

Control System Development Plan for the National Spherical Torus Experiment*

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Abstract

The National Spherical Torus Experiment (NSTX) has as one of its primary goals the demonstration of the attractiveness of the spherical torus concept as a fusion power plant. Central to this goal is the achievement of high plasma β ($= 2\mu_0 \langle p \rangle / B^2$ a measure of the efficiency of a magnetic plasma confinement system). It has been demonstrated both theoretically and experimentally that the maximum achievable β is a strong function of both local and global plasma parameters. It is therefore important to optimize control of the plasma. To this end a phased development plan for digital plasma control on NSTX is presented. The relative level of sophistication of the control system software and hardware will be increased according to the demands of the experimental program in a three phase plan. During Day 0 (first plasma), a simple coil current control algorithm will initiate plasma operations. During the second phase (Day 1) of plasma operations the control system will continue to use the preprogrammed algorithm to initiate plasma breakdown but will then change over to a rudimentary plasma control scheme based on linear combinations of measured plasma fields and fluxes. The third phase of NSTX plasma control system development will utilize the rEFIT code, first used on DIII-D, to determine, in real-time, the full plasma equilibrium by inverting the Grad-Shafranov equation. The details of the development plan, including a description of the proposed hardware will be presented.

set of corrections based on the resultant errors. In general the plasma will then respond, generating new measurements, restarting the iterative control process. In a modern computer based control system, both the boxes and the arrows in this diagram represent combinations of hardware and software. This document does not specify in detail plasma sensors, actuator control, or actuator design.

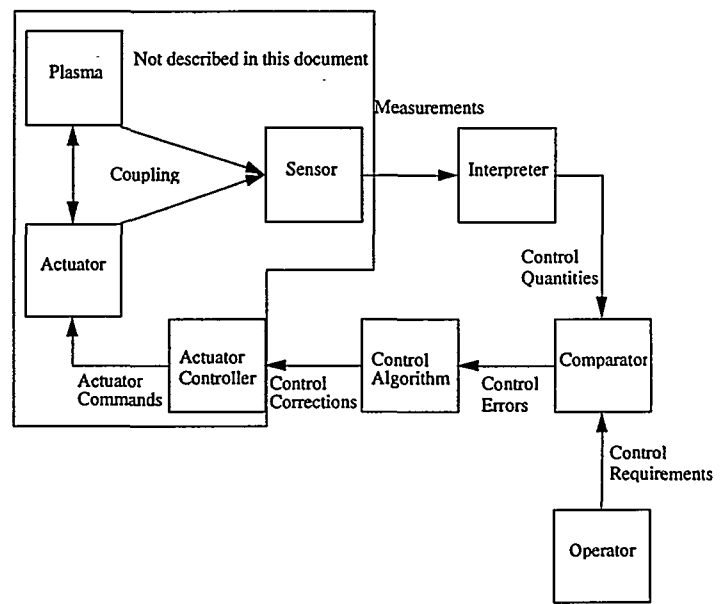


Figure 1 General control system diagram

I. INTRODUCTION

The ideal plasma control system is one that determines exactly the entire equilibrium of the plasma continuously in real time, compares the actual plasma parameters to the desired ones, and then takes the optimal corrective actions to minimize the difference between the two sets of information. The NSTX plasma control system development plan must balance this ideal against technological and fiscal realities imposed and find the optimal route to the best achievable approximation.

Plasma control systems can be generally described by the flow chart in Figure 1. The operator of the experiment has input to the system by entering the control requirements into the system and by choosing the controller algorithms. The comparator takes the difference between the control requirements and the control quantities, which are interpreted from the direct measurements. The controller then generates a

In particular, the actuators in a plasma shape controller are the poloidal magnetic field coils. The sensors to be used are poloidal field coil current detectors and magnetic field and flux sensors. The data interpreter, the comparator, the operator interface, and the control algorithm are the pervue of this document. Additionally, the communication of information between these components is described.

II. SOFTWARE DEVELOPMENT

The initial stage (Day 0) of the plasma control system will use a control algorithm that is referred to as voltage control. In this mode of operation the operator will specify current waveforms for each independent coil set on NSTX. These currents will then be used as reference values for a simple control system which controls the voltage in the power supplies. This means that data from the plasma will not be

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incorporated. The plasma current will be initiated using preprogrammed loop voltage waveforms.

Because this method does not provide adequate plasma position control, shortly after Day 0, a rudimentary plasma position control algorithm will be implemented. This stage is referred to as the second (or Day 1) stage of plasma control system development. The method of plasma control is referred to as flux difference control. The plasma position measurement system will consist of 3 flux loops and 3 poloidal field measurements. One of the flux measurements and one of the field measurements is located on the inboard midplane of the machine and will be used to control the difference in the projected flux on the inboard midplane with the average in the projected flux from the other pairs of measurements. The other flux and field loops will be located above and below the outer midplane device, measuring the vertical differential in flux as a rough measure of the plasma vertical position. The shape of the plasma will be approximately determined ahead of time by fixing the ratio of the currents in the PF coils, and then keeping the overall amplitude proportional to I_p , with the actual shape then depending on β_p and ζ . The radial position will be controlled by adding a vertical field component that is proportional to the flux difference error. The vertical control will vary the up-down asymmetric component of the coil current proportional to the error in vertical position, also from flux differencing. The plasma current will be controlled using a direct measurement of the plasma+vessel current, which is available from the Rogowski coils. An estimate of the vacuum vessel current will be available from vessel surface loop voltage measurements. The breakdown phase of the discharge will continue to be controlled using voltage control.

The final stage (Day 2) of the control system will consist of a real time plasma reconstruction algorithm, rEFIT (real-time EFIT), which is currently in use at General Atomics on DIII-D¹. This routine will calculate the flux at a series of control points using the Grad-Shafranov equation to invert the measured fluxes and fields. The errors in the control fluxes will then be used to determine the feedback changes in a PID like algorithm that uses the full Green's function matrix to determine the best guess for the next time step. Plasma current control will not change for Day 2.

The motivation behind developing these three algorithms (voltage control, flux difference control, and full boundary flux control) in sequence is to have the functionality of the control system develop in parallel with the requirements of the experiment. All three algorithms will be used in the final system. The breakdown phase of the discharge will use voltage control, the early current ramp phase will use flux difference control, the flat-top phase of the discharge will use full boundary control, and during ramp-down phase the control system will revert to flux difference control.

An existing user-interface/data server software system will be employed for the Day 1 control system. This interface also meets the requirements of the specifications for the third stage of control system development. The interface is one that is currently in use at General Atomics, on the DIII-D tokamak. The DIII-D control system interface has been developed over a number of years, and is extremely flexible. The system divides control up into categories (i.e. gas, shape, neutral beam heating, etc.). Each category is assigned a list of reference

waveforms. Each waveform is broken up into a list of phases. Phases are triggered by events, either scheduled or unscheduled. The list of waveforms depends on the algorithm(s) in use. The potential exists for each category to have multiple algorithms for each shot, and hence several lists of waveforms. Each category can also use multiple CPUs.

The interface allows both cursor and keyboard manipulation of the waveform values. The interface architecture is based on TCP/IP sockets made between IDL (Interactive Data Language) GUI interface processes (an arbitrary number of them that run independently) and a server code that runs on a host processor (not necessarily the real-time computer). The server code is called the waveserver, which communicates via sockets to processes running on the real-time host computer. At the start-of-shot event changes to the waveforms are locked out by a lockserver and the control parameters are loaded into the real-time processors by the real time host computer. This system has the advantage that remote collaborators could operate the machine from their home labs without any exotic connections or software. The only requirements are IDL and TCP/IP. The waveserver code is broken up into two parts that are referred to as infrastructure code and installation code. Roughly, these correspond to workstation software and real time software. The installation code runs on the real time host and communicates to the real time processors via local processes.

III. HARDWARE DEVELOPMENT

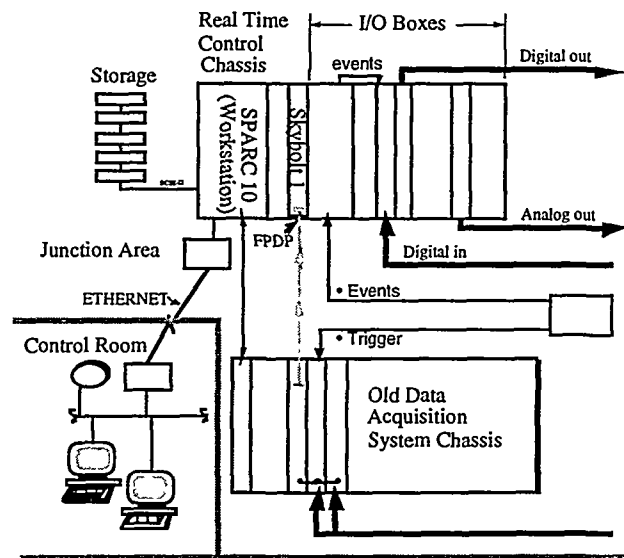


Figure 2 Hardware layout of the initial plasma control computer configuration.

The hardware for the Skybolt I Day 0 plasma control system is shown in Figure 2. The user communicates to the system using an interface that runs on a SPARC station (the host computer) that is located in one of the VME crates that houses the control system. The host is responsible for monitoring the "slow" synchronization inputs and outputs. It also handles the data storage and plotting functions. The host is also used to load the control software over the VME bus to the Skybolt I real-time computer (4x i860 processors).

The Skybolt I computer receives data from the Data Acquisition System via the FPDP. The system can send both analog and digital output signals via first the VME bus and then through the appropriate output module. Human input to the system is from X-terminals via Ethernet.

The control computer communicates to the field coil power supplies via a custom designed link referred to as the PC-link. A VME module was custom built to transmit this information over a dedicated serial fiber link. The control commands for the power supplies are also calculated on the control computer².

The Day 1 hardware upgrade will add plasma position and current measurements to the present system via analog fiber links from the machine to the remaining digitizer channels. This will allow for rudimentary feedback control of the plasma to be achieved at reasonable cost without the addition of substantial new hardware.

The Day 2 upgrade to the computer system will consist of the addition of 2 more VME crates for flux and field measurements, several additional digitizers and a new real-time computer, including a new real-time host processor. This is a substantial upgrade to the system that will provide the technical footing required for moving to real-time equilibrium reconstructions as the basis for plasma control. Real-time equilibrium reconstructions, particularly those utilizing internal plasma profile measurements, are an important prerequisite for advance plasma control scenarios.

A new fiber optic coupling device (Merlin Electronics, 9532 FPDP/SRAM Fiber module) based on the Fiber Channel Standard will connect the FPDP interfaces on the separate VME crates and combine the signals for DMA input into the Skyburst 160 input on the new Skybolt II real-time processor.

III. RESULTS TO DATE AND SUMMARY

A control system development plan for the National Spherical Torus experiment has been presented and implementation is well under way. First plasma was achieved in NSTX in February of 1999. The maximum plasma current obtained was 300kA. The Day 0 control system performed as per expectations.

The Day 1 system is currently being implemented, and should begin operations in August of 1999. The Day 1 system will be used for a period of approximately one year. It will permit rudimentary control of the plasma position and current.

At that point the installation of the final system should be complete. Requisitioning activities for the Day 2 system have already begun. Successful installation of the final system, along with the inclusion of plasma profile diagnostics, will make possible a series of experiments exploring advanced plasma control concepts.

IV. ACKNOWLEDGEMENTS

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