INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

Sawtooth and its effect on edge plasma processes

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MINISTRY OF EDUCATION, YOUTH AND SPORTS

OUTLINE

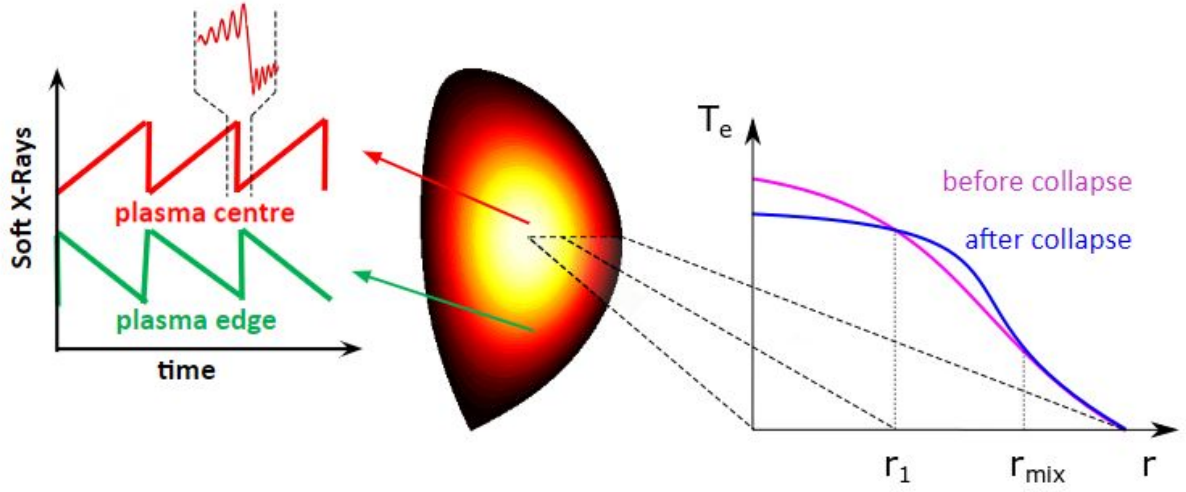
- Theoretical introduction
- Characterisation of sawtooth instability at COMPASS
- Effect of sawteeth on edge plasma
  - L-H transition
  - H-L transition
  - Occurence of edge localised mode (ELM)
  - Transition from ELMy H-mode to ELM-free H-mode
- Summary and next steps

THEORETICAL INTRODUCTION

- Changes temperature profile and magnetic topology in significant volume of plasma, and therefore affects various plasma processes

- Associated with cyclic slow increases and fast drops of the core temperature

- Routinely observed on COMPASS soft X-ray diagnostics as sawtooth pattern
    - SXR signal ~ $Z_{eff} n_e^2 \sqrt{T_e}$ + line radiation of heavy impurities



\- Limits gradient of pressure and current profiles in plasma core

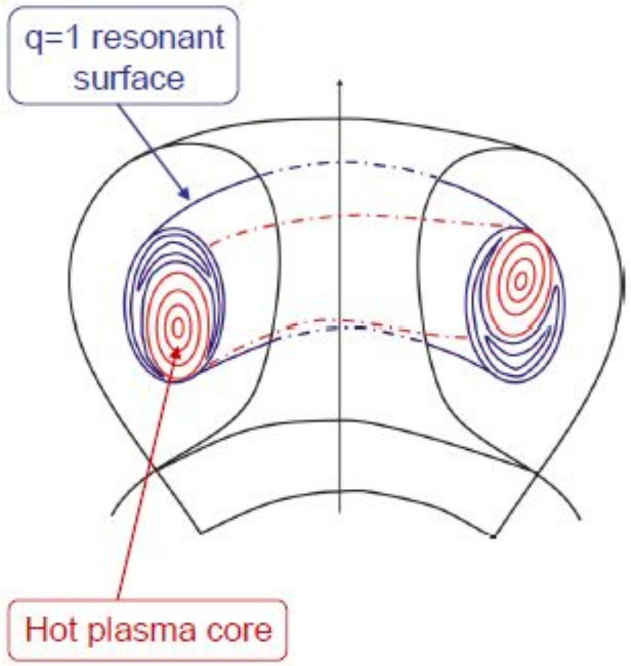
\- Longer sawteeth period shown to trigger neoclassical tearing modes (magnetic islands) below their thresholds → degradation of confinement

\+ Helps to remove impurities from plasma core

Physical background - 4 phases:

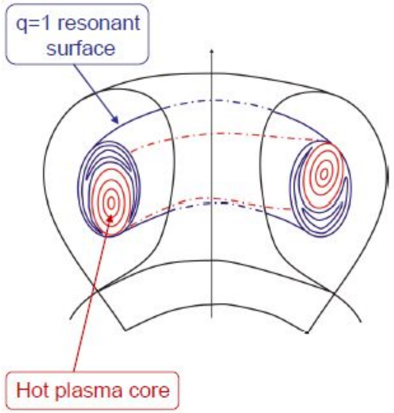
$$q = \frac{1}{2\pi}\oint \frac{rB_\Phi}{RB_\theta} d\theta$$

- **1) Ramp-up phase**
  - gradual increase of temperature and its gradient in plasma core
  - high temperature gradient → high conductivity → higher j in plasma core → higher B_Θ → **q < 1**
- **2) Precursor phase**
  - development of **internal kink** instability (m=1, n=1 mode)
  - displacement of plasma core (can be treated by energy principle)
- **3) Sawtooth crash**
  - magnetic reconnection (typically less than 100μs in tokamaks)
  - heat pulse from plasma core to the edge
- **4) Post-cursor phase**
  - oscillations indicating incomplete reconnection
  - partial reconnection model

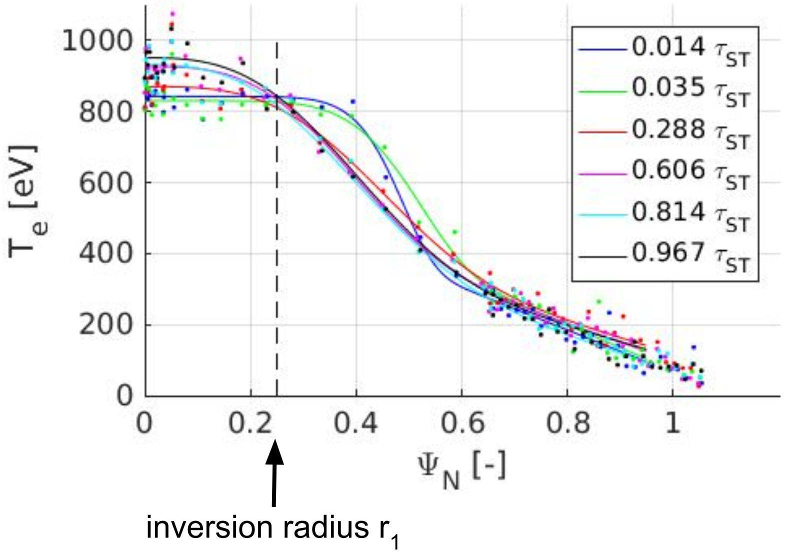


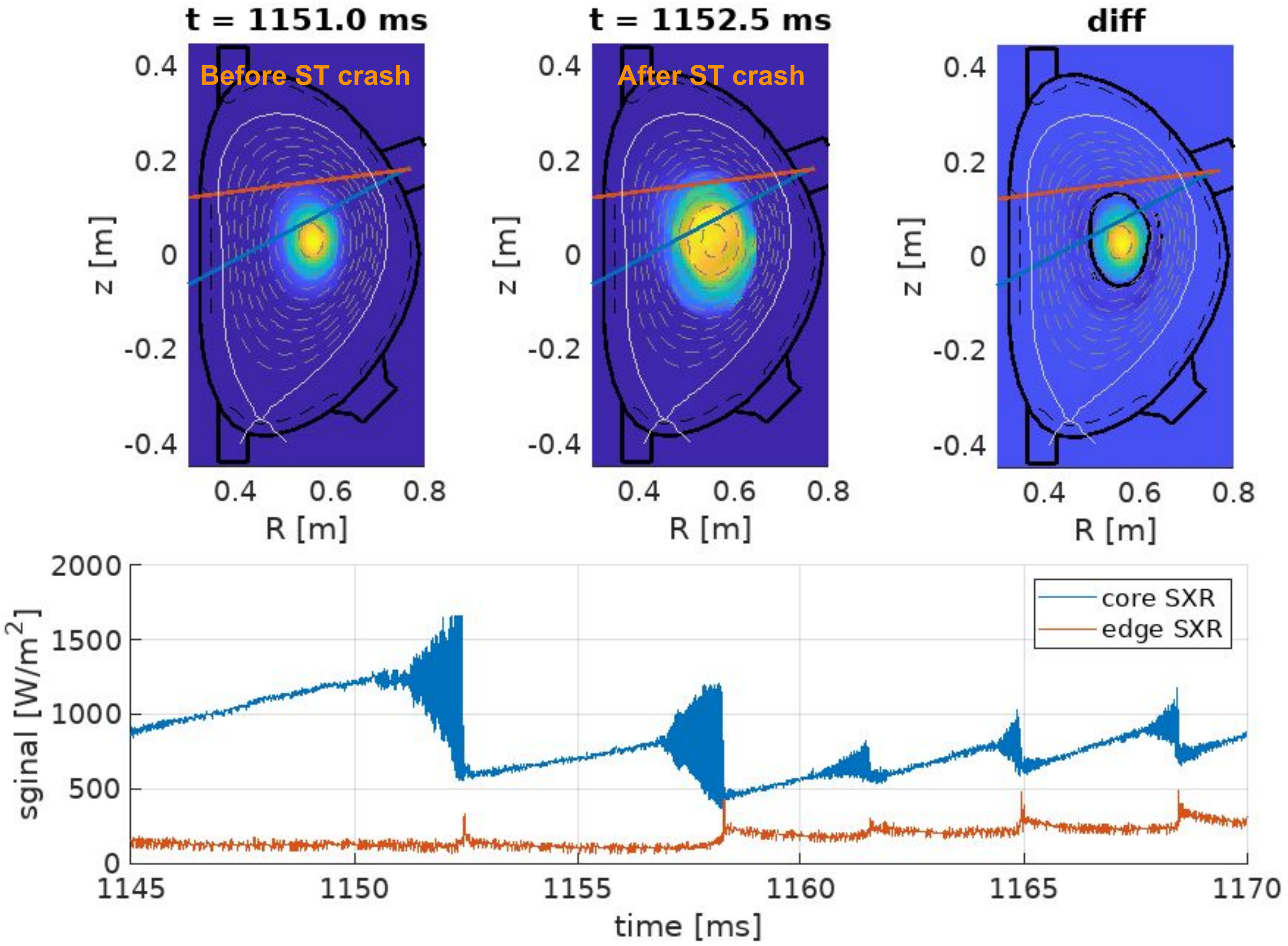
SAWTOOTH INSTABILITY AT COMPASS

SAWTOOTH INSTABILITY



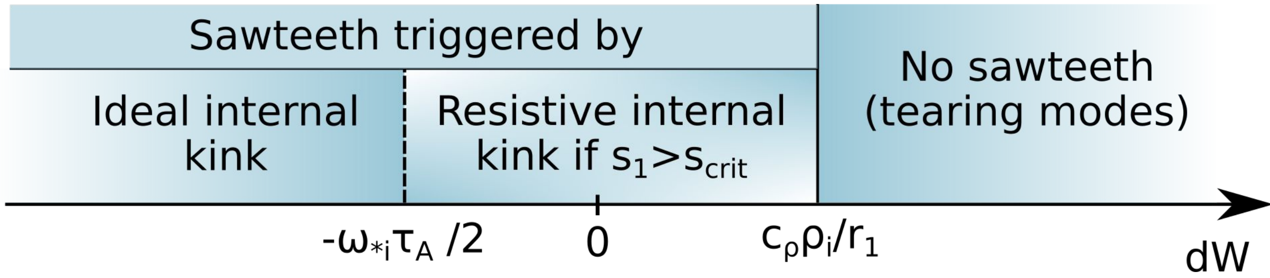
4 phases:
1. Ramp-up phase
2. Precursor phase
3. Sawtooth crash
4. Post-cursor phase





- **Porcelli heuristic sawtooth crash trigger model - based on energy principle:**
  - sawtooth crash when the change of potential energy of the kink mode due to its displacement:
    $\delta W_{MHD} + \delta W_{fast\ particles} + \delta W_{trapped\ particles} < \delta W_{crit}$

- **Triggered by ideal internal kink:**
  - $-\delta W$ sufficiently high to rely on the ideal internal kink mode model and other effects can be neglected

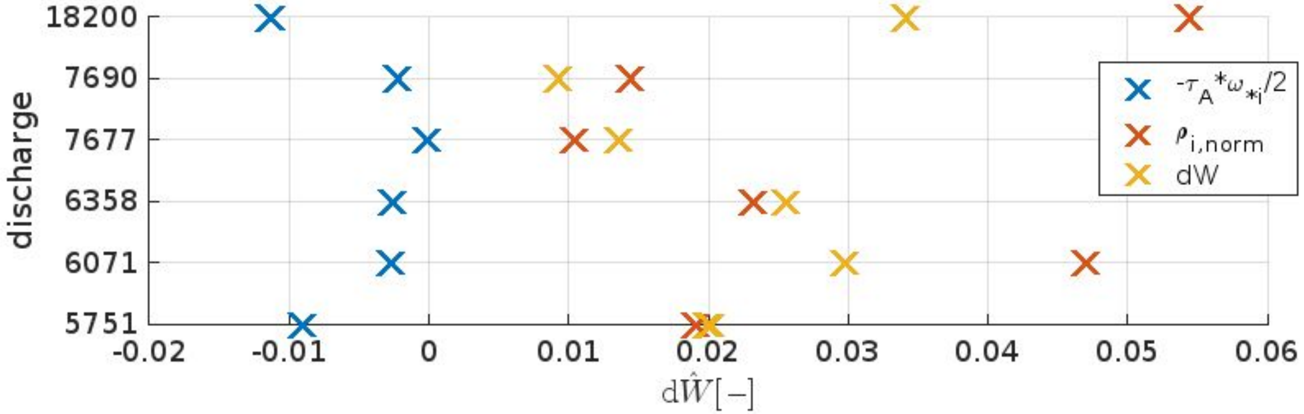


- **Resistive effects:**
  - Sawtooth crash triggered when $s_1 > s_{crit}$:

$$s_1 = \frac{r_1}{q_1}\frac{dq}{dr} > s_{crit} \approx \beta_{i1}^{7/12}\frac{r_1}{L_n}\left(\frac{r_1}{L_p}\right)^{1/6} S^{1/6}\rho_{*i}^{1/2}$$

$$q = \frac{1}{2\pi}\oint \frac{rB_\Phi}{RB_\theta}d\theta \qquad L_n = n/|dn/dr|$$

  - strong dependence on plasma density, its gradient and plasma pressure



- **COMPASS**: calculations (from METIS) indicate **resistive region** (often observed also at JET, TEXTOR …)

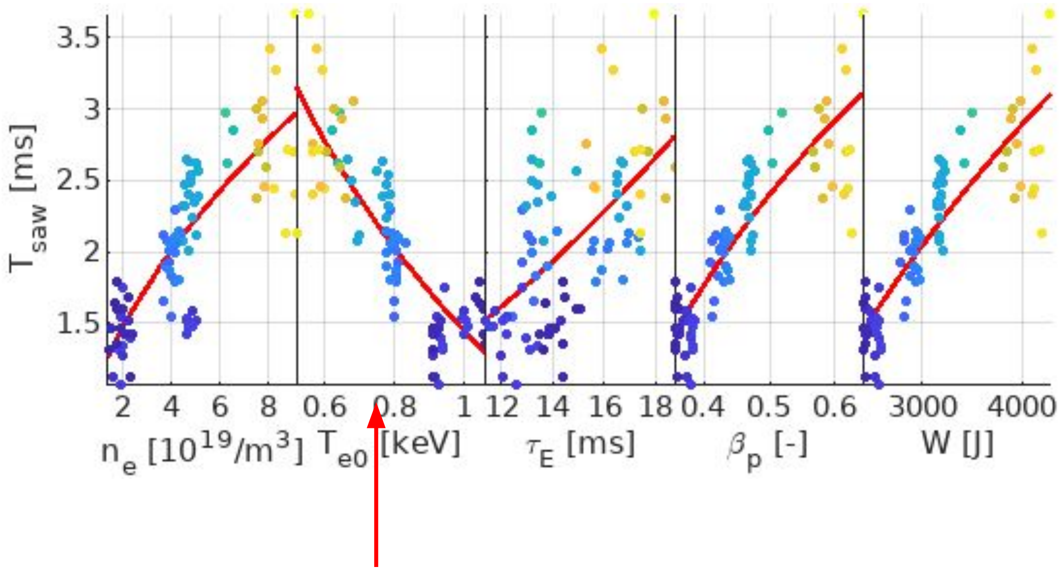
- **Sawtooth period** - time required to reach the criteria for sawtooth crash, i.e. destabilisation of kink mode

- When diffusion of current into plasma core is dominant mechanism (typically large sawtooth):
  $T_{SAW} \sim$ resistive diffusion time $= \mu\sigma r_1^2 \sim T_e^{3/2}$

- When pressure gradient and other effects play an important role in kink mode stability (q<1 necessary, not sufficient): $T_{SAW} \sim \tau_E$ [Porcelli, 1996]

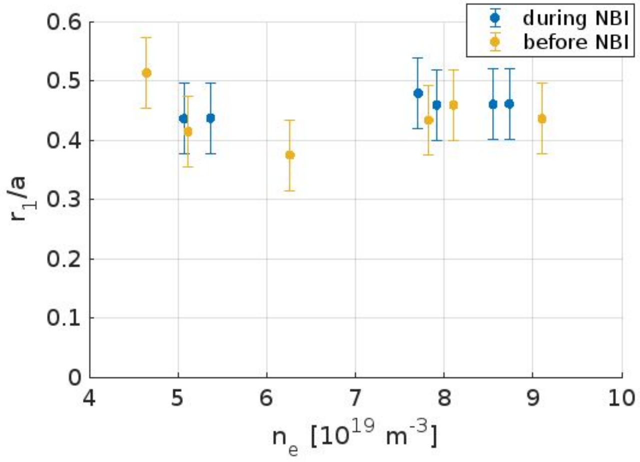
- **Inversion radius** r_1 - without significant change (below precision of the method)

Sawtooth period vs various plasma parameters during density scan (color - W):



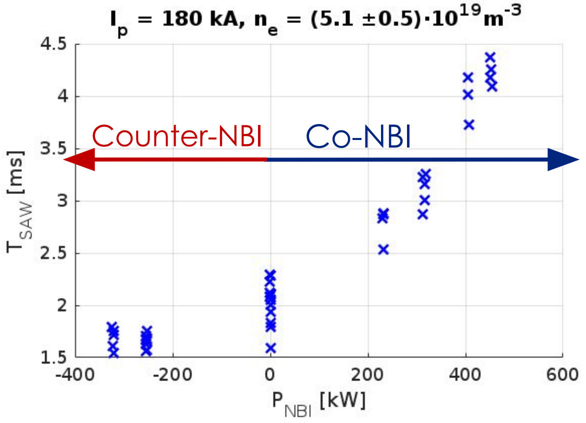
Sawtooth period rises for shorter resistive diffusion times of plasma current

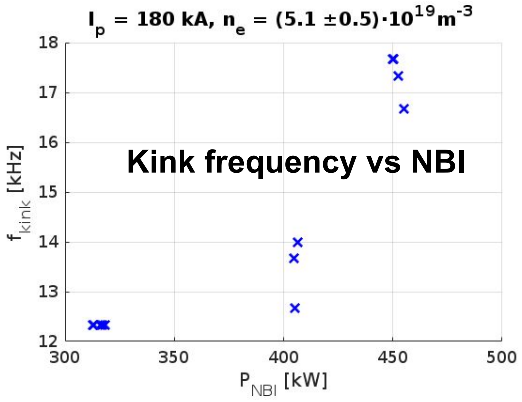
Inversion radius r_1 (from SXR tomography)

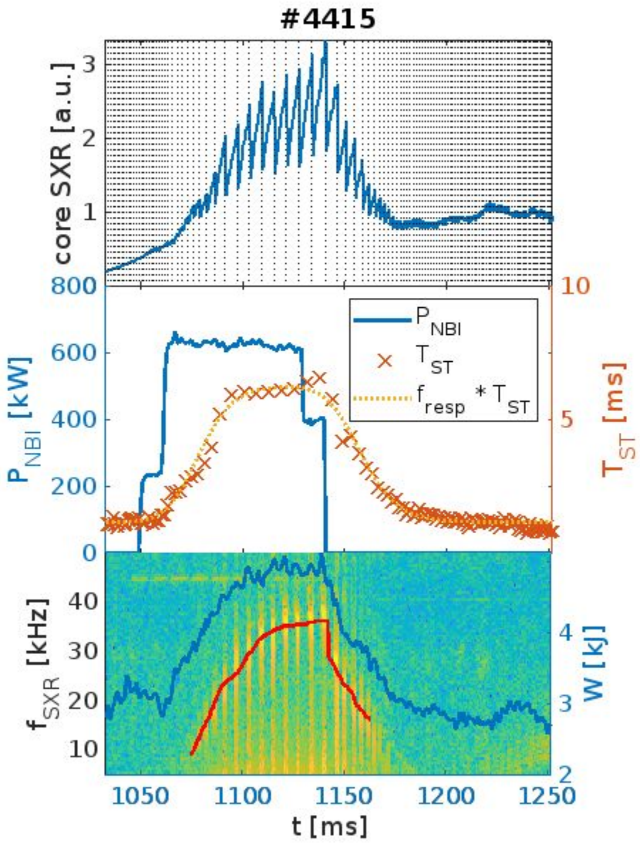


SAWTOOTH DURING NBI HEATING

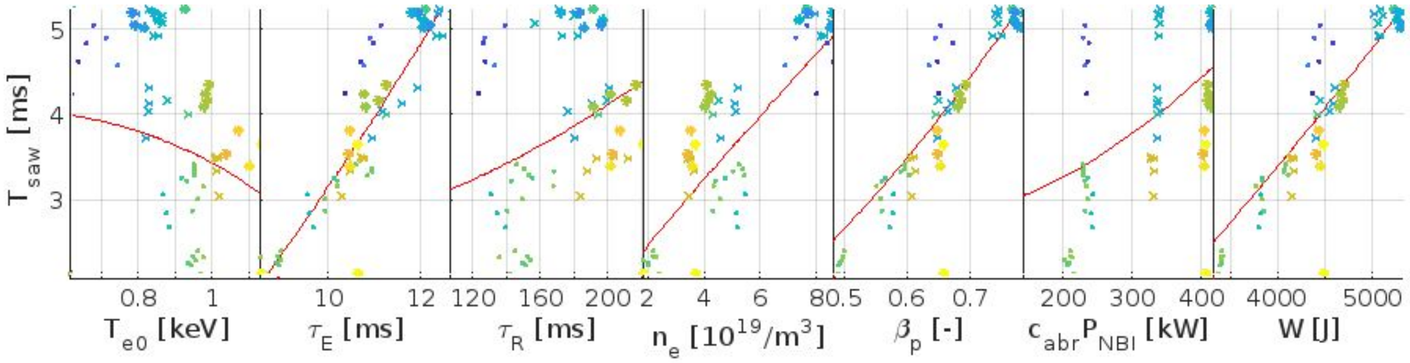
- NBI affects the kink mode stability (**δW**) via plasma rotation (centrifugal effects) and distribution of fast particles
- Increased kink frequency indicates increased tor. rotation
- Similar to JET - minimum of sawtooth period at small counter-NBI heating due to competition of stabilising effects of trapped fast particles and flow shear [Chapman, Phys. plasmas, 2007]







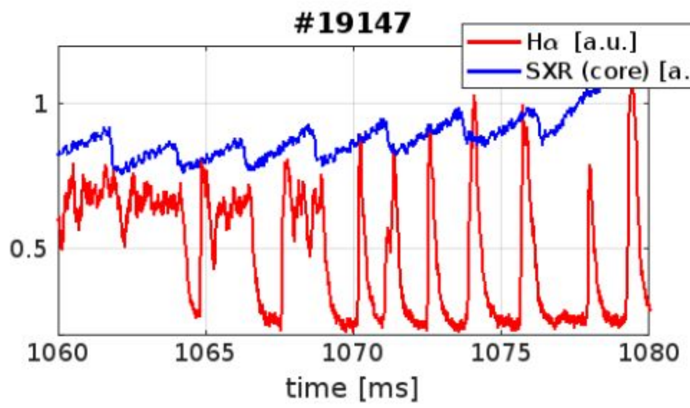
- Trends with T_{e0} and τ_R less clear but $T_{SAW} \sim \tau_E$ and $T_{SAW} \ll \tau_R$ (colors - density, NBI - marks)

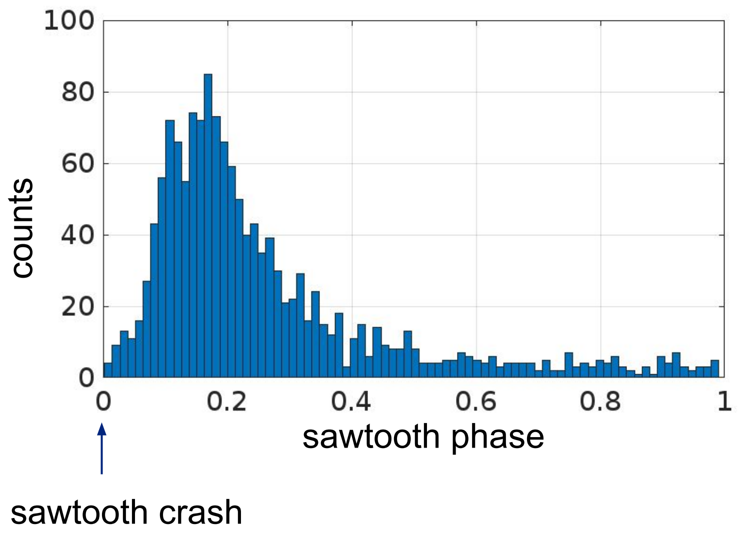


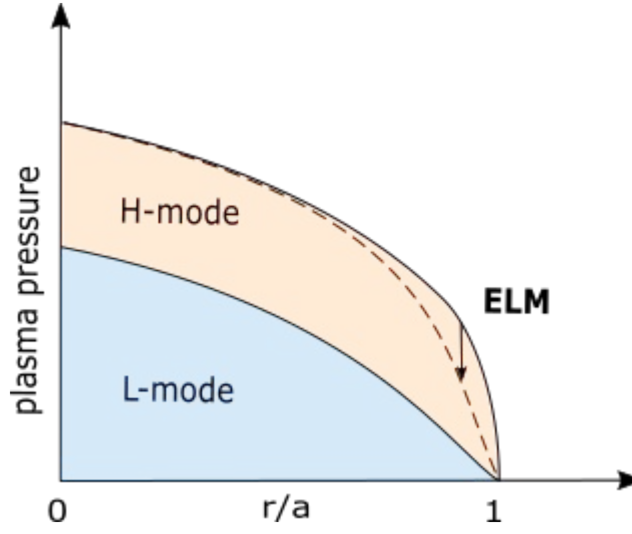
EFFECT OF SAWTEETH ON EDGE PLASMA PROCESSES AT COMPASS

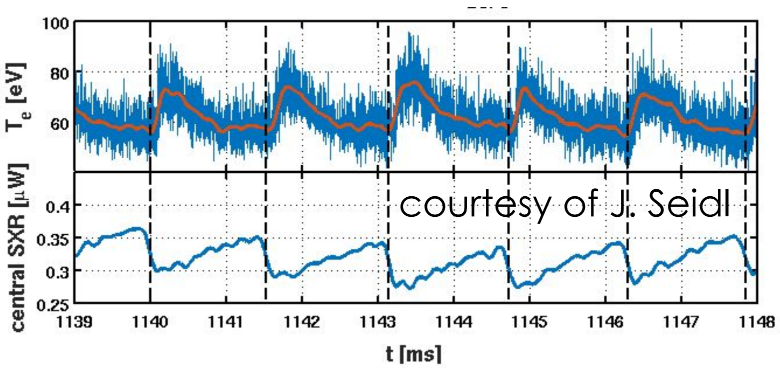
- **H-mode**: a regime with better energy confinement - formation of shear flows near plasma edge tear turbulences → the edge transport barrier

- **L-H transition** (transition to H-mode) exhibits high correlation with the sawtooth crash at COMPASS





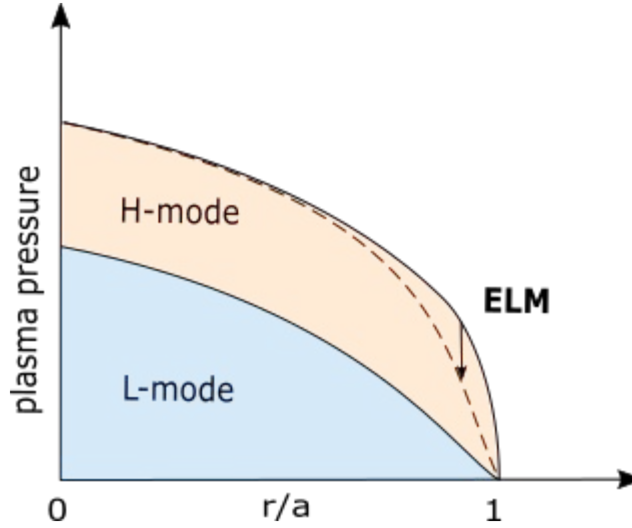


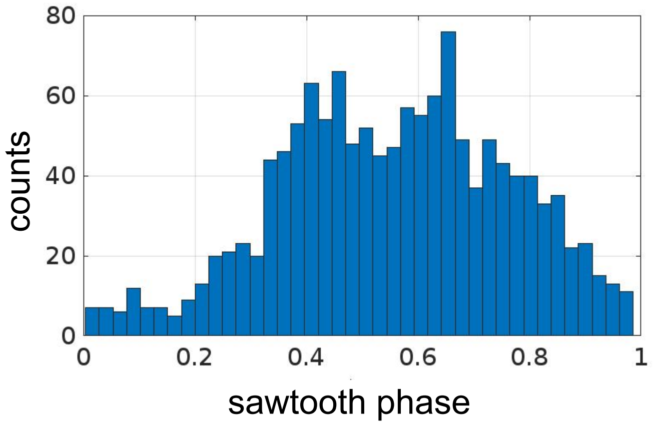


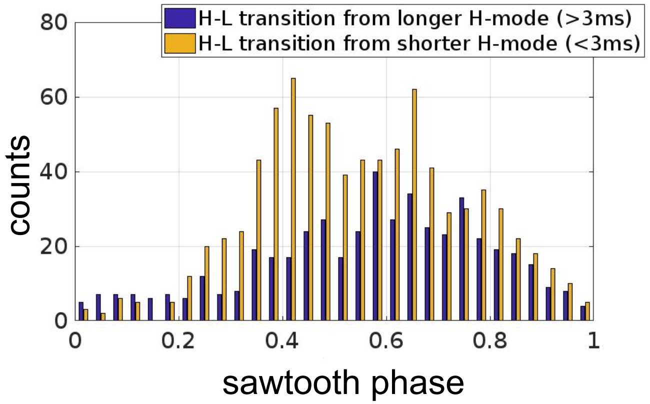
Horizontal reciprocating probe: change of edge Te after sawtooth crash can be tens of %

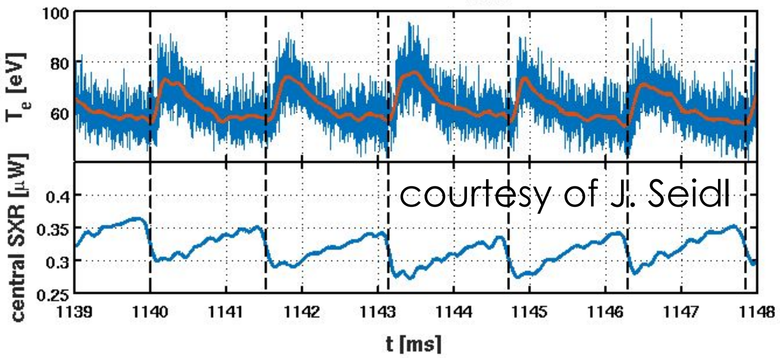
- Heat pulse from sawtooth crash can supply enough free energy for the formation of the edge shear flows and the transport barrier

- **H-L transition** (end of H-mode) is mostly avoided within 0.3 of the sawtooth phase and 0.4 ms after sawtooth crash
- The heat pulse from sawtooth crash apparently delays conditions for the H-L transition
- **Short “H-modes”** (with duration comparable to sawtooth period)
  - not fully developed H-mode but shows reduced plasma-wall interaction and formation of transport barrier
  - indication that plasma close to L-H transition
  - transition to L-mode often at cca 0.4 of sawtooth phase indicating lower plasma edge stability near condition close to L-H transition









Horizontal reciprocating probe: change of edge Te after sawtooth crash can be tens of %

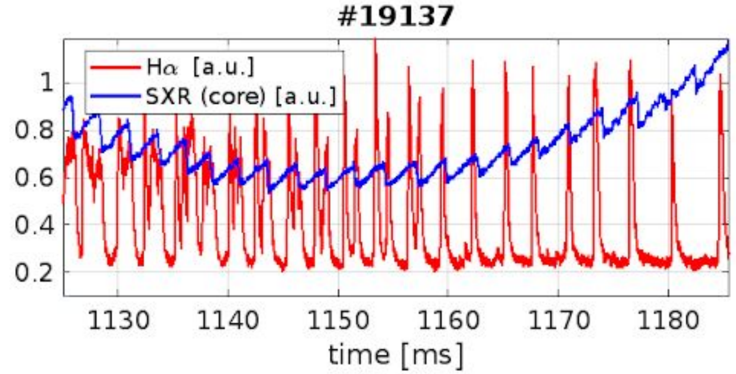
- **Edge localised mode (ELM)**
  - quasi-periodic relaxation of a transport barrier formed in H-mode
  - observed as peaks in Dα signal - increased plasma-wall interaction
  - results in high heat loads on tokamak vessel

- **ELMs** less likely to happen at 0.2 of sawtooth phase or 0.4 ms after the sawtooth crash

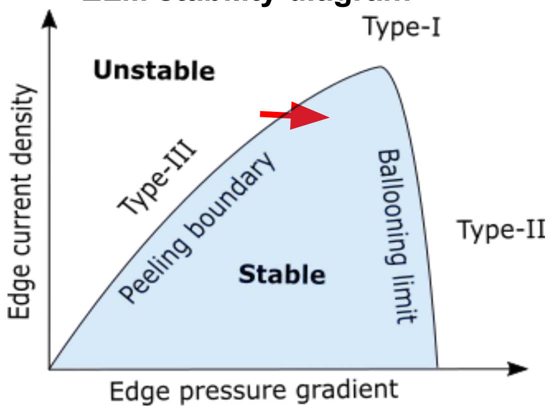
- corresponds to the delay of the L-H

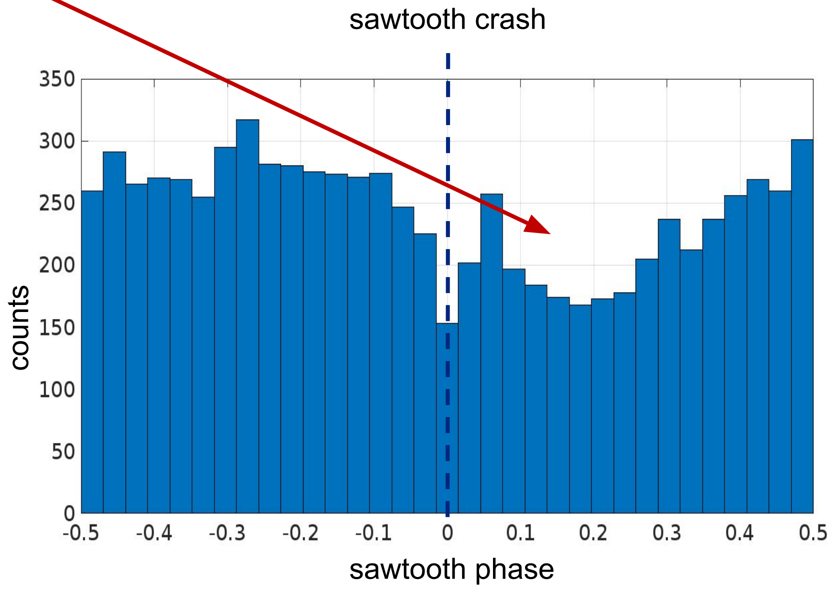
- heat pulse can increase the edge pressure gradient so that it shifts the edge plasma into the stable region for type-III ELMs

- peeling mode - driven by a high current density (similarity to kink mode) => peeling of current filaments from the confined plasma



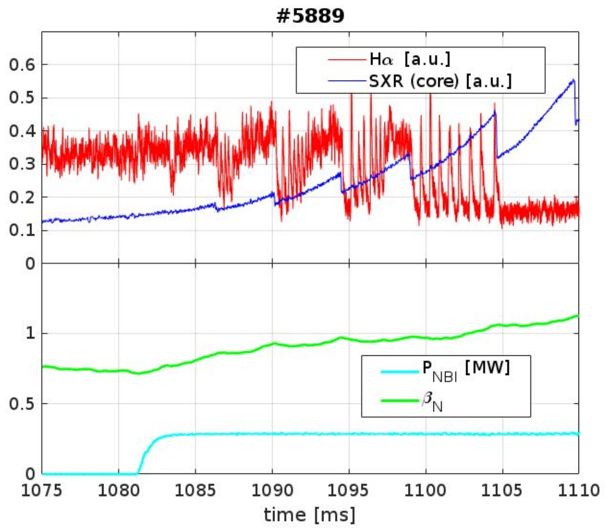
ELM stability diagram

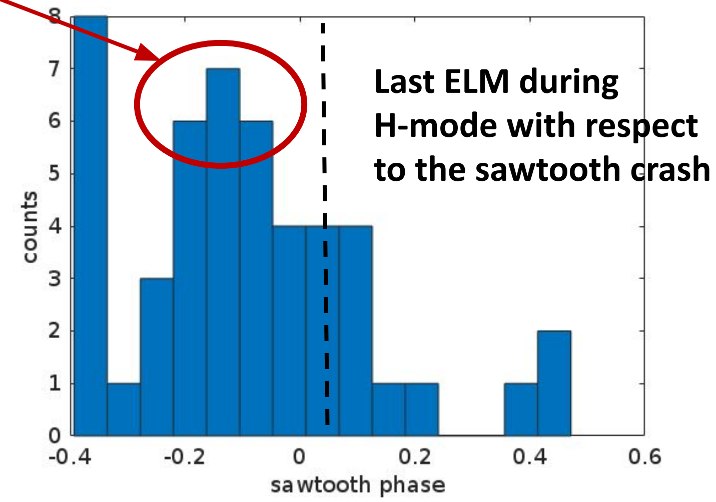




TRANSITION TO ELM-FREE H-MODE

- Increasing plasma heating → L-H transition → ELMs (small) → transition to ELM-free H-mode (unstable) → ELMs (large)
- ELM-free regime (if uncontrolled) can lead to a disruption - strong cooling via radiation of accumulated impurities
- **Transition to ELM-free H-mode** is not so strongly correlated with the sawtooth crashes as it is in the case of the L-H transition, but still **visible**
- Group of last ELMs before ELM-free H-mode occurring in the middle of sawtooth phase - indicating lower plasma edge stability





- **Sawtooth instability at COMPASS**
  - Sawtooth period $T_{SAW} \sim \tau_E$ and $T_{SAW} \ll \tau_R$ possibly negligible effect of the diffusion of the plasma current in the plasma core in comparison with other effects (pressure gradient vs. steepness of the current profile)
  - calculations based on METIS simulations indicate a resistive regime of the internal kink mode
  - NBI: stabilisation of kink mode in co-NBI, destabilisation in counter-NBI (similar behaviour at JET)

- **Effect of sawtooth instability - strong influence on plasma edge processes**
  - triggers vast majority of detected L-H transitions (0.4 ms)
  - ELMs less likely to happen after the sawtooth crash (0.4 ms)
  - can trigger transition to ELM-free H-mode
  - H-L transition is most probable in the middle of the sawtooth cycle

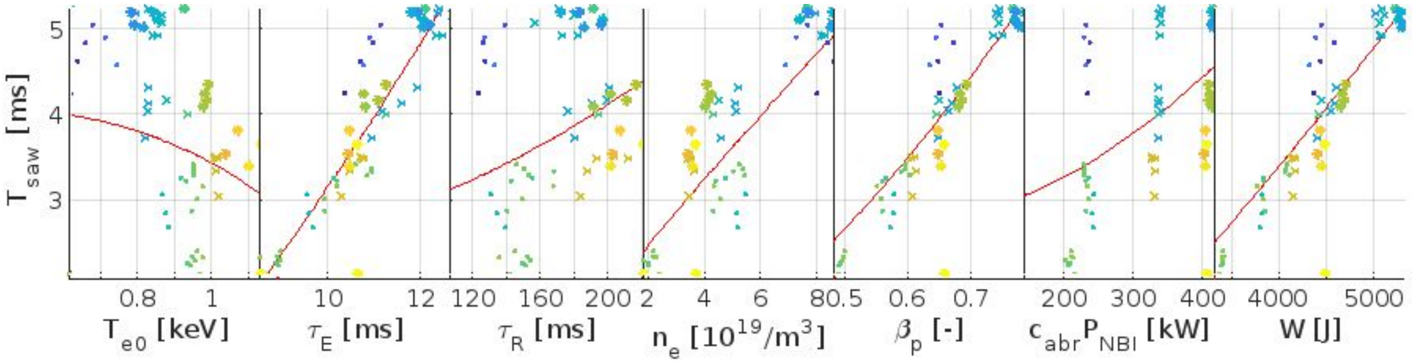
- **Next:**
  - Plasma edge stability (from simulations) vs sawtooth and ELM cycle
  - Analysis of last campaigns with additional heating power
  - Change of poloidal rotation during sawtooth cycle

BACKUP SLIDES

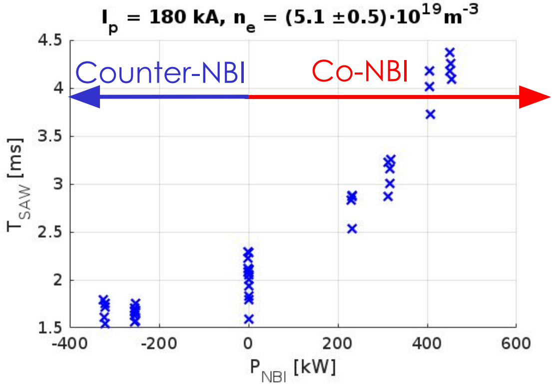
Q: The results shown in Figs. 6.13 - 6.16 seem to indicate that the sawtooth period is actually more probably sensitive to τE or W than to PNBI. In this case, what could explain the observed minimum of Tsaw for NBI in counter-current regime?

A: The results in these Figs (6.13 - 6.16) are during scan over both density and NBI, but they also show increasing trend of sawtooth period with NBI. The figures in scan over NBI and plasma density also do not contain data from counter-NBI which could bring the opposite trend with NBI.

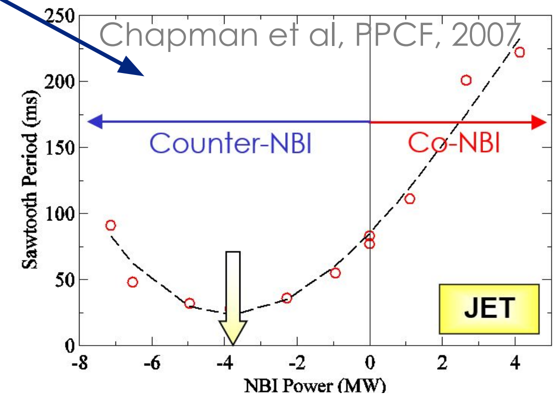
Proper analysis requires modelling - minimum of Tsaw in counter-NBI also found in JET

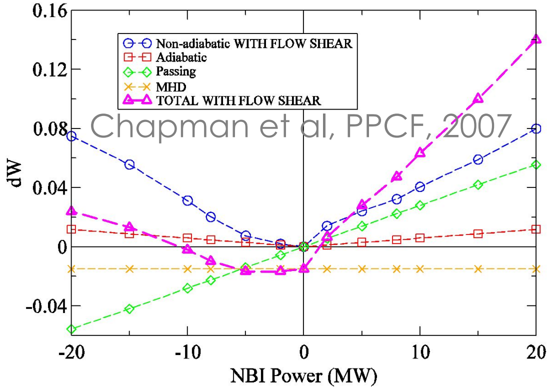


Scan over NBI and density - density represented by colors, NBI by marks



COMPASS

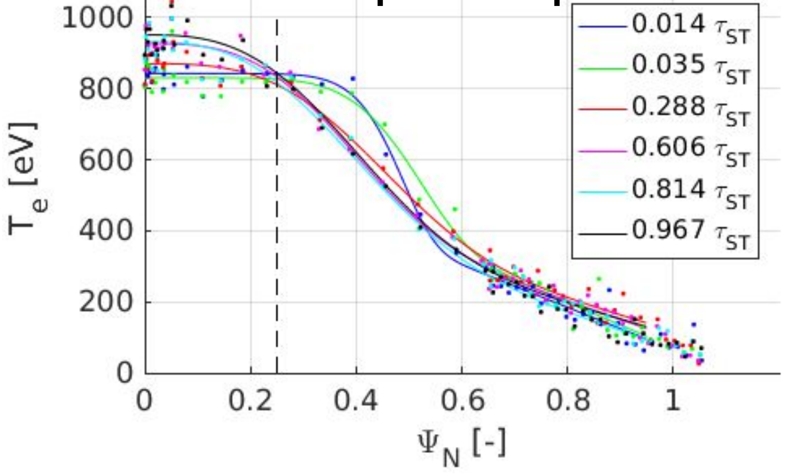




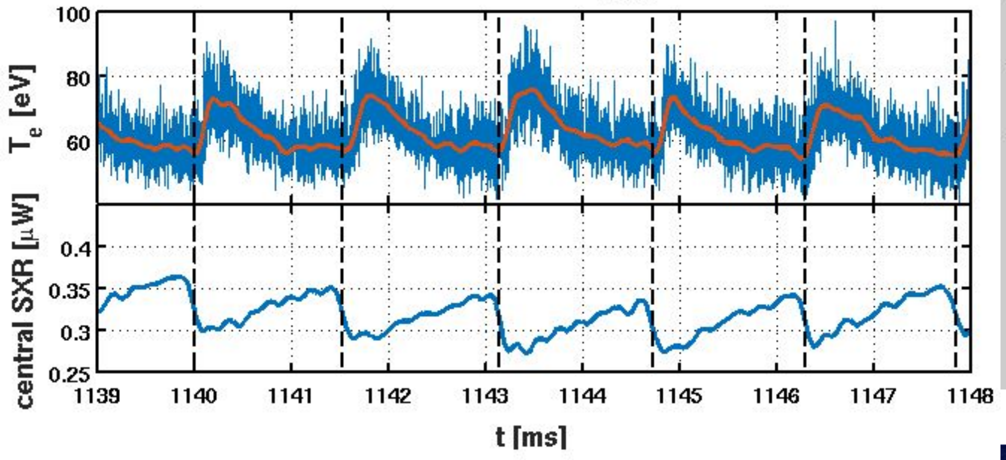
JET: In accordance with numerical models including effects of **energetic trapped** and **passing particles** and **shear flows**

SAWTOOTH INSTABILITY AT COMPASS

Electron temperature profiles



Horizontal reciprocating probe: change of edge Te after sawtooth crash can be tens of %



SXR emission $Z_{eff} n_e^2 \sqrt{T_e}$