Real-time ELM, NTM and Sawtooth control on TCV

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Introduction

MHD events remain worrisome, especially for larger machines such as ITER and beyond

TCV

- features X2 launched EC power with highly localised absorption affecting MHD phenomena

AND

- **RT** system reads diagnostics and controls TCV magnetics, EC positioning & EC timing/power

Goal ? Show you these brought together to:

- Investigate MHD phenomena (ST, ELM, NTM…)
- Control these MHD phenomena and demonstrate robust, multi actuator, multi-MHD control

Before starting:

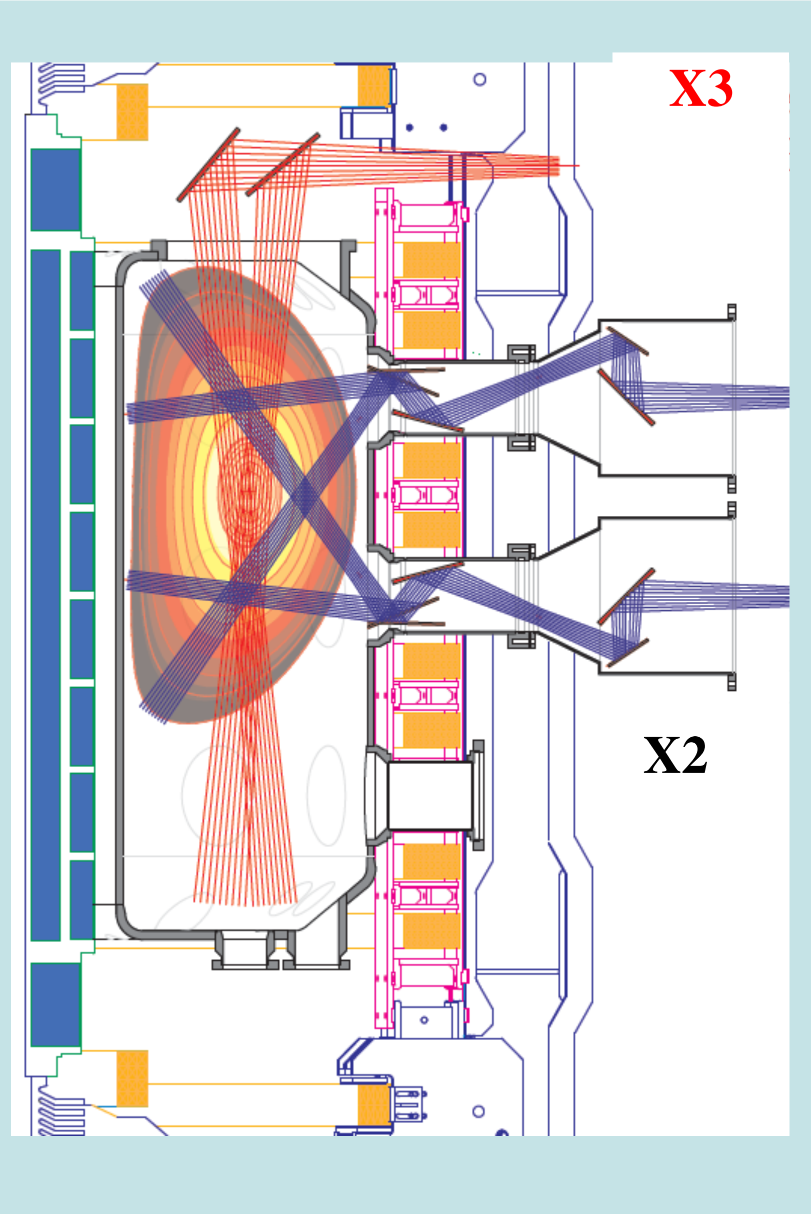
Large part of presented work derives from
2 publically available CRPP theses :

- F. Felici EPFL-Lausanne (2011), http://library.epfl.ch/theses/?nr=5203
- J. Rossel EPFL-Lausanne (2012), http://library.epfl.ch/theses/?nr=5311

Publications 2008-2012 with more submitted or planned-
(many more details available)

- J. Paley, *et al*, Plasma Phys. Control. Fusion **51** 124041 (2009)
- T.P. Goodman, *et al*, Phys. Rev. Lett. **106**, 245002 (2011)
- M. Lauret et al, Nuclear Fusion 52 062002 (2012)
- J. Rossel, *et al*, Nucl. Fusion **52**, 032004 (2012)
- F. Felici, *et al*, Nucl. Fusion **52**, 074001 (2012)
- F. Felici, *et al*, submitted to Nucl. Fusion (2012)

TCV, EC deposition and RT



Actuators

- Independent PF coils
- Multichannel ECH/ECCD (X2 & X3) (position and power)

RT system

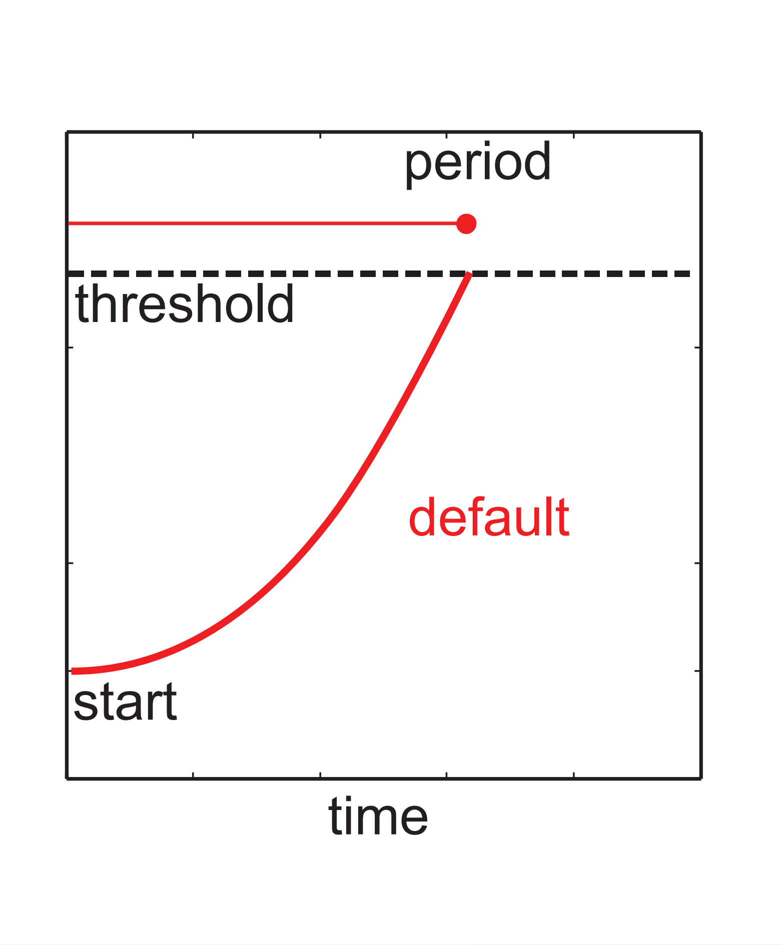
- Hundreds of acquired channels
- Multichannel high spatial and temporal resolution X-ray, interferometer, H_α…
- 4x X86 Linux nodes with reflective memory. Down to 20μs calculation time
- Matlab-Simulink® programmed
- Full integration in TCV shot cycle

S. Coda, OV/4-4, today 15:15

Names of things

A parameter evolves from a **start** value

An "event" occurs when a **threshold** is reached



Names of things

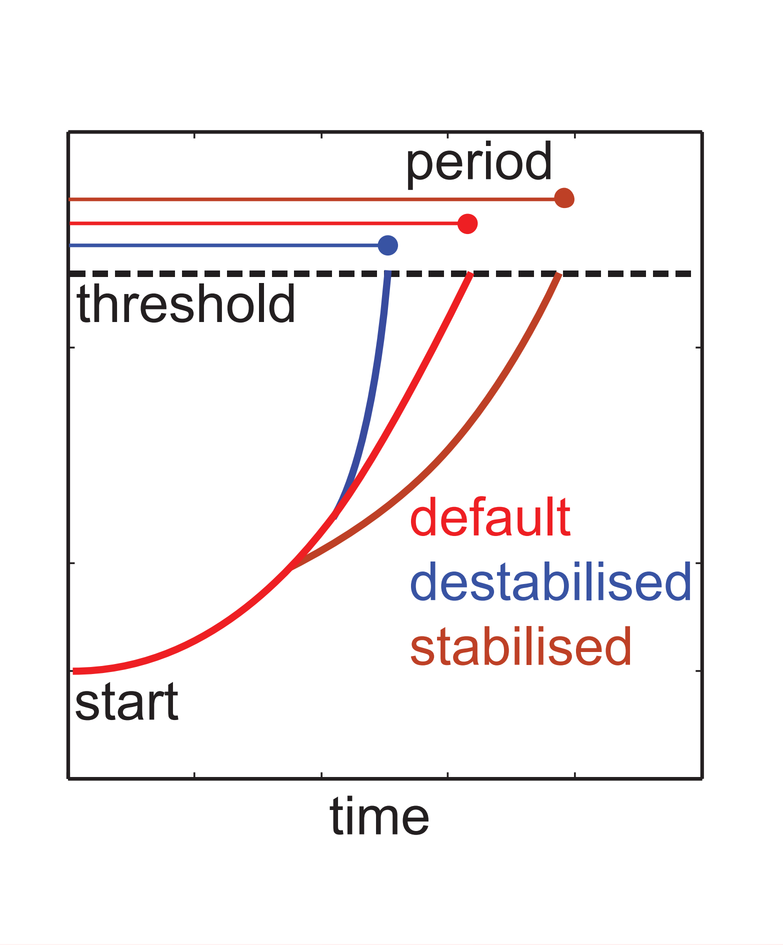
A parameter evolves from a **start** value

An "event" occurs when a **threshold** is reached

Stabilising retards evolution so event occurs later (or never)

Destabilising accelerates evolution so event occurs earlier

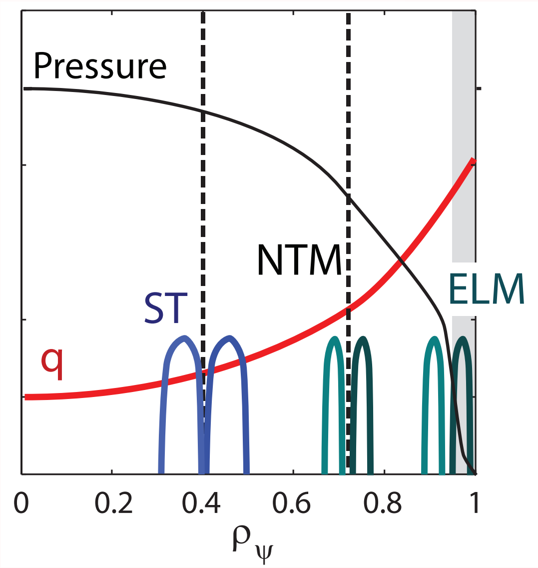
For all cases, the time from start to threshold is the **period**



MHD control by EC power and position

MHD modes *associated* with rational surfaces (ST, NTM) or are sensitive in a particular region (ELM) :

i.e. localised in the plasma



Move EC across sensitive zones

RT position feedback to change MHD

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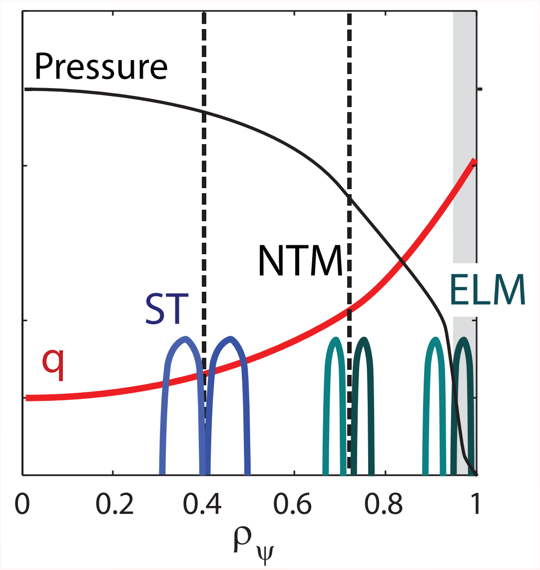
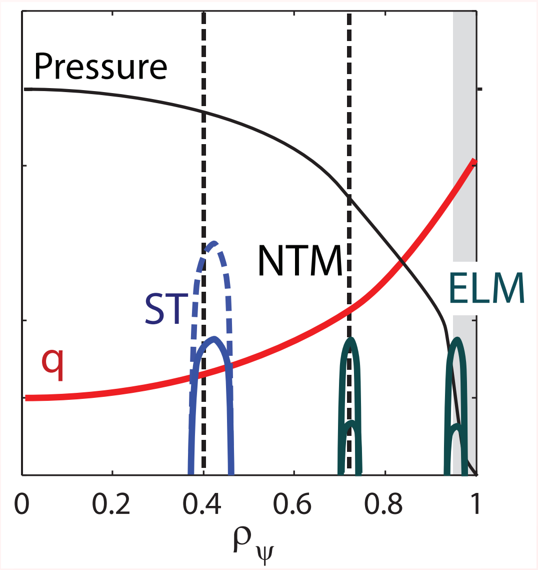


Move EC across sensitive zones

RT position feedback to change MHD



For fixed EC position

RT power control to change MHD

(much faster, in-period)

Plan

ST

- **Individual** ST period control (pacing) using **RT** ECCD power control

ELMs

- Frequency **increases** with edge EC power (Type-I)
- Frequency, at constant power, increases as EC moved **towards edge**
- **Individual** ELM period control (pacing) using **RT** power control

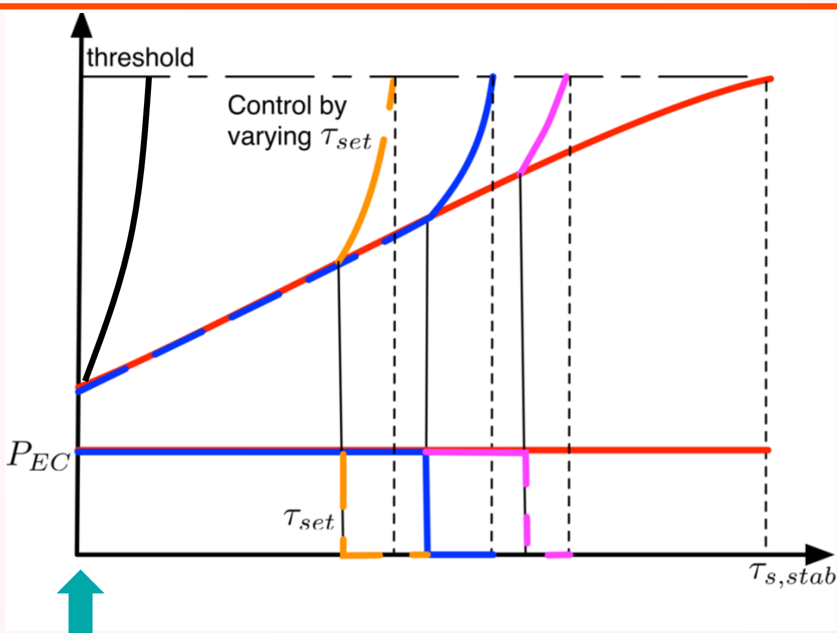
NTMs

- Controlled NTM **seeding** using long ST
- NTM **stabilisation** using RT controlled EC power
- NTM **pre-emption** using pulsed EC timed with ST-NTM seeding
- Demonstration of **multi-actuator**, **multi-MHD** instability control as for ITER

ST pacing with EC power

Synchronise to last ST (**RT**)

- Increases EC power, stabilises ST
- Reduces EC power after a chosen time (hastening next ST)



RT detected

Time of previous ST

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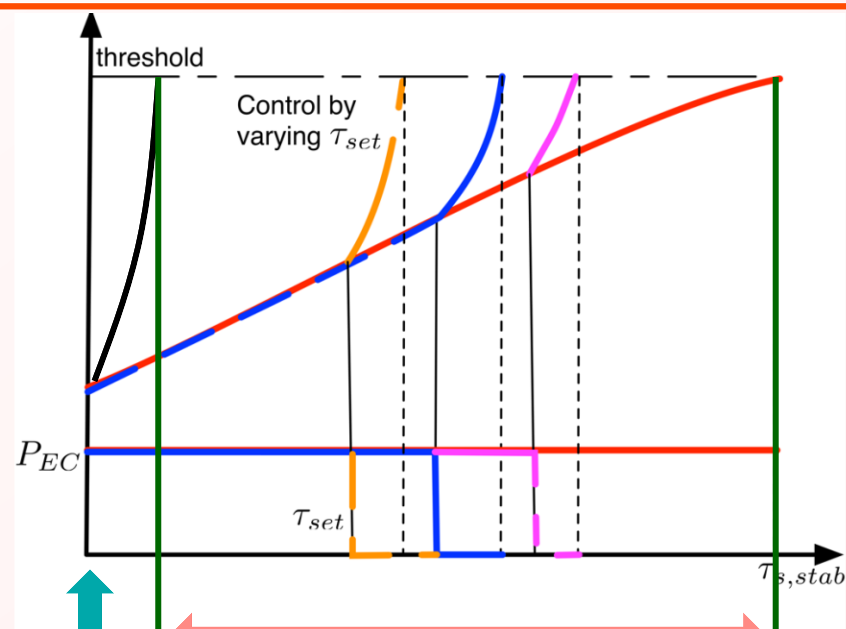
ST pacing with EC power

Synchronise to last ST (**RT**)

- Increases EC power, stabilises ST
- Reduces EC power after a chosen time (hastening next ST)
- Each individual ST period can be chosen within range



RT detected

Time of previous ST

Range over which **each** ST period can be chosen

- By programing individual EC-on periods the ST are "**paced**"

ST pacing with EC power

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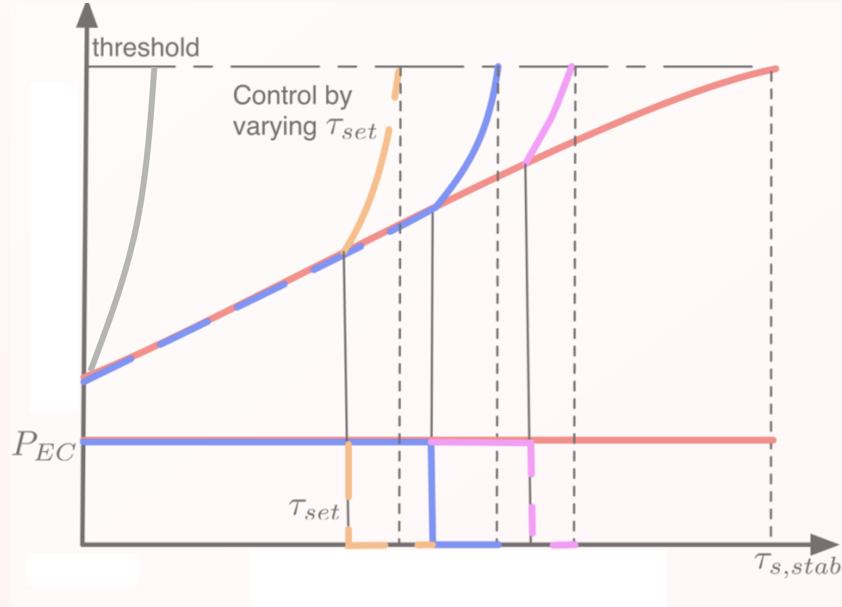
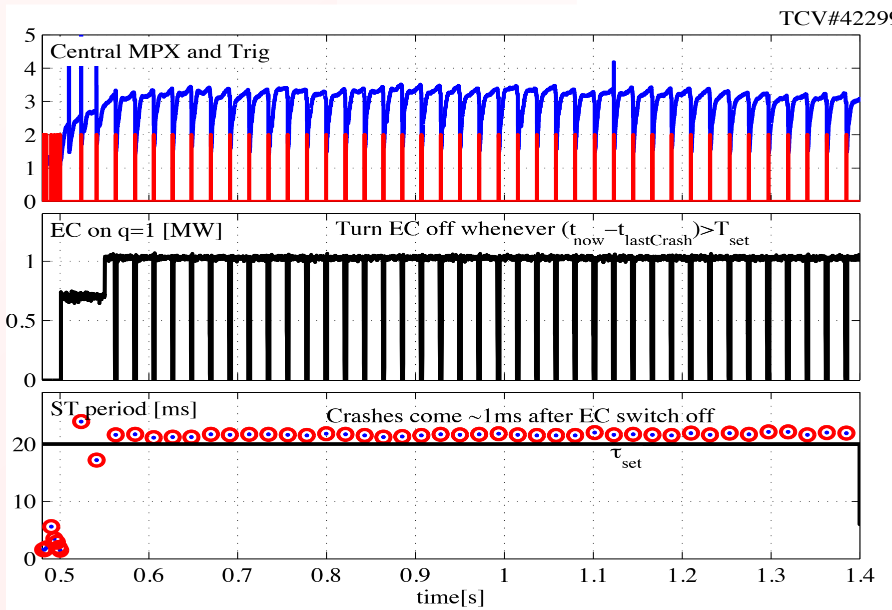


Program constant EC-on period



Xrays & crash trig

EC power @ q=1

ST period

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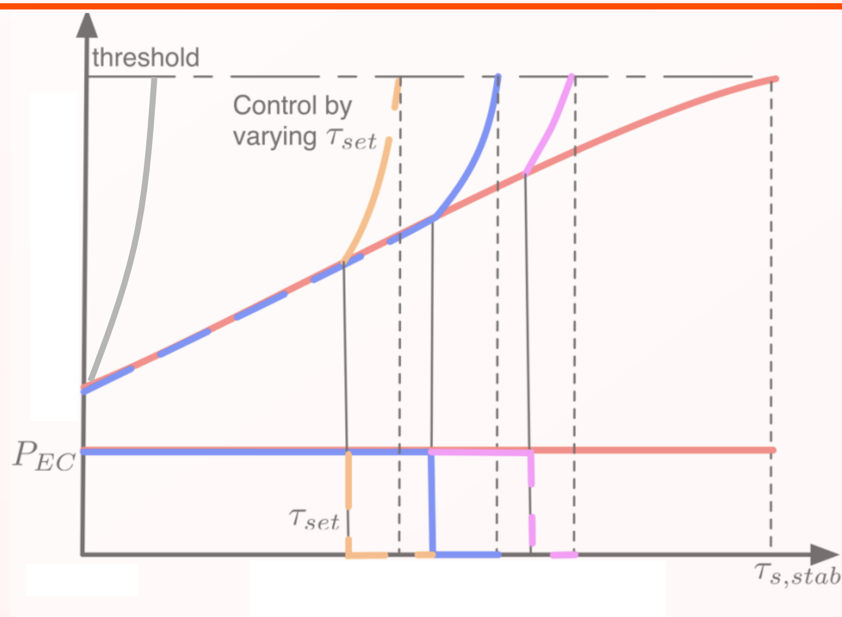
ST pacing with EC power

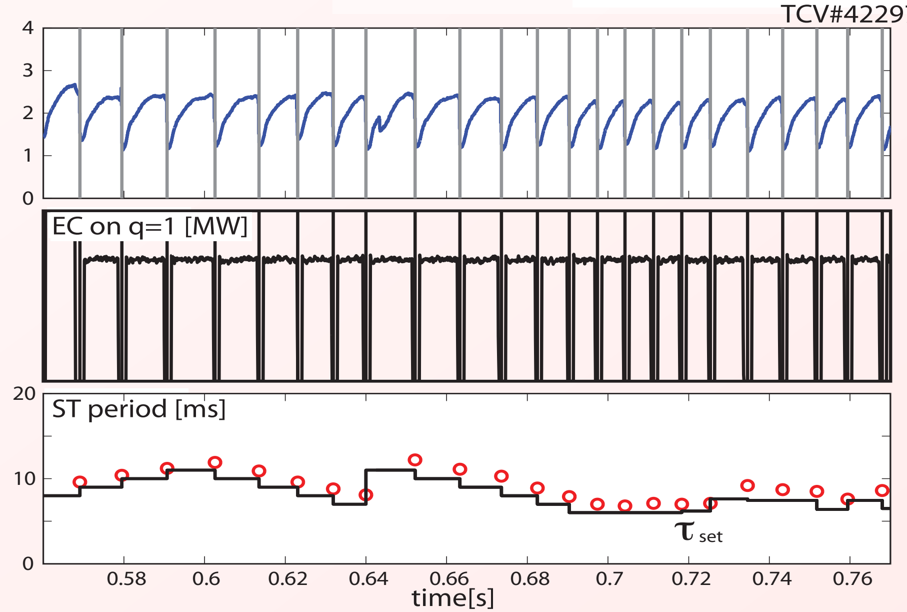
Synchronise to last ST (**RT**)
- Increases EC power, stabilises ST
- Reduces EC power after a chosen time (hastening next ST)

- Each ST can be chosen within range



Program sequence of changing EC-on periods

Each ST programmed independently starting from the previous one

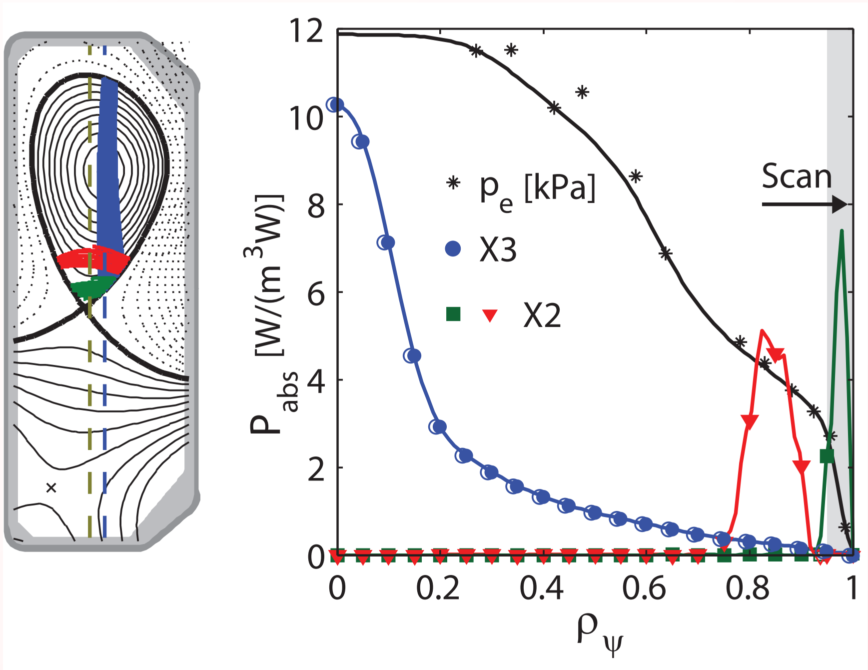


RT ELM control

Does this approach work for ELMs ?

Higher ELM frequency with edge EC

Move X2 power *towards* the edge of a Type-**I** ELMing discharge



1MW X3 (heating)

~0.5MW X2 scanned

Higher ELM frequency with edge EC

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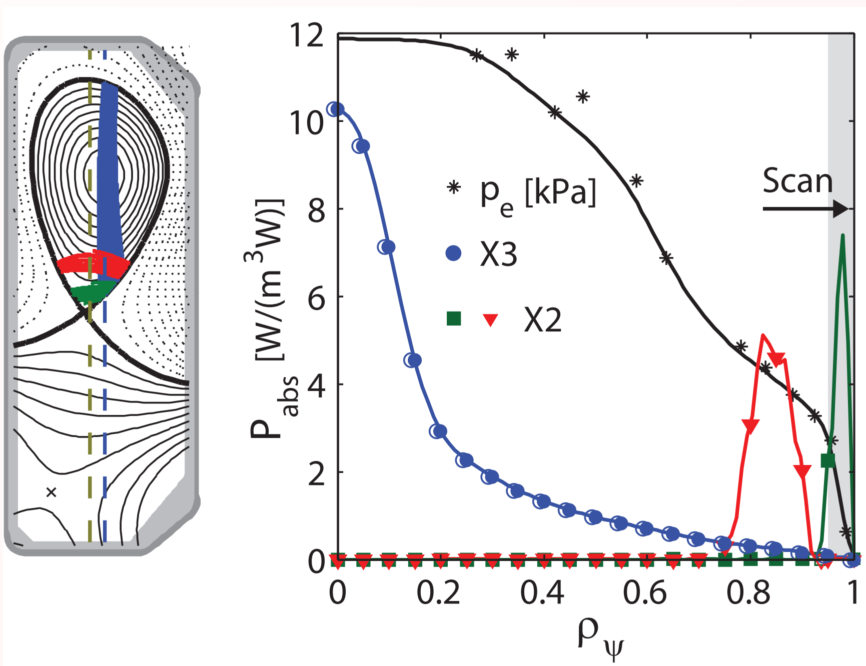

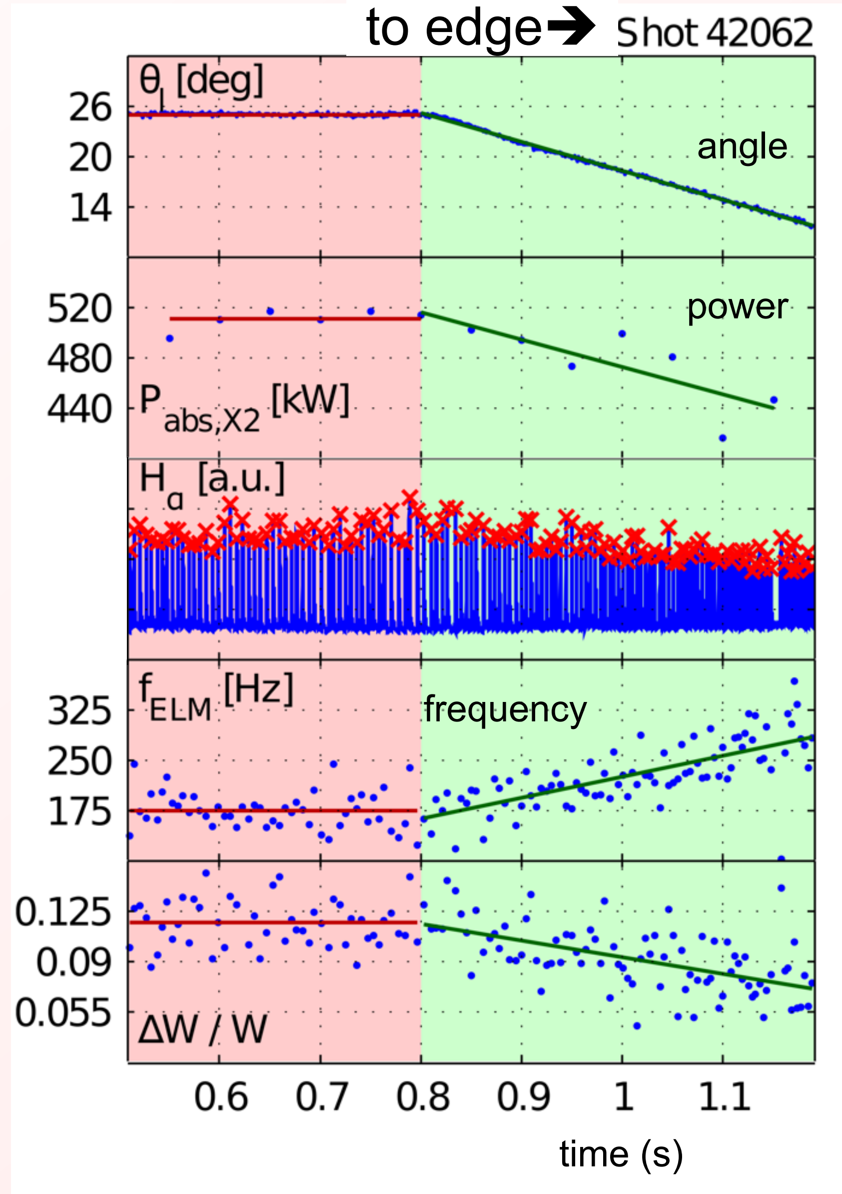

1MW X3 (heating)

~0.5MW X2 scanned

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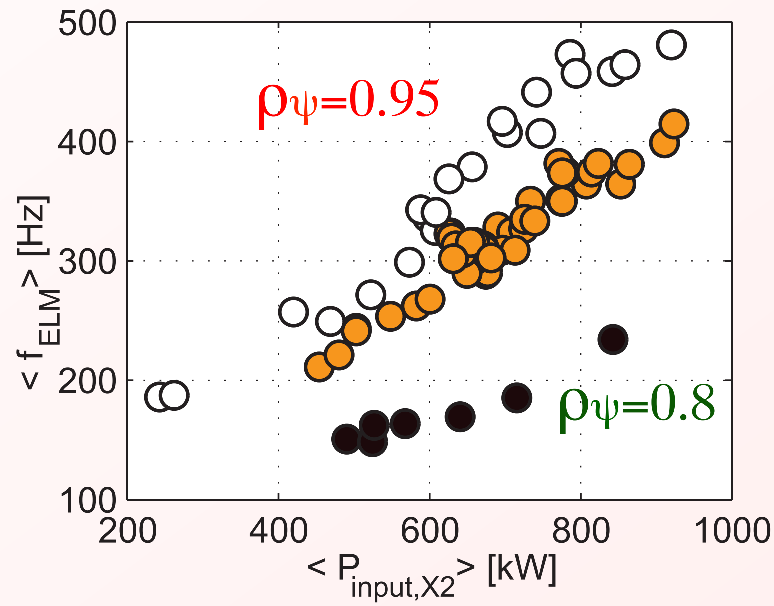
ELM frequency increases with power

Power scan at fixed position

- Effect stronger with X2 towards edge (rho=0.95)
- Does not agree with average power determining ELM period
- Much larger effect, **for the same power**, when at the edge



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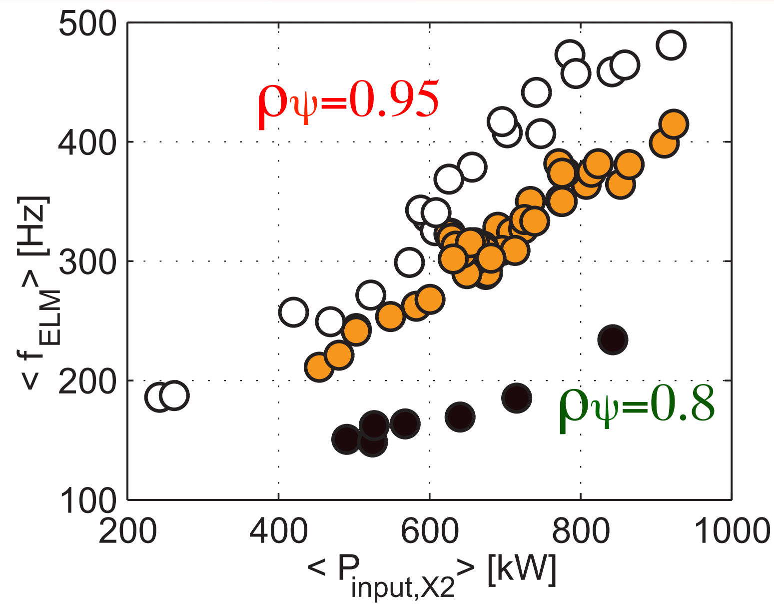
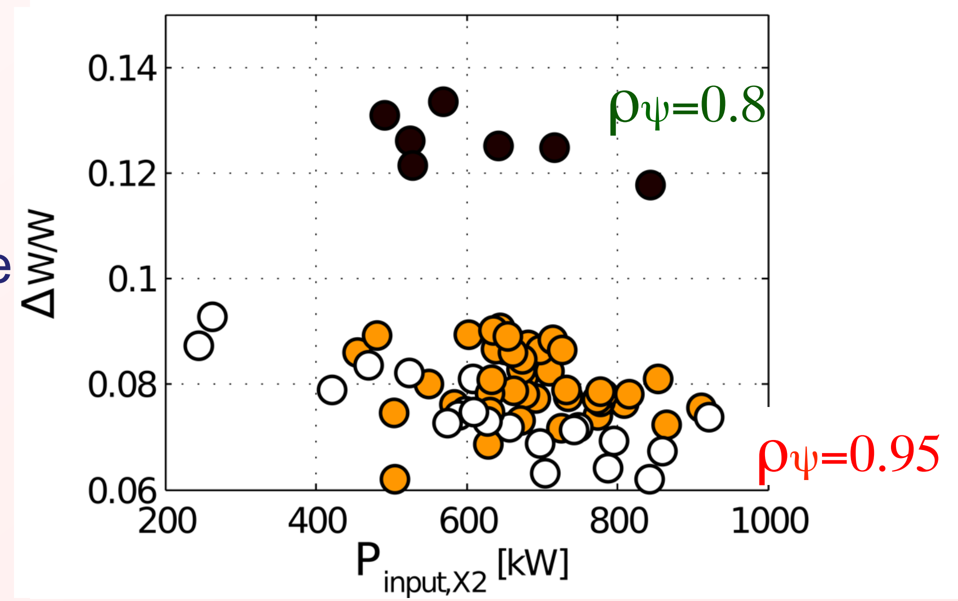


< ΔW / W > at fixed angle

- Decreasing with ELM frequency
- Decreases with EC closer to edge



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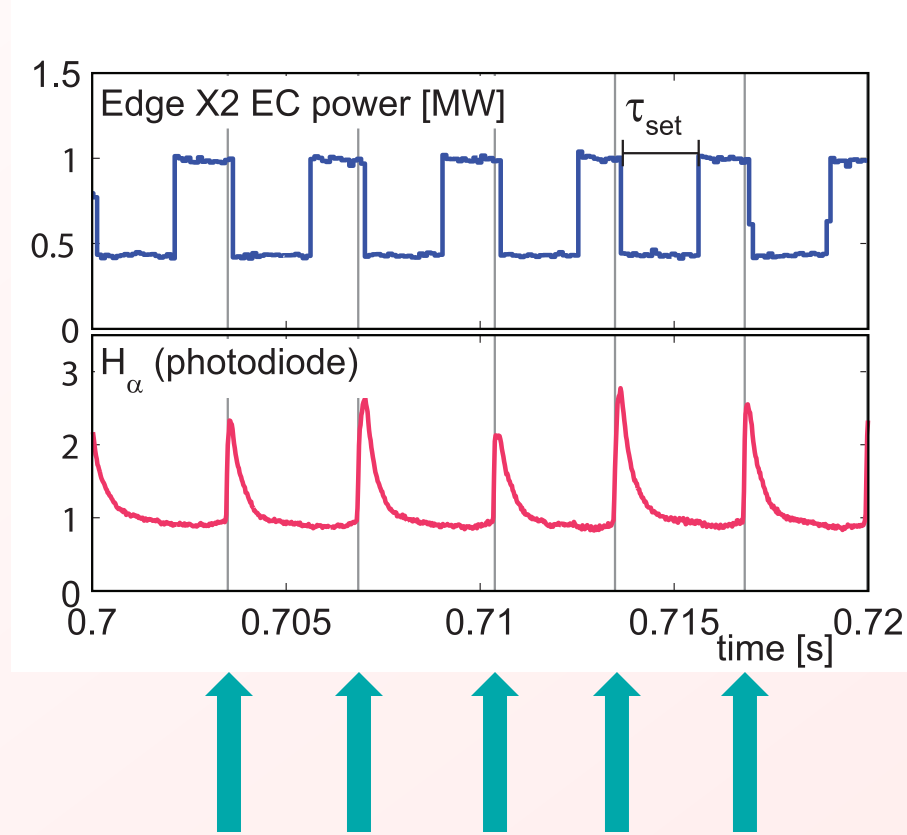
Individual ELM pacing with EC power

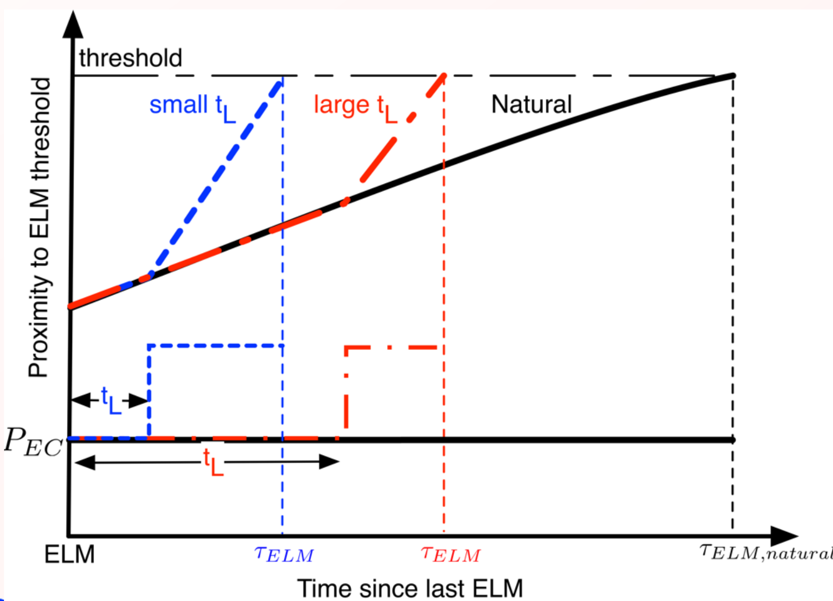
RT system detects last ELM

- Switch EC power ON at pre-set time after previous ELM
- Turn EC off when ELM detected



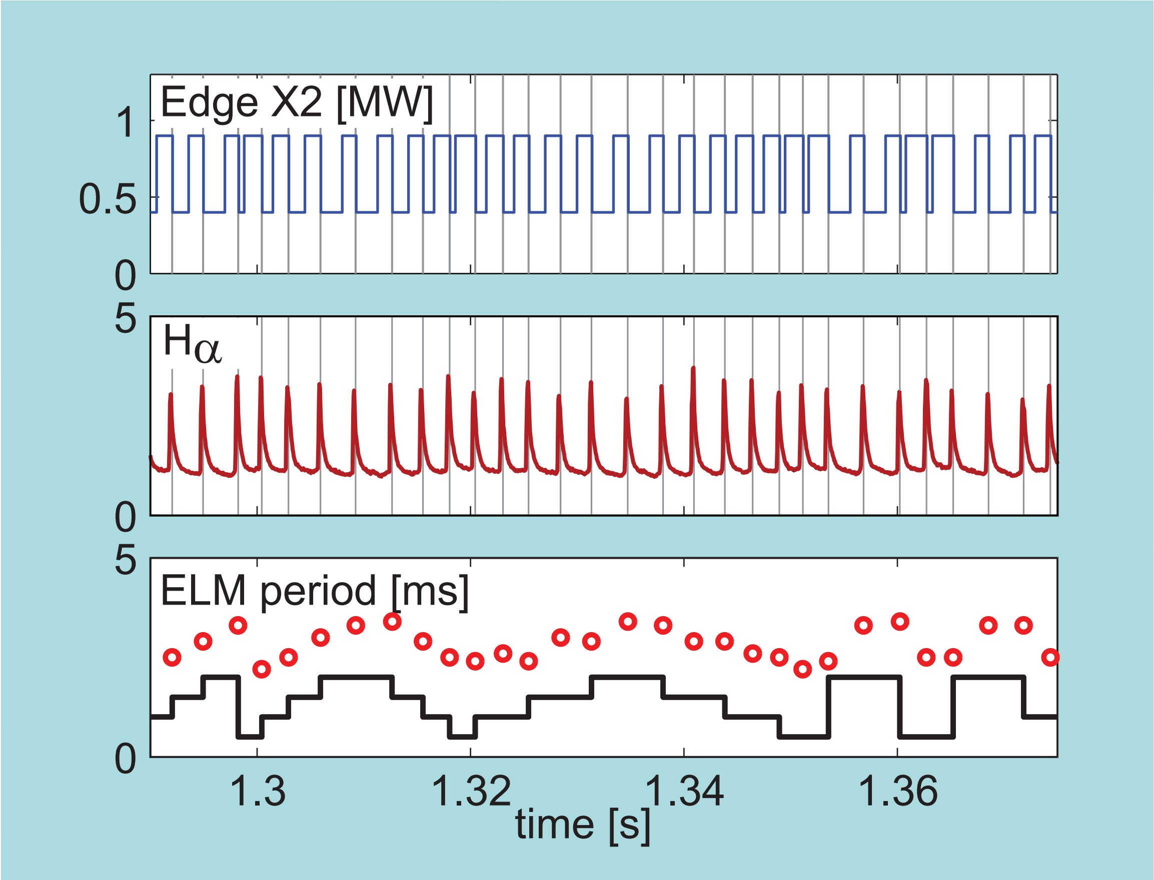
RT detected

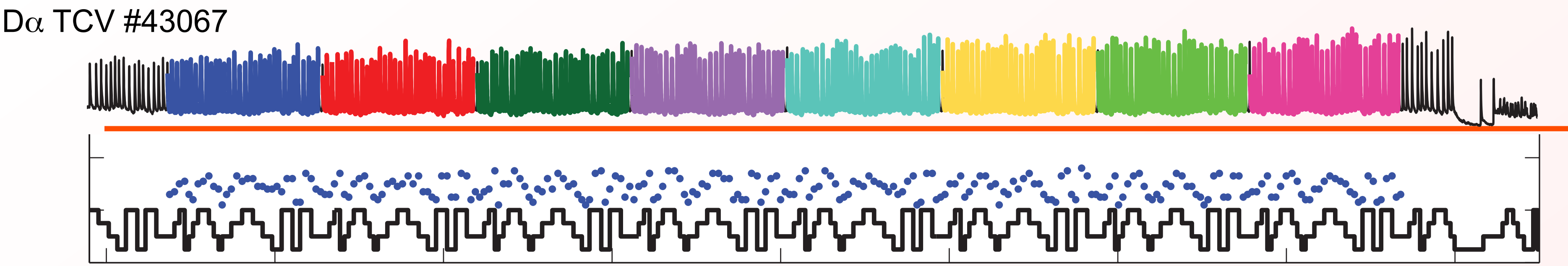
Time of previous ELM



Individual ELM pacing with EC power

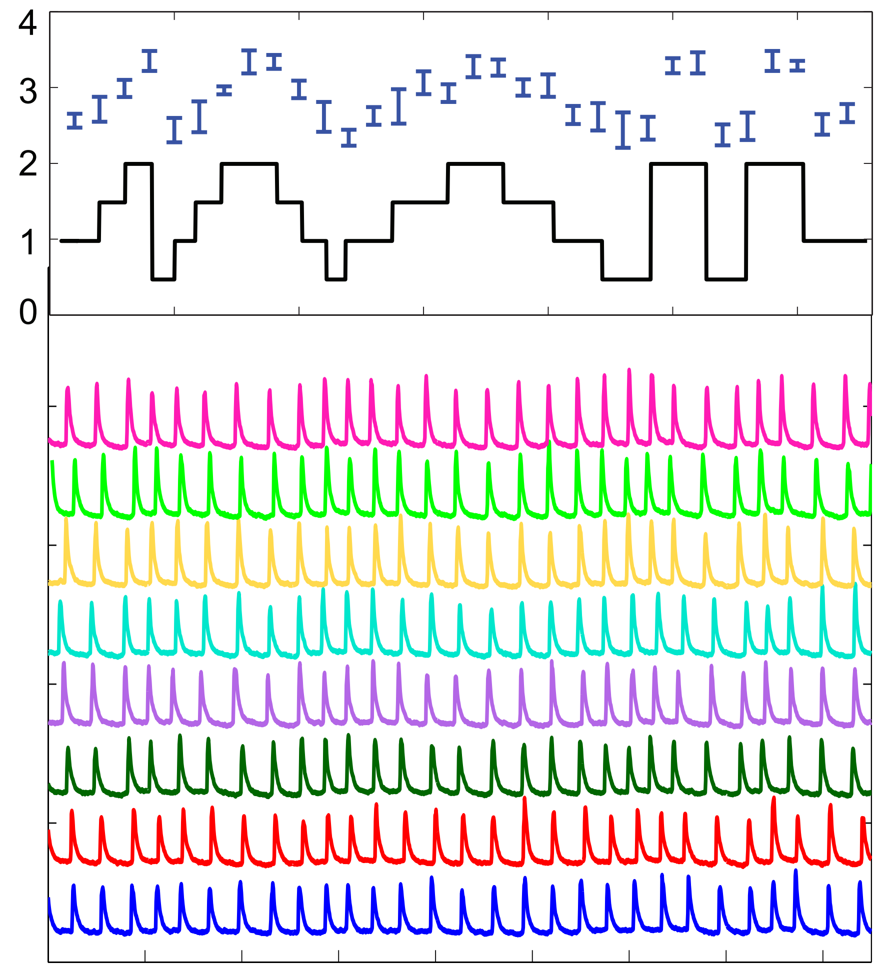
Demonstrate pacing using a "*Pseudo-Random*" sequence





ELM period (ms)
& observed uncertainty

EC “on” period (ms)
to generate sequence



- Overlaying time sequences shows excellent repeatability
- Individual ELMs are paced (next ELM period chosen at will)
- **Each ELM should be considered as an individual event**

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Compare ST and ELM limit-cycles

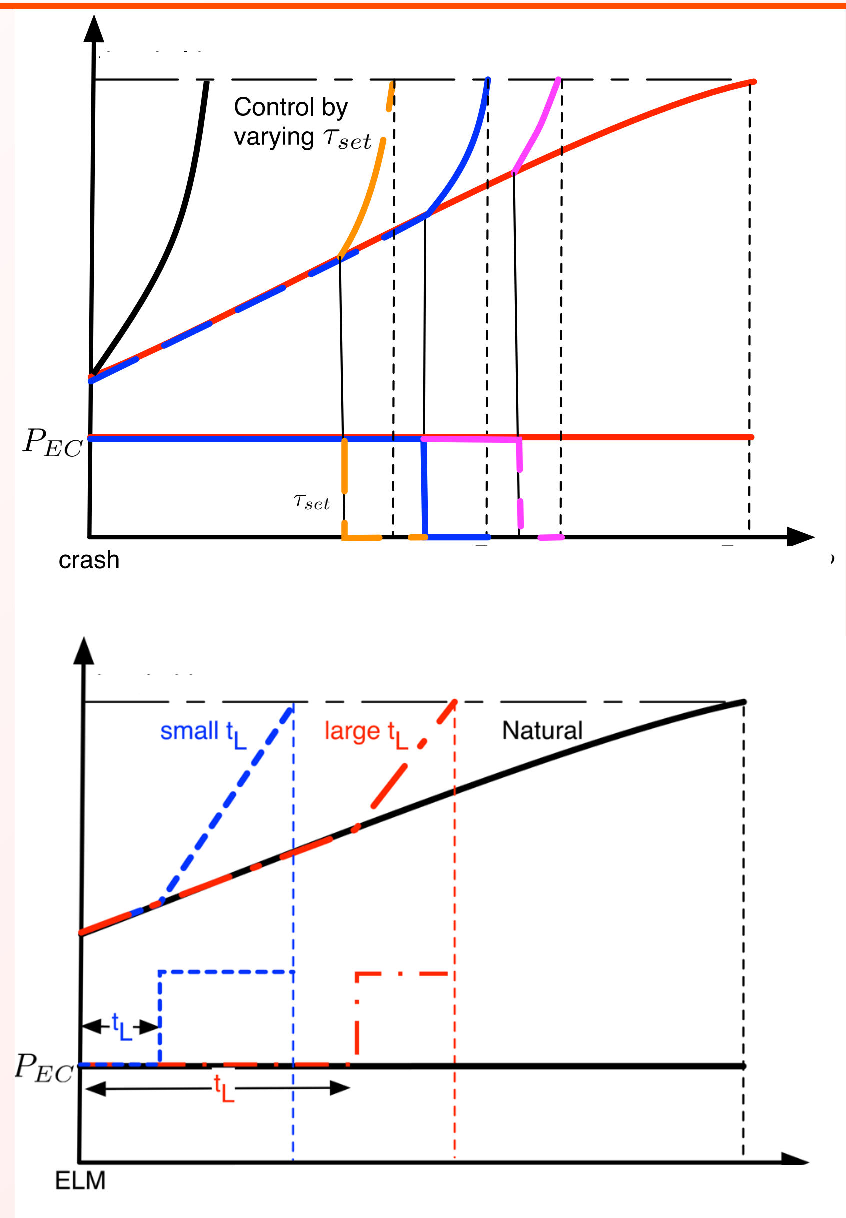
Both ST and ELM are
"limit-cycle" (& history-free)

RT ST pacing

- Stabilised ST reach next ST later (destabilising ST was also demonstrated with shorter ST periods)
- ST period governed by q=1 shear dynamics

RT ELM pacing

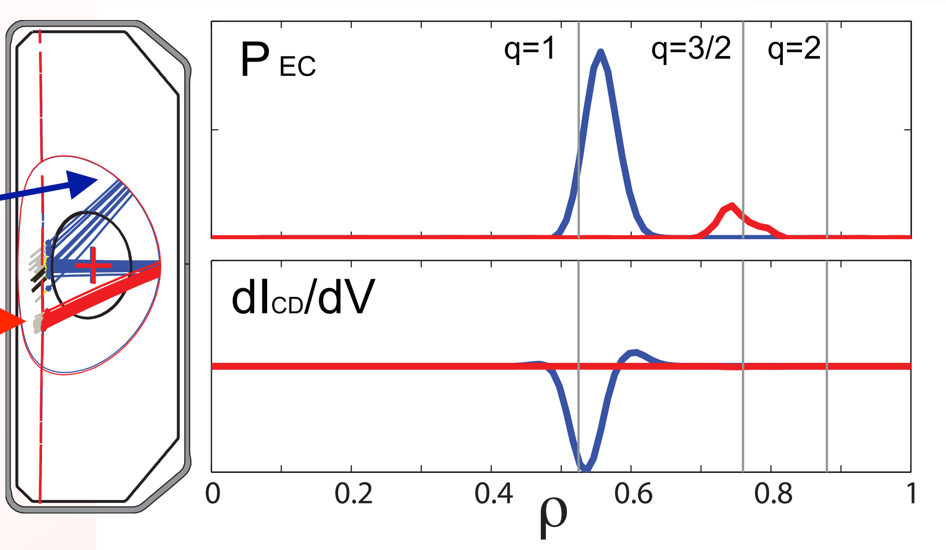
- Destabilised ELM reaches threshold earlier
- ELM period governed by integral of power in-cycle



3/2 NTM seeding and stabilisation

Long, paced ST to seed 3/2 NTMs

- Stabilising ST (pacing) @ q=1
- NTM control @ q=3/2
  - "preemptive" EC
  - stabilising EC



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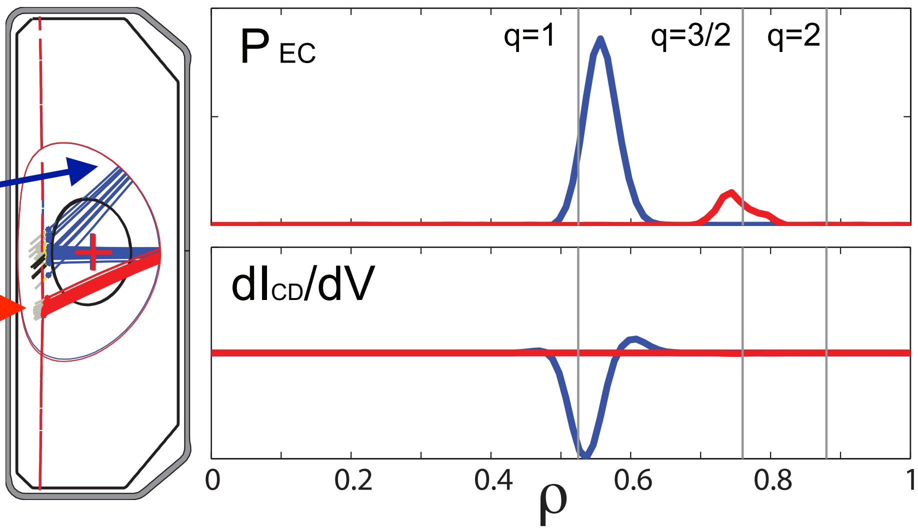
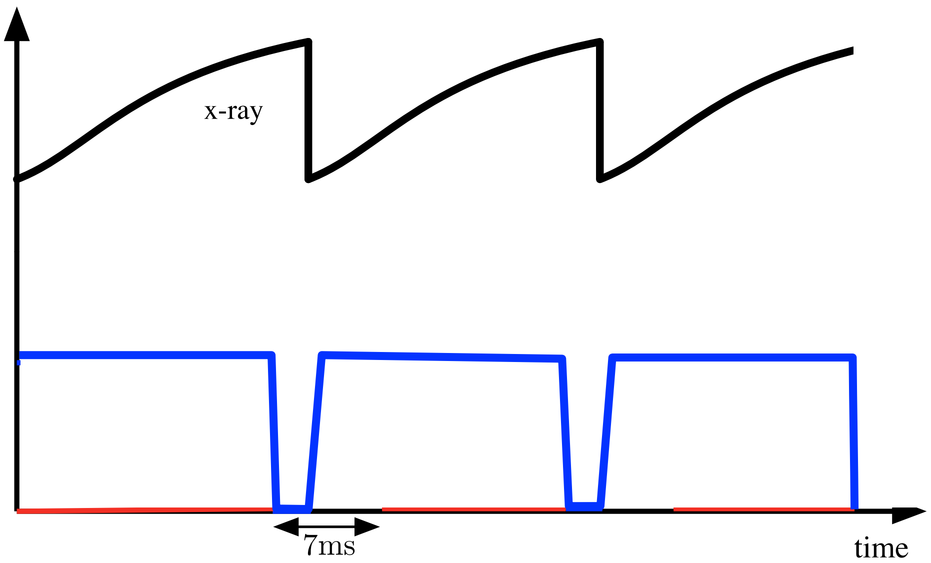


Multiple Actuator EC power

Long, paced, ST seed 3/2 NTM

EC power application



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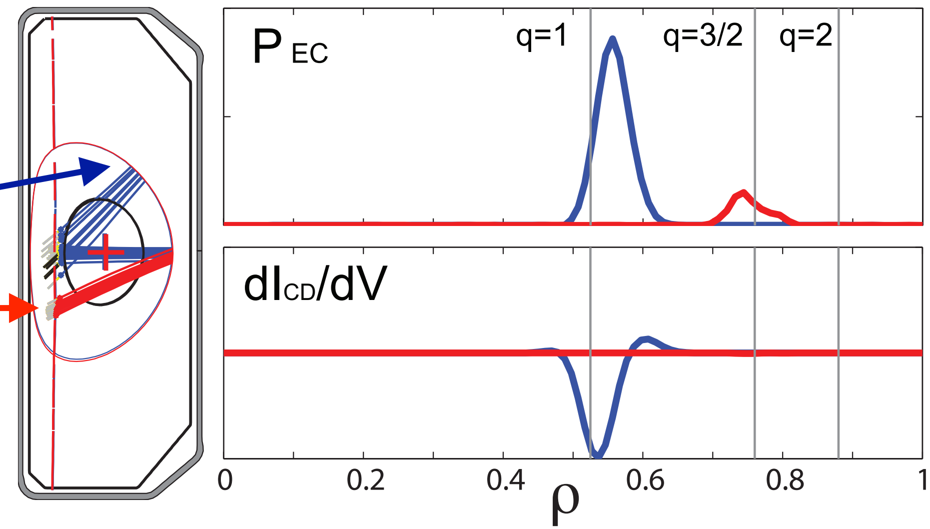


Multiple Actuator EC power

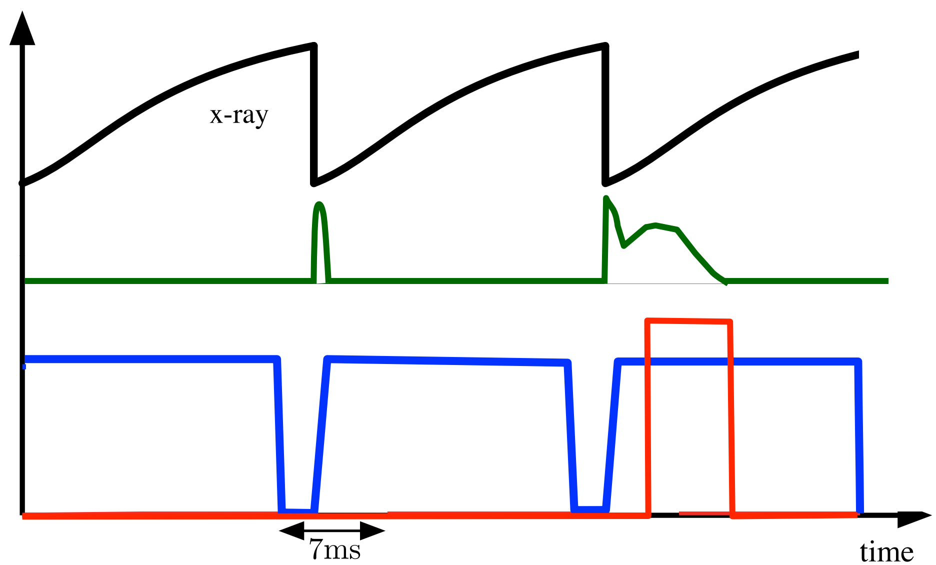
Long, paced, ST seed 3/2 NTM

NTM island width

stabilising EC

applied until mode disappears

EC power application



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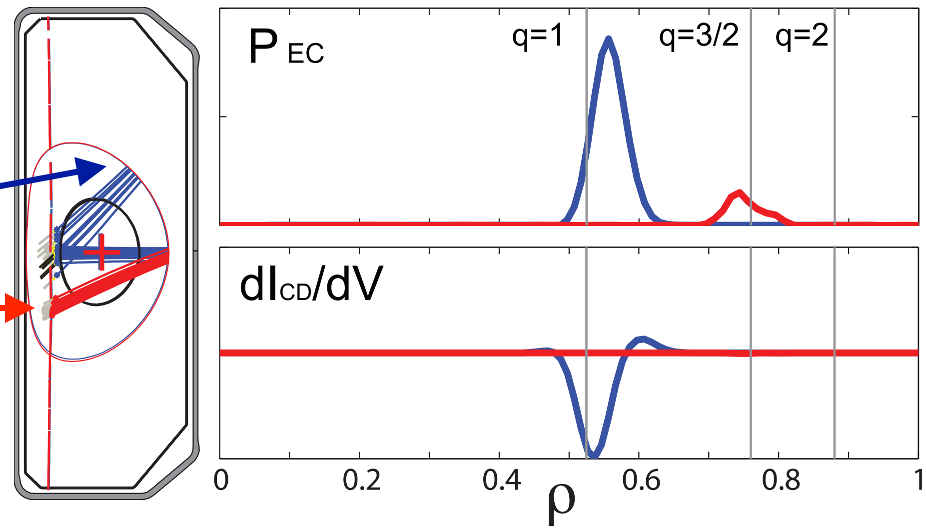


Multiple Actuator EC power

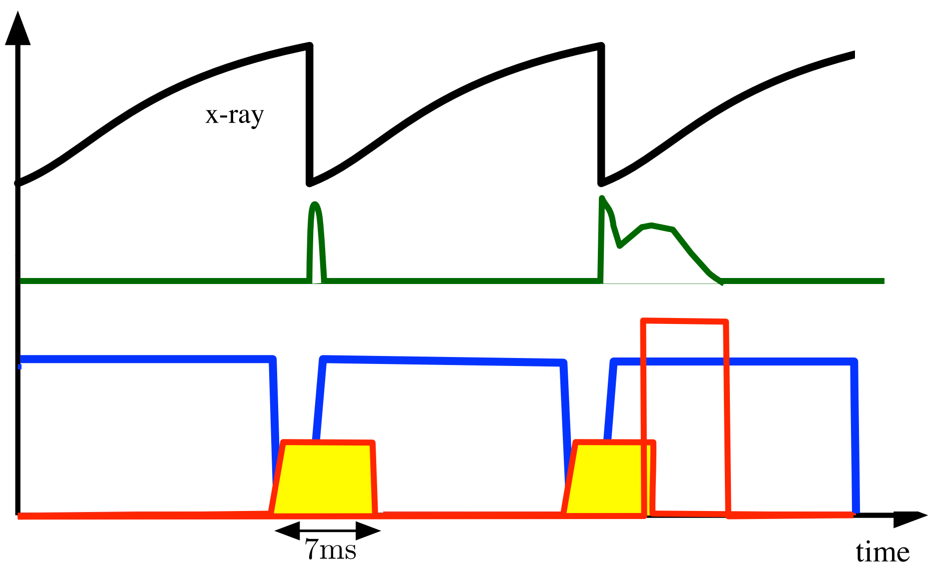
Long, paced, ST seed 3/2 NTM

RT detects NTM island width

Stabilising EC

Optional **preemptive** EC power for 7ms across ST

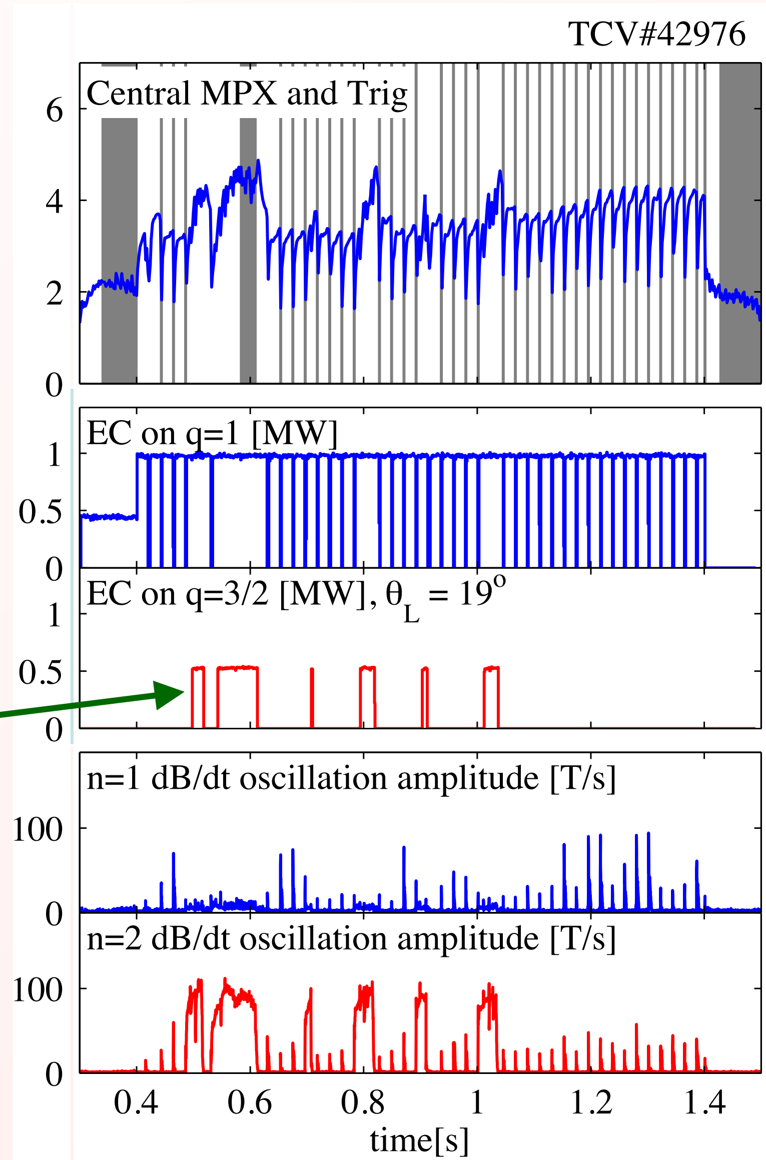
EC power application



NTM seeding & RT "Stabilisation"

- No pre-emptive
- 200kW pre-emptive
- 320kW pre-emptive

RT detected 3/2 NTM turns on "stabilisation" EC until mode disappears



Xrays & crash trig

Power A ST pacing

Power B (NTM)

MHD n=1

MHD n=2

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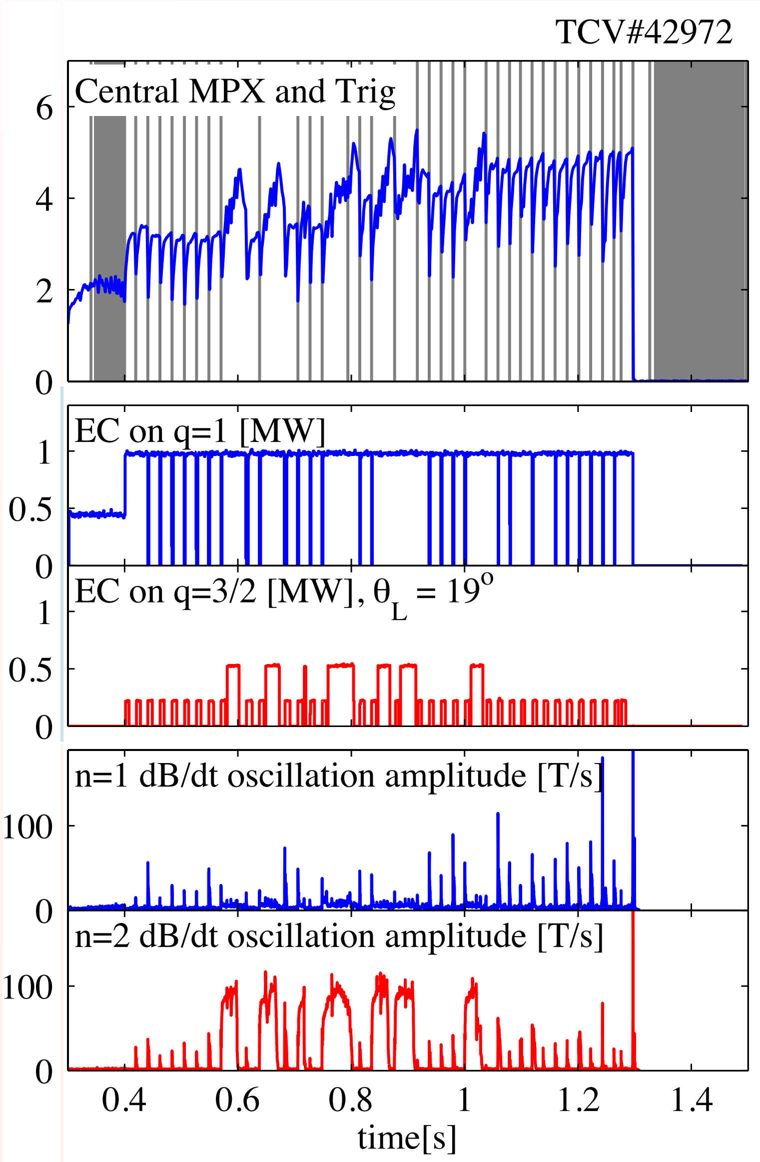
NTM seeding & RT "Stabil" & PreEmpt

- No pre-emptive
- 200kW pre-emptive
- 320kW pre-emptive

Less 3/2 NTM activity still uses "stabilisation" EC until mode disappears



Xrays & crash trig

Power A ST pacing

Power B (NTM)

MHD n=1

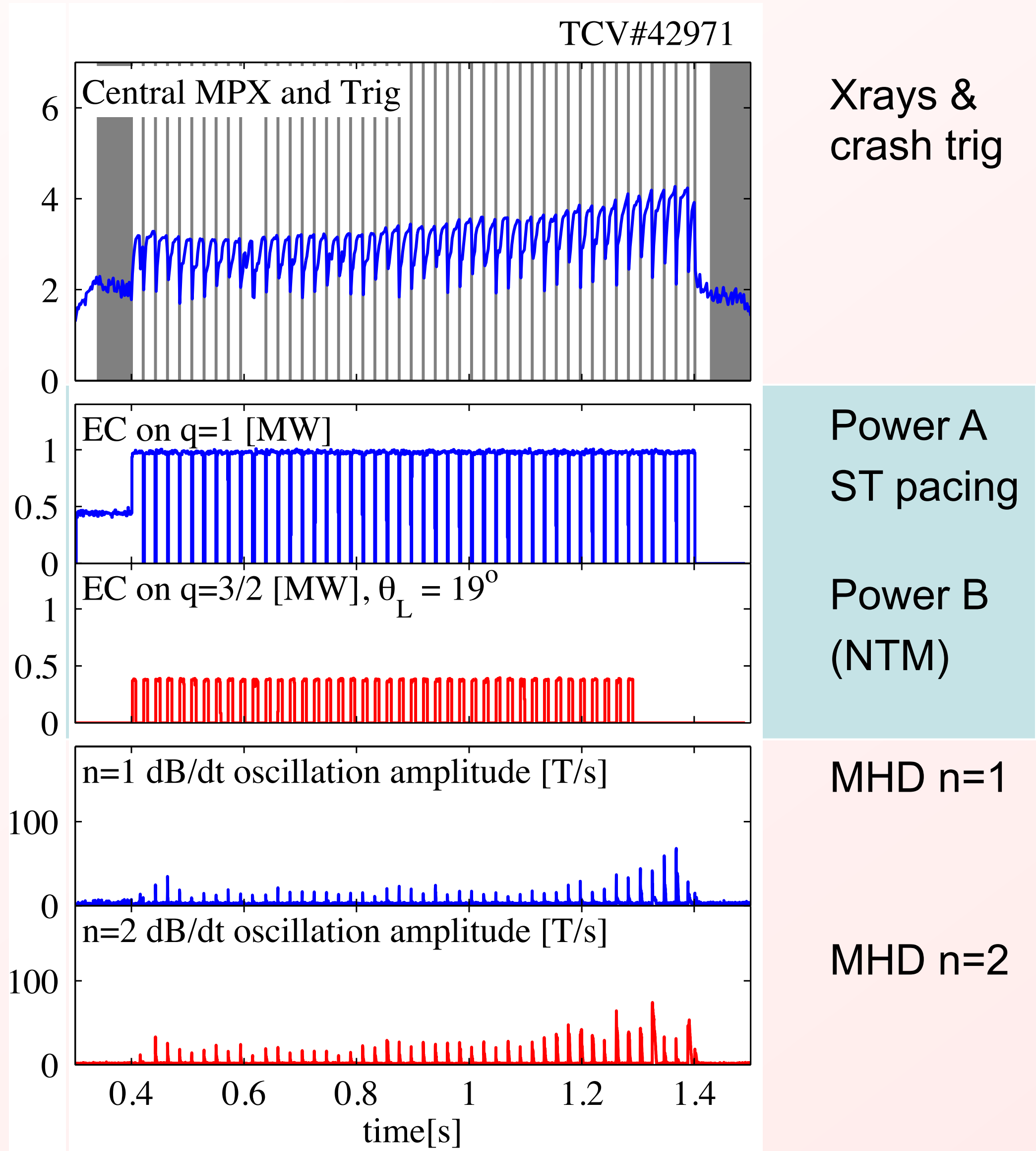
MHD n=2

NTM seeding & RT "Stabil" & PreEmpt

- No pre-emptive
- 200kW pre-emptive
- 320kW pre-emptive

7ms @320kW of pre-emptive EC sufficient to avoid NTM growing

(RT "stabilisation" still ready if NTM grows)



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Conclusions

ST

- **Individual** ST period control (pacing) using **RT** ECCD power control

ELMs

- Frequency **increases** with edge EC power (Type-I)
- Frequency, at constant power, increases as EC moved **towards edge**
- **Individual** ELM period control (pacing) using **RT** power control

NTMs

- Controlled NTM **seeding** using long ST
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- Demonstration of **multi-actuator**, **multi-MHD** instability control as for ITER

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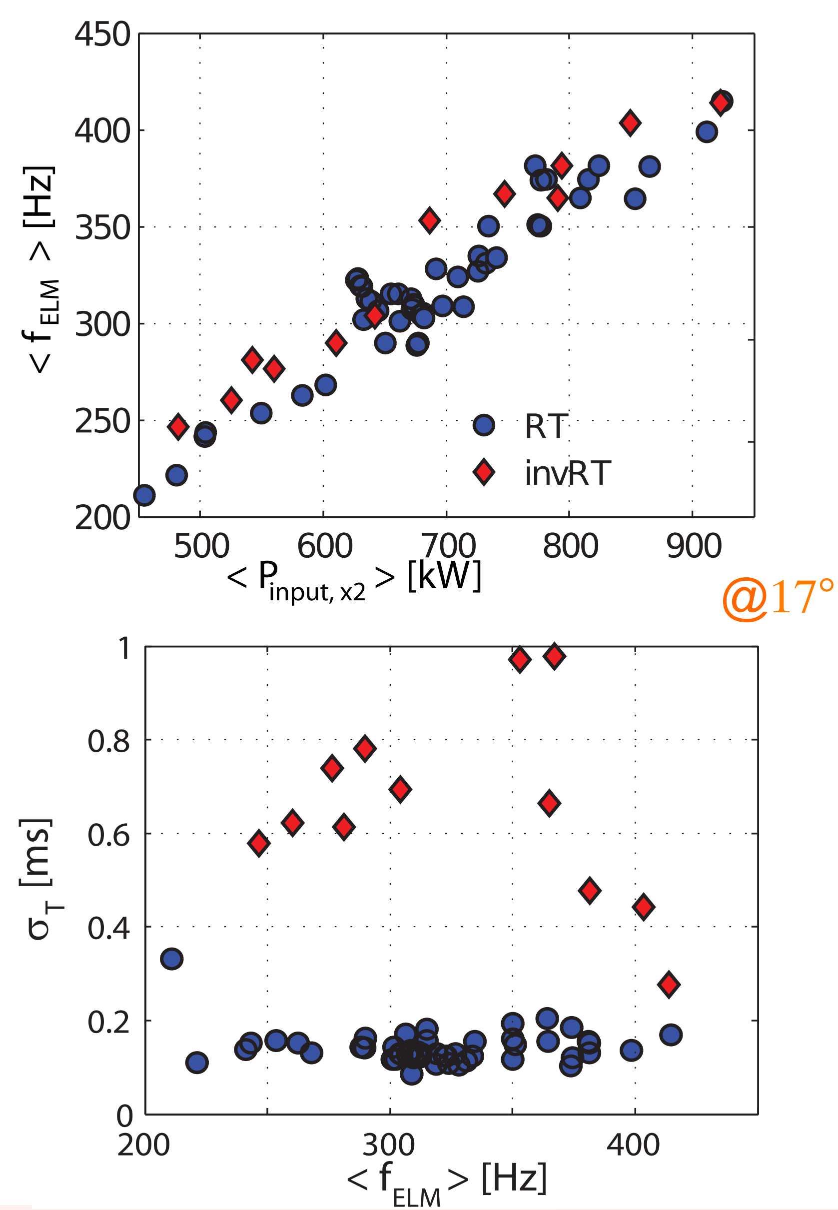
Standard Deviation of ELM period

ELM frequency with EC power

Compare :

- RT (as previously, EC off then on)
- invRT (EC on then off)



SD (relative uncertainty in ELM period)

Lower when ELM occurs together with highest EC power

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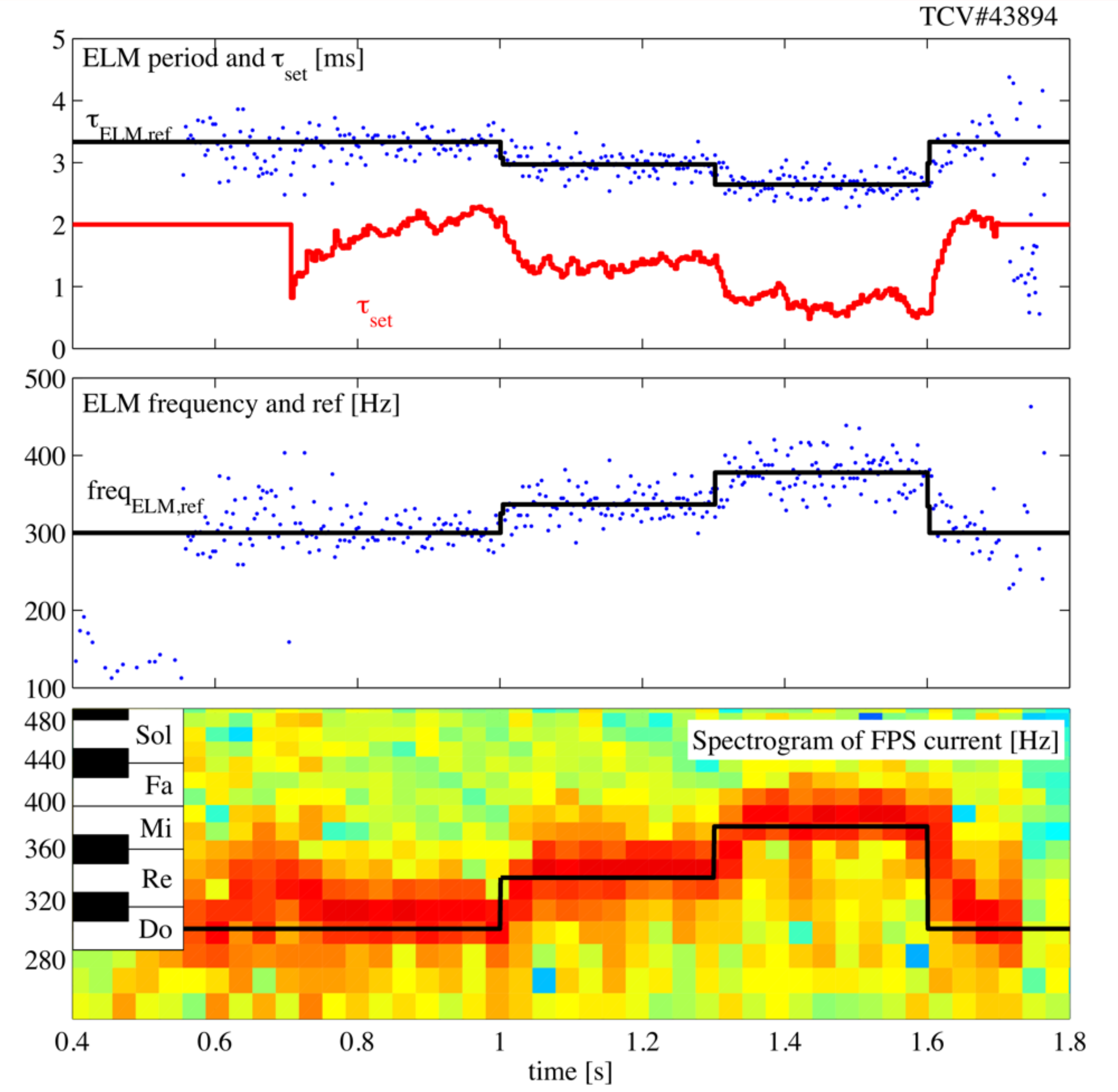
♫ Musical Interlude ♫

Feedback algorithm uses last ELM(s) to modify the next EC cut time to change ELM frequency

(ELM+TCV's fast-coil *vibrates* TCV)

The result ?

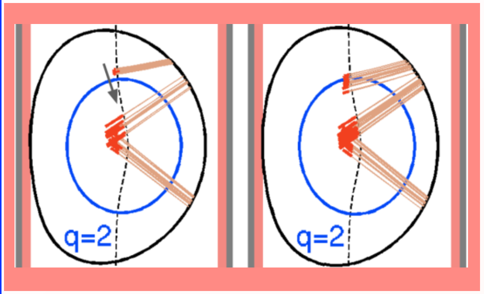
"Frère Jaques"

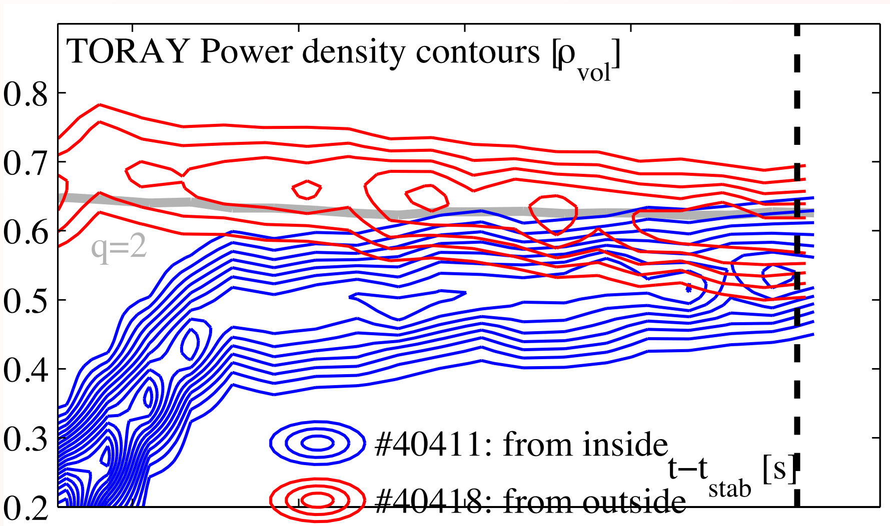


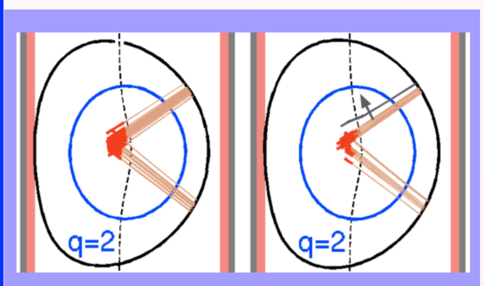
Example: 2/1 NTM island "stabilisation" by EC

Core ECCD destabilises NTM, then:

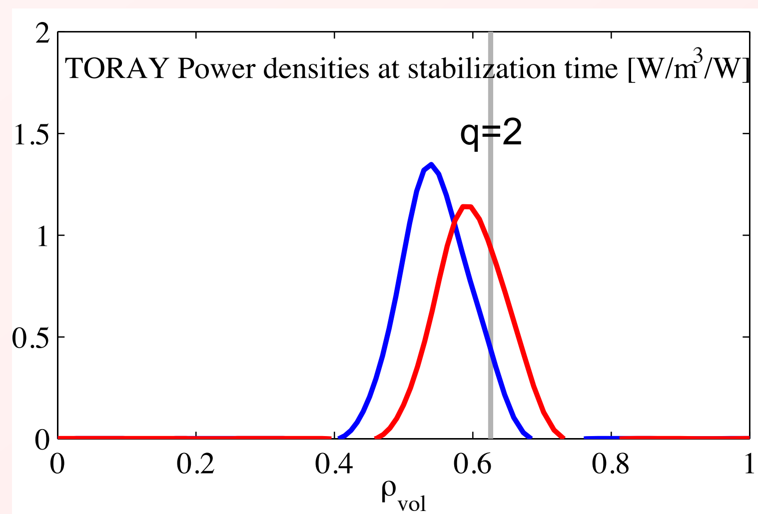
- Other EC beam swept **in**/**out**
- Scan stopped when RT senses NTM stable







Stabilisation achieved within a beam half-width



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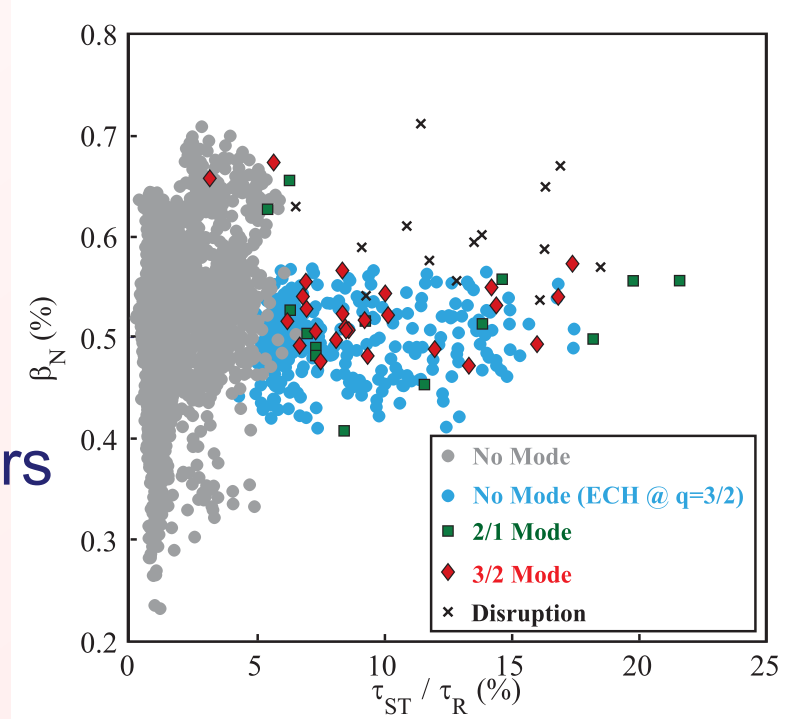
Extended operations

Eg:

Further diagnostics and actuators combined (MIMO) to increase robust operational range



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