Demonstration of Effective Control of Fast-Ion-Stabilized Sawteeth by Electron-Cyclotron Current Drive

M. Lennholm, L.-G. Eriksson, F Turco, F. Bouquey, C. Darbos, R. Dumont, G. Giruzzi, M. Jung, R. Lambert, R. Magne, D. Molina, P. Moreau, F. Rimini, J-L. Segui, S. Song, and E. Traisnel

Association EURATOM-CEA, DSM/IRFM, CEA/Cadarache, 13108 St. Paul-lez-Durance, France

(Received 3 June 2008; published 19 March 2009)

In a tokamak plasma, sawtooth oscillations in the central temperature, caused by a magnetohydrodynamic instability, can be partially stabilized by fast ions. The resulting less frequent sawtooth crashes can trigger unwanted magnetohydrodynamic activity. This Letter reports on experiments showing that modest electron-cyclotron current drive power, with the deposition positioned by feedback control of the injection angle, can reliably shorten the sawtooth period in the presence of ions with energies ≥ 0.5 MeV. Certain surprising elements of the results are evaluated qualitatively in terms of existing theory.

DOI: 10.1103/PhysRevLett.102.115004 PACS numbers: 52.35.Py, 52.50.Sw, 52.55.Fa, 52.55.Pi

For nuclear fusion reactors based on magnetic confinement to be viable energy sources, they have to operate at a relatively high ratio of plasma pressure to magnetic pressure, i.e., a high value of $\beta = p/(B^2/2\mu_0)$. The maximum achievable β is limited by the appearance of "ideal" (as opposed to "resistive") magnetohydrodynamic (MHD) instabilities. Operating at high β may be associated with the appearance of resistive MHD instabilities, in particular, so-called neoclassical tearing modes (NTMs), which can be triggered for β significantly below the ideal MHD limit [1–3]. While these modes should not have the same severe consequences for the plasma stability as the ideal ones, their presence may strongly degrade the plasma performance, and they should therefore be either suppressed or avoided. NTMs are metastable which means that they are not linearly unstable. Instead, they are often triggered by other types of MHD activity, especially crashes of long period sawteeth [4]. The prevailing theory is that such activity induces magnetic perturbations—seed islands—that allow the NTMs to be triggered.

Sawtooth activity manifests itself by periodic crashes, i.e., abrupt decreases, of the temperature in the central region of the plasma, while the temperature recovers between crashes. The crash phase is initiated by the growth of a so-called internal kink mode. Such modes develop around a magnetic surface in the plasma where the safety factor q, a measure of the field line pitch in a tokamak, is equal to unity. The presence of significant fast (nonthermal) ion pressure can have a stabilizing effect on the sawtooth instability [5,6], leading to long period sawteeth. In a nuclear fusion reactor, the 3.5 MeV alpha particles produced by fusion reactions are likely to provide such stabilization. While the resulting long quiescent periods are not in themselves detrimental to the plasma confinement, the subsequent sawtooth crashes are likely to trigger NTMs. Crashes of short period sawteeth, on the other hand, do not provide large enough seed islands for NTMs to grow [4,7]. Thus, if sawtooth crashes can be induced sufficiently frequently even in the presence of large fast ion pressure, the triggering of NTMs could be avoided. According to the model in Ref. [8], a sawtooth crash occurs when $s_1 = s(r_1)$ exceeds a threshold which can be increased by the presence of fast ions. [Here $s(r) = (r/q)dq/dr$ is the magnetic shear at minor radius r, and r_1 is the minor radius where $q = 1$.] Thus, it should be possible to modify the sawtooth period by varying s_1 through localized current drive. In particular, a decrease in s_1 would be expected to result in longer sawteeth, while an increase should produce shorter sawteeth [8,9]. Another factor to take into account is that the heating itself influences the evolution of s_1, and thereby the sawtooth period [10].

Electron-cyclotron current drive (ECCD) is the most promising means for driving radially localized current, and its use is envisaged for MHD control on ITER, which will be the first tokamak operating under reactor conditions. This Letter describes the first experiments, which clearly demonstrate that ECCD can shorten sawteeth lengthened by significant pressure of ions with energies approaching the 3.5 MeV of fusion-produced alpha particles. The fast ions in these experiments were produced by ion cyclotron resonance heating (ICRH). The shortening proved to be very reliable despite the modest amounts of ECCD power applied. As described later, the response of the sawtooth instability to ECCD seems to be largely in agreement with theoretical expectations, despite certain surprising elements. Earlier measurements of sawtooth period variation with the radial position of localized ECCD in plasmas heated by electron-cyclotron waves on TCV [10] and heated by neutral beam injection (NBI) on ASDEX-Upgrade [11] have shown good agreement with the theory in Ref. [8]. Similar results have also been reported on DIII-D and JT-60U [12]. Whereas no fast ions were present in the TCV experiments, the sawteeth in the ASDEX-Upgrade experiments were lengthened through the nonthermal pressure of neutral beam ions with energies <100 keV, i.e., far below the energy of fusion-produced alphas. On JET, in experiments where a significant central pressure of ions in the MeV range was created by ICRH, shortening of the resulting long sawteeth using ion cyclotron current drive (ICCD) near $q = 1$ was demonstrated in conditions where NTMs were likely to be triggered [13,14]. Sawteeth have also been influenced by mode conversion current drive [15]. The order of magnitude difference in the energies of NBI ions and ICRH accelerated ions is highly significant since the ion energy affects the types of resonances between ions and the instability that are possible. The encouraging results using ICCD do not translate directly to the use of ECCD. The current drive mechanisms being very different, it is not obvious that ECCD can destabilize fast-ion-induced long sawteeth as efficiently as ICCD. In fact, a recent analysis of the sawtooth shortening achieved on JET, which requires very precise location of the destabilizing ICCD current, suggest that fast ion orbit effects may be responsible for this destabilization [16]. To the authors' knowledge, the efficiency of ECCD as a tool for sawtooth destabilization in the presence of fast ions has been demonstrated only with fast ion energies <100 keV. A demonstration in the presence of MeV ions is therefore vital to gain confidence that ECCD can be relied upon for this purpose on ITER.

The experiments reported here were carried out on the Tore Supra tokamak (major radius: 2.4 m, minor radius: 0.8 m) using a toroidal field of ~3.8 T and a plasma current of 1 MA. As in Refs. [13,14], central ICRH (57 MHz) was used to create a significant central pressure of fast ions with energies in the MeV range. As no measurement of the fast ion energies was available for these experiments, the MeV energy range is inferred from earlier Tore Supra experiments where fast ion energies in excess of 0.5 MeV were systematically observed in similar ICRH heated plasmas [17]. This conclusion is corroborated by the measurement on JET of fast ions with energies of several MeV, again under similar experimental conditions [18]. The effect of co- and counter-ECCD on the sawtooth period has been explored in discharges where the capability of the Tore Supra ECCD system of varying toroidal and poloidal injection angles over a wide range [19] was exploited to sweep the ECCD deposition from outside the $q = 1$ surface to the plasma center. An overview of one such discharge with co-ECCD is shown in Fig. 1. For reference, the traces of a similar discharge without ECCD are also shown. As can be seen, the sawtooth period increases from about 25 ms in the Ohmic phase to around 80 ms when ICRH is applied, i.e., when fast ions are created. During the ECCD deposition sweep, there is a sudden drop in sawtooth period almost to the level in the Ohmic phase; when the ECCD deposition moves closer to the center, the sawtooth period goes back up to ~80 ms again. This result is particularly remarkable in two respects: the modest amount of ECCD power (~300 kW) applied and the abruptness with which the sawtooth period drops and goes back up again. The latter feature is reminiscent of results obtained with ICCD on JET [13,14]. It should be remarked that the result is very

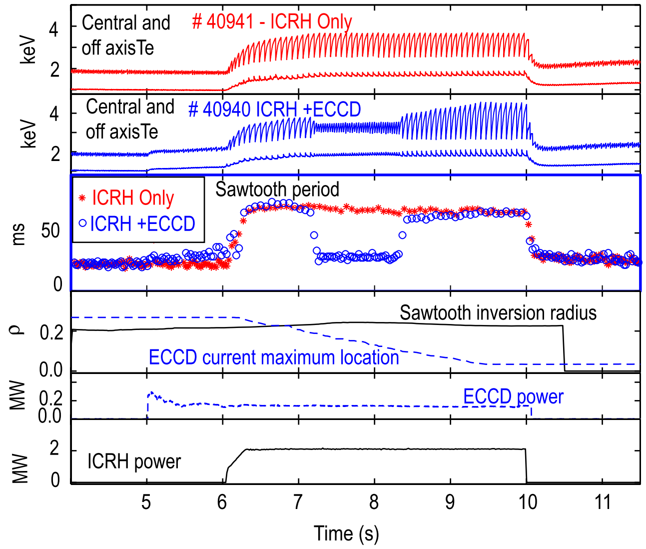

FIG. 1 (color online). Demonstration of sawtooth destabilization showing two consecutive shots with 2.3 MW of ICRH with and without ECCD. The radial ECCD location was scanned from outside the sawtooth inversion radius to the plasma center. From 7.2 to 8.3 seconds, the sawtooth period drops to 30 ms.

robust: It was reproduced in numerous discharges. Figure 2 shows the sawtooth period for a number of similar discharges with co- and counter-ECCD as a function of the distance between the measured sawtooth inversion radius and the peak of the ECCD driven current—computed with the REMA code [20]. (Note that the inversion radius should be close to the $q = 1$ surface; it signifies the position in the plasma inside which the electron temperature drops at a crash and outside which, for reasons of energy conservation, it increases.) In the case of co-ECCD, sawtooth period shortening is achieved with the ECCD current driven slightly inside the sawtooth inversion radius, while destabilization with counter-ECCD required the current to be

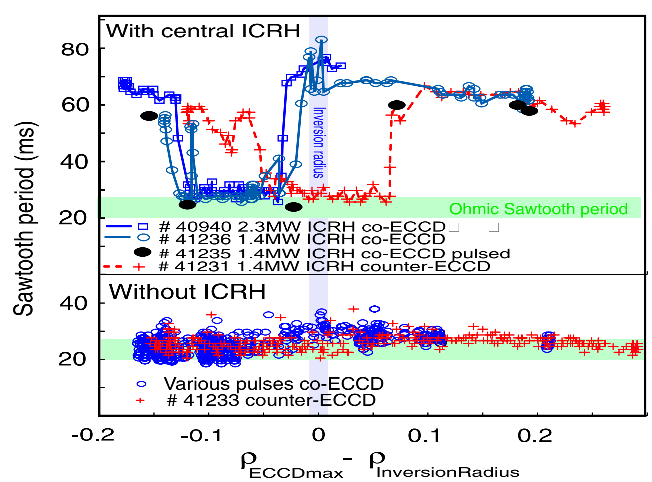

FIG. 2 (color online). Sawtooth period versus distance between ECCD location and inversion radius for co- and counter-ECCD with and without central ICRH.

driven farther from the plasma center, on or outside the $q = 1$ surface. The lower panel in Fig. 2 shows that ECCD has very little effect on the sawtooth period in Ohmic plasmas. In the present experiments, large toroidal ECCD injection angles ($\pm 28°$) were used in order to maximize the driven current (which nevertheless remained modest: $I_{\rm ECCD} \cong 4$ kA) and to allow central deposition despite the location of the EC resonance at $\rho = 0.5$. The penalty for using large toroidal injection angles is broad current drive profiles with a half width of $\cong$10 cm. The amplitude and profile of the driven current are computed by REMA using the same plasma equilibria that have been used to translate inversion radii into normalized minor radii.

Given the small ECCD driven current and its wide profile, the effect on the magnetic shear is very small. It is therefore surprising to observe such a strong effect on the sawteeth. This in conjunction with the equally surprising abrupt sawtooth period variation requires further investigation. Let us therefore discuss whether the theory presented in Ref. [8] contains a mechanism which could be responsible for the observed behavior. According to this theory, a sawtooth crash occurs when the following criteria are fulfilled: $s_1 > s_{\rm crit}$ and $\delta\hat{W} < c_\rho \hat{\rho}$, where $s_{\rm crit}$ depends on layer physics at the $q = 1$ surface, $\hat{\rho}$ is the ion Larmor radius normalized to r_1, and c_ρ is a constant of the order of unity. $\delta\hat{W} = \delta\hat{W}_0 + \delta\hat{W}_{\rm fast}$ is the normalized potential energy functional associated with the $m = 1$ mode causing the sawtooth crash. $\delta\hat{W}_{\rm fast} \sim \int x^{3/2} \frac{dp_{\rm fast}}{dx} dx$, $x = r/r_1$, depends strongly on the fast ion pressure profile $p_{\rm fast}$ and hence on fast ion orbits and energies. When $\delta\hat{W}_{\rm fast}$ is sufficiently large for $\delta\hat{W}$ to exceed $c_\rho \hat{\rho}$, no sawtooth crashes occur irrespective of whether $s_1 > s_{\rm crit}$. Given that $\delta\hat{W} \sim \delta W/s_1$, the sawtooth crash criteria can be written $s_1 > \max(s_{\rm crit}, s_W)$, with $s_W \sim \delta W/\hat{\rho}$, and thus s_1 remains determinant for the sawtooth triggering whether fast ions are dominant or not. Figure 3 shows a sketch of a possible evolution of s_1, $s_{\rm crit}$, and s_W following a sawtooth crash. s_W and s_1 both grow as the $q = 1$ surface expands after a sawtooth crash though following different trajectories with the evolution of s_W governed by the fast particle pressure inside the $q = 1$ surface. The time at which the subsequent sawtooth crash occurs—when s_1 enters the unstable region—depends critically on the difference in the evolution of s_1 and s_W. In the figure, the crash will occur at $t = t_2$, but if s_1 increases slightly faster—e.g., due to ECCD—s_1 will enter the unstable region before s_W comes into play, shortening the sawtooth period abruptly to $t = t_1$. This shows a mechanism which could be responsible both for the abrupt variation in sawtooth period and for the fact that a slight shear change can have such a strong effect. It should be noted that it is hard to explain how sawtooth shortening is achieved with co-ECCD slightly inside $q = 1$ and not with central co-ECCD as the computed increase in s_1 is largest in the latter case. Thus the suggested mechanism may explain some, but not all, of the surprising observations, and further theoretical investigations are required to ascertain whether this mechanism is responsible for the observed behavior. In the affirmative, a sharp ECCD power threshold exists below which sawtooth destabilization will not be effective.

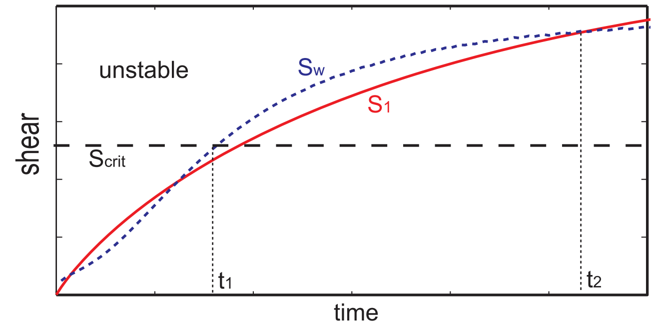

FIG. 3 (color online). Possible evolution of s_1, s_W, and $s_{\rm crit}$ after a sawtooth crash showing how a small variation in s_1 may induce an abrupt change in sawtooth period.

To explore the robustness of these results, the experiments were repeated at different values of ICRH power and plasma density. Sawtooth destabilization was achieved for the full range of available ICRH powers (0–4 MW) and over a wide range of densities. In all cases, an abrupt change in sawtooth period was observed. In Fig. 4, the sawtooth period with and without destabilizing ECCD is shown as a function of (a) ICRH power and (b) density. With destabilizing ECCD, the sawtooth period remains close to the Ohmic value irrespective of ICRH power and plasma density, while it increases with ICRH power and density without ECCD destabilization. The sawtooth period increase with ICRH power is readily explained by the increase in fast ion pressure, while the decreased sawtooth period at lower density is in agreement with observations on JET [21]. Based on the above experimental results, real time sawtooth period control was implemented varying the poloidal ECCD injection angle in real time to modify the ECCD absorption location [22]. Such control will be required in future machines for sawtooth destabilization to be a viable option for NTM avoidance. Figure 5(a) shows

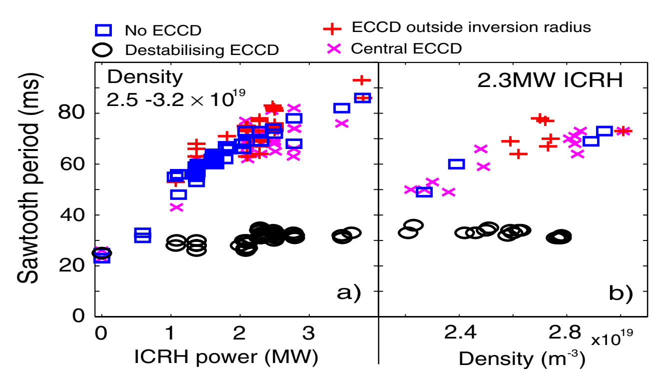

FIG. 4 (color online). Sawtooth period as a function of (a) ICRH power (volume average density 2.5–3.2 $\times 10^{19}$ m^{-3}) and (b) volume average density (ICRH power 2.3 MW).

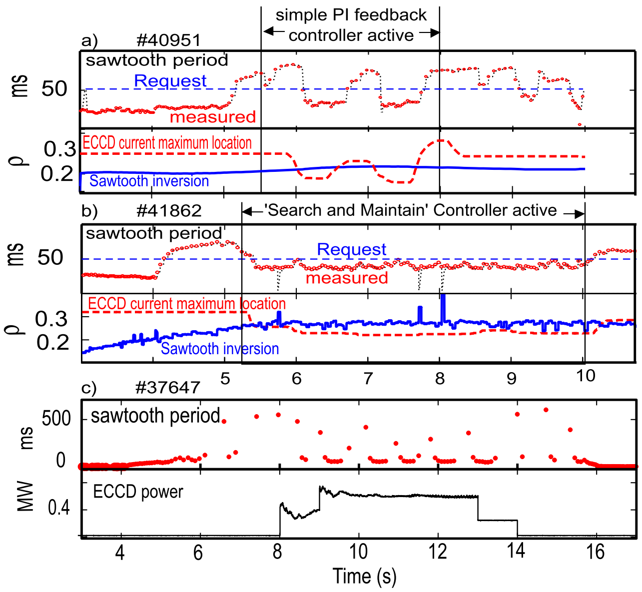

FIG. 5 (color online). (a),(b) Real time sawtooth period control with the poloidal injection angle as the actuator. (a) Oscillation with proportional-integral controller. (b) Short sawteeth obtained and maintained with search and maintain controller. (c) Shortening of 600 ms ICRH (6 MW) induced sawteeth with 600 kW ECCD (deposition not optimized).

an attempt at simple feedback control of the sawtooth period. The sawtooth period error (the difference between requested and measured sawtooth period) is used as input to a proportional-integral (PI) controller, which determines and controls the ECCD absorption location. As the requested sawtooth period in this case is between the two achievable values, the controller causes the measured sawtooth period to oscillate between these two values. To overcome this problem, a "search and maintain" control algorithm has been implemented. This algorithm initially varies the ECCD absorption location, in search of a location where the sawteeth are sufficiently short; once this has been achieved, the controller maintains the distance between the ECCD location and the measured sawtooth inversion radius, thereby maintaining short sawteeth throughout the ECCD pulse as seen in Fig. 5(b). To extrapolate such control strategies to future machines, it is essential to determine the power required for destabilization of longer "monster" sawteeth. A start in this direction has been made as shown in Fig. 5(c), where 600 ms long sawteeth have been destabilized using 600 kW ECCD [23]. The destabilization is slightly erratic, probably due to a combination of a nonoptimal location of the ECCD current and a lack of power. This discharge is nevertheless very encouraging as it indicates that the results presented above extrapolate well to higher fast ion pressures and longer sawteeth.

The experiments presented in this Letter have, to our knowledge for the first time, demonstrated that the period of long sawteeth induced by ICRH generated fast ions can be reliably shortened by modest amounts of ECCD provided this ECCD is localized correctly with respect to the $q = 1$ surface. Long sawteeth induced by up to 4 MW of ICRH were shortened virtually down to the Ohmic level by only 300 kW of ECCD. An abrupt transition between long and short sawteeth was observed when the ECCD deposition was swept radially. Moreover, variations in plasma parameters, including the fast ion pressure, hardly affected the period of shortened sawteeth. More work is needed before these results can be extrapolated to a reactor where long period sawteeth could be induced by fast fusion alpha particles. However, the reliable and systematic way in which the shortening of the sawtooth period was achieved in the discharges presented here is encouraging. Control of the sawtooth period by localized ECCD therefore appears to be a promising candidate for further exploration in the quest for developing strategies for avoiding the triggering of NTMs by crashes of long period sawteeth.

[1] O. Sauter *et al.*, Phys. Plasmas **4**, 1654 (1997).
[2] R. J. Buttery *et al.*, Plasma Phys. Controlled Fusion **42**, B61 (2000).
[3] R. J. La Haye *et al.*, Phys. Plasmas **9**, 2051 (2002).
[4] O. Sauter *et al.*, Phys. Rev. Lett. **88**, 105001 (2002).
[5] D. J. Campbell *et al.*, Phys. Rev. Lett. **60**, 2148 (1988).
[6] C. K. Philips *et al.*, Phys. Fluids B **4**, 2155 (1992).
[7] E. Westerhof *et al.*, Nucl. Fusion **42**, 1324 (2002).
[8] F. Porcelli, D. Boucher, and M. N. Rosenbluth, Plasma Phys. Controlled Fusion **38**, 2163 (1996).
[9] V. P. Bhatnagar *et al.*, Nucl. Fusion **34**, 1579 (1994).
[10] C. Angioni, T. P. Goodman, M. A. Henderson, and O. Sauter, Nucl. Fusion **43**, 455 (2003).
[11] A. Mueck *et al.*, Plasma Phys. Controlled Fusion **47**, 1633 (2005).
[12] T. Hender *et al.*, Nucl. Fusion **47**, S128 (2007).
[13] L. G. Eriksson *et al.*, Phys. Rev. Lett. **92**, 235004 (2004).
[14] S. Coda *et al.*, in *Proceedings of the 34th European Physical Society Conference on Plasma Physics, Warsaw*, Europhys. Conf. Abstr. Vol. 31F (European Physical Society, Geneva, 2007), p. 5.130.
[15] S. J. Wukitch *et al.*, Phys. Plasmas **12**, 056104 (2005).
[16] J. Graves *et al.*, Phys. Rev. Lett. **102**, 065005 (2009).
[17] A. Ekedahl *et al.*, J. Nucl. Mater. **363–365**, 1329 (2007).
[18] J-M. Noterdame *et al.*, Fusion Sci. Technol. **53**, 1103 (2008).
[19] M. Lennholm *et al.*, Nucl. Fusion **43**, 1458 (2003).
[20] V. Krivenski *et al.*, Nucl. Fusion **25**, 127 (1985).
[21] M. J. Mantsinen *et al.*, Plasma Phys. Controlled Fusion **42**, 1291 (2000).
[22] M. Lennholm *et al.*, in *Proceedings of the 15th Joint Workshop on ECE and ECRH, Yosemite* (Elsevier, New York, 2008).
[23] M. Lennholm *et al.*, in *Proceedings of the 17th Topical Conference on Radio Frequency Power in Plasmas, Clearwater, Florida*, AIP Conf. Proc. 933 (AIP, New York, 2007), p. 401.