NSTX Upgrade

TF Inner Leg Torsional Shear, Including Input to the DCPS

NSTXU-CALC-132-07-00

Rev 0

February 2, 2011

Prepared By:

____
Peter Titus, PPPL Mechanical Engineering

Reviewed By:

____
Robert Woolley

Approved By:

____
Jim Chrzanowski, NSTX Cognizant Engineer

PPPL Calculation Form

Calculation # **NSTXU-CALC-132-07** Revision # 00 WP #, 0029,0037 (ENG-032)

Purpose of Calculation: **(Define why the calculation is being performed.)**

Quantify and Qualify the Inner Leg Torsional Shear Stress for all the 96 scenarios, with and without plasma and provide a means of calculating the torsional shear in the Digital Coil Protection System (DCPS)

References **(List any source of design information including computer program titles and revision levels.)**

-See the reference list in the body of the calculation

Assumptions **(Identify all assumptions made as part of this calculation.)**

Out-of-Plane (OOP) load distribution to the components of the tokamak depend on accurate modeling of the torsional stiffness of the system. The inner leg torsional shear has been investigated with different modeling and analysis techniques to try to envelope possible uncertainties in the OOP load dstribution, and thus uncertainties in the torsional shear stress. The Global Model Results are Chosen as the most representative. The current version (Feb 2011) of the global model is assumed to adequately represent the evolving structural components (pedestal, Lid, Outer TF support).

Calculation **(Calculation is either documented here or attached)**

Attached in the body of the calculation

Conclusion **(Specify whether or not the purpose of the calculation was accomplished.)**

Shear stresses are below 24 MPa in the inner leg corners near the friction stir welded flags. Pending acceptable results from testing the CTD-101K/Cynate ester primer system, the torsional shear is acceptable. Influence coefficients for the DCPS algorithm have been generated based on the global model [2] and a single TF model.

Cognizant Engineer's printed name, signature, and date

Jim Chrzanowski ______________________________

I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

Robert Woolley ______________________________

Table of Contents

Executive Summary:

This calculation is intended to qualify the inner leg torsional shear stress and provide an appropriate algorithm for calculation of these stresses in the digital coil protection system (DCPS). The corners of the inner leg experience some current "bunching" due to the resistive and inductive behavior of the currents turning the corner at the flag extension. This produces some higher temperatures than the Design Point calculates [13] and the shear capacity of the epoxy bond degrades with higher temperature. From the global model simulations, the local Peak Shear stresses are below 24 MPa in the inner leg corners near the friction stir welded flags. The global model load files are based on the earlier +/-24ka OH scenarios and the the use of the influence coefficients allows computation of the TF torsional shear for the latest set of scenarios.

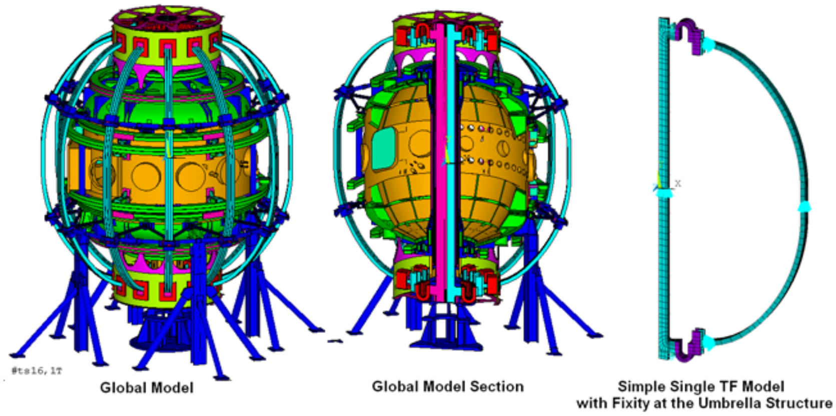


Figure 1 FEA Models Used for the Calculation if TF Inner Leg Shear Stress Influence Coefficients. The version of the global model has the overlaid plate reinforcements and the older pedestal and knuckle clevis

Based on the DCPS influence coefficient TF inner leg upper corner torsional shear, for all 96 June 3 2010 scenarios are all below 20 MPa with and without plasma. Rigorously these should have the 10% headroom applied (the coefficients do not include this) - So the torsional shear stress to compare with the allowable is 22 MPa. Pending acceptable results from testing the CTD-101K/Cynate ester primer system[14], the torsional shear is acceptable. Influence coefficients for the DCPS algorithm have been generated based on the global model [2]

For the worst PF loads considered in the global model, the peak torsional shear stress is 20 MPa – just below the allowable of 21.7 MPa. This analysis utilizes the global model described in ref [2]. The global model requires extensive set-up and run times and it has been difficult to maintain the model consistent with the design changes in the outboard structures. There have been some changes in the PF scenario as well between the CDR and FDR. The influence coefficient approach not only has utility for the DCPS, but also allows 16 load files, - 15 from the PF's and 1 from the plasma to be used in spreadsheet evaluations of the 96 scenarios with and without plasma. This replaces 192 load cases with 16load cases and spreadsheet calculations of the torsional shear.

Out-of-Plane (OOP) loads on a toroidal field (TF) coil system result from the cross product of the poloidal field and toroidal field coil current. Support of OOP loads is statically in-determinant, or multiply redundant, requiring an understanding of the flexibility of the outboard structures and the inboard stiffness of the central column. There are a number of ways in which the torsional shear stress in the inner leg of the TF can be calculated. The global model is the primary tool for this computation. A single TF model was investigated to see if the inner leg OOP forces alone dominate and if the outer structures could be ignored. This turned out to be not the case. This means that the global torsional stiffnesses of the umbrella structure, it's proposed upgrade reinforcement, the port region stiffness, the top and bottom spoke assembly stiffness, and the pedestal stiffness all will have some effect on the inner leg torsional shear

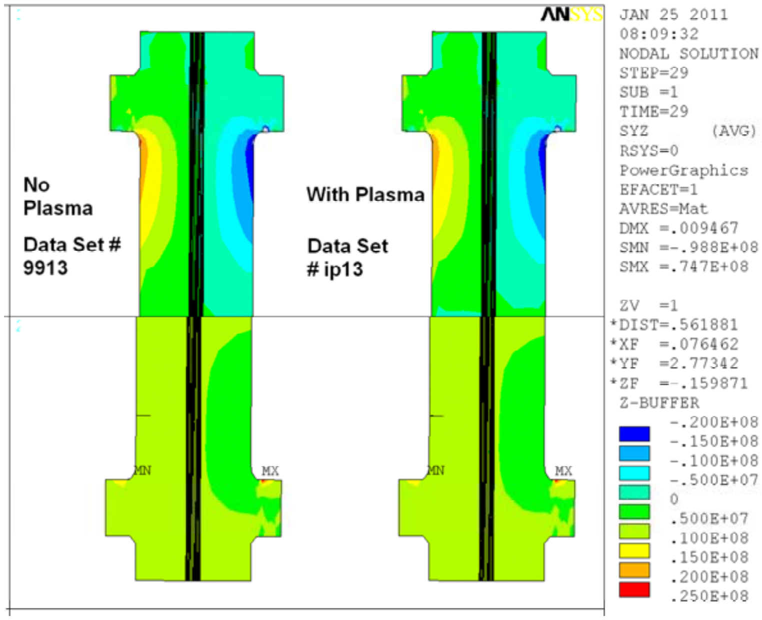


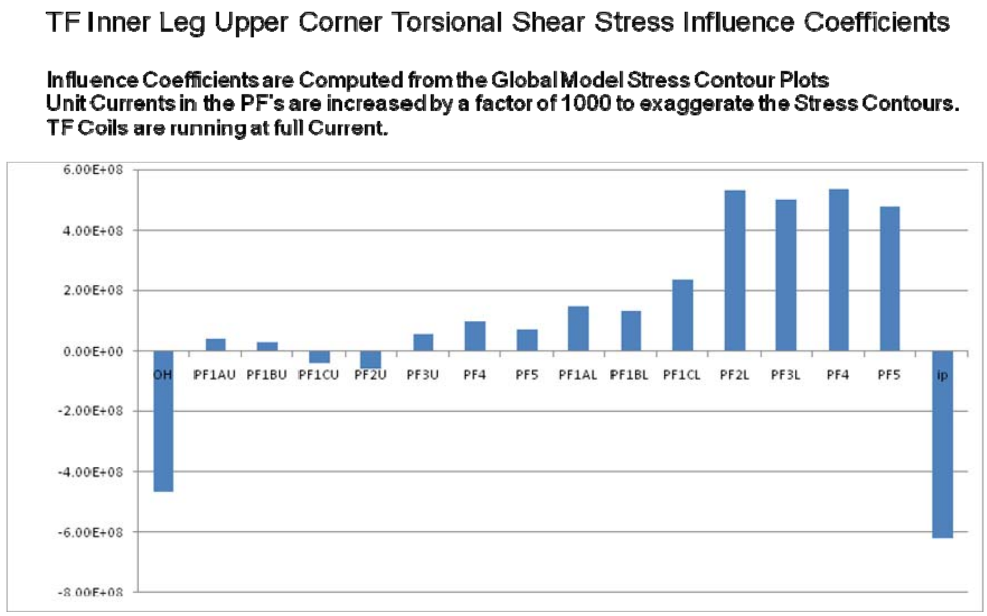
Figure 2 This shows one current set from the global model analysis, in which the plasma current effect on the torsional shear is difficult to discern. From the influence coefficient calculations it is about a 1 MPa effect (see Figure 6). The magnitude is close to 20 MPa.

Torsional shear stresses in the inner leg have been found to be slightly lower with the inclusion of the plasma in the load calculations, this has been found when applying loads calculated with and without the plasma on the global model, and also in the influence coefficient calculations.

DCPS Algorithm Summary

The out-of-plane (OOP) component of the critical stresses in the inner leg will approximately scale with the upper and lower half outer leg net moments. These are available from Bob Woolley's equations NSTXU CALC 132-03-00 [6], and are implemented in Charlie Neumeyer's Design Point [4, 5] . The moment summation of the upper half vs lower half of the tokamak is not completely useful because the stiffness of the structure will determine how much torque goes to the central column and how much goes to the outer TF and vessel structures, and the local distribution of OOP loads is important compared with the global torque.

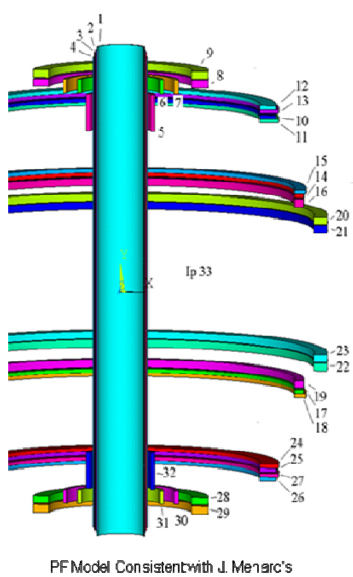
A more detailed calculation of the inner leg shear stress relies on the elastic response of the entire tokamak and the Lorentz Loads from the poloidal field distribution crossing the inner leg currents. The global model was run with full TF current and 1000kA of current in each PF coil. The torsional shear in the upper and lower inner leg radii were then determined from each of the 16 load cases that resulted.



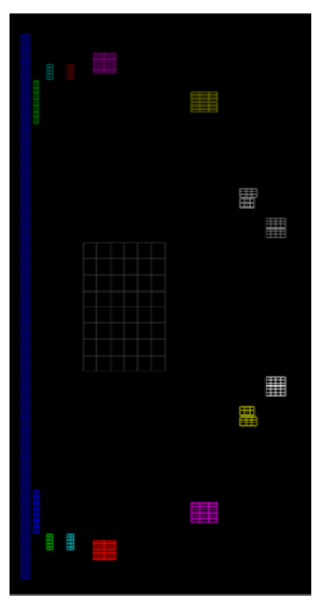
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
-4.67E+08	4.18E+07	3.07E+07	-4.06E+07	-6.22E+07	5.35E+07	9.52E+07	7.07E+07	1.48E+08	1.33E+08	2.38E+08	5.33E+08	5.04E+08	5.37E+08	4.76E+08	-6.20E+08

Figure 4 Influence Coefficients Calculated from the Global Model.

The methodology employed here has some history in the original NSTX. The coil protection calculator exercised a model of the TF system with unit PF currents and calculated stress multipliers. This is described in Irv Zatz's memo [12]. Much of the initial work on coil protection was done in support of TFTR operation. The theory is also described in Bob Woolley's DCPS system description document [1]. In Woolley's document he describes a system code which predicts elastic responses of the entire tokamak based on unit coil currents. The global model employed here is essentially this systems code. The inner leg torsional shear is a single stress component, and lends itself to the linear superposition methodology that Woolley describes. Other coil and structure performance evaluations will be based on equivalent stresses or combinations with thermal effects, that will make simple application of linear superposition less tractable. ,



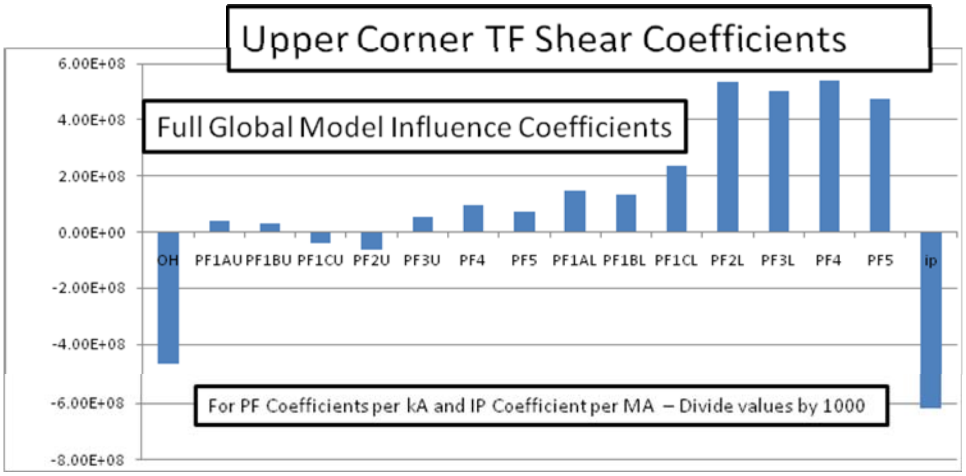
PF Model Consistent with J. Menard's 33 coil set Equilibria
Used as a starting point to create the model at right.

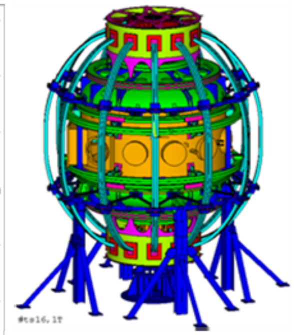


PF Model Consistent with R. Hatcher's 18 coil set Influence Matrix.

Figure 5 Coil Builds Used in the FEA analyses and the DCPS

The global model Lorentz Forces are computed for a coil set that includes all individual coil pancakes. To be consistent with the influence coefficients used in the DCPS, a regrouping of the coils is necessary.





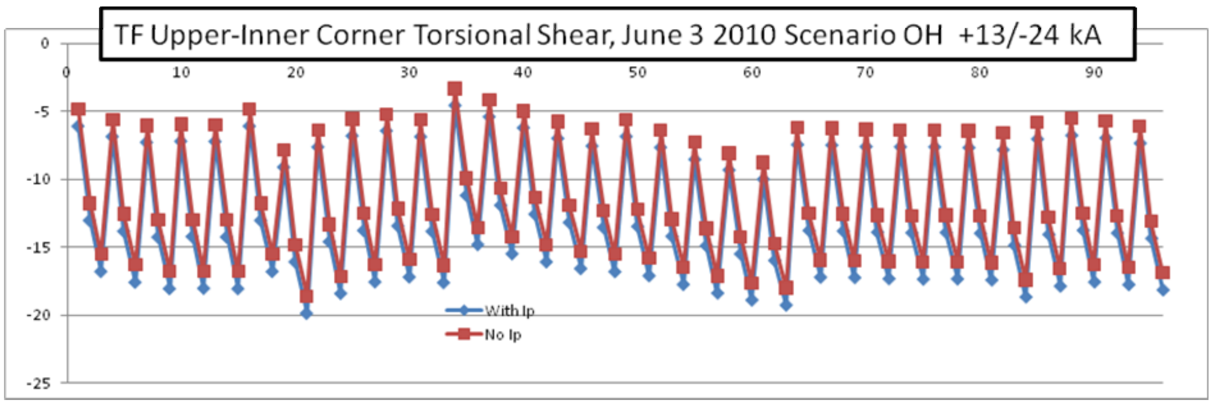


Figure 6 Torsional Shear Stresses from the influence coefficients multiplied by the Design Point Scenarios

Note that there is a shift upward of 1 MPa with no plasma. This would give an indication of the effect on the torsional shear due to a disruption. There is no dynamic load effect, and the vessel will tend to sustain the flux at the TF for some time after the disruption. The effect of the plasma and plasma change is stronger at the equatorial plane, but the total shear is smaller than at the corners.

If the fixity supplied by the crown connections, at the upper and lower ends of the inner leg, is sufficient, then only a model of the inner leg is needed. This would allow a simpler modeling of the inner leg shear, but calculations of the influence coefficients for the global model and a simpler TF model with fixity at the umbrella structures showed that there were large contributions from the outer PF coils that were suppressed by artificially fixing the umbrella structure.

Design Input

References

[1] DIGITAL COIL PROTECTION SYSTEM (DCPS) REQUIREMENTS DOCUMENT (DRAFT), NSTX-CSU-RD-DCPS for the National Spherical Torus Experiment Center Stack Upgrade, February 5, 2010 R. Woolley

[2] NSTX-CALC-13-001-00 Rev 1 Global Model – Model Description, Mesh Generation, Results, Peter H. Titus February 2011
[3] NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc I. Zatz
[4] NSTX Design Point Sep 8 2009 http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html
[5] NSTX Design Point June 3 2010 http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html
[6] OOP PF/TF Torques on TF , R. Woolley, NSTXU CALC 132-03-00
[7] NSTX Influence Coefficients, calculation # NSTXU 13 03-00, Ron Hatcher DATE: July 9 2009
[8] NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc I. Zatz
[9] "MHD and Fusion Magnets, Field and Force Design Concepts", R.J.Thome, John Tarrh, Wiley Interscience, 1982
[10] "Provisions for Out-of-Plane Support of the TF Coils in Recent Tokamaks", P. H. Titus 1999 MT16
[11] CTD Shear Stress Testing Proposal, Appendix A
[12] NSTX MEMO**#:** 13-010515-IZ-01 DATE**:** 15 May 2001 FROM: I. J. Zatz , SUBJECT: NSTX Coil Protection Calculator
[13] Coupled Electromagnetic-Thermal Analysis, Han Zhang, Calc # NSTXU-CALC-132-05-00
[14] Evaluation and Testing of Pure Cyanate Ester Resin at UKAEA. Garry Voss 27 August 2007

Drawing Excerpts

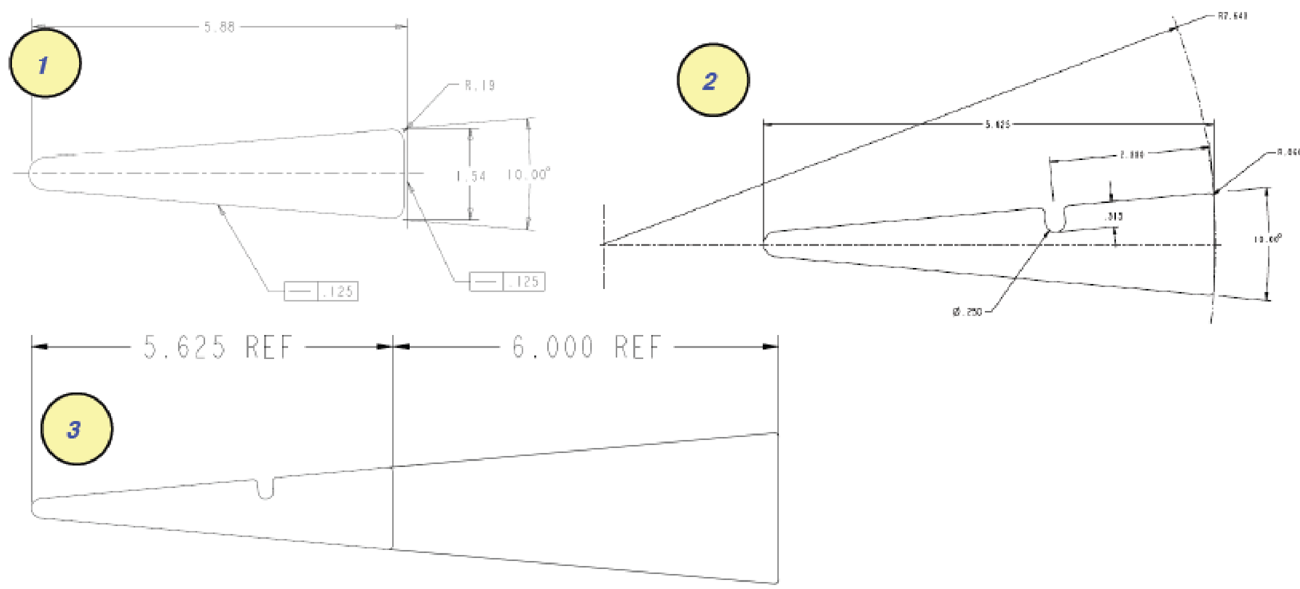


Figure 7 TF Coil Drawing Sections

Material, TF Inner Leg Epoxy Strength

The criteria document requires a static evaluation of the shear strength, but fatigue will govern.

From the GRD:

For engineering purposes, number of NSTX pulses, after implementing the Center Stack Upgrade, shall be assumed to consist of a total of ~ 60,000 pulses based on the GRD specified pulse spectrum.

The TF inner leg will be vacuum pressure impregnated (VPI) with the individual conductors primed with a Cyanate Ester system that improves bond strength an can survive the peak temperature in the inner leg corner - calculated by H. Zhang, ref [13] . This temp is a little over the original 100C limit. and a VPI/Primer system needed to be found that would survive the higher temperature and not creep or fail in fatigue. Gary Voss from MAST originally raised this issue.

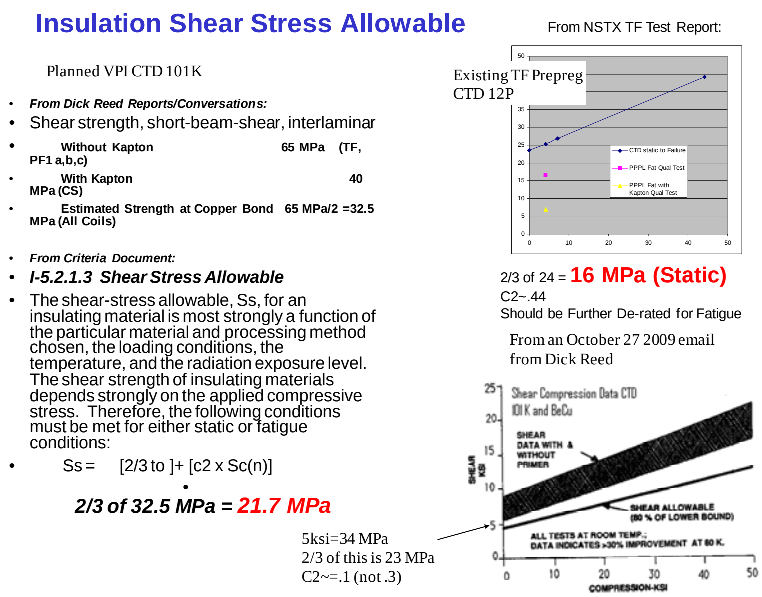


Figure 8

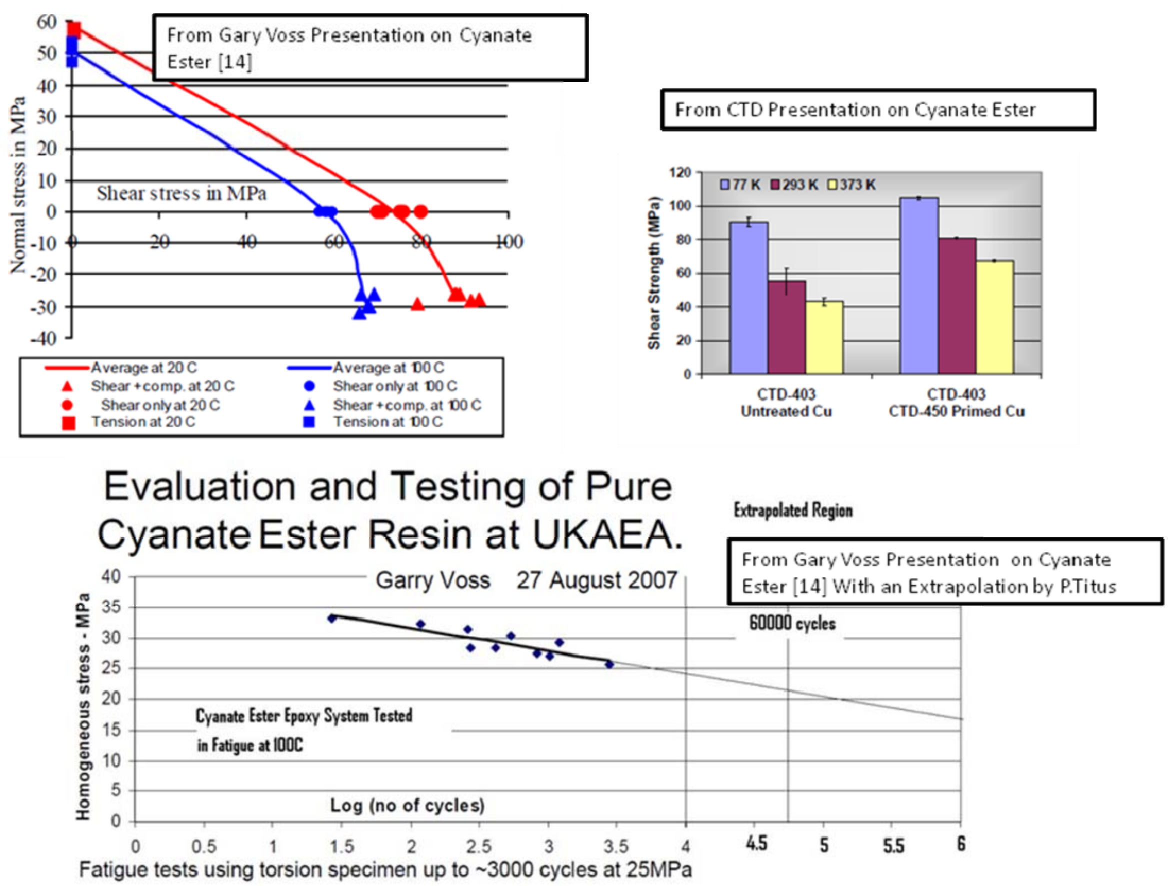


Figure 9

The fatigue strength for the required 60000 cycles based on the Cyanate Ester primer at 100C is 21.5 MPa. The allowable without compression is 2/3*21.5= 14.33 MPa. It is important that the testing currently underway at Composite Technology Development, Appendix A successfully shows higher capacity.

Global FEA Models and Results

The global model [2] has been exercised with a number of configurations to quantify the inner leg torsional shear. The slide below, Figure 10, summarized this work for the PDR. One point made in the slide is that the compressive stresses due to TF centering load wedge pressure, are small. In other tokamaks. the compressive stress improves the shear capacity of the epoxy bond. For NSTX there is minimal help from the compressive stress. There are actually some tensile stresses that develop away from the corner where the currents "bunch" This is addressed in Han Zhang's coupled current diffusion calculation[13]. A number of design evolutions effected the OOP structural stiffness's and varying degrees of the 96 scenarios were analyzed for various configurations of the machine. The global model analysis is based on generation of load files outside the structural solution in ANSYS. a Biot Savart solution is used which takes about an hour per load file. Recently these have been updated to include the 10% headroom in the design point spreadsheet load calculations and load files with and without the plasma have been run. But these are still based on an older +/-24kAOH scenario set, and the results of this analysis are updated by application of the influence coefficients.

A variety of current and earlier results are shown in this section to build confidence that the shear stresses in the inner leg are adequately calculated by both individual current set calculations and applications of teh influence coefficients.

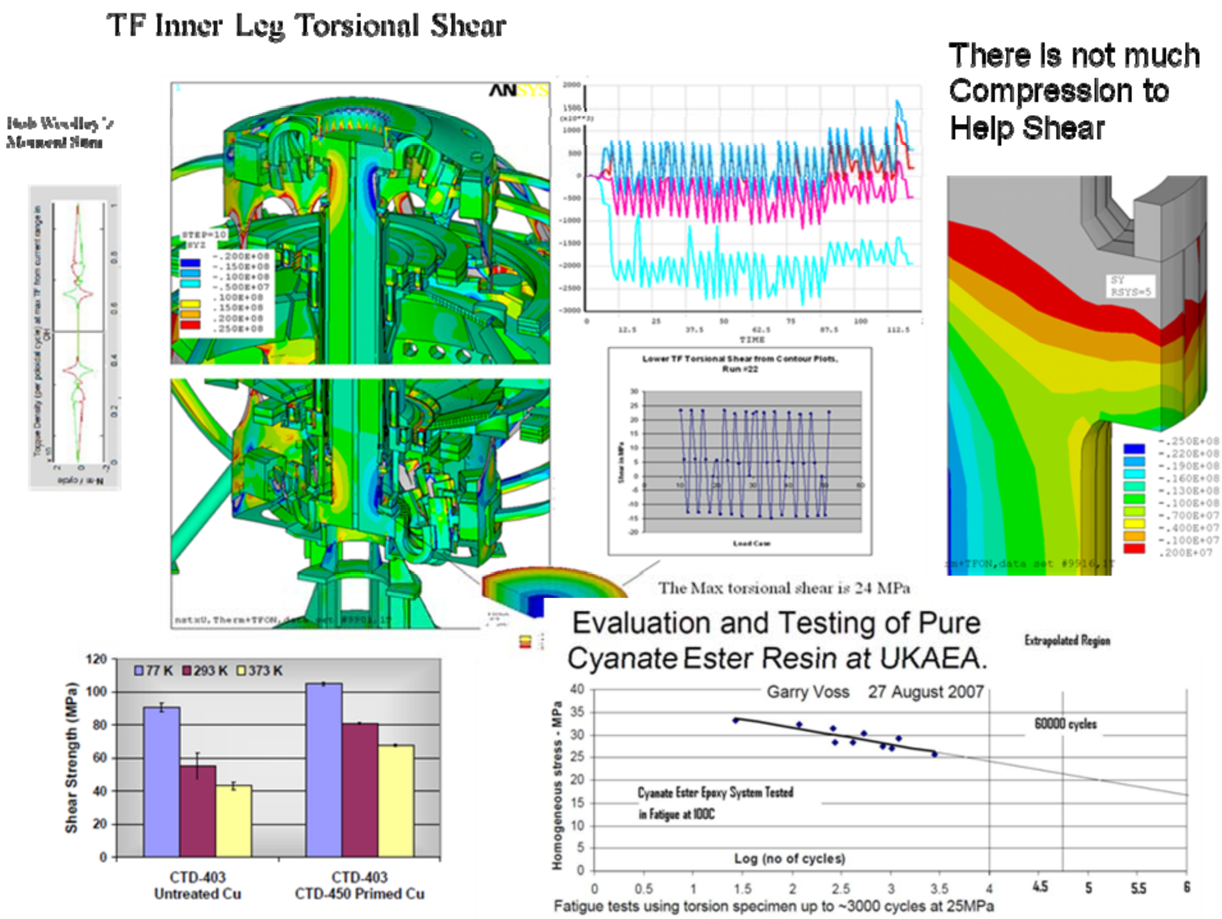


Figure 10 Initial Model Representing the Current (2010) configuration

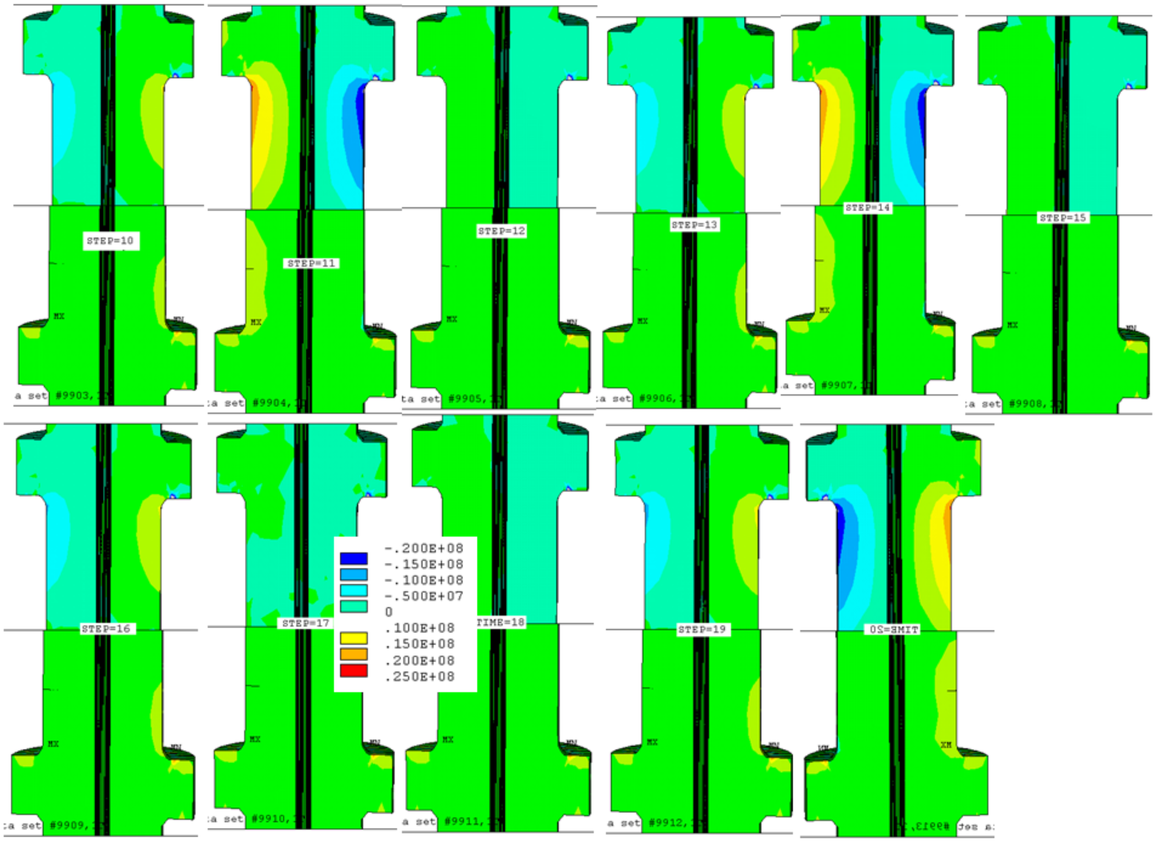


Figure 11 Torsional Shear Results from Global Run #27 [2]

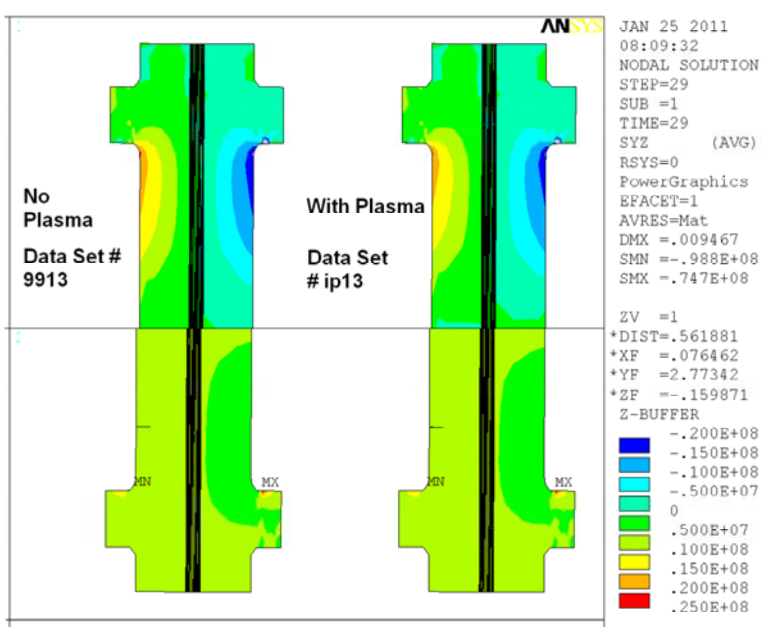


Figure 12 This shows one current set in which the plasma current effect on the torsional shear is difficult to discern.. From the influence coefficient calculations it is about a 1 MPa effect (see Figure 6). The magnitude is close to 20 MPa.

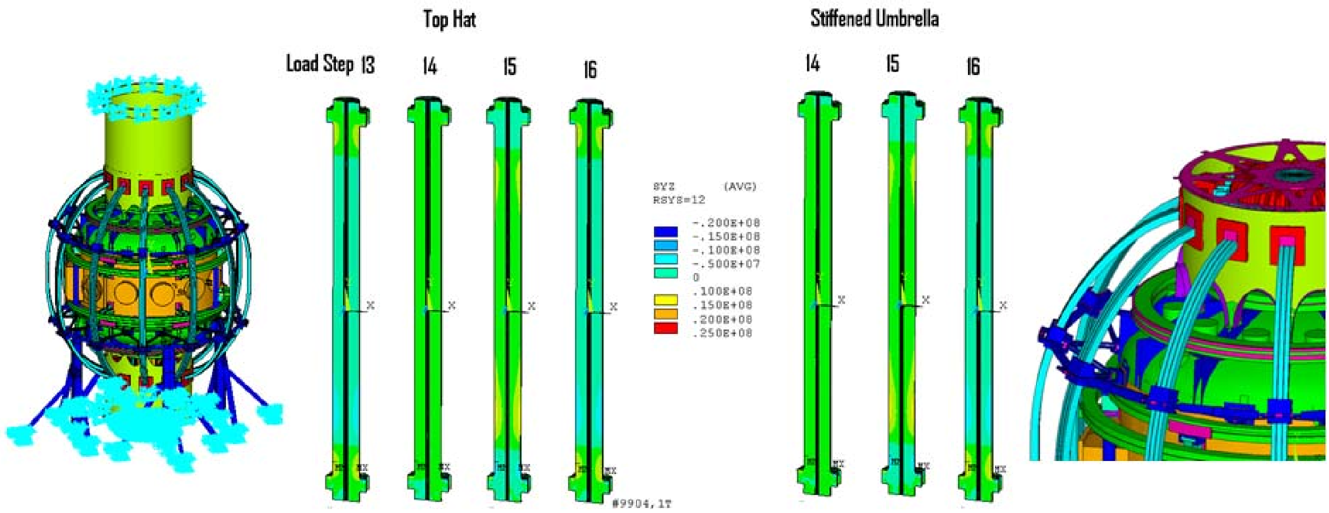


Figure 13

Torsional shear stress in the inner leg was an issue when an extension of the upper umbrella structure (Top Hat) along and struts extending to the cell walls were suggested to support the net torque of the machine and hopefully reduce the torsional loading at the vessel mid plane and other structures that were affected by the OOP loading. Competing with these reinforcements is the arch reinforcement that was proposed early in the CDR. The "top hat" did help the port region, and the umbrella legs, but did not appreciably alter the inner leg torsional shear stress. Only a few load cases were considered. It was the cost of the "top hat" installation that was unattractive.

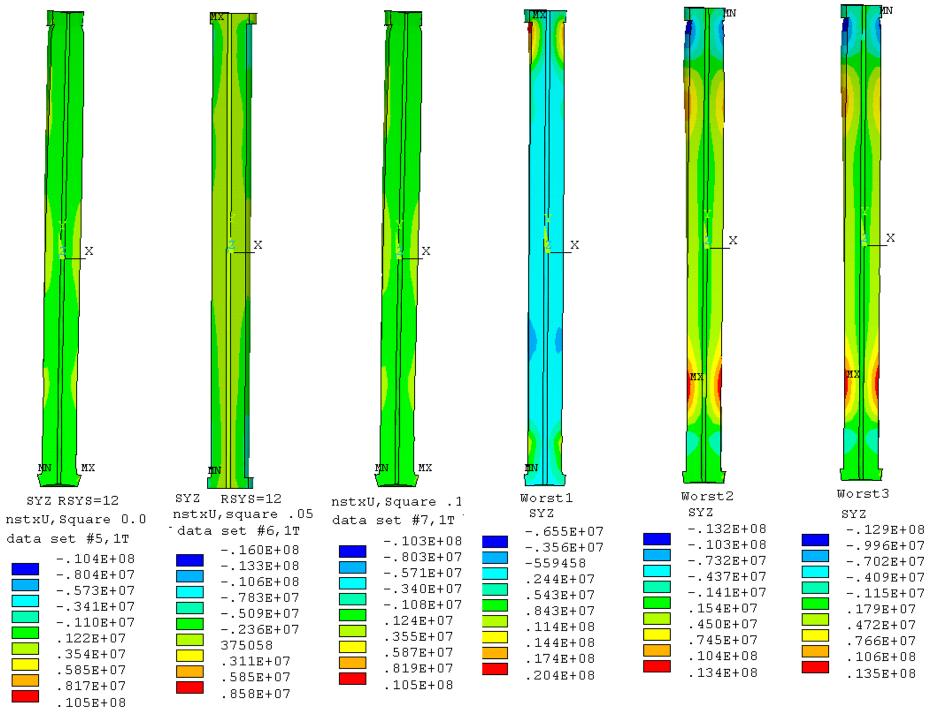


Figure 14 CDR Results

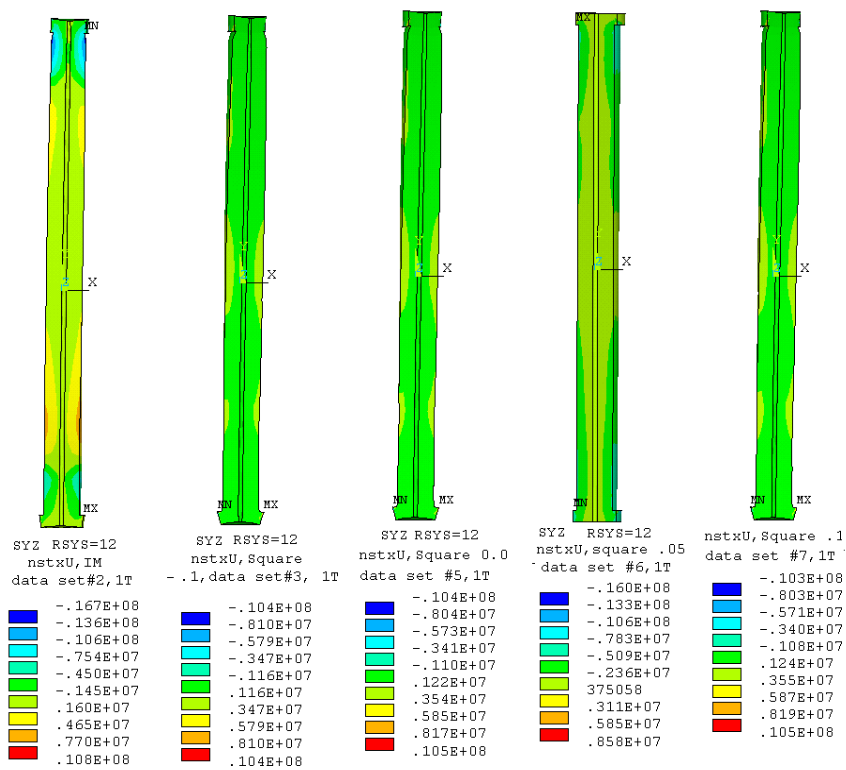


Figure 15

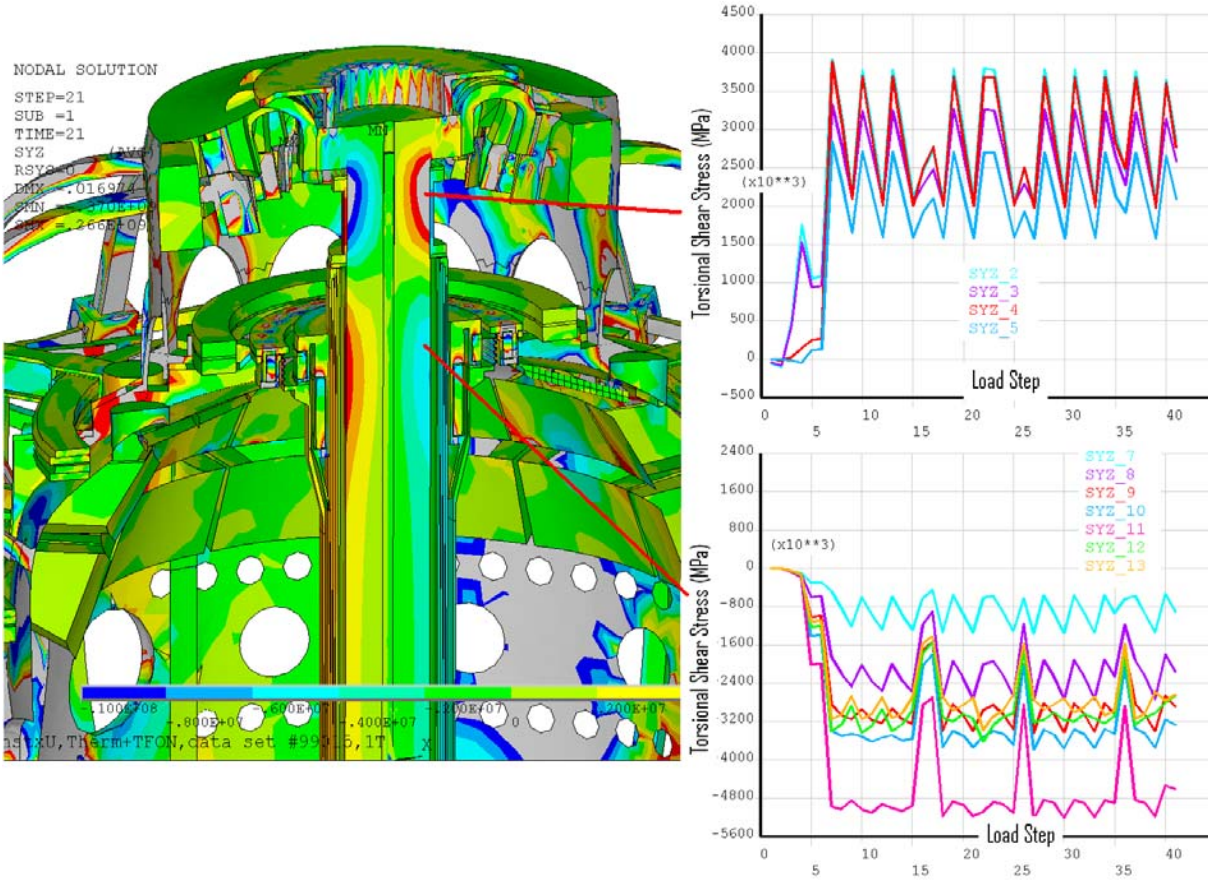
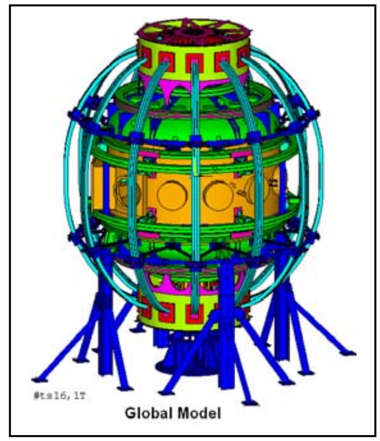


Figure 16 CDR results - Note that the time history plots are inconsistent with the contour plot results.

DCPS TF Inner Leg Torsional Shear Influence Coefficients From the Global Model



. A detailed calculation of the inner leg shear stress relies on the elastic response of the entire tokamak and the Lorentz Loads from the poloidal field distribution crossing the inner leg currents. The global model was run with full TF current and 1000kA of current in each PF coil. The influence coefficients are based on 1 kA, but it was expected that TF loading might overwhelm the loads from individual smaller coils. The model is linear and the stress due to the PF loads should be fully scalable by current. The influence coefficients are corrected in the spreadsheet. The force calculations are computed The torsional shear in the upper and lower inner leg radii were then determined from each of the 16 load cases that resulted.

Mapping the 33 Coil set to the 16 Coil Set Used for the Influence Coefficients

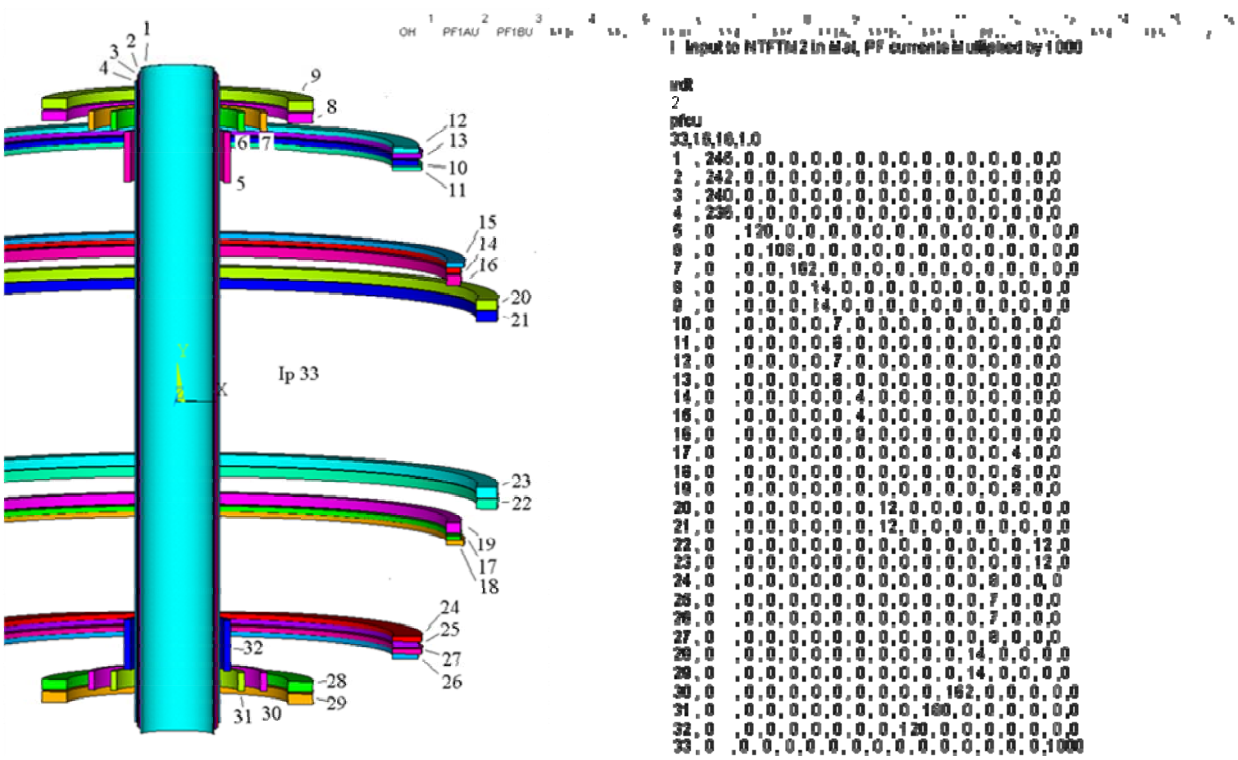


Figure 17

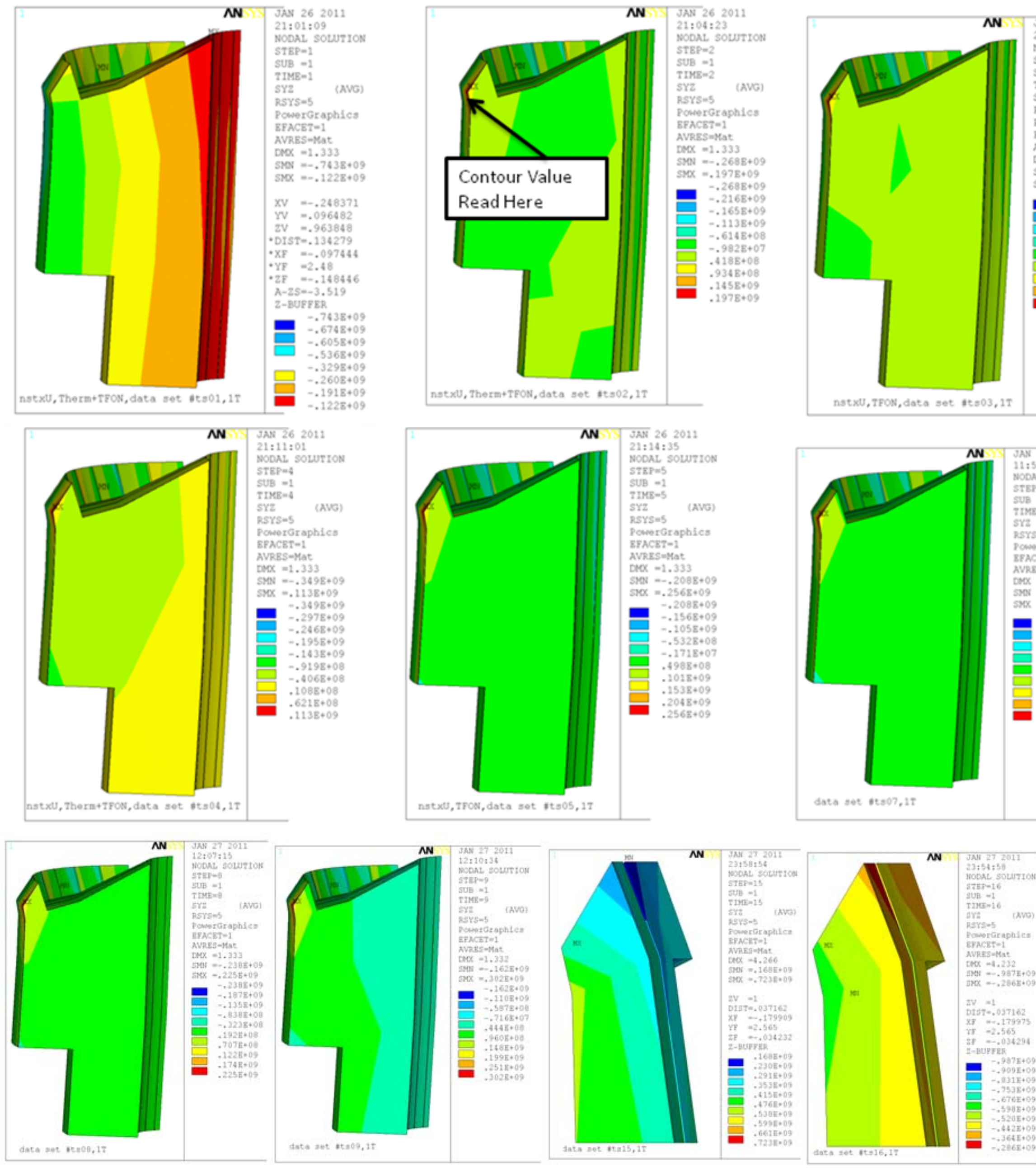


Figure 18 Selected Post Process Results from the upper Corner Shear Stress Influence Coefficients

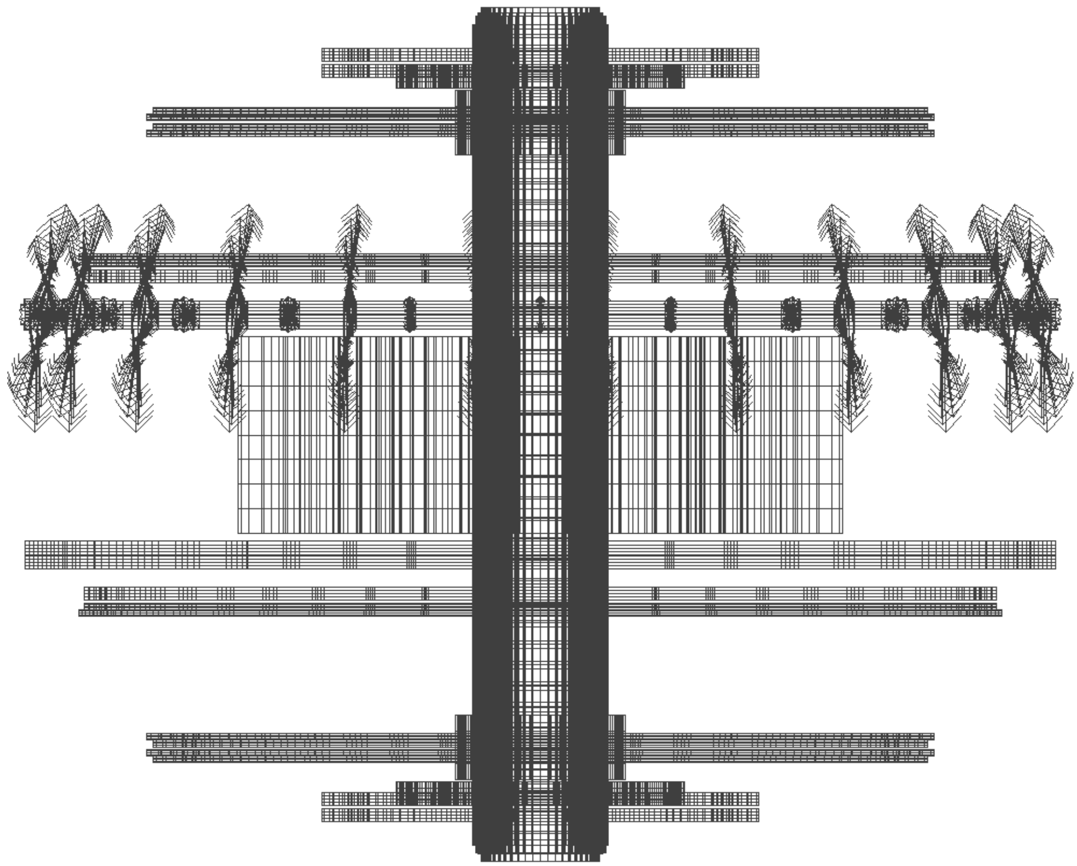


Figure 19 Forces on PF4u from a full TF current and 1 kA in PF4u. TF coils and forces have been removed to scale the much lower PF4 loads due to a kA terminal current.

Mesh generation , calculation of the Lorentz forces, and generation of the influence coefficients is done using a code written by the author of this report. The mesh generation feature of the code is checked visually and within ANSYS during the PREP7 geometry check. . The authors code uses elliptic integrals for 2D field calculations, and Biot Savart solution for 3D field calculations. These are based 2D formulations, and single stick field calculations from Dick Thomes book [8] with some help from Pillsbury's FIELD3D code to catch all the coincident current vectors, and other singularities.

The code in various forms has been used for 20 years and is suitable for structural calculations. It is also being used for calculation of load files in an NSTX global model[2]. Recent checks include NSTX out-of-plane load comparisons with ANSYS [10] and MAXWELL and calculations of trim coil fields for W7X compared with Neil Pomphrey's calculations. The analysts in the first ITER EDA went through an exercise to compare loads calculated by the US (using this code), RF and by Cees Jong in ANSYS, and agreements were good. Some information on the code, named FTM (Win98) and NTFTM2 (NT,XP), is available at: http://198.125.178.188/ftm/manual.pdf).

TF Upper Corner Shear Factors Based on the Global Model

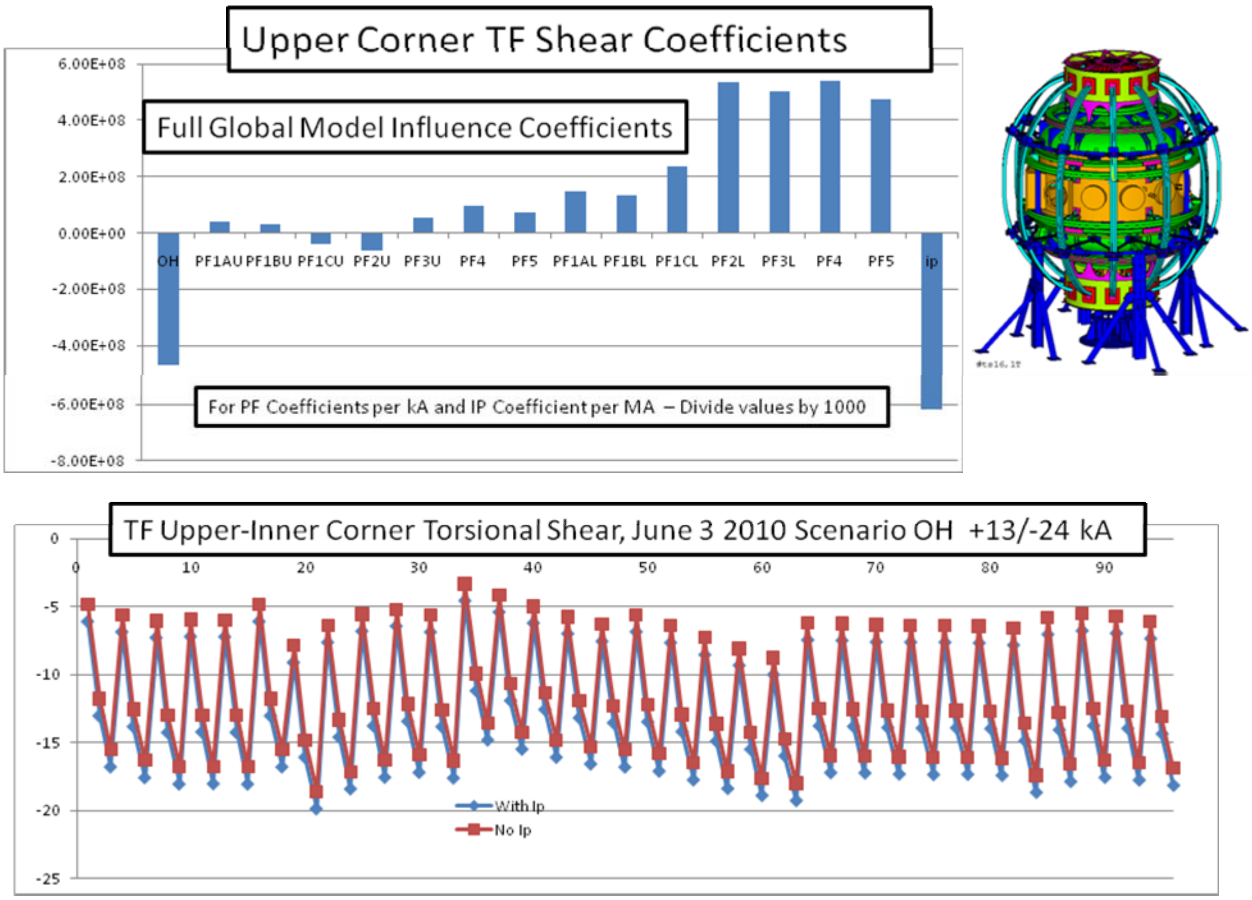


Figure 20 Global Model Upper Corner Results

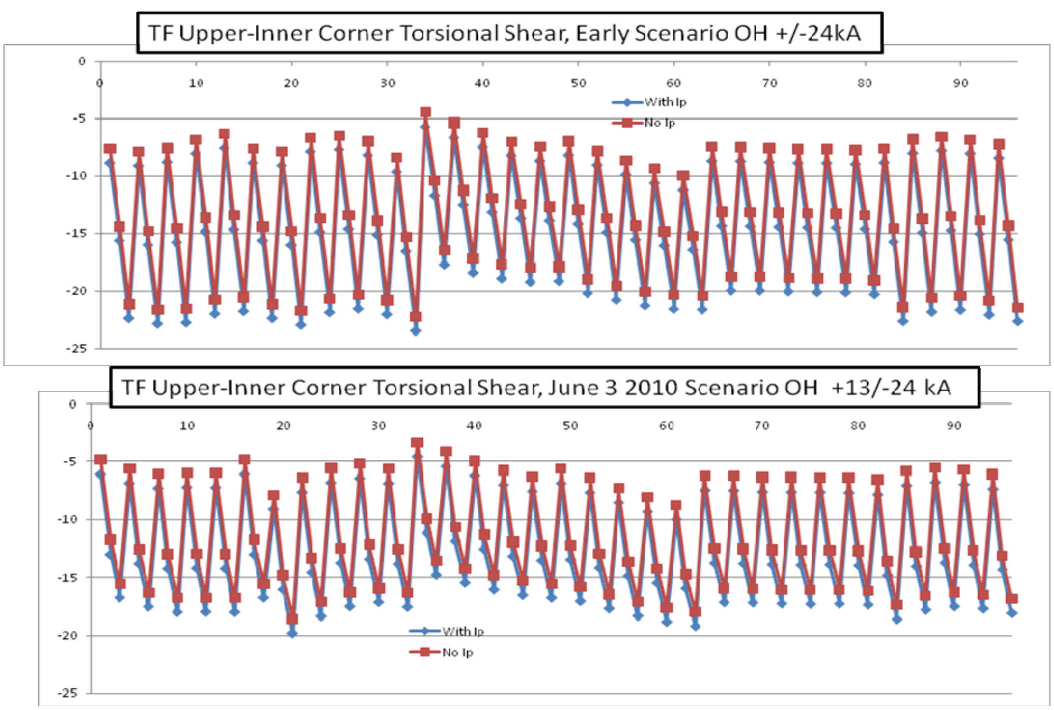


Figure 21 Global Model Upper Corner Results - Comparison of Early and Current Scenario Results.

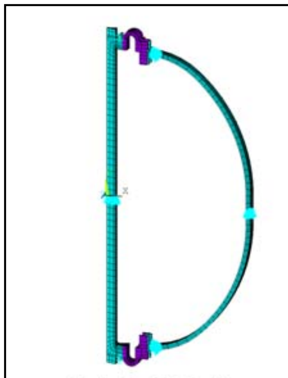
Mid-Plane Torsional Shear Factors Based on the Global Model *(LATER)*

Figure 22 Global Model Upper Corner Results

Bottom Corner Torsional Shear Factors Based on the Global Model *(LATER)*

Figure 23 Global Model Upper Corner Results

DCPS Factors from the Single TF Model With Fixity at the Crown and Umbrella Structure



Simple Single TF Model with Fixity at the Umbrella Structure

If the fixity supplied by the crown connections, at the upper and lower ends of the inner leg, is sufficient, then only a model of the inner leg is needed. This would allow a simpler modeling of the inner leg shear, but calculations of the influence coefficients for the global model and a simpler TF model with fixity at the umbrella structures showed that there were large contributions from the outer PF coils that were suppressed by artificially fixing the umbrella structure. This simpler model allows easier post processing, and with additions of stiffnesses replacing the imposed constraints, this scale of model could be useful. The results of this model are included mainly for illustration of the process (see Appendix B) and comparison with the global model results.

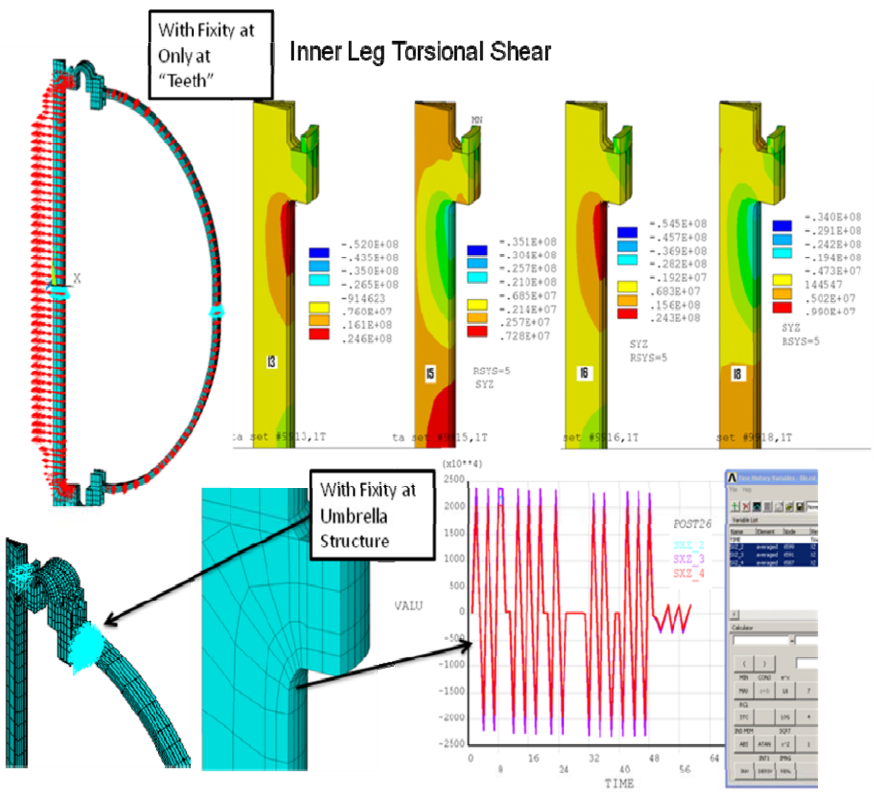


Figure 24 Single Coil Model Results for a Few Scenario Data Points.

The single TF model is cyclically symmetric. The needed CP commands in ANSYS are created by the CPCYL command (see inset). This is not needed for the global model, which includes the full 360 degrees of the tokamak.

```
csys,5
nrotate,all
cpdele,all,all
cpcyc,ux,.001,5,0,30,0
cpcyc,uy,.001,5,0,30,0
cpcyc,uz,.001,5,0,30,0
nsel,z,-40,-33.5
d,all,all,0.0
```

. The loads that used in this analysis are from a calculation of a single TF coil with fixity at the umbrella structure and no support from the knuckle clevis or ring. One of te single leg analysis uses scenario #79 to compute the loads. This has been extensively checked by D. Mangra, and T.Willard, and is consistent with the net upper half-outer leg torque calculated by Bob Woolley and included in the design point spreadsheet.

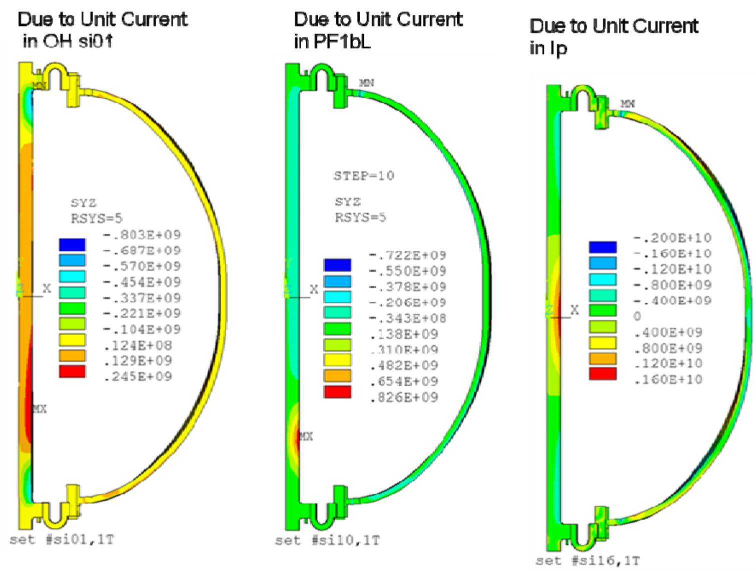


Figure 25 Single Coil Model Torsional Shear Contour Plots for 3 of the 16 Unit Loads

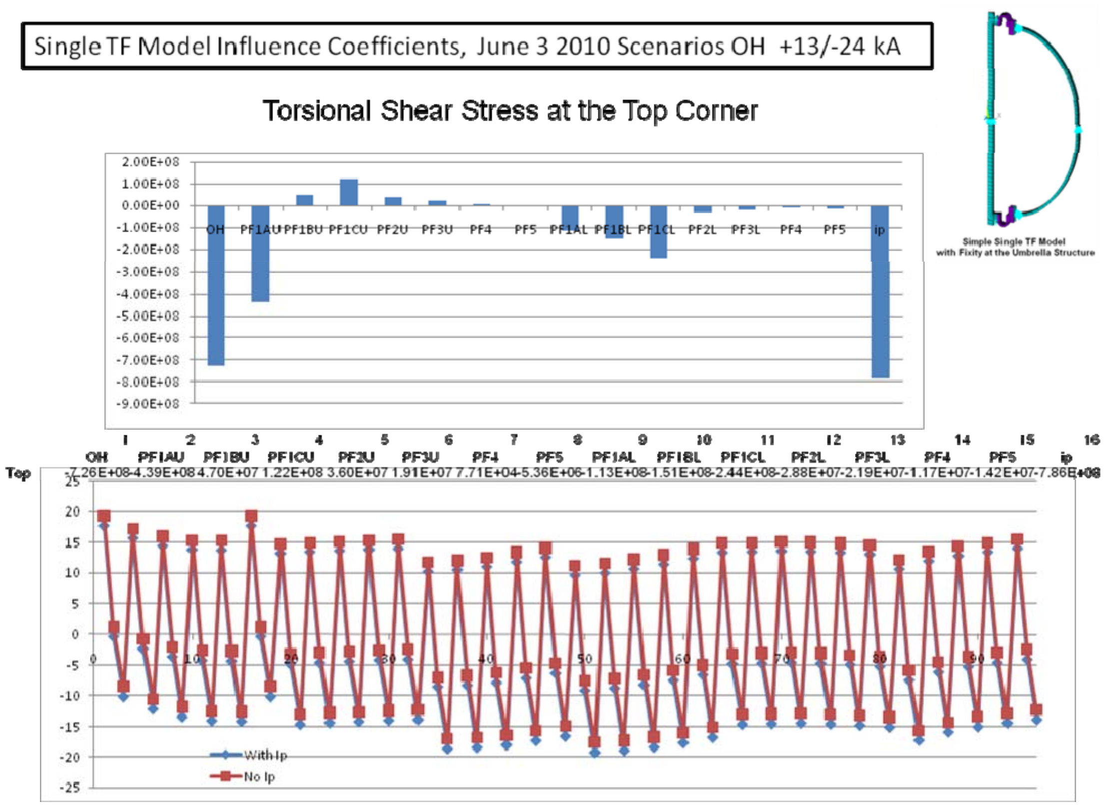


Figure 26 Single Coil Model Upper Corner Results

Mid-Plane Torsional Shear Factors Based on the Single TF Model

At the equatorial plane the torsion in the TF is more strongly affected by the presence of the plasma. The amplitude of the torsional shear is small: -8 to 4 MPa, but it shifts downward 3 to 4 MPa when there is no plasma. This magnitude might be significant with respect to the disruption effects.

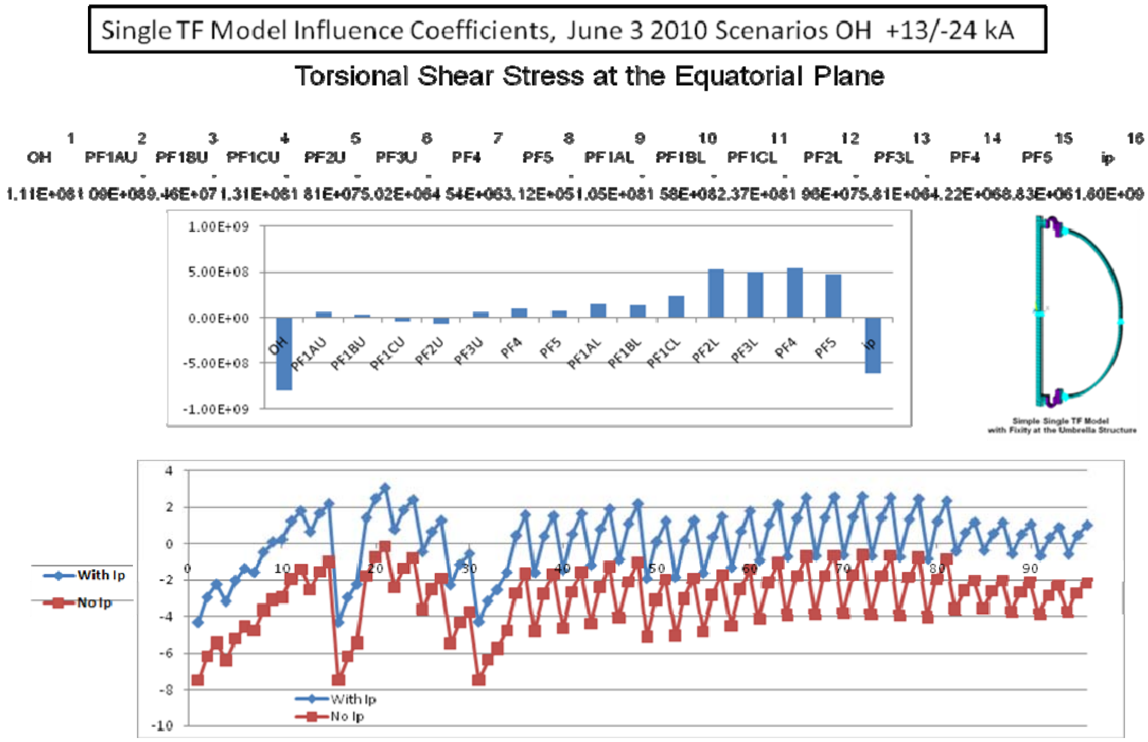


Figure 27 Single Coil Models Equatorial Plane Results

Lower Corner Shear Factors

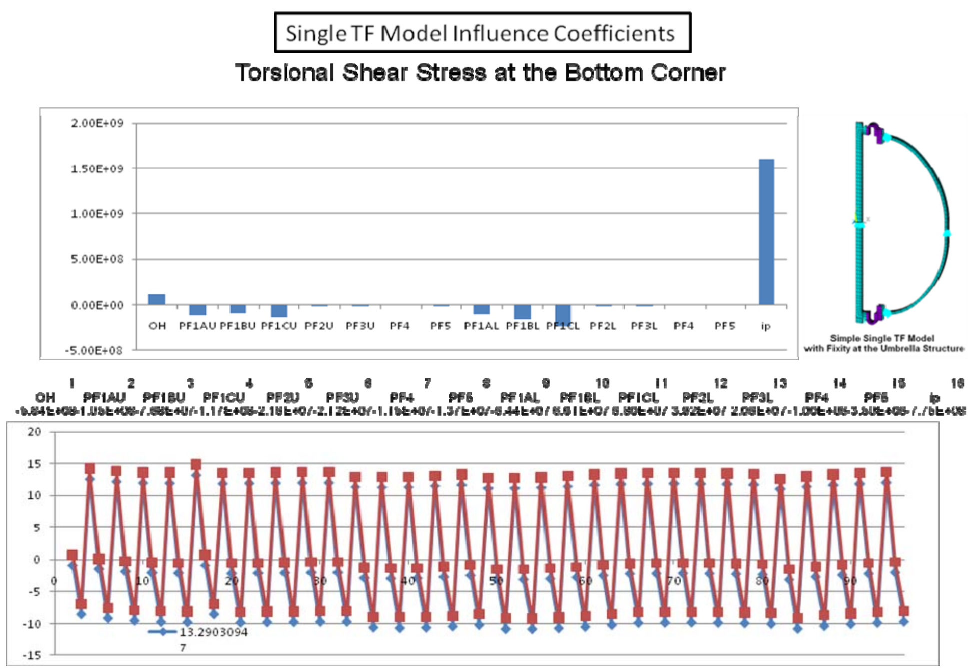


Figure 28 Single Coil Model Lower Corner Results

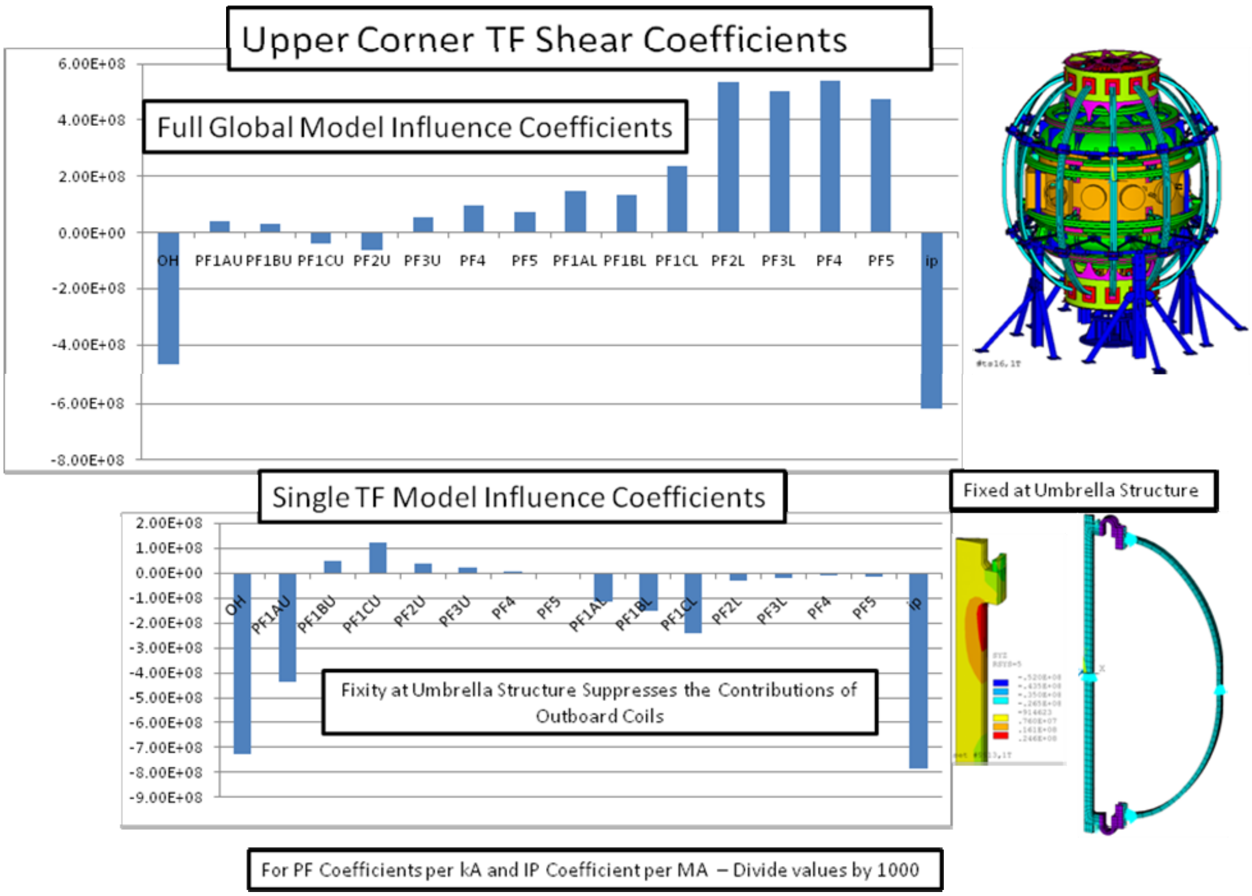


Figure 29 Comparison of Influence Coefficient Results for the Global and Single Coil Models

Suggestion for Torsional Shear Stress Estimation by Moment Summation

The distribution of torsion along the height of the TF central column is needed because there are torsional stress reversals in the central column that you won't see if you just sum the moment on the central column. These are evident in Figure 3 of this section

A useful calculation would be the build-up of torsional shear in the TF inner leg. This is calculated by summing the torsional moment from the bottom to positions along the height of the central column. This would give torque distribution and a total torque on the central column. It is assumed that the total torque is reacted equally by the top and bottom umbrella structure domes or diaphrams. Then divide by the distribution by the torsional resistance factor to get the shear stress. This could readily be implements in Charlie's system analysis program. Because the single TF FEA results are showing a dependence on the stiffness of the outer structures, torsional springs at top and bottom of the inner leg, could be added but this would not include the torque load from the outer structures.

Simple Shell Program for Determining OOP Torsionlal Shear

An early attempt at providing a simplified method for computation of the inner leg torsional shear is presented in this section. It was proposed on other reactor designs and provides some insight into the dependence of the inner leg torsional shear on external structures.

A moment summation of the upper half vs lower half of the tokamak is not useful because the stiffness of the structure will determine how much torque goes to the central column and how much goes to the outer TF and vessel structures.

I am including some results of the torque shell program I described in earlier notes. These are for the OH on only, and the “squareness” equilibria . These analyses produced a -17.7 MPa torsional shear for IM and about 4 MPa for the equilibria.

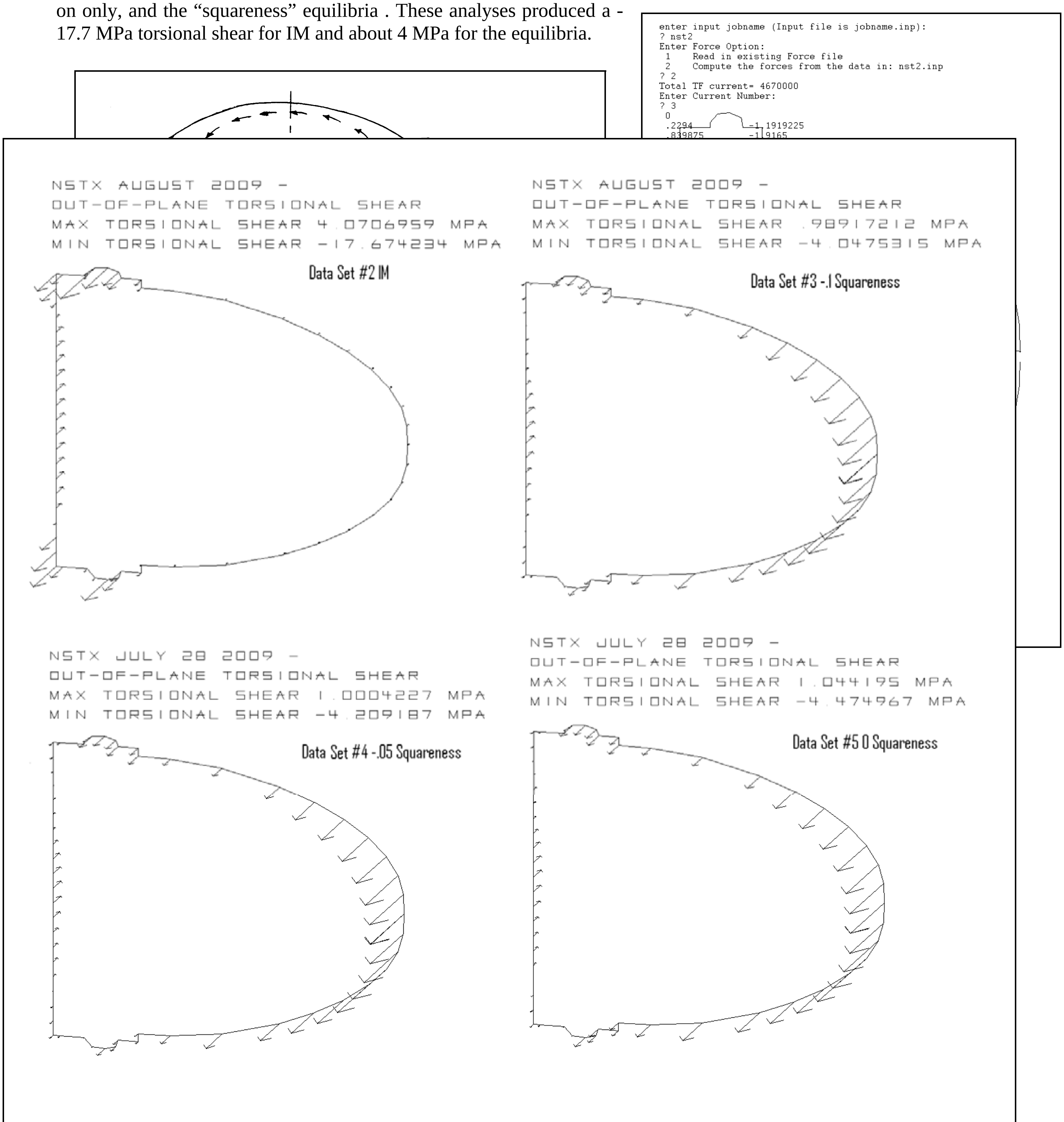


Figure 32 Torsional Shear for IM and some Equilibria

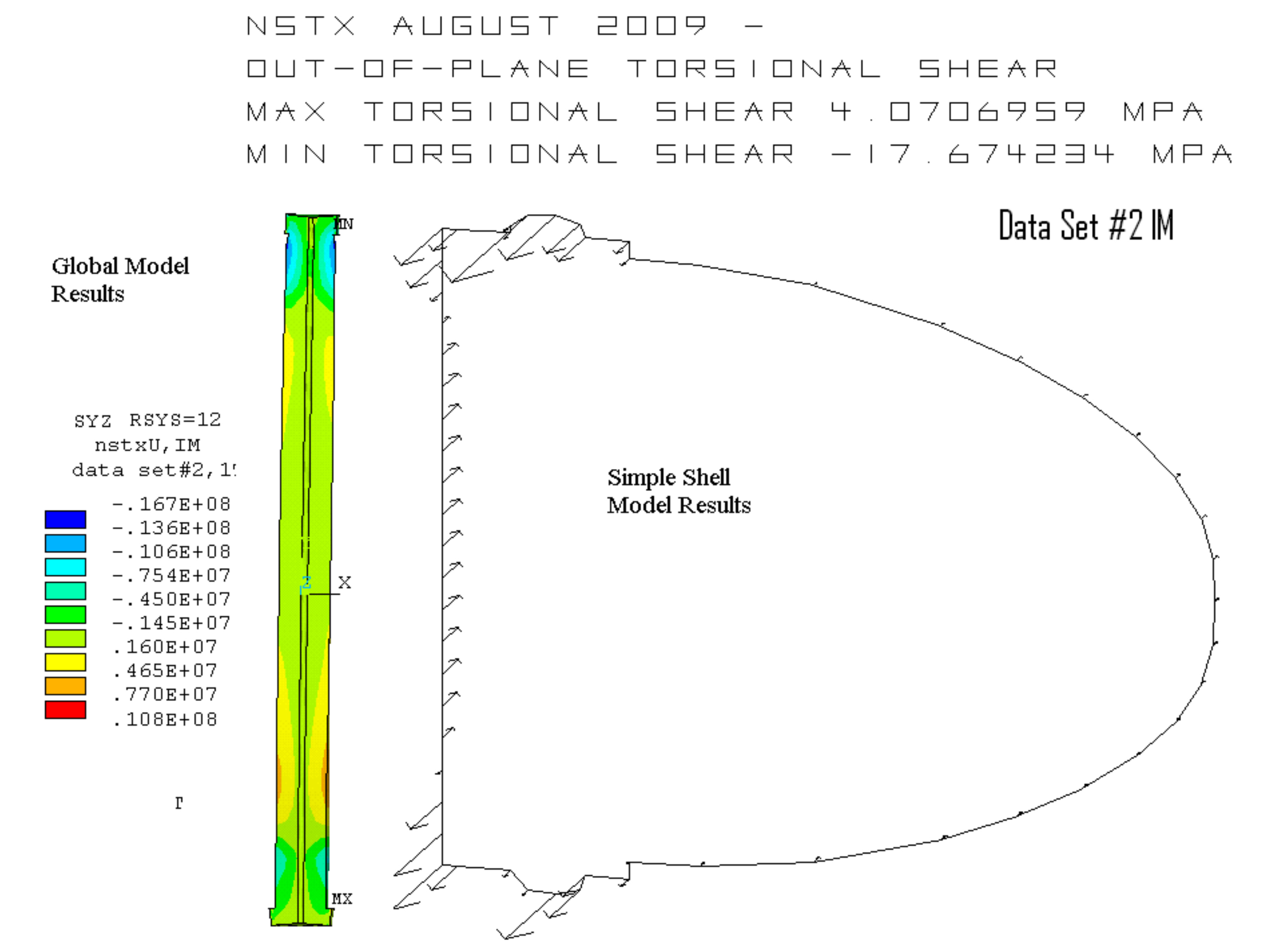


Figure 33 Comparison of Global FEA and Simple Shell Analyses

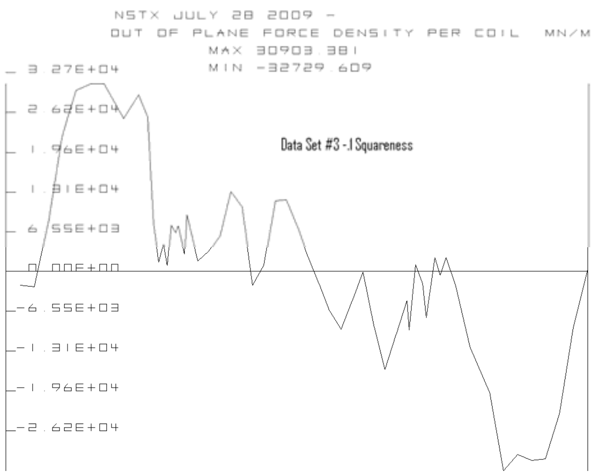


Figure 34 OOP Force Density Along TF CL starting from Outboard Equatorial Plane

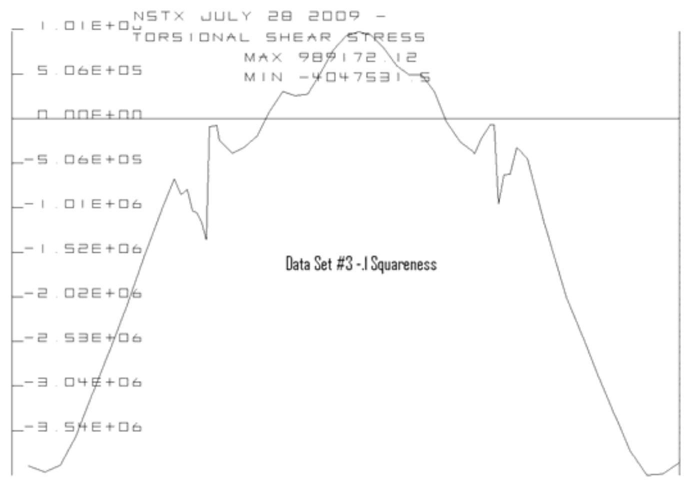


Figure 35 Torsional Shear Stress along TF CL starting from Outboard Equatorial Plane

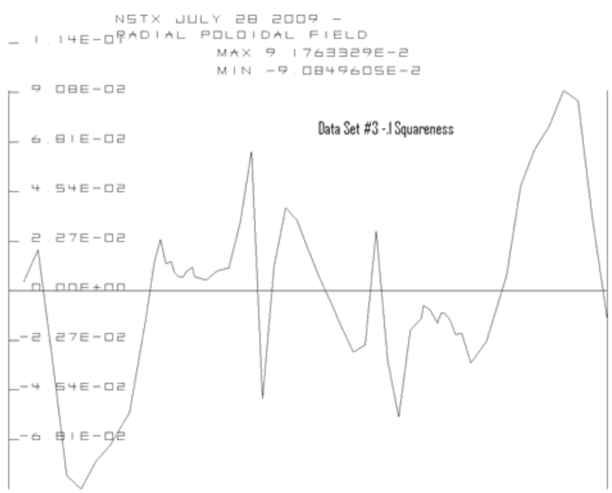


Figure 36

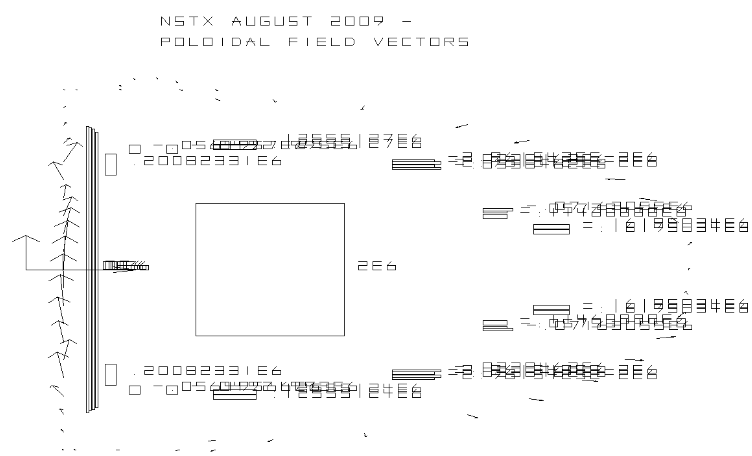


Figure 37

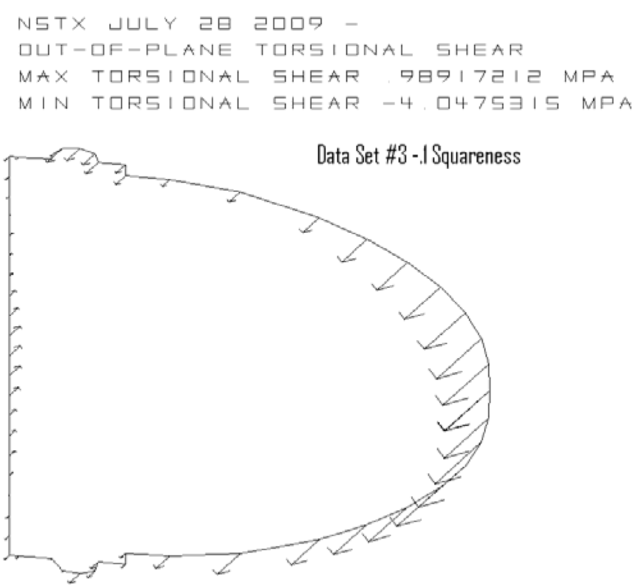


Figure 38

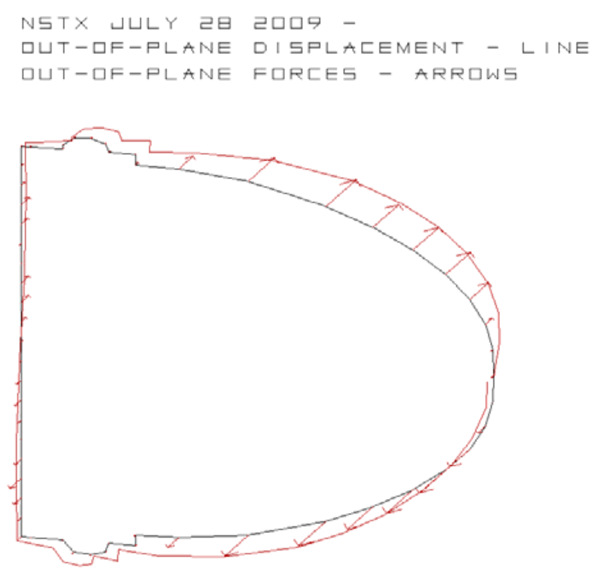


Figure 39

Appendix A
CTD Shear Stress Testing Proposal

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.

ENGINEERED MATERIAL SOLUTIONS

November 4, 2010

Princeton Plasma Physics Laboratory
Attn: Jim Chrzanowski
Forrestal Campus
US Route #1 North at Sayre Drive
MS41 C-Site EWA 345
PO Box 451
Princeton, NJ 08543-0451

Subject: Quotation for Specimen Fabrication and Shear Testing

Ref: (a) Electronic request for quotation received on October 28, November 2, and November 4, 2010

Encl: (1) CTD Q7277-012c Quotation dated November 4, 2010

Dear Jim:

Composite Technology Development, Inc. (CTD) is pleased to provide this Firm-Fixed-Price quotation for specimen fabrication and mechanical testing, as requested by reference (a). This quotation is based on following assumptions and understandings:

1. CTD will fabricate and test all specimens at the same time or on a mutually agreed upon schedule.
2. Any contract resulting from this proposal will be based on the incorporation of mutually agreeable terms and conditions.

This offer is valid for a period of 60 days. Please contact Paul Fabian for any technical questions and Ms. Lori Bass for any contractual questions regarding this quotation.

Sincerely,

Paul E. Fabian

Paul E. Fabian
Testing Program Manager
Composite Technology Development, Inc.

2600 CAMPUS DRIVE, SUITE D | LAFAYETTE, CO 80026 | PHONE: 303-664-0394 | FAX: 303-664-0392| WWW.CTD-MATERIALS.COM

Q7277-012c – Fabrication and Test Quotation
11/4/10

CTD proposes to fabricate Notched Lap Shear specimens composed of a glass/epoxy composite material that is sandwiched between two layers of a copper substrate. The overall goal of the program is to determine the adhesive shear strength between the composite material and the copper substrate with and without a primer and to then determine cyclic fatigue response. Initially, two separate sandwich panels will be fabricated, one that will include a primer that is applied to the bonding surface of the copper and another which will not use any primer to determine the best surface preparation method. Following this, a third sandwich panel will be fabricated using the best surface preparation method and these specimens will be tested for fatigue response. The materials to be used are as follows:

Copper substrate:	C10100 OFC copper (due to the unavailability of C10700 copper in sheet form)
Glass reinforcement:	S2 glass fabric, 8h satin weave, style 6781, epoxy compatible silane finish
Resin system:	CTD-101K epoxy
Primer:	CTD-450

ITEM 1: Lap Shear Specimen Fabrication

Two sandwich panels will be fabricated using CTD-101K/S-2 Glass and C101 copper using a vacuum impregnation process. The copper plates will be pre-machined so as to minimize any machining stresses following the bonding of the two copper plates together. The bonding surface of each copper substrate will be solvent cleaned, grit blasted, and solvent cleaned again in preparation for proper bonding. In addition to these surface preparation steps, the surfaces of the substrates will be primed with a Cyanate Ester primer. Following surface preparation, dry glass fabric will be placed between the two copper plates, degassed, and then impregnated with CTD-101K in a vacuum impregnation process. After cure, the sandwich panels will be machined to final dimensions for notched lap shear specimens, similar to that shown in Figure 1 but with a longer lap section of 1 inch. The copper substrates will be nominally 0.20 in. thick and the composite will be nominally 0.125 in. thick and 50% fiber volume fraction. Each fabricated sandwich panel will enable the fabrication of eight (8) individual test specimens. Specimens from one panel will be used for static testing while specimens from the other panel will be utilized for fatigue testing.

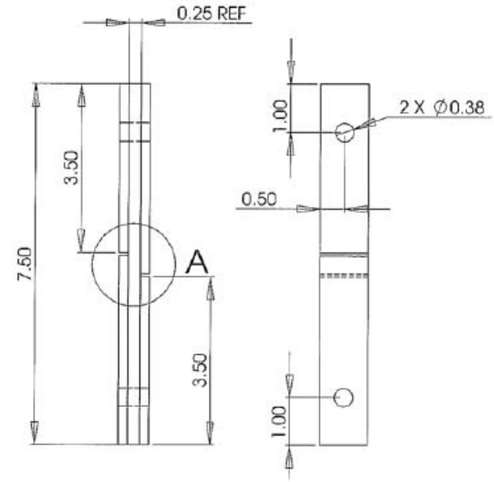


Figure 1. Typcial Notched Lap Shear specimen

ITEM 2: Lap Shear Testing

Notched Lap Shear tests on specimens fabricated in ITEM 1 will be performed at 100°C (373 K) per ASTM D3165. Specimens will be loaded in tension until failure to determine the ultimate adhesive shear strength of each set of samples. Six tests will be performed. Data deliverables will include the ultimate adhesive shear strength of each specimen and average values for each specimen group.

ITEM 3: Lap Shear Fatigue Testing

Notched Lap Shear fatigue tests on specimens fabricated in ITEM 1 will be performed at 100°C (373 K) per ASTM D3165. Specimens will be loaded in tension-tension fatigue at 10 Hz, R=0.1, and maximum stress values of 70%, 60% and 50% of their failure stress to produce an S-N curve. Two specimens will be tested in fatigue at each stress level to determine at which point the materials can withstand 60,000 loading cycles. Based on the results of the six tests performed at the three stress levels listed above, the last two specimens will be tested at other stress levels to more fully expand the S-N curve. A total of 8 fatigue tests will be performed. Data deliverables will include the fatigue results including the number of cycles to failure for each specimen and the S-N curve.

ITEM 4: Final Test Report

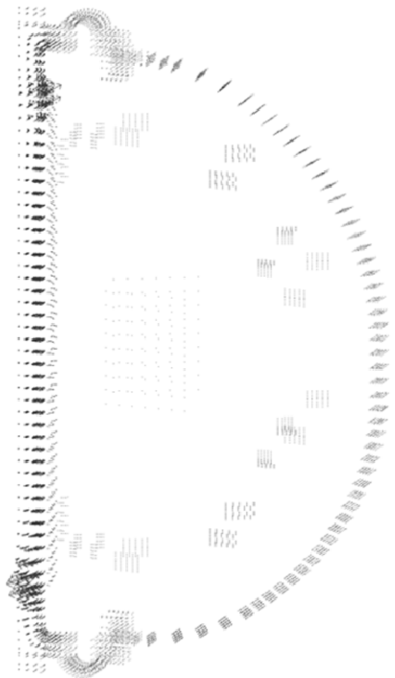
CTD will submit a final report providing a brief overview of the fabrication process and detailing the surface preparation steps. It will additionally include details on all test methods and test conditions and will be submitted at the completion of the program. All test data for each individual test, as well as average values, will be provided. All test specimens, included failed samples, will be returned to PPPL.

Item #	Test Type	Test Method	Test Temperature	Quantity	Unit Price	Subtotal
1	Specimen Fabrication	-	-	2 lots of 8	$4,864	$9,728
2	Notched Lap Shear Testing	D3165	373 K	6	$586	$3,516
3	Notched Lap Shear Fatigue Testing	D3165	373 K	8	$666	$5,328
4	Final Report	-		1	NSP	NSP
				Total Price		$18,572

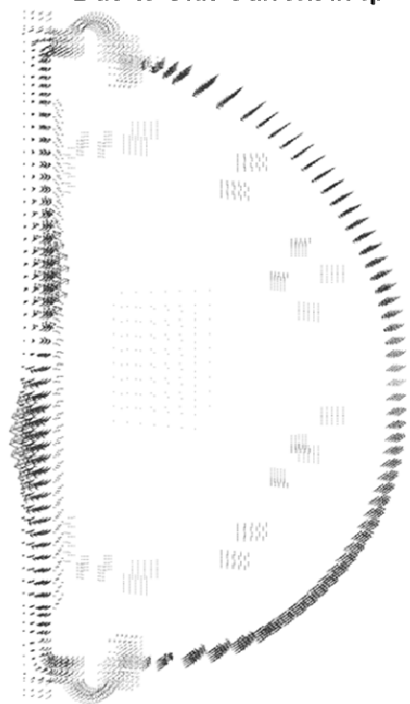
Appendix B

Force Plots for Individual Influence Coeficients

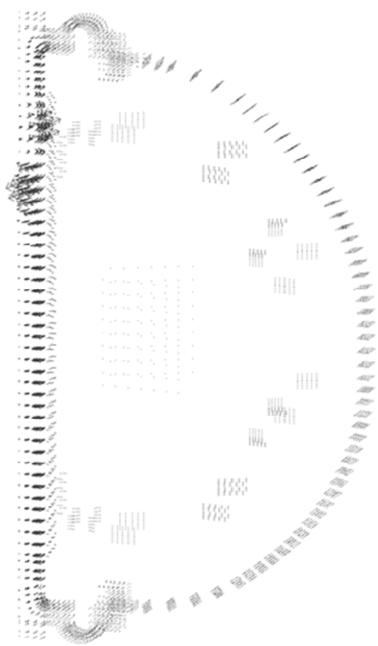
Due to Unit Current in OH si01



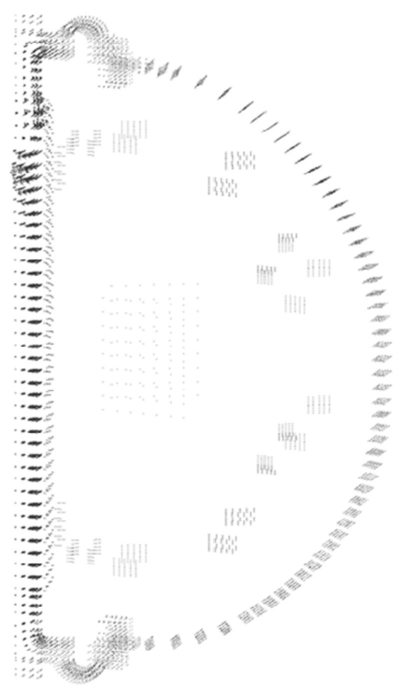
Due to Unit Current in Ip



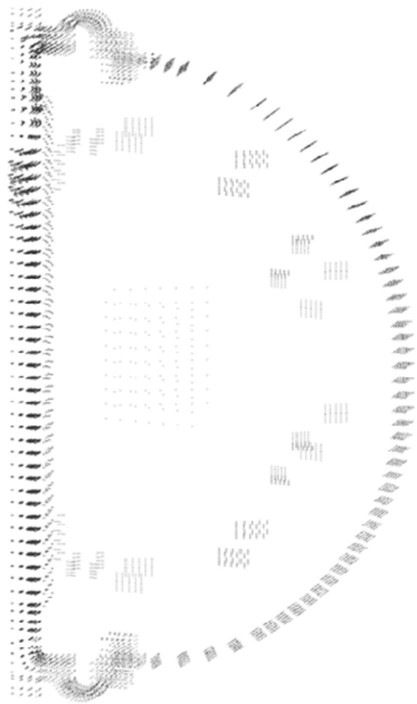
Due to Unit Current in PF1aU



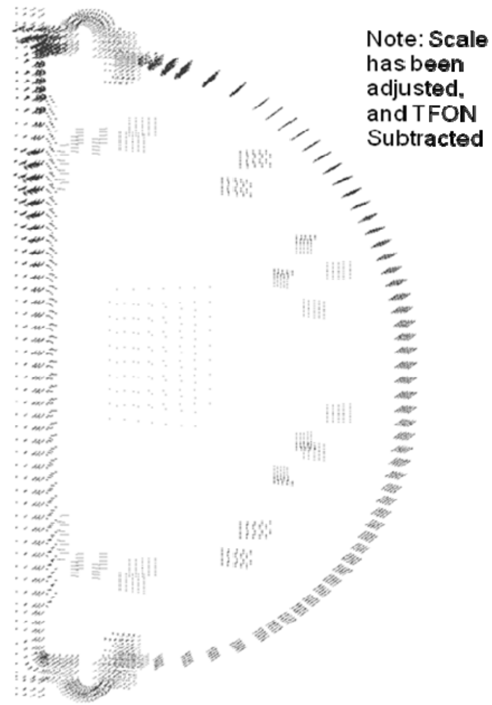
Due to Unit Current in PF1bU, si03



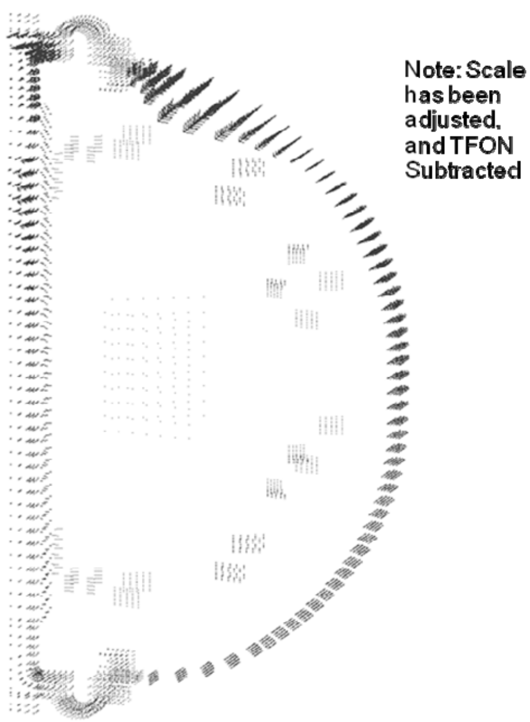
Due to Unit Current in PF1cU, si04



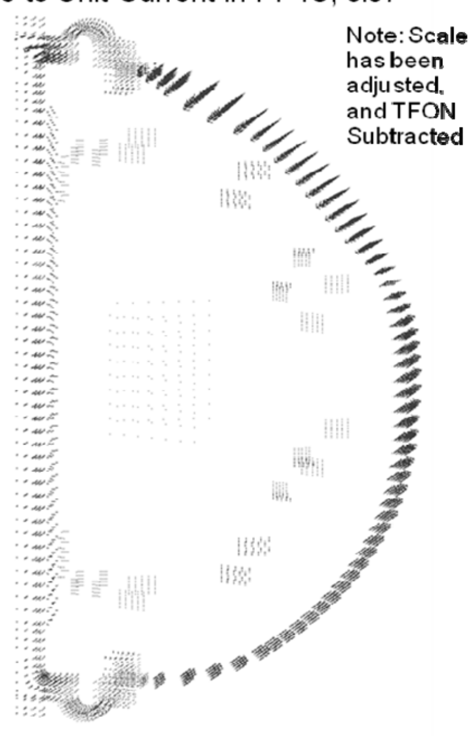
Due to Unit Current in PF2U, si05



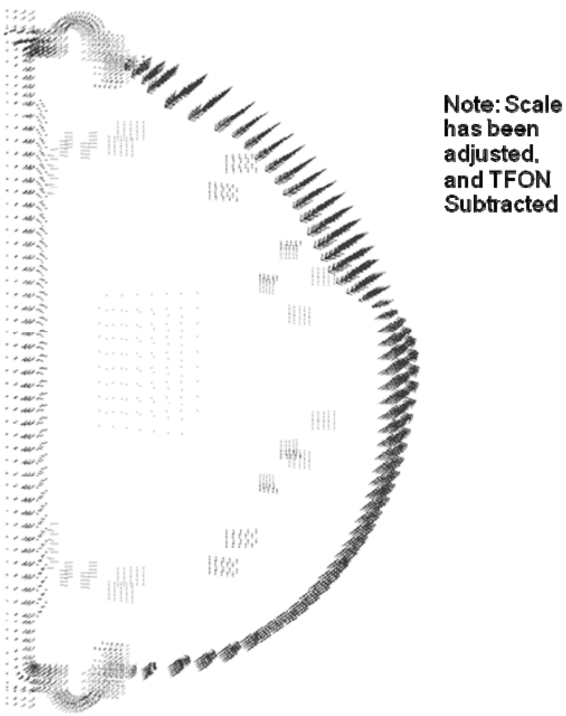
Due to Unit Current in PF3U, si06



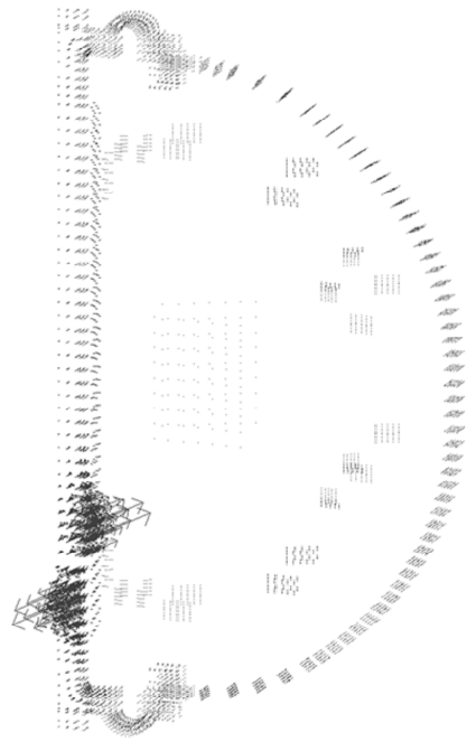
Due to Unit Current in PF4U, si07



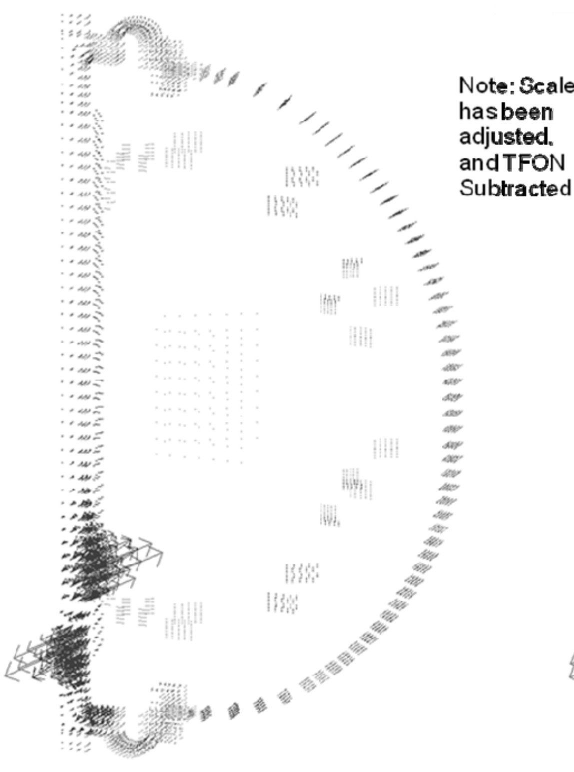
Due to Unit Current in PF5U, si08



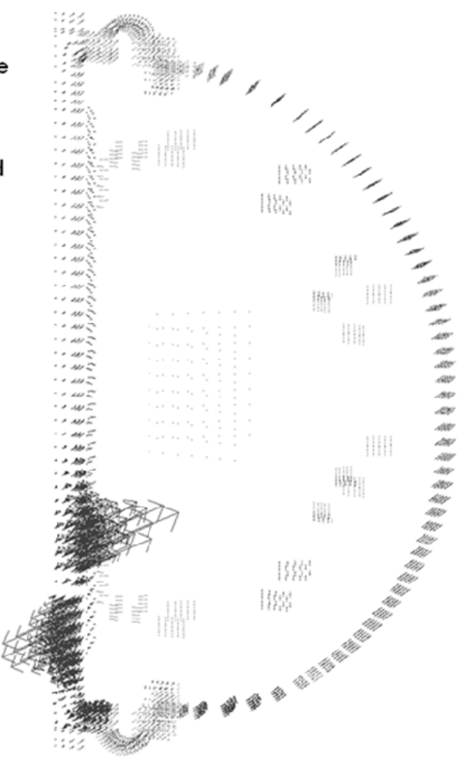
Due to Unit Current in PF1aL, si09



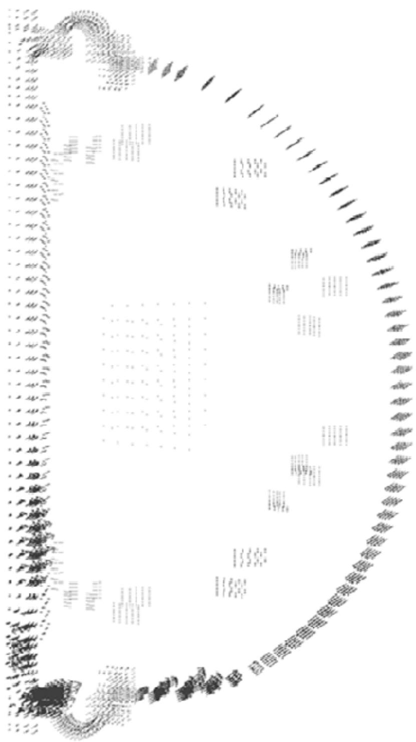
Due to Unit Current in PF1bL, si10



Due to Unit Current in PF1cL, si11

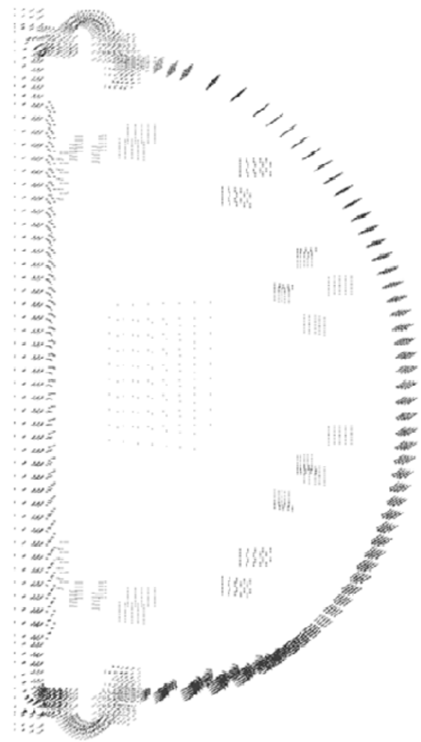


Due to Unit Current in PF2L, si12

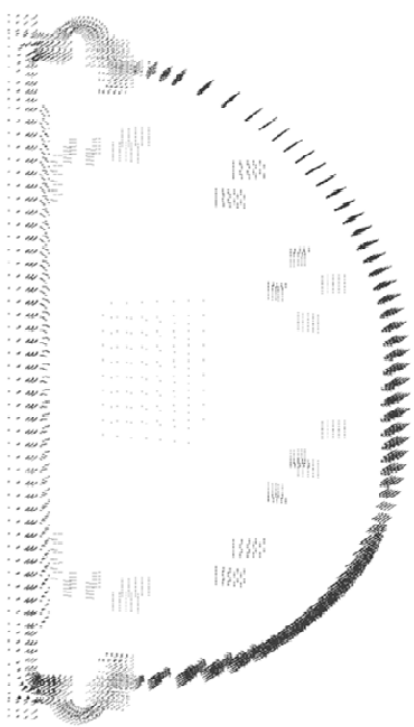


Note: Scale has been adjusted, and TFON Subtracted

Due to Unit Current in PF3L, si13



Due to Unit Current in PF4L, si14



Note: Scale has been adjusted, and TFON Subtracted

Due to Unit Current in PF5L, si15