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## ABSTRACT

A new model-based shape controller eXtreme Shape Controller (XSC) able to operate with high elongation and triangularity plasmas has been designed and implemented at JET in 2003. The use of the XSC needs a number of steps, which at present are not automated and therefore imply the involvement of several experts. To help the session leader in preparing an experiment, a number of software tools are needed. The paper describes the SW tools that are currently in the developing phase, and describes the new framework for the preparation of a JET experiment.


## INTRODUCTION

A recent JET Enhancement [1] was aimed at designing and implementing a new model-based shape controller eXtreme Shape Controller (XSC) able to operate with high elongation and triangularity plasmas. In 2003 the XSC has been implemented on a new hardware architecture and successfully tested in various experiments.

The use of the XSC needs a number of steps, which currently are not automated and therefore imply the involvement of several experts.

The first step is the definition of an initial plasma equilibrium in which the plasma is brought by the old JET Shape Controller (SC) at the end of the start-up phase. This plasma equilibrium is assumed to be the starting plasma configuration from which the plasma moves toward the operational configurations of interest (target configurations) using the XSC. For the design of the XSC, in this step, starting from the definition of an initial plasma configuration in terms of plasma current, shape and main plasma current profile parameters (poloidal beta and internal inductance), a set of equilibrium poloidal field currents has to be determined and a linearized model of the plasma-circuit dynamics generated.

The second step is the definition of the target plasma configuration. This step also requires the definition of the time instant $t_0$ in which the XSC is activated, and the transition time interval ($t_0$, $t_1$) needed for moving from the reference to the target plasma configuration.

The third step is the controller design. Since the XSC uses Singular Value Decomposition (SVD) to find the best combination of currents needed to obtain specific changes in the shape, its design, namely the determination of the controller gains, requires the selection of weights for plasma shape parameters (plasma-wall gaps) and actuators (circuit currents).

The fourth step is the assessment of the XSC scenario, based on linear or nonlinear closed-loop simulations starting at time $t_0$, which should verify that (within a given tolerance) the desired shape can be attained in the selected transition time and maintained in the presence of expected changes of poloidal beta and internal inductance. The simulations must also verify that the circuit current limits are not exceeded. If the simulation results are not satisfactory, then one or more of the previous steps must be iterated.

The last step is the creation of the configuration file containing the information needed for the Level 1 XSC session leader interface.

To help the session leader in preparing an experiment, a number of software tools should be developed. This paper describes the procedure for the preparation of a JET experiment based on the use of the XSC and describes the SW tools that are currently in development as part of the activities of a new JET enhancement aimed at the XSC engineering.

## 2. THE PROCEDURE FOR THE PREPARATION OF AN EXPERIMENT BASED ON THE XSC AND THE DESCRIPTION OF THE SW TOOLS

The procedure for the preparation of a JET experiment based on the use of the XSC is sketched in Figure 1. It consists of six separate phases: plasma modelling, definition of the target plasma, controller design, assessment of the XSC scenario, preparation of the configuration file, use of the Level 1 interface and commissioning.

Hereafter the SW tools which will be made available for each phase are shortly described focusing on the needed input information and on both the information and data obtained as outputs.

### *2.1 MODELLING TOOLS*

Plasma modeling is based on linear (*CREATE-L*) and nonlinear (*CREATE-NL*) tools [2, 3]. These tools are aimed at providing reliable plasma response models for control system design and assessment. The input quantities are the Poloidal Field (PF) circuit currents (or voltages) and a number of parameters related to the plasma current density profile. The output quantities include the signals provided by the magnetic diagnostic system of JET (fields, fluxes and flux differences) as well as plasma current and shape.

Upgraded versions of these codes have been set up on the JET configuration. With respect to previous versions, they include an upgraded equivalent axisymmetric model of the iron core, a new definition for plasma poloidal beta, a new parametrization of the current density profile, and they also take into account the eddy currents induced in the passive structures [4].

The first step is the definition of an equilibrium configuration in terms of desired plasma boundary, poloidal flux at the boundary, poloidal beta, internal inductance and total plasma current. It is usually prepared by picking an equilibrium configuration achieved in the past from the JET database. However, alternative choices can be pursued, e.g. interpolating between two configurations or prescribing a brand new form.

The inverse version of the nonlinear *CREATE-NL* code determines the full set of parameters describing the nominal equilibrium, namely a set of poloidal field circuit currents, along with the corresponding magnetic flux distribution and plasma shape. The PF currents are selected so as to minimize a cost function that takes into account the detachment of the shape from the desired boundary as well as power supply limits or other prescriptions on the PF system, as there are combinations of currents that produce very low field in the plasma region.

The result of the inverse version of *CREATE-NL* is then processed to get a forward equilibrium and a linearized response model. This task is carried out independently by two distinct tools:

*CREATE-L* and the equilibrium-linearization section of *CREATE-NL*. For both tools working on JET, the specific inputs are the PF circuit currents, the plasma current and the values of poloidal beta and internal inductance. However, the magnetic flux distribution produced by *CREATE-NL* speeds up the convergence of the equilibrium solver. Additional data, which are however fixed for a wide number of sessions, include the geometry, the iron magnetic curve, the PF coil number of turns, resistances and connections and other machine parameters.

We use two finite element tools to perform the same task, i.e. the linearization, to increase the reliability of the plasma response model, which is a key-point of the XSC performance. The linearization of *CREATE-L* is based on analytical expressions of the Jacobian matrix, which are more accurate, whereas *CREATE-NL* adopts incremental ratios, which allow to determine the effective range of applicability of the linear model. *CREATE-L* (written in FORTRAN) is also more accurate because it adopts $2^{nd}$ order elements, whereas *CREATE-NL* (written in MATLAB) uses first order triangles. The resulting linearized model for shape control provides the A to F matrices of system:

$$\dot{x} = Ax + Bu + Ew$$
$$y = Cx + Du + Fw$$

where x corresponds to the set of currents (including PF currents and total plasma current), u to the set of applied voltages, w to the profile parameters (poloidal beta and internal inductance) multiplied by the plasma current, and y to the set of observed or controlled outputs (including magnetic measurements, plasma-wall gaps, and others). The nominal (equilibrium) values of these parameters are also provided along with the system matrices.

To describe the plasma response on a faster time scale, e.g. for vertical stabilization or X-point sweeping, the contribution of the eddy currents in the passive structures cannot be neglected, and therefore the state vector x must also include degrees of freedom corresponding to the eddy current distribution in the passive structures. The system in this form is unstable for elongated plasmas.

Finally, the transient version of the *CREATE-NL* code can be used to assess the performance of the XSC in case of large variations of shape, currents or plasma parameters. Nonlinear closed loop simulations are possible, but the control algorithm should be linked to the nonlinear transient version of *CREATE-NL*. Nonlinear open loop simulations are simpler. In these cases, the time histories of the plasma parameters are prescribed along with the waveforms of the currents or voltages predicted by the closed loop linear simulation tools.

### *2.2. DEFINITION OF THE TARGET PLASMA*

The steps needed to define the parameters of a target plasma are logically the same defined in the previous section. Hence, in principle, the same SW tools can be used. However, in the case when the target plasma is sufficiently close to the initial configuration, the session leader will have the possibility of defining its parameters by means of an user friendly graphical tool, named *CREATE EGENE*, which is described in details in Section 2.5.

### 2.3 CONTROLLER DESIGN TOOLS

The tool for the calculation of the controller matrices is called *XSC Generator*. Before using this tool, the user must have already picked a nominal plasma configuration and generated accordingly a plasma-circuit linearized model using the modeling tool. The control algorithm [5] tries to find a compromise between the control effort, specified in terms of variations of the 8 coil currents used by the shape controller, and the tracking error on the plasma shape. The plasma shape is defined through 32 gaps, the X-point and two other parameters specifying the strike point positions. The control algorithm takes into account the fact that, despite the availability of 8 distinct coil currents, as a matter of fact only 5 (or 6, depending on the chosen plasma configuration) linear combination of them are independent. The attempt of using all the 8 coil currents as if they were independent would result in a high control effort, possibly violating the saturation limits, with a negligible improvement on the performance.

The input data to the *XSC Generator* that must be specified by the user are:

- the nominal plasma linearized model;
- the weights on the 8 coil currents used by the shape controller (the smaller the figure, the smaller the steady-state variation of the current is);
- the weights on the 36 geometrical descriptors (the higher the figure, the smaller the expected tracking error on the selected variable is);
- the number of coil current linear combinations to use (usually 5 or 6, if all the currents are used to control the shape).

The XSC algorithm also gives the flexibility of using only a subset of the coil currents to control the shape: in the case the weight on a coil current is set to 0, that current is not used by the shape controller. This implies that for the chosen circuit we are adopting a current control, and therefore a current reference to track must then be specified. Of course, if one or more coils are in current control mode, the number of coil current linear combinations to use for the shape control must be decreased accordingly.

The *XSC Generator* tool gives as output the controller matrices that are used by the closed-loop simulation tool. It is important to underline the fact that the calculation of the controller matrices most of the times is not a one-shot procedure, basically for the following two reasons:

- the closed-loop performance that are expected once the weights have been specified are not always obtained. In this case the weights must be adjusted and other matrices calculated;
- even when the closed-loop simulation gives good results with a nominal plasma model, before testing the controller on the plant, it is advisable to test the controller behavior with different "close" linearized plasma models. Also in this case, some iterations with the XSC Generator could be needed.

### 2.4 TOOLS FOR THE ASSESSMENT OF THE XSC SCENARIO

The assessment of the XSC scenario is performed through closed loop simulations. These simulations are aimed at evaluating in advance the performance that will be attained in a single time window by the XSC during a JET discharge. To perform these functionalities a SW tool will be provided. It needs the following input data:

- the simulation time interval [$t_0$, $t_f$];
- a linearized plasma model able to describe the plasma response with respect to poloidal field coil voltages, poloidal beta, and internal inductance, variations; this model should be sufficiently reliable in the simulation time interval [$t_0$, $t_f$];
- the XSC control law algorithm;
- the plasma initial configuration at the time $t_0$; this configuration is defined in terms of initial values of the PF coil currents, the plasma current, the saddle and pick-up coil measurements;
- the reference signals for the XSC controlled variables (a set of gaps describing the plasma boundary and the plasma current);
- the predicted time behavior for the poloidal beta and for the internal inductance.

The outputs of the closed loop simulation tools are the predicted time traces for all the variables that the *CREATE-L* model can produce. It should be noted that the only obstacle toward a fully predictive simulation is the need to prescribe in advance the time behavior of the poloidal beta and of the internal inductance, which in the *CREATE-L* model are represented as external disturbances. The closed loop simulation tool will also be endowed with interfaces to help the user to define the input data and to interpret the outputs of a simulation. In particular graphical user interfaces in development will

- help the user to define the initial plasma configuration; this component is interfaced with the JET experimental database in such a way to allow the user to load the data from an experimental equilibrium;
- help the user to define the plasma configuration to be tracked by the XSC;
- help the user to interpret the closed loop simulation results; this tools will be based on a series of synoptic panels where the most important variables are displayed. The user can recognize abnormal condition (current saturations, gaps to close to the wall, etc.) through visual alarms.

### *2.5 TOOLS FOR THE GENERATION OF THE CONFIGURATION FILE*

The SW tool that will generate the configuration file needed by Level 1 to run the experiment will be named *CREATE EGENE* (*Equilibria GENErator*). The configuration file, which is an ASCII file, contains the following data:

- the shape reference in terms of controlled gaps;
- the pre-programmed references for the PF coil currents;
- the controller parameters.

Different configuration files can be specified for each time windows, therefore different controller matrices and shape references can be used during the same pulse.

Besides the automatic generation of the configuration file, *CREATE EGENE* will also give the session leader the possibility of constructing a target shape modifying the values of some gaps of the initial plasma configuration. To make this job easier, it has a graphical interface that allows the user to start from the initial plasma shape and move towards a new one changing several boundary descriptors, both for the shape and for the strike points. For each new shape *CREATE EGENE* displays the needed PF currents and it checks if they are within the limits. These currents values will be used as feed forward references for the PF coils power supplies. If some of these currents violate the limits the user can:

- modify the shape, trying to bring back the poloidal currents within the limits;
- modify the PF currents without changing the shape. To do that *CREATE EGENE* will use the linear combinations of currents that do not affect the plasma boundary, therefore the resulting shape is not exactly the same, because the new currents values are such that the error between the desired shape and the actual one is minimized in the least square sense.

Eventually the user can even change the plasma current, and li, therefore new references can be carried out changing geometrical descriptors, plasma current and external disturbances. The input data to *CREATE EGENE* are the controller parameters (as stored in the XSC Generator output file), and the equilibrium currents and plasma shape with the matrices of the plasma linearized model as generated by *CREATE-L* and *CREATE-NL*.

### *2.6. LEVEL 1 SESSION LEADER INTERFACE*

The operation of the JET experiment is a synergic effort among a large group of specialized professionals: the “Session Leaders” (SLs), scientist in charge of the experiments; the “Diagnostic Coordinators” (DC), operators of the plasma diagnostics; the “Engineers In Charge”, responsible of machine safety; and the many operators of JET systems. The essential tool that coordinates all these individuals is the Level-1, an expert system that helps the experiment preparation and set-up by providing a customized and automated user interfaces. The thousands of different parameters affecting the behavior of JET subsystems during a discharge are contained in a database called “Plant”. Level-1 is the interface that allows inspecting and changing these parameters while imposing the separation of roles and responsibilities among the different operators. The program checks the parameters against a set of operating instructions therefore contributing to the machine protection and in addition is key to the experiment repeatability, since it provides the ability to retrieve any old experiment configuration.

A good share of the information contained in the “Plant” are the Shape Controller (SC) parameters, which are divided between the SL configurations that affect the experiment evolution and the expert settings that impact on performance, safety and control stability and are occasionally tuned by the expert plasma control scientists. The main set of SC parameters describing the time sequence of plasma shape events are divided among time-windows, for each of which the user can select a combination of control variables and control techniques and reference waveforms. While the first 4 time windows that are dedicated to the plasma formation phase are most of the time copied from a few sets of pre-programmed breakdown recipes, the remaining ones are used by the SLs to program thousands of different experiments. To help the management of that much complexity and freedom, the user can choose to let Level-1 program all the parameter of a time-window, by only specifying one of the available “Plasma Scenarios” and then optionally applying any desired variation.

With the introduction of the eXtreme Shape Controller (XCS) the number of control variables have risen from 29 to 64 and the possible control scheme variation have multiplied. At the same time the relative number of valid parameter combinations has much reduced. For this reason it was chosen to completely hide the detailed selection of control scenario from the SL, which can only pick from a list of available “XSC Scenarios”. Compared to “Plasma Scenarios” these provide the user with less flexibility, because they do not allow full customization, but at the same time they present a much more user-friendly interface, showing the plasma shape reference and the effect that any parameter adjustment would have on it. In addition “XSC Scenarios” display the estimated range in circuit currents as a function of the plasma internal parameters expected variations, and allow comparing the shape with that in any past experiment. These features are accomplished by providing level-1 with a scenario configuration file that contains the controller matrix, the control variable selection, and the allowed range of variation of the shape specified as the interpolation among a set of reference configurations. This last mechanism allows for the cover of a wide range of plasma shapes while at the same time still providing a practical and fast solution for the commissioning. To validate an “XSC Scenarios” in its entire range of plasmas it is in fact only necessary to test it on the reference shapes.

## CONCLUSIONS

Various SW tools are being developed to help a JET session leader preparing an experiment with the XSC. These tools have been described in terms of input-output data, and their main features illustrated.

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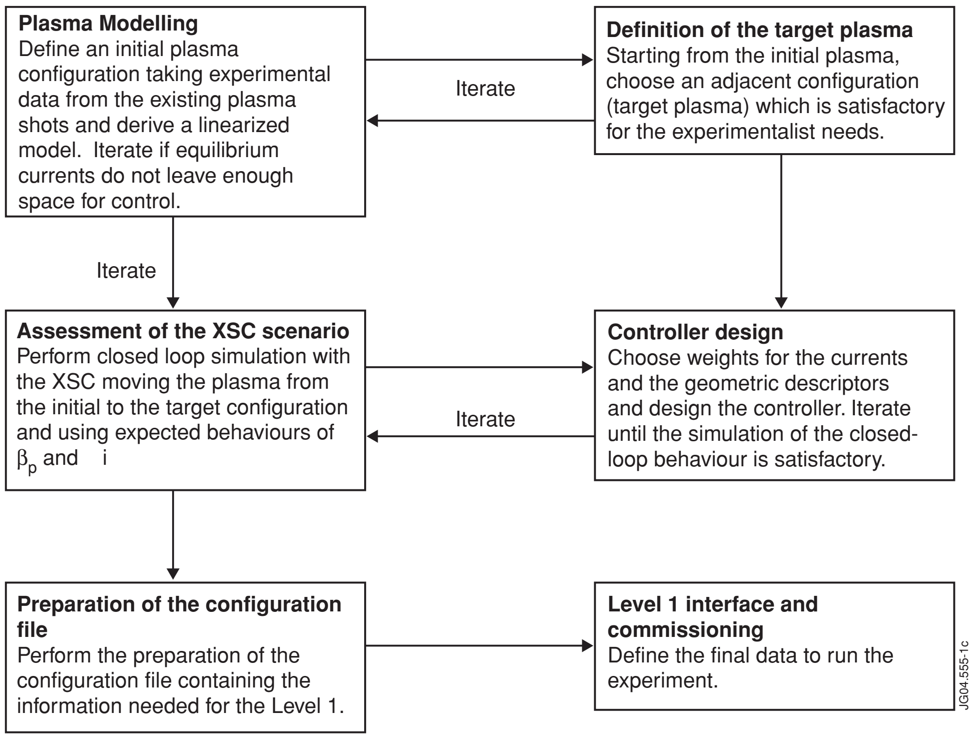


*Figure 1: Schematic of the procedure for the preparation of a JET experiment based on the XSC*