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RWM modelling in RFX-mod including 3D conducting structures

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Abstract

The 3D effects of conducting structures on Resistive Wall Modes (RWM) evolution are studied on the RFX-mod device. Toroidal coupling allows an alternative interpretation of the RWM spectrum; the effect of gaps may in some cases significantly increase the growth rate of the unstable modes, improving the agreement with experimental results.

Introduction

Resistive Wall Modes (RWMs) are kink-like instabilities, whose growth rate is on the time scale of magnetic field penetration through the metal structures surrounding the plasma, assuming that these conducting structures are close enough to the plasma. These instabilities have received, in recent years, an increasing attention, in particular in view of the steady state operations of ITER, since in some cases they will set the most stringent limit to the plasma performance. For this reason, it is of fundamental importance to make reliable predictions about the RWM stability boundary and the so-called beta limits. However, some open issues still remain in RWM modelling, e.g. regarding the estimate of the effects of plasma rotation and of the complex three-dimensional conducting structures surrounding the plasma.

In this paper we study RWM stability in the RFX-mod Reversed Field Pinch (RFP) [1], where RWMs are non-resonant current driven instabilities, generally not affected by dissipation and flow. This removes one of the modelling uncertainties mentioned above and allows us to focus on the analysis of 3D effects. To this purpose, in addition to the cylindrical code ETAW [2] and to the toroidal MHD code MARS-F [3], in this paper we use the CarMa computational tool [4], which can rigorously take into account the three-dimensional details of the conducting structures in the solution of the plasma stability problem, and can also account for multiple toroidal Fourier harmonics in the plasma response.

Computational tools and comparison with experimental results

The cylindrical code ETAW, extensively used in the past on RFP's [2], solves the linear cylindrical resistive incompressible MHD equations, using a spectral formulation and a matrix shooting eigenvalue scheme. Thin shell boundary conditions are imposed to take account of resistive wall, while the solution of the cylindrical Laplace equation in the vacuum region is analytically known in terms of modified Bessel Functions. MARS-F [3] is a toroidal stability code that solves single fluid MHD equations, including vacuum region, thin conducting shells, and feedback coils. (Other features of the code, such as sheared toroidal plasma rotation, sound wave or kinetic damping terms, are not used in this paper.) It can only treat conducting structures (walls or coils) that are axisymmetric along the major axis of the torus.

CarMa is a recently developed code [4], able to analyze RWMs taking rigorously into account the three-dimensional features of the conducting structures surrounding the plasma and able to self-consistently treat multi-modal plasma evolution. This code couples the instantaneous massless plasma response matrix to magnetic field perturbations over a surface S with a 3D volumetric integral formulation of the eddy currents problem, which describes the conducting structures by means of a three-dimensional finite elements mesh.

The RFX-mod experiment has a major radius of 2 m, a plasma minor radius of 0.459 m and a stabilizing copper shell at mean minor radius 0.513 m, of width 3 mm and a penetration time around 55 ms. This shell is made of four pieces; two of the gaps are left insulated, while the other two are short circuited, either with copper plates or via welding. Outside this shell there is another conducting structure, for mechanical purposes, on which a set of 192 saddle coils for feedback control are mounted, 4 at each of 48 equally spaced toroidal locations. Inside the shell a conducting vacuum vessel is also present. The vertical field penetration time of the overall conducting structures has been measured as slightly greater than 60 ms.

We make a Fourier decomposition of all quantities in the toroidal and poloidal directions; let us call m and n the poloidal and the toroidal mode numbers. In the cylindrical limit, it is possible to consider each (m, n) mode as evolving separately. In other words, one can distinguish the (1, n) mode from the (–1, n) mode, which is the same as the (1, –n) mode. Hence, assuming that they are both unstable, in general we have that the growth rates of such modes γ_{+n} and γ_{-n} are in general different. Conversely, when toroidal coupling is taken into account, for a given n value, all m harmonics should be considered. Hence, using a toroidal code like MARS-F for a given n value, we find two unstable modes corresponding to two different growth rates, which are however close to γ_{+n} and γ_{-n} since toroidal corrections are expected to be small in RFX-mod. Each of these two modes involves theoretically all m

values, but in practice they have a dominant $m = \pm 1$ component. Figure 1 shows the behaviour of the growth rates of such two different unstable modes for n=2 and n=3, as computed by MARS-F for various RFX equilibria with $\Theta = 1.49$, as a function of F. Here Θ (resp. F) is the ratio between the poloidal (resp. toroidal) field at the plasma boundary and the section averaged toroidal field. With an axisymmetric wall, hence also with MARS-F, each of the aforementioned unstable growth rates (e.g. γ_{+n}) correspond to two eigenmodes, which are identical apart from a rotation of $2\pi/n$ in the toroidal direction. When a three-dimensional conducting wall is considered in CarMa, like for instance a shell with a poloidal gap breaking toroidal symmetry (Fig. 2), this degeneracy is removed and the two toroidally shifted unstable eigenmodes are characterized by two distinct unstable eigenvalues (e.g. γ'_{+n} and γ''_{+n}). Hence, including both toroidal and 3D effects, for each n value one can have four unstable eigenvalues: γ'_{+n} , γ''_{+n} , γ'_{-n} , γ''_{-n} .

Two different equilibria have been considered: equilibrium A (F = -0.073, Θ = 1.43) and equilibrium B (F = –0.136, Θ = 1.49). Table I reports a comparison of the RWM growth rates, as predicted by the three codes, together with typical experimental values, measured in configurations with parameters F, Θ in the same range as simulations (no profile comparison has been carried out). Evidently, three dimensional effects give rise to a sometimes significant increase of the growth rate, which is in better agreement with experimental data than axisymmetric or cylindrical estimates. Only the copper shell has been considered in simulations; including also the other conducting structures, the simulated growth rates will decrease. This could possibly improve the agreement between CarMa 3D predictions and experimental results, while axisymmetric results would underestimate the real values further.

Conclusions

We have studied RWMs occurring in the RFX-mod device with various computational tools. The inclusion of toroidal and 3D effects, such as poloidal and toroidal gaps, allow a novel interpretation of the RWM spectrum and a more favourable comparison with experimentally measured growth rates. This work was supported in part by Italian MiUR under PRIN grant and by Consorzio CREATE.

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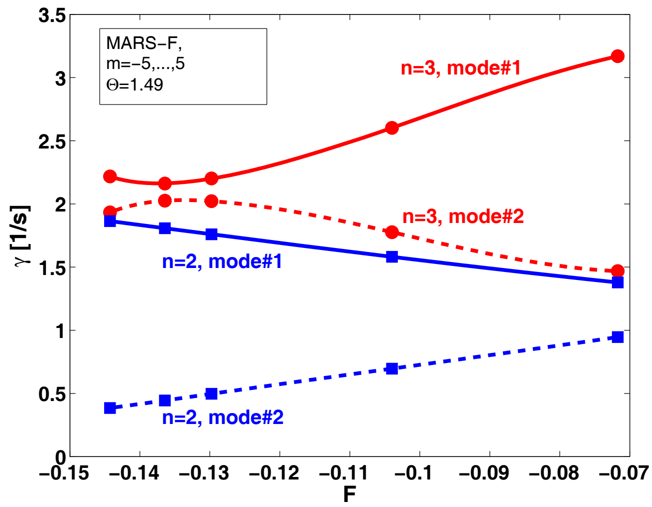

Fig. 1. Growth rates of multiple unstable RWMs due to toroidal coupling effects.

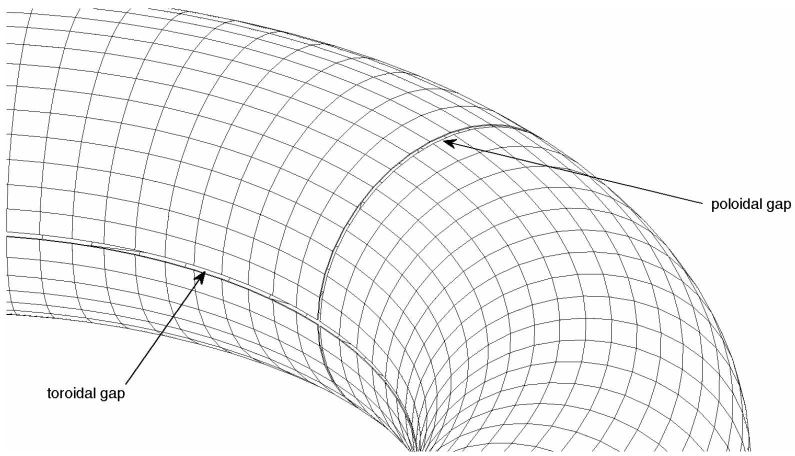

Fig. 2. Shell geometry and gaps as described in the mesh used in CarMa simulations.

	Equilibrium A				Equilibrium B			
	ETAW	MARSF	CarMa	Exp.	ETAW	MARSF	CarMa	Exp.
n=1	0.909	<0	<0	<0	<0	<0	<0	<0
n=2	1.56 1.82	0.780 1.29	0.869 0.931 1.67 1.81	N.A.	<0 2.45	0.434 1.81	0.448 0.462 2.33 2.36	N.A.
n=3	0.727 3.09	1.10 2.71	1.37 1.40 3.69 3.78	N.A.	1.82 1.90	2.08 2.16	2.61 2.64 3.13 3.26	N.A.
n=4	5.27	5.07	7.30 7.48	≈6	4.09	4.04	5.63 5.78	≈4.5
n=5	8.63	8.55	12.8 13.1	≈12	6.81	6.89	9.91 10.2	≈8
n=6	14.5	14.4	22.6 23.4	≈22	11.8	11.7	17.6 18.2	≈17

Table 1. Comparison of growth rates for two RFX-mod equilibria (all results in s^{-1}). Only unstable RWMs are considered.