RWM stability analysis in ITER including blanket modules

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Introduction

Resistive Wall Modes (RWM) are MHD instabilities (usually external kink) that often set performance limits to advanced scenarios of present and future fusion devices. The ultimate goals of RWM modelling are, on the one hand, a realistic and accurate description of experimental evidence on existing machines, and, on the other hand, a subsequent reliable extrapolation to future devices, like ITER, for which modelling is fundamental to support the design. With this in mind, in the last years huge efforts have been put by several research groups on a crucial aspects of RWM theoretical and numerical modelling, namely the inclusion of a detailed description of the conducting structures surrounding the plasma.

The CarMa code [1], a computational tool allowing the analysis of RWM in presence of 3D volumetric conducting structures, has recently made constant and significant progress. In particular, state-of-the-art fast and parallel computing techniques have been successfully applied [2], allowing an unprecedented level of accuracy in the realistic description of active and passive conducting structures.

In particular, here we focus on the quantification of the effects of ITER blanket modules on RWM stability. This is not trivial, because, first of all, such modules have a rather complex geometry, with thick (volumetric) conducting parts, including cooling channels, holes, slits, pockets, etc. Secondly, their effect is obviously beneficial on the passive stability, since their presence helps the stabilization of the mode, while it might be detrimental on the active stability, since they tend to shield out the field produced by active feedback coils.

All these effects must be carefully evaluated, which can be done only resorting to the aforementioned fast and parallel computing techniques due to the overall complexity of the resulting computational model.

The CarMa model and parallel implementation

The CarMa model [1] allows the analysis of RWM with 3D structures, including a volumetric description of the conductors in terms of a finite elements mesh. The main points regarding the parallel implementation have been already discussed in [3]; here we briefly recall the main points. The mathematical model is of the form:

$$\underline{\underline{L}}^* \frac{d\underline{I}}{dt} + \underline{\underline{R}}\underline{I} = \underline{V} \quad (1)$$

where $\underline{I}$ is a vector of discrete 3D currents, $\underline{\underline{L}}^*$ is a modified inductance matrix, which takes into account the presence of plasma, $\underline{\underline{R}}$ is a 3D resistance matrix, $\underline{V}$ is related to external voltages. The study of RWM can be made by finding the eigenvalues of the dynamical matrix resulting from (1). To this purpose, we use the inverse iteration technique, starting from an initial guess γ_0, which requires repetitive solutions of $\left(\underline{\underline{R}} + \gamma_0 \underline{\underline{L}}^*\right)\underline{I} = \underline{N}$, with $\underline{N}$ is a suitable forcing term. An iterative method (GMRES) is used; the dense matrix $\underline{\underline{A}} = \left(\underline{\underline{R}} + \gamma_0 \underline{\underline{L}}^*\right)$ is sparsified [2], so that memory requirements and computation effort grows only almost linearly with the number of the unknowns. This allows the treatment of problems of huge dimensions, otherwise unaffordable. This fast technique has been further parallelized [3], in order to tackle larger physical problems and to speed up the computation. To this purpose, two requirements have been respected: a) the computational cost to assembly the matrix $\underline{\underline{A}}$ must be equally distributed between the processors (*assembly balancing*); b) the computational cost and the memory occupation to implement the product $\underline{\underline{A}}\ \underline{I}$ must be equally distributed between the processors (*computation balancing*).

This guarantees that the computational load decreases linearly with the number of processors.

Results

In [3] only a single plasma configuration was analysed. In the present paper, we have performed a scan in the normalized beta. As starting point, We use the reference plasma for the 9MA steady state scenario designed for ITER. For the numerical convergence, we have to slightly smooth the plasma boundary near the X-point. This procedure normally does not bring a significant change to the ideal kink growth rates nor to the beta limits. The new reference equilibrium has a minimum q value of about 1.57, compared to the previous design where q_{min} was around 2.3. The amplitude of the plasma equilibrium pressure is scanned while fixing its radial profile and the edge q value, q_a = 7.138. This procedure leads to a slight variation of the total plasma current while scanning the plasma pressure. The beta limits, as computed by the MARS-F code with an axisymmetric wall, are β_{nw}= 2.545 and β_{iw}=3.545.

The blanket modules (BM) are massive conducting structures facing the plasma, that are present inside the vacuum vessel. There are 18 rows of BM, of different shape and dimensions; the total number of BM inside the torus is 432.

The BM have a rather complex geometry: the front panel facing the plasma is made of a beryllium layer, followed by a thin copper layer and a stainless steel (SS) layer. A high number of slits (around 20) in the toroidal direction is present. Each layer has several void cooling channels inside. Proceeding farther from the plasma, the shielding block is present, which is a volumetric SS structure with void cooling channels, slits, pockets etc. Slits and pockets have been represented in the mesh; conversely, the presence of void cooling channels has been taken into account via an non-isotropic equivalent resistivity, enhanced using the void fraction computed for each blanket module, for each different material and for each independent direction.

The overall discretized model, represented in Fig. 1, gives rise to 206401 degrees of freedom, corresponding to the dimensions of the fully populated matrix $\underline{\underline{L}}^*$ in (1). Using this meshing, we compute the growth rate of the n = 1 RWM for the aforementioned ITER configurations for various values of normalized beta. Some results are reported in Fig. 2. First of all, we notice that the assumption of pure holes to represent the ports is pessimistic – the more realistic description with port extensions gives rise to substantial lower growth rates, since the port extension allow the current to "bypass" the hole along a conducting path (see Fig. 1).

Including the blanket modules, the growth rates further decrease, returning to be quite close to the 2D case: in terms of passive stability analysis, the detrimental effect of ports is practically compensated by the favourable stabilizing effect due to the presence of blanket modules. However, from the point of view of active stabilization, the presence of blanket modules is not beneficial any longer, since they may provide a significant shielding effect of the magnetic field produced by active coils. This will be studied in future work.

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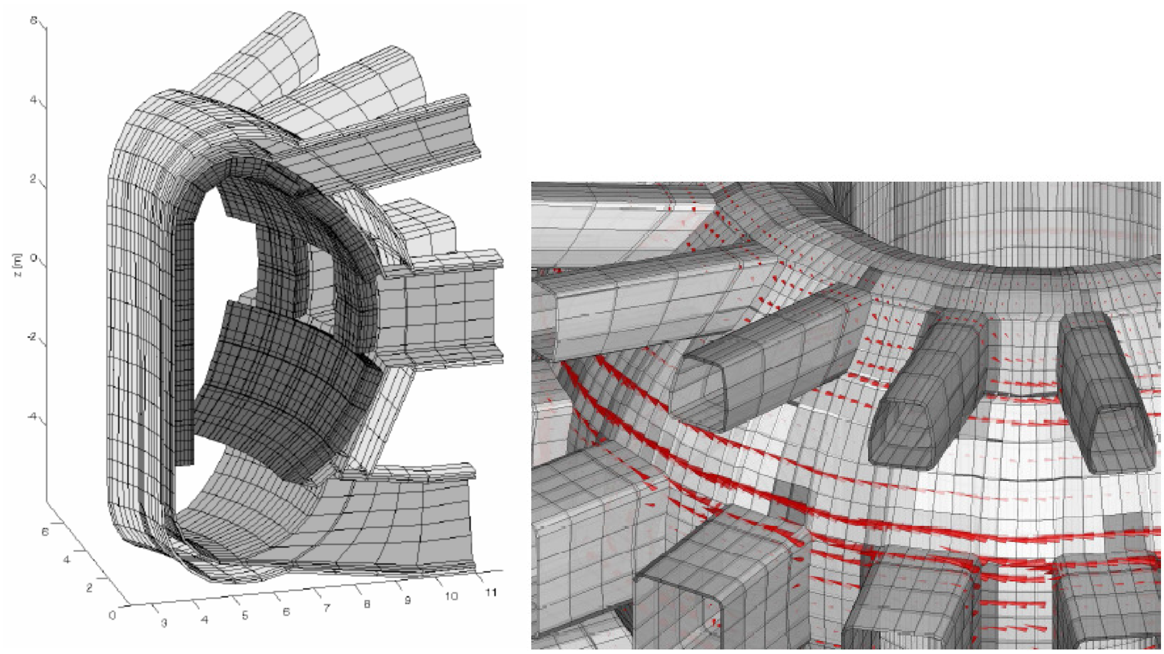

Fig. 1. Cutaway of the ITER geometry considered (the actual mesh spans 360° toroidally) and typical current density pattern corresponding to the unstable eigenvector of the system.

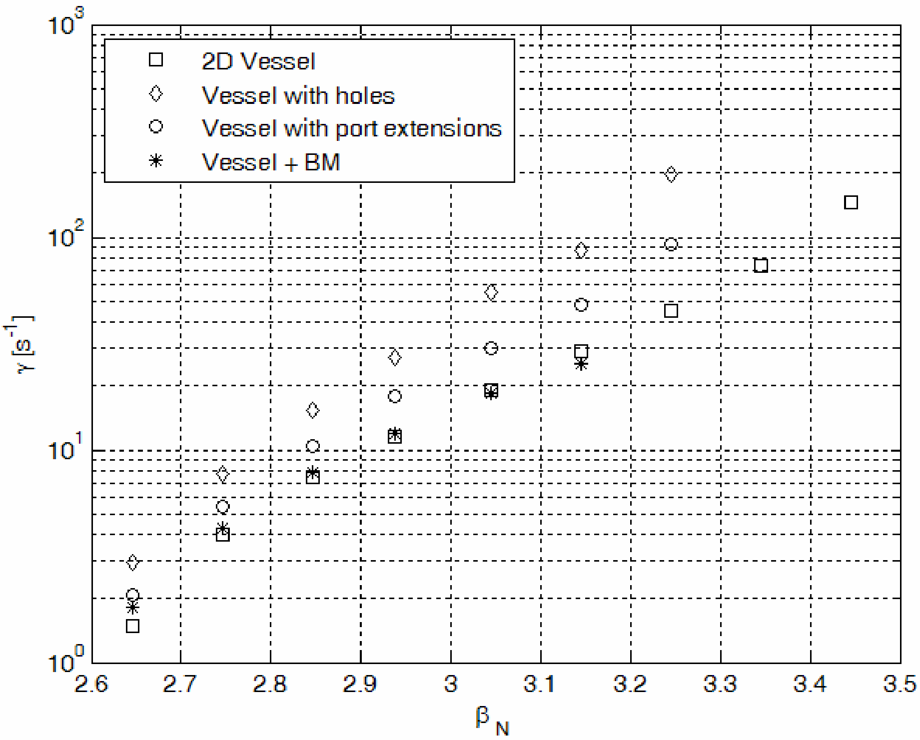

Fig. 2. n=1 RWM growth rate as a function of normalized beta, for various assumptions on conducting structures.

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