Plasma current, position and shape control in tokamaks - Part 1 (*aka* plasma magnetic control)

Advanced Course on Plasma Diagnostics and Control
Ph.D. Course in Fusion Science and Engineering
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Gianmaria De Tommasi[1]
Dipartimento di Ingegneria Elettrica e delle Tecnologie dell’Informazione (DIETI)
Università degli Studi di Napoli Federico II, Napoli, Italy

Outline

Introduction

- Magnetic (control-oriented) modelling
- Control engineering jargon & tools
- The plasma magnetic control problem

A proposal for the magnetic control architecture

- Vertical stabilization controller
- Current decoupling controller
- Plasma current controller
- Plasma shape controller
- Nonlinear validation
- Current limit avoidance system

Some experimental results

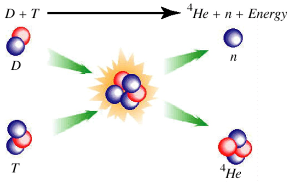
- Current limit avoidance at JET
- ITER-like VS at EAST
- MIMO shape controller at EAST

Nuclear Fusion for Dummies

Main Aim

Production of energy by means of a fusion reaction

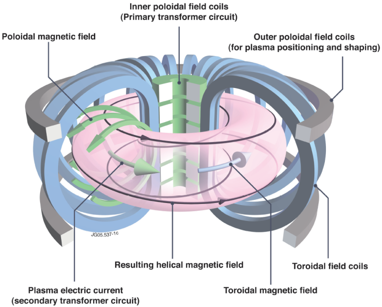
$$D + T \to {}^4\mathrm{He} + n$$



Plasma

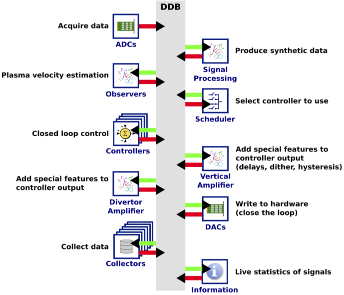
- High temperature and pressure are needed
- Fully ionised gas $\mapsto$ Plasma
- Magnetic field is needed to confine the plasma

Plasma magnetic control



- In tokamaks, **magnetic control of the plasma is obtained by means of magnetic fields produced by the external active coils**
- In order to obtain good performance, it is necessary to have a plasma with **vertically elongated cross section** ⇒ **vertically unstable plasmas**
- It is important to **maintain adequate plasma-wall clearance during operation**

Our final objective: build a control system



DDB

Acquire data – ADCs

Plasma velocity estimation – Observers

Closed loop control – Controllers

Add special features to controller output – Divertor Amplifier

Collect data – Collectors

Produce synthetic data – Signal Processing

Select controller to use – Scheduler

Add special features to controller output (delays, dither, hysteresis) – Vertical Amplifier

Write to hardware (close the loop) – DACs

Live statistics of signals – Information

192 input signals

Main (basic) assumptions

1. The plasma/circuits system is axisymmetric
2. The inertial effects can be neglected at the time scale of interest, since plasma mass density is low
3. The magnetic permeability μ is homogeneous, and equal to μ_0 everywhere

Mass vs Massless plasma

It has been proven that neglecting plasma mass may lead to erroneous conclusion on closed-loop stability.

- M. L. Walker, D. A. Humphreys
  On feedback stabilization of the tokamak plasma vertical instability
  Automatica, vol. 45, pp. 665–674, 2009.
- J. W. Helton, K. J. McGown, M. L. Walker,
  Conditions for stabilization of the tokamak plasma vertical instability using only a massless plasma analysis
  Automatica, vol. 46, pp. 1762.-1772, 2010.

Plasma model

The *input variables* are:

- The voltage applied to the active coils v
- The plasma current I_p
- The poloidal beta β_p
- The internal inductance l_i

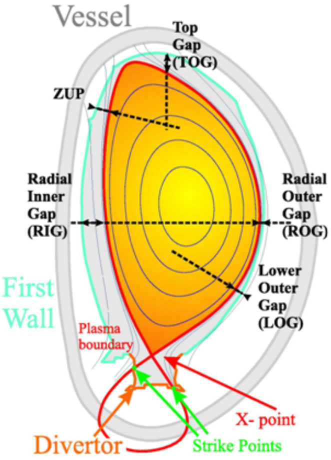
I_p , β_p and l_i

I_p , β_p and l_i are used to specify the current density distribution inside the plasma region.

Model outputs

Different model outputs can be chosen:

- fluxes and fields where the magnetic sensors are located
- currents in the active and passive circuits
- plasma radial and vertical position (1st and 2nd moment of the plasma current density)
- geometrical descriptors describing the plasma shape (gaps, x-point and strike points positions)



Lumped parameters approximation

By using finite-elements methods, **nonlinear** lumped parameters approximation of the PDEs model is obtained

$$\frac{\mathrm{d}}{\mathrm{dt}}\left[\mathcal{M}\big(\mathbf{y}(t),\beta_p(t),l_i(t)\big)\mathbf{I}(t)\right]+\mathbf{R}\mathbf{I}(t)=\mathbf{U}(t)\,,$$

$$\mathbf{y}(t)=\mathcal{Y}\big(\mathbf{I}(t),\beta_p(t),l_i(t)\big)\,.$$

where:

- $\mathbf{y}(t)$ are the output to be controlled
- $\mathbf{I}(t)=\left[\mathbf{I}_{PF}^T(t)\;\mathbf{I}_e^T(t)\;I_p(t)\right]^T$ is the currents vector, which includes the currents in the active coils $\mathbf{I}_{PF}(t)$, the eddy currents in the passive structures $\mathbf{I}_e(t)$, and the plasma current $I_p(t)$
- $\mathbf{U}(t)=\left[\mathbf{U}_{PF}^T(t)\;\mathbf{0}^T\;0\right]^T$ is the input voltages vector
- $\mathcal{M}(\cdot)$ is the mutual inductance nonlinear function
- $\mathbf{R}$ is the resistance matrix
- $\mathcal{Y}(\cdot)$ is the output nonlinear function

Plasma linearized model

Starting from the nonlinear lumped parameters model, the following plasma linearized state space model can be easily obtained:

$$\delta\dot{\mathbf{x}}(t) = \mathbf{A}\delta\mathbf{x}(t) + \mathbf{B}\delta\mathbf{u}(t) + \mathbf{E}\delta\dot{\mathbf{w}}(t), \tag{1}$$

$$\delta\mathbf{y}(t) = \mathbf{C}\,\delta\mathbf{I}_{PF}(t) + \mathbf{F}\delta\mathbf{w}(t), \tag{2}$$

where:

- **A**, **B**, **E**, **C** and **F** are the model matrices
- $\delta\mathbf{x}(t) = \left[\delta\mathbf{I}_{PF}^T(t)\ \delta\mathbf{I}_e^T(t)\ \delta I_p(t)\right]^T$ is the state space vector
- $\delta\mathbf{u}(t) = \left[\delta\mathbf{U}_{PF}^T(t)\ \mathbf{0}^T\ 0\right]^T$ are the input voltages variations
- $\delta\mathbf{w}(t) = \left[\delta\beta_p(t)\ \delta l_i(t)\right]^T$ are the β_p and l_i variations
- $\delta\mathbf{y}(t)$ are the output variations

The model (1)–(2) relates the variations of the PF currents to the variations of the outputs around a given equilibrium

Linear time-invariant systems

A **linear time-invariant (LTI)** continuous-time system is described by

$$\dot{x}(t) = Ax(t) + Bu(t)\,, \quad x(0) = x_0 \tag{3a}$$

$$y(t) = Cx(t) + Du(t) \tag{3b}$$

where $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$, $C \in \mathbb{R}^{p\times n}$ and $D \in \mathbb{R}^{p\times m}$.

A dynamical system with single-input ($m = 1$) and single-output ($p = 1$) is called **SISO**, otherwise it is called **MIMO**.

Asymptotic stability of LTI systems

Asymptotic stability

This property roughly asserts that every solution of $\dot{x}(t) = Ax(t)$ tends to zero as $t \to \infty$.

For LTI systems the stability property is related to the system and not to a specific equilibrium

Theorem - System (3) is **asymptotically stable iff** A is Hurwitz, that is if every eigenvalue λ_i of A has strictly negative real part

$$\Re(\lambda_i) < 0\,, \forall\, \lambda_i\,.$$

Theorem - System (3) is **unstable if** A has at least one eigenvalue $\bar{\lambda}$ with strictly positive real part, that is

$$\exists\, \bar{\lambda} \text{ s.t. } \Re(\bar{\lambda}) > 0\,.$$

Theorem - Suppose that A has all eigenvalues λ_i such that $\Re(\lambda_i) \leq 0$, then system (3) is **unstable if** there is at least one eigenvalue $\bar{\lambda}$ such that $\Re(\bar{\lambda}) = 0$ which corresponds to a Jordan block with size > 1.

Equilibrium stability for nonlinear systems

For nonlinear systems the stability property is related to the specific equilibrium

Theorem - The equilibrium state x_e corresponding to the constant input $\bar{u}$ a nonlinear system is **asymptotically stable if** all the eigenvalues of the correspondent linearized system have strictly negative real part

Theorem - The equilibrium state x_e corresponding to the constant input $\bar{u}$ a nonlinear system is **unstable if** there exists at least one eigenvalue of the correspondent linearized system which has strictly positive real part

Transfer function of LTI systems

Given a LTI system (3) the corresponding *transfer matrix* from u to y is defined as

$$Y(s) = G(s)U(s)\,,$$

with $s \in \mathbb{C}$. $U(s)$ and $Y(s)$ are the Laplace transforms of $u(t)$ and $y(t)$ with zero initial condition ($x(0) = 0$), and

$$G(s) = C\big(sI - A\big)^{-1}B + D\,. \tag{4}$$

For SISO system (4) is called *transfer function* and it is equal to the Laplace transform of the **impulsive response** of system (3) with zero initial condition.

Transfer function

Given the transfer function $G(s)$ and the Laplace transform of the input $U(s)$ the time response of the system can be computed as the inverse transform of $G(s)U(s)$, **without solving differential equations**

As an example, the **step response** of a system can be computed as:

$$y(t) = \mathcal{L}^{-1}\left[G(s)\frac{1}{s}\right].$$

Poles and zeros of SISO systems

Given a SISO LTI system , its transfer function is a rational function of s

$$G(s) = \frac{N(s)}{D(s)} = \rho \frac{\Pi_i (s - z_i)}{\Pi_j (s - p_j)} \,,$$

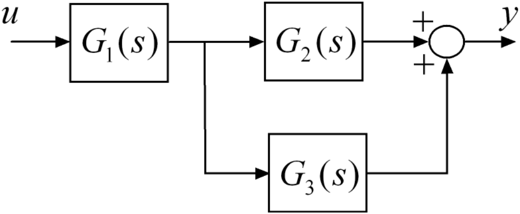
where $N(s)$ and $D(s)$ are polynomial in s, with $\deg\big(N(s)\big) \leq \deg\big(D(s)\big)$.
We call

- p_j **poles** of $G(s)$
- z_i **zeros** of $G(s)$

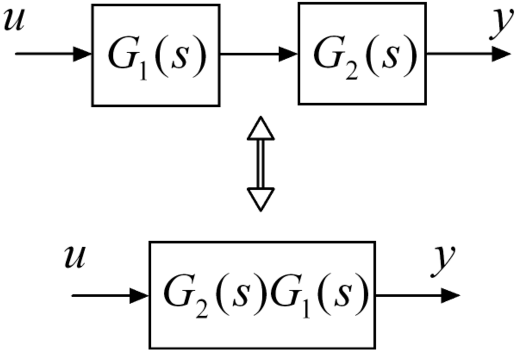
Every pole of $G(s)$ is an eigenvalue of the system matrix A. However, not every eigenvalue of A is a pole of $G(s)$

Block diagrams

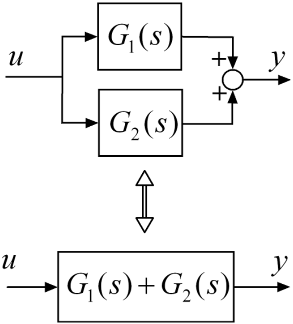
When dealing with transfer functions, it is usual to resort to *Block diagrams* which permit to graphically represent the interconnections between system in a convenient way.



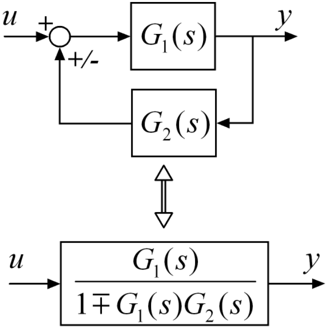
Series connection



Parallel connection



Feedback connection



Stability of interconnected systems

Given two **asymptotically stable** LTI systems $G_1(s)$ and $G_2(s)$

- the **series** connection $G_2(s)G_1(s)$ is asymptotically stable
- the **parallel** connection $G_1(s) + G_2(s)$ is asymptotically stable
- the **feedback** connection $\frac{G_1(s)}{1 \pm G_1(s)G_2(s)}$ **is not necessarily stable**

THE CURSE OF FEEDBACK!

The magnetic control problems

The plasma (axisymmetric) magnetic control in tokamaks includes the following three control problems

- the vertical stabilization problem
- the shape and position control problem
- the plasma current control problem

Vertical stabilization problem

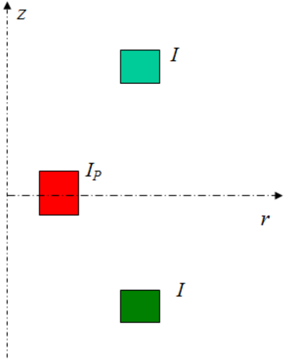
Objectives

- Vertically stabilize elongated plasmas in order to avoid disruptions
- Counteract the effect of disturbances (ELMs, fast disturbances modelled as VDEs,. . .)
- **It does not necessarily control vertical position but it *simply* stabilizes the plasma**
- **The VS is the essential magnetic control system!**

The plasma vertical instability

Simplified filamentary model

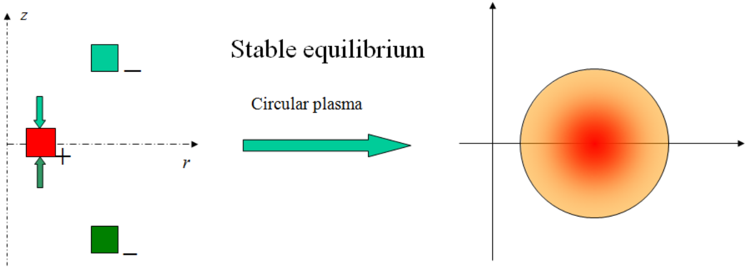
Consider the simplified electromechanical model with three conductive rings, two rings are kept fixed and in symmetric position with respect to the r axis, while the third can freely move vertically.



If the currents in the two fixed rings are equal, the vertical position $z = 0$ is an equilibrium point for the system.

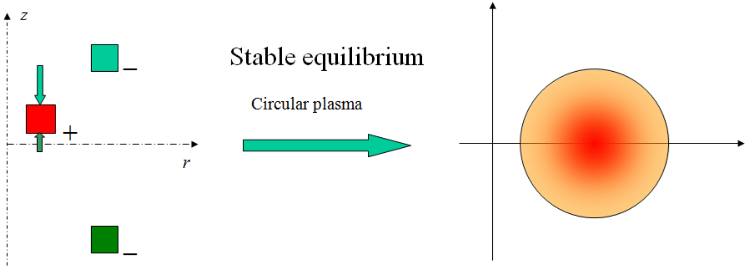
Stable equilibrium - 1/2

If $\mathrm{sgn}(I_p) \neq \mathrm{sgn}(I)$



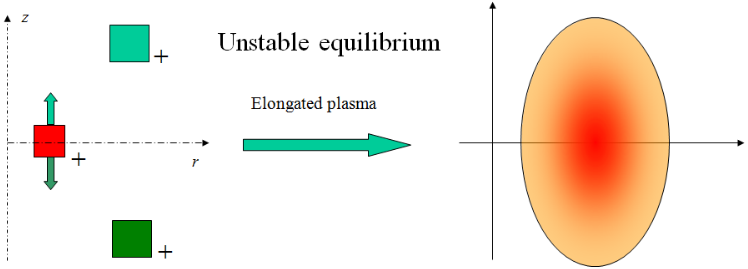
Stable equilibrium - 2/2

If $\mathrm{sgn}(I_p) \neq \mathrm{sgn}(I)$



Unstable equilibrium - 1/2

If $\mathrm{sgn}(I_p) = \mathrm{sgn}(I)$

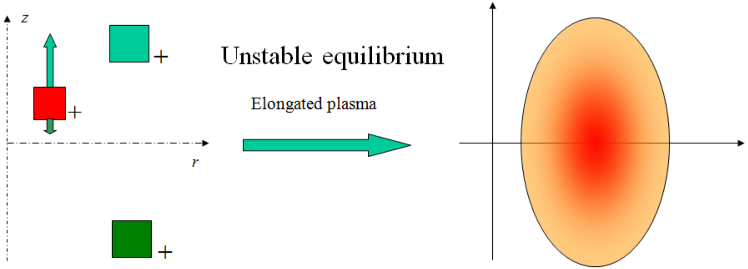


Unstable equilibrium

Elongated plasma

Unstable equilibrium - 2/2

If $\mathrm{sgn}(I_p) = \mathrm{sgn}(I)$



Plasma vertical instability

- The plasma vertical instability reveals itself in the linearized model, by the presence of an unstable eigenvalue in the dynamic system matrix
- The vertical instability growth time is slowed down by the presence of the conducting structure surrounding the plasma
- This allows to use a feedback control system to stabilize the plasma equilibrium, using for example a pair of dedicated coils
- This feedback loop usually acts on a faster time-scale than the plasma shape control loop

Shape and position control problem

- The problem of controlling the plasma shape is probably the most understood and mature of all the control problems in a tokamak
- The actuators are the Poloidal Field coils, that produce the magnetic field acting on the plasma
- The controlled variables are a finite number of geometrical descriptors chosen to describe the plasma shape

Objectives

- Precise control of plasma boundary
- Counteract the effect of disturbances (β_p and l_i variations)
- Manage saturation of the actuators (currents in the PF coils)

Plasma current control problem

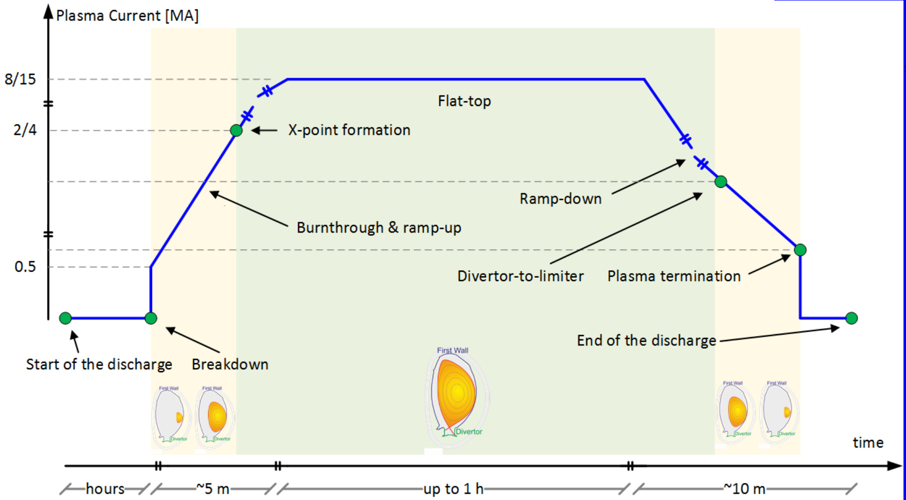
- Plasma current can be controlled by using the current in the PF coils
- Since there is a sharing of the actuators, the problem of tracking the plasma current can be considered simultaneously with the shape control problem
- Shape control and plasma current control are compatible, since it is possible to show that generating flux that is spatially uniform across the plasma (but with a desired temporal behavior) can be used to drive the current without affecting the plasma shape.

Plasma magnetic system

Motivation

- Plasma magnetic control is one of the the crucial issue to be addressed
  - **is needed from day 1**
  - **is needed to robustly control elongated plasmas** in high performance scenarios

A tokamak discharge



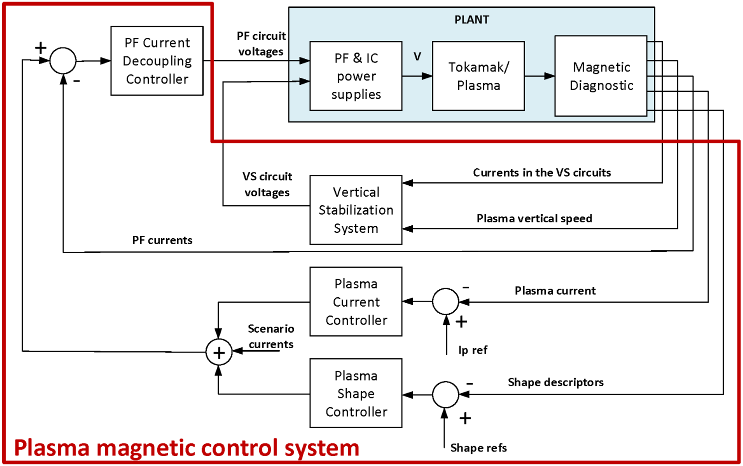
Magnetic control architecture - A proposal

- A magnetic control architecture able to operate the plasma for an entire duration of the discharge, from the initiation to plasma ramp-down
- *Machine-agnostic* architecture (aka *machine independent* solution)
- Model-based control algorithms
  - → the design procedures relies on (validated) control-oriented models for the response of the plasma and of the surrounding conductive structures
- The proposal is based on the JET experience
- The architecture has been proposed for ITER & JT-60SA (& DEMO) and has been partially deployed at EAST (ongoing activity)

R. Ambrosino et al.
Design and nonlinear validation of the ITER magnetic control system
Proc. 2015 IEEE Multi-Conf. Sys. Contr., 2015

N. Cruz et al.,
Control-oriented tools for the design and validation of the JT-60SA magnetic control system
Contr. Eng. Prac., 2017

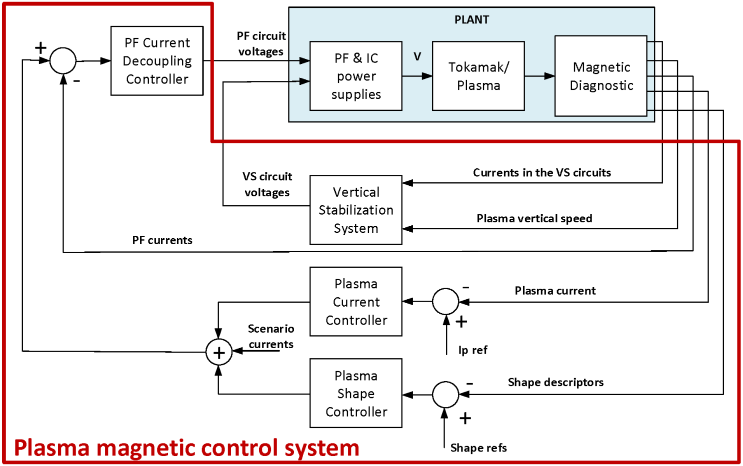
The proposed architecture - 1/2



The proposed architecture - 2/2

- **Four independent controllers**
    - Current decoupling controller
    - Vertical stabilization controller
    - Plasma current controller
    - Plasma shape controller (+ current allocator)
- **The parameters of each controller can change on the base of events generated by an external supervisor**
    - **Asynchronous events → *exceptions***
    - **Clock events → time-variant parameters**

Architecture



The vertical stabilization controller

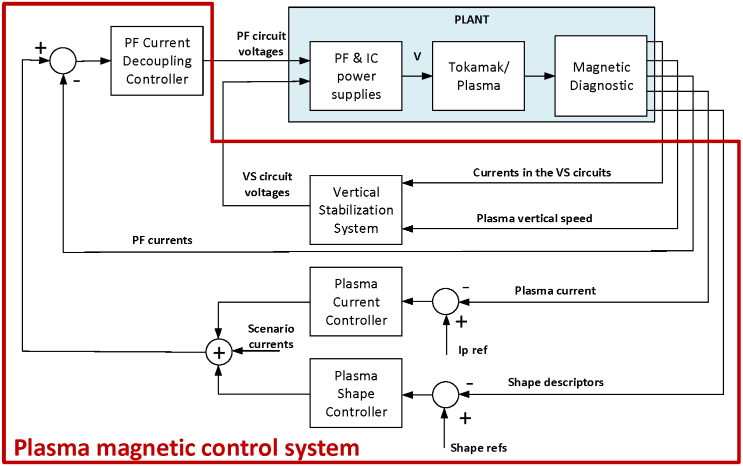
- The vertical stabilization controller has as input the centroid vertical speed, and the current flowing in the **in-vessel** circuit (a in-vessel coil set)
- It generates as output the voltage references for both the **in-vessel** and **ex-vessel** circuits

$$
\begin{aligned}
U_{IC}(s) &= F_{VS}(s) \cdot \Big(K_v \cdot \bar{I}_{p_{ref}} \cdot V_p(s) + K_{ic} \cdot I_{IC}(s) \Big) \ , \\
U_{EC}(s) &= K_{ec} \cdot I_{IC}(s) \, ,
\end{aligned}
$$

- The vertical stabilization is achieved by the voltage applied to the **in-vessel** circuit
- The voltage applied to the **ex-vessel** circuit is used to reduce the current and the ohmic power in the in-vessel coils
- The *velocity* gain is scaled according to the value of $I_p \rightarrow K_v \cdot \bar{I}_{p_{ref}}$

G. Ambrosino et al.
Plasma vertical stabilization in the ITER tokamak via constrained static output feedback
IEEE Trans. Contr. System Tech., 2011

Architecture



Current decoupling controller

- The current decoupling controller receives as input the PF circuit currents and their references, and generate in output the voltage references for the power supplies
- **The PF circuit current references are generated as a sum of three terms coming from**
  - the **scenario supervisor**, which provides the **feedforwards needed to track the desired scenario**
  - the **plasma current controller**, which generates the **current deviations (with respect to the nominal ones)** needed to compensate errors in the tracking of the plasma current
  - the **plasma shape controller**, which generates the **current deviations (with respect to the nominal ones)** needed to compensate errors in the tracking of the plasma shape

Current decoupling controller - Control law 1/2

1. Let $\widetilde{\mathbf{L}}_{PF} \in \mathbb{R}^{n_{PF}} \times \mathbb{R}^{n_{PF}}$ be a modified version of the inductance matrix obtained from a plasma-less model by neglecting the effect of the passive structures. In each row of the $\widetilde{\mathbf{L}}_{PF}$ matrix all the mutual inductance terms which are less than a given percentage of the circuit self-inductance have been neglected **(main aim: to reduce the control effort)**
2. The time constants τ_{PF_i} for the response of the i-th circuit are chosen and used to construct a matrix $\Lambda \in \mathbb{R}^{n_{PF}} \times \mathbb{R}^{n_{PF}}$, defined as:

$$\Lambda = \begin{pmatrix} 1/\tau_{PF1} & 0 & \dots & 0 \\ 0 & 1/\tau_{PF2} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 1/\tau_{PF_n} \end{pmatrix} .$$

Current decoupling controller - Control law 2/2

3. The voltages to be applied to the PF circuits are then calculated as:

$$U_{PF}(t) = \mathbf{K}_{PF} \cdot \left(I_{PF_{ref}}(t) - I_{PF}(t)\right) + \widetilde{\mathbf{R}}_{PF} I_{PF}(t) \,,$$

where

- $\mathbf{K}_{PF} = \widetilde{\mathbf{L}}_{PF} \cdot \Lambda$,
- $\widetilde{\mathbf{R}}_{PF}$ is the estimated resistance matrix for the PF circuits (needed to take into account the ohmic drop)

F. Maviglia et al.

Improving the performance of the JET Shape Controller

Fus. Eng. Des., vol. 96–96, pp. 668–671, 2015.

Current decoupling controller - Closed-loop transfer functions

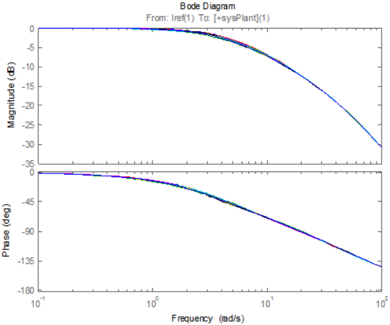


Figure: Bode diagrams of the *diagonal* transfer functions.

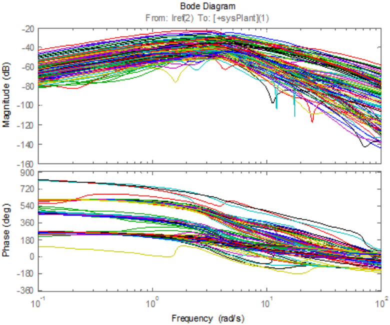
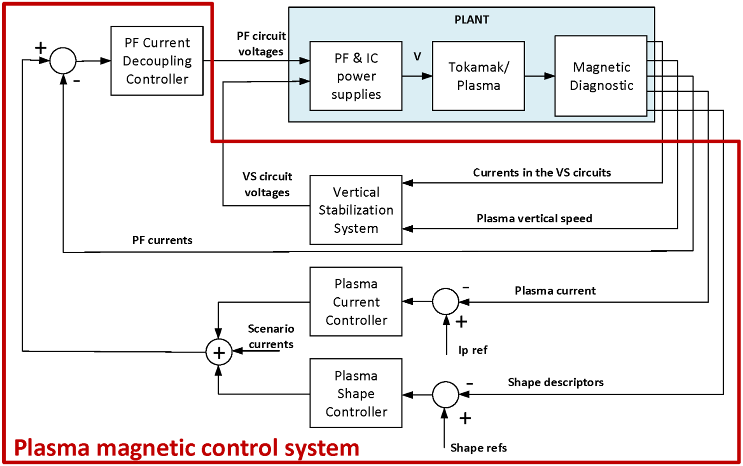


Figure: Bode diagrams of the *off-diagonal* transfer functions.

Architecture



PLANT

PF Current Decoupling Controller

PF circuit voltages

PF & IC power supplies

V

Tokamak/ Plasma

Magnetic Diagnostic

VS circuit voltages

Vertical Stabilization System

Currents in the VS circuits

Plasma vertical speed

PF currents

Plasma Current Controller

Plasma current

Ip ref

Scenario currents

Plasma Shape Controller

Shape descriptors

Shape refs

Plasma magnetic control system

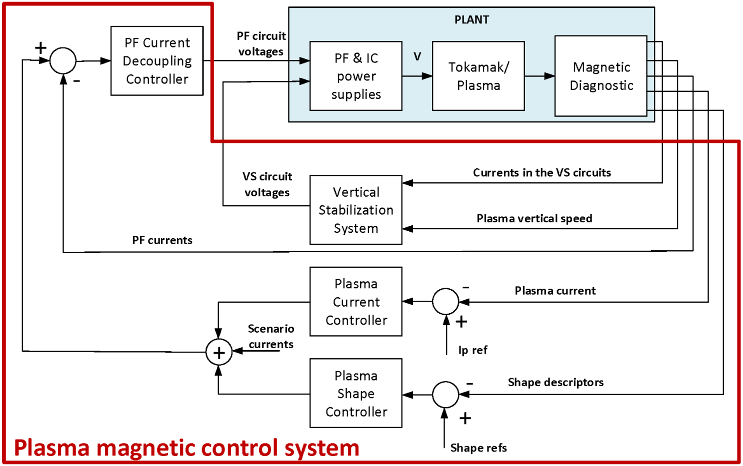
The plasma current controller

- The plasma current controller has as input the plasma current and its time-varying reference, and has as output a set of coil current deviations (with respect to the nominal values)
- **The output current deviations are proportional to a set of current $\mathbf{K}_{p_{curr}}$ providing (in the absence of eddy currents) a transformer field inside the vacuum vessel, so as to reduce the coupling with the plasma shape controller**

$$\delta I_{PF}(s) = \mathbf{K}_{p_{curr}} F_{I_p}(s) I_{p_e}(s)$$

- **For ITER** it is important, for the plasma current, to track the reference signal during the **ramp-up** and **ramp-down** phases, the dynamic part of the controller $F_{I_p}(s)$ has been designed with a **double integral action**

The plasma shape controller



Plasma shape descriptors

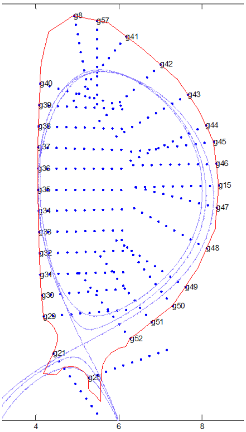


Figure: Control segments.

- Let g_i be the abscissa along *i*-th control segment ($g_i = 0$ at the first wall)
- Plasma shape control is achieved by imposing

$$g_{i_{ref}} - g_i = 0$$

on a sufficiently large number of control segments (**gap control**)

- Moreover, if the plasma shape intersect the *i*-th control segment at g_i, the following condition is satisfied

$$\psi(g_i) = \psi_B$$

where ψ_B is the flux at the plasma boundary

- Shape control can be achieved also by controlling to 0 the (**isoflux control**)

$$\psi(g_{i_{ref}}) - \psi_B = 0$$

  - $\psi_B = \psi_X$ for *limited-to-diverted* transition
  - $\psi_B = \psi_L$ for *diverted-to-limited* transition

Controlled plasma shape descriptors

- During the limiter phase, the controlled shape parameters are the position of the limiter point, and a set of flux differences (**isoflux control**)
- During the limiter/diverted transition the controlled shape parameters are the position of the X-point, and a set of flux differences (**isoflux control**)
- During the diverted phase the controlled variables are the plasma-wall gap errors (**gap control**)

Plasma shape control algorithm

- The plasma shape controller is based on the **eXtreme Shape Controller (XSC) approach**
- The main advantage of the XSC approach is the possibility of tracking a number of shape parameters larger than the number of active coils, minimizing a weighted steady state quadratic tracking error, when the references are constant signals

M. Ariola and A. Pironti
Plasma shape control for the JET tokamak - An optimal output regulation approach
IEEE Contr. Sys. Magazine, 2005

G. Ambrosino et al.
Design and implementation of an output regulation controller for the JET tokamak
IEEE Trans. Contr. System Tech., 2008

R. Albanese et al.
A MIMO architecture for integrated control of plasma shape and flux expansion for the EAST tokamak
Proc. 2016 IEEE Multi-Conf. Sys. Contr., 2016

The *XSC-like* philosophy - 1/3

- The XSC-like plasma shape controller can be applied both adopting a isoflux or a gap approach
- It relies on the current PF current controller which achieves a **good decoupling** of the PF circuits
    - Each PF circuits can be treated as an independent SISO channel

$$I_{PF_i}(s) = \frac{I_{PF_{ref},i}(s)}{1 + s\tau_{PF}}$$

- If $\delta Y(s)$ are the variations of the n_G shape descriptors (e.g. fluxes differences, position of the x-point, gaps) – with $\mathbf{n_G \geq n_{PF}}$ – then dynamically

$$\delta Y(s) = C\frac{I_{PF_{ref}}(s)}{1 + s\tau_{PF}}$$

and statically

$$\delta Y(s) = CI_{PF_{ref}}(s)$$

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The *XSC-like* philosophy - 2/3

- The currents needed to track the desired shape (in a *least-mean-square* sense) are
$$\delta I_{PF_{ref}} = C^{\dagger}\delta Y$$
- It is possible to use weights both for the shape descriptors and for the currents in the PF circuits
- The controller gains can be computed using the SVD of the weighted output matrix:
$$\widetilde{C} = QCN = USV^T$$
- The XSC minimizes the cost function

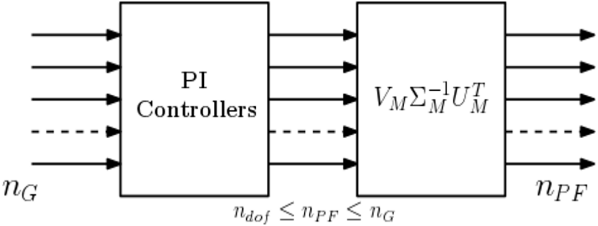
$$\widetilde{J}_1 = \lim_{t\to+\infty}\left(\delta Y_{ref} - \delta Y(t)\right)^T Q^T Q\left(\delta Y_{ref} - \delta Y(t)\right),$$

using $n_{dof} < n_{PF}$ degrees of freedom, while the remaining $n_{PF} - n_{dof}$ degrees of freedom are exploited to minimize

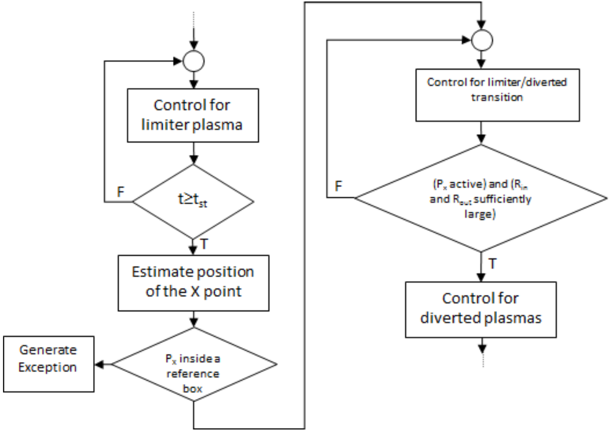
$$\widetilde{J}_2 = \lim_{t\to+\infty}\delta I_{PF_N}(t)^T N^T N \delta I_{PF_N}(t).$$

(it contributes to avoid PF current saturations)

The *XSC-like* philosophy - 3/3



Plasma shape controller - Switching algorithm



Control for limiter plasma

$t \geq t_{st}$

F

T

Estimate position of the X point

P_x inside a reference box

Generate Exception

Control for limiter/diverted transition

(P_x active) and (R_{in} and R_{out} sufficiently large)

F

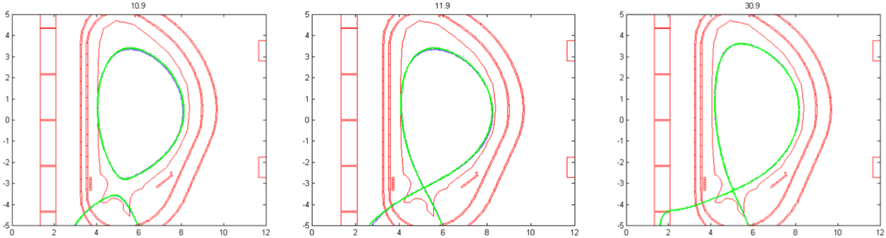
T

Control for diverted plasmas

Limited-to-diverted transition

- Results of nonlinear simulation of the limited-to-diverted configuration during the plasma current ramp-up
- Simulation starts at $t = 9.9\ s$ when $I_p = 3.6\ MA$, and ends at $t = 30.9\ s$ when $I_p = 7.3\ MA$
- The transition from limited to diverted plasma occurs at about $t = 11.39\ s$, and the switching between the isoflux and the gaps controller occurs at $t = 11.9\ s$

Plasma boundary snapshots



The Current Limit Avoidance System - 1/2

- Current in the PF circuits may saturate while controlling the current and the shape
- PF currents saturations may lead to
  - **loss of plasma shape control**
  - **pulse stop**
  - **high probability of disruption**

- A Current Limit Avoidance System (CLA) can be designed **to avoid current saturations in the PF coils when the XSC is used**

The Current Limit Avoidance System - 2/2

- The CLA uses the redundancy of the PF coils system to automatically obtain almost the same plasma shape with a different combination of currents in the PF coils
- In the presence of disturbances (e.g., variations of the internal inductance l_i and of the poloidal beta β_p), it tries to avoid the current saturations by “relaxing” the plasma shape constraints

CLA “philosophy”

- The XSC control algorithm minimizes a quadratic cost function of the plasma shape error in order to obtain at the steady state the output that best approximates the desired shape
- The XSC algorithm **does not take into account the current limits of the actuators** ⇒ It may happen that the requested current combination is not feasible
- The current allocation algorithm has been designed to keep the currents within their limits without degrading too much the plasma shape by finding an optimal trade-off between these two objectives

The plant

Plant model (plasma and PF current controller)

The plant behavior around a given equilibrium is described by means of a linearized model

$$\dot{x} = Ax + Bu + B_d d, \tag{5a}$$

$$y = Cx + Du + D_d d, \tag{5b}$$

- $u \in \mathbb{R}^{n_{PF}}$ is the control input vector which holds the $n_{PF} = 8$ currents flowing in the PF coils devoted to the plasma shape control
- $y \in \mathbb{R}^{n_{SH}}$ is the controlled outputs vector which holds the n_{SH} plasma shape descriptors controlled by the XSC (typically, at JET, it is $n_{SH} = 32$)

The controller model (XSC controller)

The XSC can also be modeled as a linear time-invariant system

$$\dot{x}_c = A_c x_c + B_c u_c + B_r r, \tag{6a}$$

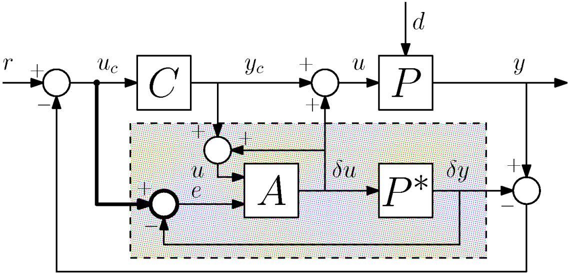
$$y_c = C_c x_c + D_c u_c + D_r r, \tag{6b}$$

under the interconnection conditions:

$$u_c = y, \tag{7a}$$

$$u = y_c. \tag{7b}$$

Block diagram of the allocated closed-loop system



Where

$$P(s) = C(sI - A)^{-1}B + D \,,$$

is the transfer matrix from u to y of (5), and

$$P^{\star} := \lim_{s \to 0} P(s) \,,$$

denotes the steady-state gain

The current allocator block

The current allocator

The allocator equations are given by

$$\dot{x}_a = -KB_0^T \begin{bmatrix} I \\ P^\star \end{bmatrix}^T (\nabla J)^T \Big|_{(u\,,\delta y)}, \tag{8a}$$

$$\delta u = B_0 x_a, \tag{8b}$$

$$\delta y = P^\star B_0 x_a. \tag{8c}$$

- $K \in \mathbb{R}^{n_a \times n_a}$ is a symmetric positive definite matrix used to specify the allocator convergence speed, and to distribute the allocation effort in the different directions
- $J(u^\star, \delta y^\star)$ is a continuously differentiable cost function that measures the trade-off between the current saturations and the control error (on the plasma shape)
- $B_0 \in \mathbb{R}^{n_{PF} \times n_a}$ is a suitable full column rank matrix

The CLA scenario

When designing the current allocator, **a large number of parameters must be specified** by the user once the reference plasma equilibrium has been chosen:

- the two matrices $P^\star$ and B_0, which are strictly related to the linearized plasma model (5)
- the K matrix
- the gradient of the cost function J must be specified by the user. In particular, the gradient of J on each *channel* is assumed to be piecewise linear

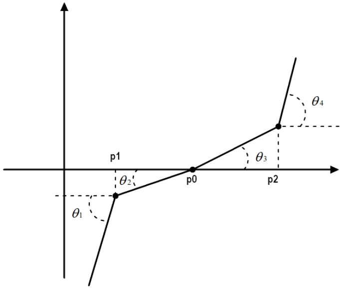
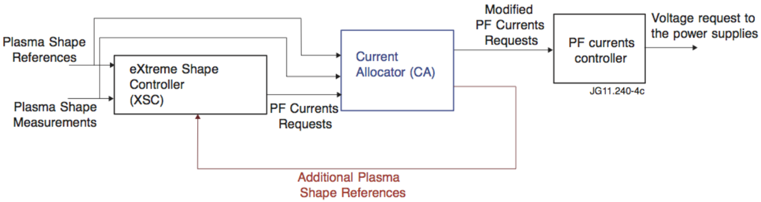


Figure: Piecewise linear function used to specify the gradient of the cost function J for each *allocated* channel. For each channel 7 parameters must be specified.

The CLA Architecture



Plasma Shape References

Plasma Shape Measurements

eXtreme Shape Controller (XSC)

PF Currents Requests

Current Allocator (CA)

Modified PF Currents Requests

PF currents controller

Voltage request to the power supplies

JG11.240-4c

Additional Plasma Shape References

The CLA block is inserted between the *XSC* and the *Current Decoupling Controller*

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Automatica, vol. 47, no. 5, pp. 981–987, May 2011

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The CLA at JET tokamak

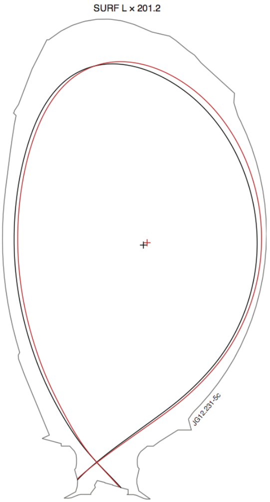


Figure: Shape comparison at 22.5 *s*. Black shape (#81710 without CLA), red shape (#81715 with CLA).

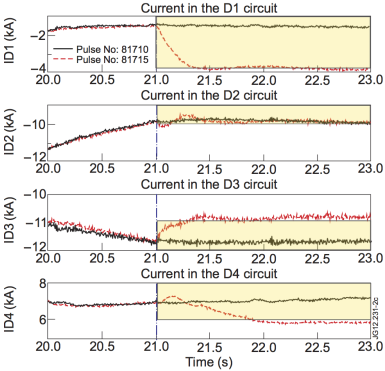


Figure: Currents in the divertor circuits. #81710 (reference pulse without CLA) and pulse #81715 (with CLA). The shared areas correspond to regions beyond the current limits enforced by the CLA parameters.

A MIMO controller for plasma shape and heat flux integrated control at EAST

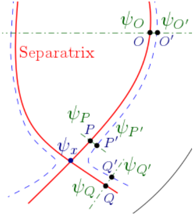
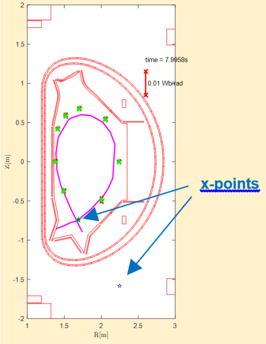


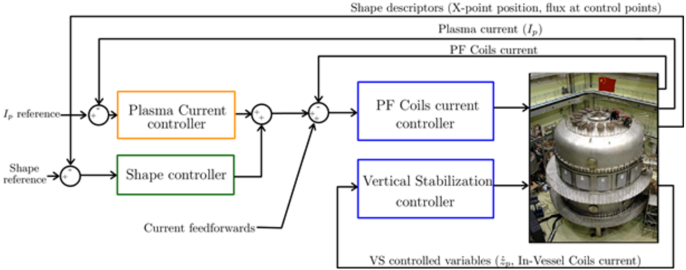
Figure: **Option #1** - integrated control of plasma shape and flux expansion.



x-points

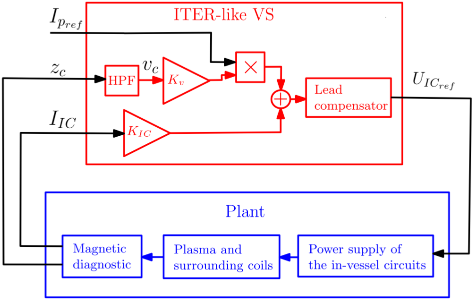
Figure: **Option #2** - integrated control of plasma shape and distance between null points.

EAST architecture



- The EAST architecture is *compliant* to the one proposed for ITER & DEMO
- **The control algorithms deployed within the EAST PCS do not satisfy the requirements needed to easily replace the shape controller**
  - **vertical stabilization is strongly coupled with plasma shape control**
  - The PF Coils current controller can be improved (better decoupling)

ITER-like VS at EAST



$$U_{IC_{ref}}(s) = \frac{1+s\tau_1}{1+s\tau_2}\cdot\left(K_v\cdot\bar{I}_{p_{ref}}\cdot\frac{s}{1+s\tau_z}\cdot Z_c(s)+K_{IC}\cdot I_{IC}(s)\right)$$

Experimental results - 1/2

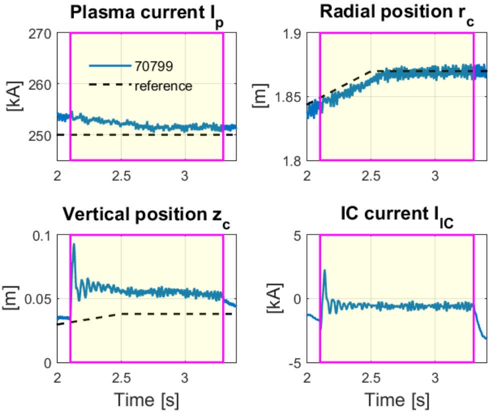


Figure: EAST pulse #70799. During this pulse the *ITER-like* VS was enabled from $t = 2.1$ s for 1.2 s, and only I_p and r_c were controlled, while z_c was left uncontrolled. This first test confirmed that the ITER-like VS vertically stabilized the plasma by controlling $\dot{z}_c$ and I_{IC}, without the need to feed back the vertical position z_c.

Experimental results - 2/2

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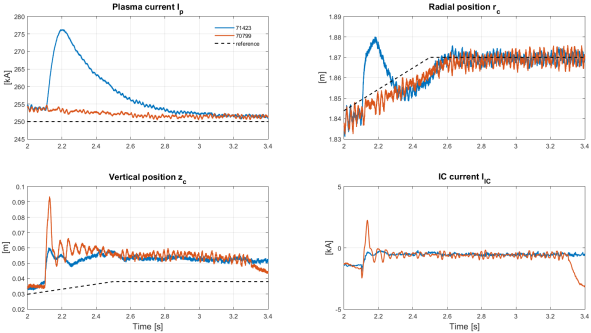

Figure: EAST pulses #70799 & #71423. Tuning of the controller parameters to reduce oscillations on z_c.

MIMO isoflux shape control at EAST

- An *XSC-like* isoflux shape controller has been tested in 2018 at EAST
- It relies on a PFC decoupling controller

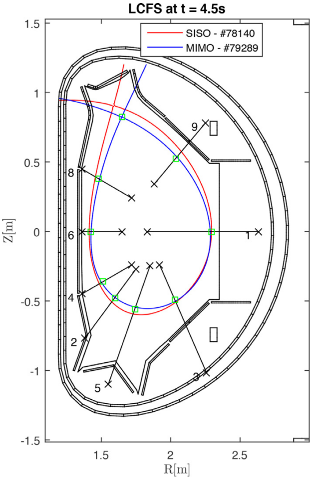

Figure: Comparison between the SISO and MIMO shape controllers (pulses #78140 and #79289). ● control points and the target X-point position.

SISO vs MIMO isoflux shape control at EAST

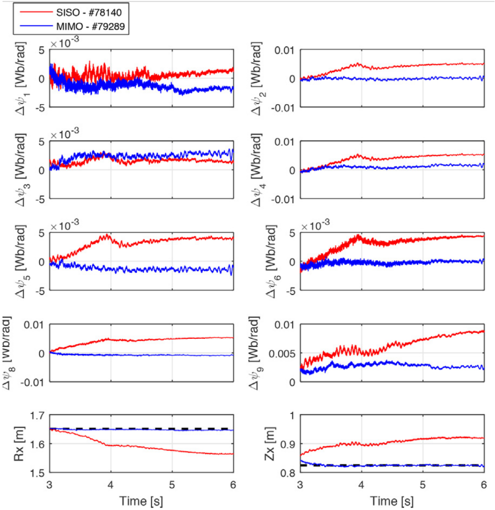

Figure: Comparison between the SISO and MIMO shape controllers (pulses #78140 and #79289). The dashed black line in the last two plots represents the X-point position reference.

Model-based tuning of MIMO gains

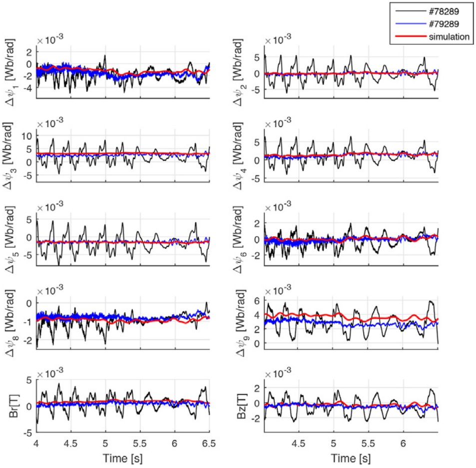

Figure: Comparison between the two pulses #78289 and #79289, and the simulation used for the design of the controller used during pulse #79289. Oscillations were successfully reduced with respect to the reference pulse #78289.

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