Control of elongated plasmas in superconducting tokamaks in the absence of in-vessel coils

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IAEA TM on Plasma Disruption and Mitigation - ITER HQ, 3 Sep 2024

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

1 Motivation

2 Control Architecture

3 Control Algorithms: decoupling via a model-based geometric approach

4 Case study: magnetic control of the JT-60SA first operation reference scenario

Contributors

The content of this presentation is based on the work made with L. di Grazia, S. Dubbioso, F. Fiorenza, D. Frattolillo, S. Inoue, M. Mattei, A. Pironti and H. Urano, published on *Nucl. Fus.* 2024
https://doi.org/10.1088/1741-4326/ad4895

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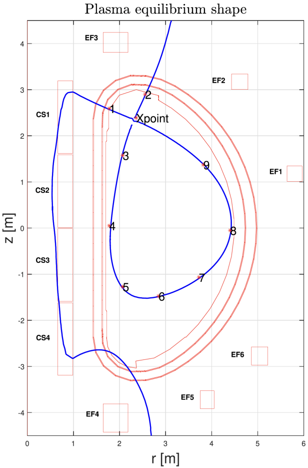

- Commissioning and first operations of superconductive tokamaks like ITER and JT-60SA envisage/have envisaged the possibility to **run discharges with elongated plasmas before the complete installation of the in-vessel components**

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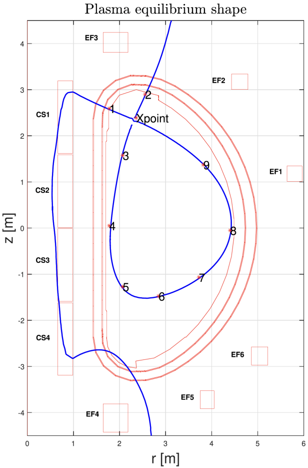
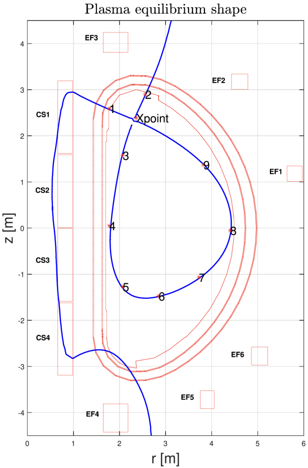


- Commissioning and first operations of superconductive tokamaks like ITER and JT-60SA envisage/have envisaged the possibility to **run discharges with elongated plasmas before the complete installation of the in-vessel components**
- The reference plasmas can be designed with a relatively low growth rate ($\gamma < 1\ s^{-1}$) and can be practically stabilized by the equilibrium control even without a **vertical stabilization (VS) system**



- Commissioning and first operations of superconductive tokamaks like ITER and JT-60SA envisage/have envisaged the possibility to **run discharges with elongated plasmas before the complete installation of the in-vessel components**
- The reference plasmas can be designed with a relatively low growth rate ($\gamma < 1\ s^{-1}$) and can be practically stabilized by the equilibrium control even without a **vertical stabilization (VS) system**
- However, due to
  - model uncertainties
  - disturbances that temporarily *move* the equilibrium far from the reference one
  - *loss* of the passive stabilization of the superconductive coils (when driven in current control mode)

  even slightly elongated *fat* plasmas may practically exhibit a relatively high growth rate ($\gamma \cong 10\ s^{-1}$)
- **Hence, plasma operation would benefit by the presence of an explicit VS system** that shares the superconductive actuators with the other plasma magnetic control tasks

The superconductive PF coils system

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- . . .however, in absence of in-vessel coils, they should be used also to guarantee plasma vertical stability and react to fast disturbance, e.g. poloidal beta variations that induce fast radial movements. . .
- . . .are shared by the various magnetic control tasks, therefore **effective actuator sharing policies among the various magnetic tasks is necessary**

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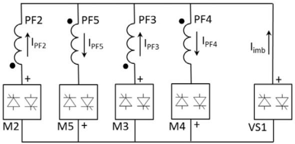

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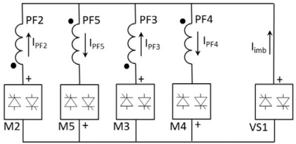

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  - **ITER** → the so-called *VS3* circuit and the corresponding dedicated power supply
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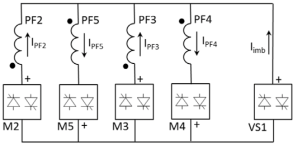

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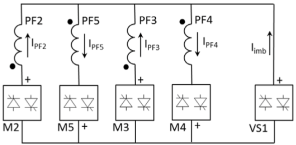
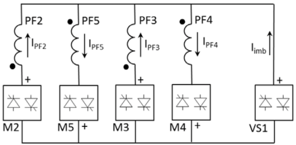
- **Even when dedicated actuator (coils + power supply) are available, effective decoupling between VS and the other magnetic control tasks is necessary (also in the frequency domain)**

Actuator sharing: the ITER VS1 example

At ITER coils PF2-PF5 are shared among

- the plasma current & shape controller, that sends voltage requests to the Main Converters MC2-MC5 **(yet another actuator sharing problem!)**
- the VS system, that sends voltage requests to the VS1 power supply





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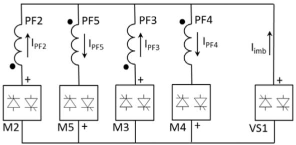
    $\rightarrow$ the VS system is a multi-input-multi-output (MIMO) control system and the voltage conversion is equivalent to a multiplication by the vector $(0\ 0\ 0\ 0\ 0\ 0\ 1\ 1\ -1\ -1\ 0)$
  - The linear combination of PF2-PF5 voltages can be treated as a **virtual actuator** (in the ITER case with a dedicated power supply)



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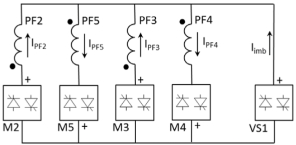

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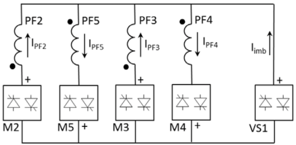

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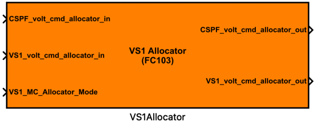
A geometric decoupling approach: the ITER PCS VS1 allocator



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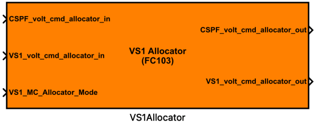

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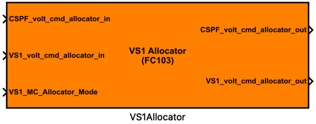

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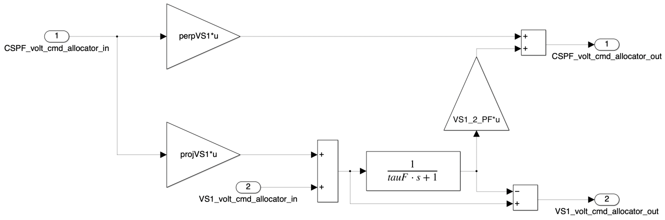
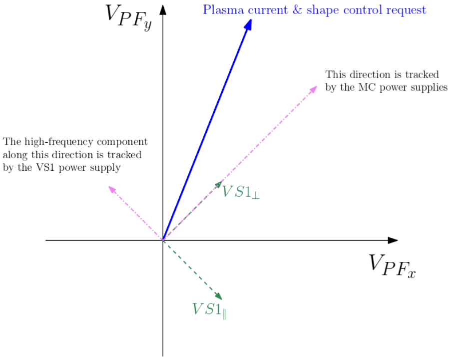
The ITER PCS VS1 allocator





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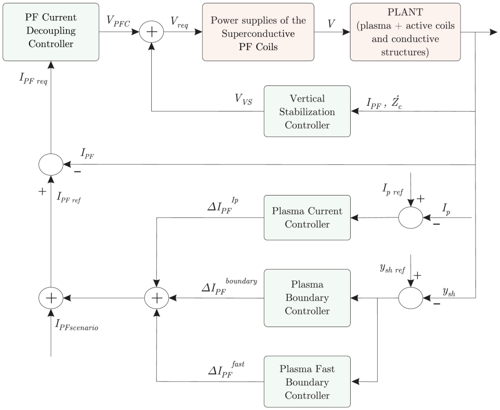

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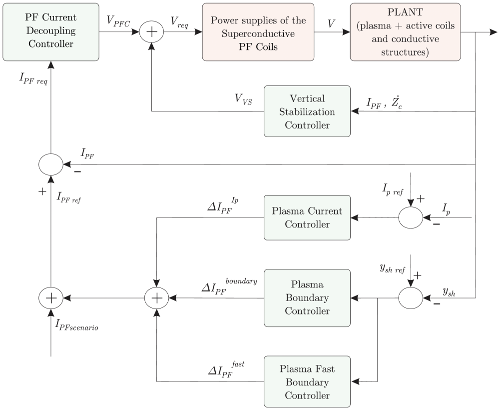
- **The ITER control approach can be easily extended to the case of no dedicated power supply and coils for the VS**

The proposed functional architecture



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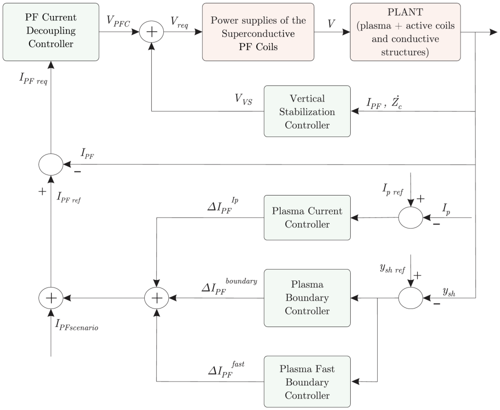

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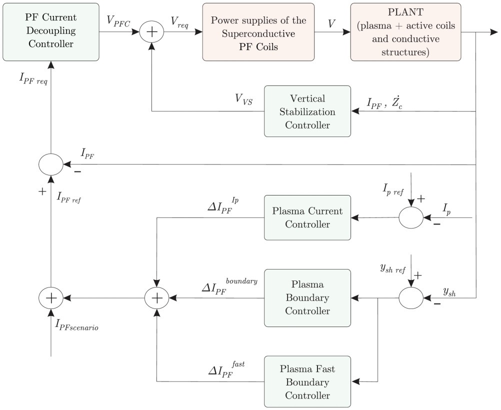

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- It exploits geometric decoupling in both the PF current and voltage spaces→ the geometric approach requires a **reliable** (control-oriented) **model** to compute the *projection* matrices

Starting from a nonlinear lumped parameters model, the following **linearized state-space model** of the plasma-circuit behaviour can be obtained:

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

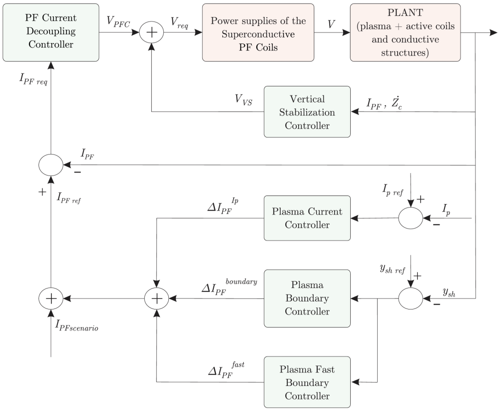
$$\delta\mathbf{y}(t) = \mathbf{C}\cdot\delta\mathbf{I}_{PF}(t) + \mathbf{F}\cdot\delta\mathbf{w}(t), \quad (2)$$

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
- $\delta\mathbf{u}(t) = \left[\delta\mathbf{V}_{PF}^T(t)\ \mathbf{0}^T\ 0\right]^T$ 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 proposed functional architecture



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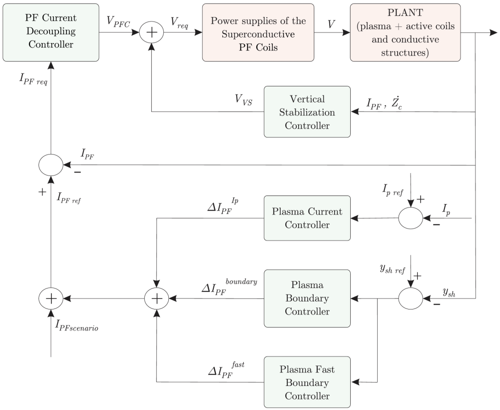
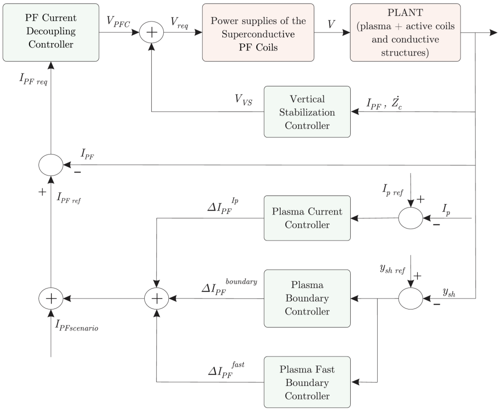


The architecture includes:

- one inner PF Current (PFC) Controller
- three outer loops, that compute corrections wrt nominal scenario currents (they share the PF currents as *actuators*)
  - Plasma Current Controller
  - Plasma Boundary Controller
  - Plasma Fast Boundary Controller **(to react to fast disturbances)**



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- a voltage-driven loop, that acts as VS system and shares (with the PFC Current Controller) the PF voltages as actuators

The PFC controller

- The design of the PFC controller exploits a standard MIMO model-based approach based on the mutual inductance matrix $\widetilde{\mathbf{L}}_{PF}$ in absence of plasma (*plasmaless*)
- The approach is the one adopted at JET (see Sartori *et al.*, *IEEE Contr. Sys. Mag.* 2006) and tested also on EAST (De Tommasi *et al.*, *Fus. Eng. Des.* 2018)

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Control law

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

where

$$\mathbf{K}_{PF} = \widetilde{\mathbf{L}}_{PF} \cdot \Lambda \,, \quad \Lambda = \begin{pmatrix} 1/\tau_{PF1} & 0 & \dots & 0 \\ 0 & 1/\tau_{PF2} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 1/\tau_{PF_n} \end{pmatrix}$$

The Λ matrix allows to set the closed-loop time constants of the PF circuits, i.e.

$$\frac{d}{dt} I_{PF} + \Lambda \cdot I_{PF} = \Lambda \cdot I_{PF_{ref}} \,,$$

hence, in closed-loop the PF circuits do not behave as superconductors anymore

How the presence of the PFC controller affects the equilibria stability

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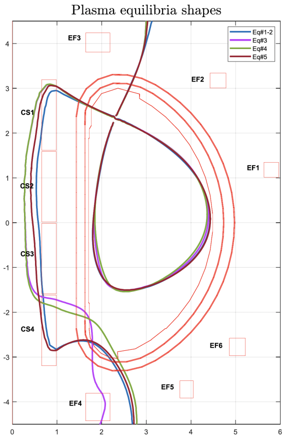

JT-60SA equilibria					
	l_i	β_p	κ	A	γ (s^{-1})
Eq#1	0.78	0.14	1.46	2.42	0.36
Eq#2	0.78	0.13	1.47	2.43	1.13
Eq#3	1.16	0.15	1.50	2.52	4.02
Eq#4	1.16	0.15	1.54	2.55	7.64
Eq#5	0.85	0.83	1.45	2.55	Stable

Growth rates comparison			
	γ (s^{-1})	γ_{NC} (s^{-1})	γ_R (s^{-1})
Eq#1	0.36	7.00	6.83
Eq#2	1.13	7.81	7.62
Eq#3	4.02	10.01	9.78
Eq#4	7.64	13.48	13.20
Eq#5	Stable	2.33	2.27

- γ_{NC} is the growth rate obtained by removing from the plasma linear model all the SC coils
- γ_R is the growth rate obtained by considering a resistance of $\sim$ 100 Ω for the PF coils (to emulate the closed-loop time constant due to the presence of the PFC)

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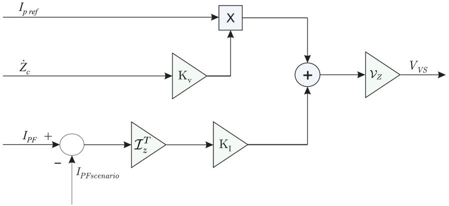
The VS controller



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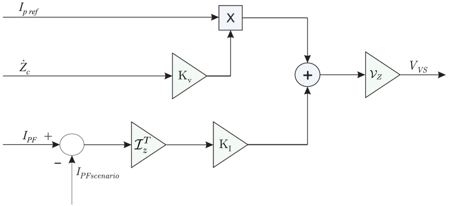

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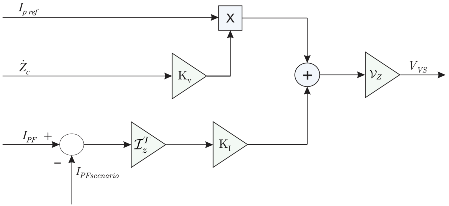

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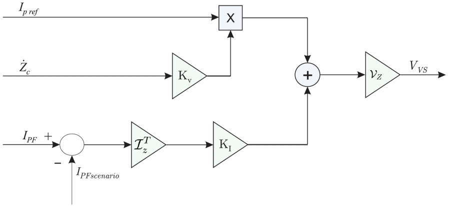

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- The linear combination of currents $\mathcal{I}_Z$ can be seen as **virtual circuit** for the VS
- The voltages V_{VS} are chosen to ideally drive the PF currents along the direction given by the vector $\mathcal{I}_Z$ (by distributing the voltages according to $\mathcal{V}_z = -\widetilde{\mathbf{L}}_{PF} \cdot \mathcal{I}_z$)

Two possible way to design the $\mathcal{I}_z$ vector are

- to select two up-down symmetric coils and scale them up by the corresponding number of turns
- to solve a Quadratic Programmin (QP) optimization problem to maximizes the radial field on a grid taking into account additional constraints. Example

$$\min \frac{1}{2} \cdot \delta \mathbf{I}_{PF} \cdot \mathbf{C}_{\widetilde{B}_z}^T \cdot \mathbf{C}_{\widetilde{B}_z} \cdot \delta \mathbf{I}_{PF} \,, \tag{3}$$

subject to

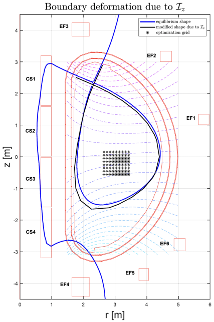
$$\mathbf{C}_{\widetilde{B}_r} \cdot \delta \mathbf{I}_{PF} \geq B_T \cdot \mathbf{1}_{n_{PF}} \,, \tag{4a}$$

$$\overline{\delta \mathbf{I}}_{PF} \geq \delta \mathbf{I}_{PF} \geq \underline{\delta \mathbf{I}}_{PF} \,, \tag{4b}$$

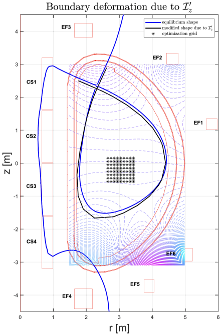
where

- $\mathbf{C}_{\widetilde{B}_z}, \mathbf{C}_{\widetilde{B}_r} \in \mathbb{R}^{m \times n_{PF}}$ are the linear relationship between the PF currents and the vertical $\widetilde{\mathbf{B}}_z$ and radial $\widetilde{\mathbf{B}}_r$ of the poloidal magnetic field on a grid of m points
- $\overline{\delta \mathbf{I}}_{PF}$ and $\underline{\delta \mathbf{I}}_{PF}$ are used to hardly limit the control effort and/or to force some of the PF coils currents to be nonpositive or nonnegative

Possible choices for JT-60SA first operations

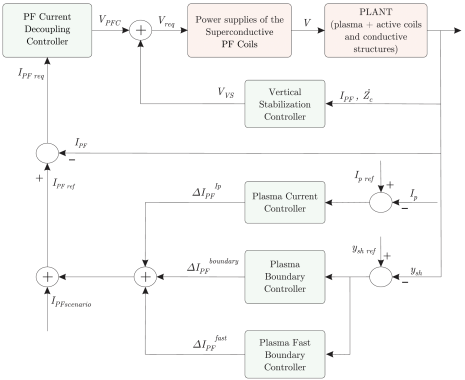


(b)



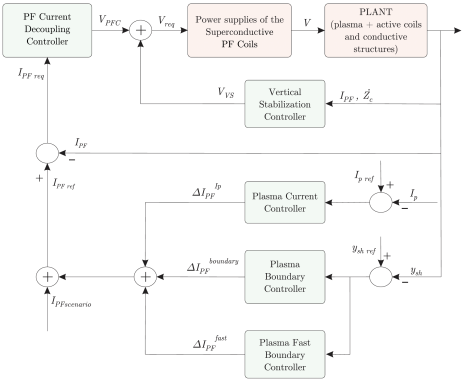
VS virtual circuit	$\widetilde{B}_{r_{\min}}$ (mT)	$\widetilde{B}_{r_{\max}}$ (mT)	$\widetilde{B}_{z_{\min}}$ (mT)	$\widetilde{B}_{z_{\max}}$ (mT)
$\mathcal{I}_z$	4.1	4.7	−0.6	0.4
$\mathcal{I}'_z$	4.1	5.6	−0.1	0.1

- $\mathcal{I}_Z = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0.76 & -0.65 & 0 & 0 \end{pmatrix}^T$ A has been designed selecting two up-down symmetric coils (EF3-EF4)
- $\mathcal{I}'_Z = \begin{pmatrix} 0 & 0 & 0 & 0 & 0.04 & -0.07 & 0.24 & -0.63 & 0.71 & -0.21 \end{pmatrix}^T$ A exploits all the EF coils (without constraining up-down symmetry)



- The **Fast Boundary Controller** is included in the proposed architecture to react to fast plasma shape variations due to external disturbances

The Fast Boundary Controller



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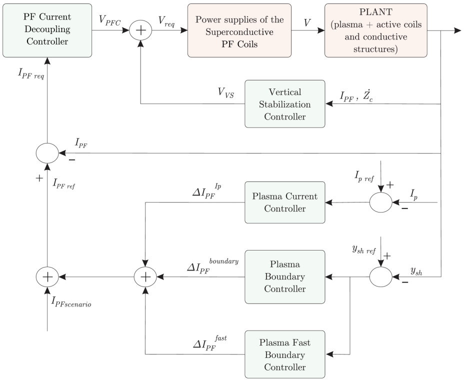
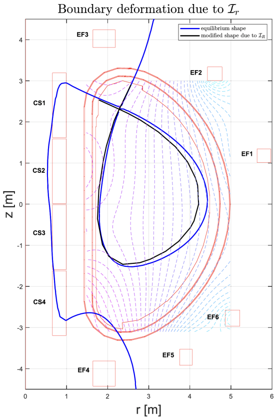


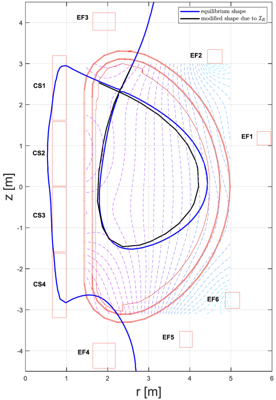
- The **Fast Boundary Controller** is included in the proposed architecture to react to fast plasma shape variations due to external disturbances
- It is designed to induce a specific deformation to balance the one caused by the foreseen disturbance, which depend also on the reference equilibrium
- The Fast Boundary Controller is exploited to promptly counteract the Horizontal Displacement Events (HDE) induced by the switching of the additional heating systems, which in turn correspond to a β_p variation



- The plasma model is exploited to compute a linear combination of PF currents $\mathcal{I}_r \in \mathbb{R}^{n_{PF}}$ (virtual circuit) that induces a plasma deformation capable to counteract the one caused by the envisaged β_p

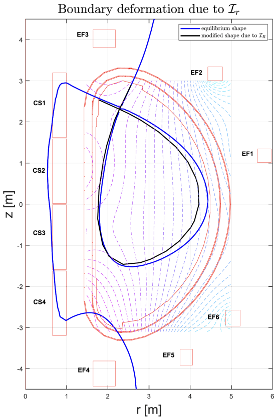
The Fast Boundary Control Direction

Boundary deformation due to $\mathcal{I}_r$



- The plasma model is exploited to compute a linear combination of PF currents $\mathcal{I}_r \in \mathbb{R}^{n_{PF}}$ (virtual circuit) that induces a plasma deformation capable to counteract the one caused by the envisaged β_p
- Being $\mathbf{C}_{sh} \in \mathbb{R}^{n_{sh} \times n_{PF}}$ the linear relationship between the currents in the PF circuits and the controlled plasma shape descriptors $\mathbf{y}_{sh} \Rightarrow \mathcal{Y}_r = \mathbf{C}_{sh} \cdot \mathcal{I}_r$ is an estimation of the plasma deformation due to $\mathcal{I}_r \rightarrow$ a reliable model is needed!

The Fast Boundary Control Direction



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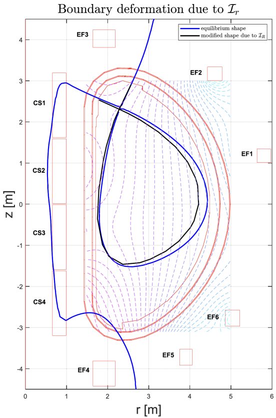

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- $\mathcal{Y}_r$ represents the *direction* in the space of the chosen plasma shape descriptors that is controlled by the linear combination $\mathcal{I}_r$
- $\mathcal{Y}_r$ is chosen to be *as similar as possible* to the mainly outboard deformation induced by β_p variations

- The couple $(\mathcal{I}_{\mathbf{r}}, \mathcal{Y}_{\mathbf{r}})$ allows to control the plasma along the desired *direction* in the space of the controlled plasma boundary descriptors by means of the Single-Input-Single-Output (SISO) controller

$$\Delta \mathbf{I}_{PF}^{fast}(s) = -\mathcal{I}_{\mathbf{r}} \cdot K_{fast}(s) \cdot \mathcal{Y}_{\mathbf{r}}^{\mathbf{T}} \cdot \mathbf{Y}_{sh}(s)$$

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- A possible choice for the dynamic part of the controller $K_{fast}(s)$ is a Proportional Integral (PI) one, i.e.

$$K_{fast}(s) = K_P + \frac{K_I}{s}$$

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    $\rightarrow$ implies decoupling with the VS
  - The diagonal transfer matrix $K_{boundary}(s)$ contains a set of n_{PF} regulators needed to improve the dynamic response of the controller

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- This allows to decouple the I_p control from both the VS and the Fast Boundary Control
- By denoting with $\mathcal{I}^{\perp}$ a matrix whose columns form an orthonormal basis of $\ker\left[\begin{pmatrix}\mathcal{I}_z & \mathcal{I}_r\end{pmatrix}\right]$, the plasma current control law is given by

$$\Delta \mathbf{I}_{PF}^{I_p}(s) = \mathcal{I}^{\perp} \cdot \mathcal{I}_{\mathbf{I_p}} \cdot K_{I_p}(s) \cdot \left(I_{p_{ref}}(s) - I_p(s)\right)$$

- $\mathcal{I}_{\mathbf{I_p}}$ is the linear combination of PF current that provides the so-called *transformer field*

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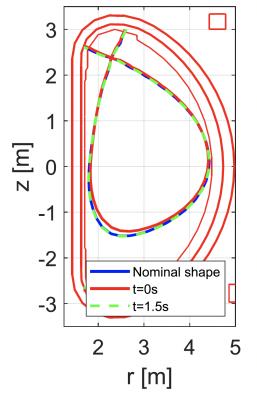
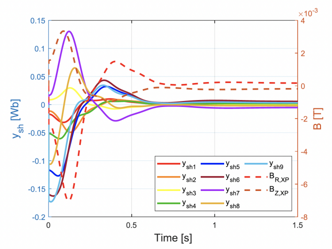
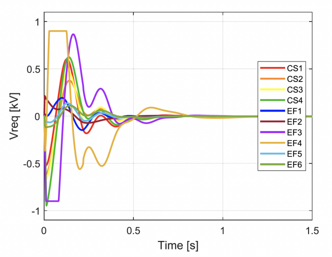
4 Case study: magnetic control of the JT-60SA first operation reference scenario

Nonlinear simulation of a 6 cm VDE

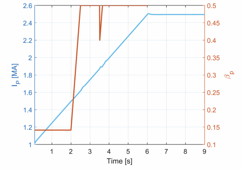


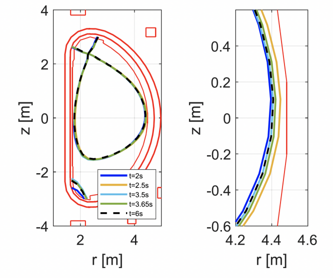


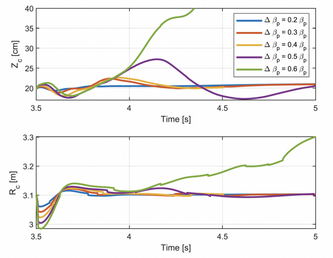


β_p drop

β_p drop during ramp-up







Conclusions

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- Control gains are tuned against the reference scenario $\Rightarrow$ reliable control-oriented (linear) plasma models are necessary for the target equilibria
- The proposed architecture is an **extension** of the one included in the ITER PCS, where the geometric approach is exploited
  - to manage actuator sharing among VS1 and Shape Control
  - to achieve decoupling between plasma shape and I_p control

Control of elongated plasmas in superconducting tokamaks in the absence of in-vessel coils

Gianmaria De Tommasi – CREATE/Università di Napoli Federico II – Italy
Email: detommas@unina.it

IAEA TM on Plasma Disruption and Mitigation - ITER HQ, 3 Sep 2024

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