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DEVELOPMENT OF MULTIVARIABLE CONTROL TECHNIQUES FOR USE WITH THE DIII–D PLASMA CONTROL SYSTEM

MILESTONE NO. 127

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1. Introduction

This report describes the successful 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. It also summarizes what is involved in the model-based MIMO design process. This first implementation of an MIMO controller on DIII–D provided good steady state control (Fig. 1), but quality of control of changing plasma shape was mixed. Plasma control was always stable however, and in fact was used to control several full shots from plasma current rampup through rampdown.

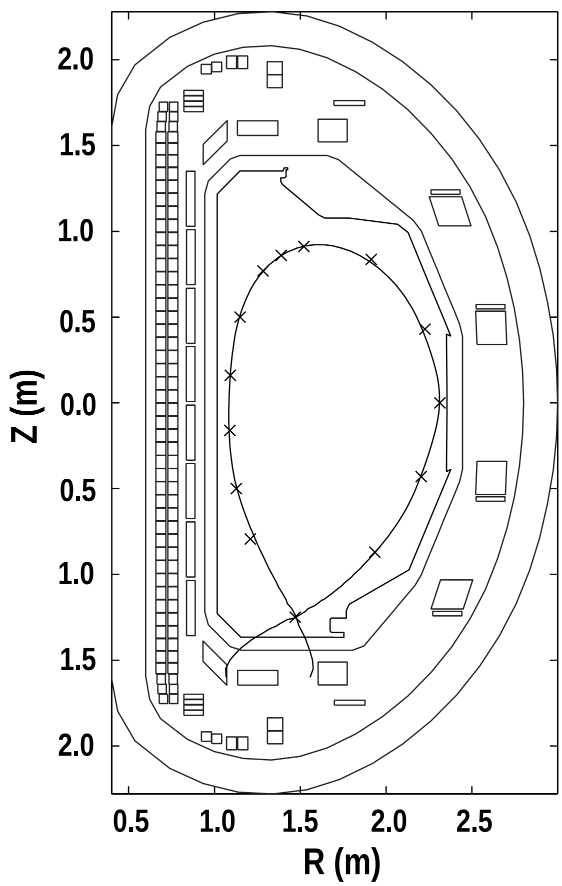

Figure 1. DIII–D cross-section showing requested plasma boundary location (x's) and actual boundary location controlled by MIMO controller in shot 99350 (time = 1490 ms).

2. Present DIIID 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 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. Real time EFIT 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.

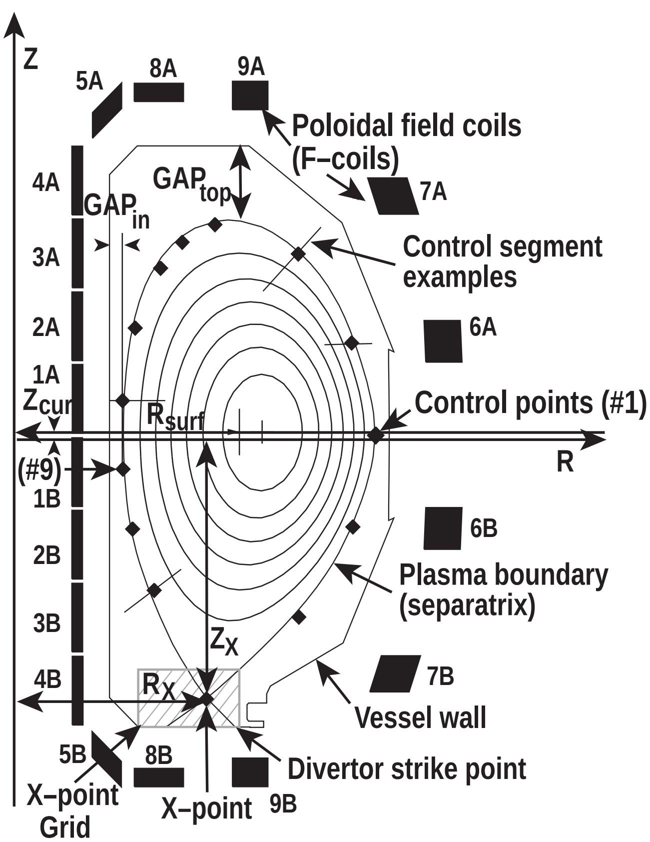

Fig. 2. Example of controlled plasma parameters in new isoflux control (R_X, Z_X, and flux at control points #1–#13 on control segments counter clockwise in the figure).

Discussion in the following is restricted to control of lower single null plasmas in DIII-D. Similar remarks hold for double null and upper single null plasmas.

Figure 3 shows an overview block diagram of the isoflux plasma shape control presently used in DIII–D. Plasma diagnostics acquired by the plasma control system (PCS) in real time are used to make an estimate of 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 isoflux shape control algorithm to produce commands to shape control power supplies (choppers) on the plasma shaping coils. 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.

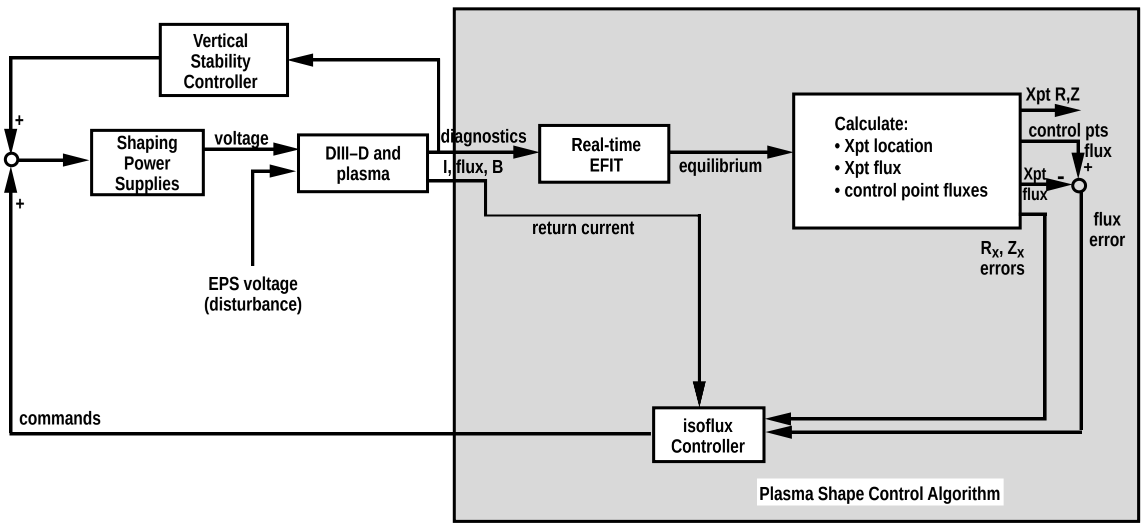

Fig. 3. Overview of existing isoflux control scheme.

The algorithm used in the present isoflux control is based on PID (proportional, integral, and derivative) operations on the control point flux errors and X–point R and Z errors, followed by multiplication by a matrix which applies gains to the PID transformed errors to produce commands to the choppers on each plasma shaping coil. The standard lower single null gain matrix is shown in Table 1. Note that the sparsity of this matrix implies that most individual shape errors are corrected through the application of only a small number of coil current changes. Control of the X–point requires coordinated action by the largest number (four) of shaping coils. A constraint on the sum of currents through coils other than the 6A, 6B, 7A, and 7B coils is dealt with by trying to minimize the “return current” (Iret in Table 1), consistent with good shape control.

Table 1. Gain matrix used in present isoflux control divided by 100.

	Isoflux error at control point, segment number:													Errors		
Coil	1	2	3	4	5	6	7	8	9	10	11	12	13	Rx	Zx	Iret
F1A								10								
F2A							16									
F3A																
F4A				-4	-4	–10										
F5A				-4	–10	–4										
F6A	16	4														
F7A			8													
F8A				–10	–4	–4										
F9A																
F1B									10							
F2B										16						
F3B											10					
F4B														10	–10	
F5B														10	–10	
F6B	16												4			
F7B												2				0.2
F8B														10	–10	
F9B														–10	–10	

3. Model based MIMO design approach

A multi-input-multi-output (MIMO) controller may be thought of as a controller with a fully populated gain matrix. MIMO controller design is nearly always model based, *i.e.*, the controller is derived from some model of the system to be controlled (the plant), because of the difficulty in determining values for all entries in the fully populated gain matrix. Most of these model based techniques also produce transfer functions (input-output transformations) analogous to the PID transforms described above. The most mature design techniques require the plant model to be linear (or linearized). Most also provide some means to incorporate a prespecified set of control objectives into the controller design. We chose to use the normalized coprime factorization (NCF) [3] design technique to design controllers for the inital control tests. In the following, MIMO will always refer to a controller with a fully populated gain matrix designed using model-based techniques.

Figure 4 illustrates how a DIII–D plasma is controlled with the MIMO controller. In contrast to the regular isoflux controller shown in Fig. 3, the output of the MIMO controller

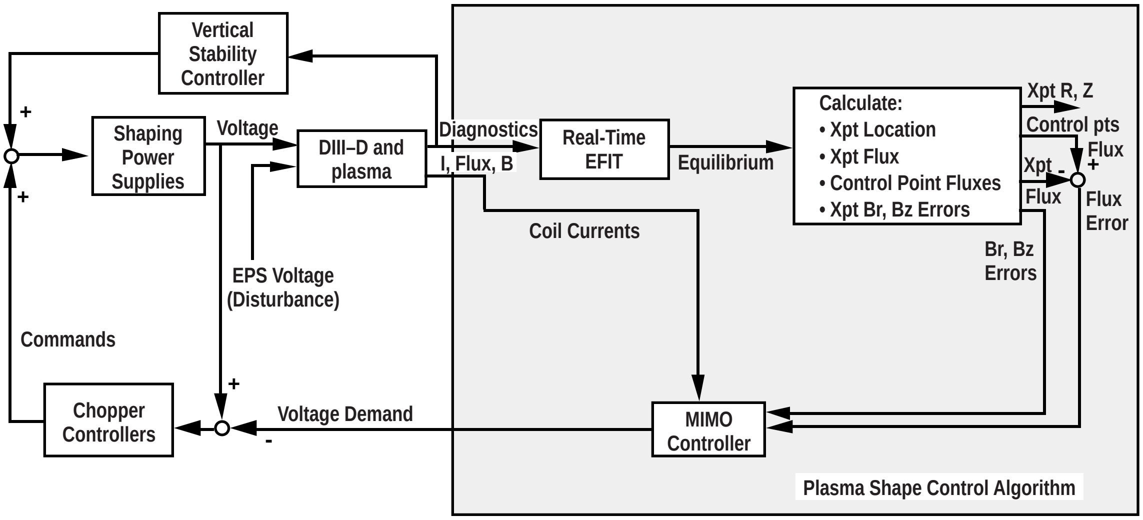

Figure 4. Overview of MIMO isoflux control scheme.

is a set of demand voltages for choppers on each shaping coil, rather than commands to those choppers. Because chopper commands do not map to known output voltages, a separate set of chopper voltage controllers executes in the PCS to provide closed loop control of the choppers and thus produce the demanded voltages. (These choppers were not previously voltage controlled.) This approach was taken to avoid having to include the highly nonlinear set of chopper models in the plant to be controlled.

Control of the X–point location using the regular isoflux technique feeds back the X–point r and z errors directly to a controller. The MIMO controller on the other hand computes a field error (ΔB_r, ΔB_z) from the X–point error (Δr, Δz) as follows:

$$\Delta B_r = \frac{\partial B_r}{\partial r}\,\Delta r + \frac{\partial B_r}{\partial z}\,\Delta z \ , \qquad \Delta B_z = \frac{\partial B_z}{\partial r}\,\Delta r + \frac{\partial B_z}{\partial z}\,\Delta z \ ,$$

and attempts to drive that error to 0. Here, partial derivatives are estimated from field values on the X–point grid (Fig. 2). This provides a transfer function from voltage to errors which is nearly linear so that the more mature linear multivariable control design tools can be used.

4. Benefits of the Model-Based Design Approach

The model-based multivariable controller design approach has both near term benefits for the DIII-D experimental program and long term benefits for next generation devices anticipated for use in the national and international fusion programs. The model-based approach to control design has several technical advantages:

(1) It provides a systematic design method for any new plasma configuration on DIII–D or on other tokamak devices. In the near term, this means less DIII–D machine time is

needed for control development, and consequently allows more flexibility in development and experimental use of new plasma shapes.

(2) It provides a systematic method for designing/evaluating control requirements for next-step devices. This means that much of the control design for a new device can be done before the machine starts up and, more importantly, many design decisions can be influenced to improved the controllability of plasmas in the device. This approach has already been used in the ITER EDA where decisions about minimizing cost had to be balanced with reduced plasma controllability; this controllability was determined via simulations using ITER design models and controllers developed from these models [9].

(3) It provides explicit methods for trading off conflicting control demands, for example, relative accuracy of gap and X–point control.

(4) It facilitates incorporation of methods for dealing with hardware constraints. For example, part of the developed DIII–D MIMO algorithm includes a method for relaxing control accuracy requirements as coil currents approach 0 or maximum values in order to avoid shot disruption.

One of the primary motivations for developing the MIMO control capability for DIII–D was the anticipation of more complex and integrated control requirements in the ongoing experimental program. Plasma shapes which are routinely being run and will be run in the near future are being modified as a result of divertor hardware installation. This complicates the control in that plasmas are now further from the PF coils than in the past, making individual control points (or gaps) less tightly coupled to a single control coil and more responsive to other previously non-controlling coils. This makes the shapes more difficult to control with a single coil to control point strategy. In addition, the manner in which coils are directly coupled together in DIII-D occasionally causes two or more coils to “fight” each other in controlling nearby plasma boundary points. Model-based, modern techniques allow off-line design and verification of controllers which incorporate knowledge of these coupled responses to design controllers which cooperatively control all boundary points simultaneously. In particular, coil “fighting” can be eliminated.

It is also anticipated that integrated controllers will be necessary for internal profile control in Advanced Tokamak discharges. Because profile and shape control are strongly coupled, effective simultaneous control could not be obtained with a shape controller which ignores the influence of profile modifications or vice-versa. Off-line model-based controller design using modern techniques seems the only practical method.

5. Overview of MIMO Development Program

The foundation of any model-based control design process is the required use of a model of the system to be controlled. In this case a model was needed which would 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 of models for the DIII–D vessel/conductors, choppers, E (Ohmic heating) and F (shaping coil) power supplies, and linearized models of the plasma [4]. To be confident that a controller based on these models will behave as predicted by the design software, one must be confident in the accuracy of the models. To this end, an extensive amount of model validation tests were conducted. These included vacuum response experiments to validate DIII–D vessel/ conductors and diagnostics models, tests of chopper response at multiple frequencies, tests of the E,F-supply responses at multiple frequencies, and piggyback tests of plasma response to various coil current perturbations [4].

One of the most difficult portions of the controller development was dealing effectively with the highly nonlinear chopper power supplies 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, it was decided to develop closed loop voltage controllers 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 response for all coils and all shots. The inner vertical control loop still bypasses this voltage control however (Fig. 4) 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 vacuum tests and in piggyback tests during plasma operations [5,6].

Part of any controller development process is the evaluation of the effectiveness of the plasma control. In the past, this has nearly always been done by running the controller on DIII–D. In the case of model-based design, a cheaper and very effective alternative method is available through the use of closed loop plasma control simulations. Since a model of DIII–D plasma response is already available, it is incorporated into an open loop simulation model of DIII–D which is then run in closed loop with the developed controller [7]. In fact, at General Atomics we have developed (and now use extensively) a method by which we can run the actual controller implemented in the operational digital plasma control system (PCS) in closed loop with the DIII–D simulation [8].

For the first experimental test of a MIMO controller on DIII–D, a particular plasma shape (lower single null) was selected, and a controller was designed and implemented in the PCS and tested during plasma operations. (Test results are discussed in the next section.) This test was primarily intended as a demonstration of feasibility.

The next step in the MIMO development is to improve the presently insufficiently accurate high beta models, then develop and implement controllers for lower single null, upper single null, and double null plasmas. The long term goal is to 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).

6. MIMO Implementation Experimental Results

Control tests using the developed MIMO plasma controller were conducted on May 10, 1999 during ohmic 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 starting with 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 5 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.

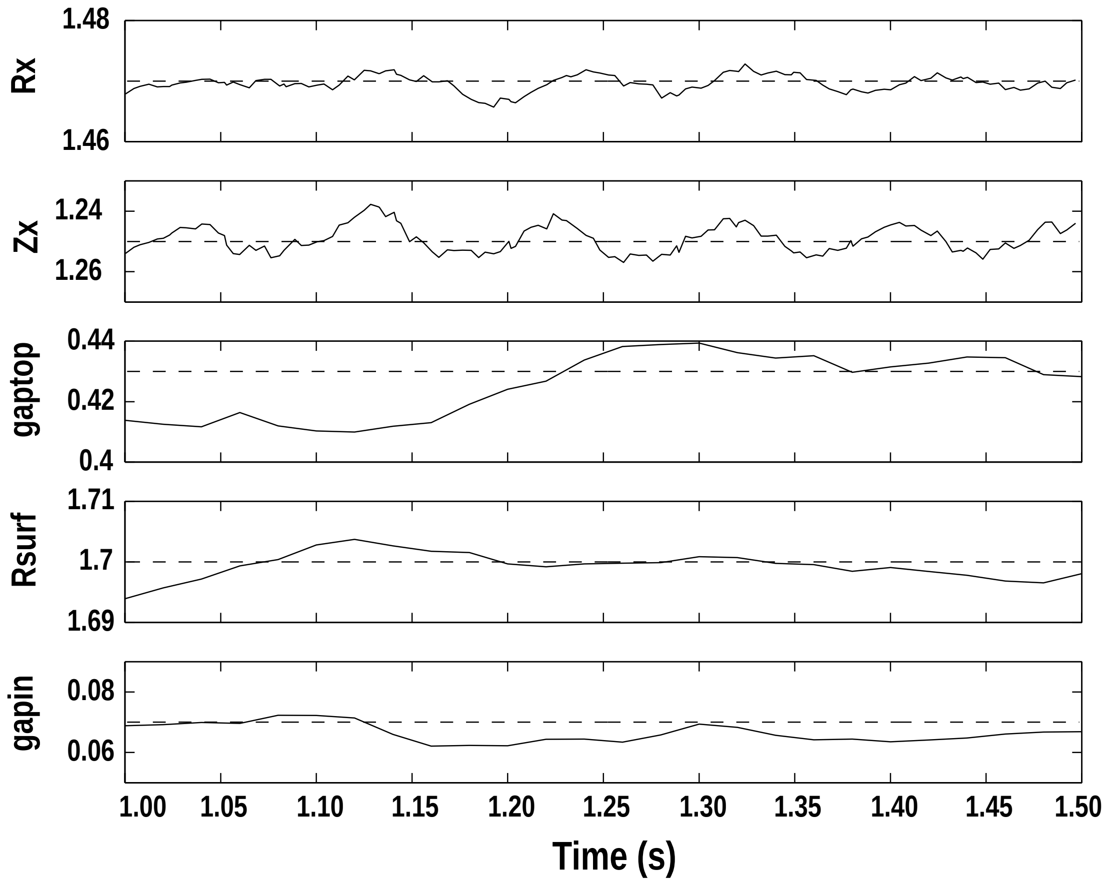

Fig. 5. Steady state control of the plasma boundary in shot 99350 (all units in meters). Plasma current flattop begins at about 1.15 seconds. Solid lines indicate achieved values, while dashed lines denote target values.

Dynamic control, *i.e.*, 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 6 shows two shots in which

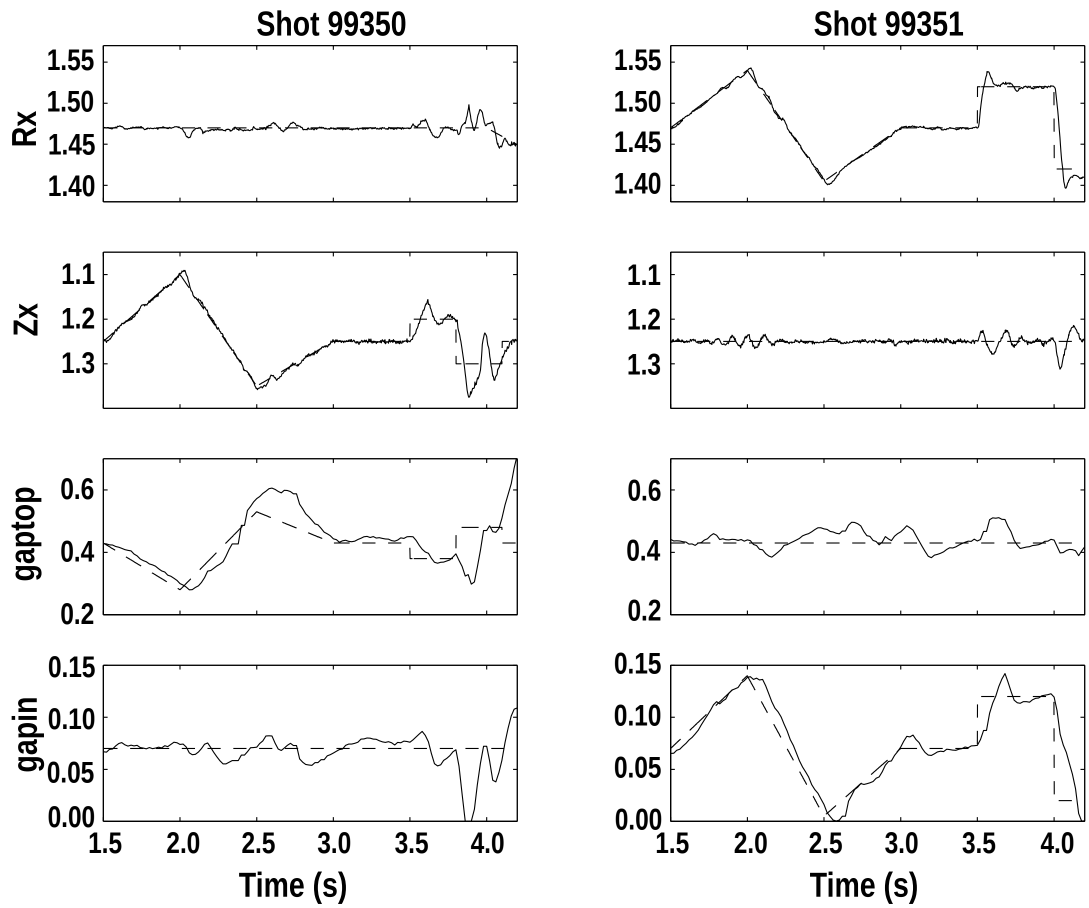

Figure 6. Example control of two shots with requested plasma shape changing over time (all units in meters). Solid lines indicate achieved values, while dashed lines denote target values.

the requested plasma shape changed with time. In shot 99350, an approximately rigid vertical motion of the plasma was programmed between 1.5 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 present inaccuracy of the model of the closed-loop vertical stability control (see Fig. 4).

Performance of the MIMO controller appears to vary somewhat with plasma internal inductance (l_i), which naturally increases throughout an ohmic discharge as the profile evolves toward its steady state condition. Figure 7 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

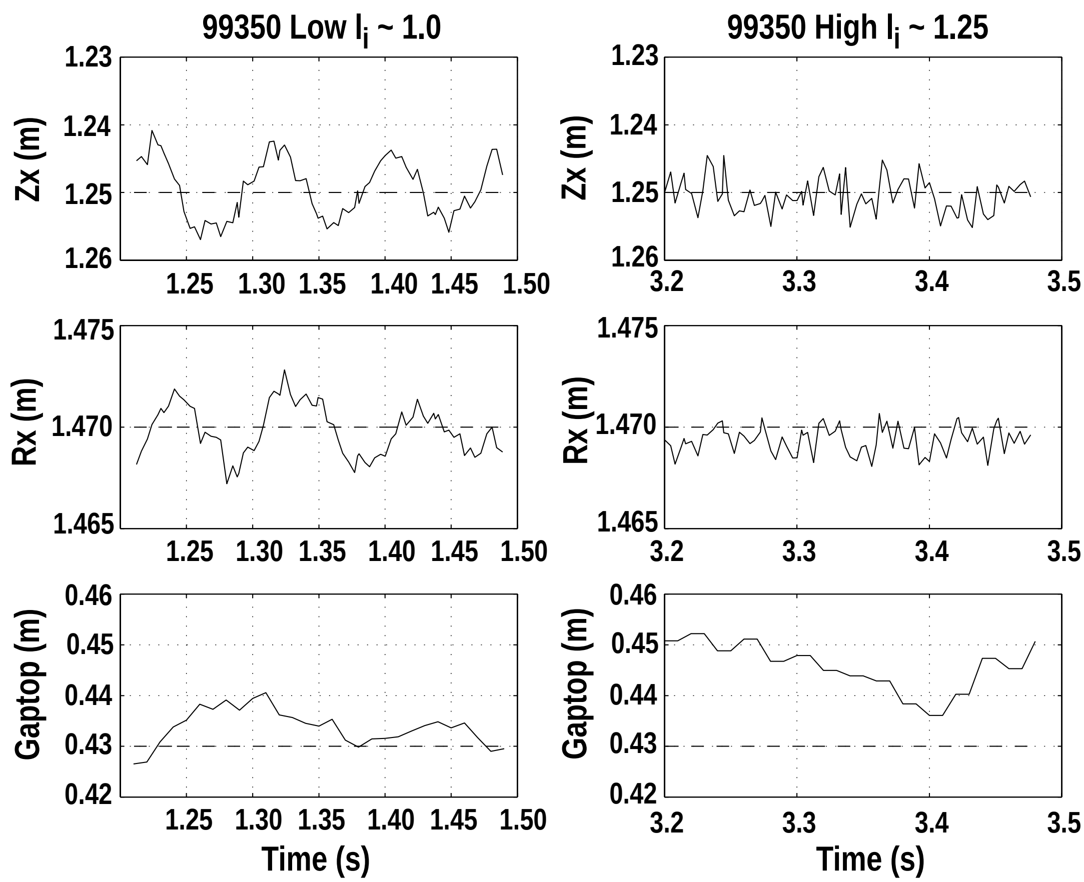

Fig. 7. Accuracy of X–point position control improves and accuracy of top gap control degrades with increasing internal inductance (discharge 99350). Solid lines indicate achieved values, while dashed lines denote target values.

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 $3.2 < t < 3.5$ sec 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. 6 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.

8. Summary

In this report, we have summarized the results of the first experimental implementation of MIMO controllers on DIII–D in completion of DOE Milestone 127. 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 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 is still work to do on obtaining desired accuracy in some models, especially that of the closed-loop vertical control. The dependence of the control accuracy on the value of li was somewhat stronger than expected, and not entirely understood. 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.

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