Sawteeth (de)stabilization by ECH and ECCD in FTU

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Introduction

The control of sawteeth (ST) is a critical issue for the plasma confinement in fusion devices. Long period sawteeth give rise to big crashes that can trigger large seed islands destabilizing Neoclassical Tearing Modes (NTMs) [1] and degrading the plasma performances at high β. On the other hand, being the sawteeth activity useful in burning plasmas to prevent ash accumulation in plasma core, it is important to destabilize the ST shortening their period, thus reducing any triggered seed island below the NTMs growth threshold. A powerful tool for the control of sawteeth period τ_{ST} is the use of the Electron Cyclotron Heating (ECH) and Current Drive (ECCD). This high localized power is capable to modify locally the plasma parameters, such as the plasma current density, through changes in the resistivity and, consequently, to act on the instability period [2-3]. The present work describes the investigation of the ST destabilization in FTU tokamak, equipped with an ECRH system of 4 gyrotrons operating at 140 GHz and delivering 0.5 MW each [4]. This activity contributes to work plan of the ITPA MHD working group on ST control for the empirical scaling of power requirement for avoiding the onset of NTMs. In order to test the ST control techniques and the conditions for setting an a-priori ST period in view of the real-time EC system working soon in FTU, induced crashes by ECH and ECCD has been investigated using 500 ms of repetitive pulses from 1-2 gyrotrons up to 0.8 MW EC total input power. Three EC modulations were used with 80% duty cycle (40ms EC on/10ms EC off), 20% (10ms EC on/40ms EC off) and 50% (4ms EC on/4ms EC off). The sawtooth crash is predicted to happen if the magnetic shear s_1 at q=1 radius (s_1= rq') is larger than a critical value s_{cr}[5]. ECH/coECCD outside r_{inv} are expected to decrease s_1 lengthening τ_{ST}, while inside to increase the shear shortening τ_{ST}. Both s_1 and s_{cr} increase during the heating phase, s_1 faster than s_{cr} (4.4% against 3.95%). The target plasma is chosen at 500 kA with line averaged electron density ~ 0.6 $10^{20}m^{-3}$. The reference ST period in ohmic phase is 6.4 cm. Working with the magnetic field B_t ramp from 5.1 to 5.9 T to move the EC absorption position from inside to outside r_{inv}, the q=1 surface, minor radius r_1 is slightly reduced from 6.5 to 5.5 cm.

ECH/ECCD as trigger of ST crash: experimental evidence

In view of a real time ST control available soon in FTU using the new EC launcher, experiments with 500 kA and field ramp ranged between 5.1/5.9T have been performed. These experiments allow investigating how the ECH and ECCD from 2 gyrotrons (800 kW) can trigger the crashes switching ON/OFF the EC power to pilot the ST frequency. Inside the q=1, crash is expected to occur at the EC on with a shorter time than τ_{ST} in ohmic phase (~ 6.4ms) due to an increase of the shear and an opposite behaviour at the EC off. In practice, we observe similar plasma reconnection times as shown in Fig. 1 on polychromator T_e traces for 3 pure heating EC modulations. Modulation with corresponding Te response are given for 10msON/40msOFF (2 top rows), 40msON/10msOFF (2 central rows) and 4msON/4msOFF (2 bottom rows) for EC deposition at r_{dep}~ 0.5_{rinv}. Regular EC 500ms pacing gives irregular crashes at ON/OFF with τ_{ST} ~1ms–5ms still less than 6.4ms ohmic value and the time delay between the first crash after EC on/off should be taken with respect to the last reconnection before EC on/off. In Fig. 1 some of such crashes at EC ON/OFF are labelled as A, B, C, D. In Fig.2 the τ_{ST} are given for the shot #34286 (80% d.c.) and #34285 (50%). In the latter shot the small EC on length (4ms < ohmic τ_{ST}) exhibits an unforeseen and opposite behaviour: the ST frequency slows down up to 8ms period >ohmic 6.4ms: ECH generally tends to stabilize ST.

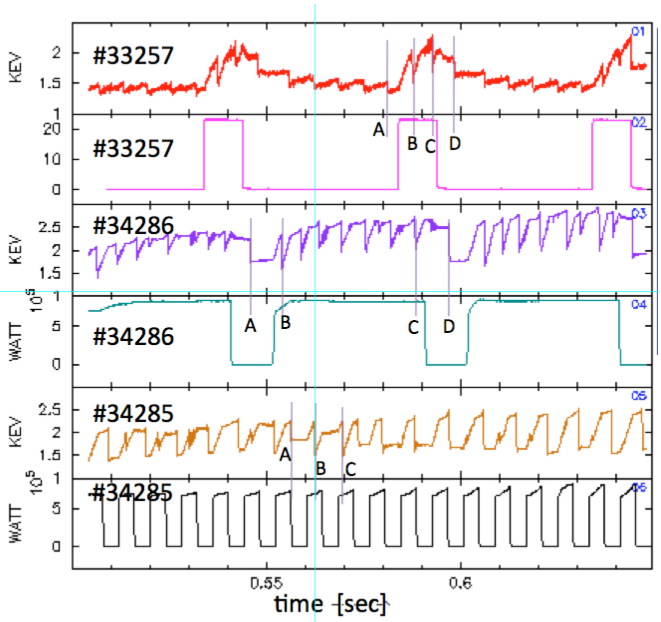

Fig.1: crash EC trigger for 3 modulation: 20% d.c. (top), 80% d.c. (centre) and 50% d.c. (bottom).

This probably because the EC_on induces the 1st crash after ~ 4ms and EC_off after ~ 2ms. Real time synchronization on the ST ramp could be performed to obtain a selected a-priori

τ_{ST}. On the other hand, we calibrated statistically the crash EC trigger on about 4 ms of period reduction (-38%ohmic one) looking also at each crashes inside the modulation. In Fig.2(a) the ST periods of #34286 are shown just before/after EC on/off and inside the EC on phase (b). In Fig.2(b) same plot is shown for #34285 shot with 50% d.c. modulation.

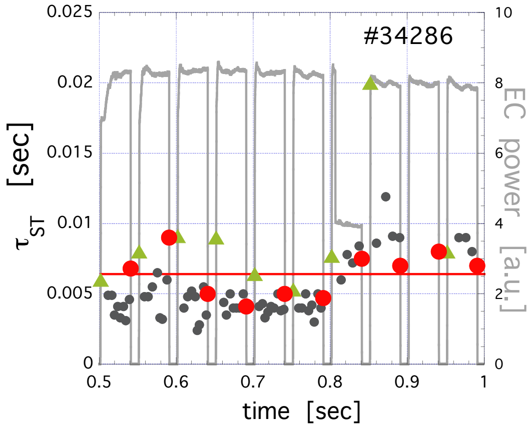

Fig.2(a): ST periods during EC modulation (black circles) and at its start/end (green triangles/red circles)

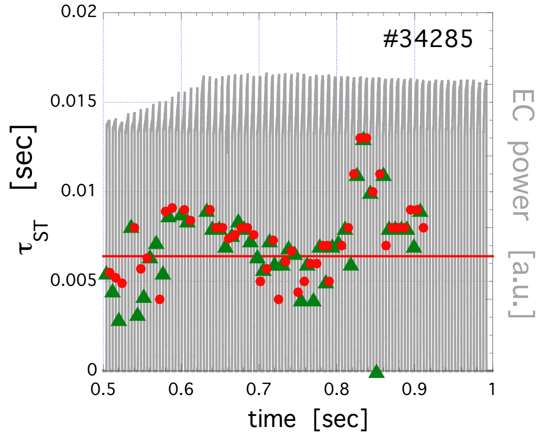

Fig.2(b): as in Fig. 2(a) for modulation 4ms EC on/ 4ms EC off. No more τ_{ST} are inside EC phase on (no black circles)

During the field ramp, ST destabilization is obtained for deposition inside q=1 (t<0.8) and stabilization for deposition outside the r_{inv} ($t > 0.8$). The nearly constant τ_{ST} ($\sim$ 4ms) at $t = 0.65$-0.8 sec corresponds to B_t=5.3-5.45 T for $r_{dep} \sim 0.5_{rinv}$, shown in Fig.3.

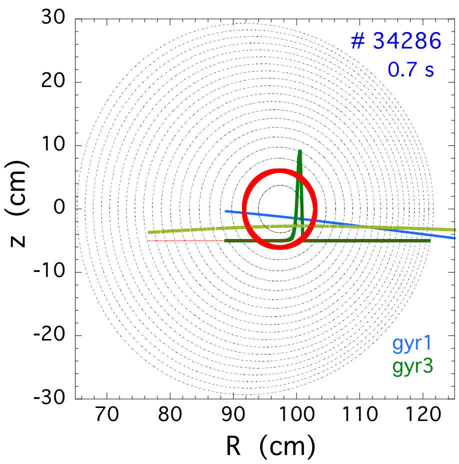

Fig.3 (a): gyrotrons, q=1, and deposition traces for #34286 at t=0.7s for B_t=5.42T

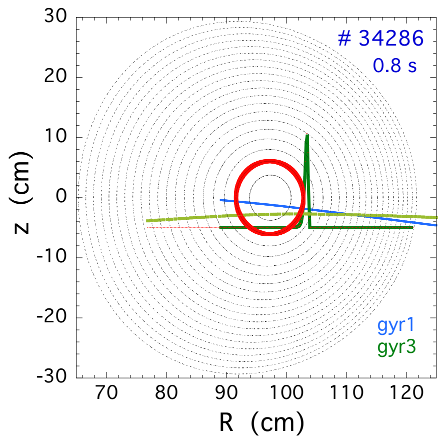

Fig.3 (b): same as Fig.3 (a) for #34286 at t=0.8s for EC deposition nearly outside q=1 surface for B_t=5.57T.

Discussion

The 3 modulations have been considered for experiments with pure heating and EC current driven (10° toroidal injection), in the same plasma current direction, in order to increase the q derivative (and the magnetic shear) inside q=1. The added co-ECCD effect produces a more slightly expected reduction in the ST periods as shown in Figs.4 for EC modulated at 20% d.c.. The EC power/current locations are obtained by using the 3D beam code ECWGB [6] and the q profile, giving the q=1 location in the Figs. 3-4, by the FASTEQ code, which reconstructs for the real time control the FTU equilibrium [7]. Such q=1 surface is found near the location of r_{inv} from polychromator.

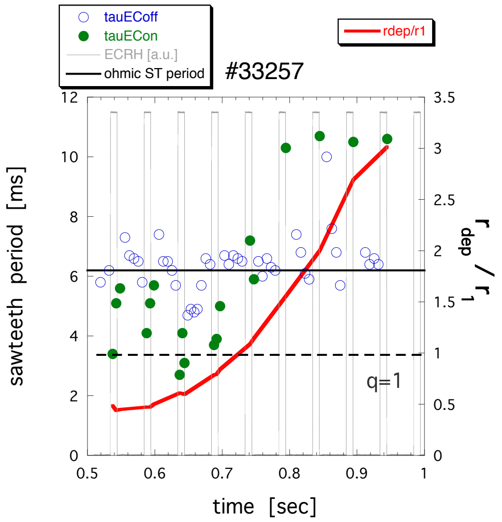

Fig.4 (a): τ_{ST} and r_{dep}/r_1 trace for #33257: ECH only

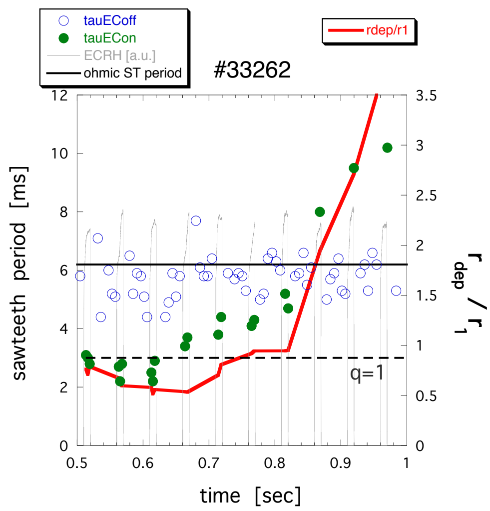

Fig.4 (b): same as Fig.4(a): ECH+coECCD

The coECCD lowers the ST period by ~ 25% (Fig.4(b)) w.r.t. case with pure heating (Fig.4(a)). During the EC off phase for both 20%/80% d.c. ohmic period is nearly recovered, but the results confirm that regular EC modulation induced irregular ST frequency and only averaged values can be considered. To obtain the destabilizing effect induced by ECH/ECCD inside q=1 for a-priori shortened ST period, a real time synchronization is required, switching on the EC power at different time on the ST slope will be next programmatic goal. Experiences with 4msON/4msOFF, producing a quite constant τ_{ST} ~ 8ms= 2 times the EC on phase at r_{dep}~ 0.5_{rinv}, suggest to try 2msON/2msOFF to obtain constant τ_{ST} ~ 4ms. Transport calculation, reconstructing the T_e temporal evolution of 12-channels polychromator, are in progress to design next real time experiments.

References

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