

Initial Results From the National Spherical Torus Experiment (NSTX)

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Introduction

With a small, high-power density, and compact fusion core, Spherical Tori (ST) can provide an attractive path to a reactor or a volumetric neutron source^{1,2}. The National Spherical Torus Experiment (NSTX) is a proof-of-principle experiment that will explore the physics of low aspect ratio in scientifically interesting and aggressive regimes³. To accomplish this mission, NSTX is designed to produce plasmas with $R/a=0.85$ m/0.68 m~1.25, $I_p=1$ MA, $B_T \leq 0.6$ T, $\kappa \leq 2.2$, $\delta \leq 0.5$, heating powers of up to 11 MW (6 MW High Harmonic Fast Waves, 5 MW, 80 keV, D⁰ Neutral Beam Injection), and operation over a wide range of shapes and configurations. The OH solenoid and PF coils on NSTX are capable of producing approximately 1 V-sec of inductive flux, which, alone, is sufficient for plasma breakdown and for increasing the plasma current to the MA level. Breakdown, however, will be assisted by EC preionization. Co-axial Helicity Injection (CHI)⁴ provides the opportunity for V-sec savings during breakdown as well as for completely non-inductive startup to about 500 kA.

One of the primary mission elements of NSTX is to explore the global confinement and local transport properties of ST plasmas. Assuming confinement slightly greater than L-mode, NSTX plasmas with auxiliary heating may be expected to achieve temperatures of up to several keV, resulting in plasma current flattop durations of up to 0.5 sec by purely inductive means. The flattop duration can be extended greatly with target plasma formed by CHI. The large field line pitch on the outboard side, and small pitch on the inboard side, increases the time the field line spends in the good curvature regime, which has benefits to both the transport and stability properties of the NSTX plasmas. The increase in good curvature, coupled with a large shearing rate due to the low toroidal field, may reduce dramatically the electrostatic and electromagnetic microinstabilities that cause transport⁵. Furthermore, aided by the presence of close fitting conducting plates to suppress external kink modes, and with optimized current and pressure profiles, plasma betas of up to 40% (normalized to the magnetic field at the geometric axis) with 70% bootstrap fractions have been calculated to be stable⁶. Tools to control the current profile include the High Harmonic Fast Waves, CHI, and bootstrap current. Sufficient current drive is available for NSTX to achieve one of its other mission objectives, which is to produce and maintain high beta plasmas non-inductively for pulse lengths of up to 5 sec, long enough to allow the current profile to approach a near steady-state condition. Lastly, the high power densities in NSTX present a challenge for power and particle control. With up to 15 MW/m² possibly expected on the divertor plates, power amelioration techniques, such as divertor sweeping and pumping, may have to be employed.

The NSTX research program will be carried out by a nationally-based team from fourteen different institutions.

Initial Operation

The NSTX device was constructed over the course of approximately two years. Borrowing in- and outside-vessel components from TFTR and smaller experiments at PPPL allowed the device to be assembled in a cost-effective and timely manner, resulting in a first plasma, which took place on Feb. 12, 1999, ten weeks prior to the original first plasma target. In preparation for first plasma, 39 hours of Deuterium Glow Discharge Cleaning (GDC) and 4 hours of Helium GDC were performed. Furthermore, the GDC filament system was used as a source of ionized electrons to aid in the plasma breakdown.

During the initial operation of the device, only a very limited number of diagnostics were installed. This set consisted of 26 flux loops, 2 plasma current Rogowski coils, and a fast framing (1000 fps) TV camera provided by team members at Los Alamos National Laboratory. The number of flux loops was sufficient for field null determination and initial plasma equilibrium reconstruction. Test measurements were in excellent agreement with code predictions of the vacuum response of the NSTX structure. The passive plate structures and most of the plasma facing components were not installed for the initial operation period; this will be done for the start of the next phase of operations starting in August, 1999.

The first three days of NSTX operation were very successful. Breakdown was achieved without the use of any pre-ionization. However, a fill pressure of approximately 5×10^{-5} Torr of D₂ was required for this, which resulted in only a brief flash with I_p limited to about 15 kA. At 3×10^{-5} Torr, no breakdown was achieved. The use of the GDC filament to provide a source of electrons resulted in breakdown at pressures above 7×10^{-6} Torr, and for pressures above 1×10^{-5} Torr breakdown was always achieved. The currents in the outer PF coils (PF3 and PF5) were programmed to provide an adequate null field region for breakdown with an OH precharge current of 18 kA (75% of the highest rated value). Only a half-swing OH (18 to 0 kA) was used for this operation period. The stray field pattern 16 msec after the start of the OH ramp is shown in Fig. 1. Note the large region of low stray field strength, ≤ 4 Gauss, which is the approximate maximum field level that can be tolerated for inductive breakdown near $R=0.8$ m. This breakdown time and location was confirmed by images from the fast TV camera.

Once reliable breakdown was achieved, the ratio of the vertical and shaping field currents in PF5 and PF3 respectively was adjusted shot-by-shot to incrementally increase the plasma current. Within two days of operation, the plasma current increased to approximately 300 kA using less than 1/3 of the total V-sec, giving good confidence in the ability to achieve the 1 MA of plasma current with ohmic heating only. The current and voltage traces for the near 300 kA plasma are shown in Fig. 2. The OH current decreased to 0 kA by 75 msec, at which time the plasma current peaked. The loop voltage, measured by a center column flux loop, was near constant at 3.5 to 4 Volts. The increase in the plasma current to the 300 kA level was accomplished by increased elongation of the plasma. Equilibrium reconstruction of the initial highest current plasmas (Fig. 3) indicated the plasma elongation to be approximately 1.7, consistent with the natural elongation of plasmas at this aspect ratio and computed I_i (~ 0.6). The reconstruction calculations also indicate a vessel current of approximately 150 kA, which is a significant fraction of the current carried by the plasma. It is therefore critical to model properly the vessel current distribution in the equilibrium reconstruction, and this vessel current distribution was verified by an independent calculation. TSC simulations of these plasmas, using the experimental PF coil currents, showed good agreement with the static reconstructions. Furthermore, the TSC simulations indicated no need for either vertical or radial feedback for these initial plasmas. A fast TV image of the plasma near peak current is shown in Fig. 4.

The next research run of NSTX will commence during the Summer of 1999. In preparation for this phase of operation, the remainder of the plasma facing components will be installed, the passive plates will be installed without toroidal or poloidal jumpers in order to minimize toroidally asymmetric stray fields produced by toroidally asymmetric structural eddy currents. Additional flux loops and B-probes will be installed before pumpdown, and other "Day 1" diagnostics that will be installed during this phase will include single channel interferometry visible bremsstrahlung detector, X-ray, ultrasoft X-ray, and bolometer arrays, X-ray pulse height analysis, a neutral particle analyzer, impurity monitors, and multi-pulse Thomson scattering. The objectives of the upcoming research run include producing controlled plasmas at significant plasma currents (≥ 500 kA) for current flat-top durations of ~ 0.5 sec, along with an assessment of the confinement properties at these parameters. Producing plasmas with high currents (up to 1 MA) will be attempted as well. Also during the upcoming run, non-inductive startup techniques will be implemented using CHI, and auxiliary heating during the main plasma phase will be provided by up to 4 MW of High Harmonic Fast Wave Heating.

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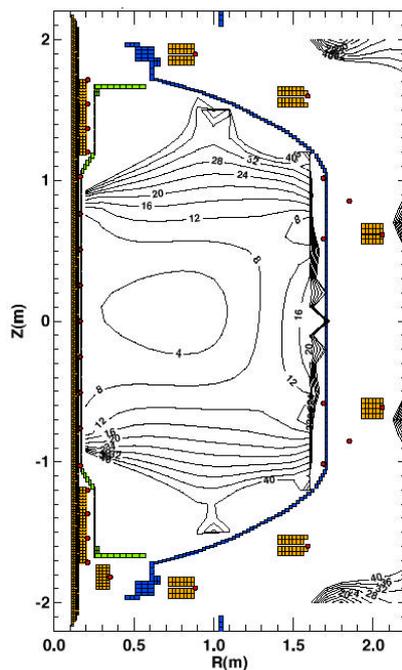


Figure 1: Field configuration 16 msec after the start of the OH ramp. Contours denote the level of stray magnetic field in Gauss.

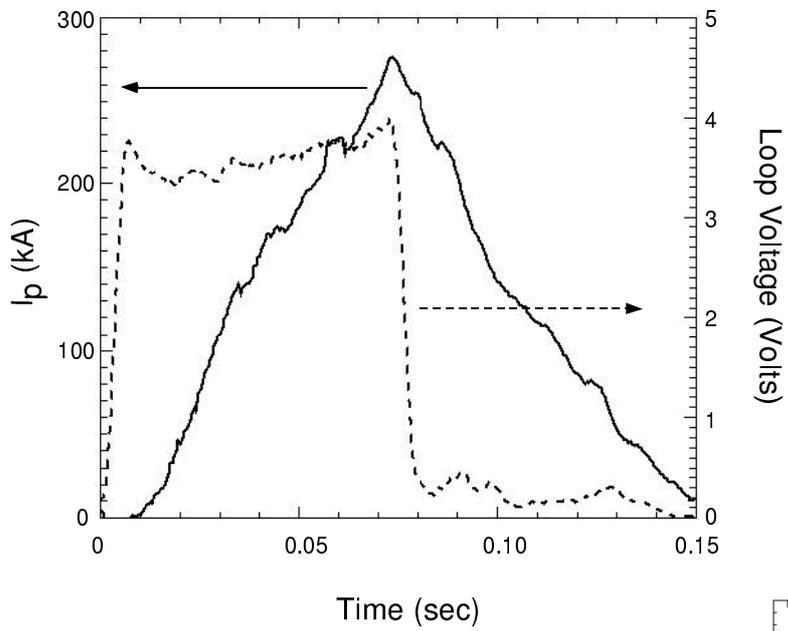


Figure 2: Plasma current and voltage traces for the highest current NSTX discharge.

Figure 3: EFIT equilibrium reconstruction of a 300 kA NSTX plasma.

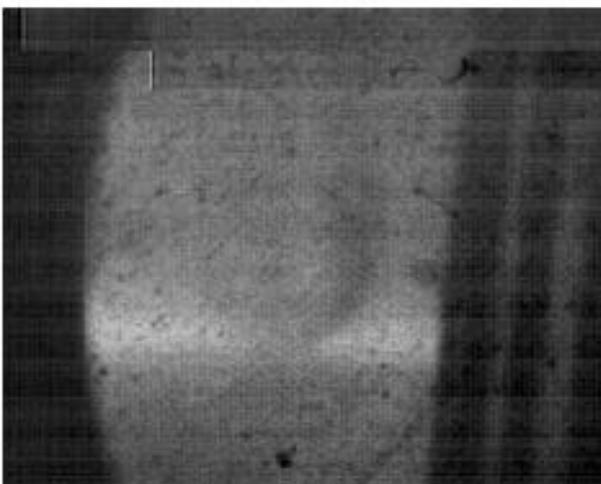
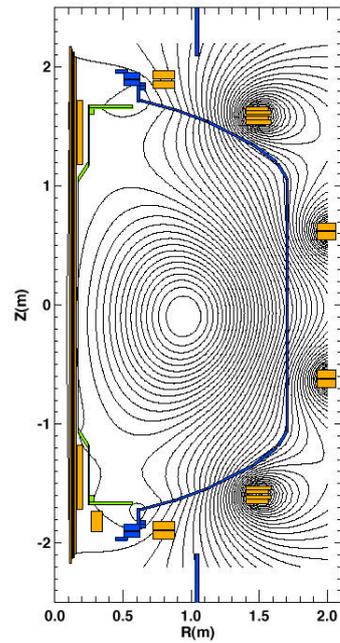


Figure 4: Fast TV image of NSTX plasma. The center column is on the right.