# Analysis of Vertical Stability and Resistive Wall Modes in RFX-mod Tokamak Discharges Including 3D Effects

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## 1. Introduction

The RFX-mod experiment (R/a = 2.0/0.46 m), originally designed to produce high current Reversed Field Pinch plasmas (plasma current up to 2 MA), is currently operated also as a low current tokamak (Bt ~ 0.55 T, Ip ~150 kA @ $q_a \approx 2$). Circular, double-null [1] and single null configurations have been successfully already achieved. Such tokamak configurations may be prone to several MHD instabilities, usually classified resorting to the toroidal mode number *n*: current-driven *n*=1 Resistive Wall Modes [2], due to relatively low safety factor; *n*=0 RWM (vertical instability) [1], due to non-vanishing elongation of the plasma configuration. For the active control of these instabilities, RFX-mod is equipped with a state-of-the-art MHD control system made by 192 (4 poloidally x 48 toroidally) independently fed active coils, with more than 600 magnetic sensors acquired in real time; the feedback system is operated under the MARTe framework.

In particular, we investigate the 3D effects of the conducting structures on different response models of n=0 RWM (vertical instability). Several computational tools will be applied: linearized axisymmetric models (CREATE_L [3]), linearized 3D models (CarMa0 [4]), nonlinear evolutionary equilibrium models including 3D volumetric structures (CarMa0NL [5]). The different assumptions and approximations of the various models allow a clear identification of the key phenomena ruling the evolution of the n=0 vertical instability in RFX-mod tokamak discharges and hence provide fundamental information in the planning and the execution of related experiments and in refining the control system design.

## 2. Mathematical and numerical models

The main assumption is to neglect the plasma mass on the time-scale of interest, which is supposed much longer than the Alfvén time-scale related to plasma inertia. The plasma is assumed to move instantaneously through a sequence of MHD equilibria. This assumption is used for all the computational tools adopted in this study. The linearized axisymmetric plasma response model (CREATE_L [3]) reproduces the features of the plasma behavior relevant for the control of plasma current, position and shape. The plasma is characterized by a small number of global parameters (total plasma current $I_p$, poloidal beta $\beta_p$, internal inductance $l_i$): the model is linearized around a reference configuration in which the state variables are the coil, passive and plasma currents and the profile quantities are seen as disturbances. Assuming an axisymmetric system, Grad-Shafranov equation is solved. The time evolution of the magnetic field is determined by solving the free-boundary equilibrium problem coupled to the circuit equations for the external conductors and similar equation for the total plasma current regarded as an integral form of the Ohm's law. The numerical solution is obtained by using a 2D finite element method in which the unknown is approximated by means of piecewise polynomial functions. The overall plasma response model can be recast in a circuit equation in terms of modified inductance and resistance matrices or equivalently in a state space form. The CarMa0 [4] computational tool self-consistently couples the linearized plasma response model, computed as in CREATE_L, with a 3D time-domain eddy currents integral formulation, which requires only the discretization of the conducting structures. A surface *S* is chosen in between the plasma region and the conducting structures, through which the interaction can be decoupled as follows. The instantaneous plasma response to a given set of magnetic flux density perturbation on *S* is computed as a plasma response matrix. The effects of 3D structures on plasma is evaluated by computing the magnetic flux density on *S* due to 3D eddy currents. The currents induced in the 3D structures by plasma are computed by using an equivalent surface current density on *S* which produces the same magnetic field as plasma outside the coupling surface. The overall plasma response model can again be recasted in a state space-form. The idea of CarMa0NL [5] is to describe the plasma by solving the non-linear axisymmetric perturbed equilibrium problem, through Newton-Raphson iterations. In this way it is possible to treat self-consistently the non-linear evolution of an axisymmetric plasma surrounded by 3D volumetric conducting structures, providing the means to study situations such as disruptions, ELMs, limiter-diverted transitions, current quenches, etc.

**3. Results**

The equilibrium data of an open loop Single Null (SN) shot ($I_p$=59 kA, $B_t$=0.55 T) have been derived and used to produce the linearized plasma response model by means of CREATE_L code. Table 1 compares the plasma equilibrium parameters obtained with CREATE_L and with the MAXFEA 2D equilibrium code, while Fig. 1 shows the plasma boundary and a comparison of equilibrium values of magnetic fields at sensors.

The dynamical model is characterized by 194 states corresponding to the currents of the active circuits (8 FSC, 4 magnetizing winding (M) sectors, 2 MHD saddle coil null currents), the passive structures (60 Inconel vessel, 59 copper shell, 59 toroidal support structure) and the plasma. The presence of poloidal and inner equatorial cuts in the shell has also been implicitly taken into account by imposing that their total current be null. A vertical instability n=0 is exhibited by the model with a slow growth rate (<10 $s^{-1}$), consistent with the experimental evidence [1]. The model outputs include both the direct estimate of the gaps and the magnetic measurements (poloidal fluxes and poloidal field components). A similar model has been used successfully on double-null discharges [1].

The RFX-mod 3 mm thick shell, clamped over the vacuum vessel, provides the main stabilizing contribution (Table 2) and is characterized by poloidal and inner equatorial gaps, which have been reproduced in the 3D realistic mesh; the toroidal support structure has been neglected. In addition, a fictitious 3D axisymmetric mesh has been generated and used in computations in order to provide a reference and a cross-check with axisymmetric models for the entire procedure. In this case, the modified inductance matrix L* computed over the 3D axisymmetric mesh by CarMa0 has been compared with the CREATE_L results, providing a relative error around 1% and an excellent agreement on growth rates (Table 2).

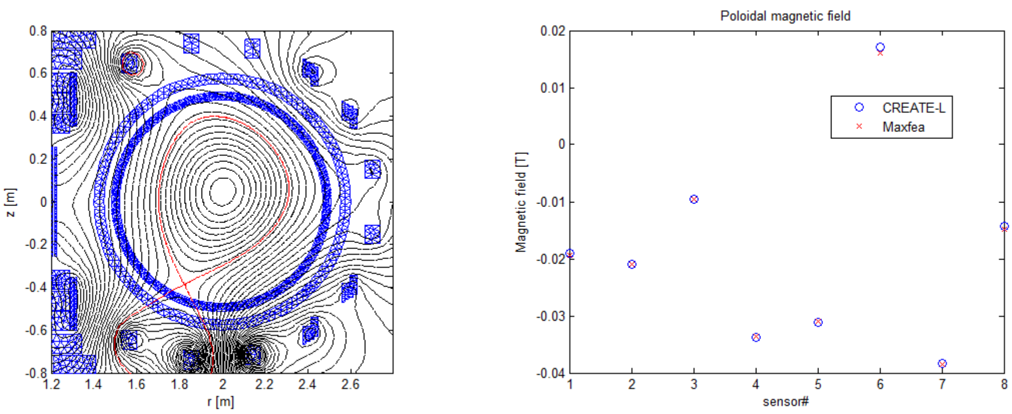


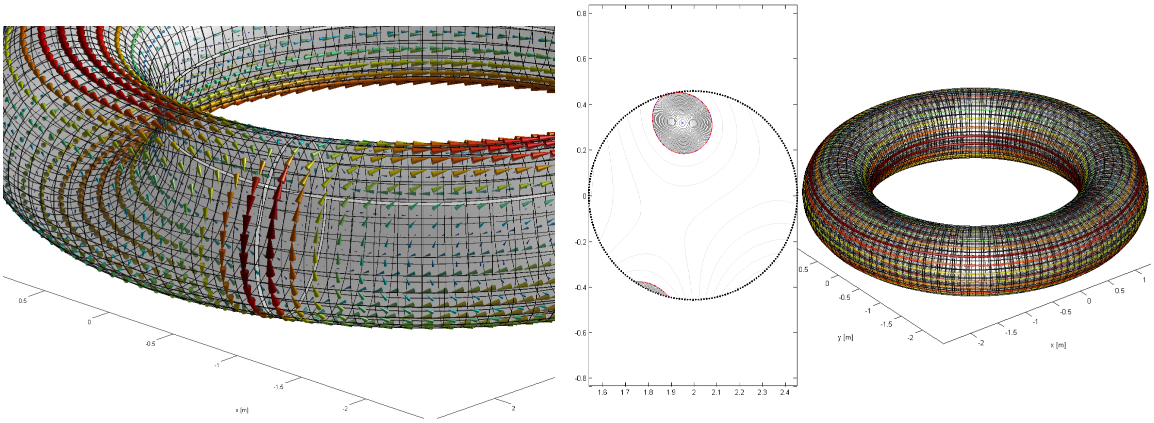

Fig. 1. Plasma boundary and comparison of equilibrium fields.

| | $l_i$ | $\beta_p$ | $R_{X\text{-}point}$ [m] | $Z_{X\text{-}point}$ [m] |
|---|---|---|---|---|
| *CREATE_L* | *1.04* | *0.102* | *1.822* | *-0.387* |
| *MAXFEA* | *1.06* | *0.111* | *1.827* | *-0.384* |

Table 1. Plasma equilibrium values computed by CREATE_L and MAXFEA

| | CREATE_L | CarMa0 (3D axisymm.) | CarMa0 (3D realistic) |
|---|---|---|---|
| $\gamma_{tot}$ [$s^{-1}$] | 7.36 | 7.33 | 7.55 |
| $\gamma_{vessel\ only}$[$s^{-1}$] | 335.4 | 334.2 | N.A. |

Table 2. Comparison of growth rates



(a) (b)

Fig. 2. Current density patterns and plasma configurations: (a) unstable mode; (b) plasma current quench

From Table 2, we notice that the introduction of the gaps in the shell has a small destabilizing effect. The pattern of the induced current density distribution in the shell is shown in Fig. 2a, where gaps location and their effects on the current distribution are visible. Finally, a fictitious linear plasma current quench event has been considered with CarMa0NL; a typical current density pattern and the corresponding plasma configuration are reported in Fig. 2b.

**4. Conclusions and perspectives**

In this paper we have applied several different computational tools to model the evolution of the n=0 RWM (vertical instability) for SN configurations of RFX-mod. The comparison of different codes and models allows a thorough assessment and cross-check of the results. The next step will be the inclusion of further details in the conducting structures (e.g. the support structure), the comparison with experimental results and the utilization of these models for experimental planning and analysis.

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[1] G. Marchiori et al., *41st EPS Conference on Plasma Physics*, Berlin, June 2014, paper P5.040

[2] G. Marchiori et al., *38th EPS Conference on Plasma Physics*, Strasbourg, June 2011, paper P2.110

[3] R. Albanese and F. Villone, *Nucl. Fusion* **38** (1998) 723

[4] F. Villone et al., *Plasma Phys. Control. Fusion* **54** (2012) 085003

[5] F. Villone et al., *Plasma Phys. Control. Fusion* **55** (2013) 09500