CONTROL of SAWTEETH PERIODS by PULSED ECH/ECCD in FTU tokamak

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(*)See Appendix of P. Buratti et al., paper OV/P-01, this Conference

INTRODUCTION

- Fusion plasma operations can be limited in standard scenarios at high β by resistive instabilities, called Neoclasical Tearing Modes (NTMs), that degrade the plasma confinement
- The onset of these modes, due a finite seed perturbations shaped as magnetic islands can be associated to long sawtooth crashes [1]
- The control of sawtooth periods (τ_{ST}) is then a key physics issue for the plasma confinement and their shortening can reduce any triggered large seed island below the NTMs growth threshold allowing to achieve maximum β and high plasma performances

POWERFUL TOOL for SAWTEETH CONTROL

- A powerful tool for sawteeth control is the use of high localized electron cyclotron heating (ECH) and current drive (ECCD) capable to modify the plasma current density changing the resistivity with effect on sawtooth period [1-3]
- ECCD power pulses have been used [4,5] as trigger of sawtooth crashes to test conditions for an a-priori constant τ_{ST}
- In FTU similar experiments have been performed with an ECRH system of 4 gyrotrons operating at 140GHz and delivering 0.5 MW each: 500ms of repetitive pulses from 2 gyrotrons up to 0.8 MW [6]

PURPOSES of the present work

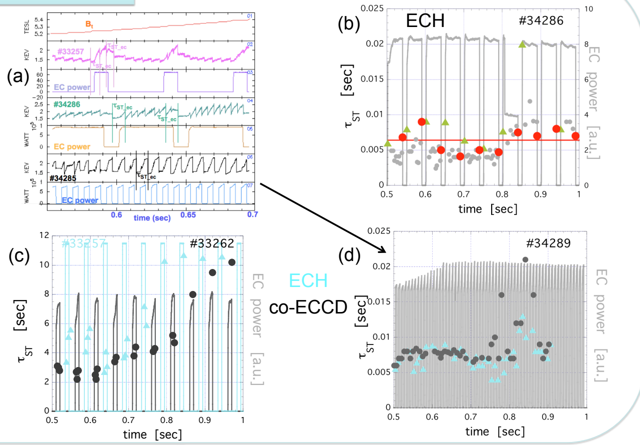
- The aim of this work is to investigate in which experimental conditions the sawtooth crashes can be forced to a constant periodicity using the EC power modulation trying to predict how a given sawtooth period can be obtained
- In particular, we focus our interest to the destabilization of sawteeth, i.e. to shortening τ_{ST} below the "natural" ohmic value inside the q=1 surface by using fast ECH and coECCD modulations in order to investigate locking of the sawtooth period to EC modulation as experimentally seen for 125 Hz EC pulses and 50% duty cycle.

SAWTOOTH CONTROL EXPERIMENTS

- in **FTU** high magnetic field compact tokamak (R_0 = 0.93 m, a = 0.3 m, B_0 = 4-8 T) ***experiments have been performed to investigate the sawtooth control by injecting EC power modulation*** for 500 ms from 2 gyrotrons up to 0.8 MW in a target plasma at 0.5 MA, 0.6 10^{20} m^{-3} line average electron density and magnetic field ramp from 5.1 T to 5.9 T to move EC absorption from inside to outside the inversion minor radius r_{inv} at q=1 surface
- **focus on destabilization of sawteeth inside the q=1** *shortening* τ_{ST} below the ohmic value of ~ 6 ms by ***ECH/co-ECCD pulses at 20 Hz (20% and 80% duty cycle) and 125 Hz (50% d.c.)*** **(a)**
- **EC effect on ST periods** investigated looking both at time delay $\tau_{ST,ec}$ between 2 crashes before/after EC on/off phases and at crash dynamics during the EC on phase **(a), (b), (c), (d)**
- **ST** *destabilization* at ***irregular periods with 20 Hz*** EC pulses has been observed both with ECH/ coECCD injection: τ_{ST} decreases to 3-4 ms (50%-35% below the ohmic value) with ECH and to 2 ms (~67% below $\tau_{ST,ohmic}$) with coECCD **(b), (c)**
- **ST** *(unforeseen) stabilization* at ***regular periods* above the ohmic τ_{ST}** (~30%) ***with 125 Hz EC pulses*** has been observed ***for heating and coCD inside q=1*** ***(d)***

=> new interesting evidence of τ_{ST} locking to EC pulse period => strategy to set an a-priori constant τ_{ST} by using faster EC modulation (> 125 Hz)

(cases of locking already observed in TCV but for EC deposition outside the q=1 [5] ***)***



SIMULATIONS with JETTO TRANSPORT CODE

- transport simulations have performed with JETTO transport code [7]
- **ST instability (crash) condition** has given **by a critical shear $s_{1,cr} < s_1$ magnetic shear** [8] and **complete reconnection by the Kadomtsev model** [9] with $s_{1,cr}$ is expressed for the ***ion-kinetic regime*** in FTU as [8,10] :

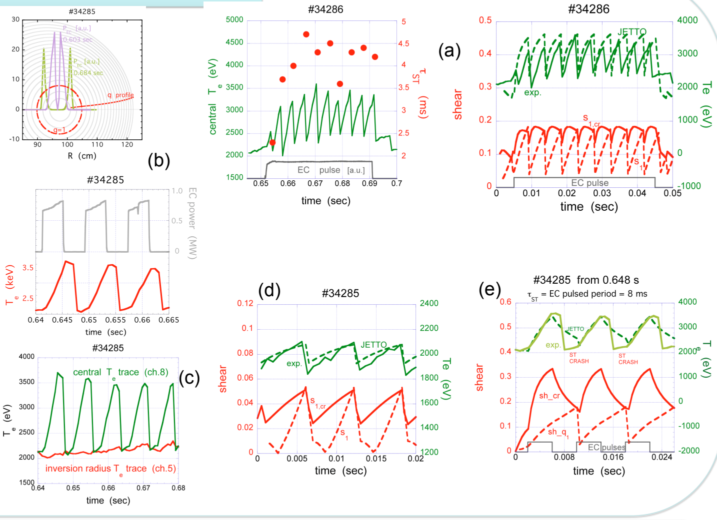
$$s_{1,cr} = c_*^{-7/6} [\pi T_i / 2(T_e + T_i)]^{1/3} \tau_A^{7/6} (\omega_{*e}\, \omega_{*i})^{7/12} (r_1/\rho_i)^{2/3} S^{1/6}$$

with τ_A the Alfven time, $\omega_{*e,i}$ the e-/ion diamagnetic frequency, r_1 the q=1 minor radius, ρ_i the ion Larmor radius, $S=\tau_\eta/\tau_A$ the Reynolds number being τ_η the resistive diffusion time

- ***simulations*** performed taking ***factor c_**** and ***electron heat diffusivity χ_e*** as ***free parameters***
- **ST dynamics simulated for 20 Hz/d.c. 80% EC pulses (a)**: best fit with c_*=0.86 and χ_e=1.09 m^2/s
- **ST periods well reproduced for EC deposition inside the q=1 and for 3 EC pulses at 125 Hz/50% d.c. (b)** : good agreement between measured **(c)** and calculated T_e evolution and crash dynamics is found for the ohmic **(d)** and heating **(e)** phases taking c_*=1.33 and χ_e=0.38 m^2/s
- **local confinement time $\tau_c = r_1^2 / \chi_e$ is compared with resistive time $\tau_\eta = \mu_0 r_1^2 / \eta$:**
  - **for 20 Hz EC modulation : τ_c = 2.6 ms , τ_η = 260 ms**
  - **for 125 Hz EC pulses : τ_c = 7.1 ms , τ_η = 360 ms**

=> transport results indicate that allowed τ_{ST} is of order of τ_c for the same level of power density profile width and location

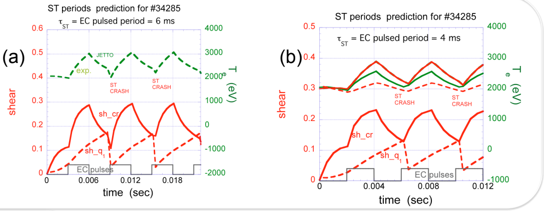
=> more transport is required to simulate τ_{ST} locking to faster pulsed EC period
(simulations of ST period locking already performed with a simple model considering constant $s_{1,cr}$ [11] ***)***



PREDICTION of MODE LOCKING by EC MODULATION FASTER than 125 Hz

- the **feasibility of locking of τ_{ST} experimentally demonstrated** in FTU discharge #34285 ***inside q=1*** is a starting point to investigate how faster ECH/ECCD modulations can couple the sawteeth frequency
- **2 faster EC power modulations have been simulated by JETTO :**
  - **167 Hz / 50% d.c. with prediction of τ_{ST} reduction to EC pulse periodicity = 6 ms (a)**
  - **250 Hz / 50% d.c. with prediction of τ_{ST} reduction to EC pulse periodicity = 4 ms (b)** (T_e traces at 3 radii inside q=1 are shown)
- **comparison of characteristic times gives:**
  - **for 167 Hz EC modulation : τ_c = 5.7 ms , τ_η = 267 ms ,** ***χ_e=0.48 m^2/s***
  - **for 250 Hz EC pulses : τ_c = 3.5 ms , τ_η = 260 ms ,** ***χ_e=0.78 m^2/s***

=> again transport results indicate that the ***minimum allowed τ_{ST} is of order of τ_c***



CONCLUSIONS

- **transport calculations** using JETTO code have been performed to reproduce ST periods inside q=1 with focus on shots with fast 125 Hz EC pulses and observed ST periodicity locked to EC power frequency
- this **new evidence of ST locking** suggested to investigate how an **a-priori τ_{ST} can be predicted** by using faster EC modulation
- **predictive results for 167 Hz / 250 Hz Ec pulses** indicate that ***inside q=1*** **the minimum allowed ST period** is of the order of **local confinement time** for the same level of EC power density profile width and location ***=> more transport required , higher χ_e***
- **Key questions for future work**: 1) can this locking be found also for machines in collisionless regime and high β like ITER ? 2) how much is it important the ratio between the resistive and local confinement time, 3) how can these results change in presence of fast particles? In this case the ST periodicity control should be easier due the small dependence of $s_{1,cr}$ on gradients

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