DESTABILISATION OF FAST ION STABILISED SAWTEETH USING ELECTRON CYCLOTRON CURRENT DRIVE ON TORE SUPRA

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1. INTRODUCTION. Fast ions – fusion produced alpha particles in future reactors or ICRH accelerated ions in present tokamaks - can stabilise the 'sawtooth' instability, resulting in long sawteeth and large sawtooth crashes, which are prone to trigger unwanted MHD modes such as Neoclassical Tearing Modes (NTMs) [1,2]. On the other hand, the evidence is that short period sawteeth do not to trigger NTMs [3,4]. Thus NTMs may be avoided if short sawteeth can be maintained, even in the presence of significant fast ion pressure. The theoretical expectation that the sawtooth period decreases with increased magnetic shear at q=1 [5] have been experimentally confirmed in plasmas without significant fast ion pressure using local ECCD on TCV [6] and ASDEX Upgrade [7]. Experiments on JET have demonstrated that in plasmas with significant central fast ion pressure, generated by ICRH, NTM triggering can be avoided by shortening the sawtooth period, through the use of localised Ion Cyclotron Current Drive (ICCD) to increase the shear at q=1 [8,9]. Similar experiments on Tore Supra using central ICRH and off axis ECCD, showed that the sawtooth period could be strongly modified by the application of modest amounts of ECCD [10]. In the JET and Tore Supra results which were achieved with significant central fast ion pressure the precise location of the ECCD was seen to be critical for achieving sawtooth destabilisation.

2. EXPERIMENTAL RESULTS [11]. The experiments reported here were carried out on Tore Supra using a toroidal field of ~3.8T and a plasma current of 1MA and as in [8,9,10] ICRH (57MHz) was used to create significant central fast ion pressure. To investigate the effect of ECCD on the sawtooth period, 300kW ECCD was swept from off-axis (outside the $q = 1$ surface) to central deposition by moving mobile mirrors in the torus vacuum chamber [12]. Figure 1 shows an overview of 3 discharges: two with 1.4MW ICRH and co- or counter-ECCD respectively and one with counter- ECCD only. In the first two discharges the sawtooth period increases from the ohmic value of ~25ms to ~70ms when ICRH is applied, i.e. when fast ions are created and start stabilising the sawteeth. When ECCD is added – starting off axis – no effect is initially observed. When the ECCD deposition region moves towards the plasma centre a sharp dip in sawtooth period is seen over a modest range of deposition radii. The radial location of the ECCD current shown is calculated using the REMA code [13] while the sawtooth inversion radius, which should be close to the q = 1 surface, is measured with the ECE diagnostic. Clear sawtooth destabilisation is observed both for co- and counter- ECCD with the destabilisation phase appearing earlier (corresponding to more off-axis deposition) for counter- ECCD than for co-ECCD. When the (now central) ECCD is switched off towards the end of the discharge the central electron temperature drops by almost 1keV confirming the significant central heating. In contrast the effect of ECCD is hardly discernable in the discharge without ICRH.

The ICRH results are particularly remarkable in two respects: the modest amount of ECCD power; and the abruptness with which the sawtooth period drops and goes back up again. The latter feature is reminiscent of other results obtained when fast ions are present [8,9,10]. The present results, which were reproduced in a significant number of discharges, clearly demonstrate that ECCD can efficiently shorten the sawtooth period even in the presence of central fast ion pressure, provided the ECCD is appropriately positioned. In one shot –shown in figure 2 - executed to verify the correct absorption of the ECCD power, the injection angles were scanned as in the above shots, but the ECCD power was applied in short pulses of 50ms every 1000ms. The sawtooth period is observed to transit to short sawteeth for two of the ECCD pulses, while the long ICRH induced sawteeth remain for all other pulses.

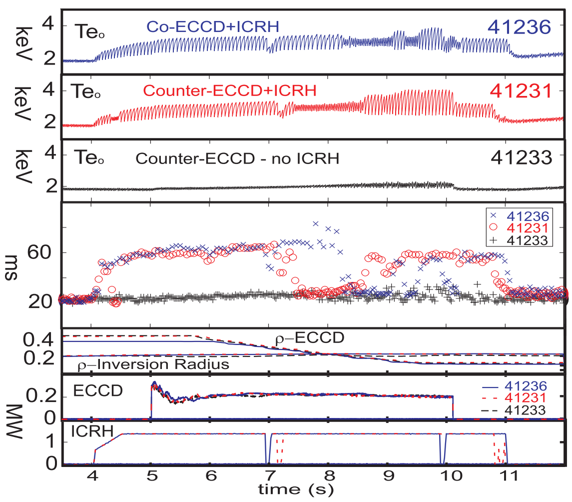

Fig.1. ECCD deposition scans. Sawtooth destabilisation seen for co-and counter ECCD in ICRH heated discharges.

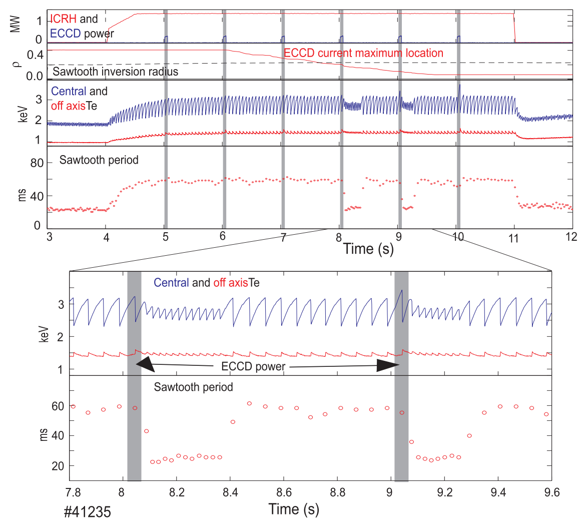

Fig. 2. ECCD Deposition scan with 50ms co-ECCD pulses every second. Short sawteeth seen following 4th and 5th pulse.

The detailed response of the sawteeth for the pulses where an effect is observed reveals that the transition to short sawteeth appears after the ECCD power is switched off and that the destabilising effect remains for up to 300ms, indicating that processes with long time constants are involved. Whether this interesting behaviour can be explained solely by time constants or whether a hysteresis mechanism has to be invoked remains an open question.

Fig. 3 shows the sawtooth period as a function of the distance between the sawtooth inversion radius and the peak of the ECCD deposition for a number of discharges similar to the ones shown in figure 1. This figure suggest that sawtooth destabilisation can be achieved with co-current drive somewhat inside the $q = 1$ surface while current drive at or slightly outside q=1 is required in the counter-current case. The points taken from the pulsed discharge added as full circles in figure 3 are in good agreement with the points achieved with continuous pulses. It is interesting to note that while effective sawtooth shortening can be obtained with both co- and counter-current ECCD, none of them did produce any significant lengthening of the sawtooth period irrespective of the localisation of the ECCD current (at least not in the series of discharges reported here).

To confirm that sawtooth destabilisation can be achieved over a range of parameters and to investigate whether the abrupt change in sawtooth period is a universal feature, the experiments were repeated at different values of ICRF power and plasma density. Sawtooth destabilisation was achieved for the full range of available ICRF powers (0-4MW) and over a wide range of densities. In all cases the same abrupt change in sawtooth period was observed. Figure 4 shows the sawtooth period as a function of the injected ICRF power and as a function of the density in the presence and absence of destabilising ECCD. It is seen that the destabilised sawtooth period is virtually independent of ICRF power and plasma density and that this period is only slightly higher than the ohmic period. In the absence of ECCD the sawtooth period is seen to increase with ICRF power and with density. If ECCD is added –

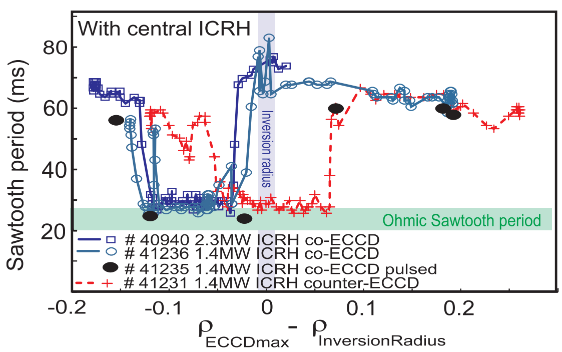

Fig. 3. Sawtooth period as a function of ECCD location relative to sawtooth inversion radius for co- and counter- ECCD

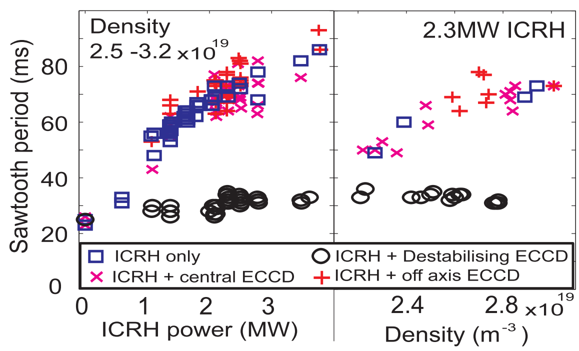

Fig. 4. Sawtooth period dependence on ICRH power and plasma density, with and without ECCD destabilisation

but with the current driven inside (x) or outside (+) the destabilisation region, only a small variation in the sawtooth period with respect to the ICRF heating only situation is observed. The increase of the sawtooth period with ICRF power in the absence of ECCD destabilisation is readily explained by the increase in fast ion pressure, while the decrease of the sawtooth period for lower density is in agreement with observations on JET [14].

Further experiments have demonstrated that the sawtooth period can be switched reliably between short and long sawteeth using a closed loop controller. Such control will be required in future machines for sawtooth destabilisation to be a viable option for NTM avoidance. Though successful, these experiments highlighted the difficulty associated with the abrupt change in sawtooth period [15,16]. If this phenomenon is universal – as it seems to be at present - the control algorithms implemented on future tokamak devices have to take this into account and better physics understanding of this phenomenon would be very helpful.

3. CONCLUSIONS. The experiments presented in this paper have, to our knowledge for the first time, demonstrated that the period of fast ion stabilised sawteeth can be reliably shortened with modest amounts of ECCD localised correctly with respect to the q=1 surface. The Sawtooth period was seen to transit abruptly between long and short period sawteeth as the ECCD deposition was swept radially while the period of shortened sawteeth was seen to be rather insensitive to variations in plasma parameters, including the fast ion pressure. Control of the sawtooth period by localised ECCD therefore appears to be a promising candidate for developing strategies for avoiding NTM triggering by crashes of long period sawteeth, though experiments demonstrating that even longer ‘monster’ sawteeth can be reliably destabilized would be desirable.

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