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ABSTRACT

In recent experiments at JET, ICRF waves were used to either stabilise or destabilise sawteeth, and consequently control the formation of the seed island responsible for the appearance of Neoclassical Tearing Modes (NTMs) known to limit the tokamak performance. Two scenarios were studied in deuterium plasmas with a hydrogen concentration of 5 to 10%. Firstly, using a toroidal magnetic field B_0 of 2.5T, the fundamental hydrogen cyclotron resonance layer ($\omega=\omega_{cH}$) was positioned at the High Field Side (HFS) at the sawtooth inversion radius (R_{inv}~$R_{q=1}$). With $+90^o$ phased wave, monster sawteeth were obtained that triggered NTMs. Secondly, ICRF waves at the 2^{nd} harmonic hydrogen cyclotron resonance ($\omega=2\omega_{cH}$) positioned at the Low Field Side (LFS) with B_0 between 1.2T and 1.6T, was used to reduce the sawtooth period and increase the NTM β_n onset level.

INTRODUCTION

Efficiency of the plasma containment is represented by $\beta = \langle p\rangle/(B_0^2/2\mu_0)$ or by $\beta_N = \beta(\%)/[Ip(MA)/a(m)\,B_0(T)]$ where p is the plasma pressure, B_0 is the magnetic field at the plasma centre, Ip is the plasma current and a is the plasma minor radius (~0.9m in JET). The maximum achievable β is limited by macroscopic unstable modes described by the ideal MHD, this limit being relatively high in standard H-mode plasmas. However, it has been found, in the last few years [1-3], that pressure driven tearing modes can be destabilised at β values much lower than the ideal limit. These modes form islands near resonant magnetic surfaces, at q=3/2 and 2/1 in particular. Once a seed island is formed and becomes sufficiently wide to locally flatten the pressure profile, it perturbs the self-generated bootstrap current which further destabilises the mode. The driving term, the perturbed bootstrap current, is proportional to the local pressure gradient and inversely proportional to the island width. A finite seed island, generally generated by sawtooth activity, is required before the island can be further destabilised by the bootstrap current. The main detrimental effect of the q=3/2 NTM is a loss of energy and particle confinement. In the past, direct stabilisation of NTM using Electron Cyclotron Current Drive (ECCD) has been demonstrated [4]. We present here a new scheme for avoiding NTMs by controlling the sawteeth activity to keep the seed islands smaller than the critical width. Past experiments, have shown that ICRF waves can be used to affect the sawteeth activity in two ways. The first is sawtooth stabilisation due to a high fast-ion pressure in the plasma core [5-7], when the minority ion cyclotron resonance layer is located near the plasma centre. The second is a sawtooth stabilisation or destabilisation due to modifications of the current profile around q=1 surface in response to the current driven by fast ions [10-11], and obtained using -90^o or $+90^o$ phased waves, with the cyclotron resonance layer located close to the q=1 surface.

DECREASE OF β_N AT NTM ONSET, USING WAVES AT $\omega = \omega_{CH}$

Sawtooth control using asymmetric spectrum waves. The capability of the JET A2 antennas to produce fast ion current drive large enough to stabilise or destabilise the sawteeth was studied. The fundamental hydrogen cyclotron resonance Rres was positioned at the HFS and moved between 2.5m and 2.9m (corresponding to a B_0 ramp between 2.3T and 2.7T), 5MW of ICRF power was applied with a frequency of 42MHz. One can see on Fig.1, that for $+90^o$ phasing a clear sawtooth stabilisation was obtained when R_{res}~R_{inv}, followed by a sawtooth period decrease as the resonance layer moves further toward the plasma centre. For –90 phasing, sawtooth destabilisation was observed until 20.2s then stabilisation when R_{res} moves inside R_{inv}. Modelling with FIDO [12] code suggests that the current drive profiles have different gradients at R_{res}~R_{inv} with $+90^o$ and -90^o phasing. Moreover, the fast ion pressure inside the q=1 surface, which is higher with $+90^o$ than with -90^o phasing, is expected to play a role. In the previous experiments (with the JET A1 antennas), the effect on the sawtooth could be explained entirely by a magnetic shear modification but in the experiments presented here, both modification of the magnetic shear and of the plasma pressure appear responsible for the sawtooth modification [13]. Decrease of β_N for the NTMs onset. The fundamental H cyclotron resonance layer was positioned HFS near the inversion radius (B0 fixed at 2.5T). An NBI power ramp was added to the 5MW of ICRF power. One can see on Fig.2, that with $+90^o$ phasing a long sawtooth period of 650ms was obtained. After this sawtooth crash, an NTM was triggered even though the • value was very low (1.2). In the case of -90^o phasing, shorter sawtooth periods were obtained (~200ms), no NTMs were triggered and the discharge reached β_N~2 with sawteeth throughout the high power phase (up to 20MW of combined heating). Analysis of other similar discharges, give us a critical value β_N^{CRIT} ~ 0.7 above which NTMs are metastable. In pulse no: 51802, no NTMs were triggered even with $\beta_N > 2\ \beta_N^{CRIT}$. In pulse no: 51794, and all other similar discharges, NTMs were triggered at the first crash after a long sawtooth with $\beta_N > \beta_N^{CRIT}$. This is the first clear experimental demonstration of the crucial role of the seed island for determining the β_N value at which NTMs are destabilised.

INCREASE OF β_N AT NTM ONSET USING WAVES AT $\omega = 2\omega_{CH}$

In JET, NTMs are not generally destabilised with NBI alone at high magnetic field (>2.5T). At low field and using the 2nd harmonic H cyclotron resonance ($\omega = 2\omega_{cH}$), the potential for ICRF waves to control seed islands and NTMs, can be tested.

Minority current drive at 2nd harmonic H cyclotron resonance. On the experiments illustrated in Fig.3, the 2nd harmonic H cyclotron resonance layer was positioned LFS and moved between 3.5m and 3m (corresponding to a B_0 ramp between 1.6T and 1.3T), 4.5MW of ICRF power was applied with a frequency of 42MHz. Accordingly with initial FIDO modelling results [14] which gives similar current drive profile with $+90^o$ and -90^o phasing, the sawtooth period obtained experimentally was similar with the two phasings. Maxima in the sawtooth period were observed when R_{res}~R_{inv} and when the resonance layer moves toward the plasma centre. Minima were observed when the resonance was well outside (t~22.5s) or just inside the inversion radius (t~25.5s).

Increase of β_N for NTM onset. Based on the results in pulse no: 51800 with -90^o phasing and the 2nd harmonic H cyclotron resonance layer positioned LFS, two specific magnetic fields were chosen and an NBI power ramp was added to the 4.5MW of ICRF power. The resonance layer for the pulse no: 52083 was positioned at 3.3m (with B_0=1.57T which corresponds to a high sawtooth period in pulse no: 51800) and for the pulse no: 52079 at 3.45m (B_0 = 1.47T which corresponds to a small sawtooth period in pulse no: 51800). One can on Fig.4 that for the pulse no: 52079 an NTM was triggered at β_N~2.3 and that for the pulse 52079 an NTM was only triggered at β_N ~3.6 (near the ideal limit). It should be noted that for the pulse no: 52083, after 27s the coupled ICRF power decreased dramatically because of large ELMs. This may explain the appearance of the NTM mode at 28s, as the sawtooth activity is no more controlled. Similar results were obtained with -90^o phased waves and the 2 nd harmonic H cyclotron layer HFS.

CONCLUSION

It was confirmed experimentally that by stabilising sawteeth, large seed islands could be obtained, which triggered NTMs at very low β_N. Furthermore, it was shown that is was possible to use ICRF waves at the 2^{nd} harmonic hydrogen cyclotron resonance to produce minority current drive in order to destabilise the sawteeth so as to maintain a small island size and so reach higher β_N.

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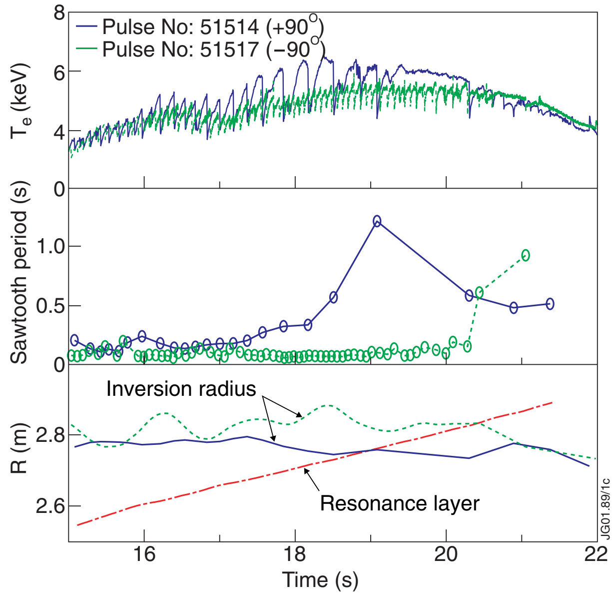

Figure 1: Time traces of central (2.9m to 3.3m) electron temperature from ECE, sawtooth period, sawtooth inversion radius and fundamental hydrogen cyclotron resonance layer.

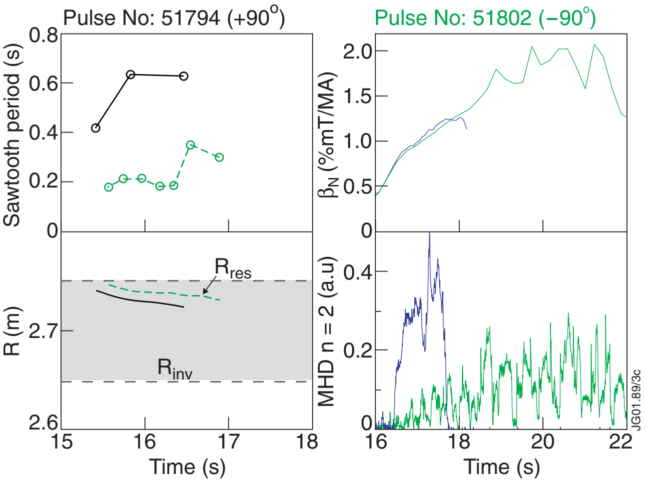

Figure 2: Time traces of sawtooth period, inversion radius R_{inv}, fund. H cyclotron res. layer R_{res}, β_N and n=2 mode amplitude. A power suply trip linked to the NTM, ended pulse no: 51794 at 17.8s

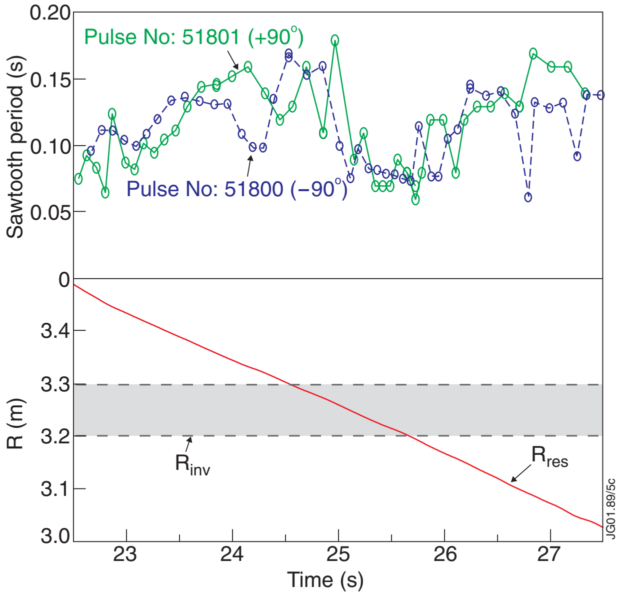

Figure 3: Time traces of sawtooth period, sawtooth inversion radius and 2nd H cycl. res. layer.

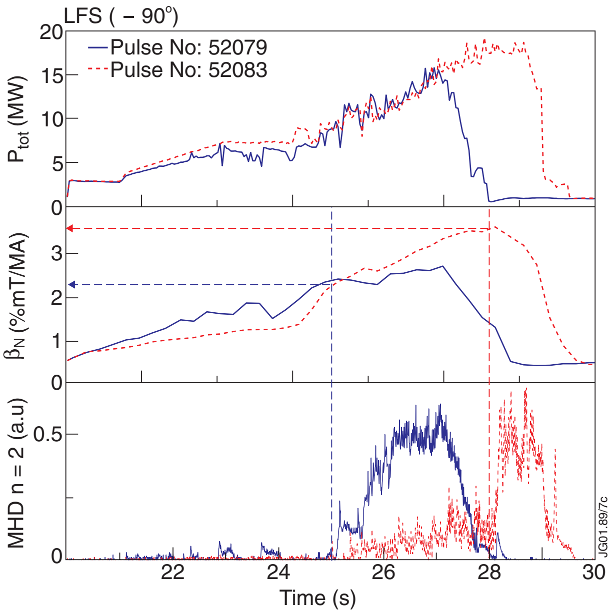

Figure 4: Time traces of total power P_{tot}, β_N and mode n=2 amplitude with ICRF waves at nd