Experimental Verification of Sawtooth Control by Energetic Particles in Ion Cyclotron Resonance Heated JET Tokamak Plasmas

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Experimental evidence from the JET tokamak is presented supporting the predictions of a recent theory [J. P. Graves, et al, Phys. Rev. Lett. 102, 065005 (2009)] on sawtooth instability control by toroidally propagating ion cyclotron resonance waves. Novel experimental conditions minimised a possible alternate effect of magnetic shear modification by ion cyclotron current drive, and enabled the dependence of the new energetic ion mechanism to be tested over key variables. The results have favourable implications on sawtooth control by ion cyclotron resonance waves in a fusion reactor.

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Magnetohydrodynamic (MHD) stability of plasmas in the presence of energetic ions is a crucial issue for present and future large tokamak experiments. Such ions include 3.5 MeV fusion alpha particles, and energetic minority ions produced by auxiliary heating methods such as neutral beam injection (NBI) and from ion cyclotron resonance frequency (ICRF) waves. Ions trapped within the region of lower magnetic field strength have been shown [1–3] to stabilise an instability known as the sawtooth, located within the core localised $q = 1$ rational surface, thereby lengthening the period between sequential plasma relaxations[4]. Without an effective means of shortening the period of sawteeth, the relaxation event can trigger [1, 5] secondary performance degrading instabilities located closer to the tokamak edge.

A new explanation was recently given [6] for the highly effective nature of sawtooth control using toroidally propagating ICRF waves with off-axis resonance in tokamaks. Energetic passing ions influence the MHD internal kink mode instability (thought to be responsible for sawteeth) when they are distributed asymmetrically in parallel velocity. Such populations are generated by toroidally aligned NBI, and it's effect on sawteeth is well documented [7, 8], but parallel velocity asymmetry is also a natural feature of minority ion populations in resonance with toroidally co or counter propagating ICRF waves. This letter reports novel dedicated JET experiments which have been devised in order to neutralise an alternative sawtooth control mechanism [9, 10] involving changes in the equilibrium current due to ICRF, and permit comparison with recent theory [6] across physical parameters. In the experiments presented here, negligible change to the net equilibrium current was assured by choosing ^{3}He minority ICRF in a deuterium majority plasma (^{3}He)D, whereby the current dragged [9, 11] by the background plasma tends to cancel the ^{3}He current. The experiments reported here are important not least because it had been widely accepted that the poor current drive efficiency arising from minority ^{3}He resonant toroidally propagating waves would not [9, 12] provide sawtooth control in deuterium or deuterium-tritium reactor relevant plasmas. Minority ^{3}He experiments prior to Ref. [9] had reported results [1, 2] with resonance close to the magnetic axis, thereby lengthening sawteeth through the well recognised effect (e.g. [3]) of an axially peaked fast ion pressure. Subsequent sawtooth relevant experiments have, until now, primarily employed high concentration ^{3}He (e.g. [13] and refs. therin), leading to mode conversion and direct electron heating close to the $q = 1$ surface, and consequently efficient local current profile and sawtooth modification. In contrast, and contrary to the predictions of Refs. [9, 12] the novel experiments outlined in this letter show that sawtooth control by toroidally propagating ICRF waves, with $q = 1$ localised resonance on low concentration minority ^{3}He, is in fact extremely effective, as predicted by the fast ion mechanism [6]. This demonstrates the viability of sawtooth control using ICRH in ITER [14], which is primarily expected to employ ^{3}He minority [12].

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*See the Appendix of F. Romanelli et al., Fusion Energy Conference 2008 (Proc. 22nd Int. FEC Geneva, 2008) IAEA, (2008) The effectiveness of minority ^{3}He ICRF for controlling sawteeth, and its importance, is illustrated in Fig. 1. The only difference between the two pulses is that the direction of the toroidally propagating ICRF waves is counter-tangent to the plasma current in pulse 78737 (-90° antenna phasing), and co-tangent in pulse 78739 (+90° antenna phasing). In both pulses the early NBI phase increases the sawtooth period to 300ms from Ohmic (without auxilary heating) sawteeth of around 80ms. At 18s, 4.5MW of ^{3}He ICRF is applied on the high field side of the $q = 1$ rational surface, indicated by the resonance position and soft-x-ray resolved inversion major radius in Fig. 1. The toroidal magnetic field is then ramped very slowly from B =2.9T to B =2.96T, whilst changing the current proportionally in order to keep the q profile stationary. It is seen that for -90° phasing the sawtooth period is reduced to a minimum of 100ms, close to that of Ohmic sawteeth, while for +90° phasing, the sawteeth become extremely long. The longest sawtooth period is more than 1 second, and the crash triggers a saturated amplitude resistive mode, specifically a neoclassical tearing mode (NTM) [15], as indicated by the $n = 2$ toroidal mode number magnetic signal shown in Fig. (1). This is a rare observation of an NTM in a low confinement mode plasma with low normalized beta ($\beta_N \approx 0.8$, where beta is a figure of merit for a fusion plasma, defined as the ratio of plasma pressure to magnetic pressure), and thus highlights the crucial importance of sawtooth control.

Resolving the mechanism responsible for the sawtooth experiments in JET is very important for predictions of sawtooth control capability in ITER. A widely accepted necessary criterion for instability [16] is given by the kinetic-resistive $m = n = 1$ internal kink mode threshold:

$$\frac{\pi \delta \hat{W}}{s_1} < \hat{\rho} \tag{1}$$

where $\delta \hat{W}$ is the potential energy of the internal kink mode (with linear growth rate $\gamma = -\omega_A \pi \delta \hat{W}/s_1$, $\omega_A = v_A/3^{1/2}R_0$, v_A the Alfvén velocity and R_0 the major radius at the magnetic axis), s_1 is the magnetic shear at the $q = 1$ rational surface, where $s = (r/q)dq/dr$ and $\hat{\rho}$ is the Larmor radius of the background thermal ions normalised to the $q = 1$ minor radius r_1. In moderate sized present day machines [17, 18] convincing evidence exists showing that sawteeth are shortened by increasing s_1 through localised electron cyclotron current drive (ECCD) techniques such that (1) might be met more rapidly following the previous sawtooth crash. However, in ITER, $\delta \hat{W}$ will typically be very large and positive due to the stabilising effect of trapped fusion alpha particles, whilst $\hat{\rho}$ will be much smaller than in most present day experiments. Consequently, in ITER, an actuator will have to generate a very large change in s_1 in order to satisfy (1). By contrast, the fast ion mechanism proposed in Ref. [6] generates a change in the macroscopic energy of the internal kink mode due to 'RF' ions, $\delta \hat{W}_{RF}$, and as a result, it is envisaged that the criterion for instability (e.g. (1)) can be met even when there is a significant stabilising trapped ion population in the core, and especially in conjunction with enhanced s_1, via e.g. an additional ECCD actuator. In the JET experiments presented here, a low power NBI ion population plays the role of alpha particles, thus initially lengthening the sawteeth via the the stabilising contribution $\delta \hat{W}_{NBI}$ both from trapped fast ions [1, 3], and asymmetrically distributed passing ions [7, 8]. These sawteeth are controlled by the effect [6] of ICRH generated energetic passing ions intersecting the $q = 1$ radius, thus reducing, or changing the sign of, the total fast ion contribution $\delta \hat{W}_{RF} + \delta \hat{W}_{NBI}$.

It is now shown that sawteeth are modified by ICRH even for pulses with low auxiliary power. Diagnostic neutral beams with a power of 1.4MW were used in pulses 76189, employing 3MW of ICRF with -90° phasing, and 76190, employing 2MW ICRF with +90° phasing, both with low concentration (up to 0.5%) minority ^{3}He. The configuration is essentially the same for all the pulses described here and is shown in Fig. (2). The toroidal magnetic field was ramped upwards from around 2.88T to 2.96T, and the plasma current was ramped proportionally. Figure 2 plots the sawtooth period for 76189 and 76190 as a function of the ^{3}He resonance position. It is seen that the sawtooth period is strongly modified as the resonance position is shifted relative to the sawtooth inversion radius, shaded in red. The pulse with -90° phasing exhibits a narrow window of sawtooth destabilisation, while the +90° phasing pulse exhibits the opposite.

The experimental objective of generating negligible minority ion current is now addressed. The MSE diagnostic in JET has a typical accuracy of 10% of the current density ($\approx$ 1.3MA/m^2 at r_1), which precludes the direct measurement of the ICRF driven current because, as seen below, it is typically two orders of magnitude smaller than the total current density, even in the absence of the plasma drag current. Shown in Fig. 3 is a SELFO [19] calculation of the fast ion current density $j_h = eZ_h \int dv^3 \, v_\parallel F_h$ for pulse 76189 at 21s, where F_h is the ICRH distribution function. For the simulation of this pulse, with $-90°$ phasing, SELFO employs a spectrum of toroidal wave numbers with maximum power for $n_\phi = -15$, while the simulation of 76190 (+90° phasing) has maximum power for $n_\phi = 15$. The asymmetry in toroidal wave number spectra, due to the antenna phasing, gives rise to Fisch currents [11] and currents due to preferential detrapping [20] of co and counter circulating ions. SELFO calculates these currents in addition to currents that are insensitive to antenna phasing which arise from the guiding centre drift orbits of predominantly trapped and barely passing ions. However, the plasma is dragged [9, 11] along with the fast ions, such that the total current is proportional to a drag coefficient j_d, giving $j_{tot} = j_h \times j_d$. The fast ion current is subject to momentum conservation, quasi-neutrality and the balance of collision rates of electrons on all ion species

[9, 11], giving

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

where $G = 1.46A(Z_{eff})\epsilon^{1/2}$, A is a weak function of Z_{eff} and i denotes ion species other than hot (h). In Fig. 3 it is seen that j_h has a dipole structure, with maximum current around 30 kA/m^2. Due to the minority ion mass number $m_h = 3$ and charge $Z_h = 2$, deuterium bulk ion population, carbon and beryllium impurities, and moderate $Z_{eff} \approx 1.8$, the effect of the plasma drag, shown also in Fig. 3, is to lower the net driven current density by at least 90% within the $q = 1$ surface, so that the change in the shear Δs due to current drive is negligible, as also shown in Fig. 3. It is therefore concluded that the sawteeth were not controlled by the effect of ICRF current drive on s_1. Moreover, that the trend in the sawteeth is opposite for +90 and -90 phasings rules out the possibility that the sawteeth were modified simply by the effect of localised electron heating.

Employing the SELFO generated distribution function for pulses 76189 and 76190 in the drift kinetic code HAGIS [21], together with an MHD displacement supplied from linear ideal MHD numerical calculations, reveals the corresponding fast ion contribution to $\delta\hat{W}$ without recourse to approximation of wave and guiding centre interaction. Figure 4 compares the observed signature of the sawtooth period with the fast ion potential energy when plotted with respect to the difference between the ^{3}He resonance position and the measured and averaged inversion radius. The narrow region over which the sawteeth are sensitive to the ICRF deposition, also visible in Fig. 2, is recovered by the simulations, which assume $r_1 = r_{inv}$. The sign of the RF ion $\delta\hat{W}$ contributions is consistent with the observed effect on the sawteeth, and the amplitude is larger than the resistive threshold $s_1\hat{\rho}/\pi$, and all other contributions to $\delta\hat{W}$ including that from the NBI ions. We note from Fig. 4 that the response of the trapped ions is dwarfed by the passing ion response, as expected from the mechanism described in Ref. [6].

By exploiting the knowledge of the fast ion control mechanism derived in [6], it has been possible to reduce its effect, and the corresponding sawtooth control, thereby providing further experimental evidence in support of the theory. The aim is to reduce the finite orbit width of the fast ions, which scales with the hot ion temperature as $\Delta_r \propto T_h^{1/2}$. Referring e.g. to Stix [22], the hot ion temperature is proportional to the ICRH power, and inversely proportional to the minority ion density. Keeping the ICRH power constant ensures that the well known stabilising kinetic effects [3] (proportional to the trapped ion pressure $\approx n_h T_h$ profile inside $q = 1$) are not strongly modified from pulse to pulse over a range of ^{3}He concentration far below mode conversion, and hence in addition prevents significant current drive. Pulse 78740 shown in Fig. 5 employs approximately 4.5MW of -90° phasing ICRH with relatively high minority ^{3}He concentration (up to 3% of the electron density). This can be compared directly with the otherwise identical pulse 78737, detailed also in Fig. 1, employing -90° phasing with relatively low minority ^{3}He concentration (up to $n_h/n_e = 0.6\%$). The several-fold increase in ^{3}He concentration in 78740, relative to 78737, is consistent with the deliberate increased opening of the ^{3}He gas valve. The two pulses exhibit the same signature with respect to the scan in resonance position, but the amplitude of the effect is reduced for increased concentration, as expected for the fast ion mechanism, and contrary to the current drive mechanism [9] (currents remain negligible).

Detailed verification that the fast ion mechanism [6] is consistent with the experiments shown in Fig. 5 is undertaken by SELFO/HAGIS simulations evaluating the stability of JET pulses 78737 and 78740. Figure 6 plots the ICRH ion contribution to $\delta\hat{W}$, upon variation of $r_1 - r_{res}$, for $n_h/n_e = 0.01$ and $n_h/n_e = 0.03$, relevant for 78737 and 78740 respectively. It is seen that the range in $r_1 - r_{res}$ over which ICRH has a destabilising effect is independent of concentration. However, the strength of destabilisation of counter propagating ICRH waves on the internal kink mode is more sensitive to concentration than would be expected from the simple relation $\Delta_r \propto (n_e/n_h)^{1/2}$. For $n_h/n_e = 0.01$ the effect of ICRH dominates Eq. (1), while for $n_h/n_e = 0.03$ the effect of ICRH is much smaller than the combined effect of NBI and MHD, as expected from experiments (Fig. 5). Finally, if the ^{3}He concentration is too low, minority power absorbtion is reduced, and enhanced minority ion energies lead to broader hot ion deposition, and losses, and a reduced impact on sawteeth, as indicated by the simulation in Fig. 6 employing $n_h/n_e = 0.0015$.

This letter verifies that the kinetic response of highly energetic ions on the internal kink mode, described in Ref. [6], is sufficient to explain highly effective sawtooth control techniques (e.g. Refs. [9, 10]) by toroidally propagating ICRF waves with resonance tangential to the $q = 1$ surface. This has been achieved by creating experiments capable of eliminating all other known control mechanisms. Furthermore, more advanced experimental verification was undertaken by variation of the amplitude of the analytically derived fast ion mechanism. That fast ions can so dramatically, and directly, affect sawteeth is encouraging for ITER, especially where control solely via the magnetic shear is expected to be more challenging.

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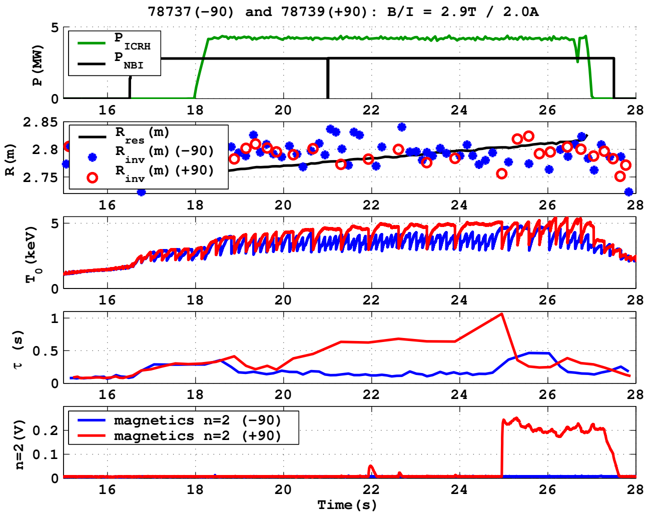

FIG. 1: Time traces of NBI and ICRH power, ^{3}He resonance position and inversion radius, central electron temperature, sawtooth period and $n = 2$ magnetics amplitude for pulses 78737 (blue, -90° phasing) and 78739 (red, +90° phasing).

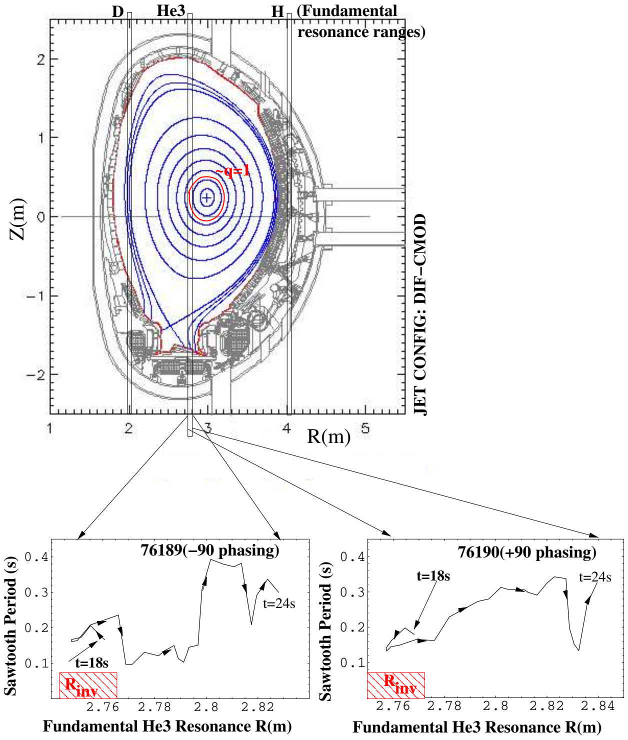

FIG. 2: Colour online: Showing the configuration, and the approximate resonance ranges and locations of ^{3}He, D and H over the range of the toroidal magnetic field $2.88T < B < 2.96T$. Shown also are the corresponding changes to the sawtooth period in ^{3}He minority pulses 76189 (-90° phasing) and 76190 (+90° phasing), and the range of the inversion radius given by the red box.

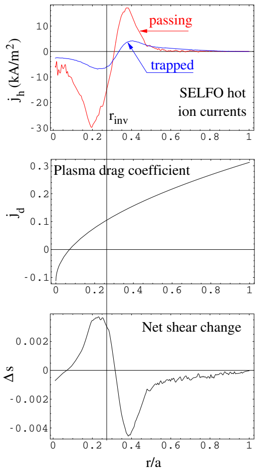

FIG. 3: Colour online: Plotting the passing and trapped contributions to the fast ion current j_h for pulse 76189, the plasma drag coefficient j_d, and change in magnetic shear Δs.

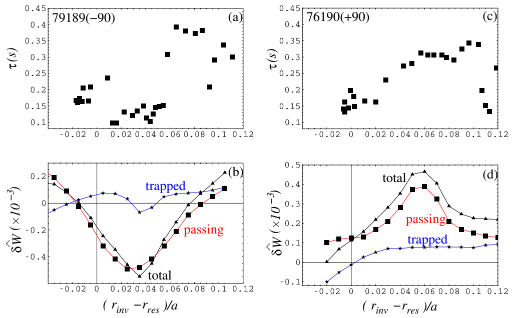

FIG. 4: Colour online: Showing (a) and (c) the sawtooth period for respectively pulses 76189 (-90° phasing) and 76190 (+90° phasing) plotted with respect to the difference between the smoothed average of the sawtooth inversion minor radius and the ^{3}He resonance minor radius. Plotted in (b) and (d) are corresponding ICRH ion contributions to δW assuming $r_1 = r_{inv}$.

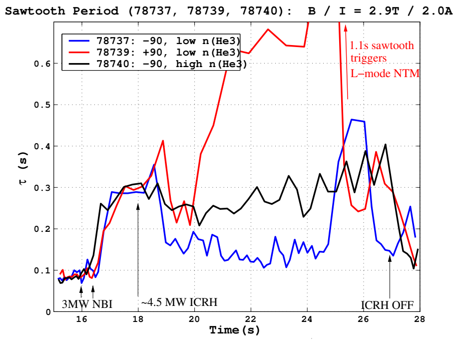

FIG. 5: The sawtooth period for 78737 (-90° phasing, low concentration ^{3}He), 78740 (-90° phasing, high concentration ^{3}He) and 78739 (+90° phasing, shown also in Fig. 1).

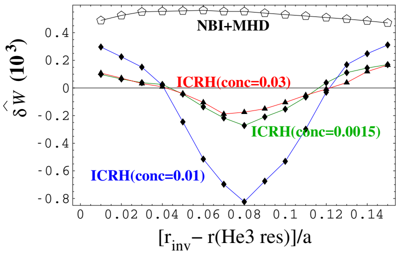

FIG. 6: Colour online: Stability ($\delta\hat{W}$) calculations, plotted with respect to $r_1 - r_{res}$. Curves with $n_h/ne = 0.01$ and $n_h = 0.03$ correspond approximately to the conditions of 78737 and 78740 respectively. The NBI and MHD contributions are also shown.