Non-linear evolution of RFX-mod tokamak equilibria during L-H transition including 3D wall effects

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Introduction

The achievement of an ELMy Ohmic H-mode regime was the aim of executing shaped tokamak discharges [1] in the RFX-mod experiment (R = 2.0 m, a = 0.46 m). In recent experiments, D-shaped upper single null tokamak plasmas with edge polarized electrode have been performed in order to induce the L-H transition [2]. The new experimental data give the opportunity of a further development in the electromagnetic modelling of the overall system. The aim is modelling the non-linear time evolution of the plasma discharge during the L-H transition, taking into account the effects of both 3D volumetric passive conducting structures and plasma global parameters variations, such as plasma total current and poloidal beta, by using the evolutionary equilibrium code CarMa0NL [3]. Since the CarMa0NL computational tool solves the non-linear axisymmetric perturbed equilibrium problem, the starting point of the analysis is the reproduction of the static equilibrium in the early time instants of the flat top phase by using the CREATE_L code [4]. This code provides also a linearized plasma response model on the basis of which the RFX-mod plasma shape feedback controller has been designed successfully for L-mode tokamak discharges [5]. It is well known that several experimental parameters (such as first wall conditioning, number and position of X-points, plasma shape and plasma dynamics) can play a key role in the transition to H-mode by modifying the L-H power threshold. Therefore, a careful control of the magnetic configuration is necessary for the achievement of the H-mode regime. The modelling activity is focused on a double purpose: providing a good linearized model for those plasmas with edge polarized electrode, both in the pre-transition state and also in the H-mode regime, and then increasing the level of complexity by including a 3D wall description and a non-linear time dependent analysis.

Modelling activity

Static equilibria of different shots, characterized by a clear L-H transition, have been reproduced by using the 2D axisymmetric linearized model CREATE_L and, as a benchmark, the 2D MAXFEA equilibrium code [6]. In this phase, an iterative procedure has been used in order to estimate the proper plasma current density parametrization coefficients, by minimizing the
normalized chi-square on the poloidal magnetic field measurements at the inner surface of the stabilizing shell [7]. Since this method is insufficient for a reliable evaluation of plasma current profile [8], in the future we plan to improve it using the model-based plasma state reconstructions provided by the RAPTOR code [10]. A circular plasma discharge (shot 39100) has been selected in order to reproduce the non-linear evolution from the early moment of the flat-top phase (i.e. t = 0.1 s) to the end of the discharge, including both the L-H transition (roughly at t = 0.6 s), the back-transition (roughly at t = 1 s), and the end of the discharge as shown in Fig. 1. Upper single null shots have been analyzed for the static equilibrium reproduction as well.

The time evolution of the plasma equilibrium is determined by solving a non-linear set of equations [3] where the values of the total plasma current and active coil current variations are imposed from experimental values at each time instant. In both linear and non-linear analysis it is assumed a current density profile parametrized by three parameters [7], each one associated to physical quantities (i.e. internal inductance, poloidal beta and safety factor on axis). The non-linear analysis treats three of these parameters as time varying disturbances. The parameter related to $\beta_p$ is computed, as shown in Fig. 1, by imposing a fit to the experimental time behaviour of $\beta_p$, which is in particular associated to the L-H transition. The main approximation in this analysis involves the other two parameters of the plasma current density profile which are related to the plasma internal inductance; both values have been kept constant during the whole time evolution, even in the transitions. The reason of this choice is determined by multiple factors: first of all the lack of dedicated plasma diagnostics in RFX-mod to determine the current density profile; secondly, the iterative procedure has not allowed achieving the same agreement between the computed and measured poloidal field values and internal inductance estimation as in the L mode configuration case.

**Results**

All the analyzed RFX-mod tokamak discharges at the first time instant of the flat top phase are circular plasmas since the shape controller is started later in time. The static equilibrium reproductions have revealed, for both the computational tools CREATE_L and MAXFEA, a remarkable sensitivity of the normalized chi square for the poloidal magnetic field to the plasma current variations. It is under investigation if this dependence is due to a peculiar vacuum mag-
Figure 2: Time evolution of the poloidal magnetic field relative percentage error at different poloidal angle positions.

The reference equilibrium configuration at \( t = 0.1 \text{s} \), with plasma current \( I_p = 56.311\text{kA} \) (2.8% more than the experimental value), \( \beta_p = 0.367 \) (\( \beta_{pexp} = 0.361 \)), \( l_i = 1.131 \) (\( l_{iexp} = 1.076 \)) has been successfully reproduced with a normalized chi-square final value of 0.43. This value means an over/under estimation of the poloidal magnetic field values at the sensors within 10%. It is important to notice that the agreement for all these shots is well below the past successful analysis for the RFX-mod tokamak discharges probably due to the presence of the edge polarized electrode. The eight poloidal magnetic field values have been computed for the entire time evolution in correspondence of 4 toroidal angles. The experimental mean values of these fields have been compared with the simulated values of CarMa0NL, showing a maximum error of 20% from the first time instant up to several milliseconds after the back-transition. The behaviour is not well reproduced for all the poloidal angle positions as shown in Fig. 2 even in the time instants where the agreement between the CarMa0NL plasma boundary and the real-time plasma boundary computed from experimental data [9] is excellent. In terms of boundary the agreement between the non-linear computation and the computation based on experimental data increases as the time evolves in particular at the first time instants of the H-mode. As it is possible to see in Fig. 3 and Fig. 4, the blue line is the boundary reconstructed from experimental data and the red line is the CarMa0NL result. The non-linear computation yields a clear deviation of the horizontal position of the plasma at the final stages of the H-mode and during
A change in the plasma shape at the last time instants of the discharge with different horizontal positions is noticed in both boundary reconstructions. This preliminary analysis suggests that the main assumption of keeping constant two of the three parameters of the plasma current density function is inadequate and restrictive to model the transition phenomena to new states of plasma equilibrium. For this reason, in near future we plan to modify the present approach by varying in time all the three parameters of the current density profile parametrization keeping as a validation criterion the agreement between experimental data and the model in terms of computed magnetic field at sensors positions and plasma boundary. This will be important to validate a model being applied to investigate various plasma events (e.g. minor disruptions, L-H transition) both in RFX-mod and other tokamak devices.

References

[2] L. Marrelli et al., submitted at this conference paper P5.014