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Coupling Between Sawteeth and Tearing Modes in TCV

G.P. Canal, B. Duval, F. Felici, T. Goodman, J. Graves, A. Pochelon, H. Reimerdes,
O. Sauter, D. Testa and the TCV Team
Ecole Polytechnique Fédérale de Lausanne (EPFL) - Centre de Recherches en Physique des Plasmas, Association EURATOM - Confédération Suisse, CH-1015 Lausanne, Switzerland

Introduction

In long pulse tokamak discharges, the achievable beta, $\beta = \frac{\langle p \rangle}{B_0^2/2\mu_0}$, where $\langle p \rangle$ is the average pressure and B_0 the toroidal magnetic field in the plasma centre, is often limited to values below ideal MagnetoHydroDynamic (MHD) stability predictions [1]. The modes responsible for this limitation have been identified as resistive tearing modes, which form magnetic islands at resonant surfaces with low order rational values of the safety factor q, in particular at the q = m/n = 3/2 and q = 2/1 surfaces, where m and n are the poloidal and toroidal mode numbers, respectively. Although these tearing modes are generally found to be linearly stable, a sufficiently large seed island can flatten the pressure profile across the island, which perturbs the neoclassical bootstrap current resulting in a further growth of the island. Hence, these instabilities are called Neoclassical Tearing Modes (NTMs). A key feature of NTMs is the need for some trigger mechanism to create the seed island. A sawtooth crash can provide such a trigger, but other perturbations like fishbones or Edge Localized Modes (ELMs) have been seen to trigger NTMs, too. While NTMs grow on a relatively slow resistive timescale (tenths of milliseconds), JET and other machines have observed that NTMs can be generated “practically instantaneously” (tens of microseconds) at the time of the sawtooth crash [2]. NTMs are one of the most critical limiting plasma instabilities for the baseline scenario in ITER and an improved understanding of the coupling between sawteeth and tearing modes could indicate ways to avoid the coupling, and facilitate safe operations at higher plasma pressures.

Use of electron cyclotron heating to control sawtooth period and tearing stability

On TCV, Electron Cyclotron Heating (ECH) and Current Drive (ECCD) applied in the vicinity of the q = 1 surface radius are used to control the sawtooth period [3]. The deposition location of the ECH power is moved with respect to the q = 1 flux surface by simultaneously varying the toroidal magnetic field and the plasma current in order to keep q_{edge} constant in a limited plasma (δ = 0.3 and κ = 1.4). The sawtooth period is increased by moving the deposition location from the plasma centre towards the q = 1 surface. ECH and ECCD have also been applied in the vicinity of the q = 3/2 surface in order to vary the classical tearing parameter Δ' and, hence, the stability of the 3/2 tearing mode.

MHD activity following sawtooth crashes

In order to gain a better insight into the magnetic perturbations generated at the sawtooth crash and also to improve the understanding of the link between sawteeth and the seeding of tearing modes, the triggered modes have been characterized. The fact that the sawtooth crash is detected at the edge by the magnetic coils means that the perturbation is a global phenomena, and thus, affects the whole profile. The generation of these modes takes place within 10-50 microseconds of the sawtooth crash, which is too short to be resolved by temporal Fourier techniques, and an instantaneous toroidal mode decomposition is used instead. Since the growth rate and variation of the phase velocity of the modes immediately following the crash are not negligible, the toroidal mode decomposition is carried out using integrated magnetic signals [4].

The analysis of the magnetic signals reveals that when a sawtooth (Figure 1(a)) triggers a 3/2 mode, it generally appears within one mode revolution (10-50 μs - Figure 1(b) and (c)) and the phase velocity of these modes initially differs from the characteristic n = 1 mode, associated with the sawtooth instability. Hundreds of microseconds (> 300 μs) after the crash, the phase velocities of the n = 1, 2 and 3 modes become the same. Once the modes lock to each other, energy can be transferred and while the 3/2 mode grows and saturates, the other modes decay away. TCV observations also indicate that when the phase locking occurs on a shorter time scale (< 300 μs), the 2/1 mode usually dominates. When its amplitude is large enough (about 2.5 mT), the mode immediately locks to the wall, which generally leads to a disruption.

Measurements of the line-integrated soft X-ray emission are used to identify the presence of a magnetic island. The flattening of profiles across the island leads to an oscillation of the emissivity at the mode frequency with a 180 degree phase jump across the island. Such a phase jump is typically detected a few hundred microseconds after the crash. However, the need for Fourier analysis, the finite channel spacing as well as the line integration limits the detectible island size.

Trigger conditions

TCV experiments demonstrate that the sawteeth with long duration can trigger instabilities leading to confinement degradation or disruptions depending on the normalized beta values, Figure 1(d). For moderately shaped plasmas with $q_{edge} \approx 2.6$ without ECH/ECCD applied in the vicinity of the q = 3/2, sawteeth may trigger 3/2 or 2/1 tearing modes once their period exceeds 6% of the characteristic resistive current redistribution time τ_r. For even longer sawtooth periods, the 2/1 tearing mode generally locks to the wall leading to a disruption. These observations are consistent with experimental observations from other machines [5].

Since the coupling is expected to strongly depend on toroidicity, q_{edge} has been varied in

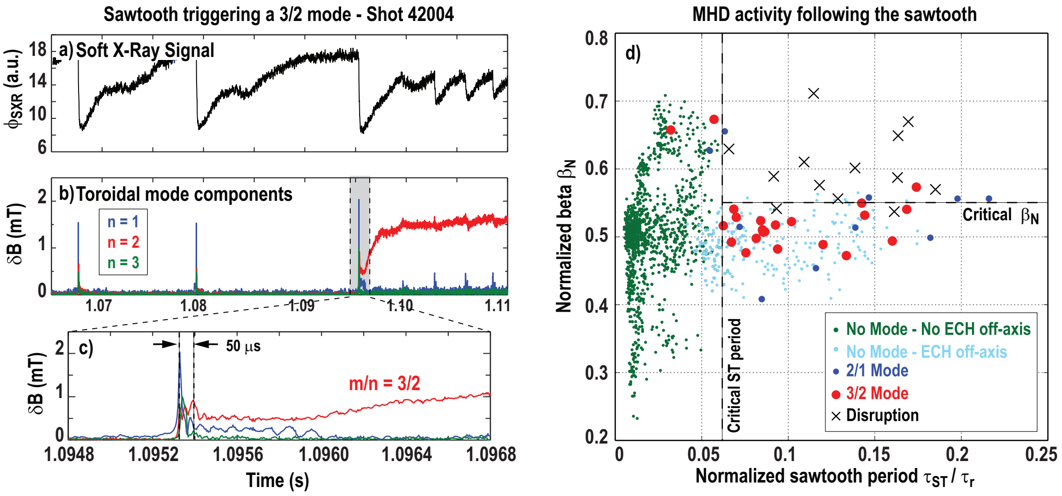

Figure 1: *a) Line integrated soft X-ray measurement showing typical sawtooth crash. b) Toroidal mode decomposition of the integrated magnetic signal showing a typical behaviour of a 3/2 tearing mode. c) A smaller time interval shows the fast phase of the tearing mode onset, which is typically a few tenths of microseconds. d) Database of the MHD activity following sawteeth as a function of normalized* β *and normalized sawtooth period for plasmas with* B_T *= 1.18 - 1.21 T,* I_p *= 280 - 310 kA,* q_{edge} *= 2.5 - 2.7,* P_{ECH} *= 0.5 - 1 MW,* δ_{edge} *= 0.3,* κ_{edge} *= 1.4*

order to modify the q = 1 radius. Figure 2 shows that the magnetic perturbation generated at the sawtooth crash increases with sawtooth period. For higher values of q_{edge}, this increase becomes smaller, which can be understood by a smaller q = 1 radius decreasing the driver for the seed. It also indicates that the onset condition is better described by a critical perturbed magnetic field amplitude than a critical sawtooth period.

Comparison between TCV observations and NTM triggering models

Various trigger mechanisms have been proposed to explain the coupling between sawteeth and tearing modes. Most models can be characterized as a forced seeding process [6]. In toroidal geometry, the dominant m/n = 1/1 and 2/2 mode components have 2/1 and 3/2 satellite harmonics, respectively. Numerical simulations have shown that the character of these components can quickly change from a resistive kink to a tearing mode [7, 8]. This island can then serve as a seed for the NTM. The quick formation of the 2/1 and 3/2 modes in TCV within 30 μs is consistent with the time scales of $\approx$ 100 characteristic Alfvén times found in the simulations [7].

Alternatively, a seed could be created through the sawtooth crash creating a tearing-mode-unstable current profile [9]. However, this island should then grow on a resistive time scale out of the noise, which is inconsistent with the fast mode generation observed in TCV.

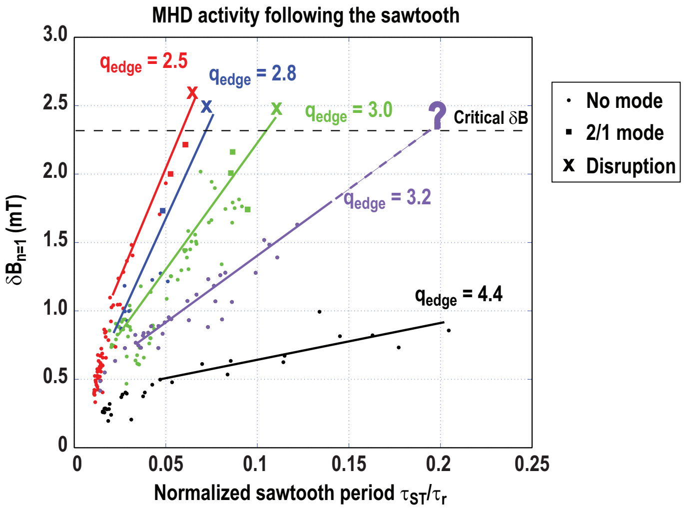

Figure 2: *n = 1 magnetic perturbation generated at the sawtooth crash as a functions of the sawtooth period for different* q_{edge} *values.*

Summary

In TCV, sawteeth of sufficient duration can trigger 3/2 or 2/1 tearing modes even at low values of β_N well below to the ideal MHD stability limit. The critical sawtooth period that can trigger a disruption is found to increase with q_{edge}. The magnetic perturbations generated at the sawtooth crash increase with increasing sawtooth periods and decrease with increasing values of q_{edge}. The TCV observations also indicate that there is a critical perturbed magnetic field amplitude, which is independent of sawtooth period and q_{edge}. ECH/ECCD applied in the vicinity of the q = 3/2 is found to stabilize such modes. At low q_{edge} and sufficiently high values of β_N, the sawtooth triggered 2/1 mode generally locks to the wall causing disruption. The TCV observations are consistent with a forced seeding process.

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References

[1] O. Sauter et al, *Phys. Plasmas* **4**, 1654 (1997).
[2] J. Graves et al, *Nucl. Fusion* **50**, 052002 (2010).
[3] T.P. Goodman et al, *Phys. Rev. Lett.* **106**, 245002 (2011).
[4] P.A. Duperrex et al, *Nucl. Fusion* **32**, 1161 (1992).
[5] I.T. Chapman et al, *Nucl. Fusion* **50**, 102001 (2010).
[6] C.C. Hegna, *Phys. Plasmas* **6**, 130 (1999).
[7] A.M. Popov et al, *Phys Plasmas* **9**, 10 (2002).
[8] D.P. Brennan et al, *Nucl. Fusion* **45**, 1178 (2005).
[9] P. Maget et al, *Plasma Phys. Control. Fusion* **47**, 357 (2005).