Design and Development of the Current Limit Avoidance System for the JET tokamak

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Outline

Introduction

The Current Allocation Algorithm

CLA implementation at JET tokamak

CLA commissioning

(Very preliminary) Experimental results

The Current Limit Avoidance System - 1

- The Current Limit Avoidance System (CLA) has been recently designed and implemented **to avoid current saturations in the poloidal field (PF) coils when the eXtreme Shape Controller (XSC) is used to control the plasma shape**
- PF currents saturations may lead to
  - **loss of plasma shape control**
  - **pulse stop**
  - **high probability of disruption**

The Current Limit Avoidance System - 2

- The CLA uses the redundancy of the PF coils system to automatically obtain almost the same plasma shape with a different combination of currents in the PF coils
- In the presence of disturbances (e.g., variations of the internal inductance l_i and of the poloidal beta β_p), it tries to avoid the current saturations by "relaxing" the plasma shape constraints

CLA "philosophy"

- The XSC control algorithm minimizes a quadratic cost function of the plasma shape error in order to obtain at the steady state the output that best approximates the desired shape
- The XSC algorithm **does not take into account the current limits of the actuators** ⇒ It may happen that the requested current combination is not feasible
- The current allocation algorithm has been designed to keep the currents within their limits without degrading too much the plasma shape by finding an optimal trade-off between these two objectives

Plant model (plasma and PF current controller)

The plant behavior around a given equilibrium is described by means of a linearized model

$$\dot{x} = Ax + Bu + B_d d, \quad (1a)$$

$$y = Cx + Du + D_d d, \quad (1b)$$

- $u \in \mathbb{R}^{n_{PF}}$ is the control input vector which holds the $n_{PF} = 8$ currents flowing in the PF coils devoted to the plasma shape control
- $y \in \mathbb{R}^{n_{SH}}$ is the controlled outputs vector which holds the n_{SH} plasma shape descriptors controlled by the XSC (typically, at JET, it is $n_{SH} = 32$)

The XSC

The controller model (XSC controller)

The XSC can also be modeled as a linear time-invariant system

$$\dot{x}_c = A_c x_c + B_c u_c + B_r r, \tag{2a}$$

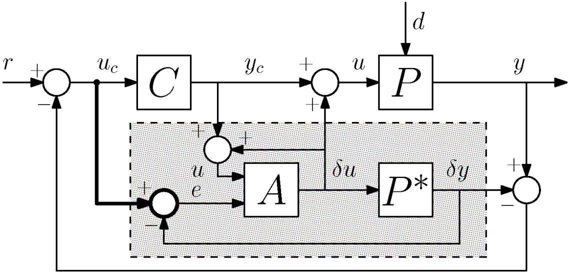
$$y_c = C_c x_c + D_c u_c + D_r r, \tag{2b}$$

under the interconnection conditions:

$$u_c = y, \tag{3a}$$

$$u = y_c\,. \tag{3b}$$

Block diagram of the allocated closed-loop



Where

$$P(s) = C(sI - A)^{-1}B + D\,,$$

is the transfer matrix from u to y of (1), and

$$P^{\star} := \lim_{s\to 0} P(s)\,,$$

denotes the steady-state gain.

The current allocator

The allocator equations are given by

$$\dot{x}_a = -KB_0^T \begin{bmatrix} I \\ P^\star \end{bmatrix}^T (\nabla J)^T \Big|_{(u\,,\delta y)}, \quad (4a)$$

$$\delta u = B_0 x_a, \quad (4b)$$

$$\delta y = P^\star B_0 x_a. \quad (4c)$$

- $K \in \mathbb{R}^{n_a \times n_a}$ is a symmetric positive definite matrix used to specify the allocator convergence speed, and to distribute the allocation effort in the different directions
- $J(u^\star, \delta y^\star)$ is a continuously differentiable cost function that measures the trade-off between the current saturations and the control error (on the plasma shape)
- $B_0 \in \mathbb{R}^{n_{PF} \times n_a}$ is a suitable full column rank matrix,

The CLA scenario

When designing the current allocator, **a large number of parameters must be specified** by the user once the reference plasma equilibrium has been chosen:

- the two matrices $P^\star$ and B_0, which are strictly related to the linearized plasma model (1)
- the K matrix
- the gradient of the cost function J must be specified by the user. In particular, the gradient of J on each *channel* is assumed to be piecewise linear

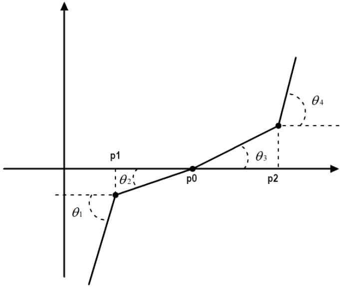
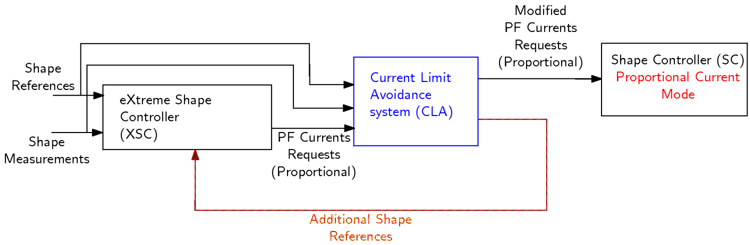


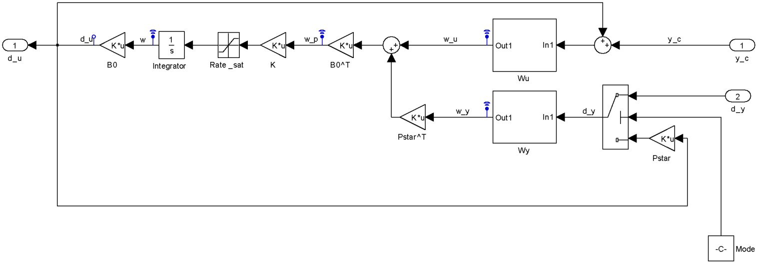
Figure: Piecewise linear function used to specify the gradient of the cost function J for each *allocated* channel. For each channel 7 parameters must be specified.

The CLA Architecture



The CLA block is inserted between the XSC and the Shape Controller set in *Current Control Mode*

The CLA block diagram



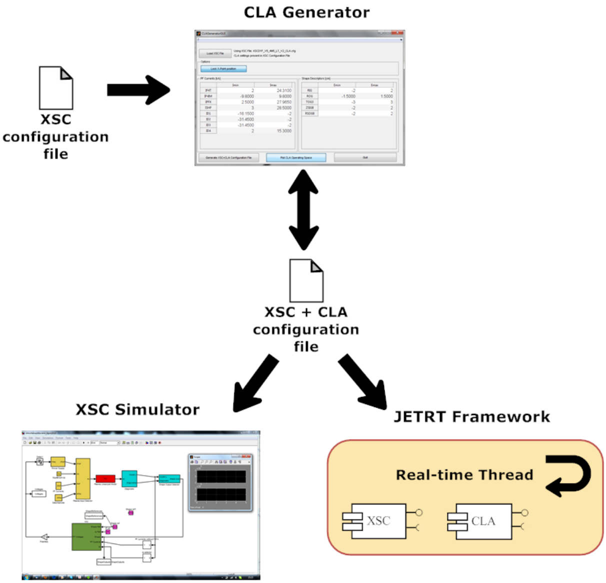
Implementation of the CLA at the JET tokamak

- The CLA modifies the PF current requests computed by the XSC before sending them to the PF current controller
- The CLA block **has been implemented as an independent and isolated plug-in** within the *JETRT framework* (the MARTe ancestor)

The CLA Tools

- The *CLA Tools* are a set of Matlab/Simulink graphic applications developed to ease the design and validation of a *CLA scenario*
- The CLA Tools extend the capabilities of the *XSC Tools* that were developed to assist the development cycle of the XSC at JET
- The CLA scenario is stored as a *configuration file* (text file), and can be used
  - to perform validation via closed-loop simulations
  - to setup the real-time C++ code running on the plant system

Workflow of the CLA tools



Offline validation of the CLA

- The coding of the CLA GAM was performed *by-hand*
- Different tests have been carried out to validate the implementation
- In particular:
  - the CLA GAM outputs have been compared with the outputs of the CLA Simulink block feeding both with the same inputs
  - closed-loop simulations using the CLA GAM and the CREATE plasma model have been performed.

T. Bellizio et al.
A MARTe based simulator for the JET Vertical Stabilization system
Fusion Engineering and Design, vol. 86, no. 6–8, pp. 1026–1029, Oct. 2011.

- **All the tests listed above have been done in the office, but NOT on the plant hardware!**
- The message exchange (CLA scenario) between the JET pulse scheduling system (*Level 1*) and the CLA plant system has been tested

Missing offline tests

Perform closed loop simulations with the CLA plant system

- A lot of tests were done before testing the CLA on the real plant during an experiment
- 99% of the bugs/problems were found and fixed/solved...
- ...**but there is still the 1% !**
- To fix this remaining 1% it would be very useful to run closed loop simulations using the real plant system

What is the problem at JET ?

Why we do not run closed loop simulations with the plant systems

- **First: the JET tokamak is a 30 years old machine!**
- A plant system (e.g., the CLA) interacts with a large number of other (usually very different) systems, which "runs" different (and sometimes very old) technologies!
- Moreover, your project may be not "on top of the list" (usually there are priorities)
- In practice, running closed loop simulations with the real plant system may be almost impossible (in terms of time, effort, resources, etc.)
- Nevermind...there is the commissioning :-) !

Where the problem came from ?

- During the CLA commissioning the remaining 1% caused a problem
- This problem was not found during the offline tests because was related to the *interaction* between the JET pulse scheduling system (Level 1) and the CLA
- In particular, the problem was related to the routine the processes the Level 1 message and setup all the CLA parameters
- During the offline tests we had simply bypassed this ancillary routine, since the external systems were not available

Lesson learned (for ITER)

Lesson learned

- It is important to have a test facility that allows the developers to validate the real system (ITER PCS?) against a plant model
- This test facility should include (almost) all the interactions with other external systems (pulse scheduling system, data collection system, etc.)

CLA commissioning at the JET tokamak

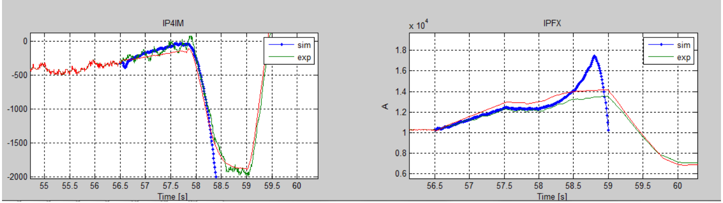
- The commissioning of the CLA has been carried out in from September to November 2011 during the restart phase of the JET tokamak
- A number of experiments have been carried out to check the correctness of the implementation
- In each experiment the allowed range for the current in each PF coil was modified in such a way that at least one current would hit a limit

Commissioning strategy

- During the commissioning a simulation has been performed before running each experiment
- **But soon after the first tests:**
  - **the simulations results were substantially different from the simulations**
  - **we were not able to reproduce the experiment in simulation, using both the CLA Tools and running closed loop simulations with the real C++ code**
- The remaining 1% problem was not a *simple* coding problem

Playback of a JET pulse

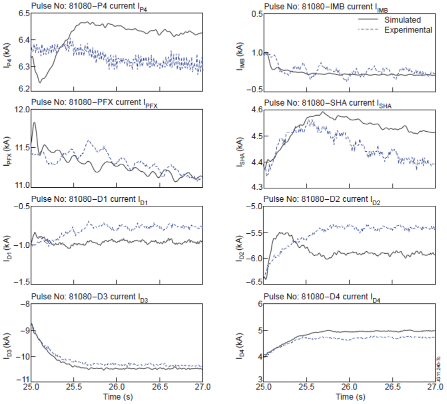
- Once the experimental data are available it is possible to playback a JET pulse in the office
- **This feature is very useful and allows us to use the debugger !**



By using this feature we fixed the problem!

Example - 1

- The CREATE-L model of the JET reference pulse (#81076 at $t = 24.9\ s$) for the CLA commissioning was used to carry out the simulations.
- Given the reference scenario, the planned test was to limit the maximum absolute value of the current in the *D3* coil to 10.5 *kA* by using the CLA system
- The simulation results have been confirmed during the JET pulse #81080, when the CLA has been enabled between 25 and 27 seconds



Example - 2

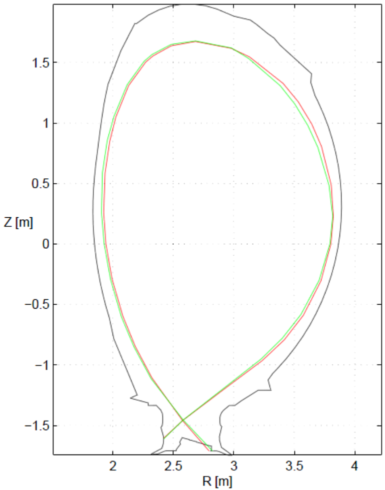


Figure: Comparison between the reference shape (red curve) and the shape obtained in simulation (green curve) when the limit $|I_{D3}|_{\max} \leq 10.5\ kA$ is imposed.

Example - 3

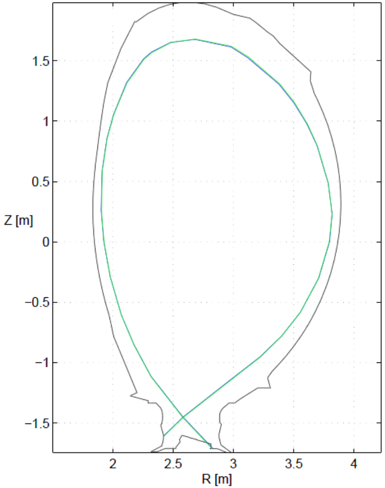
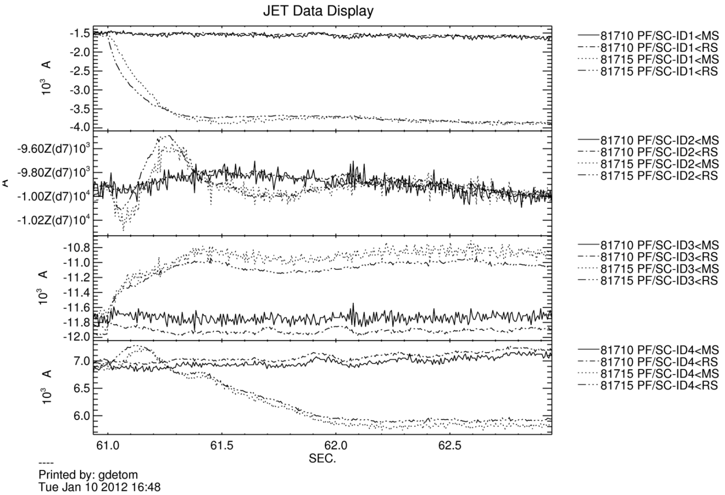


Figure: Comparison between the experimental shape of JET pulse #81080 at $t = 27\ s$ (blue curve) and the shape obtained in simulation (green curve) when the limit $|I_{D3}|_{\max} \leq 10.5\ kA$ is imposed.

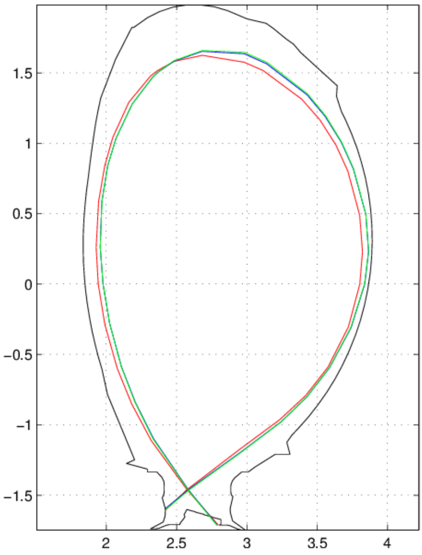
The first proposed experiment - January 2012

- The *Experiment #1* of the JET parasitic experiment Px-2.1.7 was carried out on January the 9th 2012
- During commissioning pulse #81078 the four divertor currents were limited and **a soft stop was triggered due to the error on plasma shape**
- The XSC and CLA behavior were reproduced in simulation and it was shown that the problem was due to non-optimal weights of the CLA cost function
- A new CLA scenario was designed to solve this problem, by tuning the parameters of the cost function
- This optimized scenario was commissioned in November 2011, but it was not been possible to re-run pulse #81078
- The limitation of the four divertor coils represents a severe constraint for plasma shape control
- Experiment #1 was aimed to repeat pulse #81078

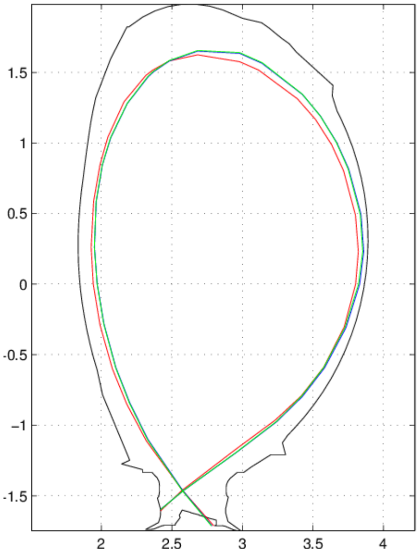
The currents in the divertor coils



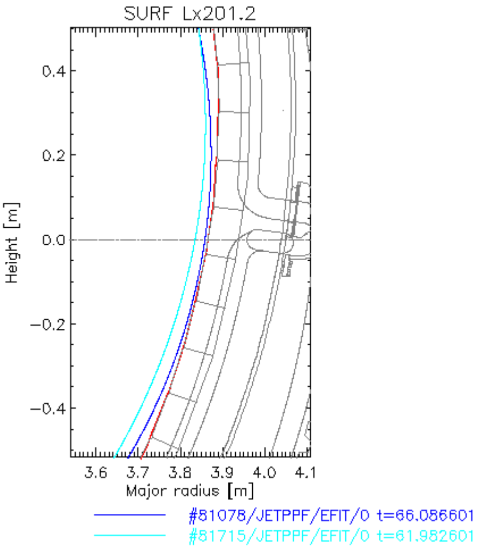
The plasma shape @62s



The plasma shape @63s



Comparison between #81078 and #81715



References

The current allocation at JET

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