XSC Tools: A Software Suite for Tokamak Plasma Shape Control Design and Validation

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***Abstract*—This paper describes a set of graphic tools for the design and validation of the new plasma shape controller [eXtreme Shape Controller (XSC)], which has been recently implemented at the Joint European Torus tokamak. The XSC enables operation with high elongation and high triangularity plasmas. The software suite, which is called XSC Tools, has been developed to automate the design procedure of the XSC. These tools make use of graphic user interfaces to allow the nonspecialist users to prepare for new operative scenarios, without the help from modeling and control specialists. Once a new controller is generated, all its parameters are saved into a text file, which is used to perform the validation of the scenario via simulations. The same file is then loaded by the real-time code running on the plant, without any further processing. This feature guarantees that the controller, which is running on the plant, is exactly the same one validated through simulations. An additional effort has been made in order to make the XSC Tools machine independent, i.e., to enable their use on the different tokamaks.**

***Index Terms*—Control-system validation, software tools, tokamak control.**

I. Introduction

TOKAMAKS [1] are the most promising confinement devices in the field of thermonuclear fusion. Recently, many experiments in operating tokamaks and, as a consequence, a lot of effort in the research on tokamak control, have focused on the so-called advanced tokamak (AT) scenarios [2]–[4]. An AT plasma can be defined as a plasma where the following conditions are simultaneously obtained: stationary state, a high plasma kinetic pressure, a large fraction of self-driven current, and a sufficiently good particle and energy confinement. AT scenarios are aimed at allowing steady-state operation without the need to drive a large amount of plasma current by external noninductive drive systems, thus making it more efficient.

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In this context, several problems need to be adequately resolved to achieve this simultaneous plasma performance [5], [6]; thus, the role of automatic control is becoming more and more significant. New control systems should be designed in order to achieve the requirements for an economically attractive steady-state fusion power plant.

In particular, the plasma shape control system plays an essential role, since an accurate plasma-boundary control is needed to obtain the vertical elongated plasmas with high triangularity required in the AT scenarios. Triangularity and elongation describe how far the plasma cross section is from a circle.

These extreme shapes allow to achieve high values of β, which is the plasma kinetic energy to magnetic energy ratio, and, thus, to increase both plasma density and confinement time [7].

Other important reasons to precisely control the plasma shape are the optimization of the coupling with the additional heating systems, the avoidance of wall interactions, and the divertor shape optimization for pumping.

In order to achieve and maintain the extreme shapes, the feedback controller needs to regulate many different points all around the plasma boundary. This task is complicated by the fact that plasma shapes that are characterized by a large elongation make the vertical stabilization even difficult to guarantee in the presence of unexpected large disturbances such as the edge-localized modes.

To control the plasma shape with the needed accuracy, the boundary is usually described by plasma-wall distances, which are called gaps, by the locations of the strike points on the divertor tiles and the position of the X-point (see Fig. 1). Therefore, a model-based multi-input–multi-output approach is needed to design the shape controller, in order to achieve the high performance request. H_∞ approach [8] has been successfully validated on the Tokamak à Configuration Variable (TCV) to control at the same time the plasma current, vertical position, and some plasma-boundary descriptors [9], [10]. In [11], Walker *et al.* propose a solution adopted on the DIII-D tokamak which emphasizes the X-point control accuracy over the shape accuracy. A general discussion on the design of plasma position, current, and shape controllers, including the choice of the controlled variables, can be found in [12].

To effectively control the extremely shaped plasmas, the entire boundary needs to be specified, i.e., a large number of geometrical descriptors need to be controlled.

The eXtreme Shape Controller (XSC) [13] has been developed to control the whole plasma boundary controlling

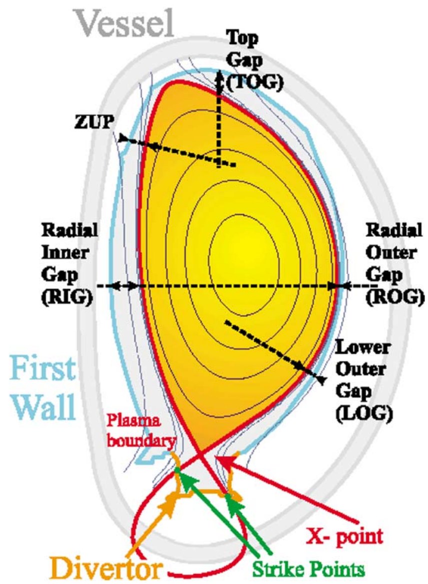


Fig. 1. Plasma-boundary descriptors. This figure shows the strike points and the X-point, together with the gaps that are typically controlled on the JET tokamak. Note that a gap is not strictly the distance between the plasma surface and a point on the wall but rather the distance measured on a fixed line. This definition simplifies the calculation and provides a good linear relationship between the currents in the PF coils and the geometrical descriptors.

up to 32 geometrical descriptors (gaps plus strike points and X-point), thus it can be used to obtain high performance plasmas, controlling the shape in the presence of disturbances. The XSC has been successfully validated on the Joint European Torus (JET) tokamak [14] in 2003 [15], and it is now used during the experimental campaigns at JET, particularly to control the International Thermonuclear Experimental Reactor (ITER)[1]-like plasmas [16], [17] such as the one shown in Fig. 2.

The XSC minimizes, in the least-mean-square sense, the error over the controlled geometrical descriptors using the currents in the poloidal-field (PF)-coil system (Fig. 3 shows the JET PF-coil system). Its design is based on a linearized model of the plasma and PF-coil system behavior, thus the controller parameters are different for the different operative scenarios.

When preparing the XSC for a new scenario, first, a model of the plasma and of the surrounding coils must be retrieved, then the controller design and validation can be started in a typical iterative procedure. For these reasons, in the first attempts, the use of the XSC was not an easy thing. It consisted in a number of not automated steps, which required the involvement of several experts for both the plasma modeling and controller design.

Moreover, it was not straightforward to use the output of the controller-design phase, which is usually carried out using Matlab/Simulink, as an input of the C++ code, which implements the XSC control algorithm in real time and runs on the plant hardware [18].

To deal with these problems and to automate both the controller design and validation phases, a set of Matlab/Simulink

[1]The ITER is the next experimental tokamak that will be built to investigate the possibility of building a fusion power plant.

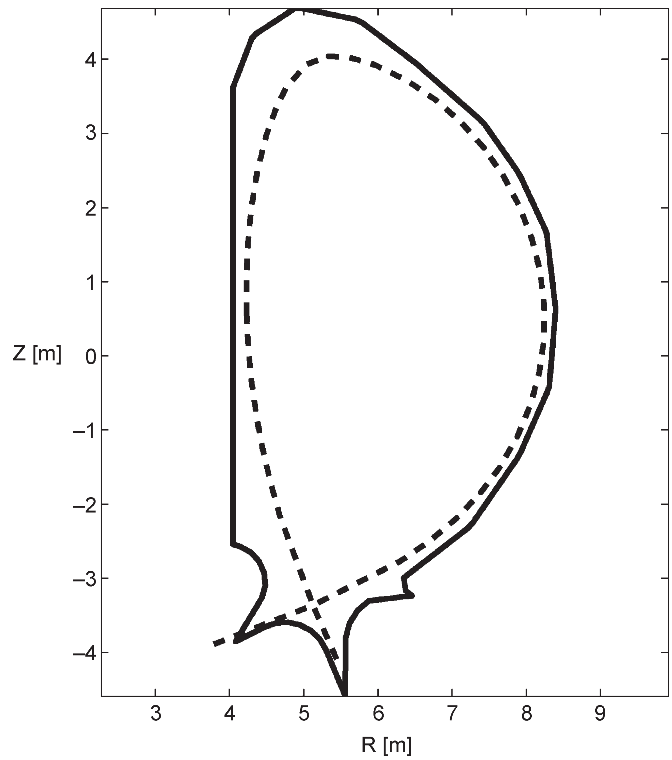


Fig. 2. Example of the elongated plasma with high triangularity. This figure shows the poloidal cross section of an ITER plasma. The solid line is the tokamak vacuum chamber, while the dashed lined is the plasma boundary.

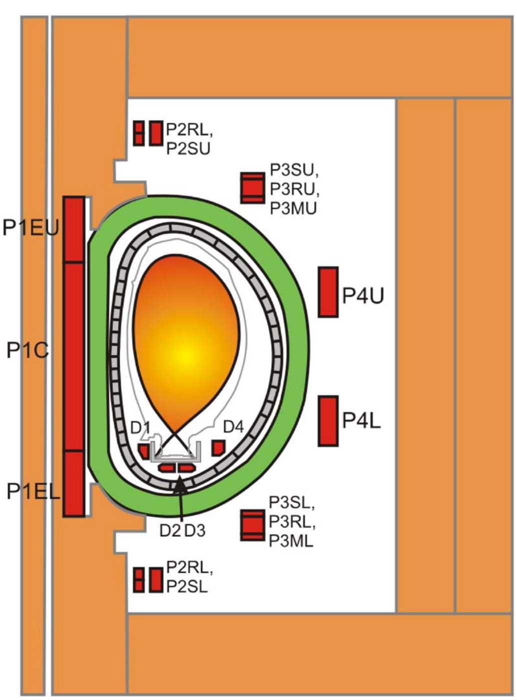


Fig. 3. JET PF-coil system. The P1 circuit includes the elements of the central solenoid P1EU, P1C, P1EL, as well as P3MU and P3ML. The series circuit of P4U and P4L is named P4, while the circuit that creates an imbalance current between the two coils is referred to as IMB. SHA is made of the series circuit of P2SU, P3SU, P2SL, and P3SL. The fast radial field circuit, which is termed FRFA, connects the P2RU, P3RU, P2RL, and P3RL. The central part of the central solenoid contains an additional circuit named PFX, which is used for plasma shape control. Finally, the four divertor coils (D1–D4) are driven separately each by one power supply.

graphic applications, which is called XSC Tools, has been developed. Using these tools, new XSC scenarios can be easily prepared and validated by a single user, without any help from both modeling and control experts.

The XSC Tools implement a friendly graphic user interface (GUI) to the plasma linearized model used for the design of the shape controller, allowing the exploitation of this model to perform analysis. These easiness of use, which makes the plasma modeling and control design tools available to non-specialist users, is the main difference between the presented suite and other proposed applications [19], [20]. The XSC Tools also allow to perform closed-loop simulations of the plasma shape control system, which are essential to validate the control algorithm and to perform all the needed checks before commissioning it on the real plant.

Furthermore, a number of text files (configuration file) have been defined as standard to exchange data among the various applications of the suite, and between the XSC Tools and the plant controller as well, solving the interfacing problem with the real-time code.

In addition, a special effort has been made during the definition of the XSC Tools in order to make them machine independent. In practice, the graphic suite permits to use the modeling tools and the XSC design tools for any tokamak, not only for JET, as far as a standard description of the reactor, which is called machine configuration file (MCF), is available. In fact, the design of the XSC is completely based on the plasma and PF-coil system model; thus, once the model is available, the controller design and validation procedure can be carried out.

This paper introduces the XSC Tools graphic suite, describing the applications for modeling, controller design, and validation. A brief discussion on modeling for the plasma shape control in tokamaks is given in Section II. Since the use of the presented tools is strictly related to the XSC, a description of the controller and of its design procedure is given in the next section. Section IV presents an overview of the tools suite, while a detailed description of each application is given in Section V. Eventually, some examples of modeling and plasma shape control validation are reported in Section VI.

II. Modeling for Plasma Shape Control in Tokamaks

This section gives a short introduction of the plasma linearized model that is used to design the XSC. For a comprehensive treatment about plasma modeling for magnetic control, refer to [21].

The system that is consist of the plasma, the surrounding passive structures, and the external PF coils is a distributed parameter system whose dynamic behavior is described by a set of nonlinear partial differential equations (PDE). Nevertheless, as far as the shape control problem is concerned, the plasma mass can be neglected; therefore, the plasma dynamic can be regarded as a sequence of equilibria. Moreover, it is possible to introduce a number of simplifying assumptions, such as axisymmetry of the tokamak, which have been confirmed experimentally in the last two decades. Given these assumptions and using approximate numerical methods, the following nonlinear lumped parameter approximation of the PDEs model is obtained

$$\frac{d}{dt}\left[\mathcal{M}\left(\mathbf{g}(t), \beta_{\mathrm{p}}(t), l_{\mathrm{i}}(t)\right)\mathbf{I}(t)\right] + \mathbf{R}\mathbf{I}(t) = \mathbf{U}(t) \tag{1}$$

$$\mathbf{g}(t) = \mathcal{G}\left(\mathbf{I}(t), \beta_{\mathrm{p}}(t), l_{\mathrm{i}}(t)\right) \tag{2}$$

where

- $\mathbf{g}(t) \in \mathbb{R}^{n_G}$ are the n_G plasma shape descriptors to be controlled;
- $\mathbf{I}(t) = [\mathbf{I}_{\mathrm{PF}}^{\mathrm{T}}(t) I_{\mathrm{p}}(t)]^{\mathrm{T}} \in \mathbb{R}^{n_{\mathrm{PF}}+1}$ is the current vector, which includes the currents in the n_{PF} PF circuits available for the plasma shape control and the plasma current I_{p};
- $\mathbf{U}(t) = [\mathbf{U}_{\mathrm{PF}}^{\mathrm{T}}(t)\ 0]^{\mathrm{T}} \in \mathbb{R}^{n_{\mathrm{PF}}+1}$ is the input voltage vector (the plasma voltage is neglected);
- $\mathcal{M}(\cdot)$ is the mutual inductance nonlinear function;
- $\mathbf{R} \in \mathbb{R}^{(n_{\mathrm{PF}}+1)\times(n_{\mathrm{PF}}+1)}$ is the resistance matrix;
- $\mathcal{G}(\cdot)$ is the output nonlinear function.

The poloidal beta $\beta_{\mathrm{p}}(t)$ and the internal inductance $l_{\mathrm{i}}(t)$ are measures of the plasma internal distributions of pressure and current, respectively. These parameters are used to take into account the changing in plasma response due to the changing of the plasma internal profiles.

Starting from (1) to (2), the following plasma linearized state space model [22], [23] can be considered

$$\delta\dot{\mathbf{x}}(t) = \mathbf{A}\delta\mathbf{x}(t) + \mathbf{B}\delta\mathbf{u}(t) + \mathbf{E}\delta\dot{\mathbf{w}}(t) \tag{3}$$

$$I_{\mathrm{p_{eq}}}\delta\mathbf{g}(t) = \mathbf{C}\delta\mathbf{I}_{\mathrm{PF}}(t) + \mathbf{F}\delta\mathbf{w}(t) \tag{4}$$

where

- $\mathbf{A}$, $\mathbf{B}$, $\mathbf{E}$, $\mathbf{C}$, and $\mathbf{F}$ are the model matrices;
- $\delta\mathbf{x}(t) = [\delta\mathbf{I}_{\mathrm{PF}}^{\mathrm{T}}(t)\ \delta I_{\mathrm{p}}(t)]^{\mathrm{T}} \in \mathbb{R}^{(n_{\mathrm{PF}}+1)}$ is the state space vector, which includes the variations of the currents in the PF circuits and of the plasma current;
- $\delta\mathbf{u}(t) = [\delta\mathbf{U}_{\mathrm{PF}}^{\mathrm{T}}(t)\ 0]^{\mathrm{T}} \in \mathbb{R}^{(n_{\mathrm{PF}}+1)}$ are the input voltages variations;
- $\delta\mathbf{w}(t) = [\delta\beta_{\mathrm{p}}(t)\quad \delta l_{\mathrm{i}}(t)]^{\mathrm{T}} \in \mathbb{R}^2$ are the β_{p} and l_{i} variations;
- $\delta\mathbf{g}(t) \in \mathbb{R}^{n_G}$ are the plasma shape descriptors variations;
- $I_{\mathrm{p_{eq}}}$ is the equilibrium value of the plasma current.

The model [(3) and (4)] relates the variations of the PF currents to the variations of the geometrical descriptors around a given equilibrium.

III. Extreme Shape Controller

The XSC-control scheme and its design procedure are briefly outlined in this section. More details can be found in [13].

A. XSC-Control Scheme

The XSC has been designed to work on a real plant such as the JET tokamak, thus the implementation details have been taken into account since the very beginning. Special efforts have been made to minimize the impact of the new shape controller

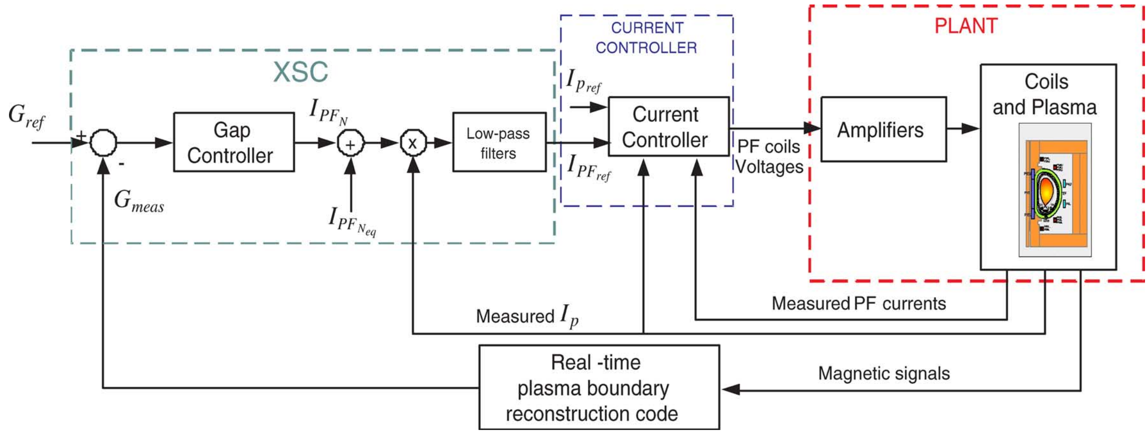


Fig. 4. Block diagram of the XSC. The gap controller computes the PF current references that control to zero the error on $\bar{n} \leq n_{\mathrm{PF}}$ linear combinations of plasma shape descriptors. These current references are then tracked by the Current-Controller block. The low-pass filter block sets the time constants for all the PF circuits to the slowest one.

on the existing control systems. For this reason, the XSC makes use of the JET shape controller [24], which is set in a current-control mode, to control the currents into the PF coils, as it is shown in Fig. 4.

The current controller performs the decoupling of the PF-coil circuits, thus each PF circuit can be treated as an independent single-input–single-output channel with a first-order response. The low-pass filters in Fig. 4 set the time constants for all the PF circuits to the slowest one τ_{PF}. Therefore, the ith PF circuit can be modeled as

$$I_{\mathrm{PF}_i}(s) = \frac{I_{\mathrm{PF}_{\mathrm{ref}_i}}(s)}{1 + s\tau_{\mathrm{PF}}} \tag{5}$$

where $I_{\mathrm{PF}_i}(s)$ and $I_{\mathrm{PF}_{\mathrm{ref}_i}}(s)$ are the Laplace transforms of the ith PF-current measurements and reference, respectively. Furthermore, plasma current I_{p} is also controlled by the current controller using a proportional controller.

It is important to notice that the design of the decoupling controller is straightforward once the resistances of the PF coils and their mutual inductances have been estimated [24], [25]. These parameters are included in (1), thus the current-controller block shown in Fig. 4 can be easily implemented when the plant model is available.

The XSC controls the whole plasma shape specifying a set of geometrical descriptors (typically 32) selecting the current into the PF coils. Its design is based on the output equation of the plasma linear model [(3) and (4)] presented in the previous section. Let $\delta\mathbf{I}_{\mathrm{PF}_N}(s)$ be the Laplace transform of the current variations in the PF coils that is normalized to the equilibrium plasma current $I_{\mathrm{p_{eq}}}$, then

$$\delta\mathbf{G}(s) = \mathbf{C}\delta\mathbf{I}_{\mathrm{PF}_N}(s) \tag{6}$$

where $\delta\mathbf{G}(s)$ is the Laplace transform of the plasma shape descriptor variations. Equation (6) is obtained neglecting the effects of $\delta\beta_{\mathrm{p}}(t)$ and $\delta l_{\mathrm{i}}(t)$. As far as the plasma shape control is concerned, these variations, together with the variation of plasma current, can be regarded as disturbances. It follows that:

$$\delta\mathbf{G}(s) = \frac{\mathbf{C}}{1 + s\tau_{\mathrm{PF}}} \cdot \frac{\delta\mathbf{I}_{\mathrm{PF}_{\mathrm{ref}}}(s)}{I_{\mathrm{Po}}}. \tag{7}$$

Thus, the geometrical descriptors have the same dynamic response of the PF currents. From (7), it follows that the shape design can be based on the $\mathbf{C}$ matrix.

Since usually $n_{\mathrm{PF}} < n_G$,[2] in principle, it is possible to control to zero the error on n_{PF} linear combinations of geometrical descriptors. The choice of the linear combinations to be controlled is carried out minimizing the following steady-state performance index

$$J = \lim_{t \to +\infty} (\delta\mathbf{g}_{\mathrm{ref}} - \delta\mathbf{g}(t))^T (\delta\mathbf{g}_{\mathrm{ref}} - \delta\mathbf{g}(t)) \tag{8}$$

where $\delta\mathbf{g}_{\mathrm{ref}}$ are the constant references to the geometrical descriptors.

Minimization of (8) can be attained using the singular value decomposition (SVD) of the $\mathbf{C}$ matrix

$$\mathbf{C} = \mathbf{USV}^{\mathrm{T}}$$

where $\mathbf{S}$ is a square diagonal matrix holding the singular values in decreasing order, while $\mathbf{U}$ and $\mathbf{V}$ are unitary matrices.

Once the SVD of the $\mathbf{C}$ matrix is performed, it could turn out that some singular values are one order of magnitude smaller than the others: At JET, this happens typically for two or three singular values, depending on the configuration. This fact implies that minimizing the performance index (8) and retaining all the singular values result in a high control effort at steady state, in terms of PF-coil currents. For this reason, the XSC achieves a tradeoff condition, minimizing a modified quadratic cost function that penalizes both the error on the controlled shape descriptors and the control effort in terms of currents into the PF coils. This is achieved controlling to zero

[2] At the JET tokamak, eight PF circuits are used to control up to 32 plasma shape descriptors.

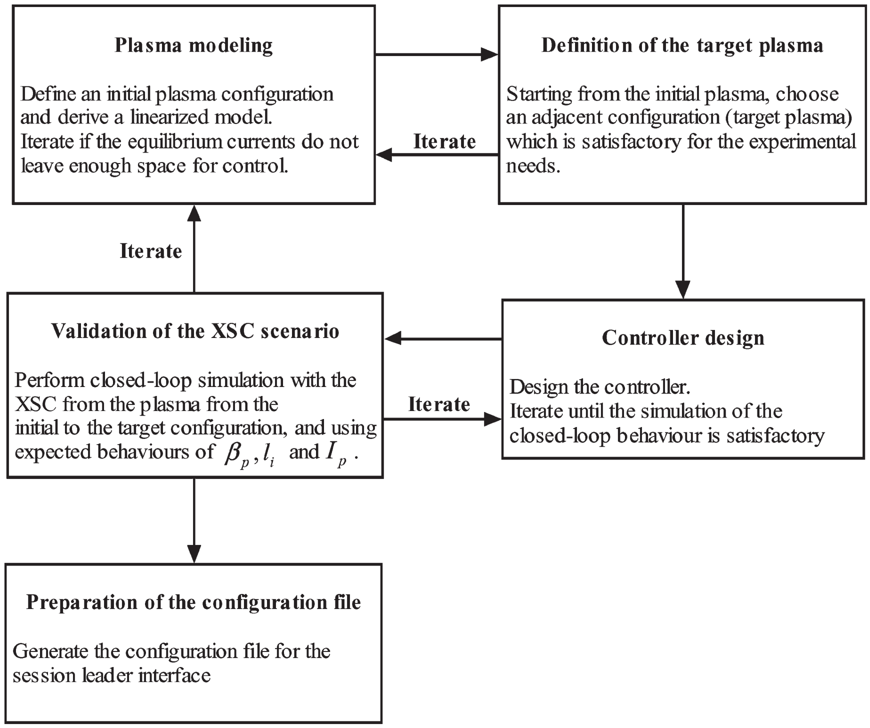


Fig. 5. Diagram of the procedure for the preparation of an experiment using the XSC. The XSC design starts from the modeling phase. A first iteration is performed to define the target plasma. Once the reference shape has been defined, a second iterative procedure starts to design and validate the controller. This phase could lead in some cases to the redefinition of the target. Once the controller behavior has been assessed, the configuration file for the real-time code is generated.

the error only for the $\bar{n} < n_{\mathrm{PF}}$ linear combination related to the largest singular values [26].

A more sophisticated version of the XSC has then been implemented introducing the weight matrices both for the geometrical descriptors and for the PF-coil currents. The reason for this lies in the fact that there are some regions of the plasma boundary where more tight requirements are requested, for instance, for the antenna power coupling. In addition, the PF-coil currents available for feedback purposes differ significantly from coil-to-coil and among different operative scenarios (i.e., some current values can be close to saturation). As a consequence, the determination of the controller gains is based on the SVD of the following weighted model-output matrix

$$\widetilde{\mathbf{C}} = \widetilde{\mathbf{Q}}\mathbf{C}\widetilde{\mathbf{R}}^{-1} \tag{9}$$

where $\widetilde{\mathbf{Q}}$ and $\widetilde{\mathbf{R}}$ are the two diagonal matrices used to weight the errors on the controlled outputs and the currents into the PF coils, respectively.

B. XSC Design Procedure

The preparation of an experiment based on the use of the XSC is sketched in Fig. 5. The procedure consists of the five phases described as follows.

1) **Plasma modeling**—The first step is the definition of the plasma equilibrium into which the plasma is brought when the XSC takes the control. The equilibrium currents in the PF coils have to be determined, and the linearized model [(3) and (4)] is generated around this equilibrium.

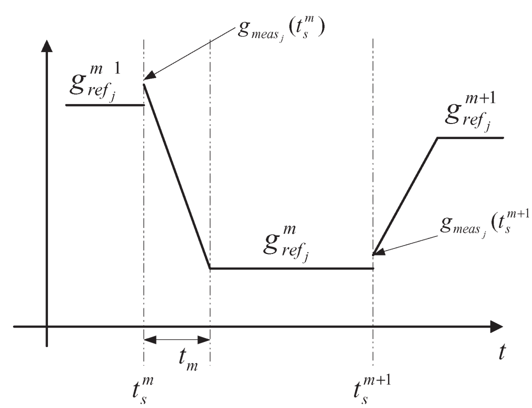


Fig. 6. XSC shape reference in a time window. When the mth time window starts ($t = t_s^m$), the reference shape goes linearly from the measured shape $g_{\mathrm{meas}_j}(t_s^m)$ to the desired one $g_{\mathrm{ref}_j}^m$.

The equilibrium values of both inputs and outputs are also provided along with the plant model.

2) **Definition of a target plasma**—This step requires the definition of the time instant in which the XSC is activated and the transition time interval needed to move from the initial to the target-plasma configuration.
3) **Controller design**—The XSC-design phase requires the selection of the plasma-boundary descriptors to be controlled and the tuning of the weight matrices $\widetilde{\mathbf{Q}}$ and $\widetilde{\mathbf{R}}$ in (9).
4) **Validation of the XSC scenario**—Assessment of the XSC via simulations must be done before using it on the plant. If the simulation results are not satisfactory, then one or more of the previous steps must be iterated.

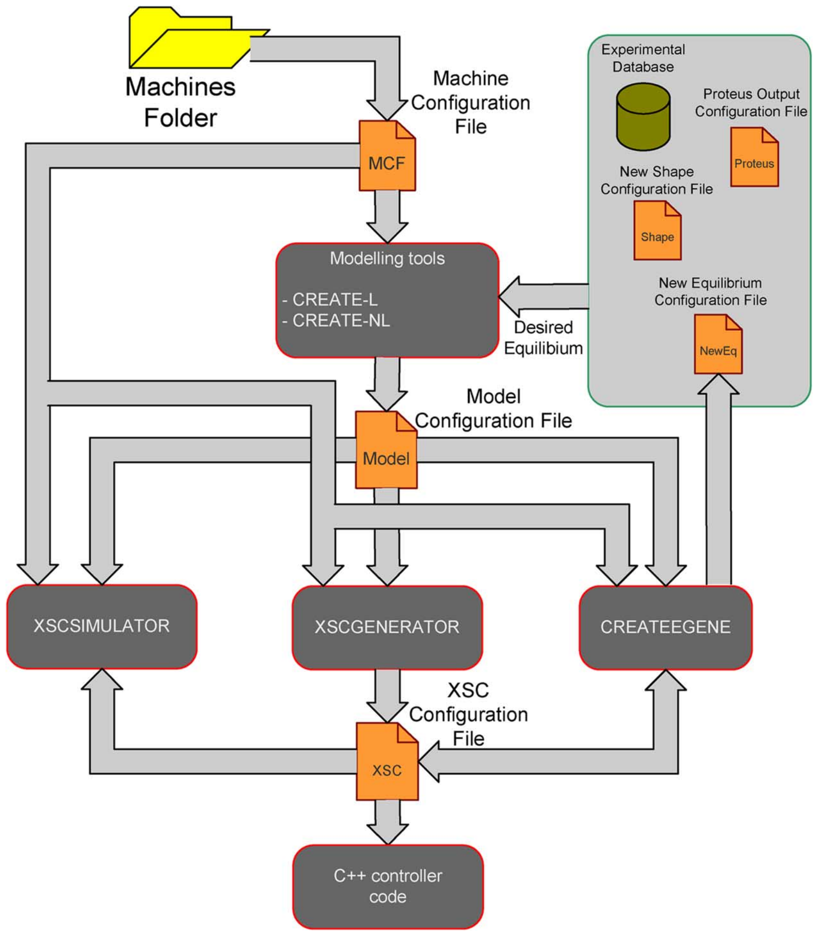


Fig. 7. XSC Tools overview. This figure shows the interaction between the five applications of the tools suite, highlighting the text files used for the data exchange among them.

5) **Preparation of the configuration file**—The last step is the creation of the configuration file containing the information needed by the session-leader[3] interface. This file is then loaded by the controller C++ code, which runs on the plant hardware [18].

The XSC can be used during the same experiment to control the different plasma shapes. In particular, at JET, the whole experimental pulse is divided into a number of time segments, which is called time windows. The session leader can choose a different plasma shape reference for each time window.

Fig. 6 shows a typical shape-reference waveform. When the mth time window starts $(t = t_s^m)$, the reference shape goes linearly from the measured shape $g_{\mathrm{meas}_j}(t_s^m)$ to the desired shape $g_{\mathrm{ref}_j}^m$, taking the transition time Δt_m. The same type of waveforms is used for the equilibrium PF currents.

Different references can be tracked with the same controller parameters as far as the linearized model [(3) and (4)] used to design the XSC can be considered valid for all the desired targets. If this condition holds for the references in each time window, the same controller gains can be used for the whole pulse. If this is not the case, different sets of parameters have to be used; thus, the design procedure described so far must be repeated for each different configuration using different linearized models. For this reason, there is a need to automate the design procedure and to make it accessible to a single nonspecialist user.

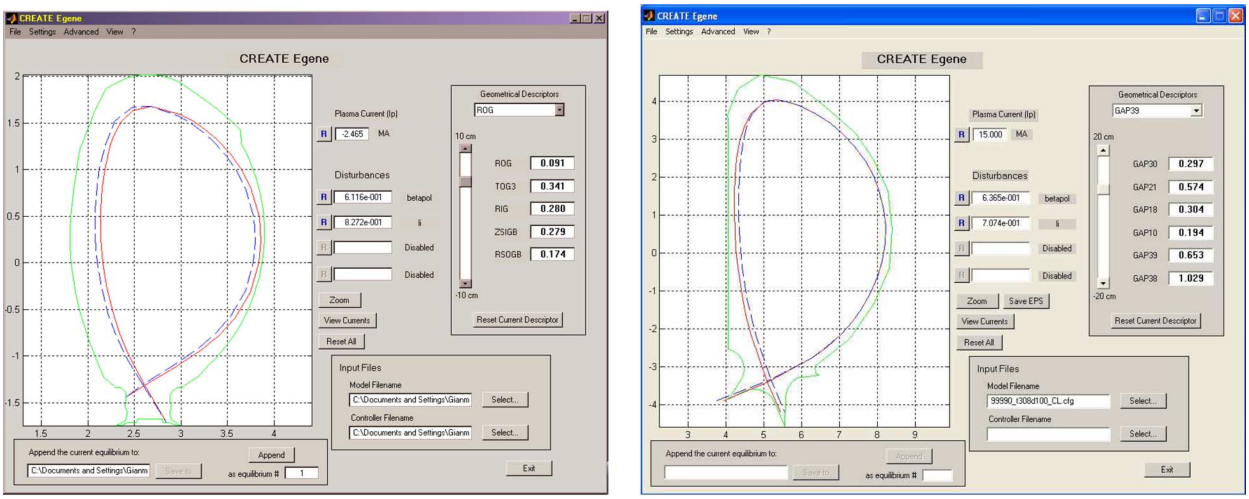
[3]The *session leader* is the person responsible for implementing an experiment.

```
LinearModel = {
    A = {
        0 = {
         -2.555945e-001 -9.734535e-004 1.805891e-002
         1.485311e-001 -4.043265e-004 5.504235e-002
         2.278284e-002 1.693944e-002 4.426001e-002
         4.302797e-002 -1.686075e-007
        }
        1 = {
         -2.137791e-002 -5.885421e-002 1.160845e-002
         -1.126685e-002 2.161848e-002 4.069193e-002
         2.091998e-002 -9.381431e-003 1.974701e-001
         4.546661e-002 1.796584e-005
        }
    ...
```

Fig. 8. Excerpts of a model file. In particular, the first two rows of the **A** matrix in (3) are shown.

IV. Suite Overview

The XSC Tools suite is a set of graphic Matlab/Simulink applications that can be installed on a desktop PC running the



(a) (b)

Fig. 9. CREATE EGENE GUI—Main window. The CREATE EGENE GUI can be customized for different tokamaks changing a configuration file. (a) Jet tokamak. (b) ITER tokamak.

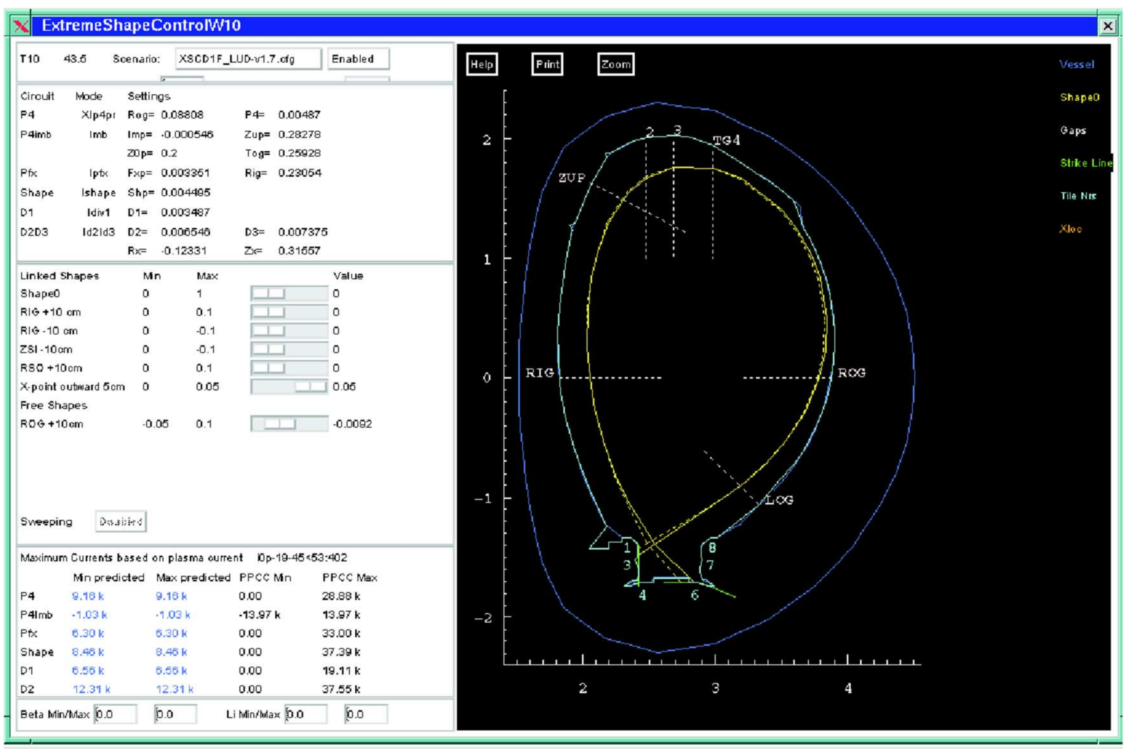


Fig. 10. XSC interface for the session leaders at JET. This interface allows the session leaders to switch ON the XSC in a given time window and to set up the desired plasma shape using a set of sliders.

Windows operating system. These tools help the user during all the design steps described in the previous section.

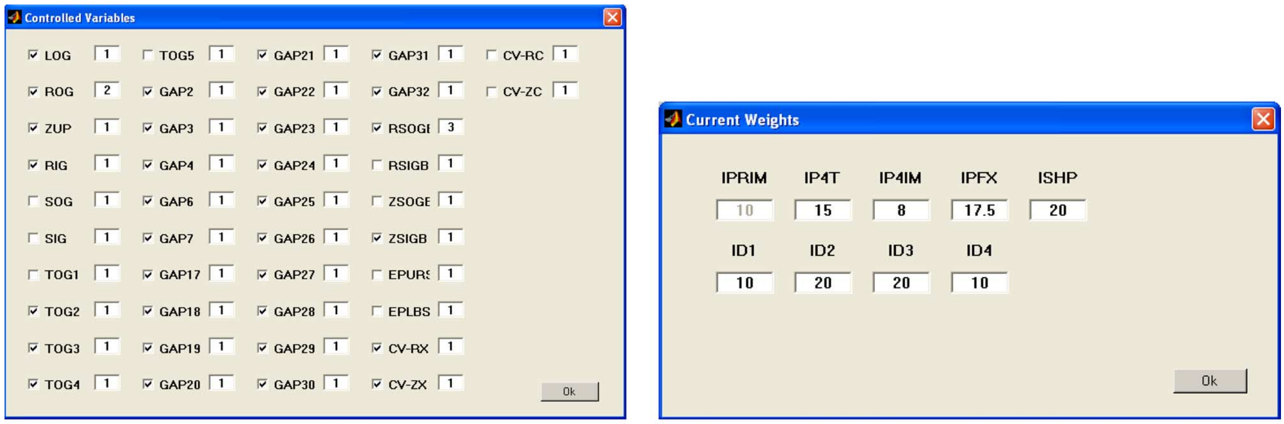
In particular, the XSC suite consists of the following five applications:

1) CREATE-L;
2) CREATE-NL;
3) CREATE EGENE;
4) XSCGENERATOR;
5) XSCSIMULATOR.

The block diagram in Fig. 7 shows the data flows among these five tools.

Starting from the MCF, which contains a standard description of the tokamak facility,[4] and from a given equilibrium, the modeling tool, either CREATE-L or CREATE-NL, generates a linearized model of the plant, storing it into the model configuration file (model file). The desired equilibrium can be specified in a number of ways, as it will be outlined later in Section V-B.

[4]Different MCFs can be specified for the same tokamak. For example, it is possible to specify a different configuration of the divertor or different polarities for the PF-coil circuits.



(a) (b)

Fig. 11. XSCGENERATOR dialog windows. This dialog window in (a) allows the user to choose the controlled variables and their relative weights (the higher the figure, the smaller the expected tracking error on the selected variable is). With the window in (b), the user can set the weights on the PF-coil currents used by the XSC (the smaller the figure, the smaller the steady-state variation of the current is). If a weight is set to 0, the corresponding current is not used by the XSC.

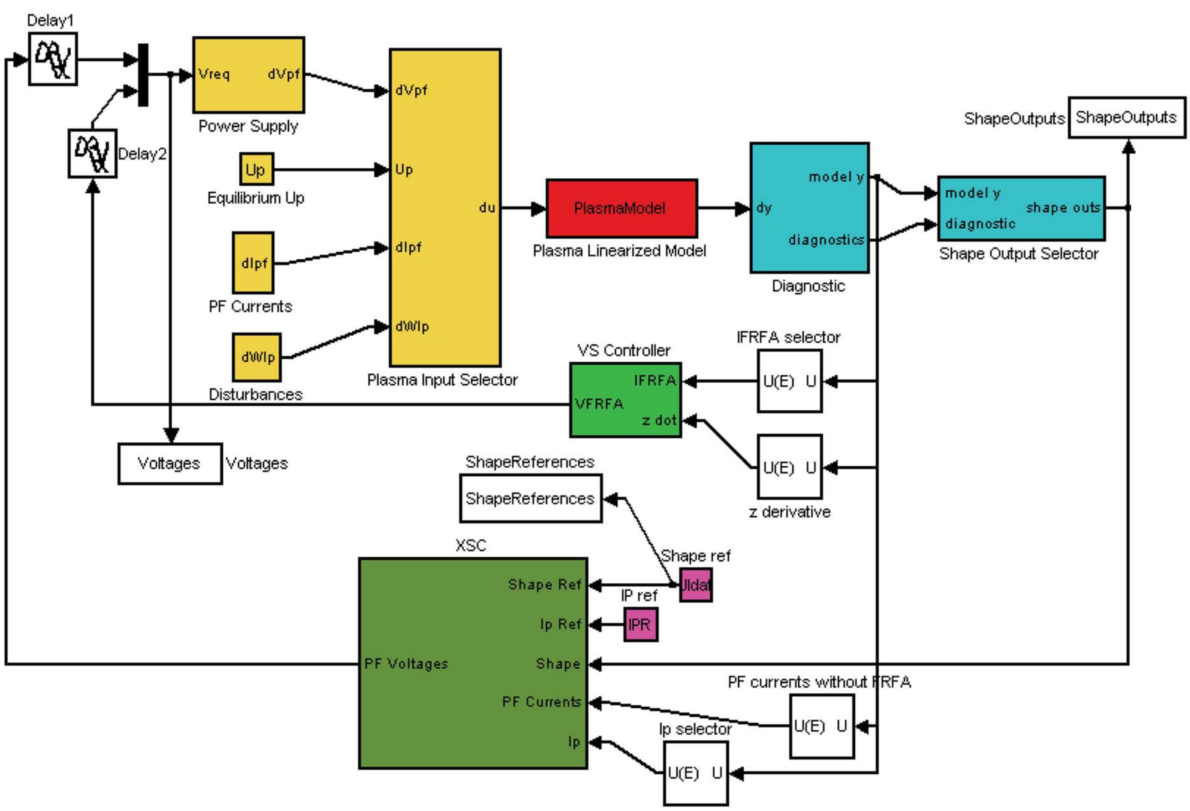


Fig. 12. XSCSIMULATOR Simulink scheme. This simulation scheme is used to validate the XSC behavior before the commissioning of the controller on the real plant.

The MCF is given as input to all the tools, in order to retrieve all the needed information about the reactor. This design choice makes the XSC Tools not related to a specific machine; indeed, they can be used for any tokamak as far as the corresponding MCF is available.

The model file is the input to CREATE EGENE, XSCGENERATOR, and XSCSIMULATOR, which are used to generate the target plasma, to design the XSC, and to carry out the closed-loop simulations, respectively.

Once the XSC is designed, it is saved into the XSC configuration file (XSC file), which is given as input to XSCSIMULATOR, together with the model file, in order to perform the scenario assessment. The XSC file is then loaded by the controller real-time code which runs on the plant hardware, without any further processing. Therefore, when using the XSC Tools, the preparation of the configuration file is implicitly done when a new controller is designed.

The files used as interface among the applications of the suite and the real-time code are simple ASCII files, wherein the information is stored as plain text. As an example, Fig. 8 shows an excerpt of a model file.

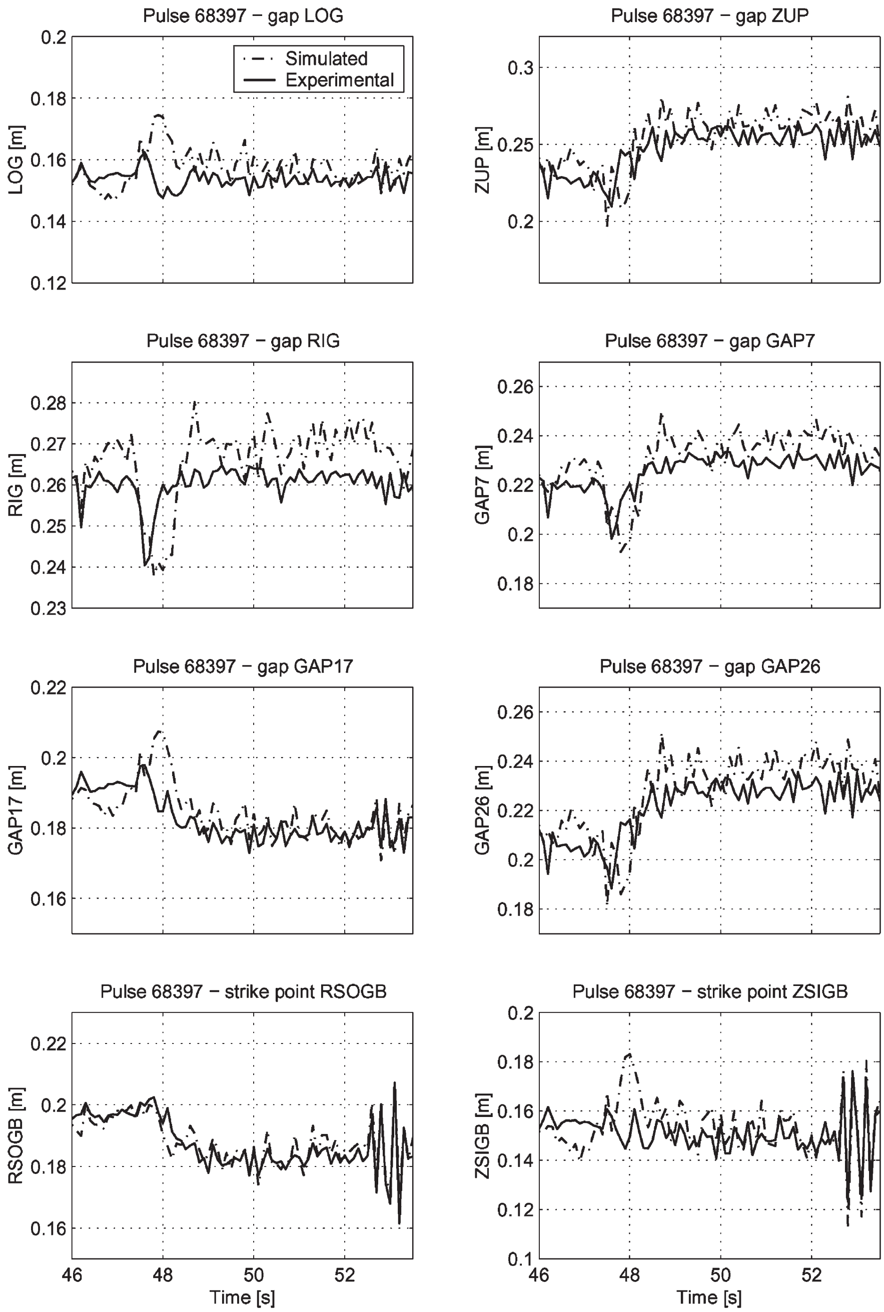


Fig. 13. Open-loop model validation for JET pulse 68397. This figure shows a (solid lines) comparison between the experimental values and the (dash and dot lines) simulated values of eight plasma-boundary descriptors.

As far as the implementation of the controller is concerned, a cross-platform real-time framework named JETRT has been developed at JET using object-oriented techniques [18]. In the JETRT framework, the control algorithm (user application) has been separated from the interfaces with the data acquisition hardware and the external systems.

In particular, the user application and the external interfaces are implemented as plug-ins. Such a modular architecture allows to easily customize the real-time system changing the control algorithm and/or the data acquisition hardware. Moreover, the user application is configured using a text file, i.e., to modify the controller parameters means to modify their values into a text file. In particular, the real-time implementation of the XSC reads the controller parameters from the XSC file.

The current version of the framework is available on different platforms such as Motorola68k/VxWorks, PowerPC/VxWorks, and others. Owing to the modularity and portability, JETRT can be used to deploy the XSC real-time code on different hardware architectures.

V. XSC Tools

A. Modeling Tools

As it has been already pointed out, the design of the XSC is based on a linearized model of the plant; thus, it is first necessary to retrieve the model using one of the two available modeling tools, either CREATE-L or CREATE-NL, whose output is the model file (see Fig. 7).

Both codes implement a finite-element method for calculating the 2-D axisymmetric plasma equilibria in the presence of ferromagnetic materials and of eddy currents induced in the passive structures. Both can produce linearized models of the plasma in the neighborhood of a certain equilibrium condition. The availability of two equilibrium codes provides a redundancy that can be used to check the validity of the linearized models.

The CREATE-L code [22], which is written in FORTRAN language, has been extensively validated via comparison with the experimental results of different tokamaks [10], [27]–[30].

CREATE-NL [23] is an upgraded version of the CREATE-L code written in the Matlab/Simulink environment. It has been validated with the JET experimental data and tested for ITER by comparison against other codes. This code has more capabilities than CREATE-L due to the possibility of using different plasma profile shapes, of introducing different outputs in a user friendly way, and of running inverse equilibrium calculation. In particular, least-square fitting of magnetic measurements is used to reproduce experimental equilibria.

In order to obtain the linearized model of the plant, the user has to specify the desired equilibrium. When using CREATE-NL, such an equilibrium can be specified in one of the following ways (see Fig. 7):

1) **Experimental database**—using the experimental data of a given experiment at a given time;
2) **Proteus output file**—using the output of the PROTEUS code [31];
3) **CREATE EGENE equilibrium**—using a plasma equilibrium generated with CREATE EGENE (see Section V-B);
4) **New shape**—using a plasma shape specified in terms of geometrical descriptors (i.e., gaps, strike points, and X-point).

CREATE-L users can specify the desired equilibrium either using a model file that is previously created with CREATE-NL,[5] or using an equilibrium generated with CREATE EGENE.

B. CREATE EGENE

Create equilibria generator (CREATE EGENE) takes the model file as input and gives to the user the possibility of constructing the target plasma, exploiting the linearized model. To ease this job, CREATE EGENE has the intuitive GUI shown in Fig. 9. It allows to start from the initial plasma equilibrium, which is specified into the model file, and move toward a new one, changing the desired shape descriptors. In addition, to modify the plasma shape, the user can also change the plasma current I_p and the plasma profile parameters β_p and l_i. When the user changes the target, CREATE EGENE solves an optimization problem, constraining the currents in the PF coils between their saturation limits. The user can also choose the values of the currents into the PF coils, either fixing the values for a set of geometrical descriptors (to obtain the same shape with another set of currents) or without constraining the plasma shape, that is exploiting the linearized model output (4) specifying the currents in the PF coils, the plasma current, and the disturbances.

[5]This option provides redundancy to check the linearized-model validity.

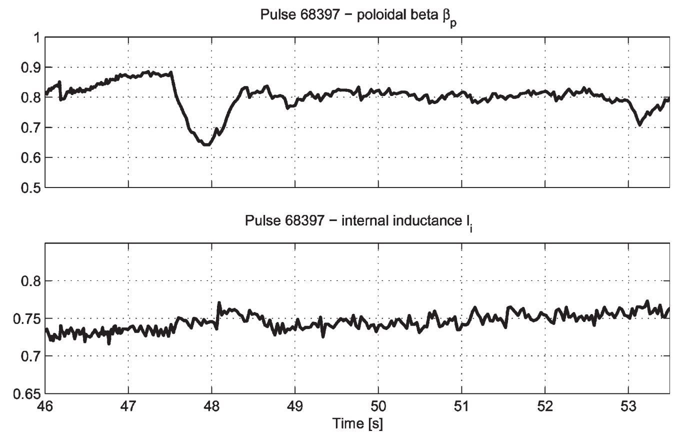


Fig. 14. JET pulse 68397—experimental values of poloidal beta β_p and internal inductance l_i. Note the β_p drop between 47.5 and 48.5 s.

The former option is used to move the currents in the PF coils far from their saturation limits, without changing the plasma shape. To do that, CREATE EGENE uses the linear combinations of currents that have a minor effect on the plasma boundary, i.e., the linear combinations related to the smaller singular values of the $\mathbf{C}$ matrix (see Section III-A). Thus, the resulting shape is not exactly the same, because the new current values are such that the error between the desired shape and the obtained one is minimized in the least-mean-square sense.

Once the target plasma is obtained, the corresponding shape and PF-coil currents are appended to the XSC file to be used as target references for the shape controller. CREATE EGENE enables to append to a given controller file as many new plasma targets as the user wants. At JET, these additional entries are used to generate the set of shape references that can be chosen for a given controller. During the preparation of the experiment, the session leader selects one of these additional equilibria or a convex combination of two or more of them (see the XSC interface used at JET shown in Fig. 10).

The target plasma produced with CREATE EGENE can also be exported into the new equilibrium configuration file to be then used as desired equilibrium input for CREATE-NL (see Fig. 7).

C. XSCGENERATOR

XSCGENERATOR is the shape controller-design tool. It takes the model file as input and automatically generates the XSC file.

XSCGENERATOR allows the user to choose all the design parameters such as the controlled variables, and the diagonal elements of the weighting matrices $\widetilde{\mathbf{Q}}$ and $\widetilde{\mathbf{R}}$ (see Fig. 11).

Once a new controller is generated, it is saved in the XSC file, which is used, without any change, by both the

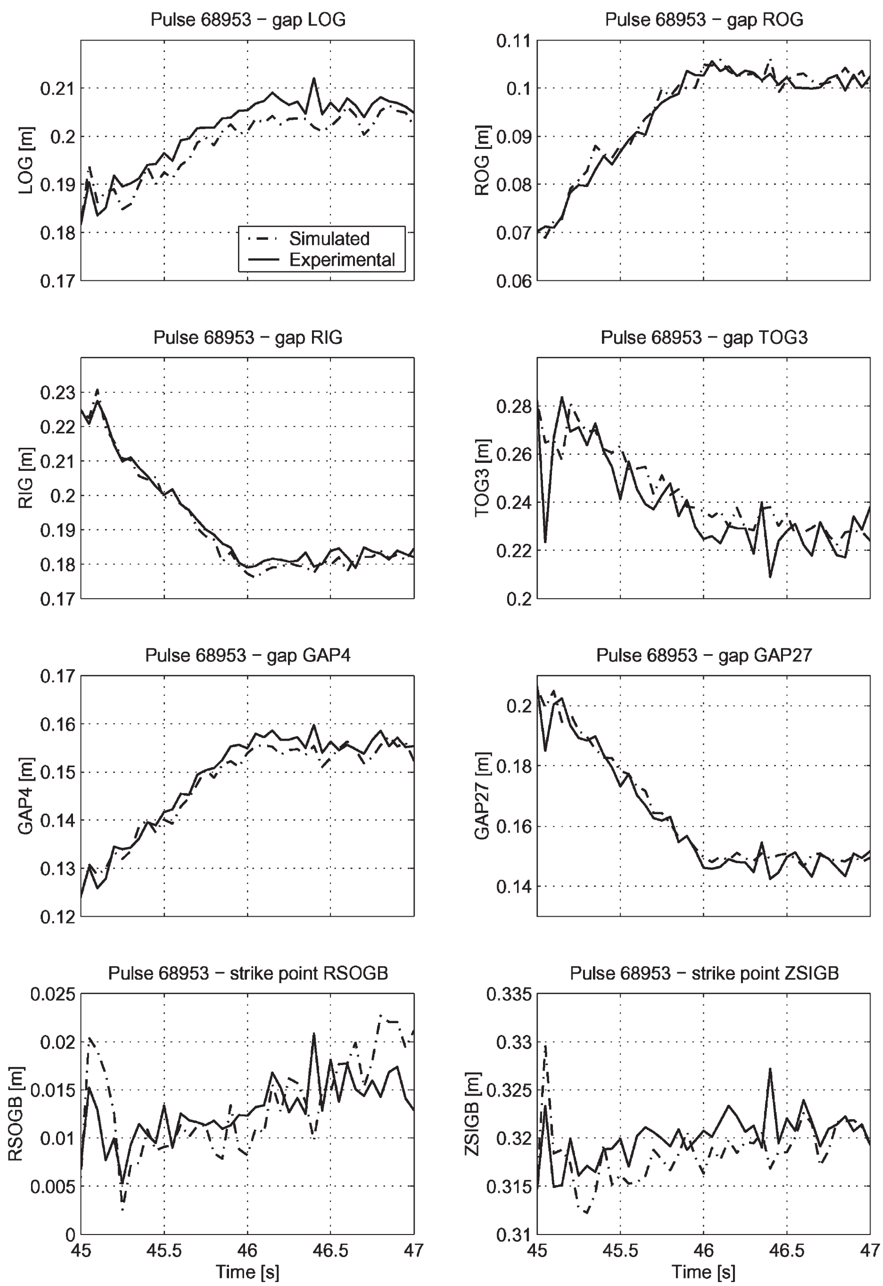


Fig. 15. XSC closed-loop simulation for JET pulse 68953—gaps and strike points. This figure shows a comparison between the (solid lines) experimental values and the (dash and dot lines) simulated values of eight plasma-boundary descriptors.

simulation tool and the real-time code running on the plant. This feature guarantees that the controller which is running on the plant is exactly the same one that is used for the scenario assessment.

XSCGENERATOR can also load the existing XSC file, giving the possibility to modify some parameters and generate a new controller during a trial-error design procedure.

It is important to point out that, in addition to plasma-boundary descriptors, the XSC can control any plasma parameter, as far as a linear relationship between the variable to be controlled and the currents into the PF coils exists. Recently, an enhanced version of the XSC has been developed to control both the plasma shape and the magnetic flux at the plasma boundary [32].

D. XSCSIMULATOR

Before the XSC file could be loaded on the plant, the controller must be validated using a simulation tool. XSCSIMULATOR takes as inputs both the Model and the XSC files, and it allows the user to perform closed-loop simulations in order to assess the experimental scenario.

The Simulink scheme shown in Fig. 12 provides a number of blocks to model each subsystem of the plant:

1) **Plasma Linearized Model**—models the plasma behavior;
2) **Power Supply**—models the PF-coil actuators;
3) **Diagnostic**—models the plant diagnostic for plasma shape and position;

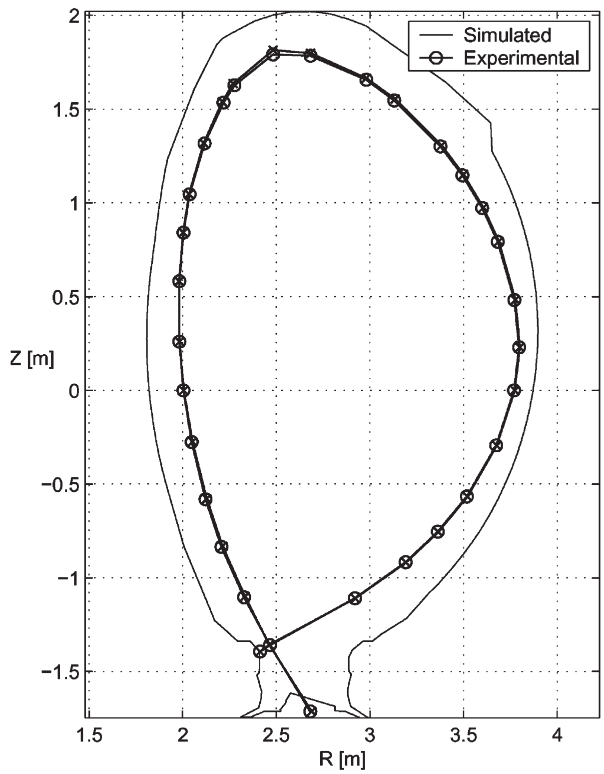


Fig. 16. JET pulse 68953—comparison between the simulated and the experimental plasma shape at $t = 47$ s.

4) **XSC**—is the XSC block;
5) **VS Controller**—it is the vertical stabilization controller block.

Note that with XSCSIMULATOR, it is possible to perform the closed-loop simulations with both the XSC and the vertical stabilization controllers. The latter control system uses the PF-coil system to control the plasma vertical position, and it is indispensable when operating with the elongated plasmas, since these plasmas are vertically unstable.

The XSCSIMULATOR GUI allows the user to:

1) choose the shape references either from the XSC file or from a model file;
2) choose either the model outputs or the plant-diagnostic outputs as shape measurements;[6]
3) choose either the model equilibrium values or the experimental values as initial conditions;
4) switch ON/OFF the vertical stabilization controller;
5) prescribe the waveforms of $I_{\rm p}(t)$, $\beta_{\rm p}(t)$, and $l_{\rm i}(t)$;
6) choose the driving mode for each PF coils, either voltage driven or current driven. This feature is used to validate the plasma linearized model comparing the open-loop simulation results with the experimental data;
7) plot the simulation results and compare them with the experimental data when they are available.

[6]The plasma linearized model provides the magnetic measurements which are the inputs to the plant-diagnostic algorithm.

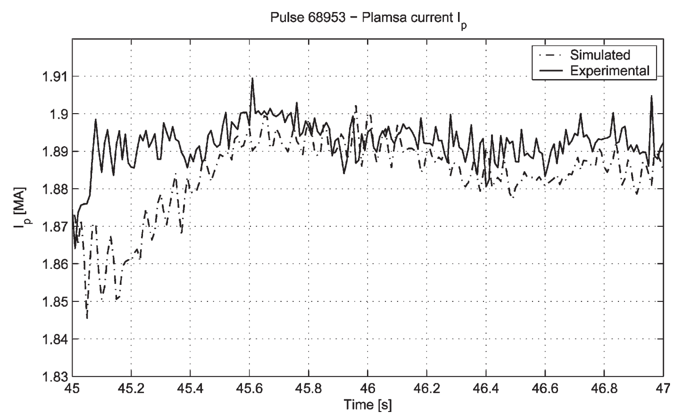


Fig. 17. XSC closed-loop simulation for JET pulse 68953—plasma current $I_{\rm p}$. The solid line is the experimental plasma current, while the dash and dot line is the simulated one.

XSCSIMULATOR allows to use a single model-controller pair for each simulation. Therefore, different simulations must be performed in order to validate the behavior of the XSC in different time windows. To achieve this, target XSCSIMULATOR gives the possibility to save the final data of a simulation and use them as initial condition for the next one. This feature allows the preparation of operational scenarios, in which different XSCs are used to control the shape constant even in the presence of big disturbances such as either a 50% increase or decrease of plasma current.

VI. Examples

Two examples of the use of the XSC Tools are presented. First, an open-loop simulation that aimed to validate the plasma linearized model is presented. Then, an example of closed-loop simulation with the XSC is shown, comparing the simulation results with the experimental data.

A. Plasma-Model Open-Loop Validation

Once a plasma linearized model has been retrieved using either CREATE-L or CREATE-NL, it should be validated via simulation using XSCSIMULATOR.

To perform such a validation, the experimental values of both currents in the PF coils and disturbances, i.e., $\beta_{\rm p}(t)$ and $l_{\rm i}(t)$, are prescribed in the model [(3) and (4)]. The user can easily set up the simulation loading the desired model file and setting all the PF coils in the current-drive mode (see Section V-D).

Fig. 13 reports a comparison between the simulation and experimental values. Six gaps and two strike points for the JET pulse 68397 are shown from $t = 46$ s to $t = 53$ s. The plasma linearized model used to perform the simulation has been obtained using the experimental data as equilibrium at $t = 49$ s.

Note that the plasma-boundary variation between $t = 47$ s and $t = 48.5$ s is due partly to the $\beta_{\rm p}$ drop shown in Fig. 14 and partly to the switch ON of a new XSC time window at 48 s, with a transition time of 0.5 s.

Starting from $t = 52.5$ s, strike-point sweeping can be noticed. This movement of the strike points is prescribed during

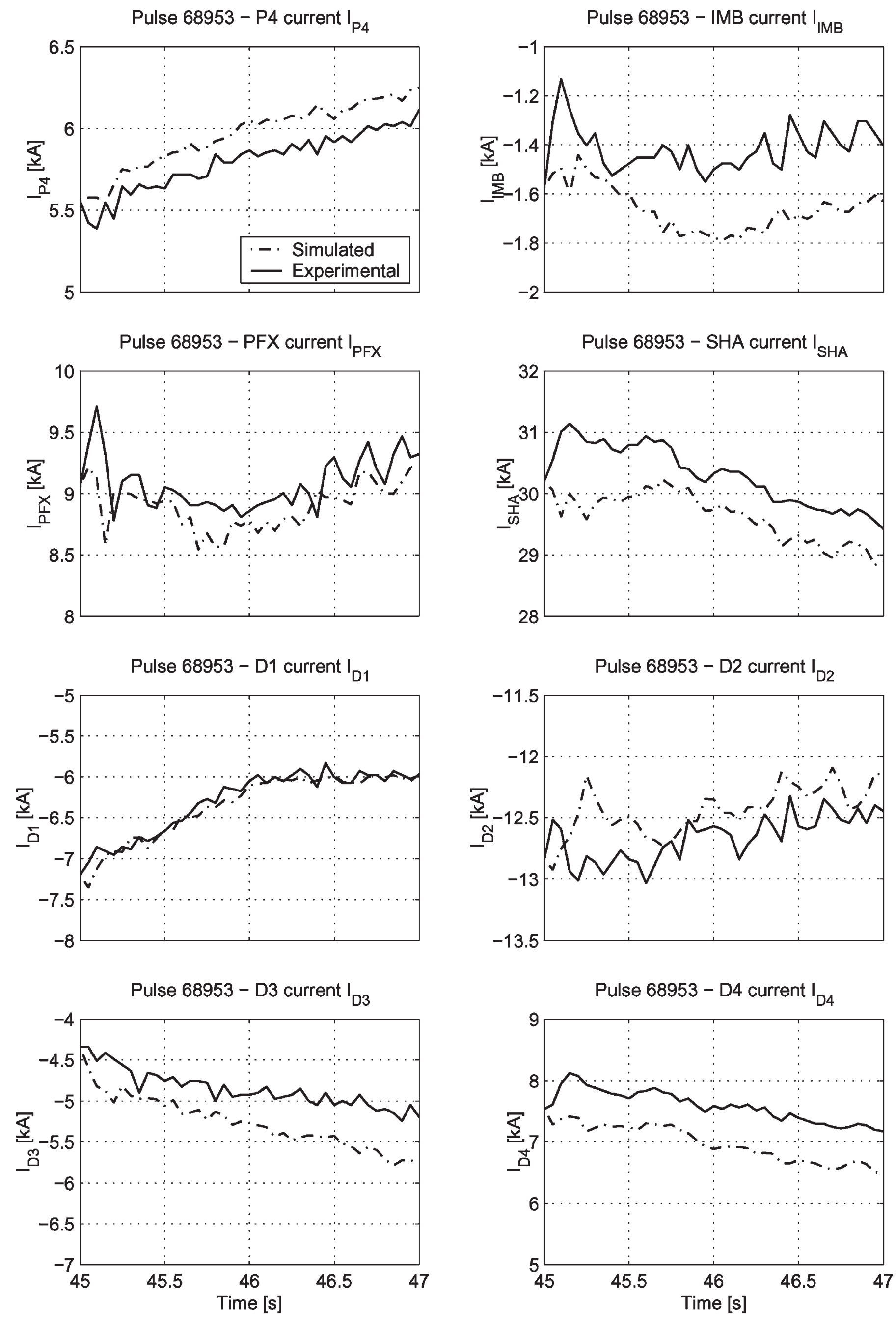


Fig. 18. XSC closed-loop simulation for JET pulse 68953—PF-coil currents. This figure shows a comparison between the (solid lines) experimental values and the (dash and dot lines) simulated values of eight currents into the JET PF circuits used for the plasma shape control.

certain experiments in order to prevent high temperatures of the divertor tiles.

It is important to point out that the plasma current is not prescribed during this simulation, but it is simulated using the corresponding equation in (3) and closing the plasma current-control loop. Thus, the plasma-model validation is an open-loop simulation only concerning the plasma shape.

B. XSC Closed-Loop Simulation

The closed-loop simulations with the XSC, whose one example is reported in this section, are used to validate the controller (see Section III-B).

Performing a number of simulations, the user can:

1) check if the target plasma shape is achieved;
2) check if the expected disturbances (namely β_{p}, l_{i}, and I_{p} variations) can be rejected without reaching the current and/or voltage limits of the PF-coil power supplies.

If one of the checks listed previously is not satisfactory, the user has to return to the controller-design phase according to the trial-error procedure introduced in Section III-B.

In the following, the simulation results for a 2-s time windows of the JET pulse 68953 are reported. The time window starts at $t = 45$ s, with a transition time of 1 s.

The simulation has been carried out using the plasma linearized model of pulse 68953 at $t = 45$ s and the XSC file which has been used on the real plant.

Fig. 15 shows a comparison between the experimental data and the simulation results. Fig. 16 shows a comparison between the simulated and the experimental plasma shapes at the end of simulation at $t = 47$ s—only a small error ($\sim$1 cm) on the plasma top can be noticed.

The comparison between the simulated experimental plasma current is shown in Fig. 17, while Fig. 18 shows both the simulated and experimental currents in the PF coils.

VII. Conclusion

A graphic suite, which is called XSC Tools, for the design and validation of the XSC has been presented in this paper. The suite automates the XSC design procedure, and it is made up of five graphic tools that help the nonexpert users to prepare operative scenarios based on the XSC, from the modeling phase to validation via simulations. All the graphic applications have been developed using Matlab/Simulink and can be installed on any desktop PC running the Windows operating system.

The final output of these tools is the XSC file, which is a simple text file that holds all the controller parameters. The XSC file can be used without any further changes to configure the real-time code that implements the controller on the plant. This feature guarantees that the controller which is running on the plant is exactly the same one validated via simulations.

The XSC Tools are currently used at JET to prepare the scenarios for the next experimental campaigns [33] and have been also used to review the capability of the ITER magnetic actuators [34].

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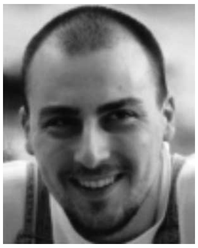

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