*32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-2.062 (2005)*

Stabilisation of Sawteeth in MAST by Toroidal Rotation

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Introduction

The control of sawteeth is vital for plasma performance, especially in devices like ITER where the mixing radius is expected to be half the size of the minor radius. Here we consider the effect that toroidal rotation has on sawtooth stability. Toroidal rotation approaching the sound speed has been shown to stabilise the n=1, m=1 internal kink mode, eliminating sawteeth [1]. However, it is important to achieve a balance between the beneficial and deleterious effects of sawteeth. Reducing the sawtooth period, and thus amplitude, has been shown to delay the onset of neo-classical tearing modes, which cause confinement degradation [2]. Sawteeth can also help to prevent impurity accumulation in the core [3].

Experimental Results

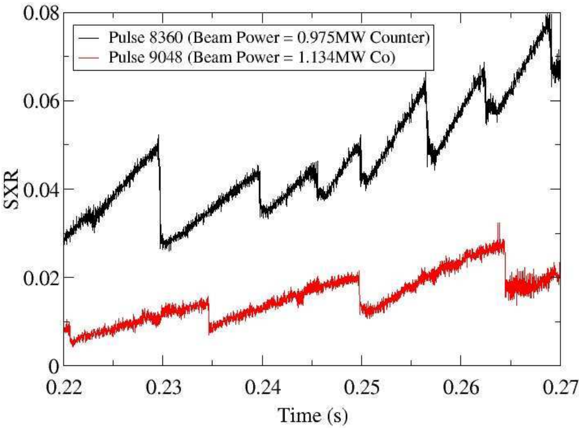

Fig 1: Soft X-ray traces showing significantly shorter sawtooth periods with counter-NBI than with co-NBI

Sawtooth behaviour has been compared in MAST plasmas with approximately matching magnetic field, flat-top current and shape. Figure 1 shows how the sawtooth period varies with beam direction. Results are consistent with previous results from JET [4] and TEXTOR [5]. The dependence of sawtooth period upon NBI heating power is very different in the co- and counter- regimes. It is found that as co-NBI power is increased the sawtooth period also increases. However, as counter-NBI power is increased, the sawtooth period first decreases to a minimum then subsequently lengthens (see Fig 2). Indeed, with counter-NBI shorter sawtooth periods can be achieved than with purely ohmic heating. It is expected that the toroidal velocity will increase monotonically with beam power. As such, these observations indicate that core toroidal rotation has a stabilising effect upon sawteeth and so plasmas with low rotation will be more susceptible to n=1 m=1 internal kink modes. The minimum in sawtooth period occurs when approximately 0.7MW counter-NBI is applied in MAST for $I_p \sim 470$kA, $B_t \sim 0.5$T, $n_e \sim 1.6\times10^{20}$m^{-3}. The reason for this is that the counter-NBI causes toroidal rotation which opposes the characteristic ion diamagnetic rotation. In a purely ohmic plasma in MAST, the sawtooth MHD precursor mode rotates in the same direction as the plasma current (ω_{*i} direction). This means that the momentum input from the counter-NBI stops the MHD rotation, which is approximately given by the sum of the ion diamagnetic frequency and the rotation frequency. At this point, the sawtooth period is minimised. The experimental data indicates that the minimum of sawtooth period is at a similar NBI-power to that at which the sawtooth precursor has null frequency (see Fig 3). This is consistent with the observations on JET and TEXTOR, within experimental uncertainty.

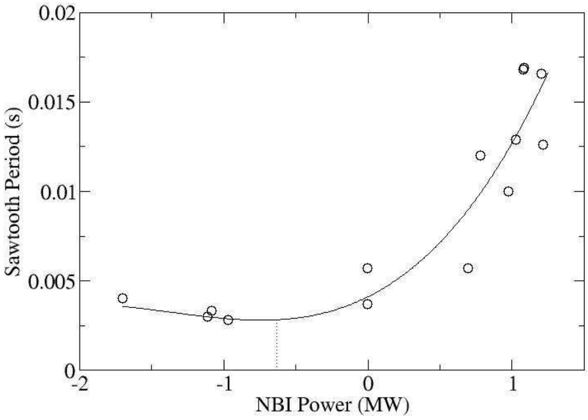

Fig 2: Sawtooth period for MAST discharges as a function of NBI power. $I_p \in [455,555]$kA, $B_t \in [0.45,0.55]$T, $n_e \in [1.3,1.8]\times 10^{20} m^{-3}$. Negative NBI Power represents counter-NBI

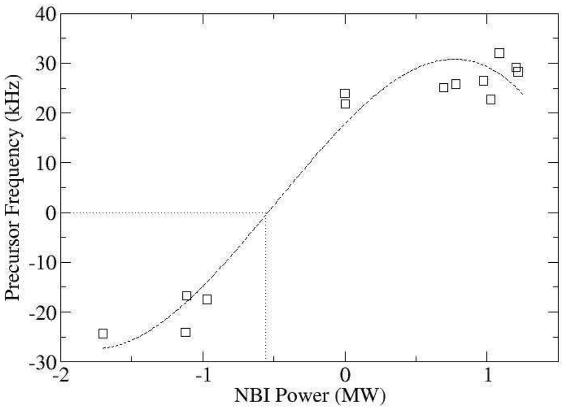

Fig 3: Sawtooth precursor frequency as a function of NBI power. Negative frequencies indicate the mode is rotating in the opposite direction

Charge exchange measurements also indicate that the core rotation is low at the minimum of sawtooth period. This is consistent with models for the internal kink instability, which predict increased instability in regimes of low sheared rotation [6].

It should be noted that in these discharges, the variation in heating power could result in stabilisation due to changes in the plasma beta. However, in the JET experiment, the sum of the injected power was kept constant whilst a mixture of co- and counter- beams and ICRH allowed for a power scan at constant total injected power. The results produced the same qualitative result that the sawtooth period reaches a minimum at a level of power input in the direction that opposes the characteristic ion diamagnetic mode rotation.

Modelling the effect of toroidal rotation on the internal kink mode

The MISHKA-DRIFT code [7] has been used to investigate the stability of the internal kink mode with respect to variations in the toroidal velocity. The MISHKA-DRIFT code was developed as an extension of the ideal magnetohydrodynamic code MISHKA-1 to investigate the finite gyroradius stabilising effect of ion diamagnetic drift frequency and toroidal rotation on MHD eigenmodes in tokamaks. The projection of the equation of motion of the plasma parallel to the equilibrium magnetic field is not considered in MISHKA-DRIFT since the effects of the perpendicular projections are dominant. The plasma motion due to the cross-field velocity is assumed to be incompressible.

MISHKA-DRIFT uses an equilibrium generated by HELENA, a code which solves the MHD equilibrium equation for a toroidal axisymmetric plasma. Thomson scattering and spectroscopy measurements were used to create the pressure profile and poloidal current profile and their derivatives for shot 8360 (a shot with counter-NBI near the point of minimum sawtooth period). The plasma β was increased until an ideally unstable n=1 internal kink mode was found (see Fig 4). Here we assume zero ion diamagnetism and toroidal rotation. The value of q on axis is 0.87.

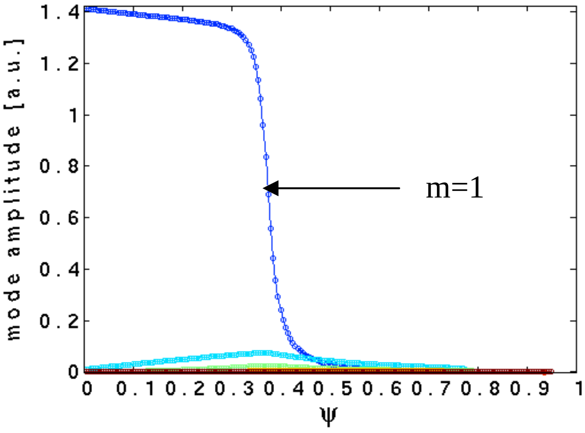

Fig 4: Radial profile of $\xi.\nabla\psi / |\nabla\psi|$ for n=1 internal kink

It is important to note that HELENA

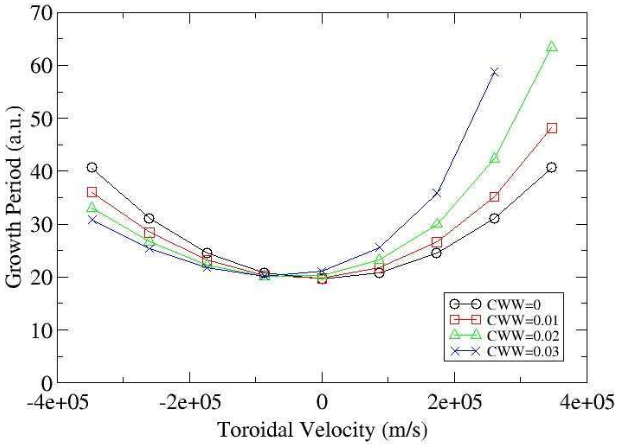

Fig 5: The growth period of the internal kink mode with respect to the toroidal velocity of the plasma at fixed β and varying ion diamagnetic frequencies, which are represented by the parameter CWW such that:

$$CWW = 1/\omega_{Bi}^{(0)}\tau_A^{(0)} \quad where \quad \tau_A = R_0/V_A(0)$$

solves the static Grad-Shafranov equation. The effect of the toroidal rotation is only considered in the stability analysis and not in the construction of the equilibrium.

MISHKA-DRIFT uses a linearly varying rotation profile, which is the best estimate of the rotation profile in MAST using charge exchange data. Different profiles were also tested and it was found that the stability of the internal kink mode was not strongly sensitive to rotation profile shape. Scans of the toroidal velocity were performed at a range of ion diamagnetic frequencies to see how the stability of the kink mode depended upon the rotation and to test the hypothesis that the characteristic frequency of the plasma determined the minimum sawtooth period (see Fig 5). It was found that the internal kink mode was strongly stabilised by rotation, and could be completely stabilised by toroidal velocities approaching the sound speed. It was also shown that as the ion diamagnetic frequency increased, the minimum of growth period of the mode occurred at higher toroidal velocity. Since the ion diamagnetism was in the co-NBI direction, the toroidal rotation required to achieve this maximum stabilisation of the mode at finite diamagnetism was in the counter-current direction. When modelled at the same ion diamagnetic frequency as measured experimentally at the time of the sawtooth, it is found that the minimum in the growth period occurs at approximately the same toroidal velocity that minimised the sawtooth period experimentally (see Fig 6). Similarly the frequency of the internal kink mode changes sign in the same way that the sawtooth precursor MHD modes did. In MISHKA-DRIFT the perturbation grows exponentially in time, so the imaginary part of the eigenvalue is a pseudo-frequency which is analogous to the frequency of the precursor mode. This strong correlation between the results indicates that the sawtooth behaviour is largely due to the toroidal rotation of the plasma.

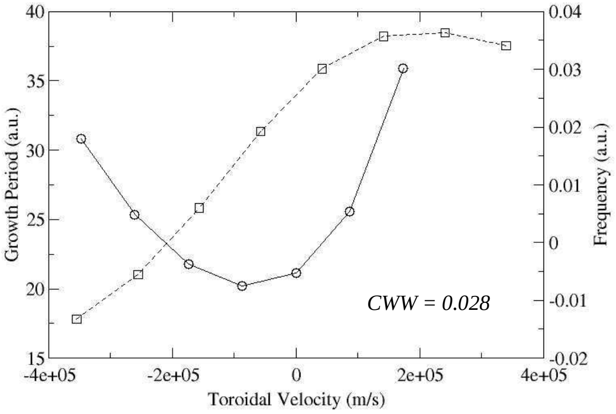

Fig 6: The growth period of the n=1 internal kink mode at the experimental diamagnetic frequency (circles – solid line) and the frequency of the mode (squares – dashed line) as a function of toroidal velocity

Analysis

Assuming that the toroidal velocity is of the order of the ion diamagnetic frequency, $v_\phi \sim \omega_{*i}$, and that the equilibrium thermal ion distribution is Maxwellian, it is possible to show that the internal kink dispersion relation is given by:

$$\left.\frac{\gamma_I}{\omega_A}\frac{s\sqrt{1+\Delta}}{3\pi}\frac{1}{\varepsilon^2}\right|_{r1} = -\delta\hat{W}$$

where the magnetic shear is given by $s=rq'/q$, $\omega_A=v_A/R_0$ and v_A is the Alfven velocity, $\varepsilon=r/R_0$, $\delta W=\delta\hat{W}.6\pi 2\xi_0^2 R_0 B_0^2 \varepsilon_1^4/\mu_0$, $\gamma_I^2=-\omega\,(\omega-\omega_{*i})|_{r1}$ and $\Delta=2q^2$ [6]. This can be evaluated in the absence of a radial electric field by transforming to a frame moving with the toroidal rotation at the resonant surface, i.e. $\omega \rightarrow \omega - \Omega_\phi$, so that

$$\gamma_I^2 = -\left(\omega-\Omega_\phi\right)\left(\omega-\omega_{*i}-\Omega_\phi\right)\Big|_{r1}$$

This elucidates the dependence of the growth period of the mode upon the ion diamagnetic frequency. It is evident that when the Doppler shifted eigenfrequency balances the diamagnetic frequency, the real part of the growth rate of the internal kink mode will be maximised. Another interpretation is that when the toroidal rotation balances the intrinsic MHD rotation (given by the sum of the ohmic plasma rotation and the diamagnetic effects) the growth period will be minimised, just as the period of sawteeth on MAST was minimised when the toroidal rotation countered the MHD rotation.

Conclusions

Previous JET and TEXTOR results regarding sawtooth period have been confirmed on MAST. The sawtooth period increases with co-NBI power. However, with increasing counter-NBI power, the sawtooth period first decreases to a minimum at 0.7MW before increasing. The sawtooth precursor mode changes direction at this beam power.

Modelling with MISHKA-DRIFT has replicated these experimental results. It has been shown that the growth period of the internal kink mode is minimised with toroidal rotation in the counter-current direction. There is good correlation between the minimum in sawtooth period and the maximum growth rate of the kink mode. The ion diamagnetic frequency determines the toroidal velocity at which the growth period of the internal kink mode is minimised.

The dispersion relation for the internal kink mode indicates that when the toroidal rotation is in balance with the MHD rotation, the growth rate will reach its maximum.

It is important to be able to control sawtooth stability to improve plasma performance. Since decreasing the period of sawteeth is known to delay the onset of NTMs, these results suggest that this could be achieved by keeping the toroidal rotation of the plasma low.

In future work the approximations in MISHKA-DRIFT are being relaxed with the development of a new code, MISHKA-FLOW, which models the perturbed vector potential in the toroidal direction rigorously, since in general this is non-zero in the presence of toroidal plasma rotation. MISHKA-FLOW incorporates a full treatment of Ohm’s Law projected both perpendicular and parallel to the equilibrium magnetic field.

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This work was funded jointly by the United Kingdom Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission.