NSTX

ANALYSIS OF TF OUTER LEG

NSTX-CALC-132-04-01

January 13, 2012

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PPPL Calculation Form

Calculation # **NSTXU-CALC-132-04** (ENG-032) Revision # **01** WP #, if any **1672**

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

For the upgrade, the TF current will increase to 130 KA, resulting in 4 times the mechanical load, both the in-plane and the out-of-plane (OOP) load. Consequently, various support structures will be over stressed, namely the umbrellas, and localized regions on the vacuum vessel (VV). To resolve these problems the load path will be modified. By adding structural support to transfer TF outer coil load to the VV at the clevis along with upgrading the clevis, maximum transfer of the OOP load can occur at this connection. This bypasses the umbrella. Furthermore, localized reinforcements will be added. Note, interference with auxiliary systems and supports was troublesome and limited the addition of trusses to help sustain the OOP load. Lastly, support rings will be added between the TF outer coils to reduce the pull-out (in-plane) loads.

In the current NSTX configuration, the TF outer coils are supported by the umbrella structure, turn buckles and tie bars. Previous analysis, based on worst case poloidal field (PF) currents, reveal some structures are over stressed >1 GPa (145 ksi). Evaluating the three components of the load in cylindrical coordinate, the radial load is carried by the cylindrical umbrella and rings. The vertical load and the OOP load are transferred through the umbrella structure producing high stress in the umbrella feet, the arches, and the VV ribs and dome. Thus, the existing support is no longer adequate.

The upgrade design replaces the turn buckles with a sturdy support ring which occupies the space of existing components. The support ring and tie bars transfer some of the in-plane and OOP load to the VV and is effective on both symmetric and asymmetric PF currents. The support ring reduces the pull-out (in-plane) load at the umbrella structure. Note, up-down asymmetric currents result in a net twist load which requires an attachment to the VV. The tie bars can take the net twist and also provided adequate OOP support for symmetric case.

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

Included in the body of the calculation

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

Currently only 7 scenario PF currents are selected to run the model, which may be not enough to reflect the worst case of every aspect. Influence factors will be calculated later.

Weldings in the umbrella and vessel reinforcement are modeled as solid bond.

TF coil and clamp are bonded but in reality there is a thick layer of epoxy which may reduce the stress concentration.

Connection between aluminum block and umbrella, and TF truss are simplified in the model. Loads can be transferred to detailed model for further analysis and calculation.

Calculation (Calculation is either documented here or attached)

See the attached document.

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

Several scenarios with larger OOP loads in TF outer coil are calculated, including symmetric and asymmetric PF current combinations. With the redesigned coil support configuration, maximum displacement has been reduced significantly, originally, from 27 mm to present 5 mm. The maximal predicted coil stress is 135 MPa. The insulation shear stress is within 13.3 MPa. Stress in umbrella arch prior to reinforcement was 304 MPa and is now 170 MPa with reinforcements. The stress in the VV is mostly within 200 MPa, except for a few areas in midplane. The loads in the aluminum blocks, clevis, ring and tie bars are transferred to detailed models for further design and analysis efforts. During VV bake-out (150 °C), the truss will load the TF outer coil producing a maximal stress of 151 MPa, which is within the allowable. Non-linear buckling analysis of the vessel was conducted using the OOP force of scenario 79 and safety factor is larger 2.4, can satisfy the requirement of 2.

Cognizant Engineer's printed name, signature, and date

Mark Smith Mark Smith

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

Checker's printed name, signature, and date

Peter Titus Peter Titus Digitally signed by Peter Titus DN: cn=Peter Titus, o, ou, email=ptitus@pppl.gov, c=US Date: 2012.02.02 11:38:25 -05'00'

Revision Status Table

Revision	Date	Description of Changes
0	9/9/2009	Initial Issue
1	1/13/2012	Updated the large displacement elastic-plastic buckling calculation with higher order elements to address the poor stiffness behavior of SOLID 45 tets and wedges

Table of Contents

List of References

[1] P. TITUS et al., “Introduction to The Analysis Effort”, http://nstx-upgrade.pppl.gov/Engineering/Systems_Engineering/Design_Reviews/CSU_Project/PeerReview-08132009/Presentations/.

[2] CHARLES L. NEUMEYER, http://nstx-upgrade.pppl.gov/Engineering/CSU_Engrg_index.htm (NSTX_CS_Upgrade_110308.xls).

[3] PETER TITUS, “TF Strut to Vessel Knuckle Clevis Connection”, NSTXU-CALC-132-09-00.

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

[5] NSTX Design Point June 2010 http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html

[6] TF to Umbrella Structure Aluminum Block Connection NSTXU-CALC-12-04-00Rev 0 December 15 2010

[7] OOP PF/TF Torques on TF , R. Woolley, NSTXU CALC 132-03-00

[8] NSTX-CALC-13-001-00 Rev 1 Global Model – Model Description, Mesh Generation, Results, Peter H. Titus June 2011

[9] NSTX Upgrade Umbrella Arch and Foot Reinforcements, Local Dome Details, NSTXU-CALC-12-07-00 Pepared By: Peter Titus, Reviewed By: Irving Zatz, NSTX Cognizant EngineerMark Smith

[10] Umbrella Reinforcement Details, by P. Titus NSTXU CALC 12-07-00

[11] "TF to Umbrella Structure Aluminum Block Connection" NSTXU-CALC-12-04-00Rev 0 December 15 2010, Prepared by Peter H. Titus

[12] Analysis of the NSTX Upgrade Centerstack Support Pedestal NSTXU-CALC-12-09-00 May 2011 WBS 1.1.2 Peter Titus Reviewed By: Ali Zolfaghari, Cognizant Engineer: Mark Smith

[13] Nstx Ring Bolted Joint, NSTX-U Calc 132-11 March 2011, Peter Rogoff, Reviewed by I. Zatz

[14] NATIONAL SPHERICAL TORUS EXPERIMENT CENTER STACK RESEARCH AND DEVELOPMENT FINAL REPORT No. 13-970430-JHC Prepared By: James H. Chrzanowski April 30, 1997 PRINCETON UNIVERSITY PLASMA PHYSICS LABORATORY (PPPL), Excerpts included in Attachment A

[15] NSTX (NATIONAL SPHERICAL TORUS EXPERIMENT) STRUCTURAL DESIGN CRITERIA, I. ZATZ, 8/01/03.

Executive Summary

Recently the umbrella reinforcement, clevis, TF clamp and truss have been re-designed. A new vacuum vessel FEA model was built, including the umbrella reinforcement, new clevis, port and cover (NBI ports are reinforced) to replace the old vessel model in the TF truss analysis. But the centerstack, pedestal assembly and crown of umbrella structure are not included These are addressed in [8], [7], [11], and [12]. The TF truss FEA model is also modified to have coil reinforcement, modified clamp geometry and tie bar dimensions.

According to the criteria document [1], the stresses in TF outer coils should within allowable of 156 MPa (Tresca) or 233 MPa (bending), and epoxy shear stress should be within 16 MPa. To avoid collision with other components, coil circumferential displacement should be less than 12.7 mm. The umbrella structure and vessel are made of stainless steel. The Tresca stress allowable for vacuum vessel is 183 MPa but that of umbrella structure is only 150 MPa. Bending allowable is 1.5 times. The PF currents can be up-down symmetric or asymmetric. Upon PF field, TF coils have OOP displacement. Upper and lower half of TF coil may deform in opposite or same direction, depending on whether PF currents are symmetric or not. Upon asymmetric PF currents, there will be a net circumferential displacement. With some scenarios, the PF currents are not high but are asymmetric and may result in even higher OOP displacement and higher coil stress, which should be pay attention to.

Several scenarios with larger OOP loads in TF outer coil are calculated, including symmetric and asymmetric PF current combinations. Total 96 scenarios should be run to find out the worst load and stress in different components. Reference [8] includes analyses of many of the components for all 96 equilibria. Calculations for individual components address the full range of equilibria. With the redesigned coil support configuration, maximum displacement has been reduced significantly, originally, from 27 mm to present 5 mm. The maximal predicted coil stress is 135 MPa, at the connection between TF clamp and ring. The FEM simulates a solid bond between the coil and clamp. In reality, an epoxy layer is between them and may reduce the stress. The insulation shear stress is within 13.3 MPa. Stress in umbrella arch prior to reinforcement was 304 MPa and is now 170 MPa with reinforcements. Some local details of the ribs that support the umbrella legs have high stresses and have been qualified by limit analysis in ref [9] using similar methods for the vessel buckling analysis presented in this calculation. The stress in the VV is within 200 MPa, except for a few areas in midplane. The loads in clevis, ring and tie bars are transferred to detailed models for further design and analysis efforts, [3], and [13]. During VV bake-out (150 °C), the truss will load the TF outer coil producing a maximal stress of 151 MPa, which is within the allowable. Non-linear buckling analysis of the vessel was conducted using the OOP force of scenario 79 and safety factor is larger than 2.4, can satisfy the requirement of 2 in the NSTX structural design criteria. In Rev 0 of this calculation, SOLID 45 elements were used. These were found to be incorrect when a high percentage of the elements are tets and wedges. The 8 node elements were replaced with higher order elements, and the simulation was re-run. Non-convergence occurred at the load factor of 2.4 but non convergence was reported as a large plastic strain in an element and was not a clear indication of collapse. Actual collapse may occur at a higher load multiplier.

Modeling

For the upgrade, the TF current will increase to 130 KA, and the PF currents double to allow a doubling of the plasma current. resulting in 4 times the mechanical load, principally the out-of-plane (OOP) load. Consequently, various support structures will be over stressed, namely the umbrellas, and localized regions on the vacuum vessel (VV). To resolve these problems the load path will be modified. By adding structural support to transfer TF outer coil load to the VV at the clevis along with upgrading the clevis, maximum transfer of the OOP load can occur at this connection. This reduces the loading in the umbrella. Furthermore, localized reinforcements will be added. Note, interference with auxiliary systems and supports was troublesome and limited the addition of trusses to help sustain the OOP load. Lastly, support rings will be added between the TF outer coils to reduce the pull-out (in-plane) loads.

In the current NSTX configuration, the TF outer coils are supported by the umbrella structure, turn buckles and tie bars. Previous analysis, based on worst case poloidal field (PF) currents, reveal some structures are over stressed >1 GPa (145 ksi). Evaluating the three components of the load in cylindrical coordinate, the radial load is carried by the cylindrical umbrella and rings. The vertical load and the OOP load are transferred through the umbrella structure producing high stress in the umbrella feet, the arches, and the VV ribs and dome. Thus, the existing support is no longer adequate.

The upgrade design replaces the turn buckles with a sturdy support ring which occupies the space of existing components. The support ring and tie bars transfer some of the in-plane and OOP load to the VV and is effective on both symmetric and asymmetric PF currents. The support ring reduces the pull-out (in-plane) load at the umbrella structure. Note, up-down asymmetric currents result in a net twist load which requires an attachment to the VV. The tie bars can take the net twist and also provided adequate OOP support for symmetric case.

A finite element model (FEM) of the relevant components was created. Recently the umbrella reinforcement, clevis, TF clamp and truss are re-designed. A new vacuum vessel model (Figure 1) was built, including the umbrella reinforcement, new clevis (Figure 2), port and cover (NBI ports are reinforced) to replace the old vessel model in the TF truss analysis. TF truss is also modified to have coil reinforcement, modified clamp geometry and tie bar dimensions (Figure 2, Figure 3). The parametric model was built using ANSYS. It includes vessel and supporting legs, umbrella structure and reinforcements; and electromagnetic representations of the PF coils, Ohmic heating (OH) coils, and innerTF coil legs; and structural and EM models of the TF outer legs and truss. Also, the TF outer coil was reinforced with additional clamps. The tie bars are pin connected to the new clevises which are welded to the VV. This design is effective on both symmetric and asymmetric PF currents. PF, OH and TF inner coils are modeled using souc36 current element and TF outer coils using solid element. The Lorenz force in TF outer coils are calculated by biot-salvart law. The results from this global model are transferred to other detailed models for further analysis, e.g. ring loads are transferred to a local model for detailed stress and bolt calculations. But the centerstack, pedestal assembly and crown of umbrella structure are not included.

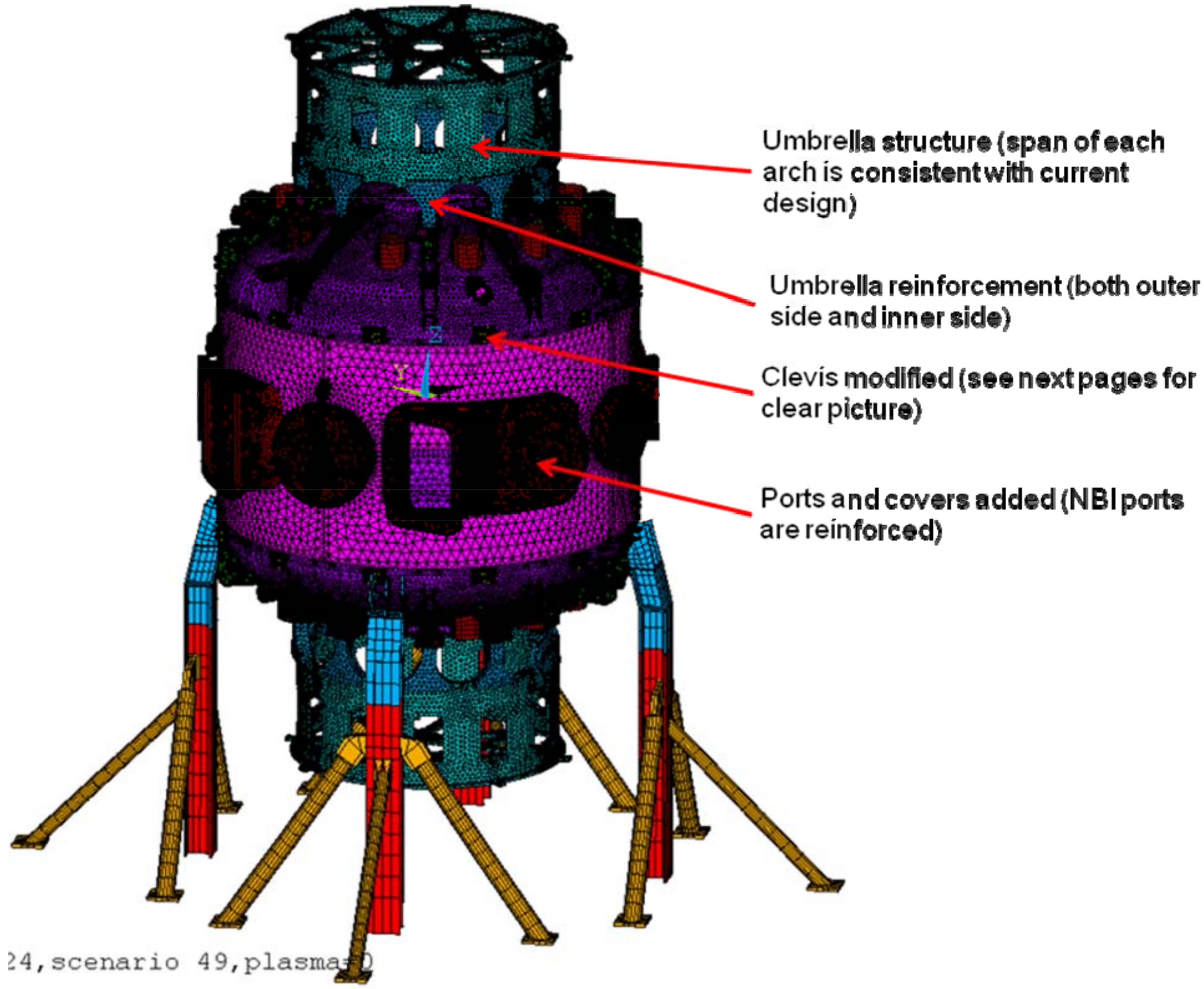


Figure 1: Changes made to vacuum vessel.

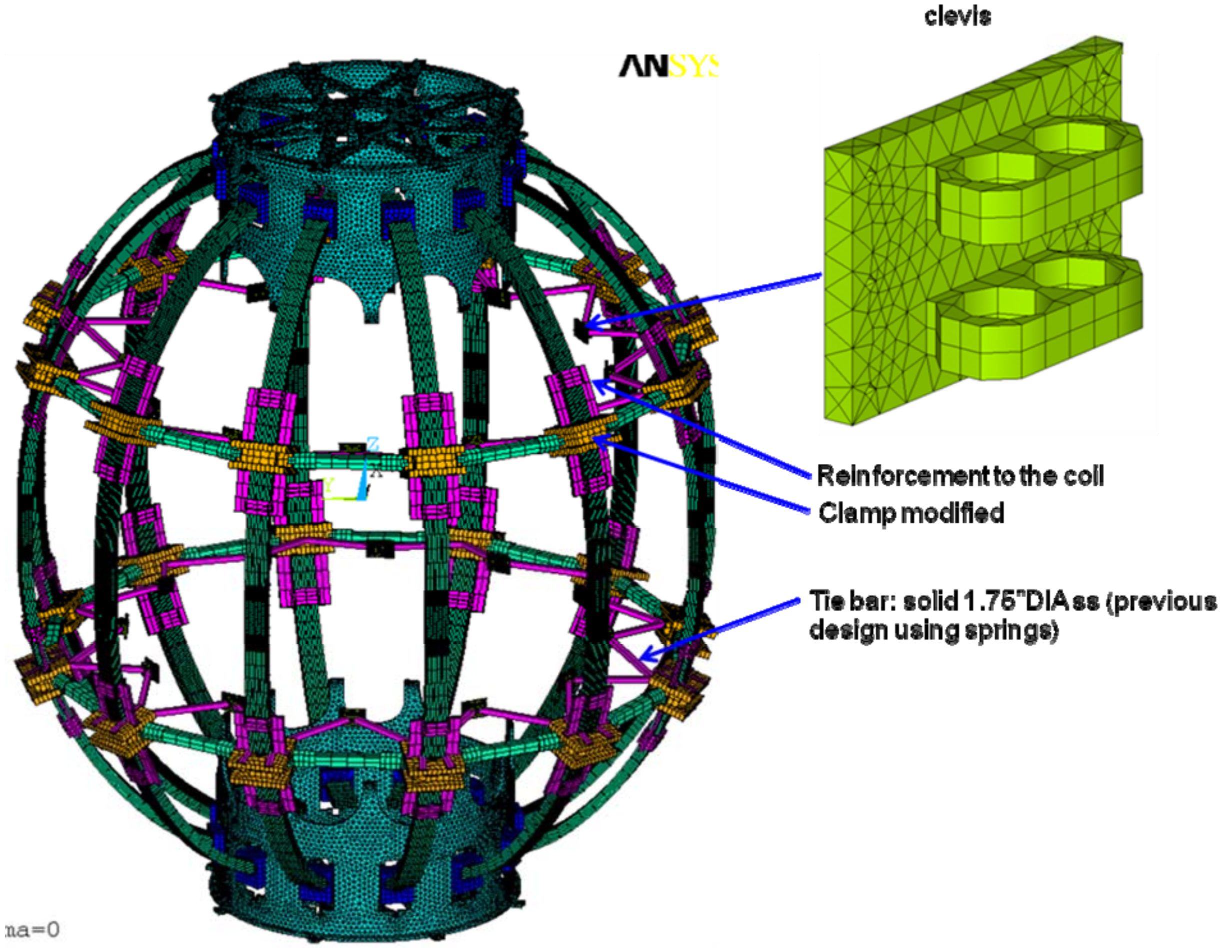


Figure 2: Changes made to TF truss.

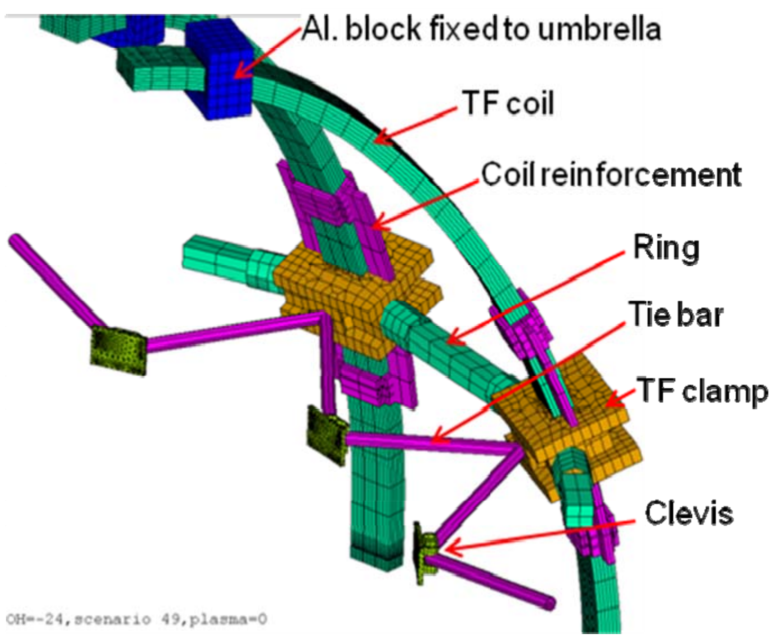


Figure 3: Modeling of TF coil and TF truss.

According to the criteria document , [4] and [1], the stresses in TF outer coils should within allowable of 156 MPa (Tresca) or 233 MPa (bending), and epoxy shear stress should be within 16 MPa. To avoid collision with other components, coil circumferential displacement should be less than 12.7 mm. The umbrella structure and vessel are made of stainless steel. The Tresca stress allowable for vacuum vessel is 183 MPa but that of umbrella structure is only 150 MPa. Bending allowable is 1.5 times. The PF currents can be up-down symmetric or asymmetric. Upon PF field, TF coils have OOP displacement. Upper and lower half of TF coil may deform in opposite or same direction, depending on PF currents are symmetric or not. Upon asymmetric PF currents, there will be a net circumferential displacement. With some scenarios, the PF currents are not high but are asymmetric and may result in even higher OOP displacement and higher coil stress, which should be pay attention to.

Several current scenarios with large TF outer coil OOP loads were evaluated which included symmetric and asymmetric PF current combinations. A total 96 current scenarios can be analyzed to ascertain the worst loads and stresses for various components. Note, the PF currents, being either up-down symmetric or asymmetric, result in the TF coils OOP displacement. The TF coil upper and lower halves could deform in the same or opposite direction depending upon the configuration of the PF currents. Upon asymmetric PF currents, there will be a net circumferential displacement. However, with some scenarios, the PF currents are not high but are asymmetric and may result in high OOP displacement and coil stress. Based on our previous analyses, adding plasma current would reduce the OOP load, and thus, to be conservative, it is set to be zero. Plasma current produces flux lines that are parallel to TF coil. Plasma current quench doesn't influence TF coil and plasma disruption effects were not included.

Results

To find out the worst case load, a 2D model was built to run 96 scenarios cases to calculate the B field and then calculate the Lorenz force, force distribution and torque. Results are shown in Figure 4. The PF currents are based on design point 030811 version and include 10% headroom. Among them, scenario 79 (up-down symmetric) has highest total OOP force and torque. Scenario 34 (up-down asymmetric) has the second highest total OOP load. Scenario 16 has higher force density near aluminum block. Also 4 other scenarios, 37,40,73,76, with higher OOP load are selected for further detailed analysis.

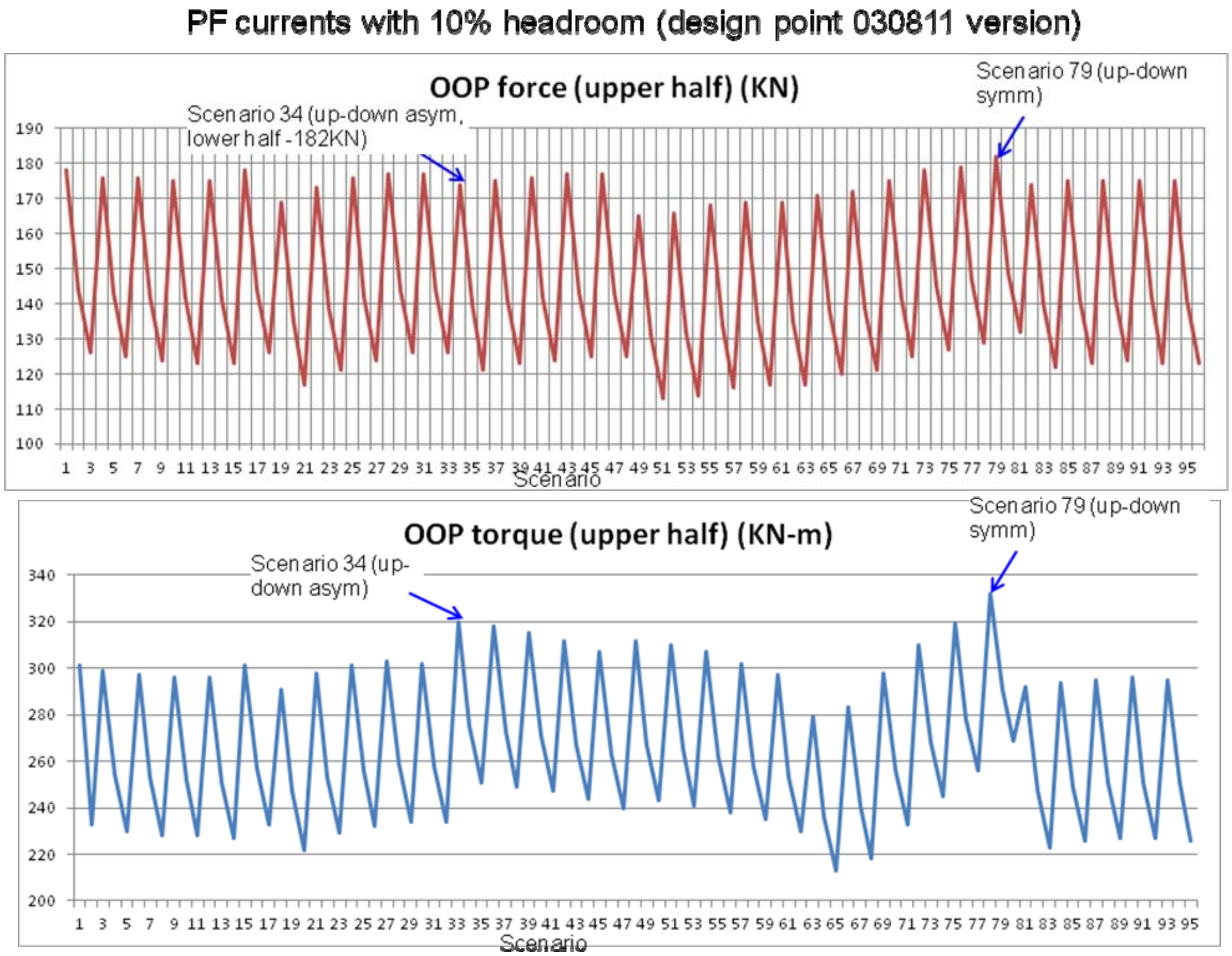


Figure 4: OOP force and torque of 96 scenarios.

Displacement

With the redesigned coil support configuration, maximum displacement has been reduced significantly, originally, from 27 mm to present 5 mm (Figure 5). The maximal predicted coil stress is 103 MPa, if with brace, and 135 MPa, if without brace, at the connection between TF clamp and ring (Figure 9, Figure 10). Before when the tie bar is set to be more compliant (to reduce the load at clevis), the coil stress is higher at the connection. At that time, adding brace is suggested. But now the clevis is re-designed and can take more load. Then the coil stress gets lower and the brace is not necessary. The FEM simulates a solid bond between the coil and clamp. In reality, an epoxy layer is between them and may reduce the stress.

To compare vessel displacement with P. Titus's global model, 7 scenarios are selected and the results are plotted in Figure 6-Figure 8.

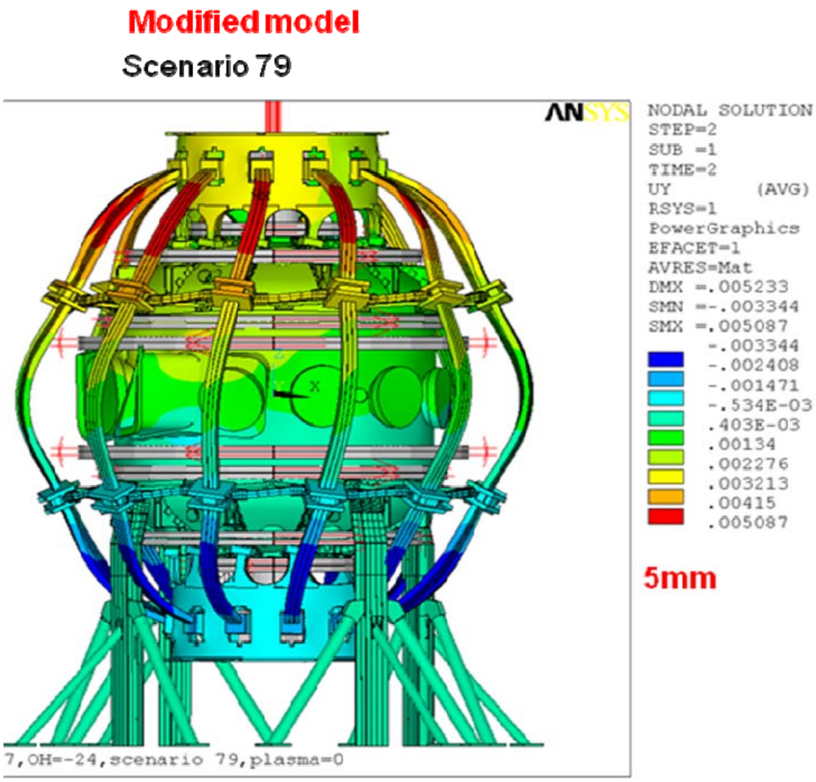


Figure 5: Circumferential displacement (m) (scenario 79).

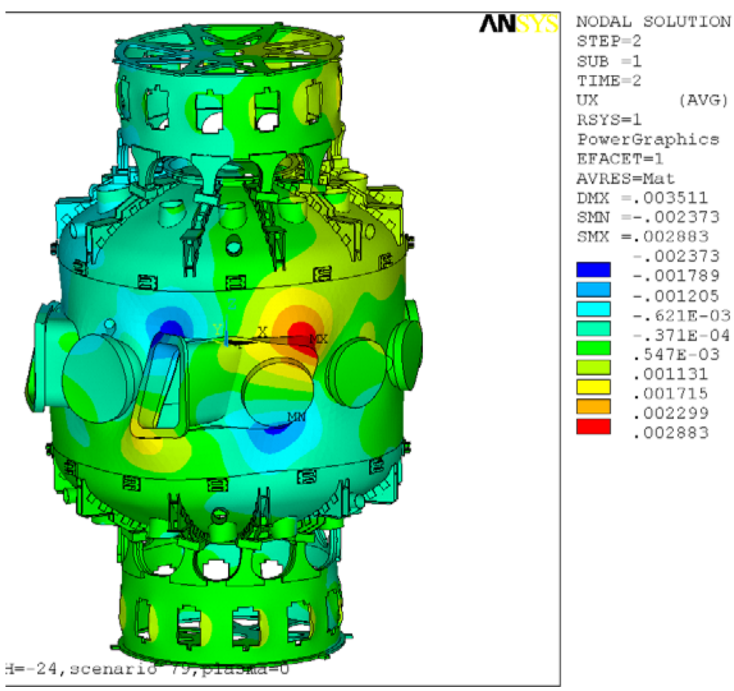


Figure 6: Vessel radial displacement Ux (m) (scenario 79)

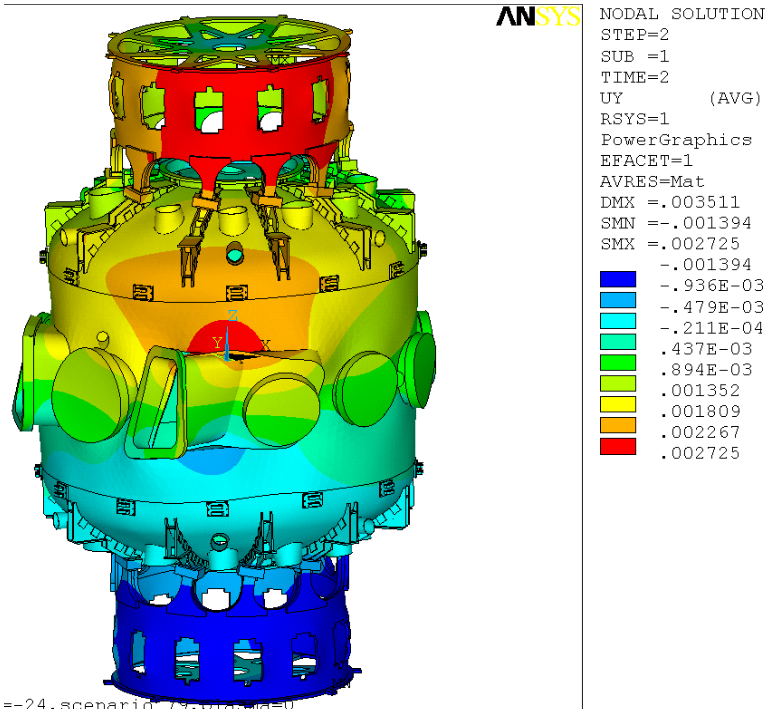


Figure 7: Vessel theta displacement Uy (m) (scenario 79)

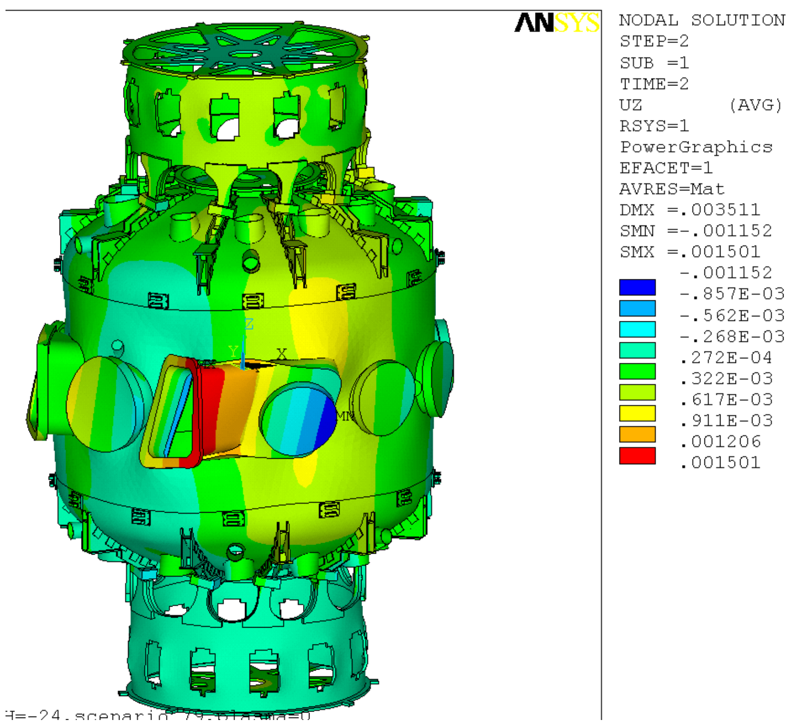


Figure 8: Vessel vertical displacement Uz (m) (scenario 79)

Coil and copper bond stresses

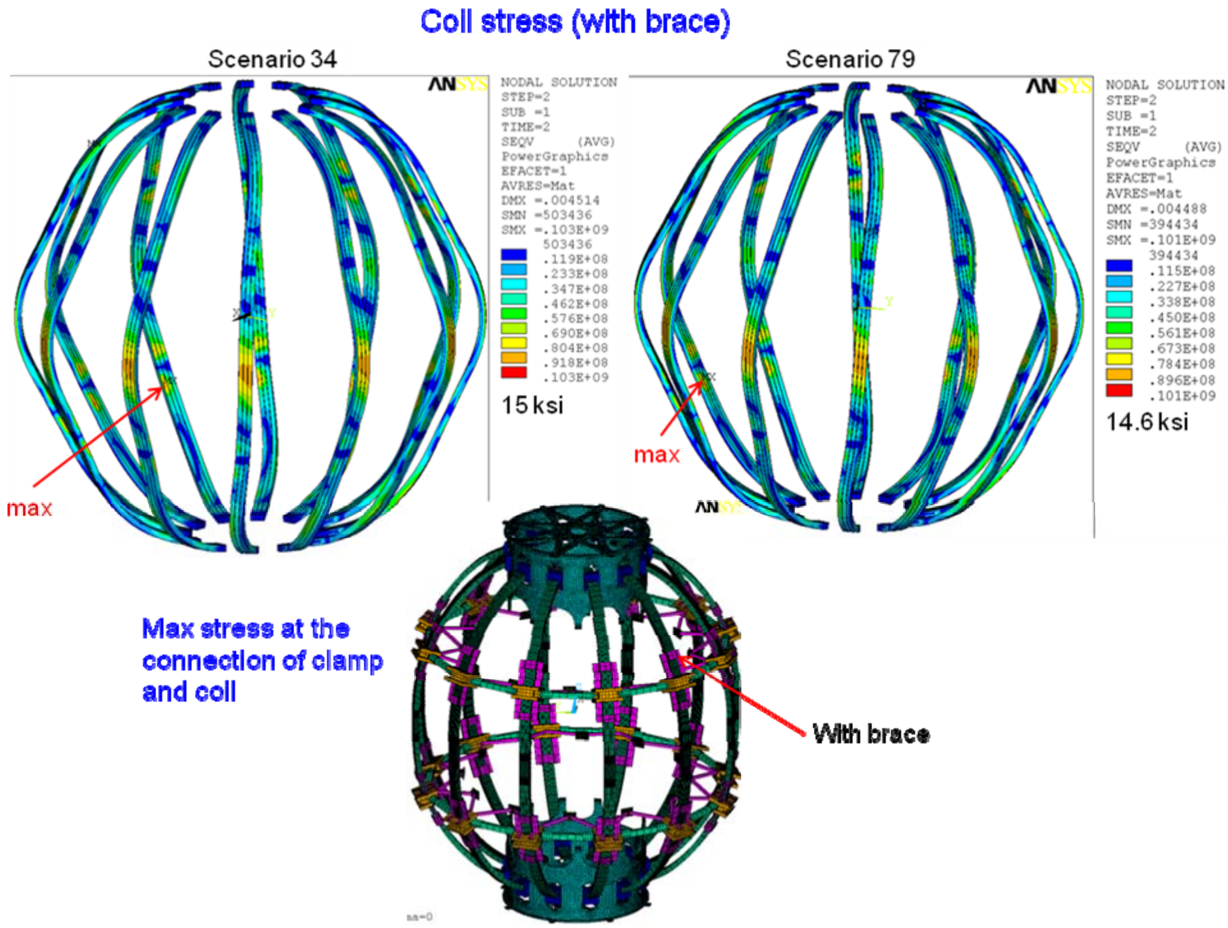


Figure 9: Coil Von Mises stress (Pa) (with brace).

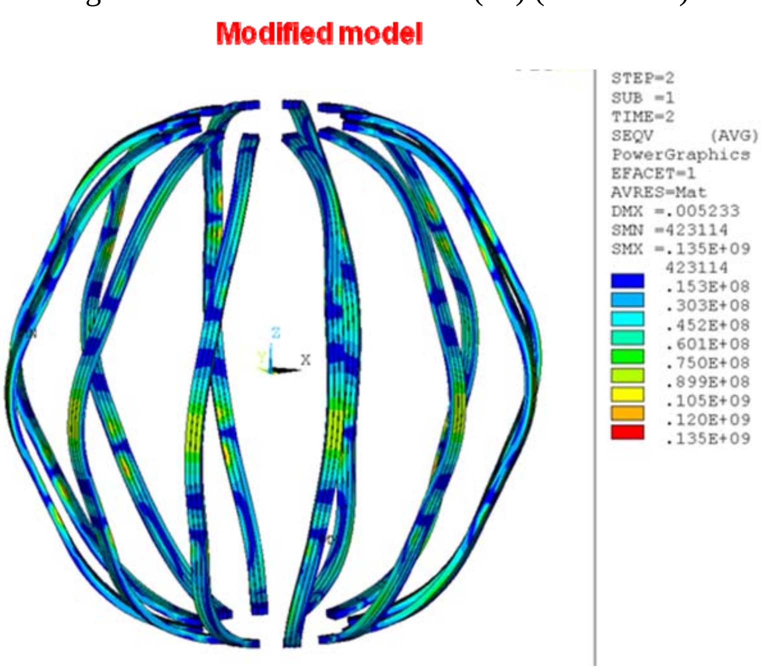


Figure 10: Coil Von Mises stress (Pa) (without brace) (scenario 79).

The insulation shear stress is within 11 MPa (Figure 11, Figure 12).

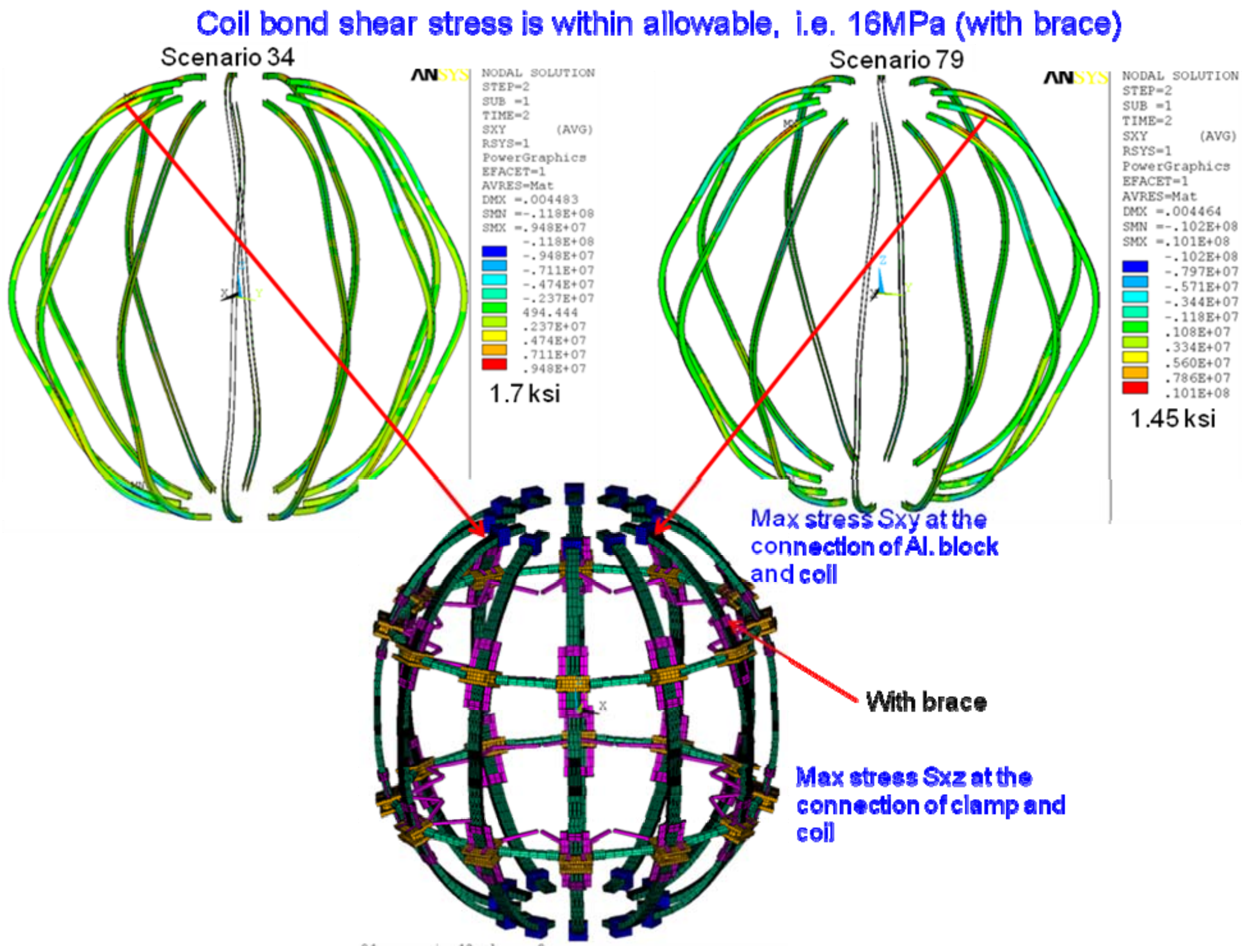


Figure 11: Coil bond shear stress (Pa), if with brace.
Shear Allowable comes from Ref [14], Attachment A

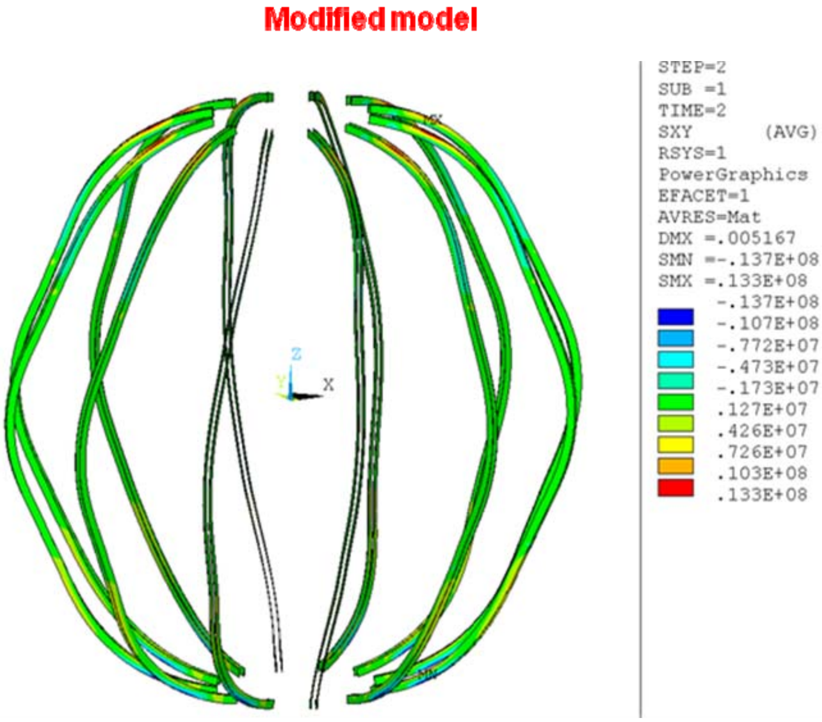


Figure 12: Coil bond shear stress (Pa), if without brace(scenario 79).

Vessel and umbrella structure stresses

The stress in most area of the VV is within 200 MPa (Figure 13, Figure 14), only a few areas reach 300 MPa, especially the midplane (Figure 14). My model is too coarse to tell all these details. A sub-model is more appropriate.

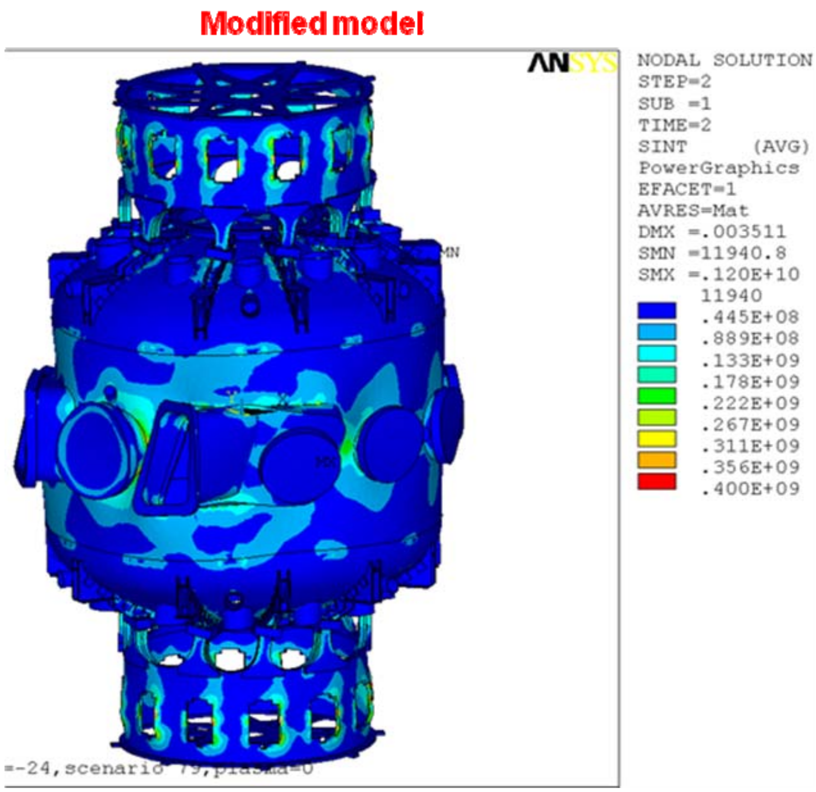


Figure 13: vessel stress (Pa) (scenario 79).

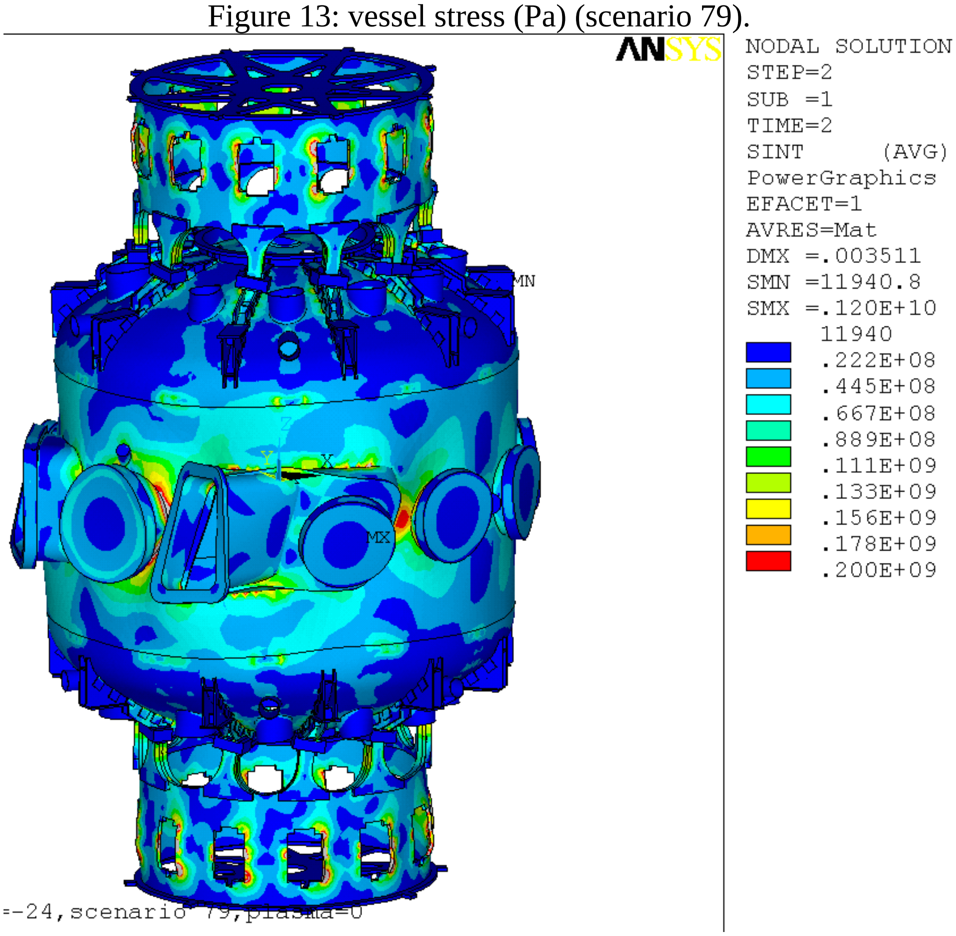


Figure 14: vessel stress (Pa) (scenario 79).

Stress in umbrella feet is much higher than vessel because I directly coupled the nodes between umbrella and aluminum blocks instead of modeling the detailed connection (Figure 15). Figure 16 shows the stress in the rib. But the rib in this model is not accurate enough to evaluate the behavior. Peter Titus and Mark Smith have more detailed analysis of this part.

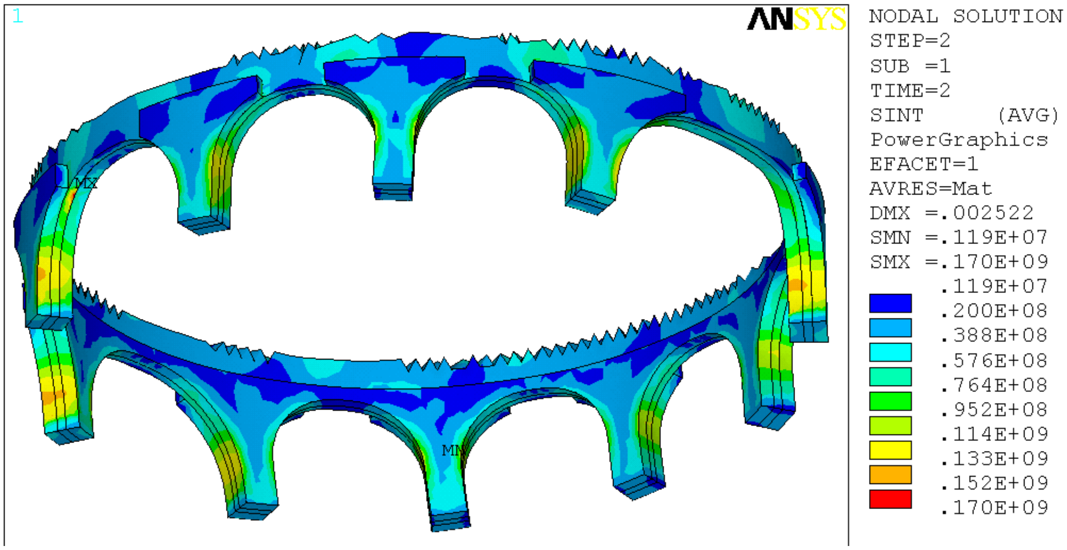


Figure 15: stress in umbrella (Pa) (scenario 79).

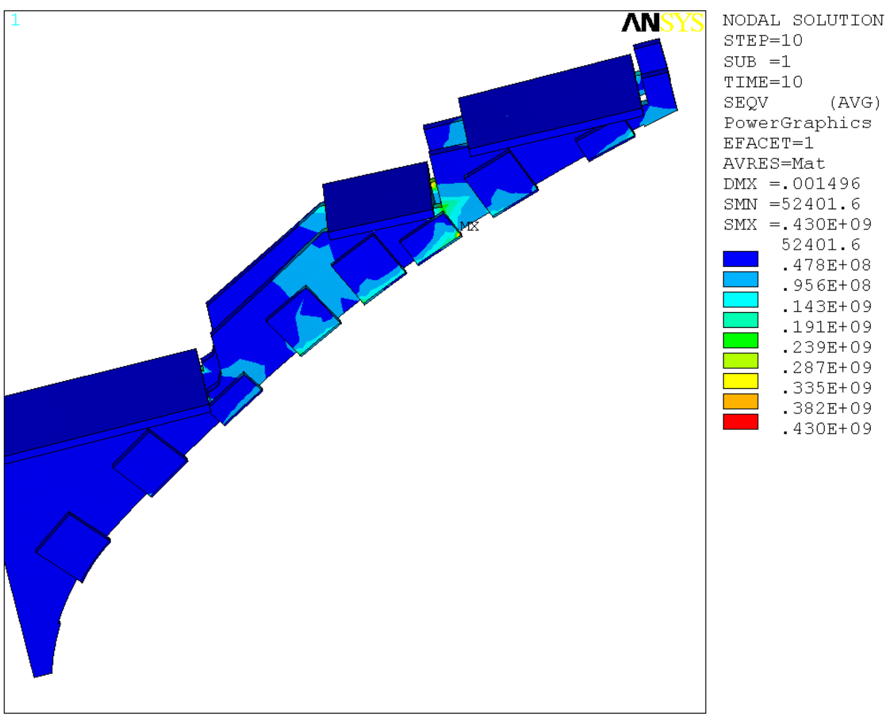
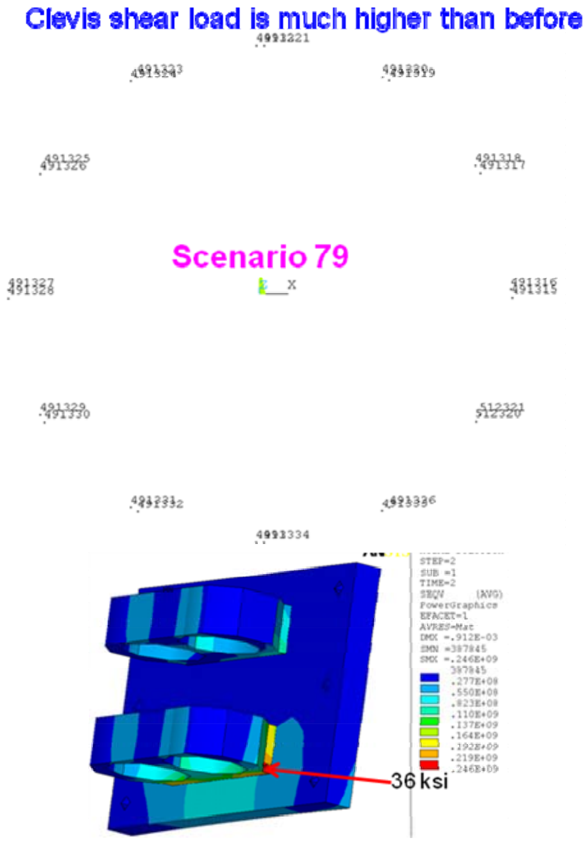


Figure 16: rib stress (Pa) (scenario 79).

Loads in clevis, ring and tie bars

The loads in clevis, ring, and tie bars are shown in Figure 17-Figure 19. These data have been transferred to Peter Rogoff to build his detailed models for further design and analysis efforts.

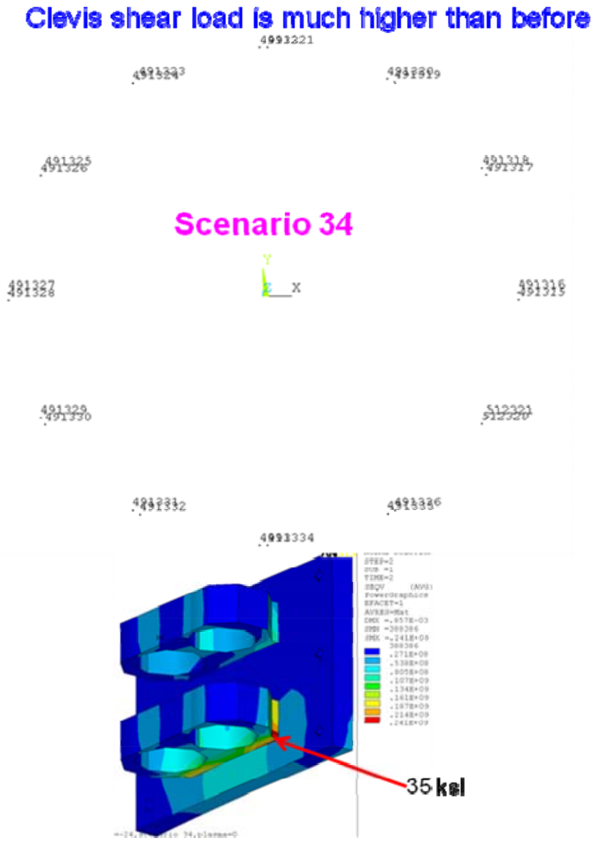
Because the clamp design has been modified several times after building this model, the clamp dimension in the model is different from the design now. Figure 20 shows the distance between the intersection of two tie bars and the coil center, for other analysts to convert the ring load in this document into their model. Peter Rogoff built the detailed model to analyze the tie bars. To compare with his result, lists the displacements and forces in the tie bars. The calculated spring constants of tie bar is similar to Peter Rogoff's result.



Cylindrical coordinate system

NODE	FX	FY	FZ
491315	-45966.	88166.	-11996.
491316	63083.	92613.	16416.
491317	-47387.	70275.	-12367.
491318	61972.	90962.	16129.
491319	-47256.	70061.	-12332.
491320	61821.	90760.	16069.
491321	-47223.	70033.	-12324.
491322	60156.	88316.	15658.
491323	-45109.	66897.	-11772.
491324	61026.	89596.	15663.
491325	-44169.	65503.	-11527.
491326	62344.	91526.	16226.
491327	-46104.	68373.	-12032.
491328	59583.	87474.	15507.
491329	-41922.	62171.	-10940.
491330	66016.	96921.	17162.
491331	-50263.	74571.	-13122.
491332	60398.	88671.	15719.
491333	-50770.	75292.	-13249.
491334	55240.	81099.	14377.
491335	-43581.	64632.	-11373.
491336	60829.	89304.	15831.
512320	-44957.	66671.	-11732.
512321	61226.	89886.	15935.

Max shear load: 163KN (previous requirement 5000 lbs=22 KN)
Max radial load: 24096 N (5428 lbs)
Max vetical load: 6242 N (1406 lbs)



Cylindrical coordinate system

NODE	FX	FY	FZ
491315	-44978.	66703.	-11738.
491316	62092.	91156.	16160.
491317	-46363.	66757.	-12099.
491318	61022.	89587.	15882.
491319	-46259.	66603.	-12072.
491320	60660.	89349.	15839.
491321	-46240.	66574.	-12067.
491322	59225.	86948.	15414.
491323	-44214.	65570.	-11539.
491324	60062.	88178.	15632.
491325	-43246.	64135.	-11286.
491326	61384.	90119.	15976.
491327	-45111.	66900.	-11773.
491328	58729.	86221.	15285.
491329	-41051.	60879.	-10713.
491330	64959.	95366.	16906.
491331	-49186.	72943.	-12836.
491332	59491.	87339.	15483.
491333	-49647.	73627.	-12956.
491334	54458.	79950.	14173.
491335	-42737.	63380.	-11153.
491336	59894.	87932.	15588.
512320	-44052.	65330.	-11496.
512321	60261.	88470.	15684.

Max shear load: 160KN (previous requirement 5000 lbs=22 KN)

Figure 17: clevis load.

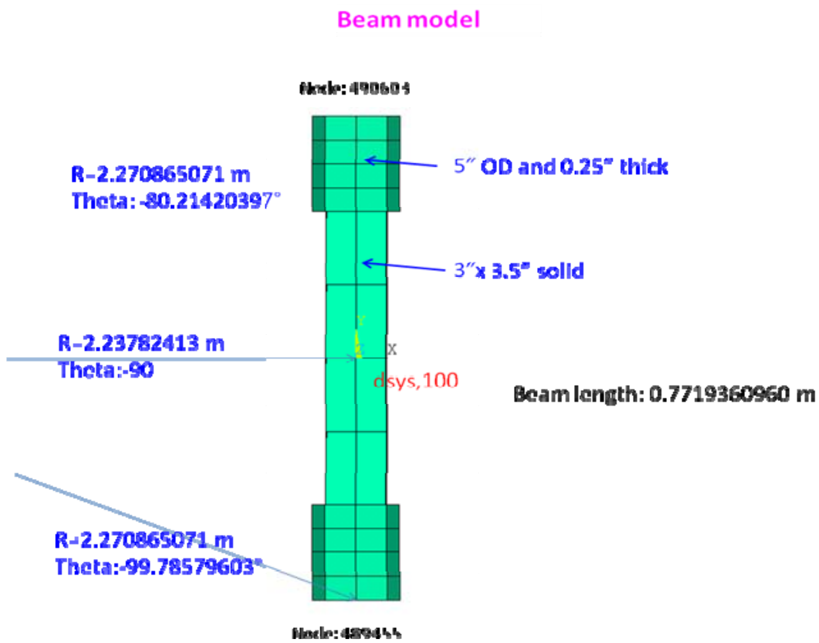


Figure 18: ring model.

Ring displacement and load (in coordinate system 100), unit in N, N-m, m

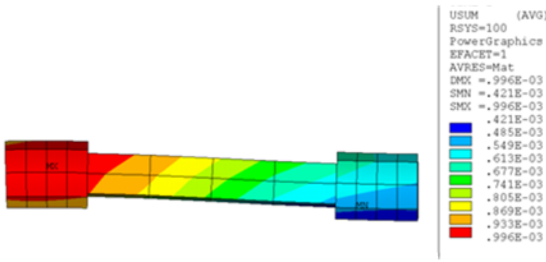
Scenario 16

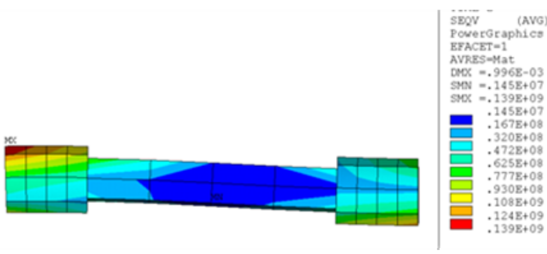
NODE	FX	FY	FZ
489455	5651.3	57809.	18745.
490603	-5651.3	-57809.	-18745.

NODE	MX	MY	MZ
489455	-6595.8	-363.37	2193.1
490603	-7874.6	363.37	2169.4

NODE	UX	UY	UZ	USUM
489455	0.27925E-03	0.38130E-03	-0.16881E-03	0.50186E-03
490603	0.23394E-03	0.32718E-03	-0.79914E-03	0.89465E-03

NODE	ROTX	ROTY	ROTZ	RSUM
489455	-0.52171E-04	-0.20034E-02	0.28184E-03	0.20239E-02
490603	-0.70086E-03	-0.15205E-02	0.27197E-03	0.16962E-02





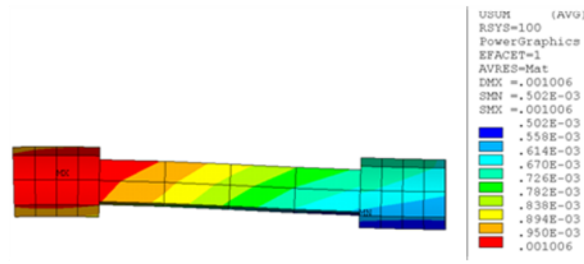
Scenario 34

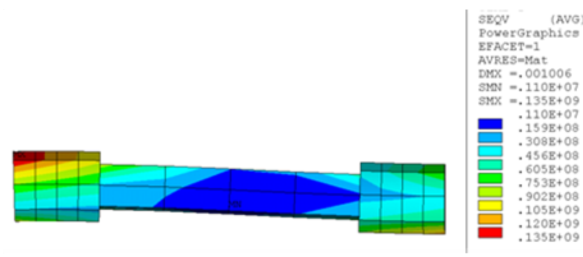
NODE	FX	FY	FZ
489455	8560.7	57547.	17742.
490603	-8560.7	-57547.	-17742.

NODE	MX	MY	MZ
489455	-6193.8	-343.14	3317.1
490603	-7502.2	343.14	3291.2

NODE	UX	UY	UZ	USUM
489455	0.32520E-03	0.45110E-03	-0.18852E-03	0.58719E-03
490603	0.20433E-03	0.39722E-03	-0.78675E-03	0.90472E-03

NODE	ROTX	ROTY	ROTZ	RSUM
489455	-0.22388E-04	-0.19983E-02	0.35719E-03	0.20301E-02
490603	-0.68609E-03	-0.15422E-02	0.34640E-03	0.17231E-02





Ring displacement and load (in coordinate system 100), unit in N, N-m, m

Scenario 37

NODE	FX	FY	FZ
489455	8022.0	57585.	18152.
490603	-8022.0	-57585.	-18152.

NODE	MX	MY	MZ
489455	-6955.3	-351.18	3108.8
490603	-7656.6	351.18	3083.6

NODE	UX	UY	UZ	USUM
489455	0.31111E-03	0.47231E-03	-0.18083E-03	0.59378E-03
490603	0.21580E-03	0.41840E-03	-0.79274E-03	0.92201E-03

NODE	ROTX	ROTY	ROTZ	RSUM
489455	-0.32526E-04	-0.20017E-02	0.35828E-03	0.20338E-02
490603	-0.69263E-03	-0.15950E-02	0.34778E-03	0.17196E-02

Scenario 40

NODE	FX	FY	FZ
489455	7452.3	57631.	18483.
490603	-7452.3	-57631.	-18483.

NODE	MX	MY	MZ
489455	-6486.5	-357.77	2888.7
490603	-7761.4	357.77	2864.1

NODE	UX	UY	UZ	USUM
489455	0.28831E-03	0.47580E-03	-0.17465E-03	0.58862E-03
490603	0.22473E-03	0.42165E-03	-0.79753E-03	0.92878E-03

NODE	ROTX	ROTY	ROTZ	RSUM
489455	-0.41041E-04	-0.20043E-02	0.35106E-03	0.20353E-02
490603	-0.69788E-03	-0.15288E-02	0.34080E-03	0.17148E-02

Scenario 73

NODE	FX	FY	FZ
489455	6559.2	57712	18984.
490603	-6559.2	-57712	-18984.

NODE	MX	MY	MZ
489455	-6684.0	-367.89	2543.6
490603	-7970.6	367.89	2519.8

NODE	UX	UY	UZ	USUM
489455	0.28994E-03	0.42718E-03	-0.16800E-03	0.54231E-03
490603	0.22912E-03	0.37315E-03	-0.80563E-03	0.91693E-03

NODE	ROTX	ROTY	ROTZ	RSUM
489455	-0.53329E-04	-0.20085E-02	0.31580E-03	0.20339E-02
490603	-0.70598E-03	-0.15198E-02	0.30577E-03	0.17033E-02

Scenario 76

NODE	FX	FY	FZ
489455	7332.3	57626.	19150.
490603	-7332.3	-57626.	-19150

NODE	MX	MY	MZ
489455	-6745.8	-371.08	2842.1
490603	-8036.8	371.08	2818.0

NODE	UX	UY	UZ	USUM
489455	0.29902E-03	0.47007E-03	-0.16366E-03	0.58066E-03
490603	0.22847E-03	0.41612E-03	-0.80972E-03	0.93813E-03

NODE	ROTX	ROTY	ROTZ	RSUM
489455	-0.54465E-04	-0.20115E-02	0.34646E-03	0.20418E-02
490603	-0.70933E-03	-0.15183E-02	0.33643E-03	0.17083E-02

Ring displacement and load (in coordinate system 100), unit in N, N-m, m

Scenario 79

NODE	FX	FY	FZ
489455	9081.4	57951	18068
490603	-9081.4	-57951.	-18068

NODE	MX	MY	MZ
489455	-6302.6	-335.12	3515.3
490603	-7644.5	335.12	3495.0

NODE	UX	UY	UZ	USUM
489455	0.19046E-03	0.12454E-02	-0.20758E-03	0.12769E-02
490603	0.32047E-03	0.11912E-02	-0.82278E-03	0.14828E-02

NODE	ROTX	ROTY	ROTZ	RSUM
489455	-0.12601E-04	-0.20282E-02	0.71193E-03	0.21496E-02
490603	-0.69334E-03	-0.15629E-02	0.70349E-03	0.18658E-02

envelope

NODE	FX	FY	FZ
489455	9081.4	57951	19150
490603	-9081.4	-57951	-19150

NODE	MX	MY	MZ
489455	-6745.8	-371.08	3515.3
490603	-8036.8	371.08	3495.0

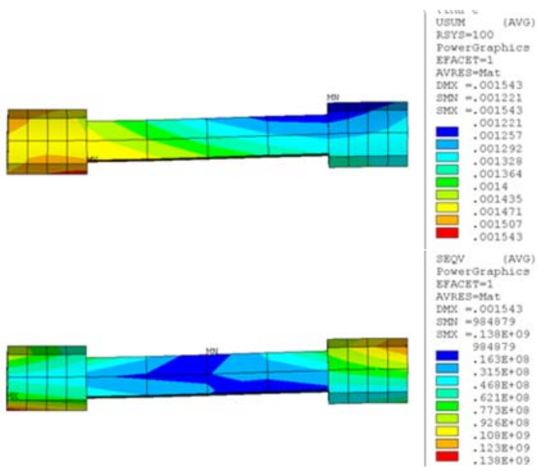


Figure 19: ring displacement and load.

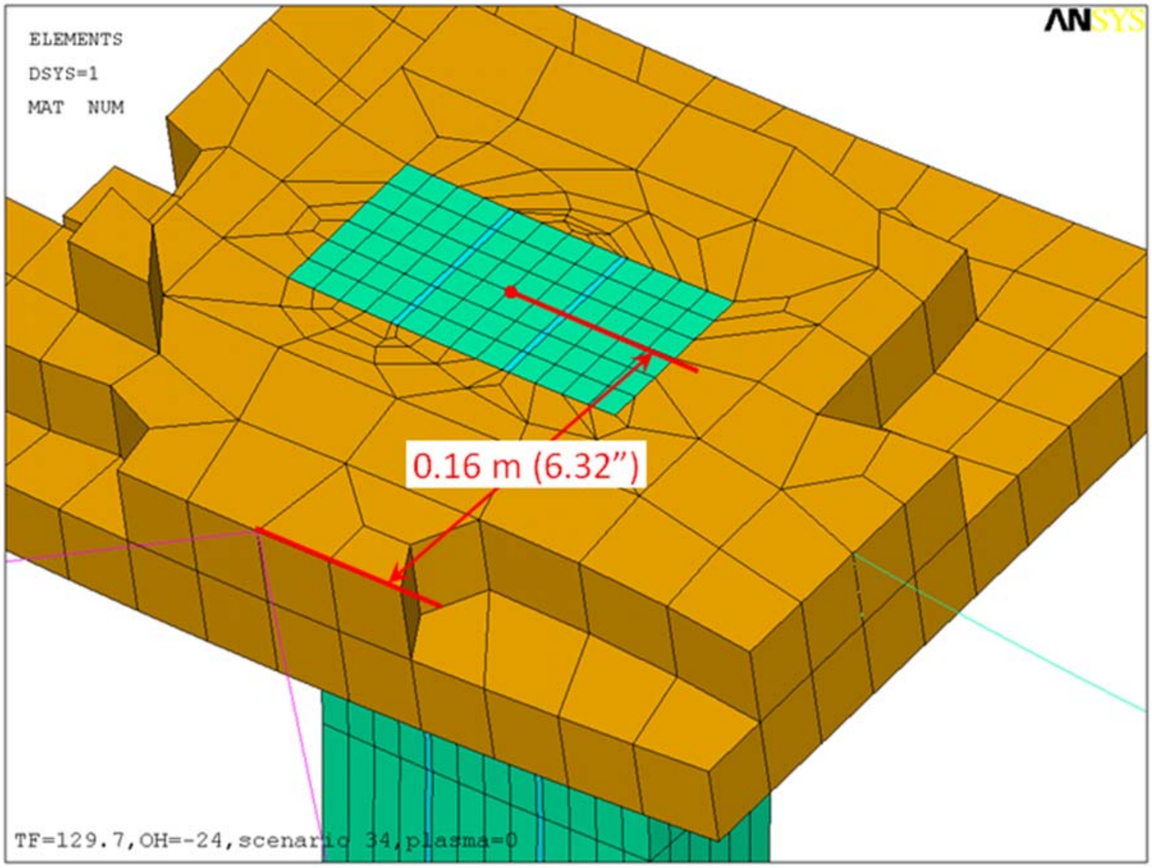
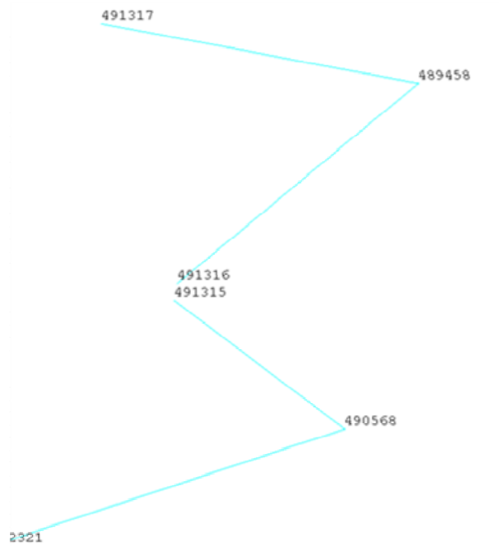


Figure 20: The distance between intersection of tie bars and the coil center.



THE FOLLOWING DEGREE OF FREEDOM RESULTS ARE IN THE GLOBAL COORDINATE SYSTEM

NODE	UX	UY	UZ
489458	0.22279E-03	0.24685E-03	-0.68286E-03
490568	0.41354E-03	0.16376E-03	-0.64356E-03
491315	0.13733E-03	-0.92968E-04	0.14817E-04
491316	0.14017E-03	-0.89517E-04	0.15242E-04
491317	0.11929E-03	-0.92183E-04	0.33916E-04
512321	0.19362E-03	-0.10211E-03	0.21742E-04

THE FOLLOWING X,Y,Z SOLUTIONS ARE IN THE GLOBAL COORDINATE SYSTEM

NODE	FX	FY	FZ
489458	11262.	-0.12359E-06	-4160.5
490568	-51001.	-0.10931E-06	-4132.6
491315	-41137.	62993.	-10977.
491316	58127.	88459.	15508.
491317	-69389.	35133.	-11348.
512321	92138.	46322.	15110.

NODE	UX	UY	UZ	X	Y	Z	X+Ux	Y+Uy	Z+Uz			bar length (m)	K (N/m)	K (lbs/in)	delta L (in)
489458	2.23E-04	2.47E-04	-6.83E-04	2.09E+00	5.61E-01	1.11E+00	2.09E+00	5.61E-01	1.11E+00						
491316	1.40E-04	-8.95E-05	1.52E-05	1.74E+00	2.90E-02	1.02E+00	1.74E+00	2.89E-02	1.02E+00	4.15E-01	0.643885	0.643662	481313391	2753832	0.00875
491317	1.19E-04	-9.22E-05	3.39E-05	1.52E+00	8.50E-01	1.02E+00	1.52E+00	8.50E-01	1.02E+00	4.18E-01	0.646145	0.646309	-4.82E+08	-2755917	-0.00642
490568	4.14E-04	1.64E-04	-6.44E-04	2.09E+00	-5.61E-01	1.11E+00	2.09E+00	-5.61E-01	1.11E+00						
491315	1.37E-04	-9.30E-05	1.48E-05	1.74E+00	-2.57E-02	1.02E+00	1.74E+00	-2.58E-02	1.02E+00	4.18E-01	0.646151	0.646309	-4.82E+08	-2755309	-0.00622
512321	1.94E-04	-1.02E-04	2.17E-05	1.53E+00	-8.47E-01	1.02E+00	1.53E+00	-8.47E-01	1.02E+00	4.15E-01	0.643879	0.643662	481367635	2754142	0.008525

NODE	FX	FY	FZ	F (N)	F (lbs)
489458	11262	-1.24E+05	-4160.5		
491316	58127	88459	15508	106977.759	24097.35
491317	-69389	35133	-11348	78599.8608	17705.06
490568	-51001	-1.09E+05	-4132.6		
491315	-41137	62993	-10977	76032.0021	17126.64
512321	92138	46322	15110	104227.879	23477.92

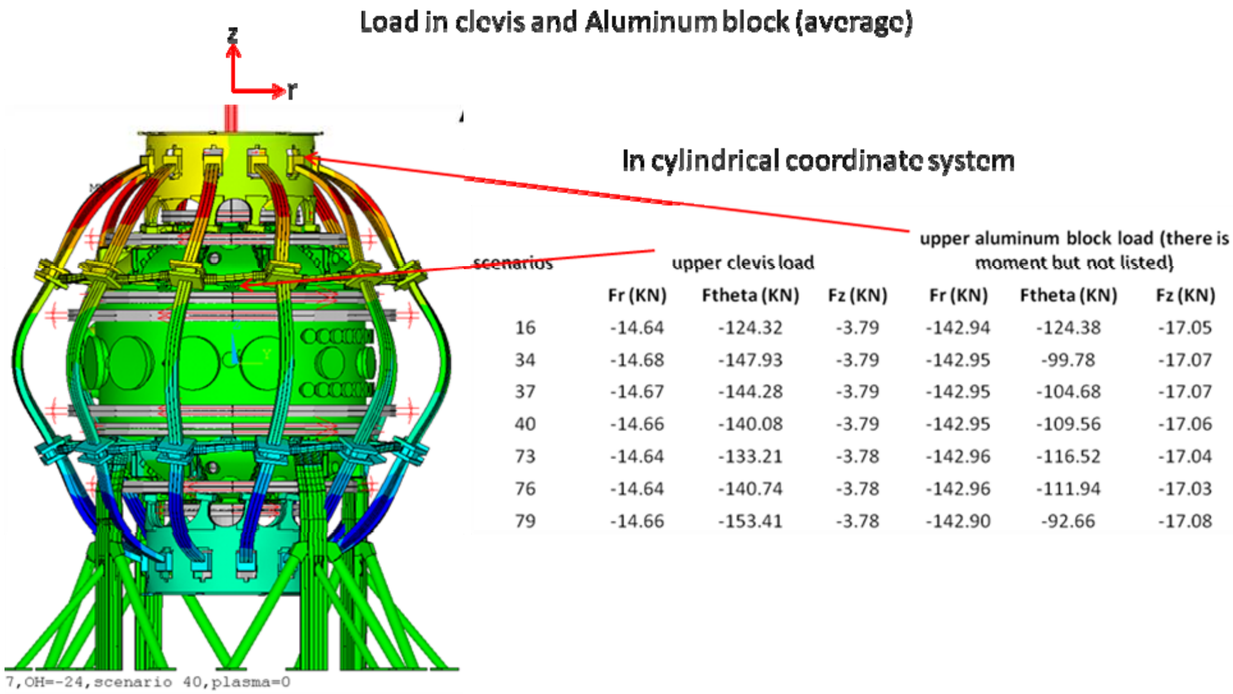
From my model
Spring rate for tension and compression are almost same
K (tension)=2,753,832 lbs/in
K (compression)=2,755,917 lbs/in

Peter Rogoff's result
K (tension)=2,774,923 lbs/in
K (compression)=4,702,195 lbs/in

Figure 21: calculation of tie bar spring constant to compare with Peter Rogoff's result.

Aluminum block loads

Figure 22 and Figure 23 list the loads in clevis and aluminum block of 7 scenarios, and in different coordinate system. Among them, scenario 16 has maximal load in aluminum block because it has higher force density in the TF outer leg section near aluminum block. Scenario 79 has maximal clevis shear load because its force density is high near PF 4 and PF 5.



scenarios	upper clevis load			upper aluminum block load (there is moment but not listed)		
	Fr (KN)	Ftheta (KN)	Fz (KN)	Fr (KN)	Ftheta (KN)	Fz (KN)
16	-14.64	-124.32	-3.79	-142.94	-124.38	-17.05
34	-14.68	-147.93	-3.79	-142.95	-99.78	-17.07
37	-14.67	-144.28	-3.79	-142.95	-104.68	-17.07
40	-14.66	-140.08	-3.79	-142.95	-109.56	-17.06
73	-14.64	-133.21	-3.78	-142.96	-116.52	-17.04
76	-14.64	-140.74	-3.78	-142.96	-111.94	-17.03
79	-14.66	-153.41	-3.78	-142.90	-92.66	-17.08

Figure 22: load in clevis and aluminum block.

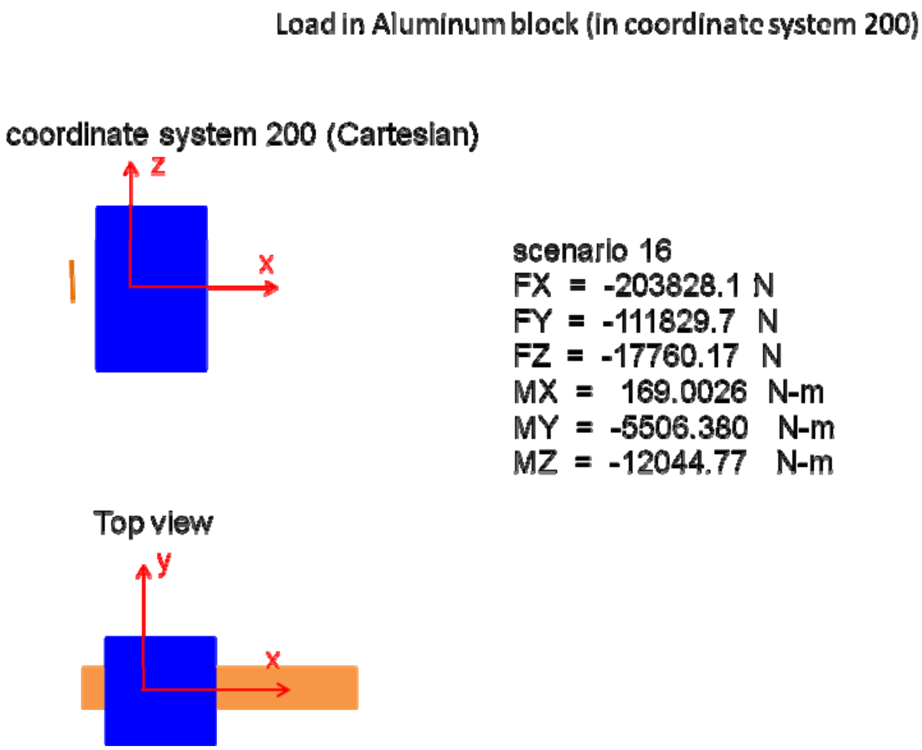


Figure 23: load in aluminum block.

Coil stress during VV bake-out

During VV bake-out (150 °C), the truss will load the TF outer coil producing a maximal stress of 151 MPa (Figure 24), which is within the allowable.

Coil stress during vessel bake-out (Pa)

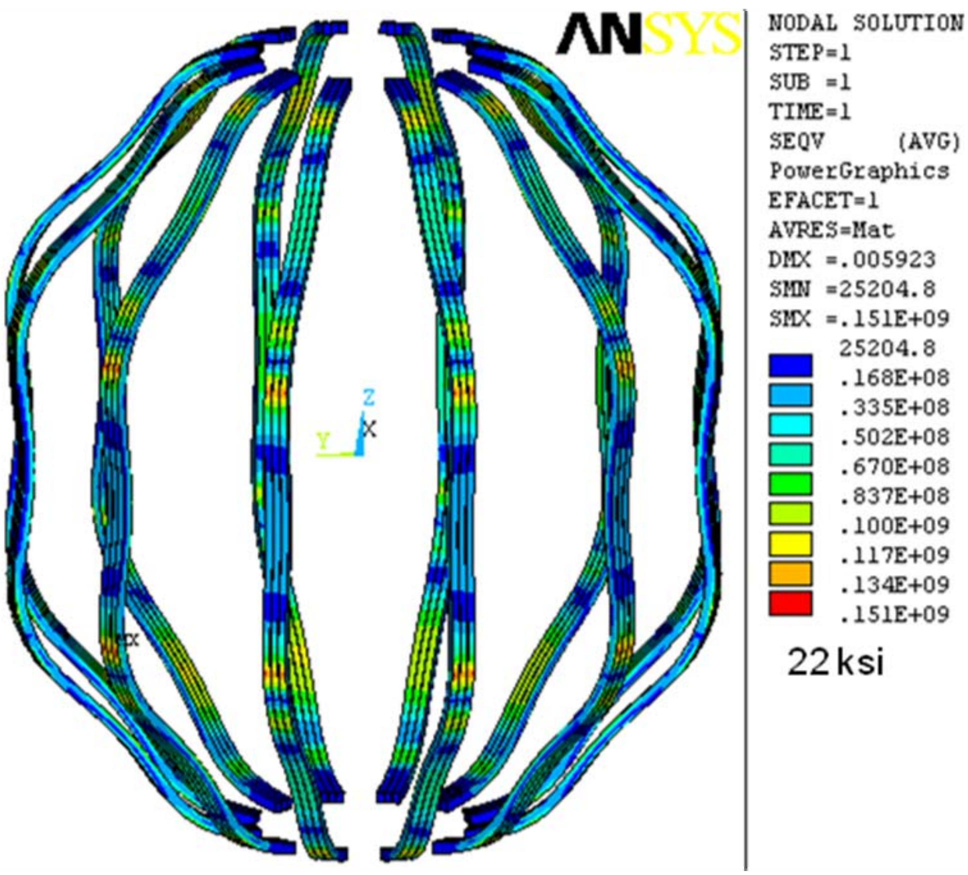
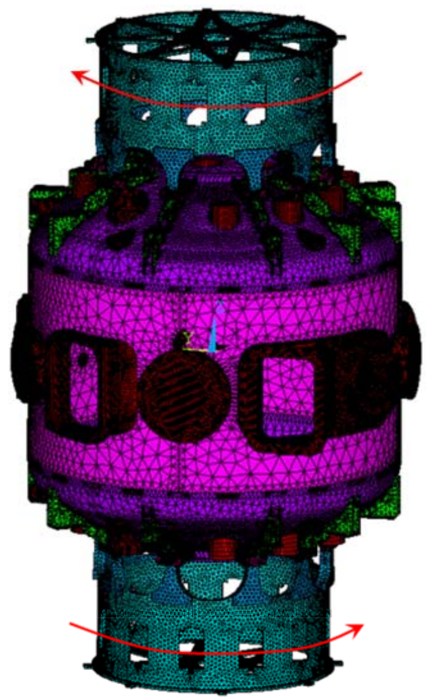


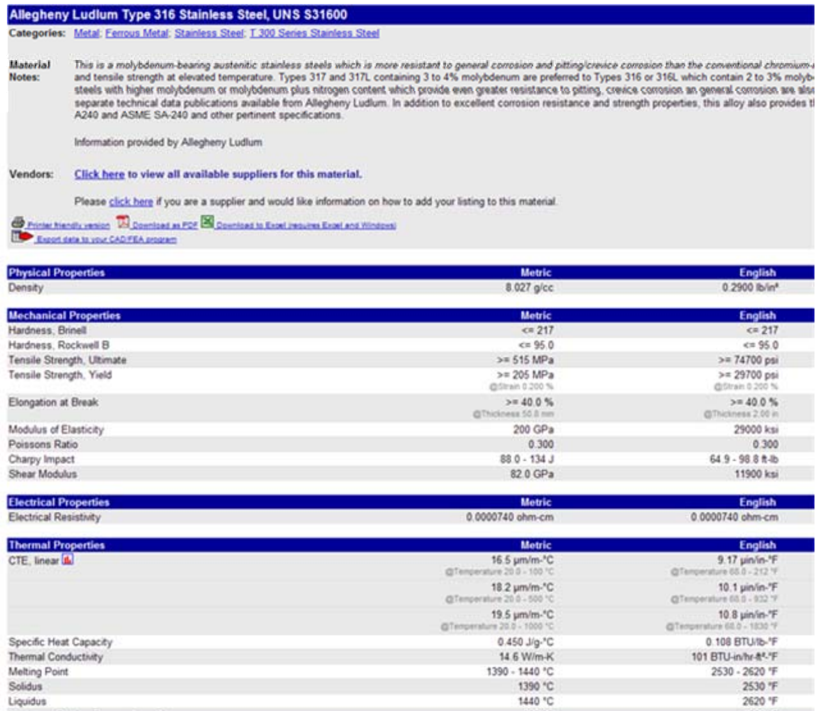
Figure 24: coil stress during vessel bake-out.

Vessel buckling analysis

To answer the chit of 9/7/2011 review, the vessel model is taken out and scenario 79 OOP load is added for a non-linear buckling analysis (Figure 25). Non-linear material property is used with yield at 310 MPa (45ksi) and arbitrary small Tang modulus of 1E8 (lower right graph in Figure 25). Young's modulus is still 200 GPa.

Vessel buckling analysis
Model (solid95 elem)





Allegheny Ludlum Type 316 Stainless Steel, UNS S31600

Categories: Metal; Ferrous Metal; Stainless Steel; T 300 Series Stainless Steel

Material Notes: *This is a molybdenum-bearing austenitic stainless steels which is more resistant to general corrosion and pitting/crevice corrosion than the conventional chromium-* and tensile strength at elevated temperature. Types 317 and 317L containing 3 to 4% molybdenum are preferred to Types 316 or 316L which contain 2 to 3% molyb- steels with higher molybdenum or molybdenum plus nitrogen content which provide even greater resistance to pitting, crevice corrosion an general corrosion are als separate technical data publications available from Allegheny Ludlum. In addition to excellent corrosion resistance and strength properties, this alloy also provides t A240 and ASME SA-240 and other pertinent specifications.

Information provided by Allegheny Ludlum

Vendors: **Click here to view all available suppliers for this material.**

Please click here if you are a supplier and would like information on how to add your listing to this material.

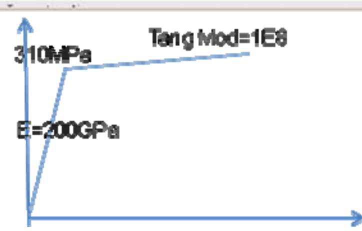
Printer friendly version Download as PDF Download to Excel (requires Excel and Windows)
Export data to your CAD/FEA program

Physical Properties	Metric	English
Density	8.027 g/cc	0.2900 lb/in³

Mechanical Properties	Metric	English
Hardness, Brinell	<= 217	<= 217
Hardness, Rockwell B	<= 95.0	<= 95.0
Tensile Strength, Ultimate	>= 515 MPa	>= 74700 psi
Tensile Strength, Yield	>= 205 MPa @Strain 0.200 %	>= 29700 psi @Strain 0.200 %
Elongation at Break	>= 40.0 % @Thickness 50.8 mm	>= 40.0 % @Thickness 2.00 in
Modulus of Elasticity	200 GPa	29000 ksi
Poissons Ratio	0.300	0.300
Charpy Impact	88.0 - 134 J	64.9 - 98.8 ft-lb
Shear Modulus	82.0 GPa	11900 ksi

Electrical Properties	Metric	English
Electrical Resistivity	0.0000740 ohm-cm	0.0000740 ohm-cm

Thermal Properties	Metric	English
CTE, linear	16.5 µm/m-°C @Temperature 20.0 - 100 °C	9.17 µin/in-°F @Temperature 68.0 - 212 °F
	18.2 µm/m-°C @Temperature 20.0 - 500 °C	10.1 µin/in-°F @Temperature 68.0 - 932 °F
	19.5 µm/m-°C @Temperature 20.0 - 1000 °C	10.8 µin/in-°F @Temperature 68.0 - 1830 °F
Specific Heat Capacity	0.450 J/g-°C	0.108 BTU/lb-°F
Thermal Conductivity	14.6 W/m-K	101 BTU-in/hr-ft²-°F
Melting Point	1390 - 1440 °C	2530 - 2620 °F
Solidus	1390 °C	2530 °F
Liquidus	1440 °C	2620 °F



Scenario 79 twisting load

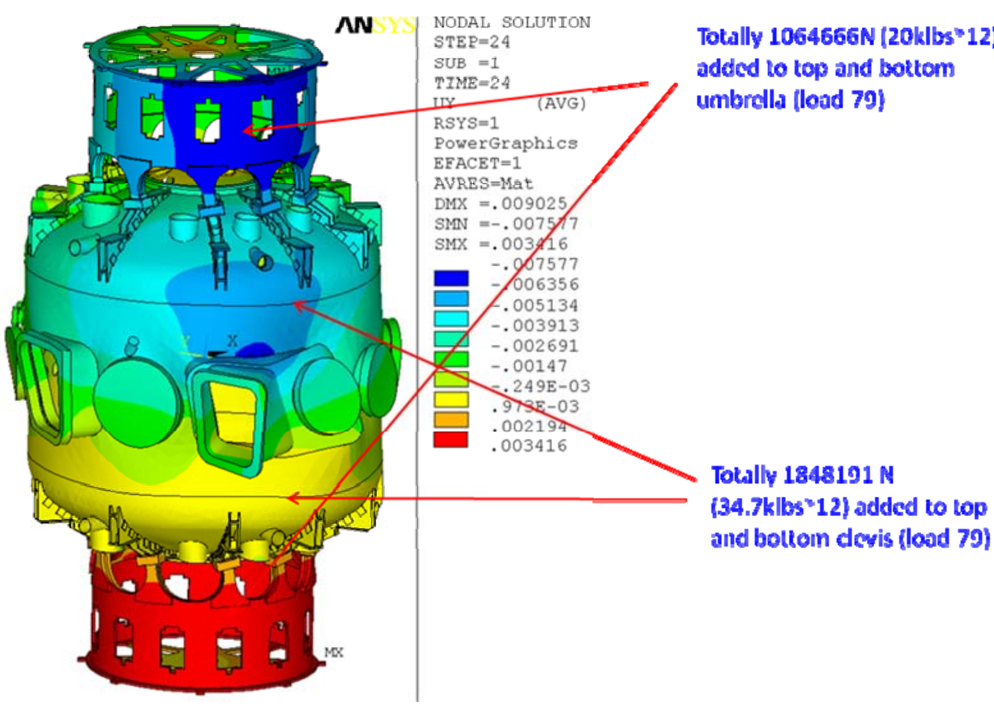


Figure 25: model for vessel buckling analysis.

Displacement Ux, Uy and Uz are plotted in Figure 26-Figure 29. Currently the model is calculated till 2.4*F_{79} and no non-linearity is found. The error message is “equivalent plastic strain increment has exceeded the specified limit value.”. According to [15], this can satisfy the FS requirement of 2. Figure 30 shows the plastic strain in load step 24 (load factor 2.4) in the vessel. A few areas in the mid-plane yield. Figure 31 and Figure 32 show the plastic strain in rib area with load factor 1 and 2 respectively.

Displacement Ux (m) in cylindrical system

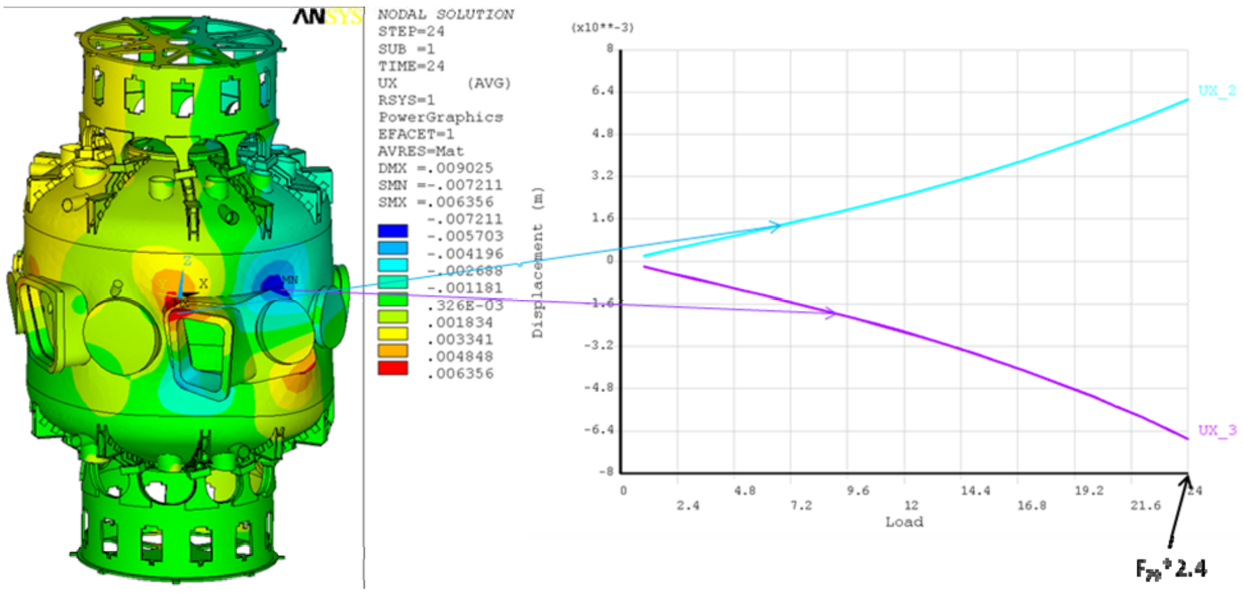


Figure 26: displacement Ux.

Displacement Uy (m) in cylindrical system

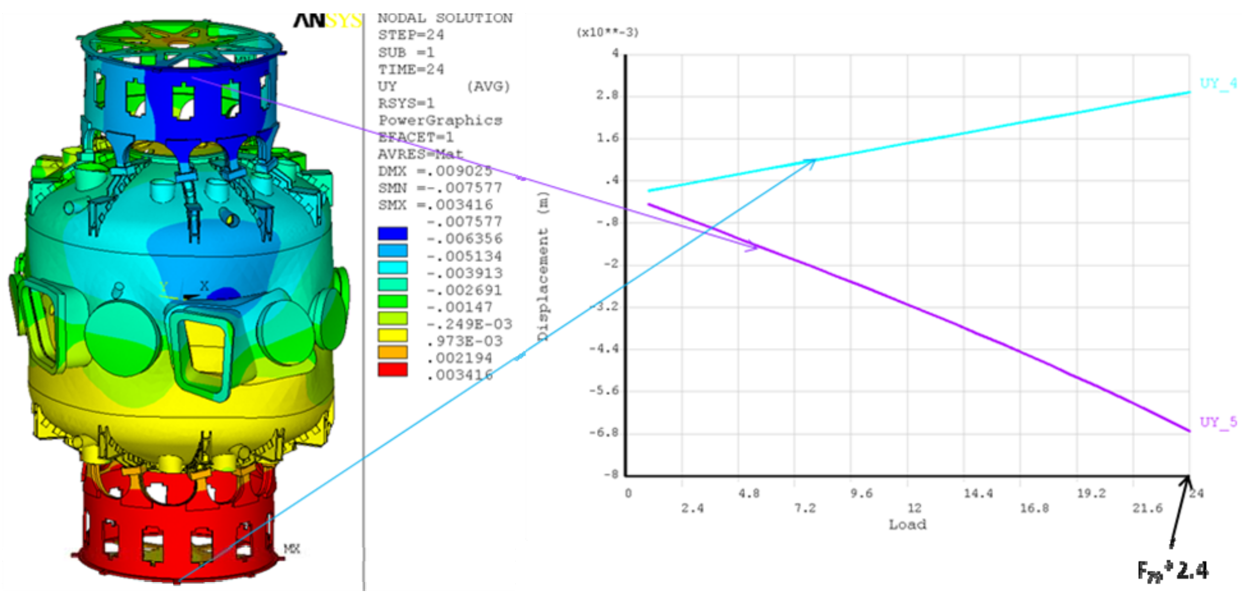


Figure 27: displacement Uy.

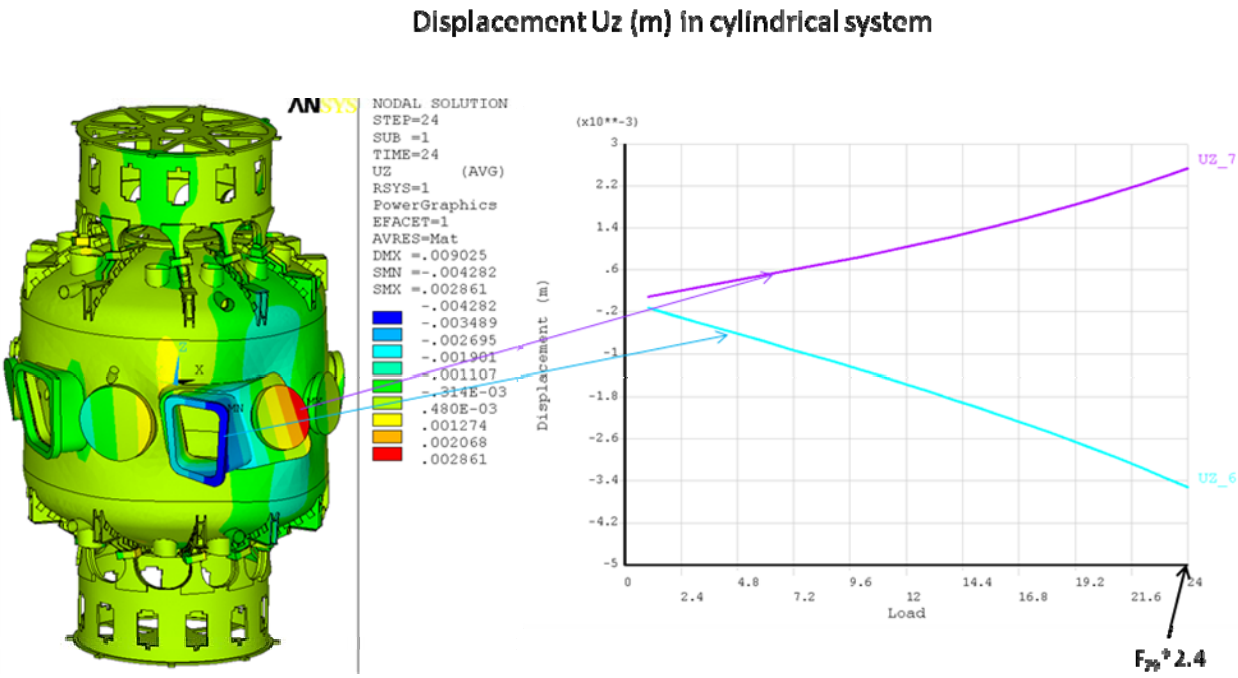
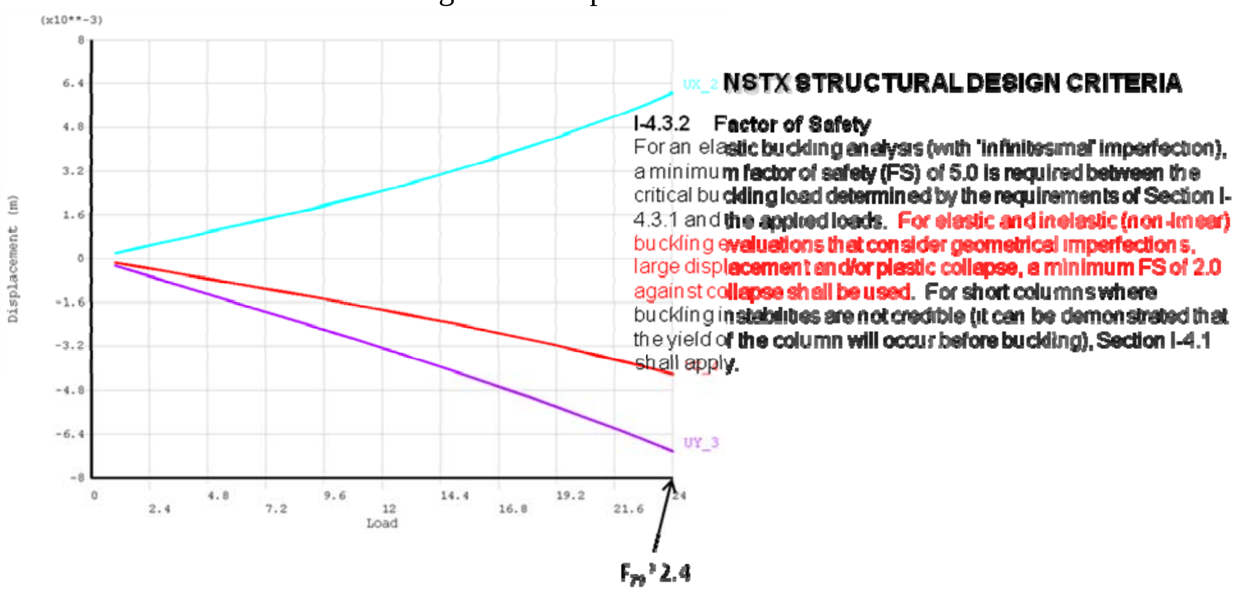


Figure 28: displacement Uz.



Calculate till 2.4 * F_{79} and still no non-linearity, means safety factor should be ~2.4, can meet the requirement.

Figure 29: displacement Ux, Uy and Uz.

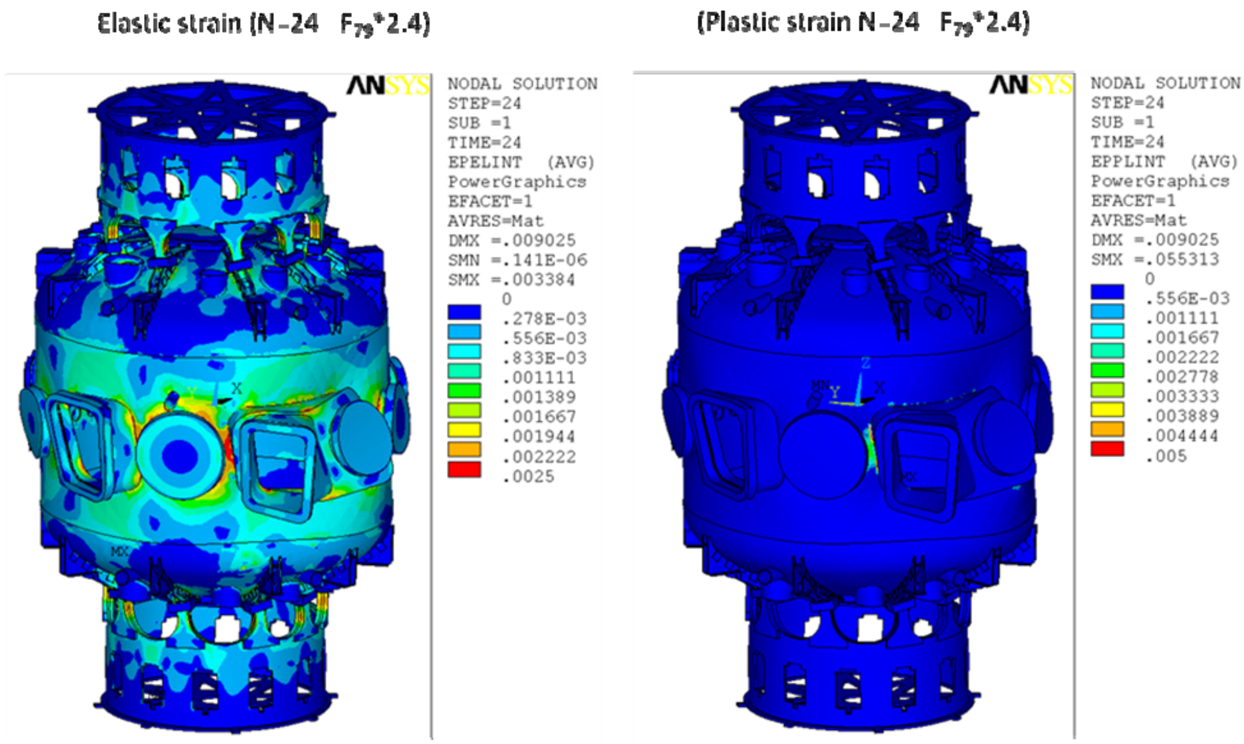


Figure 30: plot of strain.

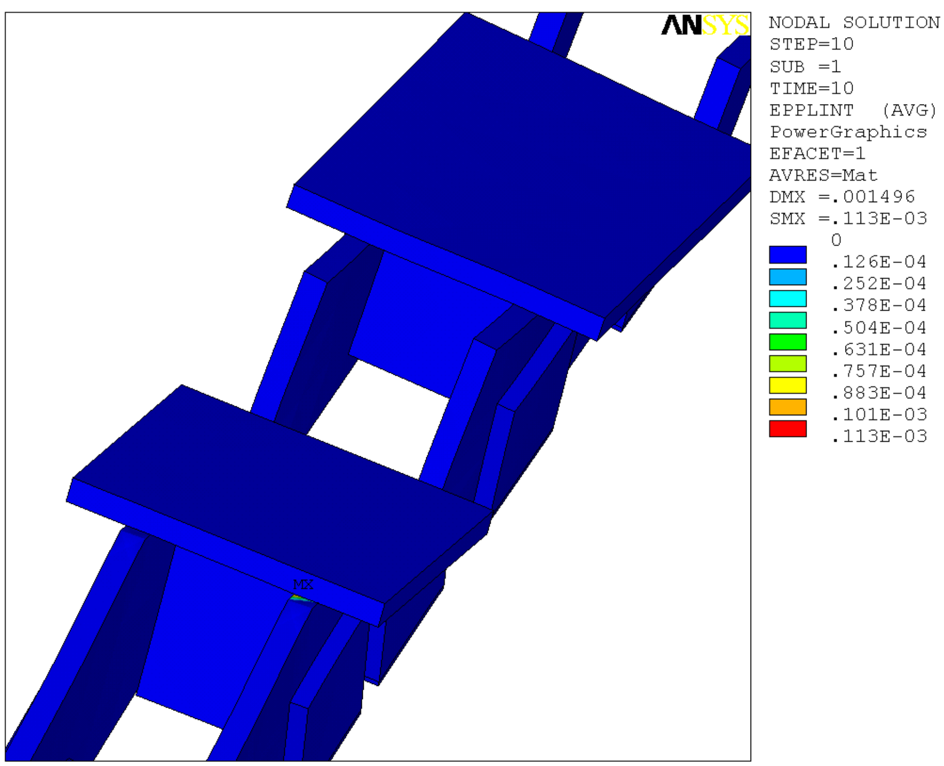


Figure 31: plastic strain in rib (1*Fy (scenario 79)).

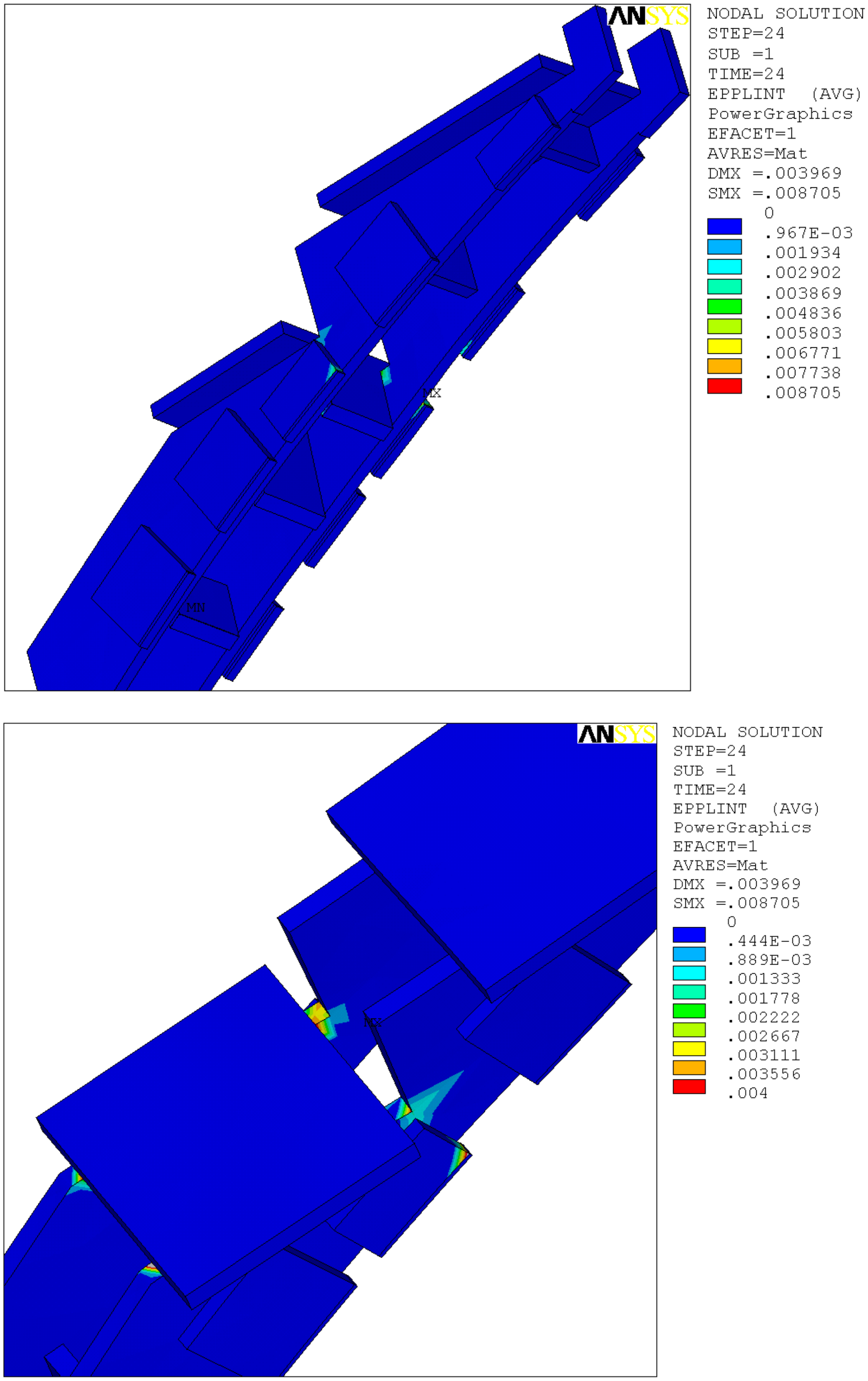


Figure 32: plastic strain in rib (2.4xFy (scenario 79)).

Appendix: Macro to create PF coils in the model

```
scenario=34

*dim,PF_scenario,array,14
*VREAD,PF_scenario(1),NSTX_CS_Upgrade_110308_PF,txt,,,,,,(scenario-1)
(E14.3,12E20.3,E16.3)


*dim,PF,array,9,12

!!up-down symmetric
!updated PF curr: 3/8/2011 (menard version)
!R (center), dR, Z (center), dZ, Turns, upper Curr,lower Curr
!(m),      (m),(m),      (m),     ,  (kA),    (kA)
! correct data
PF(1,1)=0.242083, 0.06934, 1.0604, 2.1208, 442, PF_scenario(14)*1.1,PF_scenario(14)*1.1
        ! OH
PF(1,2)=0.324434, 0.062454, 1.5906, 0.463296, 64, PF_scenario(2)*1.1,PF_scenario(13)*1.1     !
    PF1a
PF(1,3)=0.40038, 0.0336, 1.8042, 0.181167, 32, PF_scenario(3)*1.1,PF_scenario(12)*1.1
        ! PF1b
PF(1,4)=0.55052, 0.037258, 1.8136, 0.166379, 20, PF_scenario(4)*1.1,PF_scenario(11)*1.1
        ! PF1c
PF(1,5)=0.799998, 0.162712, 1.933473, 0.06797, 14, PF_scenario(5)*1.1,PF_scenario(10)*1.1    !
    PF2a
PF(1,6)=0.799998, 0.162712, 1.852600, 0.06797, 14, PF_scenario(5)*1.1,PF_scenario(10)*1.1    !
    PF2b
PF(1,7)=1.49446, 0.186436, 1.633474, 0.067970, 15, PF_scenario(6)*1.1,PF_scenario(9)*1.1     !
    PF3a
PF(1,8)=1.49446, 0.186436, 1.552600, 0.067970, 15, PF_scenario(6)*1.1,PF_scenario(9)*1.1     !
    PF3b

PF(1,9)=1.794612, 0.091542, 0.807212, 0.067970, 8, PF_scenario(7)*1.1,PF_scenario(7)*1.1     !
    PF4b
PF(1,10)=1.806473, 0.115265, 0.888086, 0.067970, 9, PF_scenario(7)*1.1,PF_scenario(7)*1.1    !
    PF4c
PF(1,11)=2.012798, 0.135331, 0.652069, 0.06858, 12, PF_scenario(8)*1.1,PF_scenario(8)*1.1    !
    PF5a
PF(1,12)=2.012798, 0.135331, 0.578002, 0.06858, 12, PF_scenario(8)*1.1,PF_scenario(8)*1.1    !
    PF5b

/title,TF=129.7,OH=%PF_scenario(14)%,scenario %scenario%,plasma=0


*do,i,1,12,1
iii=CHRVAL(i)
PF(8,%iii%)=PF(5,%iii%)*PF(6,%iii%)*1000        ! upper
PF(9,%iii%)=PF(5,%iii%)*PF(7,%iii%)*1000        ! lower
```

```
*enddo

!OH
*do,i,1,1,1
iii=CHRVAL(i)
iij=CHRVAL(i+12)
R,%iii%+15,1,PF(8,%iii%),PF(2,%iii%),PF(4,%iii%),,,      !upper
RMORE,,,1E-5
R,%iij%+15,1,PF(9,%iii%),PF(2,%iii%),PF(4,%iii%),,,      !lower
RMORE,,,1E-5
*enddo

!PF1
*do,i,2,4,1
iii=CHRVAL(i)
iij=CHRVAL(i+12)
R,%iii%+15,1,PF(8,%iii%),PF(2,%iii%),PF(4,%iii%),,,      !upper
RMORE,,,1E-5
R,%iij%+15,1,PF(9,%iii%),PF(2,%iii%),PF(4,%iii%),,,      !lower
RMORE,,,1E-5
*enddo

!PF2
*do,i,5,6,1
iii=CHRVAL(i)
iij=CHRVAL(i+12)
R,%iii%+15,1,PF(8,%iii%),PF(2,%iii%),PF(4,%iii%),,,      !upper
RMORE,,,1E-5
R,%iij%+15,1,PF(9,%iii%),PF(2,%iii%),PF(4,%iii%),,,      !lower
RMORE,,,1E-5
*enddo

! PF3
*do,i,7,8,1
iii=CHRVAL(i)
iij=CHRVAL(i+12)
R,%iii%+15,1,PF(8,%iii%),PF(2,%iii%),PF(4,%iii%),,,      !upper
RMORE,,,1E-5
R,%iij%+15,1,PF(9,%iii%),PF(2,%iii%),PF(4,%iii%),,,      !lower
RMORE,,,1E-5
*enddo

!PF4, PF5
*do,i,9,12,1
iii=CHRVAL(i)
iij=CHRVAL(i+12)
R,%iii%+15,1,PF(8,%iii%),PF(2,%iii%),PF(4,%iii%),,,      !upper
RMORE,,,1E-5
```

```
R,%iij%+15,1,PF(9,%iii%),PF(2,%iii%),PF(4,%iii%),,,      !lower
RMORE,,,1E-5
*enddo




R,31+10,2.0000,0.13000E+06,0.25400E-01,0.12700,,
RMORE,,,1E-5
R,32+10,2.0000,0.13000E+06,0.13970E-01,0.36068E-01,,
RMORE,,,1E-5
R,33+10,2.0000,0.13000E+06,0.25400E-01,0.12700,,
RMORE,,,1E-5
R,34+10,2.0000,0.13000E+06,0.13970E-01,0.36068E-01,,
RMORE,,,1E-5
R,35+10,2.0000,0.13000E+06,0.25400E-01,0.12700,,
RMORE,,,1E-5
R,36+10,2.0000,0.13000E+06,0.13970E-01,0.36068E-01,,
RMORE,,,1E-5


allsel,all
esel,s,real,,16,39
esel,r,type,,6
edele,all
allsel,all
nsle,s
cm,node_all,node
allsel,all
cmsel,u,node_all
ndel,all
allsel,all
numcmp,node
numcmp,elem

type,6
csys,1
mat,1
*do,i,1,12,1
iii=CHRVAL(i)
iij=CHRVAL(i+12)
*get,nd_mno,node,0,num,max
real,%iii%+15
N,,PF(1,%iii%),0,PF(3,%iii%)
N,,PF(1,%iii%),90,PF(3,%iii%)
N,,0,0,PF(3,%iii%)
E,(nd_mno+1),(nd_mno+2),(nd_mno+3)
```

```
real,%iij%+15
N,,PF(1,%iii%),0,-PF(3,%iii%)
N,,PF(1,%iii%),90,-PF(3,%iii%)
N,,0,0,-PF(3,%iii%)
E,(nd_mno+4),(nd_mno+5),(nd_mno+6)
*enddo

allsel,all
numcmp,node
numcmp,elem
csys,1
nrotat,all
csys,0
allsel,all
/pnum,mat,1
/num,1
eplot
```

Appendix B: macro to build a 2D model to calculate OOP load.

```
/prep7

*dim,sce,array,1
*VREAD,sce(1),scenario_num,data
(E14.3)
scenario=sce(1)

finish

FileNam='NSTX_'
FileType=scenario
FileNamAdd='_Bfield'

/filnam, %FileNam%%FileType%%FileNamAdd%

/prep7

/com, SI units
emunit,MKS
*afun,deg
pi=3.141592653589793          ! 2*ASIN(1)
muzero=4e-7*pi          ! free-space permeability
! ===========================================================
! elem
! ===========================================================
ET,1,PLANE13,0,,1                ! coil, PLANE13, AZ DOF, AXISYMMETRIC OPTION
ET,2,PLANE13,0,,1                ! air, PLANE13, AZ DOF, AXISYMMETRIC OPTION
```

```
ET,3,infin110,0,,1                                                    ! infin area, AZ
    DOF, AXISYMMETRIC OPTION

MP,MURX,1,1                    ! RELATIVE PERMEABILITY=1.0
MP,MURX,2,1
MP,MURX,3,1

! ==========================================================
! build solid model
! ==========================================================
*dim,PF_scenario,array,14
*VREAD,PF_scenario(1),NSTX_CS_Upgrade_110308_PF,txt,,,,,,(scenario-1)
(E14.3,12E20.3,E16.3)


*dim,PF,array,9,12

!!up-down symmetric
!updated PF curr: 3/8/2011 (menard version)
!R (center), dR, Z (center), dZ, Turns, upper Curr,lower Curr
!(m),      (m),(m),      (m),     ,  (kA),   (kA)
! correct data
PF(1,1)=0.242083, 0.06934, 1.0604, 2.1208, 442, PF_scenario(14)*1.1,PF_scenario(14)*1.1
        ! OH
PF(1,2)=0.324434, 0.062454, 1.5906, 0.463296, 64, PF_scenario(2)*1.1,PF_scenario(13)*1.1     !
    PF1a
PF(1,3)=0.40038, 0.0336, 1.8042, 0.181167, 32, PF_scenario(3)*1.1,PF_scenario(12)*1.1
        ! PF1b
PF(1,4)=0.55052, 0.037258, 1.8136, 0.166379, 20, PF_scenario(4)*1.1,PF_scenario(11)*1.1
        ! PF1c
PF(1,5)=0.799998, 0.162712, 1.933473, 0.06797, 14, PF_scenario(5)*1.1,PF_scenario(10)*1.1   !
    PF2a
PF(1,6)=0.799998, 0.162712, 1.852600, 0.06797, 14, PF_scenario(5)*1.1,PF_scenario(10)*1.1   !
    PF2b
PF(1,7)=1.49446, 0.186436, 1.633474, 0.067970, 15, PF_scenario(6)*1.1,PF_scenario(9)*1.1     !
    PF3a
PF(1,8)=1.49446, 0.186436, 1.552600, 0.067970, 15, PF_scenario(6)*1.1,PF_scenario(9)*1.1     !
    PF3b

PF(1,9)=1.794612, 0.091542, 0.807212, 0.067970, 8, PF_scenario(7)*1.1,PF_scenario(7)*1.1     !
    PF4b
PF(1,10)=1.806473, 0.115265, 0.888086, 0.067970, 9, PF_scenario(7)*1.1,PF_scenario(7)*1.1   !
    PF4c
PF(1,11)=2.012798, 0.135331, 0.652069, 0.06858, 12, PF_scenario(8)*1.1,PF_scenario(8)*1.1   !
    PF5a
PF(1,12)=2.012798, 0.135331, 0.578002, 0.06858, 12, PF_scenario(8)*1.1,PF_scenario(8)*1.1   !
    PF5b
```

```
/title,TF=129.7,OH=%PF_scenario(14)%,scenario %scenario%,plasma=0

*do,i,1,12,1
iii=CHRVAL(i)
PF(8,%iii%)=PF(5,%iii%)*PF(6,%iii%)*1000         ! upper
PF(9,%iii%)=PF(5,%iii%)*PF(7,%iii%)*1000         ! lower
*enddo


! coil dimentions
csys,0
*do,i,1,12,1
  rect,PF(1,i)-PF(2,i)/2,PF(1,i)+PF(2,i)/2,PF(3,i)-PF(4,i)/2,PF(3,i)+PF(4,i)/2
  rect,PF(1,i)-PF(2,i)/2,PF(1,i)+PF(2,i)/2,-(PF(3,i)+PF(4,i)/2),-(PF(3,i)-PF(4,i)/2)
*enddo

csys,0
allsel,all
*get,k_str,kp,,count
*get,l_str,line,,count
l_str=l_str+1
k_str=k_str+1
k,k_str,0,-2.5907
k,k_str+1,0,2.5907
/input,TF_coil_center,inp
*get,k_end,kp,,count

csys,0
allsel,all
*dim,TF_cent,array,(k_end-k_str-1),2
*dim,TF_FOOP,array,127
*do,i,1,(k_end-k_str-1),1
  TF_cent(i,1)=kx(k_str+1+i)
  TF_cent(i,2)=ky(k_str+1+i)
*enddo


*do,i,k_str,k_end-1,1
  l,i,i+1
*enddo
  l,k_end,k_str
*get,l_end,line,,count

allsel,all
lsel,s,line,,l_str,l_end
al,all

r_inf=8
```

```
cyl4,0,0,0,-90,r_inf/2,90,0
cyl4,0,0,0,-90,r_inf,90,0
asel,all
aovlap,all
allsel,all
nummrg,KP,1e-4
numcmp,all



allsel,all
asel,s,area,,26,27
aatt,2,,2

allsel,all
asel,s,area,,1,24
aatt,1,,1

allsel,all
asel,s,area,,25
aatt,3,,3

allsel,all
/pnum,mat,1
/num,1
aplot

! ==========================================================
! mesh
! ==========================================================
allsel,all
asel,s,mat,,1
lsla,s
lesize,all,0.025,,,,,,1
lsel,r,ndiv,,10,1000
lesize,all,0.05,,,,1,,,1
lsel,r,ndiv,,20,1000
lesize,all,0.1,,,,1,,,1
amesh,all

allsel,all
asel,s,mat,,2
lsla,s
lesize,all,0.05,,,,,,1
lsel,r,ndiv,,20,1000
lesize,all,0.1,,,,1,,,1
```

```
amesh,all

allsel,all
asel,s,mat,,3
lsla,s
lsel,r,loc,x,0
lesize,all,,,1,,,,,1
allsel,all
amesh,all


allsel,all
nummrg,node,1e-4
numcmp,all

! ==========================================================
! BCs
! ==========================================================
/pbf,js,,2
/pbc,all,,1



*do,i,1,12,1
  allsel,all
  lsel,s,loc,x,PF(1,i)-PF(2,i)/2,PF(1,i)+PF(2,i)/2
  lsel,r,loc,y,PF(3,i)-PF(4,i)/2,PF(3,i)+PF(4,i)/2
  asll,s,1
  esla,s
  bfe,all,js,1,0,0,(PF(8,i)/PF(2,i)/PF(4,i))
*enddo

*do,i,1,12,1
  allsel,all
  lsel,s,loc,x,PF(1,i)-PF(2,i)/2,PF(1,i)+PF(2,i)/2
  lsel,r,loc,y,-(PF(3,i)+PF(4,i)/2),-(PF(3,i)-PF(4,i)/2)
  asll,s,1
  esla,s
  bfe,all,js,1,0,0,(PF(9,i)/PF(2,i)/PF(4,i))
*enddo


allsel,all
csys,1
nsel,s,loc,x,r_inf
d,all,az,0
sf,all,inf
csys,0
```

```
allsel,all
/pbf,js,,0
/pbc,all,,0
eplot

save,%FileNam%%FileTYPE%%FileNamAdd%,db,,all

finish

! ============================================================
! solutions
! ============================================================
/solu
ANTYPE,STATIC

allsel,all
SOLVE

FINISH



/post1
set,last
rsys,0
csys,0

*do,i,1,127,1
  n_coil=NODE(TF_cent(i,1),TF_cent(i,2),0)
  *get,B_x,node,n_coil,B,X
  *get,B_y,node,n_coil,B,Y
  *if,i,eq,1,then
     TF_FOOP(i)=-B_x*(TF_cent(i,2)-TF_cent(i+1,2))/2*390000-B_y*(TF_cent(i+1,1)-
      TF_cent(i,1))/2*390000
  *elseif,i,eq,127
     TF_FOOP(i)=-B_x*(TF_cent(i-1,2)-TF_cent(i,2))/2*390000-B_y*(TF_cent(i,1)-TF_cent(i-
      1,1))/2*390000
  *else
    TF_FOOP(i)=-B_x*(TF_cent(i-1,2)-TF_cent(i+1,2))/2*390000-B_y*(TF_cent(i+1,1)-TF_cent(i-
      1,1))/2*390000
  *endif
*enddo

TF_FOOP_up=0
TF_FOOP_low=0
```

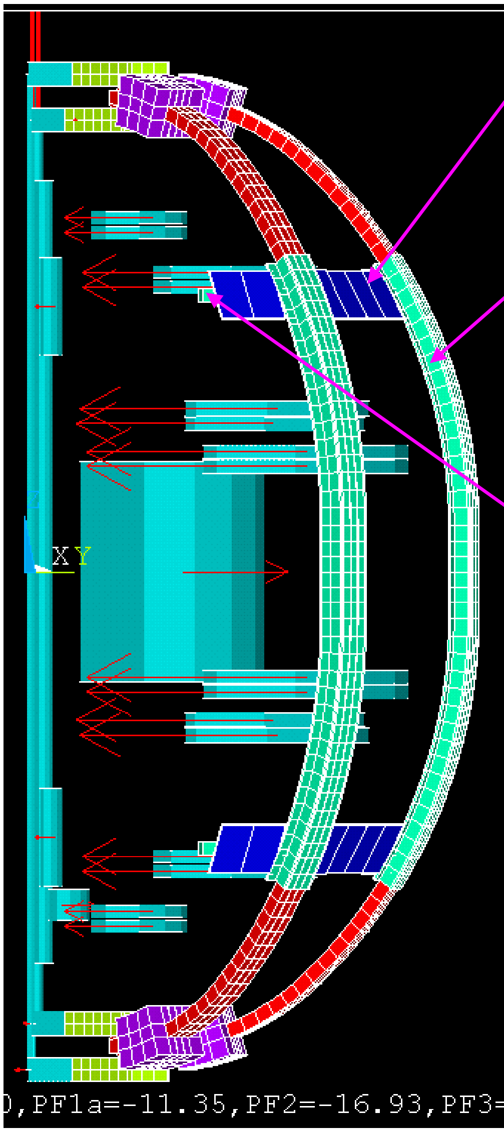
```
*do,i,1,63,1
  TF_FOOP_up=TF_FOOP_up+TF_FOOP(i)
  TF_FOOP_low=TF_FOOP_low+TF_FOOP(i+64)
*enddo


/output,TF_FOOP,data,,append
*vwrite,scenario,TF_FOOP_up/1000,TF_FOOP_low/1000,(TF_FOOP_up+TF_FOOP_low)/1000
(4E20.3)
/output

scenario=scenario+1
/output,scenario_num,data
*vwrite,scenario
(E14.3)
/output

Finish

scenario_num.data
    0.1E+01
```

Idea 1: Adding Stainless Steel Ring, Case and Tie Bars

Because the TF coil will expand upon self field, two stainless steel rings are to be added to constrain the expansion. But how to take the OOP load is still problematic. There are three ideas.

The first idea is to use tie bars linked to vacuum vessel to take both in-plane and OOP load (Figure 33). Also a stainless steel case is added to increase the stiffness of TF coil. **Error! Reference source not found.** shows the result. These analyses are done with worst case symmetric PF current. Result shows that stainless steel case is not effective because the coil is long and thin. The total force is reduced by ~20%, OOP force reduced by ~36% (from 166KN to 106KN) and vertical force increased from 11KN to 45KN. However, during vacuum vessel bake out, the tie bars will constrain the TF coils and have to be disconnected.

Figure 33: Adding Stainless Steel Cases, Rings, and Tie Bars



Stainless steel rings are added to take the in-plane force.
But how to take the out-of-plane load is still problematic:

Idea 1: adding stainless steel case to increase the stiffness of the TF coil, ring to take the in-plane expansion and tie bars linked to vacuum vessel to take the in-plane and OOP load.

Tie bars

Table 1: Calculated force on Aluminum block when adding stainless steel case, rings and tie bars

	ss case no effective			link to vacuum vessel: bar1, 2 and 3 have different orientations		
	no truss	adding case (0.5" thick, 12" wide)	adding ring (0.5x12" rect, welded)	adding bar1 (3x3" rect, pin connected)	adding bar2 (3x3" rect, pin connected)	adding bar3 (3x3" rect, pin connected)
Total end reaction force (kN)	**297**	**294**	**269**	**239**	**249**	**224**
End reaction force r (kN)	245.71	245.96	223.2	212.98	225	192.09
End reaction force theta (kN)	166.49	161.03	149.95	105.98	105.95	106.05
End reaction force z (kN)	11.956	10.3	10.155	19.366	9.2544	44.565

Idea 2: Adding Diamond Bracing to Take the OOP Load and There is No Link to the Vacuum Vessel

Upon symmetric PF current, the OOP loads from upper and lower part of the TF coil are same in value and in opposite directions. So the second idea is to use diamond truss to take the OOP load and doesn't transfer any load to vacuum vessel. Figure 34 is the model for idea 2 and Table 2 shows the result calculated with worst case symmetric PF current. The total force on Aluminum block is reduced by 17% and OOP force reduced by 39%. The total in-plane force (including Fr and Fz) increased by 7.6%.

However, since PF current is not always symmetric, it can also be asymmetric. Definition of worst case symmetric and asymmetric PF currents will be given in next section. From our analysis for asymmetric effect, the TF coils and diamond truss will have global theta rotation of 17mm (0.67") upon asymmetric PF current (Figure 35). Thus additional structure should be added to prevent global rotation upon asymmetric effect. Also, NSTX has a lot of ports and diamond bracing cannot be placed everywhere. Then further study with less diamond bracing should be carried out.

Figure 34: Adding diamond bracing to take OOP load

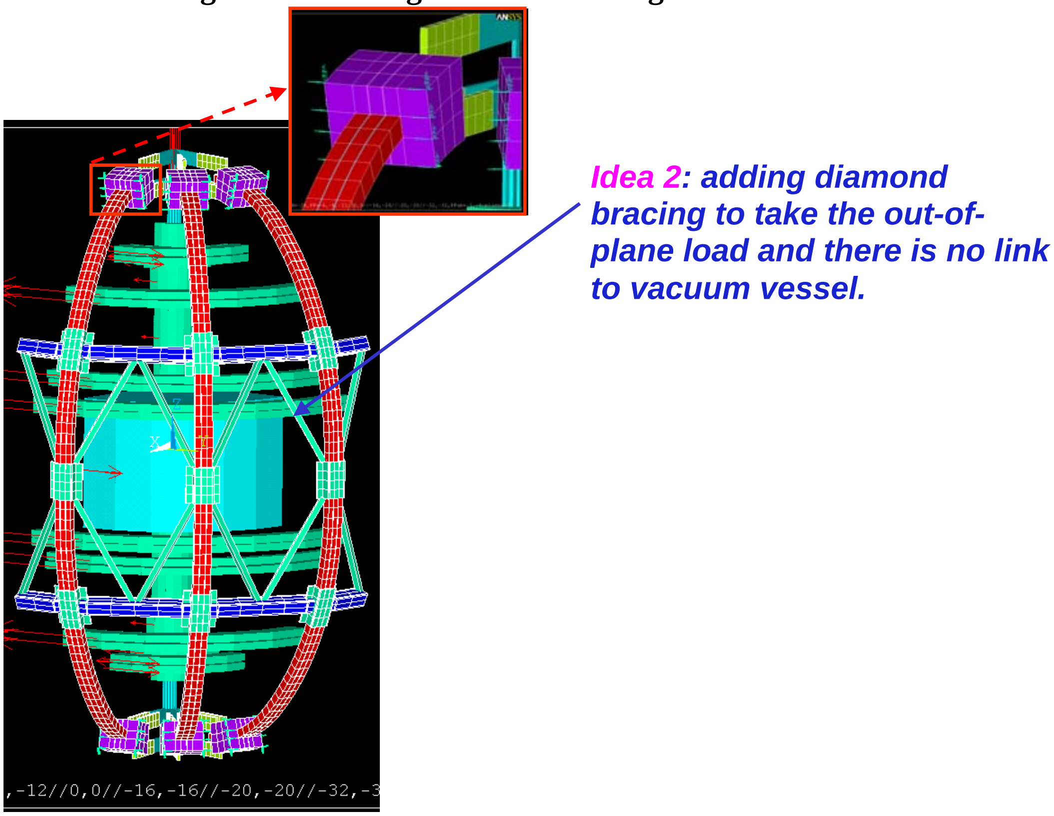
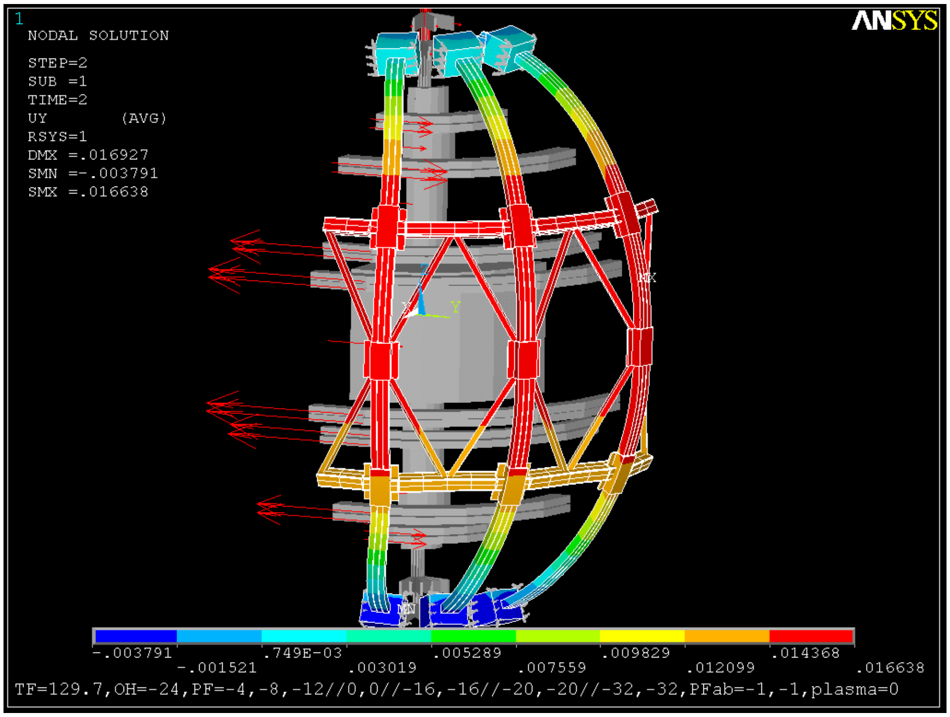


Table 2: Calculated force for adding diamond bracing

		Welded ring (hollow square tube)				Welded ring (beam: hollow rect tube) Radial: 3"	Radial: 6"	Welded ring	Pin connected ring	
	no truss	ring: 5"X5", 0.5" thick, diamond bar: 3"x3"	ring: 5"X5", 0.5" thick, diamond bar: 2"x2"	ring: 5"X5", 0.5" thick, diamond bar: 1"x1"	ring: 5"X5", 0.375" thick, diamond bar: 1.4"x1.4"	ring: 3"X6", 0.375" thick, diamond bar: 2"x2"	ring: 6"X3", 0.375" thick, diamond bar: 2"x2"	ring: 2.5"X2.5" solid, diamond bar: 2"x2"	pin connected ring: 3"x3" tie bar: 3"x3", diamond bar: 2"x2"	pin connected tie bar and diamond bar: 2"x2"
Total end reaction force (kN)	409	339	340	344	341	338	340	341	345	342
End reaction force radial (kN)	-233.8	-106	-106	-106	-107.9	-108.9	-109.4	-109.5	-107.9	-115.4
		out-of-plane force can be significantly reduced								
End reaction force theta (kN) Out-of-plane force	-313.8	-186.3	-187.9	-195.4	-191.7	-188.4	-192.5	-194.4	-199.7	-199.9
End reaction force z (kN)	-120.5	-262.3	-262.3	-262.2	-260.1	-259.1	-258.5	-258.4	-259.7	-251.7
		In-plane force increases a little (radial force decreases but z force increases a lot)								
In-plane force (KN)	263	283	283	283	282	281	281	281	281	277
Max stress in the ring (beam) (Mpa)		101	102	106	126	142	139	179	318KN (55MPa)	304KN (118MPa)
									with pin.ed ring, high stress point due to bending can be avoided	
Max axial force in the diamond bar (KN)		166.7 (29MPa)	161 (62MPa)	138 (214MPa)	151 (119MPa)	159 (62MPa)	154 (60MPa)	149 (58MPa)	147KN (57MPa)	147KN (57MPa)

Figure 35: Coil deformation upon worst case asymmetric PF currents.



Max theta displacement: 17mm (0.67")

Our mechanical engineer, D. Mangra, checked the machine carefully and provided a table listing all the available space to put diamond bracing (Table 3).

Table 3: Available space for diamond bars (Y means full diamond and numbers indicate the space for partial diamond bars, and 0 means no diamond bar)

Bay	Standard diamond bar, 1,3 upper, 2,4 lower	shorter diamond bar, 1,3 upper, 2,4 lower
A	3,4	1, 2
B	Y	
C	0	
D	0	3?
E	0	
F	0	1, 3 , 2
G	Y	
H	Y	
I	1, 3, 4	2,
J	Y	
K	3	1,
L	Y	

Since the machine has a lot of ports and full diamond bracing cannot be added everywhere, a full 360º model is built with diamond bracing added at the exact places (Figure 36). In this model, Aluminum blocks are connected to springs to simulate umbrella structure, standard (full or partial) diamonds have intersections at exactly the TF coil center to prevent coil twist, and rings are exactly at the position of existing turn buckle. The analysis is done with worst case symmetric PF currents. With pin connected rings, the maximal OOP deformation is 1.54" and non-axisymmetric (Figure 37). Coil stress is ~72.5ksi. With welded rings, maximal OOP deformation is reduced to 0.7" (Figure 8) ll non-axisymmetric and coil stress is still ~72.5ksi.

Figure 36: Full 360º model

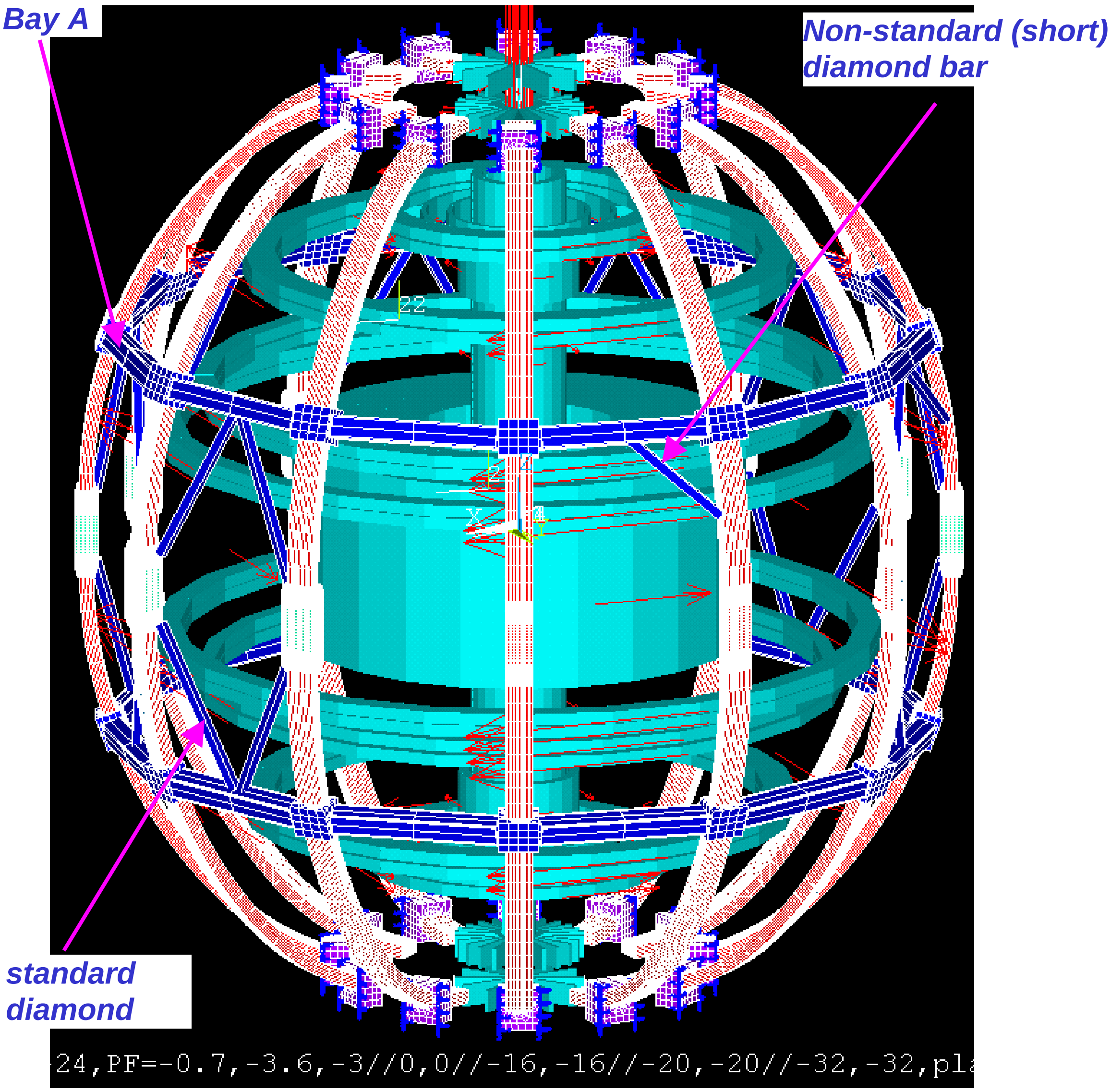


Figure 37: Coil OOP deformation and stress (with pin connected rings, diamond bracing and symmetric PF currents)

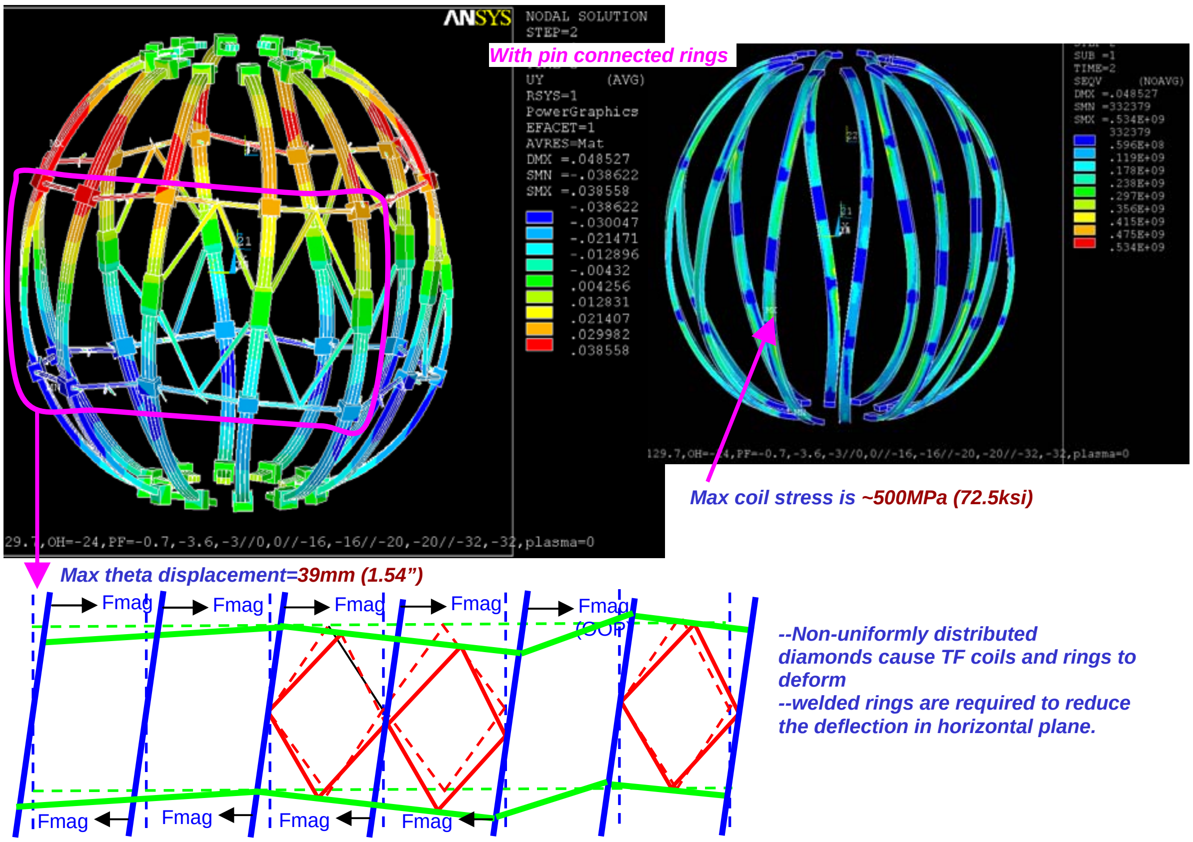
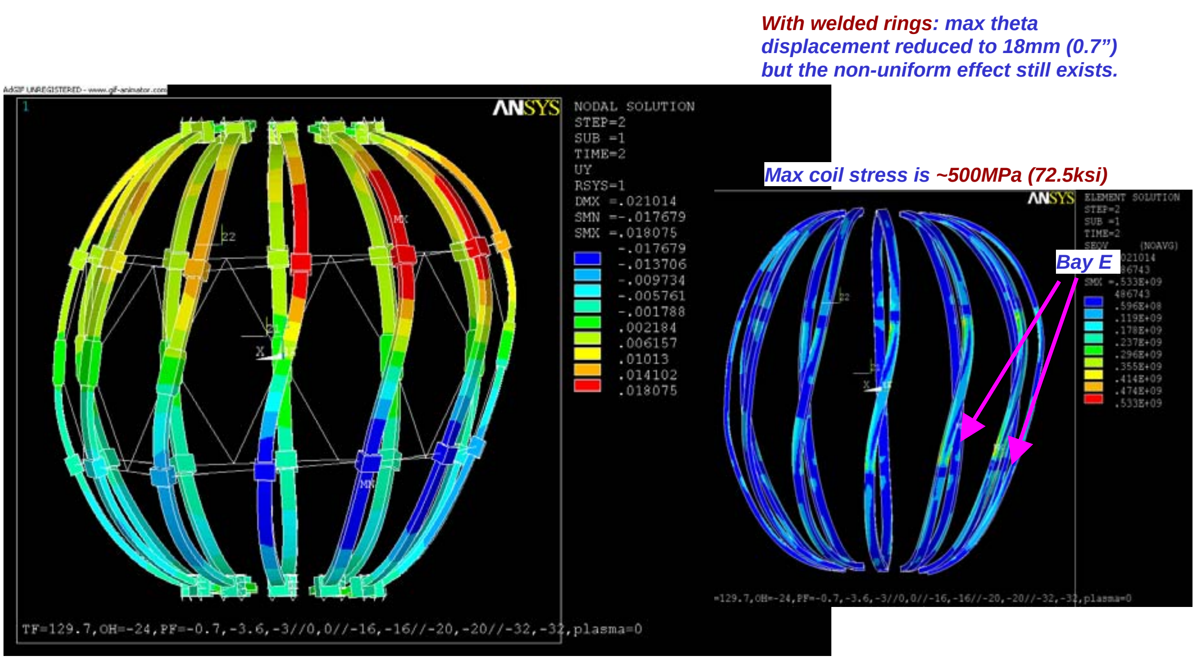


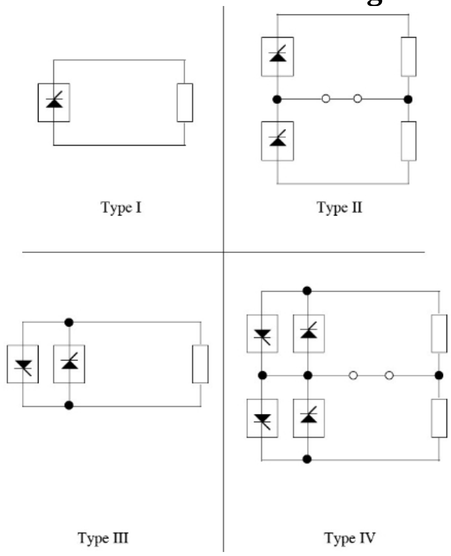
Figure 38: Coil OOP deformation and stress (with welded rings, diamond bracing and symmetric PF currents)



Definition Of Worst Case Up-Down Symmetric And Asymmetric PF Currents

Figure 39 shows the four types of PF coil connections. OH, PF4 and PF5 don't have asymmetric effect but they will increase the net load. PF1, PF2 and PF3 can have up-down asymmetric currents as shown in Table 4.

Figure 39: Four types of PF coil connections



Type I: unipolar, upper and lower coils in series (PF4, PF5)
Type II: unipolar, midpoint connection between upper and lower coils allowing difference current (PF2)
Type III: bipolar, upper and lower coils in series (OH)
Type IV: bipolar, midpoint connection between upper and lower coils allowing difference current (PF1a, PF1b, PF1c, PF3)

Table 4: Worst case up-down symmetric and asymmetric PF currents

Coil	Turns	Min Curr	Min Curr	Max Curr	Max Curr	worst case symm PF curr	worst case asym PF curr	
		(kA)	(kA-Turn)	(kA)	(kA-Turn)	(kA-turn)	(kA-turn) upper	lower
OH	508	-24.0	-12191.2	24.0	12191.2	-12191.2	-12191.2	-12191.2
PF1a	88	-0.7	-58.9	8.1	715.5	-58.9	-58.9	715.5
PF1b	20	-3.6	-71.7	4.2	84.1	-71.7	-71.7	84.1
PF1c	20	-3.1	-62.4	8.2	164.1	-62.4	-62.4	164.1
PF2a	14	0.0	0.0	20.0	280.0	0.0	0.0	280.0
PF2b	14	0.0	0.0	20.0	280.0	0.0	0.0	280.0
PF3a	15	-16.0	-240.0	8.0	120.0	-240.0	-240.0	120.0
PF3b	15	-16.0	-240.0	8.0	120.0	-240.0	-240.0	120.0
PF4b	8	-20.0	-160.0	15.0	120.0	-160.0	-160.0	-160.0
PF4c	9	-20.0	-180.0	15.0	135.0	-180.0	-180.0	-180.0
PF5a	12	-32.0	-384.0	0.0	0.0	-384.0	-384.0	-384.0
PF5b	12	-32.0	-384.0	0.0	0.0	-384.0	-384.0	-384.0

Idea 3: Adding tangential (radius) rods to take the OOP load.

To prevent the global rotation from asymmetric PF currents, P. Titus first proposed the idea of radius rod (tangential rod) (Figure 40) and they only take effect at tangential direction. Then we further think about whether we can use them to replace diamond truss.

Radius rod support structures are fixed to vacuum vessel, but they are not affected by the vessel bake out. Also no need to disconnect them during vacuum vessel bake out. They are effective on both symmetric and asymmetric PF currents.

At this time, the vacuum vessel model is available and the 360º TF coil model is further modified to integrated with the vacuum vessel model and add the radius rods and support structures (Figure 41 Because the vessel model and TF coil model are separately built and the mesh is not matched, the nodes on Aluminum block have to be coupled to the umbrella structure. But this will cause local high stress shown in Figure 45 and Figure 46. Since the double arch area on the umbrella structure has highly concentrated stress, three inch high ribs are welded to reinforce these areas. The analysis is done with both symmetric and asymmetric PF currents. The dimensions are: welded ring is 2.8"x2.8" rectangular solid, radius rods 2"x2" solid, and radius rod support structures 2"x2" solid. Figure 42 shows the photos of the intersection of the Outer TF to the umbrella structure.

Figure 40: Titus radius rod concept

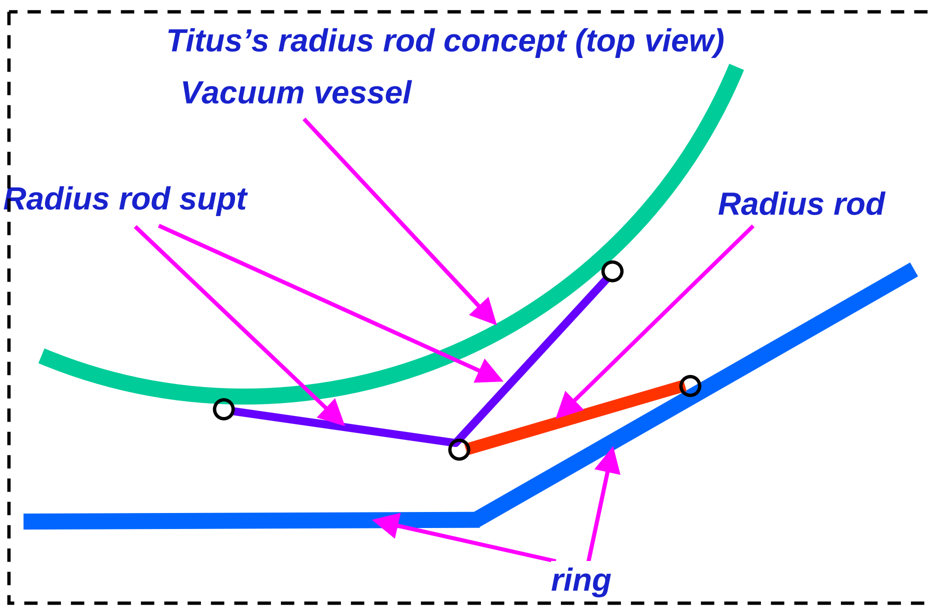


Figure 41: TF coil model integrated with vacuum vessel model and adding radius rods

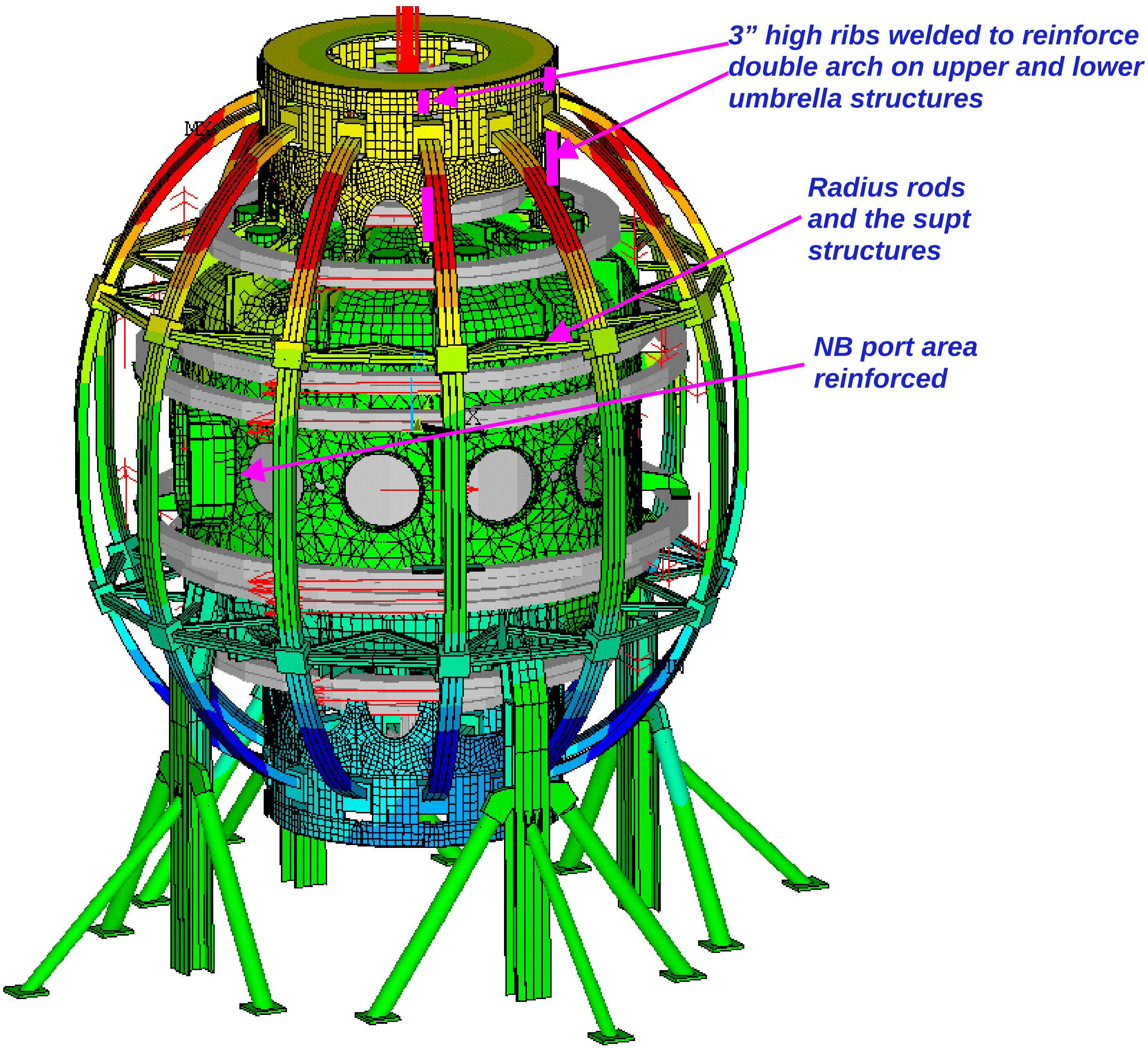
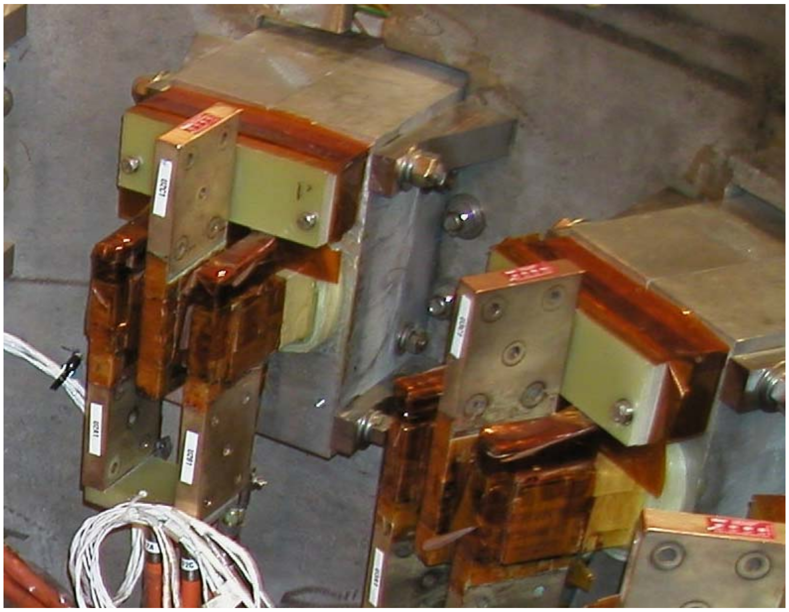


Figure 42: Detailed View of Umbrella Structure and Aluminum Block



A. View Inside the Umbrella Structure

B. View Outside the Umbrella Structure

Figure 43 shows the coil OOP deformation, maximal 6.5mm (1/4”) for symmetric PF currents, and maximal 13.2mm (0.52”) for asymmetric currents (Figure 44). shows Von Mises stress on vacuum vessel, max 46 ksi for symmetric current and 47.7 ksi for asymmetric current (Figure 46), at the Aluminum block area. It is due to the coupling of nodes on Aluminum block and umbrella structure where element discontinuity exists. At the area connected to the support structure of radius rods, the stress is ~20ksi for both symmetric and asymmetric currents. Figure 47 shows the stress at arch area, max 42ksi for symmetric and max 39.6ksi for asymmetric currents (Figure 45). Figure 49 shows the stress at the middle area of vacuum vessel, max 44.4ksi for symmetric and max 35.4ksi for asymmetric currents (Figure 50). One of the NBI ports is currently reinforced but the other not. Max stress happens at the other NBI port. So reinforcement is also recommended for the other NBI port. Figure 51 shows the coil stress, max 21.3ksi for symmetric and max 22.9ksi for asymmetric currents (Figure 52). Adding a longer stainless steel case at shown in Figure 53 may help to reduce it. Figure 54 shows the stress in the ring, max 30 ksi for symmetric and max 32.5 ksi for asymmetric current (Figure 55). For symmetric current, max load in radius rod is 18.4 klbs and min load is 4.5 klbs. For asymmetric current, max load in radius rods is 20.3 klbs and min load is 4 klbs.

Figure 43: Coil OOP deformation (m) upon Symmetric PF currents

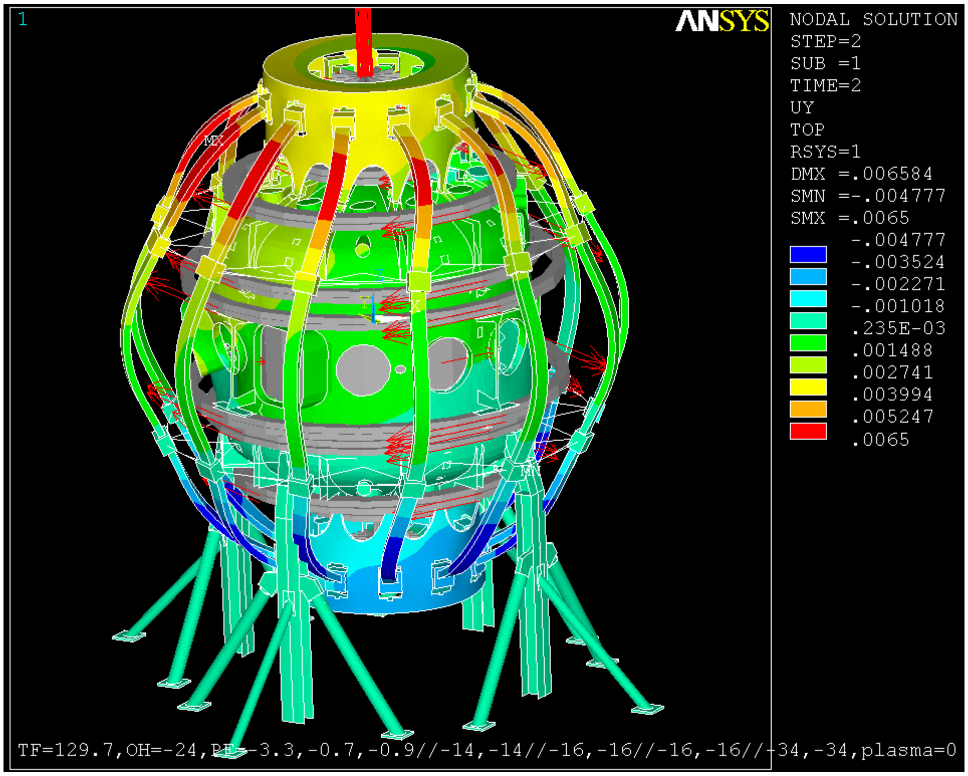


Figure 44: Coil OOP deformation (m) upon Asymmetric PF currents

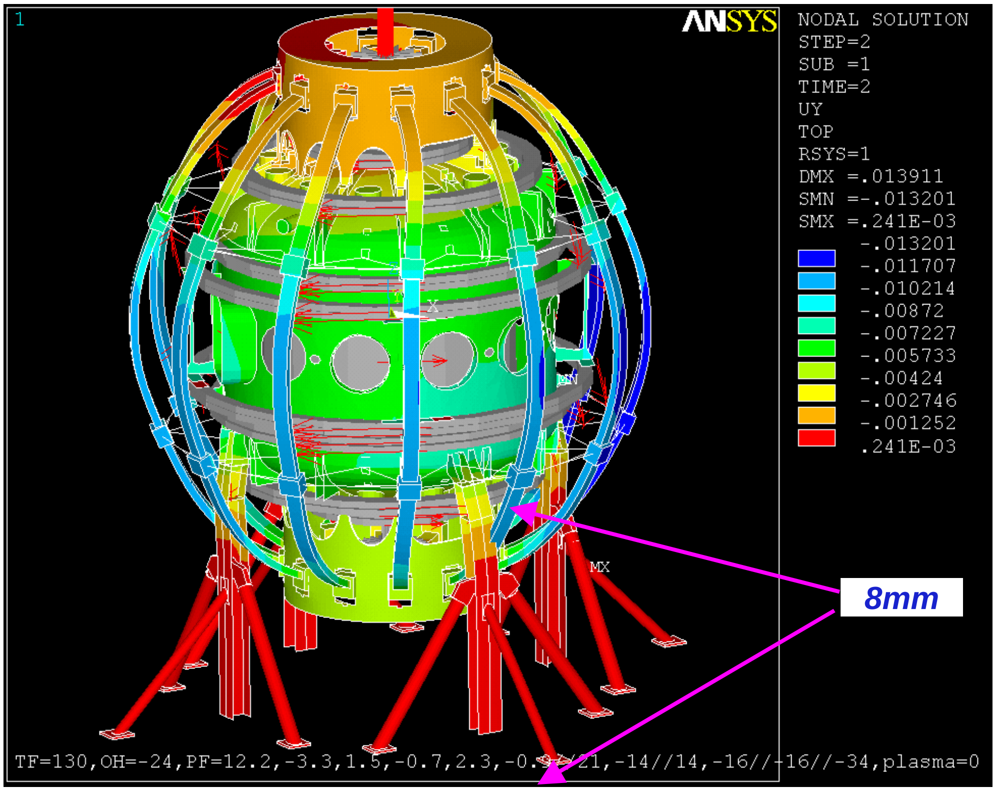


Figure 45: Vacuum vessel Von Mises stress (Pa) upon Symmetric PF currents

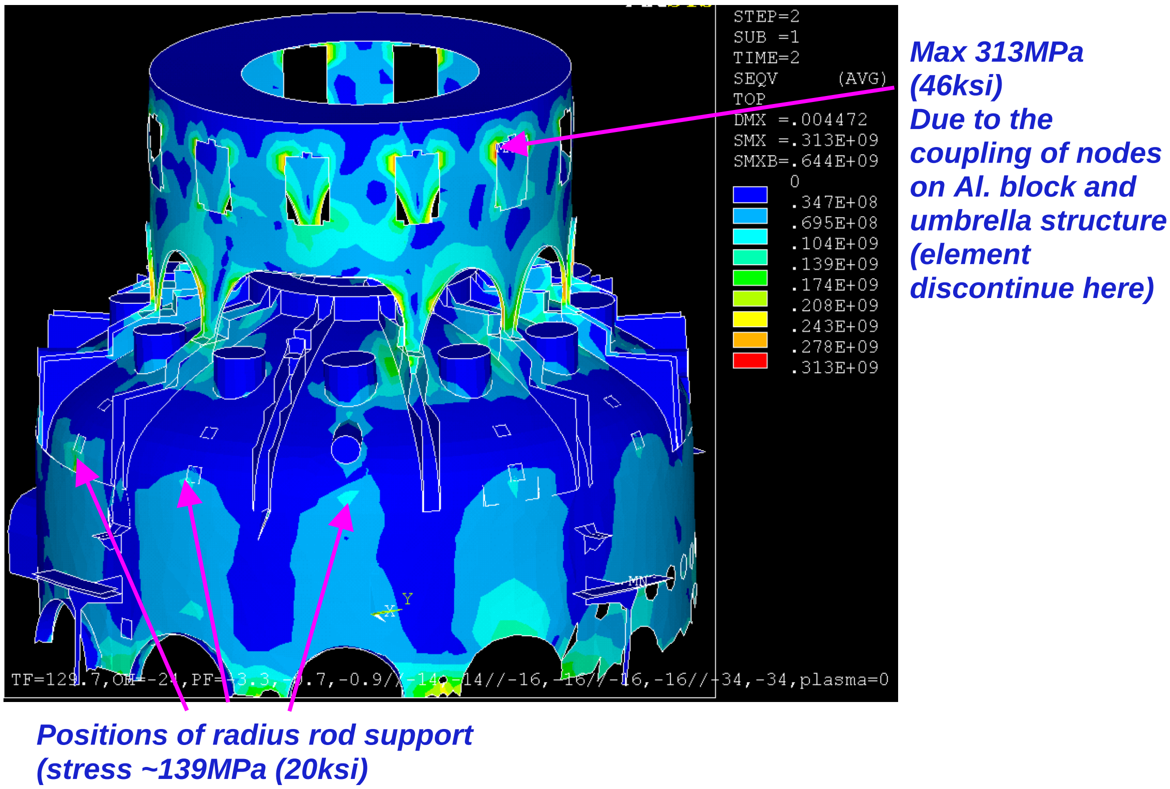


Figure 46: Vacuum vessel Von Mises stress (Pa) upon Asymmetric PF current

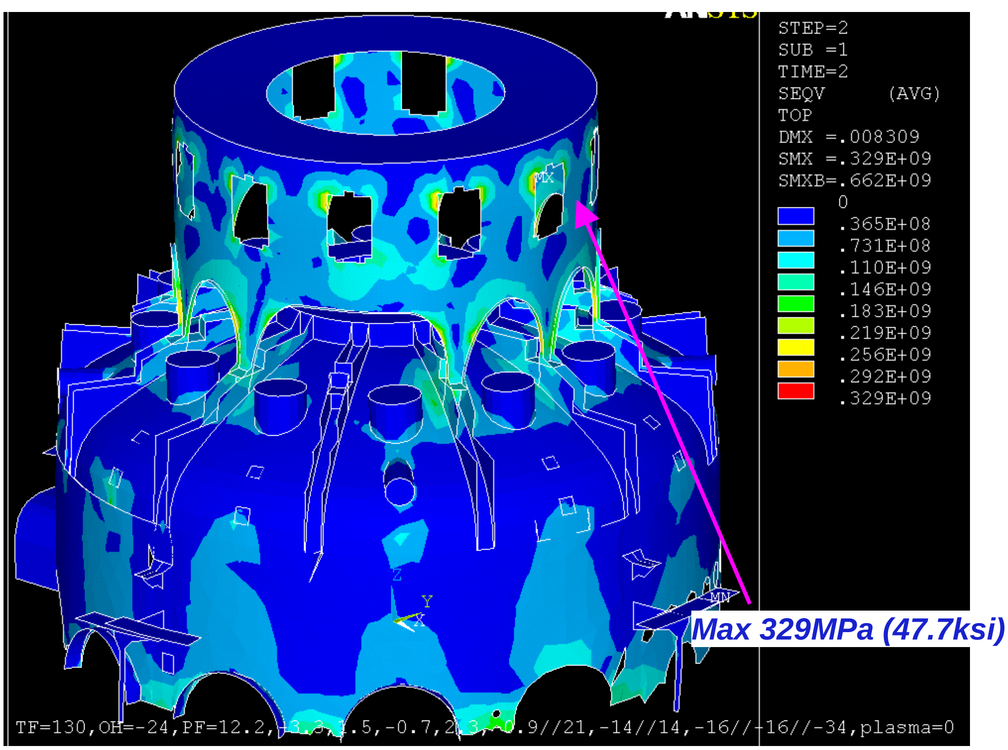


Figure 47: arch area stress (Pa) upon Symmetric PF currents

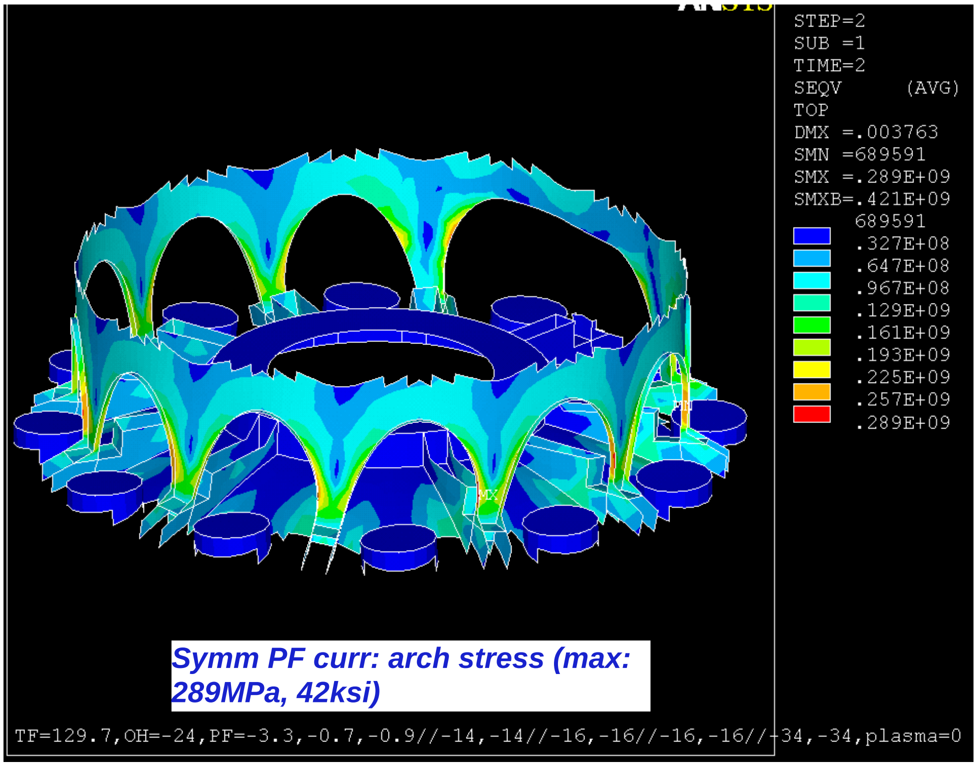


Figure 48: arch area stress (Pa) upon Asymmetric PF currents

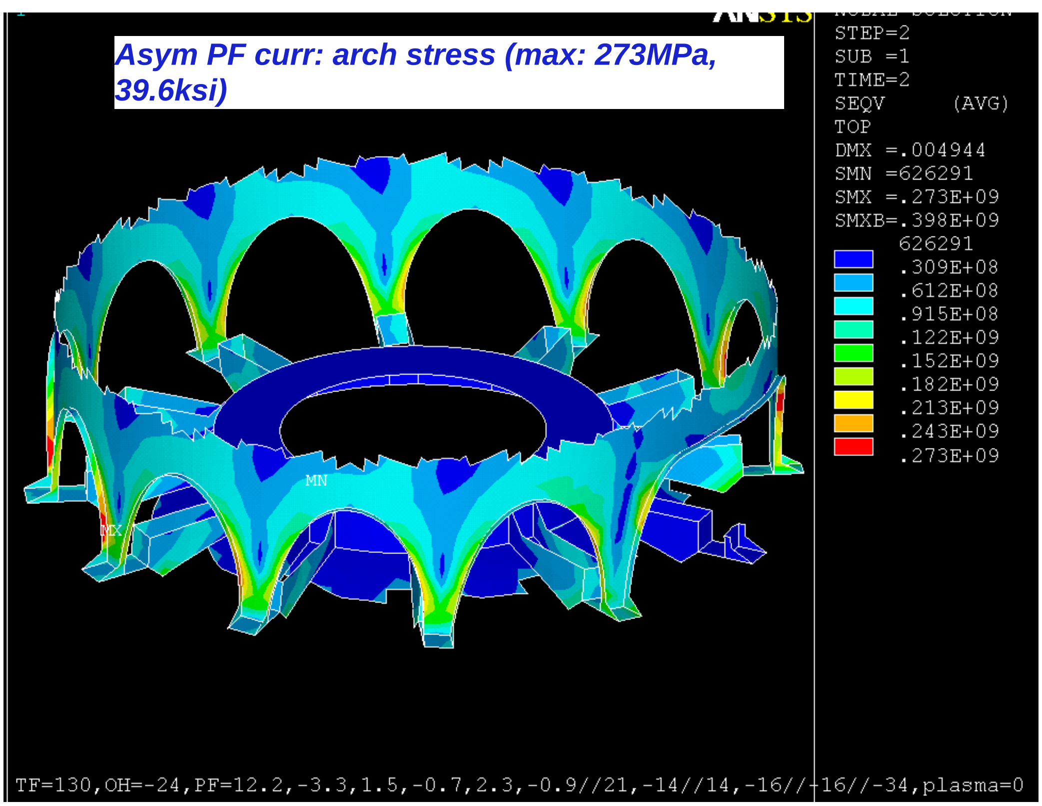


Figure 49: stress at the middle area of vacuum vessel (Pa) upon Symmetric PF currents

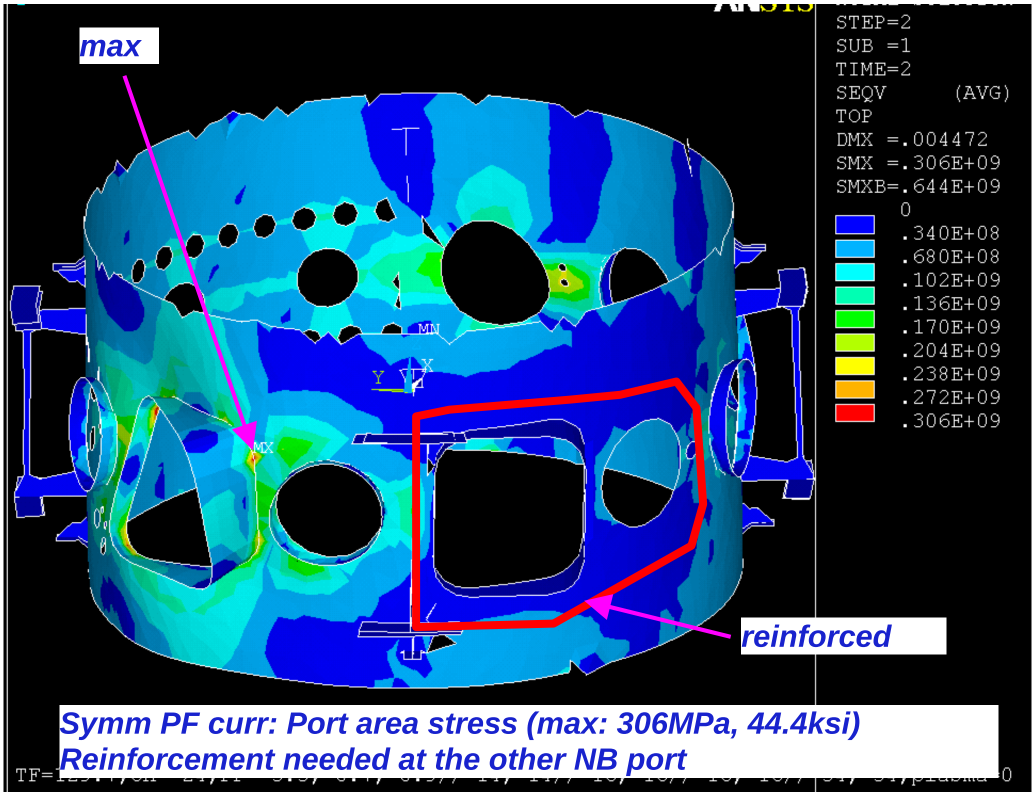


Figure 50: stress at the middle area of vacuum vessel (Pa) upon Asymmetric PF currents

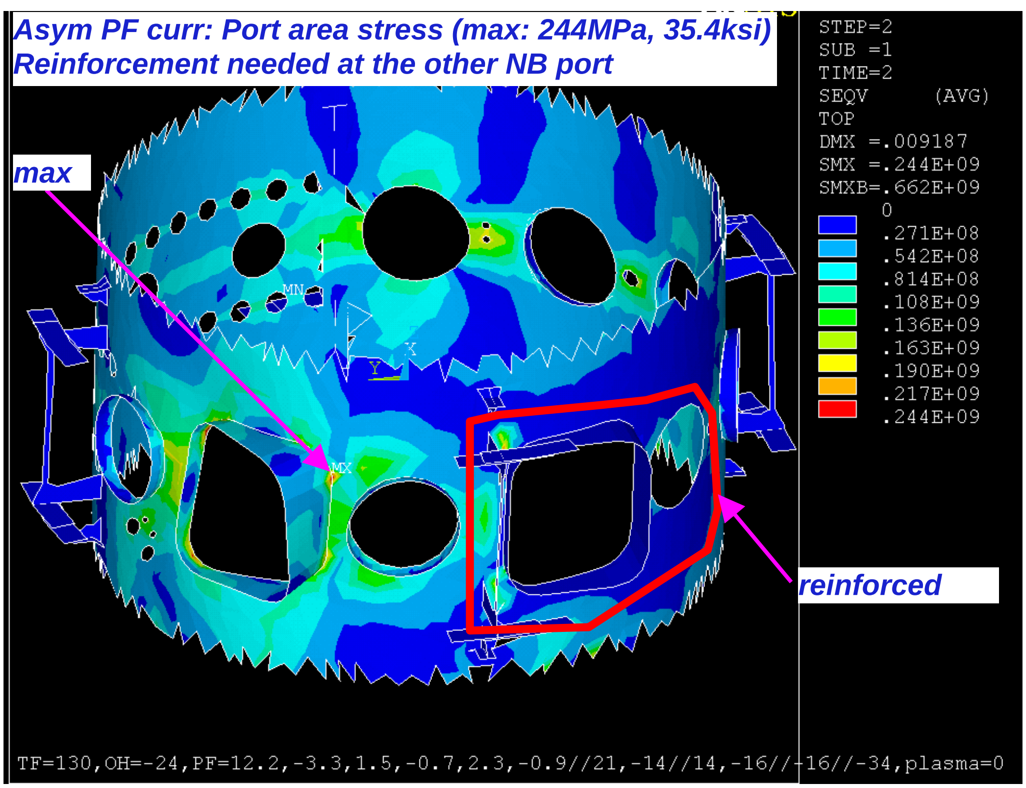


Figure 51: coil stress (Pa) upon Symmetric PF currents

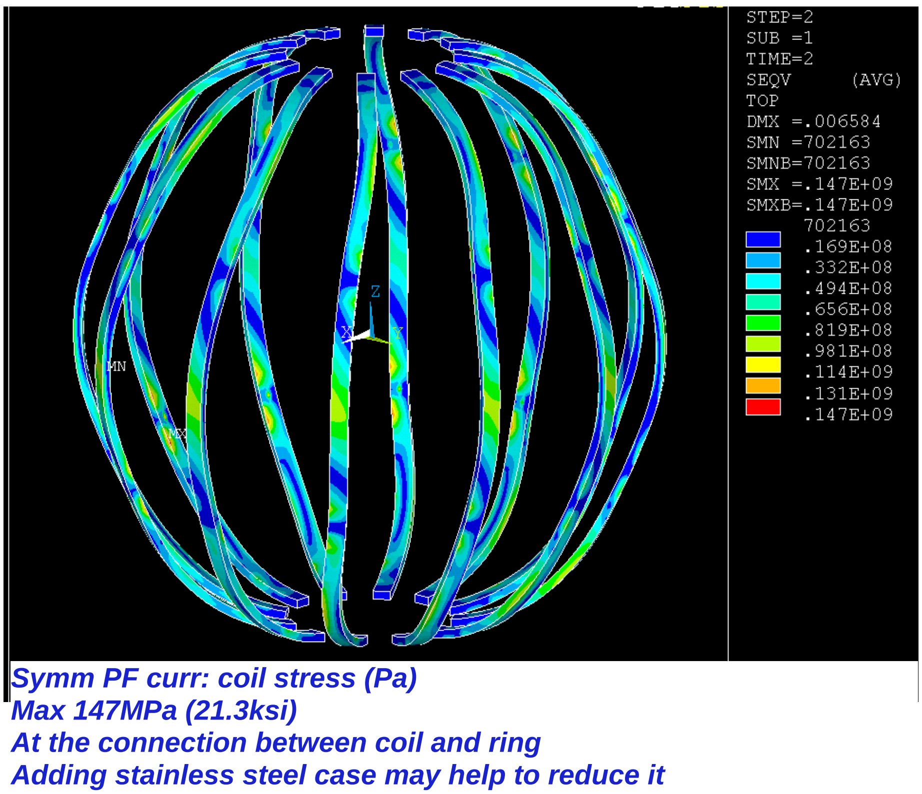


Figure 52: coil stress (Pa) upon Asymmetric PF currents

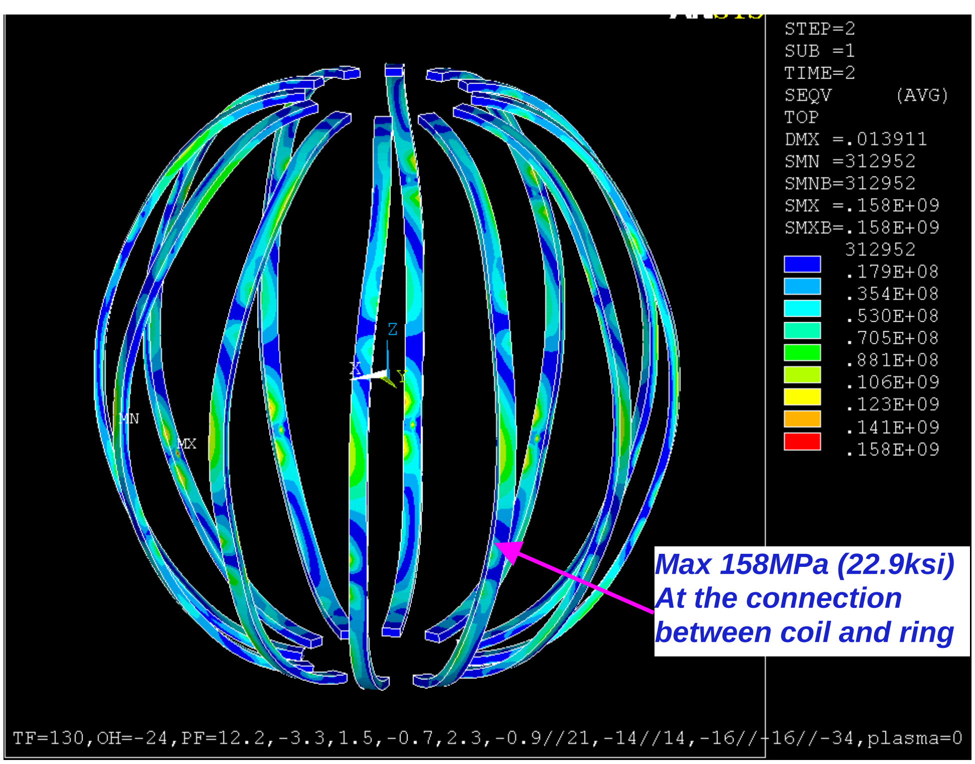


Figure 53: design of stainless steel case

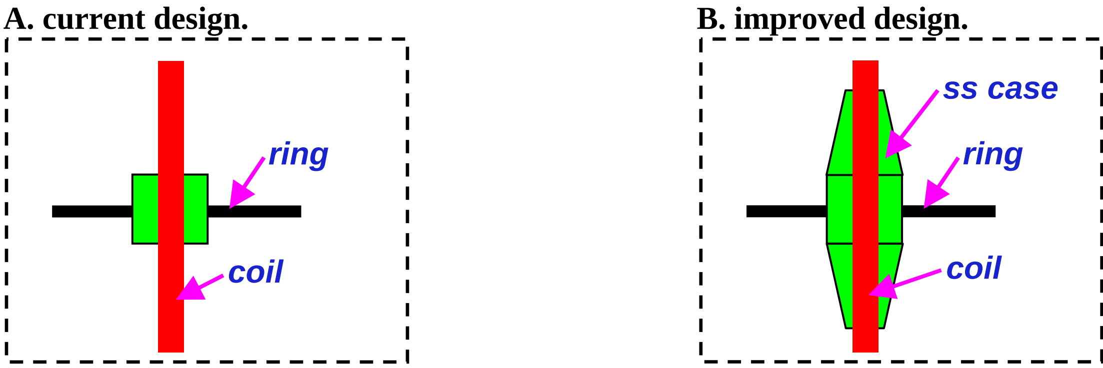


Figure 54: ring stress (Pa) upon Symmetric PF currents.

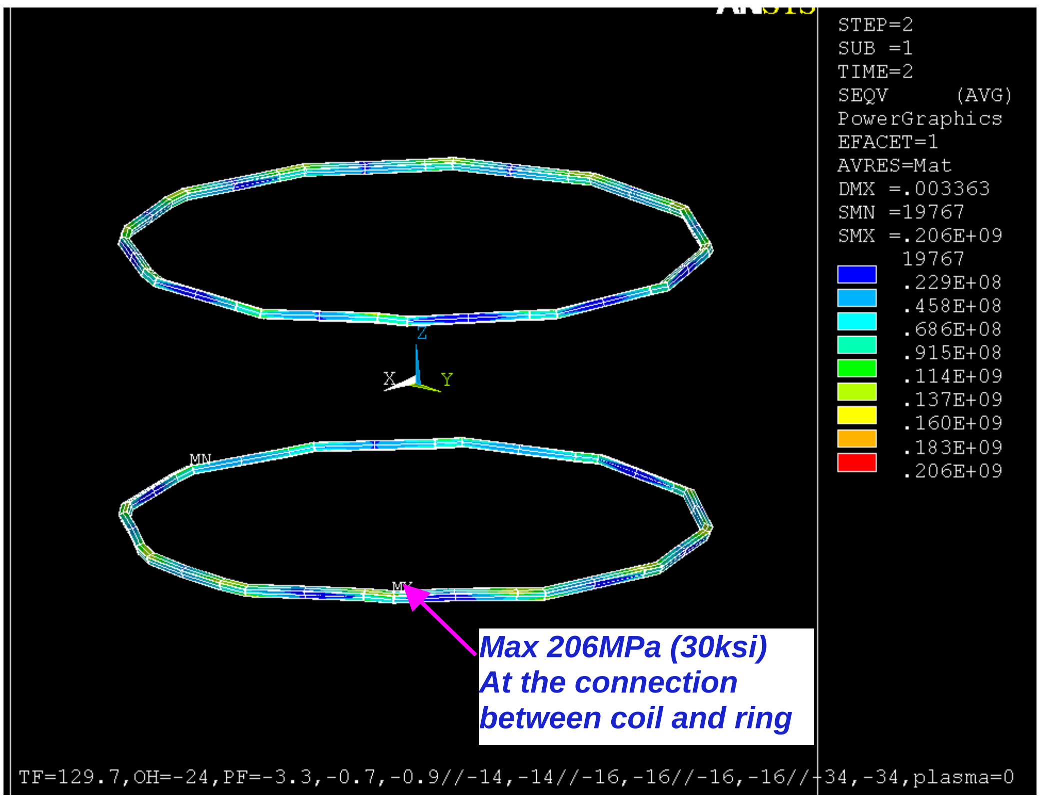
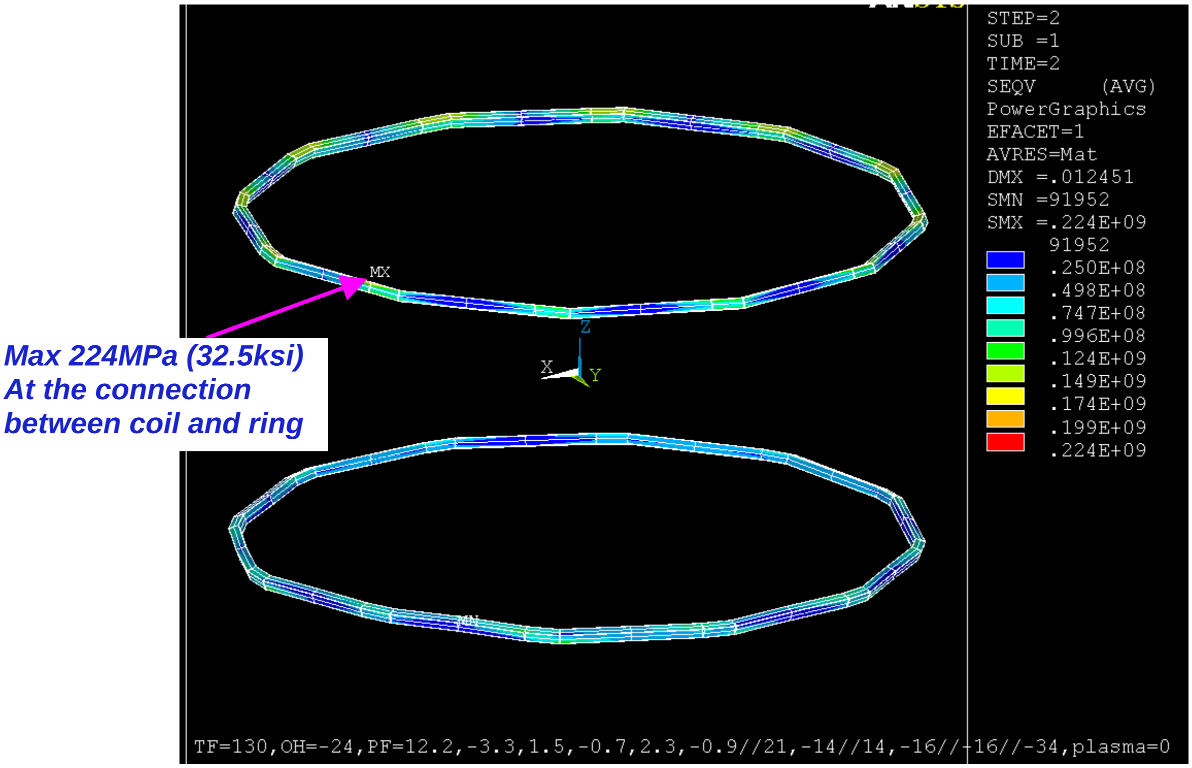


Figure 55: ring stress (Pa) upon Asymmetric PF currents



Summary

Because the TF coil current is promoted to 130KA and the load is too high for umbrella structure, additional structure must be added to take some load. Rings were added to reduce the pull-out (in-plane) loads at the umbrella structure. Various trusses (including tie bars, diamond bracing, and tangential rods) were tried reduce out-of-plane loads from the outer TF legs. Since the machine is already crowded, interference was a severe problem limiting the addition of trusses. Although we don't want to transfer more load to vacuum vessel, up-down asymmetric currents and resulting net twist required an attachment to the vessel. Tangential radius rods can take the net twist and also provided adequate OOP support for symmetric case. Tangential radius rods use the existing territory of turn buckle and there is enough room for them. Loads in the tangential radius rods allow attachment to the vessel with only modest modification and local stress of 20ksi. Vessel stresses in the umbrella structure and equatorial plane port region are acceptable or require only modest modification.

Attachment A: CTD and PPPL Testing of the CTD 112 System

From [14] NATIONAL SPHERICAL TORUS EXPERIMENT CENTER STACK RESEARCH AND DEVELOPMENT FINAL REPORT No. 13-970430-JHC Prepared By: James H. Chrzanowski April 30, 1997 PRINCETON UNIVERSITY PLASMA PHYSICS LABORATORY (PPPL)

Table No. 2-6
SHEAR/COMPRESSION FATIGUE TEST RESULTS
(TF Coil Insulation)

Insulation Tested: CTD-112P without Kapton (3) layers
Test Description: Samples were compressed 10% of nominal insulation thickness prior to cure cycle (177°C for 2 hours and 200°C for 6 hours)

Specimen ID No.	Shear Load (psi)	Compressive Load (psi)	Specimen Temp (°C)	Cycles Completed
11	2400	600	60	1,000,000
12	2400	600	60	1,000,000
13	2400	600	60	1,000,000
14	2400	600	60	1,000,000
19	2400	600	60	1,000,000
20	2400	600	60	1,000,000

=2400*6895/1000000 = 16.548MPa

Table No.2-1
DOUBLE LAP SHEAR TEST RESULTS (TF Coil Insulation)

Insulation Tested: CTD-112P without Kapton (3) layers
Test Description: Samples were compressed 10% of nominal insulation thickness during cure cycle. (177°C for 2 hours and 200°C for 6 hours)
Test Date: 2/12/97

Specimen ID No.	Cure Information	Specimen Test Temp. (°C)	Shear Load (Lbs)	Shear Load (psi)	Type of Failure
4	6 hrs.@ 200°C	21.7 *	1385	2770	Inter-laminar
5	2 hrs.@ 177°C	21.7 *	1800	3600	Inter-laminar
6	6 hrs.@ 200°C	21.7 *	1812	3624	Inter-laminar
7	6 hrs.@ 200°C	21.7 *	1385	3770	Inter-laminar
8	6 hrs.@ 200°C	21.7 *	1690	3380	Inter-laminar
9	6 hrs.@ 200°C	100	1630	3260	Inter-laminar
10	6 hrs.@ 200°C	100	640	1280	Inter-laminar
11	6 hrs.@ 200°C	100	2110	4220	Inter-laminar
12	6 hrs.@ 200°C	100	520	1040	Inter-laminar

* Room Temperature 21.7°C (71°F)

Table No.2-2
DOUBLE LAP SHEAR TEST RESULTS (TF Coil Insulation)

Insulation Tested: CTD-112P without Kapton (3) layers
Test Description: Samples were compressed 10% of nominal insulation thickness during cure cycle (177°C for 2 hours and 200°C for 6 hours).
Test Date: 2/22/97

Specimen ID No.	Cure Information	Specimen Temp. (°C)	Shear Load (Lbs)	Shear Load (psi)	Type of Failure
1	6 hrs.@ 200°C	23.9 *	1310	2620	Copper/DZ-80
2	6 hrs.@ 200°C	23.9 *	1340	2680	Inter-laminar
3	6 hrs.@ 200°C	23.9 *	1050	2100	Cu & Inter-laminar
4	6 hrs.@ 200°C	23.9 *	1810	3620	Copper/DZ-80
5	6 hrs.@ 200°C	23.9 *	1310	2620	Inter-laminar
6	6 hrs.@ 200°C	23.9 *	1330	2660	Cu & Inter-laminar
7	6 hrs.@ 200°C	23.9 *	1540	3080	Cu & Inter-laminar
8	6 hrs.@ 200°C	100	910	1820	Cu & Inter-laminar
9	6 hrs.@ 200°C	100	1335	2670	Inter-laminar
10	6 hrs.@ 200°C	60	1630	3260	Cu & Inter-laminar
11	6 hrs.@ 200°C	23.9 *	1680	3360	Inter-laminar
12	6 hrs.@ 200°C	60	1370	2740	Inter-laminar
13	6 hrs.@ 200°C	23.9 *	1240	2480	Cu & Inter-laminar
14	6 hrs.@ 200°C	23.9 *	1210	2420	Copper/DZ-80
15	6 hrs.@ 200°C	23.9 *	1340	2680	Inter-laminar
16	6 hrs.@ 200°C	23.9 *	1220	2440	Cu & Inter-laminar

* Room Temperature 23.9°C (75°F)