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Initial operation of NSTX with plasma control*

D. Gates, M. Bell, J. Ferron**, S. Kaye, J. Menard, D. Mueller, C. Neumeyer, S. Sabbagh†

Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA

***General Atomics, San Diego, CA, USA*

† Columbia University, New York, NY, USA

Abstract

First plasma, with a maximum current of 300kA, was achieved on NSTX in February 1999. These results were obtained using preprogrammed coil currents. The first controlled plasmas on NSTX were made starting in August 1999 with the full 1MA plasma current achieved in December 1999. The controlled quantities were plasma position (R, Z) and current (I_p). Variations in the plasma shape are achieved by adding preprogrammed currents to those determined by the control parameters. The control system is fully digital, with plasma position and current control, data acquisition, and power supply control all occurring in the same four-processor real time computer. The system uses the PCS (Plasma Control Software) system designed at General Atomics. Modular control algorithms, specific to NSTX, were written and incorporated into the PCS. The application algorithms do the actual control calculations, with the PCS handling data passing. The control system, including planned upgrades, will be described, along with results of the initial controlled plasma operations. Analysis of the performance of the control system will also be presented.

Power supply control

NSTX began operation in February 1999. This initial three-day run was aimed primarily at demonstrating the operation of the NSTX integrated engineering systems. Plasmas with currents up to 300kA were achieved during this phase of operation using preprogrammed coil currents. Current control was performed using an all digital feedback loop which generated firing angles for the 12 phase thyristor power supplies that power the NSTX coil systems. The software based power supply control was crucial in the rapid commissioning of the power conversion system. This was the first part (Day 0) of a three part [1] (Day 0, Day 1, and Day2) control system development plan, designed to advance control capabilities along with the needs of the experiment.

Plasma Control – Hardware and the PCS

Plasma control was first attempted during the initial research run (Day 1), which began in August 1999. The all-digital plasma control system was commissioned during a 9 day period during September-October of 1999. The Day 1 plasma control system software was written for NSTX in a format compatible with a software package known as the PCS [2] (Plasma Control Software), which was written at General Atomics for use on DIII-D. The PCS is a flexible software architecture that allows for general control algorithms to be specified and implemented relatively simply. The PCS was modified to run on an existing real-time control computer that was originally purchased for PBX-M, and that was used briefly on TFTR. The computer, a Skybolt I (Sky Computer Corp., Chelmesford, MA. USA) consists of five processors. Four of the processors are i860 processors that actually perform the real time calculations for plasma and power supply control. The fifth processor is an i906 the handles communications. The user communicates with this real-time computer through a sixth processor known as the host computer. The host computer for the NSTX control system is a SPARC-10 (also legacy equipment) running SunOS 4.3.1, built into a VME form factor. Real time software is compiled on the host computer using a proprietary parallelizing/vectorizing compiler, also from Sky Computer Corp, and loaded via the VME bus onto the real-time computer. When writing code for the PCS this interface to the real-time computer is transparent to the programmer. The PCS divides control up into categories (e.g. 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.

Plasma Control – Algorithms and sensors

The Day 1 plasma control algorithm was chosen to be the simplest algorithm that would maintain plasma position and current. This rudimentary system was chosen so as to minimize all potential technical difficulties that might prevent the initial run plan from proceeding. The position algorithm, which is based on linearized flux expansion, utilizes only three flux and three field measurements for a total of six input signals. The fluxes and fields are combined to calculate the linearized projected flux at the plasma boundary. The distance from the measurement to the plasma boundary (usually referred to as the gap) is the preprogrammed input. One magnetic field measurement and one of the flux loops is located on the plasma inboard mid-plane. The inboard flux loop is used as a reference flux and is subtracted from the other flux measurements. The outer two flux loops are located on the lower tips of the NSTX primary passive plate, as close to the plasma outboard mid-plane as is physically possible, and the remaining magnetic field coils are located as close as possible to the two outboard flux loops. The up down average of the two projected fluxes is used to control the radial centroid of the plasma, while the difference is used to control the vertical position of the plasma centroid.

The plasma current measurement on NSTX is complicated by the fact that it is not possible to have an internal plasma current Rogowski coil. With the rogowski coil outside the vacuum vessel it was important accurately to measure the vessel current, particularly during plasma current ramp up. The vessel current measurement was achieved by measuring the electric field on the surface of the NSTX vacuum vessel with voltage loops and using this information to infer the vessel current. The resistance of the vacuum vessel was calculated using an axisymmetric eddy current model, which was verified with coil only shots. Once the plasma current is known, feedback is relatively straightforward.

All the control parameters (R,Z,I_p) were controlled using proportional-integral-derivative (PID) algorithms with coefficients that can be programmed to vary during a discharge. The position and current control category consists of three phases: a startup phase wherein coil currents are brought up to their initial values, a control phase with normal I_p and position control, and a ramp down phase where the coil currents are brought back to zero. Also, if the plasma current ever falls below a minimum value set in software, an immediate transition to the ramp down phase is made. This helps avoid excessive heating of the NSTX ohmic heating coil.

Results

In order to parameterize the radial control accuracy, a shot with a naturally occurring internal reconnection event (IRE) was analyzed. These events are quite common on NSTX and are believed to be impurity related. A typical IRE has an I_p drop of ~10% accompanied by a transient change in the internal inductance. Usually the two quantities change with opposing derivatives with flux being roughly conserved initially, but with a final state that has reduced I_p. The usual effect on the plasma boundary is that the outboard major radius of the plasma moves rapidly inward, thus creating the ideal experiment for determining the response of the control system to radial plasma perturbations. Figure 1 shows the output of an EFIT [3] reconstruction of just such an event. One can see the IRE causes a displacement of the radial centroid of the plasma of ~3cm in a period of time which is on the order of the resolution of the reconstructions (1ms). The control system then responds after about a 3ms delay, caused by the latency of the present digital control system plus the finite response time of the power supplies. During this time period the eddy currents induced in the passive conducting structures n NSTX decay slightly allowing the plasma to drift out another ~2cm. The control system then acts to restore the desired major radius of the plasma on a time-scale which is determined roughly by the eddy current decay time of the NSTX vessel and conducting structures.

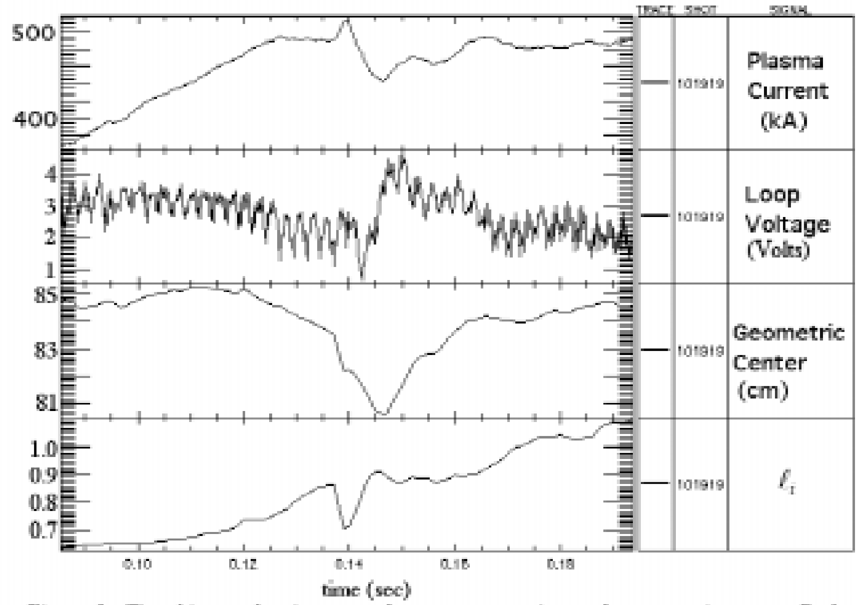

Figure 1 - Time history showing control response to an internal reconnection event. Both plasma current and radial position return to requested values in ~20ms (~vessel L/R time).

One can also see in Figure 1 the response of the I_p control system. The plasma current drops ~60kA on a slightly longer time-scale than for the radial displacement.

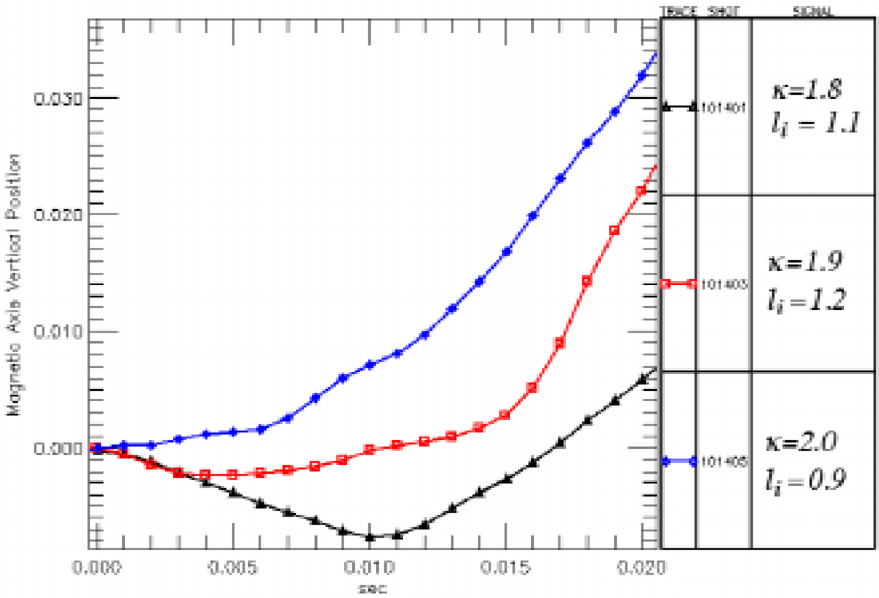

Figure 2 - Vertical position of plasmas with varying elongations and internal inductances for which position control has been turned off (time relative to turn off time)

After an similar ~3ms delay, the loop voltage, which is controlled by the ohmic heating coil first falls (in response to the momentary peak in the plasma current caused by the

IRE) then rises (in response to the loss of plasma current after the IRE). The current restores to the requested value within an error of ~10kA.

Experiments to determine the vertical response were not carried out due to time constraints. However, vertical growth rates were measured by turning of the vertical control loop. Results from a series of discharges wherein the control is turned off are shown on Figure 2. The primary global variables which determine the vertical growth rate of a plasma are the elongation, the plasma internal inductance, and the plasma-wall separation. In the series shown in Figure 2 only the elongation and internal inductance are varied, with the plasma-wall separation being held roughly fixed. The elongation is varied by changing the poloidal field coil current distribution. The internal inductance varies naturally in these discharges, rising roughly linearly as the discharge progresses. The strongly increasing internal inductance is believed to be related to impurities. The variation with elongation and internal inductance is much as expected. Quantitative dynamical analysis of the actual growth rates is ongoing using the Tokamak Simulation Code (TSC). These results will in turn be used to help improve the feedback system.

Plans and Summary

For Day 2, a new control computer/real-time data acquisition computer has been purchased that has roughly 40x the computing power that the current machine possesses. This new device, also from Sky Computers and which consists G4 processors at 333Mhz, should permit many advanced control techniques to be applied. Initially the existing system will be ported to the new computer and demonstrated. The first advanced application will be to implement the rtEFIT [4] (real-time EFIT) reconstruction algorithm originally developed on DIII-D. This algorithm is capable of inverting the Grad-Shafranov equation on a time scale useful to control the experiment. Typical inversion times on the DIII-D computer, which is of the same vintage as the Skybolt I computer currently in use on NSTX, are 25ms. Whereas actual computational times achieved need to be measured before comparisons can be made, it is safe to say that the reconstruction time on the new NSTX computer should be more than adequate. We will then develop a shape control algorithm for use on NSTX based on the reconstructed boundary flux, similar to the isoflux control algorithm in use on DIII-D. The eventual goal of this system is to incorporate MSE measurements into the reconstructions so as to provide accurate current profiles as input to an eventual current profile control system. It is important to develop the tools required to implement advanced control techniques so that the ideal of profile control can become a reality in the near future.

Within the limited goals of the Day 1 system, this phase of development for the plasma control system was a complete success. In particular, the required radial, vertical and plasma current control accuracy were obtained using the initial plasma control system.

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