NTM Prevention by ICCD Control of Fast-Ion-Stabilised Sawteeth

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1. Introduction

The MHD instabilities known as Neoclassical Tearing Modes (NTMs) [1], particularly at low rational orders (helicities m/n=2/1 and 3/2), have been shown to cause substantial loss of confinement in tokamaks, to an extent that may severely hamper the performance of a future reactor [2]. NTMs display a broad poloidal beta (β_{pol}) metastability range, in which they can only be excited by a finite seed island but, once excited, remain unstable. Efforts to prevent NTMs have therefore focused primarily on the containment of seed islands, particularly the most deleterious ones associated with the crashes of long-period sawteeth, such as can be caused by a core fast-ion population [3]. The process by which sawtooth crashes trigger NTMs is only partly understood - while a strong statistical correlation has been established between the duration [2] (rather than the amplitude) of sawteeth and the triggering of NTMs, unknown additional parameters render individual triggering events operationally unpredictable.

Ion-cyclotron current drive (ICCD) in the proximity of the sawtooth inversion radius has been used successfully to destabilise the m=1, n=1 internal kink mode [4,5], resulting in more fre-

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*See the Appendix of M.L. Watkins *et al.*, Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006), IAEA, (2006) quent sawtooth crashes and in NTM-free scenarios at β_{pol} well above the marginal stability threshold. It was also shown more recently on JET that this ICCD scheme is effective in keeping the sawtooth period short even in the presence of a substantial core fast-ion population [6]. This was a crucial test as multiple internal-kink stability criteria are involved in determining when a sawtooth crash will occur, and it is not obvious *a priori* that the stabilising effect of fast ions can be counteracted effectively with ICCD [7]. This successful result was obtained under controlled conditions, in the absence of neutral-beam injection (NBI) heating and at low β_{pol}, thus not in the reactor-relevant regime to which the methodology must ultimately be applied.

In this paper we report on the recent demonstration, for the first time, of the effectiveness of ICCD in preventing m=3, n=2 NTMs in the presence of a strong fast-ion component and at β_{pol} well above marginal stability, i.e. at values at which NTMs are routinely triggered under identical conditions without a sawtooth destabilising agent. The scenario effectively simulates the conditions expected in a fusion reactor such as ITER, where the fast-ion population will primarily be comprised of alpha particles generated by fusion reactions and NTM triggering is expected to occur in the absence of active sawtooth control.

2. Experimental results

The experiment was performed in JET by simultaneously heating the plasma with neutral beams and with waves in the Ion Cyclotron Range of Frequencies (ICRF) at two different frequencies and antenna phasings, one optimised for core fast-ion acceleration and the other for ICCD near the inversion radius. JET is equipped with four ICRF antennae composed of 4 straps each; the phase relations of the currents circulating in the straps determine the parallel-wave-number spectrum of the launched waves. The so-called $+90^0$ and -90^0 phasings imply a regular 90^0 phase increment between adjacent straps, the sign convention being positive for co-current propagating waves and negative for counter-current propagating waves. A central resonance with a $+90^0$ phasing is well known to provide the strongest core fast-ion population, owing to an inward pinch that causes the fast-ion pressure profile to peak on axis [8]. Conversely, ICCD with -90^0 phasing applied near the sawtooth inversion radius has proven most effective in destabilising the internal kink mode [9].

The main plasma parameters are as follows: magnetic field on axis B_T of the order of 2.8 T, plasma current I_p~2.2 MA, edge safety factor q_{95}=4.1, line-averaged density $2.4\text{x}10^{19}$ m^{-3}, hydrogen concentration 3-5%. The resonance at play is the fundamental hydrogen minority resonance; the ICRF frequencies are 42.2 MHz for the central resonance and 46.2 MHz for off-axis ICCD (on the high-field side).

An example of successful sawtooth period shortening is shown in Fig. 1 (left). At β_N=1.25–1.35, the sawtooth period was kept consistently shorter than 200 ms by the application of 3 MW ICCD, with 3 MW central ICRF employed to accelerate the core ion population. The case

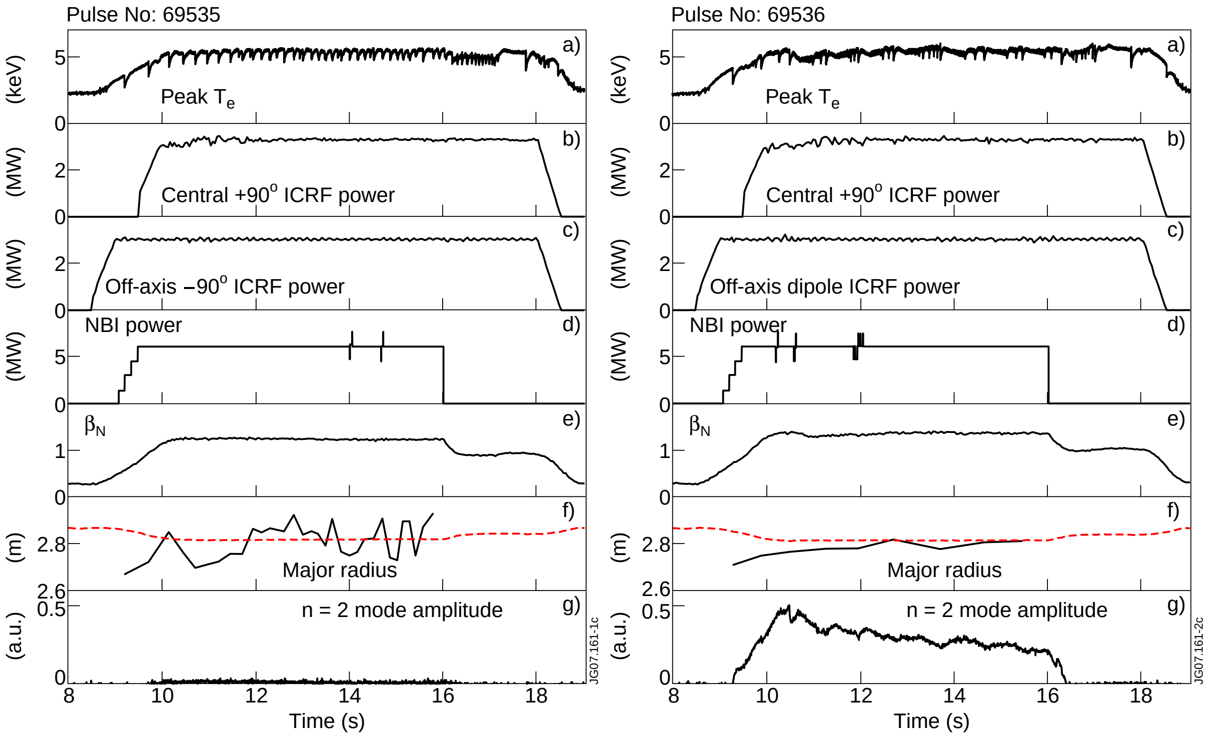

Fig. 1 JET discharges 69535 (left) and 69536 (right): (a) peak electron temperature; (b) ICRF power at 42.2 MHz; (c) ICRF power at 46.2 MHz; (d) NBI power; (e) normalised beta; (f) midplane major radius of sawtooth inversion (solid) and 46.2 MHz ICRF resonance (dashed); (g) n=2 MHD mode amplitude. The average sawtooth period in the combined ICRF/NBI phase is 180 ms in shot 69535 and 700-800 ms in shot 69536.

shown on the right-hand side of Fig. 1 is identical except for the phasing of the off-axis ICRF component, which here is dipole, providing no net toroidal wave propagation. With the same total power, the average sawtooth period is clearly much longer in the second case, and an NTM is triggered by the crash at the end of a long sawtooth during the initial heating phase. After the NTM is triggered the discharge behavior is completely altered, and in particular the sawteeth themselves become rather irregular. Similar results are obtained when the off-axis ICCD power is replaced by NBI power or simply removed altogether.

A crucial conclusion from this study is the extreme sensitivity of the sawtooth period to the location of the ICCD resonance: an accuracy of better than 0.5% in the ICCD frequency (corresponding to ~1% of the minor radius) is required for effective and reliable NTM prevention. Figure 2 displays a superposition of three discharges, identical in all aspects except for a 1% variation of the toroidal field. The variation in sawtooth duration is significant, although no NTMs were triggered in these particular detuned cases.

This sensitivity indicates that some form of feedback control of the frequency would be highly desirable in the eventual application of this technique in a fusion reactor.

3. Discussion and conclusions

The method described in this paper for controlling the sawtooth period and preventing the triggering of NTMs in the presence of a fast-ion population appears robust and readily extendable to a reactor scenario.

In view of the complex combination of effects that have to be considered in evaluating the current driven by ICRF waves, numerical simulations had previously been performed to estimate the driven current profile, using a full wave ICRF code coupled with a Monte Carlo Fokker-Planck solver [7]. The results of these simulations were consistent with experimental observations at low β [6] and suggested that ICCD near the inversion radius was indeed the key factor in keeping the sawtooth period short. Similar calculations are currently underway to simulate the experiments described in this paper, coupled with semi-analytical computations of the macroscopic internal kink stability [10].

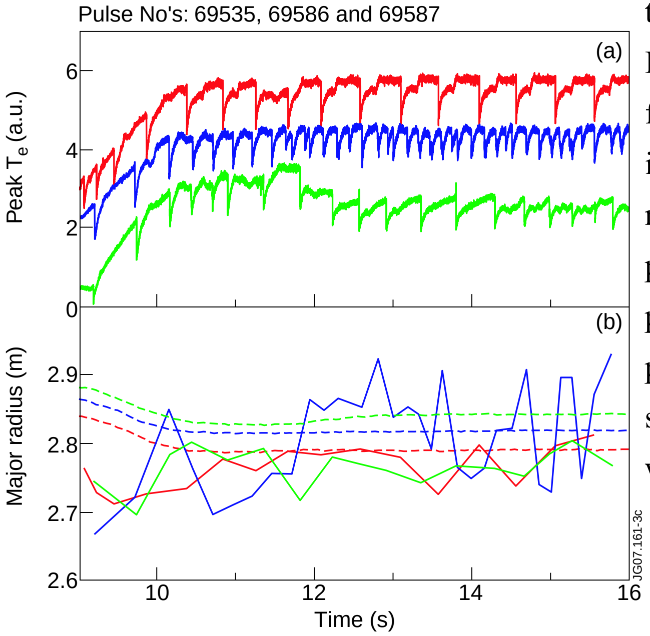

Fig. 2 *JET discharges 69535 (B_T=2.83 T, blue), 69586 (B_T=2.85 T, green) and 69587 (B_T=2.81 T, red): (a) peak electron temperature (keV with shifted offsets for clarity); (b) midplane major radius of sawtooth inversion (solid) and 46.2 MHz ICRF resonance (dashed). The average sawtooth period in the combined ICRF/NBI phase is 180 ms in shot 69535, 410 ms in 69586 and 470 ms in 69587.*

Acknowledgments

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