National Spherical Torus Experiment (NSTX) Construction, Commissioning, and Initial Operations

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Abstract- The NSTX is a new national facility for the study of plasma confinement, heating, and current drive in a low aspect ratio, spherical torus (ST) configuration. The ST configuration is an alternate magnetic confinement concept which is characterized by high β (ratio plasma pressure to magnetic field pressure) and low toroidal field compared to conventional tokamaks, and could provide a pathway to the realization of a practical fusion power source. Engineering design began in October 1995. Installation of the torus in the test cell began in October 1998. First plasma was achieved in February 1999. Following this event, with the completion of the installation of the internal hardware and RF antenna over the summer of 1999, the construction project has been declared complete, and the machine has been restarted. Operation of the machine, and production of plasma, has been quite reliable, and the experimental campaign has now begun. This paper reports on highlights of the construction, commissioning, and initial operations.

INTRODUCTION

Engineering design of NSTX began in October 1995. The final design of the main elements of the torus was completed mid-1997, and reported on at SOFE '97 [1]. A photo of the NSTX machine is shown in Figure 1, and in cross section in Figure 2.

Figure 1 – NSTX Machine

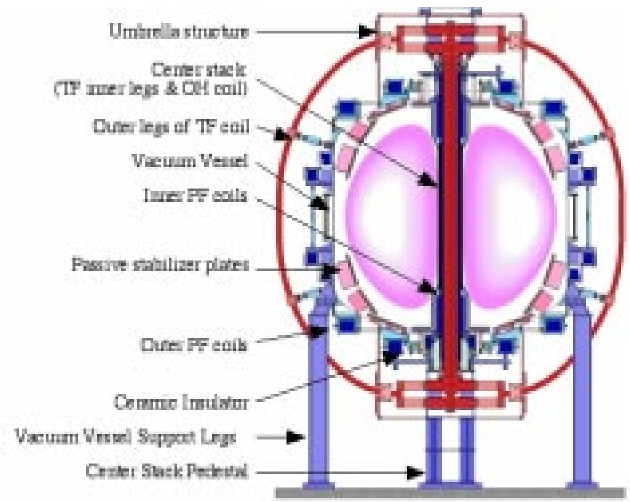

Figure 2 – NSTX Cross Section

The core of the NSTX machine consists of a narrow center stack (CS) bundle which contains the inner legs of the Toroidal Field (TF) coil, an Ohmic Heating (OH) solenoid coil and associated tension cylinder, a pair of inner Poloidal Field (PF) coils, thermal insulation, and a center stack casing which forms the inner wall vacuum vessel boundary. The CS Casing is electrically isolated from the remainder of the machine via ceramic insulator assemblies which permit the use of Coaxial Helicity Injection (CHI) as one of the means of advanced current drive. The CS bundle presents one of the main engineering challenges of NSTX since high performance is required while the radial build must be minimized. The outer vacuum vessel consists of a 5/8" continuous stainless steel structure with 12 major midplane ports. The outer PF coils are taken from the retired S-1 machine at PPPL. NSTX is installed in the Hot Cell of the D-site facility at PPPL which supported TFTR until its retirement. Extensive use of the D-Site infrastructure including magnet power supplies, and RF sources, cooling water systems, etc., is made to minimize the overall cost of the experiment.

Dimensions and ratings of the NSTX machine are given in Table 1.

Detailed information concerning the various features and supporting systems of NSTX is presented in companion papers at this conference [2-13].

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Table 1 – NSTX Dimensions and Ratings

System	***Parameter***	***Rating***
Plasma	Major Radius (R_0)	85.4 cm
	Aspect Ratio (R/a)	1.26
	Current	1.0 MA
	Ramp Time	0.2 - 0.4 sec
	Flat Top (Inductive)	0.5 sec
	Repetition Period (Ind.)	600.0 sec
	Flat Top (non-Inductive)	5.0 sec
	Repetition Period (Partial & Non-Ind.)	300.0 sec
Toroidal Field	Field @ R_0	3.0/6.0 kG
Ohmic Heating	Flux (double swing)	0.6 volt-sec
	Initiation Loop Voltage @ R_0	5.0 volt/turn
Heating/ Current Drive	High Harmonic Fast Wave (HHFW) RF	6.0 MW, 30MHz, 5 sec
	Coaxial Helicity Injection (CHI)	50kA injection @ 1kV
	Neutral Beam Injection Upgrade (NBI)	5.0 MW, 80kV, 5 sec
Pre-Ionization	Electron Cyclotron	30kW, 18GHz, 0.1 sec
Bakeout	Bakeout Temperature	350 C PFCs, 150C VV

PROGRESS AND ACCOMPLISHMENTS

Tremendous progress was made during the past year in bringing NSTX to first plasma, through the official completion of the construction project, and into the start of the research program.

11/3/98	VV placed on legs in test cell
11/12/98	Center stack installed
11/18/98	Pump down initiated
12/11/98	TF outer legs completed
12/17/98	GDC started
1/20/99	Dummy load tests completed
2/12/99	Achieved FIRST PLASMA
2/18/99	Completed Day 0 operations
7/8/99	Construction Project completed
7/20/99	Pump down initiated
9/3/99	Commence Day 1 Plasma Ops
10/15/99	Loop closed on Ip ~1MA, R, Z

COMMISSIONING

In parallel with pump-down activities and Glow Discharge Cleaning (GDC), the basic commissioning started with dummy load testing of the power supply system. A dummy load coil with inductance and resistance of the same order as the NSTX magnet coils was located in the power supply building. The tests were performed using power directly from the utility grid with one series and one parallel power supply element at a time, exercising that element to its full capability. The circuit was arranged in such a way that the test current flowed into the test cell, where it was turned around via jumpers and routed back to the power supply building. In this way the full circuit was tested, including the same current and voltage transducers, and the same control system, as is used in normal operations. As a result, very few problems were encountered when the real machine coils were connected.

Once the power supplies were connected to the machine coils, one coil system was energized at a time and the various coil protection systems were tested. Trips were exercised at both low (< 10%) and high (≈ 50-95%) of the full established "allowables", in such a way that the protection is demonstrated to work, in the first place, at low level, and in the second place with sufficient accuracy all the way to the high level. Following the single coil tests, combined field tests were performed at 50%, and then 100%, of the allowables.

At the present time, with the exception of the OH system, all circuits have been tested to the full current rating, but typically at 20% of their full $\int I(t)^2(t)dt$ rating. This includes the bipolar operation of the OH and PF3 systems. The OH system will be tested to its full rating prior to the end of the day 1 campaign which is now underway.

FIRST PLASMA

The objectives of the first plasma campaign were to perform a basic machine shakedown, with emphasis on the following systems:

- Vacuum vessel and vacuum pumping system
- Magnet coils
- Power supply systems
- Control systems

The configuration of the machine during the first plasma tests was as follows:

- No passive plates
- No ceramic insulators
- TF, OH (uni-polar), PF3, and PF5 only

- Minimum set of PFC tiles (alternating columns on center stack)
- Center stack flux loops and Mirnovs only, plus four temporary outer loops
- Power supply controller only (preprogrammed coil current control)
- Interim GDC and biased filament system
- No Electron Cyclotron Pre-ionization (ECP)

First plasma was achieved on February 12, 1999 on the fourth attempt. The first discharge was with OH only (no ECH or filament assist). By end of the testing the following week the achieved level of plasma current reached ≈ 300kA after a total of 121 shots, of which 100 were coil-only test shots and 21 were plasma shots.

DAY 0 to DAY 1 OUTAGE

After the completion of the first plasma experiment the machine was opened for the period March through August for additional installation, including all components with in the original project work scope, leading to the official end of the construction project phase. During this period the following work was performed.

- Completed internal hardware
  - Passive plates & heating/cooling lines
  - PFC tiles
- Installed HHFW RF antenna
- Installed ceramic insulators
- Installed basic sensor sets
  - Magnetic diagnostics & thermocouples
  - Instrument racks at various machine potentials
- Installed Electron Cyclotron Pre-ionization (ECP)
- Installed GDC & filament system

Figure 3 shows an interior view of the NSTX machine at the conclusion of the outage, showing the center stack, inboard and outboard divertors, and passive plates with the graphite and carbon fiber composite plasma facing tiles attached.

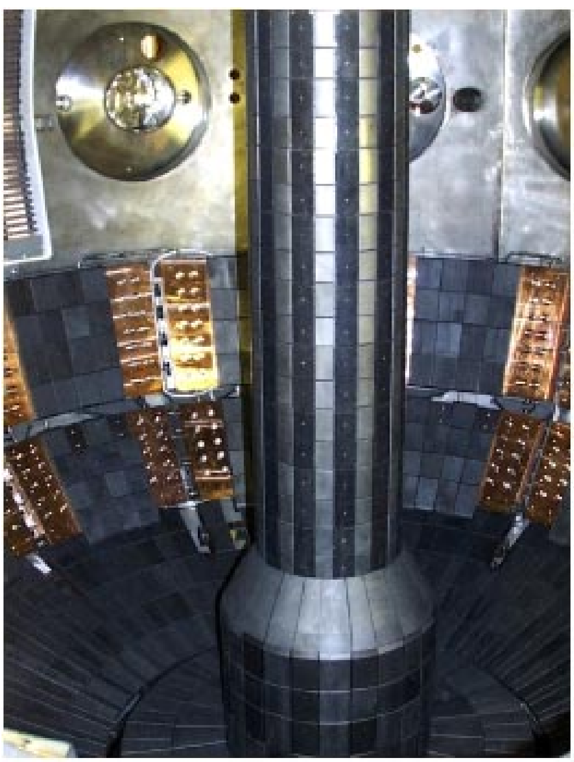

Figure 3 – In-Vessel View

DAY 1 CAMPAIGN

Objectives of the Day 1 campaign are as follows:

- Re-establish plasma operations with new internal hardware, with ECP assist
- Initiate bakeout operations
- Perform magnetic diagnostics calibrations
- Initiate closed loop plasma control
- Characterize inductive (OH) operations
- Initiate HHFW RF heating
- Initiate CHI current formation

Thus far plasma operations have been restarted, initial bakeout has been performed, diagnostic calibrations have been performed, and closed loop control on plasma current and position has been established. All plasmas have been initiated with assistance from ECP and biased filaments.

Figure 4 shows a fast camera image of the ECP ionization which forms a cylinder at the electron cyclotron resonant radius. Figure 5 shows an inductively driven plasma filling the torus volume.

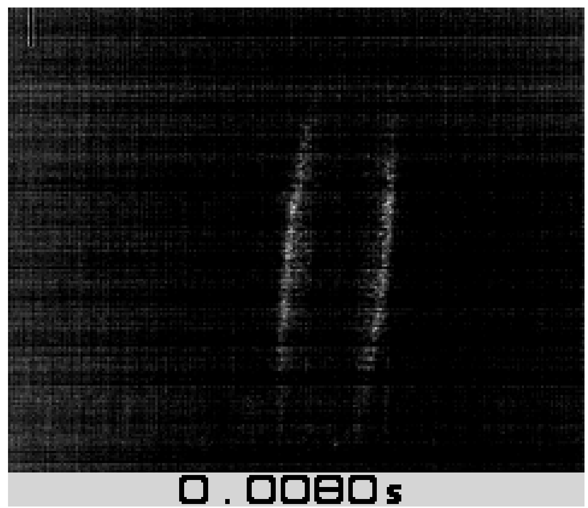

Figure 4 – Fast Camera Image of Electron Cyclotron Preionization

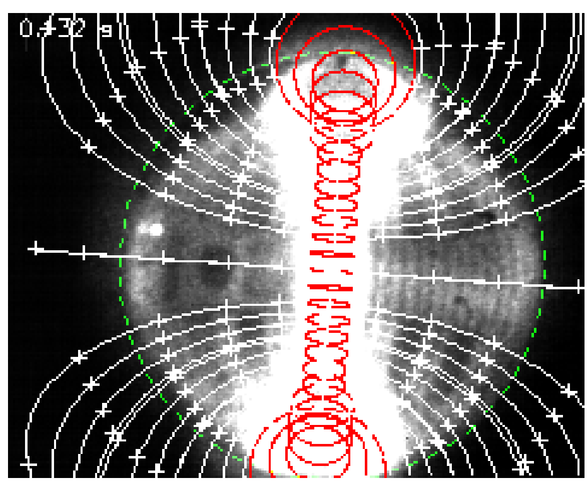

Figure 5 – Fast Camera Image of Inductively Driven Plasma

Bakeout

Once plasma was re-established, an initial bakeout was performed by passing DC current through the center stack casing, returning through jumpers at the top of the machine through the outer vacuum vessel and back out the bottom (recall that for CHI the center stack casing and outer vacuum vessel are insulated from each other). Approximately 10kW was deposited by ohmic heating of the center stack casing, which was sufficient to raise the casing to approximately 200C. During this initial test, no thermal insulation was in place on the outer vacuum vessel, so it did not heat significantly, nor did the passive plates. However, the ohmic bakeout feature was confirmed, as was the effectiveness of the center stack thermal insulation in preventing heat flow inwards to the OH coil. Installation of thermal insulation on the outer vacuum vessel is now underway. The original machine design provides for additional heating of the passive plates by circulating heat transfer fluid up to 350C through in-vessel piping connected to the plates. However, concerns about the volatility of the originally selected fluid may limit the temperature at which this system may be used. In addition, concern exists about the effect of a leak into the vessel, and the ability to then bake out the fluid from the tiles. It seems likely now that another scheme for heating the passive plates must be developed. In the meantime, the next phase of tests will determine the effectiveness of the ohmic center stack heating alone, with the benefit of the thermal insulation on the vacuum vessel. These tests will also help to quantify emissivity and heat loss characteristics so as to facilitate the design of a new heating system.

Magnetic Diagnostic Calibration

Calibration of magnetic diagnostics is an important initial step in establishing the signals needed for optimization of plasma initiation, real time plasma current and position control, as well as post-shot equilibrium reconstruction. Due to the conducting shells presented by the passive plates and the toroidally continuous vacuum vessel, detailed consideration of eddy currents in these passive structures has been essential. Toward this end, axisymmetric filament transient simulation models have been developed which involve the use of as many as 2000 elements to represent the coils and structure. The magnetic diagnostic calibration procedure has involved the comparison of measured eddy currents, fields, and fluxes against those simulated by the model, for coil-only test shots. Using this technique, gross signal errors, such as polarity reversals, have been weeded out. In addition, some systematic errors, such as effective Mirnov coil scale factors, have been corrected. In some cases small adjustments in the simulated sensor (r,z) coordinated have been necessary to obtain agreement (which is expected since some flux loops, particularly those on the exterior of the vacuum vessel, do not take perfect circular paths around the machine. Agreement now is quite good, typically less than 1% discrepancy.

Closed Loop Control

Closed loop control of plasma current, radial position, and vertical position has now been established by a process of gradual introduction of windows of increasing time duration during a pulse where the control algorithm takes over from preprogrammed current sets. Gain adjustments are being made to improve performance. The process remains to be optimized.

RELIABILITY AND AVAILABILITY

Thus far approximately 500 shots have been taken, roughly 1/2 coil-only test shots and 1/2 plasma shots. The reliability has been excellent, with the ratio of successful shots to attempted shots better than 90%. In addition, only one significant unexpected period of down time has been experienced so far, due to the failure of a cooling water pump. These good results are attributed to:

• the extensive use of former TFTR equipment, already characterized and in good working order, albeit in modified configuration

• the aforementioned dummy load test method whereby the full power supply circuit and control system was exercised in advance

CONCLUSIONS

• NSTX construction project was completed on time and on budget
• The design has changed little since SOFE ’97
• NSTX plasmas have been relatively easy to form and control
• Commissioning took place at a rapid pace with few problems
• Initial operations has been highly productive
• NSTX research program can now begin in earnest.

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