Princeton Plasma Physics Laboratory

PPPL- 4415

PPPL- 4415

A Novel Demountable TF Joint Design for Low Aspect Ratio Spherical Torus Tokamaks

Robert D. Woolley

June, 2009

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

A Novel Demountable TF Joint Design for Low Aspect Ratio Spherical Torus Tokamaks

R. D. Woolley
Princeton University Plasma Physics Laboratory
Princeton, New Jersey, USA
woolley@pppl.gov

[*]***Abstract*—A novel shaped design for the radial conductors and demountable electrical joints connecting inner and outer legs of copper TF system conductors in low aspect ratio tokamaks is described and analysis results are presented. Specially shaped designs can optimize profiles of electrical current density, magnetic force, heating, and mechanical stress.**

I. Introduction

Toroidal plasmas in low aspect ratio tokamaks (i.e. spherical torii) have a much smaller central hole than tokamaks of higher, more conventional aspect ratio, so their coil systems use demountable TF system conductors instead of the discrete wound TF coils common in the higher aspect ratio tokamaks. The demountable components include a TF Central Bundle of wedge-shaped turn conductors carrying the TF threading current from the machine's bottom to its top, and TF Outer Leg assemblies which return the current in each turn from top to bottom. At the top and bottom, TF Radial Assemblies carry TF current between inner joints with TF Central Bundle turns and outer joints with TF Outer Leg conductors.

TF Outer Leg conductors and their joints don't pose difficult design problems since they are immersed in a relatively low intensity toroidal magnetic field and they inhabit a relatively uncrowded region in which there is plenty of space available for any needed mechanical support structures. The TF Central Bundle conductors also don't pose difficult design problems although they inhabit a relatively strong toroidal magnetic field region. Due to symmetry the TF Central Bundle assembly is self-supporting since its large centering forces are internally reacted by compressive wedging.

On the other hand, design of the TF Radial Assemblies can be challenging since they are subjected to large uncompensated magnetic forces and there is little room at their jointed inner ends for mechanical support structure. The design of these assemblies and their demountable joints with Central Bundle conductors is the present subject. Optimized part shaping is the proposed technique which addresses design issues. The occasion for this consideration is a proposed upgrade of the NSTX, so that is used to illustrate the concept.

A key shaping feature configures the demountable connections between radials and centerstack conductors as lap joints, so that TF conductor current on both sides of each joint flows in the same vertical direction. The primarily consequence is that forces resulting from TF current flow increase the pressure clamping each joint closed. A second consequence is that the resistive voltage gradient distributes the current uniformly through each joint, thus reducing local hotspots. This contrasts with conventional TF radial designs such as the initial TF Flag design of the National Spherical Torus eXperiment (NSTX) in which TF current makes a sharp, right-angle turn as it passes through its demountable joints.

A second key feature is that the mechanical force holding each demountable joint closed at low TF current is provided by reacting against hoop tension in an external structural ring. This contrasts with the initial NSTX TF Flag design in which threaded fasteners cutting through joints produce local concentrations of pressure, current density and heating while also reducing net current-carrying joint areas.

A third key design feature configures the (R, Z) poloidal plane current path beyond each lap joint to follow thin flexible straps specially shaped as moment-free constant-tension curves. This contrasts with the initial TF Flag design of NSTX whose straight horizontal current path shape generated large moments requiring extremely precise structural support to avoid severe nonuniform joint pressure profiles or even joint liftoff. The use of flexible conductive straps also accommodates small misalignments resulting from assembly tolerances or thermal growth.

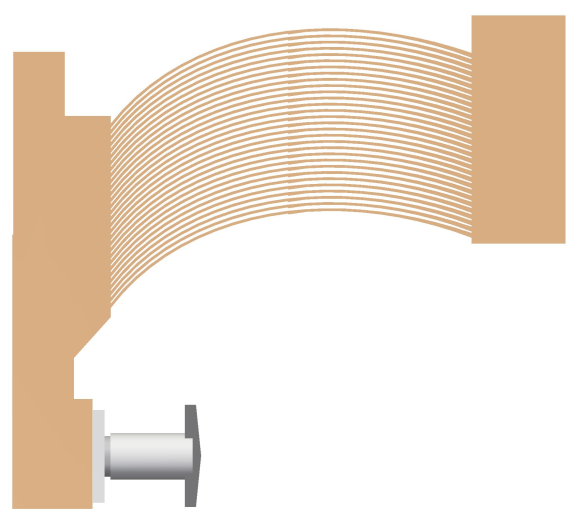

Figure 1: TF Radial Assembly

[*] This work is supported by the U.S. Department of Energy Contract No. DE-AC02-CH0911466

Boundary condition parameters for the differential equations defining the straps' constant-tension curve shapes are adjusted to minimize out-of-plane forces resulting from interaction of TF currents with the OH solenoid's magnetic field. Remaining out-of-plane forces resulting from interaction of TF currents with the variable magnetic fields generated by other PF coils and the plasma are reacted through restraining forces at inner and outer ends of the TF Radial assemblies.

II. PRIOR EXPERIENCE

A. *Existing NSTX Design*

The NSTX field coil design configuration [1], depicted in Figs 1 and 2, includes 36 Toroidal Field (TF) turns threaded vertically through the centerstack in two nested layers (12 inner & 24 outer), forming a TF Central Bundle assembly 5.33 m tall. The TF Central Bundle rests on its base on a pedestal on the floor of the test cell. An OH solenoid slides over centerstack TF turns, then rests on the same pedestal. A total of 72 Bolted TF joints and TF Radial Assemblies shaped like flags connect centerstack turn conductors to flex assemblies which in turn connect to the TF outer leg conductors. The current path turns a right angle corner at each inner bolted joint. TF outer leg conductor terminations are mechanically supported by upper and lower umbrella structures which are mounted on the vacuum vessel. In turn, the vacuum vessel is mounted on the test cell floor.

A unique design structure provides support in parallel to the bolted joints themselves for the TF Radial Assembly Flags. Support relies on epoxy/glass potting compound injected into Flag Boxes, forming sliding sleeves around flags. The Flag Boxes are bolted to annular hub-disks forming beams opposing in-plane torques and collecting out-of-plane torques. The out-of-plane torques on hub-disks are resisted by a vertically sliding spline structure that rotationally connects the top and bottom of NSTX through its vacuum vessel.

If the potting, flag boxes, hub disks, and other components such as spline and vacuum vessel attachments were sufficiently stiff, then this unique design structure would unload the bolted TF joints. It is necessary to unload them, for the bolted joints are not able to withstand even 25% of the flags' electromagnetic loading without help.

It was initially decided that the OH solenoid should be quickly replaceable with a spare. As a result, the maximum outer radius of the TF Central Bundle was set at 9.77 cm, strictly less than the 10.42 cm inner radius of the OH solenoid.

The reason for adopting the complexity of configuring the TF Central Bundle in two layers instead of one was to provide enough space for bolts to cut through the joints. Since the outer radius of the TF was 0.0977 m, a single-layer 36-turn TF design would have unduly restricted the total maximum turn width to 17 mm, including interturn insulation, threaded bolt insert, and the conducting joint area. Therefore the TF Central Bundle was configured in two layers with 24 turns in the outer portion, 12 turns in the inner portion, and the inner turns radially extended to match the outer turns' 9.77 cm radii at their bolted joints. Restricting the outer layer to 24 turns increased this total turn width to 25.5 mm.

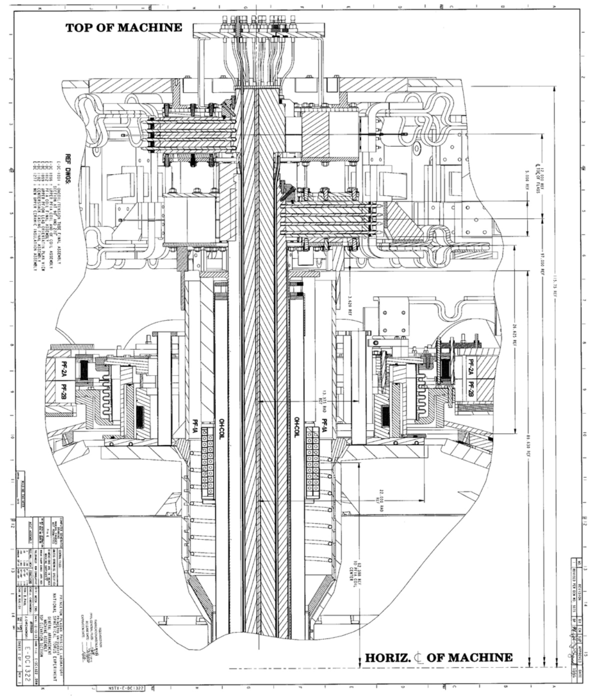

Figure 2: Existing NSTX Design

Accommodating thermal growth is a theme driving support structure design features. The 5.33 m tall TF Central Bundle contracts vertically by about 1 mm as the TF coils are cooled from 25C room temperature to the 12C temperature of the chilled cooling water system, and then it expands vertically by 8 mm during a TF pulse as the copper temperature increases from 12C to 100C. The vacuum vessel's temperature does not change significantly during a pulse, so the vertical distance between TF outer leg terminations also remains approximately constant. The TF radial connections must be able to deform without excessive strain in order to accommodate the time-varying differences between inner and outer TF heights. Since the lower ends of both inner and outer TF conductors are supported by the floor, most of the changing vertical mismatch occurs at the top.

B. *Experience With Existing Design's Performance*

This configuration has experienced difficulties since the first NSTX plasma in February 1999. An arc and fire occurred after a TF bolted joint of the first design opened while powered.. In 2003, the TF Radial Flag assemblies and their supports were redesigned and replaced The new design increased flag in-plane stiffness by using a single block of copper for each assembly, but otherwise did not significantly change the configuration's geometry or support schemes. TF joints of the second design failed due to inadequate potting quality. The third try still behaves strangely at present above 0.5 Tesla, restricting field operations to less than 0.6 Tesla. Pitting of joint contact surfaces also continues, perhaps due to localized current concentrations and arcing.

The main reliability issue has been poor performance of support features for the TF Radial Flag assemblies.

III. NSTX CENTERSTCK UPGRADE

A. Parameter Goals

It is proposed that the NSTX be upgraded to higher toroidal field and plasma current with longer pulse duration without changing its TF outer legs, vacuum vessel, or outer PF coils. The outer radius of the centerstack TF conductors would be increased from 0.0977 m to 0.1941 m, and they would be surrounded by a new OH solenoid winding with higher flux capability. The TF current-per-conductor turn would increase from 71 kA to 130 kA. The support structures would be modified as needed to accommodate the significantly stronger forces. The plasma current would increase from 1 MA to 2 MA and the plasma pulse duration would increase from 0.5 s to 5.0 s. The plasma's outer radius would remain the same while its inner radius would increase to allow for a new wider centerstack, so its major radius would increase from about 0.87 m to 0.93 m while its minor radius would decrease slightly.

B. Concerns

Current design characteristics seem to be the reason for the poor performance experience of the existing NSTX design. TF flag stiffness transmits to joints torques resulting from lateral and vertical electromagnetic forces. The design scheme involves two competing load paths, TF flag stiffness vs flag box potting compound stiffness. Without flag box support, each flag behaves like a straight beam cantilevered from its centerstack TF turn. Its long lever arm requires large forces within the joint to balance much smaller distant forces. Even with ideal support, NASTRAN studies predict joint lift-off would occur at less than the full 0.6 Ts field, but it would occur at much lower field if potting is bad.

A fundamental problem is that the horizontal current flow direction in the flags causes a vertical force and resulting torque which act to shear each joint. Magnetic forces do not clamp joints closed, they only rock joints laterally or vertically

The existing design's right-angle turn in current direction concentrates current at the joint's corner, then the current concentration jumps to new locations if and when lift-off occurs. Contact surfaces are also cut by bolts which concentrate current in heightened pressure zones surrounding bolt holes, while also reducing overall net contact area.

The proposed NSTX upgrade will increase toroidal field, plasma current, poloidal field, and pulse duration. Forces will increase at many locations by more than a factor of 3, and termperatures will also increase. It is prudent to replace the existing design with a more robust one.

IV. THE NEW DESIGN

A. Single-Layer TF

The new TF radius accommodates thirty-six 32.9 mm wide copper turns each overwrapped with an additional 0.8 mm thick insulating layer. This is sufficiently wide so a two tier TF system is not needed.

B. Lap-Joint Configuration

In the inner vertical bar portion of the TF Radial assembly above the joint carrying the full 130 kA TF turn current, the magnetic Lorenz force directed inwards is about 500 kN/m (=2900 pounds/inch). This results in a magnetic clamping pressure at the top of the joint of 16 MPa (=2900 psi) acting to hold the joint closed in addition to the mechanical pressure applied by preloaded springs acting against an external ring. The local magnetic clamping pressure diminishes to zero at the joint's bottom where TF current has fully transferred through the joint to the central TF turn conductor.

C. Constant Tension Curve Flexes

Many thin strap conductors within the TF Radial Assembly connect its inner vertical bar section to its outer bolting plate section. Their in-plane flexibility prevents them from transmitting to the joint significant moments from in-plane forces. They can also deform slightly without large forces to accommodate differential thermal expansions. Each is shaped to follow a constant-tension (CT) curve, the natural shapes in the poloidal (r,z) halfplane assumed by completely flexible conductors supported from their ends when carrying TF coil current in a purely toroidal field geometry. Other shapes deform under load to approach the CT curve shape. Using CT curves TF Radial Assemblies minimize EM loading bending moments transmitted to joint while also minimizing peak stresses due to bending moments. CT curves are defined mathematically by requiring the local radius of curvature to vary in direct proportion to the radial location, r. Fig. 3 shows a family of normalized CT curves.

A numerically controlled water-jet cutter can produce the TF radial assemblies by cutting copper plate as shown in Figs. 4 and 5 photographs of a test piece cut from aluminum.

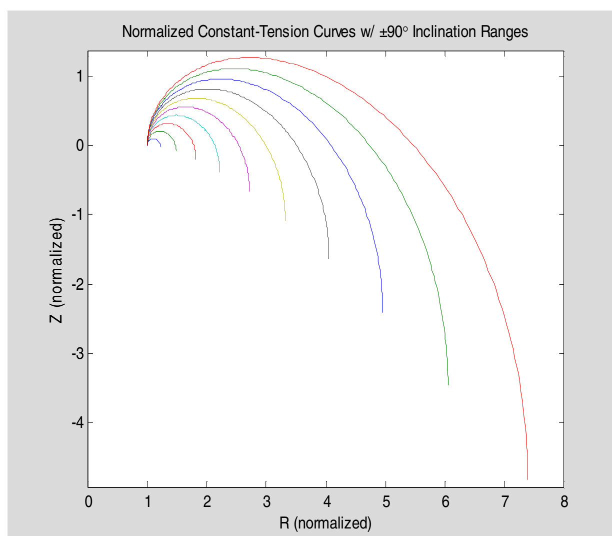

Figure 3: Constant Tension Curves

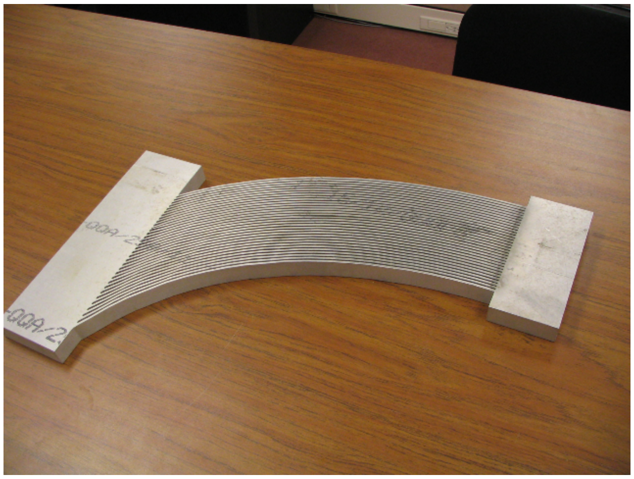

Figure 4: Test Piece Cut From Aluminum Instead of Copper Plate

Figure 5: Closeup View of Test Piece

Figs. 6-9 represent an analysis modeling the full TF-only current through a turn combined with the full 8 mm relative vertical displacement of the centerstack with respect to the outer leg. Fig. 6 shows model geometry. Fig. 7 shows current is relatively uniform through the joint, Fig. 8 shows the resulting pattern of toroidal field strength, and Fig. 9 shows the peak Von Mises stress is less than 133 MPa, which is acceptable. Combined field cases have not yet been analyzed.

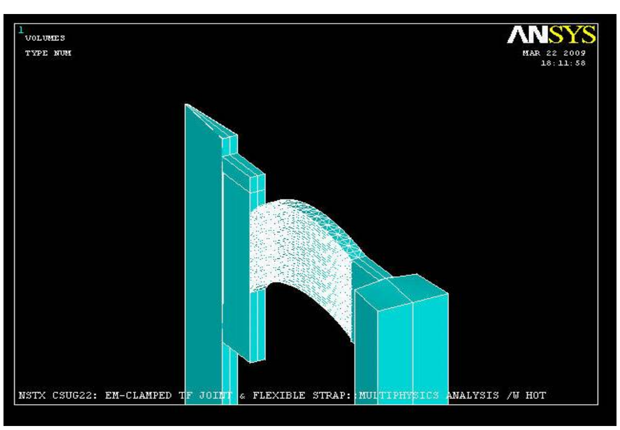

Figure 6: ANSYS Multiphysics Model

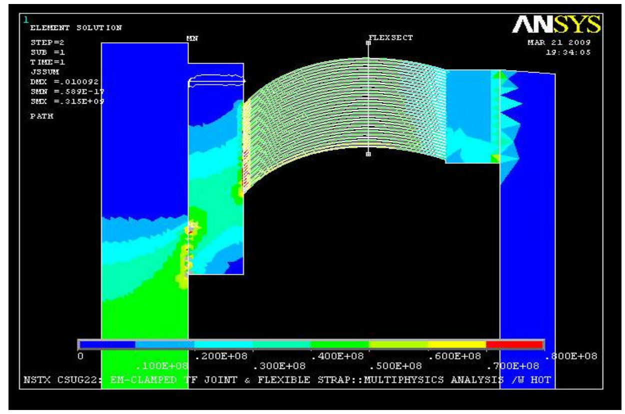

Figure 7: Calculated Current Density

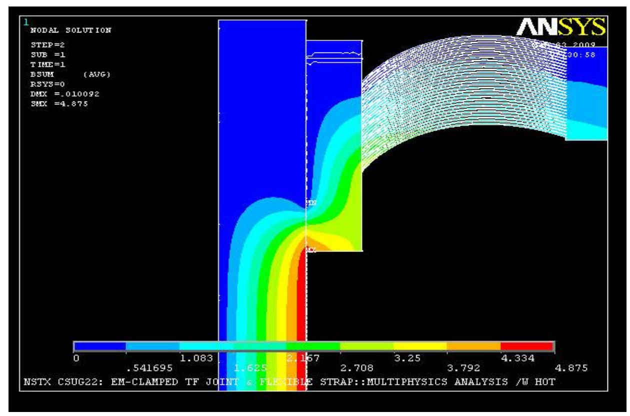

Figure 8: Calculated Toroidal Field (Tesla)

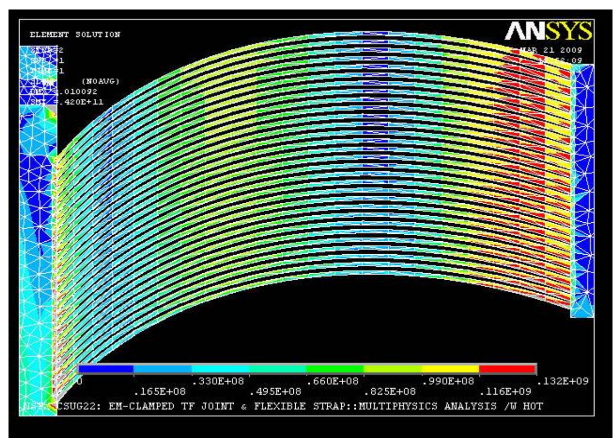

Figure 9: Calculated Von Mises Stress In CT Curve Flexes

References

[1] C. Neumeyer et al, "National Spherical Torus Experiment (NSTX) Engineering Overview and Research Results 1999 – 2000", PPPL-3491; UC-70, October 2000

[2] R. Woolley, "Analysis of NSTX TF Joint Measurements", Proceedings of the 21st SOFE, Knoxville, Tennessee, September 2005

[3] C. Neumeyer et al, "National Spherical Torus Experiment (NSTX) Center Stack Upgrade", Proceedings of the 23rd SOFE, San Diego, CA, June 2009

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov