ITER Disruption Simulations with Realistic Plasma and Conductors Modelling

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1. Introduction

Disruptions are one of the major concerns in ITER and other future tokamaks [1]. In addition to heat, particle flux, and energetic electrons impacting the first wall, significant electromagnetic loads will arise, due to the interaction of eddy and halo currents in the conducting structures with the magnetic field. Reliable modelling tools able to make predictions for future devices are hence fundamental. Two aspects must be considered for a suitable modelling of disruptions. First, a detailed model of plasma is needed, to describe its (possibly unstable) modes of evolution. Here, we use the M3D-C1 code [2], an implicit 3D extended-MHD code that uses high-order C^1 continuous finite elements. The second point is an accurate description of the conducting structures surrounding the plasma, whose geometry affects the plasma evolution itself and the actual value of electromagnetic loads. We use the CarMa0NL code [3], to treat an axisymmetric plasma in the evolving equilibrium limit with arbitrary conducting structures, and the CARIDDI code [4], a 3D volumetric eddy currents computational tool.

In this paper, we compare the results of M3D-C1 and CarMa0NL for axisymmetric disruptions in ITER, showing that, despite the substantially different assumptions made in the two codes, the predictions are very close, hence increasing confidence in the reliability of the results. The final aim is to develop a coupling scheme between M3D-C1 and CARIDDI, allowing the use of M3D-C1 plasma evolution, computed with a simplified but realistic wall geometry, as input to subsequent electromagnetic computations made by CARIDDI with a more detailed description of the structures.

2. Modelling tools

M3D-C1 evolves the 3D Extended Magnetohydrodynamic equations in time using a split-implicit time advance which allows large time steps (compared to the Alfven time). It uses high-order C^1-continuous finite elements in 3 dimensions. It includes three regions:

plasma, wall, and vacuum and allows currents to flow from the plasma to the wall region [5]. It uses (R,ϕ,Z) coordinates and an unstructured mesh in the poloidal plane which gives it flexibility to model diverted plasmas with arbitrarily shaped domains.

Assuming that the time scale of interest is much longer than Alfvén time, the plasma can be supposed to evolve through equilibrium states, whose dynamics is ruled by the electromagnetic interaction with the surrounding wall – the so-called evolutionary equilibrium approach. CarMa0NL [3] further assumes the plasma as axisymmetric, so that it solves Grad-Shafranov equations in the plasma region, coupled to eddy currents equations in three-dimensional volumetric conductors in the exterior region. The interaction is decoupled through a suitable interface surface, so that different formulations can be used in the two regions.

3. Results

The initial ITER equilibrium has been computed independently by the two codes as free boundary solution of the Grad-Shafranov equations, starting from the equilibrium profiles and the currents in the PF coils. The agreement is excellent (Table 1, Figure 1).

Parameter	**M3D-C1**	**CarMa0NL**	**Rel. error [%]**
R_{axis} [m]	6.5247	6.521	0.057
Z_{axis} [m]	0.5370	0.536	0.186
R_{xpoint} [m]	5.1482	5.146	0.043
Z_{xpoint} [m]	-3.3864	-3.406	-0.579
Poloidal boundary flux [Wb]	-12.804	-12.85	-0.359
B_{tor}@axis [T]	5.153	5.039	2.212
Tor. plasma current [MA]	14.95	15	-0.334
Internal inductance	0.815	0.816	-0.123
Poloidal beta	0.753	0.752	0.133

Table 1. Comparison of initial equilibria

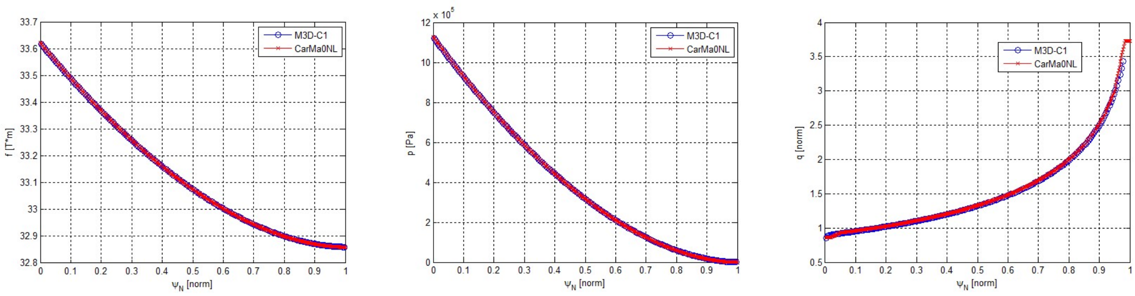

Figure 1. Initial equilibrium current density profiles.

A fictitious resistive wall located at the position of the ITER first wall has been considered, 6 cm thick. M3D-C1 assumes an axisymmetric wall; CarMa0NL considers a slice of 2° in the toroidal direction, assuming rotational symmetry with 180 replicas in the toroidal direction (Fig. 2). M3D-C1 assumes a wall resistivity of 7.4E-7 Ωm and computes a time constant of 235 ms for the wall current when a constant loop voltage is applied (no plasma). The time constant has been estimated in CarMa0NL (which assumes a resistivity of 8e-7 Ωm) in two ways. First, the slowest eigenvalues of the dynamical matrix of the plasmaless system have been computed, giving rise to 294 ms (uniform), 154 ms (up-down antisymmetric), 106 ms (inboard-outboard antisymmetric). Second, the time behavior of the wall current induced by a practically constant loop voltage has been fitted with a time constants of 254 ms. Eventually, the agreement on the wall time constant between the two codes is below 10%.

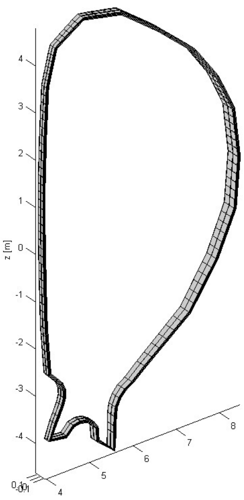

Figure 2. Wall model in CarMa0NL

Two plasma events have been considered: a hot VDE and a cold VDE. In the first event (Hot VDE), a small variation of poloidal beta (approximately 10% of the reference value) in the initial phase of the simulation is forced at the initial instants of the simulation, on a time scale very short as compared to electromagnetic times. This triggers the plasma vertical instability, so that a Vertical Displacement Event (VDE) takes place, with a significant thermal energy content in the plasma. The plasma moves upwards until it hits the wall; when the boundary value of q falls below 2, a Thermal Quench (TQ) occurs, causing poloidal beta to fall to a very low value (practically zero); this causes also a Current Quench (CQ) in subsequent instants. In the second event (cold VDE), the TQ is forced at the initial time instant of the simulation, on a time scale very short as compared to electromagnetic times. This triggers a VDE with a reduced thermal energy content in the plasma. During the vertical motion, also the CQ takes place.

In both cases, the event has been simulated in CarMa0NL by imposing a time behaviour of poloidal beta, internal inductance and toroidal plasma current identical to M3D-C1; the plasma evolution (trajectory, magnetic surface deformation etc.) is computed self-consistently.

Figure 3 shows the comparison of the trajectory for the hot VDE case, while Fig. 4 reports some snapshots of the plasma profiles and of the magnetic surfaces for the cold VDE case. The agreement is very satisfactory in all cases.

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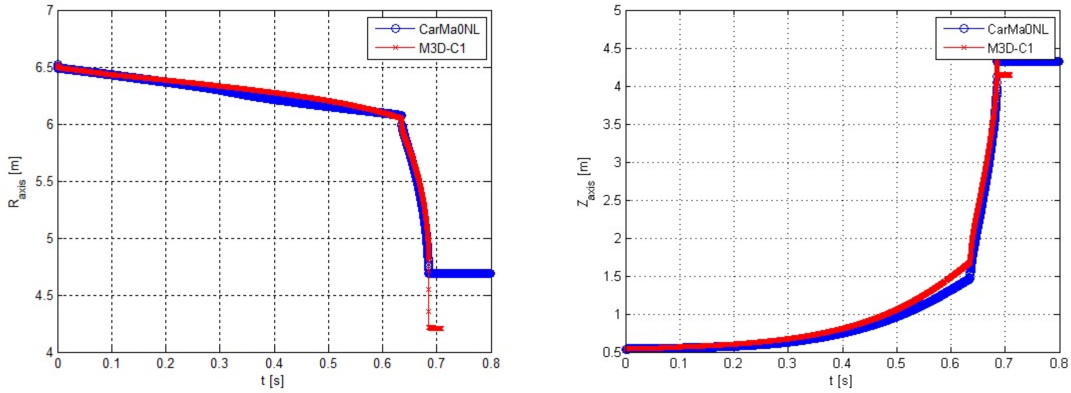

Figure 3. Hot VDE: comparison of time evolution of plasma centroid.

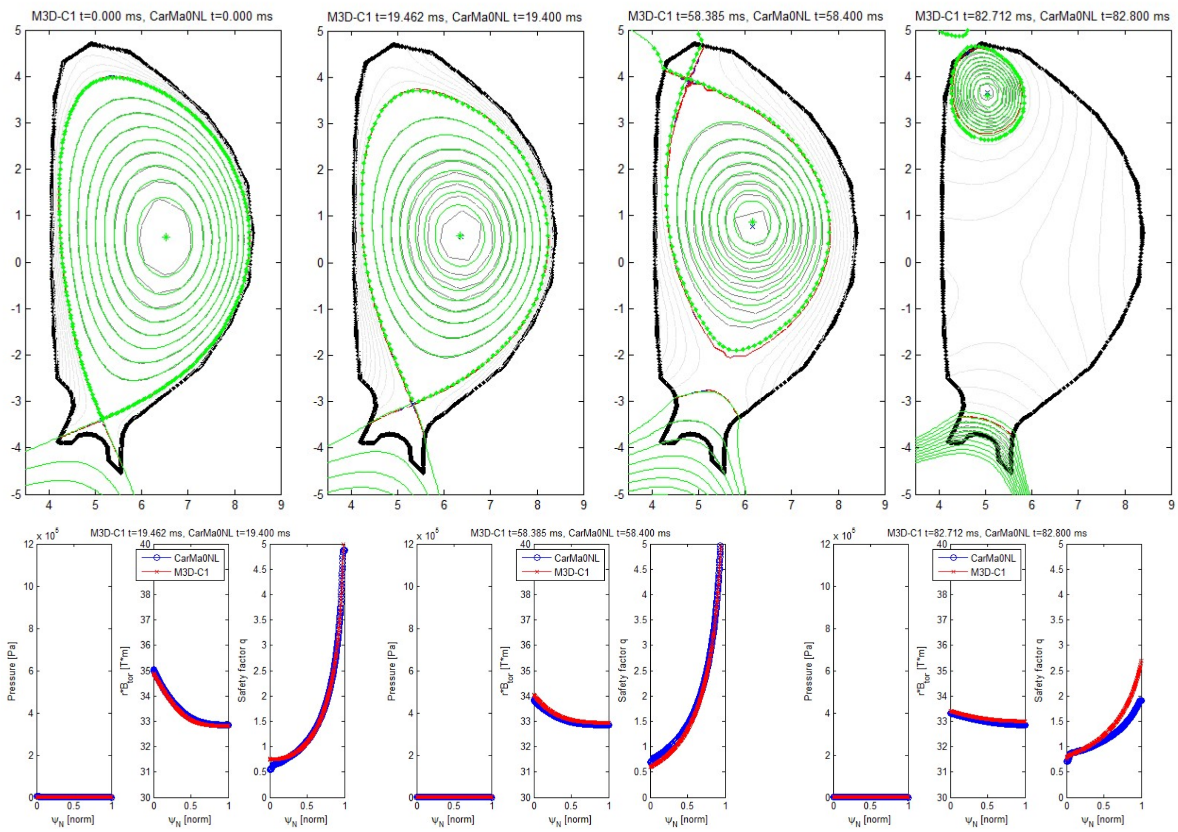

Figure 5. Cold VDE: snapshots of magnetic surface and plasma profiles.