2D AND 3D MODELLING OF JT-60SA FOR DISRUPTIONS AND PLASMA START-UP

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Abstract

One of the goals for the JT-60SA superconducting tokamak is to study practical and reliable plasma control schemes in view of the power plant. Plasma electromagnetic modelling is one of the essential tools for plasma operation in a fusion device and it requires detailed models for ensuring an accurate preparation of the magnetic controllers. In this paper, we report on the activities that have been carried out exploiting the CREATE modeling tools. In particular, 2D modelling has been exploited to study the magnetic configurations for the EC assisted breakdown, whereas 3D tools have been used to evaluate the effect of three-dimensional structures on evolutionary equilibrium of axisymmetric plasmas.

1. INTRODUCTION

The JT-60SA is a superconducting tokamak device being built as a joint international project between Japan and Europe [1] in the frame of the broader Approach agreement. One of the main goals of JT-60SA is to study practical and reliable plasma control schemes in view of the power plant. Plasma electromagnetic modelling and control are essential tools for plasma operation in a fusion device. Magnetic models are required in order to ensure an accurate preparation of the nominal scenario and a reliable design of the magnetic controllers.

To achieve these goals, suitable models are needed at different level of details. 2D equilibrium codes are used to develop the operational scenarios and to perform breakdown studies. Furthermore, three-dimensional modelling permits the assessment of 3D vessel structures effects on the plasma behaviour [2], e.g. during disruptions, as well as to study non-axisymmetric plasma instabilities [3]. On the other hand, engineering-oriented models, which are typically linear models that are valid around a given operating point, are essential for the commissioning of the magnetic diagnostics [4], and the design of control algorithms [5].

In this context, several activities have been developed in support of JT-60SA (see also [6]). Preliminary results on plasma magnetic control, have been presented in [7] and [8], where an isoflux approach has been proposed to control the plasma boundary, and has been validated against the MECS simulator. Scenarios for plasma breakdown have been developed by using TOSCA in [9], for both the half and the full pre-magnetization case. A set of alternative modelling tools based on the CREATE 2D optimization and equilibrium codes [10],[11] have been developed as additional benchmark for magnetic modelling. These tools have been exploited to perform breakdown studies [6], and to design a preliminary functional architecture of the plasma magnetic control system [5]. Furthermore, using the CarMa0NL code [2] several studies of the impact of 3D structures on plasma evolution have been carried out, ranging from pure electromagnetic analysis of the magnetic field produced by the non-axisymmetric coils [12], to nonlinear evolution of n = 0 instabilities [13].

Here, we report on the activities that have been carried out exploiting the CREATE 2D and 3D modelling tools. The paper is structured as follows: Section 2 gives an overview of the activities that have been performed exploiting the 2D linear models, which have been mainly aimed at assessing the capabilities of an axisymmetric shape and position magnetic control system. Section 3 focuses on the 2D nonlinear modelling tools that have been exploited to study the magnetic configurations for the EC assisted breakdown, while Section 4 presents the...
activity performed using the 3D modelling tools, aimed at evaluating the effect of three-dimensional structures during disruptions. Eventually some conclusive remarks are given.

2. 2D MODELLING FOR THE ASSESSMENT OF PLASMA MAGNETIC CONTROL

When dealing with plasma magnetic control, the availability of engineering-oriented models is essential to enable model-based design of control algorithms and to make performance assessment. To this aim, 2D nonlinear magnetic equilibrium codes CREATE-L [10] and CREATE-NL [11] are also capable to generate linearized models of the plasma/circuits behaviour for a given plasma equilibrium, i.e. for a given scenario snapshot¹. Being available in the Matlab/Simulink® environment, the CREATE modelling tools can be easily used to design and validate control algorithms.

In order to benchmark the CREATE 2D nonlinear magnetic equilibrium codes for JT-60SA, the output of these codes has been compared with the one obtained with TOSCA and MECS for some of the reference scenarios provided in the JT-60SA research plan, namely Scenario 1 and 2 [14]. The results obtained with the different modelling tools, in terms of shape of the plasma boundary, and growth rate, turned out to be in good agreement. As an example see the Scenario 2 equilibrium shown in Fig. 1 (for more details on the code benchmarking, the interested reader can refer to Sec. 3.1 in [5]).

FIG. 1. Comparison between the plasma shapes obtained with TOSCA (solid black) and CREATE-L (red dots) for the JT-60SA Scenario 2 at t = 18.6s (Ip = 5.5 MA). The comparison shows the good agreement between the two equilibrium codes.

FIG. 2. Simulink simulation scheme used to assess the capability of triggering ELMs using VS kicks.

¹ The availability of two different ways to generate linearized models is relevant for code benchmarking as well as to increase the reliability of the overall model-based design environment.
After the validation of the nonlinear equilibrium codes, the linear models have been exploited to design a set of algorithms to be used to assess the capabilities of the magnetic system (see [5]). This set of control algorithms includes a Vertical Stabilization (VS) controller similar to the one adopted at JET [15]. Such VS has been used in the simulation setup reported in Fig. 2 for a preliminary assessment of the possibility of triggering ELMs by means of vertical voltage kicks. In particular:

— the plasma/circuit linearized model for Scenario 2 at \( t = 116.46 \) s has been considered, whose growth rate is \( \gamma = 3.66 \) \( \text{s}^{-1} \);
— a Kicks Generator block is used to temporarily disconnect the VS so as to generate a periodic kick waveform to be applied to the in-vessel coils (i.e. a negative voltage pulse followed by a positive one);
— the in-vessel coils power supplies have been modelled as a first order transfer function with a time constant of 3 ms, in series with a pure time delay of 1.5 ms. The maximum voltage has been set equal to 1 kV for both in-vessel coils; the positive and negative kicks amplitude is equal to the saturation voltage;
— the kicks frequency has been set equal to 20 Hz. The kicks are applied for about 2/3 of the period, during which the VS is switched on, while the applied voltage is negative for about 36% of the kick time and positive for the remainder.

Fig. 3 shows the time traces of the in-vessel voltage \( V_{\text{VSU}} \) - both the request to the VS, and the actual voltage applied to the coils\(^2\) - and current \( I_{\text{VSU}} \) during kicks, as well as the correspondent vertical movement of the plasma centroid \( Z_c \). It can be noticed that the peak-to-peak vertical movement for the plasma centroid has an amplitude of about 2.5 cm.

Based on the JET experience, two conditions are required to trigger an ELM using vertical kicks [16]: i) a minimum plasma displacement greater than 1 cm (independently of plasma velocity), and ii) a minimum plasma vertical speed greater than 3.5 m/s. Although it seems that condition i) could be met at JT-60SA, the maximum vertical speed obtained in simulation is about 2 m/s. Hence, comparing this figure with the typical values for the vertical speed at JET (4-10 m/s), the preliminary indication is that it may be difficult to trigger ELMs in JT-60SA with the current envisaged setup. Indeed, the slowest time response of the overall system with respect to JET seems to have two main sources:

— the presence of the passive stabilizers that slow down the growth rate, whose typical values at JT-60SA range between 3.5 and 20 \( \text{s}^{-1} \). These are much lower than the typical JET growth rate ranging between 100 and 200 \( \text{s}^{-1} \);
— the slower dynamic response of the in-vessel power supplies, as well as the lower maximum voltage that can be applied to the coils (at JET, the maximum voltage of the ERFA power supply is 12 kV [17]).

The 2D linear model together with the library of controllers presented in [5] have been also used to assess the optimal set of gaps\(^3\) to be controlled in order to have good response of the plasma shape control system under different operative scenarios. This analysis suggests that a set of about 20 gaps equally spaced along the plasma boundary permits to control the shape with a steady-state RMS error (computed along the overall plasma separatrix) of less than 1 cm for the envisaged disturbances. The control approach adopted to perform this study is based on the singular value decomposition of the static relationship between the controlled gaps and the currents flowing in the poloidal field coils (more details can be found in [18]).

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\(^2\) The difference between the requested and the actual voltage is mainly due to the assumption on the dynamic response of the power supplies

\(^3\) Gaps are distances between the plasma boundary and the first wall that are defined along given segments.
FIG. 3. Time traces for the in-vessel coil voltage and current and vertical displacement of the plasma centroid during kicks.

3. 2D MODELLING FOR EC ASSISTED BREAKDOWN

The main objectives of the breakdown (BD) studies have been (i) to assess BD performance obtained using waveforms described in [9]; (ii) to produce an alternative optimization of the currents in coils and voltages in the main converters; (iii) to point out possible problems in obtaining BD magnetic configurations; (iv) to compute magnetic quantities (flux map, field map, electric field) needed for the evaluation of the breakdown kinetic performance in the presence of ECH assistance.

Generally speaking, the breakdown scenario has been developed assuming a central BD region and using the procedure described in [20] for the ITER ECRH assisted BD. This procedure provides optimal values of voltage time histories and initial value of the currents in poloidal field circuits.

Breakdown, burnthrough and early plasma current ramp-up are considered in the study: in particular the considered scenario segment is divided in two parts. During the first part (before breakdown time, $t < t_{BD}$) no plasma is present in the vacuum chamber. The flux state is first brought to a certain initial value by charging the CS (Central Solenoid). Then voltages are applied to ramp down CS coil currents in order to achieve a sufficiently high loop voltage, implying a high electric field in the breakdown region at time $t_{BD}$. At the same time, all the poloidal field (PF) coils voltages are controlled to achieve low values of poloidal magnetic field in this region.

Once the desired breakdown conditions take place, plasma starts to grow in current and volume. During this second phase, plasma is simulated as a massive conductor with circular poloidal cross section filling the expected breakdown region. PF voltages should be driven so as to guarantee a desired time variation of vertical magnetic field and flux in the plasma region, and a certain field index.

During both the first and second phases, eddy currents in the passive structures play an important role due to the presence of fast varying currents in the active coils. It is worth to notice that the integrated study of the two scenario phases described above is mandatory since breakdown conditions have a fundamental impact on the first part of the $I_p$ current rise. A wrong design of the active coil currents to reach breakdown conditions may result in the impossibility to ramp up the plasma current. For this reason, a plasma current rise up of 100-150 kA is taken into account although with a simplified model (massive conductor approach).

Current and voltage limits are considered: 3D effects, ferromagnetic insert or building magnetization effects, TF coils busbar effects, Cryostat passive structures are not considered. No explicit limitation is assumed on active power. Switching Network Resistors (SNR) for the different coils are optimized with a trial and error procedure. No explicit limitation is assumed on the energy dissipated in the SNR units as well as on mechanical forces on coils induced by currents.

Plasma initiation region for central-outboard breakdown is assumed circular, with centre coordinates $R = 2.7$ m, $Z = 0.0$ m, and radius $a = 0.8$ m. Five control points (see Fig. 4) are assumed to check the satisfaction of field and flux requirements, i.e.:
- at $t_{BD}$ values of the poloidal field B in the control points must be kept below 3 mT (with an isofield line at 3 mT that should contain the whole circular breakdown region).
- External loop voltage at the plasma formation region centre must be greater than 5 V at $t_{BD}$ (i.e. electric field more than 0.3 V/m)
- Once plasma is initiated the vertical field $B_z$ must vary according to the Shafranov vertical field formula, and the decay index of the vertical magnetic field has to be approximately 0.5.

Optimization results with fully charged solenoid (initial CS2-CS3 current = 20kA) are shown in Figs. 5-9, where $t_{BD}$ is assumed to be equal to 100 ms. An initial flux of about 18.4 Vs is found, and a flux loss at BD of about 0.33Vs is observed. Eddy currents in the passive structure reach a maximum value of about 450 kA. An electric field of about 0.35 V/m is achieved at the centre of the BD region at the BD time.

One of the result of the BD study is that a difficulty to guarantee the Shafranov equilibrium field needed to sustain a circular plasma after $t_{BD}$ instant was observed. This was due to the large eddy currents flowing in the passive structures, and to the limits on active coil voltages. The problem was in part overcome by delaying the BD time with respect to previous studies.

BD calculation have been repeated also for the case of half charged central solenoid with no specific problem to report.

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**FIG. 4.** Magnetic poloidal field map: isofield lines at 1-5 mT. Control points 1-5 are also drawn in the vacuum chamber.

**FIG. 5.** Loop Voltage in the centre of the BD region (black line) and in other points of the BD region.

**FIG. 6.** Plasma current time history.

**FIG. 7.** Vertical magnetic field compared with the Shafranov vertical filed. Comparison make sense in the presence of plasma (i.e. for $t > t_{BD} = 0.1s$).
4. 3D MODELLING FOR DISRUPTION STUDIES

When one of operational limits is exceeded (e.g. Greenwald density limit, safety factor at plasma edge $q_s<2$, etc.), a MHD instability grows quickly, so that the plasma “expels” rapidly most of its thermal energy – this is the so called Thermal Quench (TQ). During the TQ, which is typically very fast (a sub-ms time range is expected for the TQ at JT-60SA), a current density profile flattening takes place, giving rise to a sudden decrease of internal inductance. Consequently, the plasma current increases, experiencing a spike, in order to keep magnetic energy in the plasma approximately constant. After this initial event, the plasma cools down and its resistivity increases, so that the plasma current drops to zero (Current Quench, CQ). Due to the rapidly changing conditions, the vertical position feedback may lose control of plasma, giving rise to a Vertical Displacement Event (VDE). In fact, a VDE may occur even before the TQ-CQ, in case of loss of control for other motivations – this is the so-called “hot-plasma” VDE. In all cases, due to this vertical motion, the plasma eventually hits the wall, injecting currents directly in the structures (halo currents). In addition, rapid magnetic field variations may give rise to a high electric field that can generate superthermal electrons (runaway electrons), which are however not treated in the following.

This typical chain of events has been modelled using the CarMa0NL code [2], capable of simulating the nonlinear behaviour of plasma under the evolutionary equilibrium assumption, in presence of three-dimensional conducting structures surrounding the plasma itself. In particular, a description of the three-dimensional features of the stabilizing plate has been considered. Previous disruption-related studies with a similar description of the conducting structures have been addressed to the detailed description of the $n=0$ vertical instability potentially triggering a disruption [13] and to the analysis of the capabilities of the feedback controller to reject given disturbances before a disruption takes place [19].

The starting equilibrium is a Scenario 2 configuration at $t=18.6$ s. The event under analysis is a hot downwards VDE: the plasma is forced to move downwards with a 1 kA step in the in-vessel coil current until it hits the wall, when the TQ occurs (that poloidal beta drops to 1% of nominal value in 0.5 ms). The current density flattening is represented by a plasma current spike $\approx 5\%$, so as to keep poloidal magnetic energy almost constant inside the plasma, in around 2 ms. Immediately after, the CQ takes place, with a linear decay of plasma current to 0 in 30 ms. Fig. 10 reports the time evolution of some plasma parameters, while Fig. 11 shows the time behaviour of the current in the conducting structures. The toroidal halo current flowing in the plasma is of the order of 1.5 MA; the maximum toroidal current induced in the vessel is around 4 MA, while in the stabilizing plate is of the order of 0.7 MA.

Fig. 12 illustrates one snapshots of the equilibrium configurations at a sample instant.
5. CONCLUSIONS

The CREATE modelling tools include both 2D and 3D equilibrium codes that have been extensively validated against different fusion devices such as RFX [21], JET [22] and EAST [23], and currently used by European scientists to perform preliminary studies and code benchmarking for both ITER [24] and DEMO [25]. As part of the European contribution to physics and operation of JT-60SA in view of its operation, the CREATE tools have been benchmarked on JT-60SA and preliminary results that can guide the design and operation of control systems have been presented. This paper summarized the studies that have been carried during 2015-2018,
which mainly focused on the assessment of the magnetic control system performance, and on both breakdown and disruption studies.

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