Control of Plasma Poloidal Shape and Position in the DIII-D Tokamak[*]

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A goal of tokamak fusion research is to develop the scientific basis and enabling technology to allow the eventual design and construction of a fusion power plant. Historically, tokamak control design has been a mixture of theory driving an initial control design combined with empirical tuning of controllers to achieve satisfactory performance. This approach was in line with the focus of past experiments on simply obtaining sufficient control to study many of the basic physics issues of plasma behavior. However, in recent years the needs of existing experiments have been demanding increasingly accurate control. New tokamaks such as ITER or the eventual fusion power plant must achieve and confine burning fusion plasmas, placing unprecedented demands on regulation of plasma shape and position, heat flux, and burn characteristics. Control designs for these reactor-regime tokamaks must also function well at startup with minimal empirical optimization required. All of these design requirements imply a heavy reliance on plasma modeling and simulation. Thus, plasma control design has begun to use increasingly modern and sophisticated control design methods. This paper describes some of the history of plasma control at DIII-D as well as recent efforts to implement more modern controllers. This effort improves the control so that we may obtain better physics experiments and simultaneously develops the technology necessary for designing controllers for next-generation tokamaks. It has the added benefit that it teaches us many things about how to design tokamaks for better controllability.

DIII-D is a D-shaped tokamak with a major radius of 1.7 m and a characteristic time constant of several milliseconds for field penetration through the vacuum vessel. The time constant of the dominant instability is typically comparable to this field penetration time. Figure 1 shows a cross-section of DIII-D with lines of constant flux shown to illustrate the plasma. The primary purpose of the E-coil solenoid is to induce current in the plasma through transformer action. This both heats the plasma through resistive losses and provides a distributed current which can be shaped by external currents. The 18 poloidal field coils (F-coils) are used to control the shape and position of the plasma. Power supplies called choppers act as voltage sources in series with certain of the F-coils to provide the necessary shaping currents. Characteristics of the problem which make it challenging are the highly nonlinear nature of the plasma response and of the shaping power supplies, the high degree of coupling between the response of the plasma to various F-coils, and the fact that the plasma vertical motion is highly unstable. An additional problem is that it's difficult to determine the plasma shape (however the quantities to be controlled are defined) in real-time. Measurements which are used to estimate the shape and position are magnetic field at 29 magnetic probes on the inner side of the vacuum vessel (2 probes shown), fluxes at 41 flux loops on the outer side of the vessel and on the F-coils (1 shown), and currents in 6 E- and 18 F-coils.

The problem to be solved is the control of the shape and position of a plasma in the DIII-D tokamak. The traditional approach to solving this control problem has been to decouple controls as much as possible. In the past this has often meant that the effect on a particular plasma parameter from coils other than the coil actually being used to control that parameter were ignored. More modern efforts at shape control seek to take

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these effects into account in the control design (multivariable control). Some controls may still be decoupled, however, to minimize the size and complexity of resulting

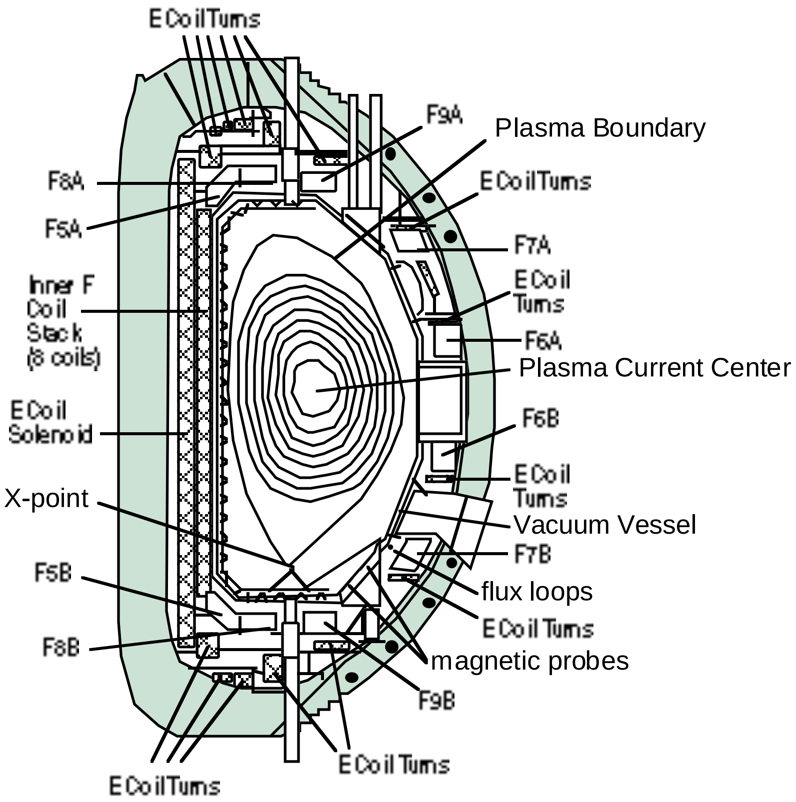

Figure 1. Cross-section of DIII-D Tokamak (torus).

controllers. For example, the response time needed for vertical position control is much faster than that needed for shaping or heating control, and is therefore handled by a separate controller. Heating control also closes the loop separately because the E-coil produces approximately constant flux across the interior of the vessel and therefore has little effect on the shape which is determined by *relative* values of flux within the interior. This decoupling of control is in contrast with proposed controllers for tokamaks such as ITER where shaping, heating, and vertical position control are integrated because of a much smaller coil set and more commensurate time scales.

Extensive work has been done at DIII-D to support the move toward more modern control. A modern digital control system has been implemented and is routinely used in plasma operations [1]. All coil/vessel systems and power systems have been modeled and validated with experimental test data [2]. Linear, nonrigid, flux-conserving models of plasma dynamics are now being generated on a routine basis using the LLNL Corsica code [3]. The dominant modes of these models (corresponding to radial and vertical motion) have been validated against DIII-D experimental data. Systematic calibration procedures are being implemented to ensure the integrity of diagnostic and command circuits used in control [4]. Algorithms for extremely accurate realtime plasma parameter estimation have been implemented and used in experimental operations [5]. External actuators (shape control power supplies) have been brought under control [6] in preparation for use with multivariable controllers.

This paper will summarize previous work in the above areas with some historical background for each. The evolution of the control platform is traced from a few differential amplifiers and variable resistors through to the present completely digital system. A short description of this digital system is provided. The development of the original analog vertical position controller is described and a short description of the process of converting this system to a purely digital controller is provided. The bulk of the paper concerns issues of plasma shaping control, which consists of two equally challenging problems (Fig. 2) - the problem of identifying what the plasma actually looks like in real time, i.e. measuring the parameters to be controlled, and the task of determining the feedback algorithm which best controls these plasma parameters.

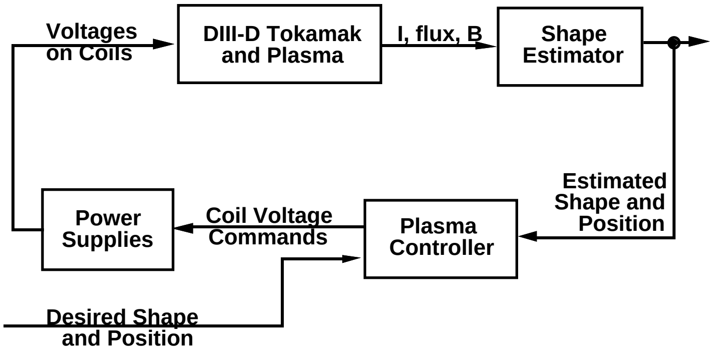

Figure 2. Block diagram of DIII-D control loop.

The evolution of methods used at DIII-D for the real-time estimation of plasma shape/position is discussed as well as the recent development, implementation, and operation of a real-time plasma equilibrium reconstruction capability based on a current profile and flux distribution consistent with the Grad-Shafranov tokamak equilibrium relation [7]. Methods for plasma control have evolved in parallel with improvements in the estimation of plasma shape and position. These are also discussed. The most recent change of control methodology has been the switch from so-called "gap control" [8] which controls plasma to vessel wall gaps to "iso-flux" control [9] which controls magnetic flux at specific locations within the tokamak vessel to enforce a desired plasma shape. Current work which seeks to exploit the new realtime equilibrium reconstruction capability and the "iso-flux" control approach is the development of true multivariable controllers which can account for the many dependencies of controlled flux and driving flux at shaping coils on currents in those shaping coils. These controllers have already been designed and are being coded into the digital plasma control system. The process of developing these controllers will be described. This includes the already completed model development and validation process for the tokamak power systems and conductors and the ongoing research into determining realistic response models for plasmas, some of which are mature enough to use in control algorithm design. A description of the control design process will also be given, including use of performance specifications and model uncertainties in the design process. A summary of performance evaluations using linear simulations will be given. If we are allowed experimental time to test our controllers on DIII-D, we will report on those results as well.

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