EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–PR(03)61

L.-G. Eriksson, A. Mueck, O. Sauter, S. Coda, M.J. Mantsinen, M.L. Mayoral,
E. Westerhof, R.J. Buttery, D. McDonald, T. Johnson, J.-M. Noterdaeme,
P. de Vries and JET EFDA contributors

# Destabilisation of Fast Ion Induced Long Sawteeth by Localised Current Drive in the JET Tokamak

# Destabilisation of Fast Ion Induced Long Sawteeth by Localised Current Drive in the JET Tokamak

L.-G. Eriksson[1], A. Mueck[2], O. Sauter[3], S. Coda[3], M.J. Mantsinen[4],
M.L. Mayoral[5], E. Westerhof[6], R.J. Buttery[5], D. McDonald[5], T. Johnson[7],
J.-M. Noterdaeme[2, 8], P. de Vries[6, 9] and JET EFDA contributors*

[1]Association EURATOM-CEA, CEA/DSM/DRFC, CEA-Cadarache, F-13108 St. Paul lez Durance, France
[2]Max-Planck IPP-EURATOM Assoziation, Garching, Germany
[3]EURATOM Confédération Suisse, CRPP-EPFL, Lausanne, Switzerland
[4]Helsinki University of Technology, Association Euratom-Tekes, Finland
[5]EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon Oxon OX14 3DB, UK
[6]FOM-Rijnhuizen, Ass. EURATOM-FOM, TEC, Nieuwegein, The Netherlands
[7]EURATOM-VR Association, Stockholm, Sweden
[8]Gent University, Department EESA, Belgium
[9]The Stichting voor Fundamenteel Onderzoek der Materie FOM, The Netherlands
* See annex of J. Pamela et al, “Overview of Recent JET Results and Future Perspectives”,
Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).

Preprint of Paper to be submitted for publication in
Physical Review Letters

## ABSTRACT

In a tokamak fusion reactor the energetic alpha particles will transiently stabilise the Magnetohydrodynamic activity causing sawtooth oscillations, changing the underlying physics governing this activity. The crash events terminating such sawtooth free periods have been shown to provide seed islands for Neo Classical Tearing modes [O. Sauter et al., Physical Review Letters 88, 105001 (2002)], which in their turn degraded the plasma performance. Consequently, it is desirable to prevent the occurrence of long sawtooth free periods. A possibility is to use localized current drive near the q = 1 surface. This letter provides the first experimental proof of principle for the application of this method in the different physics regime associated with fast ion induced long sawteeth on the JET Tokamak.

## INTRODUCTION

An important figure of merit for a fusion plasma is the $\beta$ value, defined as $\beta = p/(B^2/2\mu_0)$ (ratio of plasma pressure to the magnetic pressure, where B is the main confining magnetic field). A high performance reactor grade plasma must operate at a relatively high $\beta$ value, and much research has been devoted to investigating the factors limiting the achievable $\beta$. Upper limits on $\beta$ are set by ideal (i.e. non-resistive) Magnetohydrodynamic (MHD) instabilities. However, in recent years it has been recognised that a type of non-ideal resistive instability, the so called Neo-classical Tearing Modes (NTM), are destabilised at considerably lower $\beta$ values than ideal MHD modes [1, 2]. Thus, unless NTMs can be avoided, they could significantly limit the performance of a fusion plasma.

The NTMs give rise to magnetic islands near resonant surfaces corresponding to rational values of the safety factor $q$ ($q$ is a measure of the magnetic field line pitch in a tokamak). However, stabilizing effects dominate for small island sizes [2]. As a consequence, a finite size seed island is required for destabilization of NTMs. Such a seed island could be provided by another form of MHD activity, viz. sawtooth activity. Especially crashes after long sawtooth free periods have been found to be prone to trigger NTMs [3]. Sawtooth activity arises when the safety factor goes below one in the centre of the plasma. So-called internal kink modes then become unstable, magnetic islands appear, and a sudden redistribution of the central part of the plasma takes place. This manifests itself as an abrupt drop (a crash) of the central temperature. These events are repeated and the time trace of the central plasma temperature has a sawtooth like appearance. The presence of a significant fast ion, i.e. non-thermal, pressure in the centre of the plasma can transiently stabilise the internal kink modes [5], allowing the radius of the $q$=1 surface to expand and periods between crashes to become long. This phenomenon is in certain circumstances referred to as monster sawteeth [6]. In a reactor plasma, long sawtooth free periods could arise due to the strong presence of energetic fusion born alpha particles; and the possible appearance of seed islands capable of destabilising NTMs in connection with the crashes of such long sawteeth is therefore of considerable concern for a reactor plasma. It should be noted, however, that the periods in between crashes have no detrimental effects.

It has been demonstrated experimentally that the triggering of NTMs is strongly linked to the periods between the sawtooth crashes, and that they can be avoided by shortening the sawtooth period [3, 4]. One can therefore conjecture that the size of the seed islands responsible for triggering NTMs depends on the sawtooth period. Thus, developing methods for shortening the sawtooth period appears important in preparing for reactor operation. A possible way forward is to apply localized current drive near the $q$=1 surface. Although it is well established, both theoretically and experimentally [5, 7], that an increase of the magnetic shear ( $(1/q)dq/dr$ ) near the q=1 surface has a destabilizing effect on internal kink modes associated with sawtooth oscillations in plasmas without a significant fast ion pressure, it is not evident that fast ion induced long sawteeth can be destabilised as easily. As discussed in some detail below, the crash criteria are different. Thus, before localised current drive near the q=1 surface can be considered as a credible candidate for destabilization of fast ion induced long sawtooth periods in a reactor, a proof of principle is needed on present day tokamaks. In this letter we present results from experiments carried out on the JET tokamak which, to our knowledge, are the first to demonstrate that localized current drive indeed is a viable method for avoiding long fast ion induced sawteeth. In the experiments, long sawtooth free periods were created by the presence of fast ions accelerated by heating with waves in the Ion Cyclotron Range of Frequencies (ICRF). The localized current drive was also provided by ICRF waves, but at a different frequency via the minority Ion Cyclotron Current Drive (ICCD) mechanism.

The most efficient scenario for creating long sawteeth in JET is to use hydrogen minority heating in deuterium plasma (H)D, where a small fraction of H ions ($n_H/n_D$ ~5%) absorb the ICRF power and are accelerated to high energies. Presently on JET, only ICCD induced by the absorption of ICRF waves has a proven track record of providing a well-localized current perturbation [8]. The ICRF power is absorbed in the vicinity of the cyclotron resonance layer ($\omega = n\omega_{ci}(R)$, where $\omega_{ci}$ is the ion cyclotron frequency of a resonating species and $n$ is the harmonic number of the interaction), and a fast ion current is driven in the neighbourhood of the flux surface that is tangent to the cyclotron resonance layer in the equatorial plane. The fact that the localisation of the driven current can be controlled by moving the cyclotron resonance makes ICCD particularly suitable for affecting the magnetic shear near the $q$=1 surface. Thus, the power delivered by the ICRF system on JET had to be used for both creating the long sawtooth free periods and for the localized current drive.

The capabilities of ICCD to stabilise and destabilise sawteeth have been studied in recent experimental campaigns on JET [8, 9] It has been found that that ICCD is particularly efficient at destabilising sawteeth for (H)D heating when predominantly counter current propagating waves and cyclotron resonances near the $q$=1 surface on the high field side are used. However, it must be emphasised that these experiments, and also previous ones [7, 10] on sawtooth destabilisation by localised currents, were carried out without a strong fast particle pressure. For such cases, the crash criterion is satisfied when the growth rate of the most unstable resistive internal kink mode exceeds diamagnetic frequencies. This criterion can be re-written in a simple formula stating that the crash is triggered when $s_1 > s_{1crit}$ [7], where $s_1$ is the shear at $q$=1 and $s_{1crit}$ a critical shear depending on the plasma profiles and gradients at $q$=1. In this regime it is clear that the modification of the time evolution of $s_1$, through local current drive, can lead to strong modification of the sawtooth period [10]. In the case of fast particles stabilised sawteeth, the crash criterion is different and depends on the magnitude of the stabilising contribution of fast particles to the potential energy $\delta W_f$ [5]. There is a crash when $\delta W_f$ decreases below a certain threshold. As $\delta W_f$ is proportional to $1/s_1$, one can try to shorten the sawtooth period by increasing $s_1$. However as $\delta W_f$ is large and decreases significantly only when the radius of $q$=1 increases significantly, it is not clear that one can affect the sawtooth period significantly solely with local current drive for such fast particle stabilised sawteeth. For this reason it is necessary to investigate experimentally whether localised current drive is capable of destabilising them or not.

ICCD and its effect on the magnetic shear is a complex phenomenon with several factors playing a role, see e.g. [11]. The first ICCD effect to be considered was the mechanism proposed by Fisch [12], where a fast ion current with a dipole structure, positive on one side of the cyclotron resonance and negative on the other, is driven by passing ions resonating with directed (i.e. travelling) waves. The relative sign of the current perturbation on either side of the cyclotron resonance layer depends on the direction of the wave propagation with respect plasma current. However, the ICRF interaction tends to drive the resonating ions into the trapped region, limiting the efficiency of the Fisch mechanism. The number of trapped resonating ions starts to dominate when the ratio of the ICRF power to the number of resonating ions is sufficiently high. On the other hand, the trapped ions also produce a current with a dipole structure close to their cyclotron resonance [11]. However, since the ion velocity on the inner leg of a trapped orbit always is in the counter current direction and in the co-current direction on the outer leg, the sign of the local fast ion current with respect to the plasma current cannot be changed by the direction of propagation. Nevertheless, the direction of propagation has an important effect on the spatial distribution of the fast resonating ions and the relative fraction of topologically different orbits they occupy [11, 13, 14]. As a result, the driven fast ion current is strongly affected by the direction of propagation even when the mechanism proposed by Fisch is not dominant.

A locally driven current with a dipole structure creates neighbouring regions of lower and higher magnetic shear. Consequently, whether the driven current has a stabilising or destabilising effect on the sawtooth oscillations depends sensitively on the relative position of the cyclotron resonance and the $q$ = 1 surface, the relative size of the regions of positive and negative driven currents and the strengths of the driven currents. The latter factors depend strongly on the plasma conditions, especially on the concentration of resonating ions (it was around $n_H/(n_H + n_D \sim 4\text{–}5\%$ in the experiments reported here), and the applied ICRF power. As a consequence, it was necessary to fine-tune the position of the cyclotron resonance layer, $\omega = \omega_c\,(R)$, in the experiments to optimise the destabilising effect.

The same minority species, hydrogen, was used for both creation of monster sawteeth and ICCD. The slight concern one could have with this is the use of directed waves for driving the localised current. The absorption of directed ICRF waves leads to a drift of the turning points of the resonating trapped ions inward/outward when the waves propagate predominantly in the co-/counter-current direction [13, 14], i.e. co-current propagating waves should give rise to a greater peaking of the fast ion pressure profile while counter current propagating waves should lead to a broader profile. For the experiments reported here, counter current propagating waves were used for ICCD. Owing to the Doppler broadening of the cyclotron resonance, there is then a risk that the fast hydrogen ions in the centre absorb a fraction of the power intended for ICCD, possibly leading to a less peaked fast ion pressure profile inside the $q = 1$ surface and therefore to shorter sawtooth periods. Thus, a set of experiments had to be designed to exclude this possibility and to demonstrate more conclusively that the localised current drive was the crucial factor in shortening the sawtooth periods.

The ICRF antennas in JET each have four current carrying straps, and the currents in the straps can be phased relative to each other. For $+90^o$ $(-90^o)$ phasing between the currents in adjacent straps, the antennas launch waves propagating predominantly in the co-(counter-) current direction. In view of the limited ICRF power available and the need to have a high fast ion pressure inside the q = 1 surface for creating monster sawteeth, $+90^o$ phasing was used for the ICRF power with a wave frequency corresponding to a H cyclotron resonance near the magnetic axis. The experimental sequence for the demonstration of long sawtooth destabilisation with ICCD was to first launch 3MW of $+90^o$ ICRF power to establish fast ion induced long sawteeth, the $-90^o$ ICRF power for ICCD was then applied and the discharge was allowed to develop into a semi steady state. In order to locate the optimal position of the cyclotron resonance position for destabilising pre-formed monster sawteeth with ICCD, a number of discharges were carried out where the vacuum magnetic field in the centre of the tokamak was varied in small steps between 2.66 and 2.79T. The plasma current was kept at 2.6MA in all of the discharges. A summary of the discharges carried out in this series of experiments is given in Table 1 (including three reference discharges described below). The best result was obtained in Pulse No: 58934 at 2.76T. A frequency of $f$=42 MHz was used for the $+90^o$ ICRF power aimed at establishing monster sawteeth, corresponding to an H cyclotron resonance close to the magnetic axis (R ≈ 35m); and the frequency of the ICRF power destined for ICCD was $f$=47 MHz, locating its H cyclotron resonance close to the $q = 1$ surface, around 25cm on the high field side (R ≈ 2.75m). Figure, 1 shows an overview of this demonstration discharge. A clear destabilisation of the monster sawteeth occurred a short period after the ICRF power for ICCD was turned on, it went from about $\tau_{saw}$=200-250ms to around 80ms. The traces of the inversion radius of the sawteeth (closely linked to the q=1 surface) and the cyclotron position show that the distance between them was evolving briefly after the application of the ICCD power, and before the conditions become optimal for destabilisation. This discharge provides a strong indication that localised current drive near the $q$=1 surface is a feasible method for avoiding long sawtooth free periods in a reactor.

Before we can draw any firmer conclusion, however, we need to exclude the possibility that the destabilised sawteeth in Fig.1 were caused by a decreased fast ion pressure inside $q = 1$. As discussed above, parasitic absorption of $-90^o$ ICRF power by the fast hydrogen ions in the centre could have had an effect on the fast ion pressure. In the worst-case scenario, all the $-90^o$ power would be absorbed by the fast hydrogen ions in the centre. To investigate this we did one reference discharge where the frequency for the 3MW $-90^{o}$ power was changed to give a central resonance, ensuring that both the $+90^{o}$ and $-90^{o}$ powers were deposited in the centre. However, one could argue this would give more absorption in the centre than our demonstration discharge had in reality. Another reference discharge was therefore necessary. To limit the total power absorbed in the centre but at the same time provide a fast ion pressure profile as broad as could realistically be imagined, a reference discharge with 1.5MW of $+90^{o}$ power, 1.5 MW of $-90^{o}$ power and central H cyclotron resonances for both was carried out. The significance of this discharge is that it had the maximum possible fraction of $-90^{o}$ power absorbed in the centre while keeping the total central power at the 3MW used to establish the monster sawteeth in the demonstration discharge. A final reference discharge was produced where the $-90^{o}$ ICCD power was exchanged for $+90^{o}$ ICCD power. This was done to demonstrate that $+90^{o}$ phasing produces a different effect on the sawteeth when the conditions for destabilisation are near optimal for $-90^{o}$ ICCD, i.e. there are likely differences in the driven currents. The electron temperatures for the demonstration discharge and the reference discharges are shown in Fig.2. The sawtooth periods in all the reference discharges are longer than the destabilised sawteeth in the demonstration discharge. Thus, one can say with considerable confidence that the destabilisation of the sawteeth in the demonstration discharge was indeed due to the localised current drive provided by the ICCD. The result of the scan of the vacuum magnetic field also gives us an idea about the sensitivity of the resonance position. The difference in terms of sawtooth period between B=2.76 T and B=2.71T, corresponding to a change in the resonance position by about 5cm, is considerable. This is consistent with the time delay in the destabilising effect of the ICCD shown in Fig.1. Furthermore, simulations of sawtooth destabilisation with ECCD performed on TCV [10] shows a similar sensitivity to the relative distance between the $q$=1 surface and the resonance position. Thus, for the localised current drive to be of practical use for destabilising long sawteeth, it is probably necessary to implement a feedback on the position of the driven current.

In summary we have presented experimental results that provide evidence for the ability of localised current drive to destabilise fast ion induced long sawtooth periods. If not destabilised, the termination of such long sawtooth free periods, induced for instance by the presence of energetic alpha particles in a reactor, could provide magnetic seed islands capable of triggering NTMs and thus impairing the plasma performance. In view of the serious threat posed by NTMs to the plasma performance in a reactor, its success might well depend on having a capability of destabilising fast ion induced long sawteeth. In the present study, minority Ion Cyclotron Current Drive provided the localised current drive needed for the destabilisation of long sawtooth free periods. This method could be utilised under reactor conditions as well. Another possibility is to use Electron Cyclotron Current Drive (ECCD). An important advantage of both these methods is the possibility of fine tuning the localisation of the driven current by small variations of the confining magnetic field.

## REFERENCES

[1]. O. Sauter et al., Physics of Plasmas **4**, 1654 (1997).
[2]. R.J. Buttery et al., Plasma and Controlled Fusion **42**, B61 (2000).
[3]. O. Sauter et al., Physical Review Letters **88**, 105001 (2002).
[4]. E. Westerhof, et al., Nuclear Fusion **42**, 1324 (2002).
[5]. F Porcelli, D Boucher and M N Rosenbluth, Plasma Physics & Controlled Fusion **38** (1996) 2163.
[6]. D. J. Campbell et al., Physical Review Letters **60**, 2148 (1988).
[7]. V.P. Bhatnagar, et al., Nuclear Fusion **34**, 1586 (1994).
[8]. M.L. Mayoral et al., submitted to Physics of Plasmas.
[9]. M. Mantsinen, et al., Plasma Physics and Controlled Fusion **44**, 1521 (2002).
[10]. Angioni, T. P. Goodman, M. A. Henderson, O. Sauter, Nucl. Fusion **43** (2003) 455
[11]. T. Hellsten et al., Phys. Rev. Lett. **74**, 3612 (1995).
[12]. N.J. Fisch, Rev. Mod. Physics, **59**, 175 (1987).
[13]. L.-G. Eriksson, et al., Phys. Rev. Lett. **81**, 1231 (1998).
[14]. M.Mantsinen, at al., Phys. Rev. Lett. **89**, 115004-1 (2002).

| Pulse No: | $P_{RF}$ (MW) (phasing) | $P_{RF}$ (MW) (phasing) | $f_{RF}$ | $<\tau_{saw}>$ ms between 23 <t< 24s | Comment |
|---|---|---|---|---|---|
| 58934 | 2.76 | 3 (+90$^o$) / 3(−90$^o$) | 42/47 | 80<br>250 (16-18s) | Demonstration discharge, −90$^o$ for off axis ICCD |
| 58939 | 2.76 | 3 (+90$^o$) / 3(−90$^o$) | 42/**42** | 600-800 | Reference with central res. for both +90$^o$ & −90$^o$ |
| 58940 | 2.76 | **1.5** (+90$^o$) / **1.5**(−90$^o$) | 42/**42** | 200-250 | Reference with central res. for both +90$^o$ & −90 |
| 58941 | 2.76 | 3 (+90$^o$) / 3(**+90$^o$**) | 42/47 | 550-700 | Reference with +90$^o$ for off axis |
| 58935 | **2.66** | 3 (+90$^o$) / 3(−90$^o$) | 42/47 | 500-600 | $B_{vac}$. scan |
| 58936 | **2.74** | 3 (+90$^o$) / 3(−90$^o$) | 42/47 | 100 | $B_{vac}$. scan |
| 58937 | **2.79** | 3 (+90$^o$) / 3(−90$^o$) | 42/47 | 90-100 | $B_{vac}$. scan |
| 58938 | **2.71** | 3 (+90$^o$) / 3(−90$^o$) | 42/42 | 500 | $B_{vac}$. scan |

*Table 1. Main features of the discharges in the reported series of esperiments. $B_{vac}$ is the vacuum magnetic field at the geometrical centre of the tokamak (R=2.96 m). The values in bold are the main differences with the demonstration*

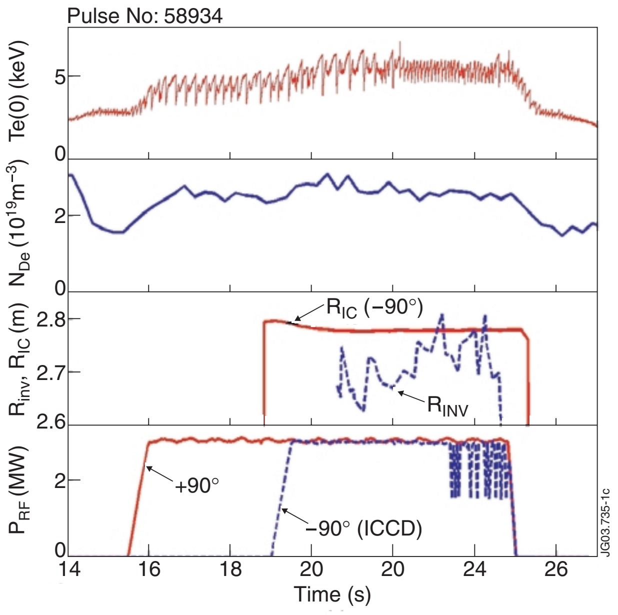

*Figure 1: Overview of a discharge where monster sawteeth were destablised by ICCD, (a) central electron temperature measured by ECE; (b) central electron density ; (c) major radius positions in the equatorial plane of the sawtooth inversion radius and the cyclotron resonance for the –90$^o$ ICCD power; (d) ICRF power, +90$^o$ central resonance solid line, -90$^o$ ICCD dashed line.*

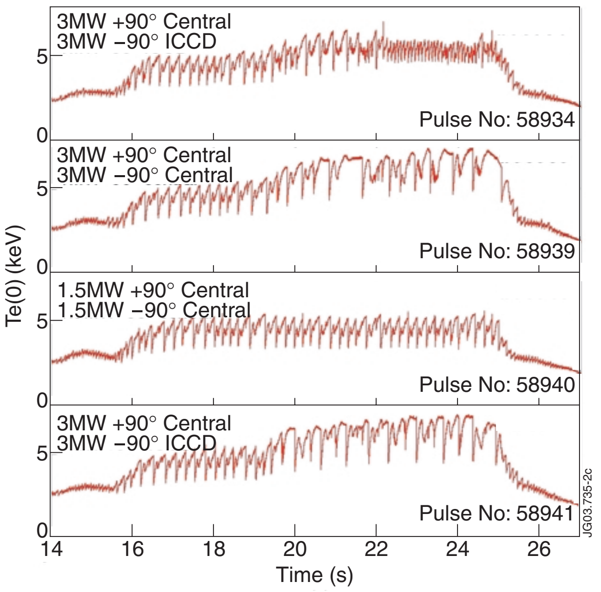

*Figure 2: Electron temperatures for the demonstration discharge in Fig.1 and for the 3 reference discharges. The timing of the power wave forms are the same as in Fig.1.*