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Nonlinear 3D analysis of JT-60SA n=0 instabilities

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1. Introduction

The JT-60SA experiment [1-2] (major radius R~3m, typical aspect ratio A~2.5-2.6, maximum plasma current 5.5 MA) is a superconducting tokamak device being built as a joint international project between Japan and Europe. One of the most important goals of JT-60SA is to study practical and reliable plasma control schemes suitable for a power plant. In particular, one of its design requirements is to sustain high beta plasmas exceeding the no-wall ideal stability limits. To this purpose, diverted configurations with rather high elongations (up to around 1.90) and triangularities (up to around 0.50) are needed.

This gives rise to several MHD instabilities - in particular the so called Resistive Wall Modes (RWMs) with various toroidal mode numbers n. The characteristics of these instabilities (growth rates, stability margins etc.) depend on features of the conducting structures surrounding the plasma - not only the vacuum vessel, but especially the double-wall conducting shell, which has a strongly three-dimensional geometry, due to holes needed to access the interior of the tokamak for various purposes. Previous studies [3] have been dedicated to the analysis of $n>0$ RWM (external kink) with the linearized CarMa code [4], highlighting the 3D effects on passive stability properties.

In this paper, we investigate the $n=0$ instability in presence of three-dimensional conducting structures with the CarMa0 and CarMa0NL codes [5-6], able to describe the evolution of an axisymmetric plasma through equilibrium states in presence of 3D conductors, both linearizing the plasma equations and taking into account its fully nonlinear behaviour. With the aid of these codes, we investigate the 3D effects on the growth rate of the Vertical Displacement Events (VDEs) and the so-called Best Achievable Performances (BAP), i.e. the maximum controllable plasma perturbation for given limitations in the power supplies of active control coils.

2. Modelling

The details about the modelling tools can be found in [5-6]; here we simply recall the main points. The electromagnetic interaction between the plasma region (say P) and the unbounded region hosting the 3D conductors (say *V*) is decoupled using a coupling surface *S* located in between. The equations are the following:

- Plasma equilibrium equations in *P*
- Eddy currents equations in *V* (1)
- Coupling conditions on *S*

In (1) it is assumed that the plasma evolves through equilibrium states, which means that the typical time scale of interest is much slower than Alfvén time, so that plasma mass can be neglected. We also assume that the plasma equilibrium is axisymmetric, so that Grad-Shafranov equations are solved, either linearized (CarMa0 [5]) or fully nonlinear (CarMa0NL [6]). From the numerical point of view, in the plasma region we use a differential formulation in terms of magnetic flux as primary unknown; the resulting equations are solved using second-order triangular finite elements.

In the external 3D conductors, we solve eddy currents equations using an integral formulation, so that only the conducting materials must be discretized, via a volumetric finite elements mesh. In the particular case under analysis in the present paper, starting from a CAD description of JT-60SA, a hexahedral mesh has been created [3] (Fig. 1). For validation purposes, also an axisymmetric 3D mesh has been considered (Fig. 1 - only half a sector is reported). From the numerical point of view, edge elements are used as basis functions to expand electromagnetic quantities, in order to impose the correct continuity conditions.

On the coupling surface, suitable matching conditions are introduced, imposing that the total magnetic flux is due to currents flowing both in the plasma and in the structures.

3. Results

Three different configurations have been investigated, corresponding to the so-called Scenario 2 at different time instants (Table 1).

First of all, we compute the growth rate of the n=0 RWM (vertical instability) under different assumptions, using also an axisymmetric linearized plasma response model (CREATE_L [7]); the results are reported in Table 2. Evidently, the agreement between CarMa0 and CREATE_L is quite good on axisymmetric meshes, hence validating the procedure. The 3D effect on growth rate is detrimental and in the range of 10% - 20%; it should be noted that this is only due to the stabilizing plate, since the vessel is assumed axisymmetric in all computations. The effect of the superconducting PF coils on the growth rate is very significant, due to their zero resistance, when they are assumed as short circuited so that eddy currents can be induced in them as in conventional passive stabilizers.

Another set of results is about the recovery from perturbations, defined as any unexpected event (ELMs, minor disruptions, H-to-L transitions etc.) which may alter the plasma axisymmetric equilibrium configuration and hence may excite the n=0 RWM if no action is taken. In particular, we quantify the so called Best Achievable Performances (BAP) [8], i.e. the maximum plasma perturbation which can be rejected by any vertical feedback control system, given the voltage and current limitations of the power supplies. The BAP are computed with suitable simulations carried out with the CarMa0NL code: following a given perturbation, the plasma starts moving vertically; a voltage step of maximum allowed amplitude is applied to control coils to try to “catch" the plasma and bring it back to its original position, so that currents in the coils ramp up to maximum allowed amplitude. If the plasma does not invert the direction of its vertical movement, then the perturbation under consideration is not recoverable. The actuator used in the present case is made by the in-vessel coils (23 turns each) connected in antiseries, with a resistance of 0.1 Ω, a maximum voltage of 1 kV and maximum current of 5 kA. The power supply has been modelled by a pure 1.5 ms delay plus a 3 ms first-order filter. The first set of perturbations considered are pure beta drops (which is a simplified model for H-to-L transitions and minor disruptions, neglecting effects on plasma current), whose results are reported in Fig. 2. Evidently, beta drops in the range of 0.4 - 0.5 may be recovered within the limits; the most stringent limit seems the voltage saturation, since the current limit is not reached. Slightly more optimistic results are obtained with a 2D mesh, probably due to slightly slower growth rate. Also ELMs (modelled as in [9]) have been considered; they are easily recoverable within available voltage and current limits. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Parameter	*Config. A: t=4.6s*	*Config. B: t=5.7s*	*Config. C: t=18.6*
Ip [MA]	1.42	5.5	5.5
Centroid Rc, Zc [m]	2.911, -0.085	2.979, 0.038	2.974, 0.018
X-point Rx,Zx [m]	2.353, -2.290	2.313, -2.200	2.322, -2.204
Elongation	1.79	1.79	1.78
Triangularity	0.32	0.50	0.48
Internal inductance	0.85	0.85	0.75
Poloidal beta	0.20	0.52	0.76

Table 1. Plasma parameters for the three configurations used (Scenario 2 at different times)

Code	*Mesh*	*Config. A*	*Config. B*	*Config. C*
CREATE_L	2D - only passive	24.3	19.1	17.8
CarMa0	2D - only passive	24.6	19.4	18.3
CarMa0	3D - only passive	28.8	23.1	21.4
CREATE_L	2D - active + passive	8.35	4.60	3.89
CarMa0	2D - active + passive	8.32	4.95	4.31
CarMa0	3D - active + passive	9.22	5.47	4.68

Table 2. Growth rates [s^{-1}] with different assumptions

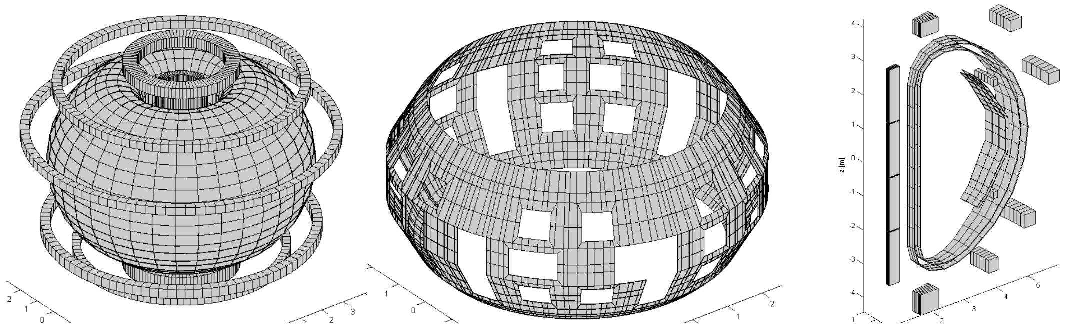

Fig. 1. 3D meshes used: 3D and axisymmetric cases

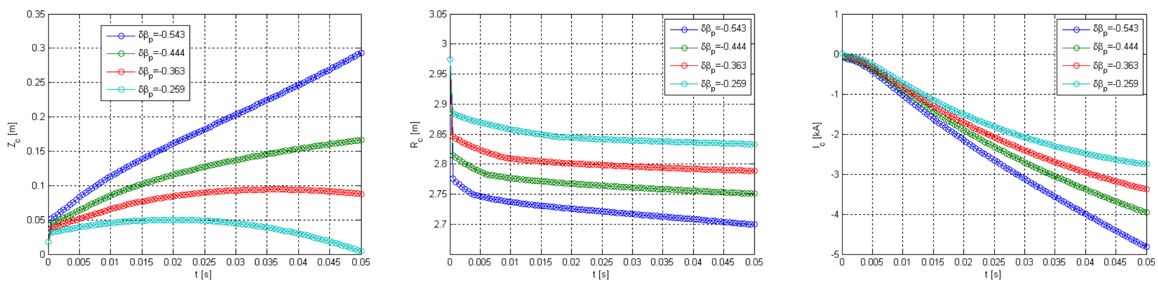

Fig. 2. Time behaviour of various quantities following a beta drop starting from Config. C.