Implementation and testing of a shape control system in RFX-mod Tokamak discharges

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Introduction

In past years the Reversed Field Pinch RFX-mod has also been operated as a low current Tokamak to perform experiments of active control of MHD modes particularly harmful to a prospective reactor. The stabilization of m=2, n=1 mode has been achieved for 150 kA plasma currents in circular shape discharges at q(a)<2 [1]. In order to test the system capability of stabilizing such modes in improved confinement regimes, the possibility of producing D-shaped plasma discharges has been explored. Preliminary experiments were carried out in open loop in 2011. In the meantime a completely new plasma position and shape control system was designed and its performances simulated with the finite element 2D MHD equilibrium code MAXFEA. According to the simulation results, feedback control of the D-shape configuration was capable of meeting the design requirements. As a first step, the recent experimental campaign in Tokamak configuration was partially dedicated to demonstrate the possibility of a stable feedback controlled operation with an elongated plasma. In the paper the identification of the transfer function between a dedicated Field Shaping (FS) coil current distribution and the plasma elongation, the design of the control system, its implementation and successful testing are described.

The identification of the transfer function between Field Shaping current distribution and plasma elongation

In order to speed up the implementation it was preferred to maintain the original framework of the equilibrium control system. This was based on the separate generation of two FS coil current distribution for the decoupled control of the winding m.m.f. and the magnetic vertical field, respectively dedicated to the plasma m.m.f. compensation and the plasma horizontal position control [2]. Since only 2 out of 8 degrees of freedom allowed by the 8 independent power supplies of the Field Shaping coils were used, it was possible to add a third

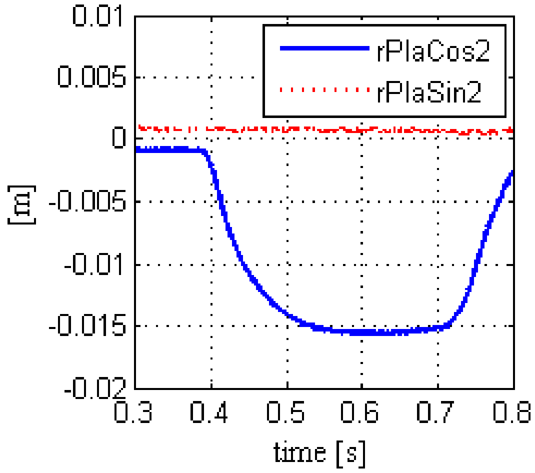

Fig. 1. Shot 33613: cos(2ϑ) and sin(2ϑ) harmonics of the plasma radius after a FS coil cos(2ϑ) current step at t=0.4 s

independent set of coil current references distributed according to a cos(2ϑ) law for the control of the plasma elongation. This simple dependence on ϑ is due to the arrangement of the FS coils approximately along a circumference around the vessel in a high aspect ratio machine such as RFX-mod and to the connection in series of the couples of coils symmetric with respect to the equatorial plane. As a consequence only the control of the elongation along the vertical/horizontal axes is possible with the standard FS coil configuration. In this context the plasma elongation can be expressed by means of the amplitudes of the cos(2ϑ) and sin(2 ϑ) harmonics of the plasma radius r(ϑ) function, defined as the distance of the plasma boundary from the vacuum vessel centre (major radius R=1.995 m). This quantity is calculated as a function of ϑ along the direction corresponding to the poloidal angle of the poloidal flux loops. In particular, the harmonics up to the 3rd order were already computed in the algorithm used for the determination of the plasma horizontal and vertical shift and they were easily added to the MARTe real-time data-pool.

After some preliminary analyses on a 2D equilibrium code, a series of open loop shots were

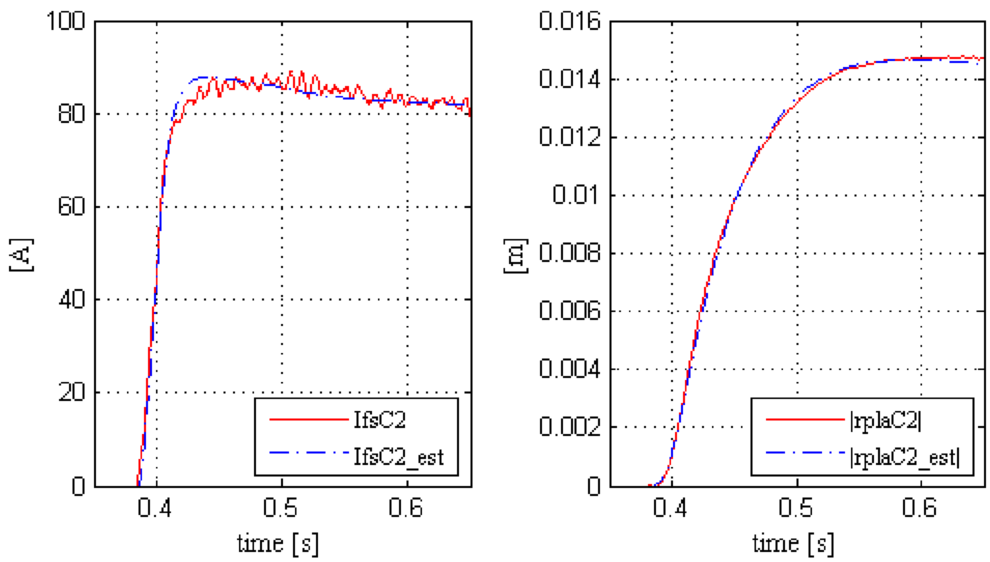

Fig.2. Shot 33613: comparison of experimental and estimated response of FS coil cos(2ϑ) current distribution and cos(2ϑ) harmonic of plasma radius.

executed to determine the transfer functions between the cos(2ϑ) current distribution reference and the actual FS coil currents and between the FS coil current distribution and the plasma elongation. The plasma response in terms of plasma radius 2nd order harmonics is shown in fig. 1, where the FS current "nearly step" reference was applied at t=0.4 s. For these initial open loop tests a low value of the corresponding elongation (1.07) was cautiously chosen taking into account the circular shape of the vacuum vessel.

The transfer functions were calculated by means of a standard prediction error estimate method. As it can be seen in fig. 2, two first order functions, with time constant 9 ms and 47 ms, respectively, allow an accurate reproduction of the system responses.

Feedback control of the plasma elongation

A feedforward block and a PI regulator were designed and integrated in the equilibrium control system. The desired elongation is converted into an absolute value of ellipticity and the difference between this reference and the cos(2ϑ) harmonic of the plasma radius processed by the regulator. The output is then converted into a cos(2ϑ) current distribution reference which is added to the other current references for the FS coil power supplies. Since a current reduction can be required for some coils and only first quadrant operation of the power supplies (positive voltage and current) is possible, additional resistances have been connected to speed up the coil current free evolution to the desired values. In shot 33825 a 3 cm "nearly step" reference of plasma radius cos(2ϑ) harmonic was applied at t=0.35 s, the plasma response is shown in fig. 3 (left) along with the reference. The steady state accuracy

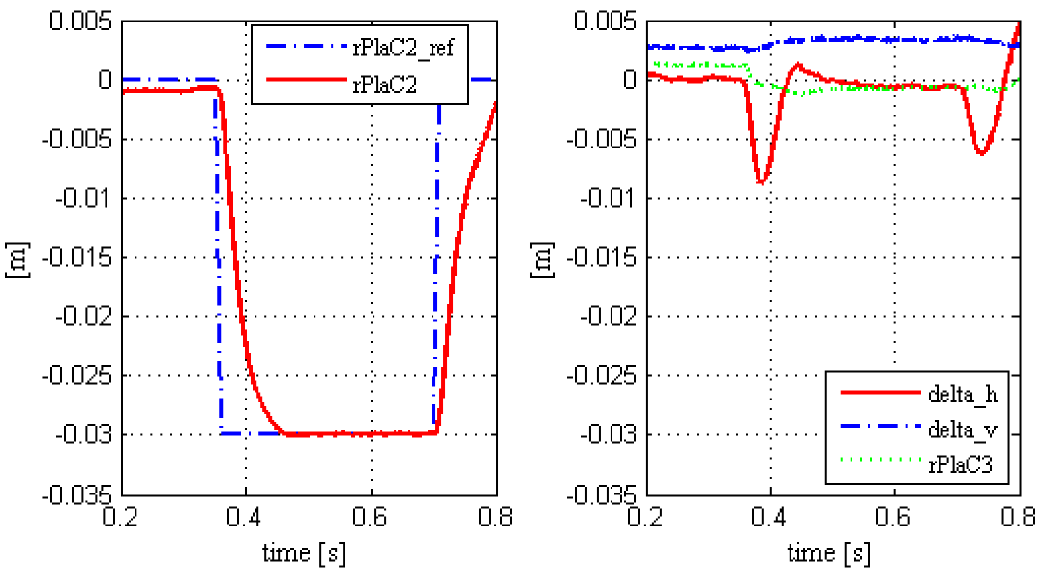

Fig. 3. Shot 33825: feedback control of the plasma elongation (left). Horizontal and vertical shift and plasma triangularity are negligibly affected (right).

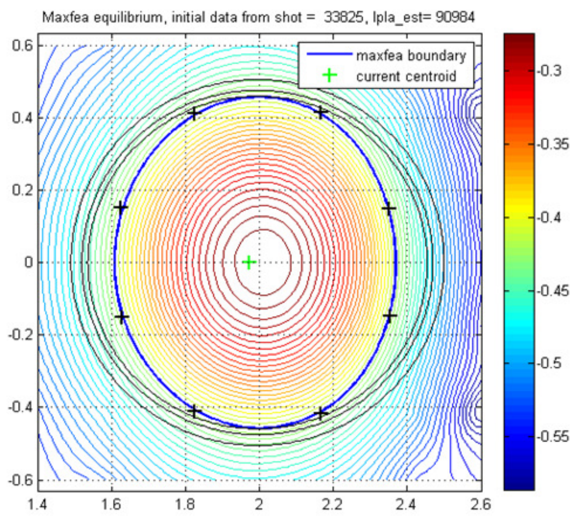

Fig. 4. Shot 33825: poloidal flux map reconstruction by a 2D equilibrium code (k=1.15).

was preferred to the response promptness in the design taking into account both the above-mentioned limit of the power supplies and the need to avoid an excessive shrink of plasma section due to possible overshoot of the response. In the same figure the evolution of the plasma horizontal and vertical shift and plasma radius cos(3ϑ) harmonic (the only component of triangularity which could be affected by the standard FS coil configuration) are presented. The perturbation of the horizontal position is due to the small vertical field created by the cos(2ϑ) distribution in a toroidal geometry which is then promptly recovered by the plasma horizontal shift control loop. This perturbative effect was calculated and a feedforward compensation could be added if required. The variations of the other quantities are negligible Equilibrium data analyses were performed by means of MAXFEA 2D code; an example of poloidal flux map reconstruction with an elongation k=1.15 is shown in fig. 4.

Conclusions

A first plasma shape feedback control scheme has been designed and successfully implemented in the circular section machine RFX-mod operated in Tokamak configuration. Elongated plasma discharges have been produced in an accurate and repeatable way. The revision of the existing control system design is presently in progress with the aim of obtaining D-shaped plasma discharges. It includes the implementation of a newly upgraded algorithm for the real time determination of the plasma boundary along with the position of the X-points. The test of a multivariable controller capable of exploiting the available degrees of freedom allowed by the FS coil power-supplies is also foreseen.

References

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