Plasma Boundary Flux Control at JET

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Outline

1. Motivations
2. Plasma Shape Control – the eXtreme Shape Controller
3. Plasma Boundary Flux Control
4. Experimental Results

Advanced Tokamak Scenarios

AT plasmas

An *Advanced Tokamak* (AT) plasma is a plasma with:

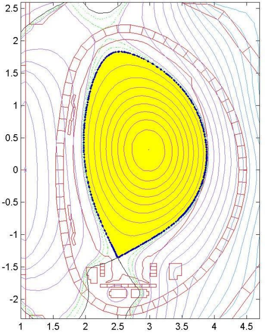
- high plasma kinetic pressure;
- a large fraction of self-induced current;
- a good particle and energy confinement.

- AT scenarios are aimed at allowing steady-state operation without a large amount of externally driven current.
- AT scenarios are aimed to increase the efficiency of a tokamak reactor.

Plasma shape control in AT scenarios

To achieve AT plasma performance, accurate shape control is needed:

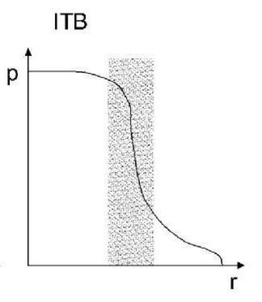
- to obtain the shapes required to achieve high β;
- to optimize the coupling with the additional heating systems;
- to optimize divertor shape for pumping;
- . . ..



Plasma profile control in AT scenarios

Control of the plasma internal pressure and current profiles in AT regimes is needed:

- to improve the energy confinement;
- to increase the noninductive current fraction (*bootstrap current*).
- One way to increase the boostrap fraction is to generate an *internal transport barrier* (ITB), which also causes a reduction of turbulence and therefore an increase of confinement.
- ITB triggering strongly depends from the current density profile.



Plasma boundary flux control

- Steady-state scenarios should in principle be fully noninductive, and zero loop voltage should be maintained at the plasma boundary.
- Obtaining effective and routine boundary flux control is an essential step in AT regime.
- **An integrated approach for the control of the plasma shape and boundary flux has been developed at JET, and it has been tested on ITER-relevant plasmas**.

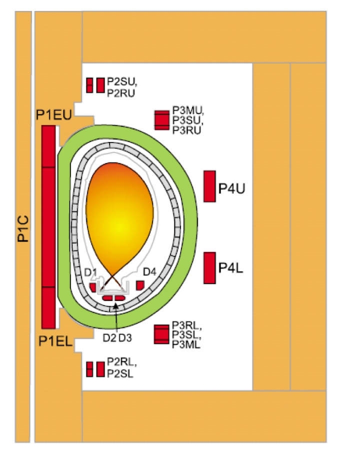
The JET Tokamak

A simplified plasma linearized model relates the variations of the currents in the *poloidal field* (PF) coils to the variations of the geometrical descriptors around a given equilibrium:

$$\delta\dot{\mathbf{x}}(t) = \mathbf{A}\delta\mathbf{x}(t) + \mathbf{B}\delta\mathbf{u}(t),$$
$$I_{p_{eq}}\delta\mathbf{g}(t) = \mathbf{C}\ \delta\mathbf{I}_{PF}(t),$$

where:

- $\delta\mathbf{x}(t) = \left[\delta\mathbf{I}_{PF}^{T}(t)\ \delta I_p(t)\right]^{T}$ includes the currents in the eight PF circuits available for shape control, and the plasma current I_p;
- $\delta\mathbf{u}(t) = \left[\delta\mathbf{V}_{PF}^{T}(t)\ 0\right]^{T}$ is the input voltages vector;
- $\delta\mathbf{g}(t)$ are the shape descriptors variations;
- $I_{p_{eq}}$ is the equilibrium value of the plasma current.



The eXtreme Shape Controller - 1

- The *eXtreme Shape Controller* (XSC) controls the whole plasma shape, specified as a set of 32 geometrical descriptors, calculating the PF coil current references.
- Let $\mathbf{I}_{PF_N}(t)$ be the PF currents normalized to the equilibrium plasma current, it follows that

  $$\delta\mathbf{g}(t) = \mathbf{C}\ \delta\mathbf{I}_{PF_N}(t).$$

  It follows that the plasma boundary descriptors have the same dynamic response of the PF currents.
- The XSC design has been based on the **C** matrix. Since the number of independent control variables is less than the number of outputs to regulate, it is not possible to track a generic set of references with zero steady-state error.

The eXtreme Shape Controller - 2

- The XSC has then been implemented introducing weight matrices both for the geometrical descriptors and for the PF coil currents.
- The determination of the controller gains is based on the SVD of the following weighted output matrix:

$$\widetilde{\mathbf{C}} = \widetilde{\mathbf{Q}}\ \mathbf{C}\ \widetilde{\mathbf{R}}^{-1} = \widetilde{\mathbf{U}}\ \widetilde{\mathbf{S}}\ \widetilde{\mathbf{V}}^{T},$$

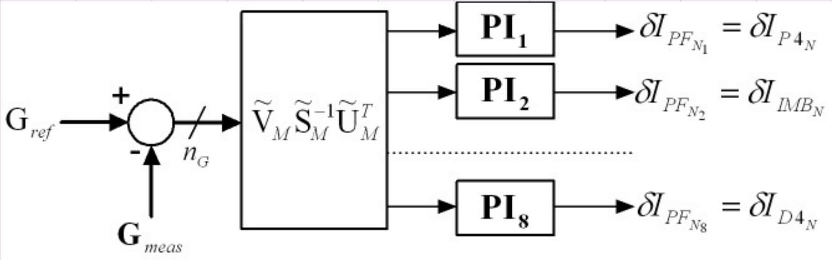
  where $\widetilde{\mathbf{Q}}$ and $\widetilde{\mathbf{R}}$ are two diagonal matrices.
- The XSC minimizes the cost function

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

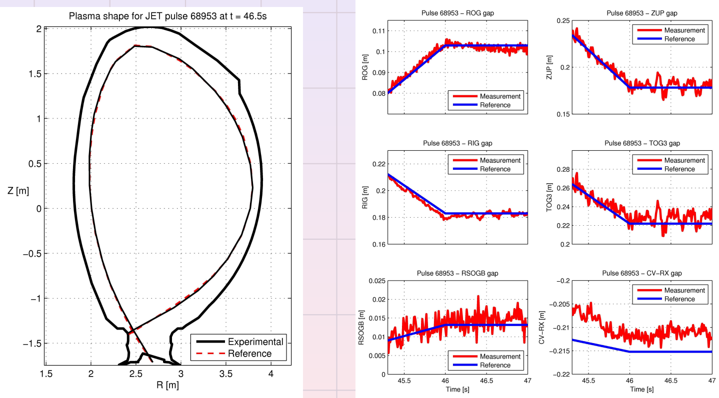
  using $\bar{n} < 8$ degrees of freedom, while the remaining $8 - \bar{n}$ degrees of freedom are exploited to minimize

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

XSC - control scheme



XSC - experimental results



(a) JET pulse 68953 - plasma shape at $t = 46.5s$.

(b) JET Pulse 68953 - plasma shape descriptors time traces.

Figure: JET pulse 68953.

Plasma Boundary Shape Control at JET with XSC

- The boundary flux controller for the JET tokamak has been implemented using the XSC architecture.
- The actuator that has been chosen to control the plasma boundary flux ψ_b is the current in the *P1* circuit. The other circuits are much less efficient and therefore it is much worth to use them for the shape control.
- When controlling ψ_b, the control of the *P1* current is released to the XSC. A new actuator is then available to the XSC and it is used to control ψ_b, with negligible influence on the shape.
- When the XSC controls ψ_b the plasma current is not controlled, and it is left floating between given bounds.

Plant model

Plant model

In order to design the plasma boundary flux controller, a SISO model in the form

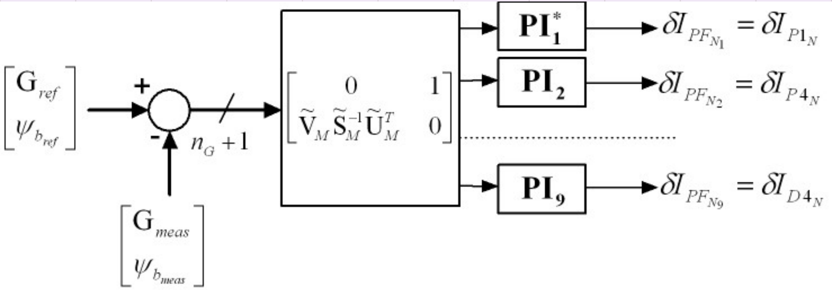
$$\delta\psi_b(s) = W(s)\delta I_{P_1}(s), \tag{1}$$

is needed.

To obtain a model in the form (1):

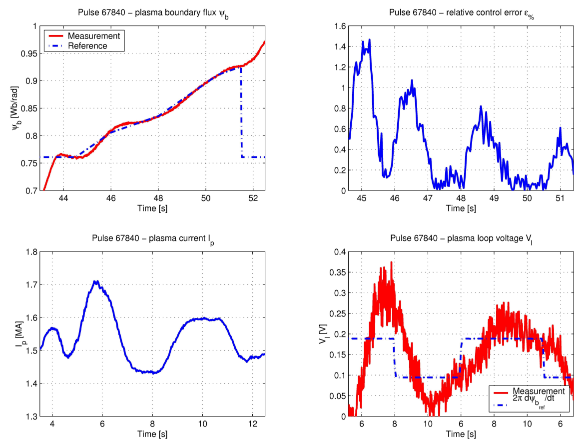
1. the loop consisting of the XSC and the plant model has been considered.
2. a model order reduction has been performed so that a low-order model is obtained. (A balanced model reduction has been performed, arriving to a model of the fourth order).

XSC with boundary flux control

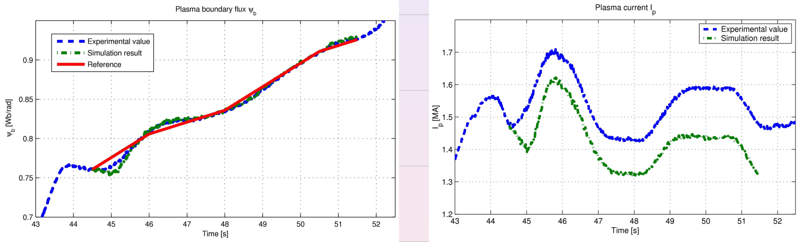


Constant v_{loop}

v_{loop} modulation



Simulation vs. experiment

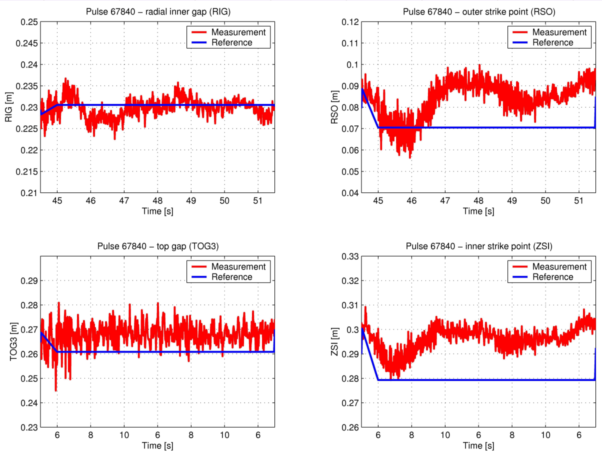


(a) Plasma boundary flux $\psi_b(t)$.

(b) Plasma current $I_p(t)$.

Figure: Simulation of the plasma loop voltage modulation experiment.

v_{loop} modulation - plasma shape



Future works

- In the future, the XSC with boundary flux control will be integrated in a more general scheme with the objective of obtaining a centralized controller for the plasma shape, boundary flux, current and pressure profiles.

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