# ENGINEERING DESIGN OF THE NATIONAL SPHERICAL TOKAMAK EXPERIMENT

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## ABSTRACT

The National Spherical Tokamak Experiment (NSTX) is an ultra low aspect ratio device with a plasma current of 1 MA. The tokamak features auxiliary heating and current drive with a close-fitting conducting shell to maximize the plasma pressure. NSTX is designed for an experimental pulse length that will demonstrate quasi-steady state non-inductively driven advanced tokamak operation. The design also takes maximum advantage of existing facilities and components from previous Princeton devices to reduce the overall program costs.

## I. INTRODUCTION

The mission of the NSTX device is to assess the physics performance of the spherical tokamak (ST) in reactor relevant regimes. ST issues including non-inductive start-up, current sustainment and profile control, confinement scaling, $\beta$-limit scaling, scrape off layer and disruption physics can be explored in reactor relevant regimes characterized by high beta (30-45%), high bootstrap fraction (40-80%), a fully relaxed non-inductively sustained current profile, an ultra-low aspect ratio ($R/a \sim 1.25$) with a high natural elongation $\kappa \sim 2$ and low collisionality for MHD stability and bootstrap current profile.

The NSTX device is currently being designed to achieve this mission using the design parameters outlined in Table 1.

As Table 1 indicates, the main goal of NSTX is to investigate the advanced spherical tokamak plasma properties at the 1 MA level. This level of current is a meaningful step up from the present 100-300 kA level ST experiments such as CDX-U and START. The 1 MA level plasma current for an ST is also projected to be similar in plasma performance to the medium size conventional tokamak experiments such as PLT and PDX. The minimum aspect ration of 1.25 was chosen to allow exploration of extremely low aspect ratio plasmas. The 5 second pulse length will allow full relaxation of the plasma current profile for the advanced ST scenarios. Given this plasma current, aspect ratio and pulse length, the minimum size of the TF center leg is defined which, in turn largely determined the remainder of the plasma and device parameters.

| NSTX Parameters | | |
|---|---|---|
| Major Radius (cm) | 85.5 | |
| Minor Radius (cm) | 68 | |
| Aspect Ratio | 1.26 | |
| Plasma Current (MA) | 1 | |
| Toroidal Field (Tesla) | 0.32 (5.0 s) | |
| | 0.64 (0.6 s) | |
| | 0.64 (60.0 s) | (upgrade) |
| Pulse Length (s) | 5 | |
| | 60 | (upgrade) |
| Start-Up | Ohmic Heating, Coaxial Helicity Injection (CHI) | |
| Auxiliary Heating and Current Drive | CHI, Fast Wave (6 MW delivered) | |
| | Neutral Beam Injection | (upgrade) |

Table 1

To minimize the overall cost of the device, NSTX makes extensive utilization of existing facilities at the Princeton Plasma Physics Laboratory (PPPL). Among these facilities and components are the Princeton Large Torus (PLT) test cell which contains concrete shielding walls allowing high power neutral beam injection; the vacuum vessel and PF coils from the S-1 Spheromak; the Princeton Beta Experiment-Modification (PBX-M) power supplies to power the toroidal (TF) and poloidal field (PF) coils, as well as the capacitor banks (for CHI); and powerful existing ICRF and NBI hardware and infrastructure.

## II. CONFIGURATION

Figure 1 shows an elevation view of the overall configuration of NSTX. The device consists of a stainless steel vacuum vessel which is mounted on the PLT base platform. The outer PF coils are supported directly from the vacuum vessel. The toroidal field is supplied by twelve TF coils surrounding the vacuum chamber. The most critical feature of the ultra-low aspect ratio NSTX design is the centerstack assembly which contains the

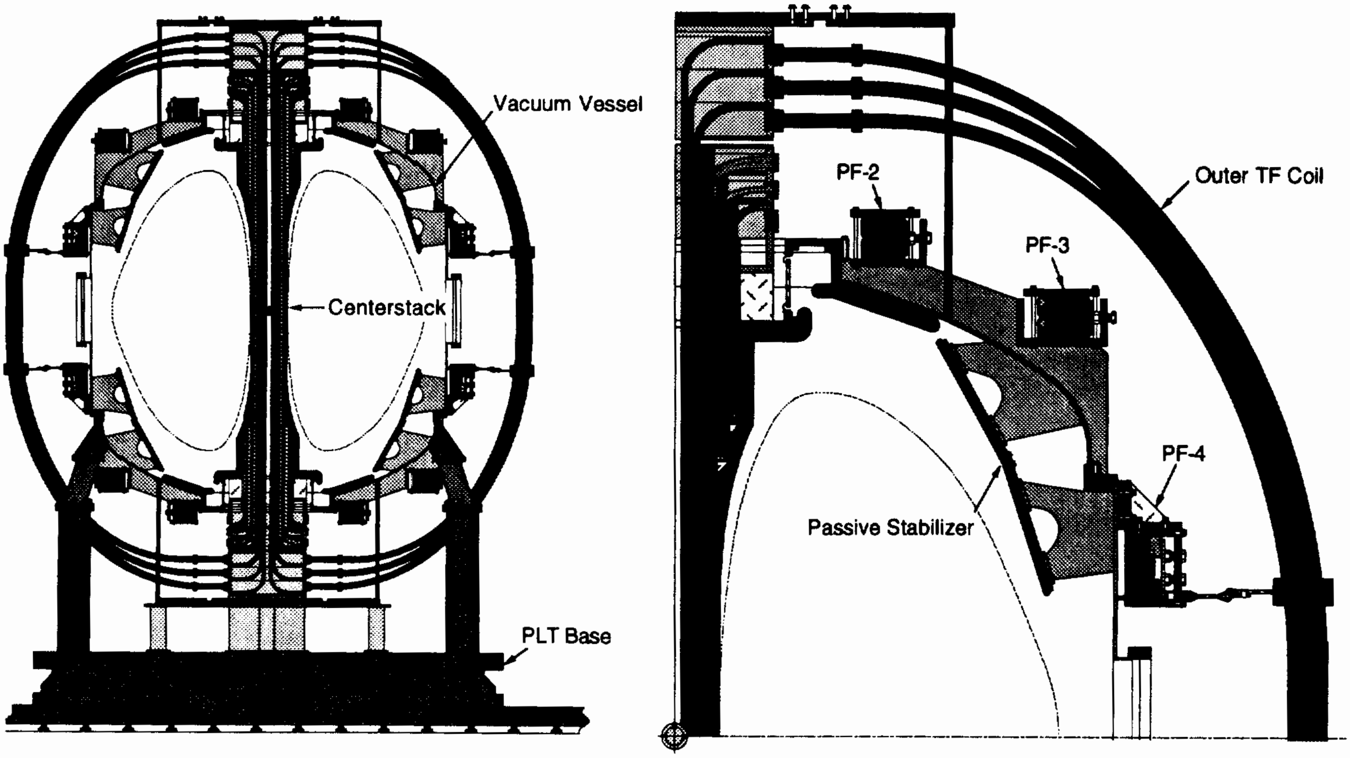

Figure 1. NSTX Configuration

inner TF bundle, the OH I and II solenoid bundles and PF-1 surrounded by an Inconel case.

### A. Vacuum Vessel

The two stainless steel halves of the S-1 Spheromak vacuum chamber serve as the upper and lower domes of the NSTX vacuum vessel. The two domes are connected through a 2 meter long cylindrical section made of 1.27 cm. thick stainless steel. This configuration forms a vacuum vessel that is 3.4 meters in diameter and 3.75 meters in height. An umbrella structure is attached to the upper and lower domes of the vacuum vessel to react the electromagnetic loads from the toroidal field coils.

In addition to the 11 ports in each of the domes, 12 large diameter ports, as well as a number of smaller ports, are provided in the cylindrical section to accommodate plasma heating, diagnostics and vacuum pumpingMetal vacuum seals are used to insure a high vacuumenvironment within the chamber as well as accommodate high temperature (350°C) bakeout.

A key feature of the NSTX vacuum vessel assembly is the electrical isolation of the outer vessel from the centerstack for operation of the CHI system for non-inductive tokamak start-up and edge current drive. Upper and lower alumina rings are installed at the machine vertical centerline ports of the upper and lower vacuum vessel domes. The ceramic rings are isolated from operational and bakeout loads by bellows attached to the top and bottom of each ring.

### B. Plasma Facing Components

Outer passive stabilizers, four poloidal limiters, upper and lower divertor strike plates and inner wall armor make up the plasma facing components within the NSTX vacuum vessel.

The passive stabilizers consist of a series of conically shaped 1.27 cm. thick copper plates. Each stabilizer is segmented into two poloidal and twelve toroidal plates. The individual plates are attached to toroidal support rings which are supported from the vessel wall. The surfaces of the copper plates are protected with 2.54 cm. thick graphite tiles.

Four poloidal limiters are installed to protect the High Harmonic Fast Wave launchers. Graphite tiles are used for the poloidal limiters as well as the inner wall armor. Carbon-carbon composite tiles are used for the upper and lower divertor strike plates.

### C. Toroidal Field Coils

The toroidal field coils consist of the inner TF coil bundle and the outer legs. The inner TF bundle is part of the centerstack assembly and is described in a later paragraph. The twelve outer TF coil legs are composed of six - 5 cm. by 7.6 cm. copper conductors. Each of the 72 conductors in the outer legs is water cooled through a 1.25 cm. cooling passage. The outer legs of the TF coils, which have an outside radius of nearly 2.5 m., are supported through the lower vacuum vessel umbrella structure to the PLT base. Connection to the inner TF conductors is made through demountable, flexible connectors. This feature allows the centerstack assembly to be removed and replaced for future machine upgrades.

## D. Poloidal Field Coils

Four pairs of coils make up the NSTX poloidal field coil system. PF Coil #1 is part of the centerstack assembly. The EF coils from the S-1 Spheromak are used for the outer PF coils, #2, 3 and 4. The outer PF coils are located symmetrically about the horizontal centerline of the device. Each coil is supported from the vacuum vessel using a sliding joint mechanism to prevent loading of the PF coils during vacuum vessel bakeout .

PF-2 has a mean radius of 80.0 cm. and is located beneath the upper and lower vessel umbrella structures. The coil is made up of two individual coils; 2a and 2b, each containing seven layers of 2.04 cm. x 3.23 cm. copper conductors with two turns per layer.

The PF-3 coil has a mean radius of 149.0 cm. and is attached to the upper and lower vessel domes. The coil is made up of two individual coils; 3a and 3b, each containing eight layers of 2.04 cm. x 3.23 cm. copper conductors with two turns per layer.

PF-4 is mounted to the center cylindrical section of the vessel and has a mean radius of ~179.0 cm. The coil is made up of three individual coils; 4a, b and c each containing 2.04 cm. x 3.23 cm. copper conductors with two turns per layer. PF-4a has three layers; PF-4b has four layers and PF-4c has five layers.

## E. Centerstack

The centerstack assembly consists of the inner legs of the TF coils, the Ohmic Heating solenoid, PF #1 and the centerstack casing.

The 72 conductors of the inner TF legs occupy the core of the centerstack assembly. A cross-section of the centerstack radial build is shown in Figure 2. Four different conductor cross sections are used to make up the individual turns in TF inner bundle. Each of the conductors has a 0.64 cm. diameter coolant passage which allows the conductor to be cooled down between pulses from an operating temperature of ~100°C to 20°C in less than 5 minutes. To provide the required electrical insulation, each turn is wrapped with a single layer of half-lapped Kapton polyimide film followed by a single layer of Fusa-Fab glass cloth to provide a total turn-to-turn and layer-to-layer insulation thickness of .040-in. The inner TF bundle is built up in four radial layers but the conductor shapes have been chosen to allow the bundle to be fabricated in quadrants. The four individual quadrants are assembled to form the cylindrical bundle and then overwrapped with Fusa-Fab.

The OH-1 solenoid surrounds the TF inner legs. This coil is comprised of four layers of copper conductors with 193 turns each. Cooling water supplied at a temperature of 20°C flowing through 0.476 cm. diameter coolant passages permits cooldown times of less than 10 minutes for the OH-1 solenoid The OH-1 coil uses two different conductor sizes to satisfy the operating requirements and minimize the overall length of the winding. A rectangular conductor, 1.0 cm. wide x 1.4 cm tall is used for the middle 147 turns. The winding then transitions at both the upper and lower ends to a conductor size of 1.4 cm. x 4.2 cm. Each turn is wrapped with a single layer of half-lapped Kapton polyimide film followed by a single layer of Fusa-Fab glass cloth. The OH-1 solenoid is then overwrapped with two layers of half-lapped Fusa-Fab.

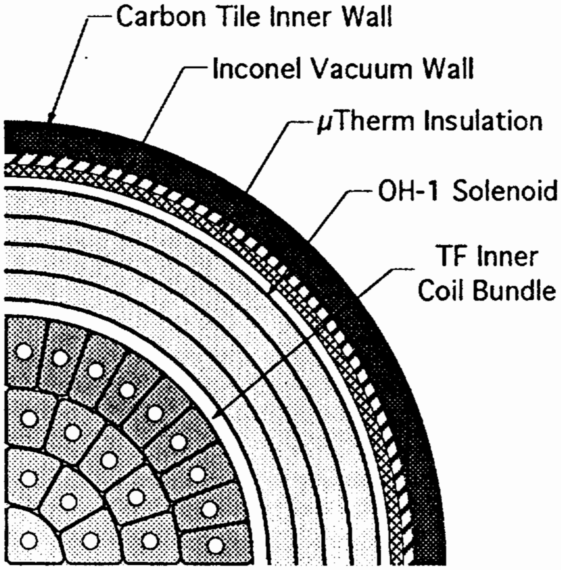

Figure 2. Centerstack Radial Build

The OH-2 solenoid is made up of a pair of copper coils with 2 layers of 45 turns of square conductor, 2.0 cm. x 2.0 cm. Each turn is insulated in the same manner as OH-1 and has a 0.9 cm. diameter coolant passage. The OH-2 coils are located symmetrically about the horizontal midplane of the machine and surround the OH-1 coil near the upper and lower ends.

PF Coil #1 also consists of a pair of coils and surrounds the OH-2 coils. These coils consist of two layers of 38 turns of square conductor, 1.6 cm. x 1.6 cm. Each turn of the PF-1 coils is insulated with the same combination of Kapton and Fusa-Fab.

The centerstack assembly is encased in a 0.4 cm. thick Inconel shell. A 0.5 cm. thick layer of Microtherm thermal insulation is positioned between the case and the outermost coils (OH-1 at the mid-plane and PF-1 at the upper and lower ends) to protect the coil insulation from the 350°C bakeout temperature.

Adequate clearances are maintained between the various centerstack components to facilitate insertion of the individual coil assemblies into the centerstack case. These gaps are filled with a soft insulation after assembly to minimize load transfer between the various coils and the effects of differential thermal growth. The compact radial build results in a centerstack with an overall diameter of 35.2 cm. This dimension is critical to maintaining the ultra-low aspect ratio of 1.25 for NSTX.

## III AUXILIARY HEATING AND CURRENT DRIVE

The auxiliary heating and current drive systems consist of High Harmonic Fast Wave Heating (HHFW), Electron Cyclotron Heating (ECH), Coaxial Helicity Injection (CHI) and Neutral Beam Injection (NBI). The NBI systems will not be in place for baseline operations, but provisions for future NBI installation will be made (space, utilities etc.)

The electron cyclotron heating (ECH) system is used to provide pre ionization for plasma breakdown, power for ionization and heating during start-up, and plasma heating and/or current drive during discharge flat-top. The ECH system consists of a microwave source, transmission system, and launching structure.

The ECH system uses in-vessel launchers which direct the microwave radiation toward the desired absorption location. Each launcher is connected through a vacuum window to the external transmission system. The transmission system, which consists of a waveguide and special components for power measurement, transports the microwave power from the rf sources to the vacuum window. The rf sources provide the microwave power and include local controls and interlocks.

The High Harmonic Fast Wave Heating (HHFW) and Current Drive system provides electron heating power to the NSTX plasma, via the fast magnetosonic wave; non-inductive current drive, and control over the heating/current drive deposition profile, through the antenna phasing. The HHFW system consists of the rf generators, transmission lines, tuning and matching systems, rf feedthroughs and internal transmission lines, antennas with Faraday shields and protective limiters,

The HHFW system utilizes twelve stripline antennas mounted on the vacuum vessel wall in the gap between the upper and lower passive stabilizers. The antennas are toroidally located between the NSTX vacuum vessel midplane ports. Each antenna consists of a current strap, a backplane, a Faraday shield, and a local (bumper) limiter structure. Each antenna is fed by a single coaxial rf vacuum feedthrough, mounted on either the upper or lower ports on the lateral wall of the vacuum vessel. Short internal runs of coaxial or shielded stripline transmission line connect the feedthroughs to the antennas. Short runs of transmission line external to the vacuum vessel are supported from the NSTX structure; the remainder of the transmission line runs are mechanically isolated from the feedthrough through bellows assemblies. Each antenna strap will be excited in parallel with a second strap. Each pair of antenna straps is impedance matched using a line stratcher and stub, and fed by one of the six rf generators.

The six existing generators will be operated at no more than three frequencies (minimum of four adjacent straps at each frequency) in the range of 30 - 50 MHz. All rf generators operating at any single frequency are phase locked to provide control over the wavenumber spectrum excited in the plasma at that frequency. Amplitude modulation control and feedback is required for generator operation and is provided by the existing phase, amplitude modulation, and feedback controls. The generator controls are local to the generators.

The CHI system is designed to allow for non-inductive start-up and to provide edge current drive for long pulse operation if it proves needed. The CHI system relies on the ceramic breaks that electrically isolate the center stack from the outer vacuum vessel. Bus connections to the two sides of the breaks are used to bring the energy from the CHI power supply, which will consist of a capacitor bank for start-up assistance and a rectifier for long pulse edge current sustainment

The NBI system is not part of the baseline program, however the baseline NSTX design does ensure that NBI can be incorporated easily as an upgrade. The NBI system is used for plasma heating and current drive as well as plasma rotation. The NBI system will consist of up to four NB injectors installed in the corners of the test cell and firing through ports in the vessel. In-vessel armor will be needed for the beam shine through strike points. Exact beam aiming angles will be determined by physics considerations and strike point compromises.

## IV. PLASMA DIAGNOSTICS

The NSTX plasma diagnostics provide information on discharge parameters and guide NSTX operations for optimized performance. Table 2 lists the diagnostics for the baseline NSTX design. Those diagnostics which are essential for machine operations are called Day One diagnostics, and are indicated with an asterisk in Table 2 and include Multichannel Thomson Scattering System (TVTS), Charge-Exchange Recombination Spectroscopy (CHERS), and Motional Stark Effect Polarimetry (MSE.) Although Mirnov coils are not critical for machine operations, they are also listed as Day One diagnostics because they have to be installed as part of the NSTX assembly process.

After plasma operations on NSTX begin, the near-term emphasis will be on detailed measurements of plasma profiles for understanding the basic confinement and transport properties of short pulse, ohmically-heated

NSTX discharges. Since current profile measurements are particularly important, special emphasis will be placed on installing the MSE diagnostic and its dedicated diagnostic neutral probe beam.

The long-term objective is to upgrade and expand the diagnostic set for the study of fluctuations and transport in long pulse, auxiliary-heated NSTX plasmas. In addition, plasma diagnostics will provide input for advanced plasma control systems.

| Day One and Baseline Diagnostics Summary | |
|---|---|
| Multichannel TVTS (single pulse) | $T_e(r)$, $n_e(r)$ |
| CHERS (with neutral probe beam) | $T_i(r)$, $v_f(r)$ |
| MSE (with neutral probe beam) | $j(r)$ |
| Multichannel bolometer | $P_{rad}(r)$ |
| Visible continuum array | $Z_{eff}(r)$ |
| 1 mm microwave interferometer | $n_e l$ |
| Survey spectrometer (SPRED) | Impurities |
| Soft X-ray imaging system | Fluctuations |
| Mirnov coils* | Fluctuations |
| Flux loops | Fluctuations |
| Rogowski coils* | $I_p$ |
| Flux Loops* | Magnetics |
| $H_a$ detectors | Edge recycling |
| Langmuir probes | Edge parameters |
| Visible camera* | Plasma control |
| IR camera* | Heat loads |
| Residual gas analyzers | In-vessel gases |

Table 2

## V. POWER SYSTEMS

The NSTX Power Systems consist of the AC Power Systems, the TF Power Conversion System, the PF/OH Power Conversion System, and the CHI Power Conversion System. The NSTX device will utilize the existing PBX-M motor generators and PF rectifiers as well as some spare equipment from TFTR to satisfy the initial power requirements.

For the AC power systems, all of the equipment associated with 480V and above has been in service for several years, with the exception of the 13.8 kV S4 equipment, which is new. The AC power distribution to the C-site MG, HHFW sources, PF-2-8 rectifiers, and NBI sources have also been in service for several years. Similarly, AC power distribution to NSTX auxiliary equipment will make use of existing equipment down to the 480V level.

In addition to the existing C-site MG sets, the TF Power Conversion System will make use of the existing DC distribution circuits, line disconnect and grounding switches, ground fault detectors, and control system. The C-site MG sets consist of three rotating shaft line-ups, each consisting of a motor, flywheel, and four DC generators. The NSTX TF load requires the use of one of the three existing shaft line-ups, nominally shaft #1 which includes generators #1 through #4. These four generators will be connected two in series and two in parallel. The existing bus link and disconnect switch arrangement permits the selection of any of the three sets of four generators. The only constraint is that the directly paralleled generators should be from the same rotating shaft.

The PF/OH Power Conversion System consists of two distinct subsystems, namely that which feeds the PF-1 (OH) coil, and that which feeds the PF-2 - PF-4 coils. The PF-1 coil will be supplied with DC power using a pair of series connected 12-pulse rectifiers from the D-Site TFTR inventory. The current reversal required for bipolar OH operation will be achieved using a commutating resistor introduced into the load circuit while the rectifier polarity is reversed.

The CHI Power Conversion System will make use of two of the D-site TFTR capacitor banks and associated capacitor charge/discharge (CCD) equipment, and will share one of the two 12-pulse rectifiers used for the PF-1 (OH) system. Also, two D-site TFTR Power Diode Assemblies will be utilized. To achieve the required discharge current waveform the capacitor banks will be discharged via the CCD units, and a rapidly rising voltage will be impressed on the CHI electrodes, with the rate of rise determined by snubbers located in the CCD and power diode units. To limit the voltage across the CHI electrodes (and the center stack casing potential to ground), a non-linear resistor will be connected across the terminals. If conduction through the plasma occurs at the expected low voltage (≤ 2 kV) then the non-linear resistor will conduct minimal current. However if the voltage rises beyond this level (e.g. to lack of a plasma load) the non-linear resistor will conduct a heavy current and limit the voltage. Once conduction of the non-linear resistor is sensed, a crow bar thyristor will be fired to bypass the resistor and short circuit the load.

## VI. CENTRAL INSTRUMENTATION AND CONTROLS

The NSTX Central I&C system provides all supervisory control and monitoring of the NSTX facility. The system includes the Plant Control and Monitoring (asynchronous routine control and monitoring); the Synchronization System (synchronization of triggered actions from master clock events); the Real Time Data Communications System (high-speed syncronous communication between the plasma control processor, associated fault porcessor and various measurement and control poitns in the NSTX facility); the Safety Interlock System (master supervisory control of experiment); Access Control System (control and monitoring of access to hazardous areas); and the Data Acquisition System (periodic sampling, acquisition and display of regularly sampled data, and acquisition and display of data sampled and stored by remote devices.)

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