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Modeling of the magnetic field errors of RFX-mod upgrade

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HIGHLIGHTS

- Field errors generated at the gaps.
- Local coils.
- 3D electromagnetic analyses.

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ABSTRACT

After several years of successful RFX-mod operations, both in RFP and Tokamak configurations, an upgrade of the machine has been conceived. In particular, the vacuum vessel might be removed with the aim of improving passive MHD control and enabling plasma rotation at higher currents. In this paper, a detailed analysis of the new magnetic front-end is presented, with particular emphasis on the computation of the magnetic field errors generated at the poloidal gaps during transient phases of the discharge. At this purpose, a non-linear MHD equilibrium code, MAXFEA, has been used to provide the input data for the 3D electromagnetic analyses in the time domain carried out with the CAFE code.

1. Introduction

RFX [1] was originally designed with a toroidal complex consisting of a vacuum vessel (VV) composed of 72 wedge-shaped elements and a thick aluminium shell with two poloidal and two equatorial cuts (i.e. *gaps*). After several years of operation, a major modification [2,3] has been introduced: the thick aluminium shell has been replaced with a thin copper shell and a stainless steel Toroidal Support Structure (TSS) has been installed to house the 192 actuators (saddle coils) of the new active control system of MHD modes.

After a decade of successful experimental campaigns of RFX-mod, further modifications are now conceived [4]. In particular, the VV might be removed to improve the passive MHD stabilisation, by increasing the plasma-shell proximity ratio, and allow the plasma rotation at higher currents, presently limited by the braking torque caused by the eddy currents induced in the VV. The removal of the VV implies the realisation of a new vacuum boundary on the TSS, see [4].

In this paper, a detailed analysis of the new magnetic front-end of RFX-mod (in short *RFX-mod2*) is presented, with particular emphasis on the electromagnetic model and formulation used to compute the magnetic field errors generated at the poloidal gaps of the conducting structures during the transient phases of the discharge (i.e. plasma current ramp-up).

The two-dimensional finite-element code MAXFEA, solving the ideal MHD free-boundary non-linear equilibrium problem [5], has been used to provide the input data for the three-dimensional electromagnetic analyses carried out with the CAFE code. The main numerical results are then summarised in Section 3.

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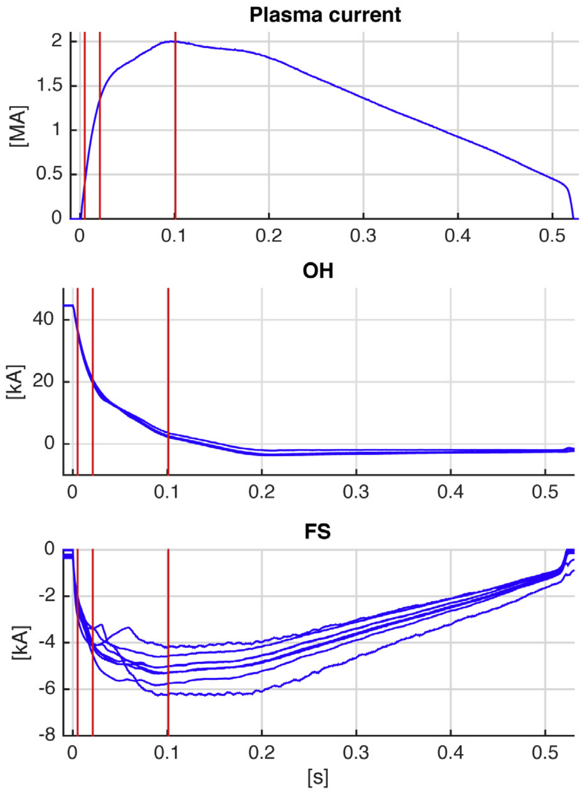

Fig. 1. MAXFEA input: experimental currents. Top to bottom: plasma current, *ohmic heating* (OH) and *field shaping* (FS) currents.

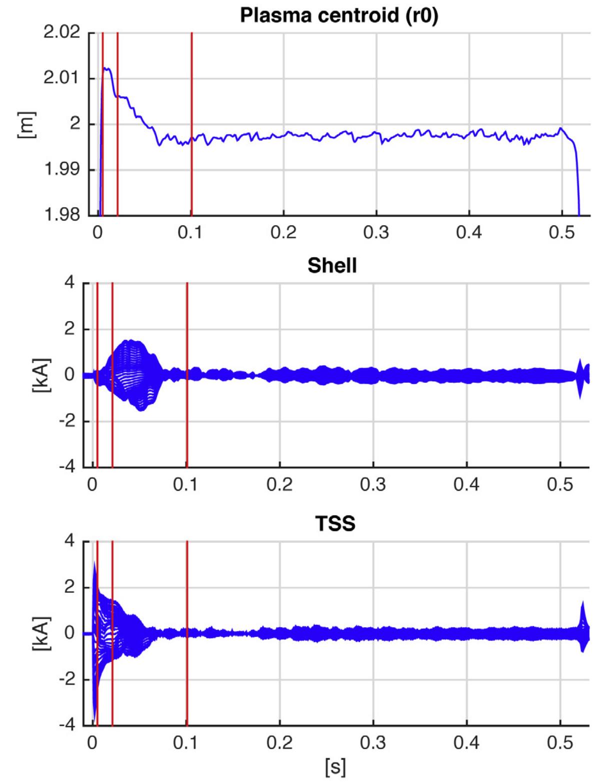

Fig. 2. MAXFEA output. Top to bottom: plasma centroid (radial position r_0), axisymmetric eddy currents induced in the shell and TSS.

Table 1
TSS and shell gaps configuration.

	N	Type	Gap width
TSS			
Poloidal	2	Butt joint	50 mm
Inner toroidal	1	High resistivity	Plate
Outer toroidal	1	Short circuit	–
Shell			
Poloidal	2	Butt joint	5 mm
Inner toroidal	1	Short circuit	–
Outer toroidal	1	Butt joint	5 mm

2. Electromagnetic model and formulation

2.1. RFP reference discharge at 2MA

The MAXFEA code has been used to simulate a reference shot (#29262: Reverse Field Pinch discharge at 2 MA) using as input the experimental signals shown in Fig. 1: PF coils currents, both *ohmic heating* (OH) and *field shaping* (FS), and plasma current. The eddy currents induced in the axisymmetric conducting structures of RFX-mod2 (shell and TSS) during the transient phases (e.g. plasma current ramp-up and ramp-down) are computed self-consistently in MAXFEA.

Fig. 2 shows a subset of the output, namely the radial coordinate of the plasma centroid and the eddy currents induced in the axisymmetric conducting structures surrounding the plasma. The former is a key parameter of the plasma model used in the three-dimensional analyses, while the latter are used as reference for the eddy currents computed in the three-dimensional structures in regions far from the poloidal gaps which break the axysimmetry of the problem (see Table 1).

In the three-dimensional time-domain simulations, described in Section 3, a simplified plasma model is adopted, based on $N_e = 12$ current filaments, symmetrically distributed on a circumference inside the plasma region (radius $a_f = 0.1$ m, centred in ($r_f = 2$ m, $z_f = 0$ m), see Fig. 3). The time evolution of the *Ne* currents are obtained by imposing that this set of currents has the same plasma current moments up to a given order. In the present case, the lowest order plasma current moments associated to the plasma current and plasma centroid coordinates, computed by MAXFEA, are considered, which allow to reconstruct the plasma effect on the conducting structure with a sufficient accuracy (the synthetic measurements at the sensors closest to the shell are approximated within 5%). Note that the configuration is symmetric with respect to the equatorial plane. Therefore only the plasma current and the radial coordinate of the centroid are considered.

Fig. 3 shows the flux map computed by means of the simplified model at three time instants along the plasma current rise ($t_1 = 5$ ms, $t_2 = 20$ ms, $t_3 = 100$ ms).

2.2. Formulation

A discrete geometric formulation for eddy-current problems over hexahedral grids is used, which is based on the formulation of the CAFE code, presented in [6], extended to time domain. Three sub-domains are identified in the three-dimensional domain: the conductive region $\mathcal{D}_c$, the non-conductive region $\mathcal{D}_a$ (air or vacuum) and the source region $\mathcal{D}_s$.

By combining the discrete Ampère's and Faraday's laws, a symmetric algebraic system of equations can be obtained in terms of the

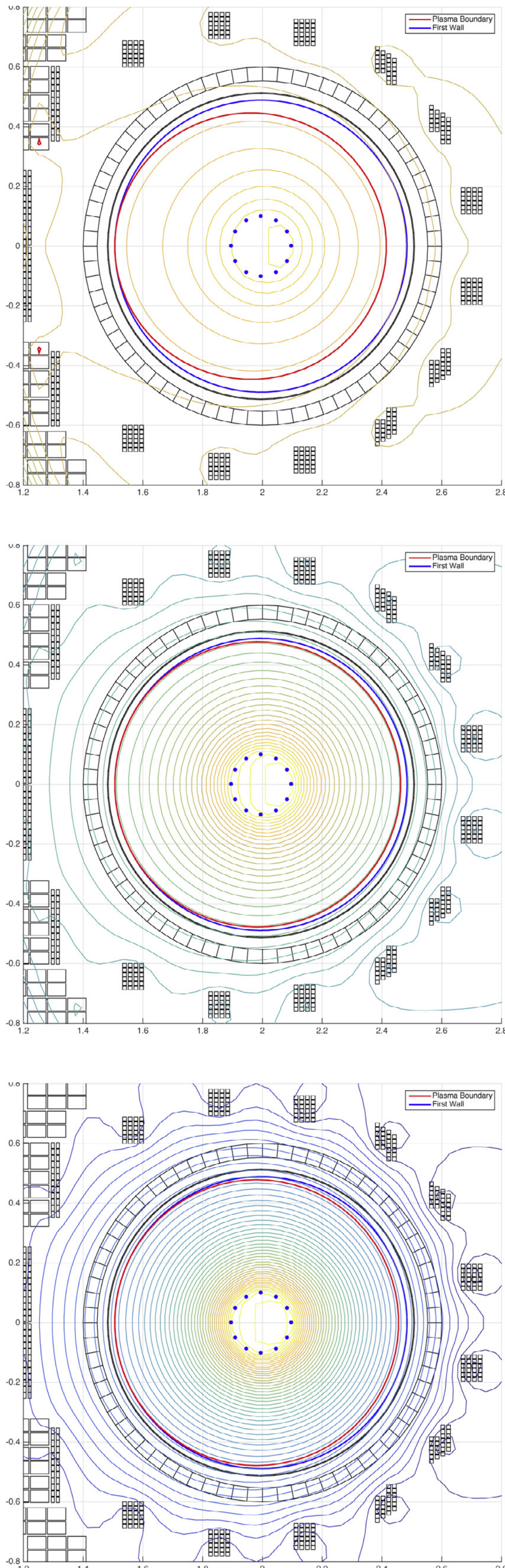

Fig. 3. MAXFEA equilibrium snapshots. Top to bottom: $t_1 = 5$ ms ($I_p = 400$ kA), $t_2 = 20$ ms ($I_p = 1300$ kA), $t_3 = 100$ ms ($I_p = 2000$ kA).

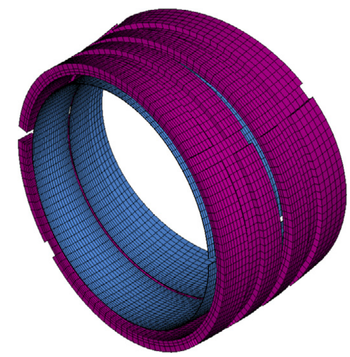

Fig. 4. Detail of the RFX-mod2's electromagnetic model: the TSS (magenta) is discretised in 174,904 hexahedra and the shell (cyan) in 135,864 hexahedra. The mesh elements corresponding to non-conductive regions are not shown for intelligibility. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

unknowns $\mathbf{A}_r$ (circulations of the magnetic vector potential along the mesh edges e, due to the eddy-currents in $\mathcal{D}_c$)

$$\mathbf{K}\mathbf{A}_r(t) = \mathbf{0} \qquad \forall e \in D_a \cup D_s$$
$$\mathbf{K}\mathbf{A}_r(t) + \mathbf{M}_\sigma \frac{\mathrm{d}}{\mathrm{d}t}\mathbf{A}_{rc}(t) = -\mathbf{M}_\sigma \mathbf{A}_{0c}\frac{\mathrm{d}s(t)}{\mathrm{d}t} \qquad \forall e \in D_c$$

where $\mathbf{K} = \mathbf{C}^T\mathbf{M}_\nu\mathbf{C}$; $\mathbf{C}$ is the incidence matrix between face and edge pairs, $\mathbf{M}_\nu$ and $\mathbf{M}_\sigma$ are square symmetric positive-definite matrices constructed as described in [7–9]; $\mathbf{A}_{rc}$ contains the unknowns in D_c; $s(t)$ is a function of time that describes the evolution of the sources (poloidal field coils or equivalent plasma currents), as described in [10], while the entries of the array $\mathbf{A}_{0c}$ can be pre-computed by means of the *Biot-savart*'law. The resulting discrete algebraic system of equations is solved by the classical Crank–Nicolson method.

2.3. 3D model

The model of RFX-mod2 used in the electromagnetic analyses consists of 1,781,088 elements and 1,791,196 nodes. In particular, 310,768 elements have been used to discretise the conducting structures, featuring the gaps configuration summarised in Table 1. A detail of this model is shown in Fig. 4.

3. Numerical results

The 3D electromagnetic analysis in the time domain, has allowed to assess the deformation of the magnetic field configuration at the poloidal gaps with respect to the unperturbed region (toroidal position 90° apart) during the *ramp-up* phase of the discharge (see Fig. 1). The pattern of the currents induced in the conducting structures (shell and TSS) at $t = 20$ ms is shown in Fig. 5; the radial magnetic field at the plasma edge ($a = 0.489$ m), at the same time, is shown in Fig. 6.

The maximum discrepancy (at $\theta = 90°$ and $\theta = 270°$) is of the order of 50 mT and it decays at the flat top phase, when the magnetic field configuration is imposed mainly by axisymmetric sources (PF coils and plasma), while the eddy currents in the conducting structures are much lower than before. A better uniformity of the radial field at plasma edge, along the toroidal direction, is present at $t = 100$ ms, as shown in Fig. 7.

The first numerical results confirm the need of a local correction coil system to mitigate the error fields at the poloidal gaps, both during the plasma current ramp up and at the beginning of the *flat top*, for the butt joint gap configuration. The gap correction coil system used in the first operations at RFX, in the early 90s [11], which is able to compensate the effect of a 1 mT forcing vertical field at 50 Hz at the plasma boundary with a current of 1.8 kA, in

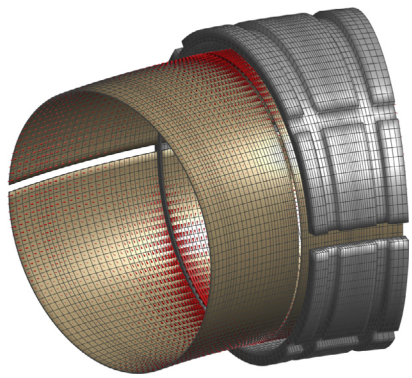

Fig. 5. 3D pattern of the currents flowing in the RFX-mod2 conducting structures (shell, TSS) during the plasma current ramp up ($t = 20$ ms). Red cones: current density (a.u., not to scale). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

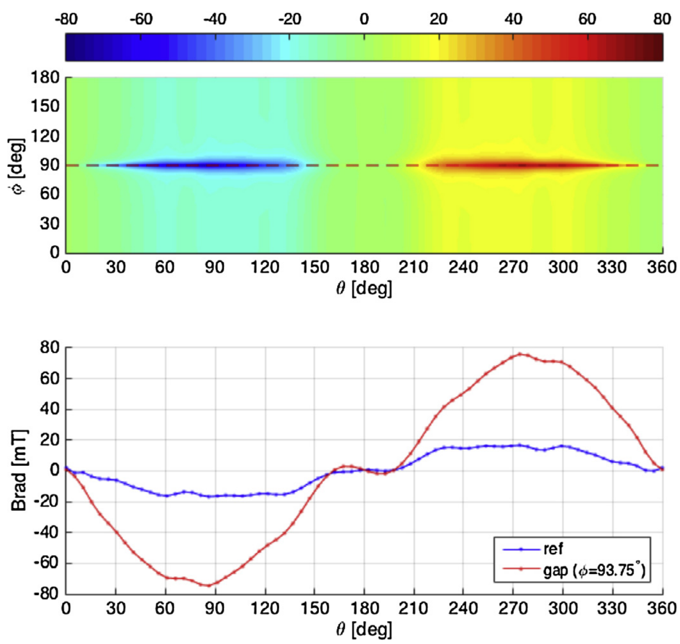

Fig. 6. Top: radial component of the magnetic field at the plasma edge ($a = 0.489$ m) at $t = 20$ ms (rectified view of the torus). Bottom: comparison of the radial field at the gap and 90° apart (reference).

the new machine configuration as shown in [12], has been considered as an effective solution, provided a substantial refurbishment of the system to achieve the electromagnetic requirements and to overcome the mechanical interference with structures not present in RFX. On the other hand, these results also suggest to investigate an alternative, more conservative, solution based on overlapped gaps, which require to develop also a new assembling procedure of the machine to cope with specific mechanical requirements.

4. Conclusions

A 3D model has been implemented with all the relevant details for the electromagnetic analyses of RFX-mod upgrade. The preliminary results have shown that an active correction system is mandatory to compensate the error field due to the butt joint gap configuration of the new conducting structures. On the other hand, these results also suggest to investigate an alternative, more conservative, solution based on overlapped gaps.

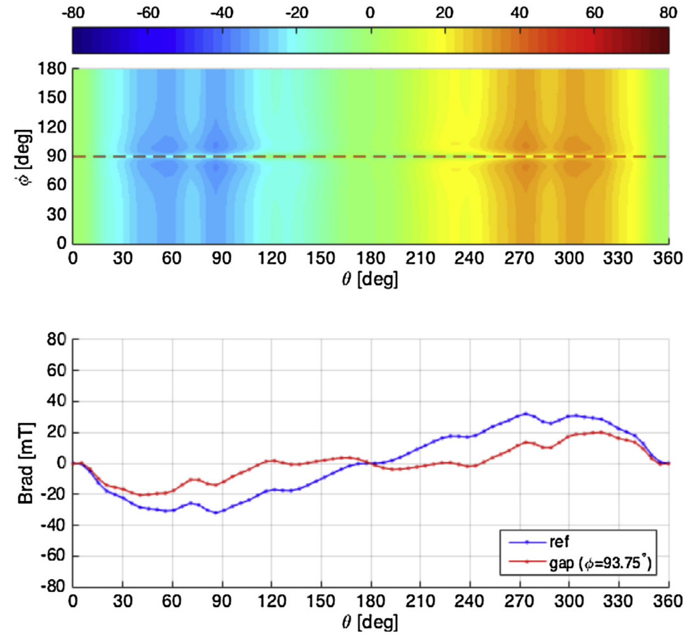

Fig. 7. Top: radial component of the magnetic field at the plasma edge ($a = 0.489$ m) at $t = 100$ ms (rectified view of the torus). Bottom: comparison of the radial field at the gap and 90° apart (reference).

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