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The National Spherical Torus Experiment (NSTX) will be upgraded to provide increased toroidal field, plasma current and pulse length. This involves the replacement of the so-called center stack, including the inner legs of the Toroidal Field (TF) coil, the Ohmic Heating (OH) coil, and the inner Poloidal Field (PF) coils. In addition the increased performance of the upgrade requires qualification of remaining existing components for higher loads.

Initial conceptual design efforts were based on worst-case combinations of possible currents that the power supplies could deliver. This proved to be an onerous requirement and caused many of the outer coils support structures to require costly heavy reinforcement. This has led to the planned implementation of a Digital Coil Protection System (DCPS) to reduce design-basis loads to levels that are more realistic and manageable. As a minimum, all components must be qualified for the increase in normal operating loads with headroom. Design features and analysis efforts needed to meet the upgrade loading are discussed. Mission and features of the DCPS are presented.

Keywords: Spherical Torus, design, coils

1. Introduction

The NSTX [1] at PPPL is a world leading spherical torus (ST) research facility and is the centerpiece of the U.S. ST research program. In the 10 years of operation the NSTX has demonstrated the benefits 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 [2] (NSTX CSU) project is to expand the NSTX operational space and thereby the physics basis for the next-step ST facilities. The plasma aspect ratio A (= ratio of major radius R_0 to minor radius a) 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. The new center stack will provide a toroidal magnetic field at the major radius R_0 of 1 Tesla (T) compared to 0.6T in the original NSTX device, and will enable operation at plasma current I_p up to 2 Mega-Amp (MA) compared to the 1MA rating of the original device (Table 1). A second neutral beam is also being added.

The upgrade of the center stack (Fig. 1) requires a new inner TF bundle, flexible joints connecting to the outer TF legs, OH coil, inner PF coils, inconel center stack casing vacuum interface and plasma facing components (tiles). The structural support for the outer PF coils and outer TF legs will also be modified to handle the higher magnetic field loads.

2. Design Features

2.1 TF Bundle

As part of the upgrade the TF bundle must be increased in current-carrrying capacity to meet the new field requirements. The outer TF legs were originally designed to support an increase in TF current to this level and will not require replacement. The new bundle will utilize 36 wedge shaped conductors with a friction stir welded stub at both the lower and upper end with a bolted connection to flex connections to the outer TF legs. The TF operates at 129,778 amps @ 1013 volts. The conductors are fabricated from OFHC copper and the lead extension stubs from higher strength copper alloy (Cu-Cr-Zr). Each conductor is provided with a cooling passage (0.305 inch dia.) soldered into a groove on one side of the wedge. All of the NSTX upgrade coils will be vacuum pressure impregnated using a CTD resin system CTD-101k, which is a 3-component epoxy system with a long pot life and low viscosity to aid the impregnation procedure. Shear bond strength of the cured epoxy-glass composite is 40 Mpa @ 373 K. Turn insulation is rated for 3.8KV. Torque generated from the TF field is reacted through a G-10 cogged ring mated to each end of the bundle.

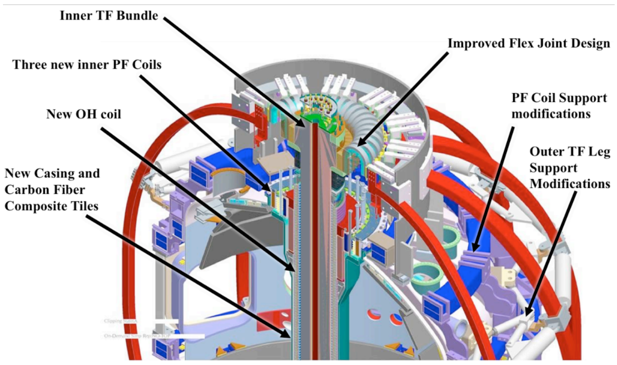

Fig.1 Components being upgraded.

2.2 OH Coil

The upgraded OH coil is designed for 6077 volts @ 24,000 amps. It is a 884 turn coil wound in four layers, water cooled using 8 cooling paths. The OH coil design

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features a co-axial lead located near the pedestal support at the bottom end to minimize lead stresses due to thermal expansion. In line brazes will be required at layer to layer joints using a TIG-braze procedure similar to joints developed for the existing NSTX OH coil. The OH coil will be wound in place on a 0.10” thick cylinder of moldable mandrel material cast over the cured TF bundle. The Aquapour mandrel material is designed to easily wash away after coil curing to leave a 0.10” air gap between the TF bundle and OH coil for thermal expansion and motion between the two coils. The TF bundle lead extension design traps the OH coil on the bundle once the OH is wound. The OH final conductor size is 0.6105 x 0.6598 inch with a 0.225 inch ID cooling passage.

Table 1: NSTX Upgrade Performance Requirements

	NSTX	NSTX-CSU
Major Radius R_0 [m]	0.8540	0.9344
Aspect Ratio	1.266	1.500
Plasma Current, I_P [MA]	1.0	2.0
Toroidal Field B_t [T]	0.55	1.0
Pulse Length, T_{pulse} [s]	1.0	5.0
Rep Rate $T_{repetition}$ [s]	600	2400
Center Stack Radius $R_{centerstack}$ [m]	0.1849	0.3148
Antenna Rad, $R_{antenna}$ [m]	1.5740	1.5740

2.3 Flex Connections

The TF bundle is connected to the outer TF legs using a high strength copper alloy flex connection. The flex joint has been designed to minimize magnetic loads by moving its position upward and outward into a lower field region. Each flex connection consists of 31 Laminations x .078” thick Full-Hard C15100 Cu-Zr copper alloy. The mechanical joint to the TF bundle conductor is made up using 5/8” studs and a nut style multi-jackbolt tensioner, called Torquenut™. The Torquenuts™ permit precise tensioning of the fasteners in the restricted access space under the flex connector loops. Analysis of the flex design included Stresses, buckling on the laminations and contact pressure and thread stresses in the bolted joint (Ref. 1). The maximum Tresca stress in the laminations is 18.9 ksi which satisfies the NSTX Structural Design Criteria with a fatigue strength in excess of 60k cycles. Shear stress in the copper threads in the TF stub extensions is 34.8 ksi which satisfies the design criteria of < 0.4 Sy=37.5ksi. Contact pressure in the joint 2600 psi which exceeds the minimum requirement of 1100 psi.

2.4 Inner PF Coils

There are three new upper and lower PF coils planned as part of the center stack upgrade, PF1A, B and C (Fig. 2). The PF1A and B coils are wound on their support structures. The PF1A coil will be mounted to the center stack casing and the PF1B structure. The PF1B coil structure will be welded to the center stack casing flange. The PF1C coil is wound on a removable mandrel and then installed and Vacuum Pressure Impregnated into its stainless steel support structure which is part of the ceramic break system. The resin system used for all of the coils is CTD101K.

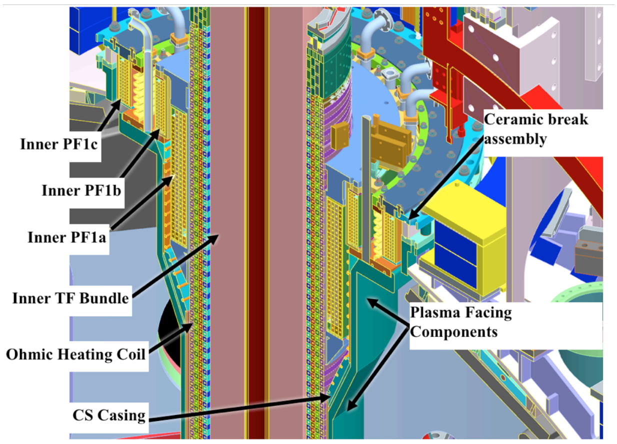

Fig.2 Components being upgraded.

Table 2: Inner PF Coil Requirements

	Units	PF1A	PF1B	PF1C
Number of coils	-	2	2	2
Voltage	Volts	2026	2026	2026
Current	KA	18.3	13	15.9
T/T Voltage	Volts	31.7	5.6	5.6
Number of Turns	n	64	32	20
ESW	sec	4.6	5.5	5.5
Conductor Width	inch	0.551	0.633	0.705
Conductor Height	inch	1.1	0.392	0.603
Cooling Hole Diameter	inch	0.205	0.126	0.126
Turn insulation thickness	inch	0.022	0.029	0.029
Ground insulation thickness	inch	0.144	0.144	0.072

2.5 Center stack Casing

The center stack casing provided the inner vacuum wall for the NSTX vacuum vessel. It is fabricated from rolled and welded Inconel 625 plate. There are upper and lower flanges and conical transitions that are Inconel forgings that are welded to the cylindrical sections. The ends of the casing are protected from misalignment and thermal expansion loads by a formed Inconel 625 metal bellows approximately 40” diameter. Active cooling provision will be provided on the atmospheric side of the Inboard Divertor regions. Organ pipes on each end are provided for diagnostic access of thermocouple, Langmuir and Mirnov sensor connections. The casing is also used as a resistive heating element for the 350C PFC bakeout and is provided with electrical connections for the power supply buss-work.

2.6 Plasma Facing Tiles

The vacuum surface of the center-stack casing is provided with a layer of carbon fiber composite material varying in thickness from 0.75 to 2.0”. The 600 tiles will be a combination of 2D and 3D weave composite depending on the thermal and mechanical requirements. The inboard divertor region (upper and lower flange), which will see a peak heat load (double null) of 8.15 MW/m^2, is covered with 2” thick 3D tiles fastened with T-bars and self-locking threaded fasteners. Tiles on the center-stack cylindrical sections will be fabricated from 0.75” thick 2D carbon fiber composite material and fastened using a weld nut and self-locking threaded fasteners. The backsides of some tiles are modified for the installation of diagnostics sensors and the routing of a center-stack gas injection system.

2.7 Coil Support Structure Design

The conservative initial analysis of the existing machine attempted to qualify the existing vacuum vessel, TF and PF coil support structure to the full power supply limits. The analysis was based on worst-case combinations of the full on power supply currents. The resulting structure concepts were large and expensive and required significant field modifications to the existing vacuum vessel, structural mounting points and existing PF coil support ribs. In addition the modifications would have to be implemented on an operating experiment which was cluttered with external diagnostics and auxiliary equipment. The modifications were judged to be costly, risky and difficult to implement so a different approach was taken. To prevent mis-operations where the power supplies deliver current combinations and consequential forces/stresses beyond the design-basis envelope a Digital Coil Protection System (DCPS) is being implemented to constrain the operating envelope. The design described below is based on analysis using the operating conditions described in Table 1, and qualified for the increase in normal operating loads, a doubling of plasma current and toroidal field or roughly a factor of four. The support structure modifications have been designed to be installed in small modular sections with a minimum of in-situ field work. Provisions have been made for adjustments at the time of installation

2.7.1 PF 2 and 3 Coil Supports

The existing PF2 and 3 Coils are mounted to stainless steel pads welded to the upper and lower vacuum vessel domes. The only modifications required are increasing the size of the pad fillet welds from 1/8 to 5/16” and replacing the stainless steel fasteners with Inconel 718. The welds attaching the ribs to the domes have been inspected and qualified by analysis to meet the normal operating loads. The PF 2 supports are required to take 47.5 kips and the PF 3 are qualified for 138.8 kips.

2.7.2 PF 4 and 5 Coil Supports

The existing PF 4 and 5 coils are mounted through clamps to right angle brackets which are welded to the cylindrical section of the vacuum vessel. There are six brackets mounted under every other outer TF coil leg (Fig. 3). The existing supports will be supplemented with six additional supports mounted in the six unused locations under the shadow of the six remaining outer TF legs. The new supports will also add a large support column to resist the attractive magnetic forces between the upper and lower PF 4-5 pairs. To accommodate thermal growth only two clamps 180º apart (one being nearest the electrical leads) will provide radial constraint. The maximum allowable slip due to thermal growth for both coils is 0.12 inches. Also for PF5 only, the upper and lower coil shape must remain true, with respect to each other, to a tolerance of 0.12 inches.

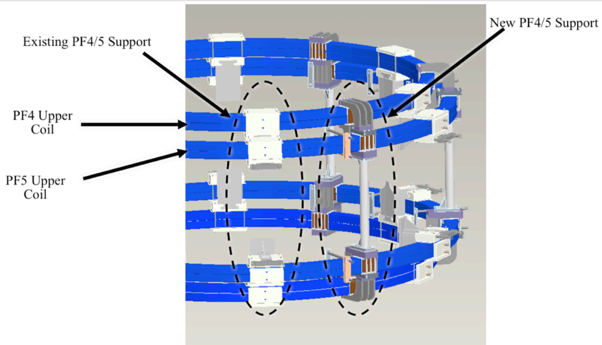

Fig.3 Upgraded PF 4 & 5 Coil Supports

2.7.3 Outer TF Coil Supports

The increased EM loads will excessively stress and deflect the existing TF coil outer legs. Consequently, the upgrade support structure must mitigate the stress within the outer legs (specifically the epoxy, and copper –epoxy interface). The upgraded supports must resist inplane bursting forces of 85,000 lbf and out of plane forces of 40,000 lbf each. In addition, the support must constrain the TF outer legs to a maximum deflection when loaded. This constraint applies to the region of the coil legs located between the top and bottom of the existing TF outer leg clamps (Fig. 4). The maximum deflection for this region is 0.75 inch. The support system couples a finite portion of load to the VV via a compliant member (i.e. a spring) and through an existing clevis. The design parameters for these two items are listed in table 9. To ensure that the supports can be easily installed the following design constraints for the TF outer support were included, 1) no direct modifications to the existing TF outer leg clamps, 2) no load coupled through the existing TF outer leg clamps, and 3) structural members are not to extend more than 3 inches (radially) beyond the existing TF clamps.

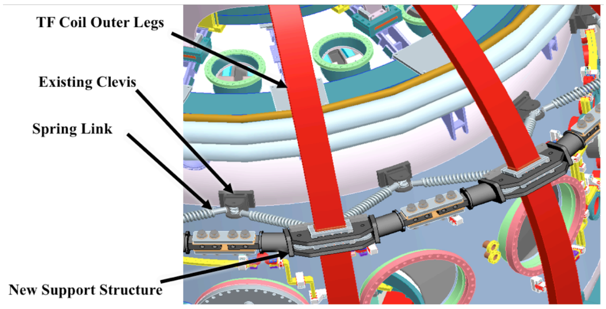

Fig.4 Upgraded Outer TF Supports

2.8 Digital Coil Protection System

In cases where the coil structural supports cannot be qualified to the worst case power supply limits without significant cost impact or technical risk, the design may be based on the nominal plasma equilibria cases with 10% headroom. Algorithms may be implemented in the DCPS to shutdown power supplies before loads outside the qualified structural envelope are encountered. The DCPS is being design with reliability such that its probability of failure is less than 10^6 / year. The DCPS will prevent accidental (either human or equipment failure) overload beyond the design conditions of the structure which the power supply system could generate even while each individual power supply is operating within allowable current range.

Approximately 100 force-based and 14 thermal algorithms are anticipated. The update rate of each type will be 1mS for the force-based and 10 mS for the thermal. Redundant current measurements for each coil and plasma current will be provided as inputs. The outputs will be separate TF and PF/OH level 1 fault lines. A local secure user interface will be used for setup and the system will interface with the NSTX controls system (EPICS) including pre- and post- event signal digitization and display.

2.9 Analysis

The analysis initially attempted to qualify the structural modifications for full power supply limits. Early on in the conceptual design it was realized that the modifications required to meet this requirement would be overly expensive and risky to implement on the operating experiment. Many diagnostics and auxiliary equipment would have to be relocated or redesigned to make room for the massive structure. A decision was made to qualify for the minimum and maximum loads from 96 scenarios identified in the General Requirements Document design point. Additionally calculations were required to specify an algorithm for computing the critical stresses, temperatures and loads for the DCPS limits.

2.10 Fabrication R&D

The fabrication of the TF bundle conductors requires a welded connection to a stub on either end. Using a conventional copper weld or braze would soften the metal and weaken the connection. Friction stir welding was investigated at Edison Welding Institute in Ohio. The tests were designed to develop a new procedure to weld the main TF conductor (CDA 10700) to the stub (CDA18150). The procedure required modifications to the mandrel tool, an offset to the tool travel of 2 mm and a reduction in the travel speed to 5 inches per minute. In the weld area, strengths greater than that of the CD 10700 and ductility greater than 15% were achieved.

Winding the OH Coil overtop of the TF bundle while maintaining a gap of 0.10 inch between the two coils also presented a challenge. A method was devised where a temporary spacer was created by molding a 0.10 inch thick layer of Aquapour onto the TF bundle before winding. Tests were conducted to verify the ability to remove the material after coil winding and cure. A sample was molded in a clear acrylic mold to create a 0.10 inch plate of the cured molding compound. The material was easily washed away with a jet of room temperature water introduced via a 0.08 inch diameter water tube. Separate tests were conducted to verify the OH conductor could be safely wound over the dried Aquapour without damaging the materials. Future tests planned will include the winding of a full sized short section of the TF bundle and OH coil.

3. Schedule

The NSTX center stack upgrade has successfully passed it Preliminary Design Review and a US Department of Energy Cost and Schedule review in August 2010. The upgraded center stack and associated structural repairs are planned to be installed during a 2 year outage starting in April 2012.

4. Conclusion

The NSTX - CSU will provide added physics capability and extend the useful life to an already successful experiment while providing good value to the sponsors.

Acknowledgments

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