ANALYSIS OF ION CYCLOTRON CURRENT DRIVE AT $\omega \approx 2\omega_{cH}$ FOR SAWTOOTH CONTROL IN JET PLASMAS

M.J. Mantsinen[1], M.-L. Mayoral[2], O. Sauter[3], E. Westerhof[4], C. Angioni[3], L.-G. Eriksson[5], A. Gondhalekar[2], T. Hellsten[6,7], T. Johnson[6], K.G. McClements[2], F. Nave[8], F. Nguyen[5], S. Podda[9], J. Rapp[10], S. Sharapov[2] and contributors to the EFDA-JET workprogramme[*]

[1]*Helsinki University of Technology, Association Euratom-Tekes, Finland*
[2]*Euratom/UKAEA Fusion Association, Culham, United Kingdom*
[3]*CRPP, Association EURATOM-Confédération Suisse, EPFL, Lausanne, Switzerland*
[4]*FOM-Rijnhuizen, Association Euratom-FOM, TEC, Nieuwegein, The Netherlands*
[5]*Association EURATOM/CEA, CEA Cadarache, Saint-Paul-Lez-Durance, France*
[6]*Alfvén Laboratory, Association Euratom-VR, Stockholm, Sweden*
[7]*EFDA Close Support Unit, Culham, United Kingdom*
[8]*Associação EURATOM-IST, Centro de Fusão Nuclear, Lisboa, Portugal*
[9]*Associazione EURATOM-ENEA sulla Fusione, Frascati, Rome, Italy*
[10]*Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, EURATOM Association, TEC, Jülich, Germany*

Introduction Developing schemes for reducing the detrimental effects of sawteeth is an important objective in JET operation. To this end, minority hydrogen (with $\eta_H = n_H/(n_D+n_H) \approx$ 5-15%) ICRF heating and current drive at $\omega \approx 2\omega_{cH}$ in deuterium plasmas has been used to reduce the sawtooth period and amplitude. By helping to keep the size of the m=3/n=2 neoclassical tearing mode (NTM) seed island smaller than a critical value and thereby delaying onset of NTMs, the ICRF scheme also allows a higher normalised beta, β_N, and improved plasma performance to be obtained [1,2]. In the following, these experimental observations are modelled and elucidated.

Numerical modelling tools The PION code [3] calculates the time-evolution of the ICRH power deposition and distribution functions of the resonating ions, using measured plasma parameters. To calculate the spatial profile of the current driven by the resonating ions for required time-slices, the 3-D Monte Carlo code FIDO [4] is used. In the FIDO simulations presented here, the plasma parameters are taken at a given time point during the discharge from the JET database, and the wave characteristics are consistent with those given by PION.

Results Experiments were carried out with the $\omega \approx 2\omega_{cH}$ resonance either on the high (HFS) or low field side (LFS). Up to 4.5-5 MW of ICRH power was applied at a frequency of 42 MHz using either +90° or –90° phasing.

LFS $\omega \approx 2\omega_{cH}$ resonance The possibility to affect the sawtooth period with ICRH was studied in ICRH-only discharges with a ramp in the magnetic field B and the plasma current to change the resonance location with respect to the inversion radius (constant q). With the $\omega \approx 2\omega_{cH}$ resonance on the LFS (discharge 51800 with –90° phasing, η_H of 12% and a B ramp from 1.6 to 1.35T), minima in the sawtooth period were observed as the LFS resonance moved through the inversion radius in time (Fig. 1). It is difficult to explain such behaviour in terms of sawtooth stabilisation by the fast ion pressure alone [5], since this is expected to give rise to more stabilisation the further the resonance is inside the q=1 surface.

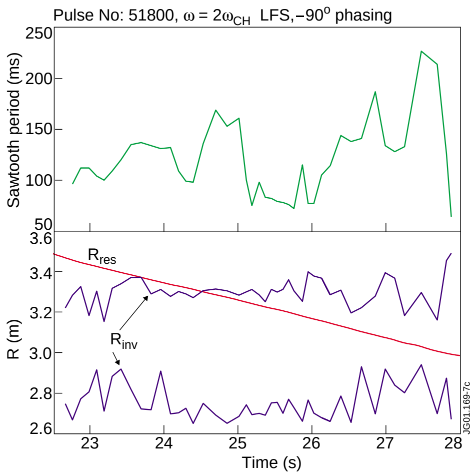

Figure 1 Sawtooth period and $\omega \approx 2\omega_{cH}$ *resonance and inversion radius locations for discharge 51800.*

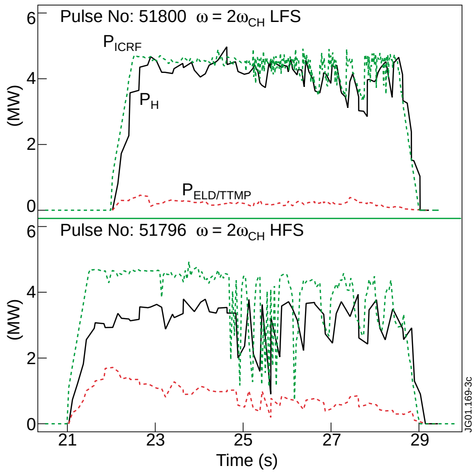

Figure 2 Power partitioning as given by PION for discharges 51800 and 51796, respectively.

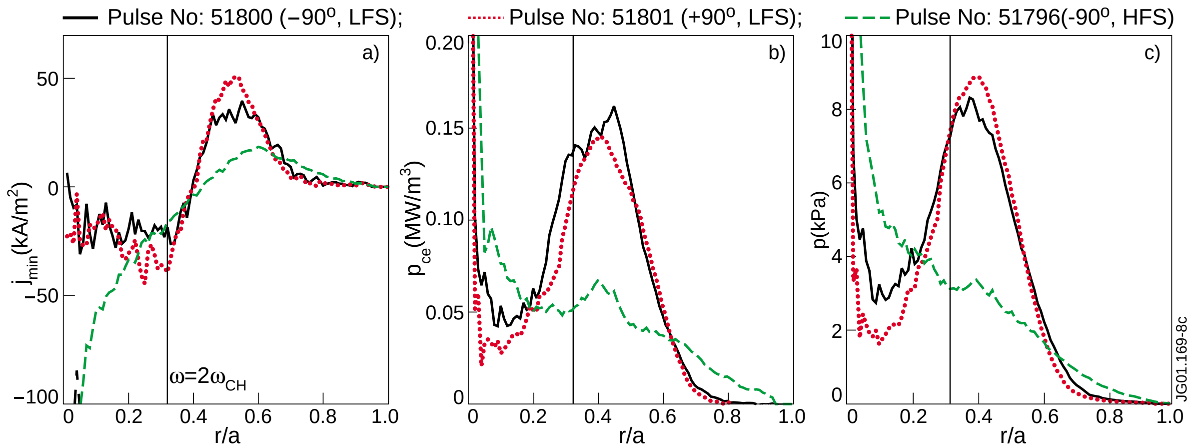

Figure 3 Current density driven by ICRH-accelerated protons, collisional electron heating power density and fast proton pressure profile as given by FIDO for discharges 51800, 51801 and 51796.

According to PION, about 95% of the ICRH power is absorbed by H and the rest by direct electron damping (Fig. 2). The calculated tail temperature of the fast protons is about 5-10 times the critical energy E_{crit} of about 20 keV at which protons transfer energy equally to background electrons and ions. Consequently, mainly collisional electron heating is obtained. The current density driven by fast protons, together with collisional electron heating and fast proton pressure profiles, as computed using the FIDO code are shown in Fig. 3. The current perturbation decreases the magnetic shear in a narrow (≈10cm) region just outside the resonance layer and increases the shear on both sides of this narrow region. These results are consistent with the minima in the sawtooth period with the resonance on either side of the inversion radius (cf. Fig. 1). The net contribution to the local current density, after correcting for the back current carried by electrons, is about 3-6%. PRETOR transport code calculations with a sawtooth crash trigger model [6] show that the magnitude of the driven current is large enough to affect the sawteeth in the present experimental conditions. With the resonance well inside the q=1 surface, sawtooth stabilisation by fast ion pressure [5] (Fig. 3c) becomes important. The electron power deposition (Fig. 3b) is also sufficiently localised to affect sawteeth according to PRETOR, lengthening τ_{saw} when the electron power deposition is localised somewhat outside and close to the q=1 surface. Localised electron heating plays a role for sawteeth by affecting the shear and electron pressure gradient [6].

In Fig. 3 results from FIDO modelling are also shown for discharge 51801 carried out in the same way as discharge 51800 but with +90° phasing of ICRH antennas. As we can see, not only the fast proton energy density and collisional electron heating profiles, but also the current driven by ICRH-heated protons have similar shapes to those with –90° phasing. The reason for this is that in both cases the current is dominated by a current of diamagnetic type [7], caused by the finite orbit widths of trapped resonating protons. The presence of similar populations of fast protons is supported by the similar AE mode activity driven by fast protons in the two discharges. The sawtooth behaviour is also similar [2].

These results indicate that control of sawteeth with the $\omega \approx 2\omega_{cH}$ scheme can be obtained by varying the resonance location. Based on these results, experiments with a ramp in NBI power have been performed at different magnetic fields, associated with resonance positions leading to different sawtooth periods. It has been shown that β_N at which NTMs are triggered can be increased in the presence of short-period sawteeth [1,2].

HFS $\omega \approx 2\omega_{cH}$ resonance With the resonance on HFS (discharge 51796 with –90° phasing, η_H of 9% and a B ramp from 1 to 1.35T), direct electron damping increases as compared with the LFS resonance (Figs 2 and 4). Furthermore, the contribution from the passing ions to the driven current dominates, and collisional electron heating and fast ion pressure profiles are significantly broader than for an LFS resonance (Fig. 3).

A comparison of two 1.2 T discharges with the same NBI power but one with and one without ICRH is shown in Fig 5. The anomalously high neutron rate with ICRH (up to NTM onset) correlates with the applied ICRH power and is consistent with D damping at the $\omega \approx 5\omega_{cD}$ resonance located in the plasma centre (i.e. between the $\omega \approx 2\omega_{cH}$ resonance and the low-field-side ICRH antennas). The presence of deuterons with $E >> E_{crit}$ is confirmed by high-energy NPA measurements. From the excess neutron yield we estimate that the parasitic

D absorption in the centre increases from 20% to 30% of the applied ICRH power as the beam beta increases.

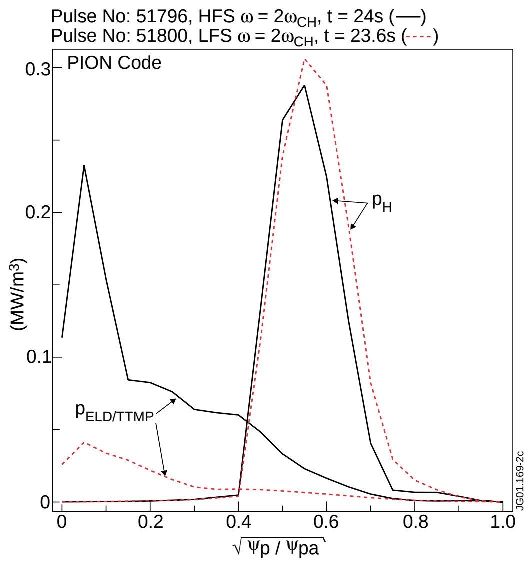

Figure 4 Calculated direct electron and H absorption profiles as given by PION for discharges 51800 and 51796 with an LFS and HFS resonance, respectively.

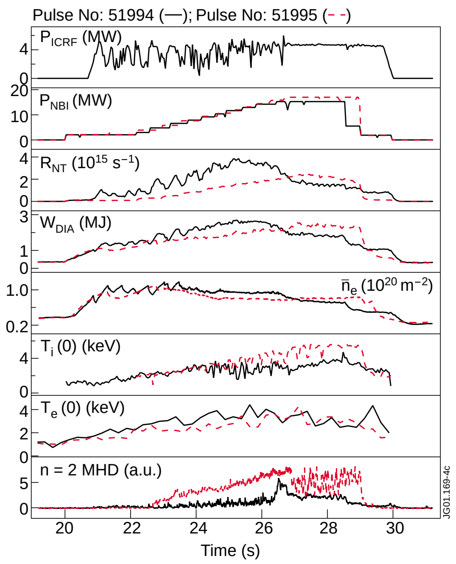

Figure 5 Overview of discharges 51994 and 51995 with and without ICRH power tuned to an LFS $\omega \approx 2\omega_{cH}$ resonance.

Conclusions ICRH-related quantities in JET experiments with ICRF waves tuned to the $\omega \approx 2\omega_{cH}$ resonance for sawtooth control have been analysed and quantified. It is found that second-harmonic hydrogen damping is maximized by placing the resonance on the LFS, which minimizes competing direct electron damping and parasitic high-harmonic D damping in the presence of D beams. The shape of the calculated current perturbation for the LFS resonance appears consistent with the experimentally observed minima in the sawtooth period when the resonance layer moves through the q=1 surface. Due to differences in fast ion orbits for LFS and HFS resonances, collisional electron heating and fast ion pressure profiles are significantly more peaked for an LFS resonance. The fast ion pressure and localised electron heating can also affect the sawteeth by providing sawtooth stabilisation when the resonance is inside or just outside the q=1 surface, respectively.

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*See appendix of the paper by J.Pamela "Overview of recent JET results," Proceedings of the IAEA conference on Fusion Energy, Sorrento (2000).