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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
18 May - Padova, Italy

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 standard architecture for the plasma magnetic control system

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

Some experimental results

- Current limit avoidance at JET
- ITER-like VS at EAST

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Nuclear Fusion for Dummies

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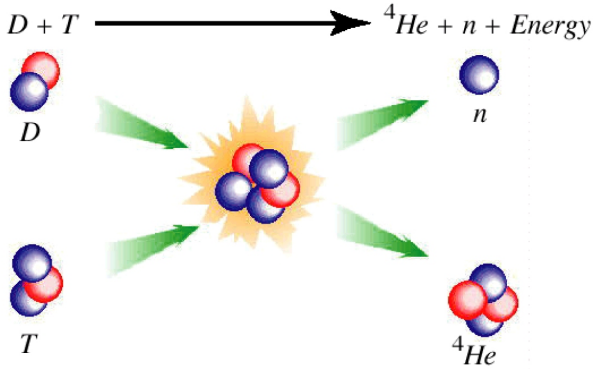
Main Aim

Production of energy by means of a fusion reaction

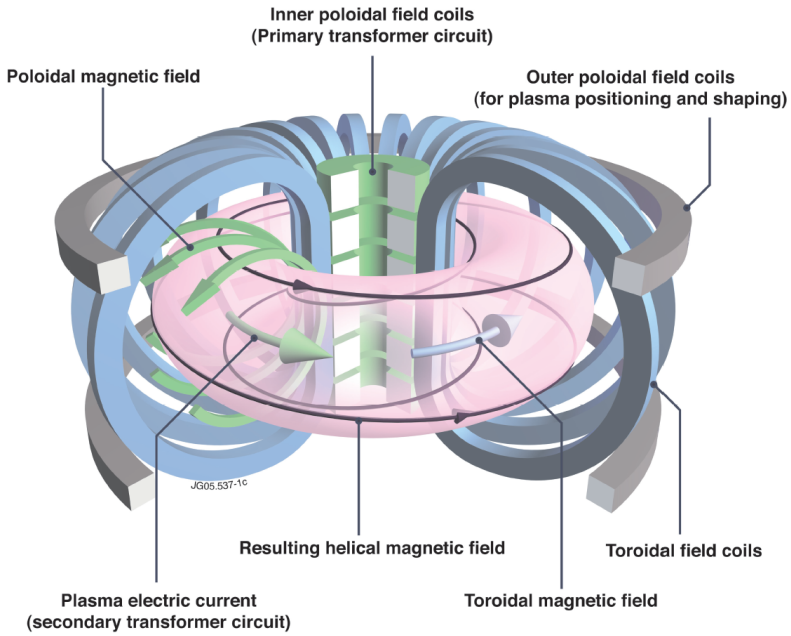
$$D + T \rightarrow {}^4\mathrm{He} + n$$



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 $\Rightarrow$ vertically unstable plasmas**
- It is important to **maintain adequate plasma-wall clearance during operation**

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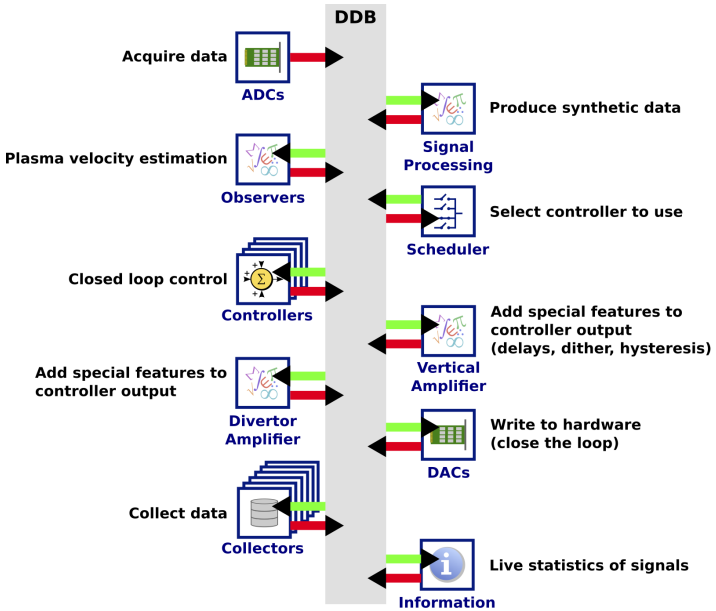
Our final objective: build a control system



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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,
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Automatica, vol. 46, pp. 1762.-1772, 2010.

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Plasma model

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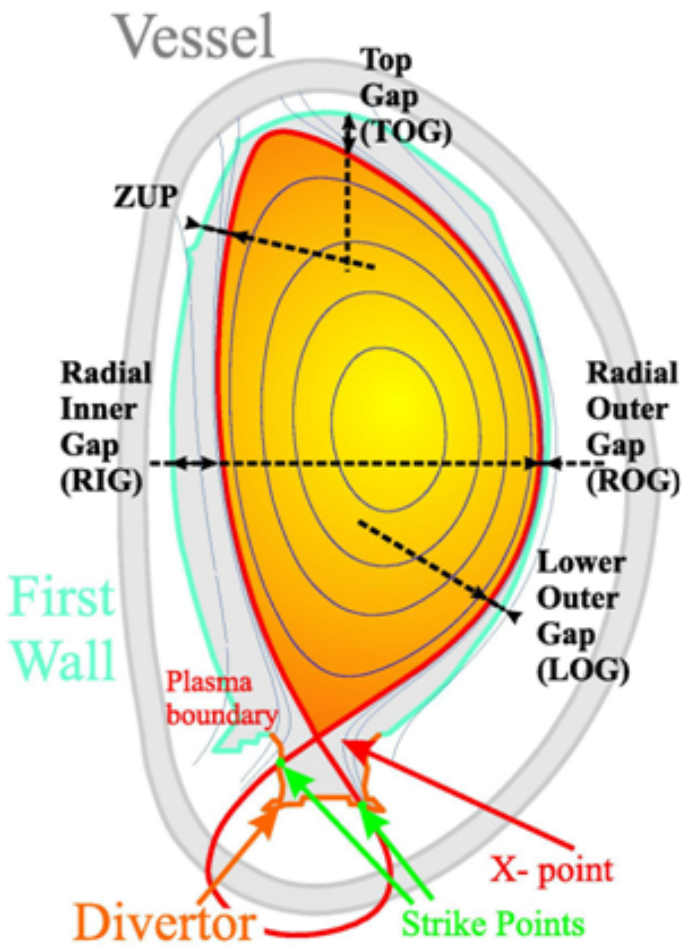
The *input variables* are:

- 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)

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Lumped parameters approximation

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

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

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

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

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Plasma linearized model

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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:

- $\mathbf{A}$, $\mathbf{B}$, $\mathbf{E}$, $\mathbf{C}$ and $\mathbf{F}$ 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**.

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Asymptotic stability of LTI systems

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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

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For nonlinear system 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.

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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:

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

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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 $\deg(N(s)) \leq \deg(D(s))$.
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 $G(s)$

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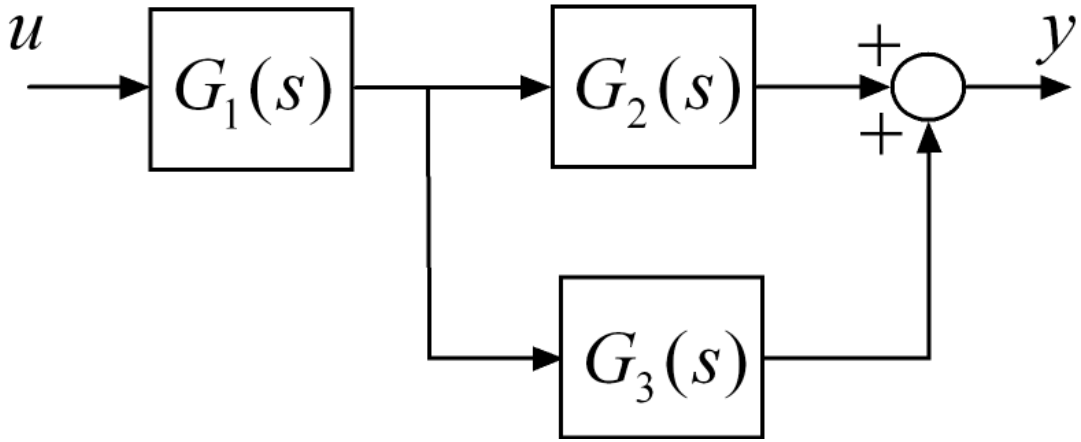
Block diagrams

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.



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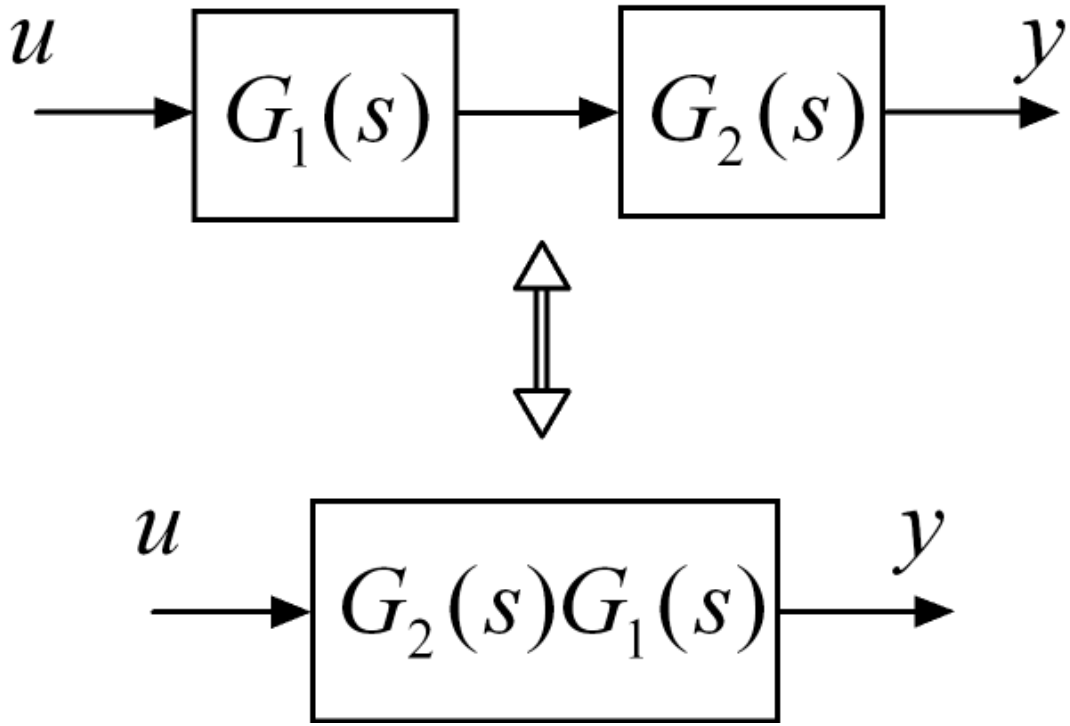
Series connection



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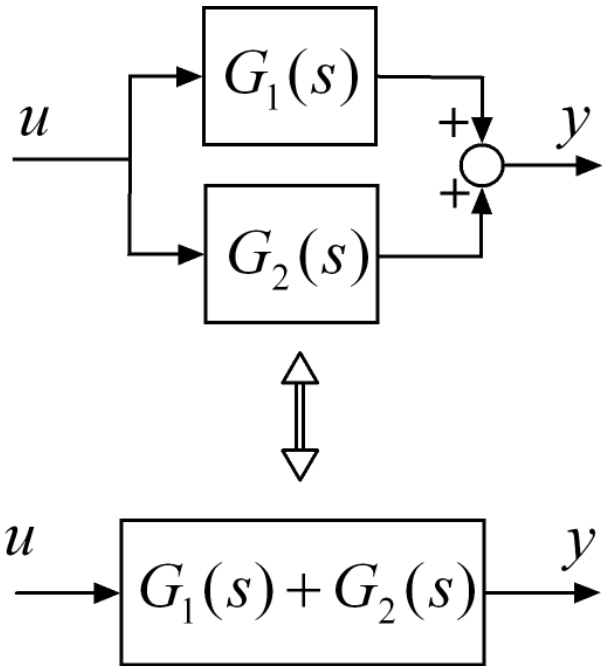
Parallel connection



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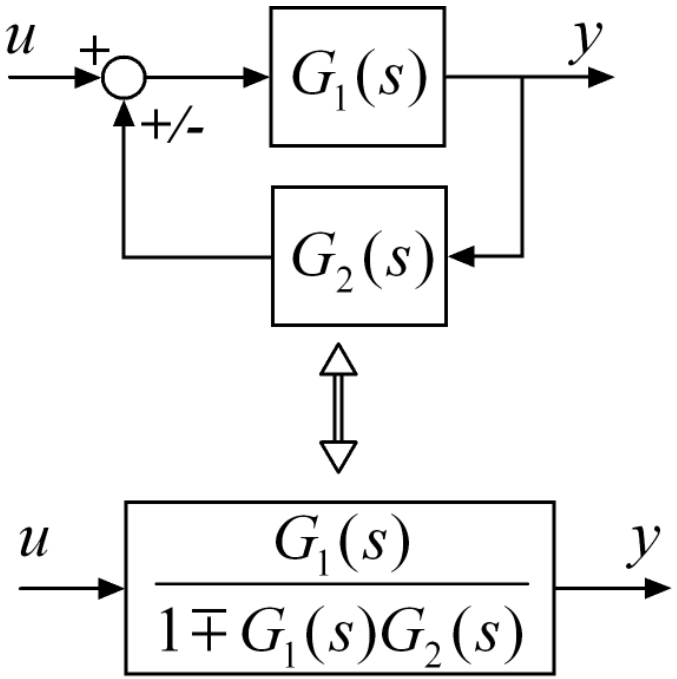
Feedback connection



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Stability of interconnected systems

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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

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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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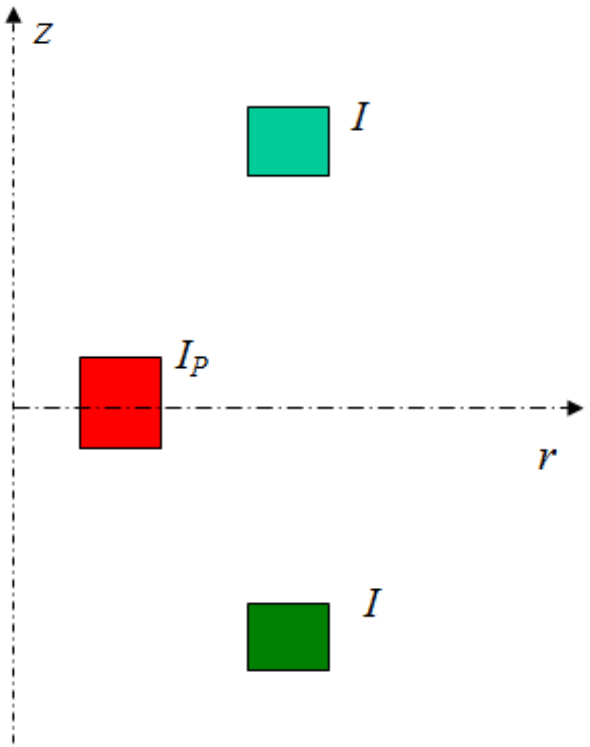
Objectives

- 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!**

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.

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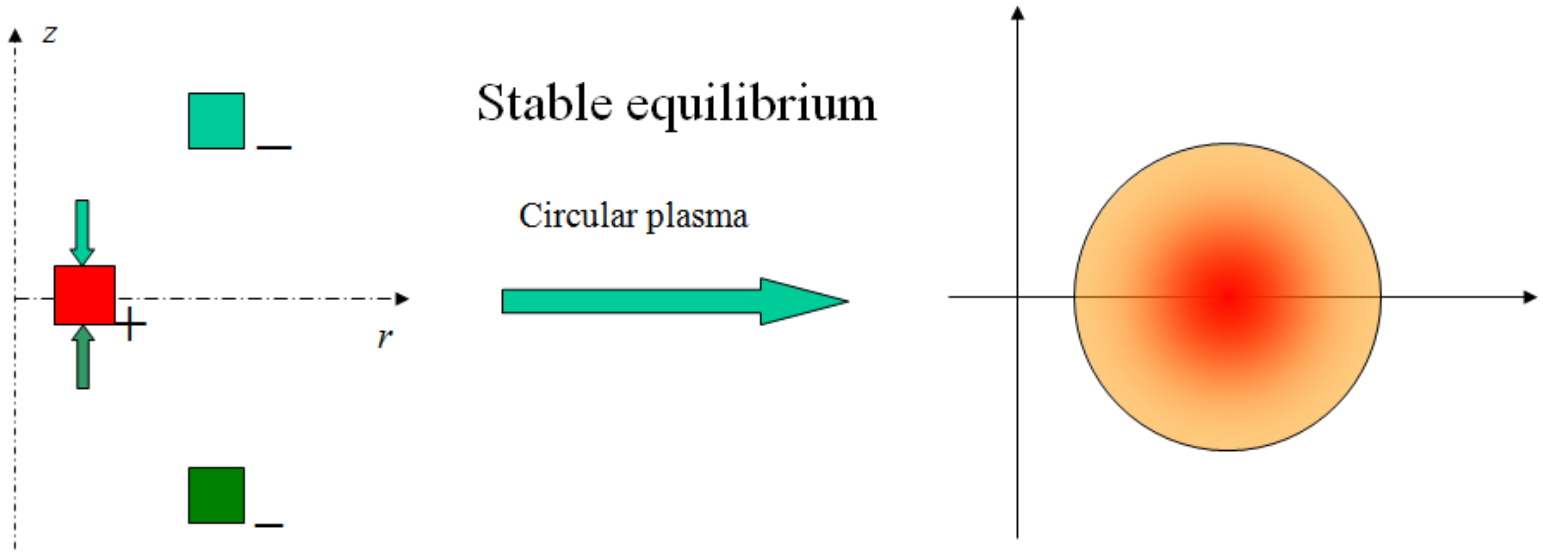
Stable equilibrium - 1/2

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



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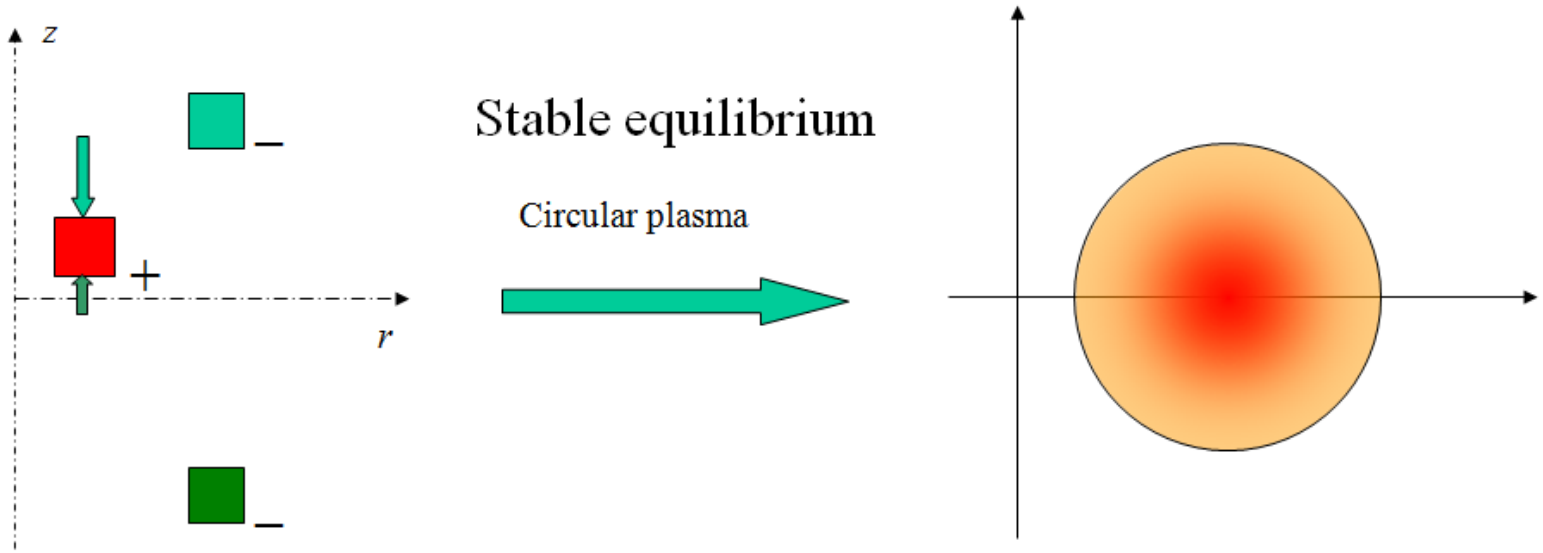
Stable equilibrium - 2/2

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



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Unstable equilibrium - 1/2

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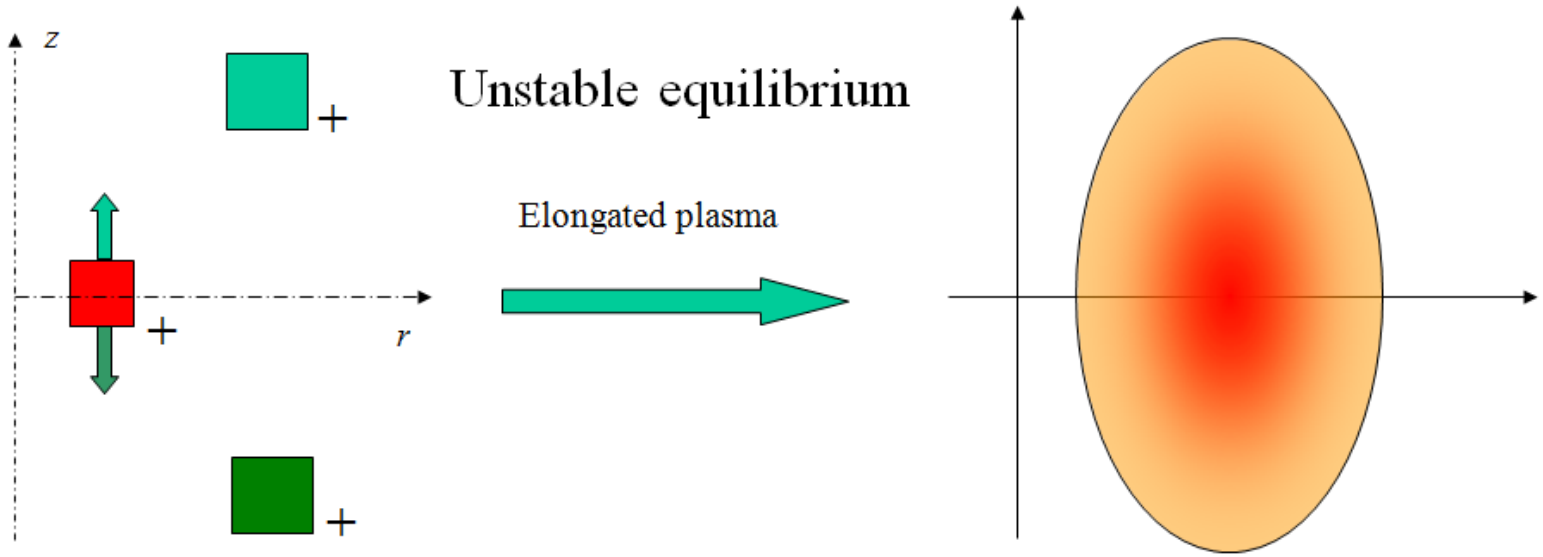
If $\mathrm{sgn}(I_p) = \mathrm{sgn}(I)$



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Unstable equilibrium - 2/2

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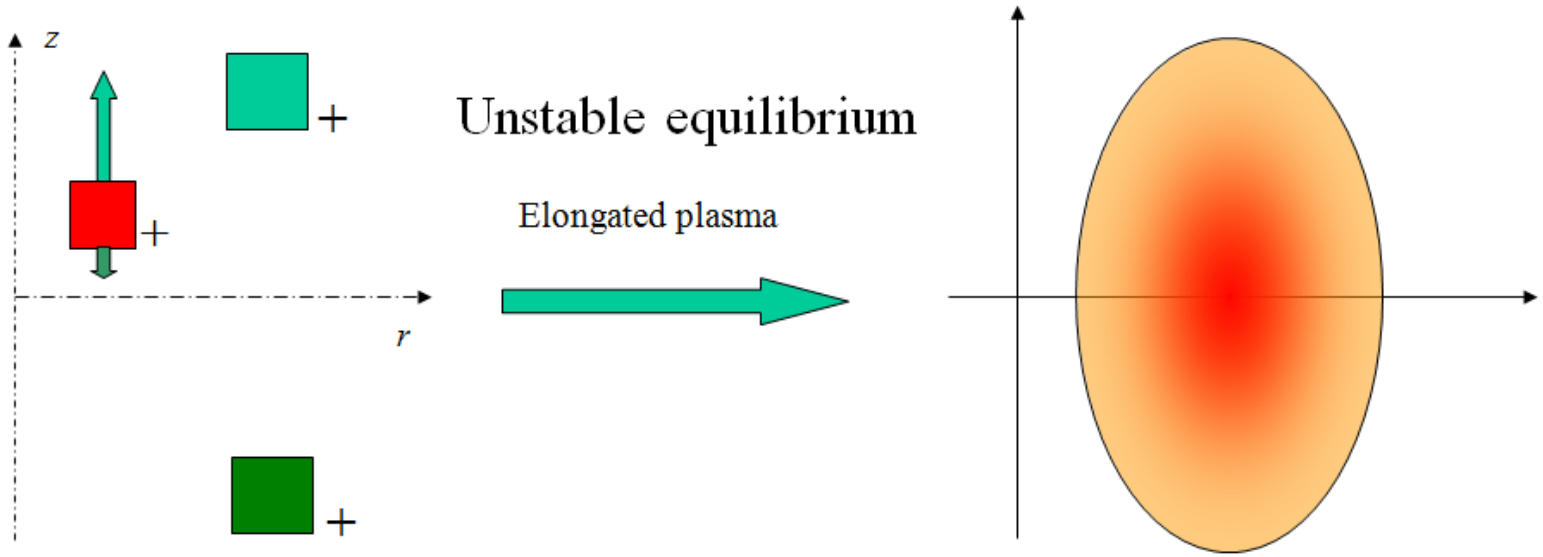
If $\mathrm{sgn}(I_p) = \mathrm{sgn}(I)$



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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

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)

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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.

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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

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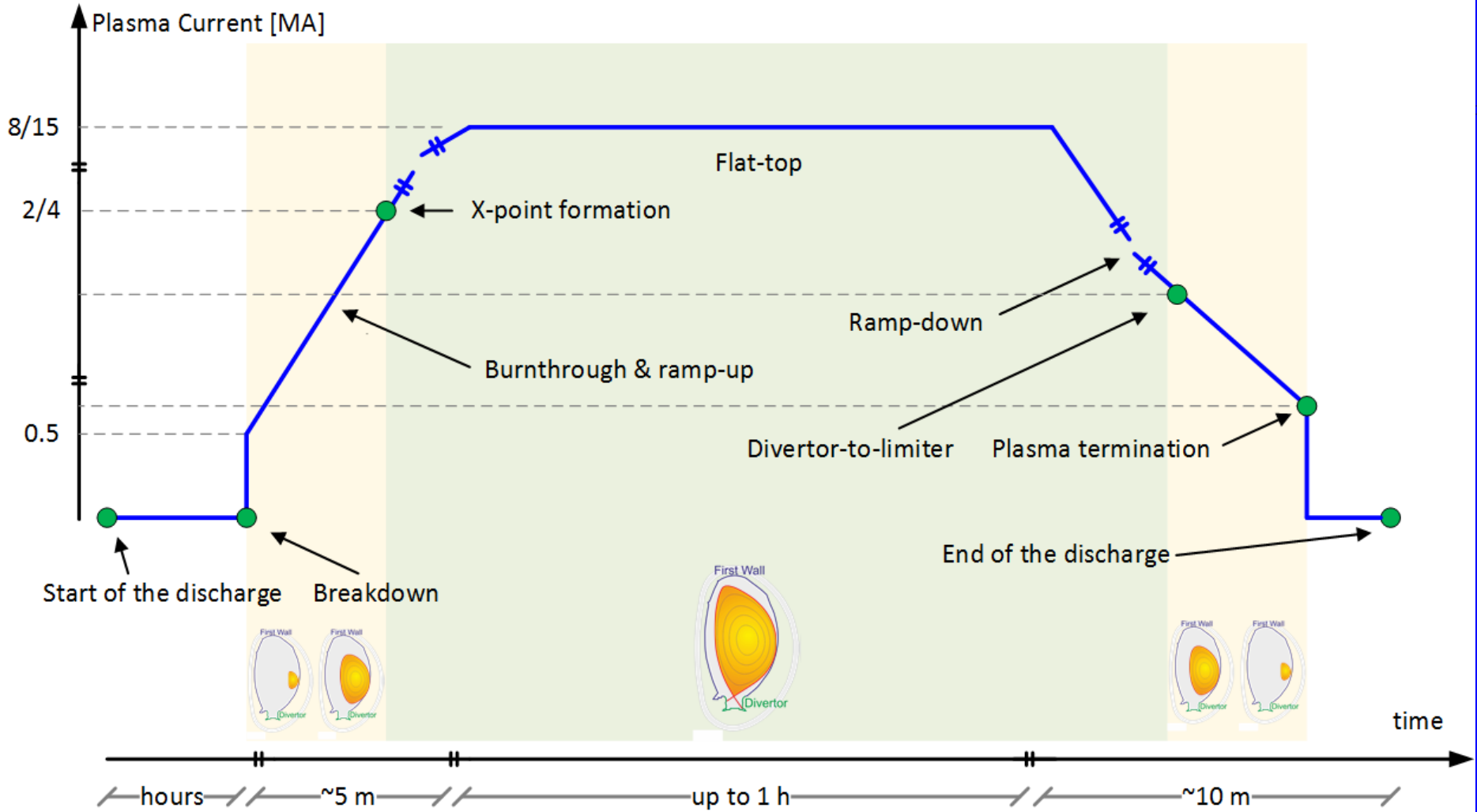

A proposal for magnetic control in ITER & DEMO (and more)

- A magnetic control system 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
  - $\rightarrow$ 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 & DEMO (& JT-60SA) and partially deployed at EAST

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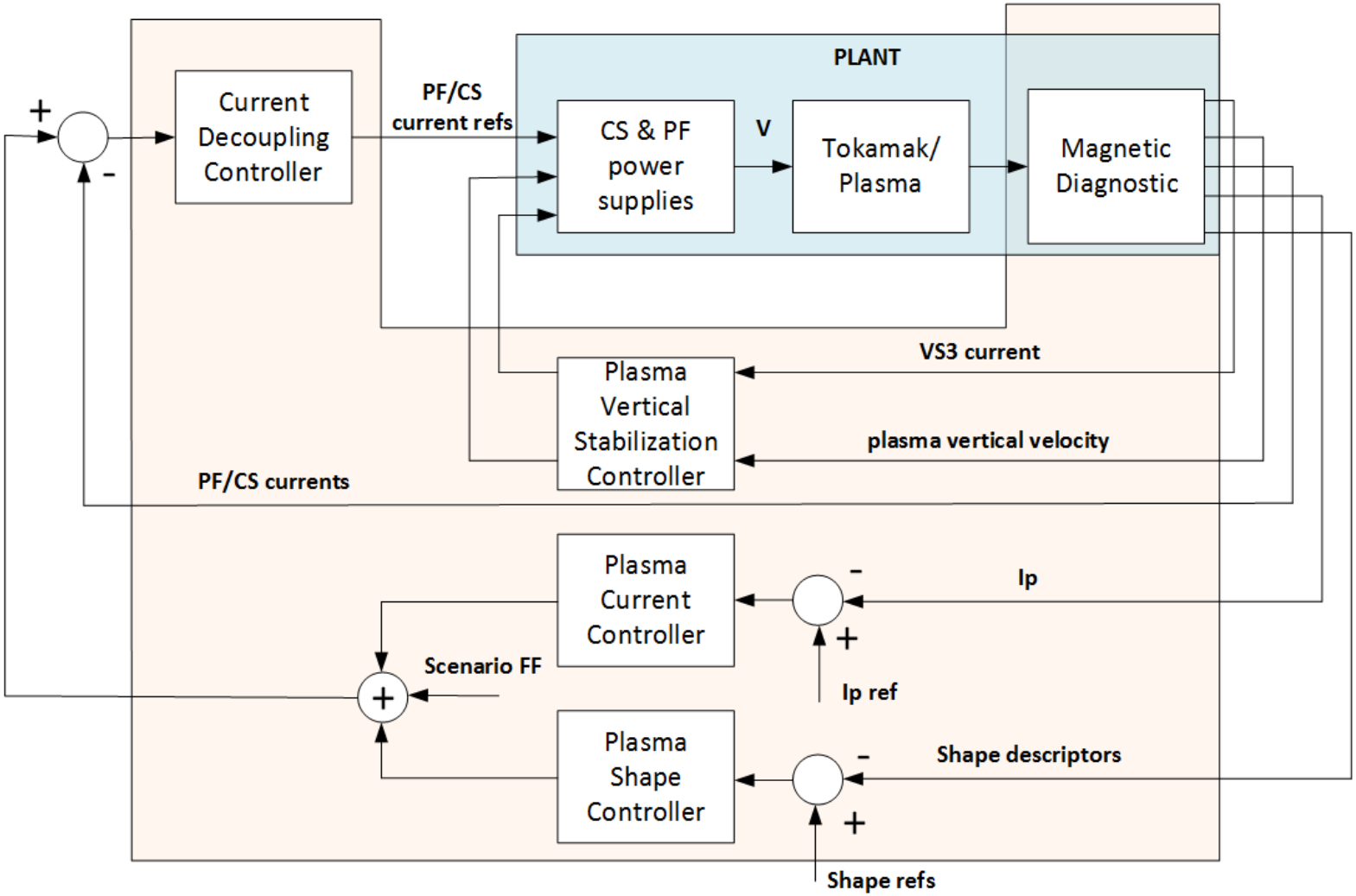
Contr. Eng. Prac., 2017

A proposal for the ITER magnetic control system

G. De Tommasi



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The proposed architecture

- **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 $\rightarrow$ *exceptions***
  - **Clock events $\rightarrow$ time-variant parameters**

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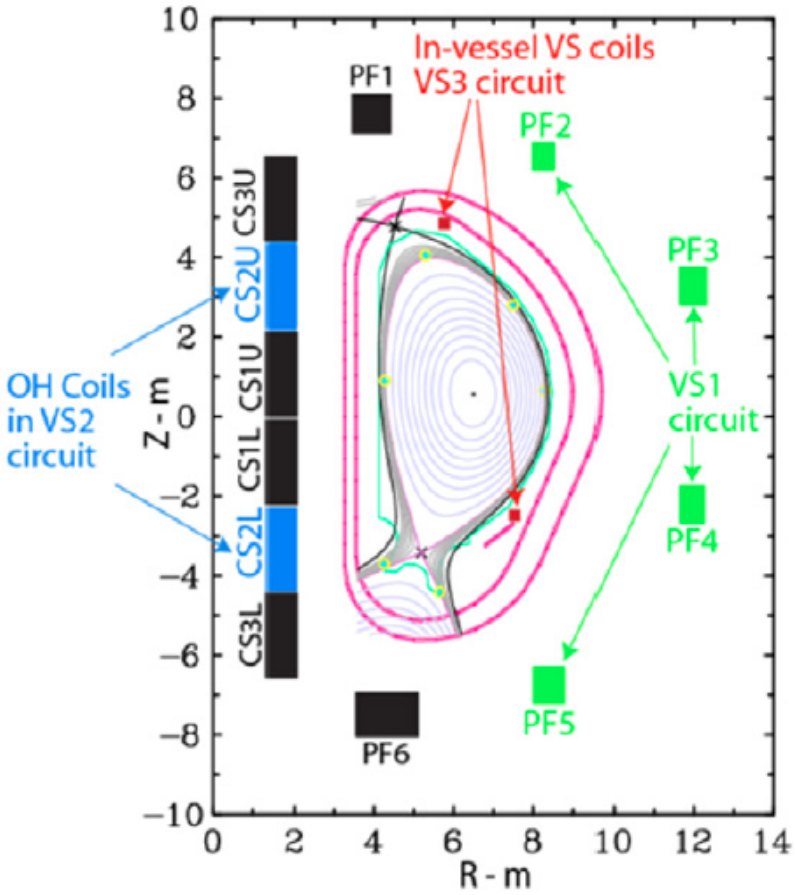
ITER PF system (as a reference)

- External superconductive coils
  - *Single coil* circuits
  - *Imbalance* circuits
- Internal copper coils



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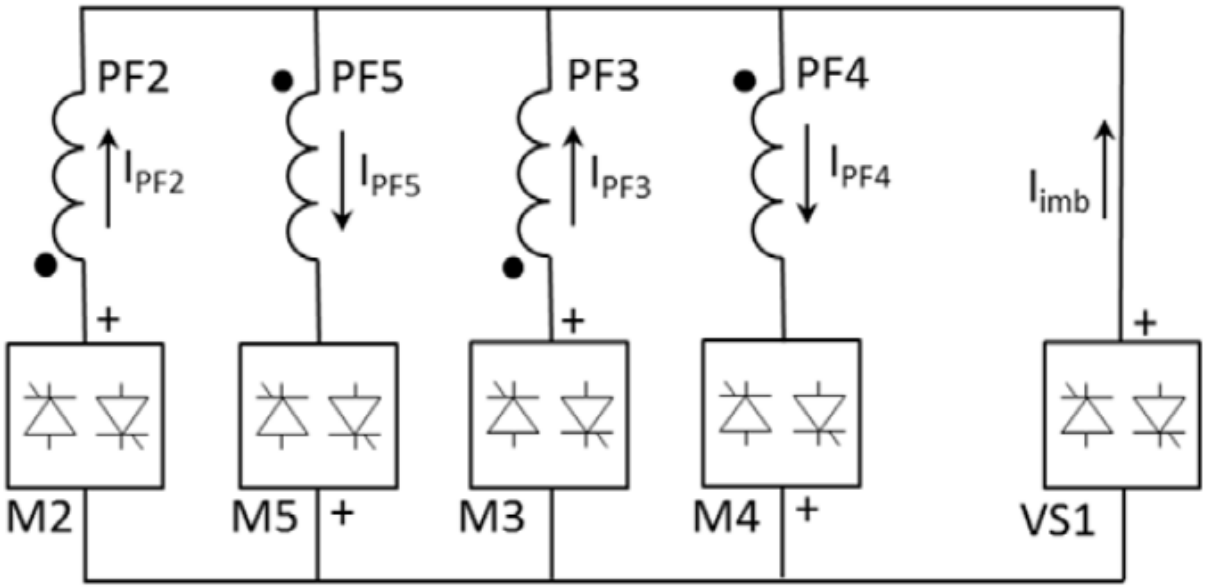
Imbalance circuits for vertical stability

The ITER *VS1* circuit



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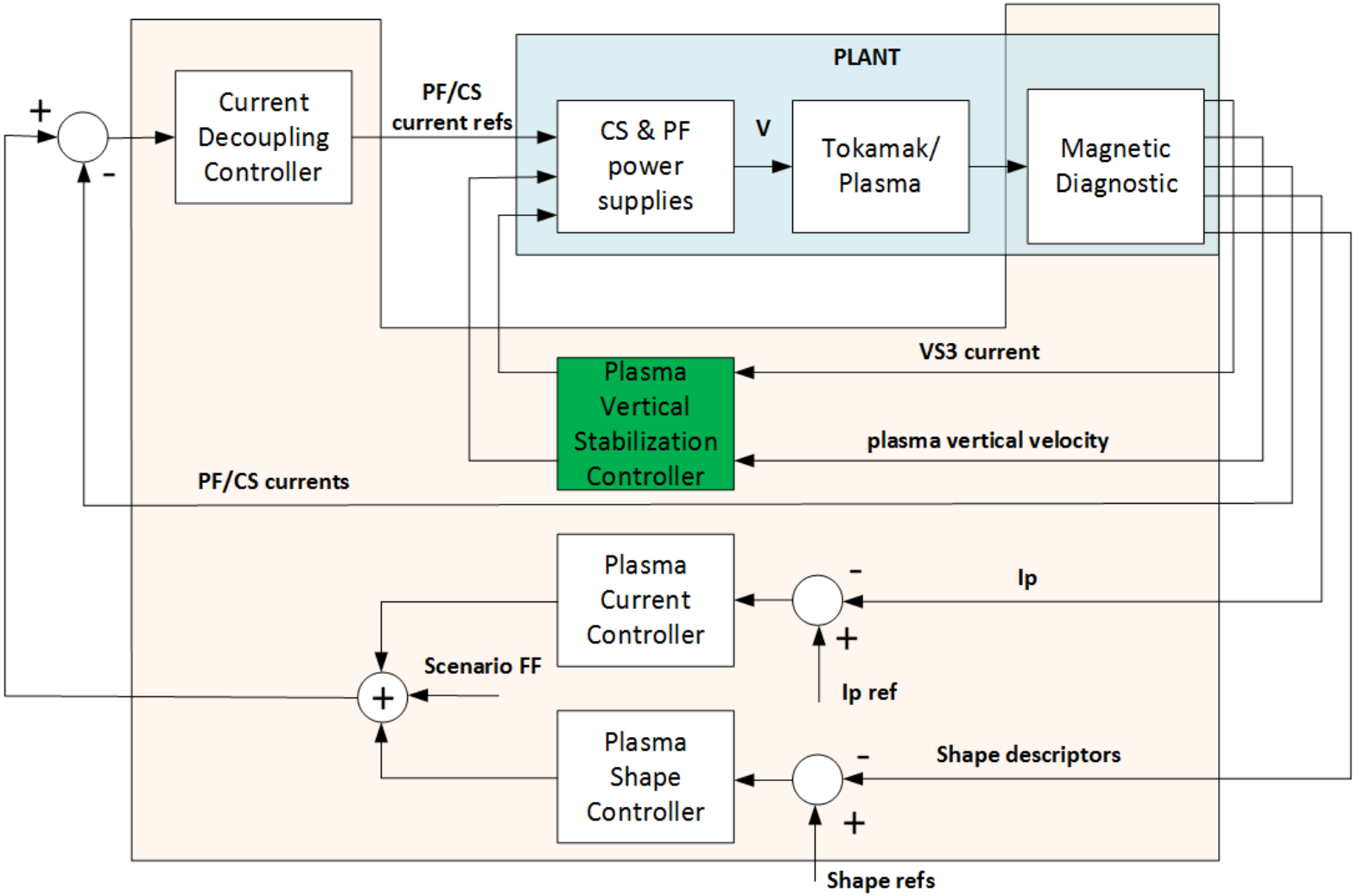

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The vertical stabilization controller

- The vertical stabilization controller receives, as input, the centroid vertical speed, and the current flowing in the $VS3$ circuit (the in-vessel coil set)
- It generates, as output, the voltage references for the $VS3$ and $VS1$ power supplies

$$V_{VS3} = \mathcal{L}^{-1}\left[F_{vs}(s)\right] * (K_1 \dot{z} + K_2 I_{VS3})$$
$$V_{VS1} = K_3 I_{VS3}$$

- The vertical stabilization is achieved by the voltage applied to the $VS3$ circuit
- The voltage applied to the $VS1$ circuit is used to reduce the current and the RMS ohmic power in the inner vessel coils
- K_1 should be scaled according to the value of I_p

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

R. Albanese et al.
ITER-like Vertical Stabilization System for the EAST Tokamak
submitted to *Nucl. Fus.*, 2017

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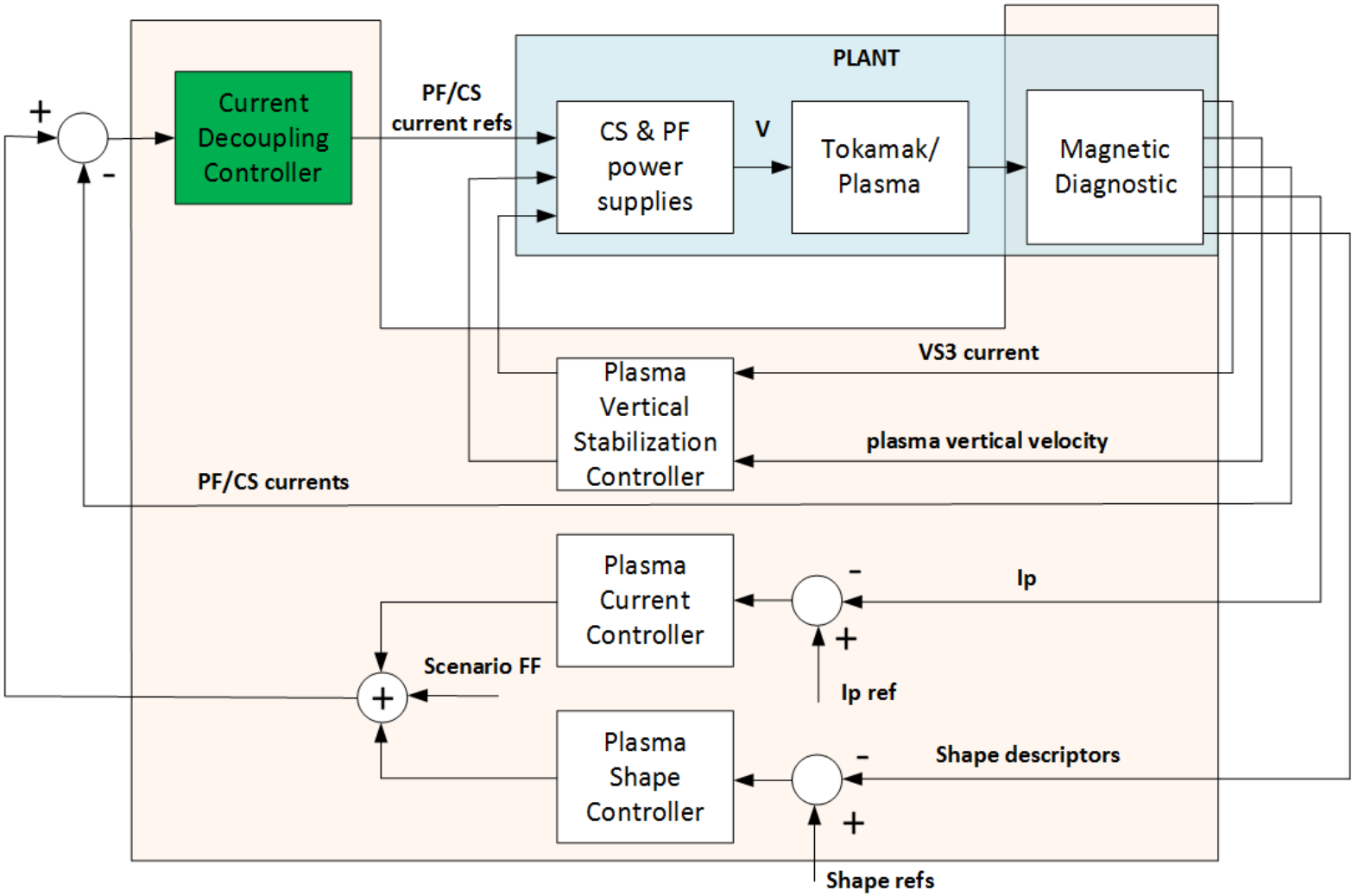

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Current decoupling controller

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- The current decoupling controller receives as input the CS & PF coil currents and their references, and generate in output the voltage references for the power supplies
- **The CS & PF coil 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

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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:

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

where

- $\mathbf{K}_{PF} = \widetilde{\mathbf{L}}_{PF} \cdot \Lambda$,
- $\tilde{\mathbf{R}}_{PF}$ is the estimated resistance matrix for the PF circuits - 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.

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Current decoupling controller - Closed-loop transfer functions

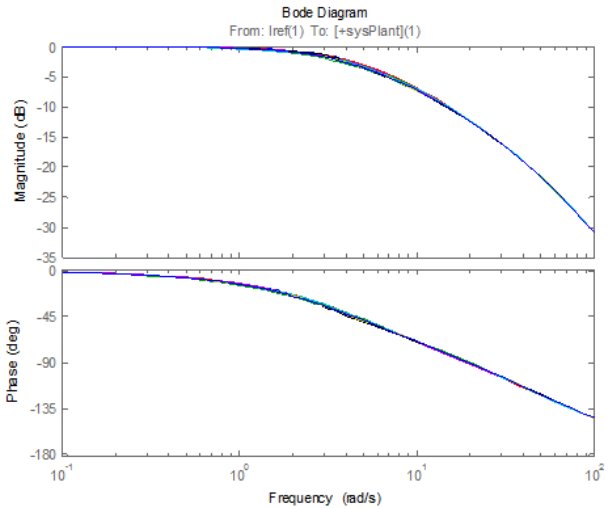

Figure: Bode diagrams of the *diagonal* transfer functions.

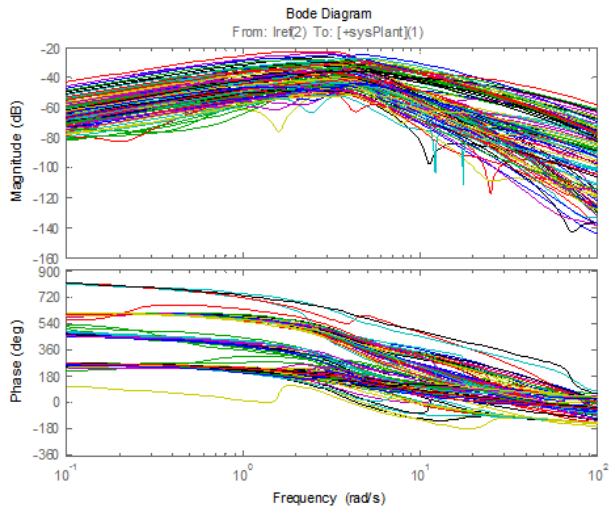

Figure: Bode diagrams of the *off-diagonal* transfer functions.

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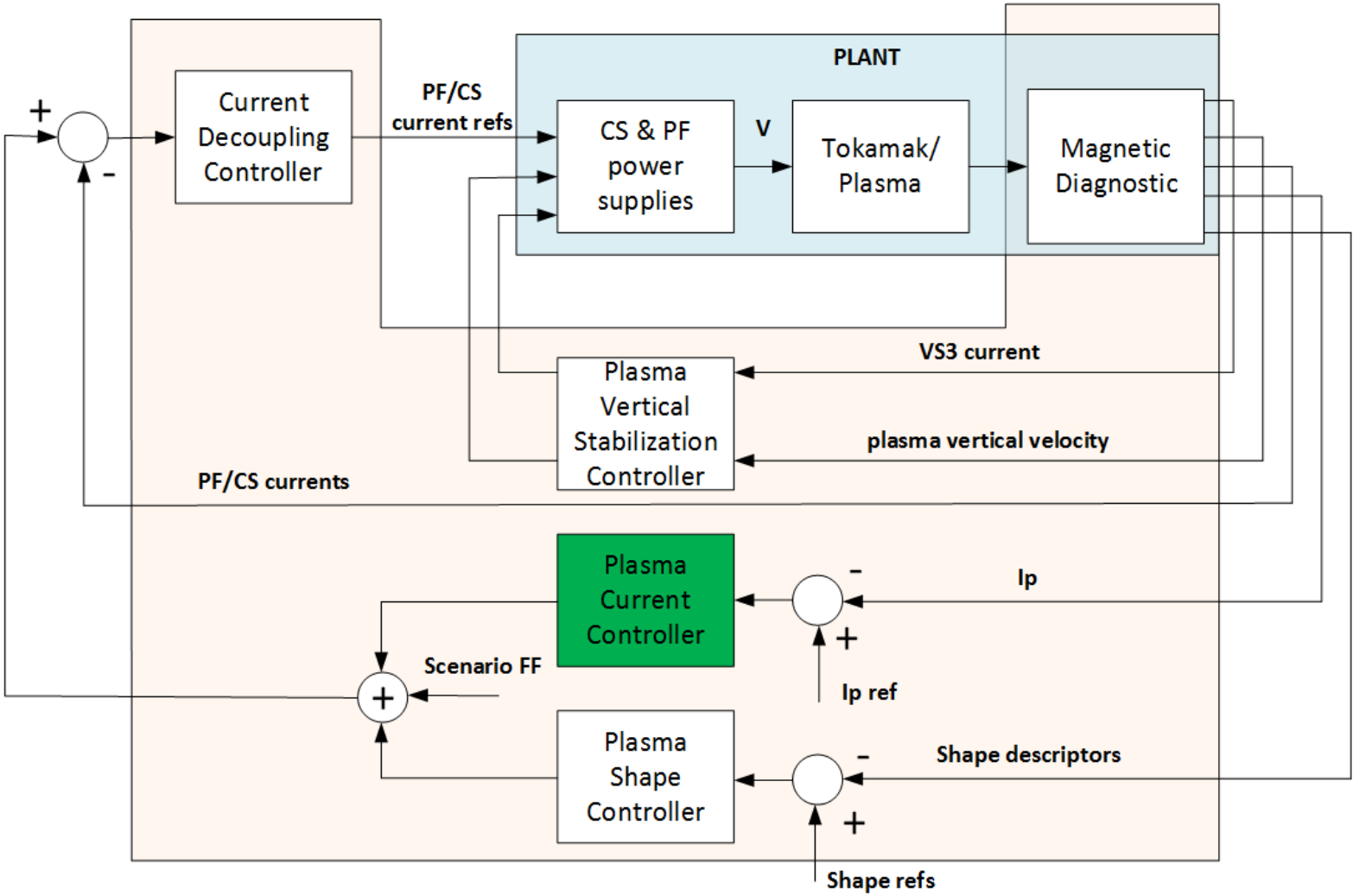

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The plasma current controller

- 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**

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The plasma shape controller

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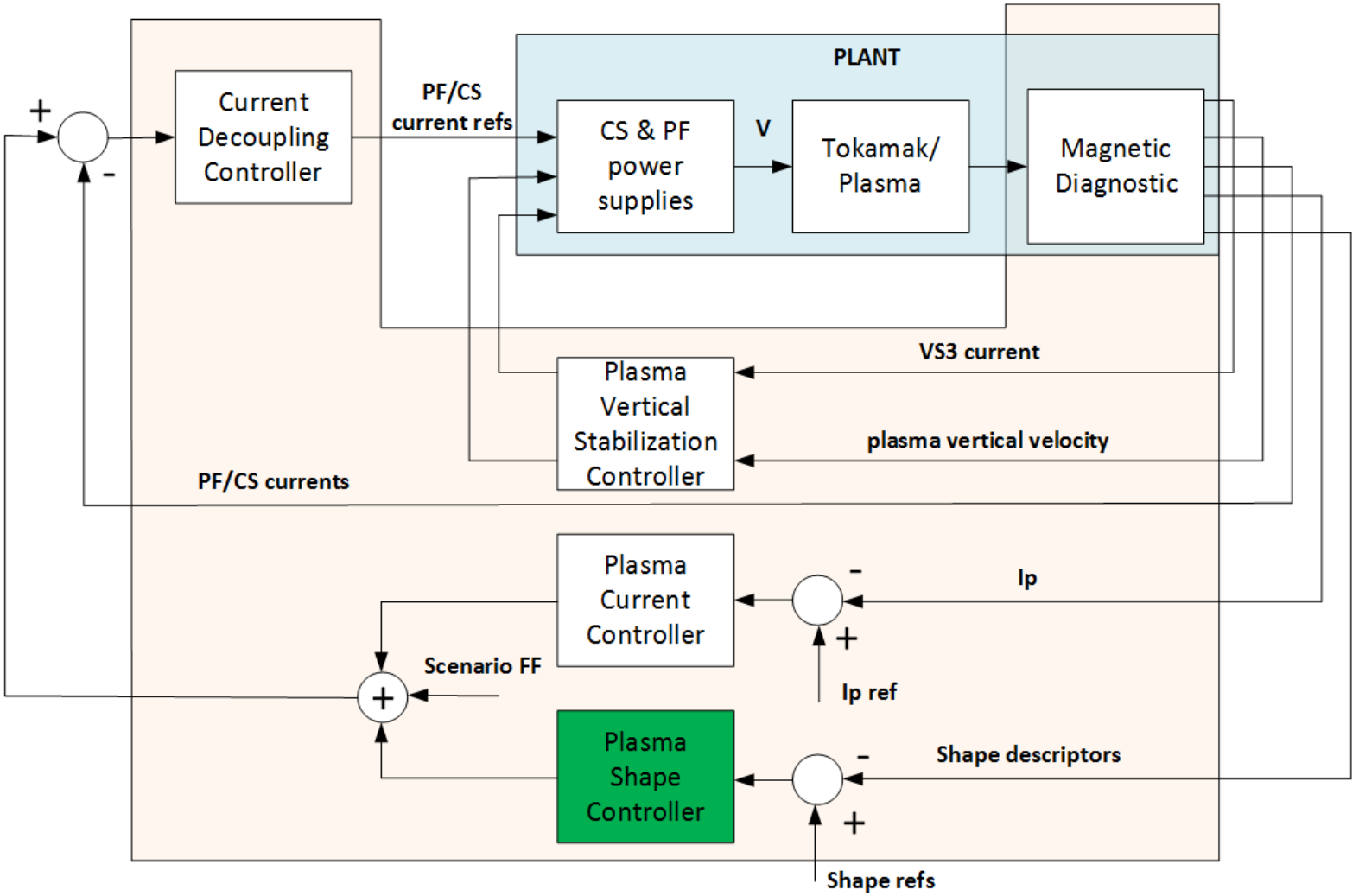

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Plasma shape descriptors

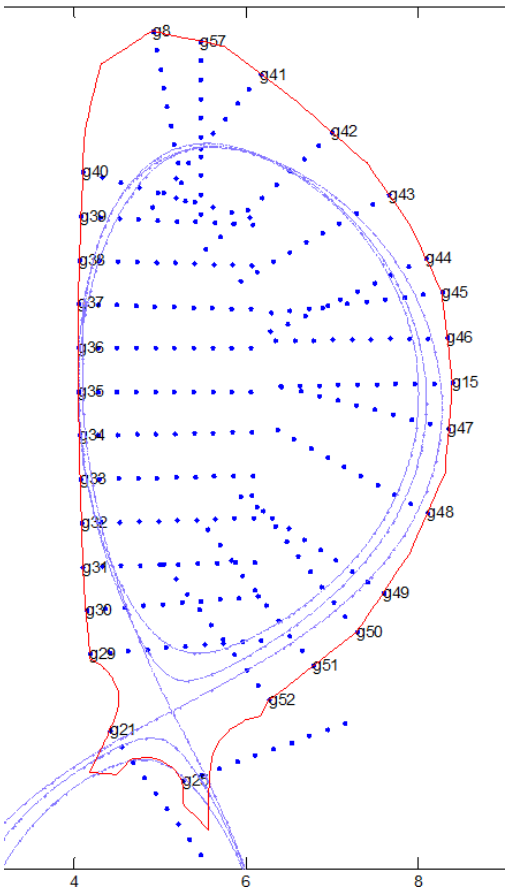

Figure: Control segments.

- 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 equation 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

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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*)

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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

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The *XSC-like* philosophy - 1/4

- 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 - 2/4

- The currents needed to track the desired shape (in a *least-mean-square* sense)

$$\delta I_{PF_{ref}} = C^{\dagger} \delta Y$$

- 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:

$$\tilde{C} = QCR = USV^T$$

- 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

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

(it contributes to avoid PF current saturations)

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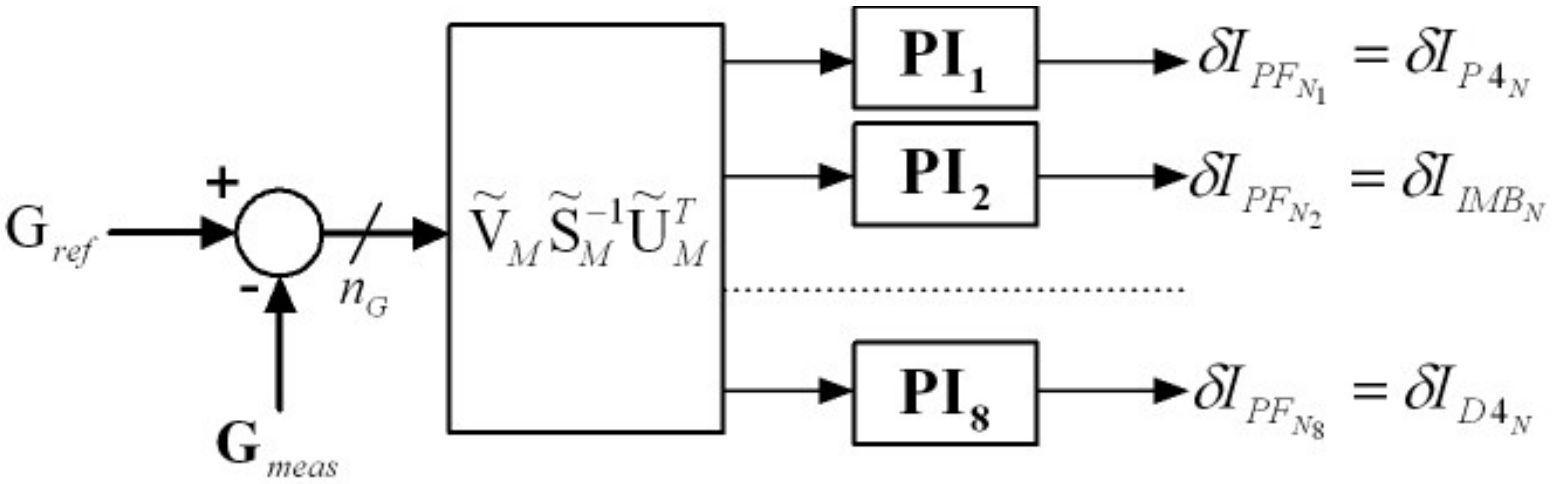
The *XSC-like* philosophy - 3/4



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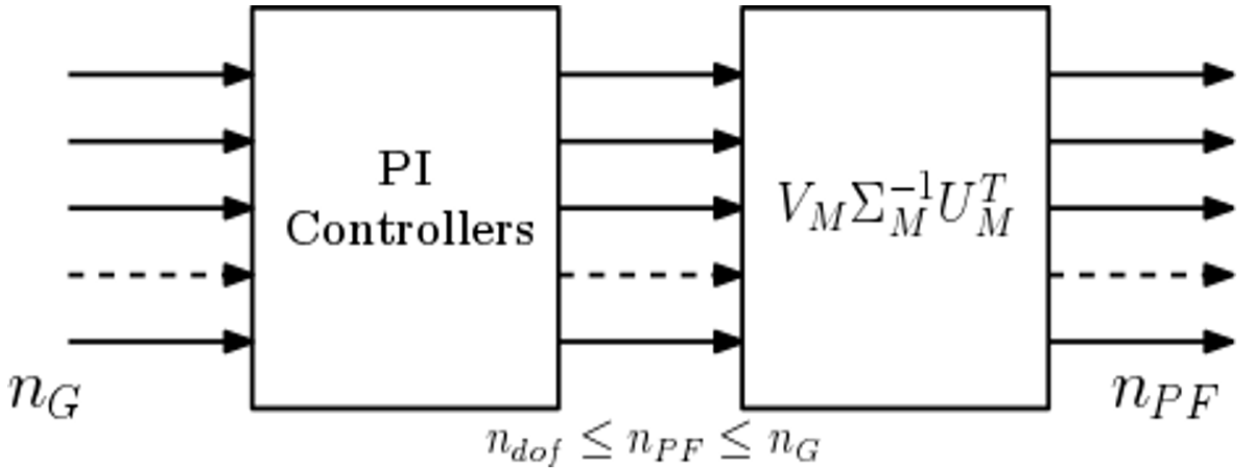
The *XSC-like* philosophy - 4/4



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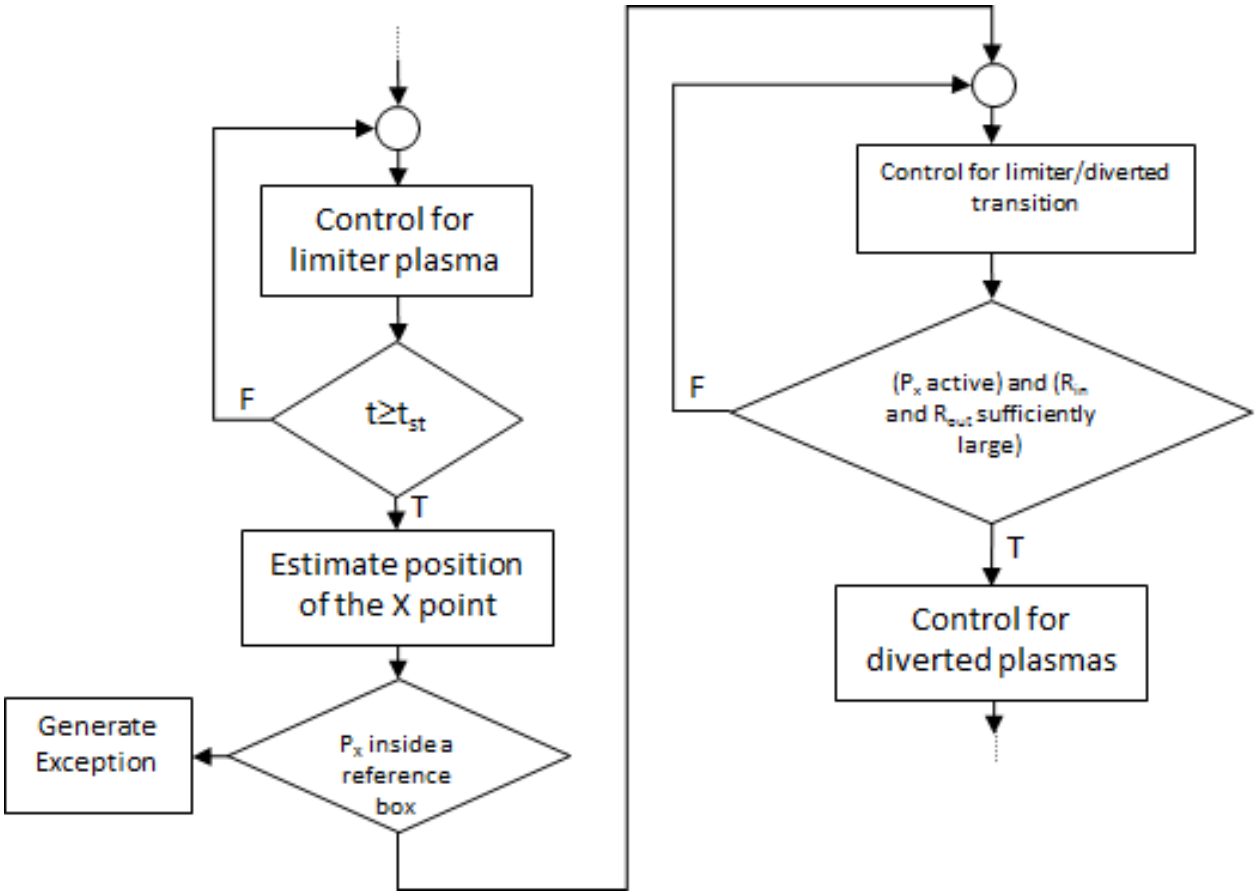
Plasma shape controller - Switching algorithm



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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 $t = 11.9\ s$

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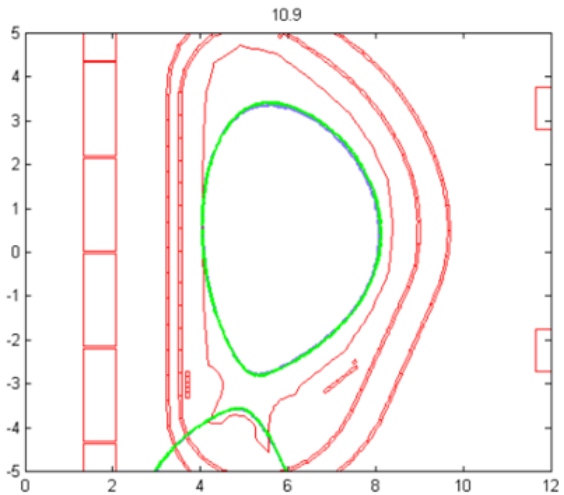
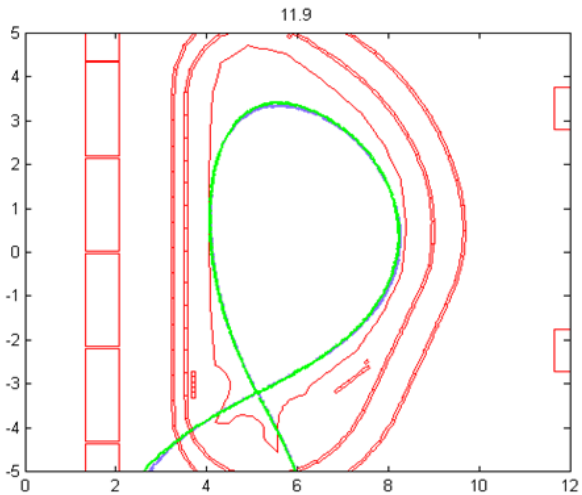
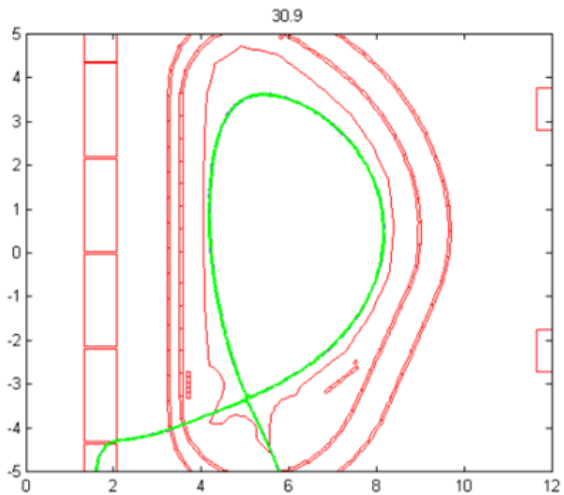
Plasma boundary snapshots







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The Current Limit Avoidance System - 1

- 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**

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The Current Limit Avoidance System - 2

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- 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** $\Rightarrow$ 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

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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 $n_{SH} = 32$)

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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:

$$u_c = y, \tag{7a}$$
$$u = y_c\,. \tag{7b}$$

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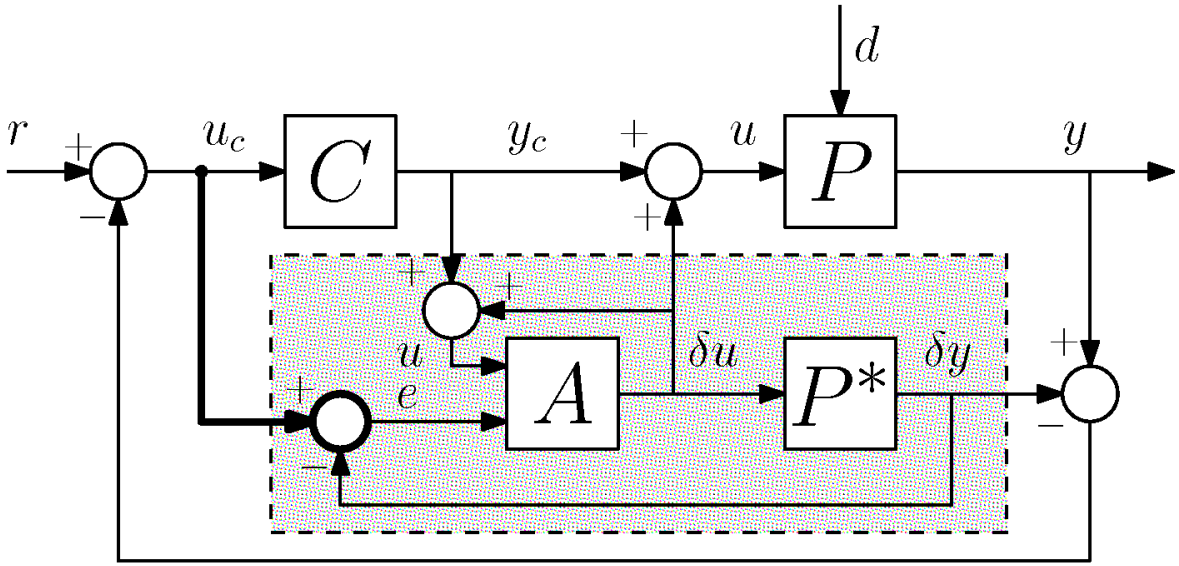
Block diagram of the allocated closed-loop



Where

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

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

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

denotes the steady-state gain.

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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,

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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

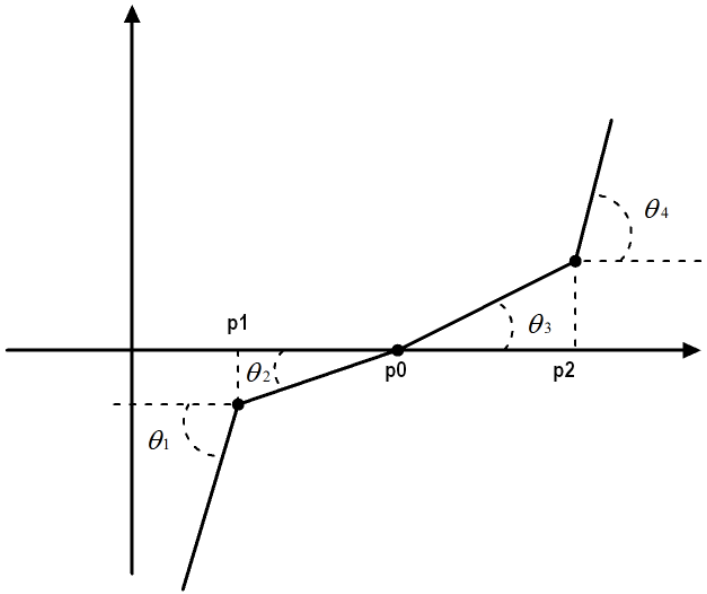

Figure: Piecewise linear function used to specify the gradient of the cost function J for each *allocated* channel. For each channel 7 parameters must be specified.

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The CLA Architecture

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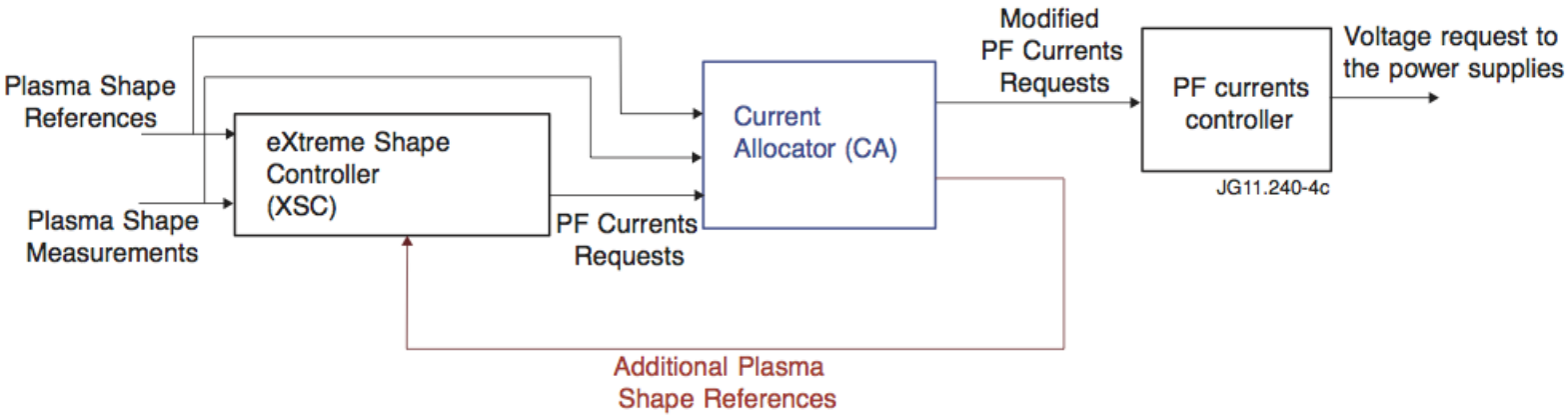

The CLA block is inserted between the *XSC* and the *Current Decoupling Controller*

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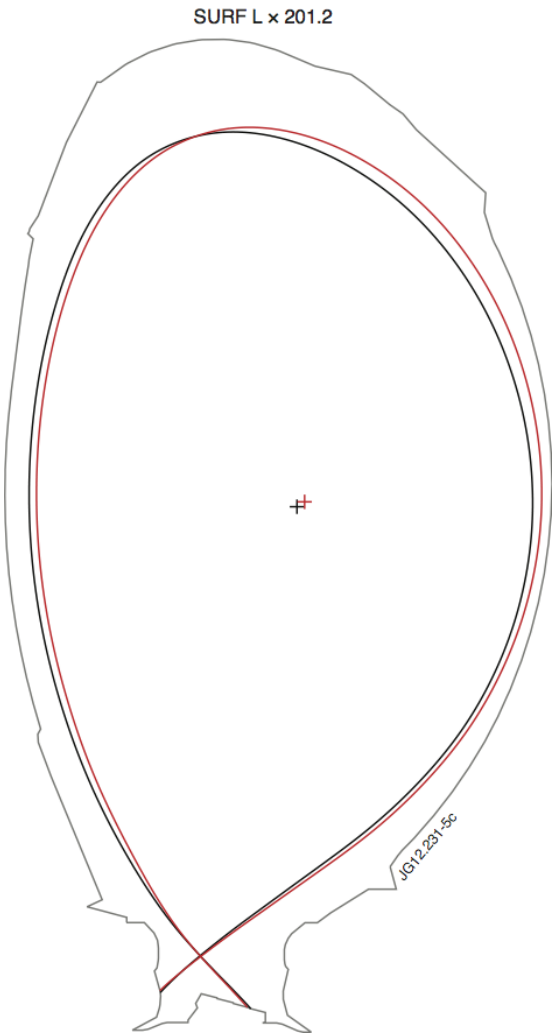

Figure: Shape comparison at 22.5 *s*. Black shape (#81710 without CLA), red shape (#81715 with CLA).

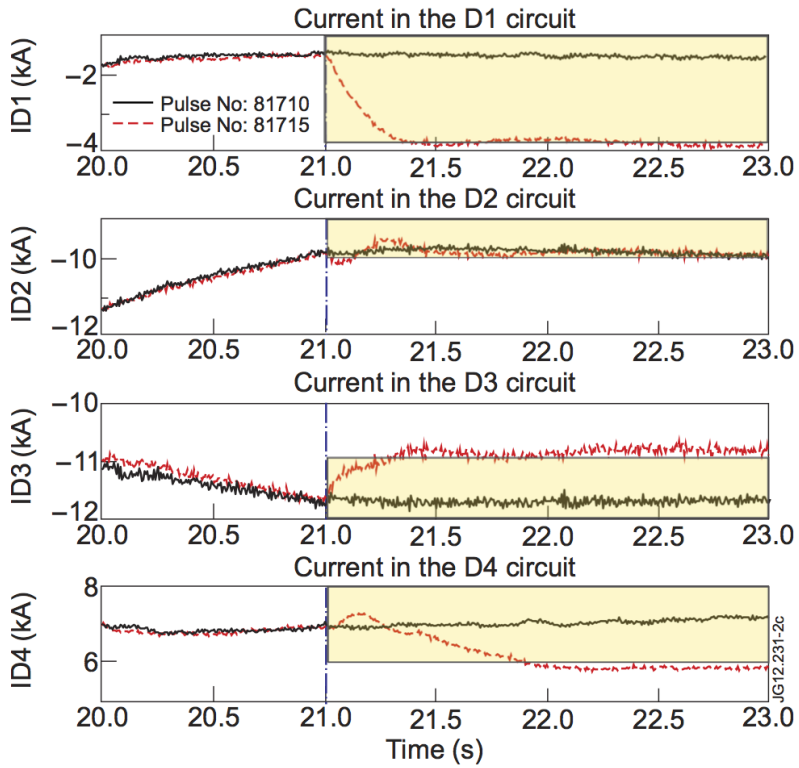

Figure: Currents in the divertor circuits. #81710 (reference pulse without CLA) and pulse #81715 (with CLA). The shared areas correspond to regions beyond the current limits enforced by the CLA parameters.

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

G. De Tommasi

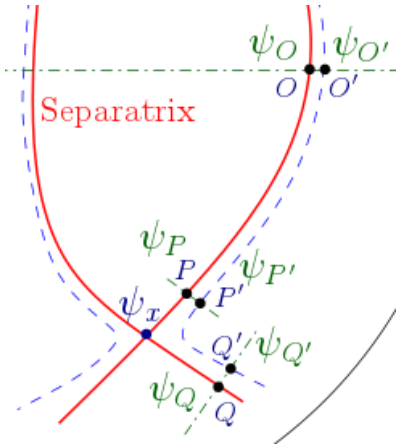

Figure: Option #1 - integrated control of plasma shape and flux expansion.

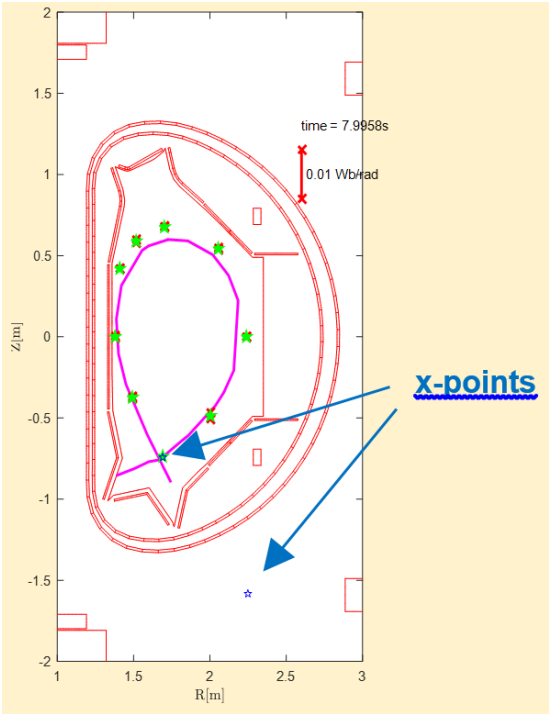

Figure: Option #2 - integrated control of plasma shape and distance between null points.

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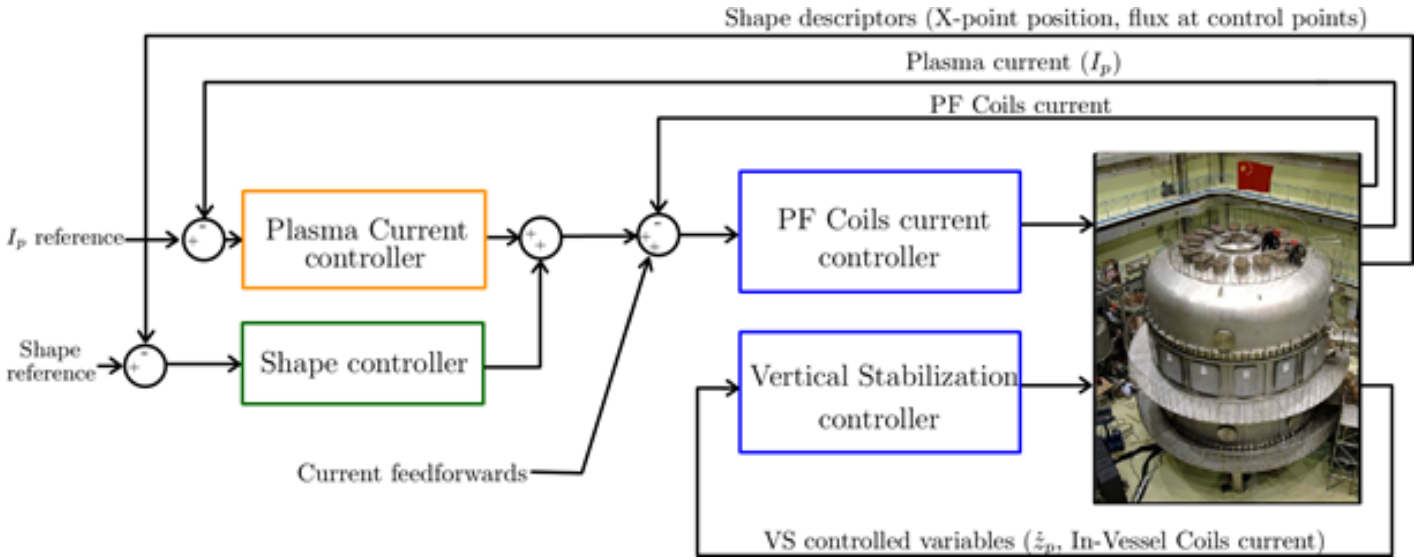

- The EAST architecture is *compliant* to the one proposed for ITER & DEMO
- **The control algorithms deployed within the EAST PCS do not satisfy the requirements needed to easily replace the shape controller**
  - **vertical stabilization is strongly coupled with plasma shape control**
  - The PF Coils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

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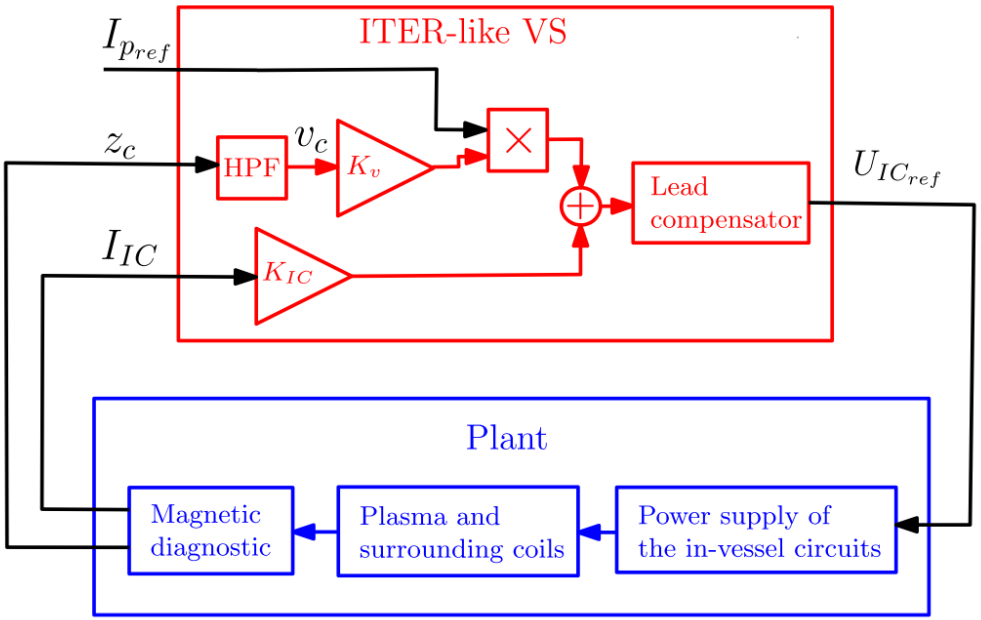
ITER-like VS at EAST



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

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Experimental results - 1/2

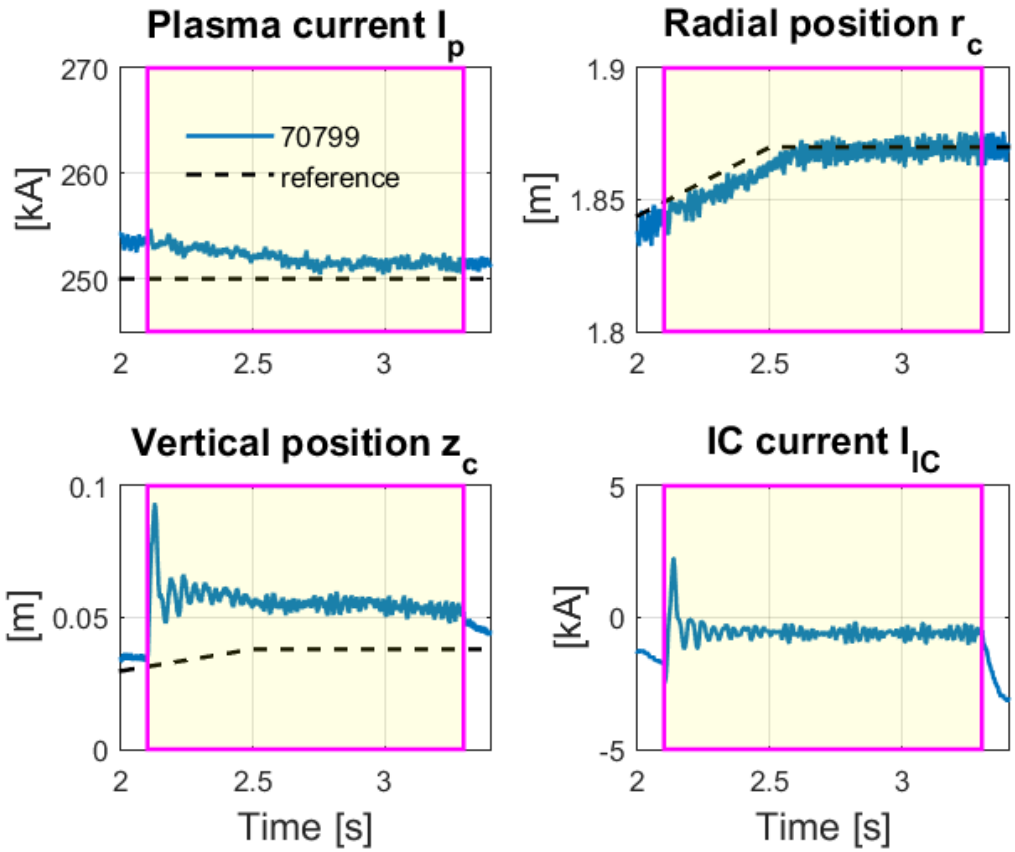

Figure: EAST pulse #70799. During this pulse the *ITER-like* VS was enabled from $t = 2.1$ s for 1.2 s, and only I_p and r_c were controlled, while z_c was left uncontrolled. This first test confirmed that the ITER-like VS vertically stabilized the plasma by controlling $\dot{z}_c$ and I_{IC}, without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

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Experimental results - 2/2

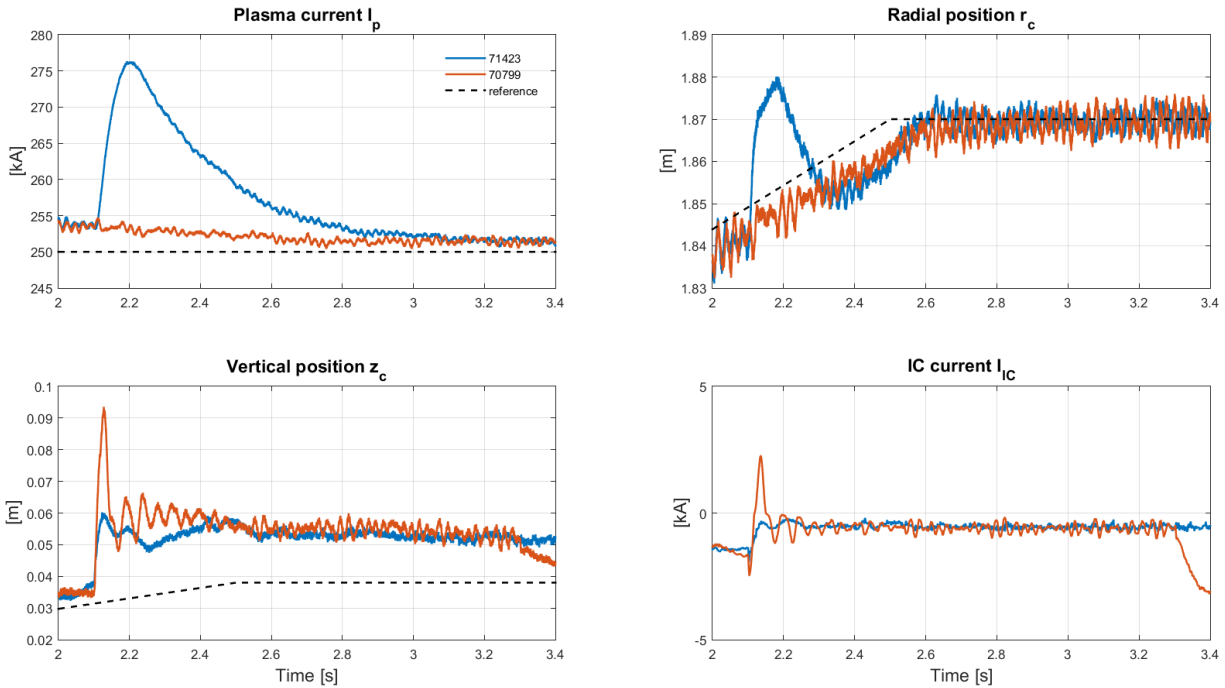

Figure: EAST pulses #70799 & #71423. Tuning of the controller parameters to reduce oscillations on z_c.

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Current decoupling controller

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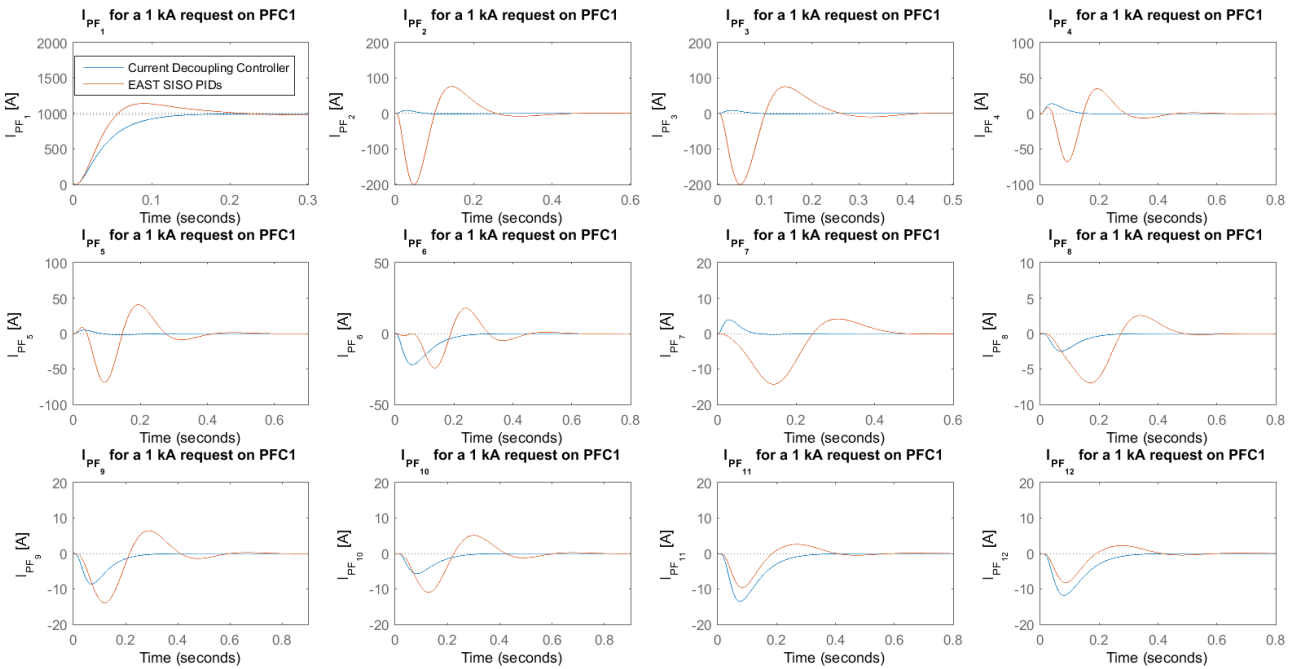

Figure: Comparison of different current control algorithms for a 1*kA* request on the EAST circuit *PFC*1. The proposed current decoupling controller improves the decoupling compared with the EAST SISO PIDs currently adopted (first tests planned in June-July 2017.

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