Real-time ELM, NTM and Sawtooth control on TCV

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IAEA 2012, October 8-13 2012
San Diego, California, USA
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](http://library.epfl.ch/theses/?nr=5203)
- **J. Rossel** EPFL-Lausanne (2012), [http://library.epfl.ch/theses/?nr=5311](http://library.epfl.ch/theses/?nr=5311)

Publications 2008-2012 with more submitted or planned-

(many more details available)

- M. Lauret *et al*, Nuclear Fusion **52** 062002 (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, $H_{\alpha}$…
- 4x X86 Linux nodes with reflective memory. Down to 20$\mu$s 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
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

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 (\textbf{RT})

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

\textbf{RT detected}

Time of previous ST
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

- By programing individual EC-on periods the ST are “paced”

Range over which each ST period can be chosen
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)
- Individual ST can be chosen within range

Program constant EC-on period

Xrays & crash trig
EC power @ q=1
ST period
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

Xrays & crash trig
EC power @ q=1
ST period
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

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

1MW X3 (heating)

~0.5MW X2 scanned
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

\[ P_{\text{input},X2} \quad \text{[kW]} \]

\[ f_{\text{ELM}} \quad \text{[Hz]} \]
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

< ΔW/W > at fixed angle
- Decreasing with ELM frequency
- Decreases with EC closer to edge
**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

![Graph showing ELM pacing with EC power](image)

**RT detected**
Time of previous ELM
Individual ELM pacing with EC power

Demonstrate pacing using a “Pseudo-Random” sequence

![Graph showing Edge X2 [MW], Hα, and ELM period [ms] over time [s]]
• 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
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
Long, paced ST to seed 3/2 NTMs

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

Multiple Actuator EC power

EC power application

Long, paced, ST seed 3/2 NTM
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

Multiple Actuator EC power

Long, paced, ST seed 3/2 NTM

NTM island width

stabilising EC

applied until mode disappears
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

Multiple Actuator EC power

EC power application

Long, paced, ST seed 3/2 NTM

RT detects NTM island width
Stabilising EC

Optional preemptive EC power for 7ms across ST
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
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
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)
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
Obligatory Intentionally Blank
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

\[
\sigma_T [\text{ms}]
\]

\[
< f_{\text{ELM}} > [\text{Hz}]
\]

\[
< P_{\text{input, x2}} > [\text{kW}]
\]

@17°
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

TORAY Power density contours \( \rho_{\text{vol}} \)

Stabilisation achieved within a beam half-width
Extended operations

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