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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2002 (Proc. 19th IAEA Fusion Energy Conference, Lyon (2002).*

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INTRODUCTION

Increased sawtooth stabilization leading to long sawtooth periods is a known observation of auxiliary heated plasmas. However, small sawtooth regimes characterised by sawtooth periods, τ_{ST} = 20-100ms, that are shorter than observed in Ohmic regimes have been obtained at JET with Ion-Cyclotron Radio Frequency (ICRF) heating [1] as well as with neutral beam injection (NBI) heating [2]. At JET, decreasing the sawtooth period is known to delay the onset of NTMs. Results of two sawtooth studies from recent JET experimental campaigns are reported here. ICRF heating is usually associated with long sawtooth periods and large crashes referred to as "monster" sawtooth (τ_{ST} > 400ms). Sawtooth stabilization is understood as increased stability of the internal kink mode from ICRF driven fast ions [3]. In contrast, JET plasmas with high fast ion energy content, obtained by applying ICRF heating to a low-density target plasma, show a very unstable sawtooth regime. As the density is increased an abrupt change from small sawteeth to monster sawteeth is observed [1]. The transition occurs for densities in the range 1.5-2$\times 10^{19}$ m^{-3}.

Another regime of small sawtooth is observed with NBI heating in counter injection and the toroidal field, B_T, reversed [2]. With counter-NBI the observed plasma rotation in the plasma core is reduced when compared with the usual B_T, co-rotating plasmas. During a recent reversed B_T experimental campaign an experiment was performed to investigate rotation effects on sawtooth stability and in particular, to assess the internal kink stability models [4] that predict increased instability in regimes of low shear rotation.

1. SAWTOOTH OBSERVATIONS WITH COUNTER-NBI

Sawtooth behaviour was compared in plasmas with matched B_T, I_p and shape in the reversed and the usual B_T machine configurations. Results from a power scan at constant density, B_T = 2.7T, I_p = 2.5MA in L-mode plasmas are shown in figures 1-3.

Earlier JET results that sawtooth periods are reduced with counter-NBI injection [2] were confirmed. For the same NBI power the observed sawtooth period with counter-NBI was significantly smaller (Fig.1). Unlike, co-NBI where the observed sawtooth period increases with power, with counter-NBI the sawtooth period decreased up to a minimum at 4MW (Fig.2). A similar trend was observed with core toroidal plasma rotation. With counter-NBI the observed plasma rotation in the core of the plasma (obtained from charge exchange measurements) is reduced when compared with co-rotating plasmas. With co-NBI the sawtooth period increased with plasma rotation. With counter-NBI the sawtooth period reduced to a minimum for plasma rotation at ~ 2kHz (Fig.3), corresponding to the minimum sawtooth period obtained as a function of P_{NBI}.

With reversed B_T, the toroidal rotation is in opposition to characteristic frequencies ω_{*i} and $<\omega_{di}>$. Plasma rotation in the core of the plasma is reduced when compared with co-NBI. A candidate mechanism consistent with the main features of the observations is the dependence of the internal kink stability on sheared toroidal rotation [4]. Kinectic effects from thermal ions in a regime where the mode frequency $\omega \sim \omega_{*i} \sim \omega_{di}$, are expected to be destabilizing.

2. SAWTEETH OBSERVATIONS WITH ICRH IN LOW DENSITY PLASMAS

Sawtooth behaviour was studied in plasmas with a high fast-ion energy content obtained by applying ICRF heating to low density discharges, with $B_T = 2.7T$, $I_p = 2.5MA$ (In the usual B_T configuration). ICRF powers of 3-6MW were applied using a minority Hydrogen heating in Deuterium plasmas. Different ICRF toroidal phases and resonant positions were considered. Here results for on-axis heating, dipole phasing, are shown. In discharges with ICRF heating only the plasma density was controlled by gas puffing (Fig.4). In others the density increased when a small amount of NBI power ($P_{NBI} = 1\text{-}1.5MW$) was added (Fig.5). In both cases, an abrupt transition from small sawtooth to monster sawtooth, was observed when the density increased.

Small sawtooth, with periods ≤100 ms are observed for central densities $<2\times10^{19}\ m^{-3}$. The density threshold is in the range $1.5\text{-}2.0\times10^{19}\ m^{-3}$ depending on heating details. For similar discharges, the critical density was lower when a small amount of NBI was added (Fig.6).

The fast ion stabilizing influence on the internal kink mode is predicted to reduce for large ICRF heating powers [3]. Modelling with the CASTOR-K code confirms that as the fast ion temperature increases ($T_{hot} \propto n_e^{-1}$) and the fast particle orbits become wider the fast ion stabilization effect decreases [5]. In this case kinetic effects of trapped thermal ions and diamagnetic effects on the ideal MHD growth rate, not included in [5], may play a role in determining the sawtooth stability.

The n = 1 sawtooth precursor and postcursor oscillations observed inside the sawtooth inversion radius during the small sawtooth regime indicate low shear rotation with $f_{MHD} = 100\text{-}500Hz$. Low shear rotation is destabilizing [3]. The observed mode frequency is $\omega<\omega_{*i}$. If NBI is applied, the mode frequency increases rapidly to values 1-2kHz, making $\omega<\omega_{*i}$. Charge exchange measurements show that the rotation profiles become peaked. The increased stability with rotation might explain the lower density threshold for transition into "monster" sawteeth that is observed when NBI is applied.

CONCLUSIONS

In the usual JET machine operation, with co-NBI the sawtooth period increases with P_{NBI}. In contrast with counter-NBI the sawtooth period decreases up to a minimum at $P_{NBI} = 4MW$. Sawtooth periods shorter than those for Ohmic heating are obtained.

A similar trend is observed with plasma rotation. Kinetic effects from trapped thermal ions can be destabilising for small sheared counter rotation [4].

With ICRF heating the sawtooth period depends sensitively on the density. A critical density ($n_e<1.5\text{-}2.0\times10^{19}\ m^{-3}$) separates the small sawtooth from the usual "monster" sawtooth. Modelling shows that for low densities the stabilizing kinectic effects from fast ions is reduced, as the orbits of the ICRF driven fast ions increases. Recent experiments indicated the possible relevance of diamagnetic and shear rotation effects on the sawtooth stability in this regime. The abrupt change in sawtooth behaviour is not yet understood.

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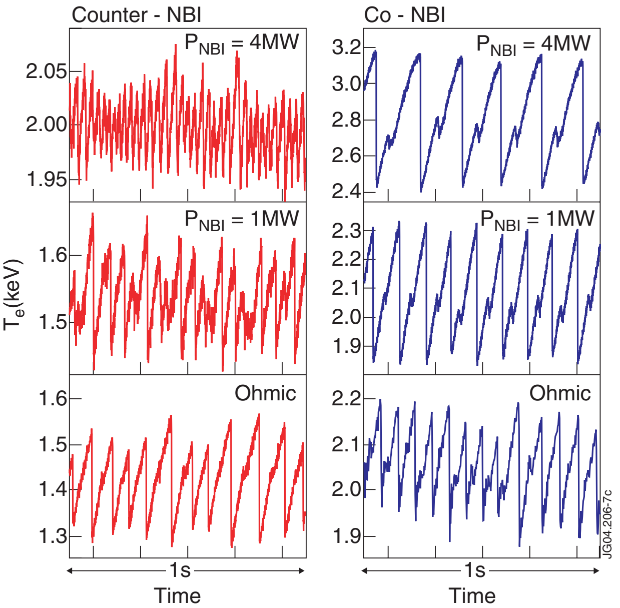

Figure 1: Central electron temperature traces for the reversed B_T (Counter-NBI) and the usual B_T (Co-NBI) configurations.

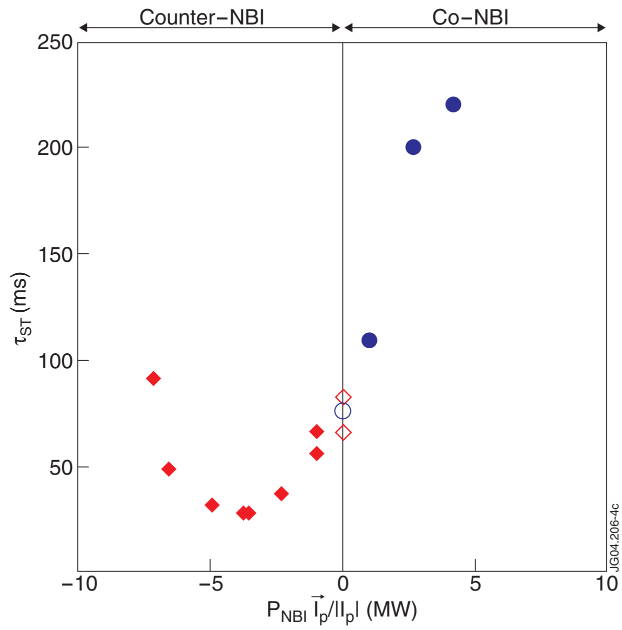

Figure 2: Sawtooth period as a function of NBI power.

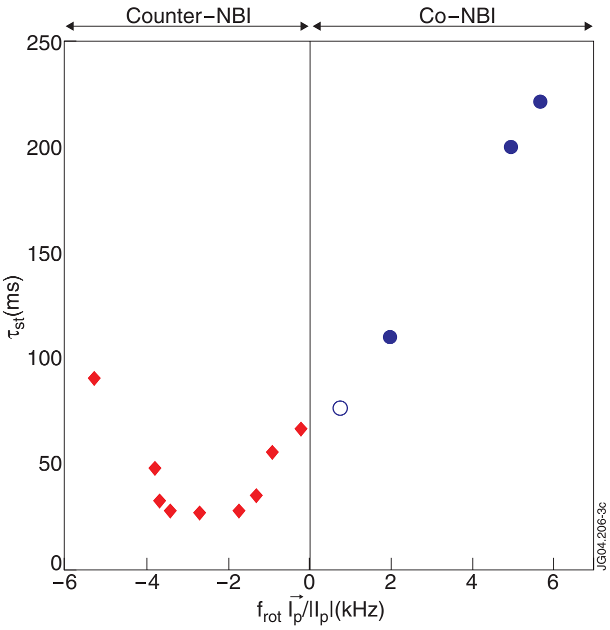

Figure 3: Sawtooth period as a function of toroidal rotation at the sawtooth inversion radius.

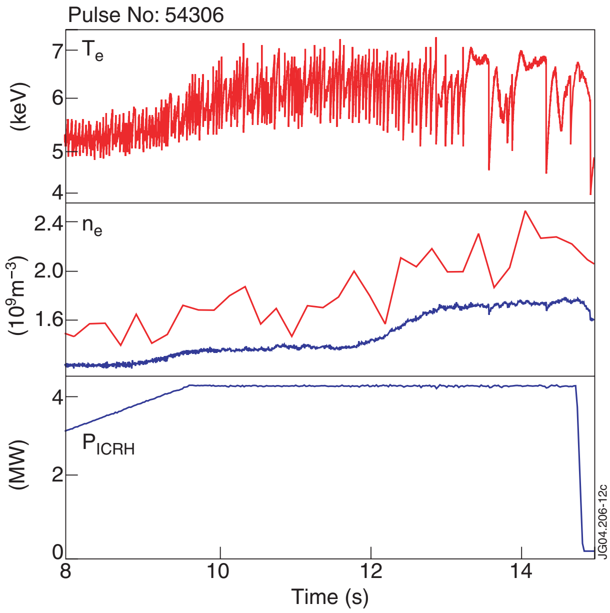

Figure 4: (a) Central Te from ECE measurement; (b) Central n_e, from LIDAR (red) and a line averaged FIR interferometer (blue) measurements; (c) ICRF power.

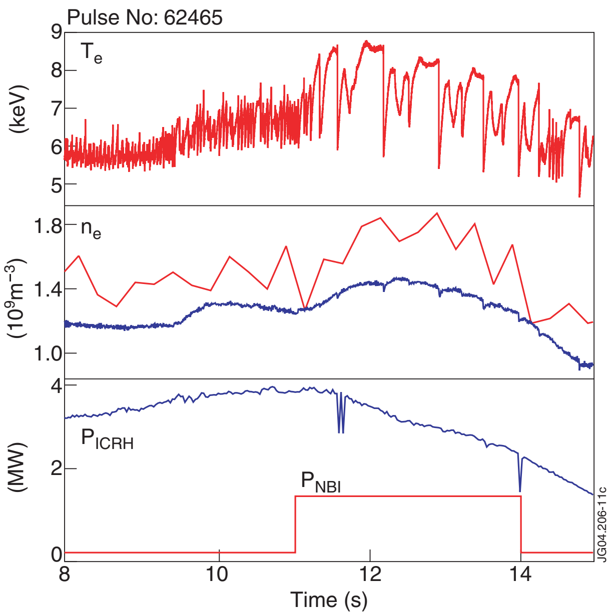

Figure 5: Traces as in figure 4, for a discharge where some of the ICRF power was substituted by NBI power.

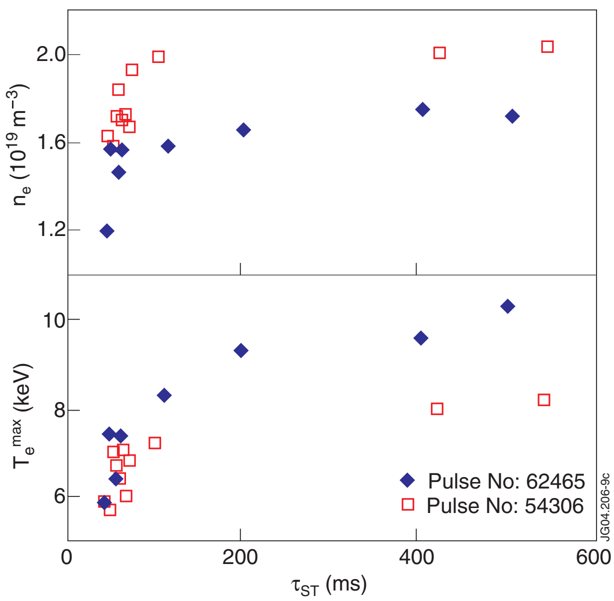

Figure 6: Central density (top) and central electron temperature (bottom) versus sawtooth period, for similar pulses with ICRF only (open) and with added NBI