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Sawtooth control mechanism using counter current propagating ICRH in JET

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Abstract

The sawtooth control mechanism in plasmas employing off-axis ICCD is reinvestigated. In particular, for counter propagating waves on the high field side, asymmetrically distributed energetic passing ions destabilise the ideal internal kink mode when the q=1 surface resides within a narrow region centred about the shifted fundamental cyclotron resonance.

Whilst fast trapped ions are known to stabilise sawteeth, this paper demonstrates that under certain conditions, energetic ions can also effectively destabilise sawteeth. Sawtooth control from energetic ions injected with near tangential unbalanced neutral beams has already been demonstrated analytically [1] and numerically [2]. It was found that when the pressure at the q=1 surface associated with passing ions propagating counter to the plasma currents differs from the pressure associated with the co-passing ions, there is a markable effect on the internal kink mode stability, which in turn is thought to determine sawtooth stability. In this paper it is shown that JET plasmas with counter propagating off-axis ICRH could share the same destabilisation mechanism as the unbalanced NBI scenarios mentioned above. It is now possible to write the internal kink mode stability criteria in terms of the fast ion current profile in the absence of the bulk plasma drag current.

We will concentrate on the key features of the minority ICRH distribution functions. This will be applied to the well documented [3, 4] JET demonstration discharge 58934. This important discharge demonstrates that an off-axis ion cyclotron resonance, with phasing to enable ion cyclotron current drive (ICCD), can destabilise (shorten period of) sawteeth even when the sawteeth are initially stabilised by trapped energetic RF ions in the core. Hence, in the latter part of the discharge two resonant surfaces co-exist. It is the sum of these two populations that ultimately require modelling in order to ascertain the internal kink mode stability.

The distribution of particles F depends only the constants of the particle motion: energy $\mathscr{E} = v^2/2$, magnetic moment $\mu = v_\perp^2/B$, toroidal canonical momentum $\mathscr{P}_\phi = Rv_\phi + Ze\psi_p/m_h$

*See appendix of M.L.Watkins *et al*, Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006), IAEA, (2006) and $\sigma = \pm 1$ (denotes sign of $v_{\parallel}$). Let us expand $F = F_0 + F_1 + ...$ in orders of the orbit width Δr about the temporal average particle radius $\bar{r}$. Writing $r(t) = \bar{r} + \Delta r(t)$ we have,

$$F_0(\mathscr{E},\mu,r) = F(\mathscr{E},\mu,\bar{r})|_{\bar{r}\to r} \text{ and } F_1(\mathscr{E},\mu,r) = -\Delta r\, G_0(\mathscr{E},\mu,r) \quad (1)$$

with

$$G_0(\mathscr{E},\mu,r) = G(\mathscr{E},\mu,\bar{r})|_{\bar{r}\to r} \text{ and } G(\mathscr{E},\mu,\bar{r}) = \frac{\partial F(\mathscr{E},\mu,\bar{r})}{\partial \bar{r}}. \quad (2)$$

In this section we describe the leading order distribution F_0. The first finite orbit width correction F_1 does not affect the even moments, but is required for evaluation of the currents.

We wish to evaluate the toroidal current density $j_\phi = eZ\int dv^3 v_\phi F$. We recall the definitions of F_0 and G_0 in Eqs. (1) and (2), and expand in the orbit width to give $j_\phi = j_{\phi_0} + j_{\phi 1}$ where

$$j_{\phi_0} = Ze\pi \int_0^\infty d\mathscr{E}(2\mathscr{E}) \int_0^{1/B_{max}} d\lambda\, B(F_0^+ - F_0^-)$$

and

$$j_{\phi_1} = -Ze\pi \int_0^\infty d\mathscr{E}(2\mathscr{E}) \int_0^{1/B} d\lambda\, B\frac{q}{r\Omega_c}\left(|v_{\parallel}|R - pR_0^2 q\omega_b\right)(G_0^+ + G_0^-),$$

with $p = 1$ for passing particles, $p = 0$ for trapped particles, and $\Omega_c = eZB_0/m$. Also superscript '$+$' and '$-$' corresponds to σ. Note that we have used the result $\Delta_r = q(v_{\parallel}R - R_0^2 q(p\sigma)2\pi/\tau_b)/(r\Omega_c)$, valid for both trapped and passing particles, where $\tau_b = 2\pi/\omega_b$ is the transit or bounce time for passing or trapped ions respectively.

A model for F is written in terms of a modified bi-Maxwellian which satisfies the lowest order Vlasov equation:

$$F = \left(\frac{m}{2\pi e}\right)^{3/2} \frac{n_c(\bar{r})(1+\sigma c(\bar{r},\lambda))}{T_\perp(\bar{r})T_\parallel^{1/2}(\bar{r})} \exp\left[m\mathscr{E}\left(-\frac{\lambda B_c}{eT_\perp(\bar{r})} - \frac{|1-\lambda B_c|}{eT_\parallel(\bar{r})}\right)\right]. \quad (3)$$

where B_c is the resonant magnetic field for the IRCH wave, and $\lambda = \mu/\mathscr{E}$. To model discharge 58934, the sum of two distributions is used to represent the two resonances. All the parameters in the model are obtained by fitting to the density, pressure and currents calculated by dedicated SELFO [5] RF wave-field simulations and distribution function. Shown in Fig. 1 (a) is a contour plot of F_0, i.e. the distribution function in absence of finite orbit corrections, plotted with respect to $v_\parallel$ and $v_\perp$ on the outboard side ($\theta = 0$) and at $r/a = 0.35$. Clearly shown is the asymmetry in $v_\parallel$, which is consistent with the lowest order flux averaged current $\langle j_{\phi 0}(r)\rangle$ at $r/a = 0.35$, and indeed the passing ion currents calculated for this discharge [4] using SELFO. Finally, Fig. 1 (b) shows $F_0 - \Delta r G_0$, i.e. the total distribution including the effects of finite orbit widths, plotted with respect to $v_\parallel$ and $v_\perp$. We now see additional asymmetries in $v_\parallel$, particularly in the trapped cone, and the corresponding trapped ion currents are consistent with $\langle j_{\phi 1}(r)\rangle$ at $r/a = 0.35$. Importantly, it is found that passing ions barely contribute to $\langle j_{\phi 1}(r)\rangle$, and trapped ions cannot contribute to $\langle j_{\phi 0}(r)\rangle$. The latter current accounts for Fisch [6] currents, and currents associated with ICRH detrapping [4].

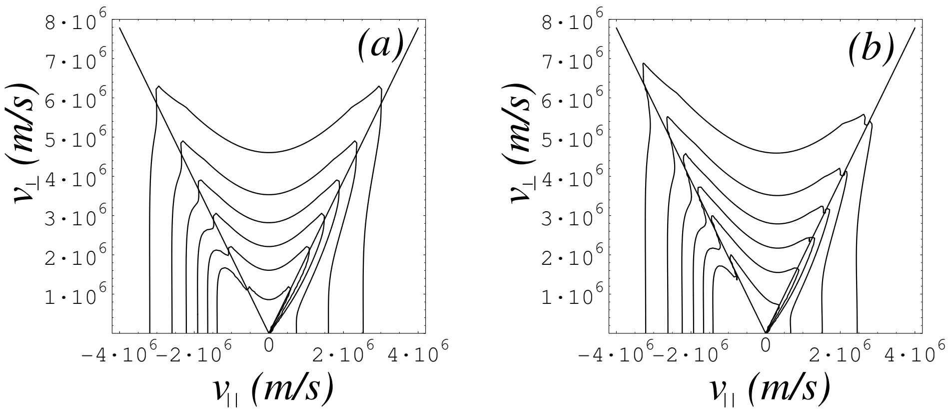

Figure 1: Showing (a) the contour plot for the lowest order distribution function F_0, according to Eqs. (3) and (1), and (b) $F_0 - \Delta r G_0$, according also to Eq. (2), for discharge 58934.

For internal kink calculations, we expand the adiabatic contribution to the distribution function δF_f about the flux label r:

$$\delta F_f = -\xi_r \left[G_0 + \frac{\Delta_r}{r} \left((2-s)G_0 - \frac{y^2}{2}(2-y^2) \left.\frac{\partial G_0}{\partial y^2}\right|_r - \left.\frac{\partial (rG_0)}{\partial r}\right|_{y^2} \right) \right] \qquad (4)$$

where $y^2 = 2\lambda B_0 \varepsilon / (1 - \lambda B_0 (1-\varepsilon))$ is a pitch angle and s is the magnetic shear. It is now possible to resolve the contribution to the potential energy $\delta\hat{W}_{r_1}$ from passing ions intersecting the $q = 1$ surface. Since both the passing ion currents, and the finite orbit contribution to the internal kink mode, both require parallel asymmetry in the distribution, it is possible to write $\delta\hat{W}_{r_1}$ in terms of the $< j_{\phi 0} >$ at the $q = 1$ surface:

$$\delta\hat{W}_{r_1} \approx -\frac{2^{1/2}}{\pi\varepsilon_1^2} \frac{1}{Z\Omega_c} \left(\frac{2\mu_0}{B_0^2} \right) T_\perp^{1/2} T_\parallel^{1/2} \left. \frac{d}{dr} < j_{\phi 0} > \right|_{r_1} . \qquad (5)$$

In Fig. 2 we compare the growth rates $\frac{\gamma}{\omega_A} = -\frac{\pi}{s_1}\delta\hat{W}$ corresponding to the fast ion contributions calculated using the drift-kinetic code HAGIS [7] with the net contribution from the semi-analytical work contained in this section, i.e. the sum of $\delta\hat{W}_{r_1}$ and other conventional fast ion contributions not involving finite orbit effects. The narrow peak in the growth rate is clearly also recovered in the HAGIS simulations, where it has been confirmed that the passing fast ions are responsible for this clear signature. HAGIS also accounts for the finite orbit width of trapped ions, and its neglect in the analytical work probably explains the differences in the comparison. Also shown is the instability threshold $-\hat{\rho} = \rho / r_1$ for the resistive internal kink mode [8] with two fluid effects in the layer.

In conclusion, a new mechanism has been proposed that can explain the highly effective nature of sawtooth control using off-axis ion cyclotron current drive. Energetic passing ions influence the internal kink mode when the distribution of ions is asymmetric in $v_\parallel$, a natural feature of co or counter propagating ICRH waves. A JET demonstration discharge [4] has been

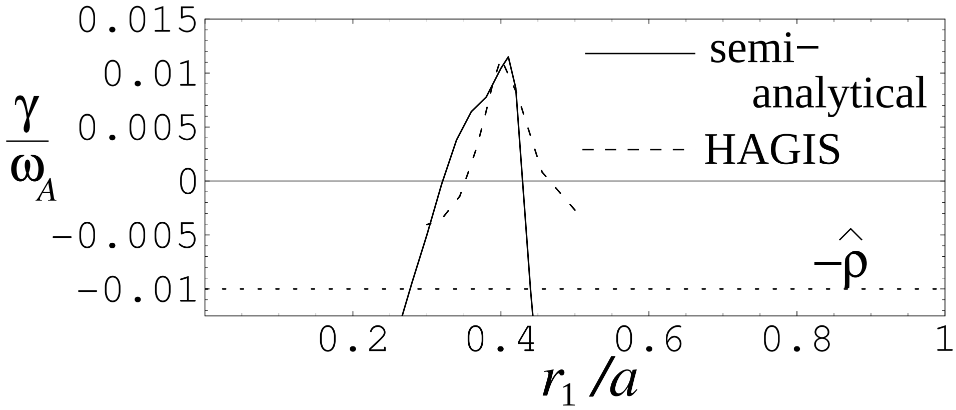

Figure 2: The fast ion growth rate as a function of r_1/a, compared with HAGIS simulations.

used to quantify the control mechanism, and demonstrate its viability. In other recent discharges [9] it has been shown that a change in the magnetic field of only about two percent can be sufficient to enable or disable sawtooth control. The corresponding change in the magnetic shear has been calculated, and was shown to be extremely modest, thus questioning the viability of the classical [6] sawtooth control mechanism relating to the change in the magnetic shear, due to ICCD, and the resulting effect on resistive MHD stability. Nevertheless, it is shown here that when a counter propagating wave is deposited sufficiently accurately on the high field side, a newly discovered fast ion effect is so strong that the internal kink mode is driven not only resistive unstable (e.g. [8]), but ideal unstable, and this in turn is consistent with measured sawteeth that are much shorter in period than those obtained in Ohmic plasmas. Furthermore, unlike the classical sawtooth control mechanism [6], the fast ion mechanism is independent of the bulk plasma drag current, which is expected [10] to limit the ICCD current drive efficiency of the proposed ICRF system for ITER.

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