First experimental results of plasma shape control using real time equilibrium reconstruction in TCV

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1. Introduction

The performance and stability of tokamak plasma configurations depend strongly on the plasma shape. The plasma shape plays a particularly important role in the stability of global magnetohydrodynamic (MHD) modes and in heat and particle transport [1-3]. We report on the first experimental results of the new plasma shape controller for Tokamak à Configuration Variable (TCV). The plasma shape control is realized using the isoflux control scheme [4]. The spatial distribution of the poloidal flux is obtained from the recently developed real-time version of the equilibrium reconstruction code LIUQE [5] (RTLIUQE), which provides an approximate solution to the Grad-Shafranov equation which best fits the diagnostic measurements. The equilibrium reconstruction and the shape control algorithm are performed on a real-time node of the TCV digital control system (SCD [6]). We also report on investigating various shape control methodologies for implementing a full shape plus position control based on poloidal flux with the help of a plasma model (RZIP) [7].

2. First experimental results of plasma shape control using real time equilibrium reconstruction on TCV

The plasma shape control is realized using the isoflux control scheme. The plasma boundary is controlled by adjusting the poloidal field coil currents to eliminate the flux error between all pairs of adjacent control points, with the explicit constraint of vanishing average boundary flux change to prevent the shaping coils from driving net flux. The control algorithm is also optimized with respect to hardware constraints, in particular to avoid solutions with large and opposite currents circulating in adjacent coils. .As a first step, a PI (proportional and integral) plasma shape control algorithm orthogonal to the position (radial and vertical) control was developed; the radial and vertical controls are then separately handled by the pre-existing control system with pre-set linear coil combinations. The spatial distribution of the poloidal flux is obtained from the recently developed real-time version of the equilibrium reconstruction code LIUQE [5] (RTLIUQE), which provides an approximate solution to the Grad-Shafranov equation which best fits the diagnostic measurements. The coil current corrections calculated by the algorithm, scaled by an appropriate gain, are added to the precalculated current references used in a separate (pre-existing) coil current control loop.

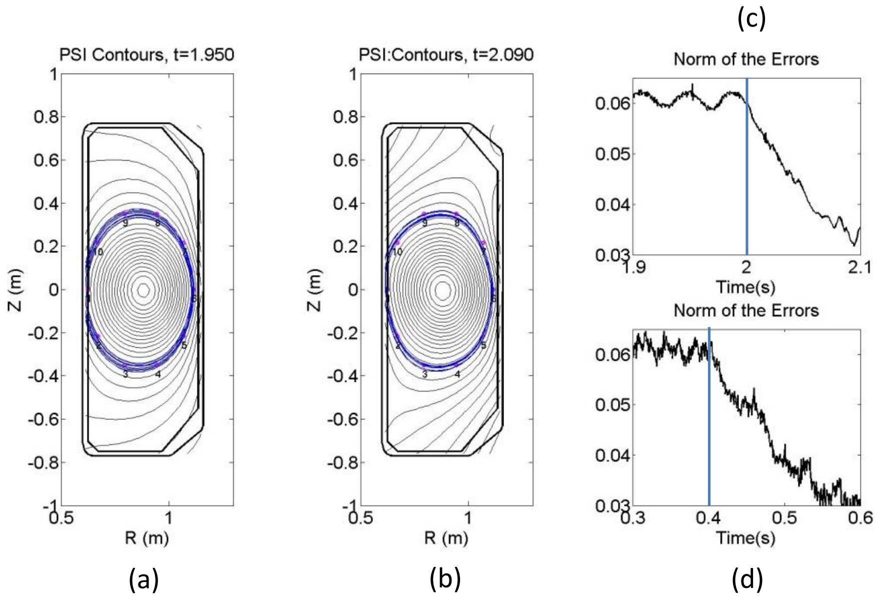


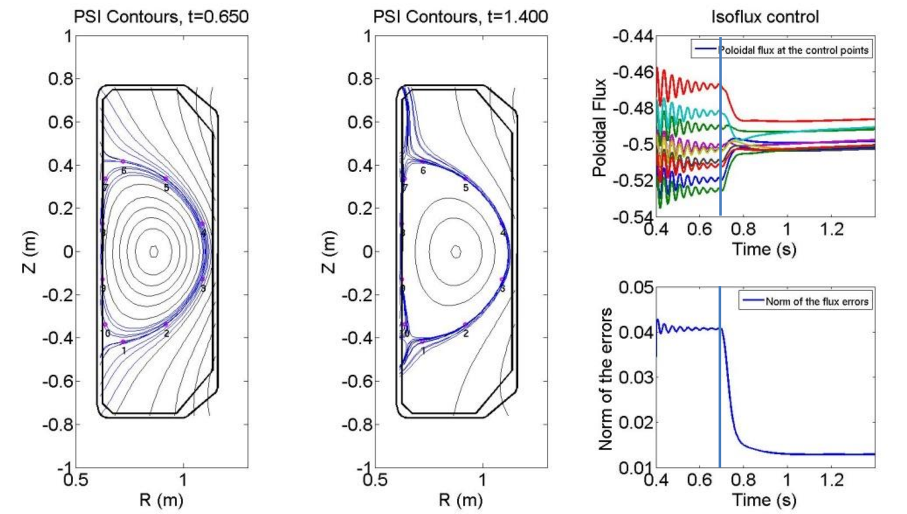
Figure 1: (a-b) Poloidal flux contours and control points before and after the switching on of the shape controller; (c) Norm of the poloidal flux error vector in normalized radial coordinate. (d) Same norm for a different shot in which the feedforward currents were deliberately misprogrammed.

Figure 1 shows a typical limiter plasma discharge with successful implementation of this shape control algorithm (a-c) and a different discharge (d) in which a deliberate shape misprogramming introduced by misprogramming the coil currents was successfully compensated by the shape controller. The errors are clearly reduced relative to the case with no feedback shape control.

3. Refinement of plasma shape control algorithm using RZIP plasma model

The linearized plasma model RZIP [7] was implemented with the TCV control system for performing offline analysis of plasma shape control algorithms. Figure 2 shows a simulation with the help of the RZIP plasma model for the existing algorithm. Our ultimate aim is to construct a control algorithm which controls simultaneously the shape plus the position of a tokamak plasma discharge. As a first step, separately minimizing (with appropriate weights) the poloidal flux differences between the uppermost and lowermost, and between the rightmost and leftmost control points would facilitate the control of the vertical and radial positions of the plasma, removing the aforementioned orthogonality. In this scheme, only analyzed through modelling so far, we have left for the moment a differential vertical control using two separate sets of linear coil combinations (operating respectively at 1 kHz and 10 kHz) to the pre-existing control system. Figure 3 shows the correction in the vertical position of the magnetic axis towards the programmed value (z_o=0), obtained by this shape control algorithm.

(d)



(a) (b) (d)

Figure 2: (a-b) Poloidal flux at the control points before and after control switch-on; (c) flux errors between adjacent control points and (d) their norm for shape control algorithm in a simulation based on linearized plasma model RZIP.

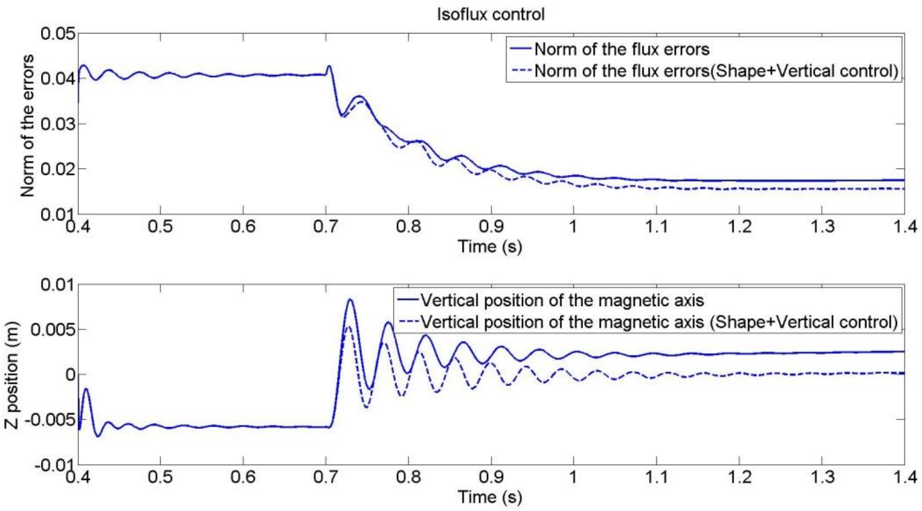


Figure 3: Norm of the poloidal flux error vector and position of the magnetic axis with and without the activation of a flux difference minimization between the top and bottom control points.

A more generalized and flexible approach is currently under study in which orthogonality would be imposed in the space of poloidal flux errors between the adjacent control points, and orthogonal observers would be constructed for vertical, radial and shape control (where the latter could be further separated by shape moments if desired). Separate controllers can then be designed and tuned separately for maximum flexibility.

4. Conclusion

A plasma shape control algorithm has been successfully implemented and demonstrated on various limiter plasma discharges on TCV. The performance and design of this controller as well as a generalized shape and position control algorithm has been studied in closed loop with the help of the linearized plasma model RZIP. A new control approach based on orthogonal observers for position and shape in the space of poloidal flux differences between the control points is under development. Progressive refinements and improvements will follow based on the analysis obtained with the help of the RZIP model. It is planned to apply these control schemes to the development of advanced plasma configurations in the next TCV campaign.

This work was supported in part by the Swiss National Science Foundation.

5. References

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