \geq 1.7$T) because the maximum achievable β_N is too low. However, using fundamental minority H heating with +90º or dipole phasing of the antennas, long sawtooth periods are induced and NTMs can be triggered at low β_N. In this way NTMs are obtained at any field with standard type scenarios in JET, which is useful to study these modes in a wide plasma parameter domain. By adding a slow power ramp-down after the mode is triggered the critical beta limit can be determined, independently of the trigger mechanism. Two examples are shown in Fig. 3, at 1.4T/1.4MA and at 3.3T/3.3MA. The first case is a NBI heating only discharge, for which the mode is triggered at $\beta_N \sim 3$, while the second case has ICRH with the +90° phasing and the mode is triggered after a long sawtooth period, at $\beta_N \sim 1$. In both cases β_N slowly decreases and the mode is stabilised near or even after the H-L back transition, that is at $\beta_N \sim 1$ or 0.5 respectively. This has been confirmed at fields between 1T to 3.3T with discharges having similar $q_{95} \sim 3.4$. Therefore standard scenarios in H-mode in JET are metastable to 3/2 NTMs. Thus, once in Hmode, the only determinant factor to trigger the mode is the existence of a seed island with a width larger than the critical island width. This is why controlling sawtooth activity has such a dramatic effect on JET. In addition, rotation has a crucial role as discussed in Ref. [10]. The low NTM onset was also observed in NBI only cases, due to long sawtooth periods obtained by an inadequate power ramp-up [11].

The ultimate goal is of course to suppress or avoid these modes. As they are metastable in Hmode discharges, the best way to prevent these modes is to control the size of the seed islands, therefore of the plasma perturbations. The idea is to destabilise the sawteeth to shorten the sawtooth period. In this way one keeps the useful particle redistributions and avoids impurity accumulation, while reducing the plasma perturbations. In order to better demonstrate the effect, we need a test case of a NTM destabilised by NBI only and therefore work at B_0<1.7T. In this case, only 2nd harmonic heating is possible to have power deposition and CD near or just outside the inversion radius. First we have studied the optimal position for sawtooth destabilisation as detailed in Refs. [7a, b]. Then we have fixed the magnetic field at an optimal value, such that the resonance position is just outside the inversion radius, and we have added a NBI power ramp to determine β_N at the onset of the mode. The result is shown in Fig. 4, where a NBI only case (in blue) and a 5MW ICRH + NBI case (in red) are shown. The total power is kept the same for both cases during the whole ramp. The discharge is at 1.2T/1.2MA, that is a very low magnetic field for JET, and the resonance position is just at the HFS of the inner inversion radius and moves towards the centre when beta increases. At 62.6s, a NTM is triggered at β_N~3 and Ptot~8MW in the NBI only case. These values are typical for these scenarios. Note that β_N drops at the mode onset. However, the NBI+ICRH case reaches β_N of 3.8 without 3/2 NTMs, close to the ideal limit. The role-over in shot 51994 at 65.2s is due to a 5/4 mode and then a 4/3 mode. At 66.1s, a 3/2 mode is triggered and β_N drops even further. Note that by that time the resonance position has shifted to the inversion radius due to β effect, however at these high b values, fishbones are present and can trigger the mode as well [2a]. Thus up to about 20MW have been coupled to the plasma without triggering 3/2 NTMs. As the NTM is metastable for $\beta_N \geq 1$, at the L-H transition, the perturbations have to be kept smaller in order to reach higher β_N values. Note also that combined heating, NBI+ICRH, usually leads to much lower NTM threshold, as discussed in the introduction, Fig. 1, and in Ref. [10] in relation to rotation effects. In Ref. [10] similar plasmas as shown in Fig. 4 are discussed, except at 1.4T/1.3MA to have central ICRH. Note that in these cases, with combined heating, β_N~2-2.5 at the mode onset. It is only by a careful choice of the resonant position, such that it destabilises significantly the sawteeth, that we are able to increase β_N at the onset of the mode in ICRH+NBI cases.

Two other important results are shown in Fig. 4. First the increase in neutron rate is even more dramatic between the value at the mode onset for the NBI only case, ~1.2 $10^{15}s^{-1}$, and for the ICRH+NBI case, 3.8 $10^{15}s^{-1}$. This confirms that a much higher performance is obtained without triggering NTMs and is the relevant improvement obtained by destabilising sawteeth. The other important effect is that the island width, for the case 52712, first increases with β_N, but then saturates to a smaller value when $P_{NBI} \geq 15$MW. It follows that better confinement is recovered, which is why both discharges have similar β_N values at 65s, even though shot 51994 has no NTMs. We call this effect “self-healing” of the mode. It can be due to increased rotation, change of”Δ’ or global profile modification, and is probably related to interruptions of the mode as observed in AUG and JET [12]. Further detailed analyses are in progress to better quantify this effect. However one should note that the neutron rate is not fully recovered and is still 20-30% below the NTM free case. This is due to the fact that even a small island decreases the central density and temperature values, which contribute much more significantly to the neutron rate than to the global stored energy.

CONCLUSION.

The main difference in β_N at the onset of 3/2 NTMs in JET between NBI and ICRH dominated discharges has been clearly related to the effects on sawteeth. Note that rotation also affects the NTM trigger [10]. Sawtooth stabilisation (long sawtooth period) has been shown to trigger NTMs at much lower β_N, as soon as $\beta_N > \beta_N$crit. Dedicated experiments have shown that JET standard discharges, with $q_{95} \sim 3.4$, are metastable to NTMs as soon as they are in H-mode. Therefore better performance without triggering NTMs can only be obtained by controlling the seed island formation and minimising the perturbations. We have shown that by adding 2nd harmonic H minority ICRH and carefully positioning the resonance layer just outside the inversion radius, such as to destabilise the sawteeth, higher values of β_N and much higher neutron rates are obtained before the NTM is triggered. Therefore, on the one hand, we have confirmed that NTMs are most likely to occur at low β_N due to alpha particle stabilisation and long sawtooth periods in ITER like standard configuration, without sawtooth control. On the other hand, the possibility of avoiding NTMs by sawtooth destabilisation has been demonstrated with ICCD. Another method can be ECCD which is very efficient in modifying the sawtooth period. Its potential should be better evaluated for future experiments, in particular as its CD efficiency is much higher near q=1 than near q=1.5.

ACKNOWLEDGEMENTS

We are grateful to the UKAEA for the efficient operation of the JET-EFDA tokamak. This work was performed in part under the EFDA. OS and CA are supported in part by the Swiss National Science Foundation.

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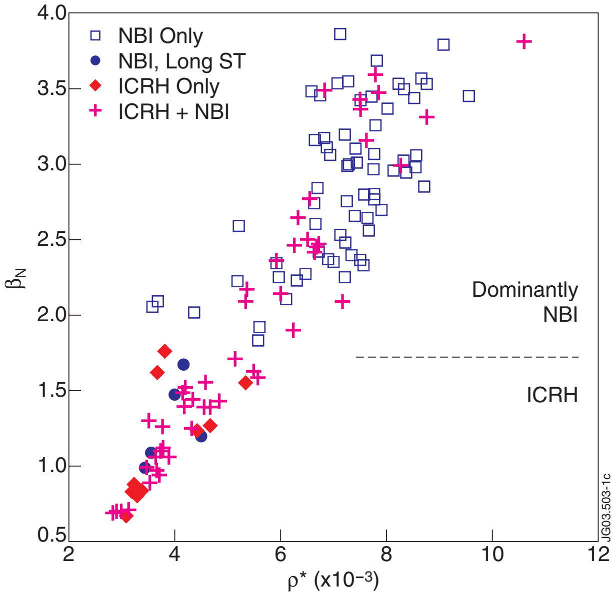

Figure 1: Global β_N, ρ^* parameters at the onset of 3/2 modes for NBI and ICRH dominated discharges.

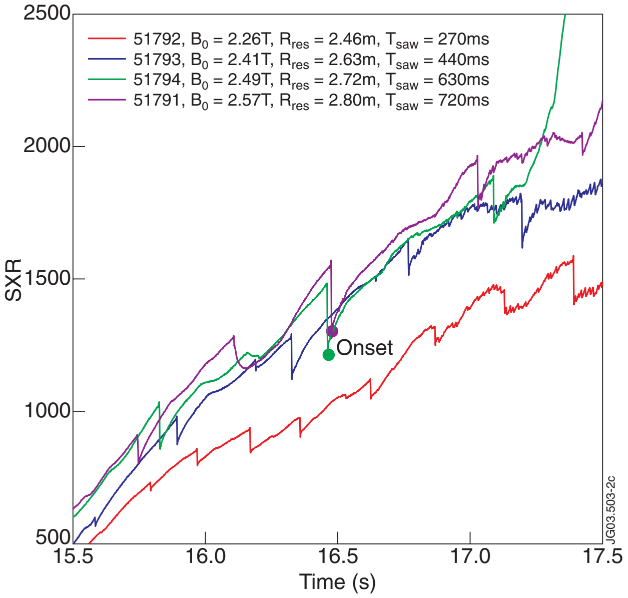

Figure 2: SXR signals for similar discharges, changing only the ICRH resonance position. Ip/B0 is kept fixed. The first two cases do not trigger NTMs even up to full power. The onset is marked for the other two cases (the HFS inversion is ~2.8m in JET)

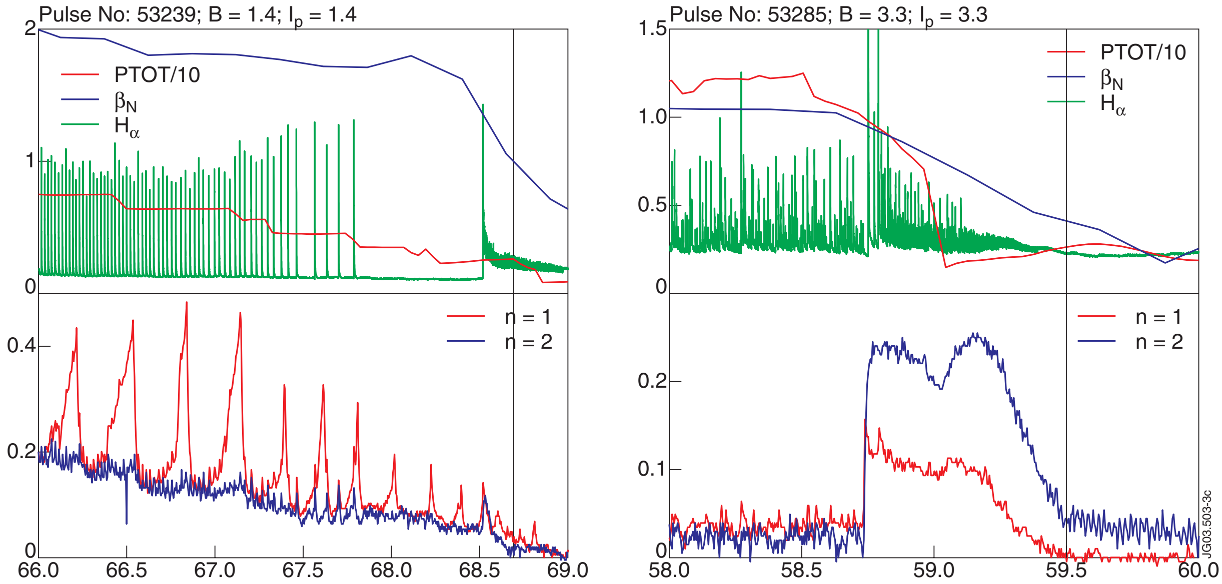

Figure 3: Power ramp-down phase, after NTMs have been triggered, for cases at low and high magnetic field. Pulse 53239 is heated by NBI only, while 53285 has NBI and 5MW of ICRH power. In both cases the mode is stabilised near the H-L transition, as seen from the H± trace.

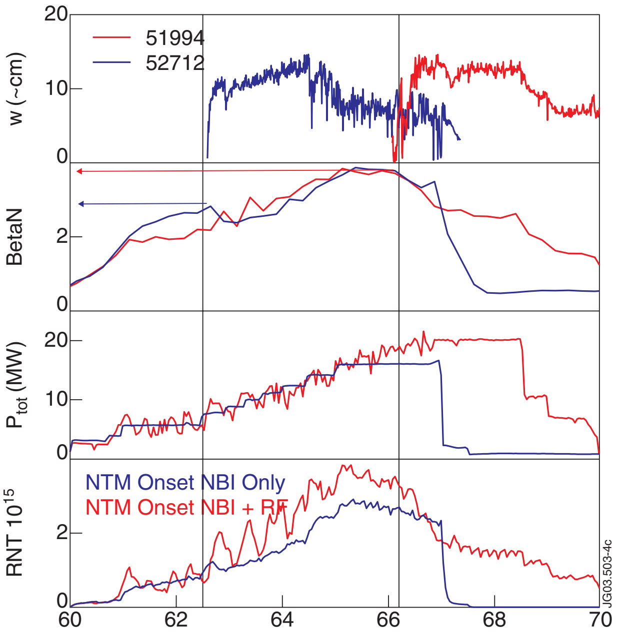

Figure 4: Similar discharges at low magnetic field, 1.2T and current, 1.2MA. The total power waveform is the same, with NBI only for 52712 and NBI+ICRH in 51994. In the ICRH case, 5MW 2nd harmonic hydrogen minority heating is coupled with the resonance just outside the inversion radius, on the HFS.