Destabilization of Fast-Ion-Induced Long Sawteeth by Localized Current Drive in the JET Tokamak

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In a tokamak fusion reactor the energetic alpha particles will transiently stabilize the magnetohydrodynamic activity causing sawtooth oscillations. The crash events terminating long sawtooth free periods can provide seed islands for neoclassical tearing modes [O. Sauter *et al.*, Phys. Rev. Lett. **88**, 105001 (2002)]. To shorten the sawtooth periods localized current drive near the $q = 1$ surface is a possibility. This Letter provides the first experimental evidence for the effectiveness of this method in the different physics regime associated with fast-ion-induced long sawteeth on the JET tokamak.

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An important figure of merit for a fusion plasma is the β value, defined as $\beta = p/(B^2/2\mu_0)$ (ratio of plasma pressure to the magnetic pressure, where B is the magnetic field). A high performance reactor grade plasma must operate at a relatively high β value, and much research has been devoted to investigating the factors limiting the achievable β. The upper limits on β are set by ideal (i.e., nonresistive) magnetohydrodynamic (MHD) instabilities. However, in recent years it has been recognized that a type of nonideal resistive instability, the so-called neoclassical tearing modes (NTM), are destabilized at considerably lower β values than ideal MHD modes [1–3]. 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]. Consequently, 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 [4]. Sawtooth activity arises when the safety factor goes below one in the center 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 sawtoothlike appearance. The presence of a significant fast ion, i.e., nonthermal, pressure in the center of the plasma can transiently stabilize the internal kink modes [5], allowing the radius of the $q = 1$ surface to expand and periods between crashes to become long [6,7]. 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; the possible appearance of seed islands destabilizing NTMs after crashes 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 found 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 [4,8]. 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 [5,9], that an increase of the magnetic shear, $s = (r/q)dq/dr$, 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 destabilized as easily. As discussed in some detail below, the crash criteria are different. Thus, before localized 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

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from experiments carried out on the Joint European Torus (JET) tokamak which, to our knowledge, are the first to demonstrate that localized current drive 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 hydrogen minority heating in deuterium plasma (H)D, where a small fraction of H ions ($n_{\rm H}/n_{\rm D} \sim 5\%$) absorb the ICRF power and are accelerated to high energies. Presently on JET, only ICCD has a proven track record of providing a well-localized current perturbation [10]. The ICRF power is absorbed in the vicinity of the cyclotron resonance layer [$\omega = n\omega_{ci}(R)$, where ω_{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 neighborhood of the flux surface that is tangent to the cyclotron resonance layer in the equatorial plane. The fact that the localization of the driven current can be controlled by moving the cyclotron resonance makes ICCD particularly suitable for affecting s near $q = 1$. Thus, the ICRF system on JET had to be used for both creating long sawtooth free periods and for the localized current drive.

In recent experimental JET campaigns [10,11], ICCD has been found to be particularly efficient at destabilizing sawteeth for (H)D heating with predominantly countercurrent propagating waves and cyclotron resonances near the $q = 1$ surface on the high field. However, it must be emphasized that these experiments, and also previous ones [9,12] on sawtooth destabilization by localized 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 rewritten in a simple formula stating that the crash is triggered when $s_1 > s_{1\rm crit}$ [5], where $s_1 = s(q = 1)$ and $s_{1\rm crit}$ is a critical shear depending on the plasma profiles 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 [12]. The crash criterion is different for fast particle stabilized sawteeth; it depends on the magnitude of their stabilizing contribution to the potential energy δW_f [5]. There is a crash when δW_f decreases below a certain threshold. As δW_f is proportional to $1/s_1$, one can try to shorten the sawtooth period by increasing s_1. However, since δW_f is large and decreases significantly only when the $q = 1$ radius increases appreciably, it is not clear whether one can affect the sawtooth period significantly solely with local current drive for fast particle stabilized sawteeth. For this reason it is necessary to investigate experimentally whether localized current drive is capable of shortening them or not.

ICCD and its effect on the magnetic shear is a complex phenomenon with several factors playing a role; see, e.g., [13]. The driven current has a dipole structure, positive on one side of the cyclotron resonance and negative on the other. Both passing and trapped resonating ions contribute to it. The sign of the contribution from passing ions depends on the propagation direction of the waves [14]. On the other hand, while the amplitude and spatial distribution of the trapped ion contribution depends on the wave direction, the sign is unaffected [13,15,16].

A locally driven current with a dipole structure creates neighboring regions of lower and higher magnetic shear. Consequently, whether the driven current has a stabilizing or destabilizing effect on the sawtooth oscillations depends sensitively on the relative position of the cyclotron resonance and the $q = 1$ surface, on the relative size of the regions of positive and negative driven currents, and on the strengths of the driven currents. The latter factors depend strongly on the plasma conditions, especially on the concentration of resonating ions [in the experiments reported here $n_{\rm H}/(n_{\rm H} + n_{\rm D}) \sim 4\%$–$5\%$], and the applied ICRF power. Consequently, it was necessary to fine-tune the position of the cyclotron resonance, $\omega = \omega_c(R)$, to optimize the destabilizing 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 localized 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-/countercurrent direction [15,16]; i.e., cocurrent propagating waves should give rise to a greater peaking of the fast ion pressure profile while countercurrent propagating waves should lead to a broader profile. For the experiments reported here, countercurrent 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 center 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 modifications of s_1 were crucial for shortening the sawtooth period.

The ICRF antennas in JET each have four current carrying straps. For +90° (−90°) 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° phasing was used for the ICRF power with a wave frequency corresponding to a H cyclotron resonance near

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

Shot #	B_{vac} (T)	P_{rf} (MW) (phasing)	f_{rf} (MHz)	$\langle\tau_{\mathrm{saw}}\rangle$ (ms) between $63 < t < 64$ s	Comment
58 934	2.76	3 (+90°)/3 (−90°)	42/47	80 (250, 56–58 s)	Demonstration discharge, −90° for off-axis ICCD
58 939	2.76	3 (+90°)/3 (−90°)	42/**42**	600–800	Reference with central res. for both +90° & −90°
58 940	2.76	**1.5** (+90°)/**1.5** (−90°)	42/**42**	200–250	Reference with central res. for both +90° & −90°
58 941	2.76	3 (+90°)/3 (+**90**°)	42/47	550–700	Reference with +90° for off-axis ICCD
58 935	**2.66**	3 (+90°)/3 (−90°)	42/47	500–600	B_{vac} scan.
58 936	**2.74**	3 (+90°)/3 (−90°))	42/47	100	B_{vac}scan.
58 937	**2.79**	3 (+90°)/3 (−90°))	42/47	90–100	B_{vac}scan.
58 938	**2.71**	3 (+90°)/3 (−90°)	42/42	500	B_{vac}scan.

the magnetic axis. The experimental sequence for the demonstration of long sawtooth destabilization with ICCD was to first launch 3 MW of +90° ICRF power to establish fast-ion-induced long sawteeth, the −90° ICRF power for ICCD was then applied, and the discharge was allowed to develop into a semisteady state. In order to locate the optimal position of the cyclotron resonance position for destabilizing preformed monster sawteeth with ICCD, a number of discharges were carried out where the vacuum magnetic field in the center of the tokamak was varied in small steps between 2.66 and 2.79 T. The plasma current was kept at 2.6 MA in all of the discharges. A summary of the discharges carried out in this series of experiments is given in Table I. The best result was obtained in discharge #58 934 at 2.76 T. A frequency of $f = 42$ MHz was used for the +90° ICRF power aimed at establishing monster sawteeth, corresponding to an H cyclotron resonance close to the magnetic axis ($R \approx 3m$); 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 25 cm on the high field side ($R \approx 2.75m$). Figure 1 shows an overview of this demonstration discharge. A clear destabilization of the monster sawteeth occurred a short period after the ICRF power for ICCD was turned on; it went from about $\tau_{\mathrm{saw}} = 200$–$250$ ms to around 80 ms. 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 destabilization. This discharge provides a strong indication that localized 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 destabilized sawteeth in Fig. 1 were caused by a decreased fast ion pressure inside $q = 1$. As discussed above, parasitic absorption of −90° ICRF power by the fast hydrogen ions in the center could have had an effect on the fast ion pressure. In the worst-case scenario, all the −90° power would be absorbed by the fast hydrogen ions in the center. To investigate this we did one reference discharge where the frequency for the 3 MW −90° power was changed to give a central resonance, ensuring that both the +90° and −90° powers were deposited in the center. However, one could argue this would give more absorption in the center than our demonstration discharge had in reality. Another reference discharge was therefore necessary. To limit the total power absorbed in the center but at the same time provide a fast ion pressure profile as broad as could realistically be imagined, a reference discharge with 1.5 MW of +90° power, 1.5 MW of −90° 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° power absorbed in the center while keeping the total central power at the 3 MW used to establish the monster sawteeth in the

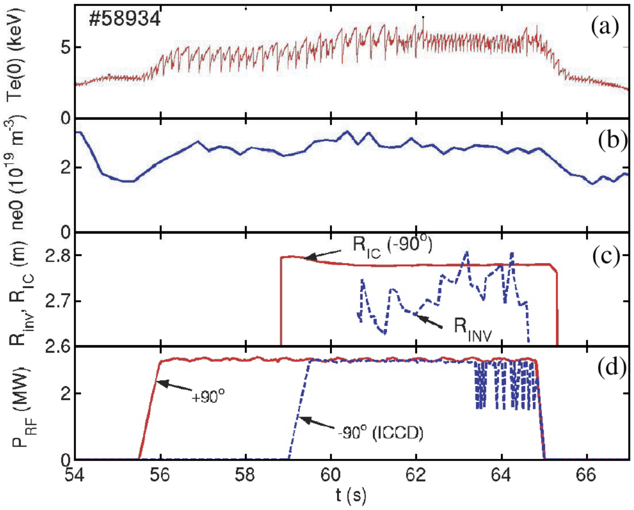

FIG. 1 (color online). Overview of a discharge where monster sawteeth were destablized by ICCD: (a) central electron temperature measured by ECE, (b) central electron density, (c) major radius positions in the equatorial plane of the sawtooth inversion radius and the cyclotron resonance for the −90° ICCD power, and (d) ICRF power, +90° central resonance (solid line) and −90° ICCD (dashed line).

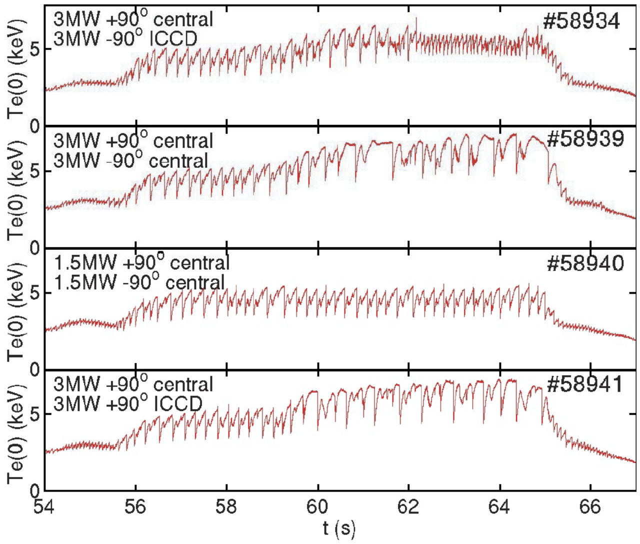

FIG. 2 (color online). Electron temperatures for the demonstration discharge in Fig. 1 and for the three reference discharges. The timing of the power wave forms are the same as in Fig. 1.

demonstration discharge. A final reference discharge was produced where the −90° ICCD power was exchanged for +90° ICCD power. This was done to demonstrate that +90° phasing produces a different effect on the sawteeth when the conditions for destabilization are near optimal for −90° ICCD. 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 destabilized sawteeth in the demonstration discharge. Thus, one can say with considerable confidence that the destabilization of the sawteeth in the demonstration discharge was indeed due to the localized 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 $B = 2.71$ T, corresponding to a change in the resonance position by about 5 cm, is considerable. This is consistent with the time delay in the destabilizing effect of the ICCD shown in Fig. 1. Furthermore, simulations of sawtooth destabilization with electron cyclotron current drive (ECCD) performed on TCV (tokamak à configuration variable) [12] shows a similar sensitivity to the relative distance between the $q = 1$ surface and the resonance position. Thus, for the localized current drive to be of practical use for destabilizing long sawteeth, it is probably necessary to implement a feedback on the position of the driven current.

Modeling of minority current drive and its effect on the sawtooth stability is a complex problem, and we will not attempt it for this Letter. However, second harmonic ICCD has been modeled and shown to provide a sufficient perturbation of s_1 to modify the sawtooth period in JET discharges without significant fast ion pressure [11]. The magnitude of the modification of s_1 in the discharges discussed here should be similar, and the considerable influence of s_1 on δW_f ($\sim 1/s_1$) should have been sufficient for modifying the sawtooth period.

In summary, we have presented experimental results that provide evidence for the ability of localized current drive to destabilize fast-ion-induced long sawtooth periods. 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. 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 destabilizing fast-ion-induced long sawteeth. In the present study, minority ion cyclotron current drive provided the localized current drive needed for the destabilization of long sawtooth free periods. This method could be utilized under reactor conditions as well. Another possibility is to use ECCD. An important advantage of both these methods is the possibility of fine-tuning the localization of the driven current by small variations of the confining magnetic field.

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