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A Software Tool for the Design of the Current Limit Avoidance System at the JET Tokamak

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(23rd IAEA Fusion Energy Conference, Daejeon, Republic of Korea (2010)).

Abstract

A Current Limit Avoidance (CLA) system has been proposed to avoid current saturations in the Poloidal Field (PF) coils of the JET tokamak when the eXtreme Shape Controller is used to control the plasma shape. The CLA uses the redundancy of the PF coil system to automatically obtain almost the same plasma shape with a different combination of control currents. This paper describes the set of graphic tools that have been recently developed to aid the design of the CLA parameters by nonexpert users.

I. INTRODUCTION

The search for new resources has become crucial in this time of increasing energy demand. Research in the nuclear fusion field tries to answer to this request. The most promising approach for nuclear fusion has proved to be the tokamak [1]. In a tokamak reactor, plasma is formed into a vacuum chamber (the vessel), and several external magnetic fields are applied to confine the plasma. One of these components is generated by means of the outer Poloidal Field (PF) coils (see Fig 1), and is used to both achieve the desired plasma configuration and to control the plasma shape and position [2].

The need for achieving increasing performance levels in present and future tokamak devices, has leveraged plasma control importance in tokamak engineering (see the special issues [3] and [4], and the book [5]). A strong motivation for improving plasma control is the need to maximize the plasma volume within the available space. In particular, the ability to control the plasma shape while ensuring good clearance between the plasma and the facing components is an essential feature of any plasma position and shape control system. The eXtreme Shape Controller (XSC [6], [7]) allows to accurately control highly elongated plasmas at the Joint European Torus (JET) tokamak [8], by driving the current in the PF coils. The XSC enables high accuracy control of the overall plasma boundary, specified in terms of a certain number of gaps¹. In its first implementation, the XSC did not handle current saturations in the PF coils [6]. Indeed, each operating scenario was carefully designed so as to prevent the currents from reaching the saturation limits in the presence of the envisaged disturbances (more details can be found in [9]).

The Current Limit Avoidance (CLA) system has been recently deployed at JET to manage current limit avoidance with the XSC [10]. The CLA is based on the technique originally proposed in [11], and it exploits the redundancy of the PF coils system to obtain “almost the same plasma shape” (in steady state) with different combinations of PF coil currents. Hence, in the presence of disturbances, it aims at avoiding the current saturations by “relaxing” the plasma shape constraints. At the steady-state, the allocator guarantees an optimal tradeoff between shape loss and distance of the coil currents from their saturation limits. The development of the CLA system at JET has been part of a package of small enhancements launched in support of the Protection of the ITER-Like Wall (PIW) project [12]. This project was aimed to improve temperature measurements of the plasma facing components and to provide a more flexible architecture for responding to the overheating of a given component.

¹A gap is the distance between the plasma surface and a point on the wall measured on a fixed line

In the present work we introduce the set of Matlab/Simulink[®] tools, named CLA Tools, that have been developed to automate the design and validation of new CLA scenarios for the JET tokamak. These tools are integrated within the XSC Tools suite [9]; moreover, the output generated by the CLA Tools allows to straightforwardly setup the real-time system which runs on the plant [13].

The paper is organized as follows: first an overview of both the dynamic allocation algorithm and the CLA architecture deployed at JET is given in Section II. The CLA Tools are then introduced in Section III, while Section IV gives an example of how the CLA Tools have been used at JET. In particular, a comparison between the simulation results and the experiments carried out during the commissioning of the CLA system in 2011, is given. Eventually some conclusive remarks are given.

2. THE CURRENT LIMIT AVOIDANCE SYSTEM AT JET

This section briefly describes the current allocation algorithm implemented by the CLA system and introduces the CLA architecture deployed at JET. A discussion on the CLA scenario is also given; a CLA scenario specifies all the parameters that are requested to run the allocation algorithm during a JET pulse. More details on the theoretical backgrounds of the current allocation algorithm can be found in [11] and [10].

2.1. THE CURRENT ALLOCATION ALGORITHM

The XSC is one of the two plasma shape control algorithms available at JET ([14], [6]). The actuators are the PF coils shown in Fig.1, that produce the magnetic field acting on the plasma, while the controlled variables are a finite number of geometrical descriptors chosen to describe the plasma shape.

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. However, since 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; to this aim, the algorithm finds an optimal trade-off between these two objectives, specified in terms of an adequate cost function.

In the following, we will model the plasma behavior around a given equilibrium by means of the linearized equations:

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

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

where the equilibrium is characterized in terms of currents flowing in the PF coil circuits, of the plasma current, of the plasma shape geometrical descriptors (a number of gaps, the x-point position, and the strike points, see also Tutorial 7 in [15]), and the plasma² poloidal beta β_p and internal ² β_p and l_i are measures of the plasma internal distributions of pressure and current, respectively.

inductance l_i . In (1), $x \in \mathbb{R}^n$ represents the plant state vector, $u \in \mathbb{R}^{n_{PF}}$ 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 $n_{SH} = 32$). Furthermore, the disturbance vector d holds the poloidal beta β_p and the internal inductance l_i , together with the variation of the plasma current I_p . Indeed, as far as the plasma shape control is concerned, the variations of β_p , l_i and I_p act as external disturbances on the system.

Furthermore, the XSC can also be modeled as a linear time-invariant system:

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

$$y_c = C_c x_c + D_c u_c + D_r r, \quad (2b)$$

under the interconnection conditions:

$$u_c = y, \quad (3a)$$

$$u = y_c, \quad (3b)$$

where $x_c \in \mathbb{R}^{n_c}$ is the controller state vector and r is the shape reference vector.

In the following we will denote with

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

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

$$P^* := \lim_{s \rightarrow 0} P(s),$$

its steady-state gain (more details can be found in [16]).

The current allocation scheme proposed in Fig.2 aims at keeping the value of the PF currents inside a desirable region, without modifying too much the steady-state shape response of the system under the action of the XSC. In order to have a measure of this trade-off, a continuously differentiable cost function $J(u^*, \delta y^*)$ is introduced, where the superscript \star on a signal denotes its steady-state value.

The current allocation is realized by inserting the CLA (block A in Fig.2) between the XSC (block C in Fig.2) and the plant, i.e., the plasma controlled by the SC in current control mode (block P in Fig.2). If we denote by $x_a \in \mathbb{R}^{n_a}$ the allocator internal state, and by $B_0 \in \mathbb{R}^{n_{PF} \times n_a}$ a suitable full column rank matrix, then the two allocator outputs read

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

and

$$\delta y = P^* B_0 x_a. \quad (5)$$

The output (4) modifies the PF current requests made by the XSC, while (5) hides the resulting steady-state change in the plasma shape to the XSC. Hiding the plasma shape change to the XSC is required in order to prevent the controller to react to these changes. When the allocator is connected to the original closed-loop system (as shown in Fig.2), equation (3) are replaced by

$$u_c = y - \delta y , \quad (6a)$$

$$u = y_c + \delta u . \quad (6b)$$

Given a constant request y_c of the XSC, by exploiting (6), the cost function J can be rewritten as a function of the allocator state x_a , i.e., $\sim J(x_a^*)$, where the dependence on y_c is omitted.

The allocator equations are given by

$$\dot{x}_a = -KB_0^T \begin{bmatrix} I \\ P^* \end{bmatrix}^T (\nabla J)^T \Big|_{(u, \delta y)} , \quad (7a)$$

$$\delta u = B_0 x_a , \quad (7b)$$

$$\delta y = P^* B_0 x_a . \quad (7c)$$

where $K \in \mathbb{R}^{n_{PF} \times n_a}$ is a symmetric positive definite matrix used to both specify the allocator convergence speed, and to distribute the allocation effort in the different directions.

The key property of the current allocator algorithm (7) is that, for each constant current request y_c^* of the XSC, it has a unique globally asymptotically stable equilibrium x_a^* of the allocator, coinciding with the unique global minimizer x_a^0 of $\tilde{J}(x_a)$. It turns out that $J(u^*, \delta y^*)$ can be chosen in a suitable way in order to penalize the plasma shape variation δy^* in addition to the PF currents δu^* .

A different point of view can be also considered by redefining the problem as keeping the value of the plant inputs inside a desirable region, meanwhile ensuring a small tracking error. To this aim, the modified allocator structure in Fig.3 is considered, and the second argument δy^* in the considered cost function J is replaced by the shape control error e^* . It turns out that the allocator equations still have the form (7), although in this case the gradient of J will be evaluated on (u, e) rather than $(u, \delta y)$.

2.2 THE CLA SCENARIO

As discussed in the previous section, the design of the current allocation algorithm is based on the linearized model of the plasma behavior (1).

Such a model-based design approach is particularly suited when highly elongated plasmas are envisaged, and where a general-purpose controller cannot meet the requirements³.

It follows that, in order to design the current allocation algorithm the user must first chose the reference plasma equilibrium, and then specify a set of parameters. Indeed, the two matrices P^* and

³We refer to general-purpose controller as a controller which is robust enough to work satisfactorily under any envisaged operational scenario but incapable of pushing the performance to the maximum.

B_0 are strictly related to the linearized plasma model (1), while the K matrix and the definition of the cost function J must be tuned by the user. In particular, the gradient of J on each channel – i.e., for each PF current and for each controlled plasma shape descriptor – is assumed to be piecewise linear, and the user should specify 7 different parameters for each one of the $n_{PF} + n_{SH}$ channels, as described in Fig.4.

Therefore, the user must specify a large number of parameters to use the CLA system. These parameters are gathered together in what is called a CLA scenario, and the CLA Tools have been designed in order to ease the specification of such a scenario by nonexpert users, as described in Section III.

2.3 CLA ARCHITECTURE

The CLA system implements the current allocator algorithm described in Section II-A. The CLA modifies the PF current requests computed by the XSC before sending them to the PF current controller.

Figure 5 shows the architecture of the JET shape controller as it has been modified in order to deploy the CLA system. In particular, the CLA system receives as inputs:

- 1) the PF current requests computed by the XSC;
- 2) the reference shape for the XSC (gaps, strikepoints and x-point position);
- 3) the shape measurements (gaps, strike-points and x-point position).

and gives as outputs:

- 1) the modified PF currents requests to be sent to the PF currents controller;
- 2) the additional references (gaps, strike-points, and x-point position) to be sent back to the XSC.

The CLA block reported in Fig. 5 has been implemented as an independent and isolated plug-in within the JETRT framework, which is the modular real-time framework adopted to deploy the XSC [13].

It is worth to notice that the proposed architecture permits to implement both the output driven allocator and the error driven allocator described in Section II-A.

3. 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, which is a given set of settings for the current allocation algorithm (see Section II-B), by nonexpert users. The CLA Tools presented in this section extend the capabilities of the XSC Tools [9] that were developed to assist the development cycle of the XSC at JET.

3.1 MODELING TOOLS

As described in Section II-A, the design of the current limit algorithm is based on the plasma

linearized model (1). Hence, the first step to be performed during the design phase is the definition of the plasma equilibrium and the generation of the corresponding linearized model.

After the installation of the ILW, the modeling tools CREATE-L [17] and CREATE-NL [18], which are part of the XSC Tools suite, have been updated in order to take into account the new geometry of the JET vessel. Moreover, also the definition of the plasma shape descriptors has been updated according to the new machine configuration.

The update of the modeling tools has been obtained straightforwardly thanks to the machine independent design of the XSC Tools. Indeed, the modeling tools rely on a standard description of a tokamak reactor, called Machine Configuration File (MCF); the new ILW configuration for the JET tokamak has been then obtained generating the corresponding MCF.

3.2. CLA GENERATOR

The CLA Generator is the tool that has been developed specifically for the CLA project. It is integrated in the XSC Tools suite and it allows a nonexpert user:

- to design a new CLA scenario;
- to modify an existing scenario;
- to perform an estimation of the operating space, in terms of maximum variations of β_p and I_i .

The CLA Generator receives as input the XSC configuration file, which is produced by the tool developed for the design of the XSC (see [9] for more details). This file also specifies the desired plasma equilibrium and the corresponding linearized model.

The Graphical User Interface (GUI) allows the user to specify the cost functions parameters described in Section II-B (see Fig.4), by simply specifying:

- a range for the current for each control coil; if the current in the coil is within the range then the cost function weakly penalizes it, while if it is outside, the current is strongly penalized;
- an allowed range for each controlled shape descriptor; if the descriptor (or the corresponding error, if the current allocator operates in the error driven mode) is within the range then it is not penalized, while if it is outside it is penalized by the cost function.

By using the CLA Generator GUI, the user can also select to lock the X-point position, which automatically set a given structure to the B_0 matrix in the CLA scenario.

Furthermore, the P^* matrix is automatically computed by the tool starting from the plasma linearized model, while a default value is used for the other parameters of the CLA scenario (the K matrix and the α , β , γ , δ parameters), and only expert users can change them.

By exposing to the user only a reduced number of high level parameters, the CLA Generator eases the design of a CLA scenario by nonexperts.

Once a CLA scenario is produced, it can be appended to the XSC configuration and saved into

the output file (see the workflow depicted in Fig.6). Such an output file can be also reloaded by the CLA Generator in order to modify the CLA scenario.

The CLA Generator can be also used to estimate the enlargement of the operating space due to the CLA, in terms of β_p and l_i variations, with respect to the one achievable with the XSC without the CLA. In order to estimate the operating space the user must specify:

- a set of limits for the plasma shape descriptors these limits specify the maximum error (with respect to the reference shape) tolerable before considering the shape error to be too big;
- the β_p and l_i ranges; the CLA Generator will perform a scan of β_p and l_i within the specified ranges.

When computing the operating space, the CLA Generator stops the search if either the maximum plasma error or a PF current saturation is reached. It is important to notice that this analysis is performed assuming a static model for both the plant and the XSC; an example of estimation of the operating space when the error driven allocator is adopted is shown in Fig.7.

Eventually, the same configuration file that holds the XSC and the CLA scenarios is used to perform both the validation, via closed-loop simulations, and the setup of the real-time C++ code running on the plant hardware (see Fig.6).

3.3. XSC SIMULATOR

Before the XSC with the CLA system could be loaded on the plant, they should be validated by means of closed-loop simulations. The XSC Tools suite provides the XSC Simulator to perform these simulations. This application takes as inputs both a linear model generated by one of the modeling tools and a configuration file that holds both the XSC and the CLA scenarios. The XSC Simulator allows the user to perform closed-loop simulations aimed at assessing the experimental scenario.

In particular, its GUI allows the user to:

- choose the shape references;
- switch ON/OFF the CLA system;
- prescribe the waveforms of $I_p(t)$, $\beta_p(t)$, and $l_i(t)$ (which act as disturbances for the plasma shape controller);
- plot the simulation results and compare them to experimental data.

As it has been done for the modeling tools, also the XSC Simulator has been updated in order to take into account the new geometry of the JET inner wall.

4. EXAMPLES

In order to commission the CLA system at JET, 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 has been modified in such a way that at least one current would hit a limit.

During these first tests, a simulation has been performed before running each experiment. As an

example, in this section, we present the procedure that has been followed to perform one of these first tests.

The first step that has been carried out has been the generation of the plasma linearized model for the reference equilibrium. To this aim, the CREATE-L model of the JET Pulse No: 81076 at $t = 24.9\text{s}$ has been generated starting from the experimental data. This plasma equilibrium corresponds to the reference shape that has been experimentally obtained by using the XSC without the CLA.

Given this reference scenario, the planned test was to limit the maximum absolute value of the current in the D3 coil to 10.5kA by using the CLA system⁴. In particular, the CLA would be enabled during a 2s time window. After the CLA scenario has been designed by using the CLA Generator, a closed-loop simulation has been performed to validate the behavior of the whole control system.

Figure 8 shows the time traces of the currents in the PF coils. Note that the current in D3 is limited within the prescribed range, while the other currents change in order to minimize the plasma shape error. Indeed, in Figure 9, the plasma shape after 2 seconds of simulation (green shape) is compared to the reference one (red shape).

The simulation results have been confirmed during the JET Pulse No: 81080, when the CLA has been enabled between 25 and 27 seconds. In particular, Fig.8 shows the comparison between the simulated and the experimental currents, while Fig.10 shows the comparison between the simulated and the experimental plasma shapes. It is worth to remark that there is no significant difference between the experiment and simulation.

As a final remark, it is worth to notice that the configuration file used to setup the plant real-time system was the same one used to setup the closed-loop simulation.

CONCLUSIONS

The CLA Tools are a set of tools that has been developed to ease the design of the operative scenarios for the Current Limit Avoidance system at the JET tokamak. These tools are integrated in the XSC Tools suite [9] and follow the same philosophy, that is helping the nonexpert users to prepare and validate CLA scenarios, by exposing them to a limited number of high level parameters. Furthermore the CLA scenario can be straightforwardly used, without any modification, to setup the real-time system running on the real plant. This feature allows one to minimize the errors due to misconfiguration of the plant system.

ACKNOWLEDGEMENTS

This work, supported by the European Communities under the contract of Association between EURATOM, CCFE and ENEA/CREATE/UniRoma2, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The authors would like to thank Dr. Fernanda Rimini, Dr. Stefan Jachmich, Dr. Peter Lomas, Prof. Raffaele Albanese, Dr. Morten Lennholm and Dr. Emmanuel Joffrin for their support during the commissioning phase.

⁴The full range for the current in D3 is $[-37 ; 0]\text{ kA}$.

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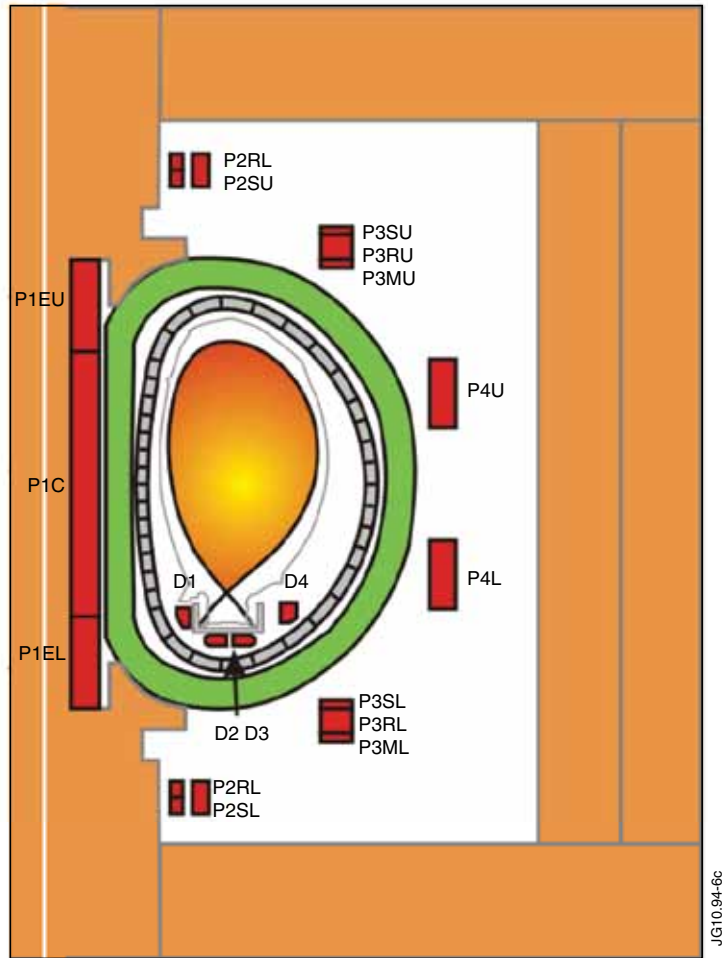


Figure 1: The JET Poloidal Field (PF) coils system is made by 10 independent circuits. The P1 circuit includes the elements of the central solenoid P1EU, P1C, P1EL, as well as P3MU and P3ML. The series circuit of P4U and P4L is named P4, while the circuit that creates an imbalance current between the two coils is referred to as IMB. SHA is made of the series circuit of P2SU, P3SU, P2SL, and P3SL. The Fast Radial Field Circuit (FRFC) connects the P2RU, P3RU, P2RL, and P3RL, and is used by the VS system. The central part of the central solenoid contains an additional circuit named PFX. Finally the four divertor coils (D1 to D4) are driven separately each one by a different power supply. Eight of these circuits, namely P4, IMB, SHA, PFX, D1, D2, D3 and D4 are used to control the plasma shape, while the P1 circuit is used to control the plasma current, and FRFC is used to vertically stabilize the plasma column.

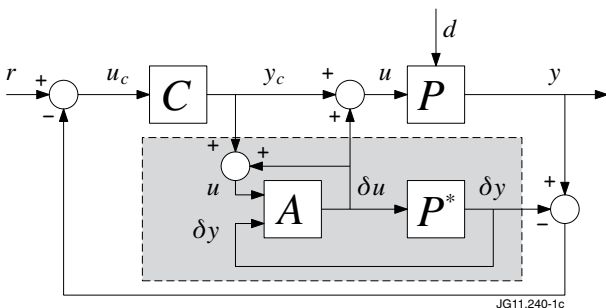


Figure 2: Block diagram of the closed-loop system. The current allocator (block A) takes the controller output as an input. The cost function J penalizes large values of y , namely the difference between the actual output y and the steady-state output value of the not allocated closed loop.

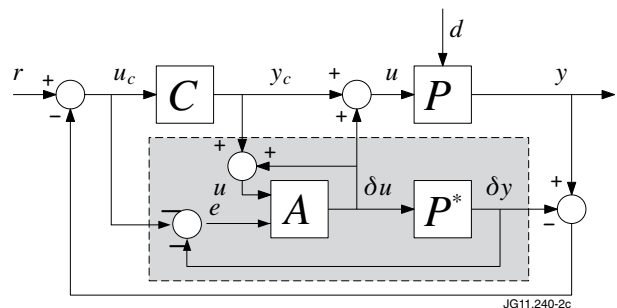


Figure 3: Block diagram of the allocated closed-loop. The current allocator (block A) takes both the controller input and output signals as an input. The cost function J penalizes large values of shape control error e .

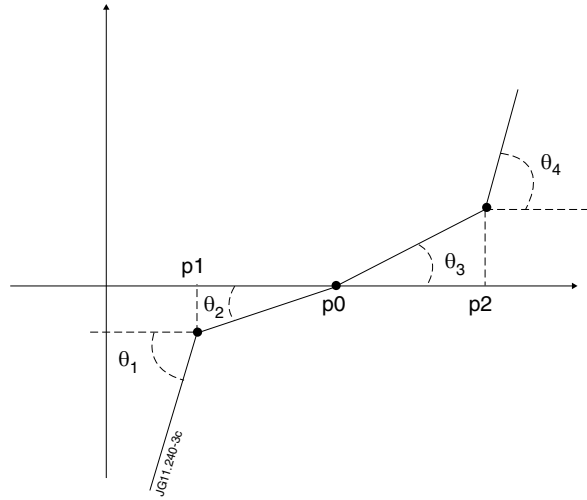


Figure 4: Piecewise linear function used to specify the gradient of the cost function J for each allocated channel. For each channel, the following 7 parameters must be specified: $\alpha = \tan(\theta_1)$; $\beta = \tan(\theta_2)$; $\gamma = \tan(\theta_3)$; $\delta = \tan(\theta_4)$, and the coordinates on the x axis of the three points p_1 ; p_2 and p_3 .

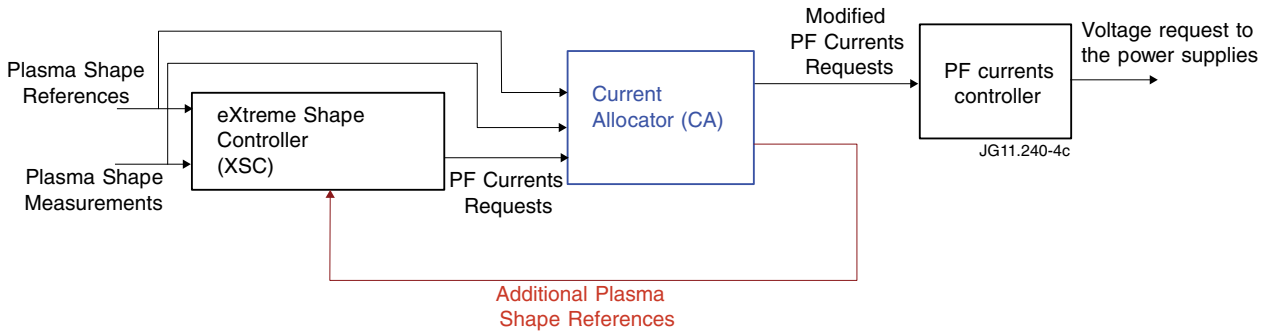


Figure 5: Architecture of the JET shape controller, including the XSC and the CLA system.

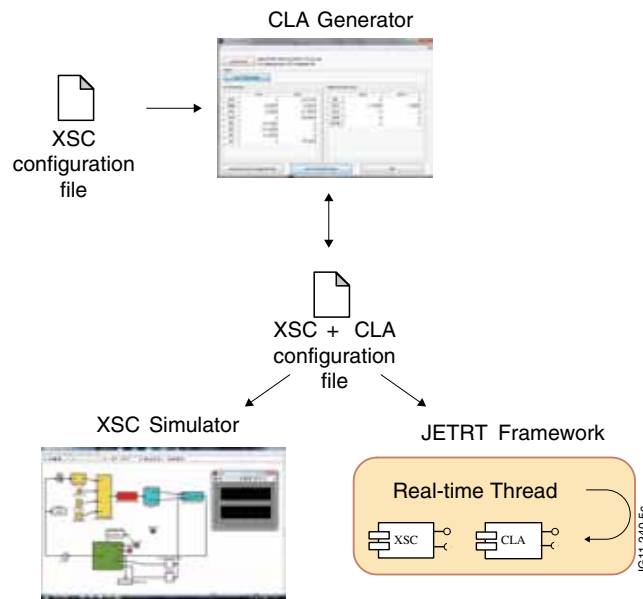


Figure 6: Workflow of the CLA Tools. The reference plasma equilibrium and the XSC scenario are given as input to the CLA Generator, which appends the CLA scenario to the configuration file. The output file can be used both to run closed-loop simulations with the XSC Simulator and to setup the JETRT real-time framework.

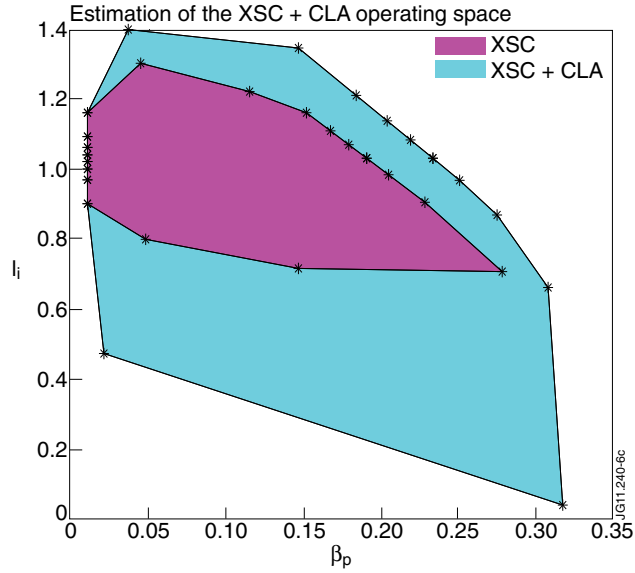


Figure 7: Example of estimation of the operating space computed by the CLA Generator with and without the CLA. The magenta area represents the operating space computed without the CLA, while the cyan area represents the operating space when the CLA with error driven allocator is used. The estimation is performed at a given plasma current assuming a static model for both the plant and the plasma shape controller.

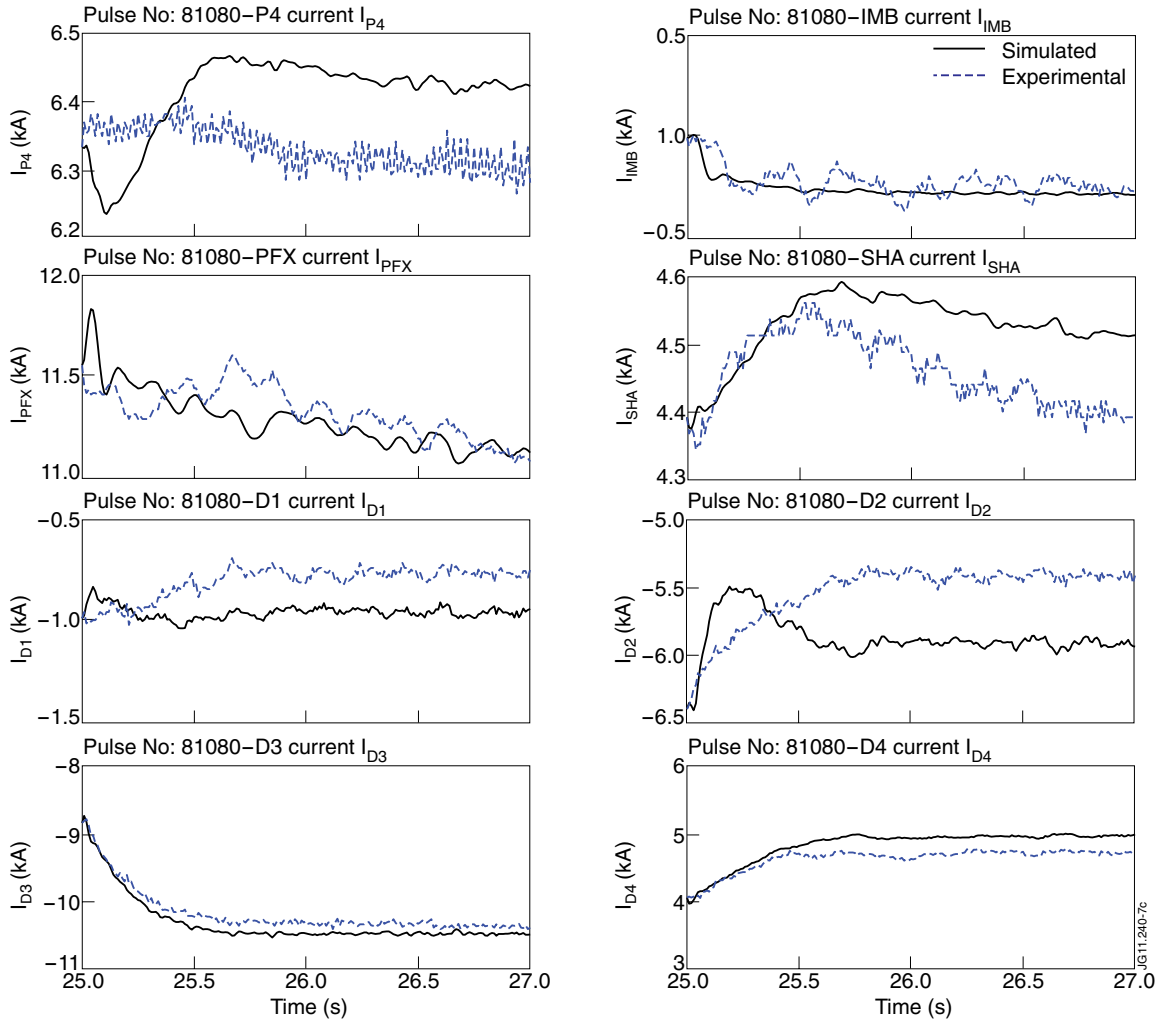


Figure 8: Comparison between the closed-loop simulation performed with the XSC Simulator and the experimental signals of the JET Pulse No: 81080. This figure shows the current in the PF coils used for the plasma shape control. In the considered case the CLA system has been used to limit $|I_{D3}|_{max} \leq 10.5kA$.

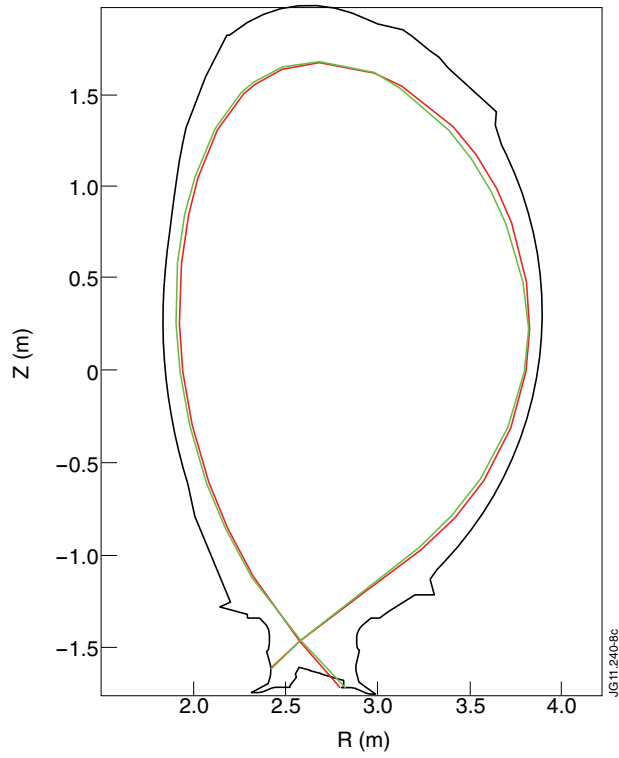


Figure 9: Comparison between the reference shape (red curve) and the shape obtained in simulation (green curve) when the CLA system is used to set the limit $|I_{D3}|_{max} \leq 10.5kA$.

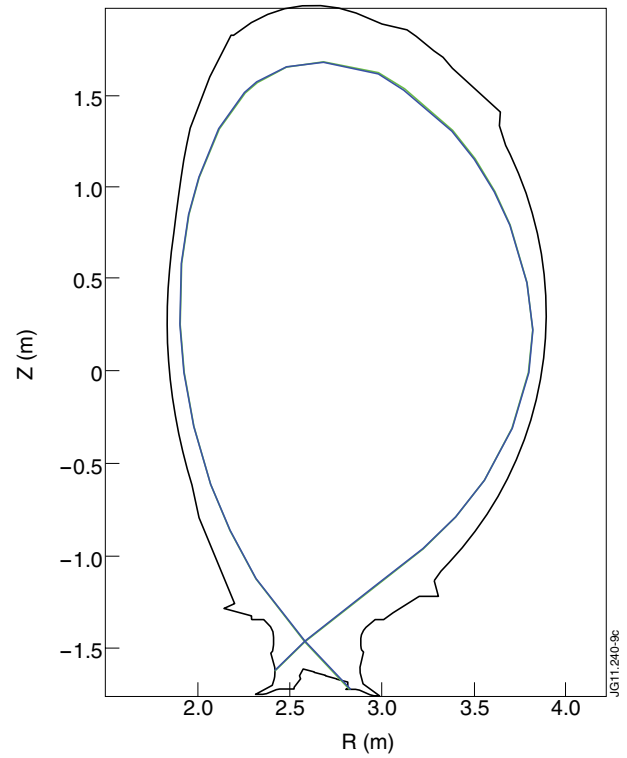


Figure10: Comparison between the experimental shape of JET Pulse No: 81080 at $t = 27s$ (blue curve) and the shape obtained in simulation (green curve) when the CLA system is used to set the limit $|I_{D3}|_{max} \leq 10.5kA$. From this comparison it turns out that there is no significant difference between the experiment and simulation.