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ABSTRACT

The control of sawteeth is likely to be of critical importance for baseline scenario operation of burning plasmas as large amplitude sawteeth have been shown to result in the triggering of neoclassical tearing modes, which in turn can significantly degrade confinement. The stabilising effects of alpha particles in burning plasmas are likely to exacerbate this, so recent experiments have identified various methods for amelioration. For example, counter neutral beam injection (NBI) operation demonstrates that shorter sawtooth periods than those in Ohmically heated plasmas can be achieved in JET, MAST and TEXTOR. It is found that whilst the energetic trapped particles are always stabilising, passing particles can be destabilising. Furthermore, the effects of sheared toroidal flow are found to cause both a change to the electric potential experienced by the particles and alter the frequency of the particles in resonance with the mode, which results in a significant change in the stabilising effect of the trapped particles, in agreement with analytic theory.

INTRODUCTION

Magnetohydrodynamic (MHD) stability of plasmas is a critical issue for baseline scenario operation of the International Thermonuclear Experimental Reactor (ITER). Based on experimental evidence, it is thought that the fusion-born α particles will lead to large amplitude sawteeth [1, 2], which have been shown to result in the triggering of other instabilities called neoclassical tearing modes (NTMs) [3], which can have deleterious ramifications for plasma confinement. As such, recent experiments have identified various methods for the control of sawteeth in order to avoid seeding NTMs whilst retaining the benefits of small, frequent sawtooth crashes, such as the prevention of core impurity accumulation [4]. One such experimental technique is to apply neutral beam injection (NBI) heating in the opposite direction to the plasma current. This has been shown to result in shorter sawtooth periods than those in Ohmically heated (or co-NBI heated) plasmas in the Joint European Torus (JET) [5], the Mega Ampère Spherical Tokamak (MAST) [6] and the Tokamak Experiment for Technology Oriented Research (TEXTOR) [7]. Furthermore, each experiment exhibits an asymmetry of sawtooth period with respect to NBI direction. This paper reports on modelling of the stability of the plasma with respect to the $n/m = 1/1$ internal kink mode – which is generally accepted to be related to sawtooth oscillations [8] – in the presence of NBI fast ions.

The trigger condition for a sawtooth collapse is believed to be associated with the linear stability threshold for a reconnecting 1/1 mode. Although this differs from the threshold for ideal MHD instability, it nevertheless depends strongly on the magnitude of the ideal potential energy, $\delta W = \delta W_{thermal} + \delta W_{hot}$. It has been proposed [1] that – provided the magnetic shear at $q = 1$, s_1, exceeds a critical value – reconnection is triggered when $c\rho r_1 > \delta W$, where c is a normalisation coefficient, r_1 is the radial position at which $q = 1$ and ρ is the ion Larmor radius. In Reference [1], a $1\frac{1}{2}$D transport code was used to study the time evolution of $s_1(t)$, $r_1(t)$ and $\delta W(t)$ in order to determine when the trigger inequality is satisfied. Typically, the ideal potential energy $\delta W(t)$ is positive (ideal stable) and reaches a quasi-stationary value on a relatively short time scale (the reheating timescale for δW_{th}, and the energy deposition timescale for δW_h), while $s_1(t)$ and $r_1(t)$ evolve on a slower timescale, determined by core resistive diffusion. Assuming that the trigger criterion can be represented by a linear time dependence for $r_1(t) \approx \hat{r_1} t/\tau_\eta$, with τ_η a measure of the resistive diffusion time, and a quasi-stationary value of $\delta W(t)$, then the sawtooth period, τ_s, can be represented in the form $\tau_s/\tau_\eta \sim (\delta W_{th} + \delta W_h)/c\hat{r_1}$ with longer ramp times predicted when δW_h is larger, and shorter ramp times predicted when δW_h is smaller. In what follows we assume that this applies so that the sawtooth period is roughly proportional to δW.

EXPERIMENTAL RESULTS

In JET, a power scan was performed at constant density in both the normal operating regime (co-NBI) and with toroidal field and plasma current reversed (counter-NBI) [5]. Sawtooth behaviour is compared in plasmas with I_p =2.5MA, B_T=2.7T, q_{95}=3.6 in Figure 1. Here we use the convention that negative beam power means injected in the counter-I_p direction, whereas positive power is injected in the same direction as the plasma current. It is found that as the co-NBI is increased the sawtooth period also increases. Conversely, as the counter-NBI is increased, the quiescent time between sawtooth crashes decreases to a minimum, $\tau_{st} \sim 27$ms significantly shorter than in Ohmic discharges, $\tau_{st}^{Ohmic} \sim 70 - 80$ms, before subsequently lengthening at high counter-NBI powers. The sawtooth period is minimised when there is approximately 3.5MW of counter-NBI, and for up to 7MW the sawtooth periods are smaller than in Ohmic plasmas.

Similar results have been obtained in MAST [6]. Sawtooth behaviour is compared in MAST plasmas with approximately matching flat-top current, magnetic fields and plasma shapes. Since MAST is a tight aspect-ratio spherical tokamak with low moment of inertia and high injected beam power, the rotation speeds are significantly higher than in previous JET results [5]. Figure 2 shows the sawtooth period from a collection of shots which conform to the following parameter ranges: $I_p \in [680, 740]$kA, $B_T \in [0.35, 0.45]$T and $n_e \in [1.6, 2.2] \times 10^{20}\mathrm{m}^{-3}$. It is evident that for counter-NBI powers up to 1.5MW the sawtooth period is comparable to, or shorter than, typical Ohmic heating sawtooth periods ($\tau_{ST}^{Ohmic} \sim 10 - 15$ms). In MAST, the asymmetric stabilisation of sawteeth has been explained in terms of the direction of strong toroidal flows relative to the ion diamagnetic drift. [6]. Whilst fast particles do have a stabilising influence upon sawteeth in spherical tokamaks, they cannot explain the experimentally observed minimum in sawtooth period. However, in larger aspect ratio devices, where the toroidal rotation is smaller, the sawtooth behaviour can only be explained by the effects of the fast ions.

THE EFFECTS OF ENERGETIC IONS FROM NBI AND MODELLING USING THE HAGIS CODE

In order to study the effects of anisotropic fast particles on the internal kink mode we use the HAGIS code [9]. HAGIS solves the Hamiltonian equations describing the guiding centre motion of ions in realistic toroidal geometry. The code has been extended to calculate the contribution of the fast beam ions to the potential energy of the internal kink mode, δW_h. The code now also includes the effects of the equilibrium flow shear, which modifies the toroidal precession frequency of the particle orbits as well as the electric potential experienced by the beam ions, $\phi_{\rm f} = rB_0 v_\zeta/q$ where $\phi_{\rm f}$ is the electric potential due to the plasma flow, v_ζ is the toroidal rotation velocity, r is the minor radius, B_0 is the equilibrium magnetic field. The eigenmode structure is computed by the MHD stability analysis code, MISHKA-F [10], which includes the effects of flows and ion diamagnetic drifts in toroidal geometry. HAGIS subsequently employs a perturbative approach to find the kinetic effects on the stability of the mode, which is justified since $\beta_{hot} \sim 0.2\beta_{bulk}$ ($\beta = 2\mu_0 p/B^2$) and it is appropriate to assume that the kinetic modification of δW does not alter the form of the perturbation, ξ. HAGIS treats the effects of finite orbits on the adiabatic response to the internal kink mode, as well as the effect of pressure anisotropy on δW_h, which have been neglected in other hybrid kinetic-MHD codes [17]. The kinetic effects of thermal ions at finite rotation have not been considered since this was examined in Reference [11].

The fast ion distribution function is separated into an equilibrium component, $f_0(\mathcal{E}^0, \mathcal{P}_\zeta^0, \mu)$, and two perturbed components, $\delta f_h = \delta f_{hk} + \delta f_{hf}$, a non-adiabatic (kinetic) and an adiabatic (fluid) part respectively. Here, the particle energy ($\mathcal{E}^0 = mv^2/2$), the canonical momentum ($\mathcal{P}_\zeta^0 = B_\zeta m v_\parallel/B - e\psi_p$) and the magnetic moment ($\mu = mv_\perp^2/2B$) are the unperturbed constants of motion, where ζ is the toroidal angle, m is the particle mass, v is the particle velocity, ψ_p is the poloidal flux, e is the fast ion charge and "$\|$" and "$\perp$" mean components parallel and perpendicular to the magnetic field respectively. Analytic theory developed for large aspect ratio circular plasmas [12] implies that these contributions to the perturbed distribution function can be expressed as

$$\delta f_{hk} \sim \sum_{l=-\infty}^{\infty} \frac{\tilde{\omega} - \Delta\Omega - n\omega_{*h}}{\tilde{\omega} - \Delta\Omega - n\langle\dot{\zeta}\rangle + l\omega_b} \frac{\partial f_h}{\partial \mathcal{E}^0} e^{-i(\omega + l\omega_b + n\langle\zeta\rangle)t} \tag{1}$$

and $\delta f_{hf} \sim \xi \cdot \nabla\psi_p \partial f_h/\partial\mathcal{P}_\zeta^0$ where $\omega_{*h} = \partial f_h/\partial\mathcal{P}_\zeta^0 (\partial f_h/\partial\mathcal{E}^0)^{-1}$ is the hot ion diamagnetic frequency, $\Delta\Omega = \Omega_E(r) - \Omega_E(r_1)$ is the sheared toroidal plasma rotation, $\tilde{\omega}$ is the Doppler shifted mode frequency, $\omega_b = 2\pi/\tau_b$ and τ_b is the poloidal orbit transit time. In HAGIS the adiabatic [13] and non-adiabatic components of the perturbed distribution function are: $\delta f_{hf} = \alpha g \partial f_0/\partial\mathcal{P}_\zeta^0 + \phi\partial f_0/\partial\mathcal{E}^0$ and $\delta\dot{f}_{hk} = -\dot{\mathcal{P}}_\zeta \partial f_0/\partial\mathcal{P}_\zeta^0 - \dot{\mathcal{E}}\partial f_0/\partial\mathcal{E}^0$ respectively, where the covariant ζ component of the magnetic field, $B_\zeta = g(\psi)$, $\mathcal{E}$ is the energy and the vector potential is given by $\mathbf{A} = \alpha\mathbf{B}_0$. Given δf, the hot particle contribution to the potential energy of the $n = 1$ internal kink mode is then calculated as [14, 1, 15]

$$\delta W_h = \frac{1}{2}\int \mathrm{d}\Gamma (mv_\parallel^2 + \mu B)\delta f_h \sum_m \kappa \cdot \xi^{(m)*}(r,t) e^{-i(n\zeta - m\theta)} \tag{2}$$

where θ is the poloidal angle, $\kappa = \mathbf{b} \cdot \nabla \mathbf{b}$ is the magnetic curvature vector and $\mathbf{b} = \mathbf{B}/B$. The displacement, ξ, is expressed in terms of the electric potential, ϕ_*, as $\xi = \mathbf{b} \times \nabla \phi_*$. Using this defintion of the displacement, Equation (2) can be simplified by using the identity $\mathbf{b} \cdot \nabla \mathbf{b} = (\nabla \times \mathbf{b}) \times \mathbf{b}$ such that $\kappa \cdot \xi^* = (\nabla \times \mathbf{b}) \cdot \nabla_\perp \phi_*$. The HAGIS calculation of δW_h has been used to reformulate the problem of finding the growth rate and frequency of another plasma instability which is driven by the population of energetic particles – the Toroidal Alfvèn Eigenmode. The result produced by calculating δW and then solving the dispersion relation [16] coincides perfectly with that obtained from the Lagrangian formulation, which acts as a benchmarking exercise for the δW_h calculation in the code.

Previous modelling has concentrated primarily on the effects of the trapped fast particles [17]. However, the neutral beam heating in JET gives rise to a predominantly passing population. Recent analytic theory [18, 19] has suggested that the co-passing energetic particles can stabilise the 1/1 internal kink mode whereas counter-passing fast ions can have a destabilising influence. Here, these effects are modelled in general tokamak geometry for the first time, and are found to be of paramount importance for analysing the asymmetric dependence of sawtooth stability with respect to the direction of the NBI. Wang *et al* [19] proposed that the non-adiabatic passing ion effects arose due to the gradient ∇f_h integrated *over* the $q = 1$ radius. In contrast, Graves [18] suggested that the non-adiabatic passing particle effects are counter-acted by an adiabatic contribution, but that an additional adiabatic contribution survives from the fast ions which *intersect* the $q = 1$ flux surface. This latter mechanism depends on $\partial f_h / \partial P_\zeta$ at $q = 1$ only and is more sensitive to localised heating. Figure 3 shows the passing particle contribution to δW_h for a non-symmetric fast ion distribution which is Maxwellian with respect to energy and Gaussian with respect to pitch angle. The distribution function is artificially taken to be zero outside a finite radius, indicated on the x-axis. It is evident that when no gradient exists in a region around $q = 1$ ($s \sim 0.3$) bounded by the orbit width, the passing ions do not contribute to the kink mode stability. The fact that unbalanced passing ions contribute only via a radial gradient in f_h close to $q = 1$ has important implications for sawtooth control in ITER using Negative NBI heating at varying deposition radii [18]. The strong contribution of the passing particles comes from ions close to the trapped-passing boundary where their orbit widths, Δ_b, are large, $\delta W_h \sim \Delta_b$.

The stabilisation of the passing fast ions is determined by a contribution to δW_h of the form $\delta W_h^p \sim -\int_0^{r_1} (\xi \cdot \nabla \langle P_h \rangle)(\xi \cdot \kappa) \mathrm{d}r$, where P_h is the hot particle pressure. First let us consider the case of on-axis co-NBI. When a co-passing beam ion is born inside the $q = 1$ surface it experiences a downward ∇B drift, which means that it stays within the $q = 1$ surface and never crosses it. The distribution function has a negative hot particle pressure gradient, $\nabla \langle P_h \rangle < 0$, so this particle will give a stabilising contribution when in the region of good curvature, but will be destabilising when in the region of adverse curvature on the outboard side. These two contributions tend to cancel, and the beam ions inside $q = 1$ (which make up the majority of on-axis NBI ions) do not affect the mode stability. However, the few ions which are born outisde $q = 1$ will only pass through the $q = 1$ surface in the region of good curvature due to the downward ∇B drift. As such, these will give a stabilising contribution to the kink mode (since elsewhere $\xi = 0$). This is illustrated in the cartoon in Figure 4. Intuitively the opposite is true for counter-passing ions which have an opposite ∇B drift upward from their flux surface; those born inside $q = 1$ will only contribute in the region of adverse curvature. Since they have a negative hot particle pressure gradient, this makes the contribution from counter-passing ions destabilising. This mechanism means that the $n/m = 1/1$ internal kink mode is stabilised by co-passing on-axis NBI ions or by counter-passing off-axis NBI ions, but is destabilised by counter-passing on-axis NBI ions or co-passing off-axis NBI ions.

MODELLING SAWTOOTH BEHAVIOUR IN JET NBI HEATED PLASMAS

In order to analyse the JET experimental results [5] concerning sawtooth stability, HAGIS has been used to calculate δW_h. Together with the contribution from MHD effects including toroidal flow, calculated using MISHKA-F, the stability of the kink mode for a range of beam powers can be evaluated. The JET discharge which has been analysed is shot 60998 (co-injected beams of 4.13MW, $I_p = 2.3$MA, $B_T = 2.5$T, $\bar{n}_e = 3.2 \times 10^{19}\mathrm{m}^{-3}$ and $v_\zeta \sim 45$km/s). The neutral beam current drive has been calculated [5] and found to be broadly deposited and less than 10% of the Ohmic current, meaning it is relatively insignificant in these discharges. The equilibria are reconstructed using the HELENA code [20], which takes as input the plasma shapes and q-profiles from EFIT [21] and the pressure profile obtained from the TRANSP Monte-Carlo transport code [22]. The position of the $q = 1$ surface is constrained by the inversion radius found from the Soft X-ray diagnostic. The pressure profile includes a contribution from the neutral beam fast particles, which are treated as isotropic at this stage.

The fast particle distribution function was obtained from TRANSP. The exact distribution function is retained, though it can be described approximately as a slowing down distribution with respect to energy and a Gaussian distribution with respect to pitch angle, centred around $\lambda = v_\parallel/v = 0.5$. The dependence of the distribution function upon energy and pitch angle is illustrated in Figure 5. By retaining the complete distribution function, the complicated dependence of the pitch angle distribution width upon the normalised poloidal flux and the particle energy is treated accurately. This is important since the degree of anisotropy of the fast particle distribution can significantly change the contribution of the trapped particles to δW_h.

The contribution to the stability of the $n = 1$ internal kink mode from each class of particles for a static plasma is shown in Figure 6. The potential energy is normalised in the same way as Reference [15] such that $\delta\hat{W}_h = \delta W_h \mu_0/(6\pi^2 R_0 \xi_0^2 \epsilon_1^4 B_0^2)$ where $\epsilon_1 = r_1/R_0$ and ξ_0 is the displacement at the magnetic axis. It can be seen that for the realistic beam distribution function employed in these simulations, the passing particles – which are often ignored in studies concerning energetic particles – are as important as the trapped particles. In accordance with analytic theory [18], the co-passing particles are strongly stabilising whereas the counter-passing particles give a destabilising contribution which nearly balances the strong stabilisation from the trapped population. Whilst only ideal stability is considered here, it has been shown [23] that including resistivity only slightly modifies the stability boundary and the instability drive is still from the asymmetric passing ions. The non-adiabatic trapped particles are always stabilising [1], and for the level of parallel anisotropy present in this distribution function, the adiabatic terms are only weakly stabilising. For perpendicular injection it may be expected that the adiabatic contribution would be significantly increased [15]. All contributions to δW_h scale linearly with respect to $\beta_{hot} \sim \mathrm{P_{NBI}}$. The contribution from the passing particles helps to explain the different sawtooth behaviour exhibited in JET when injecting the beam in different directions relative to the toroidal field, since the ∇B-drifts of the energetic particles determine whether they are stabilising or not. However, as explained below, only the inclusion of toroidal flow shear enables an understanding of the experimental minimum in sawtooth period.

The effect of toroidal flow shear is modelled by prescribing the experimental toroidal rotation profile measured by the Charge Exchange diagnostic. The co- and counter-NBI profiles are very similar and are approximately linearly sheared with respect to poloidal flux, ψ. Whilst the absolute values of the flows are only relatively small, there are strong toroidal flow *shears* present in JET, which can modify the stabilisation of the energetic ions [18]. The effect of sheared rotation on both $\Re(\delta W_h)$, which quantifies the stabilising effect of the fast ions, and $\Im(\delta W_h)$, is shown in Figure 7 and agrees well with Figure 6(b) of Reference [15].

Conservation of the third adiabatic invariant, Φ – which produces strong stabilisation from trapped fast particles [1] – is only obtained [18] when $\langle\omega_d\rangle + \Delta\Omega - \tilde{\omega} \gg 0$, where $\langle\omega_d\rangle$ is the bounce-averaged hot particle toroidal drift precession frequency. In tokamak plasmas Φ corresponds to the flux of the poloidal magnetic field through the area defined by the toroidal precession of the trapped particle orbit centres. The flux through these current loops is conserved as they expand or contract. If the fast particle pressure is peaked in the plasma core, and a kink mode causes the flux loop to contract, then the trapped fast particles are accelerated due to Φ conservation. As such, the internal energy of the particles is increased, which means that the particles take energy from the wave and so stabilise the kink mode. Since this condition is more readily satisfied for $\Delta\Omega > 0$, co-rotating plasmas with velocity shear support more effective stabilisation of the kink mode. Conversely, the stabilising effect is diminished in counter-rotating plasmas ($\Delta\Omega < 0$) since Φ-conservation is inhibited, and the stabilising contribution can only come from the fewer higher energy ions. At very large flows, Equation (1) tends to an asymptotic limit, as borne out in Figure 7, since $\Delta\Omega$ dominates both numerator and denominator in the expression for δW_{hk}. The plasma flow will only influence mode stability when $|\Delta\Omega| \sim \omega_{*i}$. As such it is the collisionless response of the low energy ions that is significantly modified by rotation. In ITER, the low rotation means that the condition for sheared flow to influence stability is unlikely to be met.

When the non-adiabatic effect of the trapped particles is modified by the sheared flow, the contribution to the stability of the internal kink mode changes significantly, as illustrated in Figure 8. For each power, the modelled toroidal flows are as measured experimentally by the Charge Exchange diagnostic. The mode frequency, $f = \omega_{*i} \sim 0.5$kHz is of the same order as the toroidal plasma rotation frequency. The minimum in mode stability occurs at approximately 3MW of counter-NBI power, in excellent agreement with the minimum in sawtooth period exhibited experimentally [5]. This minimum arises because (i) the flow shear in JET reduces the stabilising effect of the trapped ions injected counter-current, and (ii) the counter-passing ions provide a strongly destabilising contribution. In co-rotating plasmas the sheared flows amplify the stabilising contribution from the trapped ions, and the co-passing ions are also strongly stabilising.

ITER NEGATIVE NEUTRAL BEAM INJECTION

It has been proposed that sawtooth control in ITER will be achieved by Ion Cyclotron Current Drive (ICCD) [25] and Electron Cyclotron Current Drive (ECCD) [26]. However, the large alpha population is likely to significantly stabilise the sawteeth [1, 2], so increasing the magnetic shear alone may not be sufficient to cause a sawtooth crash. By using the off-axis co-passing Negative Neutral Beam Injected (NNBI) ions, the $n = 1$ internal kink mode may be sufficiently destabilised so that the sawtooth crash can be triggered using the current drive from resonance heating. The NNBI provides a mainly passing population of ions, and when the fast ions are aimed off-axis, the hot particle pressure gradient is positive, so the co-passing ions can give a destabilising contribution to δW_h, in accordance with Figure 4. Figure 9 shows the total δW_h – comprising the contribution from the alpha particles in the plasma core and the off-axis NNBI fast ions – with respect to the injected beam power. Here, an ITER equilibrium is used such that $r_1 \sim 0.2a$, $q_0 = 0.95$, $\beta_N = 1.9$ and $s_1 \sim 0.2$ and the NNBI fast particle distribution function is calculated using TRANSP [27]. It can be seen that at the maximum beam power planned for ITER [28], the kink mode is significantly destabilised by the passing ions. Further modelling of the current drive will be able to determine whether this destabilisation is sufficient to allow the ECCD to increase the local magnetic shear in order to trigger frequent small sawtooth crashes.

CONCLUSION

We have presented thorough modelling of JET discharges which exhibit asymmetric dependence of 1/1 mode stability upon the direction of neutral beam heating. The effects of anisotropy and flow shear have been included for both adiabatic and non-adiabatic trapped and passing fast particles. It is found that the passing ions, which represent the majority of energetic particles injected into JET through NBI heating, are strongly stabilising when injected in the same direction as the plasma current, but destabilising for counter-NBI. For co-NBI, the stabilising rôle of the non-adiabatic trapped ions is increased when flow shear is included. Conversely, for counter-NBI, the trapped particles are less stabilising. This means that the plasma is most unstable to $n = 1$ kink modes when heated with counter-current neutral beams, in accordance with the experimental data. The quantitative agreement of the modelling is sensitively dependent upon the distribution function and rotation profile, so the distribution function is taken from TRANSP modelling and the rotation profile is calculated using the charge exchange diagnostic. Furthermore, this model is applied to NNBI heating in ITER, where it is suggested that co-passing off-axis energetic ions can play an important rôle in destabilising the $n/m = 1/1$ internal kink mode, provided the inversion radius is sufficiently small that the fast ion population resultant from the neutral beam is peaked outside $q = 1$. It is predicted that the off-axis NNBI, perhaps with ancillary current drive, could be employed to trigger frequent small sawtooth crashes. By considering the effects of toroidal flow shear and pressure anisotropy, a complete model now exists which can accurately simulate $n = m = 1$ mode stability including kinetic effects in general toroidal geometry.

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REFERENCES

[1] PORCELLI F. *et al.*, *Plasma Phys. Control. Fusion* **38** (1996) 2163

[2] HU B *et al.*, *Phys. Plasmas* **13** (2006) 112505

[3] SAUTER O *et al.*, *Phys. Rev. Lett.* **88** (2002) 105001

[4] NAVE M *et al.*, *Nucl. Fusion* **43** (2003) 1204

[5] NAVE M *et al.*, *Phys. Plasmas* **13** (2006) 014503

[6] CHAPMAN IT *et al.*, *Nucl. Fusion* **46** (2006) 1009

[7] KOSLOWSKI HR *Fusion Sci. Technol.* **47** (2005) 260

[8] HASTIE RJ *et al.*, *Phys. Fluids* **30** (1987) 1756

[9] PINCHES SP *et al.*, *Comput. Phys. Commun.* **111** (1998) 133

[10] CHAPMAN IT *et al.*, *Phys. Plasmas* **13** (2006) 065211

[11] GRAVES JP *et al.*, *Plasma Phys. Control. Fusion* **42** (2000) 1049

[12] GRAVES JP, *Phys. Plasmas* **12** (2005) 090908

[13] CANDY J *et al.*, *Phys. Plasmas* **4** (1997) 2597

[14] BRIEZMAN B *et al.*, *Phys. Plasmas* **5** (1998) 2326

[15] GRAVES JP *et al.*, *Phys. Plasmas* **10** (2003) 1034

[16] ZONCA F and CHEN L, *Phys. Fluids B* **5** (1993) 3668

[17] ANGIONI C *et al.*, *Plasma Phys. Control. Fusion* **44** (2002) 205

[18] GRAVES JP, *Phys. Rev. Lett.* **92** (2004) 185003

[19] WANG S *et al.*, *Phys. Rev. Lett.* **88** (2002) 105004

[20] HUYSMANS GTA *et al.*, *in Proc. CP90 Conf. on Computational Physics Proc.* (World Scientic, 1991), p 371.

[21] LAO L *et al.*, *Nucl. Fusion* **30** (1990) 1035

[22] BUDNY RV *et al.*, *Nucl. Fusion* **32** (1992) 429

[23] KOLESNICHENKO Y *et al.*, *Phys. Plasmas* **12** (2005) 022501

[24] PORCELLI F, *Plasma Phys. Control. Fusion* **33** (1991) 1601

[25] ERIKSSON L-G *et al.*, *Nucl. Fusion* **46** (2006) S951

[26] MÜCK A *et al.*, *Plasma Phys. Control. Fusion* **47** (2005) 1633

[27] BUDNY RV, *Nucl. Fusion* **42** (2002) 1383

[28] AYMAR R *et al.*, *Nucl. Fusion* **41** (2001) 1301

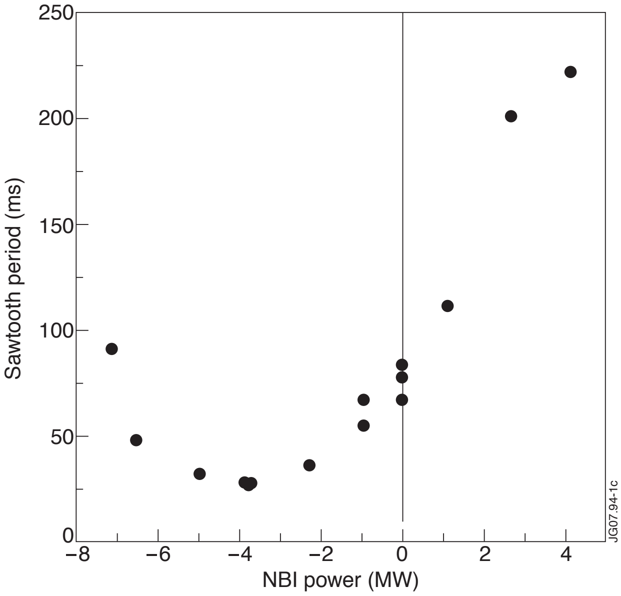

Figure 1: The sawtooth period in JET shown as a function of injected neutral beam power. A clear minimum in sawtooth period occurs when the plasma is heated with approximately 3.5MW of counter-current NBI. (Nave et al [5])

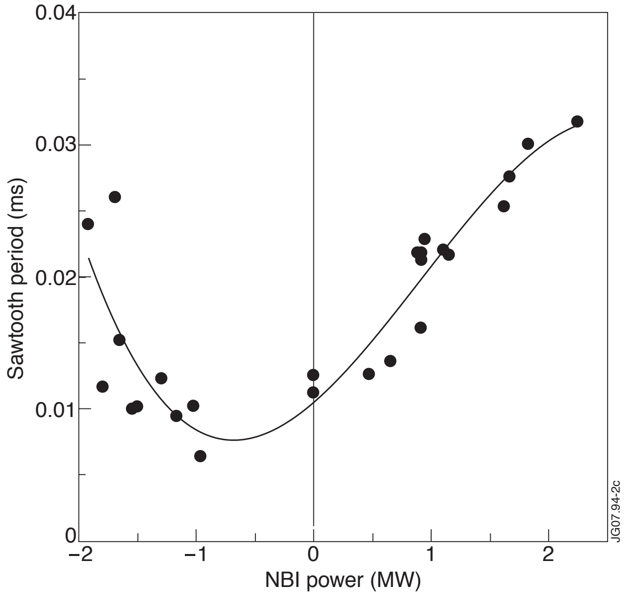

Figure 2: The sawtooth period in MAST shown as a function of NBI power. A minimum in sawtooth period occurs when the plasma is heated with 0.7MW of counter-NBI. (Chapman et al [6])

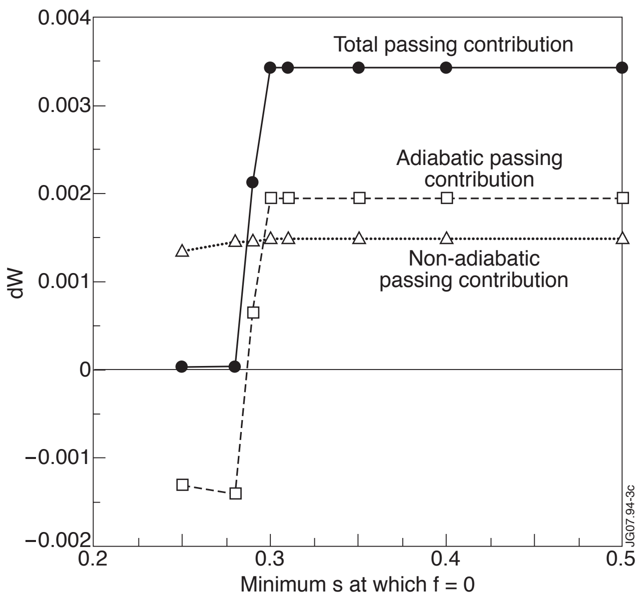

Figure 3: The contribution to δW_h *from passing ions for a hot ion distribution function nullified outside* $s = \sqrt{\psi}$ *.*

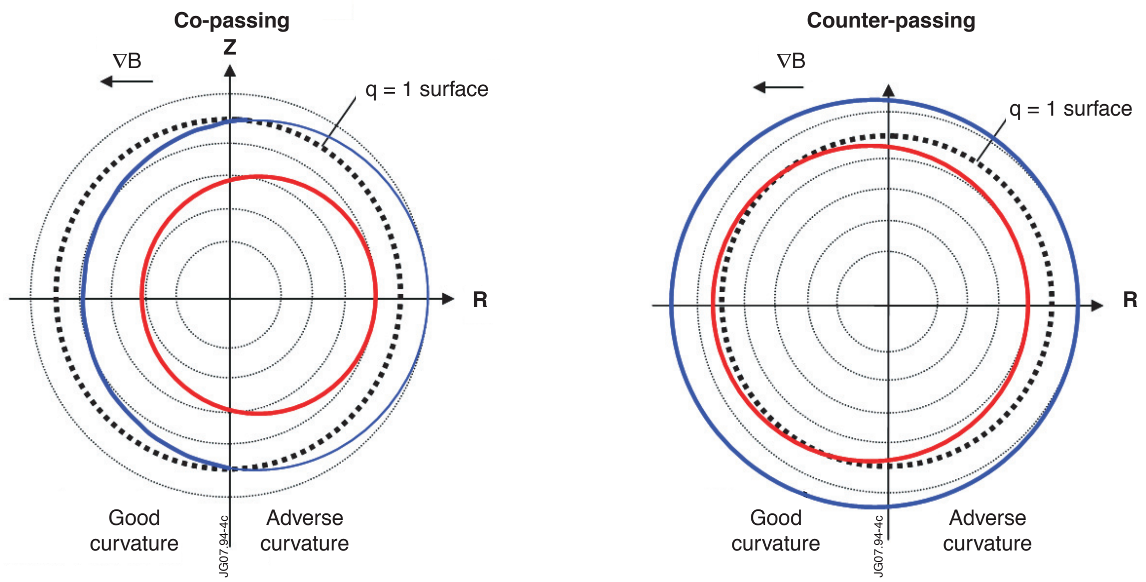

Figure 4: The co-passing ions experience a downwards ∇B-drift, which causes ions born inside the q = 1 surface to stay inside q = 1, and those born outside it, to only cross the q = 1 surface in the region of good curvature, which means that distributions with a fast ion pressure peaked inside q = 1 are stabilising, whereas those with a pressure peaked outside q = 1 are destabilising. The opposite is true of counter-passing ions.

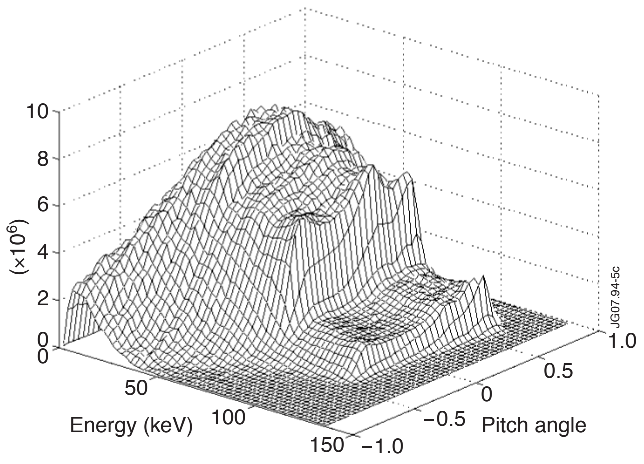

Figure 5: The fast particle distribution function as a function of particle energy and pitch angle, $\lambda = v_{||}/v$, at r a = 0.35, $\theta = 0$. The distribution function is approximately Gaussian with respect to λ for high energy particles, but approaches isotropy for low energy particles. The distribution function dependence upon λ is also biased in terms of radial location.

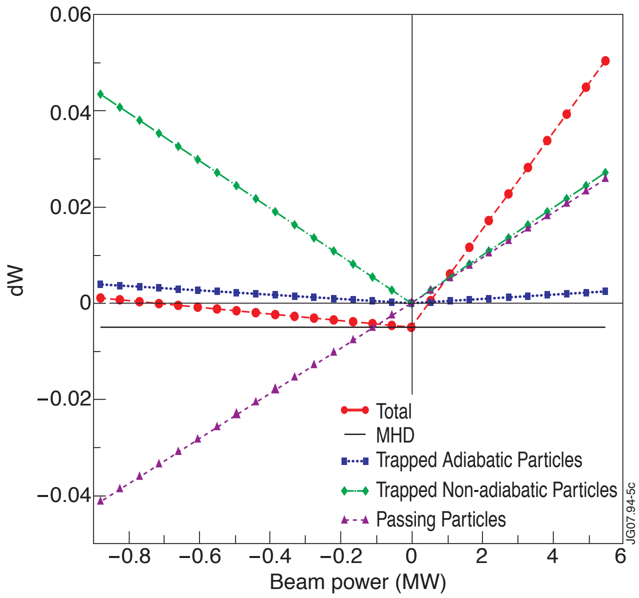

Figure 6: The contribution to δW from each energetic particle species with respect to injected beam power for a JET equilibrium (Pulse No: 60998) unstable to a 1/1 kink mode.

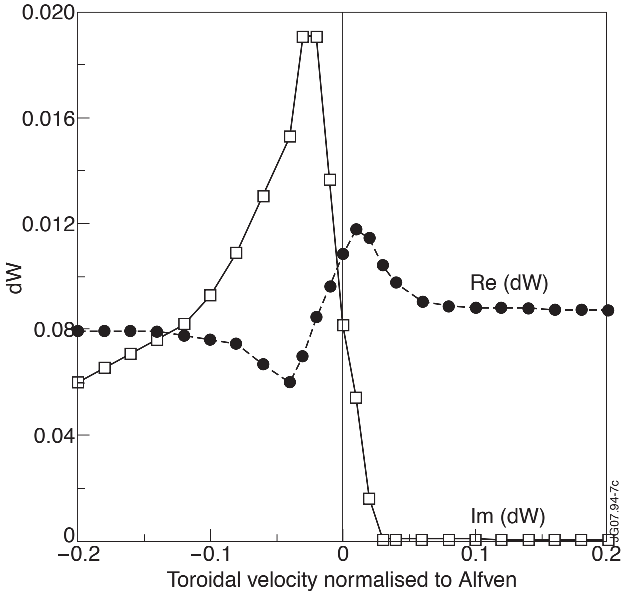

Figure 7: The contribution to Wh from non-adiabatic trapped particles for JET Pulse No: 59808 when there is a linearly sheared rotation profile with respect to radius.

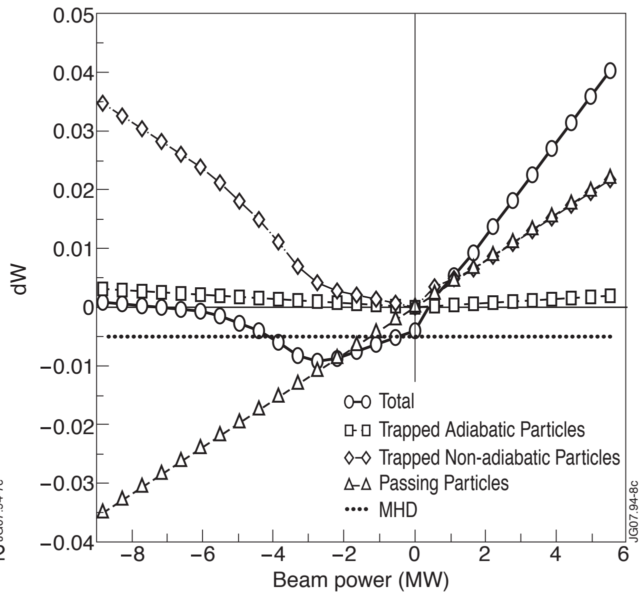

Figure 8: The contribution to δW from each energetic particle species with respect to injected beam power for a JET equilibrium (Pulse No: 60998) including flow shear effects.

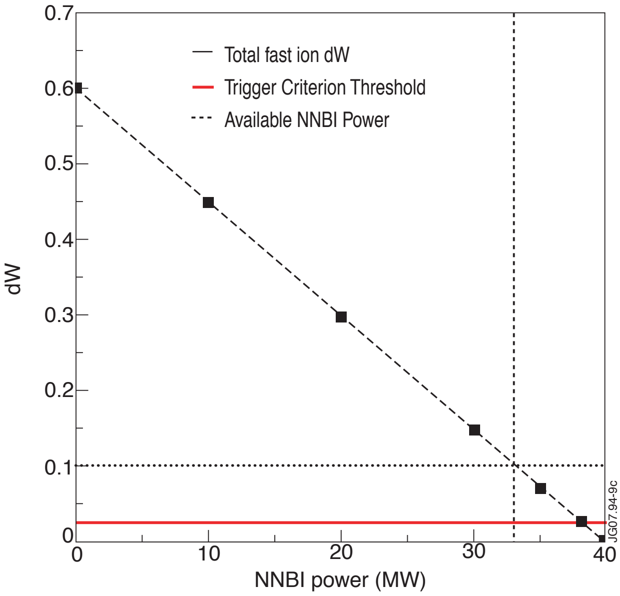

Figure 9: Total δW_h from the alpha particles and the NNBI fast ions combined as a function of injected beam power. At the power available in ITER, the kink mode is significantly destabilised by the off-axis co-passing fast ions, and the sawtooth may be triggered by electron cyclotoron current drive.