Initial Implementation of a Multivariable Plasma Shape and Position Controller on the DIII–D Tokamak

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1. Introduction

This paper describes the successful initial implementation and experimental test of a model-based multiple-input-multiple-output (MIMO) algorithm for control of plasma shape and position in the DIII–D tokamak. Figure 1 illustrates the requested (x) and actual (solid) plasma boundary during plasma discharge 99350. This first implementation of an MIMO controller on DIII–D provided good steady state control, but quality of control of changing plasma shape was mixed. Plasma control was always stable however, and was used to control several full shots from plasma current rampup through rampdown.

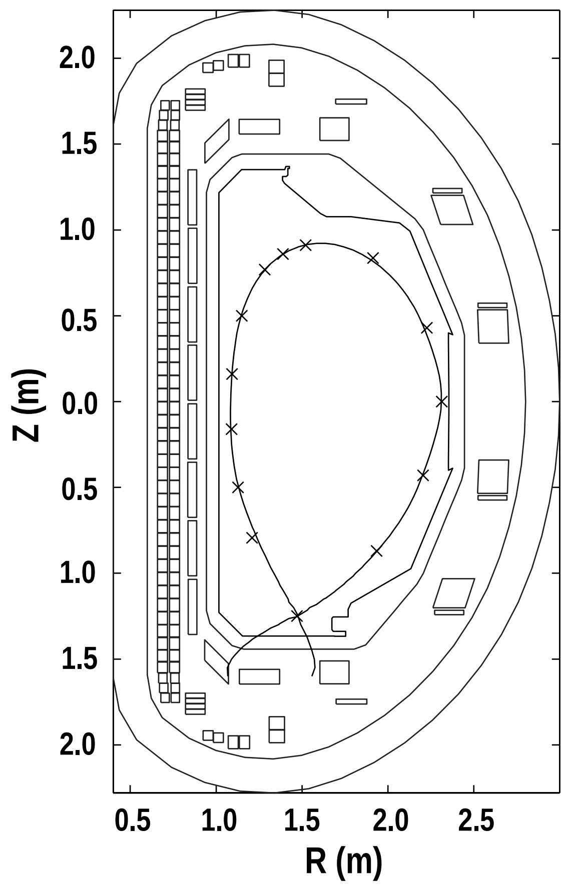

Fig. 1. DIII–D cross-section showing requested plasma boundary location (x's) and actual boundary location controlled by MIMO controller in shot 99350 (time=1490 ms.)

2. Present DIIID Plasma Shape Control

In recent years the control methodology at DIII–D has changed from its original combination of gap and "flux ratio" control [1] to "isoflux" control [2]. The isoflux control method, now in routine use on DIII–D, exploits the capability of the new real time EFIT plasma equilibrium reconstruction algorithm to calculate magnetic flux at specified locations within the tokamak vacuum vessel. Figure 2 illustrates a lower single-null plasma which was controlled using isoflux control. The real time EFIT algorithm can calculate very accurately the value of flux in the vicinity of the plasma boundary. Thus, the controlled parameters are the values of flux at prespecified control points along with the X–point R and z position. By requiring that the flux at each control point be equal to the same constant value, the control forces the same flux contour to pass through all of these control points. By choosing this constant value equal to the flux at the X–point, this flux contour must be the last closed flux surface or separatrix. The desired separatrix location is specified by selecting one of a large number of control points along each of several control segments (Fig. 2). An X–point control grid is used to assist in calculating the X–point location by providing detailed flux and field information at a number of closely spaced points in the vicinity of the X–point.

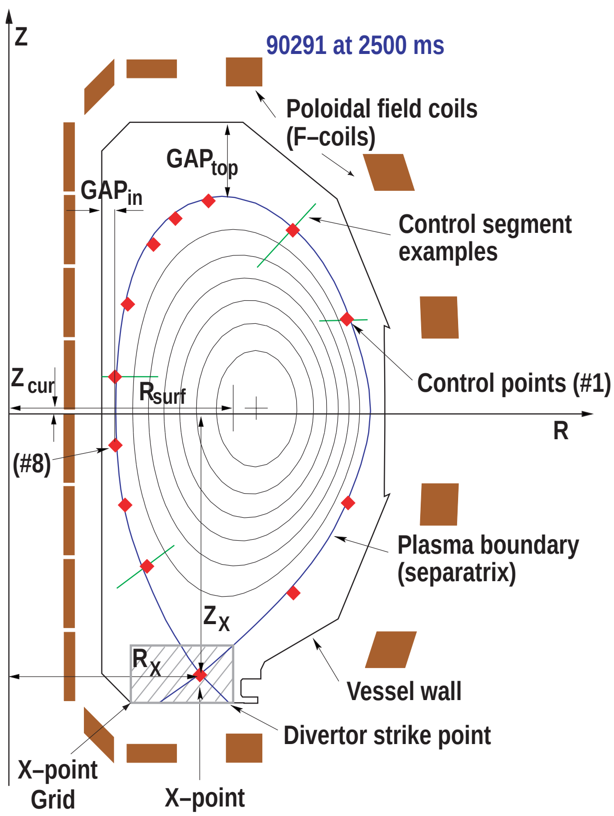

Fig. 2. Example of controlled plasma parameters in new isoflux control (R_X, Z_X, and flux at control points #1–#13 on control segments #1–#13).

The algorithm used presently in DIII–D operations is the isoflux control method with PID (proportional, integral, and derivative) operations on the control point flux and X point R and Z errors. This is followed with multiplication by a matrix gain to produce commands to the shape control power supplies (choppers) on each plasma shaping coil. The gain matrix is sparse, i.e. most individual shape errors are corrected through the application of only a small number (often one) of coil current changes. Control of the X–point requires coordinated action by the largest number (4) of shaping coils. The elements of the gain matrix and the individual PID gains applied to each error signal are empirically determined.

3. Model Based MIMO Controller

The MIMO controller developed for this initial implementation produces fully coupled multivariable control (analogous to a fully populated gain matrix). The controller design is model based, i.e. the controller is derived from a model of the system to be controlled (the plant) and incorporates knowledge of the time response of all outputs (flux and X–point errors) due to each input (chopper voltages). A linearized plant model was developed and validated [3,4] in order to use mature linear multivariable design techniques. The normalized coprime factorization (NCF) design technique [5] was used to derive the controller from the linearized plant. A single controller based on a plant linearized around a nominal plasma equilibrium was used to control the entire plasma discharge (shot).

Figure 3 shows an overview block diagram of the isoflux plasma shape control using an MIMO controller. Plasma diagnostics acquired by the plasma control system (PCS) in real time are used by the realtime EFIT algorithm to reconstruct the plasma equilibrium shape and current distribution, from which the X–point location and control point flux errors are calculated. These errors are processed by the MIMO shape control algorithm to produce demand voltages for choppers on each shaping coil. A separate set of chopper voltage controllers is used to provide closed loop control of the choppers and thus produce the demanded voltages. This constitutes the first use of chopper voltage control on DIII–D. The “standard” PID isoflux mode of shape control in DIII–D does not make use of separate chopper voltage control loops. This approach was taken to avoid having to include the highly nonlinear set of chopper models in the plant to be controlled. A fast, vertical stability control algorithm is also executed within the PCS. This controller does not actually stabilize the plasma, since it has no proportional feedback term; instead it reduces the growth rate sufficiently that the slower shape control algorithm can stabilize the plasma.

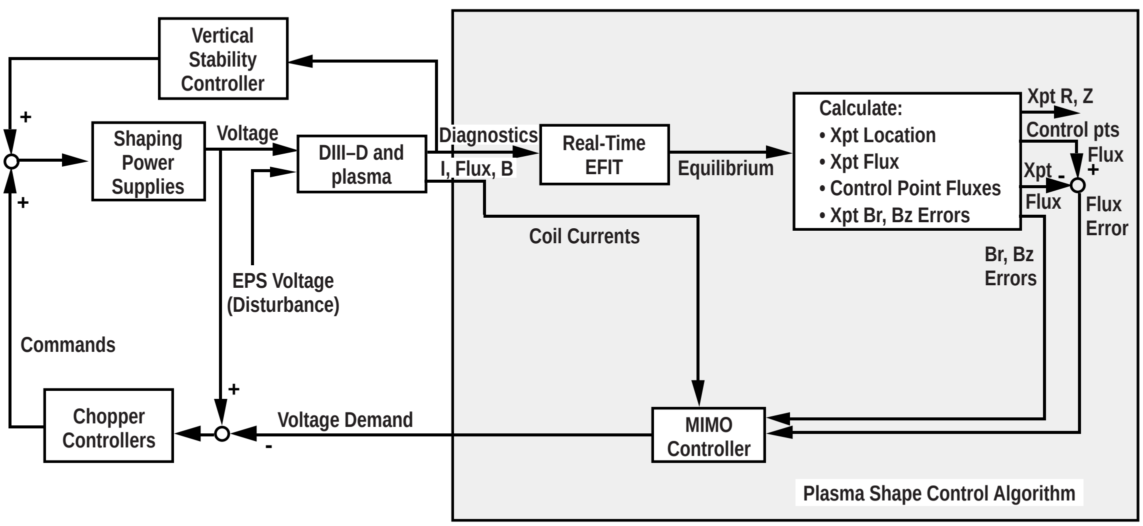

Fig. 3. Overview of MIMO isoflux control scheme.

The field error (ΔB_r, ΔB_z) is computed from the X–point error (Δr, Δz) as follows:

$$\Delta \mathbf{B_r} = \frac{\partial \mathbf{B_r}}{\partial \mathbf{r}} \Delta \mathbf{r} + \frac{\partial \mathbf{B_r}}{\partial \mathbf{z}} \Delta \mathbf{z}, \Delta \mathbf{B_z} = \frac{\partial \mathbf{B_z}}{\partial \mathbf{r}} \Delta \mathbf{r} + \frac{\partial \mathbf{B_z}}{\partial \mathbf{z}} \Delta \mathbf{z} \tag{1}$$

This was done to make the input-output behaviour more nearly equal to a linear plant. Partial derivatives here are estimated from field values on the X–point grid (Fig. 2).

This MIMO controller also operates on coil current "errors" in order to prevent coil limits from being encountered. Coil currents near 0 can cause choppers to latch (a type of fault) while currents exceeding maximum current limits will cause an overcurrent fault. In either case, the plasma shot is ended. A coil current reference vector is constructed as a heavily filtered version of actual coil currents whenever currents are not near their limits. This reference is modified so as to produce large resultant error signals when currents approach a limit.

4. Overview of MIMO Development Program

A plant model was developed to predict how a DIII–D plasma would respond to a specified change of actuator (chopper voltage on shaping coil) input. Significant effort went into development and validation of models for the DIII–D vessel/conductors, choppers, E (ohmic heating) and F (shaping) power supplies [3], and linearized models of the plasma [4].

One of the most difficult portions of the controller development was dealing effectively with the highly nonlinear shaping (chopper) power supplies (Fig. 3) whose response characteristics varied substantially from coil to coil and from shot to shot. Rather than deal with this complication each time a controller for another plasma shape is constructed, closed loop voltage controllers were developed for all the choppers. This had the effect of replacing the highly nonlinear and variable choppers with controlled voltage sources on each coil having nearly the same (approximately linear) response for all coils and all shots. The inner vertical control loop still bypasses this voltage control however (Fig. 3) in order to achieve the response time necessary for stabilization. The chopper controllers were developed independently from the plasma controller design process and were tested experimentally, both with dedicated tests and in piggyback tests during plasma operations [6,7].

In the past, evaluation of the effectiveness of the plasma control has nearly always been done by running the controller on DIII–D. As part of the model-based design, a model of DIII–D plasma response was incorporated into an open loop simulation model of DIII–D which was run in closed loop with the controller implemented in the operational digital plasma control system (PCS) [8].

For the first experimental test of an MIMO controller on DIII–D, a particular plasma shape (lower single-null, as illustrated in Figs. 1 and 2) was selected, a controller was designed and implemented in the PCS, and controller tests were performed during plasma operations. Test results from this implementation are discussed in the next section. This test was primarily intended as a demonstration of feasibility.

5. MIMO Implementation Experimental Results

Control tests using the developed MIMO plasma controller were conducted on May 10, 1999 during ohmic (inductively heated) plasma discharges 99339 through 99357. The MIMO control was first introduced in the middle of discharges, then extended to the entire plasma current rampup and flattop phases for controlled shots subsequent to and including shot 99346. Steady-state plasma shape control was quite good in general, although accuracy of the upper plasma segments (especially segments 2 and 3 – see Fig. 2) was somewhat worse than the lower segments and the X–point. Figure 4 shows requested and achieved values for some representative measurements in shot 99350 under steady state control. See Fig. 2 for definitions of these signal quantities. The plasma was generally kept within about 1 cm of the requested values when the requested shape was kept fixed.

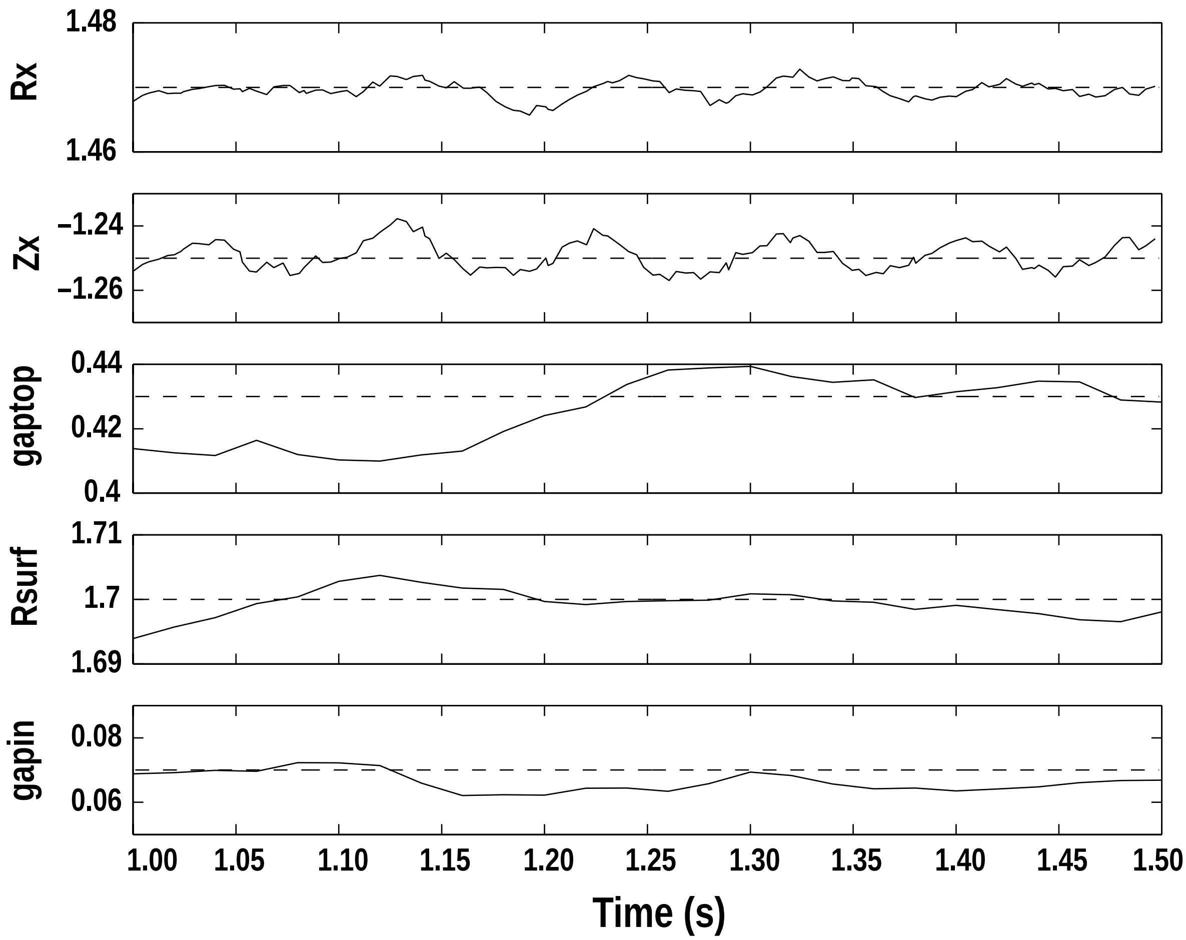

Fig. 4. Steady-state control of the plasma boundary in shot 99350 (all units in meters). Plasma current flattop begins at about 1.15 s. Solid lines indicate achieved values, while dashed lines denote target values.

Control with the requested plasma shape changing with time was not as good. Control of the X–point was still generally very good, but flux in the upper control segments followed their requests too slowly. Figure 5 shows two shots in which the requested plasma shape changed with time. In shot 99350, an approximately rigid vertical motion of the plasma was programmed between 1.5 s and 4.2 s. In shot 99351, an approximately rigid radial plasma motion was programmed in the same interval. It can be seen that the programmed radial motion was generally better behaved than the vertical motion, even during the sudden steps starting at 3.5 s. The large ringing on Zx following the requested step change also couples to the radial control to produce poor control of the inside gap (gapin). This problem is likely due to the previous inaccuracy of the model of the closed-loop vertical stability control (see Fig. 3), which has been corrected since this implementation.

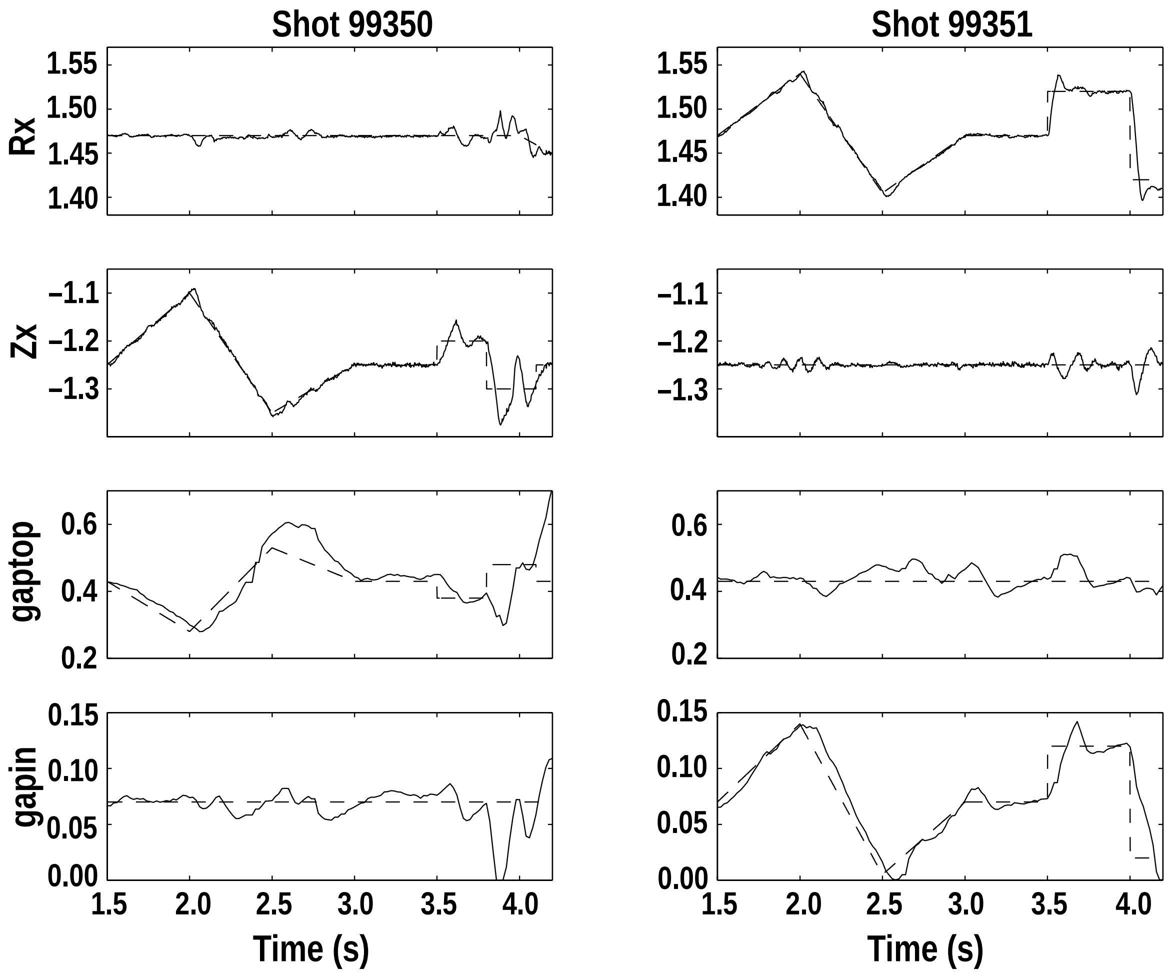

Fig. 5. Example control of two shots with requested plasma shape changing over time (all units in meters). Solid lines indicate achieved values, while dashed lines denote target values.

Performance of the MIMO controller appears to vary somewhat with plasma internal inductance (ℓ_i) – a measure of the "peakedness" of the current distribution within the plasma. The internal inductance naturally increases throughout an ohmic discharge as the profile evolves toward its steady state condition. Figure 6 illustrates X–point position control and control of the top plasma-wall gap during 300 ms intervals at low ℓ_i (~1.0) and high ℓ_i (~1.25) in discharge 99350. The standard deviation of X–point control errors decreases with increasing ℓ_i, experiencing a dramatic reduction in the amplitude of a low frequency (~ 10–11 Hz) oscillation prominently observed at low ℓ_i. The mean value of the X–point vertical (Z_x) and radial (R_x) position appears to be unaffected by the ℓ_i value. The general variation in X-point control with ℓ_i is likely the result of controller optimization for a relatively high ℓ_i equilibrium, corresponding to the plasma state in the interval 3.2<t<3.5 s in discharge 99350. The value of ℓ_i strongly affects vertical growth rate and response, which in turn strongly affects the controller design and response.

In contrast with the improvement in X–point control with increasing ℓ_i, accuracy of top gap control is clearly reduced as ℓ_i increases. Comparison of the two lowest frames in Fig. 5 shows a mean achieved gap distance (solid line) of ~0.5 cm from the target value (dashed line) in the lower ℓ_i case, while the mean error in gap distance exceeds 1.5 cm in the higher ℓ_i case. Since increasing ℓ_i corresponds to a peaking of the current profile and resulting increase in effective distance of the current channel from control coils, increased coil current is necessary to regulate the plasma surface as ℓ_i increases. The upper part of a lower single-null plasma is particularly sensitive to such changes in the current profile. It is possible that the balance of control priorities inherent in the design of this controller tended to produce insufficient current in the upper coils to accurately regulate this particular region of the separatrix in the higher ℓ_i regime. Further study of these experimental data, improvement of balance of priorities in controller design, and further experimental testing is required to determine the precise source of the effect.

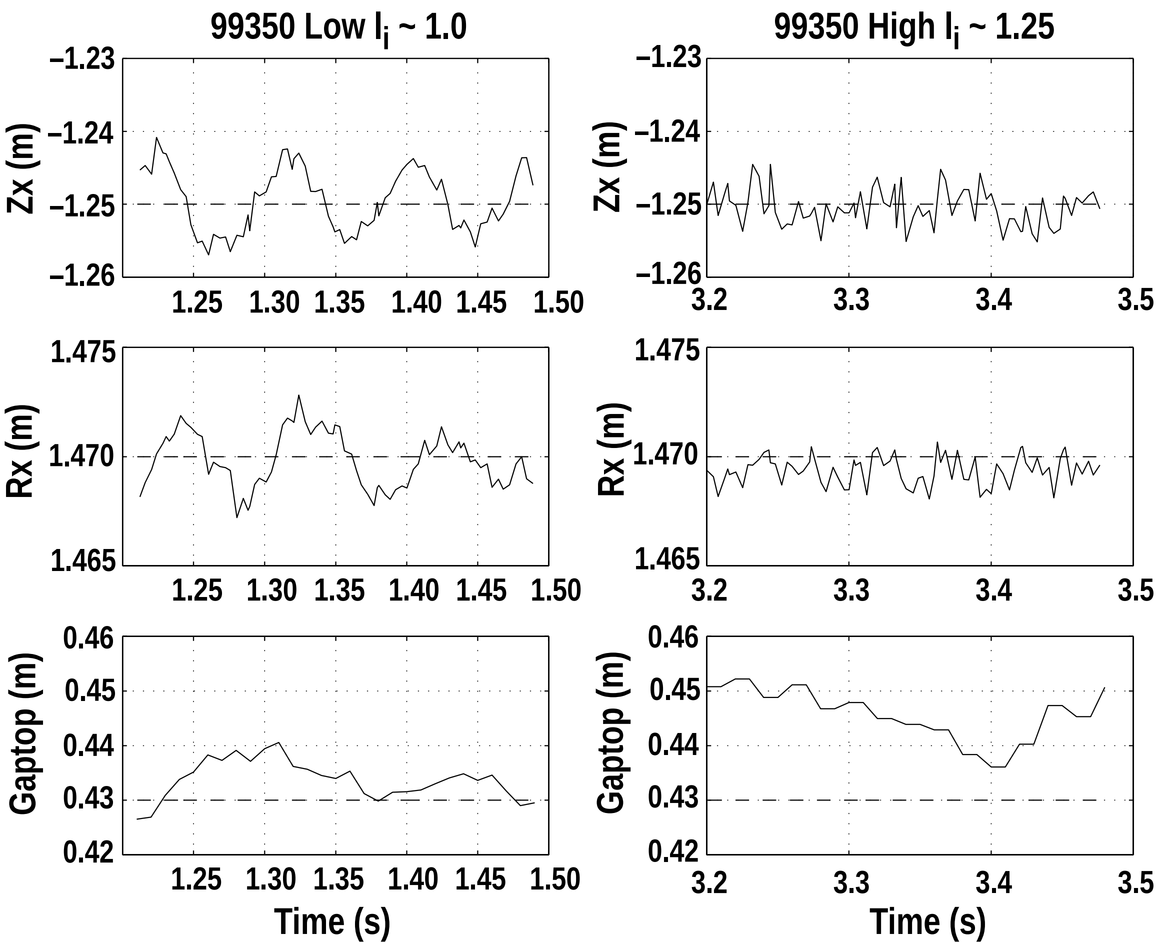

Fig. 6. Accuracy of X–point position control improves and accuracy of top gap control degrades with increasing internal inductance (discharge 99350). Solid lines indicate achieved values, while dashed lines denote target values.

Figure 7 illustrates the modification of the F-coil current reference signal in order to avoid coil current limits from ending the shot. The reference signal is initialized to the value of the F-coil current when the MIMO controller takes over. It is subsequently computed as a heavily filtered version of the F-coil current except in the case where the current approaches either 0 or a maximum current limit. In these cases, the reference is modified so as to induce the controller to "pull" the coil current away from the limit value. In Figs. 7(a) and (b), when the coil current value becomes less than 400 A, the current reference signal begins to grow larger. When the current increases to more than 400 A in Fig. 7(b), the reference signal tends back toward the measured coil current value. In Fig. 7(c), when the current comes close to the maximum limit of 5 kA, the reference signal moves down to maintain F8B current below the limit. Changes in coil current between 1.5 and 4 s seen in the plots of F5B and F8B correspond to the programmed plasma shape perturbations shown in Fig. 5.

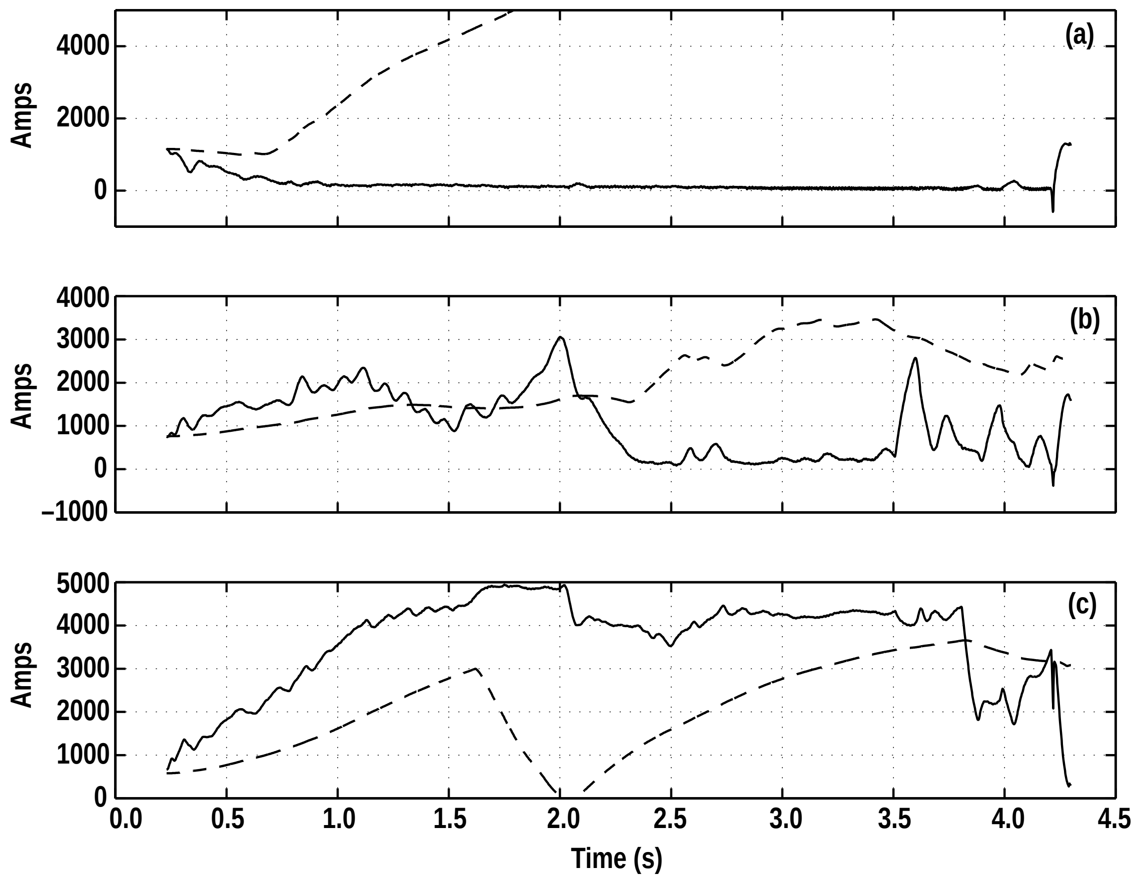

Fig. 7. F-coil current data (solid) versus algorithm-generated reference signal (dashed) in shot 99350 for F-coils (a) F4B, (b) F5B, and (c) F8B.

6. Summary

In this paper, we have summarized the results of the first experimental implementation of an MIMO controller on DIII–D. Steady state control was quite good in general, with accuracy of control of upper portions of the plasma somewhat worse than lower portions and the X–point. Quality of control in tracking of changing plasma shape requests was mixed; with X–point control remaining very good while some upper plasma to wall gaps in some shots were not very well controlled. The MIMO controller always provided stable control and approximately two-thirds of the plasma shots on the experimental test day were controlled through all of plasma current rampup and flattop by the MIMO controller. Some of the control inaccuracies which occurred were not unexpected, since there were known inadequacies in accuracy for some models, especially that of the closed-loop vertical control.

The dependence of the control accuracy on the value of ℓ_i was somewhat stronger than expected, and not entirely understood. This result may indicate a need for gain-scheduling. Overall, results of this first test of a MIMO controller on DIII–D were very encouraging. In addition, a great deal of useful data for continued model and controller development was acquired.

Additional development is needed before MIMO controllers can be routinely used during DIII–D experimental operations. The practical operational concern of preventing coil current limiting was addressed in the initial implementation. Other practical issues which must be addressed include: anti-windup for chopper voltage saturations, gain scheduling of multiple controllers (with associated techniques for achieving bumpless transfer), limiting a certain buss voltage, resolving conflicts between fast vertical and slow shaping control, and dealing with multiple unsynchronized processors with varying cycle times in the plasma control system.

In the long term, it is expected that a MIMO controller will integrate the shape control with control of plasma profiles such as pressure, radial E-field, and current profiles using feedback commands to new actuators such as counter-injection neutral beams (NB), electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD).

Acknowledgment

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