A MIMO architecture for integrated control of plasma shape and flux expansion for the EAST tokamak

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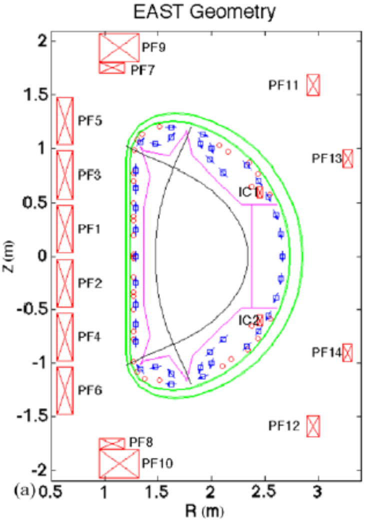
2016 IEEE Multi-Conference on Systems and Control
September 19–22, 2016, Buenos Aires, Argentina

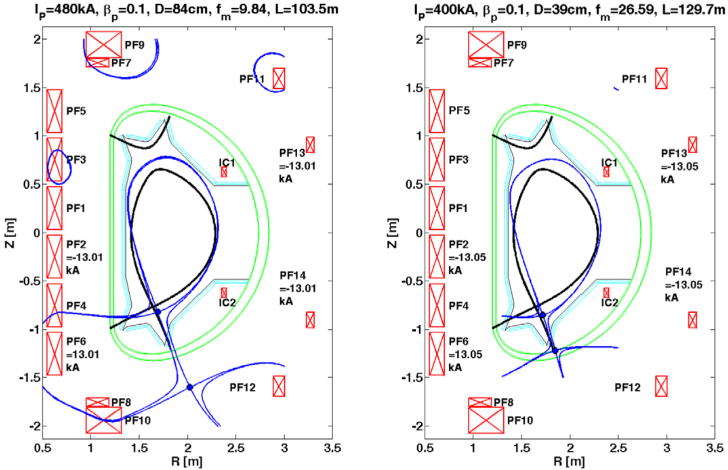
Outline

Control problem

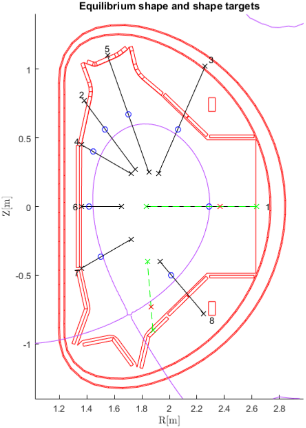
- Plasma magnetic control
  - Control the plasma current
  - Control (stabilize) the plasma vertical position
  - Control the plasma shape
- Shape control represents an effective tool to reduce the thermal load on the divertor structures
  - by performing a periodic movement of the strike-points (*strike-point sweeping*)
  - by reaching advanced magnetic configurations such as the so called *snowflake* configuration



Snowflake configurations



Isoflux plasma shape control



- 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

$$\psi(g_i) = \psi_X$$

where ψ_X is the flux at the X-point

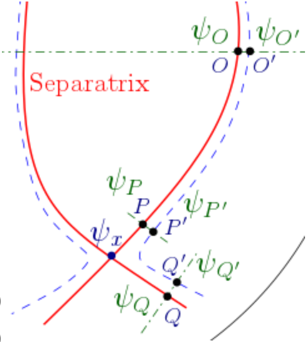
- Shape control can be achieved also by controlling to 0 the (**isoflux control**)

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

Control of plasma shape and flux expansion

- The *flux expansion* can be controlled directly by using the shape controller.
- ψ_X is the reconstructed flux at the X-point,
- ψ_O, ψ_P, ψ_Q are the fluxes reconstructed on the three points selected to control the flux expansion
- Assuming that plasma shape control is achieved, then the control of the flux expansion can be achieved by controlling (to possibly different values) the following flux differences

$$\chi_1 = \psi_{O'} - \psi_O \cong \psi_{O'} - \psi_X \,, \tag{1a}$$
$$\chi_2 = \psi_{P'} - \psi_P \cong \psi_{P'} - \psi_X \,, \tag{1b}$$
$$\chi_3 = \psi_{Q'} - \psi_Q \cong \psi_{Q'} - \psi_X \,. \tag{1c}$$



Contributions

- Validate a set of Matlab/Simulink simulation tools for the EAST tokamak
- Propose a control architecture for integrated plasma shape and flux expansion control at EAST
- This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018

The CREATE tools

- The proposed EAST simulation tools are based on the CREATE equilibrium codes
- CREATE-L and CREATE-NL+ are two plasma magnetic equilibrium codes
  - both are capable to generate linearized models that describes the behavior of the plasma/circuit dynamic around a given equilibrium

Plasma/circuits linearized model

$$\delta\dot{x}(t) = A\delta x(t) + B\delta u(t) \quad (2a)$$

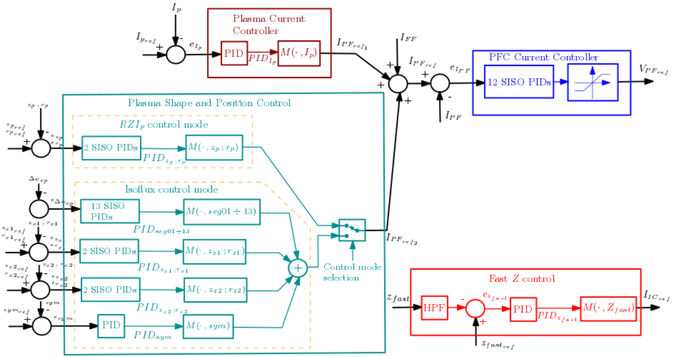
$$\delta y(t) = C\delta x(t) + D\delta u(t)\,, \quad (2b)$$

with

$$\delta x = \begin{pmatrix} \delta I_V & \delta I_p & \delta I_E \end{pmatrix}^T \text{ and } \delta u = \begin{pmatrix} \delta U_V & U_p & \delta I_C & \delta w & \delta\dot{w} \end{pmatrix}^T .$$

Existing EAST Plasma Control System (PCS)

In order to validate the CREATE models, a Simulink version of the existing EAST PCS has been built



Model validation - EAST pulse # 56603

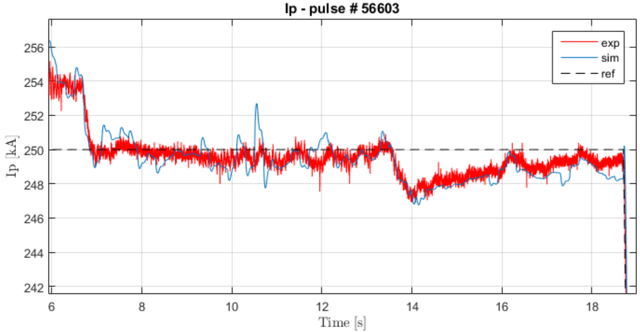


Figure : Comparison between simulated and experimental plasma current I_p.

Model validation - EAST pulse # 56603

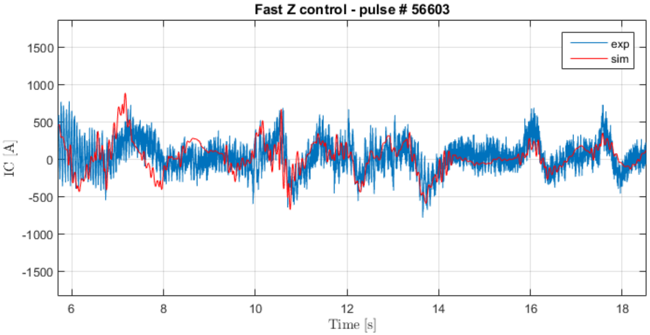


Figure : Comparison between simulated and experimental current in the in-vessel coil I_C used to control plasma vertical position z_p.

Model validation - EAST pulse # 56603

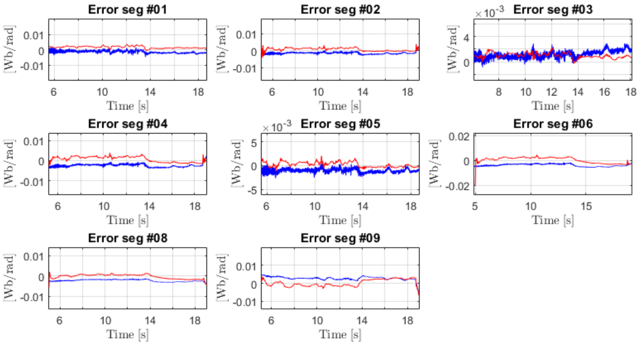
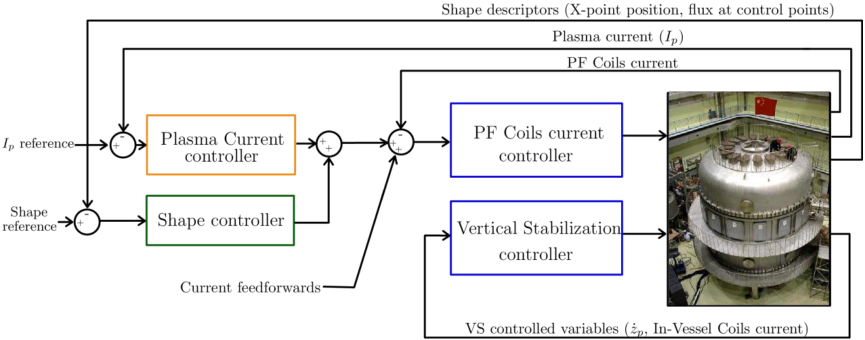


Figure : Comparison between simulated and experimental flux control errors.

Analysis of the plasma vertical stabilization with the existing EAST PCS

- By means of a model-based analysis, at EAST plasma vertical stabilization is achieved by combining the control actions of both the “Fast Z” and the Plasma Shape and Position Control
- “Fast Z” slows down the vertical instability (i.e., moves the correspondent unstable eigenvalue closer to the imaginary axis) driving the current into the invessel coils by using a fast power supply
- The plasma column is then vertically stabilized using the slowest superconductive PF circuits.
- Given such a behaviour, when designing a new shape controller the vertical stabilization should also been taken explicitly into account, making the overall control task particularly difficult

Control architecture



Proposed vertical stabilization

In order to achieve decoupling between the plasma position and the plasma shape control, the following vertical stabilization controller has been designed and validated in simulation on different equilibria

$$V_{IC}(s) = \frac{1 + s\tau_1}{1 + s\tau_2} \left(\frac{K_1(I_p)s}{1 + s\tau_3} z_{fast}(s) + K_2 I_{IC}(s) \right) , \tag{3}$$

where

- typically $\tau_1 > \tau_2 > \tau_3$;
- the plasma vertical velocity $\dot{z}_{fast}$ is obtained by filtering the real-time reconstruction of the vertical position;
- all controller parameters can be kept constant, with the exception of $K_1(I_p)$ which must be scaled according to $I_p(t)$.

Robustness analysis

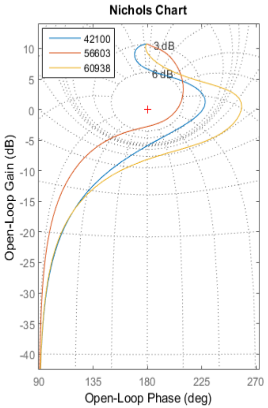


Figure : Nichols chart of the open-loop SISO transfer function for three different plasma equilibria.

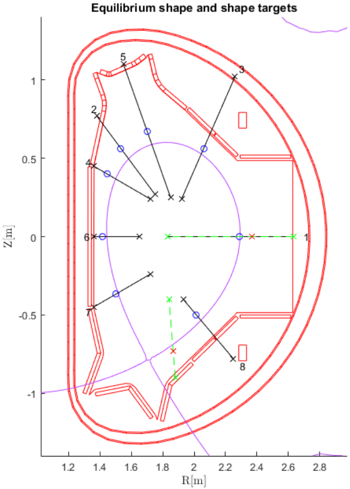
Integrated shape and flux expansion control

The design of the integrated control is based on the static model

$$\begin{pmatrix} \delta r_x(t) \\ \delta z_x(t) \\ \delta \chi_{pb}(t) \\ \delta \chi_{fe}(t) \end{pmatrix} = \begin{pmatrix} c_{r_x}^T \\ c_{z_x}^T \\ C_{pb} \\ C_{fe} \end{pmatrix} \delta I_{PF}(t) = C^* \delta I_{PF}(t) \,, \tag{4}$$

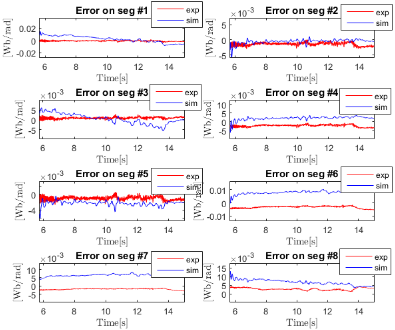
- The plant (4) is non-rightinvertible
- Given a generic set of references, the best performance that can be achieved in steady state is to control to zero the error on linear combinations of controlled variables, to be chosen using the Singular Value Decomposition (SVD) of a weighted version of the C^* matrix (*XSC-like* controller)

Control points

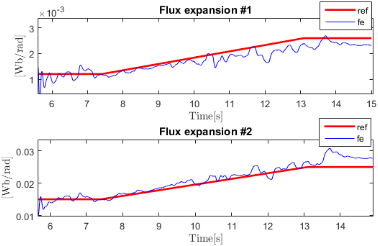


Simulation results

Flux errors at the control points



Fluxes in the at the two points in the scrape-off layer



Conclusions

- A set of simulation tools has been validated against the EAST experiment
- A new architecture for the EAST shape controller has been proposed
  - to perform integrated control of plasma shape and flux expansion
  - to decouple the vertical stabilization from the plasma shape control
- First experimentation are planned in late November 2016

Thank you!