

Fast Seeding of Neoclassical Tearing Modes by Sawtooth Crashes in TCV

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Introduction

Neoclassical Tearing Modes (NTMs) degrade plasma confinement and can interact with the wall causing the plasma rotation to stop and the mode to lock, which usually leads to a disruption. A key feature of NTMs is that they are classically stable but neoclassically meta-stable, i.e. they need some trigger mechanism to create a seed island [1], which can be provided by a sawtooth crash [2, 3]. NTMs are a critical performance limiting instability in the baseline scenario in ITER and an improved understanding of the coupling between sawteeth and tearing modes could indicate ways to avoid them and facilitate operation at higher plasma pressures. Recent TCV experiments give new insight into the coupling between sawteeth and NTMs.

Electron cyclotron heating system used to vary sawtooth and tearing mode stability

Two techniques have been used to control the sawtooth period. In the first one, the deposition location of ECRH/ECCD is moved with respect to the $q = 1$ flux surface by simultaneously decreasing the toroidal magnetic field and the plasma current in order to keep the value of q_a constant during the discharge. The sawtooth period increases when the deposition location is moved from the plasma centre towards the $q = 1$ surface. In the second technique, the sawtooth period is paced through a real-time system using feedback control of the ECRH/ECCD applied in the vicinity of the $q = 1$ surface radius [4]. Preemptive ECRH has also been applied in the vicinity of the $q = 3/2$ surface in order to study its effect on the NTM seeding process and on modifications of the tearing mode stability [5].

Fast seeding of 3/2 and 2/1 NTMs

The NTM seeding process has been found to occur within $100 \mu\text{s}$ of the sawtooth crash. This time is too short to be resolved by temporal Fourier techniques and, therefore, instantaneous toroidal mode decomposition using toroidal arrays of magnetic sensors is applied instead. The mode decomposition is carried out using integrated magnetic signals [6], since the mode amplitude changes on the same time scale as its phase (growth within one toroidal revolution) immediately following the crash. Moreover, TCV is equipped with Low Field Side (LFS) and High Field Side (HFS) toroidal arrays of magnetic sensors which are used to distinguish between even and odd poloidal mode numbers m by comparing the phases of the component with a toroidal mode number n at the low and high field side.

Figure 1(a) shows an $n = 2$ mode, which has been generated by a sawtooth crash and Figure 1(b) shows that the HFS and LFS are in phase just before the sawtooth crash, indicating an even m number. After the time of the crash the perturbation quickly becomes out of phase indicating an odd m number. The magnetic measurements therefore strongly suggest that an $m/n = 3/2$ mode is generated in a few tens of microseconds by the sawtooth crash.

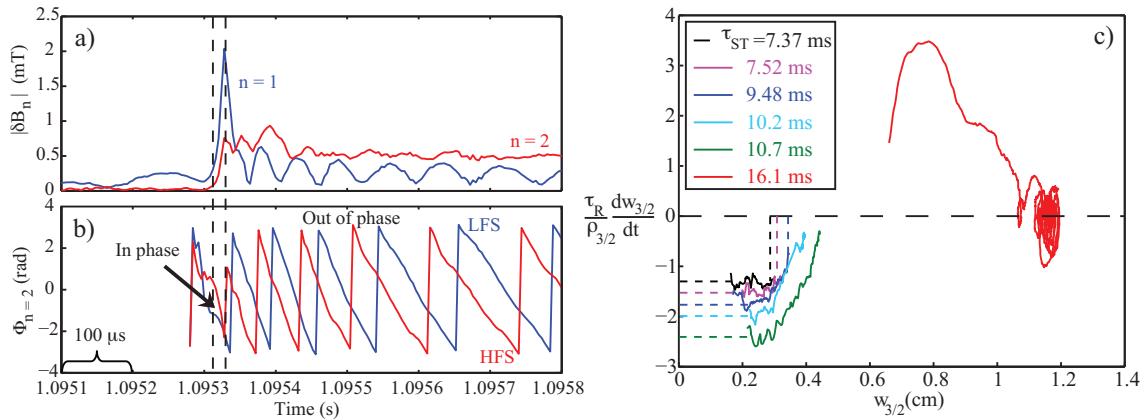


Figure 1: (a) Amplitude of $n = 1$ and $n = 2$ magnetic components generated by a sawtooth crash and (b) its phase measured at the LFS and HFS. (c) Evolution of the $m/n = 3/2$ island width in its phase-space. The colors correspond to perturbations generated by sawteeth of different duration.

Measurements of the line-integrated soft X-ray emission have been used to identify the presence of a magnetic island. Once the island is sufficiently large, the flattening of profiles across the island leads to an oscillation of the emissivity at the mode frequency with a phase inversion at the resonant surface ρ_s . Such a phase inversion starts to be visible at the HFS and LFS resonant surfaces as early as $800 \mu\text{s}$ after the sawtooth crash. Following the phase of the $3/2$ mode back in time from saturation to a few microseconds after the sawtooth crash, no transition in its behaviour is observed, strongly indicating that the $3/2$ mode generated by the sawtooth crash is already an island in tens of microseconds after the sawtooth crash time. Assuming that the measured $3/2$ perturbation is generated by an island as soon as it is detected, one can determine the phase-space diagram of its width w , Figure 1(c), which illustrates that the magnetic perturbation evolves according to the modified Rutherford equation reinforcing the evidence of a fast seed island generation. Figure 1(c) also shows that sawteeth of longer duration generate larger seed islands. Interestingly, they also affect the classical tearing mode index $\Delta'_{3/2}$ leading, counter-intuitively, to a more stable plasma immediately after the crash. The observation of fast seeding is consistent with numerical simulations [7, 8] and suggests a non-linear seeding process.

Comparing the phase difference between the $n = 1$ component of the magnetic perturbations at the LFS and HFS, it is found that, as for the $n = 2$ component, an $m/n = 2/1$ mode can also be seen within tens of microseconds after the sawtooth crash. The resonant surface of the $2/1$ NTM is closer to the plasma boundary than the resonant surface of the $3/2$ NTM. The interaction of the $2/1$ NTM with induced eddy currents in the vacuum vessel is therefore larger and leads to a reduction of the plasma rotation, which in turn leads to mode locking and disruptions. The same interaction exists for the $3/2$ NTM, but it is not strong enough to significantly reduce the plasma rotation. In these series of experiments every $2/1$ NTM led to a disruption.

Stabilizing effect of preemptive ECRH at $q = 3/2$

Sawteeth triggered NTMs have traditionally been controlled by shortening the sawtooth period (presumably by decreasing the main harmonic drive), but the coupling process can also be

controlled by reducing the driven 3/2 and 2/1 mode amplitudes. In order to investigate the effect of preemptive ECRH on the driven 3/2 mode, TCV's real-time control system has been used to keep the sawtooth period constant (about 20 ms) during low q_a discharges (about 2.6) and avoid changes in the sawtooth drive [5]. The preemptive ECRH at the $q = 3/2$ surface is switched on before each programmed sawtooth crash time and switched off after a programmed duration, which varies from 7 to 3 ms, Figure 2(a). Without preemptive ECRH sawteeth quickly trigger a 3/2 NTM.

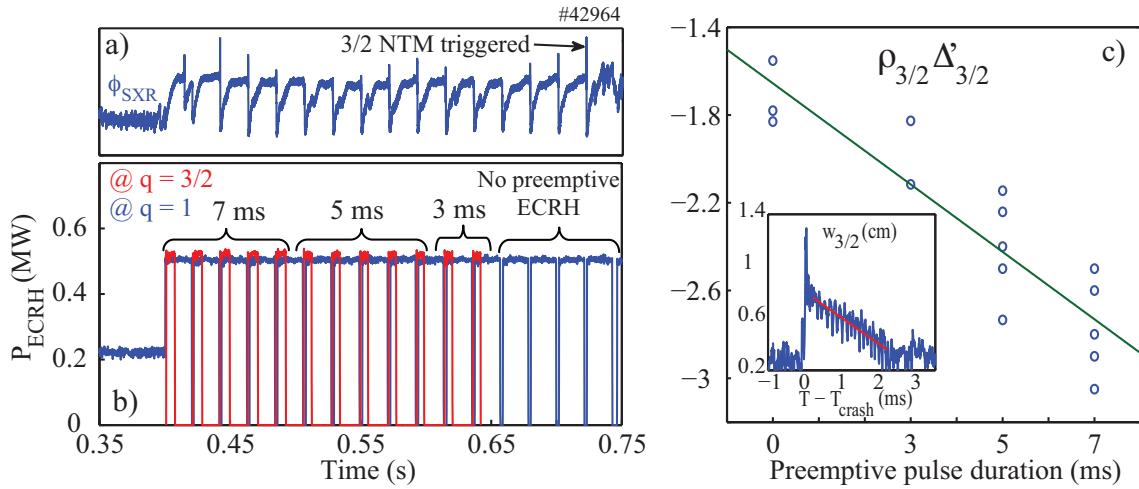


Figure 2: (a) Soft X-ray signal viewing the plasma centre. (b) Time evolution of the ECRH/ECCD power applied at $q = 1$ used to keep a constant sawtooth period (blue) and of the preemptive ECRH at $q = 3/2$ used to change tearing mode stability (red). (c) $\rho_{3/2}\Delta'_{3/2}$ measurements obtained from magnetic measurements (insert) for different values of the ECRH power averaged over the sawtooth cycle.

The magnetic measurements show that larger preemptive power averaged over the sawtooth cycle leads to a more negative $\rho_{3/2}\Delta'_{3/2}$, hence, a plasma more stable against the triggering of NTMs, Figure 2(a,b). This is consistent with the observation that the preemptive ECRH reduces the size of the seed island.

NTM onset for different sawtooth periods and q_a values

In order to address the parametric dependency of the mode coupling, a shot to shot q_a scan has been carried out. The value of q_a is kept constant while the sawtooth period is increased by moving the ECRH/ECCD deposition location through the $q = 1$ radius. The onset of an NTM then yields the longest tolerable sawtooth period, which is observed to increase with q_a , Figure 3(a). For the range of plasma parameters investigated and for q_a values above 3, only 2/1 NTMs are found to be triggered. The 3/2 NTMs have not been observed for values of q_a above 3. One possible explanation for this observation is that a 3/2 NTM is triggered when the mixing radius, which is larger at lower values of q_a , approaches the $q = 3/2$ resonant surface and the sheet currents resulting from the crash destabilize the 3/2 NTM [9]. However, this hypothesis would require a different triggering mechanism for 2/1 NTMs.

Since the $n = 1$ component of the magnetic perturbation is the main driver for the triggering of NTMs by sawtooth crashes, a characterization of its amplitude $\delta B_{n=1}$ for different q_a values

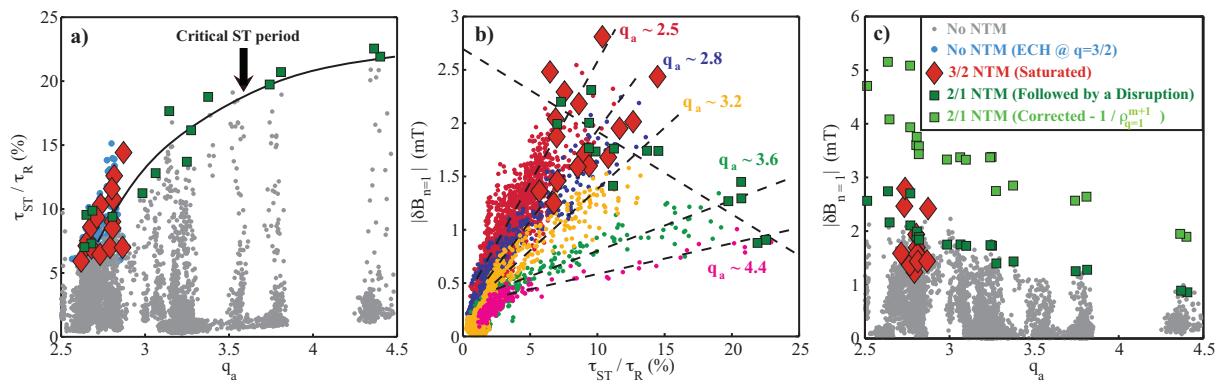


Figure 3: (a) MHD following sawteeth of various normalized sawtooth periods, τ_{ST}/τ_R at various values of q_a . Dependence of the $n = 1$ magnetic perturbation generated by the sawtooth crash on (b) τ_{ST}/τ_R and (c) q_a . The light green squares account for a correction of the mode amplitude based on a multipole decay of the magnetic perturbation from the $q = 1$ radius.

has been carried out. The relation between $\delta B_{n=1}$ and the sawtooth period depends strongly on the value of q_a , Figure 3(b). The value of $\delta B_{n=1}$, measured with the LFS probes, for a given sawtooth period, decreases with increasing q_a . The reduction of the perturbation amplitude with q_a is stronger than its increase with the sawtooth period leading to a decreasing critical magnetic perturbation for larger values of q_a , Figure 3(c). Since neither shear nor the distance between rational surfaces have been found to change with q_a , the decreasing of the critical measured magnetic perturbation with increasing q_a could be associated with a smaller $q = 1$ radius decreasing the driver for the seeding. The behavior for $\delta B_{n=2}$ is very similar to that shown in Figure 3(b) for $\delta B_{n=1}$ and both components only differ in their amplitudes.

Summary

Fast seeding of NTMs by sawtooth crashes have been observed in TCV. These observations suggest a non-linear mechanism. The preemptive ECRH at the 3/2 surface seems to affect the seeding via a reduction of $\Delta'_{3/2}$ leading to a smaller seed island. Plasmas with higher values of q_a tolerate longer sawteeth, which is partially due to a decrease of the sawtooth instability drive.

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