*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-1.026 (2002)*

Neo-Classical Tearing Mode Control through Sawtooth Destabilisation in JET

M.L. Mayoral[1], E. Westerhof[2], O. Sauter[3], B. Alper[1], R.J. Buttery[1], M. De Baar[2], T.C. Hender[1], D.F. Howell[1], M.J. Mantsinen[4], A. Müeck[5], M.F.F. Nave[6] and contributors to EFDA JET workprogramme*

1) Euratom-UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK
2) FOM-Rijnhuizen, Ass. EURATOM-FOM, TEC, PO Box 1207, 3430 BE Nieuwegein, NL
3) CRPP, Assoc. EURATOM-Confederation Suisse, EPFL, 1015 Lausanne, Switzerland
4) Helsinki Univ. of Tech., Ass. Euratom-Tekes, P.O.Box 2200, FIN-02015 HUT, Finland
5) Max-Planck-Institut,, IPP-EURATOM Ass., D-85748 Garching, Germany
6) Centro de Fusao Nuclear, Instituto Superior Tecnico, P-1049-001 Lisboa, Portugal
** See appendix of the paper by J.Pamela "Overview of recent JET results" Proceedings of the 18th IAEA conference on Fusion Energy, Sorrento 2000*

1. Introduction

Neo-classical tearing modes (NTMs) leads to significant reductions of energy and particle confinement and their control is a critical issue for tokamaks performance improvement. Above a certain threshold of the normalised plasma pressure β_N, m=3/n=2 NTMs are metastable and a finite seed island is required to trigger the modes. This seed island is generally generated by perturbations associated with a central sawtooth activity. A strategy was recently developed at the Joint European Torus (JET) to control the NTM seed island by modifying the sawtooth activity [1,2]. Ion Cyclotron Current Drive (ICCD), with waves tuned to the 2nd harmonic Hydrogen (H) cyclotron resonance frequency, is used to create shorter period and smaller amplitude sawteeth which are expected to induce smaller seed islands, thus increasing the plasma pressure at which an NTM is triggered. In a first series of experiments, summarised in section 2, it is shown that the plasma pressure threshold at the 3/2 NTM onset, ($\beta_{N,onset}$), indeed increases when ICCD is applied with a proper resonance localisation for sawtooth destabilisation but that a number of effects can limit this scenario. Experiments to improve the ICCD efficiency have also been performed and are reported in Section 3. The conclusions and prospects to develop this NTM control scheme are presented in Section 4.

2. Increased NTM threshold from ICCD sawtooth destabilisation

On JET, at high magnetic field NTMs cannot generally be destabilised with Neutral Beam Injection (NBI) only. Working at low magnetic fields B_0 between 1.2 and 1.6T and Ion Cyclotron Resonance Frequency (ICRF) waves at 42MHz (2nd harmonic H cyclotron resonance frequency) allows the capability the 'β_N increase at the NTM onset by sawtooth control' scheme, to be tested.

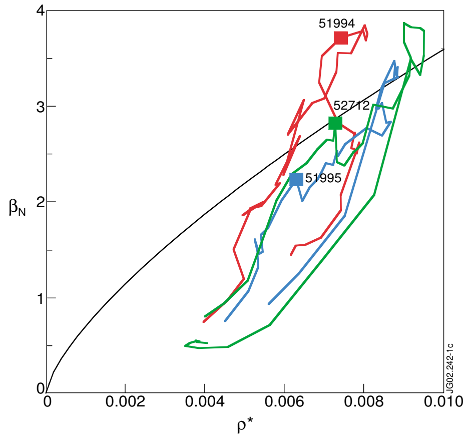

Figure 1: *β_N evolution versus $\rho*$ for discharges 51994 (with ICCD), 51995 and 52712 (NBI-only). The black curve gives the onset scaling with NBI-only.*

With NBI-only, the β_N threshold at the 3/2 NTM onset scales with the normalised ion gyroradius as $\beta_{N,onset} \propto \rho*^{0.7}$ [3]. This is not a sharp limit; the randomness of the necessary seeding perturbation causes the mode onset to spread somewhat with respect to the scaling. In Fig. 1, evolution of three discharges with B_0=1.2T is compared in terms of β_N and $\rho*$. Times of NTM onsets are indicated by squares. In 51994, about 5MW of ICCD is applied for sawtooth destabilisation. The resonance R_{2ndH} is positioned at 2.55m on the high field side (HFS) just outside the q=1 surface. In these discharges the NBI is ramped to slowly increase β_N in order to identify the NTM threshold. In 51995 and 51994 the NBI power waveforms are identical while in 52712, the NBI is identical to the total power in 51994. Whereas in both NBI-only discharges a 3/2 NTM is triggered close to the β_N from the threshold scaling, the pressure in the discharge with ICCD for sawtooth destabilisation considerably exceeds the threshold scaling before a 3/2 NTM is triggered. Table 1 lists a set of discharges in which B_0 is varied to probe the effect of varying resonance position near the q=1 surface. The $\beta_{N,onset}$ values for these discharges (incl. 51994) are given in Fig. 2 as a function of $\rho*$. For NBI-only discharges (red squares), $\beta_{N,onset}$ is close to the scaling. The discharges with added ICRF waves can be divided in three categories. In the first one, ICCD do not lead to sawteeth destabilisation. NTMs are triggered close or below to the usual threshold (pink triangles). In the discharge 52087, the resonance was most likely too far off-axis to have an effect. The second group (black square), represented by the discharge 52054 has only central ICRF and is well below the threshold scaling. The energetic ions produced lead to sawtooth stabilisation via an increase in the central fast ion pressure. In the third group (blue squares), sawteeth are destabilised by the ICCD and $\beta_{N,onset}$ increase relatively to the threshold scaling. Moreover, one can see in Fig. 3 that as the pressure increases the resonance position R_{2ndH} shifts to a smaller major radius and sawtooth destabilisation is possibly lost when the resonance crosses q = 1. This might explain why for some

N° Shot	B_0 (T)	R_{2nd} (m)	τ_{st} (ms)	t_{NTM} (s)	β_N
52077	1.29	2.78	214	24.90	2.55
52054	1.38	3.02	300	24.66	1.55
52079	1.47	3.21	307	25.50	2.35
52080	1.50	3.29	272	27.60	3.35
52082	1.53	3.34	253	28.10	3.45
52083	1.56	3.42	180	28.10	3.60
52087	1.61	3.55	231	26.37	2.65
52084	1.56	-	297	25.50	3.0
52703	1.56	-	315	27.37	3.35

Table 1: *2^{nd} harmonic H resonance radius, sawtooth period ~ 23.5 s, time and β_N at the 3/2 NTM. For discharge 52084 t_{NTM} refers to a 2/1 NTM onset.*

discharges ICCD had no net effect on the pressure threshold and why the improvement is limited in other discharges. Another limitation comes from the loss of the ICRF power (dashed parts of the curves in Fig. 3) due to the poor coupling during ELMs.

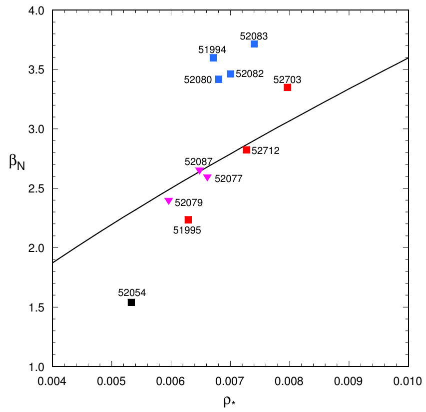

Figure 2: *β_N at mode onset versus $\rho*$ for table1 discharges. The black curve gives the onset scaling for NBI-only discharges.*

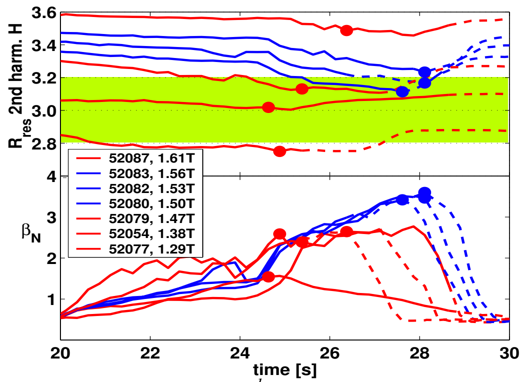

Figure 3: *Time evolution of 2^{nd} harmonic H resonance position and β_N for discharges in table1. The dots indicate the NTM onset, the dashed parts of the curve when P_{ICRF}<1MW and the shaded area the region inside R_{inv}. Reprinted from Ref. [1].*

3. Improvement of sawteeth control by ICCD

Experiments were recently performed to optimise the ICCD effect on sawteeth by changing the H concentration, the ICRF power, the wave phasing and the resonance position R_{2ndH}. Fig. 4 illustrates HFS experiments performed with B_0 ramps between 1.45 and 1.65T, 10% of H-minority and 4MW of ICRF. Optimal conditions for sawtooth destabilisation are found with R_{2ndH} on R_{inv} and –90° phasing. Indeed, due to the local modification of the q profile by the passing ions current [4], sawteeth with very small amplitude and indistinct crashes are obtained around t=23s. As R_{2ndH} goes toward the plasma centre, the fast ions pressure leads to longer period and larger amplitude sawteeth. In agreement with past experiments using central 1^{st} harmonic H resonance, the pinch effect consequences [5] are also observed with a

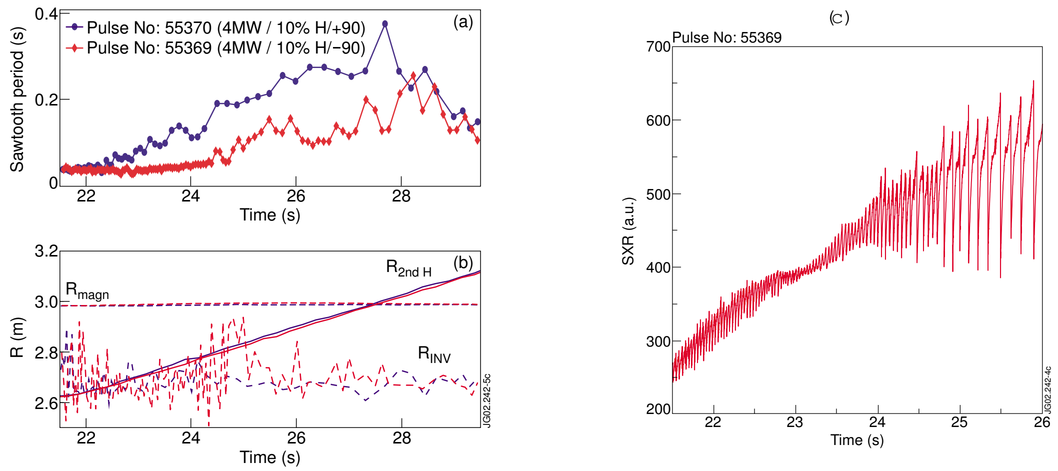

Figure 4: *Time evolution of (a) the sawtooth period; (b) the sawtooth inversion radius R_{INV}, the 2^{nd} harmonic H resonance R_{2ndH} and the magnetic axis radius R_{magn}, for discharges 55370, 55369; (c) Soft X-Ray emission (central channel) for the discharge 55369.*

2nd harmonic scenario and lead to shorter period with –90° phasing compared to +90° phasing. Experiments with R_{2ndH} low field side (LFS) and B_0 ramps between 1.9 and 1.55T are shown in Fig. 6. Because of their finite orbit width, the fast trapped ions give rive to a “diamagnetic” type current [6] and leads to the changes in the sawtooth period observed as R_{2ndH} goes towards R_{inv}, with an minima in the period slightly inside R_{inv}. It has to be noted that in agreement with past numerical studies [6,7] this current is similar with +90° and –90° phasing. Moreover, increase in the sawtooth period (t~23s) obtained in shot 55367 with R_{2ndH} outside R_{inv} could be explained by a current profile modification in the presence of more energetic fast particles [7].

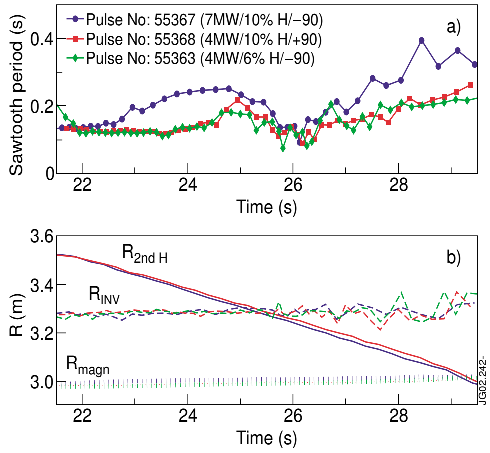

Figure 6: *Time evolution of (a) the sawtooth period; (b) the sawtooth inversion radius R_{INV}, 2^{nd} harmonic H resonance R_{2ndH} and magnetic axis radius R_{magn} for discharges 55367, 55368, 55363. In discharges 55367, 7MW of ICRH power is applied.*

4. Summary and prospects

A new strategy to control the NTMs onset was developed in recent experiments on JET. It was shown that by carefully positioning the 2nd harmonic H resonance relative to the inversion radius, the sawtooth activity could be controlled and the plasma pressure at the NTM onset significantly increased. The ICCD production with a 2nd harmonic H scenario was systematically studied in order to obtain a reliable and reproducible sawtooth control scenario with the resonance layer either low field side or high field side. In both cases the resonance position appears as a critical factor. In the next experiments, compensation of the resonance drift, as the plasma pressure increases will be performed. Preliminary tests have shown that the required changes of around 0.003T/s are technically feasible. Finally, a new trip management system, currently installed on the JET ICRF plant, is excepted to increase the averaged coupled power during ELMs and thus the ICCD performance.

References

[1] O. Sauter, *et al*., Phys. Rev. Letters **88** (2002) 105001
[2] E. Westerhof, *et al*., submitted for publication in Nucl. Fusion (2002)
[3] R.J. Buttery, *et al*., submitted for publication in Nucl. Fusion (2002)
[4] V.P. Bathnagar, *et al*., Nucl. Fusion **34** (1995) 1579
[5] L.-G. Eriksson, *et al*., Phys. Rev. Lett. **81(6)** (1998) 1231
[6] M. J. Mantsinen, *et al*., accepted for publication, Plasma Phys. Contr. Fusion (June 02)
[7] J. Carlsson, *et al.,* Phys. Plasmas **5** (1998) 2885

This work was performed under EFDA and partly funded by UK Department of Trade and Industry, Nederlanse Organisatie voor Wetenschappelijk Onderzoek , Swiss National Science Foundation and Euratom.