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ABSTRACT.

The m=3, n=2 Neoclassical Tearing Mode (NTM) destabilisation requires the pre-existence of a magnetic seed island which is often generated by the plasma perturbations associated with sawteeth. A new strategy was recently developed at the Joint European Torus (JET) to control the NTM seed island by modifying the sawtooth activity. Ion Cyclotron Current Drive (ICCD), with waves tuned to the 2nd harmonic hydrogen resonance, has been used to destabilise the sawteeth and thus to increase the plasma pressure at which an NTM is triggered. As the 2nd harmonic hydrogen damping was most effective placing the resonance RIC on the Low Field Side (LFS) of the plasma, this paper will emphasize the LFS case analysis. In these experiments a scan in the RIC position with respect to the sawtooth inversion radius, Rinv, has been performed. The results are compared to the scaling, obtained for JET discharges with NBI heating only, of the normalised plasma pressure at which the NTM is triggered β_{Nonset} (= $\beta_t[\%]a[m]B_0[T]/I_p[MA]$) with the normalised poloïdal ion Larmor radius. Two groups of discharges have been identified. When RIC is in a narrow range outside Rinv sawtooth destabilisation occurs, and β_{Nonset} is increased to a value significantly above the scaling law prediction and close to the ideal β -limit, $\beta_N \sim 4$. On the other hand, when R_{IC} is well outside Rinv, or well inside Rinv, sawtooth destabilisation is lost and β_{Nonset} is close to the scaling law values. The sensitivity to the resonance position is observed in particular during the NBI power ramp; as the plasma pressure is increased, diamagnetic effects can lead to a drift of RIC significant enough to lose sawtooth destabilisation. Increases in the β_{Nonset} values are expected with a programmed change in the magnetic field in order to compensate resonance shifts. In order to develop this strategy, ways to maintain ICCD in presence of ELMs and ways to optimize the ICCD efficiency will also be presented.

1. INTRODUCTION

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

With NBI-only, the β_N threshold at the 3/2 NTM onset scales with the normalised ion gyroradius as $\beta_{N \text{ onset}} \propto \rho^{*0.7}$ [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 ρ^* . Times of NTM onsets are indicated by squares. In 51994, about 5MW of ICCD is applied for sawtooth destabilisation. The resonance $R2_{ndH}$ is positioned at 2.55m on the high field side (HFS) just outside the q = 1 surface. In these pulses the NBI is ramped to increase β_N slowly 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 = 1surface. The β_N , onset values for these discharges (incl. 51994) are given in Fig.2 as a function of ρ^* . For NBI-only discharges (red squares), β_N , onset is close to the scaling. The discharges with added ICRF waves can be divided into three categories. In the first one, ICCD do not lead to sawteeth destabilisation. NTMs are triggered close to or below the usual threshold (pink triangles). In the Pulse 52087, the resonance was most likely too far off-axis to have an effect. The second group (black square), represented by the Pulse No: 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 β_N , onset increases 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 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.

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} . Figure 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 1st harmonic H resonance, the pinch effect consequences [5] are also observed with a 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.5. 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 Pulse: 55367 with R_{2ndH} outside R_{inv} could be explained by a current profile modification in the presence of more energetic fast particles [7].

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 2^{nd} 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 2^{nd} 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.

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No Pulse:	В ₀ (Т)	R _{2ndH} (m)	τ _{st} (ms)	t _{NTM} (s)	β _{Nt}
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	3.00
52703	1.56	-	315	27.37	3.35



Table 1: 2^{nd} harmonic H resonance radius, sawtooth period ~ 23.5s, time and β_N at the 3/2 NTM. For Pulse No; 52084 t_{NTM} refers to a 2/1 NTM onset.

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



3.6 2nd harm. H 3.4 3.2 . ອັ ແ 2.8 52087, 1.61T 52083, 1.56T 4.0 52082, 1.53T 52080, 1.50T 3.0 52079, 1.47T 52054, 1.38T 52077, 1.29T ຕີ 2.0 1.0 0∟ 20 22 26 28 30 24 Time (s)

Figure 2: β_N at mode onset versus ρ^* 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 table 1. 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].



Figure 4: Time evolution of (a) the sawtooth period; (b) the sawtooth inversion radius R_{INV} , the 2nd harmonic H resonance R_{2ndH} and the magnetic axis radius Rmagn, for Pulses 55370, 55369; (c) Soft X-Ray emission (central channel) for the Pulse No: 55369.



Figure 5: 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 Pulse No: 55367, 55368, 55363. In Pulses No: 55367, 7MW of ICRH power is applied.