Plasma magnetic control in tokamaks

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DIETI UNIVERSITA' DEGLI STUDI DI NAPOLI FEDERICO II
DIPARTIMENTO DI INGEGNERIA ELETTRICA E DELLE TECNOLOGIE DELL'INFORMAZIONE

Outline

1. The plasma magnetic control problem

2. 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

3. Some experimental results
   - Current limit avoidance at JET
   - Experiments at EAST
   - A input-output based approach

Plasma linear model

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

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

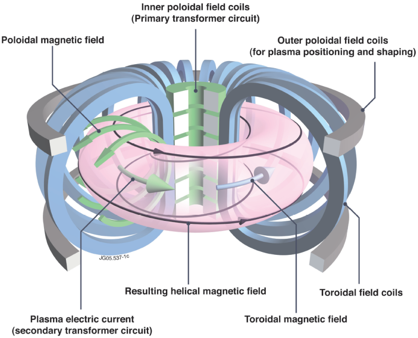
$$\delta\mathbf{y}(t) = \mathbf{C}\,\delta\mathbf{I}_{PF}(t) + \mathbf{F}\delta\mathbf{w}(t), \qquad (2)$$

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

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

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Vertical stabilization problem

Objectives

- Vertically stabilize elongated plasmas in order to avoid disruptions

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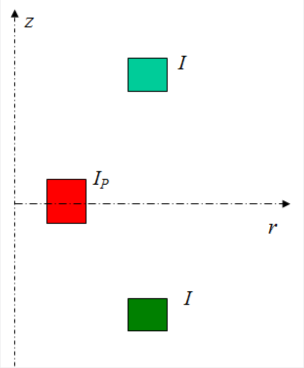
- **The VS is the essential magnetic control system!**

The plasma vertical instability

Simplified filamentary model

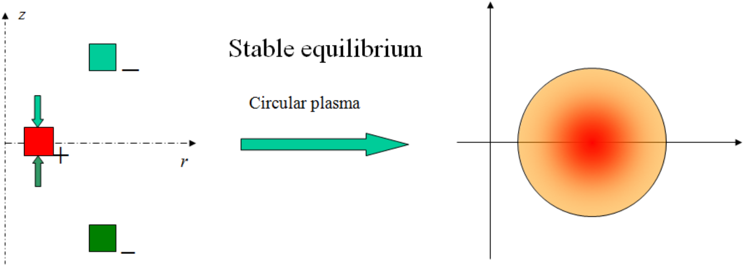
Consider the simplified electromechanical model with three conductive rings, two rings are kept fixed and in symmetric position with respect to the *r* axis, while the third can freely move vertically.



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

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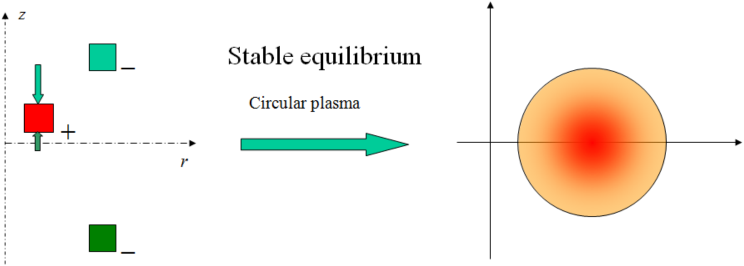

Unstable equilibrium - 1/2

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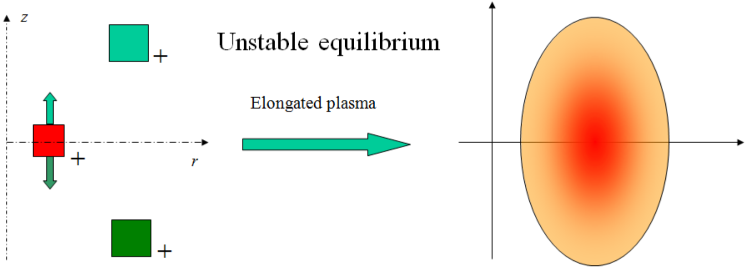

Unstable equilibrium - 2/2

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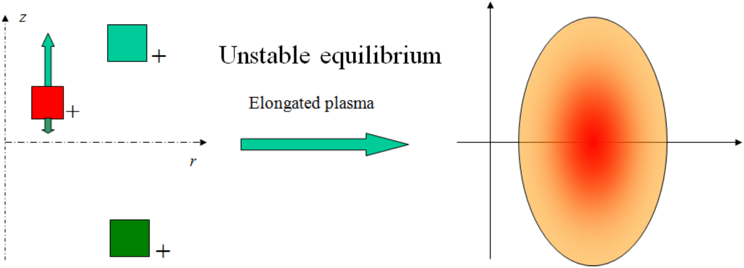

Plasma vertical instability

- **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

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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

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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

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Plasma current control problem

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- 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
  - it is possible find a linear combination of PF currents that generates a flux that is spatially uniform across the plasma
  - this linear combination can be used to drive the current without affecting (too much) the plasma shape

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Plasma magnetic system

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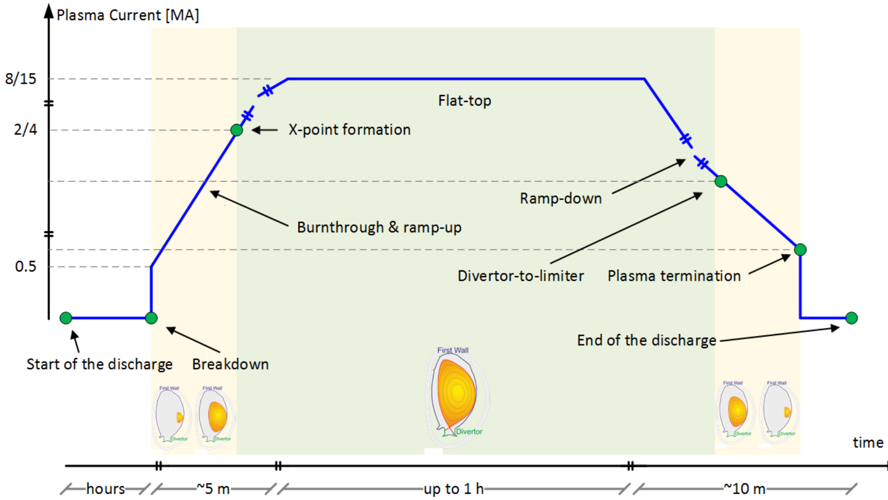
  - **is needed to robustly control elongated plasmas** in high performance scenarios

A tokamak discharge



Magnetic control architecture
A proposal

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  - → 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

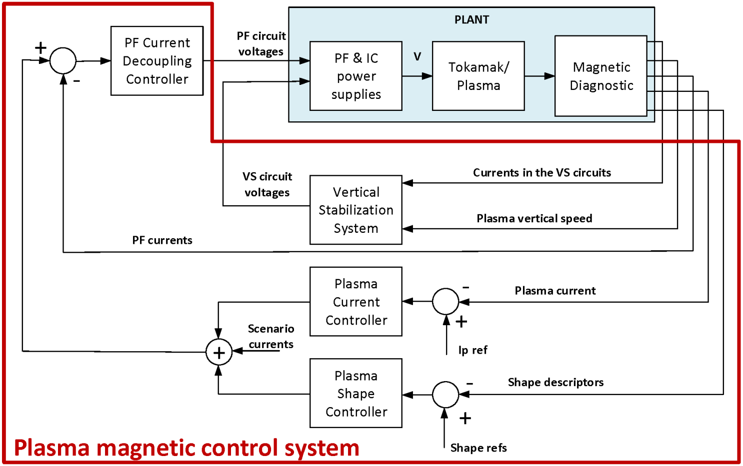
Proc. 2015 IEEE Multi-Conf. Sys. Contr., 2015

N. Cruz et al.,

Control-oriented tools for the design and validation of the JT-60SA magnetic control system

Contr. Eng. Prac., 2017

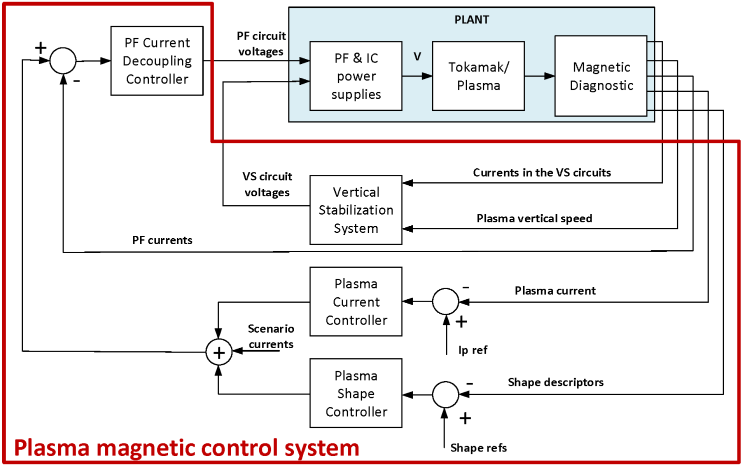
The proposed architecture - 1/2



The proposed architecture - 2/2

- **Four independent controllers**
  - Current decoupling controller
  - Vertical stabilization controller
  - Plasma current controller
  - Plasma shape controller
- **The parameters of each controller can change on the base of events generated by an external supervisor**
  - **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 \left(K_v \cdot \bar{I}_{p_{ref}} \cdot V_p(s) + K_{ic} \cdot I_{IC}(s) \right) \,, \\
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G. Ambrosino et al.
Plasma vertical stabilization in the ITER tokamak via constrained static output feedback
IEEE Trans. Contr. System Tech., 2011

G. De Tommasi et al.
On plasma vertical stabilization at EAST tokamak
submitted to *2017 IEEE Conf. Contr. Tech. Appl.*, 2017

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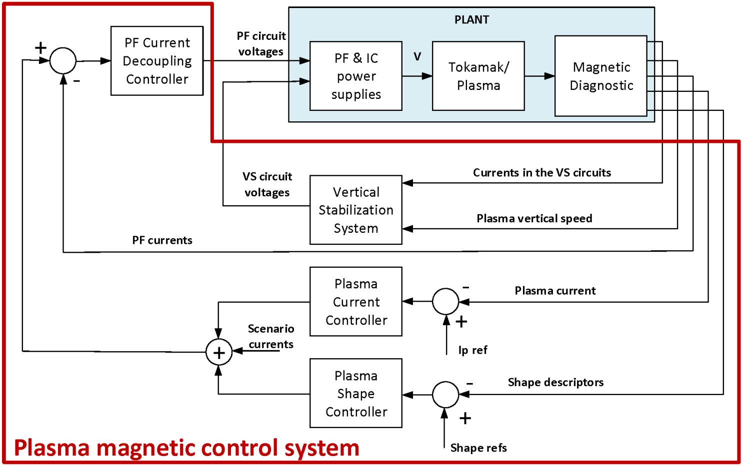

Current decoupling controller

- 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)**

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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.

Closed-loop transfer functions

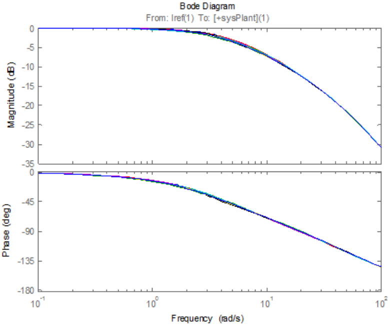


Figure: Bode diagrams of the *diagonal* transfer functions.

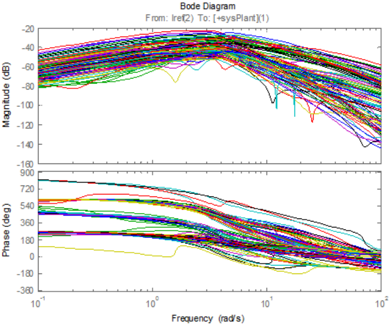
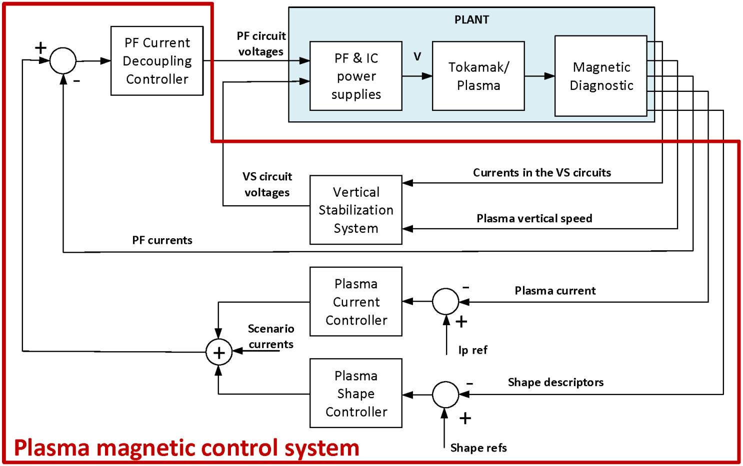


Figure: Bode diagrams of the *off-diagonal* transfer functions.

Architecture



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**

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

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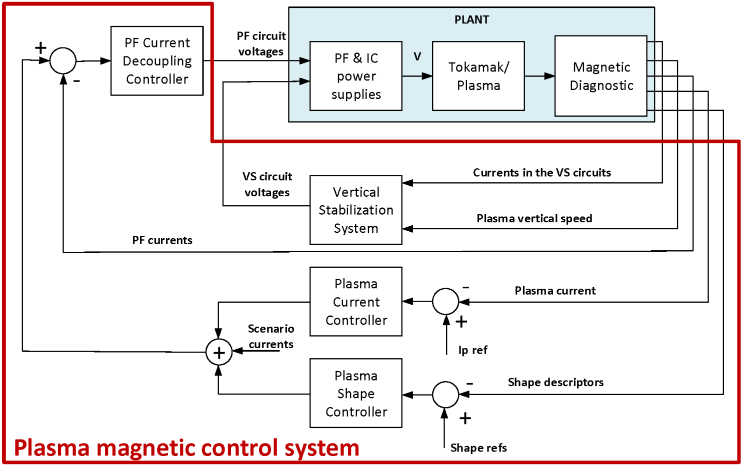
- **For ITER** it is important, for the plasma current, to track the reference signal during the **ramp-up** and **ramp-down** phases, the dynamic part of the controller $F_{I_p}(s)$ has been designed with a **double integral action**

The plasma shape controller



Plasma shape descriptors

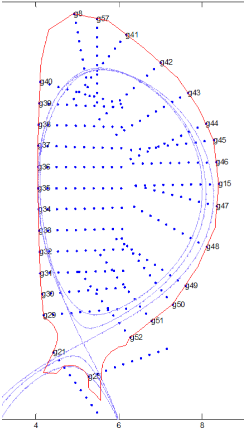


Figure: Control segments.

- 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

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

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

and statically

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

The *XSC-like* philosophy - 2/3

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- The XSC minimizes the cost function

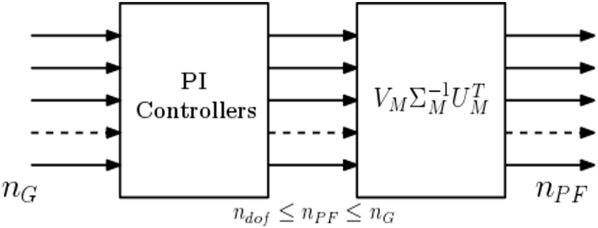
$$\widetilde{J}_1 = \lim_{t\to+\infty} (\delta Y_{ref} - \delta Y(t))^T Q^T Q(\delta Y_{ref} - \delta Y(t)) \,,$$

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

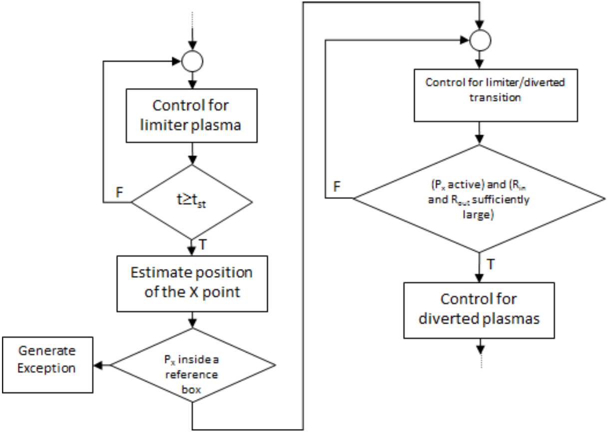
$$\widetilde{J}_2 = \lim_{t\to+\infty} \delta I_{PF_N}(t)^T N^T N \delta I_{PF_N}(t) \,.$$

(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

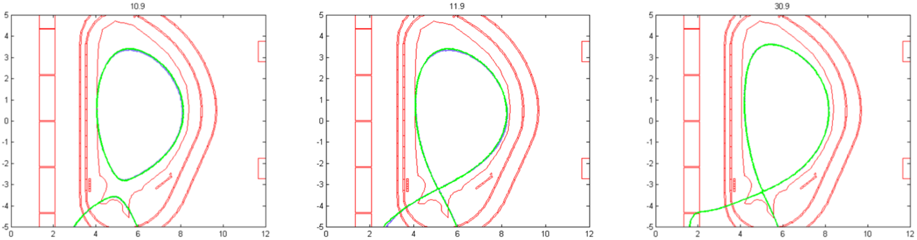
T

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

The Current Limit Avoidance System - 1/2

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- PF currents saturations may lead to
  - **loss of plasma shape control**
  - **pulse stop**
  - **high probability of disruption**

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

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

$$\dot{x} = Ax + Bu + B_d d, \tag{3a}$$

$$y = Cx + Du + D_d d, \tag{3b}$$

- $u \in \mathbb{R}^{n_{PF}}$ 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 XSC

The controller model (XSC controller)

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

$$\dot{x}_c = A_c x_c + B_c u_c + B_r r, \tag{4a}$$

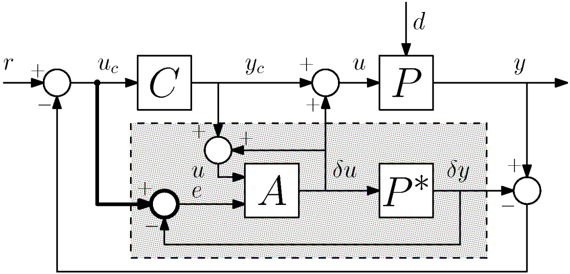
$$y_c = C_c x_c + D_c u_c + D_r r, \tag{4b}$$

under the interconnection conditions:

$$u_c = y, \tag{5a}$$

$$u = y_c\,. \tag{5b}$$

Block diagram of the allocated closed-loop



Where

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

is the transfer matrix from u to y of (3), 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

$$\dot{x}_a = -KB_0^T \begin{bmatrix} I \\ P^\star \end{bmatrix}^T (\nabla J)^T \Big|_{(u\,,\delta y)}, \tag{6a}$$

$$\delta u = B_0 x_a, \tag{6b}$$

$$\delta y = P^\star B_0 x_a. \tag{6c}$$

- $K \in \mathbb{R}^{n_a \times n_a}$ 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 (3)
- 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

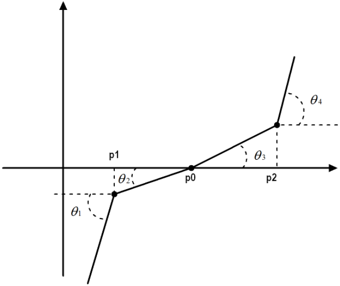
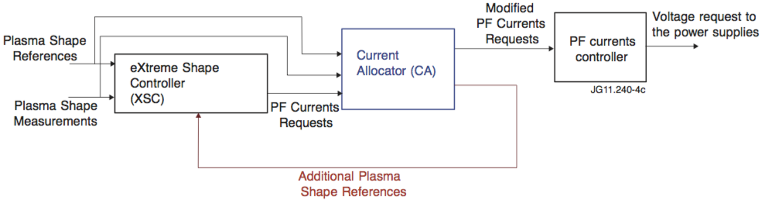


Figure: Piecewise linear function used to specify the gradient of the cost function J for each *allocated* channel. For each channel 7 parameters must be specified.

The CLA Architecture



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

Experimental results of CLA @ JET

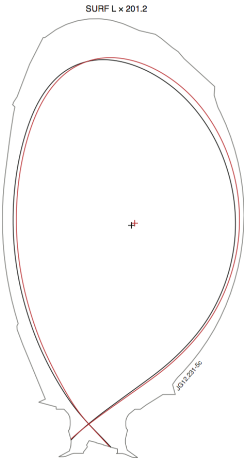


Figure: Shape comparison at 22.5 *s*. Black shape (#81710 without CLA), red shape (#81715 with CLA).

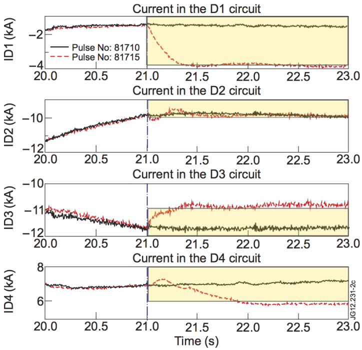


Figure: Currents in the divertor circuits. #81710 (reference pulse without CLA) and pulse #81715 (with CLA). The shared areas correspond to regions beyond the current limits enforced by the CLA parameters.

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

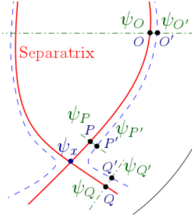


Figure: **Option #1** - integrated control of plasma shape and flux expansion.

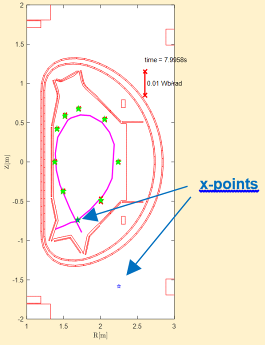
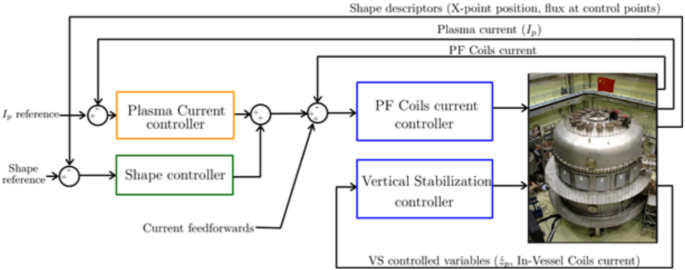


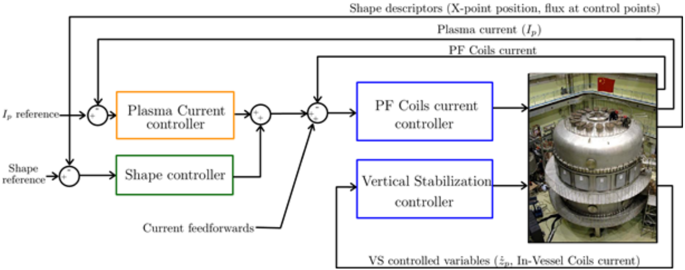
Figure: **Option #2** - integrated control of plasma shape and distance between null points.

EAST architecture



- The EAST architecture is *compliant* with the proposed one

EAST architecture



- The EAST architecture is *compliant* with the proposed one
- **The control algorithms deployed within the EAST PCS do not satisfy the requirements needed to easily replace the shape controller**

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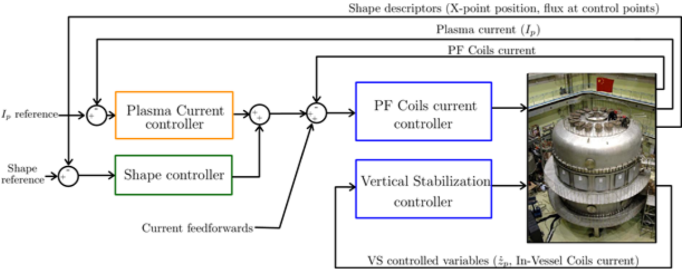
EAST architecture



Shape descriptors (X-point position, flux at control points)

Plasma current (I_p)

PF Coils current

I_p reference

Shape reference

Plasma Current controller

Shape controller

Current feedforwards

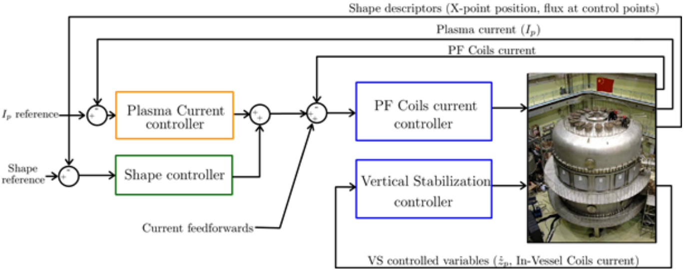
PF Coils current controller

Vertical Stabilization controller

VS controlled variables ($\dot{z}_p$, In-Vessel Coils current)

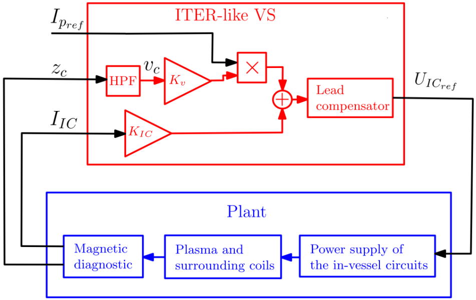
- The EAST architecture is *compliant* with the proposed one
- **The control algorithms deployed within the EAST PCS do not satisfy the requirements needed to easily replace the shape controller**
  - **vertical stabilization is strongly coupled with plasma shape control**

EAST architecture



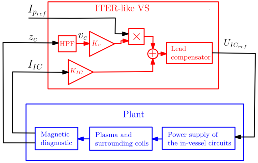
- The EAST architecture is *compliant* with the proposed one
- **The control algorithms deployed within the EAST PCS do not satisfy the requirements needed to easily replace the shape controller**
  - **vertical stabilization is strongly coupled with plasma shape control**
  - The PF Coils current controller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

ITER-like VS at EAST



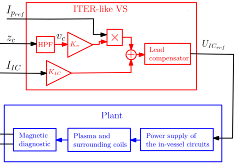
$$U_{IC_{ref}}(s) = \frac{1+s\tau_1}{1+s\tau_2} \cdot \left(K_v \cdot \bar{I}_{p_{ref}} \cdot \frac{s}{1+s\tau_z} \cdot Z_c(s) + K_{IC} \cdot I_{IC}(s) \right)$$

SISO stability margins



- The single-input-single-output (SISO) transfer function obtained by opening the control loop in correspondence of the control output is exploited to compute the stability margins (gain and phase margins)

SISO stability margins



- The single-input-single-output (SISO) transfer function obtained by opening the control loop in correspondence of the control output is exploited to compute the stability margins (gain and phase margins)
- Given the *i*-th plasma linearized model, it is possible to define the objective function

$$\begin{aligned} \mathcal{F}_i &= c_1 \cdot \left(PM_t - PM(K_v\,, K_{IC}\,, \tau_1\,, \tau_2)\right)^2 \\ &+ c_2 \cdot \left(UGM_t - UGM(K_v\,, K_{IC}\,, \tau_1\,, \tau_2)\right)^2 + c_3 \cdot \left(LGM_t - LGM(K_v\,, K_{IC}\,, \tau_1\,, \tau_2)\right)^2 \,, \end{aligned}$$

- where
  - *PM* is the phase margin
  - *UGM* and *LGM* are the upper and lower gain margins
  - c_1, c_2 and c_3 are positive weighting coefficients
  - PM_t, UGM_t and LGM_t are the desired values (*targets*) for the stability margins

Multi-objective optimization

Given N (different) plasma equilbria, it is possible to design the VS gains by solving the following multi-objective optimization problem

$$\begin{aligned} &\min_{K_v\,,K_{IC},\tau_1\,,\tau_2} \mu \\ &\text{s.t. } \mathcal{F}(K_v\,, K_{IC}\,, \tau_1\,, \tau_2) - \mu \cdot w \leq 0\,, \end{aligned}$$

where $\mathcal{F}$ is a vector function

$$\mathcal{F}(K_v\,, K_{IC}\,, \tau_1\,, \tau_2) = \left(\mathcal{F}_1(K_v\,, K_{IC}\,, \tau_1\,, \tau_2) \ \dots \ \mathcal{F}_N(K_v\,, K_{IC}\,, \tau_1\,, \tau_2)\right)^T\,,$$

where w is a vector of weights.

The EAST case study - 1/3

Table: Main plasma parameters of the considered EAST equilibria.

Equilibrium	Shape type	$I_{p_{eq}}$ [kA]	γ [s^{-1}]
46530	Double-null	281	137
52444	Limiter	230	92
60938	Upper single-null	374	194
64204	Lower single-null	233	512

The EAST case study - 2/3

Table: Maximum real part of the closed loop eigenvalues computed by applying to the j-th equilibrium the gains obtained with the single-objective approach for the i-th one, with $i \neq j$.

	46530	**52444**	**60938**	**64204**
single-objective #46530	–	-0.365	-0.088	255.99
single-objective #52444	-0.360	–	-0.358	897.01
single-objective #60938	-0.360	-0.364	–	153.57
single-objective #64204	-0.360	-0.365	-0.358	–

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The EAST case study - 3/3

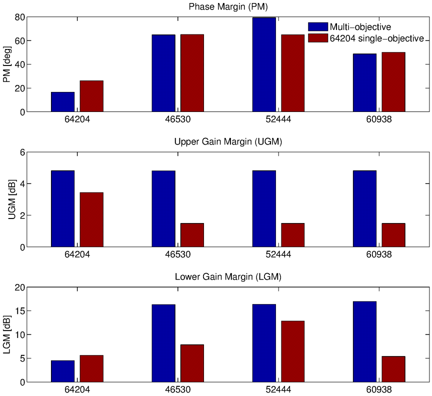

Figure: Comparison of the stability margins obtained using the multi-objective approach and by using the VS parameters obtained using a single-objective approach for the EAST pulse #64204.

Stabilizing the EAST plasma using a SISO controller - 1/2

$$\Sigma : \begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t)\,, \quad \mathbf{x}(0) = \mathbf{x}_0 \\ \mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) \end{cases}$$

- From Σ it is possible to derive the input-output relationship between the vertical speed $V_p(s)$ and the voltage applied to the in-vessel coil $U_{IC}(s)$ (the plasma)

$$W_p(s) = \frac{V_p(s)}{U_{IC}(s)}$$

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- The IC power supply is modeled as

$$U_{IC}(s) = \frac{e^{-\delta_{ps}s}}{1 + s\tau_{ps}} \cdot U_{IC_{ref}}(s)\,,$$

with $U_{IC_{ref}}(s)$ the voltage requested by the controller, $\delta_{ps} = 550\ \mu\text{s}$, $\tau_{ps} = 100\ \mu\text{s}$

Stabilizing the EAST plasma using a SISO controller - 1/2

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- At EAST the plasma vertical speed $V_p(s)$ is estimated by means of a derivative filter applied on $Z_p(s)$, i.e.

$$V_p(s) = \frac{s}{1 + s\tau_V} \cdot Z_p(s)\,,$$

with $\tau_V = 1$ ms.

Stabilizing the EAST plasma using a SISO controller - 2/2

- Putting everything together we get

$$W_{plant}(s) = \frac{s}{(1 + s\tau_v)(1 + s\tau_{ps})} \cdot W_p(s) \cdot e^{-\delta_{ps} s} \,.$$

Stabilizing the EAST plasma using a SISO controller - 2/2

- Putting everything together we get

$$W_{plant}(s) = \frac{s}{(1 + s\tau_v)(1 + s\tau_{ps})} \cdot W_p(s) \cdot e^{-\delta_{ps} s} \,.$$

- The 550 μs time delay of the IC power supply can be replaced by its third order Padé approximation

$$\frac{-(s - 8444)(s^2 - 1.34 \cdot 10^4 s + 8.54 \cdot 10^7)}{(s + 8444)(s^2 + 1.34 \cdot 10^4 s + 8.54 \cdot 10^7)}$$

Stabilizing the EAST plasma using a SISO controller - 2/2

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- **The only way to vertically stabilize EAST with a SISO stable controller (SISO strong stabilizability) is to include an integral action on the vertical speed (i.e., the vertical position z_p should be fed back**

Stabilizing the EAST plasma using a SISO controller - 2/2

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- **The only way to vertically stabilize EAST with a SISO stable controller (SISO strong stabilizability) is to include an integral action on the vertical speed (i.e., the vertical position z_p should be fed back**
- **The reason is that the plasma unstable pole is *trapped* between two non minimum phase zeros**

Parity-Interlacing-Property (PIP)

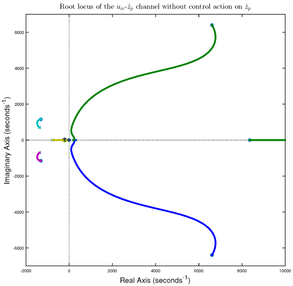
Theorem

A linear plant $W(s)$ is strongly stabilizable if and only if the number of poles of $W(s)$ between any pair of real zeros in the right-half-plane (RHP) is even.

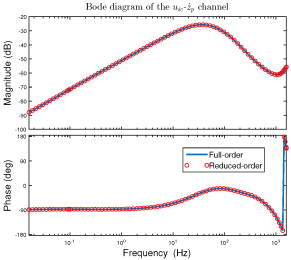
D. C. Youla, J. J. Bongiorno Jr., C. N. Lu
Single-loop feedback stabilization of linear multivariable dynamical plants
Automatica, vol. 10, no. 2, pp. 159–173, Mar. 1974

Stabilizing with a MIMO controller - 1/2

By closing the loop on $I_{IC}(s)$ we introduce another unstable pole in the $u_{ic} - \dot{z}_p$ channel



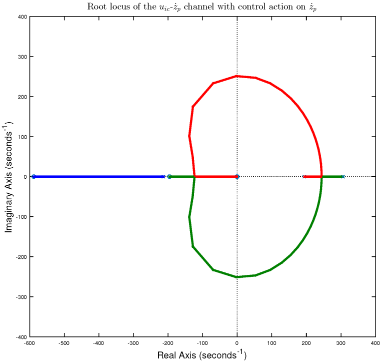
(a) Root locus of the $u_{ic} - \dot{z}_p$ channel, when the loop on the IC current is closed.



(b) Bode diagrams of the full-order and reduced-order versions of transfer function for the $u_{ic} - \dot{z}_p$ channel, when the loop on the IC current is closed.

Stabilizing with a MIMO controller - 2/2

Closing a stable controller on the vertical speed is now possible to stabilize the EAST plasma



Root locus of the u_{ic}-$\dot{z}_p$ channel with control action on $\dot{z}_p$

Figure: Root locus of the $u_{ic} - \dot{z}_p$ channel, when the loop on the IC current is also closed.

ITER-*like* VS at EAST - References

R. Albanese et al.

ITER-like Vertical Stabilization System for the EAST Tokamak

Nuclear Fusion, vol. 57, no. 8, pp. 086039, Aug. 2017.

G. De Tommasi, A. Mele, A. Pironti

Robust plasma vertical stabilization in tokamak devices via multi-objective optimization

in *Optimization and Decision Science: Methodologies and Applications, Springer Proceedings in Mathematics & Statistics*, vol. 217, pp. 305–314 , 2017.

G. De Tommasi et al.

On plasma vertical stabilization at EAST tokamak

2017 IEEE Conf. Control Technology and Applications, Kohala Coast, Hawai’i, August 2017, pp. 511-516.

Experimental results - 1/2

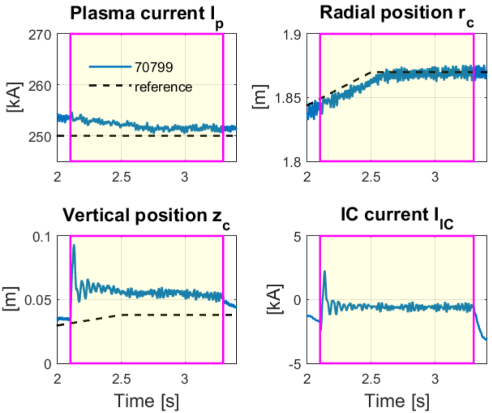


Figure: EAST pulse #70799. During this pulse the *ITER-like* VS was enabled from $t = 2.1$ s for 1.2 s, and only I_p and r_c were controlled, while z_c was left uncontrolled. This first test confirmed that the ITER-like VS vertically stabilized the plasma by controlling $\dot{z}_c$ and I_{IC}, without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

Experimental results - 2/2

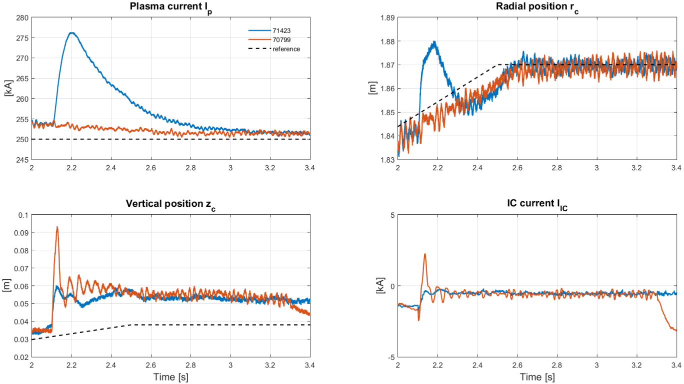


Figure: EAST pulses #70799 & #71423. Tuning of the controller parameters to reduce oscillations on z_C.

RZ control - EAST pulse #70800

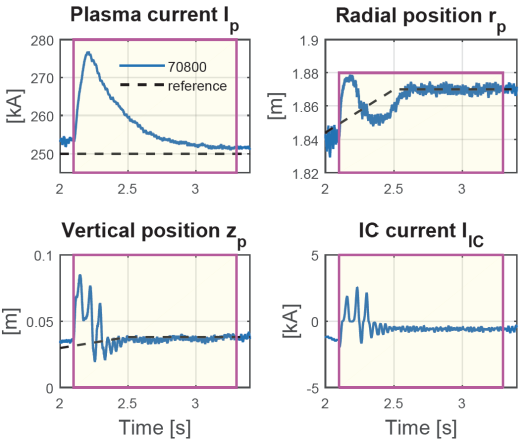


Figure: Time traces for the EAST pulse #70800, during which both the *ITER-like* VS and the model-based centroid position control were enabled from $t = 2.1$ s to $t = 3.3$ s.

Current decoupling controller - 1/2

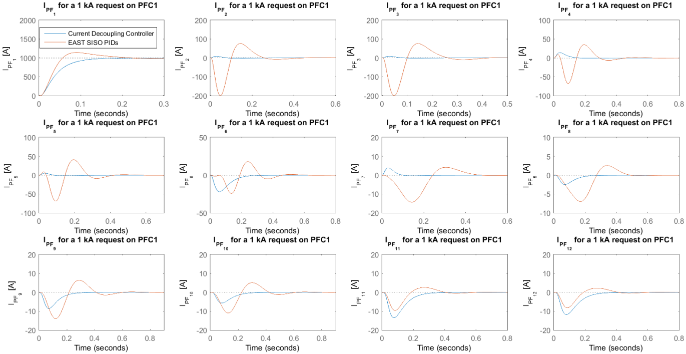


Figure: Comparison of different current control algorithms for a $1kA$ request on the EAST circuit $PFC1$. The proposed current decoupling controller improves the decoupling compared with the EAST SISO PIDs currently adopted.

Current decoupling controller - 2/2

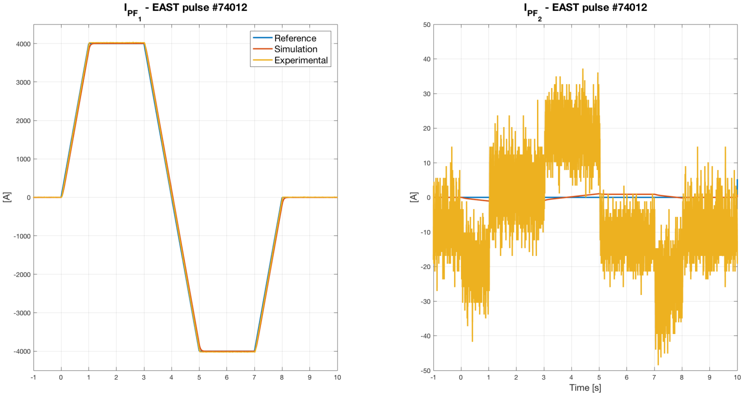


Figure: Comparison between the simulated and the experimental values for the currents in both the PF1 and PF2 circuits for the EAST pulse #74012. Note that, taking into account the measurement noise, the experimental current in PF2 is practically zero.

Conclusions

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Conclusions

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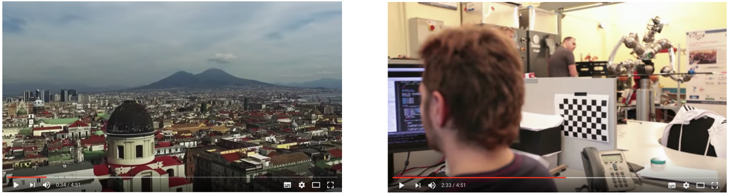
QUESTIONS?

One Erasmus experience in Naples @ FII

International Federico II on YouTube → https://www.youtube.com/watch?v=Yu2_qFCM55Q



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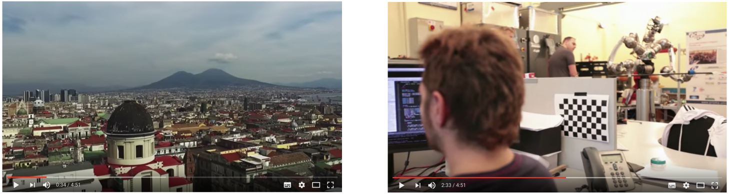
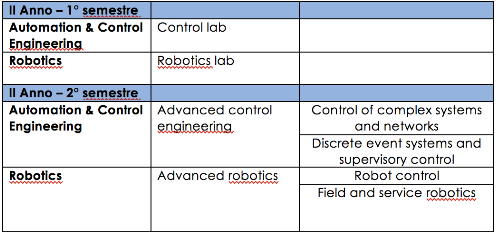


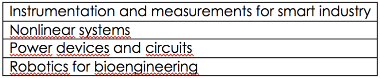
Automation and Robotics @ FII → www.automazione.unina.it

One Erasmus experience
Automation & Robotics @ FII

- Industrial automation
- Control of complex networks
- Robotics (any flavour)
- Plasma control s



II Anno – 1° semestre		
Automation & Control Engineering	Control lab	
Robotics	Robotics lab	
II Anno – 2° semestre		
Automation & Control Engineering	Advanced control engineering	Control of complex systems and networks
		Discrete event systems and supervisory control
Robotics	Advanced robotics	Robot control
		Field and service robotics



Instrumentation and measurements for smart industry
Nonlinear systems
Power devices and circuits
Robotics for bioengineering

Plasma magnetic control in tokamaks

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IST - Lisboa, Dec, 7th 2017

Thank you!

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UNIVERSITA' DEGLI STUDI DI NAPOLI FEDERICO II
DIPARTIMENTO DI INGEGNERIA ELETTRICA E DELLE TECNOLOGIE DELL'INFORMAZIONE