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Sawtooth control mechanism on JET using off-axis toroidally propagating ICRF waves

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Introduction

The restricted range of the planned ICRH antennas in ITER is such that minority ^{3}He is likely to be employed. Due to the negligible or reverse current drive contributions from minority ^{3}He, it was thought [1] that MHD control with toroidally propagating waves would not be viable. In contrast, the new explanation recently been given in Ref. [2] for the sawtooth control mechanism does not rely on net driven current, and was therefore predicted to function even with minority ^{3}He. Consequently, minority ^{3}He experiments in JET have been devised and carried out and interpreted with simulations in order to demonstrate the viability of sawtooth control using ^{3}He minority in ITER, and to conclusively show that the previously assumed classical mechanism [3] cannot explain ICRF sawtooth control experiments in JET.

Experimental Results

The objective of the experiment was for the ^{3}He resonance to pass slowly through the inversion radius on the high field side in each discharge. This was technically difficult, because the fundamental hydrogen resonance needed to remain outside the antenna region ($> 4m$) at all times. The CMOD-DIF configuration, shown in Fig. 1 (a) for discharge 76189 at 61s, was chosen because the plasma is shifted significantly over to the low field side. This configuration permitted the ^{3}He resonance to access a q=1 radius which was not compromised in size. The two pulses shown in Fig. 1 (b) had the slowest field and current ramp in the session, and the clearest sawtooth control signatures, shown clearly in Figs. 1 (a) and (b). The pulses were identical, except crucially, 76189 employed 3MW of counter-propagating waves (-90), while 76190 employed 2MW of co-propagating waves (+90).

The minority ion concentration was around 1 percent, giving fast ion tail temperatures in excess of 200 keV. Sawteeth were strongly affected when the resonance was about 2 to 6 centimetres inside the inversion radius (r_{inv}). Discharge 76189 (-90) demonstrates sawtooth destabilisation (small period) over a width of approximately 3 percent of the minor radius. For 76190 (+90), the signature of the sawtooth stabilisation is slightly broader. Nevertheless, since a contrastingly different signatures occur for +90 and -90 phasings, we have demonstrated that the

*See Appendix of F.R.Romanelli *et al.*, Fusion Energy 2008 (Proc. 22nd Int.Conf.Geneva, 2008) IAEA, (2008)

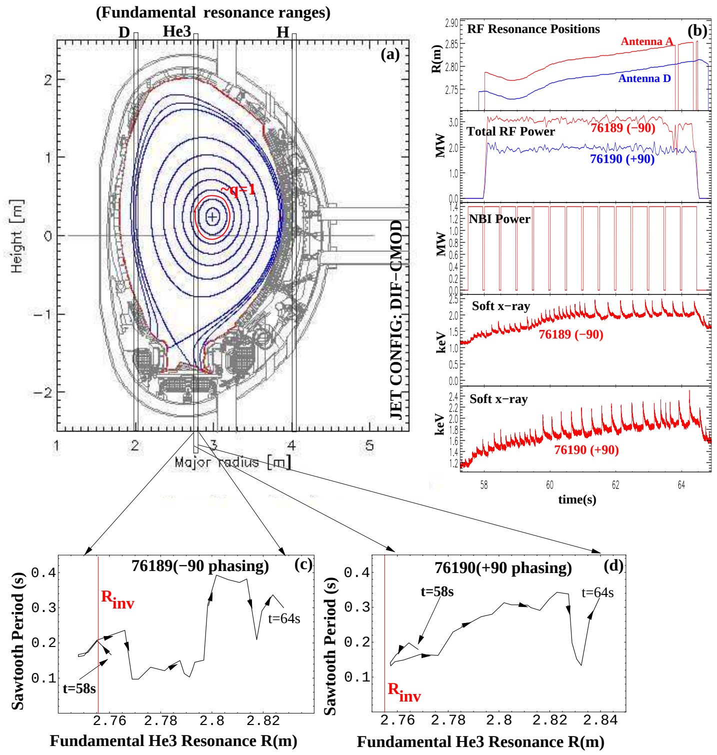

Figure 1: Showing (a) the configuration employed for discharges 76189 (+90) and 76190 (-90) shown in (b). Shown in (c) and (d) are the evolution of the sawtooth period for 76189 and 76190.

sawteeth were not merely modified by a change in the local conductivity, which nevertheless would not be expected to result in sawteeth that are highly sensitive to resonance position [4].

Verification of negligible fast ion current

The experimental objective of generating negligible net minority ion currents in the core was apparently achieved. Shown in Fig.2(a) is a SELFO [5] calculation of the fast ion current density $j_h = en_h Z_h v_h$ for discharge 76189 at 61s, where v_h is the $v_\parallel$ moment of the distribution function. However, the plasma is dragged along with the fast ions, such that the total current is proportional to a drag coefficient j_d such that $j_{tot} = j_h \times j_d$.

The fast ion current is subject to momentum conservation, quasi-neutrality and the balance of collision rates of electrons on all ion species [6], giving

$$j_d = 1 - \left[\frac{Z_h}{Z_{eff}} + \frac{m_h \sum_i Z_i n_i (1 - (Z_i/Z_{eff})}{Z_h \sum_i n_i m_i} - G \left(\frac{Z_h}{Z_{eff}} - \frac{m_h \sum_i n_i Z_i^2}{Z_h Z_{eff} \sum_i n_i m_i} \right) \right],$$

where $G = 1.46A(Z_{eff})\varepsilon^{1/2}$, A is a weak function of Z_{eff} and i denotes ion species other that hot (h). It is seen that j_h is a dipole, with maximum current around 30 kA/m^2. Due to the minority ion mass number $m_h = 3$ and charge $Z_h = 2$ and moderate $Z_{eff} \approx 1.8$ giving $A \approx 1.4$, the effect of the plasma drag, shown in Fig. 2(b) is to reverse the sign of the net current density inside $q = 1$, and to neutralise the current density (Fig. 2(c)) and the change in the shear at $q = 1$.

Simulation of the sawtooth period

In Ref. [2] it was shown that 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

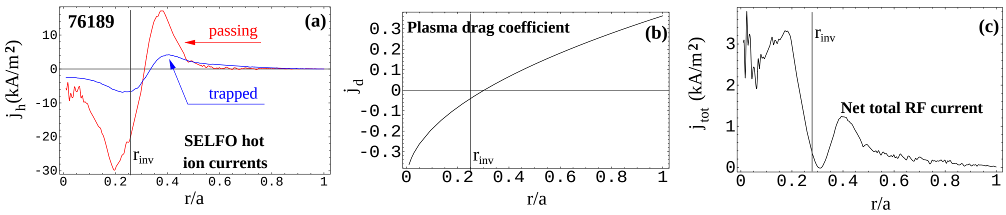

Figure 2: Showing (a) the passing and trapped ion current densities calculated from SELFO for 76189, (b) the plasma drag coefficient j_c, and (c) the small net current density.

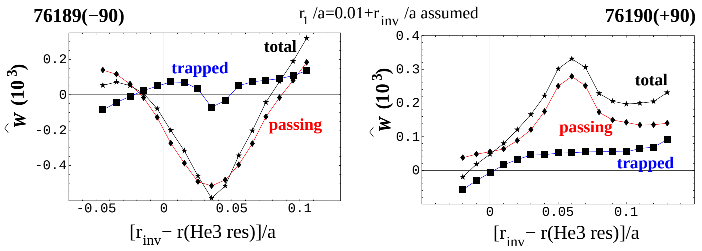

Figure 3: Showing and (a) and (b) the HAGIS evaluated potential energies of the passing and trapped fast ions for 76189 and 76190.

waves. An analytical derivation showed that the hot passing ion contribution due to $v_{\|}$ asymmetry is crudely given by,

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

where the ideal growth rate $\gamma/(v_A/R_0) = -(\pi/s_1)(\delta\hat{W}_{r_1} + \delta\hat{W}_h + \delta\hat{W}_f)$ is proportional to the sum of the fast ion $\delta\hat{W}_{r_1} + \delta\hat{W}_h$ and background plasma fluid potential energy $\delta\hat{W}_f$. In the ^{3}He experiments, $T_{\perp} \approx 200$ keV, $B \approx 2.8T$ and $d < j_{\phi 0} > /dr$ can be evaluated by taking the local radial derivative of the fast ion current dipole j_h before the plasma drag is subtracted. The results compare fairly well with HAGIS [7] simulations shown in Fig. 3 (a) and (b) for 76189 and 76190, although the HAGIS results are more sensitive to resonance location relative to r_1. The HAGIS simulations varied r_1 while keeping the resonance position and the fast ion distribution fixed. Providing the artificial r_1 scaling in the fast ion contributions is removed, similar behaviour to that of the experiments is observed when one looks at sawtooth stability with respect to the difference between the resonance position and inversion radius. For counter propagating waves there is a narrow region of strong instability (negative δW), while for co-propagating waves there is a steep transition to strong stability.

By allowing the electron and ion density and temperature profiles to evolve during the sawtooth ramp, broadly as observed in the experiment, we can simulate the time taken for ideal instability $\delta\hat{W}_{r_1} + \delta\hat{W}_f < 0$ to occur. Profiles assume full reconnection after previous crash. The fluid potential energy evolves due to evolving poloidal beta β_p, with toroidal and elongation effects [8] included $\delta\hat{W}_f = \varepsilon_1^2(\delta W_0 + \delta W_1\beta_p + \delta W_2\beta_p^2) - \varepsilon_1^2(3/2)\beta_p(\kappa-1)/(\kappa+1)$, where $\delta W_{0,1,2}$ are defined in e.g. Ref. [9], and κ is the elongation at r_1. We have demonstrated that the sawtooth mechanism for these discharges cannot be sensitive to the shear, and its evolution. Consequently, we take the shear to be fixed.

The fast ion contribution evaluated by HAGIS is assumed to increase transiently from zero

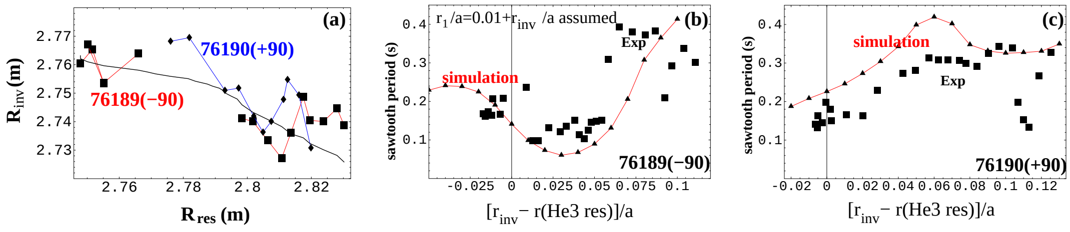

Figure 4: Showing (a) the non-stationary inversion radius, and (b) and (c) simulations of the sawtooth period and comparisons with corresponding measurements for 76189 and 76190.

within a slowing down time of the ^{3}He ions, which is consistent with the assumption that the fast ions must be transported (RF kicks and collisions) within r_1 following a crash. It should be noted that for, e.g. 76189, the width of the passing particle contribution to δW is around twice that of the 3 cm variation of R_{res} (within which the sawteeth are measured to be small). Nevertheless theory and experiment are consistent when one takes into account the measured linearly decreasing inversion major radius, R_{inv} with time. Plotted in Fig. 4(a) is a linear temporal fit of R_{inv} for sawteeth longer than 150ms, plotted with respect to the ^{3}He resonant radius. The fit will be used to re-scale the data for comparison with simulation, shown in Figs. 4 (b) and (c).

Excluding a few small sawteeth at the end of the discharge, the simulations agree well with experiments: For the -90 discharge, the passing ion contribution due to parallel asymmetry is clearly responsible for the deep and narrow well in the sawtooth period. Trapped ions begin to contribute to the stabilisation only for larger values of $r_{inv} - r_{res}$. For the +90 case, the steep transition to longer sawteeth is governed by the passing ion contribution, i.e the asymmetry mechanism. As expected, trapped ions can only begin to contribute when they are in sufficient numbers inside the $q = 1$ radius. This is increasingly the case for increasing $r_{inv} - r_{res}$.

Conclusions

Recent JET experiments demonstrate the viability of sawtooth control using ITER relevant ^{3}He minority at low concentration. Simulation of RF induced currents have been confirmed to be negligible, as expected, but the recently developed fast ion mechanism [2] has been analysed for these discharges, and shown to be consistent with the sawteeth.

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