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ABSTRACT

During a recent reversed toroidal field (B_T) campaign at JET, experiments were performed to investigate the effect on sawteeth of NBI-driven toroidal plasma rotation counter to the direction of the toroidal plasma current and B_T. A power scan at constant density has permitted analytical continuation, into the reverse B_T domain, of previous experiments with forward field and hence co-rotation. Earlier JET results were confirmed indicating that counter-NBI injection results in shorter sawtooth periods than in the Ohmic regime. This study has demonstrated that with counter-NBI the sawtooth period has a minimum at 4MW, whereas with co-NBI the period increases with power. Clearly this trend also manifests itself in terms of the toroidal plasma rotation, for which a minimum is observed for counter-rotation frequency ~ 2kHz. The kinetic effect of trapped thermal ions on the internal kink mode is identified as mechanism sensitive to the sign and magnitude of the toroidal rotation, qualitatively consistent with the main features of these observations.

1. INTRODUCTION

Developing techniques to control the m=1, n=1 sawtooth instability as a way of controlling the onset of Neo-classical Tearing Modes (NTMs) has been an important area of research in recent JET experimental campaigns. Reducing the sawtooth period was found to trigger the NTMs at higher values of normalzed beta [1, 2]. In addition, the importance of sawtooth control has been demonstrated in JET high-density ELMy H-mode plasmas where sawteeth play a beneficial role in the prevention of core impurity accumulation [3]. In order to achieve a balance between beneficial and deleterious effects it is important to understand how to maintain small, regularly occurring sawtooth crashes. Sawtooth stabilization leading to long sawtooth periods is a well known phenomenon in auxiliary heated plasmas. Nevertheless, sawtooth periods shorter than observed in Ohmic regimes have been obtained with ion-cyclotron radio frequency heating [4] as well as with counter Neutral Beam Injection (NBI) heating [5] with the toroidal field (B_T) reversed. Recently this small sawtooth regime with counter-NBI heating has been investigated in detailed experiments, the results of which are reported in this letter.

JET operation with reversed B_T is performed with the direction of the plasma current, I_p, also reversed, in order to conserve the direction of impact of the field lines on the divertor target plates. JET has two neutral beam injector boxes, each equipped with Positive Ion Neutral Injectors (PINIs), which can provide up to 20MW of NBI power [6] in total. The PINIS are grouped in tangential and nearly perpendicular banks (the latter referred here as “perpendicular” NBI). With the usual B_T polarity the beams are injected in the direction of the plasma current, whereas with B_T reversed NBI is in the direction counter to I_p, as illustrated in Fig.1. Sawtooth observations in the reversed and the usual B_T machine configuration were compared in dedicated experiments in L-mode plasmas with matched B_T, and I_p. The shape was also carefully matched owing to an outward displacement of the trapped ions’ banana orbits, large wall clearance was required for the reversed B_T operation. In addition the effects of perpendicular vs. tangential neutral injection were investigated. Results from these dedicated sawtooth experiments (section 2) as well as from a wider database (section 3), including many plasma configurations, confirmed the earlier JET observations [5] that the sawtooth period, τ_{ST}, was reduced with reversed B_T and I_p (Fig.2). Sawteeth were more unstable with counter-NBI with both perpendicular and tangential NBI, with the shortest sawtooth periods about 1/3 of Ohmic sawtooth periods.

2 . THE EFFECT OF ROTATION ON THE SAWTOOTH PERIOD

In order to study the effect of rotation on sawtooth stability, a power scan at constant density was performed in co and counter rotating plasmas. For this study, neutral beam injection was mainly in the perpendicular direction. Controlled conditions at each power level were maintained for two seconds to allow for the sawtooth repetition rate to reach a steady-state. The sawtooth period dependence on heating power was found to be very different when co- and counter-NBI plasmas were compared (Figs.3 and 4(a)). With co-NBI the sawtooth period increased with power. With counter-NBI the average sawtooth period reached a minimum, τ_{ST}^{NBI}~ 27ms, at a NBI power P_{NBI}~4MW (Fig.3). For NBI powers up to 7MW sawtooth periods were smaller than typical Ohmic heating sawtooth periods (τ_{ST}^{Ohm} ~70~80ms). This striking difference in sawtooth behaviour for the same NBI power is illustrated in Fig.2 (for pulses where P_{NBI} was ramped up and subsequently ramped down) and in Fig.3 (pulses with constant P_{NBI} used in the power scan.)

A similar dependence of the sawtooth period on the core plasma rotation velocity, obtained from charge exchange measurements [8], was observed (Fig.4(b)). With the usual B_T and Ip the sawtooth period increased with plasma rotation, whereas with reversed B_T and Ip the sawtooth period decreased to a minimum at a toroidal rotation frequency of f_{rot} ~ 2kHz. With counter-NBI the toroidal rotation speed was lower than with co-NBI for similar NBI power (see Fig.5) and its direction was opposite with respect to I_p (although the same in the lab frame, see Fig.1).

A sawtooth study in TEXTOR [9] using co-injection has also found a minimum in the sawtooth period as a function of power (for P_{NBI}~0.2MW). Observations of sawtooth MHD precursors indicated that the minimum occurred when mode rotation was zero. In JET, the sawtooth precursor always rotated in the direction of the beam injection (as indicated in Fig. 1). For counter-NBI cases the observed frequency was on average 2-3kHz higher than the plasma rotation frequency. Within the experimental uncertainties one may conclude that the minimum sawtooth period corresponds to null mode frequency consistent with TEXTOR observations. The observations in both JET and TEXTOR indicate that plasma rotation may play an important role in the sawtooth stability.

The short sawtooth periods observed earlier in reversed B_T and I_p plasmas were attributed to changes in the q-profile due to neutral beam current drive (NBCD) [5]. It was reported that NBCD caused a slightly reversed q profile with $q_{min}<1$. However, EFIT equilibrium reconstruction constrained by MSE measurements indicated that in the present experiments the q-profiles are peaked. MSE measurements however were only available for pulses with power ramps, as in the example in Fig.2. Therefore, for the power scan pulses the modification in the core current density due to NBCD, j_{CD}, was calculated with the PENCIL code [10]. j_{CD} was larger with counter-injection and increased with the input power (see Fig.6). Since the NBI driven current is in the opposite direction to the plasma current, one may expect the radius of the q=1 surface to decrease with increasing NBI power. The sawtooth inversion radius (obtained from electron cyclotron emission) give an indication of the location of the q=1 surface. The observed sawtooth inversion radius, showed no variation with power. With BT reversed, rinv decreased to a minimum. This observation appears to be inconsistent with a q profile modified by NBCD, since r(q=1) would continue to decrease with power.

The stability of the m=1 internal kink mode, believed to be responsible for the trigger of the sawtooth crash, depends on the potential energy δW associated with kink displacements. This quantity can be split into core plasma and kinetic terms. One criterion for a sawtooth crash to occur is that δW falls below a critical value δW_{crit}. Crash criteria known as the “ITER sawtooth model” given in [11], integrated into the transport code PRETOR [12], have previously been used to model the sawtooth cycle of JET discharges [13]. The increasing sawtooth period with NBI power observed in the usual B_T configuration was found to be consistent with increasing stability from kinetic effects from fast beam ions [13]. For the power scan described here, PENCIL calculations show that the fast ions pressure increased with power for both the usual and the reversed B_T cases (Fig.6). The lack of correlation between the observed τ_{ST} and fast ion pressure in the counter-NBI case indicates that the contribution from the fast particle component cannot explain the observed τ_{ST} dependence on P_{NBI}. This is partly due to the poor penetration of beam ions into the core region with reverse B_T. In addition at low NBI power the kinetic effects associated with trapped thermal ions are typically more significant than those from fast ions.

Candidate mechanisms not involving a change in the current profile for explaining the reduced sawtooth period with reversed B_T and I_p include the destabilizing effect of toroidal rotation on the kinetic response of trapped thermal ions [14], and the destabilizing effect of counter circulating NBI ions [15]. The latter can be dismissed owing to the small orbit width of NBI ions in JET. The kinetic effects from trapped thermal ions described in ref. [16] are strongly stabilizing in conventional scenarios with large co-rotation. However, the effect of sheared flow on these kinetic effects modifies the stability threshold of the internal kink mode in such a way that the critical beta for instability is much lower for small or reversed toroidal rotation. With B_T and I_p reversed the observed plasma rotation in the core is reduced and reversed with respect to the characteristic frequencies ω_{*i} and $<\omega_{di}>$(where ω_{*i} is the ion diamagnetic frequency and $<\omega_{di}>$ the average ion precession frequency.) Kinetic effects from sheared counter rotation in a regime where the mode frequency $\omega \sim \omega_{*i} \sim <\omega_{di}>$ are shown to be destabilizing in reference [14]. Detailed modeling, which will appear elsewhere, will aim to satisfy the extent to which these effects are in agreement with Fig. 4b.

3. RESULTS FROM A LARGER DATABASE

In the dedicated sawtooth experiments described above, a direct comparison of sawtooth observations in the usual and reversed B_T configurations was only possible for L-mode and early H-mode phases (P_{NBI}<8MW). Although the power threshold for L-H transition was similar [16], the ELM characteristics were different. A higher type III - type I ELM threshold was found for reversed B_T

and I_p. The different pedestal conditions led to different core plasma parameters making the comparison of pulses with the same input power more difficult. In order to extend the comparison of sawtooth behavior to higher power H-mode plasmas, data from a wide variety of experiments for edge pedestal and ELM characterization [7] with NBI powers up to 14MW, have also been analyzed. Sawtooth periods obtained with reversed B_T and I_p were compared with the sawtooth scaling obtained for NBI heating with the usual B_T and I_p, using an existent JET sawtooth database [17]. A plot of the observed sawtooth periods versus the central electron temperature is shown in Fig.7. For the co-NBI cases the sawtooth period scales with $Te^{1.7}$. The comparison confirms that sawtooth periods are generally smaller with counter-NBI for similar central T_e. Thus tokamak operation with counter-NBI is an effective way to control the sawtooth period in H-mode as well as in L-mode plasmas.

CONCLUSIONS

In summary, sawtooth periods are reduced when JET is operated with reversed B_T and I_p, i.e. with counter-NBI. The shortest sawtooth periods were measured with reversed B_T and perpendicular counter-NBI. For P_{NBI}<7MW the sawtooh period is observed to be shorter than in Ohmic pulses. With co-NBI the sawtooth period increased monotonically with power. With counter-NBI the sawtooth period reduced to a minimum at 4MW. A similar trend was observed when comparing the sawtooth period with the toroidal plasma rotation, i. e. with co-NBI the sawtooth period increased with core plasma rotation and with counter-NBI it had a minimum at f_{rot}~2kHz. Modifications to the core q profile due to NBCD effects and fast particle stabilization effects are inconsistent with the experimental results. A mechanism consistent with the main features of the sawtooth period observations involves the dependence of the internal kink stability, including the kinetic effects of trapped thermal ions, on sheared plasma rotation [14].

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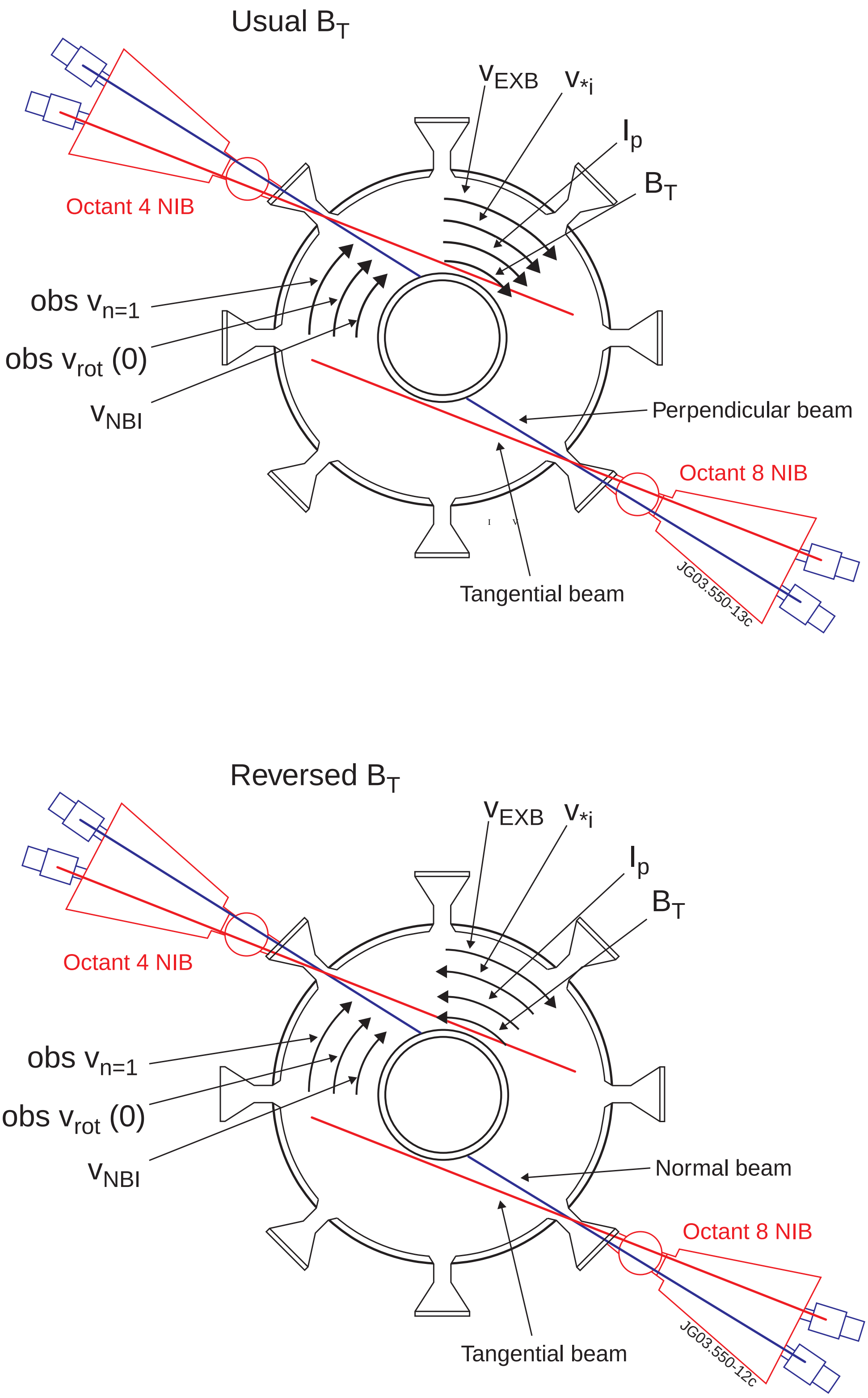

Figure 1: JET viewed from the top showing lines of NBI injection. Also indicated are directions of I_p, observed toroidal rotation at the plasma center from charge exchange measurements ($v_{rot}(0)$), toroidal rotation from NBI momentum (v_{NBI}), propagation of n=1 sawtooth precursor from magnetic pick-up coils mode analysis ($v_{n=1}$), toroidal projections of ion diamagnetic rotation (v_{*I}) and rotation from E×B drift (v_{EXB}).

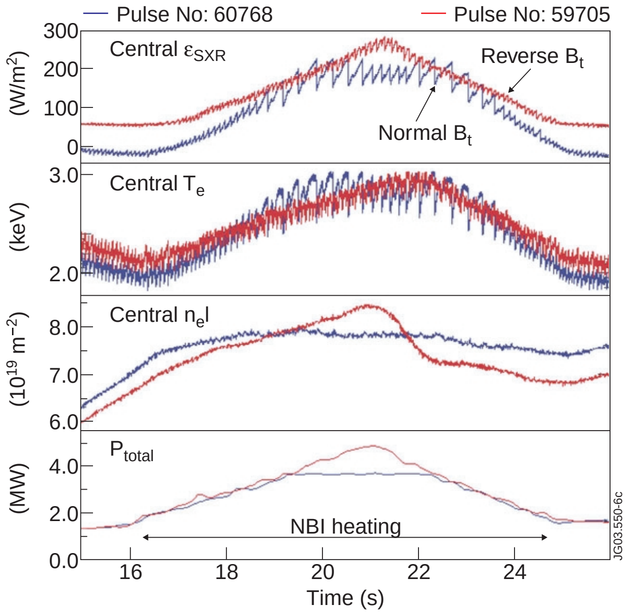

Figure 2: A pair of pulses with normal and reversed B_T polarities with matched shape (B_T=2.7T, I_p=2.5MA, q_{95}=3.6), using near-perpendicular NBI. Figure shows (a) SXR Brightness from a central line of sight (b) central electron temperature; (c) central density; (d) total heating power.

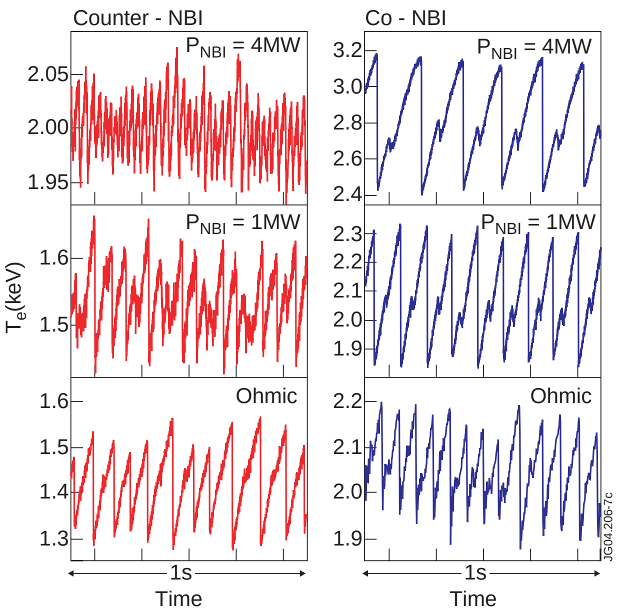

Figure 3: Central electron temperature traces showing sawtooth behavior for different input powers.

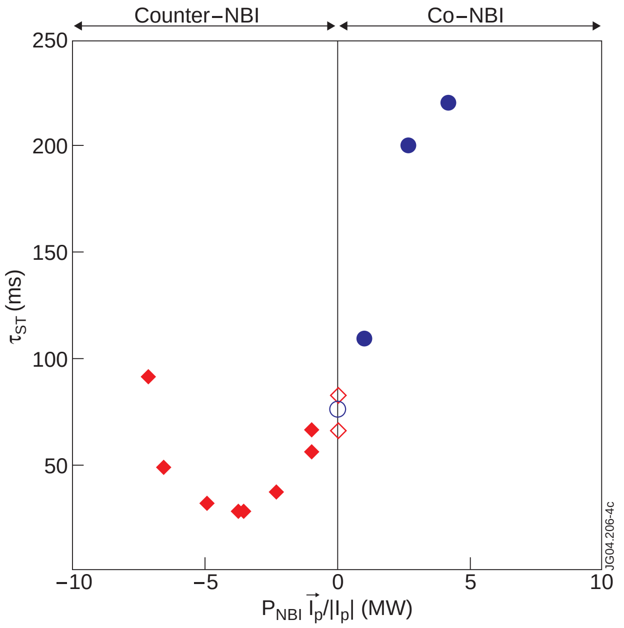

Figure 4 (a): Sawtooth period versus P_{NBI} from a power scan at constant density using mainly normal NBI (open symbols for Ohmic pulses).

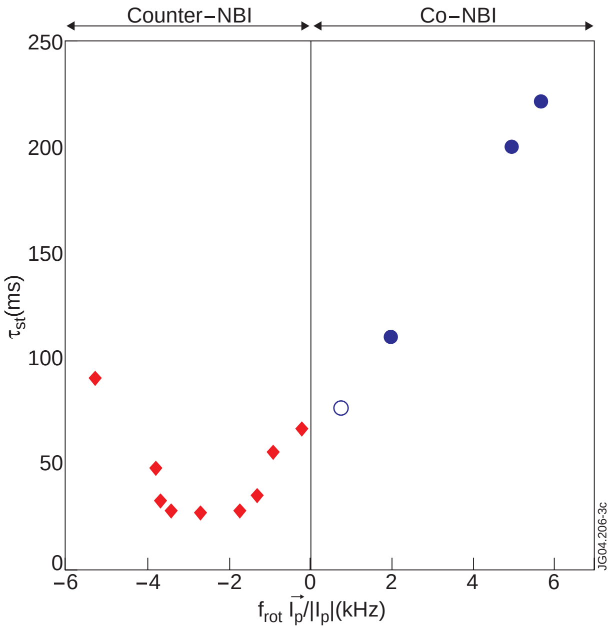

Figure 4(b): Sawtooth Period vs frequency of toroidal rotation measured at the sawtooth inversion radius. (Open symbol shows toroidal rotation frequency measured 100ms after 1MW of co-NBI in the usual B_T.)

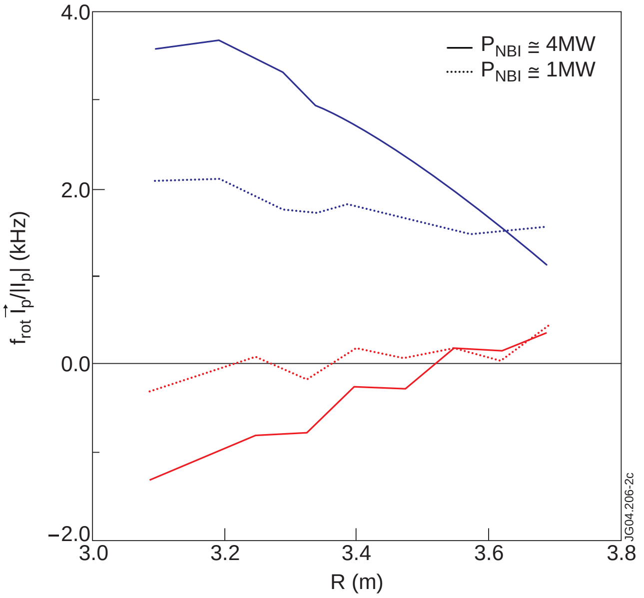

Figure 5: *Toroidal rotation frequency profiles from charge exchange measurements. (Pulses from power scan shown in Fig.4.* P_{NBI}*=4MW corresponds to min.* τ_{ST} *with counter-NBI.)*

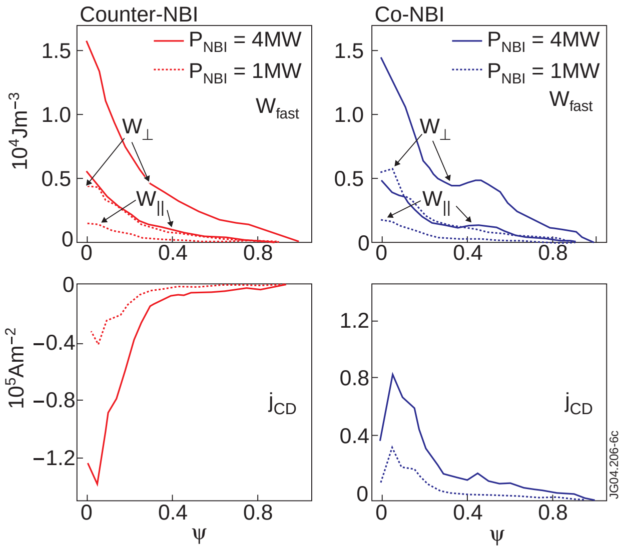

Figure 6: (a) and (b) Profiles of fast ion energy density $W_{//fast}$ *and* $W_{\perp fast}$ *calculated with the pencil code (finite orbit width effects neglected.), (c) and (d) Profiles of driven current density (*$j_{CD}/j_0 \leq 10\%$ *for co- and counter-NBI).*

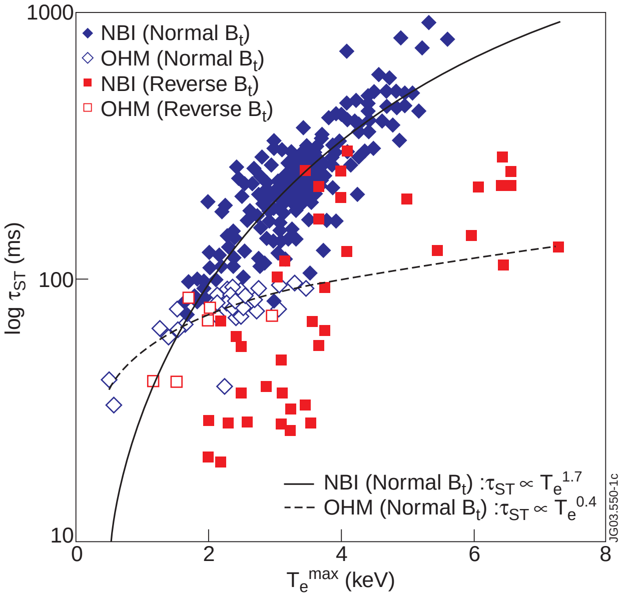

Figure 7: Sawtooth period versus maximum T_e *from a large sawtooth database (many configurations) comparing the usual* B_T *and* I_p *polarity (co-NBI) in blue and the reversed* B_T *and* I_p *(counter-NBI) in red. Open symbols are for Ohmic heating.*