

J.P. Graves, I.T. Chapman, S. Coda, T. Johnson, M. Lennholm, B. Alper,
M. de Baar, K. Crombe, L.-G. Eriksson, R. Felton, D. Howell, V. Kiptily,
R. Koslowski, M.-L. Mayoral, I. Monakhov, I. Nunes, S.D. Pinches
and JET EFDA contributors

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

“This document is intended for publication in the open literature. It is made available on the understanding that it may not be further circulated and extracts or references may not be published prior to publication of the original when applicable, or without the consent of the Publications Officer, EFDA, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK.”

“Enquiries about Copyright and reproduction should be addressed to the Publications Officer, EFDA, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK.”

The contents of this preprint and all other JET EFDA Preprints and Conference Papers are available to view online free at www.iop.org/Jet. This site has full search facilities and e-mail alert options. The diagrams contained within the PDFs on this site are hyperlinked from the year 1996 onwards.

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

J.P. Graves¹, I.T. Chapman², S. Coda², T. Johnson³, M. Lennholm⁴, B. Alper², M. de Baar⁵, K. Crombe⁶, L.-G. Eriksson⁷, R. Felton², D. Howell², V. Kiptily², R. Koslowski⁸, M.-L. Mayoral², I. Monakhov², I. Nunes⁹, S.D. Pinches² and JET-EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

¹*École Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association EURATOM-Confédération Suisse, 1015 Lausanne, Switzerland*

²*EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK*

³*EURATOM-VR Association, EES, KTH, Stockholm, Sweden*

⁴*EFDA-JET CSU, Culham Science Centre, Abingdon, OX14 3DB, UK*

⁵*FOM Instituut voor Plasmafysica Rijnhuizen, Association EURATOM-FOM, The Netherlands*

⁶*Department of Applied Physics, Ghent University, Rozier 44, 9000 Ghent, Belgium*

⁷*European Commission, Directorate General for Research, Unit J4 - Fusion Associations Agreement*

⁸*Forschungszentrum Jülich GmbH Institut für Energieforschung - Plasmaphysik 52425 Jülich, Germany*

⁹*Associação EURATOM/IST, 1049-001, Lisboa, Portugal*

* See annex of F. Romanelli et al, "Overview of JET Results", (Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).

ABSTRACT.

JET tokamak experiments employing toroidally propagating ion cyclotron resonance waves have verified a recent new theory by controlling sawteeth despite negligible wave driven current.

INTRODUCTION

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 3.5MeV 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, 2] 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 [3]. Without an effective means of shortening the period of sawteeth, the relaxation event can trigger [1, 4] the growth of instabilities located at rational surfaces closer to the tokamak edge, leading to performance degradation, and occasionally disruption.

A new explanation was recently given [5] 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 [6, 7], 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 the results of dedicated JET experiments which have been devised in order to neutralise an alternative sawtooth control mechanism [8, 9] involving changes in the equilibrium current due to ICRF. In the experiments presented here, negligible change to the net equilibrium current was assured by choosing ^3He minority ICRF, since the current dragged [8, 10] by the background plasma tends to cancel the ^3He current in the relevant region of the tokamak provided that the effective charge of the plasma is close to that of ^3He . It is shown that sawtooth control employing low concentration minority ^3He is nevertheless extremely effective, thus validating the fast ion mechanism [5], and demonstrating the viability of sawtooth control using ICRH in ITER [11], which is primarily and routinely expected to employ ^3He minority [12]. An example of both the effectiveness of minority ^3He 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 No: 78737 (-90° antenna phasing), and co-tangent ($+90^\circ$ antenna phasing) in Pulse No: 78739. In both pulses the early NBI phase increases the sawtooth period to 300ms from Ohmic (without auxiliary heating) sawteeth of around 80ms. At 18s the ^3He ICRF resonance is applied on the high field side of the $q = 1$ rational surface, indicated by the soft-x-ray resolved inversion major radius in Fig. 1. The toroidal magnetic field is then ramped very slowly from $B = 2.9\text{T}$ to $B = 2.96\text{T}$, 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, which is close to that of Ohmic sawteeth, while for $+90^\circ$ 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) [13], 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 in future fusion grade tokamaks. Resolving the mechanism responsible for the highly effective sawtooth experiments in JET is very important for predictions of sawtooth control capability in ITER. A widely accepted necessary criterion for instability [14] is given by the kinetic-resistive $m = n = 1$ internal kink mode threshold:

$$\frac{\pi \delta \hat{W}}{s_1} < \hat{\rho} \quad (1)$$

where $\delta \hat{W}$ is the potential energy of the internal kink mode (normalized such that the linear growth rate $\gamma = -\omega_A \pi \delta \hat{W} / s_1$, with $\omega_A = v_A = 3^{1/2} R_0$, 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 [15, 16] 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. [5] generates a change in the macroscopic energy of the internal kink mode corresponding to the fast 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 , brought about for example with an additional ECCD actuator. In the JET experiments presented here, a low power NBI ion population plays the role of alpha particles, thus generating a stabilising contribution $\delta \hat{W}_{NBI}$ both from trapped fast ions [1, 2], and asymmetrically distributed passing ions [6, 7]. It will be seen that 3MW of NBI in JET can generate moderate sized sawteeth [1], with a period close to the energy confinement time. These sawteeth are controlled by the effect 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 Pulse No's: 76189, employing 3MW of ICRH with -90° phasing, and 76190, employing 2MW ICRF with $+90^\circ$ phasing, both with low concentration (up to 0.5 percent) minority 3He. 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 Pulse No's: 76189 and 76190 as a function of the ^3He 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 $+90^\circ$ phasing pulse exhibits the opposite.

The experimental objective of generating negligible minority ion current is now addressed. Shown in Fig.3 is a SELFO [17] calculation of the fast ion current density $j_h = en_h Z_h v_h$ for Pulse No: 76189 at 21s, where v_h is the $v_{||}$ 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 $j_{\text{tot}} = j_h \times j_d$. The fast ion current is subject to momentum conservation, quasi-neutrality and the balance of collision rates of electrons on all ion species [8, 10], giving

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

where $G = 1.46A(Z_{\text{eff}})^{-1/2}$, A is a weak function of Z_{eff} and i denotes ion species other than hot (h). It is seen that j_h has a dipole structure, with maximum current around 30kA/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 $Z_{\text{eff}} \approx 1.8$ giving $A \approx 1.4$, the effect of the plasma drag, shown also in Fig.3, is to lower the net driven current density by at least 90 percent within the $q = 1$ surface, so that the change in the shear s 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 $+90^\circ$ and -90° phasings rules out the possibility that the sawteeth period was modified by the effect of localised heating on the local conductivity profile and hence the resistive diffusion time.

SELFO also generates the fast ion distribution functions in three dimensional phase space for Pulse No's: 76189 and 76190. Feeding these into the drift kinetic code HAGIS [18], together with an MHD displacement supplied from linear ideal MHD numerical calculations, reveals the corresponding fast ion contribution to the potential energy. 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 ^3He resonance position and the measured and smoothed 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 $r_1 = r_{\text{inv}}$. The sign of the fast 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.

By exploiting the knowledge of the fast ion control mechanism derived in [5], it has been possible

to selectively eradicate it, and the corresponding sawtooth control, thus completing the empirical proof of the theory. The aim is to reduce the nite orbit width of the fast ions, which scales with the hot ion temperature as $\Delta r \propto T_h$. Referring e.g. to Stix [19], the hot ion temperature is inversely proportional to the minority ion concentration. Pulse No: 78740 shown in Fig.5 employs -90° phasing ICRH with relatively high minority ^3He concentration (up to 3 percent of the electron density). This can be compared directly with the otherwise identical Pulse No: 78737, detailed also in Fig.1, employing -90° phasing with relatively low minority ^3He concentration (up to $n_h/n_e = 0.6$ percent). It is seen that for Pulse No: 78740, the application of ICRF, and the scan in resonance position does little to the sawtooth period, and as a result the period is essentially governed by the core localised fast ions generated by 3MW of NBI. In order to highlight the signature of the sawtooth period with resonance position at low ^3He , the $+90^\circ$ phasing Pulse No: 78739 is also shown in Fig.5.

Verification that the fast ion mechanism is consistent with experiments shown in Fig.5 is undertaken by SELFO/HAGIS simulations evaluating the stability of JET Pulse No's 78737 and 78740. Figure 6 plots the ICRH ion contribution to $\delta\hat{W}$, upon variation of $r_1 - r_{\text{res}}$, for $n_h/n_e = 0.01$ and $n_h/n_e = 0.03$, which are relevant for 78737 and 78740 respectively. Note that simulations with $n_h/n_e = 0.005$ and $n_h/n_e = 0.01$ are almost identical. It is seen that the range in $r_1 - r_{\text{res}}$ 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 argument above based on Stix [19]. For $n_h/n_e = 0.01$ the effect of ICRH is more important than the effect of the remaining contributions to stability (MHD effects, stabilising role of NBI ion population), 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 shown in Fig.5. Finally, if the minority concentration is too low, power absorbtion to the minority ions is reduced, while resonant ions become highly energetic leading to broader hot ion deposition, and losses. Inclusion in Fig.6 of a simulation employing $n_h/n_e = 0.015$ shows that moderately low ^3He concentration is the optimal choice for sawtooth control.

This letter verifies that the kinetic response of highly energetic ions on the internal kink mode, described in Ref. [5], is sufficient to explain highly effective sawtooth control techniques (e.g. Refs. [8, 9]) 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 selectively eliminating 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.

ACKNOWLEDGEMENTS

This work, supported by the Swiss National Science Foundation, and by the European Communities

under contract of Association between EURATOM and Confederation Suisse, was carried out within the framework of the European Fusion Development Agreement The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

- [1]. D.J. Campbell, *et al*, Physics Review Letters **60** 2148 (1988)
- [2]. R.B. White, *et al*, **60**, 2038 (1988)
- [3]. S. von Goeler, W. Stodiek and N. Sautho, Physics Review Letters **33**, 1201 (1974)
- [4]. O. Sauter, *et al*, Physics Review Letters **88**, 105001 (2002)
- [5]. J.P. Graves, I.T. Chapman, S. Coda, L.-G. Eriksson and T. Johnson, Physics Review Letters **102**, 065005 (2009)
- [6]. J.P. Graves, Physics Review Letters **92**, 185003 (2004)
- [7]. I.T. Chapman, *et al*, Plasma Physics Controlled Fusion **50**, 045006 (2008)
- [8]. V.P. Bhatnagar, *et al*, Nuclear Fusion **34**, 1579 (1994)
- [9]. L.-G. Eriksson, *et al*, Physics Review Letters **92**, 235004 (2004)
- [10]. N. J. Fisch, *et al*, Reviews of Modern Physics **59**, 175 (1987)
- [11]. ITER Physics Basis Editors, Nuclear Fusion **39**, 2137, (1999)
- [12]. M. Laxåback and T. Hellsten, Nuclear Fusion **45**, 1510 (2005)
- [13]. R. Carrera *et al*, Physic Fluids **29**, 899 (1986)
- [14]. F. Porcelli, D. Boucher and M.N. Rosenbluth, Plasma Physics Controlled Fusion **38**, 2163 (1996).
- [15]. C. Angioni *et al*, Nuclear Fusion **43**, 455 (2003)
- [16]. M. Lennholm, Physics Review Letters **102**, 115004 (2009)
- [17]. J. Hedin, *et al*, Nuclear Fusion **42**, 527 (2002).
- [18]. S.D. Pinches, *et al*, Computer Physics Communication **111**, 133 (1998).
- [19]. T.H. Stix, Nuclear Fusion **15**, 737 (1975).

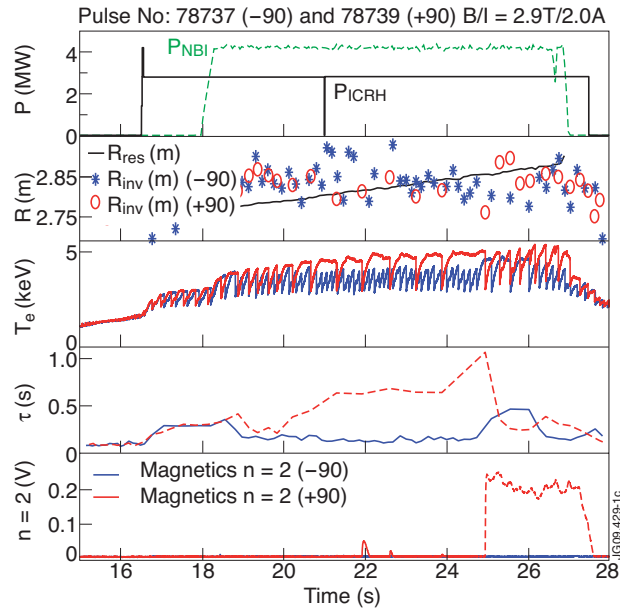


Figure 1: Showing the time traces of NBI and ICRH power, the ^3He resonance position and inversion major radius, central electron temperature, sawtooth period and $n = 2$ magnetics amplitude for Pulse No's: 78737 (blue, -90° antenna phasing) and 78739 (red, $+90^\circ$ antenna phasing).

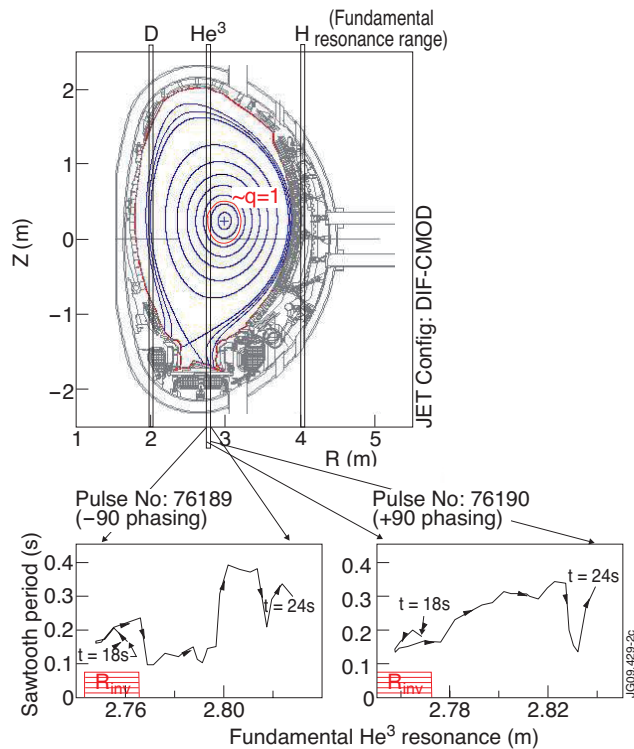


Figure 2: Showing the configuration, and the approximate resonance ranges and locations of ^3He , D and H over the range of the magnetic field $2.88\text{T} < B < 2.96\text{T}$. Shown also are the corresponding changes to the sawtooth period in ^3He minority Pulse No's: 76189 (employing -90° phasing) and 76190 (employing $+90^\circ$ phasing), with start and end times labelled, and the range of the inversion radius given by the red box.

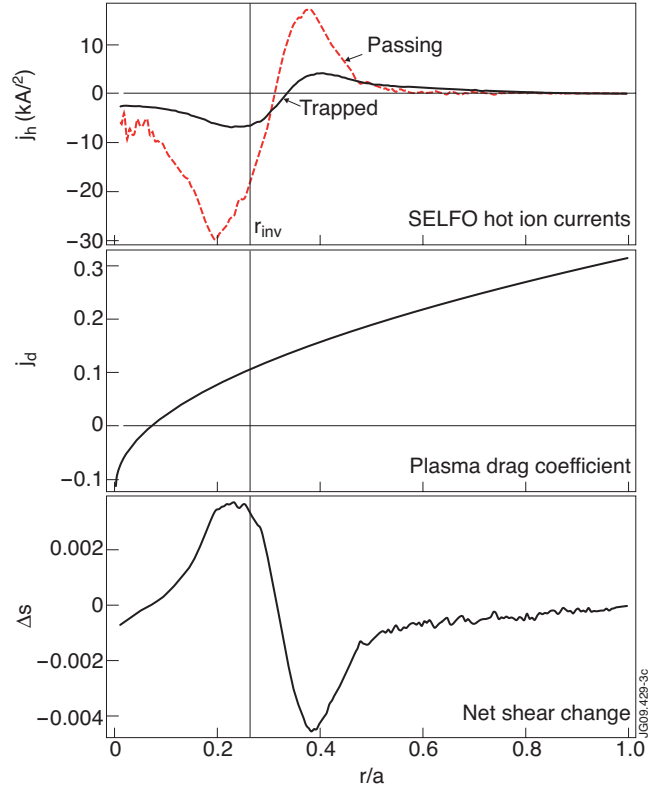


Figure 3: Plotting the passing and trapped contributions to the fast ion current j_h for Pulse No: 76189, the plasma drag coefficient j_d , and change in magnetic shear Δs .

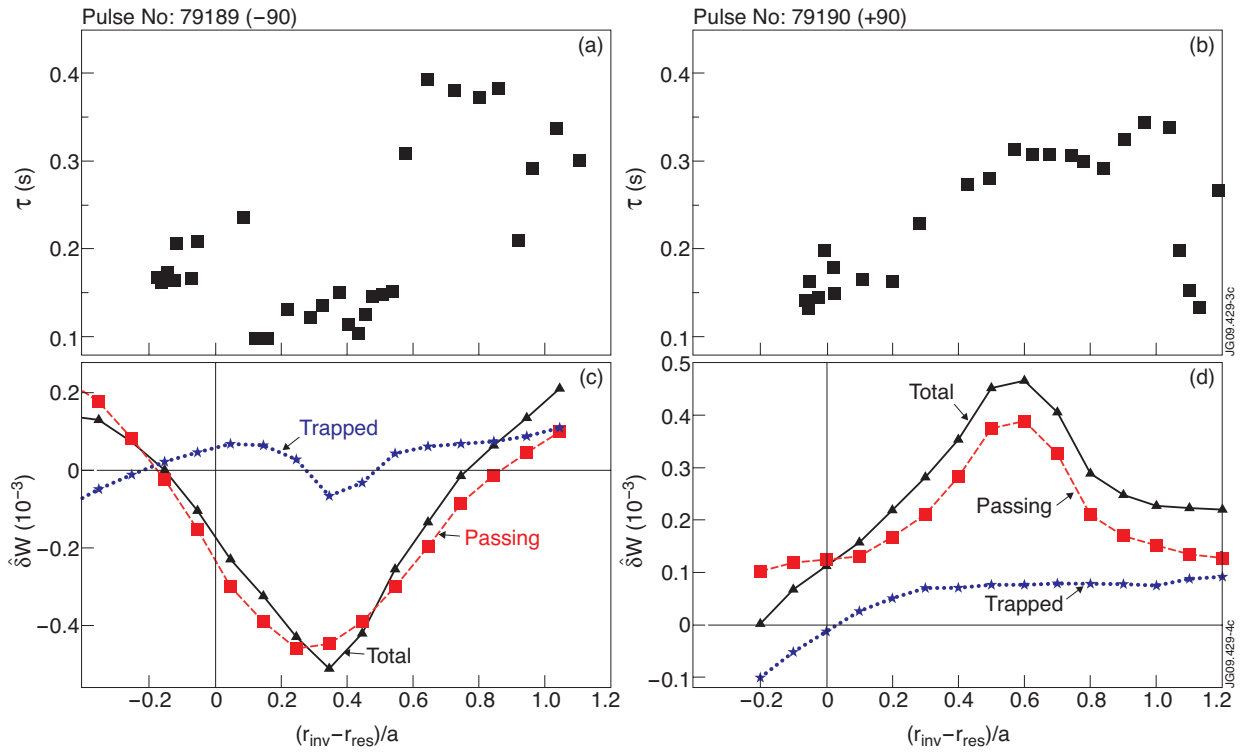


Figure 4: Showing (a) and (c) the sawtooth period for respectively pulses 76189 (-90° phasing) and 76190 ($+90^\circ$ phasing) plotted with respect to the difference between the smoothed average of the sawtooth inversion minor radius and the ^3He resonance minor radius. Plotted in (b) and (d) are corresponding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

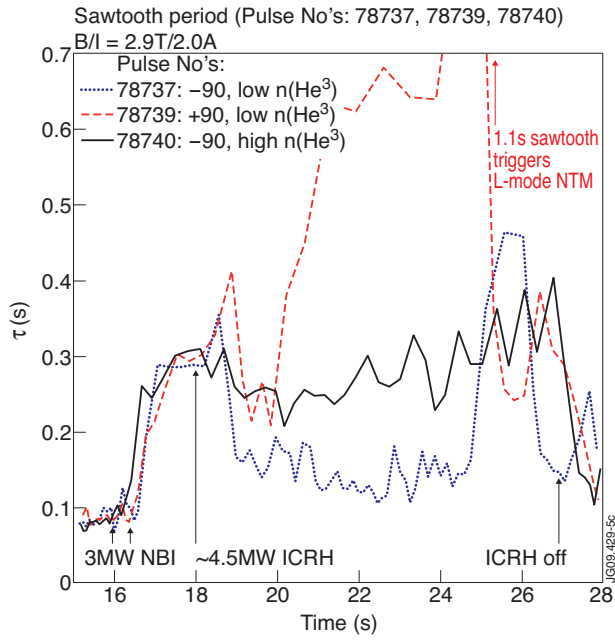


Figure 5: The sawtooth period for Pulse No's: 78737 (-90° phasing, low concentration ^3He), 78740 (-90° phasing, high concentration ^3He) and 78739 ($+90^\circ$ phasing, shown also in Fig.1).

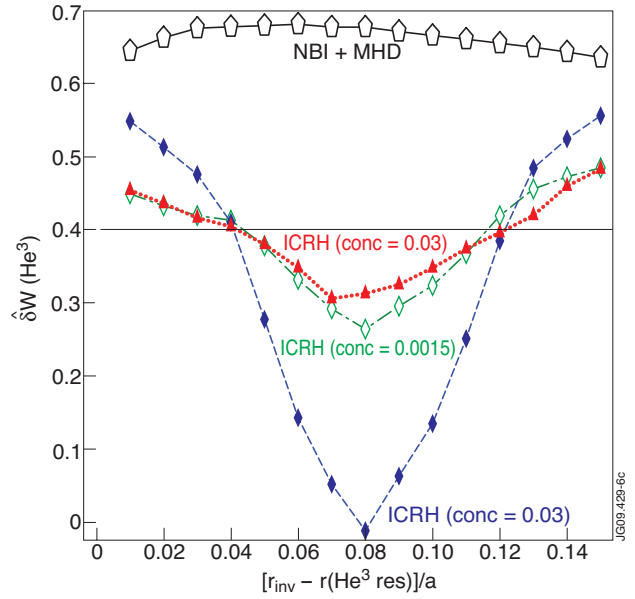


Figure 6: Comparing the effect of minority ion concentration via SELFO/HAGIS simulations of δW , plotted with respect to $r_1 - r_{\text{inv}}$. Curves with $n_h = n_e = 0.01$ and $n_h = 0.03$ correspond approximately to the conditions of Pulse No's: 78737 and 78740 respectively. The NBI and MHD contributions are also shown.