NSTX Upgrade

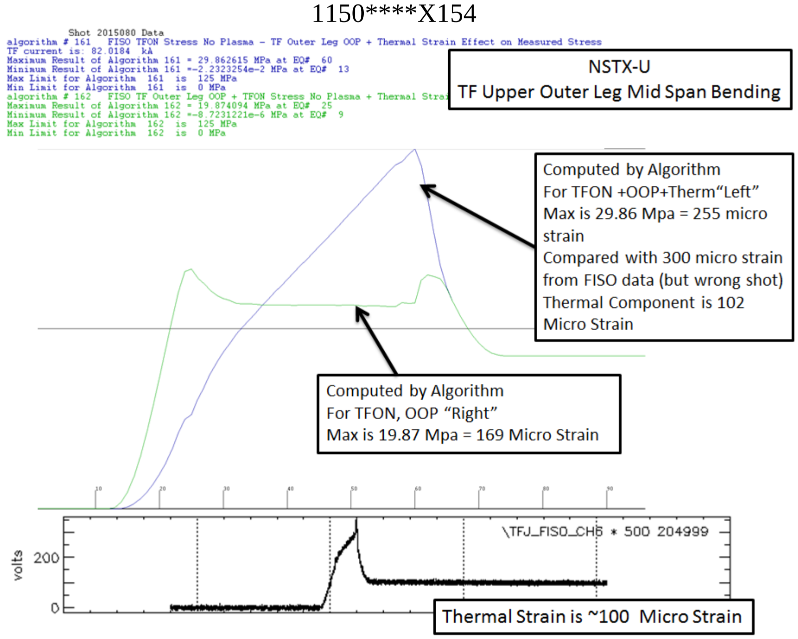
DRAFT

Instrumentation Results Evaluation

NSTXU-CALC-10-05-00

December 7 2016

1150****X154



Sample of a Comparison betweenm FISO Results and Calculated Results for the TF Outer Leg Strain

Prepared By:

Peter Titus, ______________________________

Reviewed By:

Preparer	Sections	Signature	Reviewer	Sections	Signature
P. Titus					

PPPL Calculation Form

Calculation # **NSTXU-CALC-10-05-00-** Revision # **0** ____ WP #, **1903**
(ENG-032)

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

Benchmarking structural instrumentation is employed on NSTX to allow comparison of calculated structural performance and measured structural performance. This is needed to verify the algorithms used in the DCPS and to ensure behavior of NSTX components are as envisioned in the calculations. It is intended that none of the instrumentation would be used to interrupt a shot. Only the DCPS and other power supply interrupts would be used for this purpose. The benchmark instrumentation will produce data that will be evaluated after a shot is complete. The results will then be compared with the DCPS algorithm predicted values. It is the purpose of this calculation to evaluate the instrumentation data as it becomes available.

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

These are included in the body of the calculation, in section 6.2

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

There are some assumptions used in each of the assessments, but the purpose of the instrumentation effort is to verify modeling and assumptions made in the qualification calculations.

Calculation (Calculation is either documented here or attached)

These are included in the body of the following document

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)
Task 1 : the DCPS launching load for the OH coil based on an envelope of the 96 EQ, should remain. – The effective modulus of the OH stack is 18 GPa (vs. 117 GPa for copper) and to date no excessive creep has been measured

Cognizant Engineer’s printed name, signature, and date

____

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

Checker’s printed name, signature, and date

Reviewed By:

Reviewer	Sections	Signature

2.0 Table of Contents

3.0 Revision Status Table

Rev	Date	Description
DRAFT	11-2016	DRAFT Original Issue

4.0 Executive Summary

PURPOSE & INTRODUCTION

Benchmarking structural instrumentation is employed on NSTX to allow comparison of calculated structural performance and measured structural performance. This is needed to verify the algorithms used in the DCPS and to ensure behavior of NSTX components are as envisioned in the calculations. It is intended that none of the instrumentation would be used to interrupt a shot. Only the DCPS and other power supply interrupts would be used for this purpose. The benchmark instrumentation will produce data that will be evaluated after a shot is complete. The results will then be compared with the DCPS algorithm predicted values. An important distinction for this calculation and the instrumentation program [3] is to define the difference between benchmark, protection, and interlocks.

Benchmarking is for validating structural models. Can be done "at leisure"

Protection is a post-shot warning that a limit may have been reached.

May result in a change to the next shot.

Similar to the old TF joint monitoring system.

Interlocks interdict the shot in progress.

Requires realtime instrumentation.

No real time interlocks are planned for the instrumentation program or from the results of this calculation

Table 1.0-1 Measurement Tasks Descriptions

Task		Additional Description	Purpose
1	**Preload Mechanism LVDT**	Displacement of Belleville Stack	*(Benchmark and Protection)*
2	**CHI Gap Tile Temperature Sensors**	Thermocouple in CHI Gap Tiles	*(Benchmark and Protection)*
3	**Mid-plane Halo Current Sensors**	Halo Currents in Center Column Tiles .	*(Physics Benchmark and Protection)*
4	**PF1c Case CHI Gap Temperature Sensors**	Thermocouple contacting outer case shell pf PF1c. See Task 2	*(Benchmark and Protection)*
5	**Vessel Twist Measurements**	J,K cap and global laser twist displacements as a measure of the torque the vessel is supporting	*(Benchmark)*
6	**Spoked Lid Torque**	Strain Gauge measures Out-of-Plane Load/ Stress	*(Benchmark)*
7	**Spoked Lid Thermal Flex**	Strain Gauge measures Flex of Upper Lid due to centerstack expansion	*(Benchmark)*
8	**Casing Halo Loading Top Flange Load Cell**	Centerstack Casing Halo loading at top flange – This will be shimmed against PF1c mandrel flange. Measuring the shim load provides some measure of the severity of the halo load.	*(Physics and Structural Benchmark and Protection)*
9	**Passive Plate Accelerometer(Internal)**	Located mid-span on the back of the passive plates, measures response to disruption	*(Physics and Structural Benchmark and Protection)*
10	**Passive Plate Mounting Accelerometers (External)**	Indication of severity of "Loose Bolt/ Copper Lozenge"	*(Protection)*
11	**TF Outer Flag Voltage**	Individual joint contact voltage taps	*(Benchmark and Protection)*
12	**Flex Strap Instrumentation**	Displacement sensors checking OOP response, DLF and buckling	*(Benchmark)*
13	**PF 4 and 5 Thermal Displacements**	LVDT's measuring ovalization of expanding PF4/5	*(Benchmark and Protection)*
14	**TF Truss Loads**	Outer TF Truss Strut Loads –Strain gauges	*(Benchmark)*

		on the struts	
15	**Outer Leg Bending**	Fiso or Bragg grating fiberoptic strain gauges monitor TF Outer Leg Insulation	*(Benchmark and Protection)*
16	**TF Joint Resistance**	Voltage taps mounted on cooling tubes provide trending data for general joint health	*(Protection)*
17	**CHI Busbar Rogowski Coils**	Halo Current quantification for assessment of load in the centerstack	*(Protection)*
18	**High Z Tile Thermocouples**	Future High Z Tile Instrumentation	*(Protection)*
19	**TF Joint Thermal Stickers**	Provide thermal indication of general joint health	*(Protection)*

Evaluation of the instrumentation results must be compared with results from the calculations appropriate for the shots from which the instrumentation data comes. This entails utilizing the algorithms developed for the DCPS with input from actual shots. In some of the comparisons, data from shot 205080 is used. The time dependent current for this shot was extracted using MDS+. This time dependent data was input to an algorithm for the measured data, and the calculated and measured results compared. When thermal effects are being included in the measurements, the DCPS algorithms must be augmented with the appropriate thermal effect. The algorithms that were used are those developed as input to the DCPS coding. These came from filed calculations in which the algorithms were implemented in EXCEL or in a TRUE BASIC code [7]

4.1 Task 1, Section 7.1 OH Preload mechanism loading – Displacement of Belleville Stack

Data was taken during the 2015 run period, OH effective “smeared” modulus was measured as 18 GPa as opposed to Energized compression at

The OH displacement from Lorentz Forces is .33 inches/20,000 amps.the DCPS launching load for the OH coil based on an envelope of the 96 EQ, should remain. – The effective modulus of the OH stack is 18 GPa (vs. 117 GPa for copper) and to date no excessive creep has been measured

4.2 Task 2 Section 7.2 CHI GAP Tile Thermocouples

4.3 Task 3 Section 7.3 Halo Current Measurements in Centerstack Tiles

4.4 Task 4 CHI Gap PF1c Outer Case Temperature Monitor

7.4

4.5 Machine Twist Measurements, Vessel Bay J,K cap twist displacements

4.6 Task 6 Spoked lid stresses – Linear with torque applied to Inner TF collar 7.6

The DCPS does not monitor the spoked lid stress. We have data from FISOs but the values are pretty low from the initial run periods. The DCPS does calculate a variety of net torques - Upper halves, Upper-outer leg torques etc - and keeps them below the 96EQ values.

4.7 Spoked Lid Stresses –Linear with thermal growth of TF

4.8 Centerstack Casing Halo loading at top flange

4.9 Passive Plate Accelerations (Internal)

4.10 Passive Plate Accelerations (External)

5.0 Digital Coil Protection System.

The instrumentation covered by this calculation is not intended to be a part of the DCPS. The benchmark instrumentation will produce data that will be evaluated after a shot is complete. The results will then be compared with the DCPS algorithm predicted values, and with calculation predicted values.

6.0 Design Input

6.1 Criteria

Stress Criteria are found in the NSTX Structural Criteria Document[4]. The conservatism of this document [4]is intended to envelope the uncertainties in modeling, fabrication and operation. The appropriate criteria for this calculation is that measured results can be reconciled with the calculated results. Measured results that are within the original design margin would be acceptable. Measured results that follow the predictive behavior of the analysis models would be acceptable as long as the DCPS algorithms are conservative. Engineering judgement will be required to evaluate each circumstance.

6.2 References

[1] NSTX Upgrade General Requirements Document, NSTX_CSU-RQMTS-GRD Revision 5, C. Neumeyer, June 14 2012

[2] NSTX-U Design Point Spreadsheet, **NSTXU-CALC-10-03-00** C. Neumeyer, http://w3.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html

[3] NSTX-PLAN-12-207 NSTX-U Structural Benchmark Instrumentation, December 2016, P. Titus

[4] NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc I. Zatz

[5] NSTX-U Global Model – Model Description, Mesh Generation, and Results NSTX-U CALC 10-01-02 Rev1 December 2011, P. Titus, Available at: http://nstx-upgrade.pppl.gov/Engineering/Calculations/index_Calcs.htm

[6] "Installation of TF Outer Leg (TFOL) FISO Strain Gauges" D-NSTX-IP-3831 5/20/2016

[7] NSTX Upgrade DRAFT DCPS Check Calculations NSTXU-CALC-13-07-00 November 18 2016 Including the True Basic "DCPS" Algorithm simulation

[8] TF Outer Repaired Flags Integrity Measurements Investigation Data ReviewD-PTP-NSTX-CL-051 (MPC) 1150****X350, A. Brooks, Kevin Lamb, Hans Schneider, June 25 2015

[9] Stress Analysis of ATJ Center Stack Tiles and Fasteners NSTXU-CALC-11-03-01, A Brooks

[10] NSTXU CALC 133-03 Centerstack Casing Stress Summary

[11] NSTXU CALC 133-05-01 Halo Current Analysis of the Centerstack Casing

[12] ANALYSIS OF TF OUTER LEG, NSTX-CALC-132-04-01, January 13, 2012 Prepared By: Han Zhang

[13] Vessel Rework for the Neutral Beam and Thomson Scattering NSTXU-CALC-24-01-00 Rev 0 February 1, 2011 Prepared By: Tom Willard

[12] NSTX Structural Analysis of PF1, TF and OH Bus Bars NSTX-CALC--55-01-02 February 15, 2011 , Rev 2 June 2015, Andrei Khodak

[13] NSTX Upgrade Analysis of Existing and Upgrade PF4/5 Coils and Supports – With Alternating Columns. NSTXU-CALC-12-05-01 Rev 0 December 2011 Rev 1 April 2016, P. Titus, checked by I. Zatz

[14] PF-2&3 Lead Clamps Design Review 04/02/2015 By Neway Atnafu

[15] Email from Scott Gifford Apr 27 to Neway, and P. Titus: Gentlemen the pictures for the PF 2-3 Supports are in the photo drop.P:\Photo Drop\PF 2-3 Supports

[16] Flex Cable Catalog, Northern Connectivity Systems Inc Commodore Machine Company 1749 Northwood Drive, Troy Michigan
[17] NSTX Upgrade PF 2/3 Terminal and Flex Bus Analysis NSTXU-CALC-55-02-01
[18] Centerstack Upgrade PF Coil System Upper PF1a Bus Assembly, Drawing #E-DC1804
[19] PF-1aU Bus Bending FDR Slides S.P. Gerhart, Last Updated 5/26/2016
[20] Analysis of Existing & Upgrade PF4/5 Coils & Supports – With Alternating Columns, NSTXU-CALC-12-05-00, Prepared By: Peter Titus, Reviewed by Irv Zatz, Cognizant Engineer: Mark Smith WBS 1.1.2

[21] Analysis of the PF1c Mandrel/Case CHI Gap, Thermal/Structural Analysis, Including the Proposed Thermal Shield Design NSTXU-CALC-133-15-0
[22] Peer Review: CHI Bus Current Measurements Earth 21st century Stefan Gerhardt
[23]
[35] NSTX Upgrade OH Preload System and Belleville Springs, NSTXU-CALC-133-04-00 October 2010, P. Rogoff, Checked by test by Tom Kozub

[27] NSTX Upgrade Centerstack Casing and Lower Skirt Stress Summary NSTXU-CALC-133-03-00 Rev 0 August 2011 Prepared By: Peter Titus

[30] Halo Current Analysis of Center Stack NSTXU-CALC-133-05-00 Prepared By: Art Brooks, Reviewed by: Peter Titus, Cognizant Engineer: Jim Chrzanowski, WBS 1.1.3 Magnet Systems,

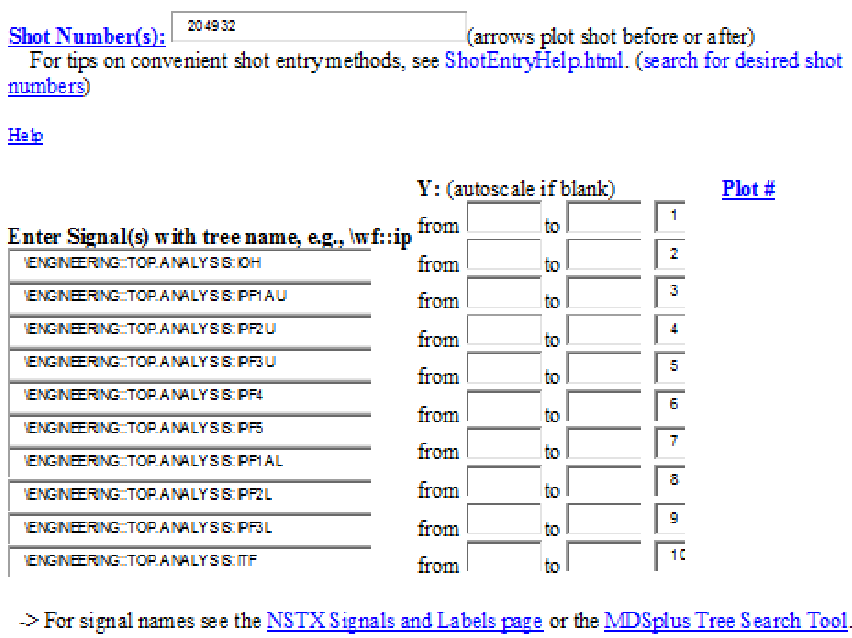
6.3 Photos and Drawing Excerpts

Figure 6.3-
Figure 6.3-2

Figure 6.3-3
Figure 6.3-4

6.4 Input Currents

A representative scenario for the early 2016 run period is shot 205080. The currents for this shot are extracted from recorded data using the MDS+ webtools


Shot Number(s): 204932 (arrows plot shot before or after)
For tips on convenient shot entry methods, see ShotEntryHelp.html. (search for desired shot numbers)

Help

Enter Signal(s) with tree name, e.g., \wf::ip	Y: (autoscale if blank)			Plot #
	from	to	1	
\ENGINEERING::TOP.ANALYSIS:OH	from	to	2	
\ENGINEERING::TOP.ANALYSIS:PF1AU	from	to	3	
\ENGINEERING::TOP.ANALYSIS:PF2U	from	to	4	
\ENGINEERING::TOP.ANALYSIS:PF3U	from	to	5	
\ENGINEERING::TOP.ANALYSIS:PF4	from	to	6	
\ENGINEERING::TOP.ANALYSIS:PF5	from	to	7	
\ENGINEERING::TOP.ANALYSIS:PF1AL	from	to	8	
\ENGINEERING::TOP.ANALYSIS:PF2L	from	to	9	
\ENGINEERING::TOP.ANALYSIS:PF3L	from	to	10	
\ENGINEERING::TOP.ANALYSIS:TF	from	to		

-> For signal names see the NSTX Signals and Labels page or the MDSplus Tree Search Tool.

Figure 6.4- MDS+ Data Names for the Currents

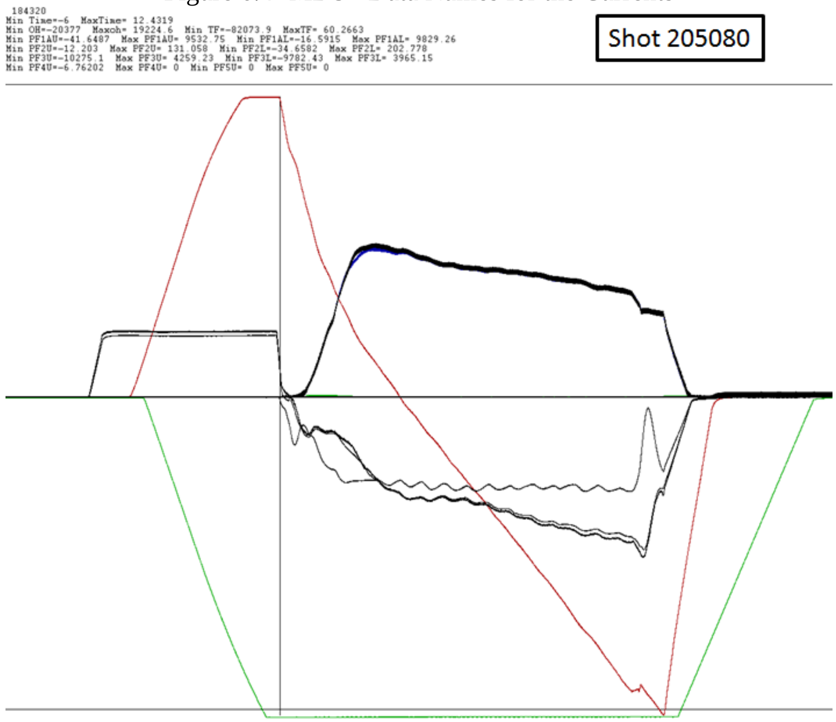


Figure 6.4-5 Shot 205080 Currents (True Basic "DCPS" Program [7] Plot)

Figure 6.4-6 Shot 205080 Currents (EXCEL Plot from MDS+ Data)

7.0 Results Evaluation of Instrumentation Tasks

7.1 Task 1 OH Preload Measurement

Task 7.1 Purpose

The preload mechanism applies a vertical load on the OH to offset the launching load on the OH from Lorentz force interactions with the remaining PF coils.

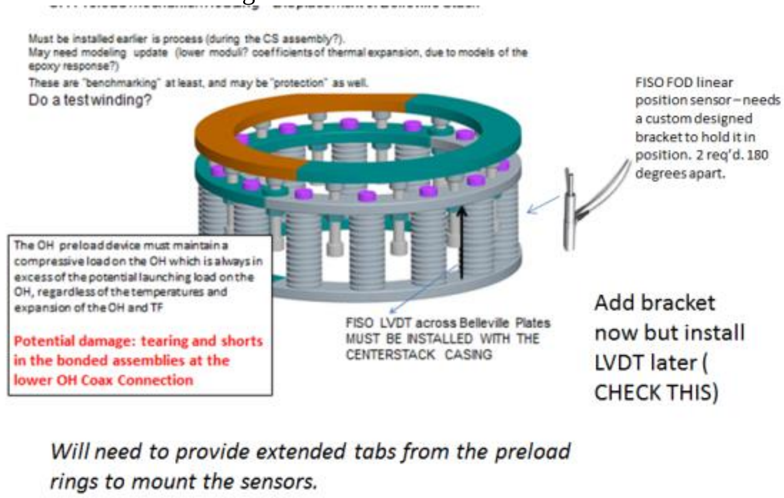


Figure 7.1-1

The initial preload compression has been set at 17 mm. To benchmark the calculations, the displacements being absorbed by the Belleville spring stack must be measured and compared with the calculations. There is a potential for relaxation of the preload from creep/settlement of the load carried by the OH VPI system. Provision has been made to adjust the preload after operation has begun. CTD is being tasked to measure the creep rate for the CTD 425 system, and this will provide an indication of the frequency of required preload adjustment.

Task 1 Calculations Effected:

NSTX CALC 133-04 OH Preload Mechanism

Task 1 Requirements

The table/figure below is from Peter Rogoff's calculation, NSTX CALC 133-04. The nominal range is: 23.87-9.47 = 14.4 mm. Since we are trying to model some degree of unexpected displacements, a LVDT that can measure at least 2 cm is recommended.

If the LVDT is zeroed when the preload is imposed, then the LVDT would have to measure

(17.87-9.47) = (plus) 8.4 mm When the TF is hot and the OH is cold
(17.87-23.87) = (minus) 6 mm. When the OH is hot and the TF is cold
(8.4-6.0) = (plus) 2.4 mm When the TF is hot and the OH is also hot

The first indication we will have of a variation in the design parameters will be if the preload system jacking screws have to be tightened more than the nominal compression of 17.87 mm to actually achieve the desired 17.87 mm of Belleville spring stack compressive displacement. They should be almost one to one, i.e. for reasonable moduli, the elastic behavior should be very small compared with the thermal displacements. The preload elastic coil displacements are ~1/10 mm, Lorentz displacements are ~ 1 mm

Performance Summary

And

Input to digital coil protection system

System scenario	Compression mm	Force on OH N	Force on OH lbs.*	Tensile Stress N/mm	Fatigue Cycles
Pre Load	17.87	162,512	36,520.	849.	-----
TF hot OH hot	15.47	142,268.	31,970.	731.	2 Mil. +
TF hot OH cold	9.47	89,698.	20,157.	459.	high
TF cold OH hot	23.87	211,582.	47,546.	1185.	500,000

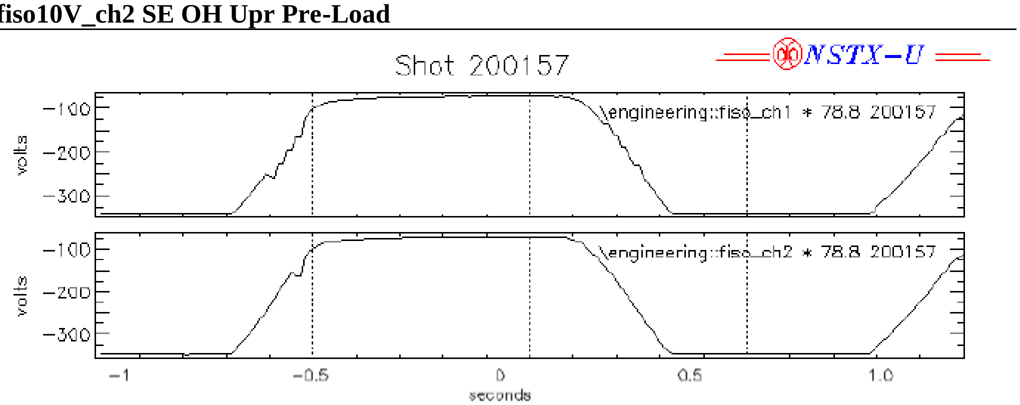
Thermal expansions:
FT = 8.4 mm
OH= 6.0 mm

* Allowable OH launching loads.

Note: For supporting calculation see power point files for full details.

Figure 2.1-2

#1 pc_fiso10V_ch1 NE OH Upr Pre-Load
#2 pc_fiso10V_ch2 SE OH Upr Pre-Load



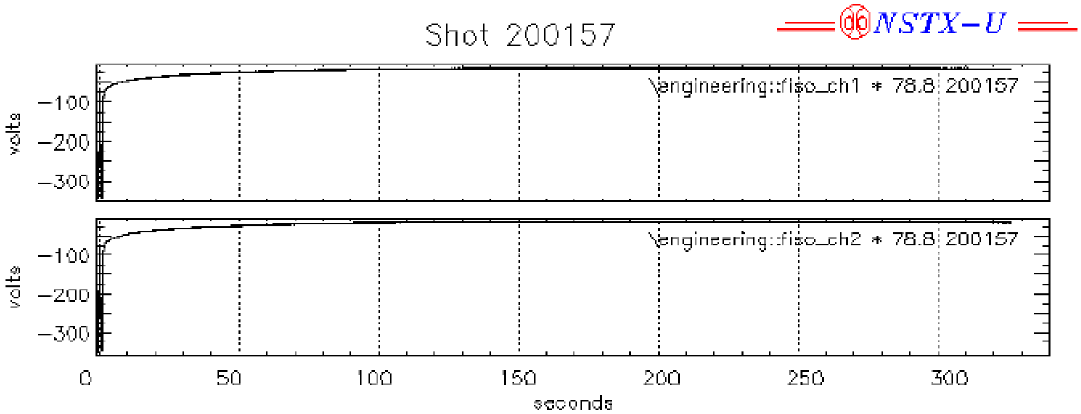
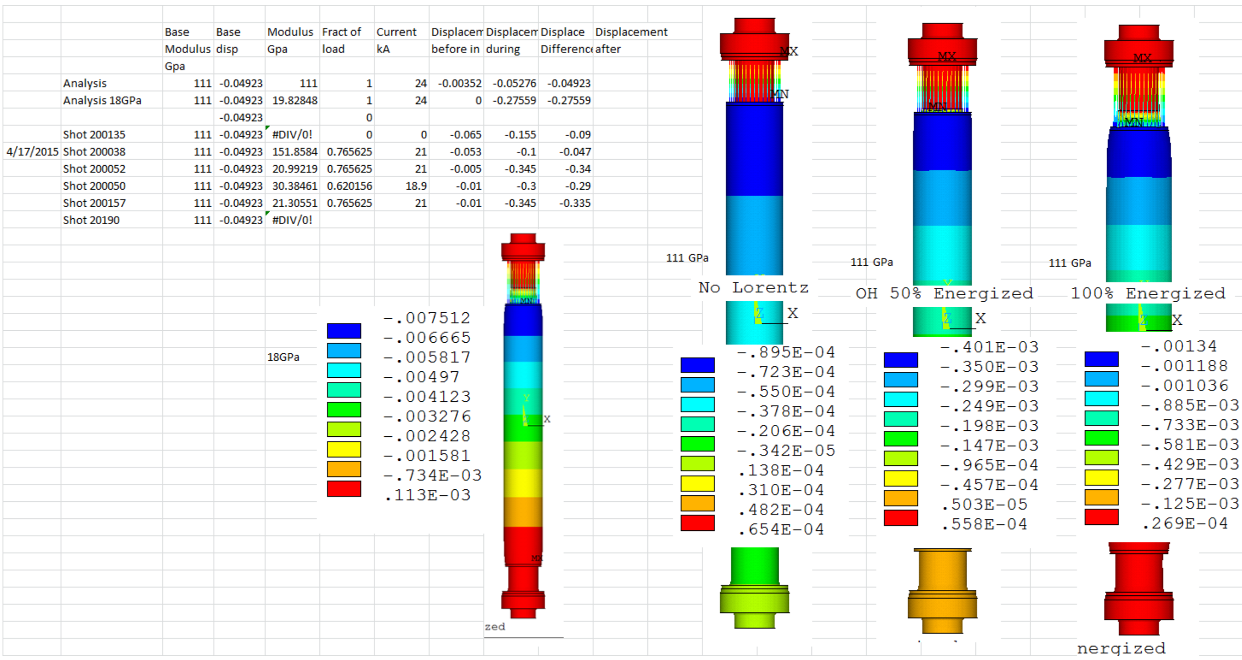


Figure 2.1-3 Combined Shot, TF and OH



		Base Modulus Gpa	Base disp	Modulus Gpa	Fract of load	Current kA	Displacem before in	Displacem during	Displace Difference	Displacement after
	Analysis	111	-0.04923	111	1	24	-0.00352	-0.05276	-0.04923	
	Analysis 18GPa	111	-0.04923	19.82848	1	24	0	-0.27559	-0.27559	
			-0.04923		0					
	Shot 200135	111	-0.04923	#DIV/0!	0	0	-0.065	-0.155	-0.09	
4/17/2015	Shot 200038	111	-0.04923	151.8584	0.765625	21	-0.053	-0.1	-0.047	
	Shot 200052	111	-0.04923	20.99219	0.765625	21	-0.005	-0.345	-0.34	
	Shot 200050	111	-0.04923	30.38461	0.620156	18.9	-0.01	-0.3	-0.29	
	Shot 200157	111	-0.04923	21.30551	0.765625	21	-0.01	-0.345	-0.335	
	Shot 20190	111	-0.04923	#DIV/0!						

Figure 2.1-4 2

Estimate of the Modulus from Measured LVDT Data

An axial modulus of 18 GPa would fit well. The hoop modulus would remain at 111 GPa

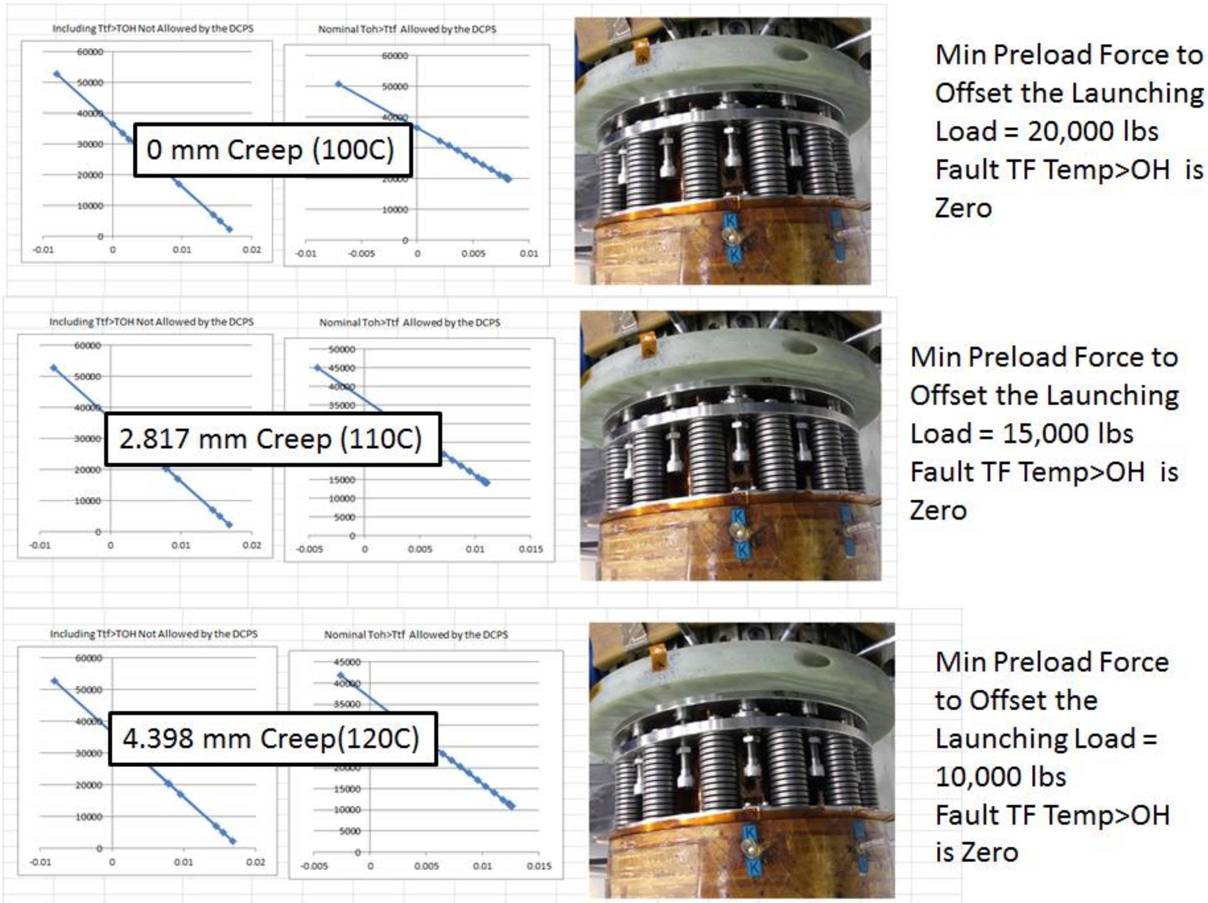


Figure 3.1- 4 Preload Compression vs Displacement as Measured by the LVDT

2015 Combined Physics Shots

Email from John Dong

Attached are the Dec 2015 ISTP 50%(shot 202263) and 100%(shot 202283) OH ISTP shots.
FISO data can be retrieved through this Web Page:
http://nstx.pppl.gov/nstx/Software/WebTools/mdsmultisig.html

The Shot Number default field entry is a blank(will give you the most recent shot number)
The "Enter Signal(s) with tree name" field should have the FISO signal names(i.e. \TFJ_FISO_CH1 * 78.8 for the first line and so forth for the other channels of interest)
The "Y" and "Plot Ranges:" are self explanatory
FISO Channel Assignments
FISO Chan 1: NE OH(Bay D) Upper Pre-Load
FISO Chan 2: SE OH(Bay J) Upper Pre-Load
FISO Chan 3: Bay E/F Upper Lid Outside
FISO Chan 4: Bay E/F Upper Lid Inside
FISO Chan 5: Bay E/F Lower Lid Outside
All the sensors are displacement sensors and the " * 78.8" is the conversion factor to convert the digitizer value to mils.

I have attached a screen shot to plot the 100% OH ISTP shot.

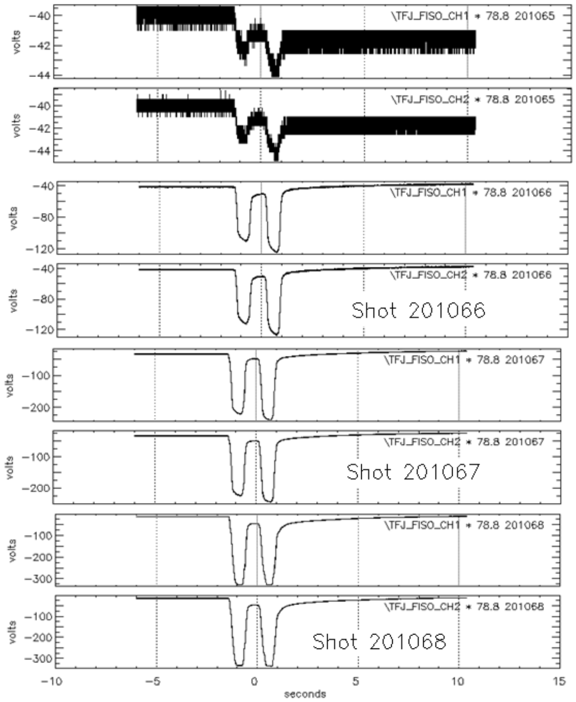
25%, 50%, 75%, 100% Combined Physics Shots

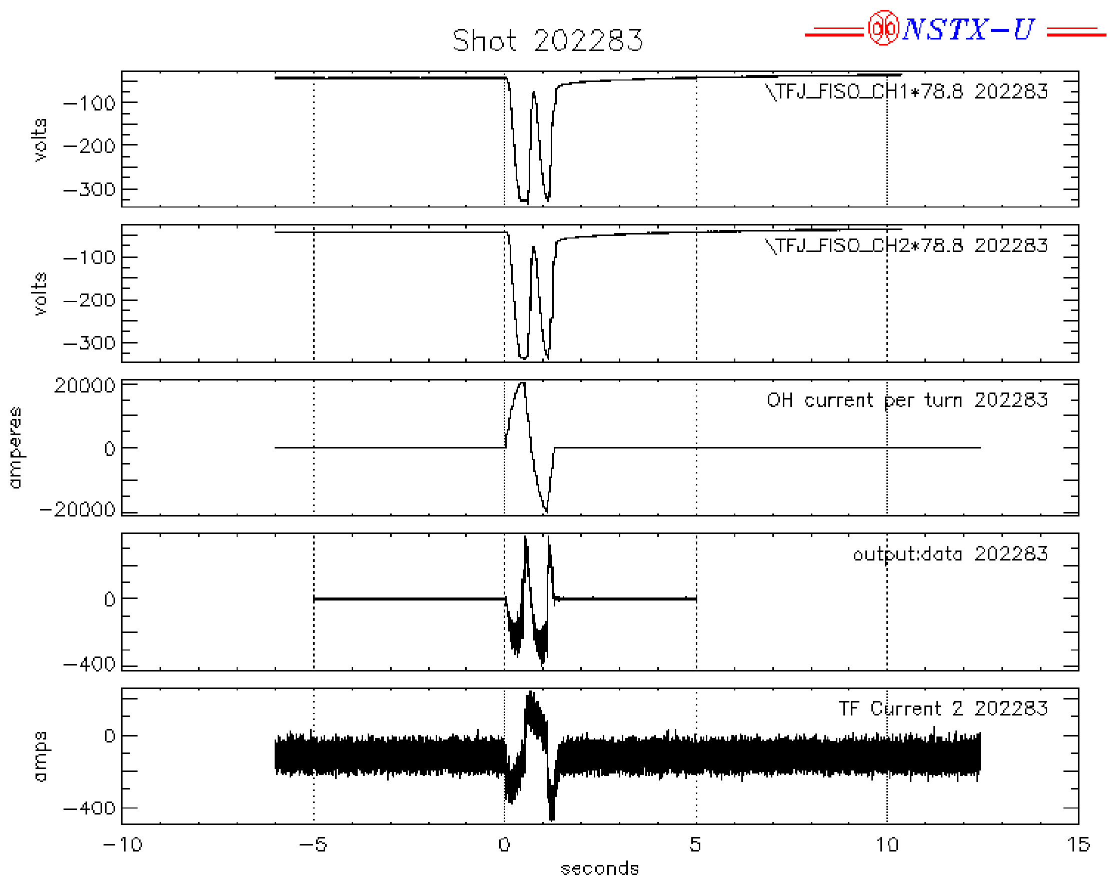
8/10/2015 10:19:45 AM 201065 TEST SHOT status: GOOD Inadequate: None 25% Physics Combined Field Shot TF-OH, PF3-U, PF3-L, PF525% Physics Combined Field Shot TF-OH, PF3-U, PF3-L, PF5

8/10/2015 10:31:08 AM 201066 TEST SHOT status: GOOD Inadequate: None 50% Physics Combined Field Shot TF-OH, PF3-U, PF3-L, PF550% Physics Combined Field Shot TF-OH, PF3-U, PF3-L, PF5

8/10/2015 11:11:24 AM 201067 TEST SHOT status: GOOD Inadequate: None 75% Physics Combined Field Shot TF-OH, PF3-U, PF3-L, PF575% Physics Combined Field Shot TF-OH, PF3-U, PF3-L, PF5

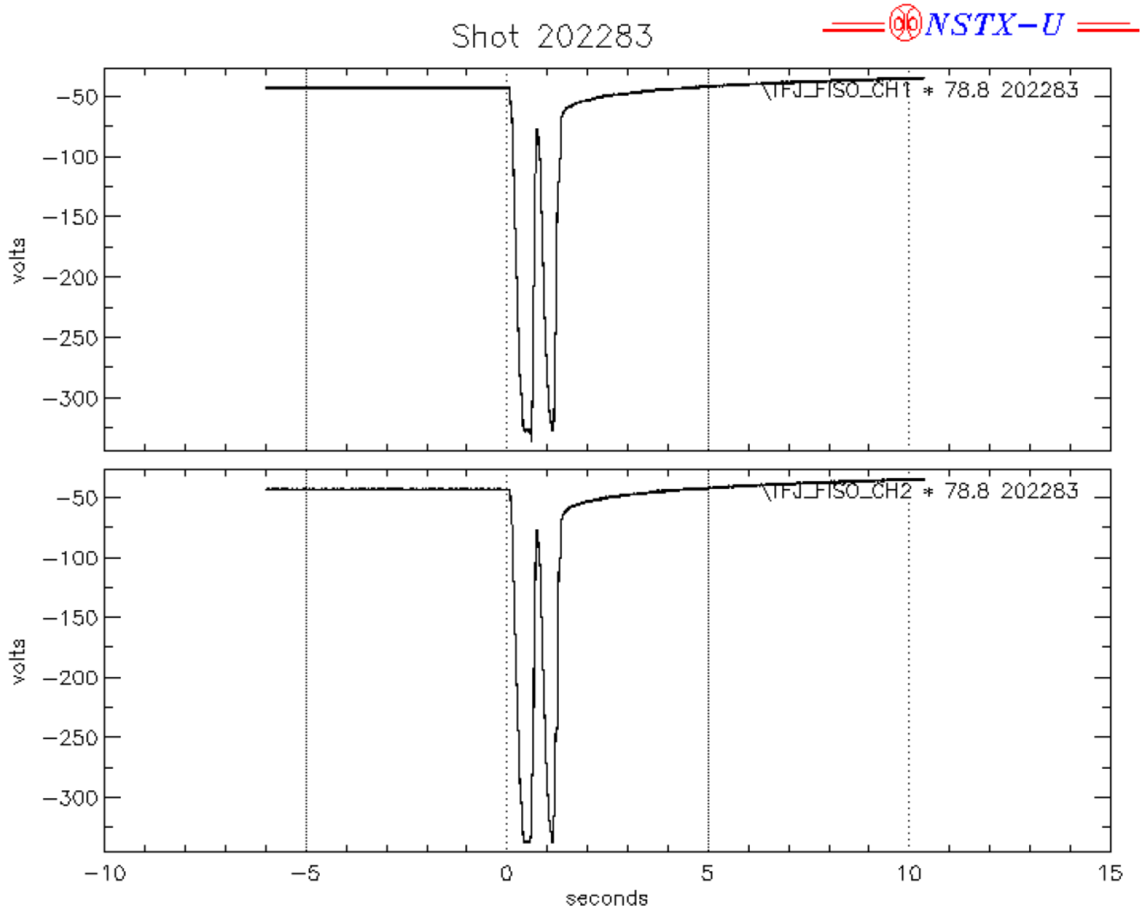
8/10/2015 11:38:16 AM 201068 TEST SHOT status: NO GOOD Inadequate: None 100% Physics Combined Field Shot TF-OH, PF3-U, PF3-L, NG -PF5 FCC DCPS tripped-100% Physics Combined Field Shot TF-OH, PF3-U, PF3-L, NG -PF5 FCC DCPS tripped-

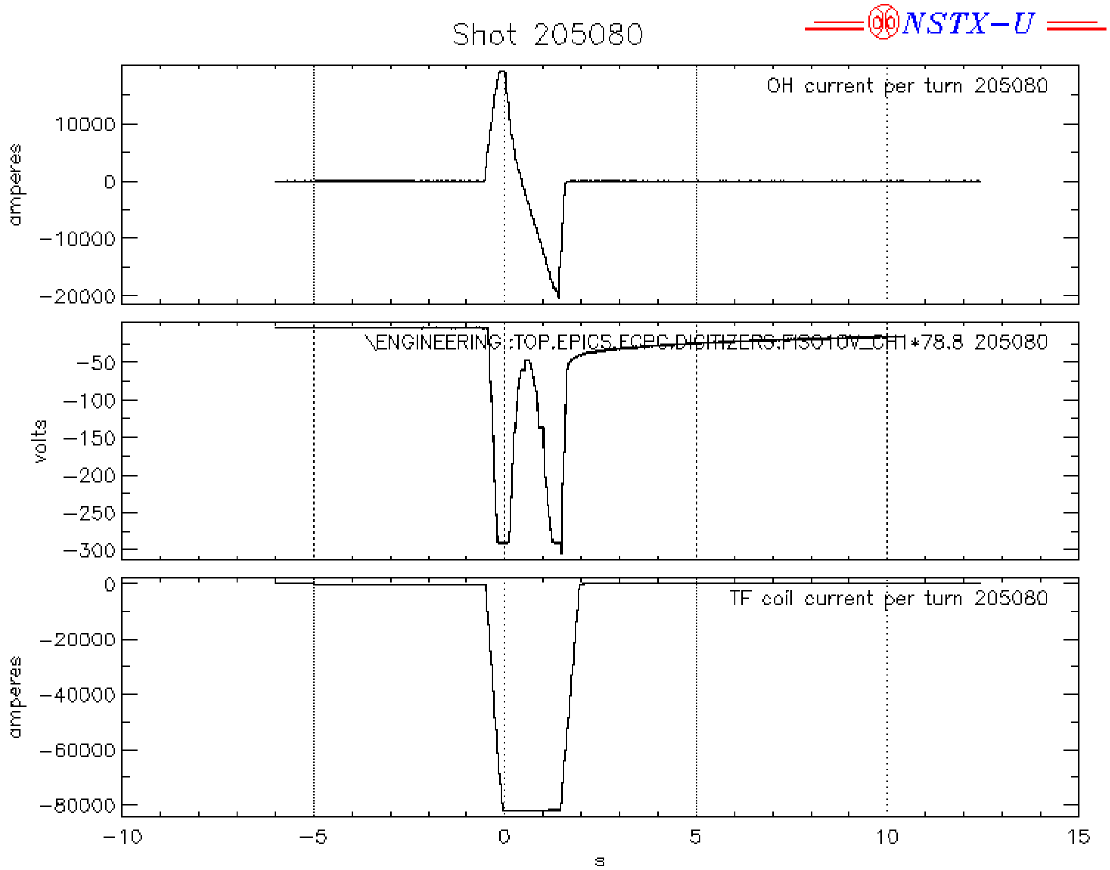


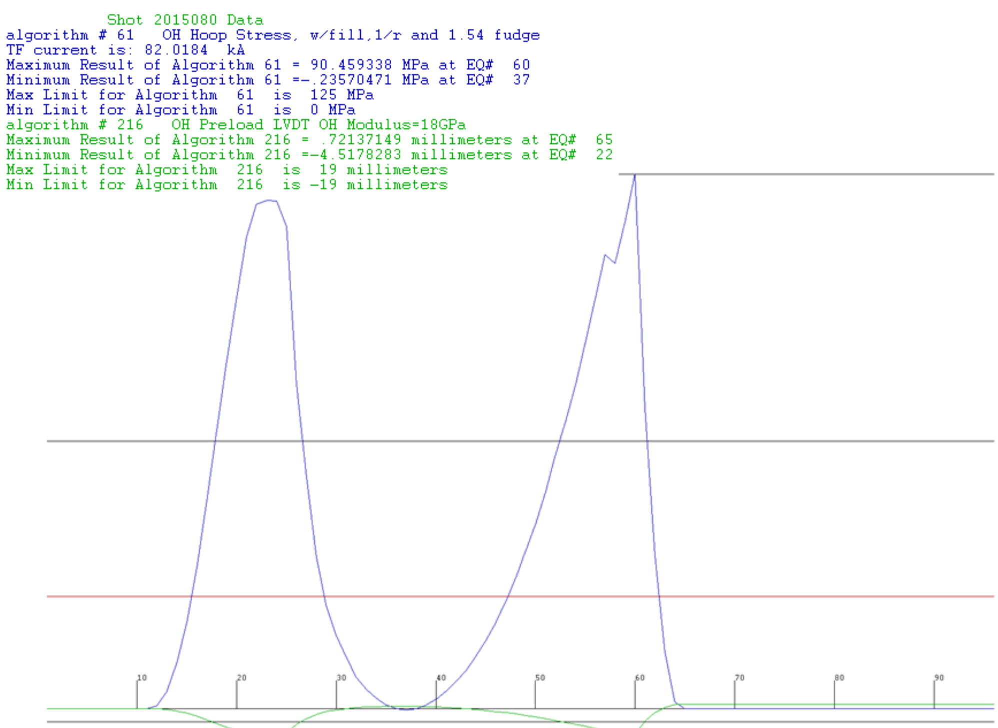


In this shot the thermal expansion is low - The OH displacement from Lorentz Forces is .33 inches/20,000 amps

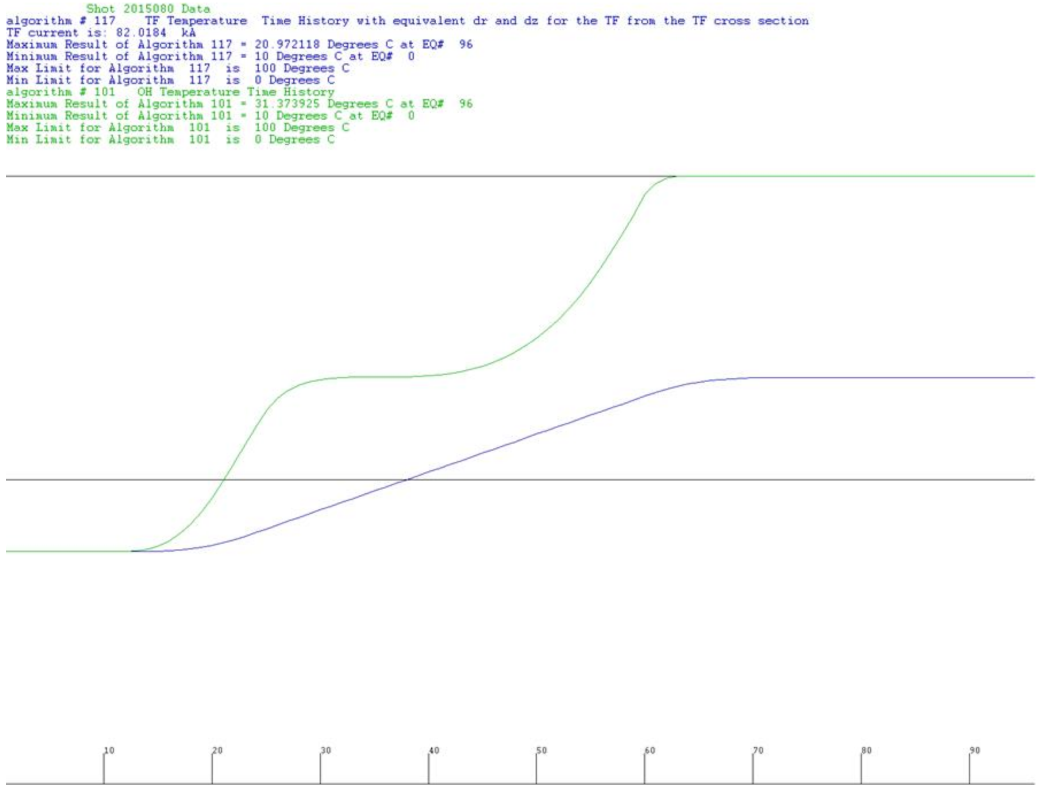
12/18/2015 nstxops.pppl.gov (780×600)







OH Hoop Stress(Upper,blue) and Preload LVDT Displacement(Lower, Green) from [7]



TF Temperature (Lower,blue) and OH Temperature(Upper, Green) from [7]

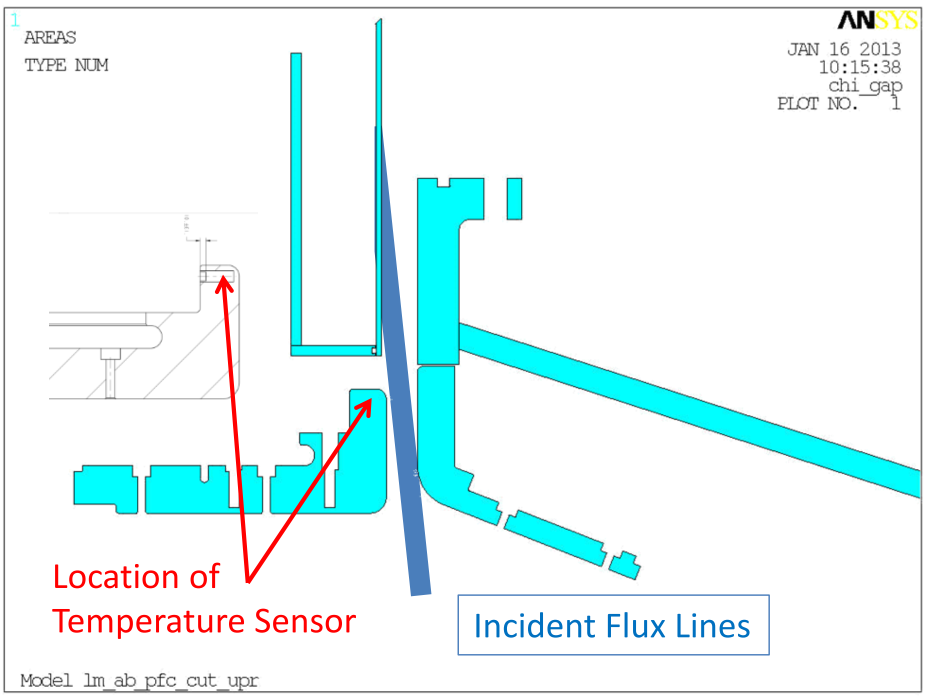
7.2 Task 2 CHI Gap Tile Thermocouples

Effected Calculation: Stress Analysis of ATJ Center Stack Tiles and Fasteners NSTXU-CALC-11-03-01

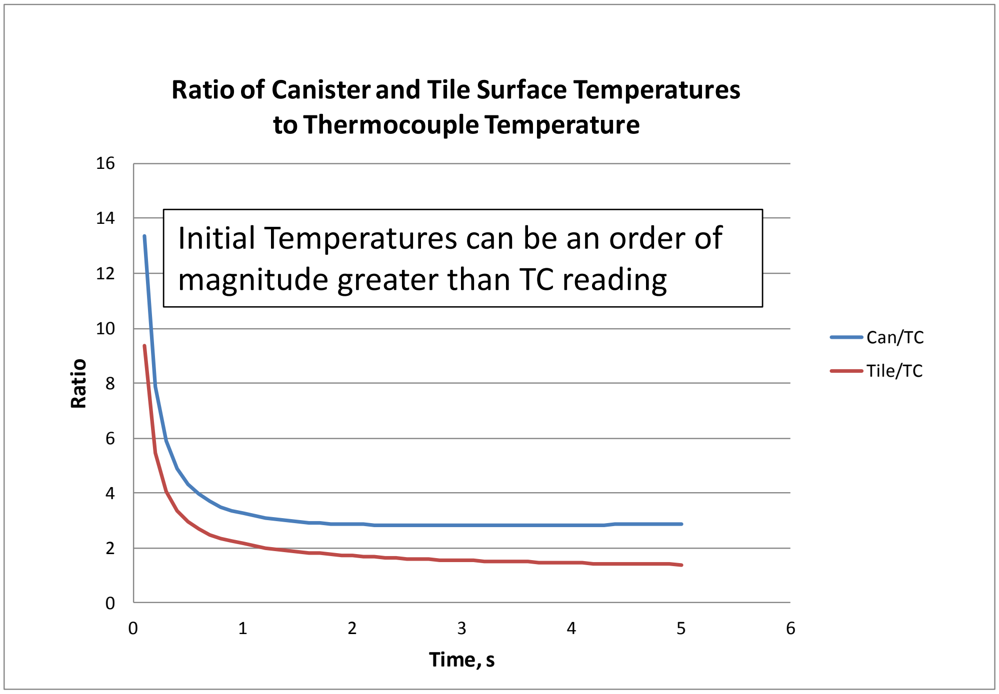
Temperature Limit:

The CHI gap tile was instrumented to provide an indication of the heat flux entering the CHI gap which might thermally load the PF1c case outer shell. In this sense, ther purpose of this task is identical to Task 4 in which a thermocouple on the PF1c Outer shell is directly monitored.

The CHI Gap between the IBD and OBD permits heat flux to impinge on the PF1c coil canister. Direct measurement of the thermal response of the canister is being considered by thermal imaging. In parallel, thermocouples are installed in the IBDhs tile as close to the canister as possible. The response of the thermocouple will be used to estimate the surface heat fluxes in the CHI Gap. Since the thermocouple is imbedded in the tile its response will be delayed. The temperature response of the thermocouple location was compared below to surface temperature to verify the response time was adequate to protect the canister and coil.



The results show the thermocouple response appears adequate to extrapolate the tile surface temperature, and associated heat flux, for long pulses (ie greater than 1 sec).

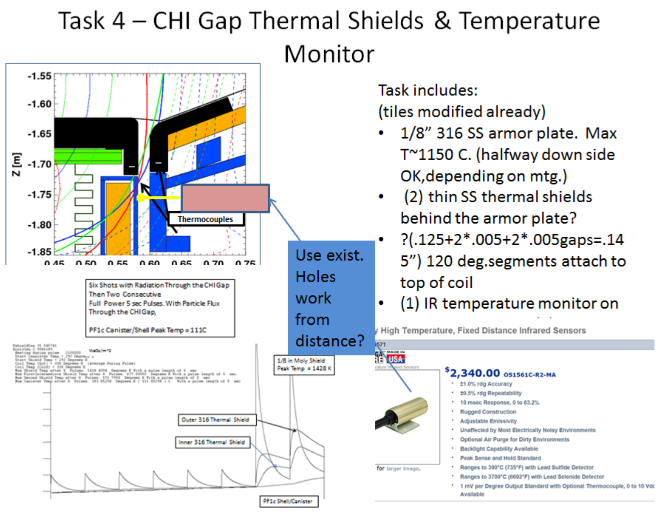


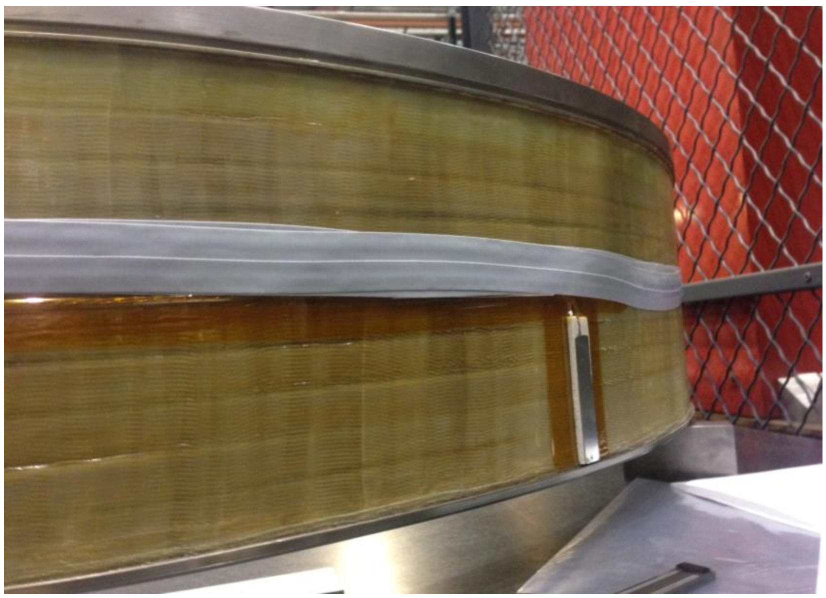
7.3Task 4 CHI Gap PF1c Outer Case Temperature Monitor

Affected Calculation:

[21] Analysis of the PF1c Mandrel/Case CHI Gap, Thermal/Structural Analysis, Including the Proposed Thermal Shield Design NSTXU-CALC-133-15-0

Thermocouples have been installed in the CHI Gap Tiles and the installation of these will not be covered by the benchmark instrumentation task. A thermocouple has been installed in contact with the outer PF1c case near where the highest heat flux is expected.The CHI gap tile temperature and PF1c case temperature should be monitored together. These will be monitored during operation as well as The original proposal





Thermocouple intended to read the casing temperature

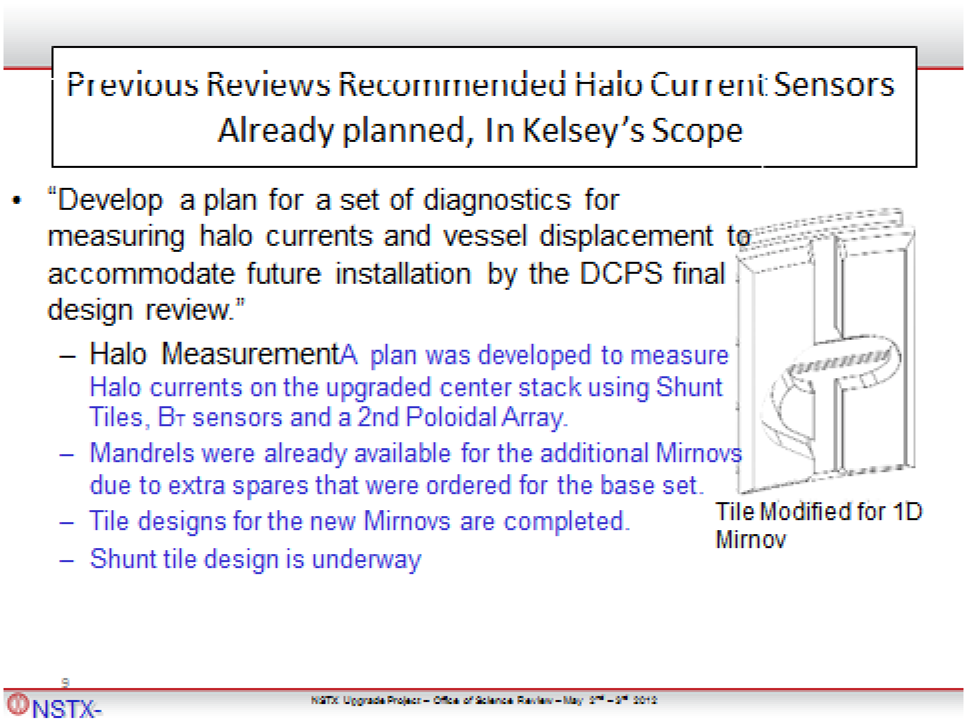
Task 7.4 Halo Current in Centerstack Tiles

Calculations Effected:

[27] NSTX Upgrade Centerstack Casing and Lower Skirt Stress Summary NSTXU-CALC-133-03-00 Rev 0 August 2011 Prepared By: Peter Titus

[30] Halo Current Analysis of Center Stack NSTXU-CALC-133-05-00 Prepared By: Art Brooks, Reviewed by: Peter Titus, Cognizant Engineer: Jim Chrzanowski, WBS 1.1.3 Magnet Systems,

The amount of halo current flowing in the centerstack casing and the non-axisymmetry of these currents produce lateral loads on the centerstack casing that must be reacted by the bolted connections at the base of the centerstack, and the shims that fill the gaps between the upper-casing flange and the PF1c upper case. .The GRD Table 2-2 includes the Upgrade design levels of halo current. For 2MA plasma, a peak halo current of 700kA was considered. A toroidal peaking factor of 2:1 was considered in the design the toroidal dependence of the halo current is $[1 + \cos(\phi - \phi_0)]$, for $\phi = 0$ to 360^o where ϕ is the toroidal angle. Tiles at the equatorial plane have been fitted with 1D Mirnov coils and can be monitored early in the operation of NSTX-U. The tilted Mirnov's measure toroidal field and will respond to vertical currents in the centerstack and provide some indication of the current center and thus peaking factor by variations in the toroidal field around the circumference of the casing. A database of Ip, Halo currents and peaking factor should be developed as soon as there are significant disruptions.

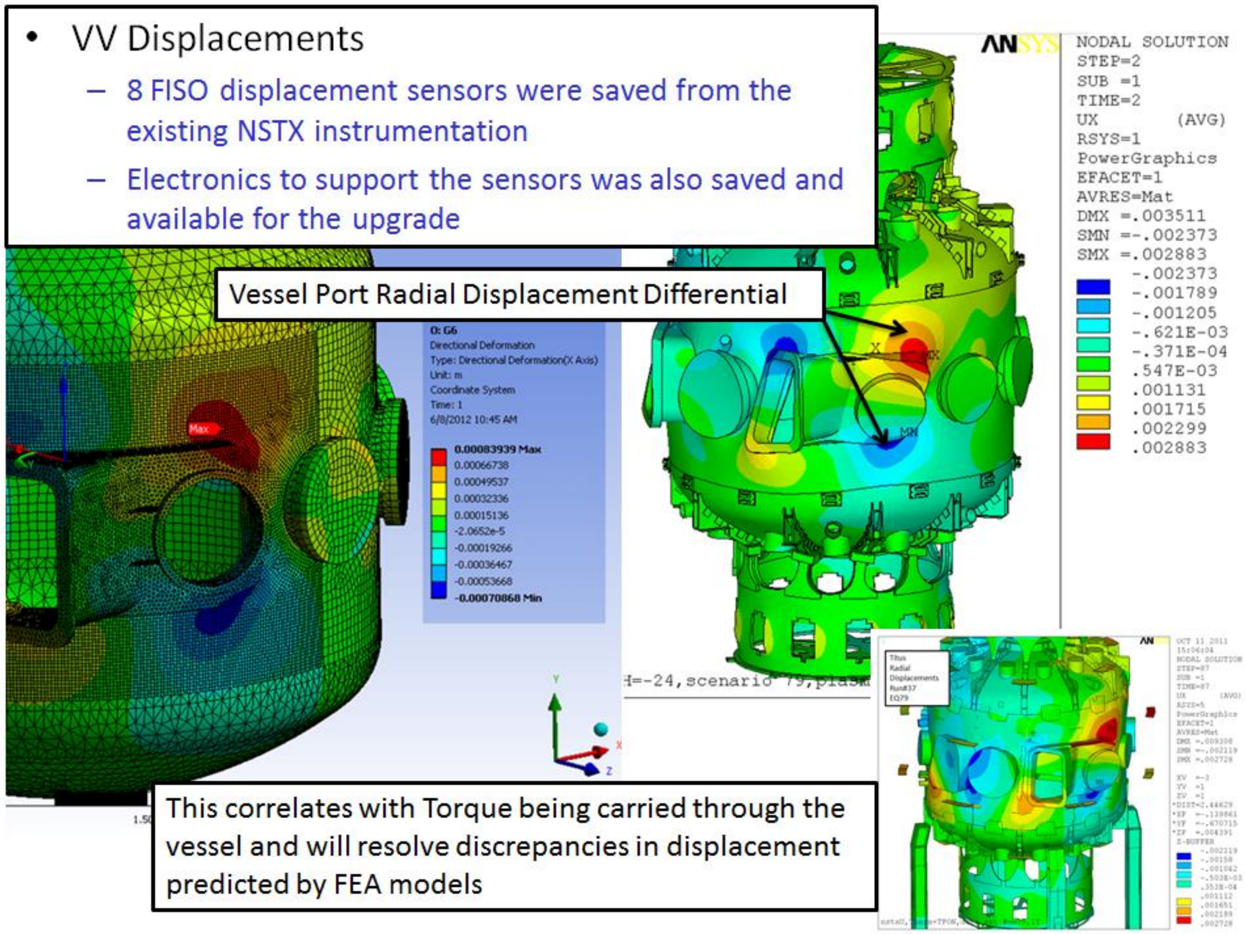


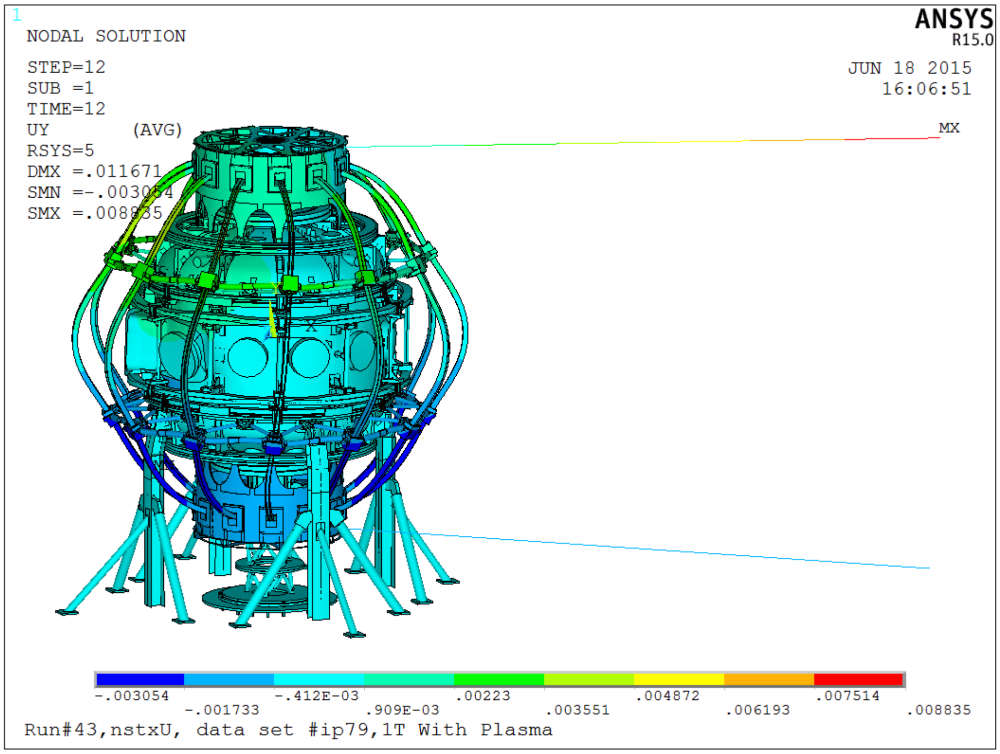
The lateral load at the base of the centerstack casing for the halo specification in the GDR is 50,000 lbs, Loading on the NSTX-U centerstack can be scaled from measured Ip, Halo currents and peaking factor , and confirmed by a future conversion of the upper shims to load cells –See Task 2.8

7.5 Task 5 Torque Benchmark Including Vessel Bay J,K cap twist displacements and Laser Mirror as a Measure of the Torque the Vessel is Supporting

Calculations Effected:

Vessel Rework for the Neutral Beam and Thomson Scattering NSTXU-CALC-24-01-00 Rev 0 February 1, 2011 Prepared By: Tom Willard
[5] Global Analysis of NSTX-U NSTXU-CALC-10-01-02, P. Titus





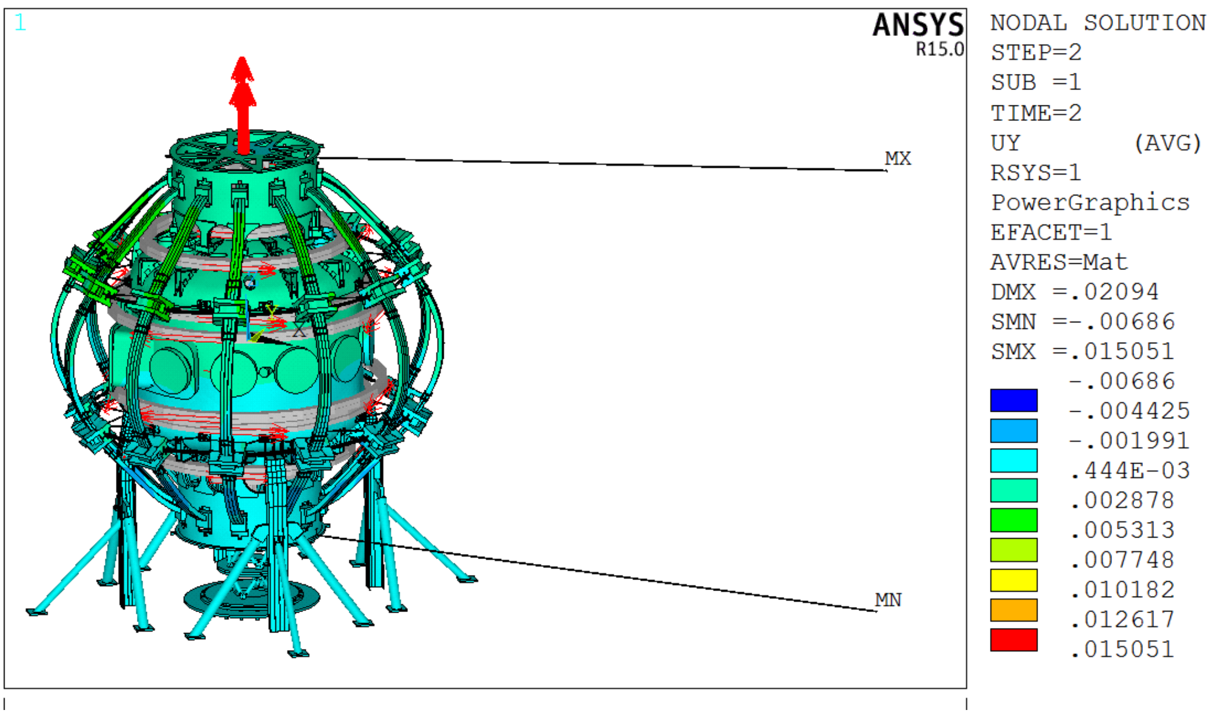
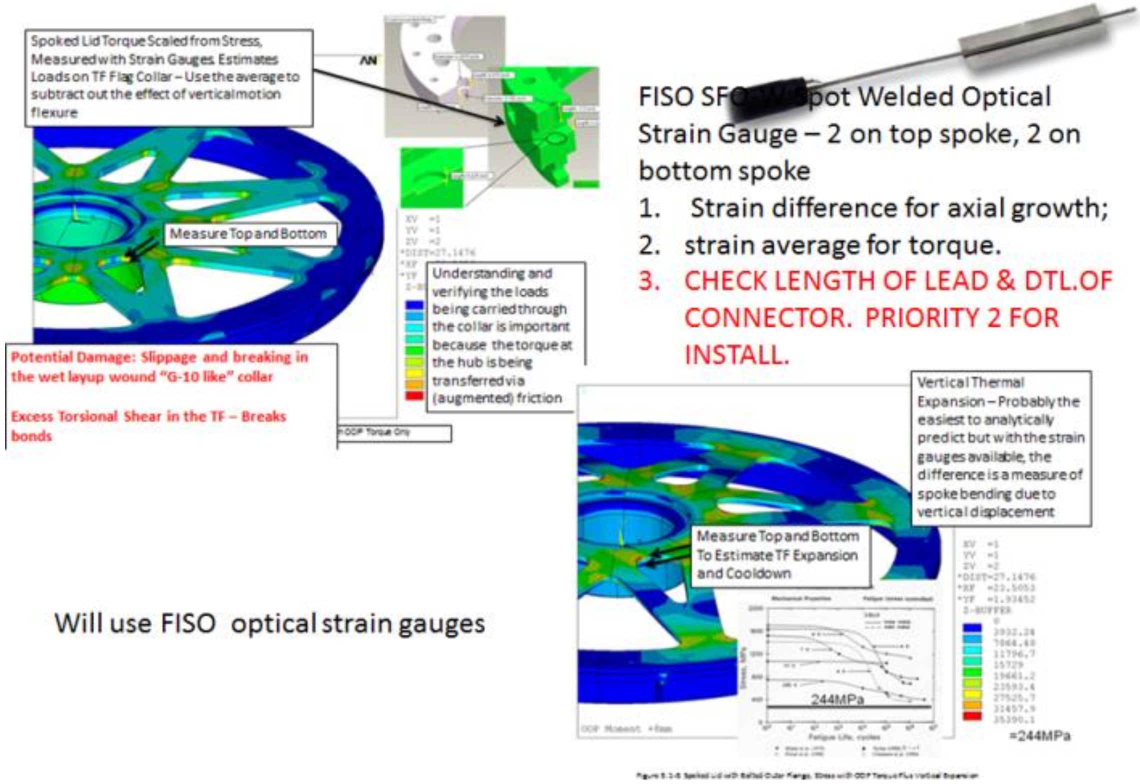


Table Top Umbrella Structure Twist Angle

	Eq 79	**22kA OH , 80k ATF**	

Titus (Analysis)	**.01444**		
Han (Analysis)			

7.6 Task 6 and 7 Spoked Lid Stresses for Torque Measurement and Centerstack Thermal Expansion



Task 6 and 7 Purpose:

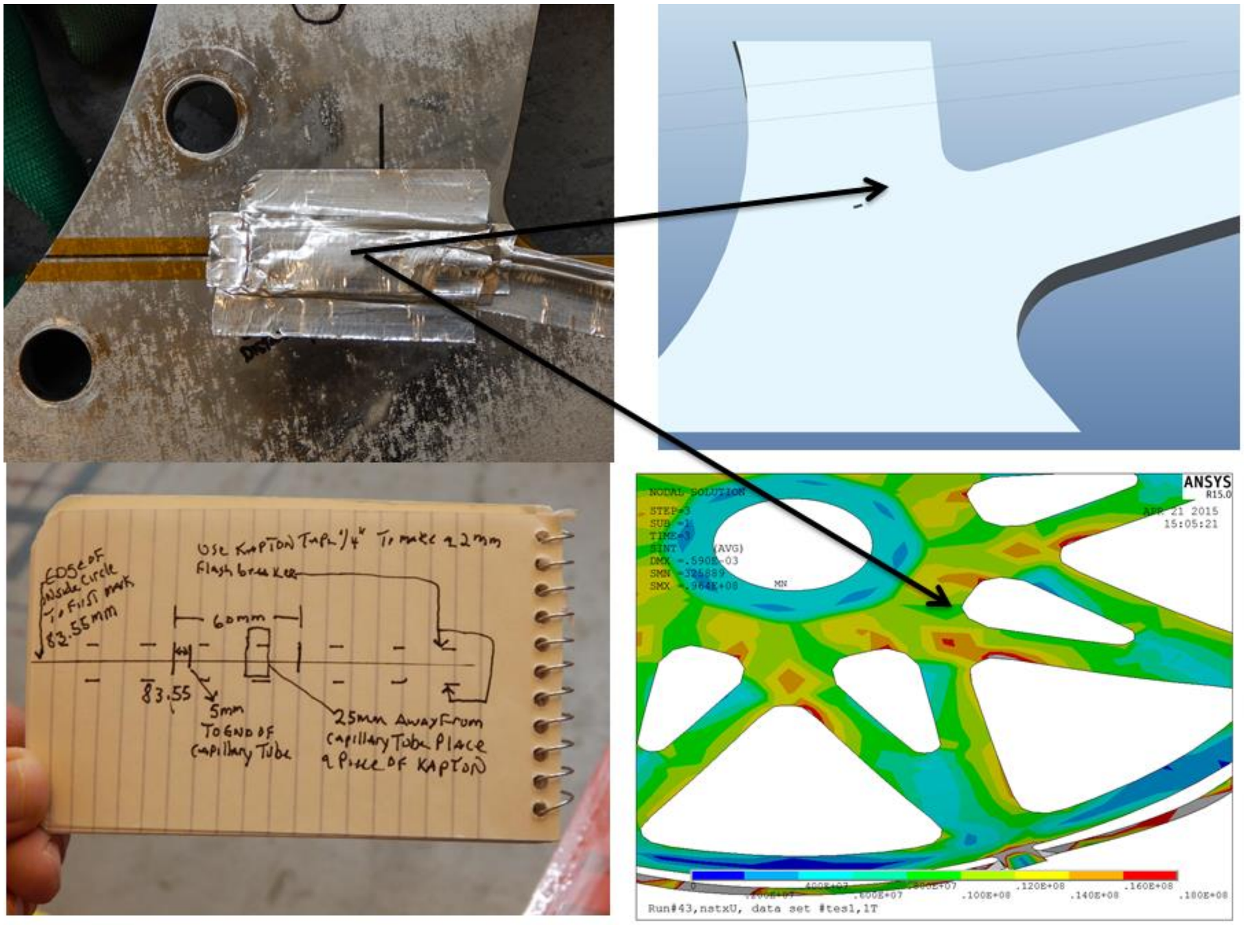
To benchmark global torque calculations. And to monitor the friction joint integrity. For the upper spoked lid, the loading is transferred through the spoked lid and the TF flex. For the lower spoked lid, the torque is transferred through the spoked lid, bellows and straps as well as the pedestal to ground and back through the main braced legs. Understanding the torque load distribution is important for demonstrating acceptable loads in the TF inner leg, bellows, TF crowns as well as the spoked lid itself. Spoked lids relie on precompressed high friction bolted connections. The TF collar wet layup design was replaced with a segmented machined collar, made from much stronger high pressure G-10 laminate. Measuring and monitoring the spoked lid torque will allow confirmation of the behavior of the segmentation. Instrumenting a spoked lid with strain gauges at top and bottom of the spoke leg affords a measure of thermal expansion of the TF as well as the torque. The difference will provide the stress due to thermal expansion of the TF and the average of the strain gauge signals will correlate with the torque carried by the lid.

Task 6 and 7 Calculations Effected:

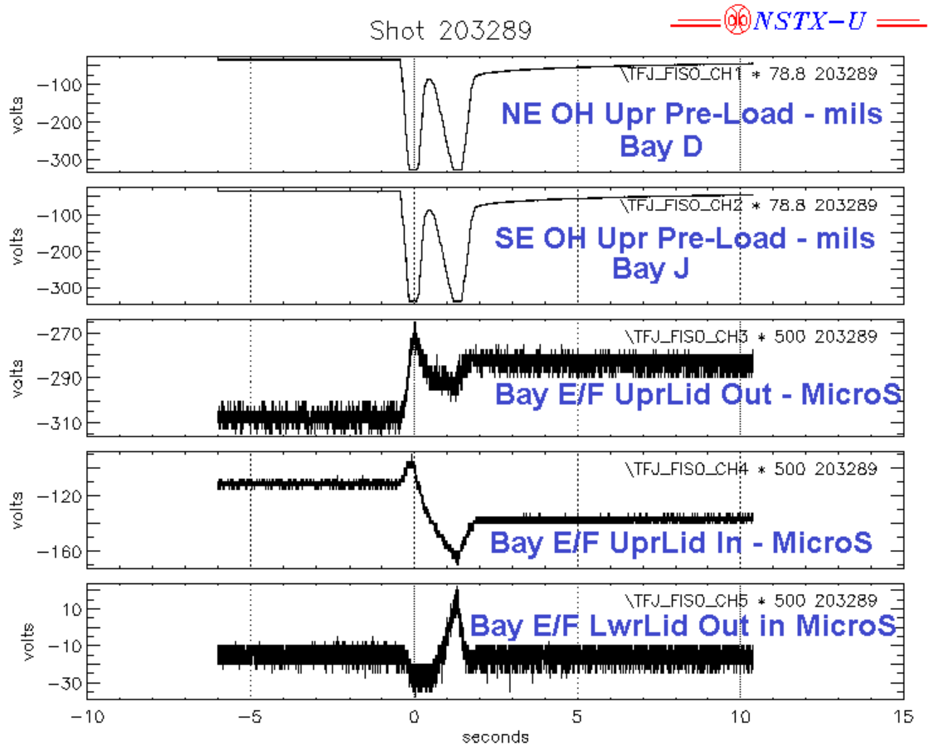
NSTXU CALC 132-08 TF Flag Key (Includes TF Crown)
NSTXU CALC 10-01-02 Global Model [5]
NSTXU CALC 12-08-02 Spoked Lid
NSTXU CALC 12-09-01 Pedestal

Task 6 and 7 Requirements

- Optical strain gauges are required to allow data taking during a shot without concern for EM interference. FISO strain gauges are recommended because the system was successful in NSTX and some of the components and expertise already exist at PPPL
- Background poloidal field will be less than 0.2T
- Top and bottom spoked lids should be instrumented.
- Connectors should be provided to allow lid removal without having to remove the strain gauges
- On each of the top and bottom lids, one of the 8 spokes should be instrumented with strain gauges at top and bottom of the spoke leg.
- Each spoke consists of 2 legs of a truss. The high stress location is near the inner hub end of the spokes – see the powerpoint figure or consult the calculation.
- Paired strain gauges on top and bottom of a leg should be aligned with at a high stress location in the stress contour plot and should be positioned above and below each other within .25 inches. .
- Installed position of the strain gauges should be recorded to allow matching the measured results with stresses from the model.
- A time history of the strain gauge difference should be recorded for each lid, and during each shot to be compared with the global torques calculated in the DCPS



#3 pc_fiso10V_ch3 Bay E/F Upr Lid Outside
#4 pc_fiso10V_ch4 Bay E/F Upr Lid Inside
#5 pc_fiso10V_ch5 Bay E/F Lwr Lid Outside


Shot 203289
NSTX-U
\TFJ_FISO_CH1 * 78.8 203289
NE OH Upr Pre-Load - mils
Bay D
\TFJ_FISO_CH2 * 78.8 203289
SE OH Upr Pre-Load - mils
Bay J
\TFJ_FISO_CH3 * 500 203289
Bay E/F UprLid Out - MicroS
\TFJ_FISO_CH4 * 500 203289
Bay E/F UprLid In - MicroS
\TFJ_FISO_CH5 * 500 203289
Bay E/F LwrLid Out in MicroS
volts
seconds

7.8 Task 8 CS Casing Halo Loading at Top Flange

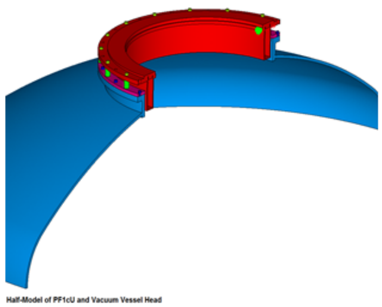
The analysis of the casing assumed 8 bumpers. 6 were installed. These take the lateral load on the centerstack casing caused by non-axisymmetric halo currents.

From Len's PF1 coil calculation (NSTXU-CALC-133-01-02:

Contact between the two coils at a single bumper is an extreme case and represents a (4) bumper configuration with the load direction such that only one bumper is engaged. If more bumpers are incorporated into the design, then the overall stiffness will be a higher, and the load will be carried by more structure. In this conservative calculation, the results from the applied 252 kN load are scaled by 0.441 to determine the stresses due to a 25 kip load through this upper support load path. Fig. 4.5-3 shows a plot of the PF1c coil case stress. Ignoring the contact stress identified by a single red spot, the general stress field is <300 MP. Linearization shows a MEM+BEND stress of ~200 MPa (<1.5Sm or 276 MPa). However, the lateral load could reach ~200 kN (45 kip). With a scale factor applied to the 252 kN load case of 0.794 (not 0.441), the MEM+BEND stress would be ~200 x (45 kip/25 kip) or 360 MPa. At this stress level, the number of bumpers must increase from four to at least six. Eight bumpers (one every 45°) is a reasonable distribution and leads to a more robust design.

Conclusion: A series of (8) bumpers should be located between the PF1bU mandrel top flange OD and the PF1cU case flange ID. This will result in a center casing upper support stiffness to ground of >420 kip/in. Brooks' dynamic simulation of halo currents and forces should adopt this effective stiffness value.

I would interpret this as 8 bumpers with a local capacity of up to 45000 lb



This is a half symmetry model that was later scaled

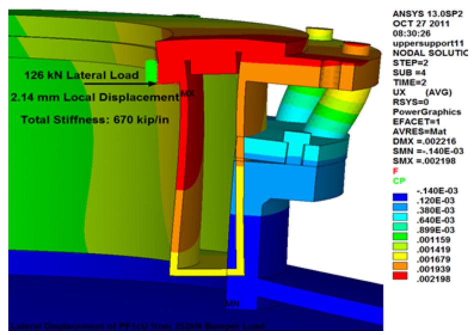
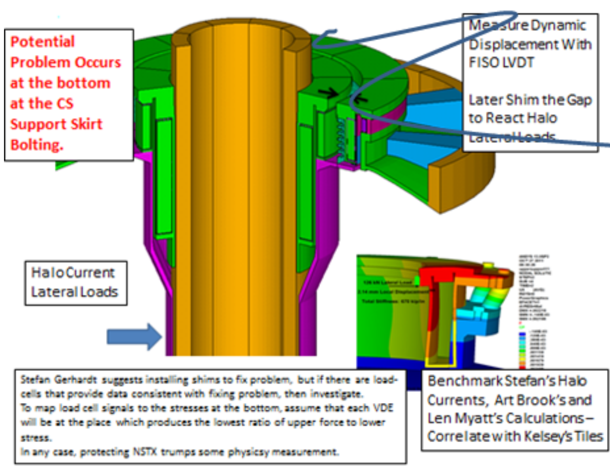
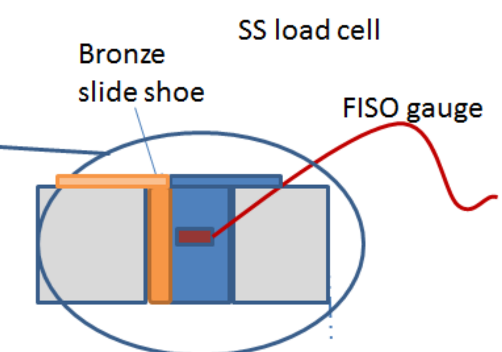


Figure 3.8-1





load shell/shims: custom fitted in gaps 60 deg. apart at top of the machine.

INSTALL BASIC SHOES FOR FIRST OPERATION – ADD FISO GAUGES LATER CHECK IF STD. PIEZOELECTRIC LOAD CELL WILL WORK IN MAG FIELD TRY INVERTING AND SIMPLIFYING IT.

Task 8 Purpose

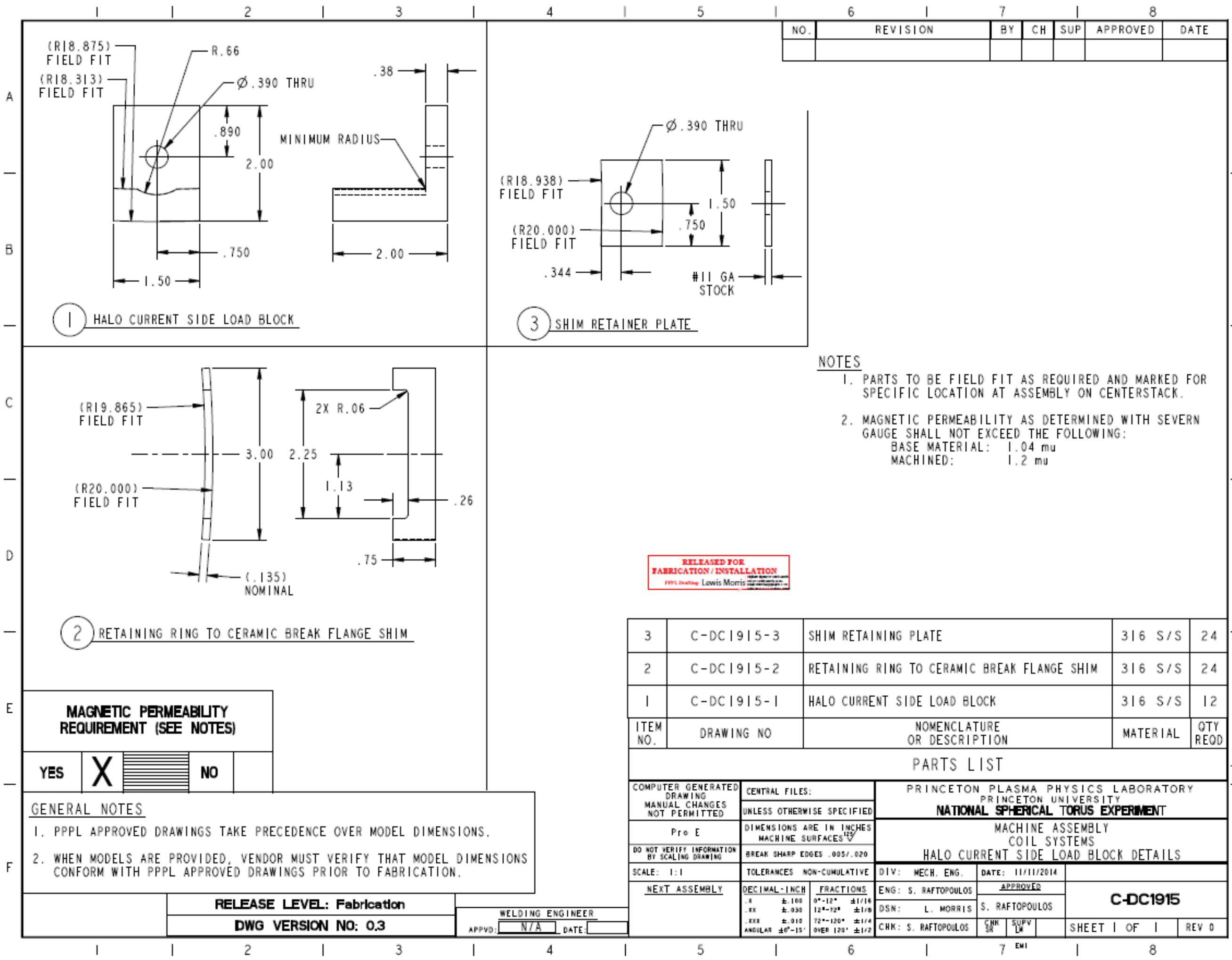
The purpose of this instrumentation is Physics , and Structural Benchmark and Protection. Halo loading is uncertain in the new machine configuration. Initial installation of the shims will limit loading on the bellows. Later conversion to load cells will quantify the magnitude of the loading. Evaluation of the halo currents from Task 3 instrumentation will provide an indication of how the mid plane halo loads integrate to produce net side loads on the casing. Forces measured at the top of the casing will also benchmark predictions and limits on the casing and bellows stresses. These load measurements will add to other halo loading measurements – Mirnov coils in the casing (Task 3) and CHI bus bar ground current measurements (Task 17)

Task 8 Calculations Effected:

[10] NSTXU CALC 133-03 Centerstack Casing Stress Summary
[11] NSTXU CALC 133-05-01 Halo Current Analysis of the Centerstack Casing

Task 8 Requirements

- Six shims/load cells are required (This is mainly due to stress limits in the casing flange)
- Load cells should have a response time in the millisecond range
- Load cell capacity should be > 50,000 lbs
- Load cells must not be effected by the EM background to allow data taking during a shot



HALO CURRENT SIDE LOAD BLOCK
RETAINING RING TO CERAMIC BREAK FLANGE SHIM
SHIM RETAINER PLATE
NOTES
1. PARTS TO BE FIELD FIT AS REQUIRED AND MARKED FOR SPECIFIC LOCATION AT ASSEMBLY ON CENTERSTACK.
2. MAGNETIC PERMEABILITY AS DETERMINED WITH SEVERN GAUGE SHALL NOT EXCEED THE FOLLOWING:
BASE MATERIAL: 1.04 mu
MACHINED: 1.2 mu
MAGNETIC PERMEABILITY REQUIREMENT (SEE NOTES)
YES X NO
GENERAL NOTES
1. PPPL APPROVED DRAWINGS TAKE PRECEDENCE OVER MODEL DIMENSIONS.
2. WHEN MODELS ARE PROVIDED, VENDOR MUST VERIFY THAT MODEL DIMENSIONS CONFORM WITH PPPL APPROVED DRAWINGS PRIOR TO FABRICATION.
RELEASE LEVEL: Fabrication
DWG VERSION NO: 0.3
3 C-DC1915-3 SHIM RETAINING PLATE 316 S/S 24
2 C-DC1915-2 RETAINING RING TO CERAMIC BREAK FLANGE SHIM 316 S/S 24
1 C-DC1915-1 HALO CURRENT SIDE LOAD BLOCK 316 S/S 12
ITEM NO. DRAWING NO NOMENCLATURE OR DESCRIPTION MATERIAL QTY REQD
PARTS LIST
PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY
NATIONAL SPHERICAL TORUS EXPERIMENT
MACHINE ASSEMBLY
COIL SYSTEMS
HALO CURRENT SIDE LOAD BLOCK DETAILS
DATE: 11/11/2014
ENG: S. RAFTOPOULOS
DSN: L. MORRIS
CHK: S. RAFTOPOULOS
C-DC1915
SHEET 1 OF 1
REV 0

7.9 Task 9 Passive Plate Accelerations (Internal)

Passive plate accelerations.

- See https://www.endevco.com/6233c-100/.
- Outstanding issues include vacuum compatability, cabling inside and through the vessel (feedthroughs).
- This is probably "protection", in the sense that there is not really any model to benchmark

The Endevco® model 6233C series piezoelectric accelerometers are designed for high temperature vibration measurement of gas turbine engines. The unit features high sensitivity, ruggedized connector, and 3 point mounting. The 6233C is designed for continuous operation to +900°F with long Mean Time Between Failure (MTBF). The accelerometer is a self-gengenerating device that requires no external power source for operation.

S. Gerhardt bought one of the accelerometers and qualified it up to 450C, accepted the magnetic properties of the cables, and passed the accelerometer on to C. Gentile's vacuum shop for vacuum qualification. The accelerometers were found to be acceptable and they have been installed.

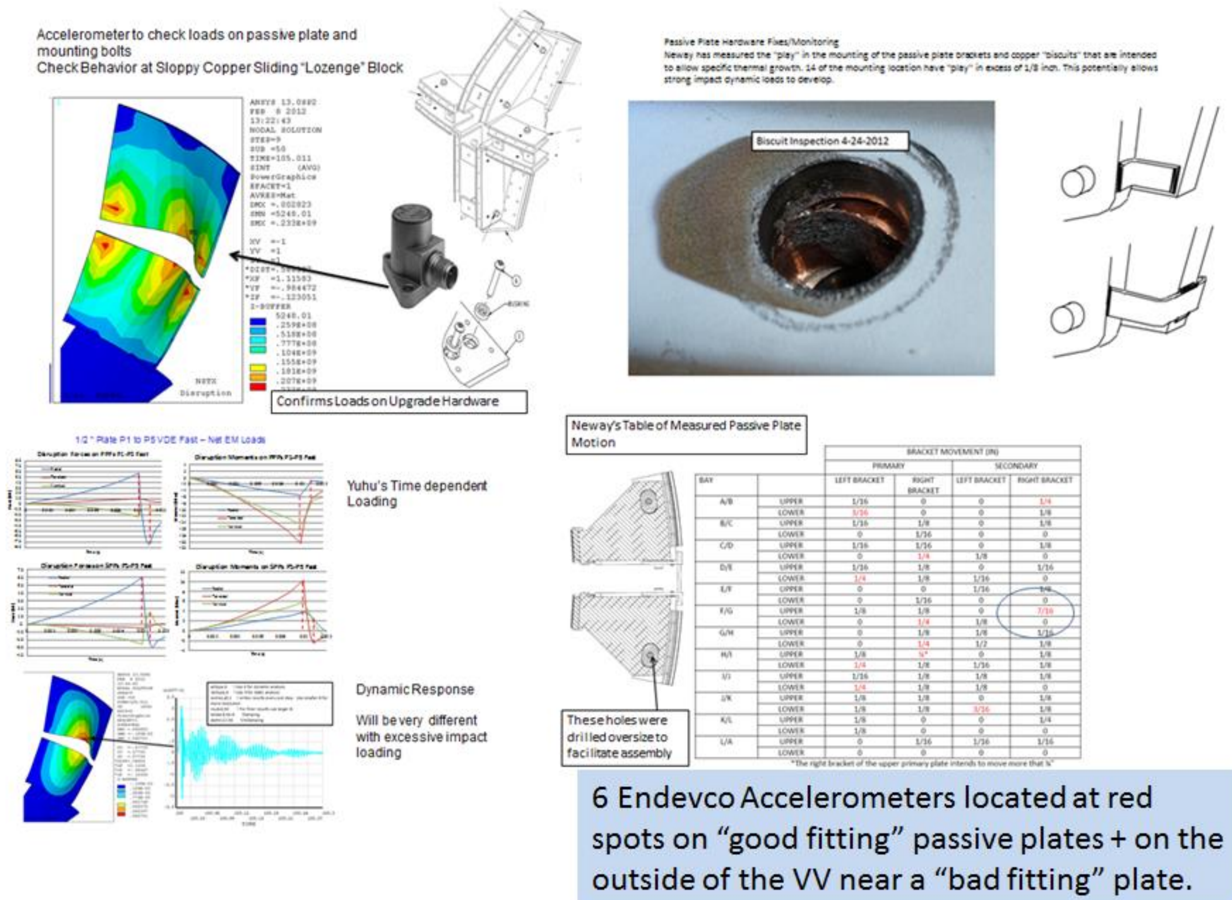
Applications Engineer
Jim Mathews
Meggitt Sensing Systems
office: (949) 487-5598
fax: (949) 661-7231
cell: (949) 412-8770
jim.mathews@meggitt.com
14600 Myford Road
Irvine CA 92606
United States

This was evidently replaced by Endevco2276

7.10 Task 10 Passive Plate Accelerations (External)

During the reinforcement of the passive plate fastener system, it was discovered that the passive plate mounting brackets move in and out and exhibit more free play than intended in the original design. The copper biscuits imbedded between the stainless steel plates were believed to have larger diameter holes than the original design. A partial disassembly of the brackets was performed to identify the cause of the movement (free play) between the parts. To minimize the cost of the investigation it was decided to remove a few of the 5/8” bolts used to fasten the brackets and investigate the root of the problem. Four 5/8” bolts (two with movement and two with no movement) were removed for inspection. Two of these bolts (one with movement and one fixed) had arcing effects on their surfaces and the rest did not. Arcing in other areas of the stainless steel plates was also seen; see Figure 3.10-1 for more detail. This indicates that the arcing had less to do with the brackets movement and more to do with a lack of grounding.

Figure 3.10-1 Photo showing the arcing on bolts and stainless steel plates



BAY		BRACKET MOVEMENT (IN) PRIMARY LEFT BRACKET	PRIMARY RIGHT BRACKET	SECONDARY LEFT BRACKET	SECONDARY RIGHT BRACKET
A/B	UPPER	1/16	0	0	1/4
	LOWER	3/16	0	0	1/8
B/C	UPPER	1/16	1/8	0	1/8
	LOWER	0	1/16	0	0
C/D	UPPER	1/16	1/16	0	1/8
	LOWER	0	1/4	1/8	0
D/E	UPPER	1/16	1/8	0	1/16
	LOWER	1/4	1/8	1/16	0
E/F	UPPER	0	0	1/16	1/8
	LOWER	0	1/16	0	0
F/G	UPPER	1/8	1/8	0	7/16
	LOWER	0	1/4	1/8	0
G/H	UPPER	0	1/8	1/8	1/16
	LOWER	0	1/4	1/2	1/8
H/I	UPPER	1/8	¼*	0	1/8
	LOWER	1/4	1/8	1/16	1/8
I/J	UPPER	1/16	1/8	1/8	1/8
	LOWER	1/4	1/8	1/8	0
J/K	UPPER	1/8	1/8	0	1/8
	LOWER	1/8	1/8	3/16	1/8
K/L	UPPER	1/8	0	0	1/4
	LOWER	1/8	0	0	0
L/A	UPPER	0	1/16	1/16	1/16
	LOWER	0	0	0	0

*The right bracket of the upper primary plate intends to move more that ¼"

The copper biscuits through bolt-holes were also examined. As shown in Figure 2, the holes on the biscuits were slotted, not rounded as designed. Wear or erosion of copper materials was not seen; however wear of the bolt material was seen inside the copper biscuit. This leads to the conclusion that the copper biscuits were machined at some point in the past.

The passive plate design engineer, who has installed the passive plates and related parts when the NSTX was originally built, confirmed that the holes on the copper biscuits were machined for alignment purposes.

The movement of all 96 brackets was measured. These measurements identified the brackets with the worst movement. Table 1 shows the amount of movement of the brackets. Note that the copper biscuits were designed to allow 1/8" radial movement and up to 3/8" vertical movement.

Figure 3.10- 2: Photo shows a round hole on the copper biscuit and stainless steel material sticking on the copper

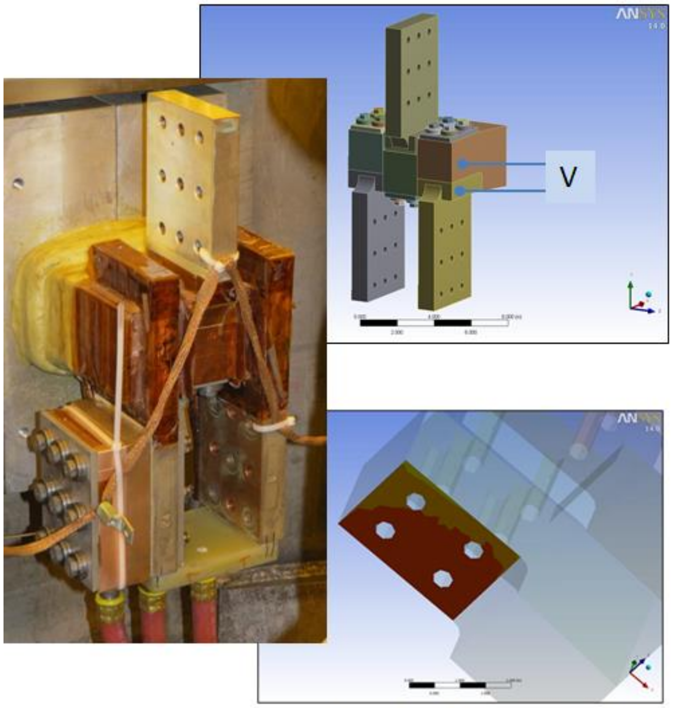
BRACKET MOVEMENT (IN)

BAY		PRIMARY LEFT BRACKET	PRIMARY RIGHT BRACKET	SECONDARY LEFT BRACKET	SECONDARY RIGHT BRACKET
A/B	UPPER	1/16	0	0	1/4
	LOWER	3/16	0	0	1/8
B/C	UPPER	1/16	1/8	0	1/8
	LOWER	0	1/16	0	0
C/D	UPPER	1/16	1/16	0	1/8
	LOWER	0	1/4	1/8	0
D/E	UPPER	1/16	1/8	0	1/16
	LOWER	1/4	1/8	1/16	0
E/F	UPPER	0	0	1/16	1/8
	LOWER	0	1/16	0	0
F/G	UPPER	1/8	1/8	0	7/16
	LOWER	0	1/4	1/8	0
G/H	UPPER	0	1/8	1/8	1/16
	LOWER	0	1/4	1/2	1/8
H/I	UPPER	1/8	¼*	0	1/8
	LOWER	1/4	1/8	1/16	1/8
I/J	UPPER	1/16	1/8	1/8	1/8
	LOWER	1/4	1/8	1/8	0
J/K	UPPER	1/8	1/8	0	1/8
	LOWER	1/8	1/8	3/16	1/8
K/L	UPPER	1/8	0	0	1/4
	LOWER	1/8	0	0	0
L/A	UPPER	0	1/16	1/16	1/16
	LOWER	0	0	0	0

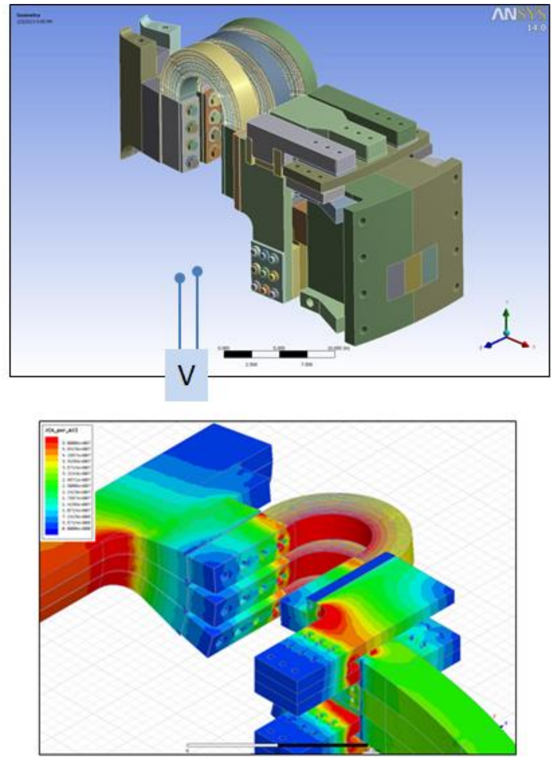
*The right bracket of the upper primary plate between bays H/I has enough free play to move more that ¼" but the Helium Tube to which it is attached prevents the movement.

7. 11 Outer Flag

The braze joints at the flags connected to the outer leg had failed. The braze joints were replaced with a mechanical connections. These have been inspected and the resistance across the joint measured and compared with the original as-installed resistances [8] Two locations, coils A and G, have been measured and are included in [8].

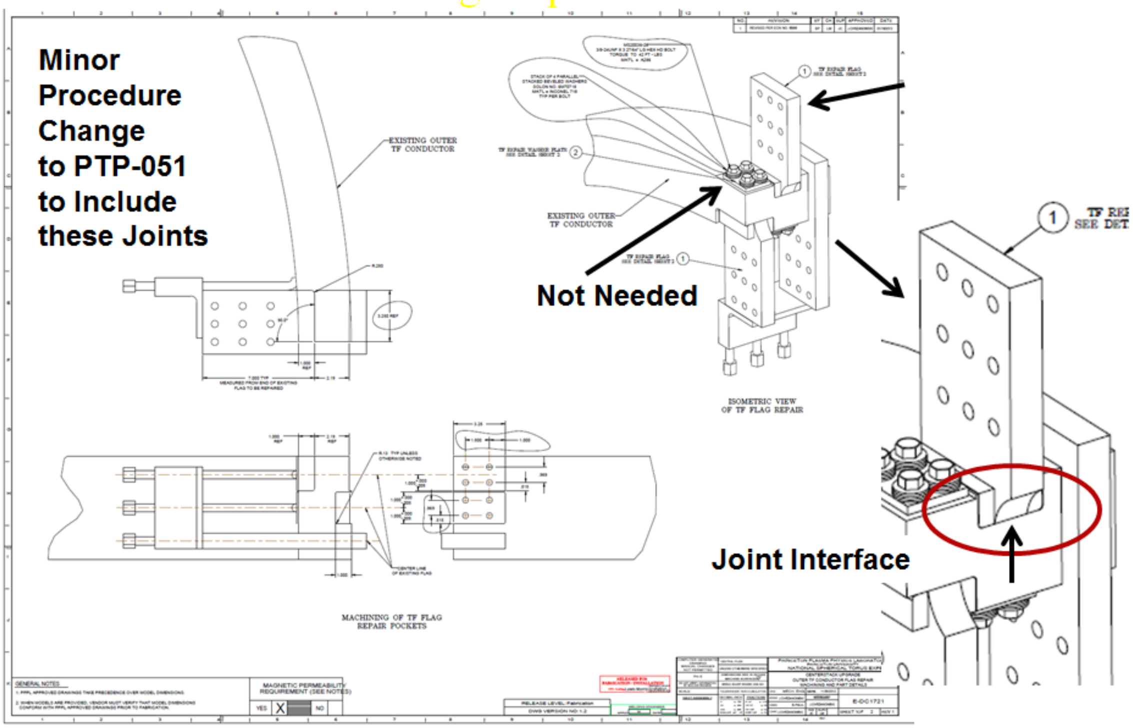


New TF Outer Leg Bolted Joint Design: Contact Status
No Separation: Bolt Pretension = 6750 lbf



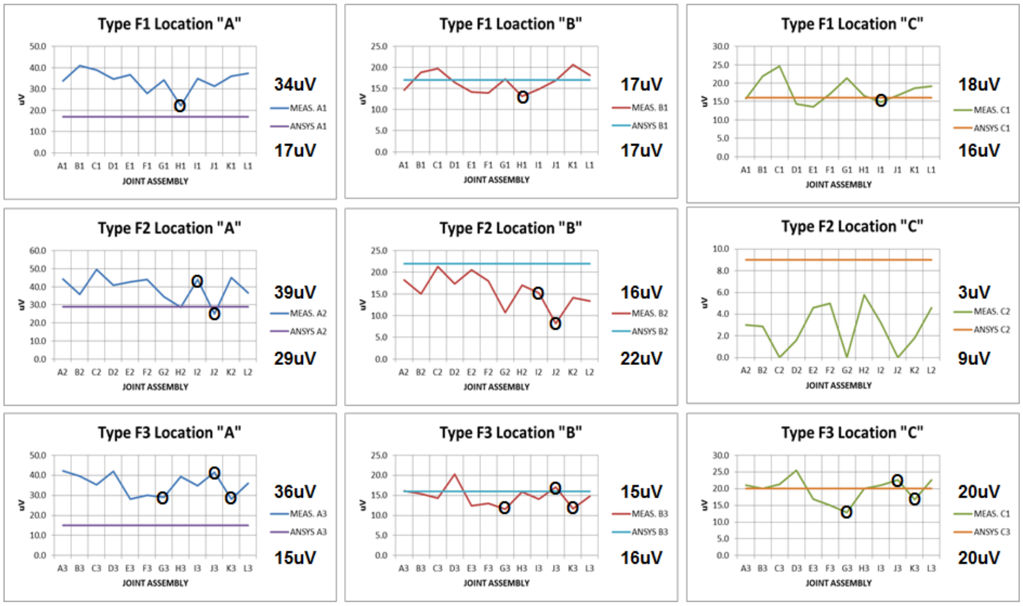
Maxwell Results: Current Density1

Outer TF Flag Repair – Bolted Joints



Hans Schneider

Measured Data vs. ANSYS Model

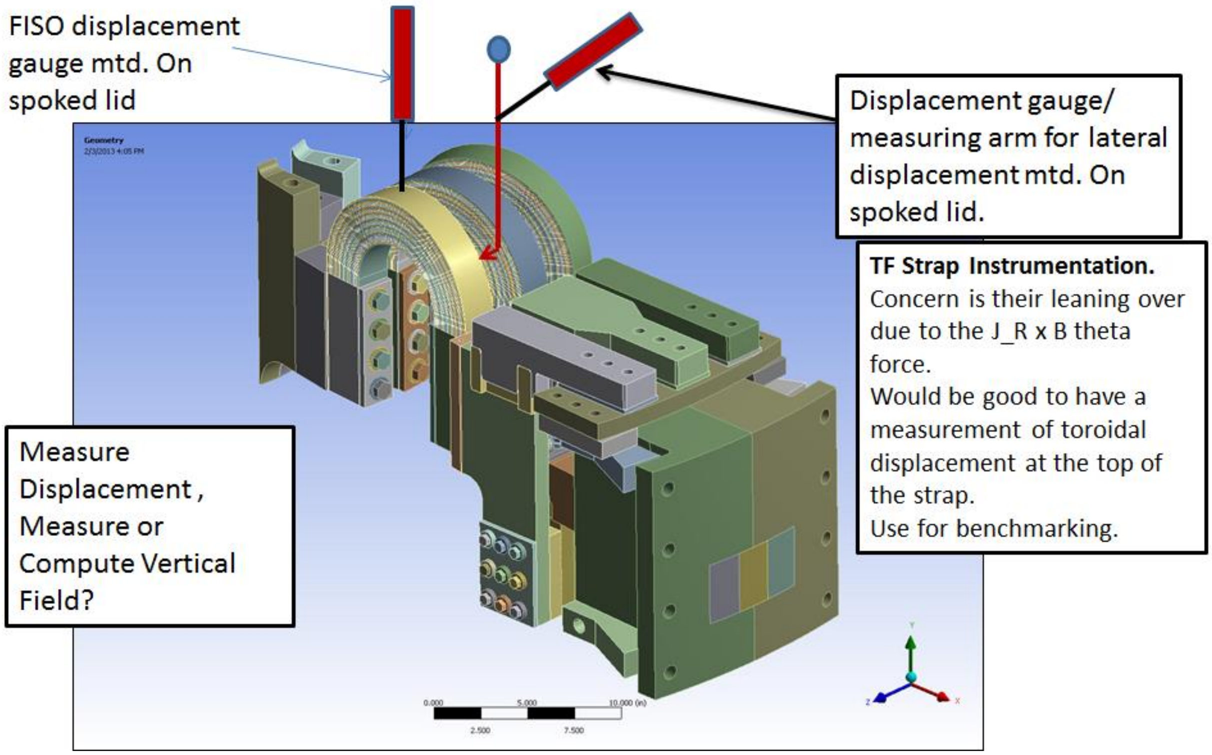


Hans Schneider

O = NO SPACER
Single Joint

PPPL PRINCETON PLASMA PHYSICS LABORATORY

7.12 TF Inner Joint Strap Instrumentation



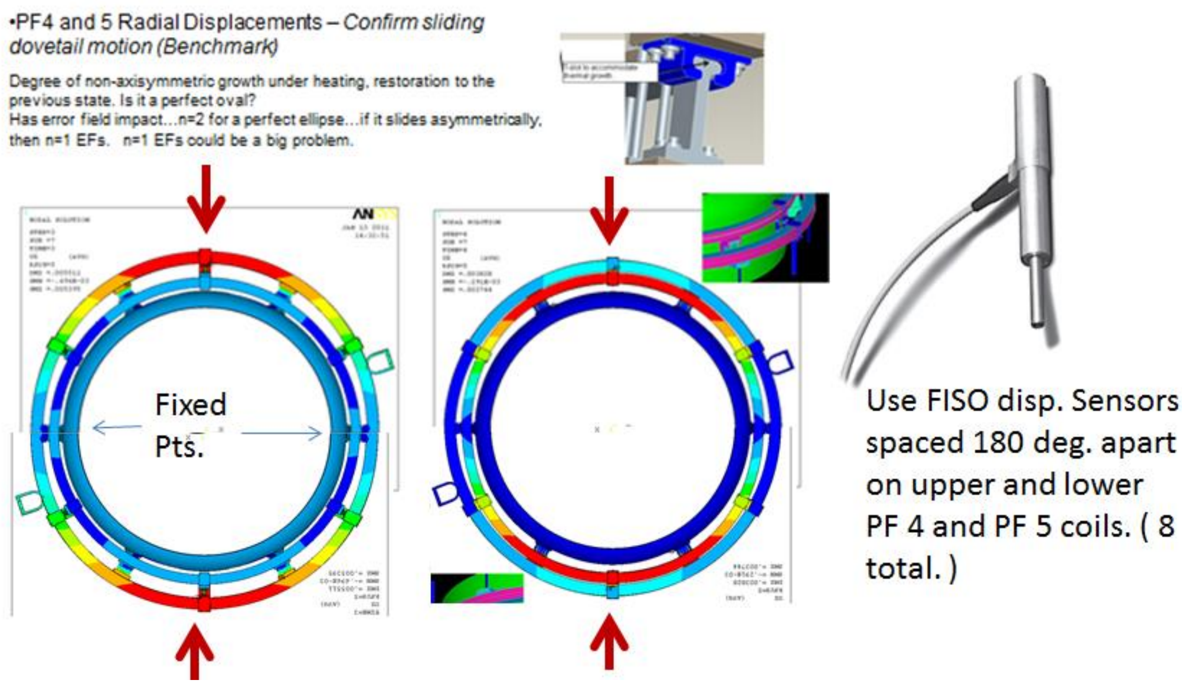
7.13 Task 13 PF 4 and 5 Radial Displacements

Effected Calculation:

[20] Analysis of Existing & Upgrade PF4/5 Coils & Supports – With Alternating Columns, NSTXU-CALC-12-05-00, Prepared By: Peter Titus, Reviewed by Irv Zatz, Cognizant Engineer: Mark Smith WBS 1.1.2

Task 13 Purpose

In the upgrade, both PF4 and 5 will be operated to their full I^2 t limit of 100C. Expansion of the coils must be allowed. Sliding supports are provided. N=1 errors , corresponding to a global shift of the coil are not allowed. N=2 or oval deformations are deemed an acceptable compromise. To allow the N=2 oval deformation, one pair of opposing supports are fixed, and the remainder are sliding. To demonstrate that the sliding supports behave as predicted, and to monitor the centered alignment of the coils, measurements of the radial motion of the coils at the unconstrained support points is needed. This will certainly be needed at start up, and later as well to monitor the sliding supports are not experiencing a failure in the lubrication or jamming due to an asymmetry. During construction, some asymmetries were introduced to allow installation of diagnostics.



During the bake-out in September 2015, Aluminum tape tabs were added to the sliding supports to indicate motion and restoration of the position to the initial constructed position. Verbal reports from the technicians and written reports in the run copy of the bakeout procedure, indicated that the slides returned to their installed position.

7.14 Task 14 Outer TF Truss Strut Loads

Two components of NSTX-U TF Outer Leg system will be instrumented with a sufficient number of strain sensors to monitor the outer legs, and the truss elements that connect the outer legs to their primary support, the vacuum vessel.

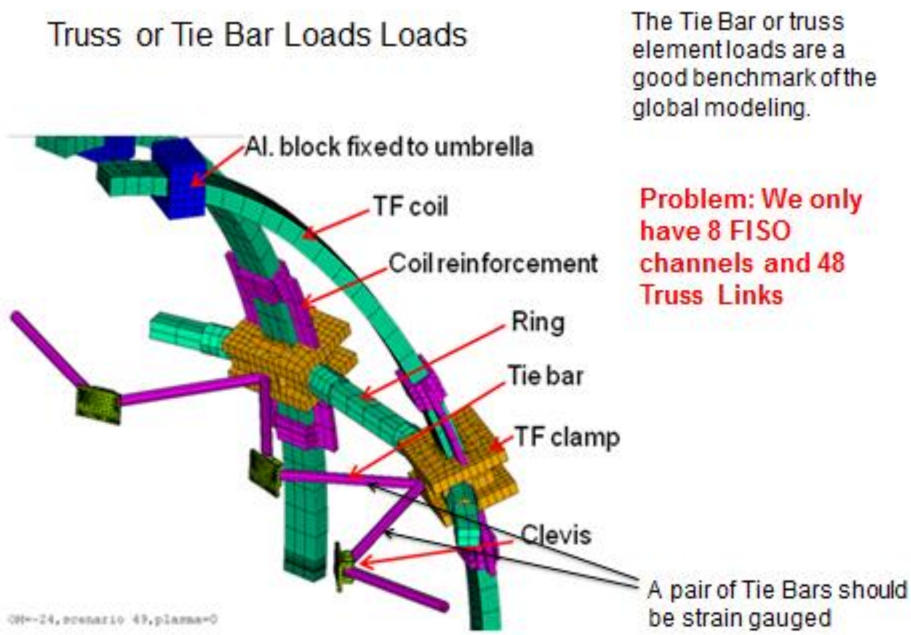


Figure 7.14-1 Truss Strain Gauge Locations

There is a concern with non-uniform loading in the trusses due to variations in tightening of the rods and variation in the stiffnesses of the areas where the clevises are welded to the vessel shell. The clevis details are stressed at their fatigue limit assuming uniform loading, and they have been identified as needing periodic inspection to make sure the pins and clevis holes are not developing cracks. The FBG design is very attractive in that non-uniform tie rod tension once measured during operation can be adjusted during almost any down time. Leaving non-uniform tierod loading will lead to fatigue failures in the clevis details.[14]. In a November 29 email, Mark Smith indicated that the trusses are adjusted to fit only. – Not uniformly tensioned. The backlash is probably small but I would put a light equal torque on each of the struts at installation to bias the backlash in a known direction, and to start operation with equal loading. There are a few pieces of the truss system that were fatigue limited. I would think that a +/- 20% variation in loading at the strut attachments could lead to an early fatigue failure. We are planning a full coverage of the truss links in the fiber Bragg grating strain gauge system, so we will have an indication of loading distribution during operation.

7.15 Task 15 – Outer Leg Bending Stress

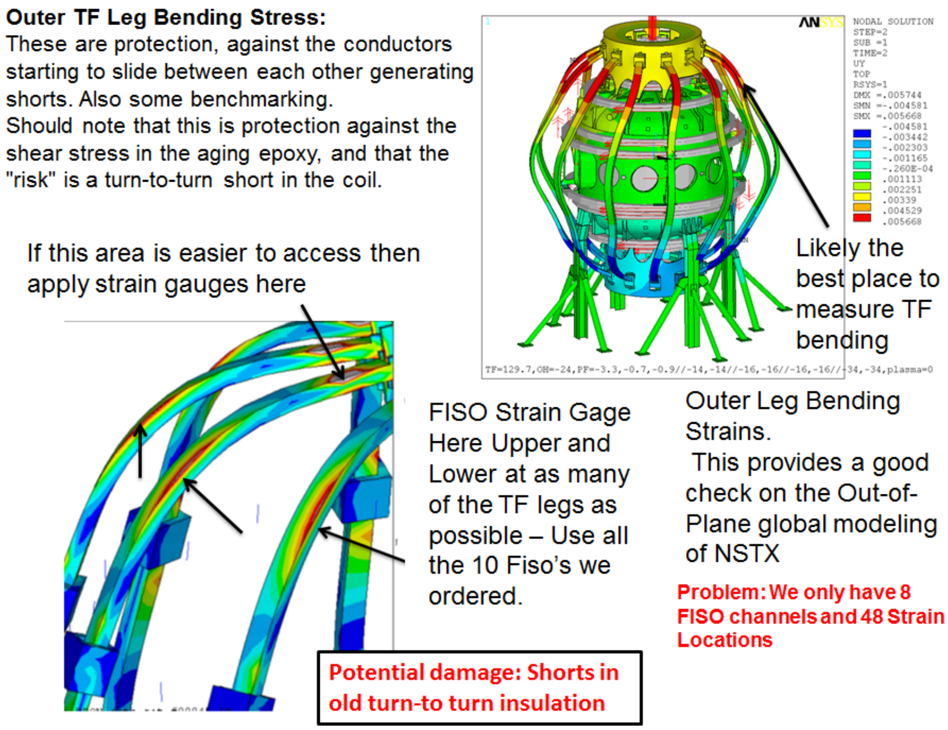
Task 15 Calculations effected:

[12] ANALYSIS OF TF OUTER LEG, NSTX-CALC-132-04-01, January 13, 2012 Prepared By: Han Zhang
[5] NSTX-U Global Model – Model Description, Mesh Generation, and Results NSTX-U CALC 10-01-02 Rev1 December 2011, P. Titus, Available at: http://nstx-upgrade.pppl.gov/Engineering/Calculations/index_Calcs.htm

The aim of this strain measurement system is to monitor the insulation shear bonds between the 3 conductors of the TF outer legs. The shear stress in these bonded layers is proportional to the TF outer-leg out-of-plane bending.

Bending of the outer leg due to out-of-plane (OOP) loads is supported partly by shear in the bond between the three conductors that are bonded together to form the outer leg. Bending stress in the outer conductors will provide an indication of the integrity of the shear bond. If the three conductors act together, as a beam , the metal bending stress in the outer conductors is as analyzed and shown in figure 3.15-1. If the bond fails, then the bending stress will increase. This can cause a failure due to fretting motion in the insulation or overstress in the copper conductors, or failures in the water cooling tubes.

- This is intended to confirm the out-of-plane bending strength and electrical integrity of the TF outer legs
- We need a basis for transitioning from .6 T to .8 T.
- This is intended to give a first indication of the health of the insulation system that develops the full bending section of the coil.
- Insulation that fails in shear may tear or crack and degrade electrically
- We have "Old" Outer TF coils with DZ-80 (Prepreg) insulation and two ? One Installed? Using CTD 425.
- Jim Chrzanowski expressed concern over the health of the old insulation



- Figure 7.15-1 Outer leg bending stress and proposed FISO locations

Bending of the outer leg due to out-of-plane (OOP) loads is supported partly by shear in the bond between the three conductors that are bonded together to form the outer leg. Bending stress in the outer conductors will provide an indication of the integrity of the shear bond. If the three conductors act together, as a beam , the metal bending stress in the outer conductors is as analyzed and shown in figure 3.15-1. If the bond fails, then the bending stress will increase. This can cause a failure due to fretting motion in the insulation or overstress in the copper conductors, or failures in the water cooling tubes.

7.15.1 Understanding and Benchmarking the Results

The aim of the FISO Outer Leg Strain measurements and the new Fiber Bragg Grating system is ultimately to monitor the insulation shear bonds between the 3 conductors of the TF outer legs. The shear stress in these bonded layers is proportional to the TF outer-leg out-of-plane bending. The strain gauges measure the sum of the effects of TF in-plane loading, Thermal expansion due to heat-up, and TF outer leg out-of-plane bending.

Item	Description	Sensor Type	Range	Serial Nmbr	GageFactor
1	NE OH(BayD) Upr Pre-Load	Displacement	-390 to +390	-	8053284
2	SE OH Upr(Bay J) Pre-Load	Displacement	-390 to +390	DF10005	8053355
3	Bay E/F Upr Lid Outside	Strain	-5000 to +5000	SF05136	1001034
4	Bay E/F Upr Lid Inside	Strain	-5000 to +5000	SF05135	1001044
5	Bay E/F Lwr Lid Outside	Strain	-5000 to +5000	SFO5134	1001054
6	TF COIL "A"	Strain	-5000 to +5000	SF15175	1001342
7	TF COIL "B"	Strain	-5000 to +5000	SF05133	1001036
8	TF COIL "C"	Strain	-5000 to +5000	SF15171	1001385
9	TF COIL "D"	Strain	-5000 to +5000	SF15174	1001430
10	TF COIL "E"	Strain	-5000 to +5000	SF15097	1001322
11	TF COIL "F"	Strain	-5000 to +5000	SF15098	1001371
12	TF COIL "G"	Strain	-5000 to +5000	SF15173	1001355
13	TF COIL "H"	Strain	-5000 to +5000	-	-
14	TF COIL "I"	Strain	-5000 to +5000	-	-
15	TF COIL "J"	Strain	-5000 to +5000	SF16016	1001445
16	TF COIL "K" - New	Strain	-5000 to +5000	SF15169	1001359
17	TF COIL "L" - New	Strain	-5000 to +5000	SF15177	1001466

The figure below shows the MDS+ plot output for three of the installed FISO TF outer leg strain gauges. The data shown is for shot 205080 which was a clean shot done prior to the PF1a failure. The FISO gauges measure all the sources of strain including in-plane “bursting” load on the TF, out-of–plane bending from the interaction with the PF field, and the thermal strain due to expansion of the warming TF. The FISO strain gauges were installed in accordance with [6]

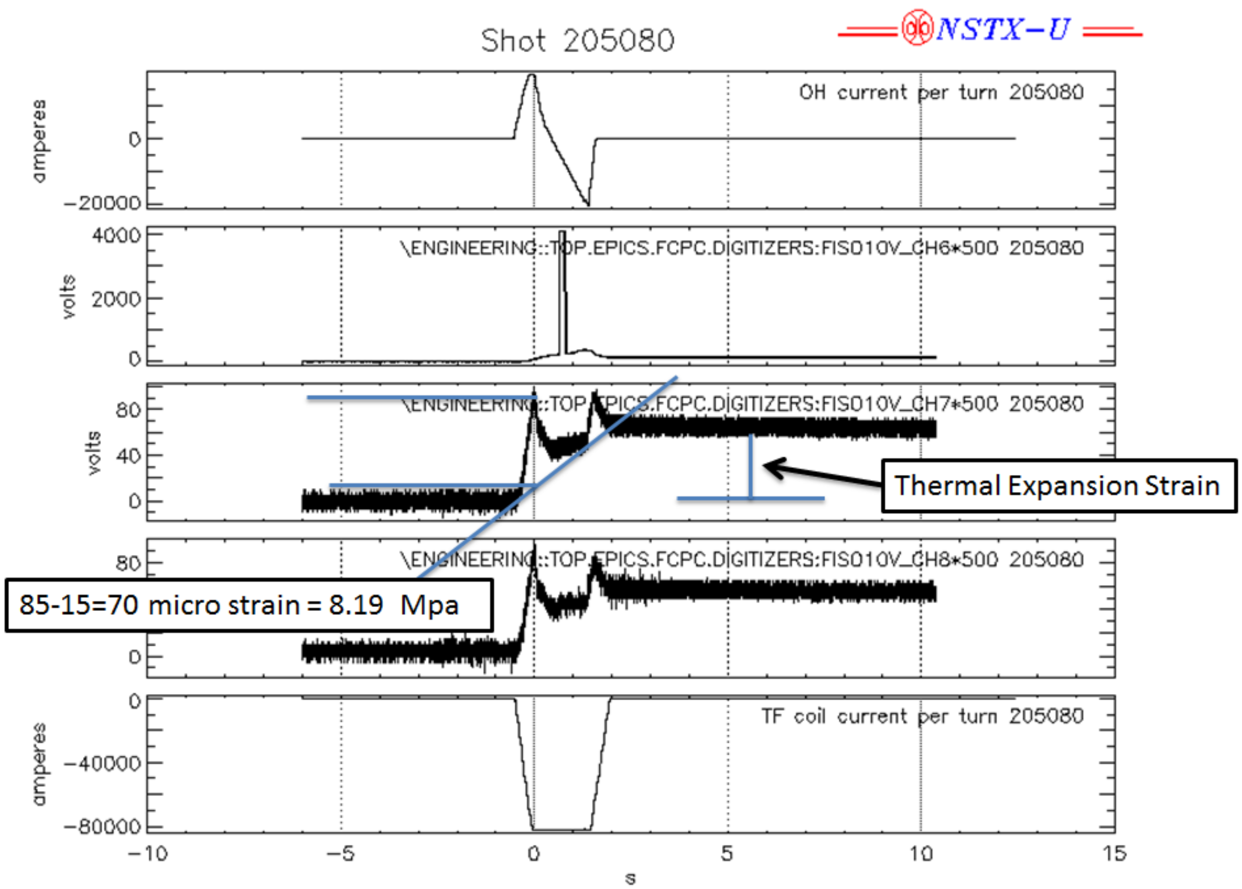


Figure 4.5-1 MDS-+ Plots from the FISO Strain Gauges

The upper plot (number 1) in figure 4.5-1 is the OH current which is one contributor to the out-of-plane loading. The bottom plot (number 5 is the TF current that is a measure of the in-plane tensile loading. Plots 2,3,and 4 are the total bending strain in three different upper outer legs. The shift in strain before and after the shot shown in plots 3 and 4 is a measure of the thermal strain that results from the expansion of the TF outer leg. To evaluate just the bending due to the out-of-plane loading, in-plane and thermal strains must be subtracted out of the total strain.

Scale Factors

For benchmarking with analysis, appropriate scale factors to be applied to the TF current will be needed for the in-plane strain and thermal strain. The TF end temperature will be needed to quantify the thermal strain. Then the in-plane component and thermal strain should be subtracted out of the total strain and these values summarized in a calculation.

With TF Only Loading, and 130 kA terminal current, the stress in the upper outer leg is 30.6 MPa or 261 micro strain. This will scale with the square of the current so for 80 kA the expected stress is 11.5 MPa or a strain for in-plane loading is 99 micro strain. In figure 3.5-1 the total stress is about MPa for the upper outer TF leg. Thus the out-of-plane stress is MPa.

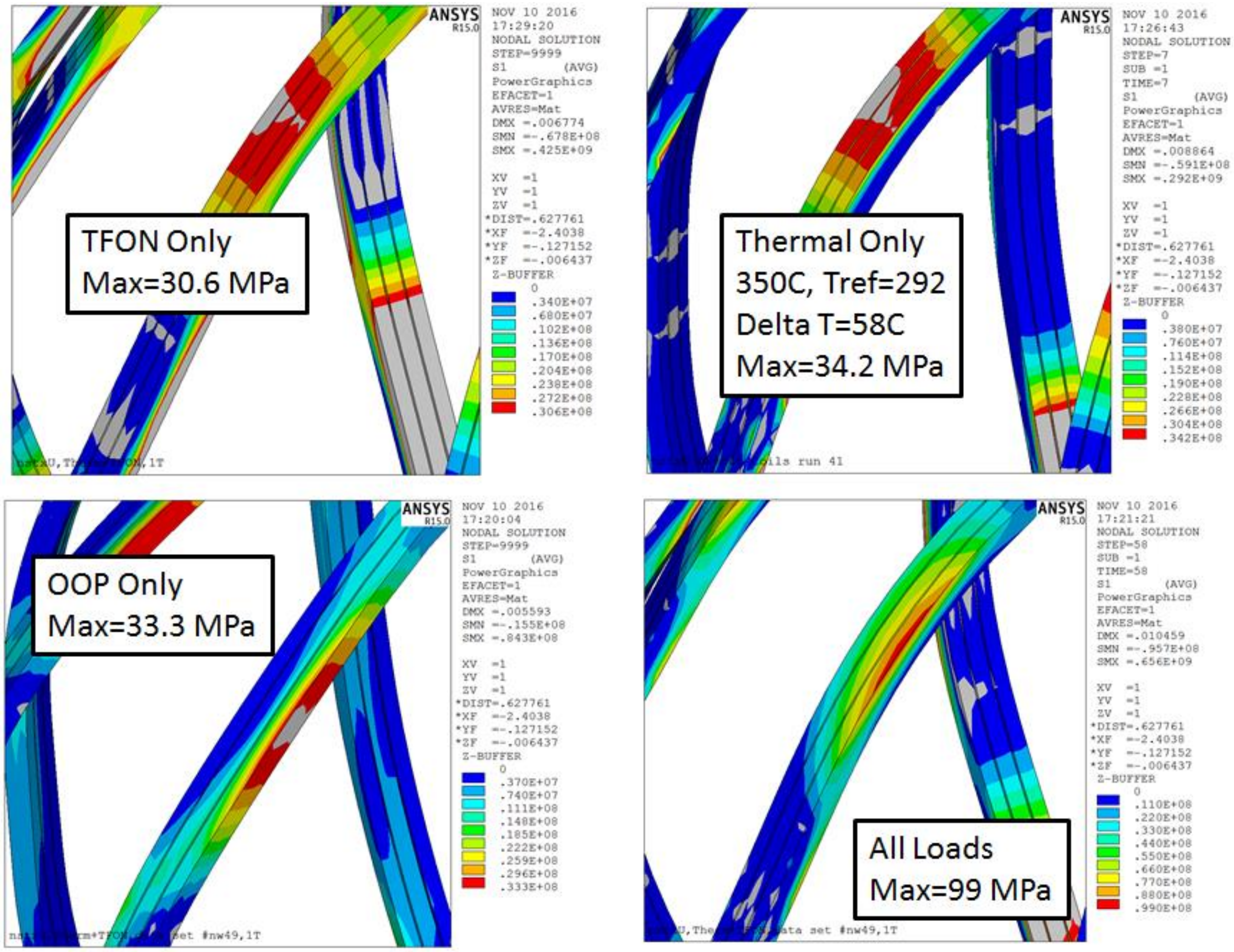


Figure 4.5-2 Stress Components from The Global Model Run

Table 4.5-1 Stresses for TF Upper Outer Leg Midspan

	Thermal (MPa)	TFON Only	TFON +Thermal	Total TFON OOP +Therm	OOP Only From Components	OOP (ANSYS Load Case Subtraction)
Base Load	Delta=58 C	135kA				
Load Step	7		8	58		
Upper Outer TF	34.2	30.6	65.7	99	99-65.7=33.3	33.3

When measured data is available, the other outer leg segments, near the equatorial plane and lower span should be evaluated.

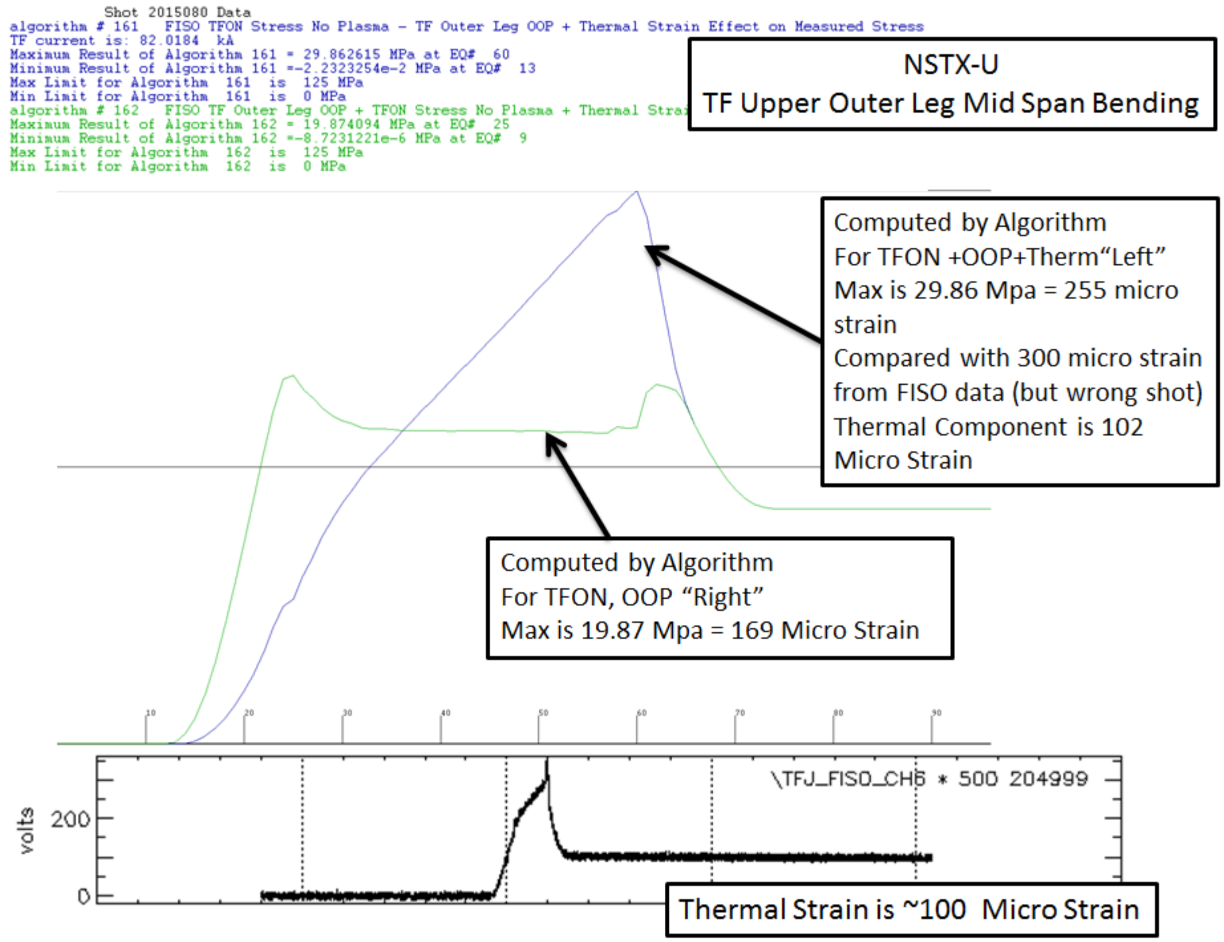


Figure 4.5-3 Computed and Measured TF Outer Leg Stress and Strain – OOP Adds

In figure 4.5-3, the outer-upper TF leg bending stress has been computed from influence coefficients for the sum of TFON+OOP, and for the OOP load only. A two peak plot is produced, for the TFON +OOP case, similar to the plot measured by the FISO strain gauges. In the FISO measurement, the thermal strain is included and this shifts the before and after strain. The measured strain is 100 micro strain and the predicted is about 150. This can be a calibration error with the FISO gauges (John Dong provided the factor of 500), or the installed gauges may not be at the same location as was used to compute the stresses from the global model -Or the analysis needs improving.

For the monitoring of the results, consistency from coil to coil, and shot to shot will be important.

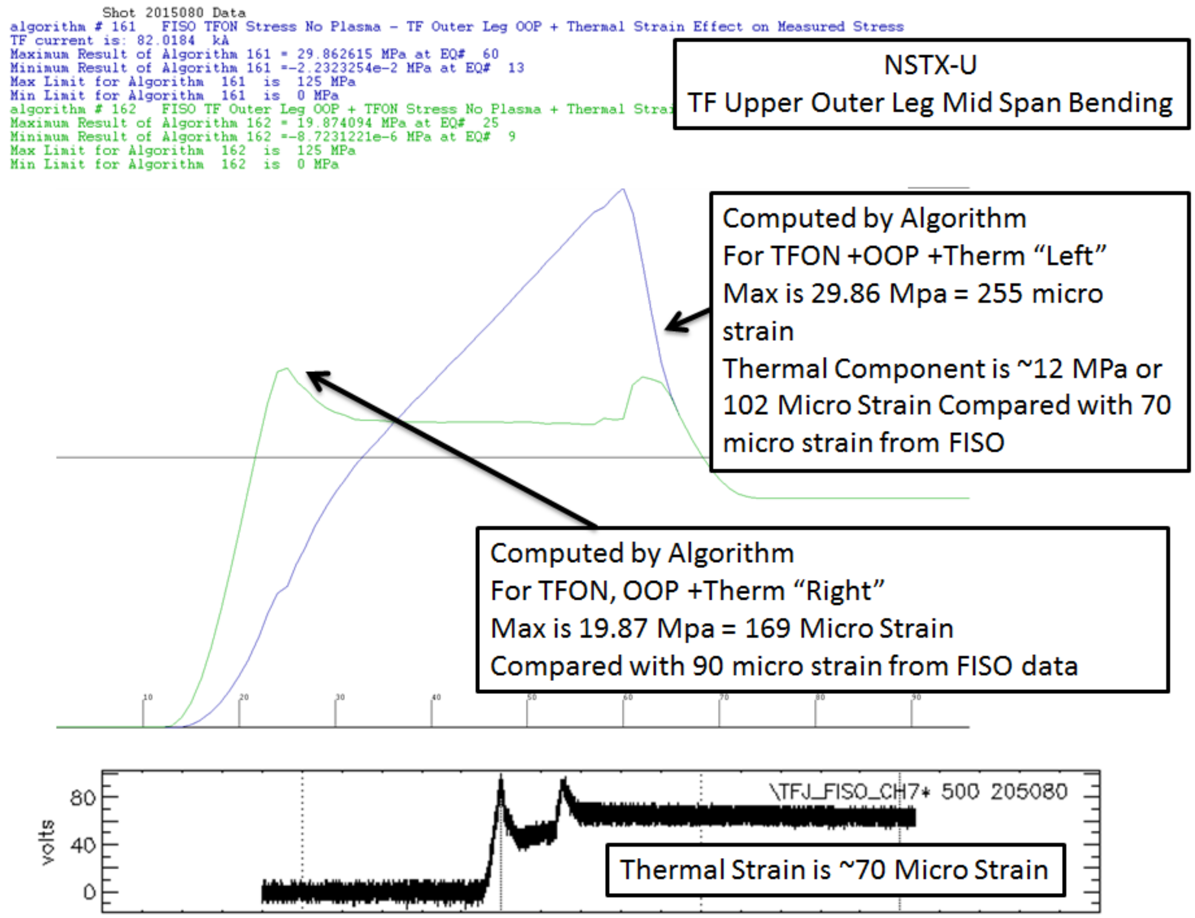


Figure 4.5-4 Computed and Measured TF Outer Leg Stress and Strain – OOP Subtracts

Figure 4.4-4 includes FISO data for the case where the strain gauge is on the opposite edge of the coil from the situation plotted in figure 4.4-3. The shape of the curves of the computed total and FISO measurement are similar – These are for two different shots, because John Dong swapped the input to the FISO box. Once installed, we will be able to determine whether the OOP part should be additive or subtractive. If we want to subtract out the before and after shot thermal strain we will either need a measured TF temperature or do a j^2t calculation on the TF current profile.

There are two approaches possible for the outer leg instrumentation. The first is to apply FISO strain gauges on the legs and only monitor a few of them at a time. The number of FISO channels is limited to eight and five of them are already being used for the preload mechanism and the spoked lid strain gauges. Ten new gauges have been purchased as of March 2016 so they will have to be swapped in and out to get coverage of a good sampling of the TF coils.

. Due to schedule constraints, and a desire to run NSTX-U up to .8 T (as of Feb 2016 it is at .61T), FISO strain gauges were purchased and applied.

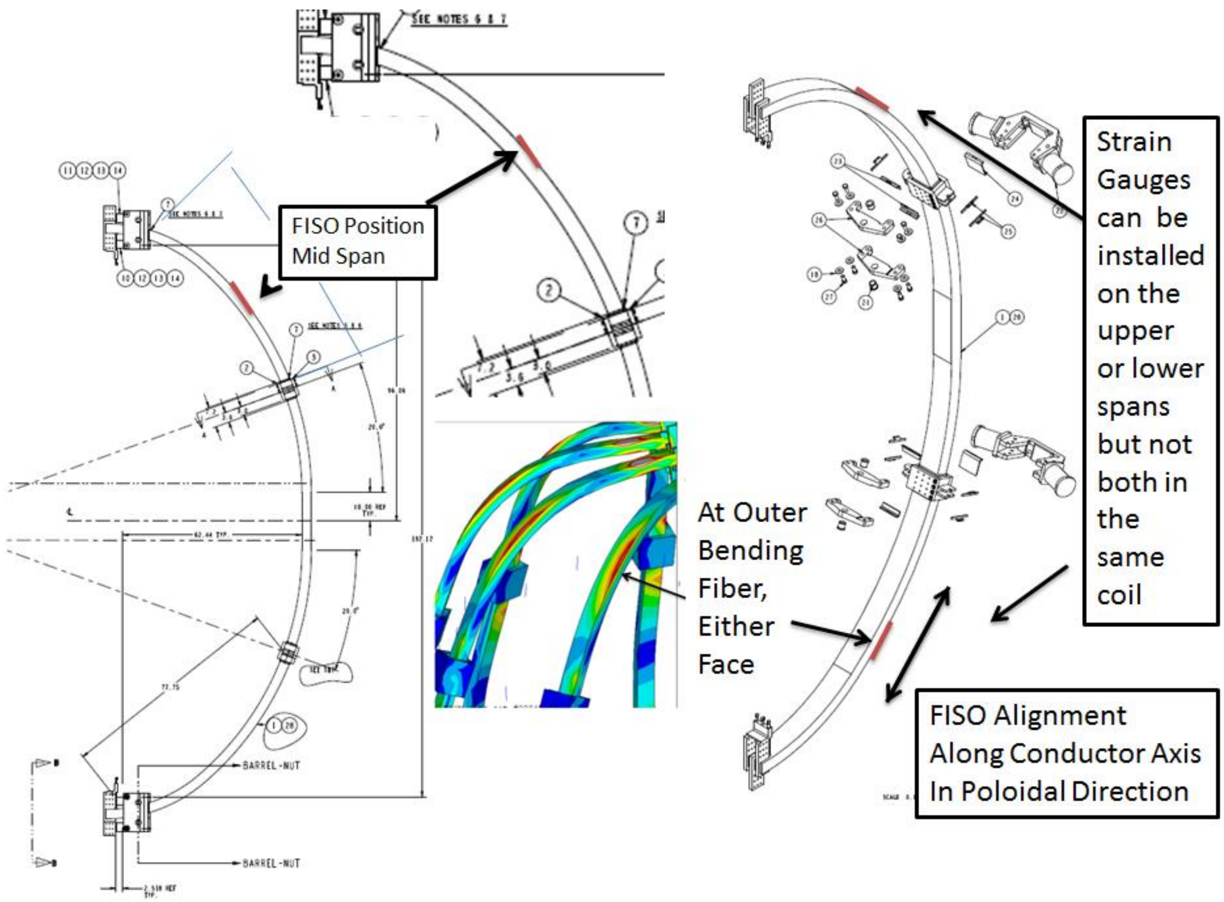
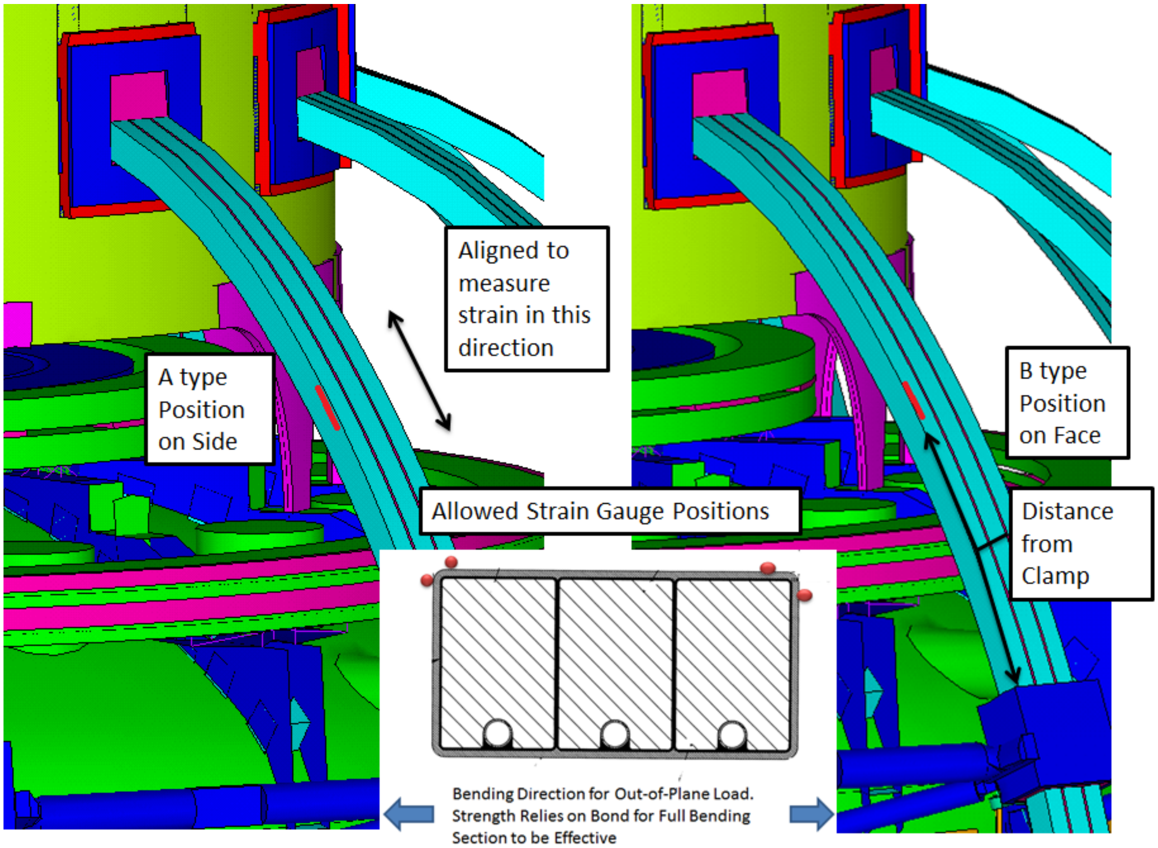


Figure 7.15-2 Interim Installation of FISO Strain Gauges and proposed FISO locations

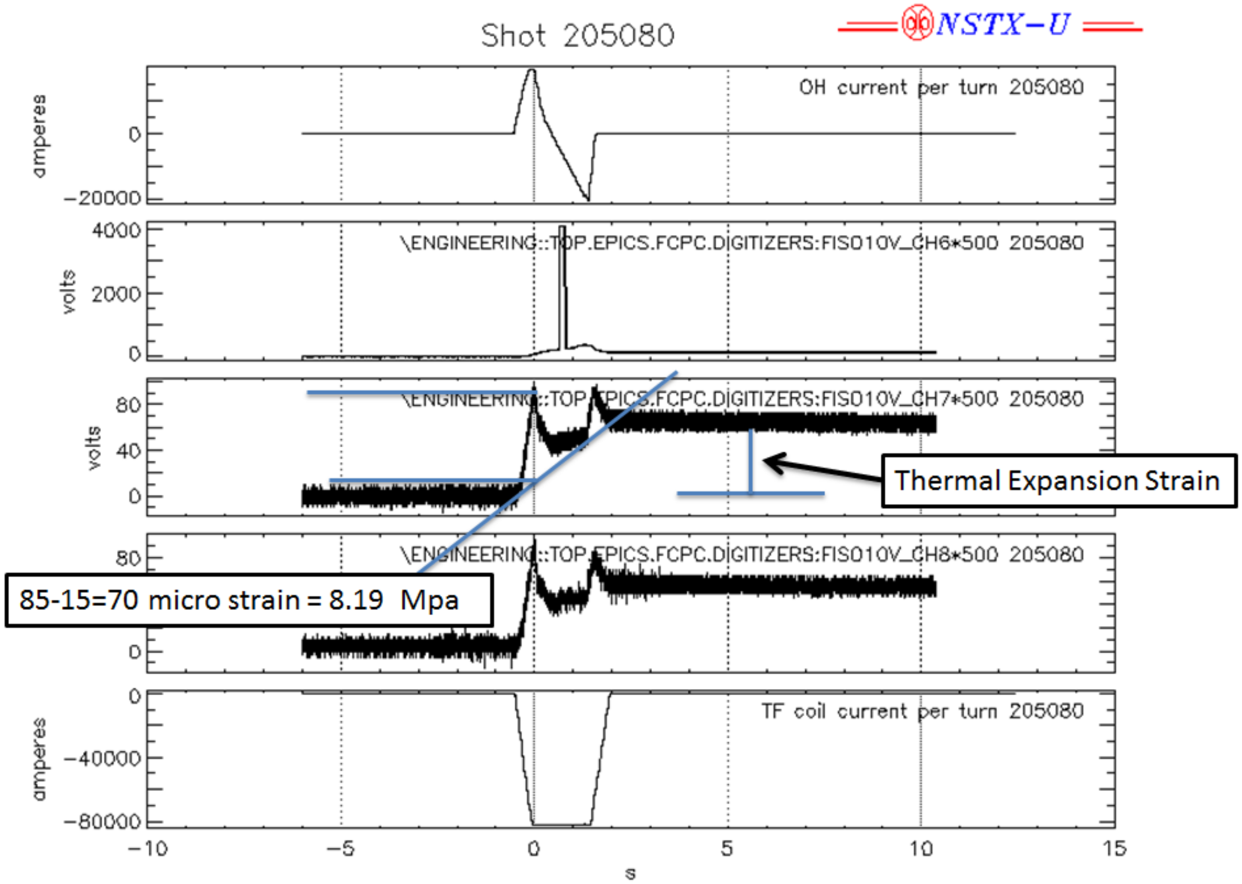


The second approach to monitoring the TF outer leg bending is to purchase a system that has the potential of monitoring all the outer legs and many other locations (i.e Task 14 section 7.14, the truss links) In June of 2013, Hans Schneider suggested such a system.

Figure 7.15-3 MICRON Integrator Box, Handles 320 channels per box and is ~$40k

The Fiber Bragg Grating (FBG) instrumentation system recommended for high channel count/multiple measurement type on NSTX-U is based on a National Instruments hardware.

The figure below shows the MDS+ plot output for three of the installed FISO TF outer leg strain gauges. The data shown is for shot 205080 which was a clean shot done prior to the PF1a failure. The FISO gauges measure all the sources of strain including in-plane “bursting” load on the TF, out-of–plane bending from the interaction with the PF field, and the thermal strain due to expansion of the warming TF.



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Scale Factors

With TF Only Loading, and 130 kA terminal current, the stress in the upper outer leg is 30.6 MPa or 261 micro strain. This will scale with the square of the current so for 80 kA the expected stress is 11.5 MPa or a strain for in-plane loading is 99 micro strain. In figure 3.5-1 the total stress is about MPa for the upper outer TF leg. Thus the out-of-plane stress is MPa.

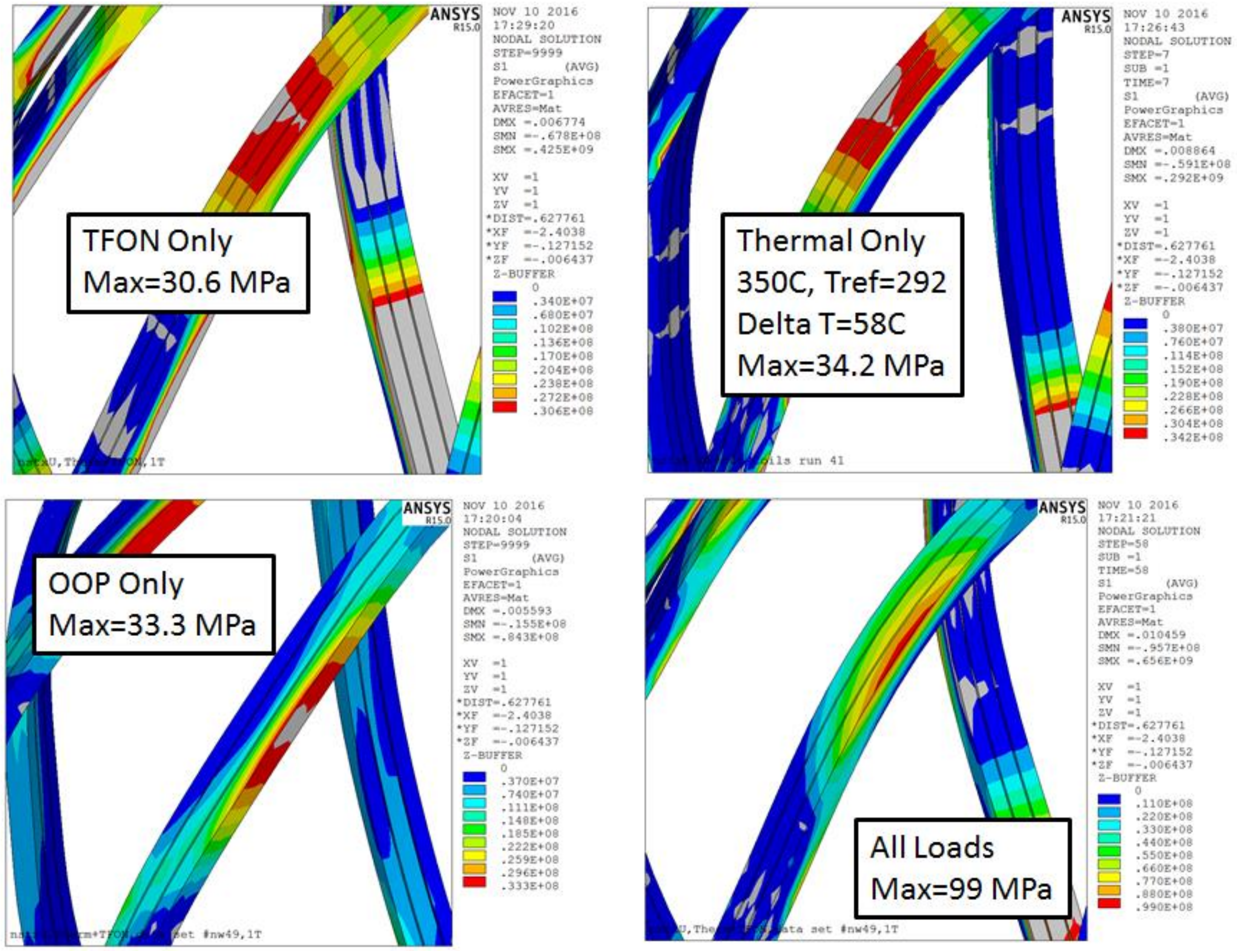

Figure 4.5-2 Stress Components from The Global Model[5] Run

Table 4.5-1 Stresses for TF Upper Outer Leg Midspan

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Load Step	7		8	58		
Upper Outer TF	34.2	30.6	65.7	99	99-65.7=33.3	33.3

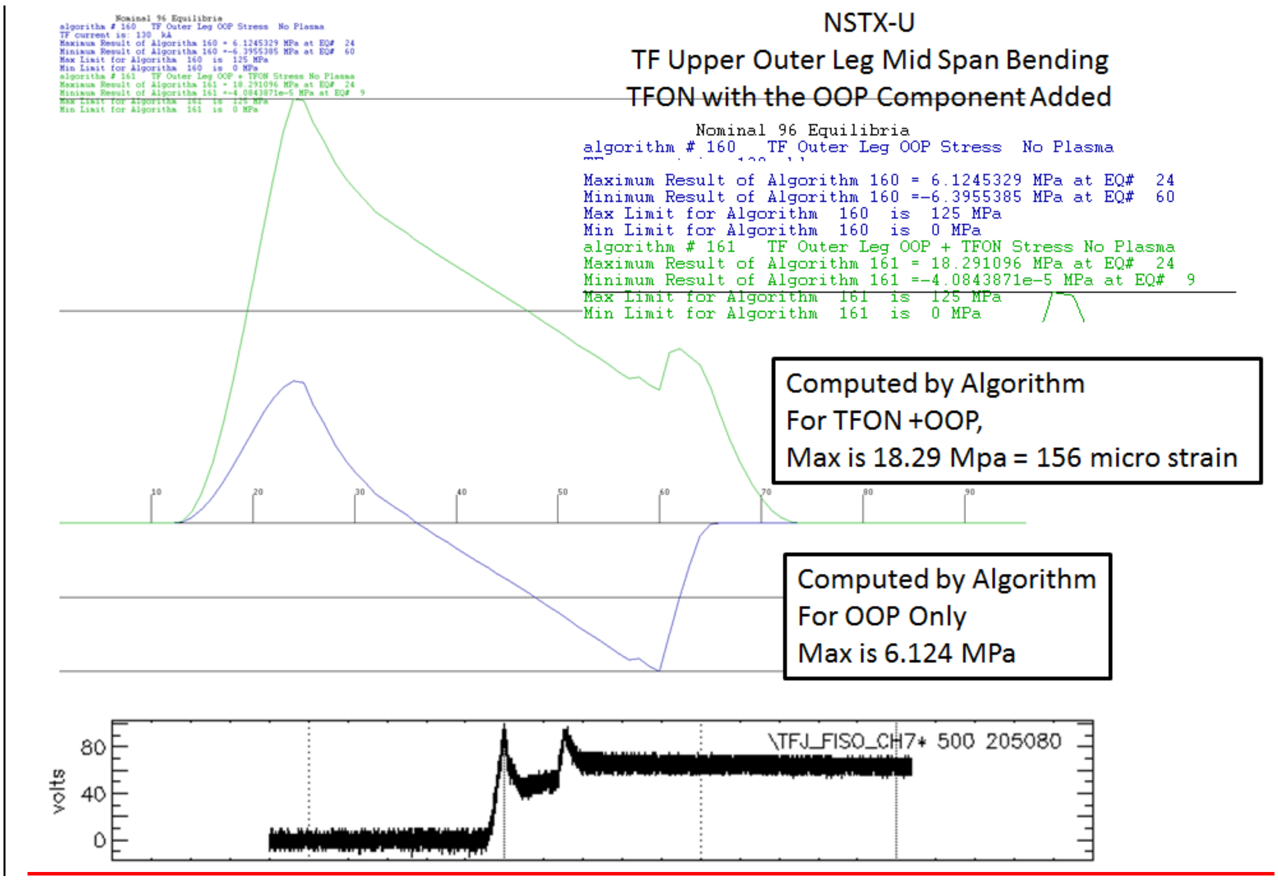

Figure 4.5-3 Computed and Measured TF Outer Leg Stress and Strain – OOP Adds

In figure 4.5-3, the outer-upper TF leg bending stress has been computed from influence coefficients for the sum of TFON+OOP, and for the OOP load only. A two peak plot is produced, for the TFON +OOP case, similar to the plot measured by the FISO strain gauges. In the FISO measurement, the thermal strain is included and this shifts the before and after strain. The measured strain is 90 micro strain and the predicted is 156. This can be a calibration error with the FISO gauges (John Dong provided the factor of 500), or the installed gauges may not be at the same location as was used to compute the stresses from the global model -Or the analysis needs improving. For the monitoring of the results, consistency from coil to coil, and shot to shot will be important.

One additional point is that the results vary depending on which side the strain gauges are mounted on. This determines if the OOP component adds to or subtracts from the TFON and thermal strains.

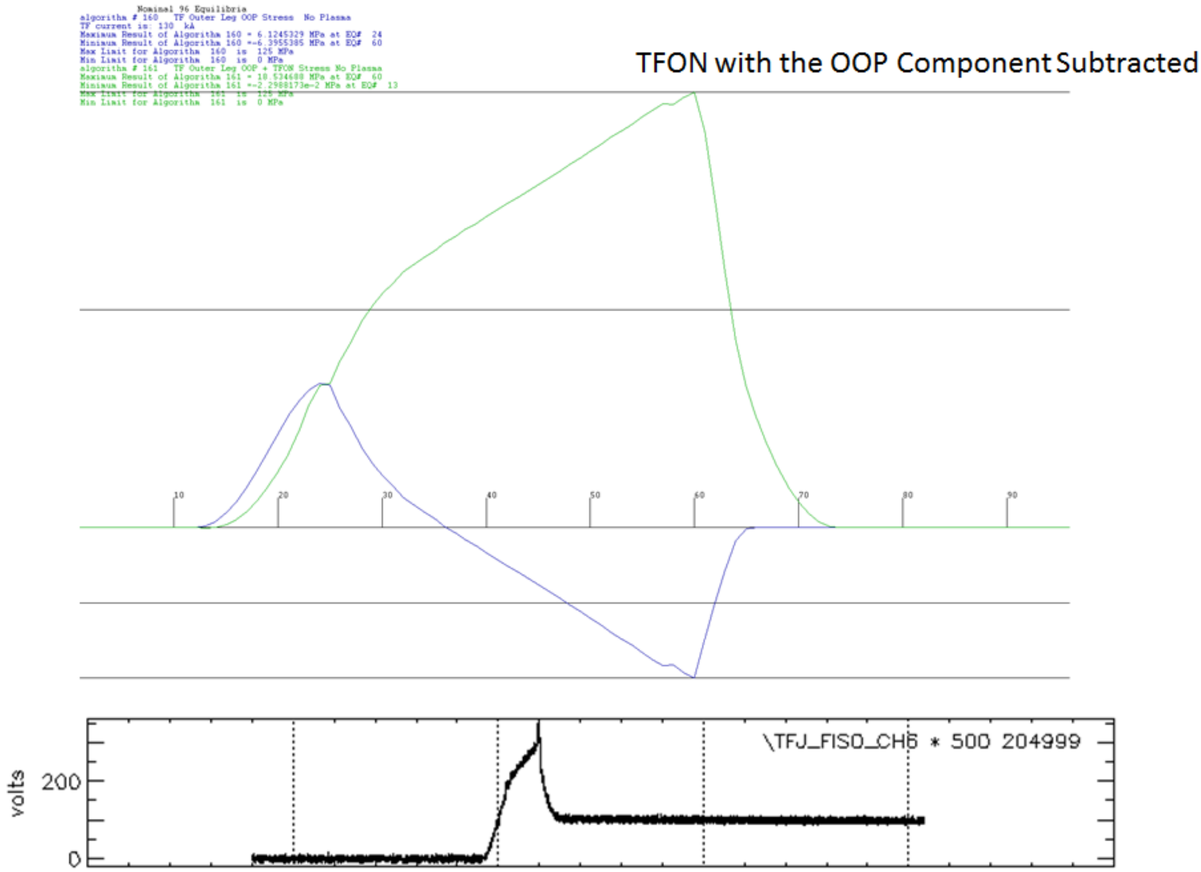

Figure 4.5-4 Computed and Measured TF Outer Leg Stress and Strain – OOP Subtracts

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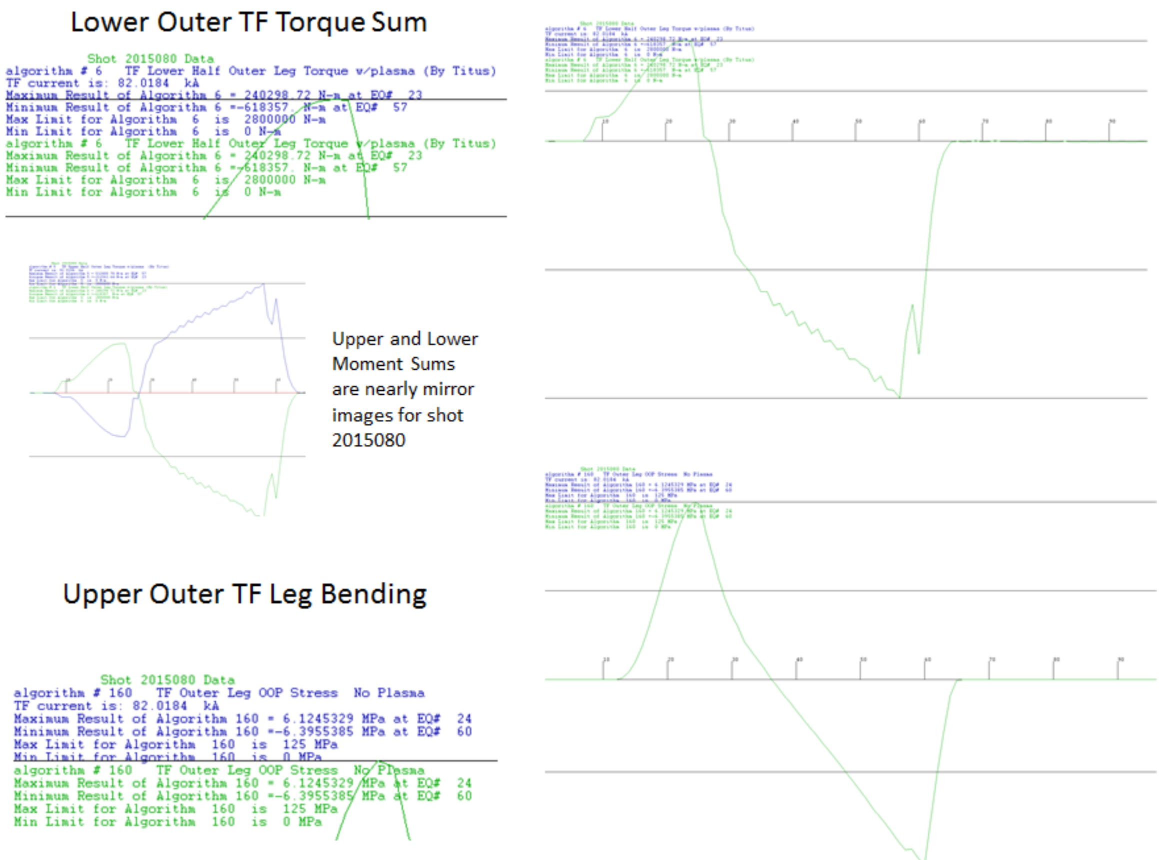
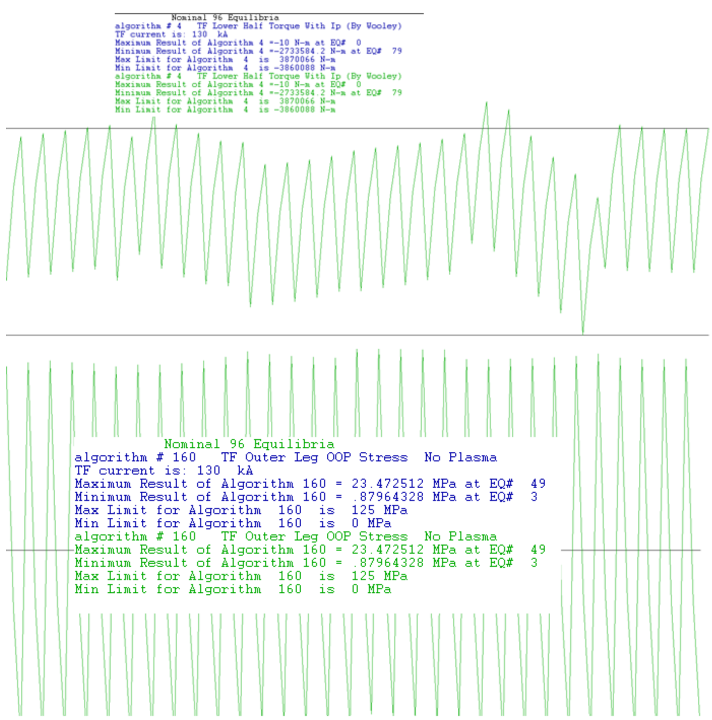
7.15.2 Comparison with DCPS Upper-Outer Torque Sums

At present (November 2016), TF outer leg bending is not included in the DCPS directly. The torque components, upper-outer leg torque, and Lower outer leg torque are tracked and are limited to the maximum values from the 96 equilibria. In the figure below, a torque value and the results from the TF outer leg bending algorithm (currently not implemented in the DCPS) are plotted for comparison. Lower moment and upper leg stress results are mixed in the comparison to have similar signed results. . For shot 2015080 the moments are up-down symmetric.



For shot 2015080 the profile of the outer-leg bending and outer leg torque is similar. Below is a comparison of the torque and outer leg algorithm for the 96 equilibria.



Aside from the existence of peaks which correspond to the large OH currents, the variations among the 96 equilibria do not seem similar.

Acceptance Criteria

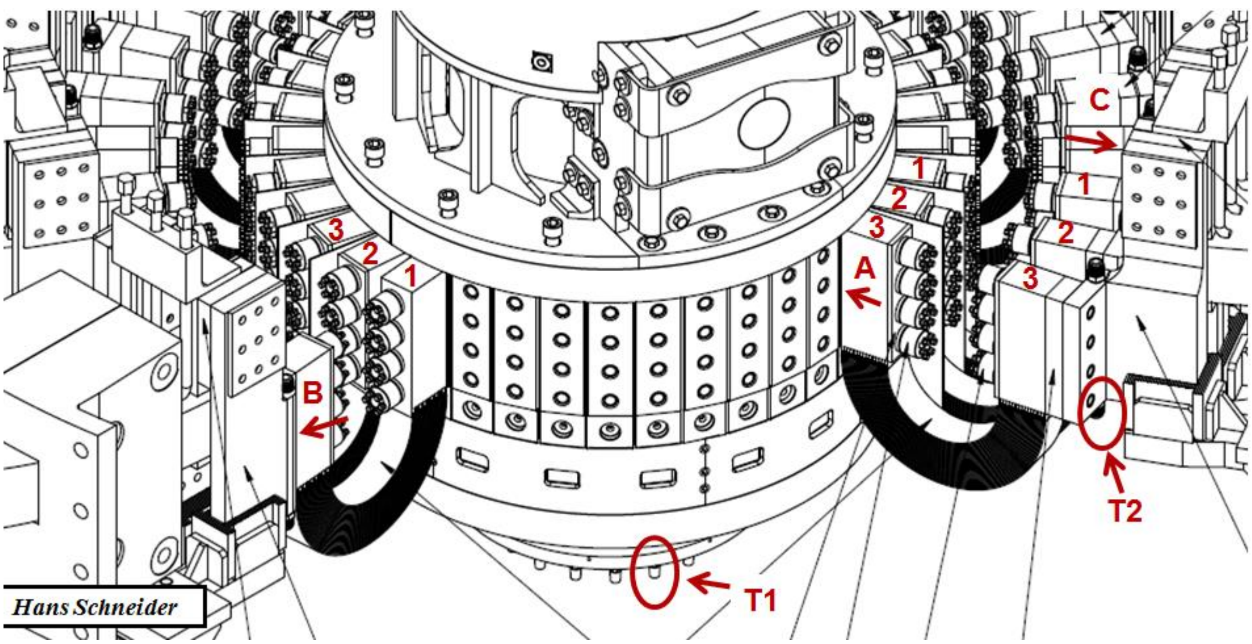
Experience with repeatability will yield the best indication of what changes should be considered a 2 problem. Coil to coil comparisons are the most practical measure of coil health. If all 12 coils consistently produce the same strain as their neighbors within 3% then the coils can be considered healthy. Trending will show the progression of change and give an indication of when it will be prudent to stop operating and inspect the coil.

Shot to shot comparisons will be difficult to compare because the TF and PF current levels will vary, as will the temperature strain. A DCPS – like algorithm [7] is available that will compute the TF OOP bending stress and insulation shear stress. This is what is used in figures 4.4-3, and 4. This could be implemented as a part of the visualization of the strain – comparing computed with measured values directly.

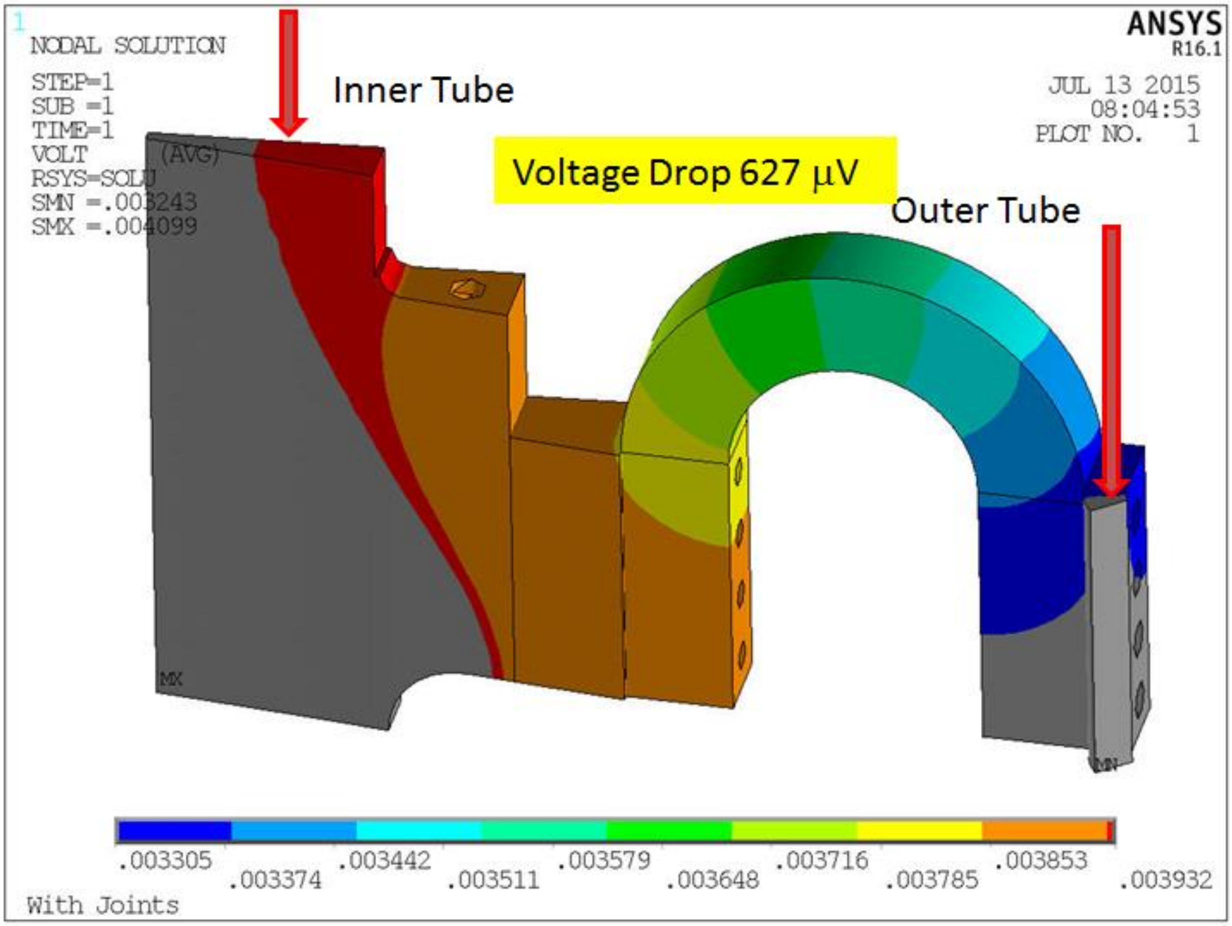
7.16 Task 16 TF Joint Resistance Measurements

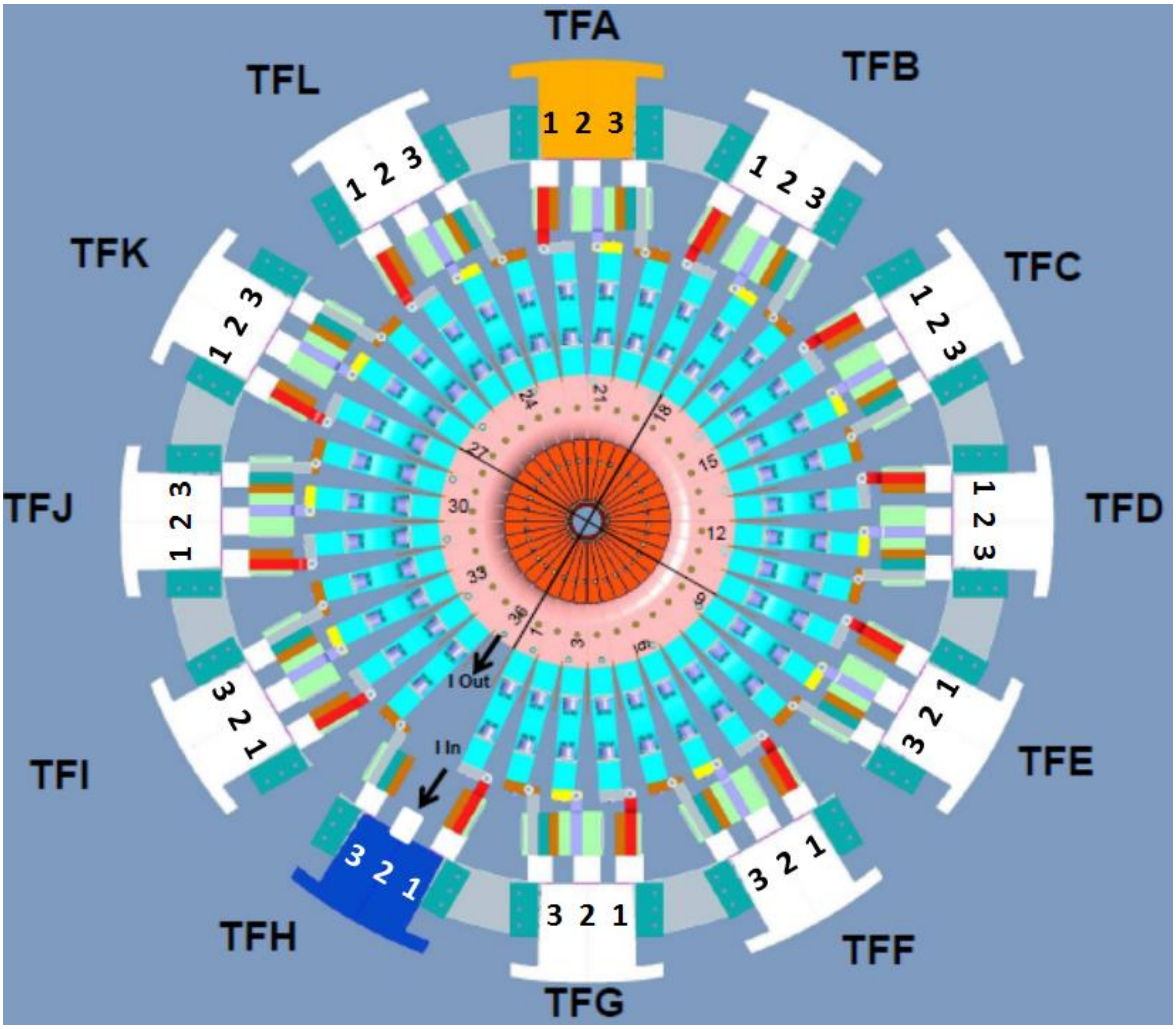
7.16.1 TF Flex Joint Voltage Drop

During the re-assembly of the TF coil joints, Hans Schneider took voltage measurements across the joints to confirm adequate assembly with good electrical contact. Additionally Hans took measurements across the inner joint regions from points T1 and T2. These are coolant connection s and include many joints and much bulk copper. During operation, and during maintenance down times, the voltage across these points should be recorded and compared with previous periods.



Two repaired flag locations are of interest, but since there are many original braze joints that have been straightened and remain in service, all the joint should be checked. This would amount to 72 measurements during a maintenance period. Some portion of these connections should be monitored in service. This is accomplished by running a low (1kA) static current before and after the first and last shots of a run period. After an initial baselineing, I would like to include in-service voltage monitoring. I would like to trend voltage data for "good" and repaired joints. I would add the TF voltage taps to "easy" places like the cooling tubes.. As Hans points out there is a lot of bulk copper between these points, so it will be difficult to see a change in a bolted connection through all the rest of the conductors and joints. It is expected that thes might be 1% effects but that by comparing joint to joint, pulse to pulse, and run period to run period, initial stages of contact deterioration can be detected.





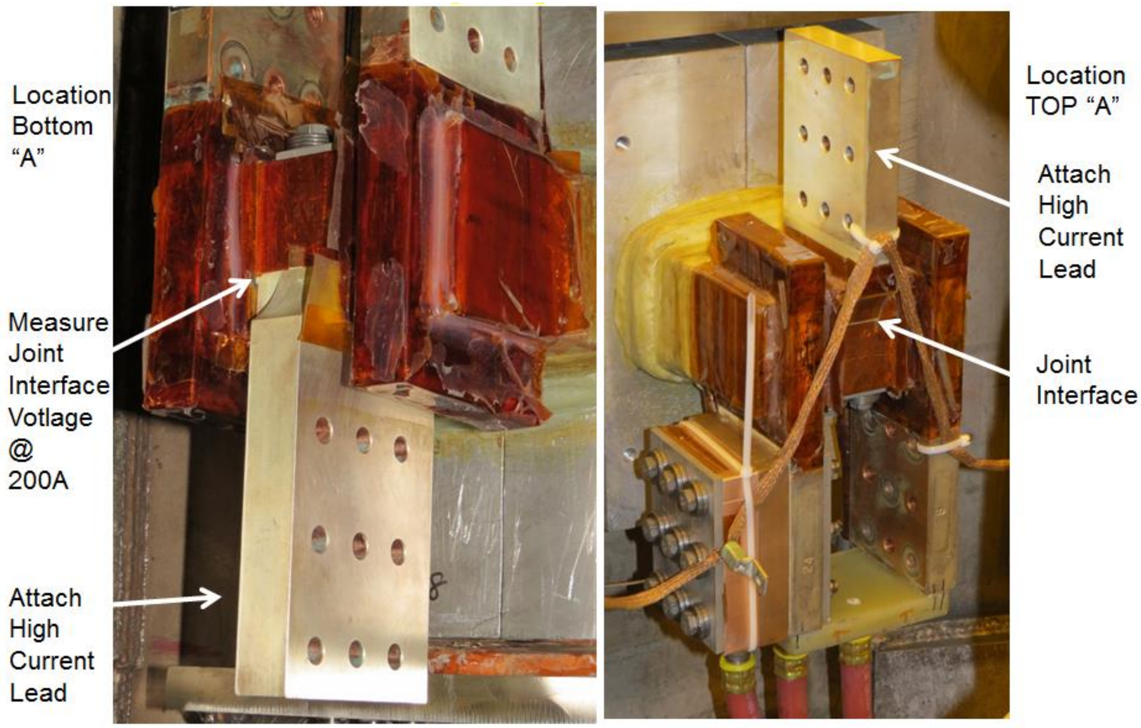
ys these are about 1% effects, which I think we will be able to see comparing similar shots or with the "front or back porch" constant DC test. I don't think it is practical or safe to try to tap across individual joints. With the trending data we could zero in on troublesome areas later.

I haven't put much thought to instrumenting the OH coax. My sense is that we restored consistent engineering margins with the potting and outer joint bolt upgrade. So I would just rely on future inspections.

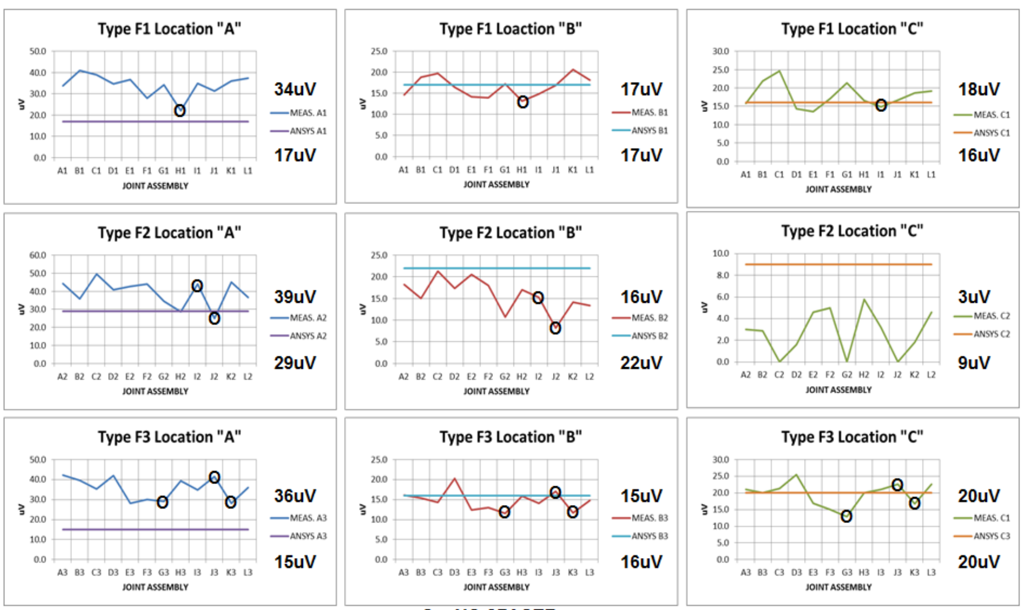
This is probably worth a review to choose the locations, methods and timing of the voltage taps.

7.16.2 TF Outer Repaired Flags Integrity Measurements

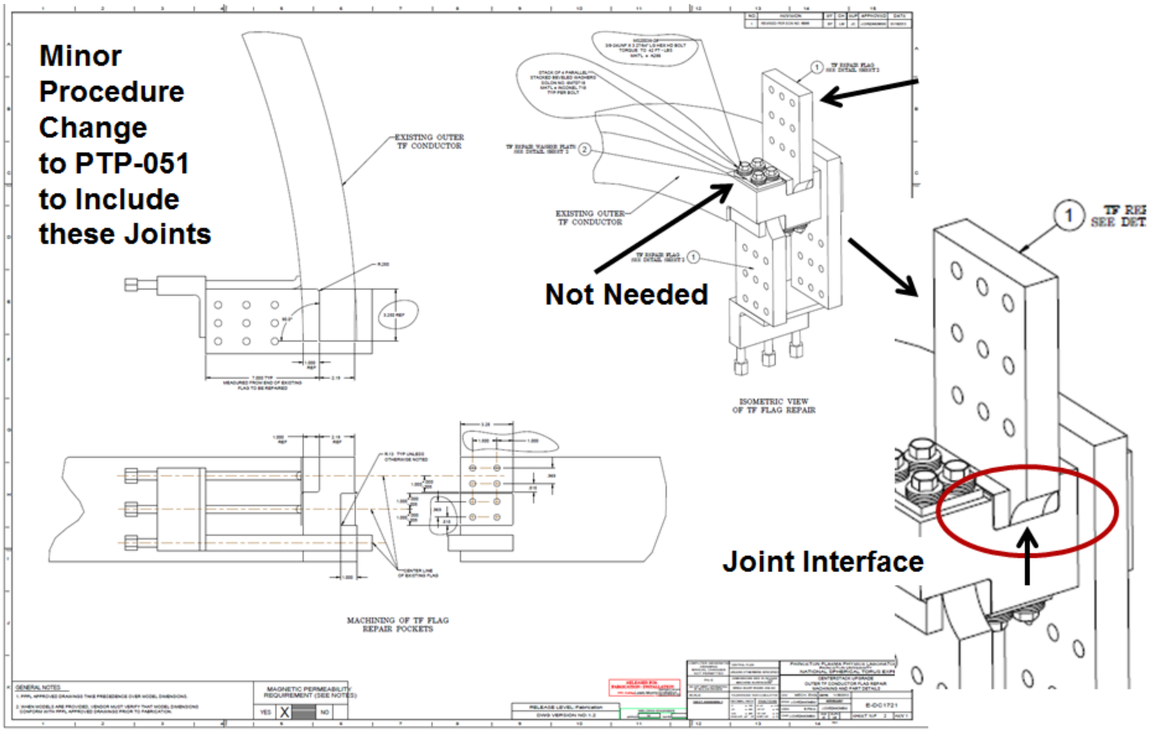
Voltage measurements were made on the repaired flags in accordance with D-PTP-NSTX-CL-051(MPC) (under charge #1150****X350). Results were reported June 25 2015



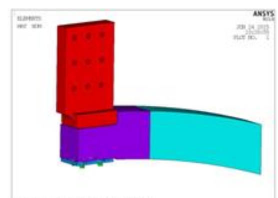
Measured Data vs. ANSYS Model

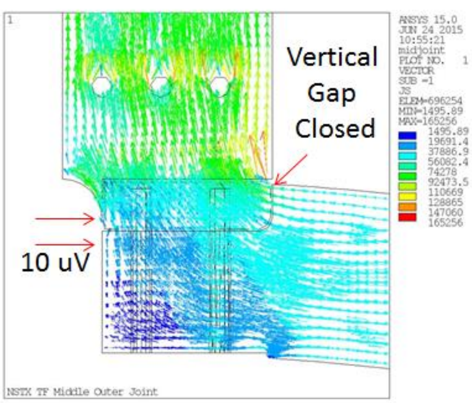


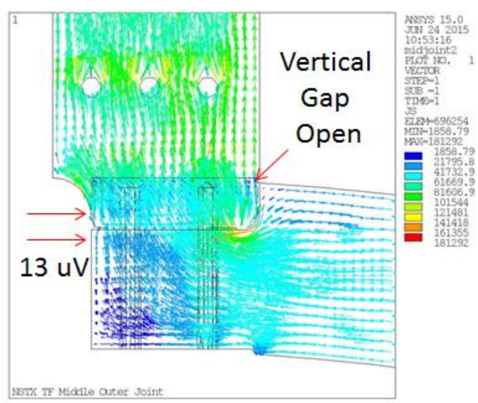
O = NO SPACER
Single Joint



Joint Resistance Will Vary
if Contact is made on Vertical Leg





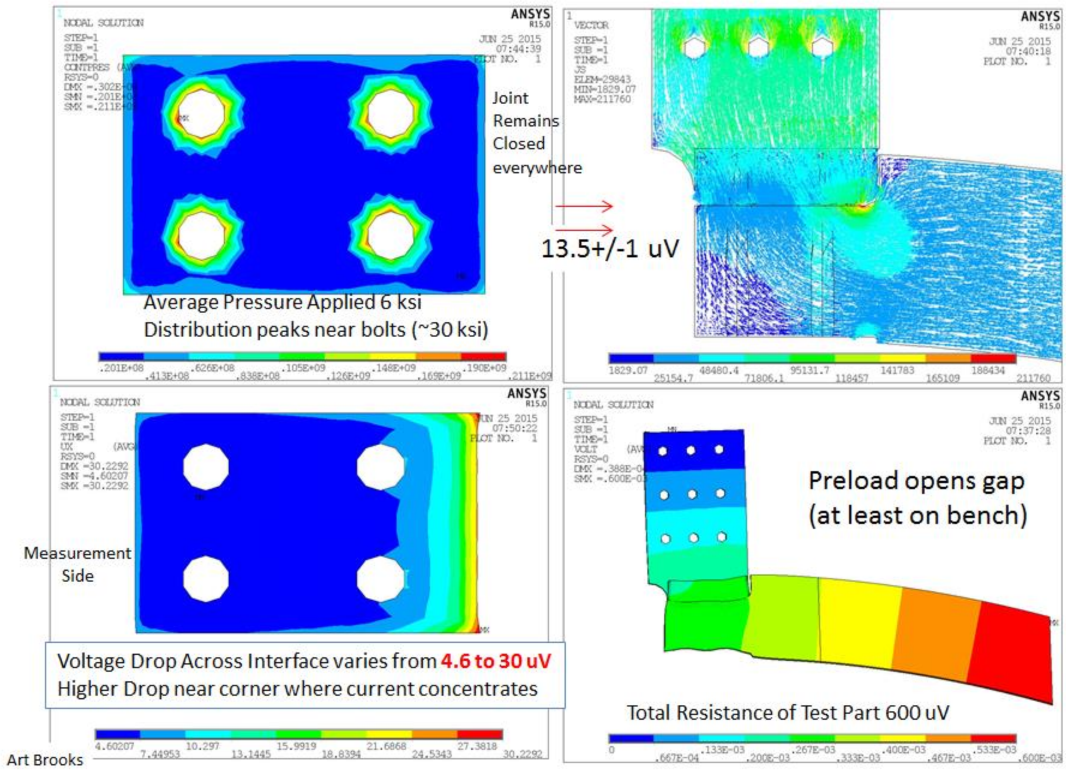


There is no clearance by design so intermittent contact likely

Results don't yet include impact of pressure distribution on joint electrical conductance

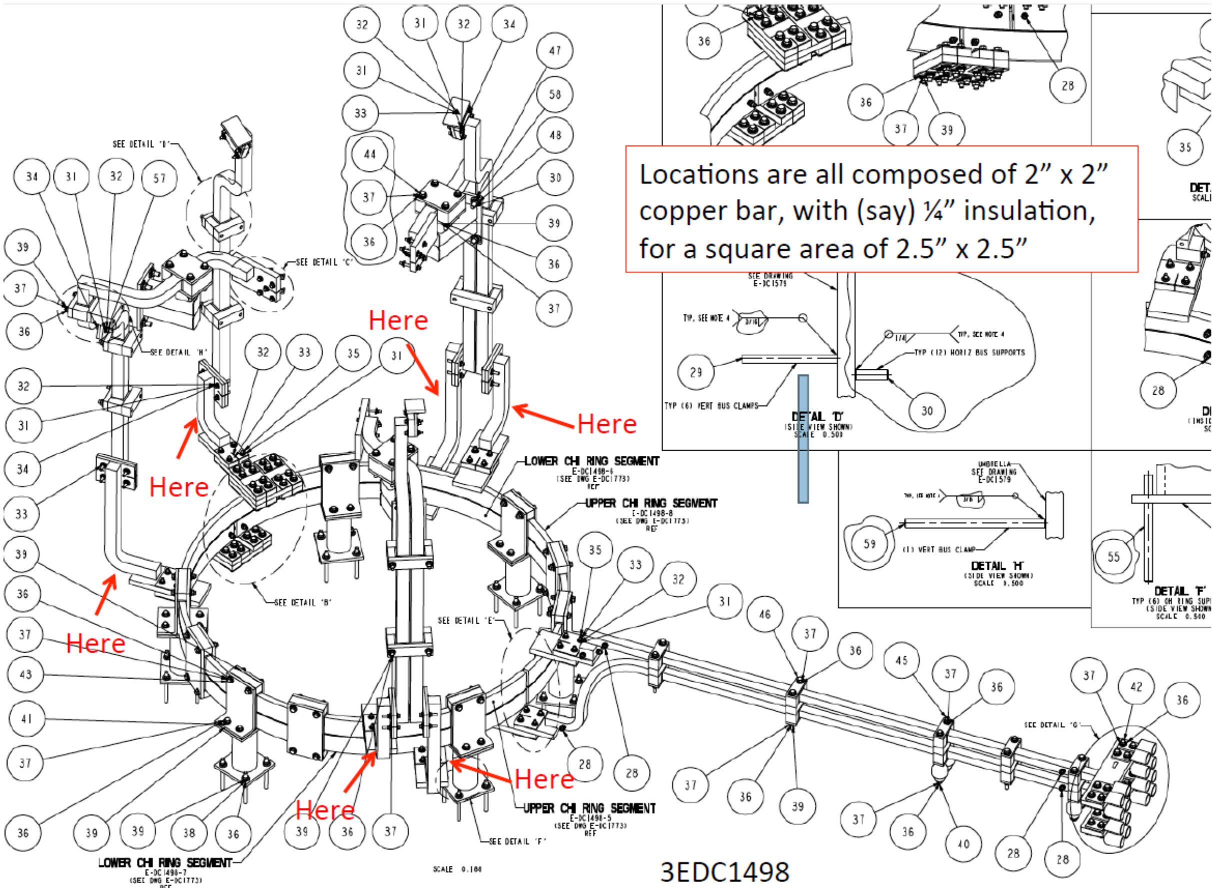
Art Brooks

Finer Mesh with Conductance Dependent on Local Pressure



7.17 Task 17 CHI Bus Bar Current Measurements

Current flowing in the CHI bus bars is an indication of the magnitude of the halo currents flowing in the machine. This is of a few measurements intended to monitor halo current loading.



Stefan Gerhardt has this covered in a separate task [22] , but it is a measure of the halo current severity and non-axisymmetry that will contribute to other measurements of the disruption behavior of NSTX-U

\I_HCCHIINAMP
\OPERATIONS::TOP.HALOCUR.ROGOWSKI.CURRENT:IHCCHIINAMP Sum of Rogoski signals on the inner CHI bus
\I_HCCHIOUTAMP
\OPERATIONS::TOP.HALOCUR.ROGOWSKI.CURRENT:IHCCHIOUTAMP Sum of Rogoski signals on the outer CHI bus

7.18 Task 18 High Z Tiles

Kelsey Tresemer and Mike Jaworski have this covered. This should be monitored in the context of other thermal measurements and add this to the Sichta COE page.

7.19 Task 19 TF Thermal Stickers

Appendix A emails

November 29 2016 email from Mark Smith:

Pete,
The TF struts are adjusted to fit, per as-built, dimensions of the machine.
They are not tightened, nor preloaded to produce a preloaded strut condition.
So, snug fit, no preload.