Real-time control of MHD instabilities with multi-source EC actuators

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Sawtooth crashes are the main perturbations that can trigger neoclassical tearing modes (NTMs) in the standard scenario of tokamak plasma operation. NTMs degrade performance or, potentially, lead to a disruption and therefore need to be either prevented or removed. New experiments in the tokamak à configuration variable (TCV) demonstrate sawtooth pacing [1] by real-time control of the auxiliary electron-cyclotron (EC) power, and sawtooth locking [2] for a specific range of modulation periods and duty-cycles. The periods of individual sawteeth τ_s can be controlled by both methods; and simulations using ASTRA and a sawtooth crash model show that the application of EC power near the $q = 1$ radius slows the increase of the magnetic shear at $q = 1$ and that subsequent rapid removal of the EC power allows the shear to reach a critical value that triggers the sawtooth crash shortly thereafter, consistent with experimental observations [3]. Whether disruptions and/or NTMs are generated at the crash depends on τ_s in TCV plasmas with a low q_{edge} [4].

Similarly, individual ELMs are also controlled in real-time by appropriate EC power pulses.

TCV has a major (minor) radius of 0.8m (0.24m) and an installed additional heating power (electron cyclotron only) of 4.5MW from nine 0.5MW gyrotrons; 3 at $f = 118GHz$ (3^{rd} cyclotron harmonic: X3) and 6 at $f = 82.6$GHz (X2). X3 gyrotrons share one steerable antenna; whereas, each X2 gyrotron has its own steerable antenna. Gyrotron electron beams are powered in clusters of three. For experiments described here, only X2 EC actuators are used with real-time (feedback) control; X3 provides constant feedforward heating (0.8MW) in ELM pacing experiments.

Pacing is a real-time control method in which sawtooth stabilizing electron-cyclotron current drive (ECCD) power is deposited at the $q = 1$ surface for a set time, τ_{set}, then removed until a sawtooth crash occurs. Once the crash is detected, the power is again turned on and the cycle is repeated. Locking does not require real-time sawtooth detection but relies instead on the natural tendency of the sawtooth cycle to lock to the driving power pulse-period. Locking has been shown to occur within a certain region of duty-cycle vs. pulse-period space, as expected by simulations [5]. Experimental results on TCV [2] are summarized in Fig. 1 where open circles represent successful locking and $\times$'s indicate combinations of period and duty-cycle where the sawteeth do not lock to the EC pulse period. The solid line running through the center of the success-region indicates the relation between period and duty-cycle that was programmed in the real-time control system to demonstrate (green circles) that the locking phenomenon can be used to obtain the same control over the period as pacing (black circles). Though locking does not require real-time crash detection (as pacing does), the locking controller was built only after the success region had been mapped out. It can be seen that the pacing results (where only the 'on-time' is set) naturally fall within the success-region but are at its high duty-cycle edge because the start of the *paced* EC pulse is synchronous with the crash (phase delay $= 0$); whereas, sawteeth can *lock* with a non-zero phase delay. (The delay from when the stabilizing power is removed to the moment of the crash is similar in both pacing and locking.)

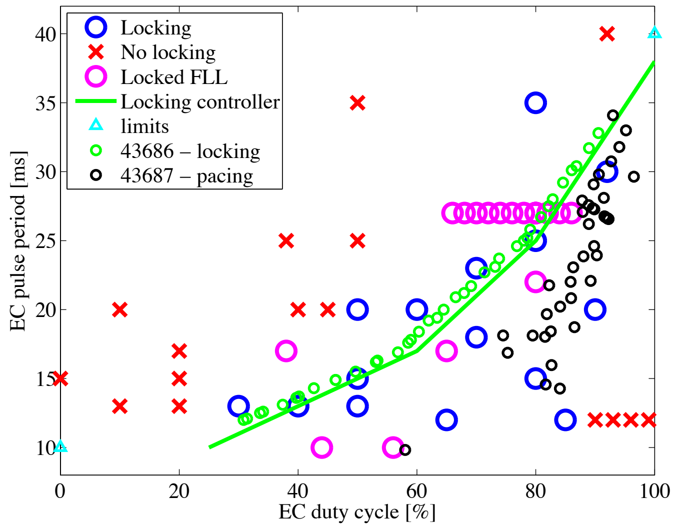

Figure 1: Sawtooth control map of locking and pacing duty cycle and period. Open circles indicate successful control and red $\times$ sybols indicate no locking.

Figure 2 shows that long-period sawteeth occur when the EC deposition location is swept across the $q = 1$ surface (HFS, B_ϕ sweep, constant q_{edge}), but that we can *clip* the sawtooth period to a non-disrupting value (here ~ 0.02s) during the sweep by pacing. Here we use 1MW of ECCD near $q = 1$ plus 0.5MW of off-axis heating near $q = 3/2$. Without the off-axis EC, 3/2 NTMs are generated by the paced sawtooth crashes. This provides a good target setup for the preemptive EC experiments described below; there, the magnetic field has a constant value of -1.207T and 3/2 NTMs are expected.

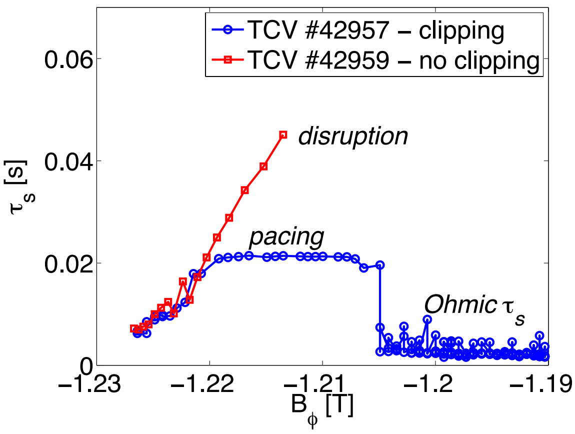

Figure 2: Sawtooth periods during a deposition sweep, without (squares) and with (circles) clipping. $\tau_{set} = 0.02$s for TCV # 42957.

Multi-source real-time EC actuator experiments were performed to preempt NTMs using short pulses of off-axis heating aligned to the $q = 3/2$ resonant surface and regular, predictable, sawtooth crashes generated by pacing. Since the time of the crash is determined by the pacing actuators near the $q = 1$ surface, it is possible to apply the off-axis power only when needed, i.e. at the time of the crash. To this end, the off-axis EC power is turned on when the pacing actuators are turned off and is kept on for 7ms (sufficient time for magnetic perturbations measured by the mirnov coils, due to the crash, to disipate [4]). The crash occurs $1 \rightarrow 2$ms after the pacing power is turned off and the off-axis power turns on with a delay of ~ 0.7ms, thus a few hundreds of µs before the crash.

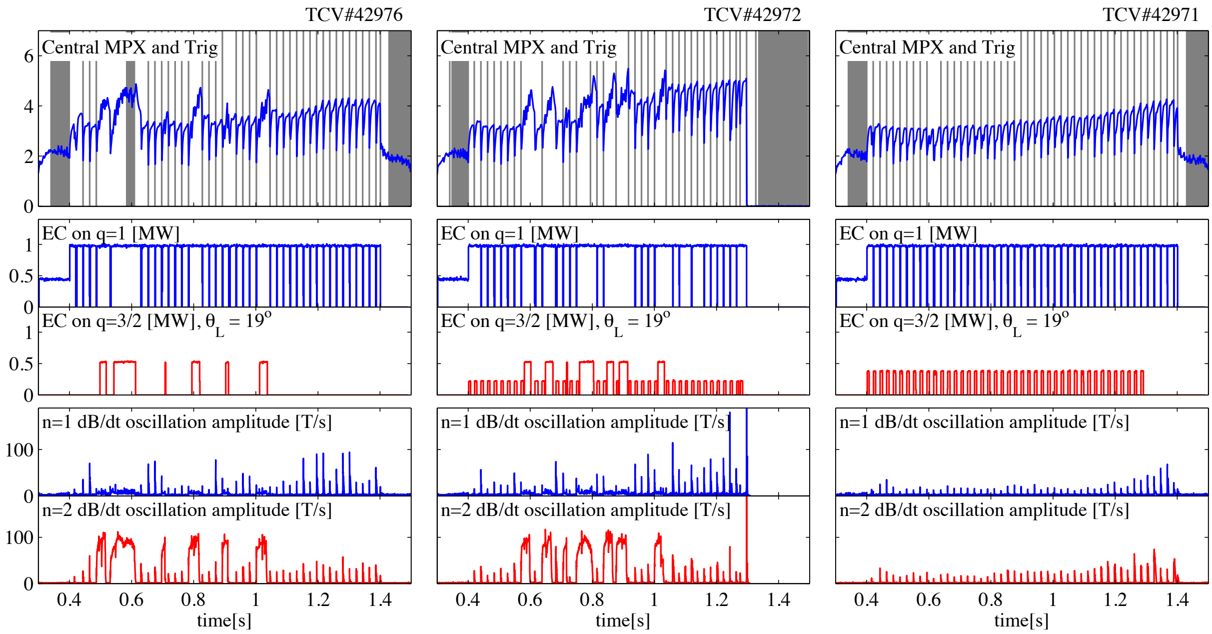

Figure 3: Multi-EC actuator NTM preemption and/or suppression discharges based on sawtooth pacing. Left: 0.0MW preemptive power, Middle: 0.2MW preemptive power pulses, Right: $n = 2$ NTM avoidance by 0.32MW, 7ms, preemptive pulses on the $q = 3/2$ surface. From [6].

In parallel, a second control algorithm is used to quell any 3/2 modes that might appear if preemption doesn't work. In this parallel algorithm, when a mode is detected for longer than 10ms, pacing stops, (second row: EC on $q = 1$) the off-axis power is switched to full power, (here, 0.5MW) and is kept on until the mode disappears; the control system then switches back to the preemption algorithm. Switching between these two algorithms is done automatically and repeatedly, as necessary. Figure 3 shows a scan of the off-axis preemptive power in three separate discharges, from 0.0MW to 0.2MW and finally 0.32MW. The time trace of the central chord a line-integrated soft-X ray detector signal is shown in the top row of each panel. Saw-tooth crashes that are identified by the real-time control algorithm are shown as vertical gray lines. In the two left-hand panels (TCV # 42976 & 42972) the preemptive power is too low to prevent the growth of the $n = 2$ mode (bottom row: oscillation amplitude) at every crash, so the off-axis EC power (third row: EC on $q = 3/2$) is seen to increase to 0.5MW until the mode is suppressed; then pacing is resumed. In the right-hand panel, the 0.32MW preemptive pulses avoid the growth of the mode reliably at every crash. Preemption efficiently avoids NTMs (average power is $7\text{ms}/21\text{ms} \cdot 0.32\text{MW} \simeq 0.1\text{MW}$).

Sawtooth pacing relies on *removal* of the stabilizing EC power at the $q = 1$ surface. Alternately, Type I ELMs occur more frequently when heating power is *increased*. Thus we might expect that ELMs can be *paced* if, like sawteeth, there is little or no time history in their behavior. To test this, X2 power is deposited slightly inward from the edge pedestal, kept low for a fixed period of time, τ_{set}, then increased until an ELM is detected, then repeated (roughly the inverse of the power waveform for sawtooth pacing). TCV shot # 43067 used a random series of 32 such power pulses, repeated eight times, to prove successful control of the period of *individual* ELMs. At each ELM, τ_{set} is changed to one of four different values. The resulting ELM periods, τ_{ELM}, are binned according to τ_{set}. Figure 4 summarizes the results: statistically, individual ELMs are longer when τ_{set} is larger, and the ELMs occur when the integrated edge-deposited power reaches some approximately constant value, regardless of the ELM period. The energy loss per ELM found to be roughly constant with period; in contrast to results from experiments in which the EC *deposition location* is moved towards the plasma edge during a discharge (at constant input power and decreasing first-pass absorption). There, the energy lost per ELM decreased as the ELM period decreased [7]. Similar experiments are planned in plasmas with Type III ELMs.

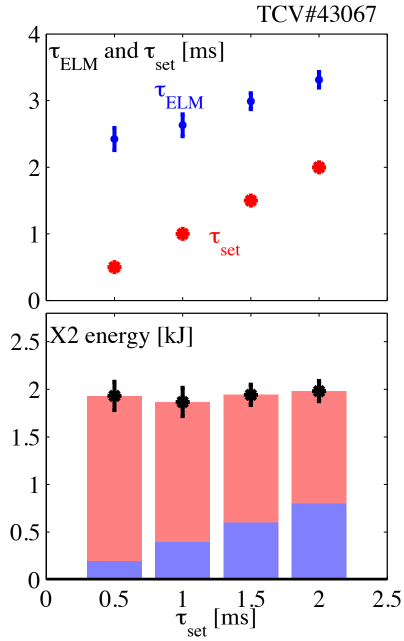

Figure 4: Top: τ_{ELM} and τ_{set} vs. τ_{set}; Bot: Total (red) and low-portion (blue) X2 energy per ELM (mean and STD for each τ_{set}). From [6].

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References

[1] T.P. Goodman, *et al.* Phys. Rev. Lett., vol. **106**, 245002 (2011).
[2] M. Lauret, *et al.* Nucl. Fusion **52** (2012) 062002.
[3] D. Kim, *et al.* 39th EPS Conference on Plasma Physics (2012).
[4] G. Canal, *et al.* 38th EPS Conference on Plasma Physics ECA, 35G, P1.080 (2011).
[5] G. Witvoet, *et al.*, Nucl. Fusion **51** (2011) 103043.
[6] F. Felici, Ph.D. thesis **5203**, Ecole Polytechnique Fédérale de Lausanne EPFL (2011).
[7] J. X. Rossel *et al.*, Nucl. Fusion **52** (2012) 032004.