Fast seeding of NTMs by sawteeth and the use of non-continuous ECRH for their preemption

Gustavo Paganini Canal

in collaboration with

B.P. Duval, F. Felici, T.P. Goodman, J.P. Graves, A. Pochelon, H. Reimerdes, O. Sauter, D. Testa and the TCV Team

Ecole Polytechnique Fédérale de Lausanne (EPFL) - Centre de Recherches en Physique des Plasmas (CRPP), Lausanne, Switzerland

Princeton, New Jersey

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Outline: Fast seeding of NTMs by sawteeth and the use of non-continuous ECRH for their preemption

- Introduction
- The TCV ECRH/ECCD system setup for ST control and NTM preemption
- Diagnostics and data analysis required to observe the fast NTM seeding
- Experimental evidences of the fast seeding of NTMs by sawtooth crashes
- Effect of geometrical factors on the NTM seeding
- Non-continuous preemptive ECRH used for NTM preemption
- Summary

More details: G.P. Canal, *et al.*, Nuclear Fusion 53 (2013)

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NTM is a limiting instability for the ITER Q = 10 scenario

- **Deleterious effects of Neoclassical Tearing Modes (NTMs)**
  - Degradation of plasma confinement [**Sauter, Phys. Plasma 1997**]
  - Interaction with the resistive wall causes plasma rotation to stop
    - → Mode locking causes exit from the H-mode
    - → Continued island growth may lead to disruption [**Luce, Phys. Plasma 2004**]

- **Typical tokamak plasmas are linearly stable against NTMs but they are non-linearly unstable**
  - NTMs can be destabilized by other instabilities

- **Several kind of instabilities can seed the NTMs**
  - Fishbones [**Gude, NF 1999**], ELMs [**Rice, NF 1999**], **Sawteeth** [**La Haye, NF 2000**]

- **ITER Q = 10 scenario with dominant α-heating will have sawteeth (ST) of long duration** [**Hender, NF 2007**]

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Sawtooth crashes with sufficient long periods may trigger NTMs at low values of β_N

Figure 4 from Chapman, NF 2010

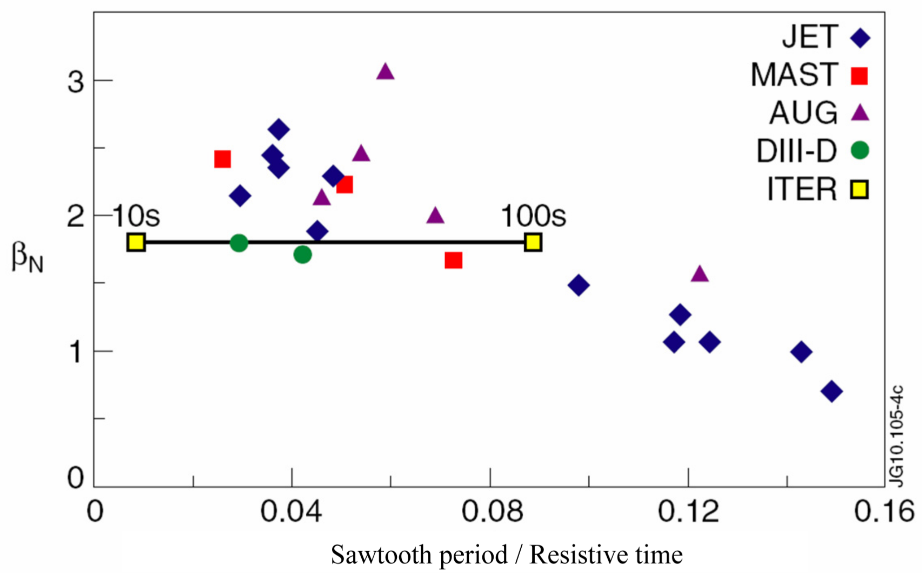

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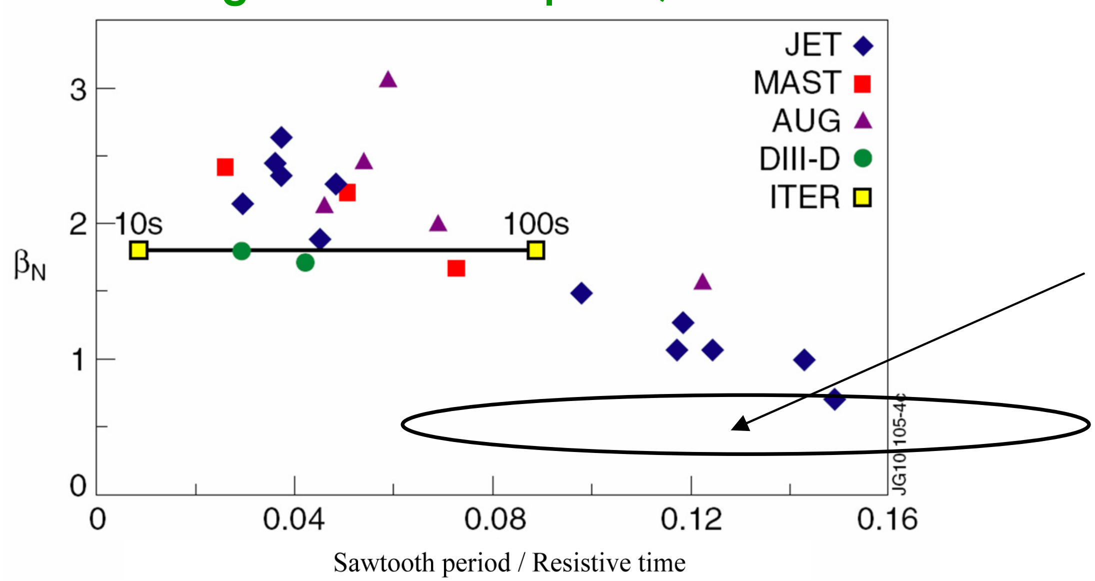
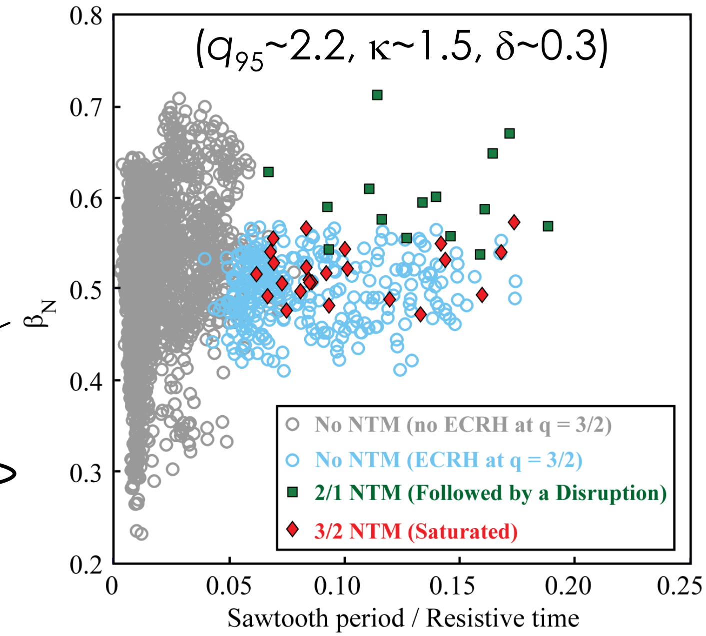
Figure 4 from Chapman, NF 2010



Occurrence of ST triggered NTMs in TCV



- Improved understanding of the NTM onset could lead to safer operation at higher plasma pressures

Strategy to identify the seeding mechanism behind sawtooth triggered NTMs

- **Replicate sawtooth triggered NTMs under controlled conditions:**
  - Accurate control of the sawtooth period (τ_{ST})
  - Reproducible discharges

- **To avoid ST triggered NTMs the coupling process must be affected by either:**
  - Affect the driving mode (1/1 and harmonic 2/2)
    - → Control of the ST period
  - Affect the driven modes (2/1 and 3/2 modes)
    - → Preemptive ECRH

- **In TCV, the natural sawteeth are too short to trigger an NTM**
  - Use TCV capabilities to increase the sawtooth period and trigger NTMs in a controlled environment

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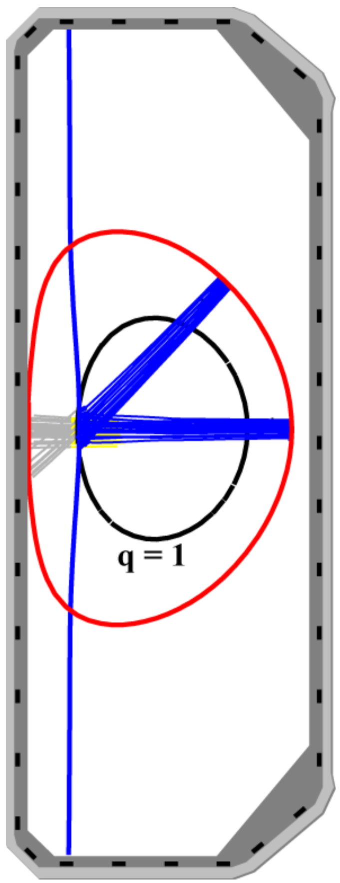
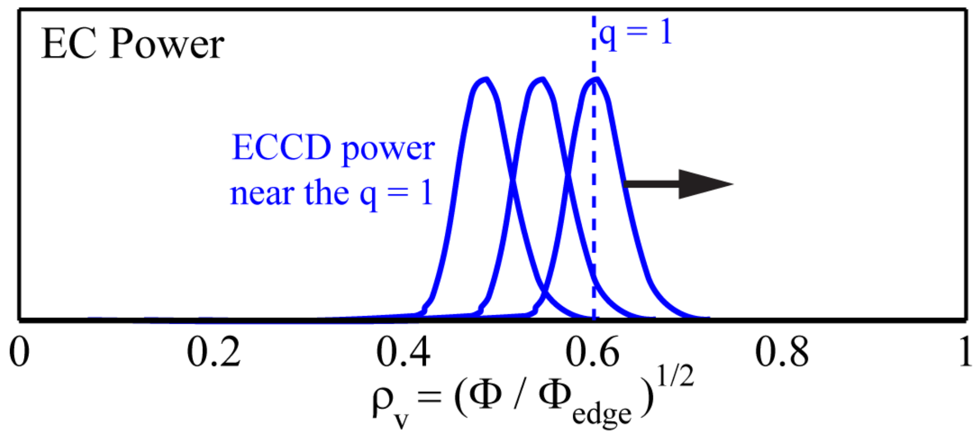
TCV's ECRH/ECCD system is capable of controlling the period of individual sawteeth

- **Two techniques have been used to control the sawtooth period:**
  - Move the ECCD deposition location across the *q* = 1 surface





➢ ST period increases when the ECCD deposition location crosses the *q* = 1 surface from plasma center towards the edge

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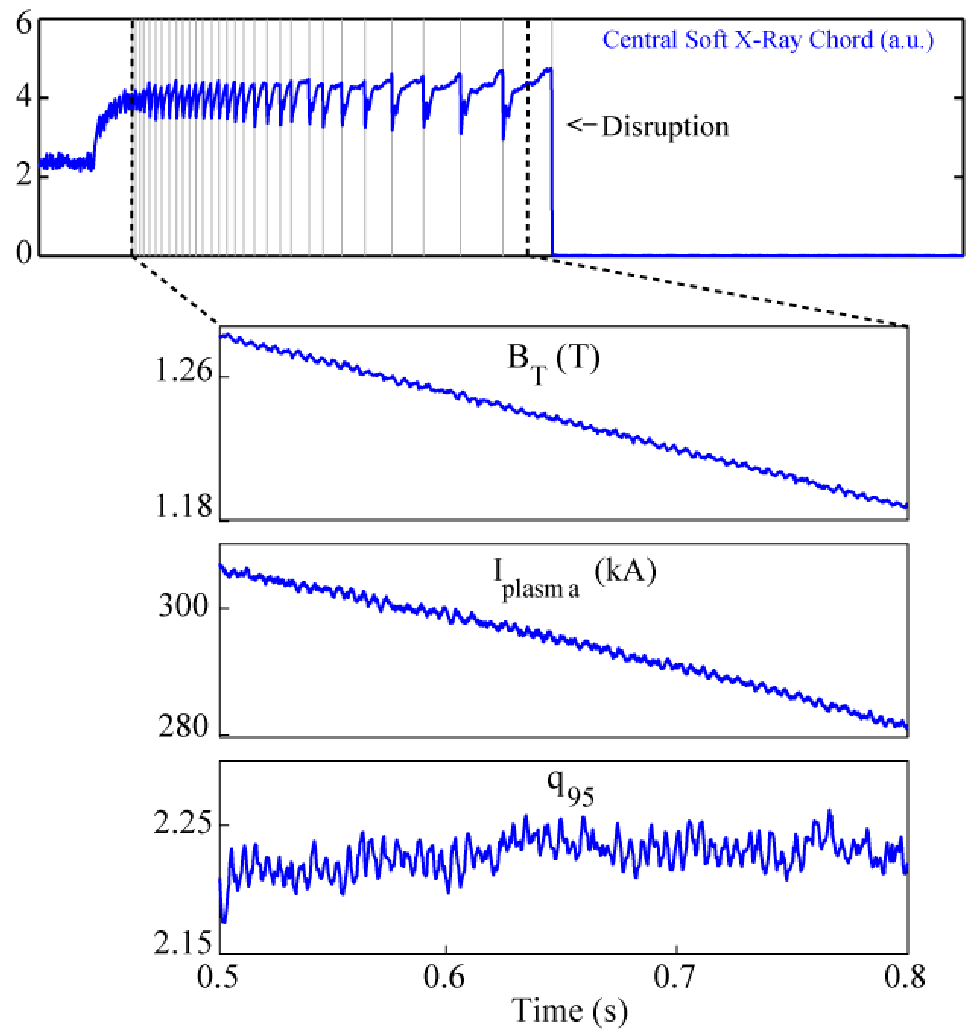

TCV's ECRH/ECCD system is capable of controlling the period of individual sawteeth

- **Two techniques have been used to control the sawtooth period:**
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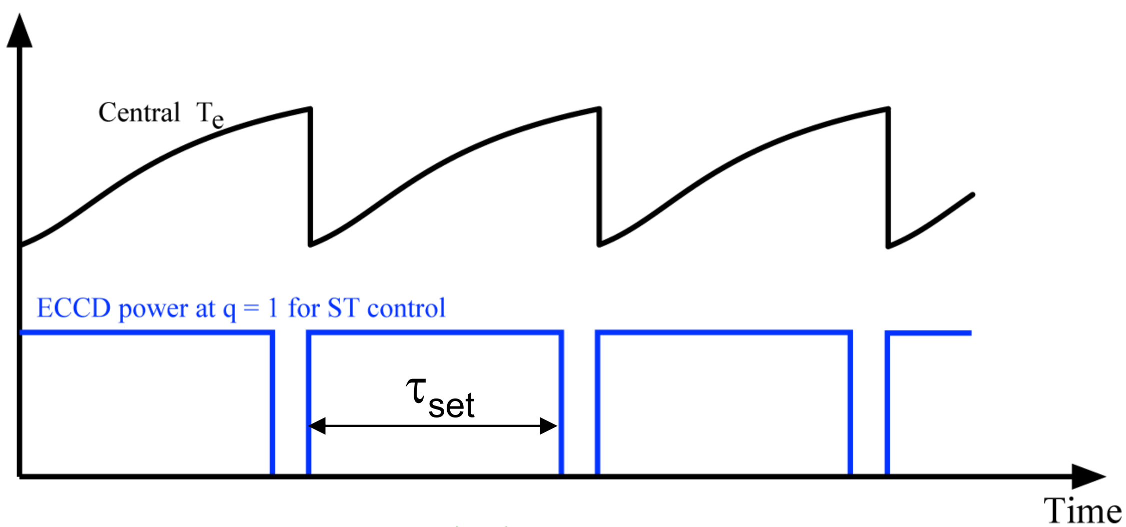
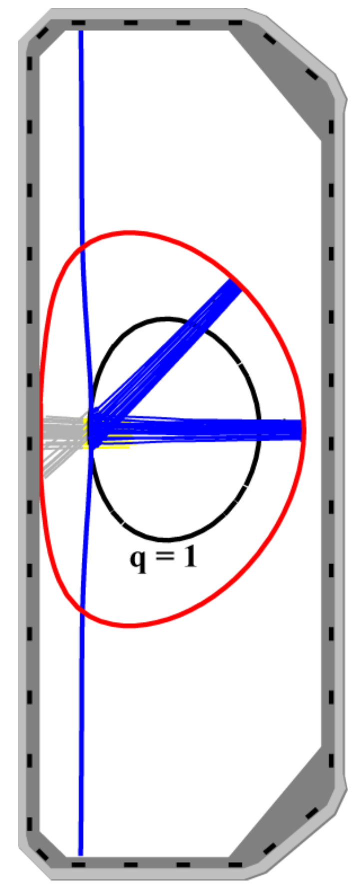
  - Feedback control of the ECCD power at the *q* = 1 surface





More details in *Goodman, PRL 2011*

➢ ST crash occurs within 1 ms following the cessation of the ECCD power at the *q* = 1 surface

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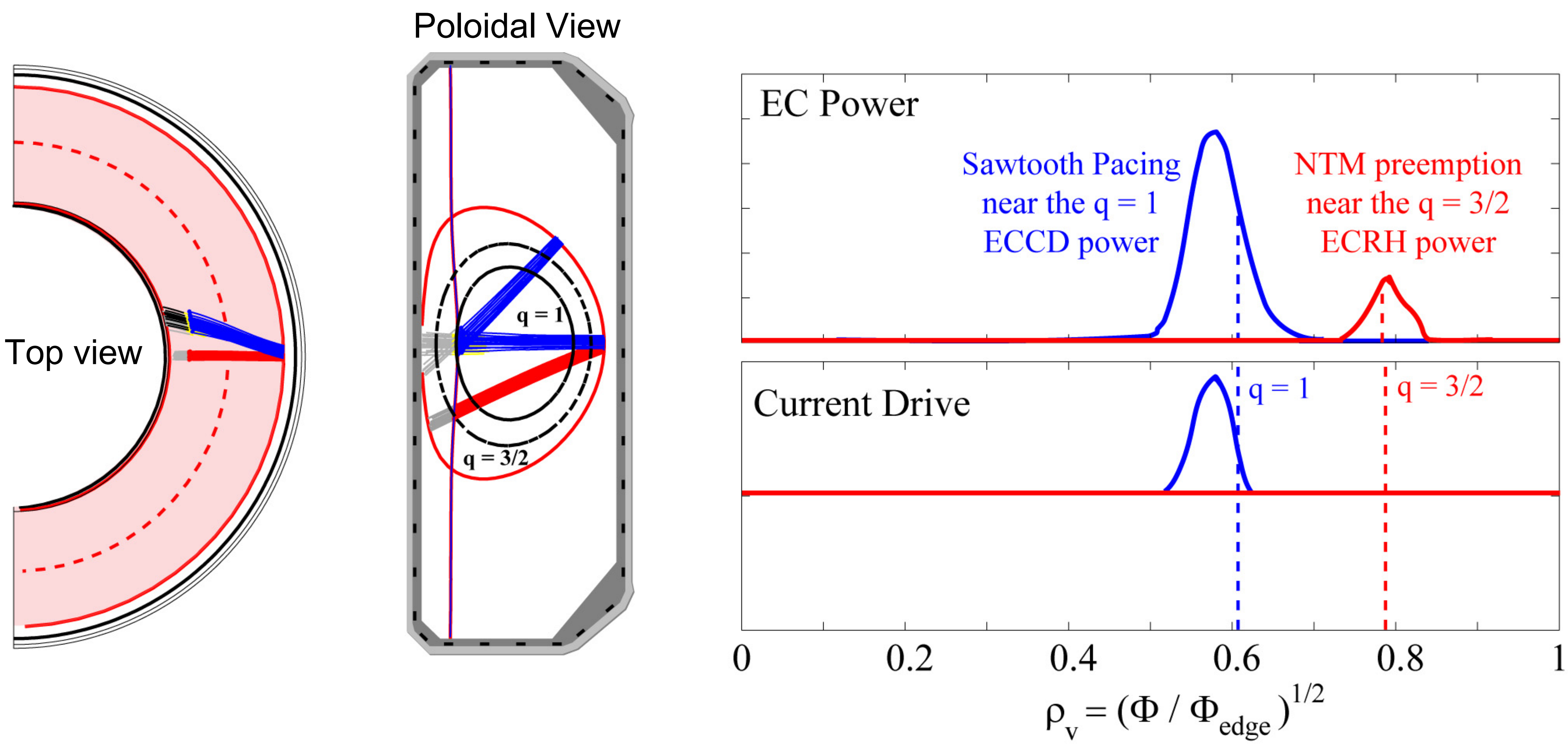
ECRH/ECCD system setup used for combined ST control and NTM preemption

- **ECRH pulses are applied near the *q* = 3/2 surface for varying the stability of the 3/2 driven mode**



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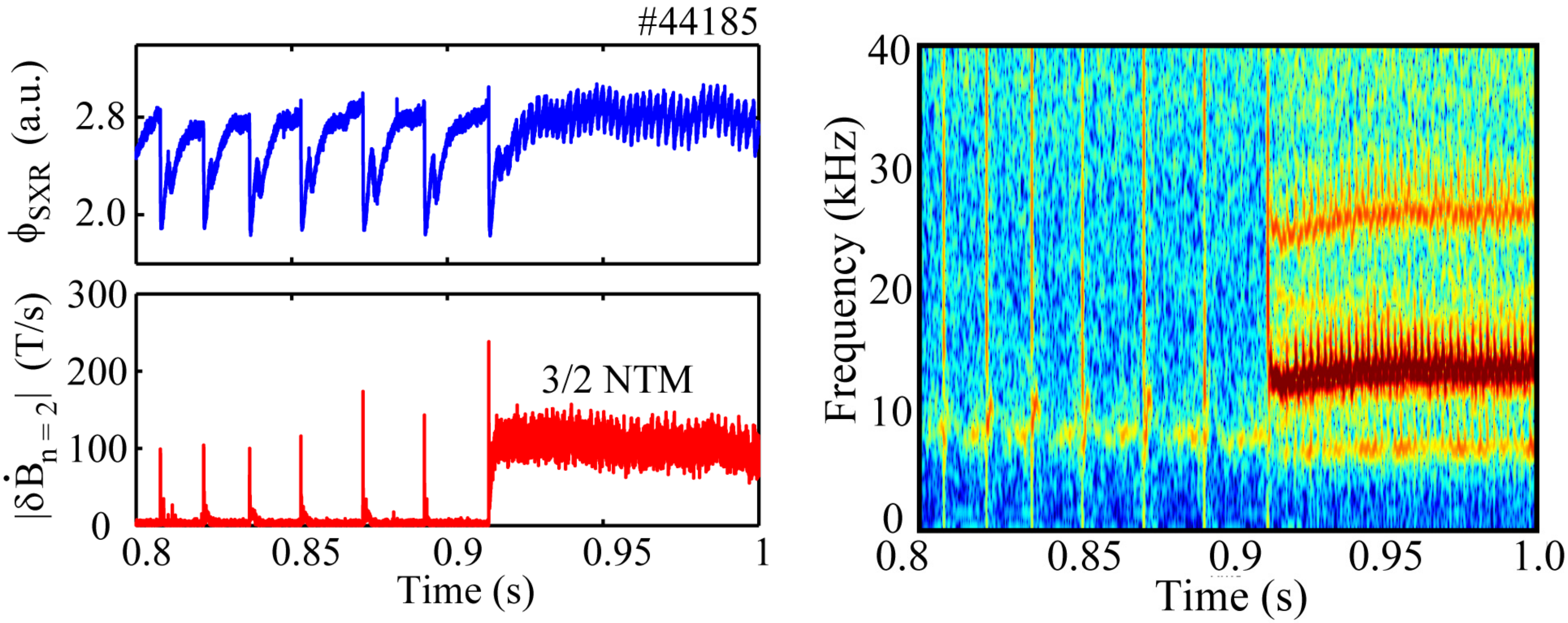
Period of individual sawteeth is gradually increased until an NTM is triggered

- **τ_{ST} is increased by moving the ECCD deposition location across the *q* = 1 surface**



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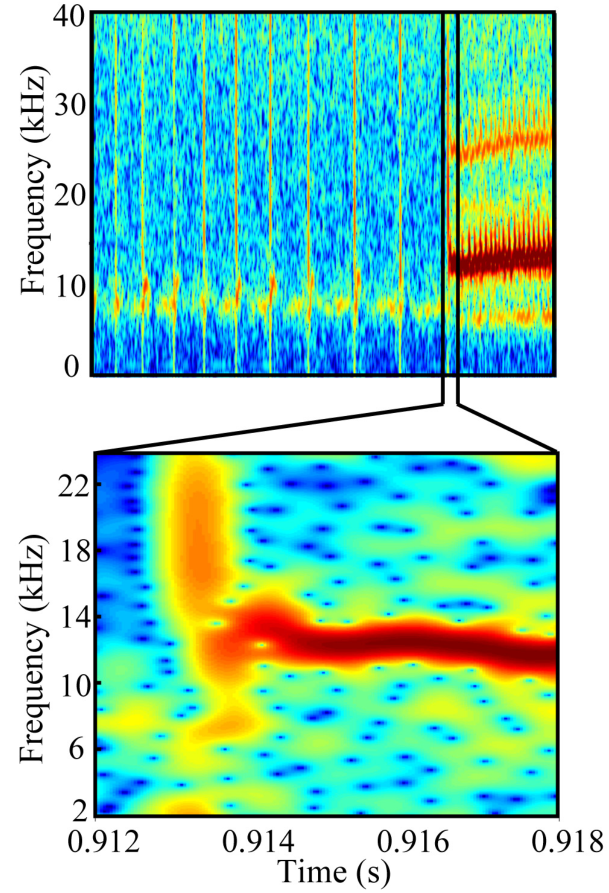
Appropriate techniques are needed to correctly diagnose the fast seeding of NTMs

- **The NTM seeding process occurs in short time scales**
  - Time interval is too short to be resolved by temporal Fourier techniques



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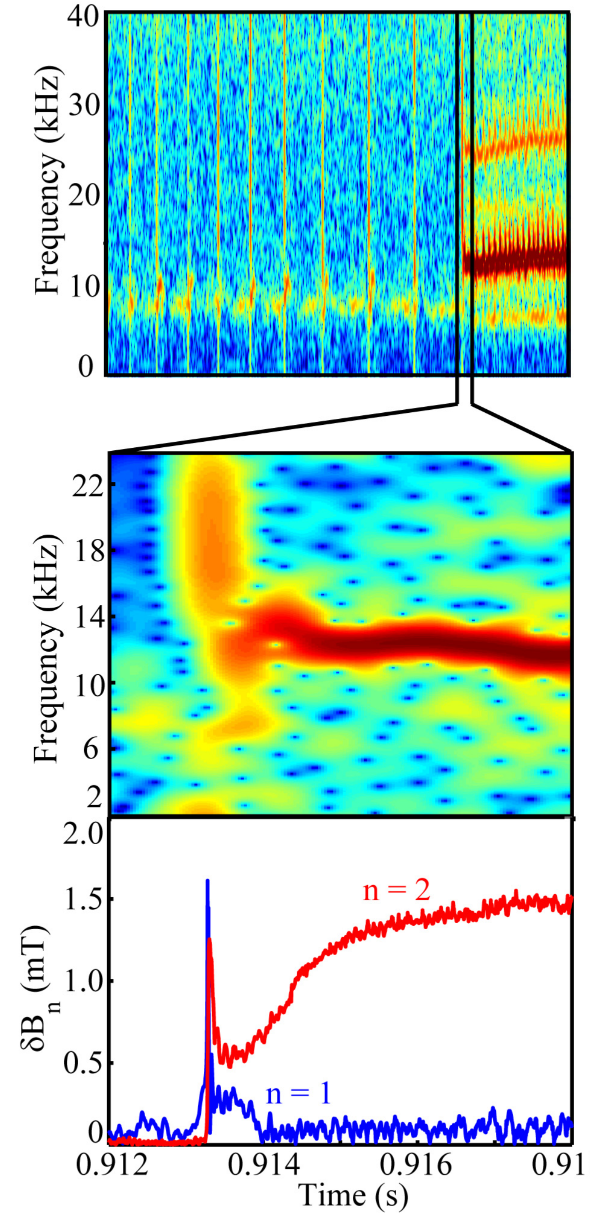
- **The NTM seeding process occurs in short time scales**
  - Time interval too short to be resolved by temporal Fourier techniques
  - Spatial Fourier decomposition using the toroidal array of magnetic probes



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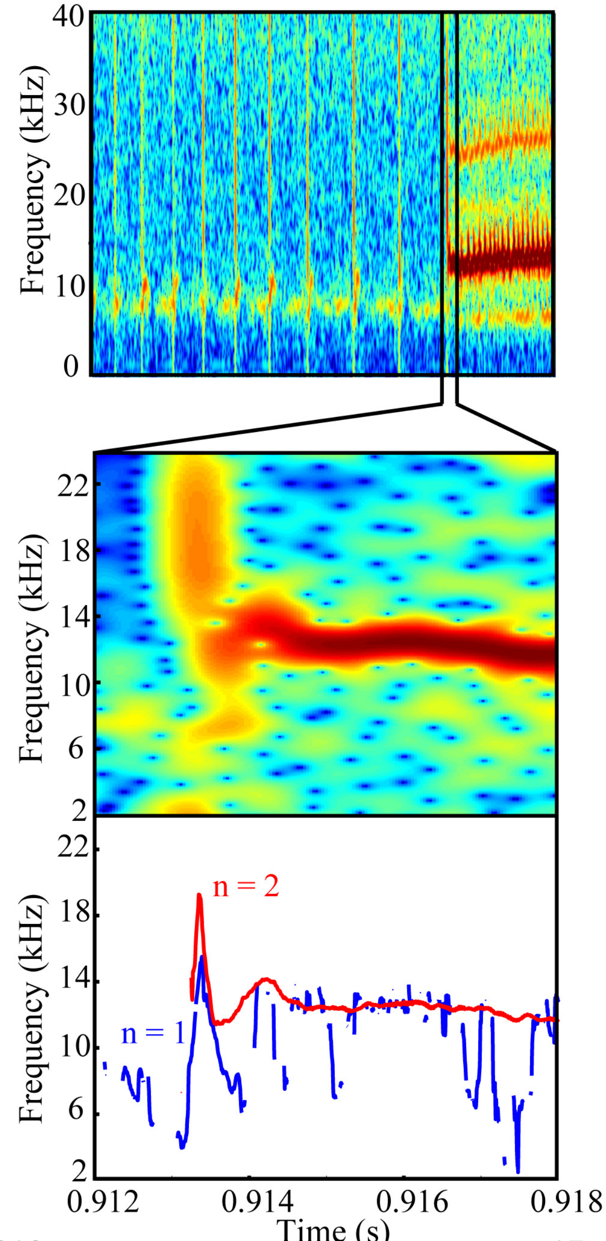
Appropriate techniques are needed to correctly diagnose the fast seeding of NTMs

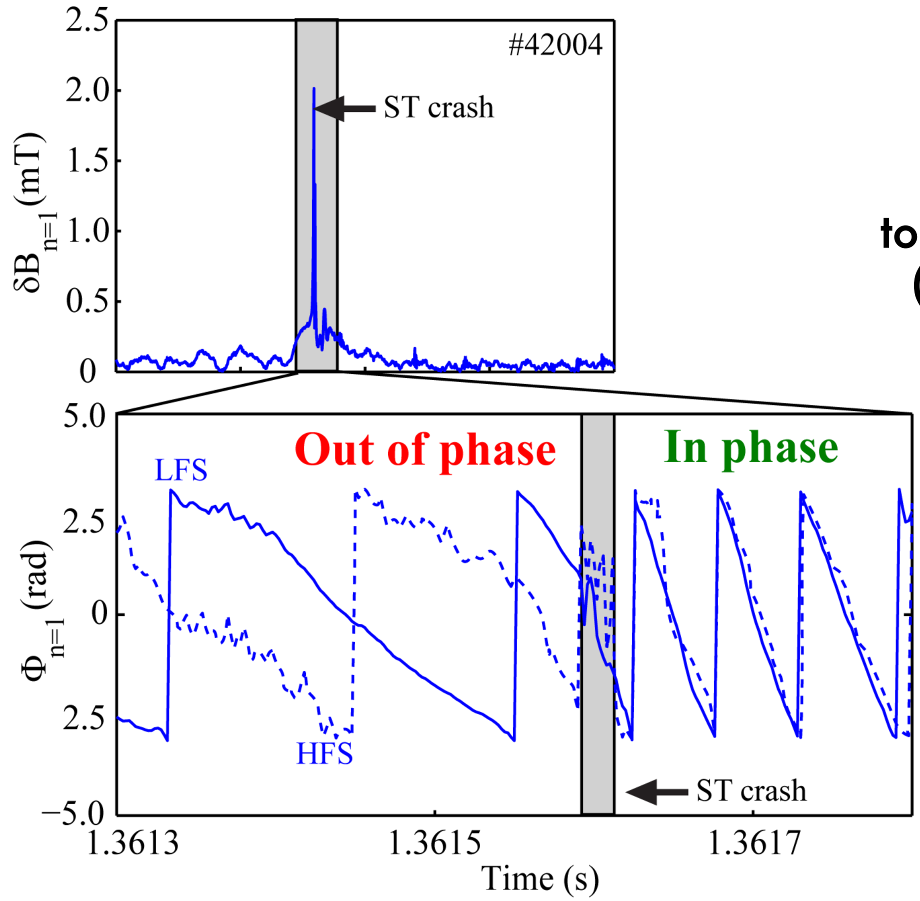
- **The NTM seeding process occurs in short time scales**
  - Time interval too short to be resolved by temporal Fourier techniques
  - Spatial Fourier decomposition using the toroidal array of magnetic probes

- **The variation of the phase velocity of the mode during the seeding process is not negligible**
  - Toroidal mode decomposition carried out using integrated magnetic signal

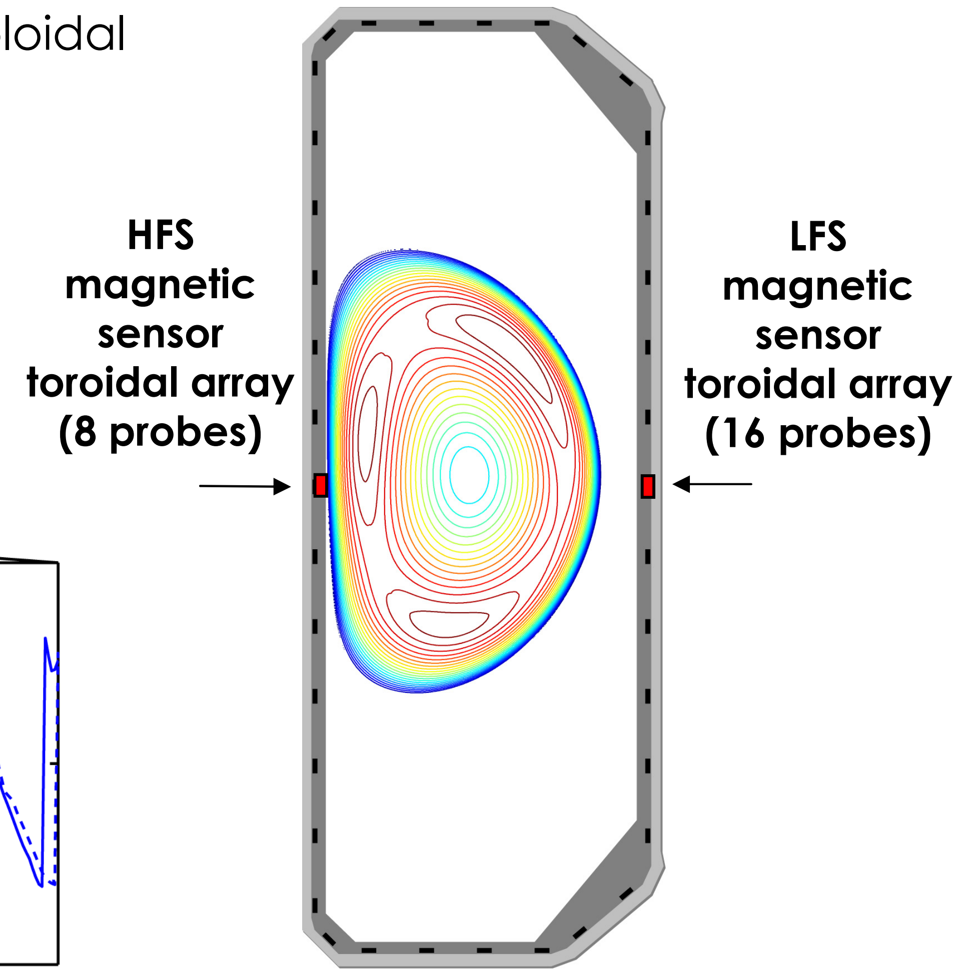


Appropriate techniques are needed to correctly diagnose the fast seeding of NTMs

- **Modes with same toroidal mode number can be separated using the LFS and HFS toroidal arrays**
  - Distinguishes between **odd** and **even** poloidal mode numbers (e.g. m/n = 1/1 and 2/1)



Magnetic fluctuation diagnostic



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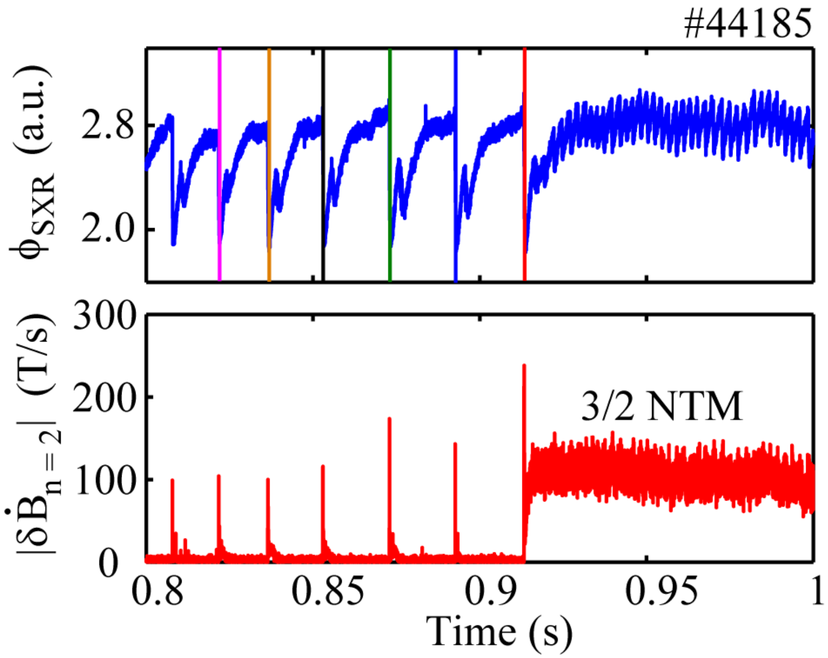
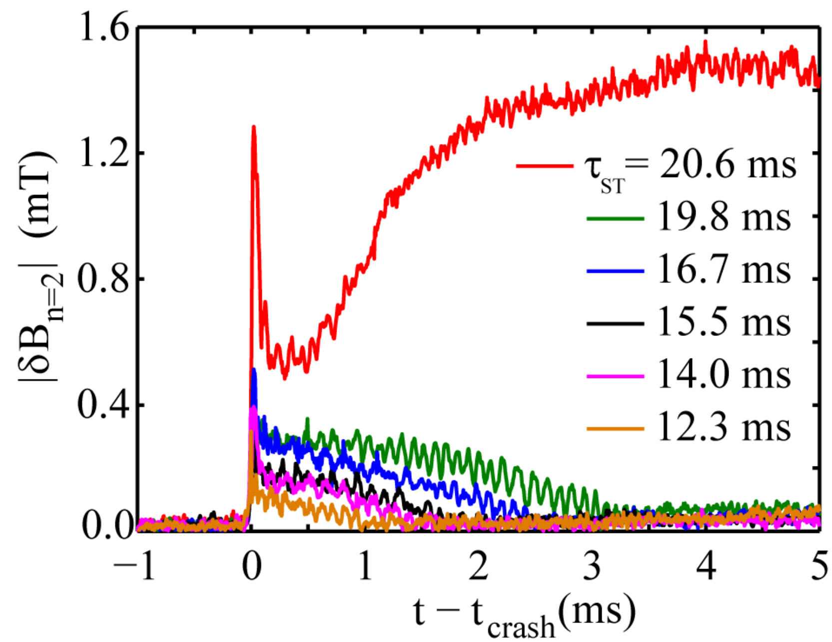
n = 2 magnetic perturbations generated by ST crash increase with ST period

- τ_{ST} is increased by moving the ECCD deposition location across the q = 1 surface





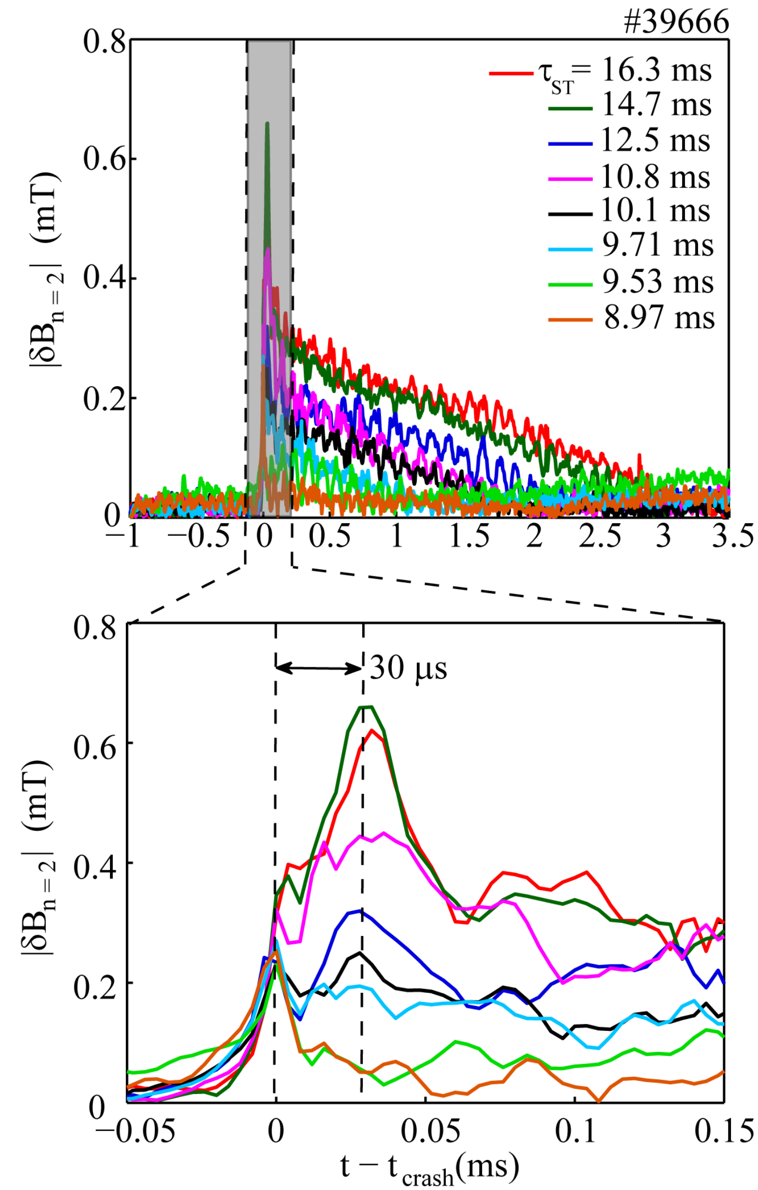
➢ **3/2 NTM is triggered once ST generated *n* = 2 mode is large enough**

Evidence of the presence of a seed island within 30 μs after the ST crash

- τ_{ST} is gradually increased by moving the ECCD deposition location across the *q* = 1 surface

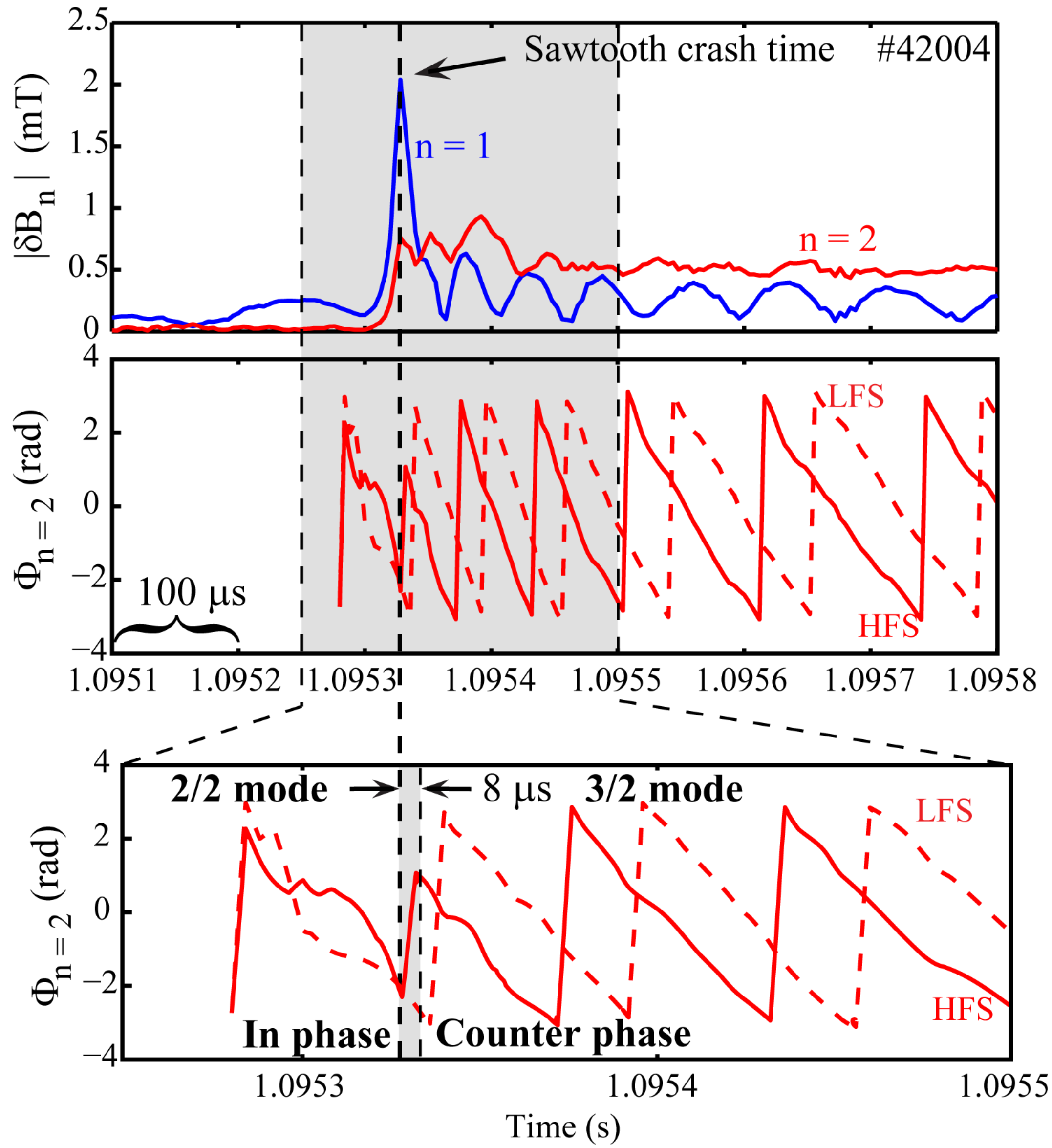
➢ ***n* = 2 mode amplitude peaks around 30 μs after the ST crash**

→ Growth within one toroidal revolution of the mode



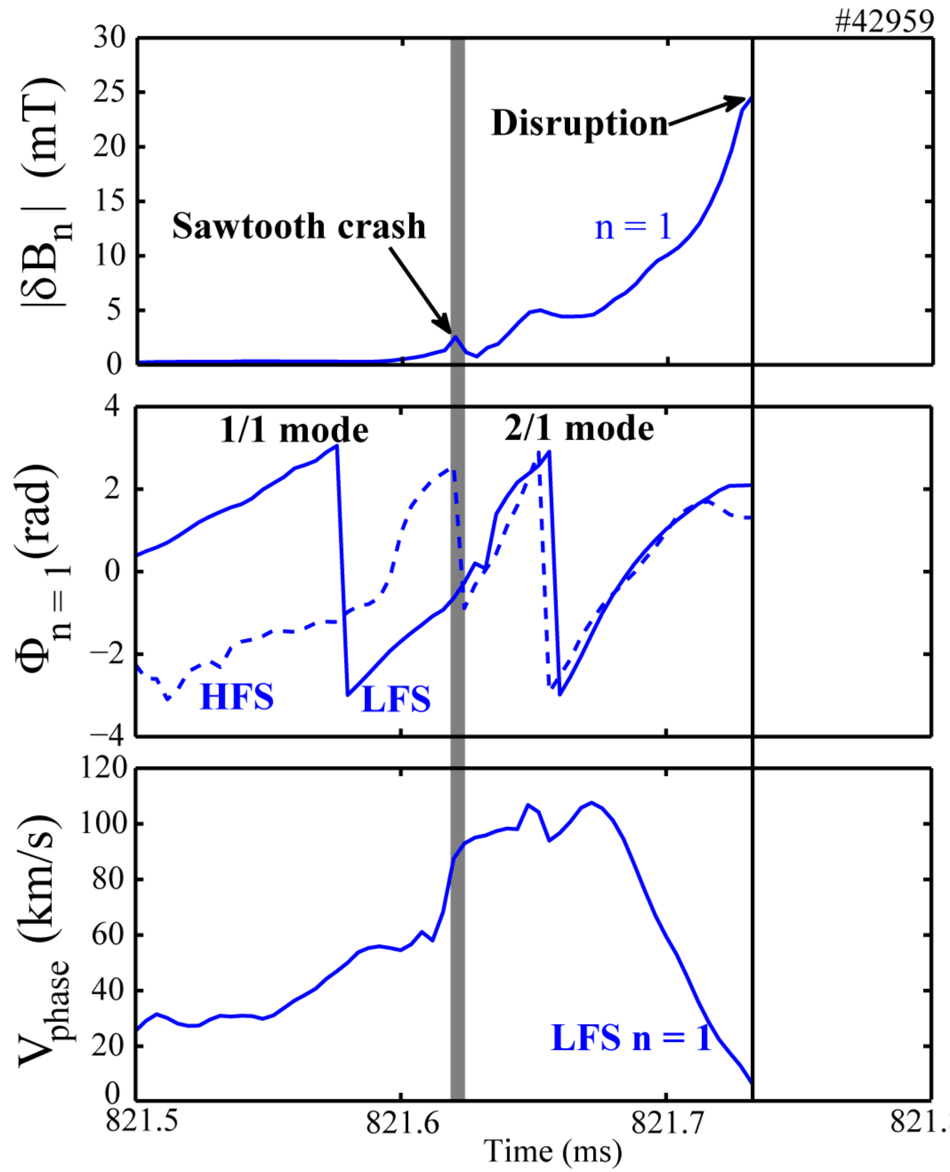
Magnetic measurements show the fast triggering of 3/2 and 2/1 modes by ST crashes

- **3/2 mode is generated within 10 μs of the ST crash**
- **Magnetic measurements suggest that the 2/2 mode generates a 3/2 mode**



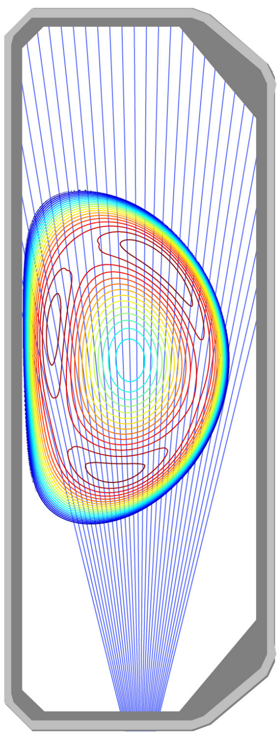
Magnetic measurements show the fast triggering of 3/2 and 2/1 modes by ST crashes

- **3/2 mode is generated within 10 μs of the ST crash**
- **Magnetic measurements suggest that the 2/2 mode generates a 3/2 mode**
- **The same kind of behavior is observed for the 2/1 modes**
  - → 1/1 mode drives a 2/1 mode
  - → All observed 2/1 modes led to disruptions (within 100 μs)

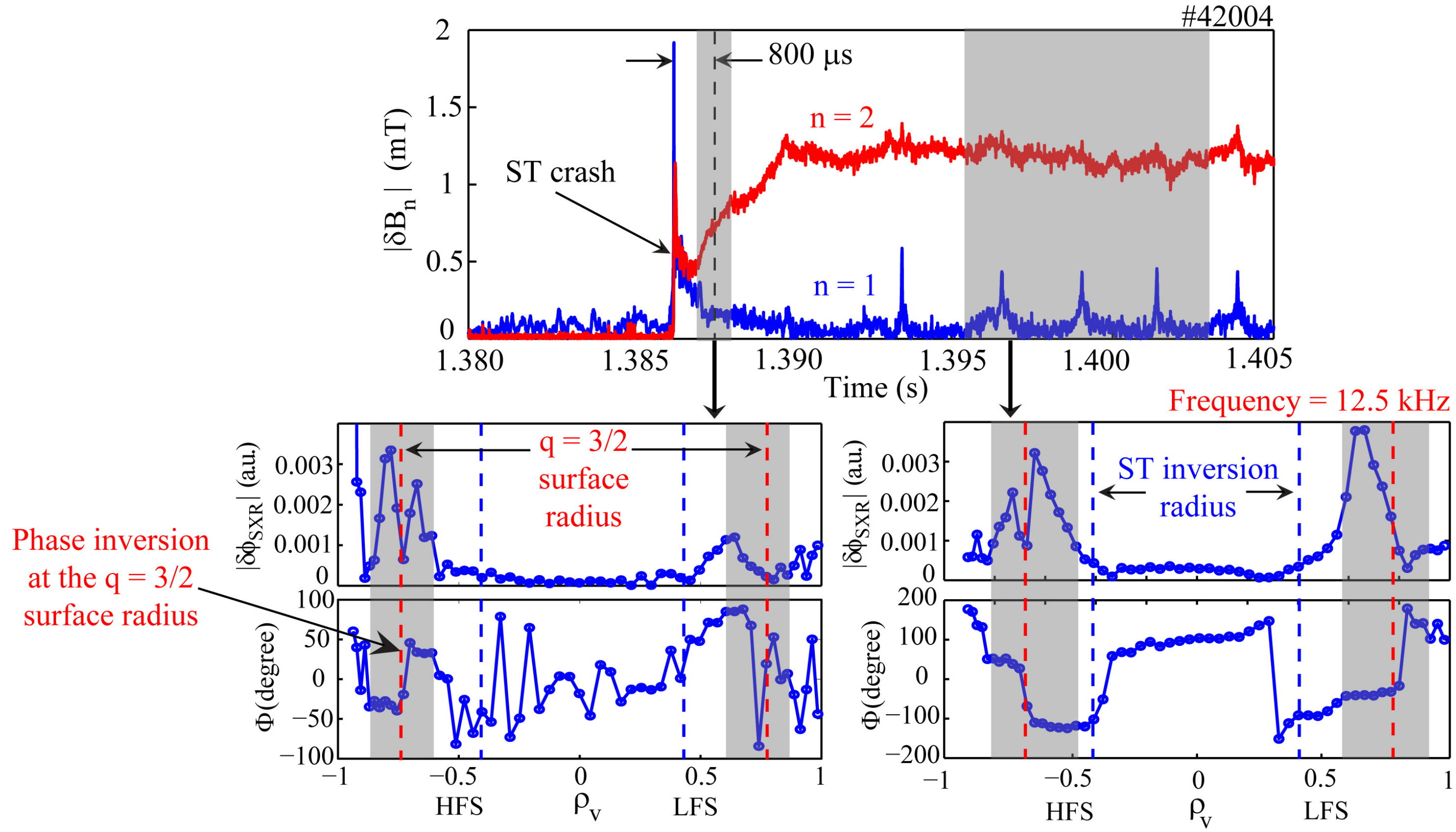


Soft X-ray measurements revels the presence of a magnetic island within 800 μs of the ST crash

- **Soft X-ray signals show phase inversion at resonant surfaces (signature of a magnetic island)**
  - Many issues limit the detectable island size



Soft X-Ray Camera



➤ **No changes in behaviour when tracing the magnetic measurements back in time until a few μs after the sawtooth crash**

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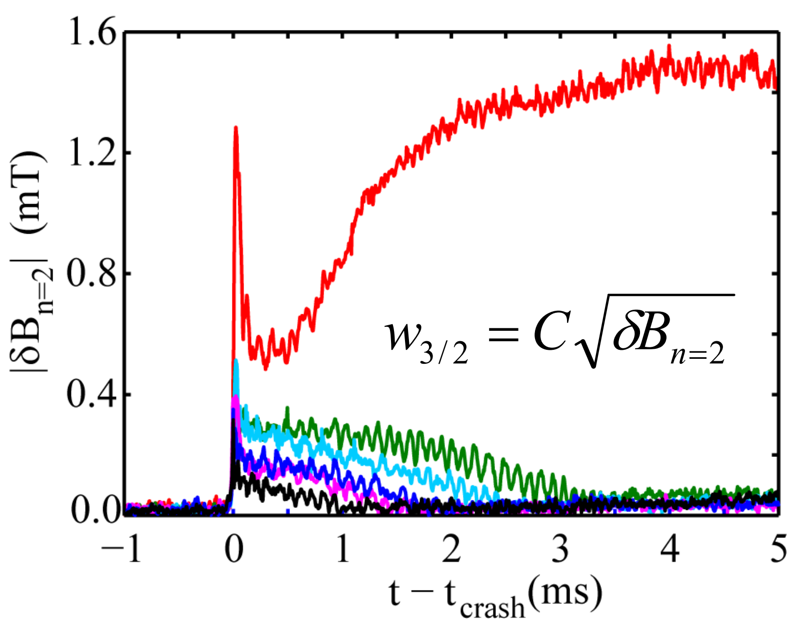
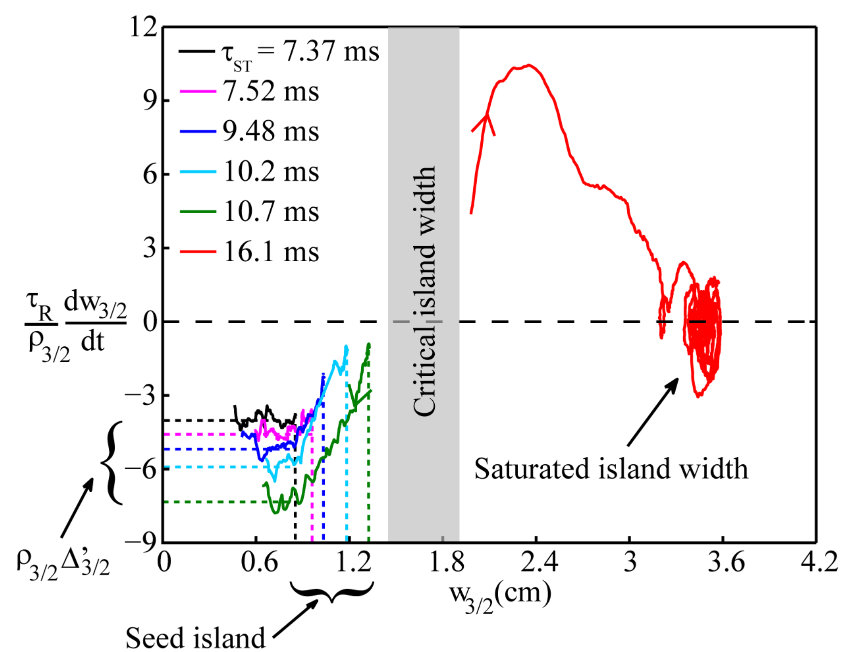
Sawtooth almost instantaneously generates a 3/2 and 2/1 seed island

- **The magnetic perturbation evolves according to the modified Rutherford equation:**

$$\frac{\tau_R}{\rho_s}\frac{dw}{dt} = \rho_s\,\Delta_0' + \rho_s\,a_{bs}\,\frac{w}{w^2 + w_d^2} + \rho_s\,\frac{a_{GGJ}}{\sqrt{w^2 + 0.2w_d^2}}$$





- **Experimental observation of fast NTM seeding is consistent with numerical simulations [Popov, Phys. Plasmas 2002 and Brennan, NF 2005]**

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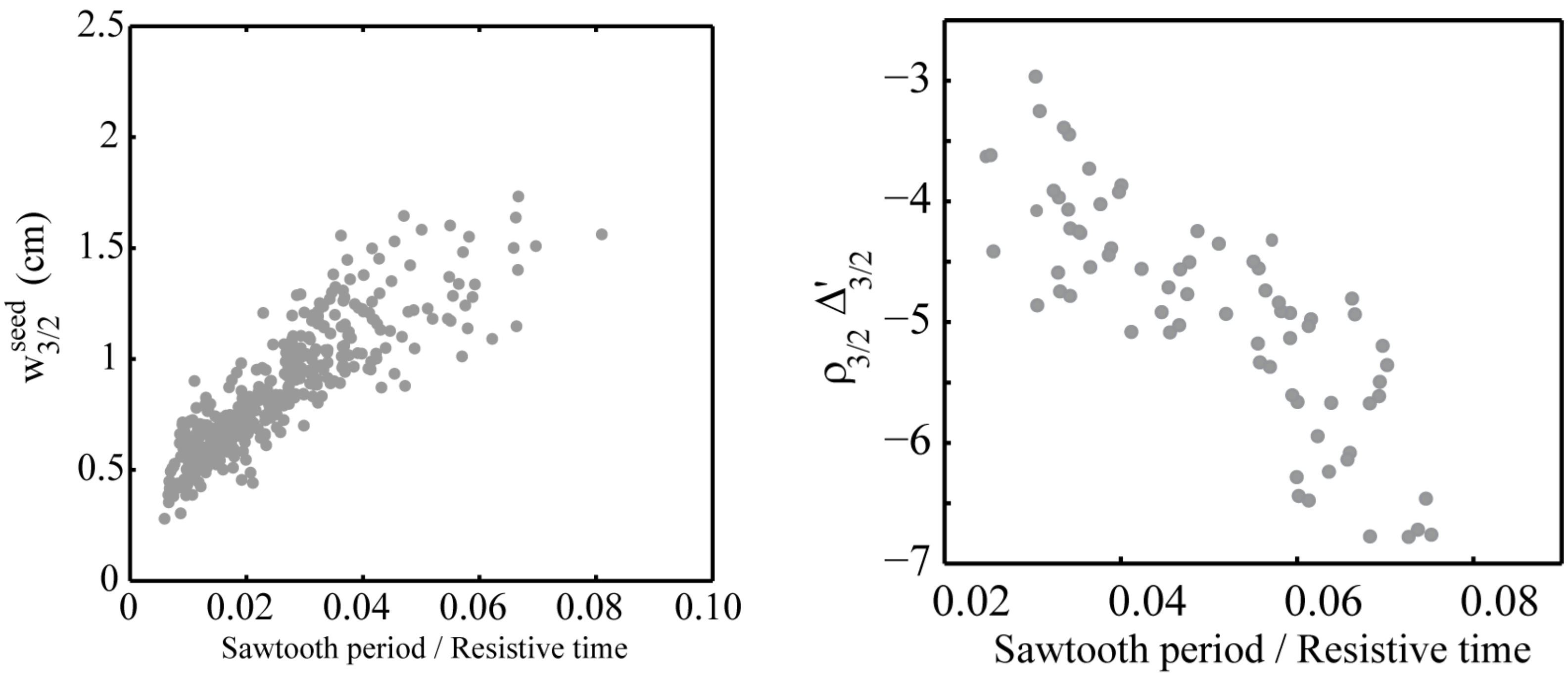
Plasma is more NTM-susceptible for larger values of τ_{ST}

- **In TCV, two effects from the ST crash compete:**
  - → Larger seed islands are found for longer ST periods
  - → Longer ST period leads to more stable plasmas against tearing modes



- **Although these two effects compete, the plasma becomes more prone to trigger NTMs at larger values of ST period**

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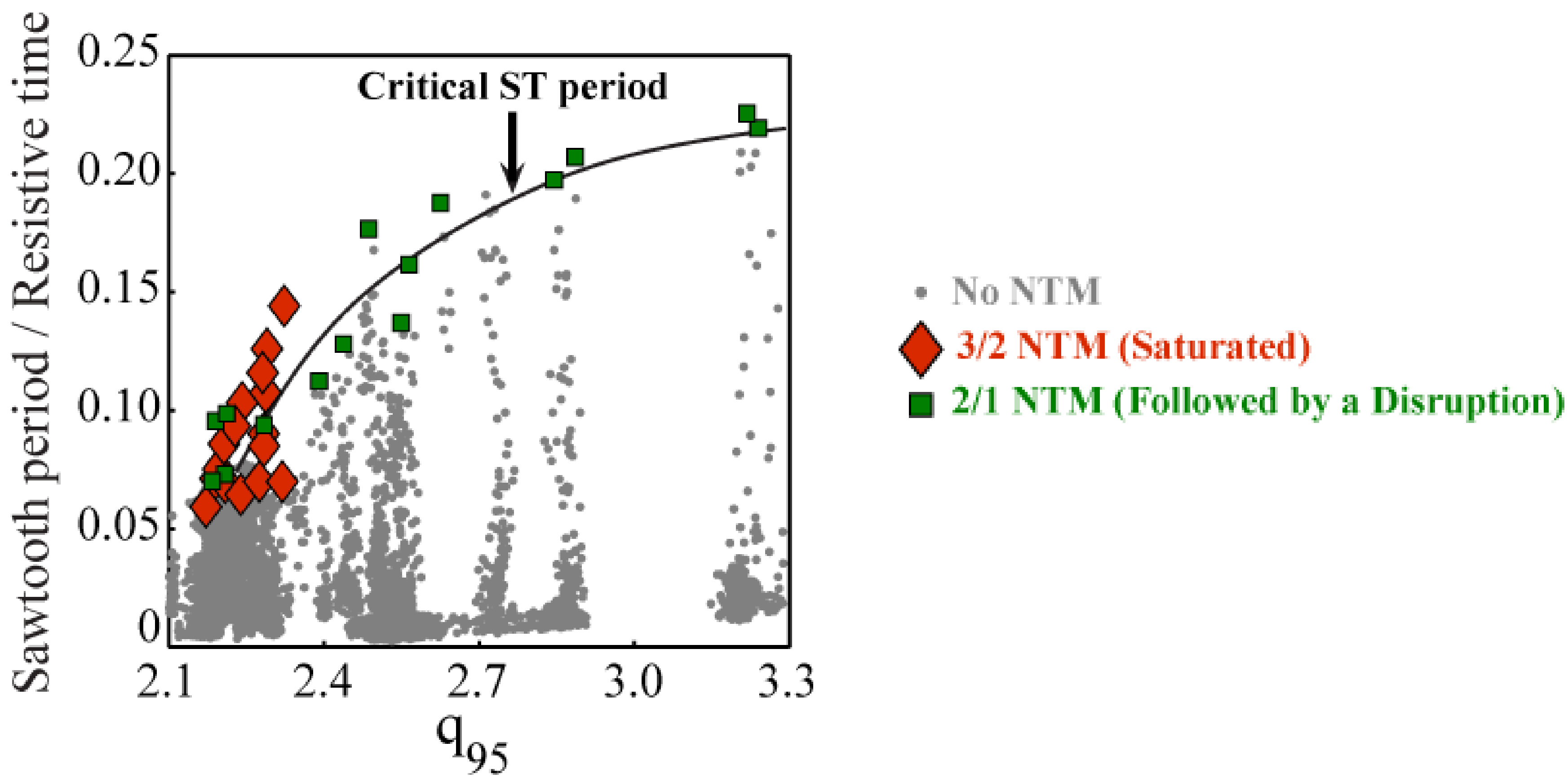
Plasma geometrical factors are expected to affect the seeding of NTMs

- **Coupling between sawtooth mode and driven modes is expected to depend on [Fitzpatrick, NF 1993]:**
  - *q* = 1 surface radius (Toroidicity)
  - Distance between the *q* = 1 and the NTM rational surface
  - Magnetic shear
  - Plasma shape

- **Part of parametric dependences was addressed by shot-to-shot q_{95} scan**
  - The τ_{ST} is increased by moving the ECCD deposition location across the *q* = 1 surface

Critical sawtooth period is found to increase with q_{95}

- **The sawtooth period is increased until an NTM is triggered**
  - Repeat discharges at different values of q_{95}



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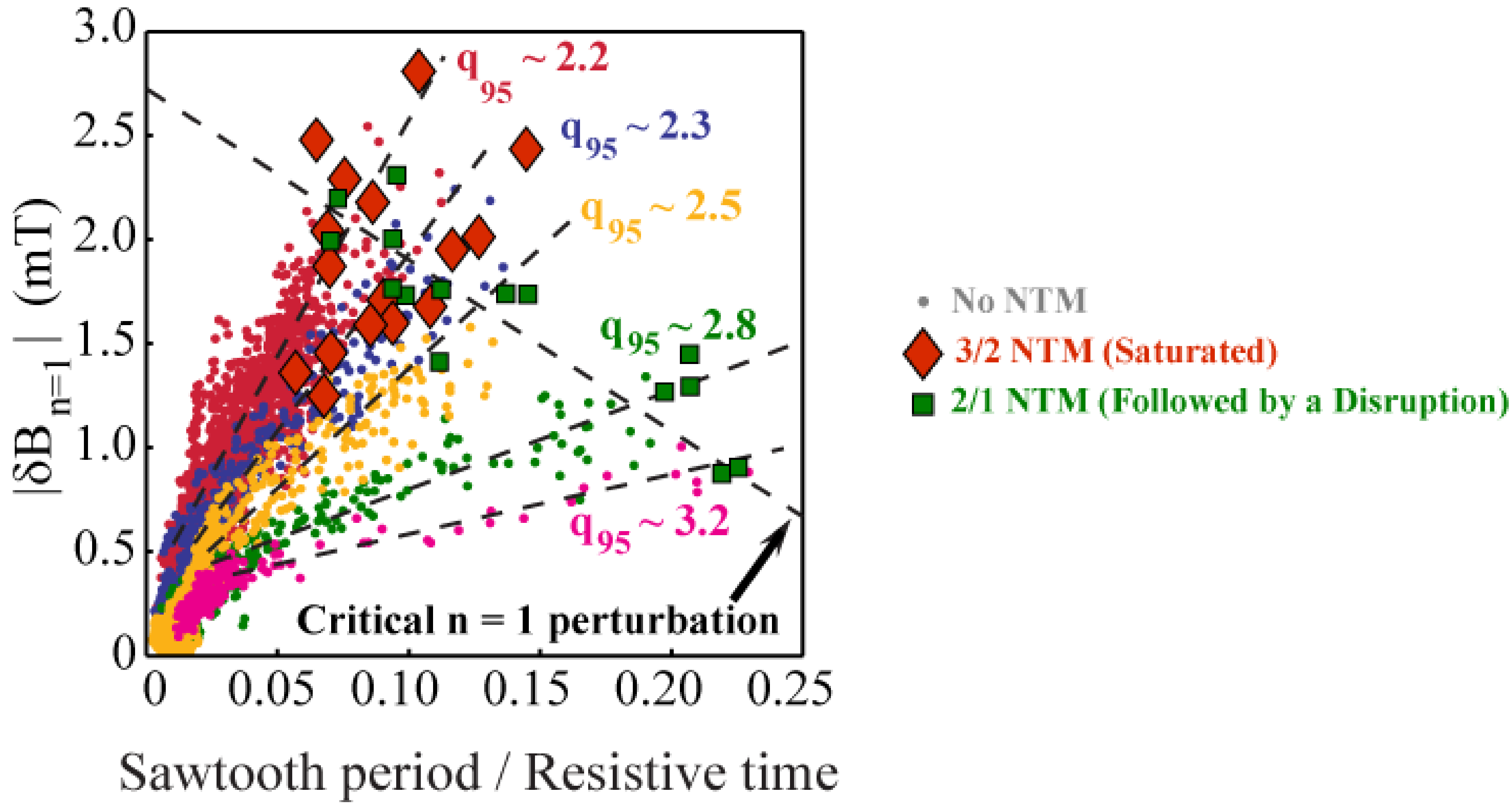
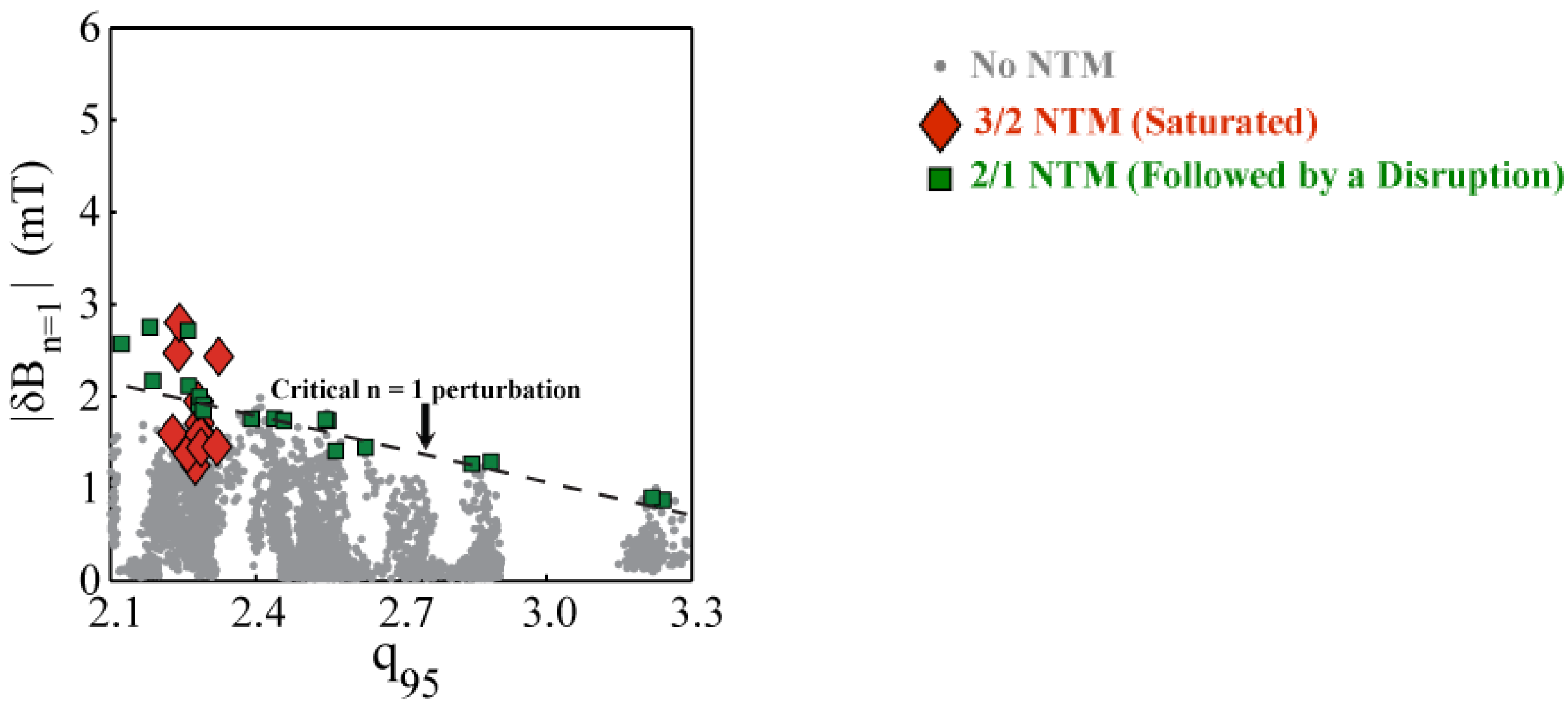
Amplitude of the driving mode increases with τ_{ST} and is found to decrease with increasing q_{95}

- n = 1 magnetic perturbation is the main driver for the NTM seeding



Smaller amplitude of the main driver is sufficient to destabilize an NTM at larger q_{95} values

- **Smaller q = 1 surface radius is observed at larger q_{95} values**
  - Larger distance between the q = 1 surface and the magnetic probes



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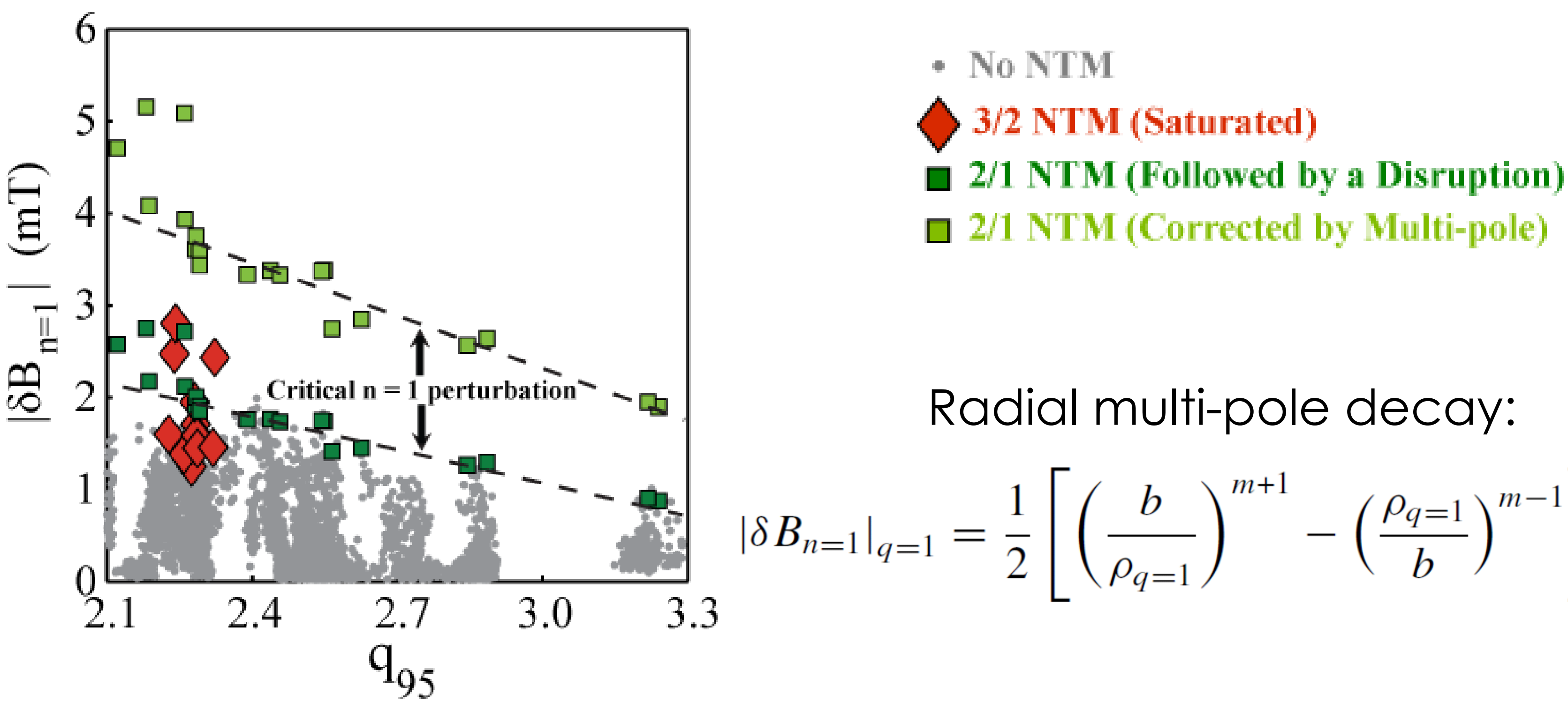


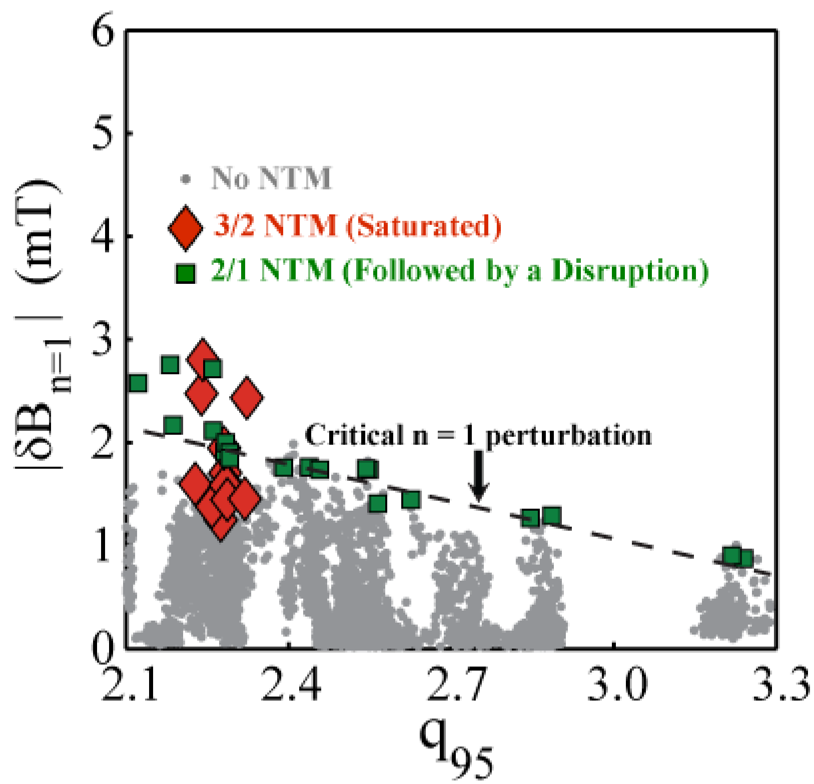
Radial multi-pole decay:

$$|\delta B_{n=1}|_{q=1} = \frac{1}{2}\left[\left(\frac{b}{\rho_{q=1}}\right)^{m+1} - \left(\frac{\rho_{q=1}}{b}\right)^{m-1}\right]|\delta B_{n=1}|$$

→ Radial multi-pole decay does not explain the decrease in the critical $\delta B_{n=1}$ for larger q_{95} values

Plasmas with higher values of q_{95} are found to be more efficient for avoiding ST-triggered NTMs

- **β_{pol} is found to increase by 70% when q_{95} is increased from 2.1 to 3.3**
  - Increase of bootstrap term and decrease of the critical island width



At larger q_{95} values:

→ Smaller amplitude of the driver $\delta B_{n=1}$ is sufficient to generate a seed island larger than the threshold island size

→ Smaller ST-generated seed islands due to smaller $q = 1$ surface radius

- **These two effects compete, however, the plasma becomes more stable against the triggering of NTMs at larger q_{95} values**

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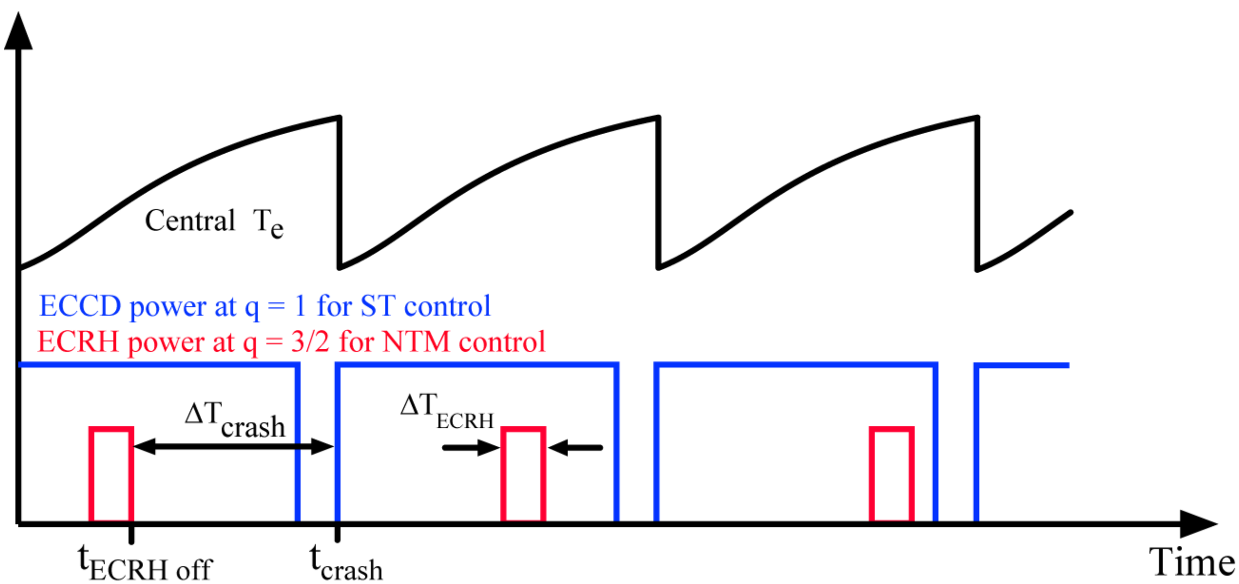
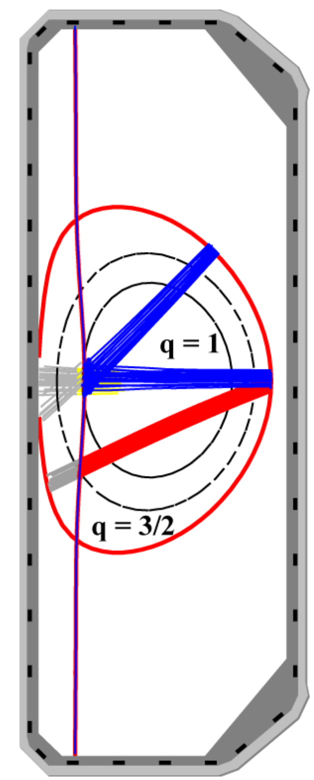
Effects of non-continuous preemptive ECRH on the NTM seeding

- **Continuous preemptive ECRH decreases the fusion gain factor Q**
- **Non-continuous preemptive ECRH requires knowledge of the next ST crash**





➢ **Two parameters are used to quantify the improvements:**

- ST-generated seed island width, $w_{3/2}^{seed}$
- Classical tearing mode index, $\Delta'_{3/2}$

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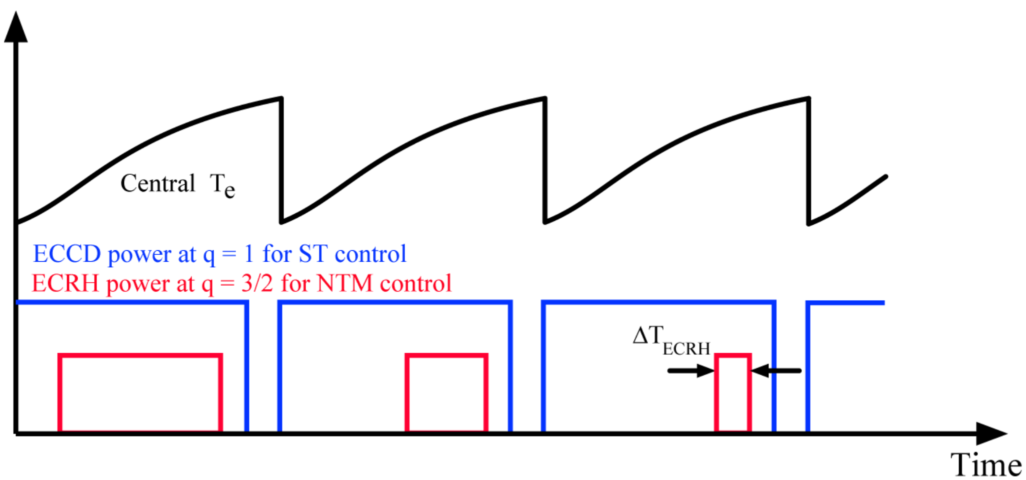
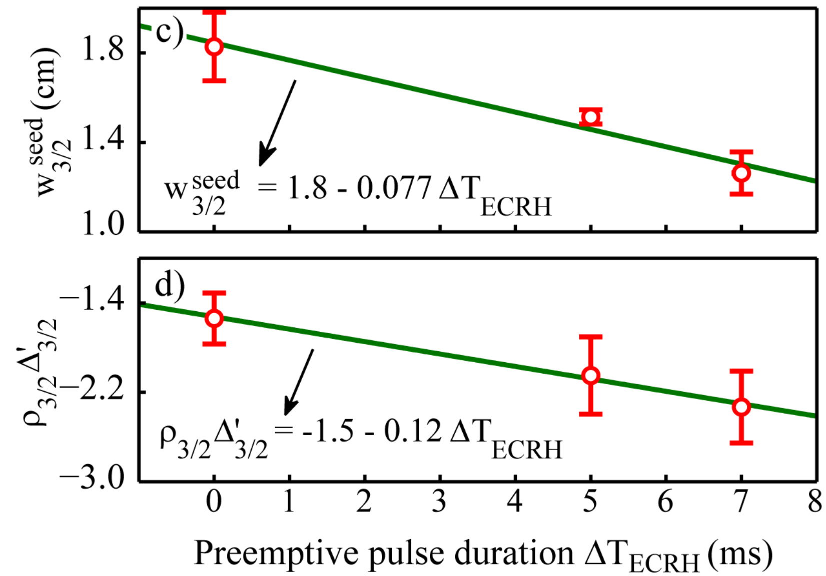
Longer preemptive ECRH pulses lead to more stable plasmas against ST triggered NTMs

- **Programmed ST period is kept constant (τ_{ST} = 21 ms)**
- **Decrease preemptive ECRH pulse duration (ΔT_{ECRH})**





- **Smaller ΔT_{ECRH} leads to smaller seed island width**
  - → Reduction of the driven modes (m/n = 2/1 and m/n = 3/2)
- **Smaller ΔT_{ECRH} leads to more stable plasmas against tearing modes**
  - → Indicates a larger critical island width

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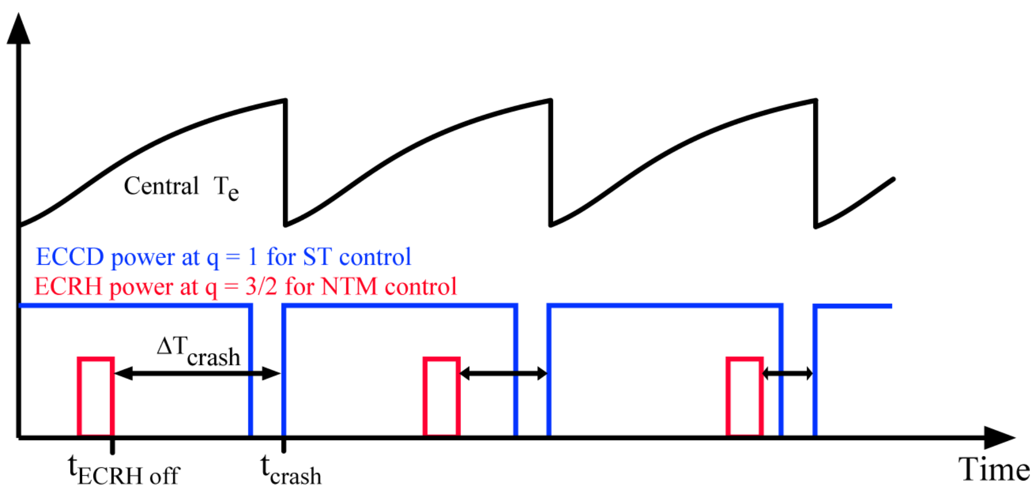
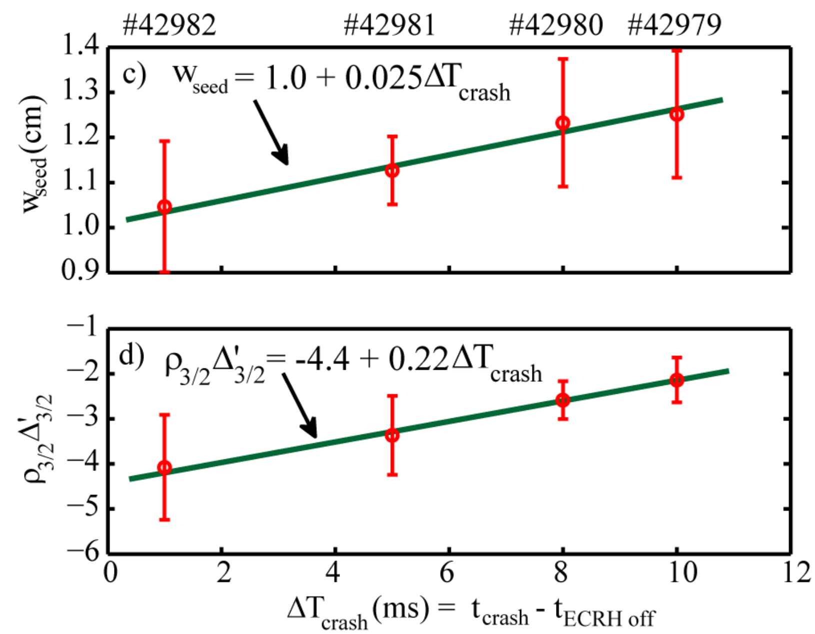
Preemptive ECRH pulses closer to the next programmed ST crash are more efficient for NTM preemption

- **Programmed ST period is kept constant (τ_{ST} = 21 ms)**
- **Move the preemptive ECRH pulse closer to the next programmed ST crash**
  - ECRH pulse duration is kept constant at 7 ms

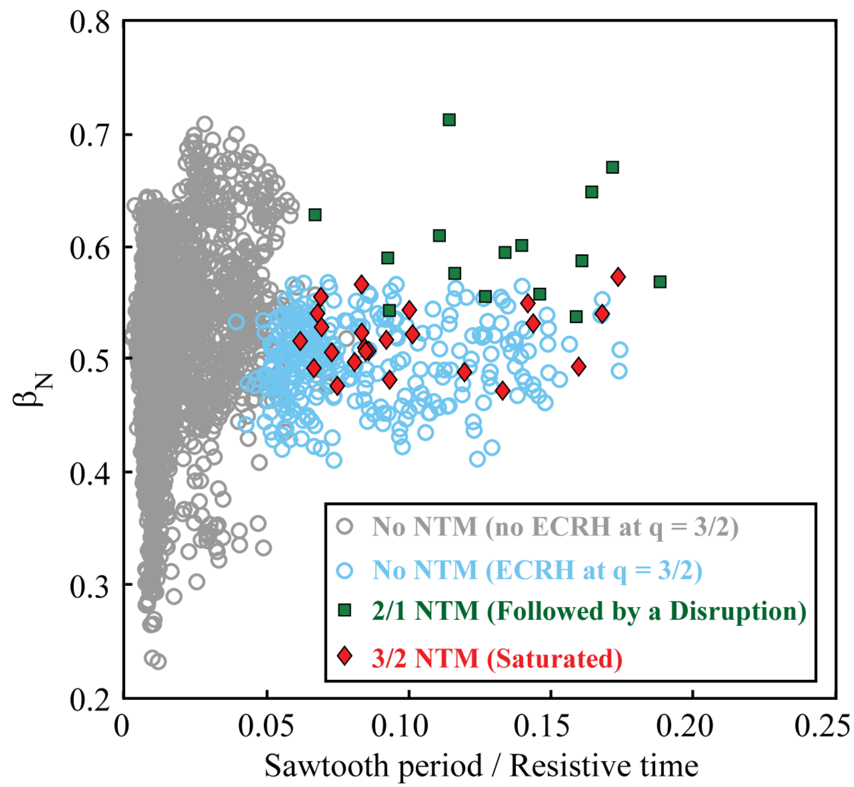




- ➢ **Smaller ΔT_{crash} leads to smaller seed island width**
  - → Reduction of the driven modes (m/n = 2/1 and m/n = 3/2)
- ➢ **Smaller ΔT_{crash} leads to more stable plasmas against tearing modes**
  - → Indicates a larger critical island width

Non-continuous preemptive ECRH enlarges the plasma operational domain

- **Preemptive ECRH pulse leads to smaller ST generated seed island and larger critical seed island width**
  - → Crashes of ST with longer duration are needed to trigger NTMs



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Effect of the preemptive ECRH pulses to the equilibrium current density profile

- **Beneficial effect of preemptive ECRH is modeled by assuming a local characteristic time for current redistribution τ_{local}**

$$\rho_{3/2}\Delta'_{3/2} \approx \rho_{3/2}\Delta'_0 - \delta A\,\frac{P_{\mathrm{ECRH}}\,\Delta T_{\mathrm{ECRH}}}{\tau_{\mathrm{local}}}\left(1 - \frac{\Delta T_{\mathrm{crash}}}{\tau_{\mathrm{local}}}\right)$$

- **Sketch of the resulting time evolution of $\rho_{3/2}\Delta'_{3/2}$:**

Typical parameters:

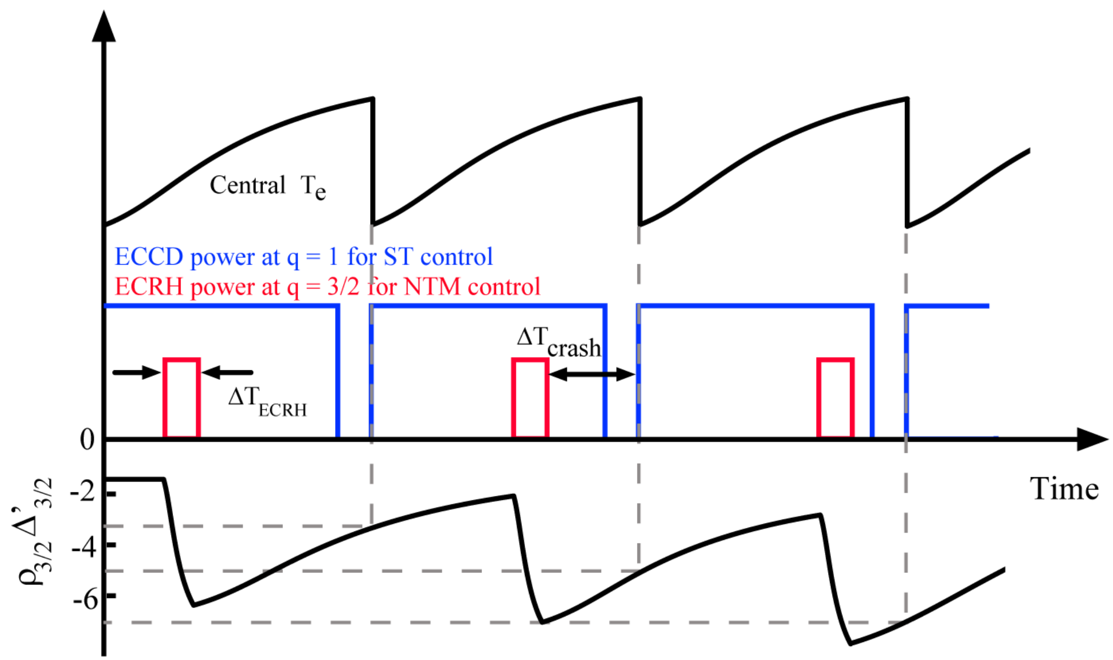
$\tau_{ST} \approx 21$ ms

$\Delta T_{ECRH} = 5$ ms

From linear regression:

$\tau_{local} \approx 13$ ms $\approx \tau_R/30$

$\delta A = 11$ MW^{-1}



CRPP

Experiments have focused on the effect of preemptive ECRH/ECCD during the NTM seeding process

- **Modification of the current density profile by ECRH/ECCD may not be efficient in larger tokamaks**
- **However, preemptive stabilization may still remain efficient by using ECRH/ECCD deposition inside the seed island [Felici, NF 2012]**
- **This effect is represented in terms of $\rho_{3/2}\Delta'_{ECRH}$ and $\rho_{3/2}\Delta'_{ECCD}$, which have a specific dependence on the island width and can be included in the proposed model by:**

$$\rho_{3/2}\Delta'_{3/2} = \rho_{3/2}\Delta'_0 - \left[\delta A \left(1 - \mathrm{e}^{-\frac{\Delta T_{\mathrm{ECRH}}}{\tau_{\mathrm{local}}}}\right)\mathrm{e}^{-\frac{\Delta T_{\mathrm{crash}}}{\tau_{\mathrm{local}}}} + \delta B\left(w_{3/2}\right)\right] P_{\mathrm{ECRH}}$$

→ δA represents the effect of ECRH on Δ' in the absence of an island

→ $\delta B(w_{3/2})$ accounts for ECRH/ECCD deposited within an existent island

CRPP

Summary: Accurate knowledge of the time of the next ST crash is important for efficient EC power usage

- TCV's capability of accurately control the τ_{ST} of individual sawteeth provides an excellent environment for the study of ST triggered NTMs
- In TCV, an increase in the τ_{ST} results in an increase of the ST-generated seed island widths and in more stable plasmas after ST crashes
- Experimental evidences that seed islands for both 3/2 and 2/1 NTMs are already present within tens of μs after the sawtooth crash
- Plasmas with larger q_{95} are more stable against the triggering of NTMs
- Non-continuous preemptive ECRH improves the fusion factor Q and is found to enlarge the plasma operational domain

CRPP

More details: G.P. Canal, et al., Nuclear Fusion 53 (2013)