GA-A25527

ADVANCES IN INTEGRATED PLASMA CONTROL ON DIII-D

by
M.L. WALKER, J.R. FERRON, S.H. HAHN, D.A. HUMPHREYS,
Y. IN, R.D. JOHNSON, J.S. KIM, R.J. LA HAYE, J.A. LEUER,
B.G. PENAFLOR, A.S. WELANDER, AND B. XIAO

JULY 2006

GENERAL ATOMICS

DISCLAIMER

GA-A25527

ADVANCES IN INTEGRATED PLASMA CONTROL ON DIII-D

by

M.L. WALKER, J.R. FERRON, S.H. HAHN,* D.A. HUMPHREYS, Y. IN,† R.D. JOHNSON, J.S. KIM,† R.J. LA HAYE, J.A. LEUER, B.G. PENAFLOR, A.S. WELANDER, AND B. XIAO‡

This is a preprint of a summary paper to be presented at the 24th Symposium on Fusion Technology, September 11–15, 2006, Warsaw, Poland, and to be published in *Fusion Engineering and Design.*

*National Fusion Research Center, Dae Jeon, Korea.
†FAR-TECH, Inc., San Diego, California.
‡Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, P.R. China.

Work supported by the U.S. Department of Energy under DE-FC02-04ER54698 and DE-FG03-99ER82791

**GENERAL ATOMICS PROJECT 30200
JULY 2006**

ABSTRACT

The DIII-D advanced tokamak physics program requires extremely high performance from the DIII-D plasma control system, including simultaneous accurate regulation of plasma shape, stored energy, density, and divertor characteristics, as well as coordinated suppression of magnetohydrodynamic instabilities. To satisfy these demanding control requirements, we apply the integrated plasma control method, consisting of construction of physics-based plasma and system response models, validation of models against operating experiments, design of integrated controllers that operate in concert with one another, simulation of control action against off-line and actual machine control platforms, and optimization through iteration of the design-test loop. The present work describes progress in development of physics models and development and experimental application of new model-based plasma controllers on DIII-D. We also describe the development of the control software, hardware, and model-based control algorithms for the superconducting EAST and KSTAR tokamaks.

1. INTRODUCTION

Modern control techniques are increasingly being applied to development of plasma controllers for tokamaks. That is, controllers are developed off-line using modern control design tools and testing based on models of system behavior. We use the term integrated plasma control to refer to a control development approach that integrates and partially automates the multiple steps of model-based controller design and implementation. A benefit of this approach is that it enables extrapolation of control models and methods with confidence to future devices by emphasizing models derived from first-principles physics knowledge. It also provides a method for testing both effectiveness and on-line implementation of new controllers, important for present experiments, in which experimental time is limited and expensive, and critical for next generation experimental devices, in which experiments are not yet available.

A suite of tools, developed at DIII-D over the past decade to support integrated control design, includes software for electromagnetic and magnetohydrodynamic (MHD) modeling, model validation, model-based controller design and analysis, and offline simulations with detailed plasma and system models including nonlinear effects. The tools execute in the Matlab® and Simulink® environments, which are international standards for control development. Development of tokamak and plasma models for shape control is performed using a generic “toolbox” for tokamak modeling, which develops a circuit model for all toroidal conductors [including vessel, passive stabilizers, and plasma facing (PF) coils] in parallel with a linearized response model for the plasma. The plasma response model originates with a plasma equilibrium and uses linearized rigid displacements of the plasma current distribution [1]. The circuit model and linearized plasma response are combined to form a modified plasma-in-tokamak circuit model. The constructed models are used for design and off-line testing of controllers. They are also integrated into testing of the real time implementation of these and other algorithms in the plasma control system (PCS) through the use of a “simulation server” (simserver) detailed device and plasma simulation to confirm implementation and operation under realistic hardware/software conditions [2]. The simserver connects directly to the PCS and provides simulated tokamak and plasma data in response to PCS control commands. The PCS itself provides a powerful environment for implementation and programming of control algorithms, as well as an architecture that can support realtime use of many cpus communicating on a fast network (up to 24 in the present DIII-D configuration) [3]. As a result, the DIII-D PCS has been adapted for use by NSTX, MAST, KSTAR, EAST, and Pegasus. The integrated control tools have been used to generate models and simserver simulations for all of the above devices except MAST. Similar capabilities are in various stages of development and use for modeling and control of resistive wall modes (RWM), neoclassical tearing modes (NTM), and plasma disruptions.

2. MODEL-BASED DESIGN FOR RWM STABILIZATION

Plasma response models that are both relatively simple and adequately represent the growth of the RWM are required for linear control analysis and design. They must be sufficiently predictive to allow analysis of next-generation devices in the absence of experimental data and must be simple enough to facilitate the model-based design process using modern control design software. Plasma response models used in RWM analyses are typically low order, representing a small number (often one) of helical plasma modes. We use the plasma dynamic model described in [4], which employs a parameter (Cpp) to scale the instability of a mode originally derived by a linear stability code from equilibrium data. This representation has the substantial advantages for control design that the mode representation using this parameter maps directly to a linear model and the eigenmode shape can be held invariant to scaling of Cpp. The latter property is advantageous for evaluating robustness of control. For an m/n=3/1 helical RWM, two separate surface current distributions are included to represent the $\sin\phi$ and $\cos\phi$ components required to describe arbitrary toroidal phase ϕ. The intrinsically multivariable plant therefore has two degenerate eigenvalues corresponding to the two unstable modes.

Several approaches have been used to model conducting structures. Large numbers of discrete elements are sometimes used to accurately model high spatial frequencies that can be supported by a conducting wall. Comparisons with experimental data in [4] showed that a smaller number of “picture frame” shaped conducting wall elements can provide a reasonable predictive capability. Eigenmode representations of the conducting structure can accurately describe the mapping from wall to plasma with a relatively small number of modes because of the general conformality of the conducting surface to the plasma surface. However, a sufficiently large number of eigenmodes must be included to represent the coupling of control coils to walls [5]. The number required to describe this coupling is less than typical discrete element representations, since the wall model need only account for the effect on the plasma of modes excited by the control coil. A convergence study is required to establish sufficiency of a given choice of eigenmode number. Models of DIII-D require more than 15 eigenmodes to converge in the dynamic description of all relevant sensor-conductor-plasma couplings and their frequency responses.

Substantial advances have been made using model-based methods incorporated into RWM stabilization controls. Experiments have shown that a model-based Kalman filter can simultaneously reject edge localized mode (ELM) disturbances and detect RWM growth [5]. Work has begun on development of model-based controllers for experimental use, derived from the same models used in these filters.

3. MODEL-BASED CONTROLLERS FOR NEOCLASSICAL TEARING MODE STABILIZATION

A neoclassical tearing mode (NTM) can be avoided or suppressed by applying continuous or modulated electron cyclotron current drive (ECCD) that is well aligned with the island. Previously, NTMs in DIII-D were successfully suppressed using continuous ECCD and two coupled control algorithms for achieving the necessary alignment of the NTM island and the ECCD deposition region [6]. Validated models of island response to ECCD were used to design the nonlinear controllers, which vary plasma position or toroidal field to achieve alignment.

More recently, upgrades to DIII-D PCS hardware and software have been made in preparation for experiments to evaluate the effectiveness of ECCD modulation on NTM suppression. Data from a toroidal array of Mirnov probes is used to detect the phases of NTMs with different toroidal mode numbers n. The command signal to the gyrotrons is generated by a separate waveform-generator-CPU which outputs a pulse train with frequency and phase controlled by commands from the PCS. This process is illustrated using simulated data in Fig. 1. A signal model of the form $s_k(t) = A_1 \exp\left[i\left(\phi_1(t) + \alpha_k\right)\right] + A_2 \exp\left[i\left(\phi_2(t) + 2\alpha_k\right)\right]$ is assumed for each probe, where α_k is toroidal angle of the probe and ϕ_1, ϕ_2 are the phases of the $n = 1$ and $n = 2$ modes. Combining signals leads to a matrix equation $Pa = s$, where $a = [A_{1c}(t) \quad A_{1s}(t) \quad A_{2c}(t) \quad A_{2s}(t)]^T$ is the set of cosine and sine coefficients and $s = [s_1 \quad s_2 \quad \cdots \quad s_9]^T$. A least squares fit to the signal model at each time t is found by solving for a using the pseudoinverse of P. Commands are sent to gyrotrons to coincide with the island O-point, corresponding to the downward zero crossing of the 2/1 NTM signal. For purposes of this illustration, the ECCD deposition point is assumed to be at the toroidal and poloidal angles $\phi = 0$ and $\theta = 0$. In actual operation, the deposition angles will be determined by the TORAY-GA [7] code and used to shift the phase of the computed signals $A_{1c}(t)$ and $A_{2c}(t)$.

Figure 2 shows an integrated Simulink simulation that incorporates a model of NTM response to modulated ECCD. The top set of blocks (in blue) integrates the NTM model with the equilibrium (shape) evolution model. A rigid shift of the plasma current distribution and an unchanged pressure profile (thus approximately rigid q-surface shift) are assumed when a linearized plasma model [1] is used. When the linearized model is replaced by a nonlinear code such as DINA [8], the current profile (and thus the q-surfaces) and pressure profile are evolved self-consistently. The deposition location is constant in time and obtained using a TORAY calculation. In the model that evolves each m/n mode (lower right), the phase is evolved using a pre-programmed variation of the rotation frequency as input, then the growth rate of the m/n NTM is computed using a version of the modified Rutherford equation [9] which has been further modified to include dependence on the difference in helical coordinates between the ECCD deposition location and island O-point. In the triggering logic, the (poorly understood) initial NTM growth is represented by applying an artificial positive growth rate of 2 cm/50 μs for 50 μs, after which the island size is sufficiently large that the modified Rutherford equation model of mode growth can be applied. The effect of plasma rotation on NTM signals observed by magnetic sensors [e.g. Mirnov probes, lower left, and motional Stark effect (MSE) diagnostic] is also modeled, with a frequency that can vary in time. The simulation can model current deposition at several locations simultaneously.

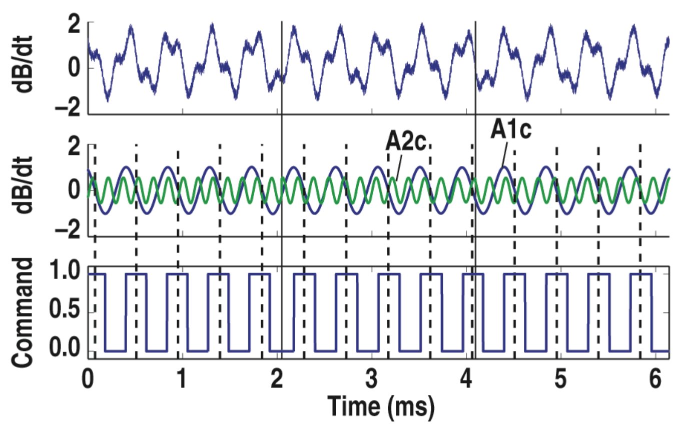

Fig. 1. Simulation of synchronization of gyrotron commands with 2/1 NTM: (a) derivative of magnetic probe signal, (b) extracted 2/1 and 3/2 NTM signals, (c) commands to gyrotrons to suppress 2/1 mode.

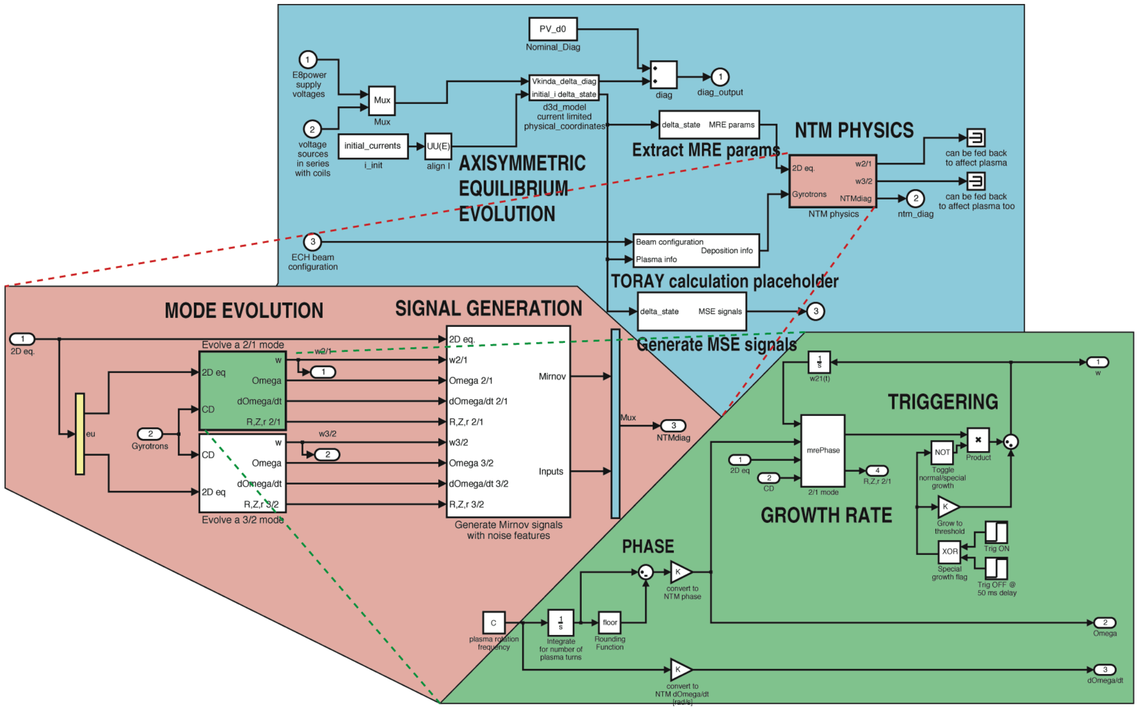

Fig. 2. Structure of Simulink® NTM simulation.

4. MODEL-BASED SHAPE CONTROL AT DIII-D

Plasma boundary control performance in tokamaks is limited by capabilities of installed PF shaping coils and their power systems, which are constrained by superconductor operating limits and for reasons of cost. Achievable boundary shapes face limits defined by the algebraic number of PF coils, their spatial distribution, and by allowable ranges of coil currents and voltages. The ability to dynamically regulate these shapes is further constrained by noise and disturbance in the feedback loop and by voltage limitations. Tokamak operations seek to extract the maximum performance within these limitations, which often leads to operation near or at current and voltage limits. The requirement to optimize boundary control in the presence of limits is complicated in DIII-D by the need to produce good performance for a wide range of shapes, as well as by a uniquely constrained poloidal field (PF) coil circuit, which completely couples the responses of 14 of the 18 PF coils.

Model-based control of chopper voltage and accurate models of PF current response to chopper voltages (including modifications of that response due to the plasma) have enabled implementation of feedforward trajectories on DIII-D. Prior to these developments, it was impossible to implement feedforward control at DIII-D because of the nonlinearity of the power supplies and the completely coupled PF coils. Since feedback control at DIII-D is based on voltage, a voltage feedforward trajectory is required. An on-line calculation of optimal coil currents needed to minimize plasma boundary errors, constrained by the current limits of the device, was developed to compute feedforward trajectories. This provided an opportunity to deal simultaneously with proximity to current limits and adapting trajectories to account for actual rather than off-line predicted current profiles. The first issue is immediately relevant to DIII-D operation and both issues are important to operation of long pulse devices. The use of feedforward trajectories also allows reduced feedback controller gains. The method and experimental validation of this approach are described in [10].

A series of experiments during the 2005 DIII-D campaign included those described in Ref. [10] as well as a final experiment (shot 123357) in which a fully integrated controller, including the on-line trajectory calculation, was demonstrated. Figure 3 shows traces of several isoflux error signals [11] and the X-point R and Z position during this demonstration. At time = 1.8 s, control of the discharge was handed off from the PID-based isoflux controller [11] normally used in DIII-D operations to the MIMO controller.

Control was returned to the PID controller at t = 5 s. This equilibrium was considered well-controlled by the PID controller. As can be seen from the figure, steady-state control during the MIMO phase improved for some of the isoflux errors and degraded for others. X-point control is generally slightly better, with the exception of a period near the end of the MIMO phase due to an error in implementation, in which an inner control loop, regulating centroid Z position, opposed the control by the outer shape control loop. As expected, accurate shape control is much easier to achieve with a good nominal feedforward trajectory.

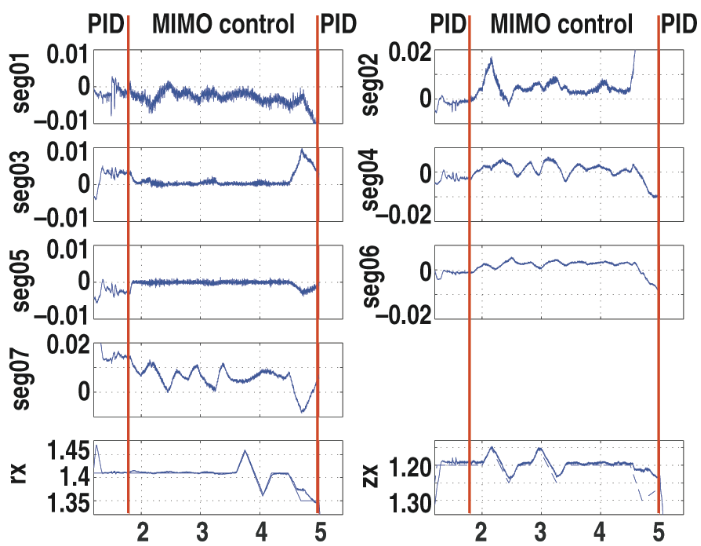

Fig. 3. Experimental shape control results in shot 123357. Segment 1 through 7 plots represent error signals at target isoflux control points.

5. MODEL-BASED CONTROL FOR NEW DEVICE COMMISSIONING AND CONTROL

Based on experience with existing devices such as DIII-D and NSTX, the integrated control approach has been applied to development of control systems for the EAST, KSTAR, and Pegasus tokamaks. Each of these devices has chosen an adaptation of the DIII-D plasma control system as the basis for its plasma control system software. Each has also adopted some (or, in the case of EAST, all) of the hardware architecture of the DIII-D PCS.

Extrapolation to new devices from models used on existing devices is made possible through the use of first-principles physics models (without "tuning"), validation of these models on existing devices, and standardization of implementation, so that the *same* code that is used to build the validated models is also used to build the models for devices under construction. The ability to develop an entire control system ready for the first day of tokamak operations is enabled by the "hardware-in-the-loop" simulation capability provided by the simserver [2].

For each new device, the development of the PCS based control software (and hardware, in the case of EAST) proceeds in parallel with construction of tokamak-and-plasma response models and simserver simulations. PCS development is facilitated by the functional partitioning of the PCS source code. The *infrastructure* code is device-independent and requires no modification for a particular device. The *common* code represents prototypes for codes commonly used at multiple PCS installations, which can often be used without modification. The *installation* code (e.g. control algorithms, reflecting coil geometry and circuit connections, and plasma control parameter definitions) must be developed unique to each device. A version of the PCS software (and hardware) is first established with no control algorithms. Then, basic control algorithms are implemented, beginning with feedforward control, PID feedback control, and simple parameter estimators. Parameters include centroid R and Z and plasma current for circular limited plasmas, and extend to a small number of gaps and X-points for elongated and diverted plasmas. Plasma response models are used to design the estimators and control gains for these simple controllers. Finally, simservers are generated from these plasma models and used to test (and debug) PCS implementations of control algorithms in closed loop simulation.

6. SUMMARY

Efforts at DIII-D over the past decade have resulted in a suite of tokamak physics models and model-based control development tools in an integrated control development environment. These integrated plasma control tools developed for DIII-D have enabled solutions for a wide variety of problems encountered in high performance AT operation. Kalman filters constructed from dynamic RWM models have been shown experimentally to simultaneously reject ELM disturbances and detect RWM growth, and are now being applied to development of multivariable controllers for experimental use. Models of NTM growth were used to develop controllers that successfully stabilized the NTM in DIII-D experiments and refinements of these models that include modulated ECCD are now being used to design controllers that will attempt to synchronize ECCD modulation with the NTM O-point in a rotating plasma. An on-line method for feedforward trajectory calculation for plasma boundary control has been experimentally demonstrated; this method is a candidate solution for generating feedforward trajectories in long pulse devices.

Model-based design techniques and the ability to extrapolate validated control models constructed from first principle physics have been crucial to the development of control software and algorithms for the KSTAR and EAST devices whose construction is not yet complete. Detailed simulations using these validated models have allowed testing and confirmation of control algorithm implementation in real time control software prior to experimental implementation and minimized the need for experimental tuning.

REFERENCES

[1] M.L.Walker and D.A.Humphreys, “Valid Coordinate Systems for Linearized Plasma Shape Response Models in Tokamaks,” to be published in Fusion Science and Techology (2006).

[2] J.A. Leuer, et al., Proc. 20th IEEE/NPSS Symp. on Fusion Engineering, San Diego, California, 2003 (Institute of Electrical and Electronics Engineers, Inc., Piscataway, New Jersey) p. 397.

[3] B.G. Penaflor, et al., Fusion Eng. and Design **71**, 47 (2004).

[4] C.M. Fransson, et al., Phys. Plasmas **10**, 3961 (2003).

[5] Y. In, et al., Phys. Plasmas **13**, 062512 (2006).

[6] R.J. La Haye, et al., Phys. Plasmas **9**, 2051 (2002).

[7] K. Matsuda, IEEE Trans. Pl. Sci. **17**, 6 (1989).

[8] R.R. Khayrutdinov, et al., J. Comput. Phys. **109**, 193 (1993).

[9] F.W. Perkins, et al., Proc. of 24th European Conf. on Controlled Fusion and Plasma Physics, Berchtesgaden, 1997 (European Physical Society, Petit Lancy, 1997).

[10] M.L. Walker, et al., Proc. 44th IEEE Conf. on Decision and Control and European Control Conf., Seville, Spain, 2005, pp. 8233-8239.

[11] J.R. Ferron, et al., Nucl. Fusion **38**, 1055 (1998).

ACKNOWLEDGMENT

This work was supported in part by the U.S. Department of Energy under DE-FC02-04ER54698 and DE-FG03-99ER53297.