Plasma magnetic diagnostic and control at ITER & DEMO (& EAST)

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with contributions of the CREATE team
(and many colleagues from CCFE, ENEA, IST, ASIPP, . . .)

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Ettore Majorana Foundation and Centre for Scientific Culture
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Outline

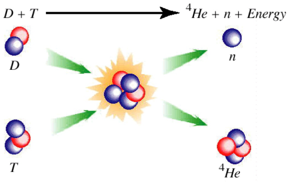
1. **Introduction**
   - Magnetic (control-oriented) modelling
   - Control engineering jargon & tools
   - The plasma magnetic control problem
2. **The proposed architecture for ITER (as a reference)**
   - ITER magnetic diagnostic
   - Vertical stabilization controller
   - Current decoupling controller
   - Plasma current controller
   - Plasma shape controller
   - Nonlinear validation
3. **The DEMO case**
   - Vertical stabilization at DEMO
4. **Experiments at EAST**
   - ITER-like vertical stabilization at EAST

Nuclear Fusion for Dummies

Main Aim

Production of energy by means of a fusion reaction

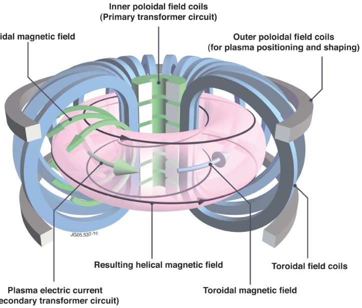
$$D + T \rightarrow {}^{4}\mathrm{He} + n$$



Plasma

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

Plasma magnetic control



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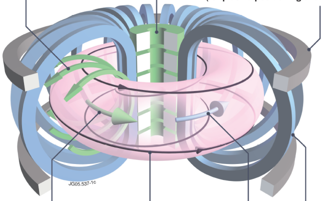
Plasma magnetic control



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- In order to obtain good performance, it is necessary to have a plasma with **vertically elongated cross section** $\Rightarrow$ **vertically unstable plasmas**

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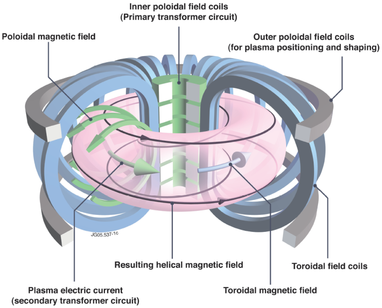

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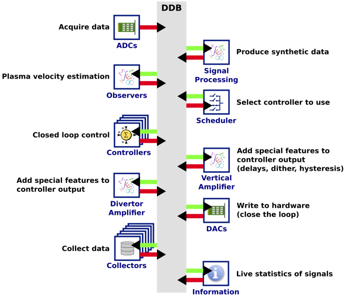
- In order to obtain good performance, it is necessary to have a plasma with **vertically elongated cross section** $\Rightarrow$ **vertically unstable plasmas**
- It is important to **maintain adequate plasma-wall clearance during operation**

Our final objective: build a control system



Main (basic) assumptions

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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

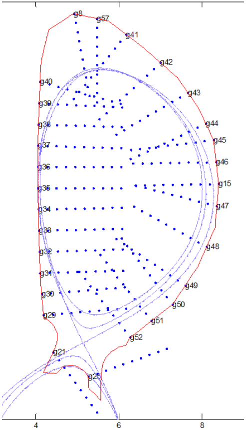
I_p , β_p and l_i

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

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

where:

- $\mathbf{y}(t)$ are the output to be controlled
- $\mathbf{I}(t) = \big[\mathbf{I}_{PF}^T(t)\ \mathbf{I}_e^T(t)\ I_p(t)\big]^T$ 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 $I_p(t)$
- $\mathbf{U}(t) = \big[\mathbf{U}_{PF}^T(t)\ \mathbf{0}^T\ 0\big]^T$ 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:

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

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

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**.

Asymptotic stability of LTI systems

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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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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

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

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

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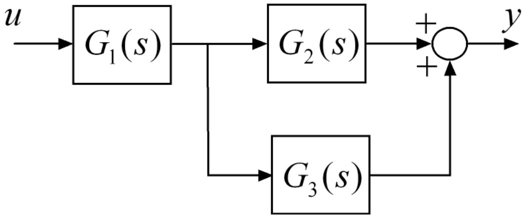
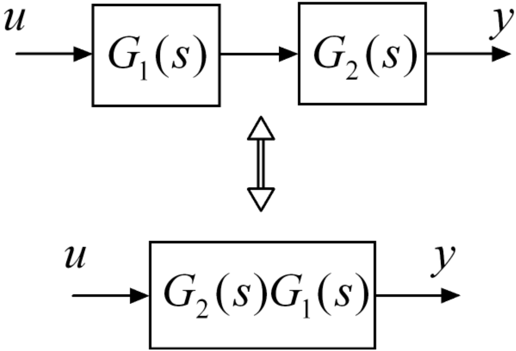
Every pole of $G(s)$ is an eigenvalue of the system matrix A.
However, not every eigenvalue of A is a pole of $G(s)$

Block diagrams

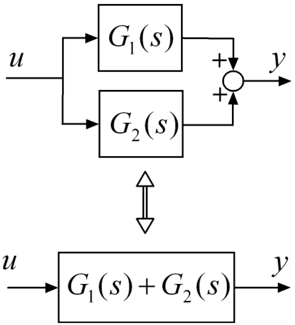
When dealing with transfer functions, it is usual to resort to *Block diagrams* which permit to graphically represent the interconnections between system in a convenient way.



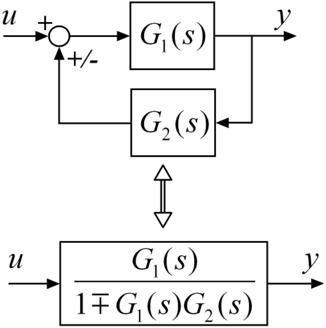
Series connection



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
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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

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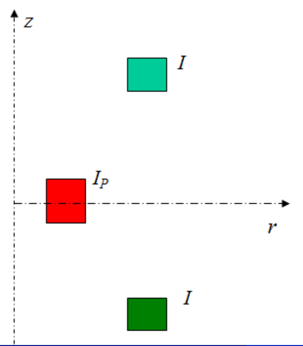
- **The VS is the essential magnetic control system!**

The plasma vertical instability

Simplified filamentary model

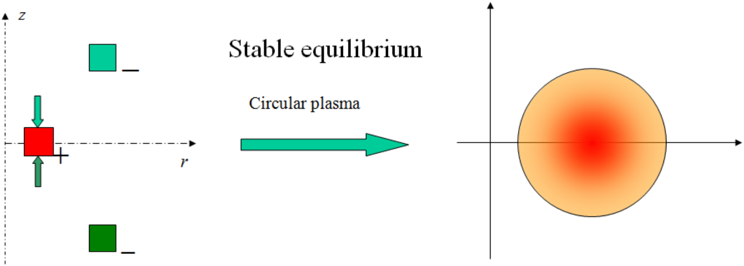
Consider the simplified electromechanical model with three conductive rings, two rings are kept fixed and in symmetric position with respect to the r axis, while the third can freely move vertically.



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 $\text{sgn}(I_p) \neq \text{sgn}(I)$



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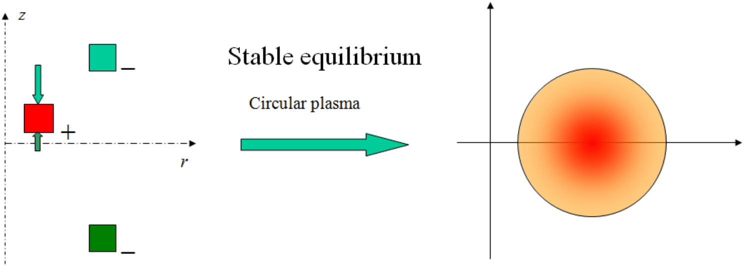

Unstable equilibrium - 1/2

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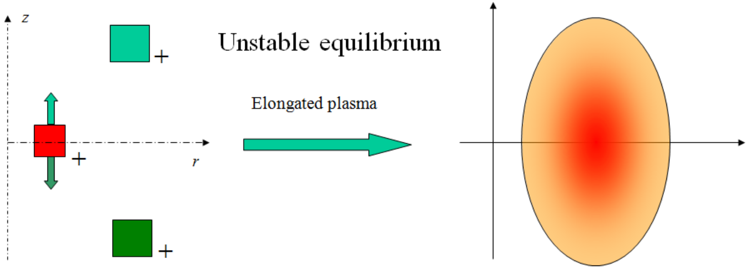

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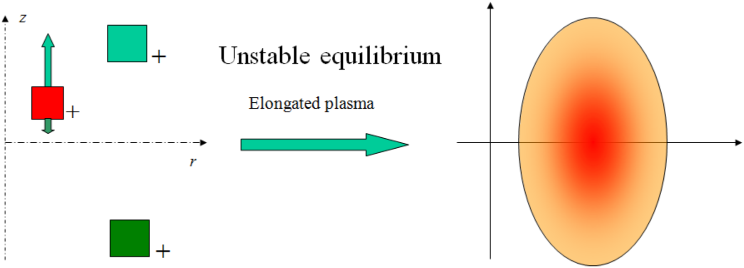

Plasma vertical instability

- 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

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)

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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, 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.

I need a break. What about you?

QUESTIONS?

Plasma magnetic system

Motivation

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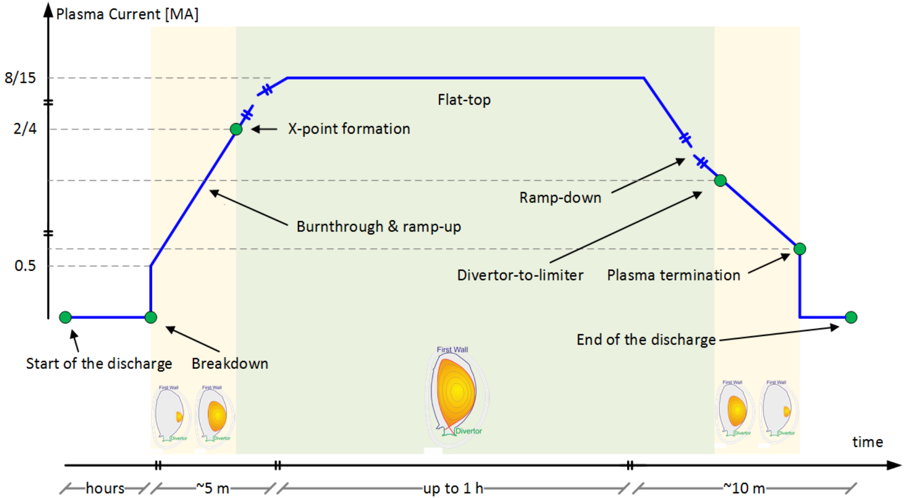
  - **is needed to robustly control elongated plasmas** in high performance scenarios

A tokamak discharge



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

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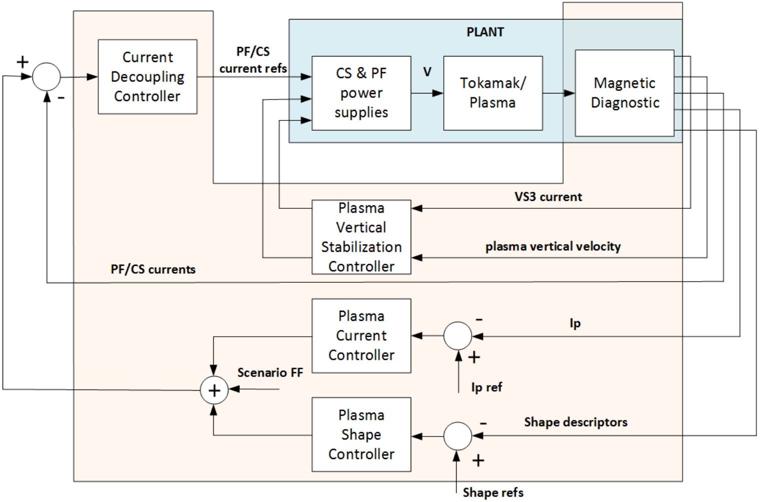
  - $\rightarrow$ the design procedures relies on (validated) control-oriented models for the response of the plasma and of the surrounding conductive structures
- The proposal is based on the JET experience
- The architecture has been proposed for ITER & DEMO (& JT-60SA) and partially deployed at EAST

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

A proposal for the ITER magnetic control system



The proposed architecture

- **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**

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- At ITER
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  - averaging on 3 sectors is sufficient to reduce the noise to acceptable levels
  - **The current studies for DEMO suggest to averaging measurements on at least 6 different sectors**

Example - ITER in-vessel *AA* probes

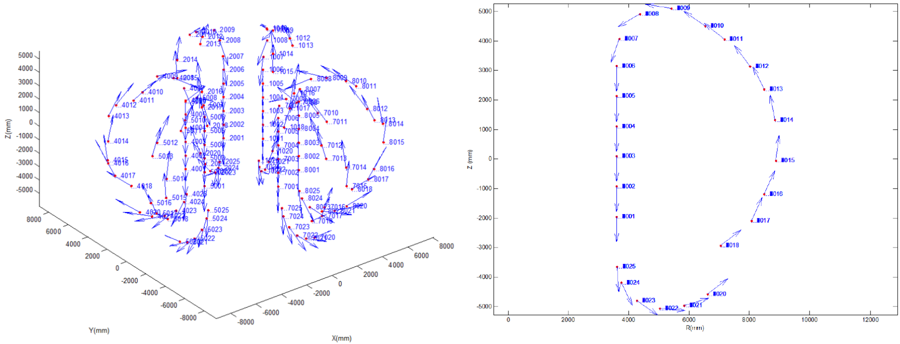

Figure: Positions of the *AA* probes in the ITER tokamak, according to the current design. The *AA* probes measure the magnetic field in six different sectors. On the right side the arrangement of the probes on one sector is shown.

In-vessel & out-vessel probes

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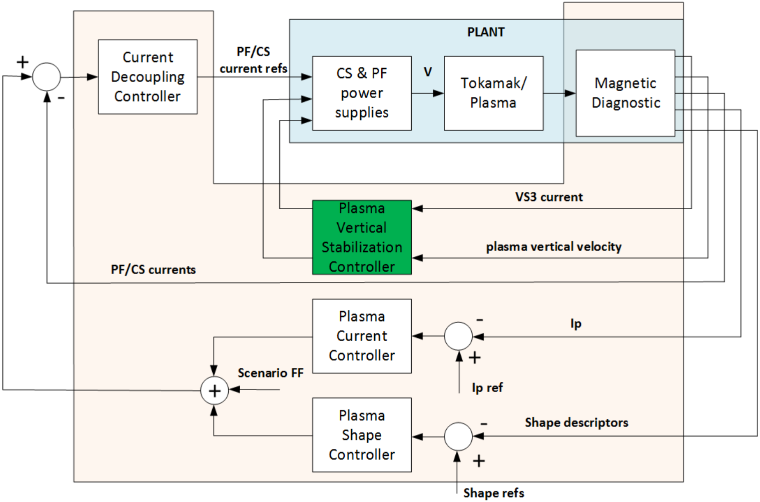
- In-vessel probes are used as **default** to reconstruct the plasma parameters that need to be controlled in real-time
- The use of out-vessel probes is currently envisaged only as **backup**, as a complete or partial replacement of the in-vessel coils

Architecture



The vertical stabilization controller

- The vertical stabilization controller has as input the centroid vertical velocity, and the current flowing in the $VS3$ circuit (an in-vessel coil set)
- It generates as output the voltage references for the $VS3$ and $VS1$ power supplies (which are the PF outboard coils)

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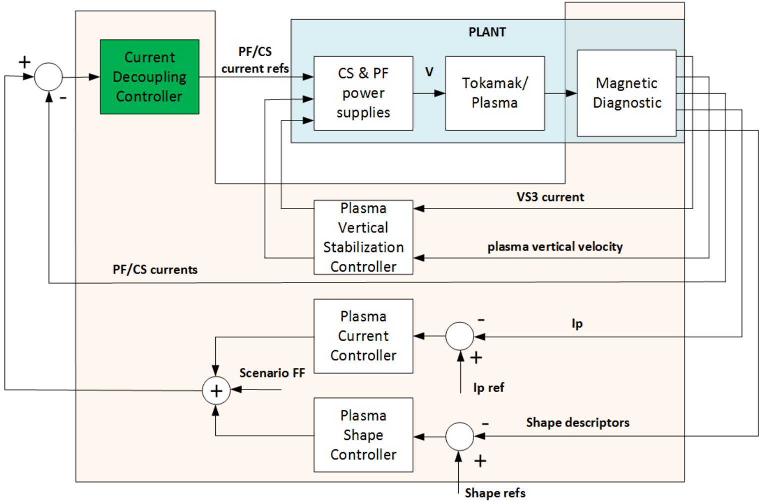

Current decoupling controller

- The current decoupling controller receives as input the 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

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:

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

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.

Current decoupling controller - Closed-loop transfer functions

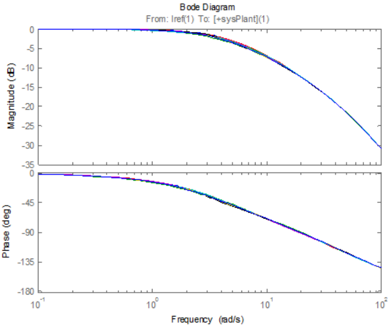


Figure: Bode diagrams of the *diagonal* transfer functions.

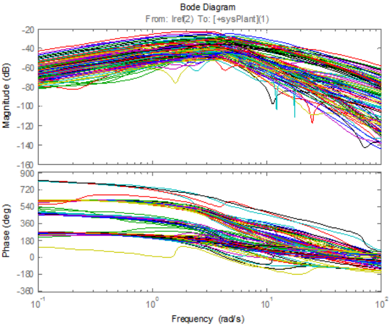
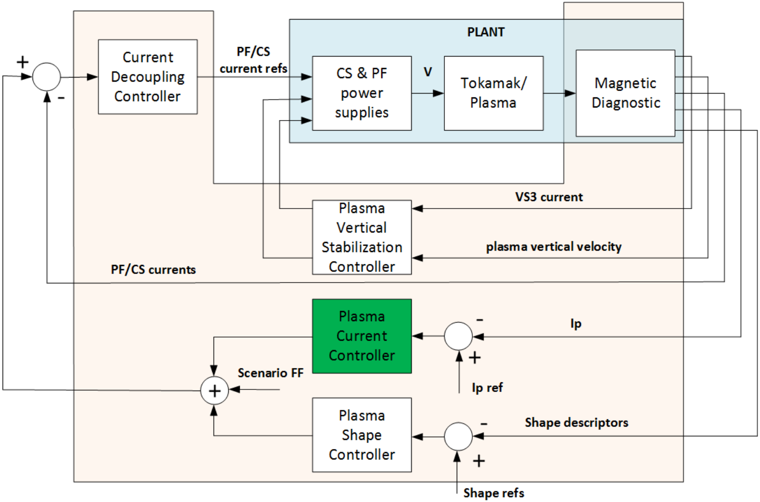


Figure: Bode diagrams of the *off-diagonal* transfer functions.

Architecture



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**

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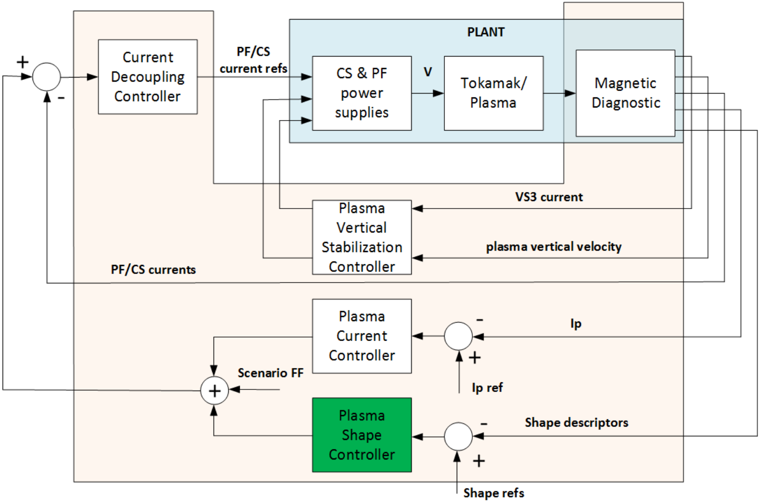
- **For ITER** it is important, for the plasma current, to track the reference signal during the **ramp-up** and **ramp-down** phases, the dynamic part of the controller $F_{I_p}(s)$ has been designed with a **double integral action**

The plasma shape controller



Plasma shape descriptors

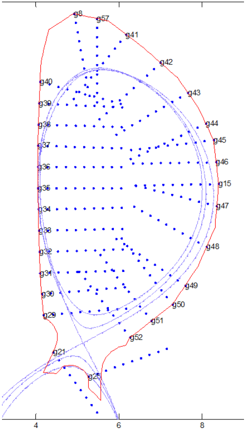


Figure: Control segments.

- 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 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

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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and statically

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

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

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- The XSC minimizes the cost function

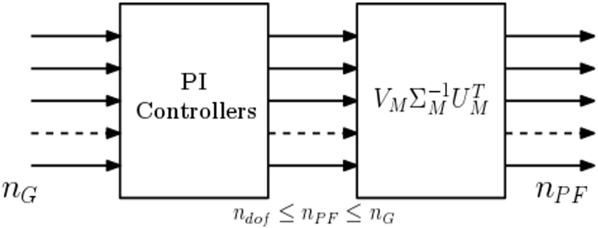
$$\widetilde{J}_1 = \lim_{t \to +\infty} (\delta Y_{ref} - \delta Y(t))^T Q^T Q (\delta Y_{ref} - \delta Y(t)) \,,$$

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

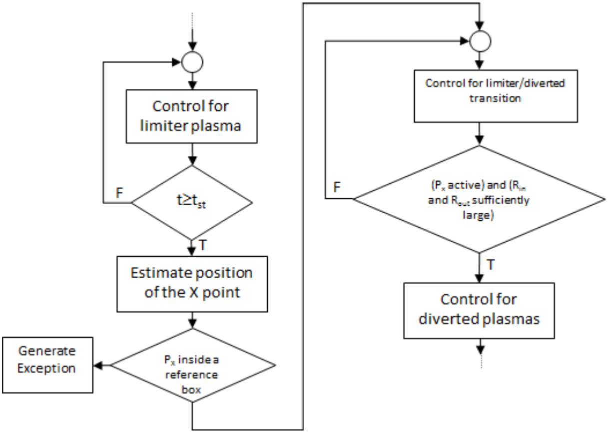
$$\widetilde{J}_2 = \lim_{t \to +\infty} \delta I_{PF_N}(t)^T R^T R \delta I_{PF_N}(t) \,.$$

(it contributes to avoid PF current saturations)

The *XSC-like* philosophy - 3/3



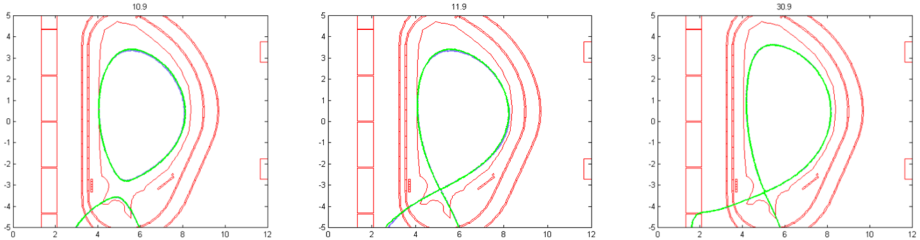
Plasma shape controller - Switching algorithm



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



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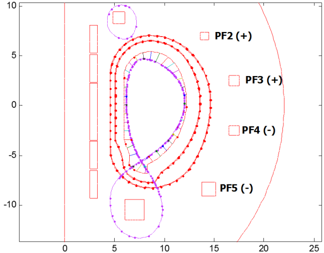
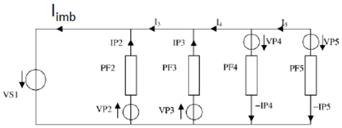
- The vertical velocity is controlled by the *imbalance* circuit that makes use of the $PF2-5$ coils

$$I_{imb} = I_{PF2} + I_{PF3} - I_{PF4} - I_{PF5}$$





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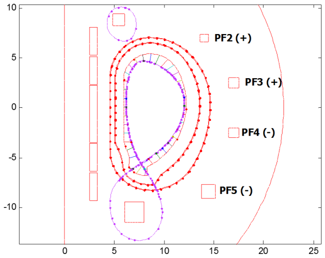

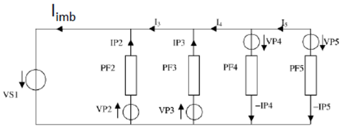

- The nominal (scenario) imbalance current should be as close as possible to zero to minimize the control power

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  - a *fast* one, to be used only if in-vessel probes are available **(it does not stabilize the plasma if out-vessel coils are used to reconstruct the vertical position)**
  - a *slow* one, can be be used also if out-vessel probes are used to reconstruct the plasma vertical position

Performance assessment - 1/3

- The performance of the DEMO VS have been evaluated in the presence of a VDE of 5 cm
- The vertical position reconstructed by using 60 measurements coming from in-vessel probes

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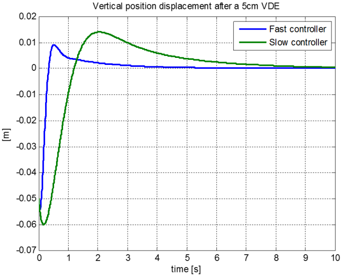
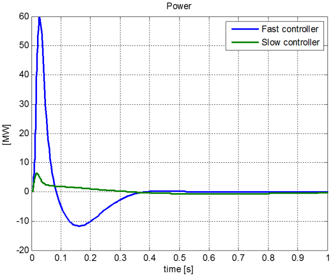




Performance assessment - 2/3

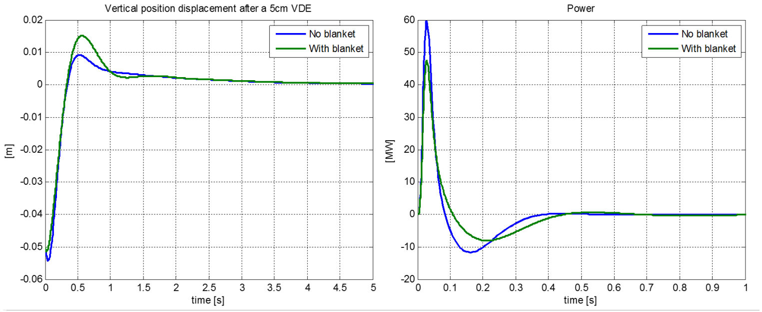
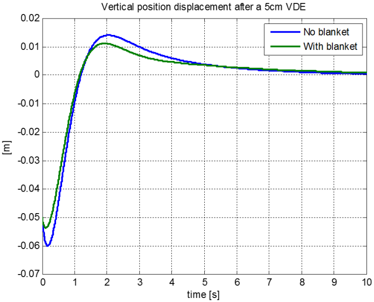


Figure: Effect of the blanket on the performance of the *fast* VS for DEMO.

Performance assessment - 3/3



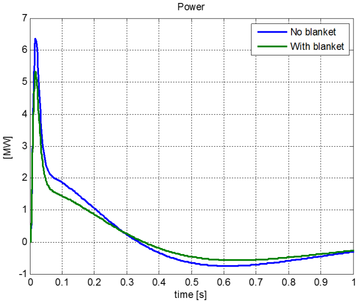


Figure: Effect of the blanket on the performance of the *slow* VS for DEMO.

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Probe irradiation in DEMO

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- In-vessel probes are only partially shielded by the blanket

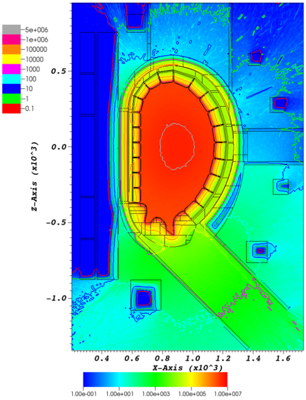


Figure: Irradiation map in DEMO in Gy/hr (T. Eade - CCFE).

Possible location of the DEMO in-vessel probes

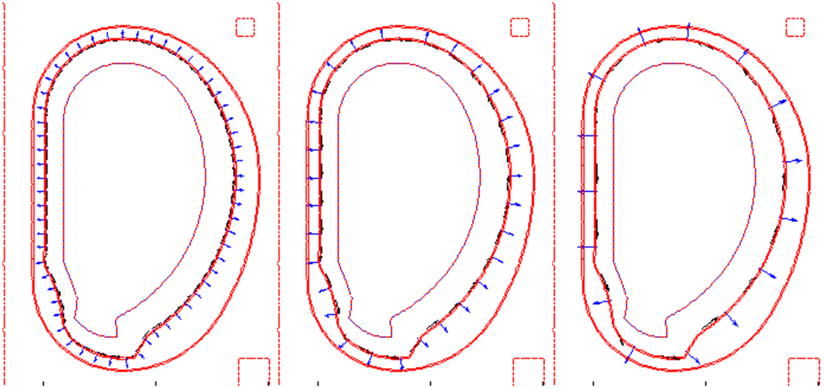


Figure: Tangential and normal pick-up coils used for the estimation of the basic plasma quantities (three different configurations: 118, 60, and 30 probes).

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

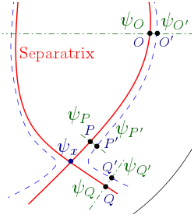


Figure: **Option #1** - integrated control of plasma shape and flux expansion.

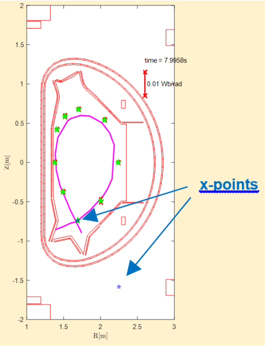
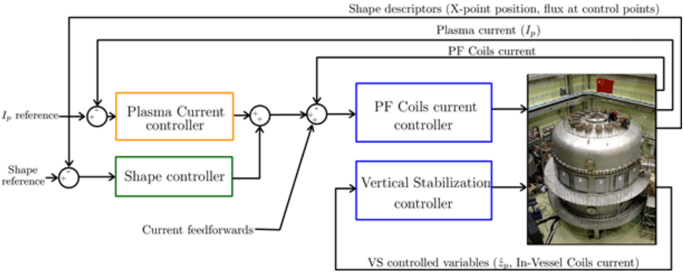


Figure: **Option #2** - integrated control of plasma shape and distance between null points.

EAST architecture



- The EAST architecture is *compliant* to the one proposed for ITER & DEMO

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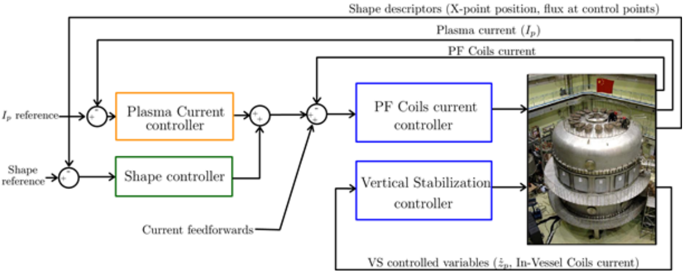

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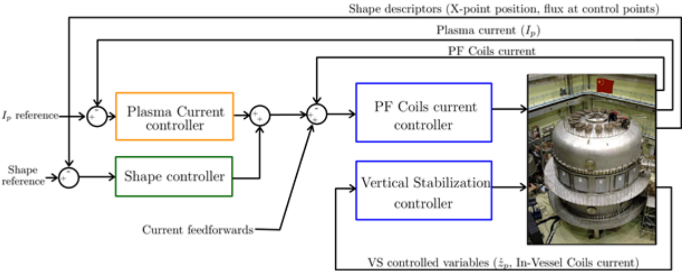

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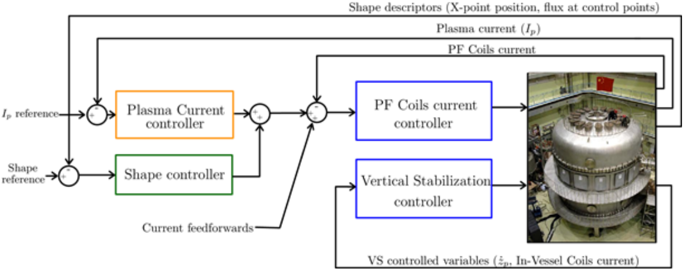

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- **The control algorithms deployed within the EAST PCS do not satisfy the requirements needed to easily replace the shape controller**
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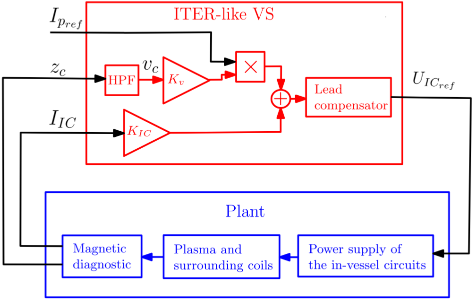
  - The PF Coils current controller can be improved (better decoupling)

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

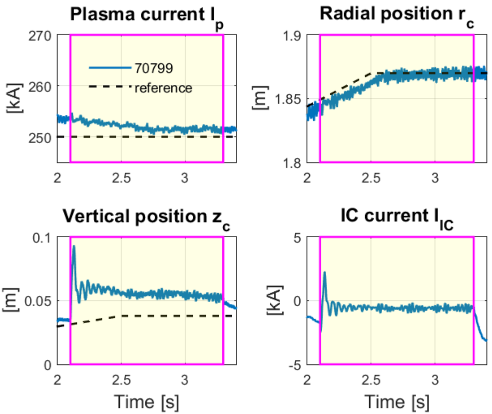


Figure: EAST pulse #70799. During this pulse the *ITER-like* VS was enabled from $t = 2.1$ s for 1.2 s, and only I_p and r_c were controlled, while z_c was left uncontrolled. This first test confirmed that the ITER-like VS vertically stabilized the plasma by controlling $\dot{z}_c$ and I_{IC}, without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

Experimental results - 2/2

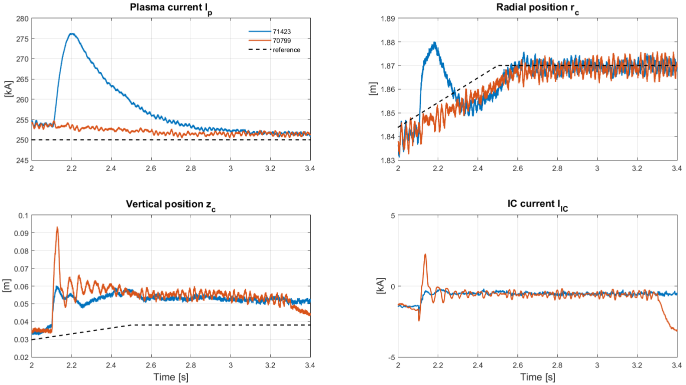


Figure: EAST pulses #70799 & #71423. Tuning of the controller parameters to reduce oscillations on z_c.

Current decoupling controller

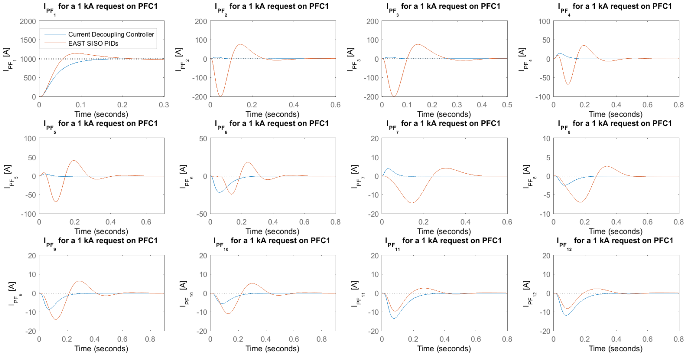


Figure: Comparison of different current control algorithms for a 1*kA* request on the EAST circuit *PFC*1. The proposed current decoupling controller improves the decoupling compared with the EAST SISO PIDs currently adopted (first tests planned in June-July 2017.

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MORE QUESTIONS?

Thank you!