On the Control System Preparation for Experiments on ELM Pacing with Vertical Kicks on TCV

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Outline

Motivation
Tokamak à Configuration Variable
Advanced Plasma Control System
Plasma Model for Optimal Control
Vertical Stabilization Controller
Simulations & Results
Conclusions & Future Work
Magnetic Triggering of ELMs

<table>
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<tr>
<th>H-Mode Plasmas</th>
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<td>- Higher confinement regimes</td>
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<td>- Higher fusion rates, expected to operate for ITER scenarios</td>
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<td>- Steep density and temperature gradients drive localized MHD ELMs</td>
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<th>Benefits of ELMs</th>
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<td>- Control particle exhaust (impurities)</td>
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<td>- Control excessive plasma internal energy</td>
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<th>Risks of ELMs</th>
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<td>- Excessive energy release into the plasma facing components may lead to erosion or melting, reducing the components life cycle</td>
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By controlling the ELM frequency it is possible to reduce the energy expelled per ELM – Mitigating the damage for Tokamak parts.
Magnetic Triggering of ELMs

- ELM pacing with vertical kicks was obtained in 2002 in TCV
  - Ohmic plasmas
  - Type III ELMs
    [A Degeling et al. EPS conf. 2002, P-2.078]
    [A Degeling et al. PPCF 45, 2003, 1637]
- Reproduced in AUG in 2004
  - Type I ELMs
    [Y. Martin et al. EPS conf. 2004, P-4.133]
    [S.H. Kim et al. PPCF 51, 2009, 55021]
- Physics study at JET later
  - Type I ELMs
    [E. de la Luna et al. Nucl. Fusion 56 (2016) 026001]
Magnetic Triggering of ELMs

Main Goals

- Assess the type I ELMs pacing potential with vertical kicks
- Assess the role of the displacement amplitude vs velocity
- Evaluate the impact of ELM pacing on confinement and heat losses

Assessment Tools

- Estimation of the ELMs / kicks synchronisation rate
- Estimate the frequency range of synchronisation
- Evaluate the synchronisation rate in different perturbation cases
- Estimation of confinement and heat losses
TCV Tokamak

Flexible Actuators
- 16 independently controllable PF Coils
- In-vessel coils with fast power supplies

Accurate Diagnostic
- Hundreds of magnetic measurements
  - magnetic probes
  - flux loops
  - coil current measurements

Flexible Digital Control Systems
- Distributed, scalable, modular
- Easily change the control hardware between discharges
TCV Plant Control System

Control a Subsystem State-Machine Using MDS+ Remote Calls
APCS Integration

Similar Compilation State-Machine for Remote Control of the Algorithm Construction
APCS Integration

GUI for APCS control and status

TCV-APCS Advanced Plasma Control System
18-OCT-2013 18:00:10
Actual shot 49281

The APCS window allows:
- select or deselect SCD and DSP control systems
- move system from one state to another
- survey system states
- launch related windows: summer, timers, etc

The APCS is configured and controlled automatically by TCVPC. It is not allowed to set the APCS manually!
Please contact the person in charge

APCS State-Machine
And MDS+ Remote Calls
Advanced Plasma Control System

- 4 DSP parallel system in each module
- Shared memory and full mesh communication between DSPs
- 1 ADC and 1 DAC per DSP
- 5 μs control cycle

Module Highlights

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Plasma Control Modelling

Purpose of the Model

- Simulate
- Predict
- Confirm our understanding of the plasma behaviour
- Goal: Build the best possible vertical plasma stabilization controller

Types of Modeling and System Identification

- **White box model** – Built on the inside knowledge of the physical laws that govern the system
- **Black box model** – Built using experimental data to determine the system behaviour based on the response of stimulus using system identification techniques
- **Grey box model** – Initially built on the physical knowledge of the system and tuned based on experimental data
Plasma Control Modelling

**Plasma Rigid Model**
- Model based in a constant current distribution
- The quantities that are left free:
  - Radial and vertical position centroid
  - Total plasma current

**Advantages**
- Simple model easy to implement
- No complete plasma equilibrium reconstruction
- Explicit to the control variables
- It is a control oriented model!
Plasma Control Modelling

**RZIP Model**

- Derived from
  - The equilibrium equation of the vertical forces in the plasma
  - The plasma current circuit equations

\[
M(s)x + \Omega x = u
\]

\[
x = \begin{pmatrix}
I_c \\
zI_p0 \\
RI_p0 \\
I_p
\end{pmatrix}
\]

\[
u = \begin{pmatrix}
V_c \\
0 \\
-\mu_0 I_p0^2 s\Gamma \\
0
\end{pmatrix}
\]

\[
M = \begin{pmatrix}
M_c & (M'_z)^T & (M'_R)^T & (M'_p)^T \\
M'_z & \alpha & 0 & 0 \\
M'_R & 0 & M_{33} & M_{34} \\
M'_p & 0 & M_{43} & L_p0
\end{pmatrix}
\]

\[
\Omega = \begin{pmatrix}
\Omega_c & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & \Omega'_p & \Omega_p
\end{pmatrix}
\]

Measurement of the open loop plasma equilibrium response in TCV

A. Coutis et al 1999 *Nucl. Fusion* 39 663
The best model is not always the most accurate, but the one that permits the construction of a robust stable controller, according to the performance specifications.

**RZIP Model**

\[ Msx + \Omega x = u \]

**System Diagonalization**

Different time scale actuation

**52\text{nd} Order Transfer Function**

Plasma Position vs In-Vessel Coil Voltage

Balanced Realization Method

Eliminates the states with small influence in the behaviour of the TF

**2\text{nd} Order Transfer Function**

\[ \frac{X(s)}{U(s)} = \frac{n_1 s + n_2}{s^2 + d_1 s + d_2} \]
Why?
- Time optimal control of an LTI system is bang-bang controller
- Switched FPS mode of operation

Motivations
- Developments on optimal control theory
- Bang-bang controller implementations of lower order models
- Minimize control time with only one control switch
- Plan the control action ahead
  - temporary lost of observer
  - in the presence of ELMs

Constraints
- High sensibility to
  - Perturbations
  - Parameter variations
- Difficult system modelling
Optimal Control Algorithm

Algorithm for Switch and Final Time Prediction

Step 1 Define Initial Direction

Step 2 Trace the path from initial position

Step 3 Trace the path back from final position

Step 4 Find the intersection point

Step 5 Store switch time (intersection) and final time.

Optimal Control Application

Prediction of State Trajectories

Definition of Controllable Zones
Near Optimal Implementation

- Regions defined according to distance to set point
- Controller “hardness” defined as the bang-bang controller signal level

Variable controller - State machine

- Introduction of a linear behaviour to the non-linear controller
- Improvement of stability
Plasma Elongation Improvement for the same discharge conditions

**PID Controller**

Plasma Elongation ($k$) (#49567)

**Near Optimal Controller**

Plasma Elongation ($k$) (#49564)
Near Optimal Control

PID Controller

Near Optimal Controller

Plasma Position

0.5 s

0.65 s

Plasma Velocity

0.5 s

0.8 s

Plasma Disruption

Improvement of 100% in time before disruption
Near Optimal Control

PID Controller

Controller Signal

Coil Current

0.5 s  0.65 s

Plasma Disruption

Near Optimal Controller

Controller Signal

Coil Current

0.5 s  0.8 s
Simulation & Implementation Scheme

Feedback Simulator using Matlab / Simulink

Reference Position

Disturbance Generator

Fast Power Supply Model

Coil Input Voltage

Plasma Model (Complete)

Vertical Stabilization Controller Algorithm

Controller signal

d(zIp)/dt Observer

Plasma velocity

zIp Observer

Plasma position

Programmed Feed-forward

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Page 23
Test Discharges – Vertical Kicks

- First tests using a growing perturbation in opposite direction to the previous one
- Evaluation of the plasma displacement in consequence of the magnetic perturbation
- Show fast recovery of the plasma position after each perturbation.
Preliminary Results

- Analysis show mild evidence of synchronism of magnetic perturbations with ELM events.
- Increase in ELM frequency due to magnetic perturbations induces lower energy release per ELM when compared with discharges without perturbations.
- Further discharges are needed to continue the work.
FPS Fast Switching Limitation

- FPS has a limited number of switches during a discharge before the safety circuit turns FPS off.

- According to the figure it is possible to minimize the number of switches by using higher reference voltage for less time.

- This method should be tested for the continuation of the research plan.
Conclusions, Problems and Future Work

- An optimized vertical stability controller was presented to improve the plasma recovery after magnetic perturbations.
- VS controller was prepared to induce magnetic perturbations at programmable frequency, amplitude and direction.
- Problems with the FPS protection system prevented the use of the FPS for a thorough study during a complete discharge.
- Further inspection of the FPS usage and protection system is needed to continue this work.
- Optimized use of the FPS is proposed to mitigate the problem.
- This research encourages a more detailed and systematic study of the influence of the perturbations in TCV plasmas.