National Spherical Torus Experiment (NSTX) Center Stack Upgrade

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Abstract— **The purpose of the NSTX Center Stack Upgrade project is to expand the NSTX operational space and thereby the physics basis for next-step ST facilities. The plasma aspect ratio (ratio of plasma major to minor radius) of the upgrade is increased to 1.5 from the original value of 1.26, which increases the cross sectional area of the center stack by a factor of ~ 3 and makes possible higher levels of performance and pulse duration.**

I. INTRODUCTION

The NSTX [1] is the world's highest performance spherical torus (ST) research facility and is the centerpiece of the U.S. ST research program. Since starting operation in 1999, NSTX has established the attractiveness of the low-aspect-ratio tokamak ST concept characterized by strong intrinsic plasma shaping and enhanced stabilizing magnetic field line curvature. The purpose of the NSTX Center Stack Upgrade project is to expand the NSTX operational space and thereby the physics basis for next-step ST facilities. The plasma aspect ratio (ratio of major to minor radius) of the upgrade is increased to 1.5 from the original value of 1.26. The higher value of A matches the value found to be optimal in studies of future ST devices, and also increases the cross sectional area of the center stack by a factor of ~ 3 and makes possible higher levels of performance and pulse duration. The new center stack will provide a toroidal magnetic field at the major radius R_0 of 1 Tesla (T) compared to 0.55T in the existing NSTX device, and will enable operation at plasma current I_p up to 2 Mega-Amp (MA) compared to the 1MA rating of the existing. Plasma flat top duration is extended to 5.0 seconds from the present 0.5 second capability. This extension benefits substantially from another upgrade project which will add a second Neutral Beam Injection (NBI) line to NSTX such that flat-top current sustainment can be achieved non-inductively using NBI current drive.

The NSTX center stack (CS) consists of the inner legs of the toroidal field (TF) coil surrounded by an ohmic heating (OH) solenoid and a several poloidal field (PF) shaping coils, all housed in a vacuum-tight metallic center stack casing (CSC) covered by plasma facing tiles. Since the TF coils include a demountable joint between the inner and outer legs, and the CSC includes a bellows and vacuum seal connection to the outer vacuum vessel, the entire center stack assembly is removable as a modular unit. Thus the upgrade will be accomplished by replacing the existing CS with an entirely new assembly with new TF inner legs, OH and PF coils, CSC, and plasma facing tiles. The TF outer legs, originally designed with an upgrade in mind, are retained but with enhancements to their structural supports.

This paper reports on engineering features of the upgrade based on design activities now underway.

II. DESIGN POINT

Spreadsheet studies were performed using the XL Solver to find an optimum design point given the constraints and boundary conditions. Initial studies were performed to understand the fundamental limits on performance given basic engineering constraints (e.g. conductor temperature, stress, etc.) independent of facility infrastructure limits (e.g. power). Guided by these results and tempered by the limitations of a spreadsheet study in terms of its ability to capture complex structural/mechanical behavior the design point given in Table I was selected for conceptual design development.

TABLE I NSTX CENTER STACK UPGRADE DESIGN POINT

	Base NSTX	NSTX Upgrade
R_0 [m]	0.854	0.934
A	1.266	1.500
I_p [MA]	1.0	2.0
B_t [T]	0.55	1.0
T_{pulse} [s]	0.5	5.0
$T_{repetition}$ [s]	600	1200
$R_{center\_stack}=R_0$-a [m]	0.185	0.315
$R_{antenna}=R_0$+a [m]	1.574	1.574

In arriving at this design point, guided by the prior results, we fixed B_t, I_p, and plasma flat top time at the values listed in Table I and allowed the XL Solver to solve for the radius of the TF inner leg consistent with B_t, plasma flat top time, TF current trajectory up to flat top and down via L/R decay (fault case) per the power supply characteristics, and limits on temperature rise. The remaining annular space in the center stack is given to the

OH coil and the Solver finds the correct number of coil turns such that the first swing of the OH current provides the required flux to ramp the plasma current to flat top. This is in fact the requirement since for the upgrade the plasma flat top current sustainment comes from non-inductive current drive (NBI, with a second beam line being added) and bootstrap. However, as it turns out, the OH coil has not reached a temperature limit given this conditions so a second swing is possible. The OH coil and power supply will therefore be designed to provide a second swing up to the full amp-turns of the first swing, although this is not possible for the full 5 second pulse length.

Waveforms of the TF, OH, and plasma current (divided by 10) for the base and upgraded device are given in Figure 1.

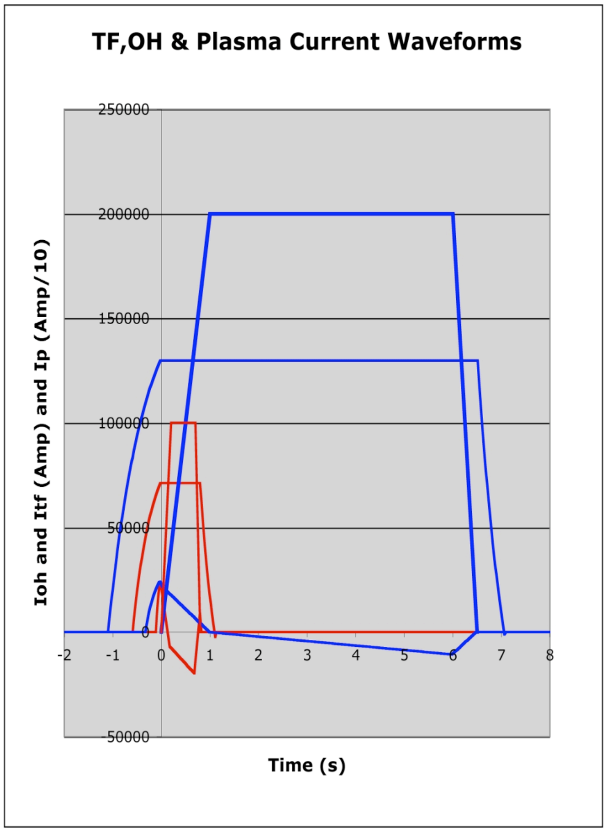

Figure 1 TF, OH, and Plasma Current Waveforms
(Red = base, NSTX Blue = upgrade)

III. Modifications to Existing NSTX Device

Although the cross sectional area of the center stack is greatly increased, there are still some very challenging features of the upgrade arising from the much higher fields and forces.

With B_t increasing to 1T and R_0 to 0.934m the TF current per turn increases to 130kA from 71kA on the existing machine. With higher I_p the PF currents must also be increased. The central field of the OH increases to 7.3T from 6.9T on the existing machine.

The challenge of the demountable TF joint is substantially increased. The torsion on the TF inner leg increases by ~ 1.9. The in-plane and out-of-plane forces on the TF outer leg are each increased by a factor of ~ 3.3.

The following is a summary of the modifications required to the NSTX device and facility to accommodate the upgrade (refer to Figure 2).

- Completely replace center stack
  - new TF inner leg assembly, same height and # turns as existing
  - new TF joints and radial limbs
  - new OH solenoid, same height as original
  - new inner PF coils PF1a, 1b, 1c
  - new center stack diagnostics (including Ip Rogowski)
  - new center stack casing and PFC tiles
- Retain existing TF outer legs but with enhanced supports
- Retain existing outer PF coils but with enhanced supports
- Structural upgrades to vacuum vessel, umbrella, legs, and center stack support pedestal
- Upgraded TF power supply rated for 1kV/130kA

Whether or not additional items such as internal hardware will require modification due to higher I_p and disruption forces is still under assessment.

A. TF Inner Leg and OH coil

The TF inner leg will consist of a single layer of 36 wedge shaped conductors, as contrasted with the existing design which has an inner layer of 12 turns and an outer layer of 24 turns. The OH coil will be similar to the existing one with four layers wound two-in-hand such that there are eight parallel water cooling paths. A side-by-side comparison of the existing and upgraded center stack showing the TF inner leg and OH coil as well as the inner PF coils is given in Figure 3.

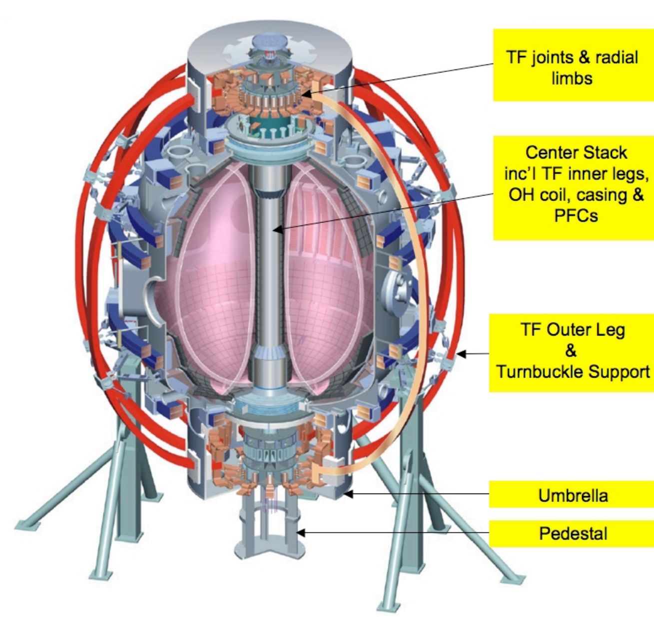

Figure 2. Existing NSTX Device and Components to be Modified for Upgrade

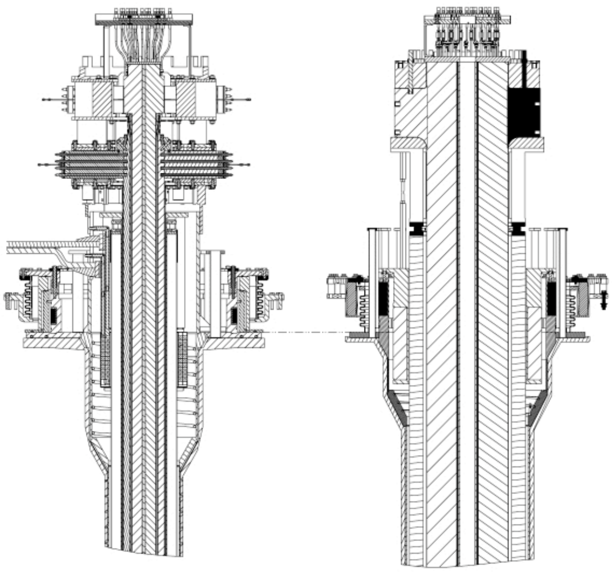

Figure 3 Existing (left) and new Upgrade (right) Center Stack Assemblies

B. *TF Joint*

The demountable inner leg of the ST is a key feature which is also very challenging [2]. The current density is quite high and adequate contact pressure must be maintained at the joint under all conditions of electromagnetic loading. Currents, fields, and forces are quite high and in some cases bidirectional. The TF inner leg assembly experiences substantial axial thermal growth which has to be accommodated by the radial limbs without causing high stresses or moments which would spoil the contact pressure at the joint. The area is quite congested and access to fasteners is difficult. The radial limbs must make up for fabrication tolerances on the inner legs and assembly tolerances on the outer legs.

In order to develop a robust solution for the NSTX center stack upgrade four concepts have been independently developed and are now under assessment as shown in Figure 4. Concepts 1-3 are basically different than 4 since the TF inner legs do not include any extensions at the ends so that the OH coil can be separately manufactured and installed/removed repeatedly. In concept 4, radial extensions would be friction stir or e-beam welded to the wedge shaped turns yielding the advantage of jointing at a greater radius (lower field, greater surface area) but has the disadvantage of the fabrication of the TF and OH being linked, and the OH coil being trapped.

The essential features of the joint concepts are:

Concept 1: Bolted joint with inserts, constant tension shaped radial, flexibility both in-plane & out-of-plane, torque transmitted to lid

Concept 2: Jacking ring joint connection, flexibility in-plane, self-supported against torque

Concept 3: Jacking ring joint connection, constant tension shaped radial, flexibility in-plane, self-supported against torque

Concept 4: friction stir or e-beam welded extensions, bolted joints with inserts, flexibility in-plane, torque transmitted to lid

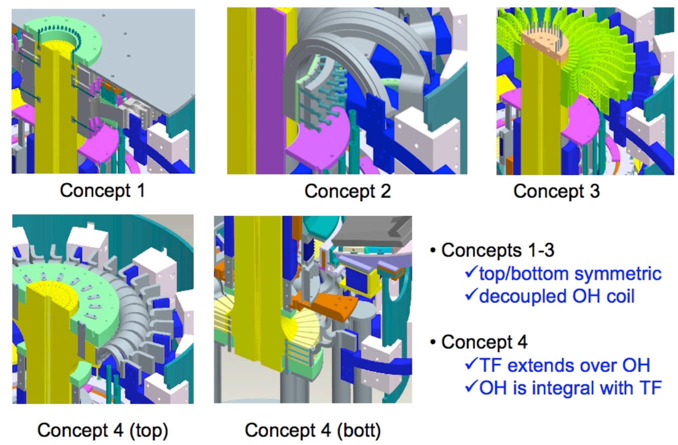

Figure 4 Concepts for TF Joint

More detailed development of the designs, including electrical, thermal, electromagnetic, and structural is underway to guide in the final concept selection which could in fact prove to be a hybrid of the concepts described.

C. *TF Outer Legs*

The existing NSTX machine supports the TF outer legs (twelve legs, each one containing three turns) through three load paths, namely 1) the ends are anchored into the upper and lower umbrella structures, 2) turnbuckles/struts connected leg to leg at two elevations, one above and one below the midplane, each forming a toroidal ring, and 3) turnbuckles/struts connected from each outer leg to the vacuum vessel. Stress analysis showed that the existing configuration was not adequate for the higher loads (factor of ~ 3.3 on both in-plane and out-of-plane) in two regards. First the torque and pull-out loads imposed on the umbrella structure were found to be excessive (see Figure 5). Second, high local stresses were identified on the vacuum vessel, especially around the mid-plane where there are large port cut-outs.

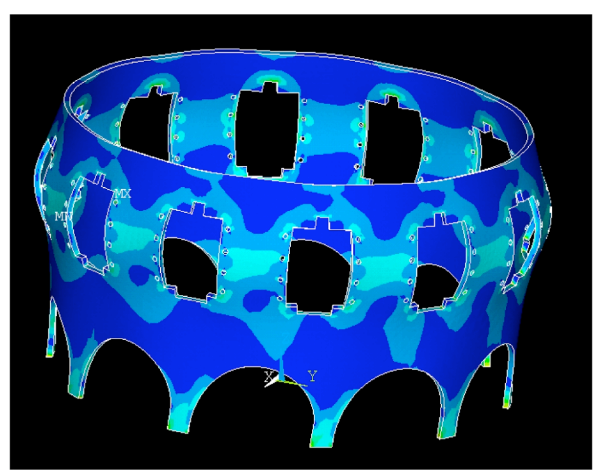

Figure 5 Stress and Deformation Pattern of Umbrella

To address the umbrella issue, additional material will be added by welding in the archways (normal to the plane of the cylinder creating an I-beam section) and around the rectangular openings where the outer leg anchors are inserted.

To address the vacuum vessel issue, the turnbuckle support system will be replaced by an upgraded support structure which will reduce the loads transmitted to through the vacuum vessel.

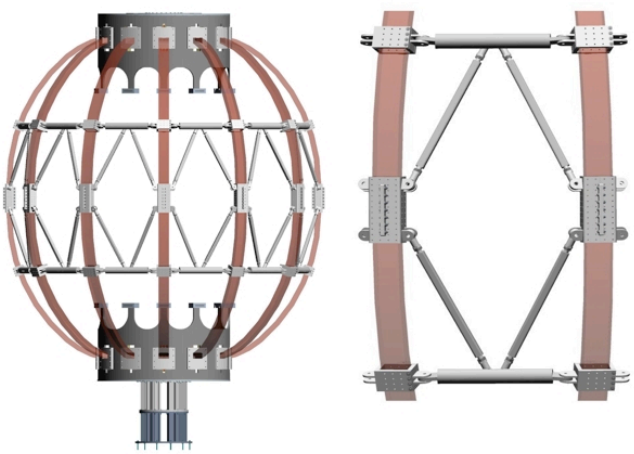

Figure 6 TF Outer Leg Support Structure

As shown in Figure 6, toroidal rings are formed by struts connected between pairs of outer legs. These react a portion of the in-plane magnetic pressure via hoop tension and significantly reduce the loads imposed on the umbrella structure. An out-of-plane load path is supplied by "V-braces" which perform a function similar to "X-braces" without blocking the mid-plane ports.

D. TF Power Supply

The existing 72kA NSTX TF power supply uses four parallel branches of 6-pulse thyristor rectifier sections rated 1kV/24kA-6 seconds, with each branch carrying a nominal share of 18kA. The transformer phase shifts of the rectifiers are such that the four parallel units form a 24-pulse system. Each rectifier is one of a pair which comprise a 12-pulse power supply unit. For the NSTX TF system only 1kV is required so the second unit is connected in series but is excluded from the circuit by a mechanical bypass switch and is available as a spare. Current balance between the four parallel units is determined by the balance of the impedance of the branches as well as the precision of the firing circuits and feedback control is performed on the total TF current.

For the upgrade, in order to produce a 130kA pulse with a flat top duration of 6.5 seconds, several modifications and improvements are planned including the following:

- Eight parallel paths, nominal current 17.25kA/branch
- Upgraded digital firing control and fault detection systems in each power supply unit
- Feedback control on each branch current
- Extra series rectifier section placed in electronic bypass, rather than mechanical bypass

The enhanced digital control and feedback on each branch current will enforce current sharing amongst the eight parallels. The extra series section in bypass acts like a diode and prevents backflow of very large fault currents from parallel rectifiers in case of faults within one rectifier section.

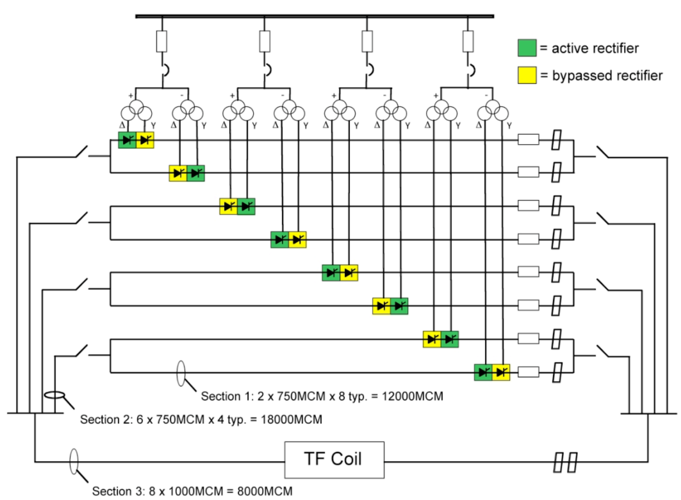

Figure 7 TF Power Supply

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