Magnetic equilibrium and instability control

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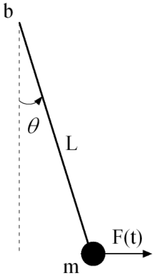
Outline

1. Why closed loop control? (repetita iuvant)

2. Plasma magnetic control
   - Current decoupling controller
   - Plasma current controller
   - Plasma shape controller
   - Vertical stabilization controller

A pendulum



- mass m
- length L
- rotational friction b

State space model of a pendulum

Let

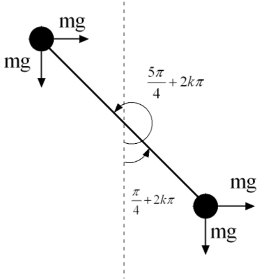
$$x(t) = \begin{pmatrix} x_1(t) \\ x_2(t) \end{pmatrix} = \begin{pmatrix} \theta(t) \\ \dot{\theta}(t) \end{pmatrix} \qquad u(t) = F(t) \qquad y(t) = x_1(t) = \theta(t)$$

Then

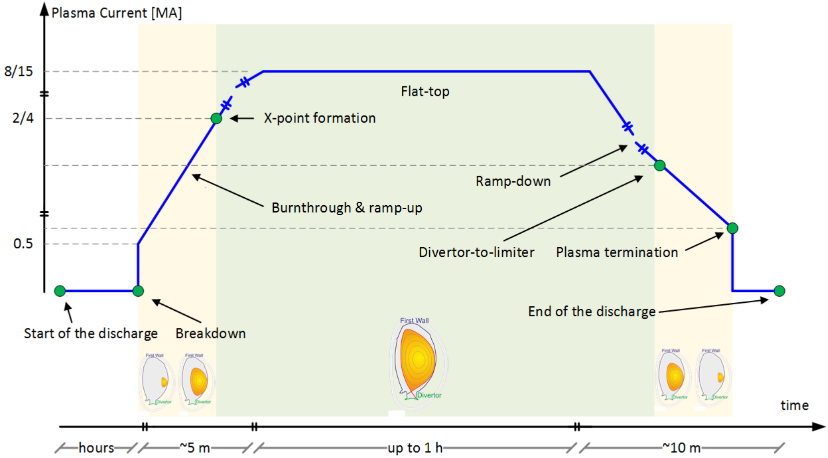
$$\begin{aligned} \dot{x}_1(t) &= x_2(t) \\ \dot{x}_2(t) &= -\frac{g}{L}\sin x_1(t) - \frac{b}{mL^2}x_2(t) + \frac{1}{mL}\cos x_1(t)u(t) \\ y(t) &= x_1(t) \end{aligned}$$

If $\bar{u} = mg$, by letting $f(\bar{x}, \bar{u}) = 0$ it is possible to compute the equilibrium points (states)

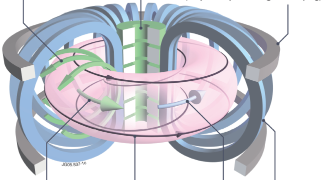
$$\bar{x}_k = \begin{pmatrix} \frac{\pi}{4} + k\pi \\ 0 \end{pmatrix}$$



A tokamak discharge



The currents in the Poloidal Field (PF) coils can be used to control the plasma equilibrium (current, shape and position) $\rightarrow$ no more a SISO problem (as the pendulum $\rightarrow$ MIMO control system



Plasma (axisymmetric) magnetic control

- deals with the control of the equilibrium (*plasma configuration*)
- includes
    - the shape and position control problem
    - the plasma current control problem
    - the vertical stabilization problem
- is needed to *robustly* control the equilibrium (against model uncertainties + unmodeled behaviours + disturbances)

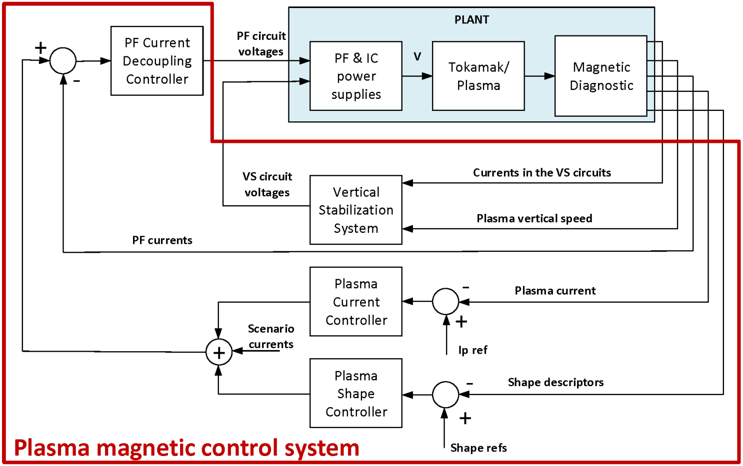
The plasma axisymmetric control system

- A magnetic control system shall be able to operate the plasma for the 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 and is currently one of the proposal for ITER

M. Ariola and A. Pironti
Plasma Shape Control for the JET tokamak
IEEE Contr. Sys. Magazine, 2005

F. Sartori *et al.*
The Joint European Torus - Plasma position and shape control in the world's largest tokamak
IEEE Contr. Sys. Magazine, 2006

The proposed architecture - 1/2



The proposed architecture - 2/2

- **Four independent controllers**
  - Current decoupling controller
  - Vertical stabilization controller
  - Plasma current controller
  - Plasma shape controller
- **The parameters of each controller can change according to events generated by an external supervisor**
  - **Clock events $\rightarrow$ time-variant parameters**
  - **Asynchronous events $\rightarrow$ exception handling**

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
- $\mathbf{I}(t) = \begin{bmatrix}\mathbf{I}_{PF}^T(t) \ \mathbf{I}_e^T(t) \ I_p(t)\end{bmatrix}^T$ 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 $I_p(t)$
- $\mathbf{U}(t) = \begin{bmatrix}\mathbf{U}_{PF}^T(t) \ \mathbf{0}^T \ 0\end{bmatrix}^T$ 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 linear model

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

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

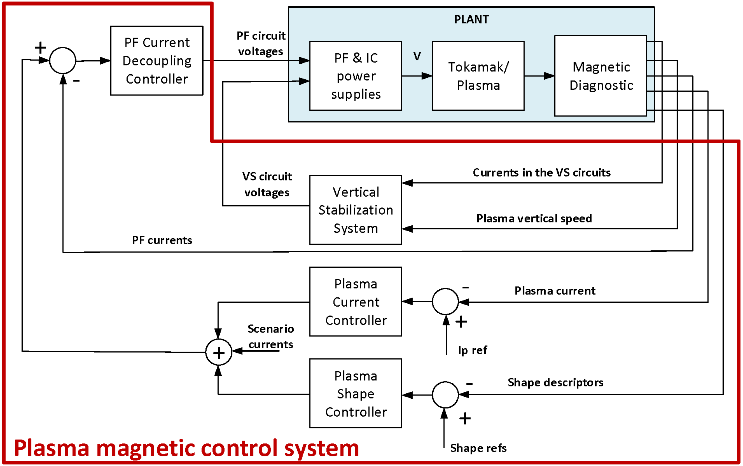
$$\delta\mathbf{y}(t) = \mathbf{C}\,\delta\mathbf{x}(t) + \mathbf{F}\delta\mathbf{w}(t), \tag{2}$$

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

Architecture



Current decoupling controller

- The current decoupling controller receives as input the PF circuit currents and their references, and generate in output the voltage references for the power supplies
- The PF circuit current references are generated as a sum of **three terms** coming from
  - a **supervisor**, which provides the **feedforwards needed to track the desired scenario (usually specified in the *pulse schedule*)**
  - 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

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:

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

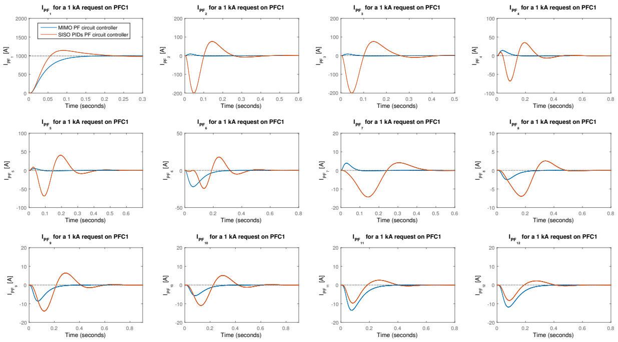
3 The voltages to be applied to the PF circuits are then calculated as:

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

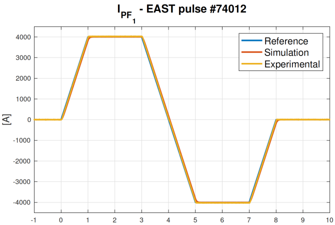
where

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

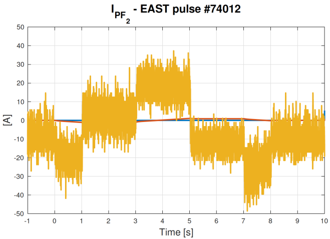
F. Maviglia *et al.*
Improving the performance of the JET Shape Controller
Fus. Eng. Des., vol. 96–96, pp. 668–671, 2015.



Simulation showing the comparison between a MIMO PF current controller designed exploiting a model-based approach, and the *EAST standard* PF current controller based on SISO PIDs



(a) PF1 current

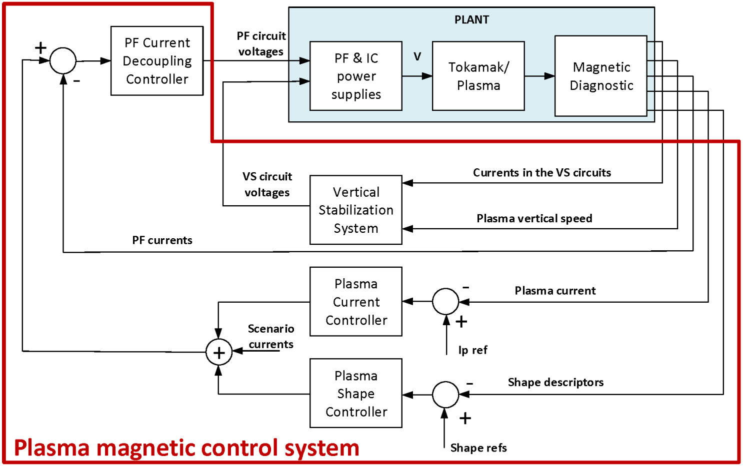


(b) PF2 current

Comparison between the simulated and the experimental values for the currents in both the PF1 and PF2 circuits for the EAST pulse #74012

- Plasma current can be controlled by using the current in the PF coils
- **Shared actuators (PF currents)** $\rightarrow$ the problem of tracking the plasma current can be considered simultaneously with the shape control problem
- Shape control and plasma current control are compatible
  - it is possible find a linear combination of PF currents that generates a flux that is spatially uniform across the plasma
  - this linear combination can be used to drive the current without affecting (too much) the plasma shape

Architecture



The plasma current controller

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

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

- **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 $F_{I_p}(s)$ can been designed so as to include **double integral action**

Shape and position control problem

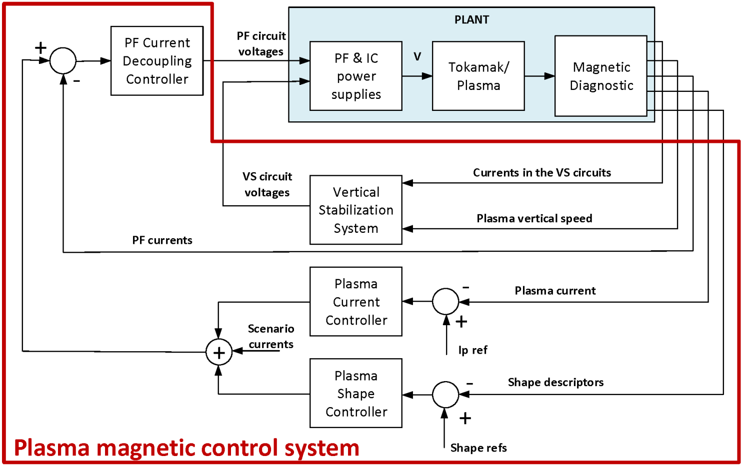
- At the beginning of the discharge usually only the position of the centroid is controlled
- Plasma shape controller is switched on as far as plasma boundary reconstruction is sufficiently accurate (depending on eddy currents)
- The controlled variables are a finite number of plasma shape descriptors

Objectives

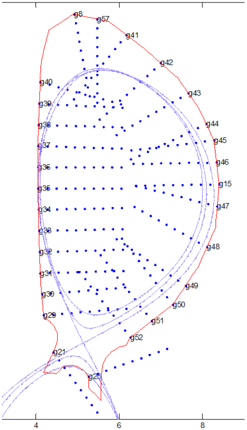
- Precise control of plasma boundary despite uncertainties
- Counteract the effect of disturbances (β_p and l_i variations)
- Manage saturation of the actuators (currents in the PF coils)

G. De Tommasi *et al.*
Nonlinear dynamic allocator for optimal input/output performance trade-off: application to the JET Tokamak shape controller
Automatica, vol. 47, no. 5, pp. 981–987, May 2011

The plasma shape controller



Plasma shape descriptors



Control segments

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

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

  on a sufficiently large number of control segments (**gap control**)
- Moreover, if the plasma shape intersect the i-th control segment at g_i, the following condition is satisfied

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

  where ψ_B is the flux at the plasma boundary
- Shape control can be achieved also by controlling to 0 the (**isoflux control**)

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

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

Controlled plasma shape descriptors

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

- One possible solution to the plasma shape control problem is 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, by minimizing a weighted steady state quadratic tracking error, when the references are constant signals
- The design is based on a plasma linearized state space model

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

A. Mele *et al.*
MIMO shape control at the EAST tokamak: Simulations and experiments
Fus. Eng. Des., 2019

R. Ambrosino *et al.*
Model-based MIMO isoflux plasma shape control at the EAST tokamak: experimental results
Proc. 2020 IEEE Conf. Control Technology and Applications (CCTA), 2020

- 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

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

The *XSC-like* philosophy - 2/3

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

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

- It is possible to use weights both for the shape descriptors and for the currents in the PF circuits
- The controller gains can be computed using the SVD of the weighted output matrix:

$$C = QCN = USV^T$$

- The XSC minimizes the cost function

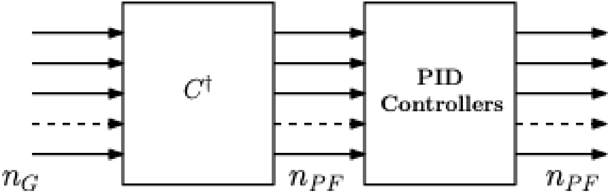
$$\widetilde{J}_1 = \lim_{t\to+\infty} \left(\delta Y_{ref} - \delta Y(t)\right)^T Q^T Q\left(\delta Y_{ref} - \delta Y(t)\right),$$

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

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

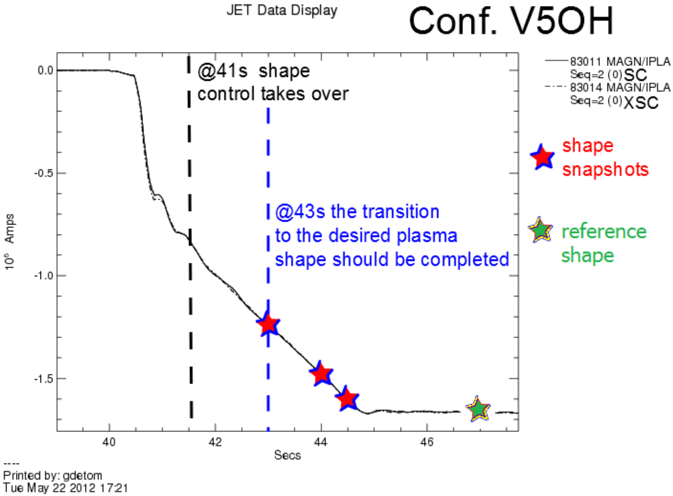
(it contributes to avoid PF current saturations)

The *XSC-like* philosophy - 3/3



- #83011 – plasma ramp-up with standard JET SC
- #83014 – plasma ramp-up with XSC

G. De Tommasi *et al.*
Shape Control with the eXtreme Shape Controller During Plasma Current Ramp-Up and Ramp-Down at the JET Tokamak
J. Fusion Energy, 2014


JET Data Display
Conf. V5OH
@41s shape
control takes over
@43s the transition
to the desired plasma
shape should be completed
83011 MAGN/IPLA
Seq=2 (0) SC
83014 MAGN/IPLA
Seq=2 (0) XSC
shape
snapshots
reference
shape
0.0
-0.5
-1.0
-1.5
10⁶ Amps
40
42
44
46
Secs

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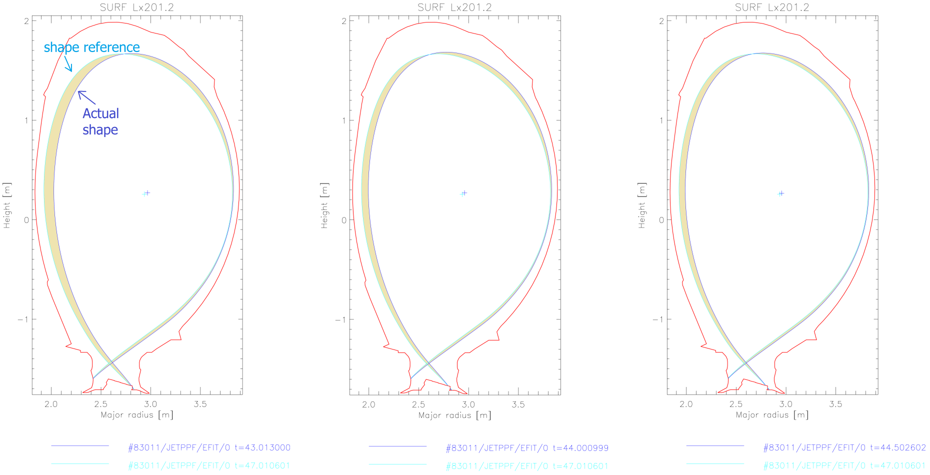
#83011 - Shape tracking during the ramp-up with SC

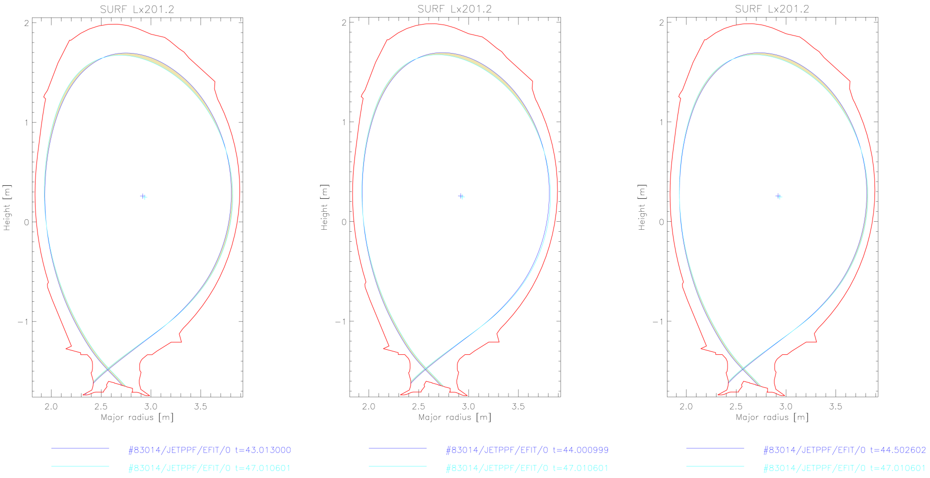


@43s @44s @44.5s

#83011 - Comments

- Bad shape control in the inner side
- This is mainly due to the fact that P4 is used to control ROG, while RIG is not controlled

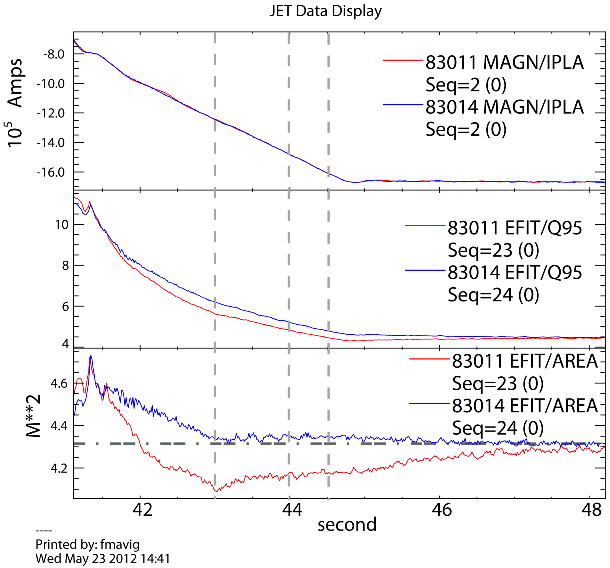
#83014 - Shape tracking during the p-up with XSC



@43s @44s @44.5s

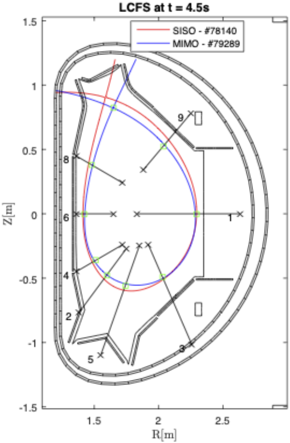
- The biggest error in shape control is in the top outer region (remember the XSC minimizes the shape error in least mean square sense!)
- This error could be reduced by increasing the error in a different region (i.e. in the divertor region)
- Good shape tracking in both RIG and ROG regions, and good tracking of strike points and x-point position

Plasma surface and q95



Isoflux XSC at EAST

- Comparison between the SISO and MIMO shape controllers (pulses #78140 and #79289)
- The LCFS at t = 4.5 s is shown together with the control points and the target X-point position

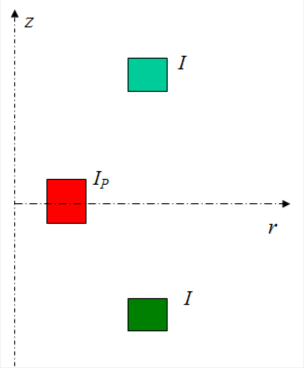


Objectives

- 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!**

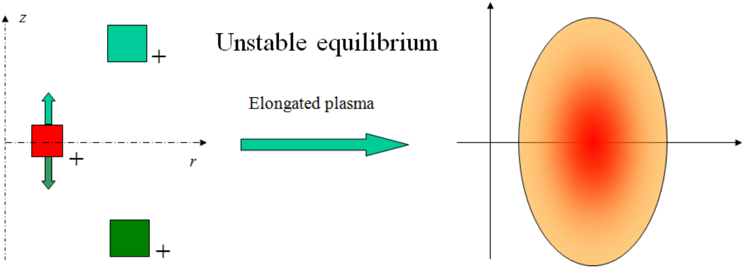
Simplified filamentary model

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.



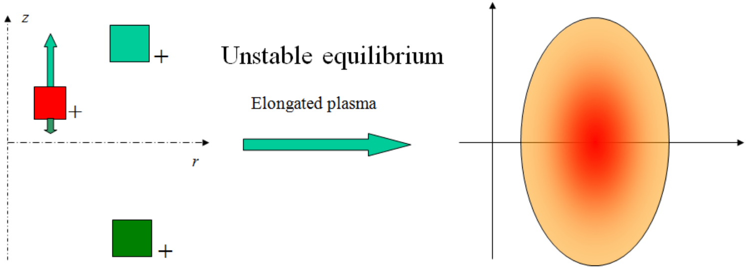
If the currents in the two fixed rings are equal, the vertical position $z = 0$ is an equilibrium point for the system.

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



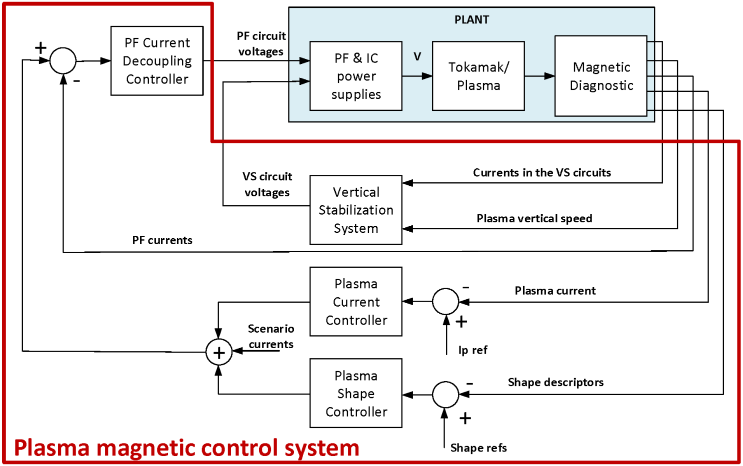
Unstable equilibrium - 2/2

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



- **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**

Architecture



The vertical stabilization controller

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

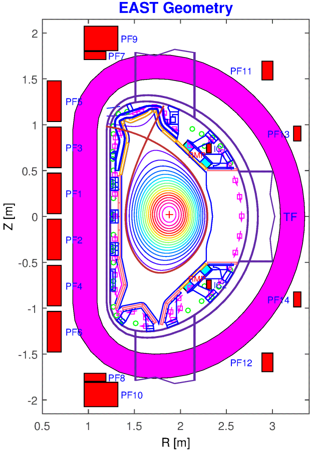
$$
\begin{aligned}
U_{IC}(s) &= F_{VS}(s) \cdot \left(K_v \cdot \bar{I}_{p_{ref}} \cdot V_p(s) + K_{ic} \cdot I_{IC}(s) \right) \ , \\
U_{EC}(s) &= K_{ec} \cdot I_{IC}(s) \ ,
\end{aligned}
$$

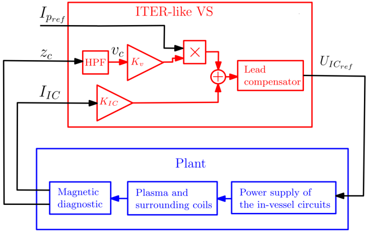
- The vertical stabilization is achieved by the voltage applied to the **in-vessel** circuit
- The voltage applied to the **ex-vessel** circuit is used to reduce the current and the ohmic power in the in-vessel coils
- The *velocity* gain is scaled according to the value of $I_p \rightarrow K_v \cdot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

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

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

- The proposed approach includes (just) three gains and (if needed) a lead compensator $F_{VS}(s)$
  - the *speed* gain K_v
  - the gain on the in-vessel current K_{ic}
  - the gain on the imbalance current K_{ec}
- the proposed structure is rather *simple*, i.e. there are few parameters to be tuned against the operational scenario
- such a structure permits to envisage effective *adaptive* algorithms, as it is usually required in operation
- . . .**but how to design these (few) gains?**. . .
- . . .**and how to *adapt* (tune) them in real-time?**
- Let's see how to design the gains for the EAST tokamak following a model-based approach

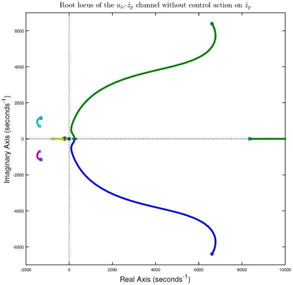




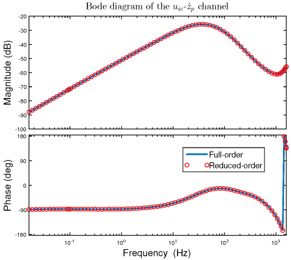
$$U_{IC_{ref}}(s) = \frac{1+s\tau_1}{1+s\tau_2} \cdot \left(K_v \cdot \bar{I}_{p_{ref}} \cdot \frac{s}{1+s\tau_z} \cdot Z_c(s) + K_{IC} \cdot I_{IC}(s) \right)$$

Stabilizing the EAST plasma - 1/2

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



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



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

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

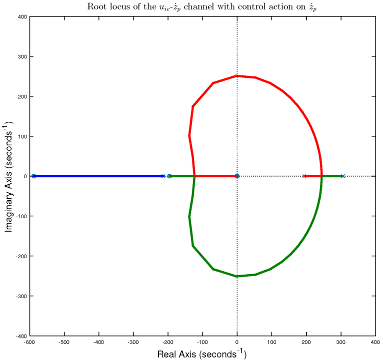


Figure: Root locus of the $u_{ic} - \dot{z}_p$ channel, when the loop on the IC current is also closed.

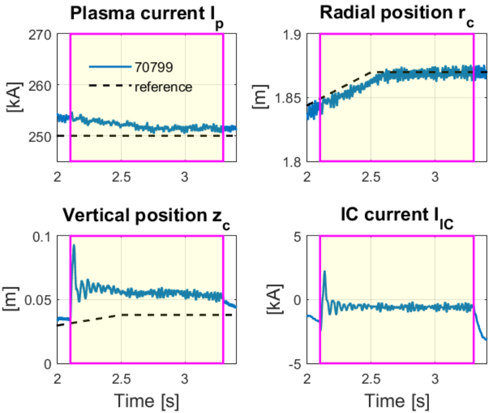


Figure: EAST pulse #70799. During this pulse the *ITER-like* VS was enabled from $t = 2.1$ s for 1.2 s, and only I_p and r_c were controlled, while z_c was left uncontrolled. This first test confirmed that the ITER-like VS vertically stabilized the plasma by controlling $\dot{z}_c$ and I_{IC}, without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

Conclusive remarks

- Plasma equilibrium and vertical stability control are probably the most understood and mature of all the plasma control problems in a tokamak
- Magnetic control can be designed exploiting model-based approaches
- Data-driven approaches based on machine learning are also possible

  J. Degrave, F. Felici *et al.*
  Magnetic control of tokamak plasmas through deep reinforcement learning
  Nature, 2022

  - Are they suitable for a fusion power plant (licensing)?

Conclusive remarks (cont'd)

- **The VS gains need to be adjusted/adapted during the pulse, to achieve the required level of robustness**
  - The gains should be also scheduled/adapted as function of the growth rate
  - . . . **an estimation of the growth rate in real-time is needed!**
- A possible alternative to achieve robustness is to resort to *model-free* approaches

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Magnetic equilibrium and instability control

11th ITER International School (IIS2022)
July 25–29, 2022, San Diego, CA, USA

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Thank you!

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