NSTX

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

NSTX Centerstack Upgrade Analysis Effort

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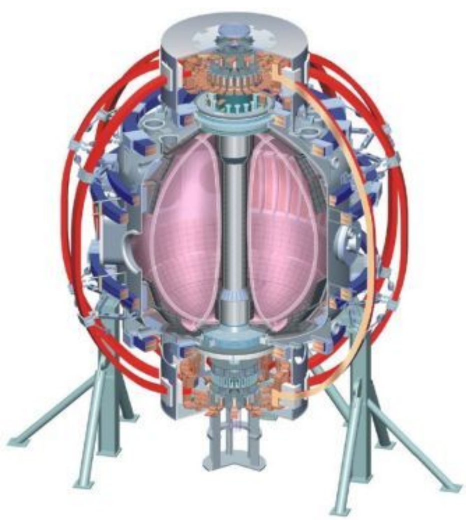
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

Peter H. Titus

H.Zhang,S.Avasarala,A.Zolfaghari,A.Brooks,L.Myatt

NSTX Centerstack Upgrade Conceptual Design Review
LSB, B318
October 28,29, 2009



Culham Sci Ctr
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ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Historically What is Available – Aside from a Wealth of Operating Experience

- http://nstx.pppl.gov/nstx/Engineering/NSTX_Eng_Site/Technical/General/Calculations/NSTX_Engr_Calcs.html

- Coils: Spreadsheet with hoop influence coefficients, Cooling optimizations, ACOOL,FCOOL,KCOOL
- Vessel: HM Fan did analyses of PF and TF loading and vacuum
- Heat Balance: Art Brooks did extensive bake-out, and operational heat loads. These were never benchmarked against measured performance in the machine
- Disruption:

  ORNL Design and Analysis, Charlie specified disruption loads, HM Fan analyzed these and calculated DLF's (Mostly Less than 1.0) Not clear if the segmented passive plates were ever modeled as non-toroidally continuous

NSTX CSU Calculation Index October 2009

131 - Poloidal Field Coils	Woolley	NSTX-CALC-131-01-00 • Body of Calculation • OH&PF coil set geometry • Poloidal field vectors and poloidal fluxes throughout NSTX given any user-input set of coil and plasma currents	NSTX CSU Poloidal Fields (06262009)	No
132 - Toroidal Field Coils	Titus	NSTX-CALC-132-01-00	Coupled Electromagnetic-Thermal Analysis (04072009)	No
	Titus	NSTX-CALC-132-02-00	Coupled Electromagnetic-Thermal Analysis (04202009)	No
	Woolley	NSTX-CALC-132-03-00	Out-Of-Plane (OOP) PF/TF Torques on TF Conductors in NSTX CSU	No
	Han	NSTX-CALC-132-04-00	Analysis of TF Outer Leg	YES
	Han	NSTX-CALC-132-05-00	TF Coupled Thermo Electromagnetic Diffusion Analysis	YES
	Willard	NSTX-CALC-132-06-00	TF Flex Joint and TF Bundle Stub	YES
	Titus	NSTX-CALC-132-07-00	Maximum TF Torsional Shear	YES
133 - Center Stack	Myatt	NSTX-CALC-133-01-00	Structural Analysis of the PF1 Coils & Supports	YES
	Avasarala	NSTX-CALC-133-02-00	Thermal Stresses on the OH-TF Coils	YES
	Titus	NSTX-CALC-133-03-00	Center Stack Casing Disruption Inductive and Halo Current Loads	YES

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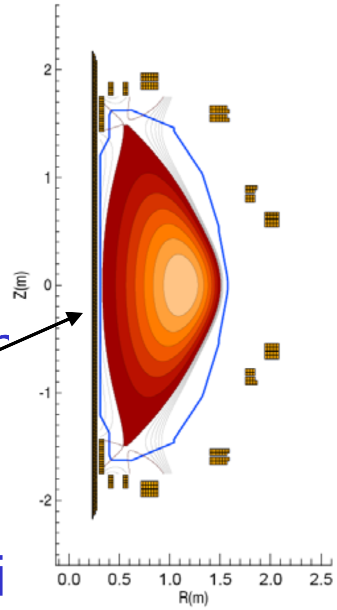
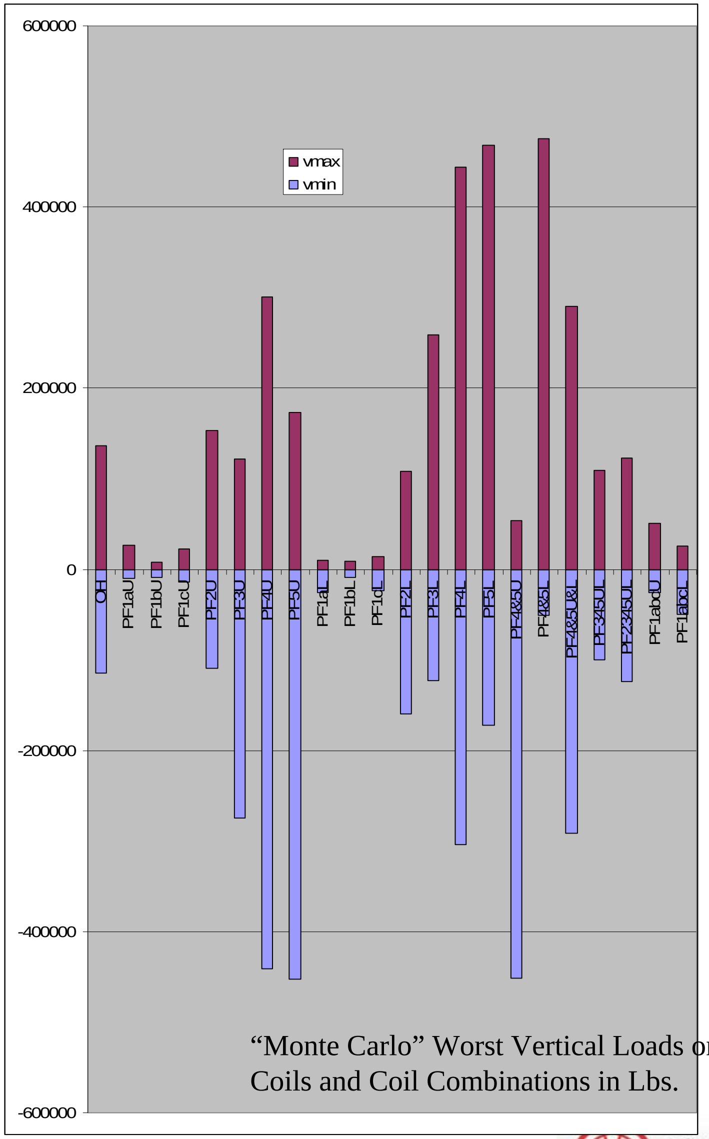
NSTX CSU

Analytic Sources of Lorentz Loading

- Loads
  - Equilibria –Jon Mer
  - 10% "Headroom" – Charlie Neumeyer
  - Power Supply Maxi and Minima – Charlie Neumeyer
  - Influence Coefficients – Ron Hatcher, Bob Woolley
  - Monte Carlo (Worst that Power Supplies Can Produce) – Titus
  - EXCEL solver – Charlie Neumeyer





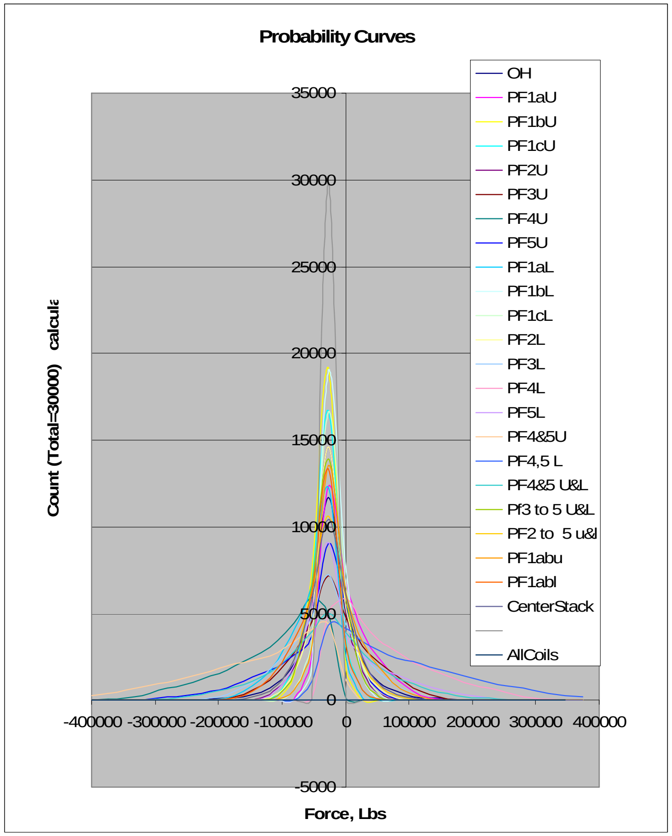
"Monte Carlo" Worst Vertical Loads on Coils and Coil Combinations in Lbs.

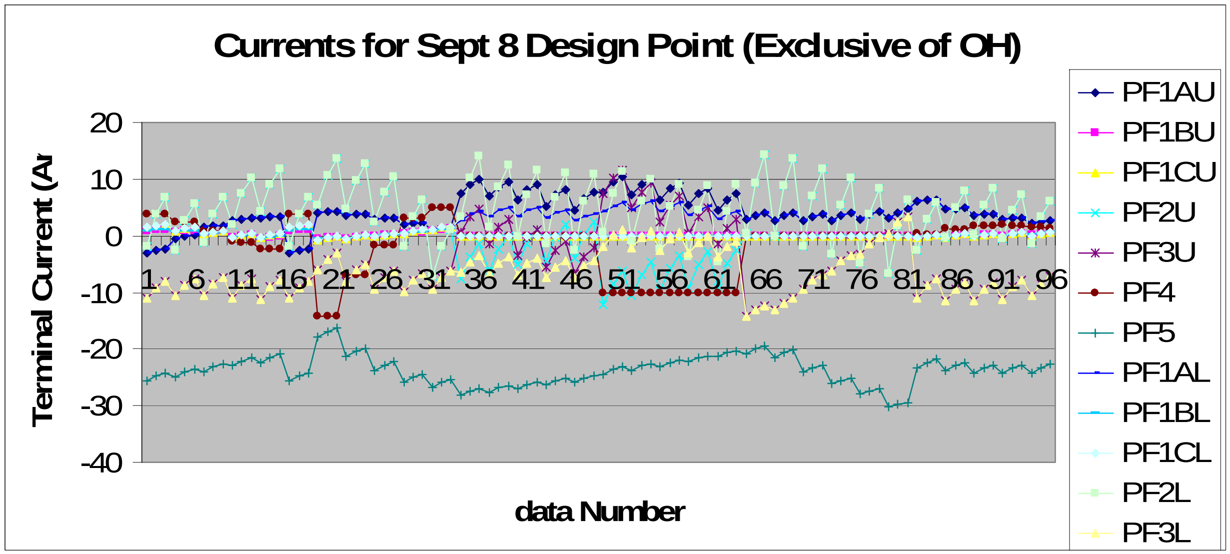
We are Still Evaluating the Appropriate Loading Design Basis.
Present Analyses based on Worst Case Currents Provide Conservatisms That Will Be Translated into Cost Savings During the PDR

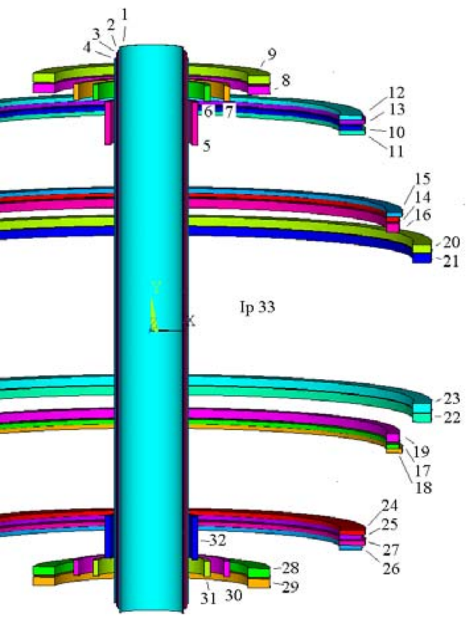
- Worst Case Power Supply Limits – Loads Determined for Individual Coils and – Combined using Excel Solver or Monte Carlo. Probabilistic Treatments are Possible

If “Onerous” Base Qualification on:
90 Normal Operating Scenarios Which Are Analyzed to Envelope the Normal Stresses.

-Then Rely on Machine Protection System

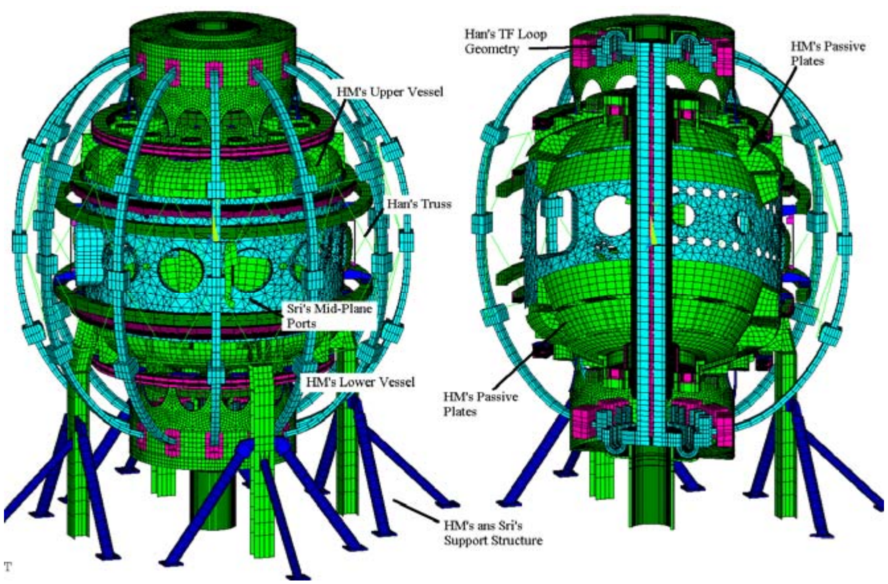


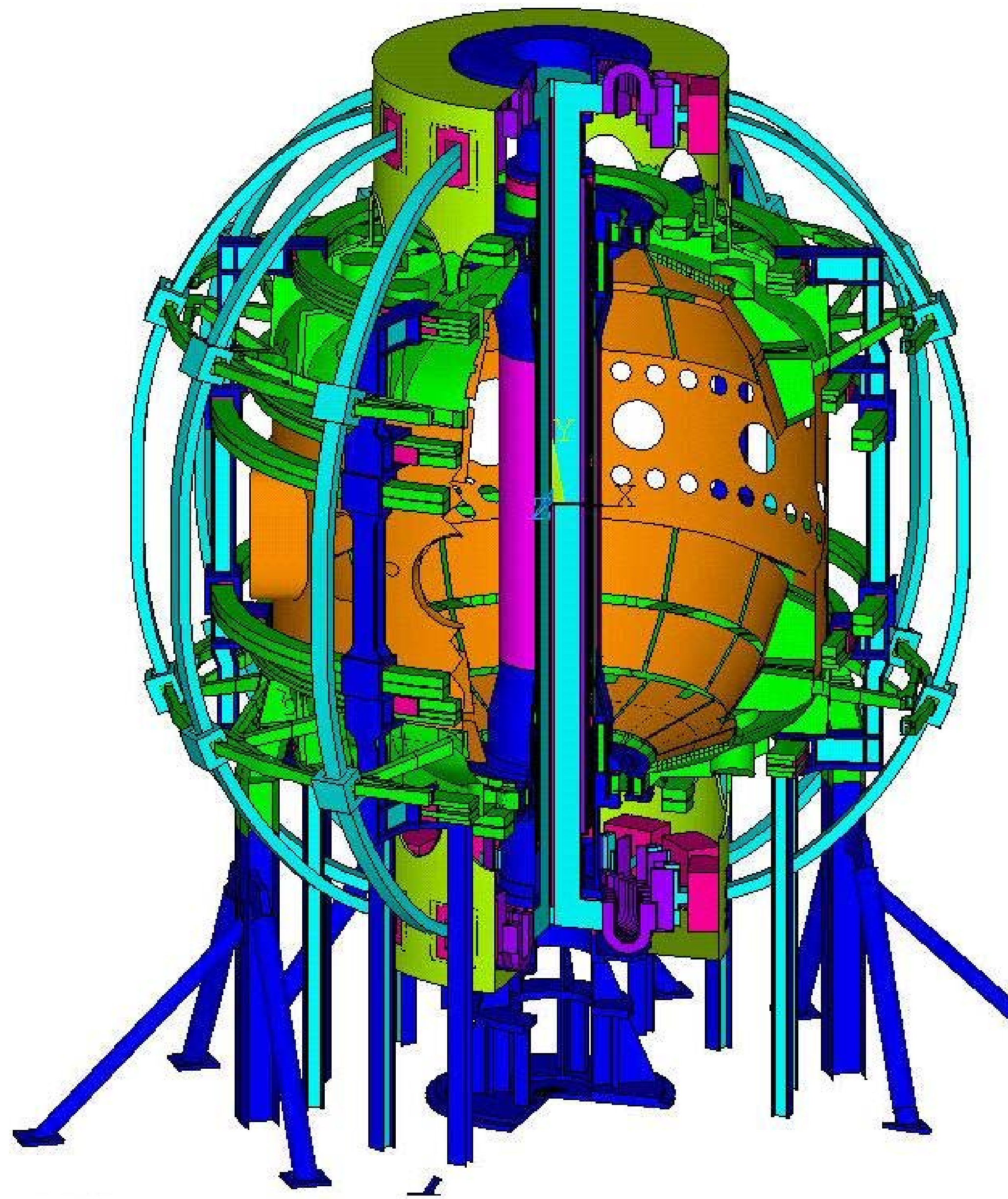




- **Global Model Is Used For:**

- **Selecting Worst Cases**
- **Scoping Studies**
- **Cross-Checking other Models**





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Criteria – Allowables for Coil Copper Stresses

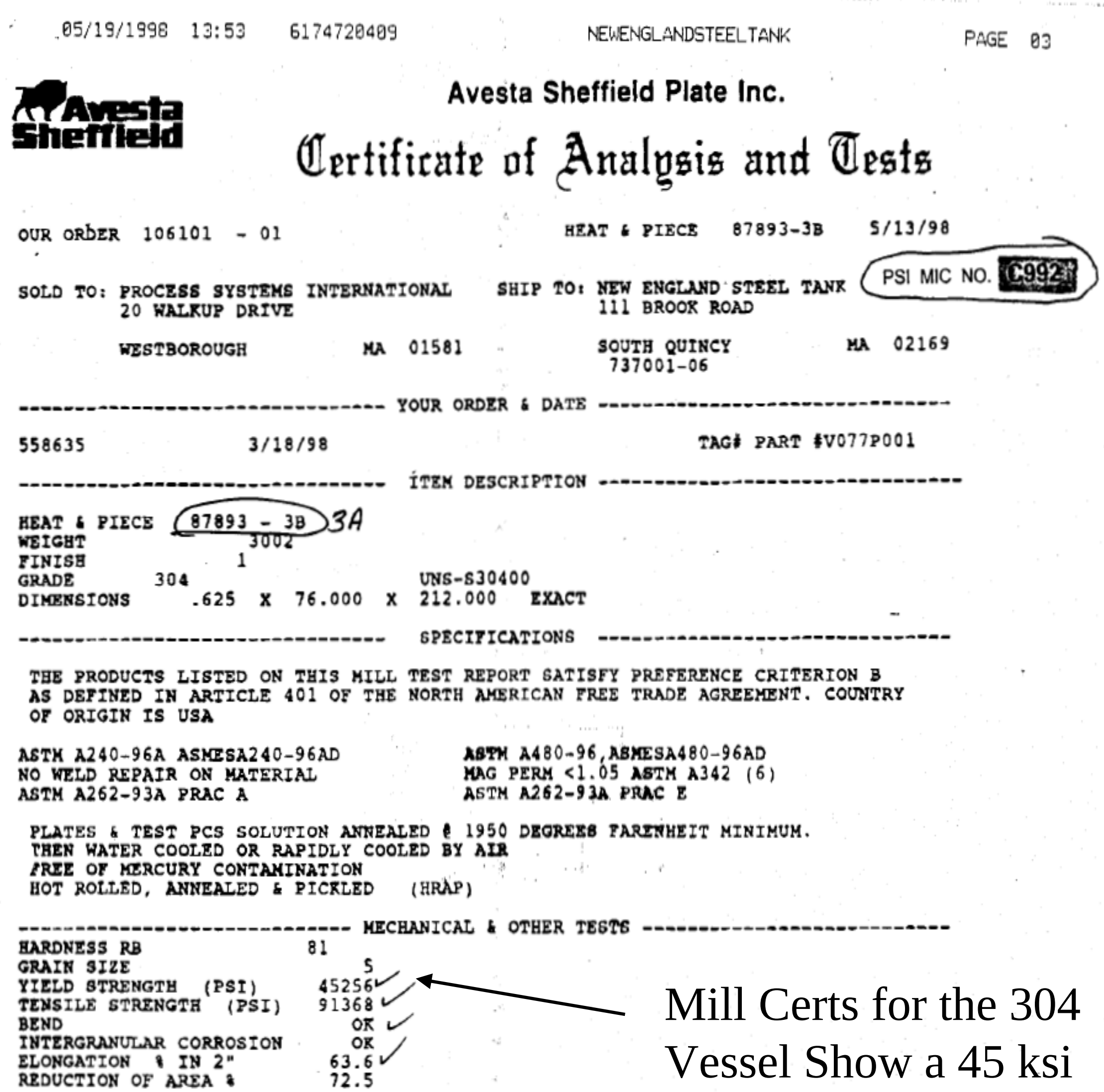
The TF copper ultimate is 39,000 psi or 270 MPa . The yield is 38ksi (262 MPa). Sm is 2/3 yield or 25.3ksi or 173 MPa – for adequate ductility, which is the case with this copper which has a minimum of 24% elongation. Note that the ½ ultimate is not invoked for the conductor (It is for other structural materials) . These stresses should be further reduced to consider the effects of operation at 100C. This effect is estimated to be 10% so the Sm value is 156 MPa.

- From: I-4.1.1 Design Tresca Stress Values (Sm), NSTX_DesCrit_IZ_080103.doc
- • (a) For conventional (i.e., non-superconducting) conductor materials, the design Tresca stress values (Sm) shall be 2/3 of the specified minimum yield strength at temperature, for materials where sufficient ductility is demonstrated (see Section I-4.1.2). *****
- It is expected that the CS would be a similar hardness to the TF so that it could be wound readily. For the stress gradient in a solenoid, the bending allowable is used. The bending allowable is 1.5*156 or 233MPa,

Room Temperature Allowables for 316 and 304 SST

•

Material	Sm	1.5Sm
316 LN SST	183Mpa (26.6 ksi)	275Mpa (40ksi)
316 LN SST weld	160MPa (23.2ksi)	241MPa (35ksi)



05/19/1998 13:53 6174720409 NEWENGLANDSTEELTANK PAGE 03

Avesta Sheffield

Avesta Sheffield Plate Inc.

Certificate of Analysis and Tests

OUR ORDER 106101 - 01 HEAT & PIECE 87893-3B 5/13/98

PSI MIC NO. C992

SOLD TO: PROCESS SYSTEMS INTERNATIONAL
20 WALKUP DRIVE
WESTBOROUGH MA 01581

SHIP TO: NEW ENGLAND STEEL TANK
111 BROOK ROAD
SOUTH QUINCY MA 02169
737001-06

------ YOUR ORDER & DATE ------

558635 3/18/98 TAG# PART #V077P001

------ ITEM DESCRIPTION ------

HEAT & PIECE 87893 - 3B 3A
WEIGHT 3002
FINISH 1
GRADE 304 UNS-S30400
DIMENSIONS .625 X 76.000 X 212.000 EXACT

------ SPECIFICATIONS ------

THE PRODUCTS LISTED ON THIS MILL TEST REPORT SATISFY PREFERENCE CRITERION B AS DEFINED IN ARTICLE 401 OF THE NORTH AMERICAN FREE TRADE AGREEMENT. COUNTRY OF ORIGIN IS USA

ASTM A240-96A ASMESA240-96AD
NO WELD REPAIR ON MATERIAL
ASTM A262-93A PRAC A

ASTM A480-96,ASMESA480-96AD
MAG PERM <1.05 ASTM A342 (6)
ASTM A262-93A PRAC E

PLATES & TEST PCS SOLUTION ANNEALED @ 1950 DEGREES FARENHEIT MINIMUM.
THEN WATER COOLED OR RAPIDLY COOLED BY AIR
FREE OF MERCURY CONTAMINATION
HOT ROLLED, ANNEALED & PICKLED (HRAP)

------ MECHANICAL & OTHER TESTS ------

HARDNESS RB	81
GRAIN SIZE	5
YIELD STRENGTH (PSI)	45256
TENSILE STRENGTH (PSI)	91368
BEND	OK
INTERGRANULAR CORROSION	OK
ELONGATION % IN 2"	63.6
REDUCTION OF AREA %	72.5

Mill Certs for the 304 Vessel Show a 45 ksi Yield

Insulation Shear Stress Allowable

- ***From Dick Reed Reports/Conversations:***

- Shear strength, short-beam-shear, interlaminar
- **Without Kapton 65 MPa (TF, PF1 a,b,c)**
- **With Kapton 40 MPa (CS)**
- **Estimated Strength at Copper Bond 65 MPa/2 =32.5 MPa (All Coils)**

- ***From Criteria Document:***

- ***I-5.2.1.3 Shear Stress Allowable***
- The shear-stress allowable, Ss, for an insulating material is most strongly a function of the particular material and processing method chosen, the loading conditions, the temperature, and the radiation exposure level. The shear strength of insulating materials depends strongly on the applied compressive stress. Therefore, the following conditions must be met for either static or fatigue conditions:
- Ss = [2/3 to]+ [c2 x Sc(n)]

- ***2/3 of 32.5 MPa = 21.7 MPa***

NSTX Fatigue

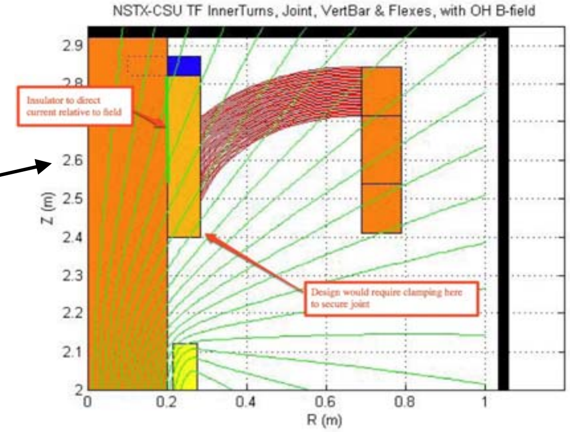
- NSTX is designed for approximately 3000 full power and 30,000 two-thirds power pulses.
- A fatigue strength evaluation is required for those NSTX components with undetectable flaws that are either cycled over 10,000 times or are exposed to cyclic peak stresses exceeding yield stress.
- Any NSTX component without cyclic tensile loading and loaded only in compression shall not require a fatigue evaluation. When a fatigue strength evaluation is performed, it shall apply both to base metal and the weld regions. It is essential that the quality and history of all materials used be known and documented prior to testing or fabrication.

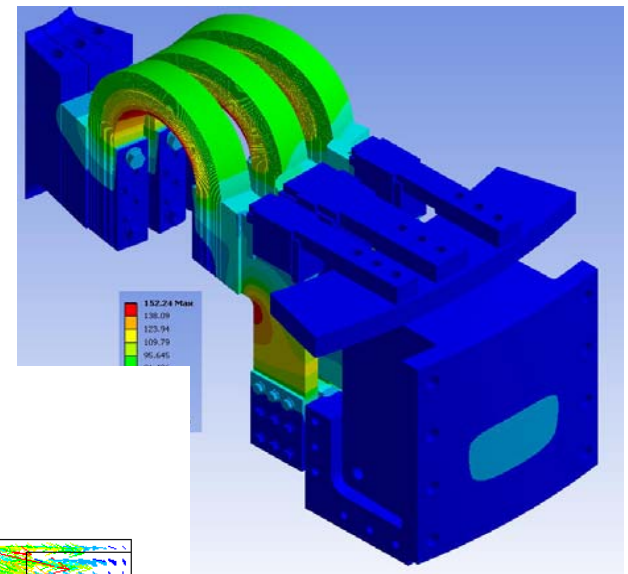
Definition of the Aged Condition for “Used” Components?

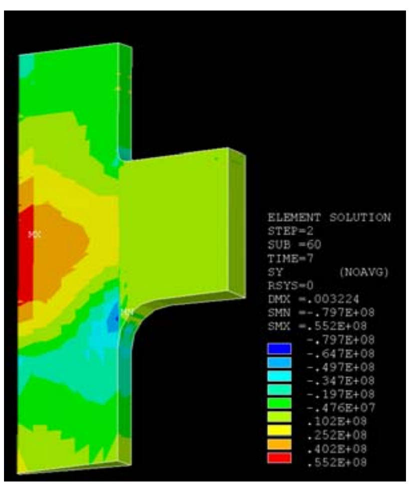
For engineering purposes, number of NSTX pulses, after implementing the Center Stack Upgrade, shall be assumed to consist of a total of ~ 60,000 pulses based on the GRD specified pulse spectrum.

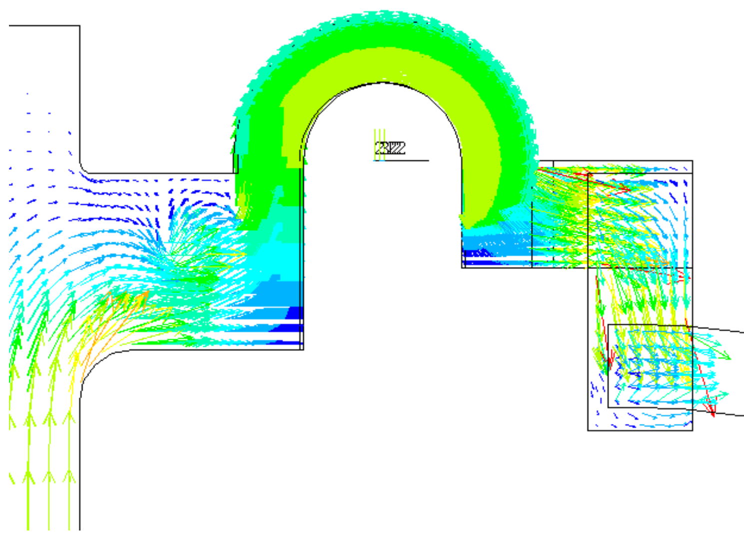
TF Inner Flex Joint Qualification

- Center Stack TF
  - Concept, Initial Analysis -Woolley
  - TF Inner Joint Stress, Contact Pressures – Tom Willard, Bruce Paul Designer
  - TF Current Diffusion – Han Zhang, Titus
  - TF Torsional Shear Titus, Woolley
  - TF Stress, Insulation Tension Stress Titus, Han Zhang

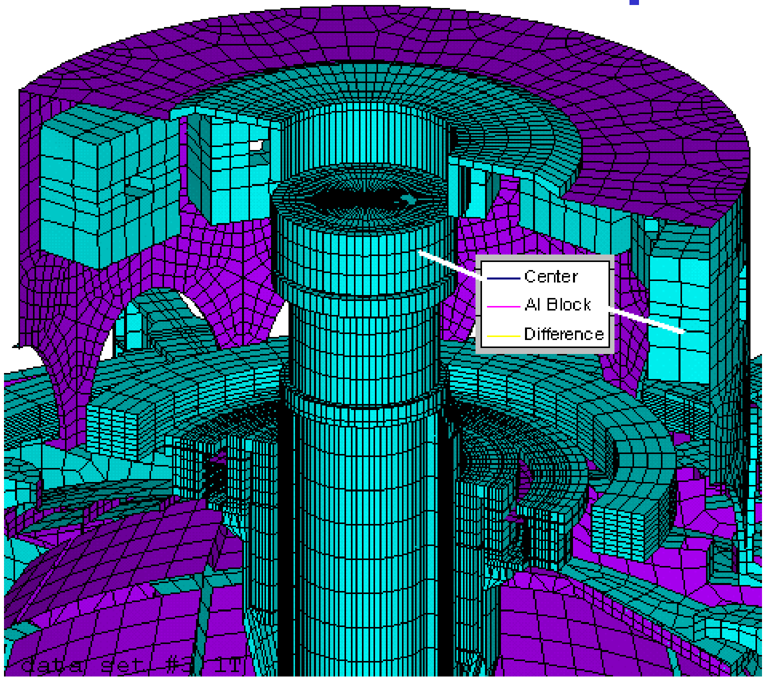


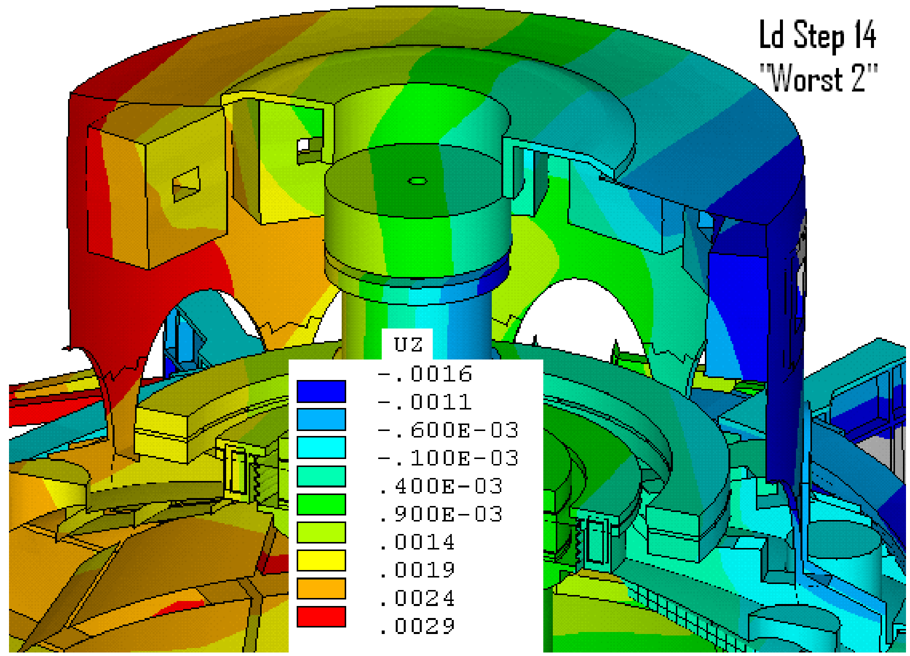


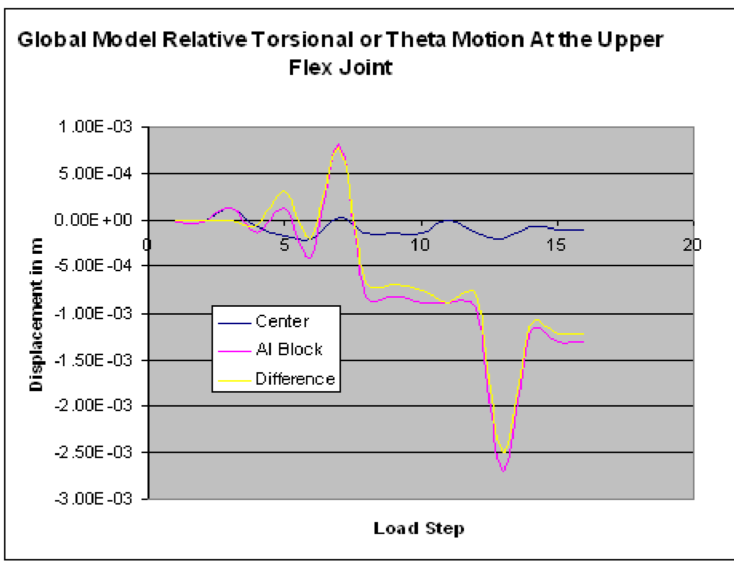


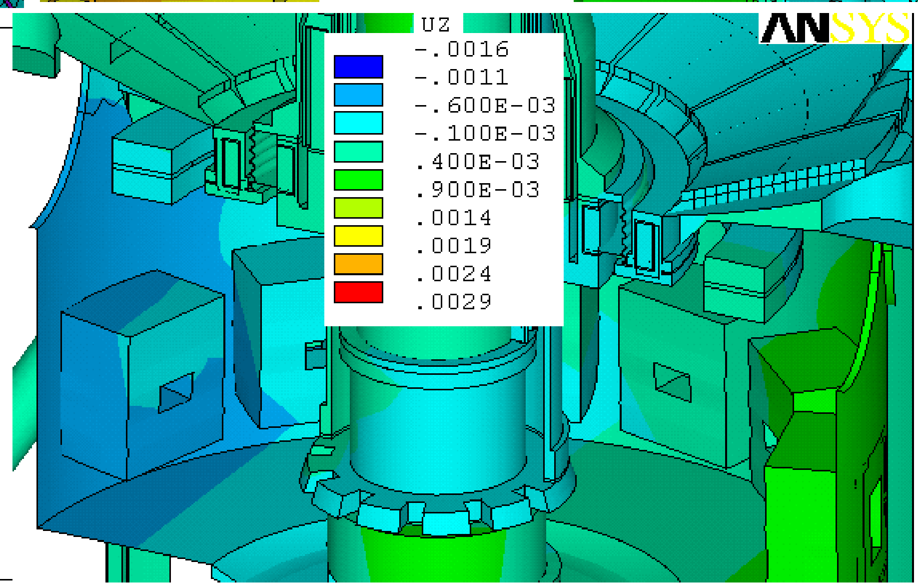


Relative Out-of-Plane Displacement Across the Flex Joint



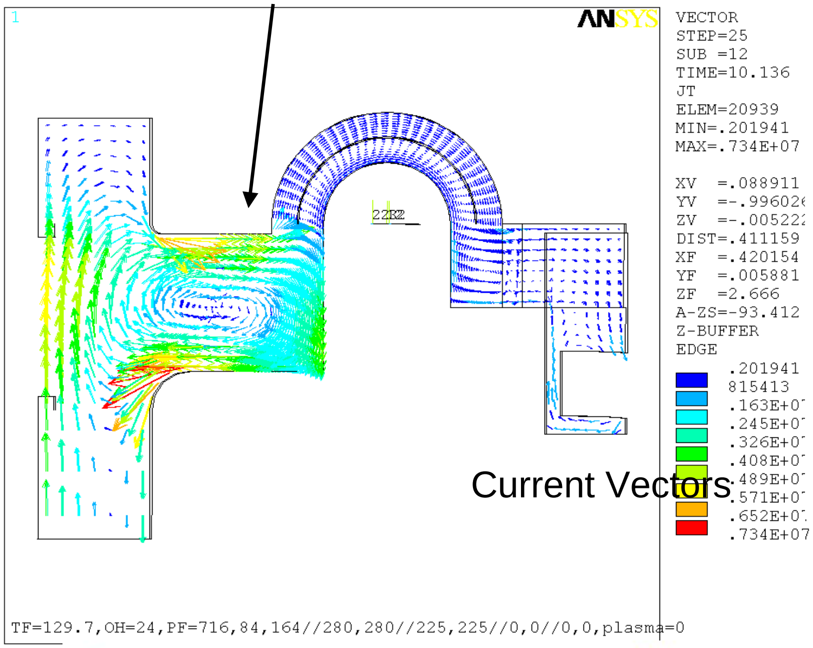




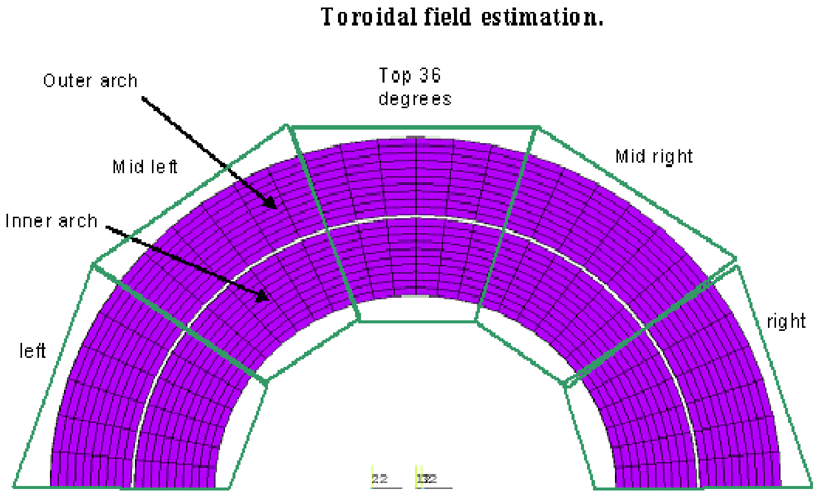


Current Diffusion Model was Used to Qualify CuCrZn Flag Extensions and Allow Stronger Inserts and Bolts

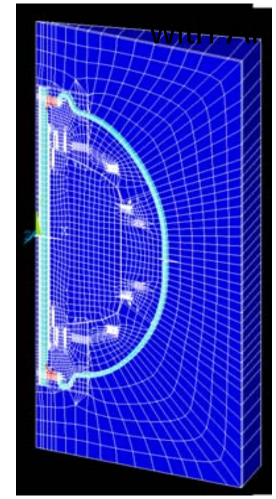
NSTX-CSU Coupled Transient Electromagnetic-Thermal Analysis – With a Structural Pass – Used to Provide TF Field at the Strap, Inductivly Driven Current Densities and Temperatures (H. Zhang)

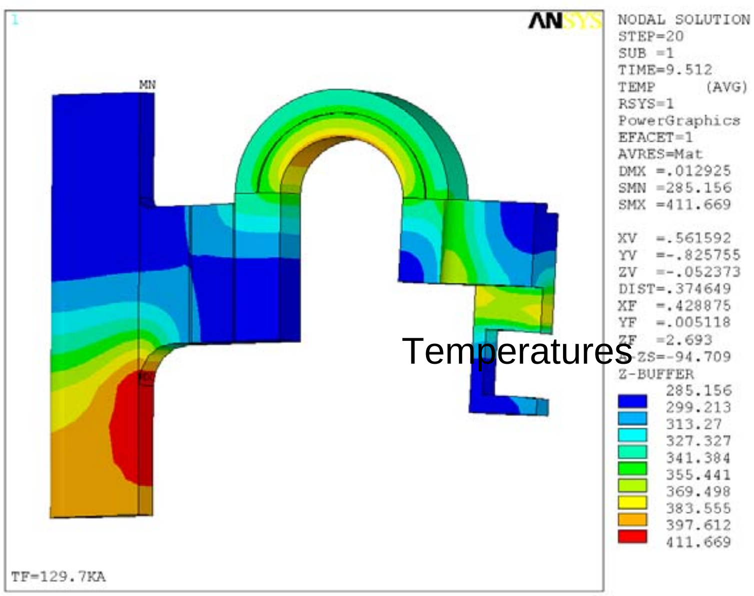


Current Vectors

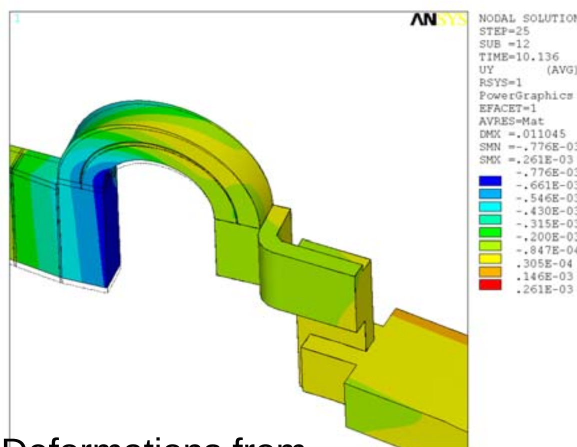


EM Model



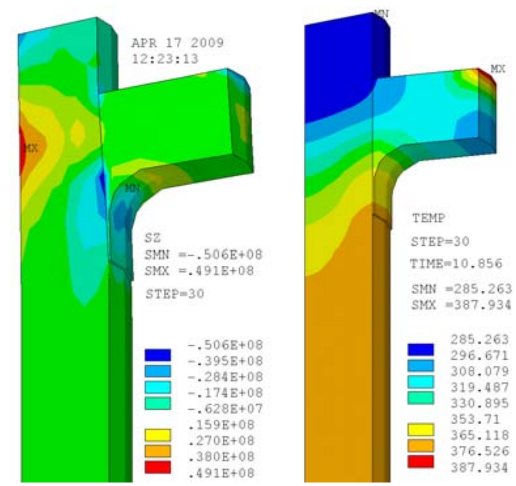


Temperatures



Deformations from Structural Pass

Thermal De-Wedged Region - Through Thickness Insulation Tension Stress



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Outer Leg Reinforcement (H.Zhang)

In-Plane and Out-of-Plane Loads Increase by a factor of 3.5

The only support structure of TF outer leg is the umbrella structure

From previous analysis, with the worst case PF currents, the umbrella structure will have very high stress of >1GPa (145 ksi).

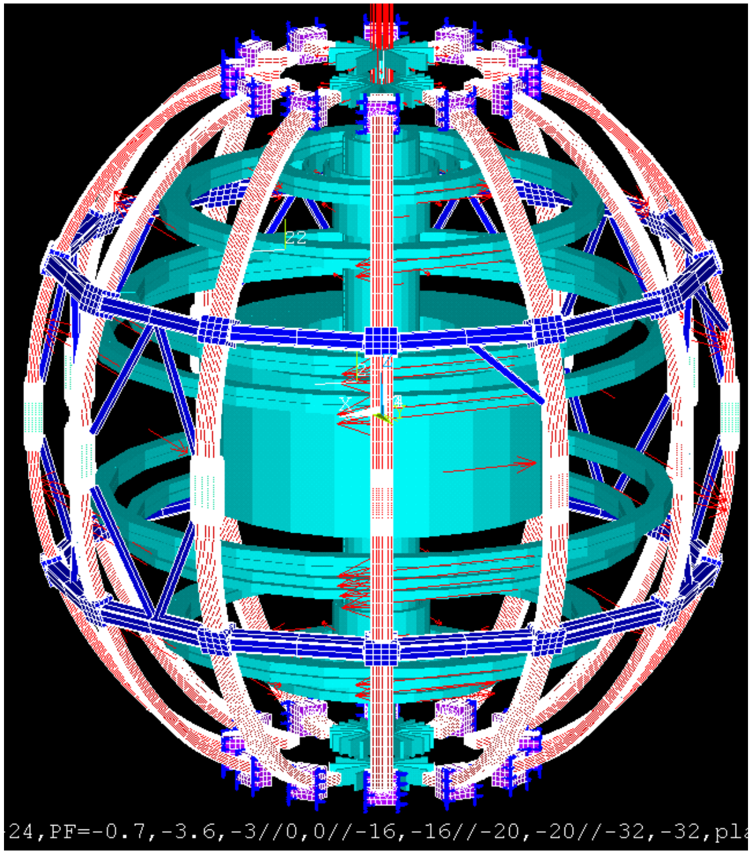
An evolution of reinforcements were tried:
- Ring (to Support In-Plane TF Bursting Loads)
- Beam Strongback (Both in-Plane and OOP Loads)
- Ladder Truss
- Diamond Truss
- Tangential Radius Rods (OOP Only)

.

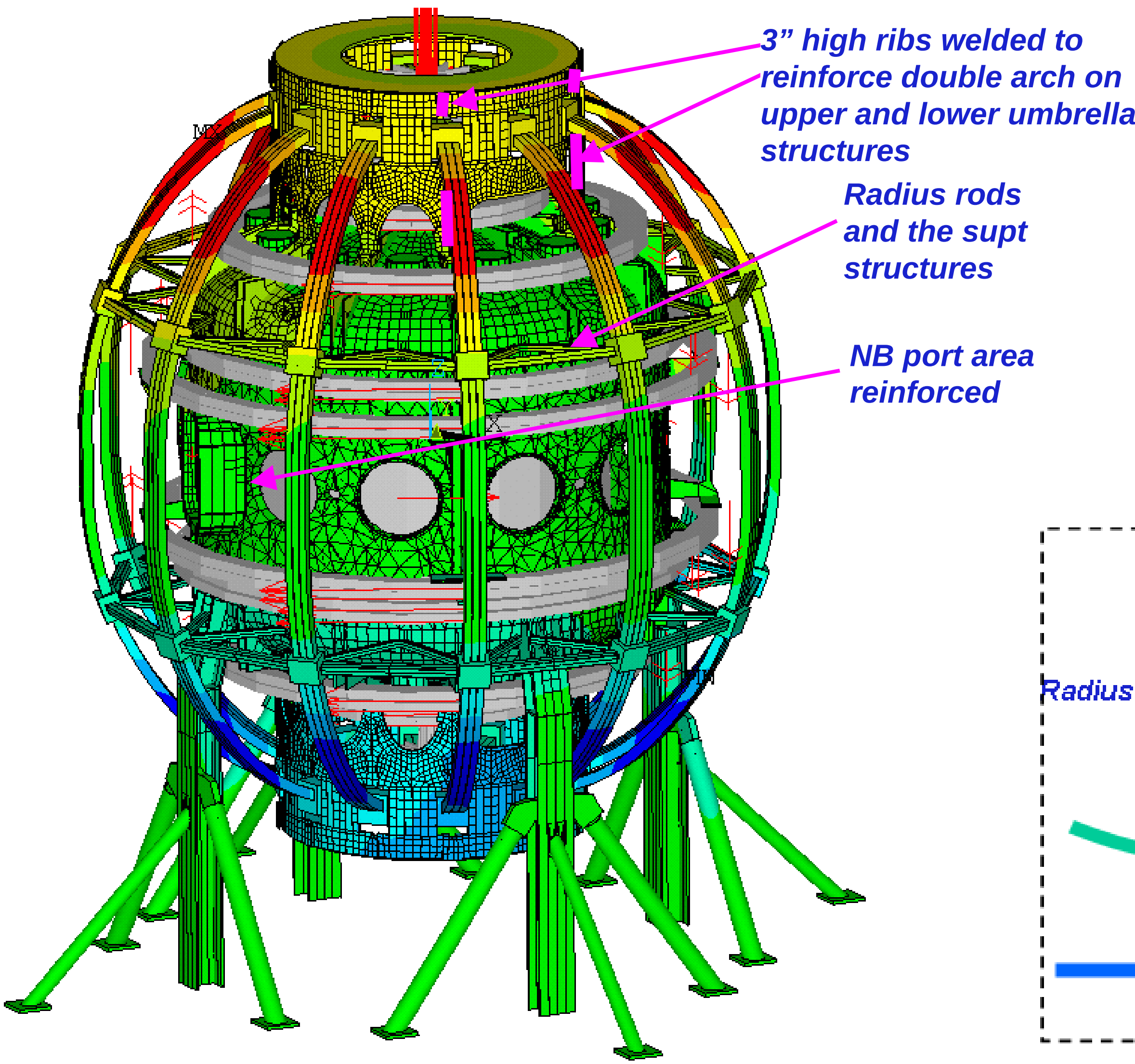
Many port bays could not accommodate the diamond trusses

Preferred Solution: Ring + Tangential Radius Rods

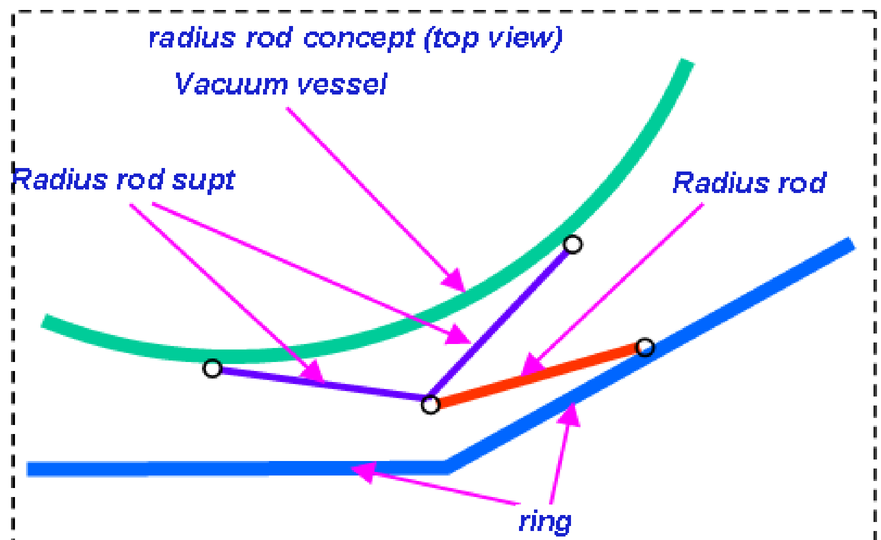
Diamond Truss Concept Analyzed with Missing Truss Components Where Interferences Could not be Fixed.



Outer TF, Vessel, Umbrella Structure, Reinforcements

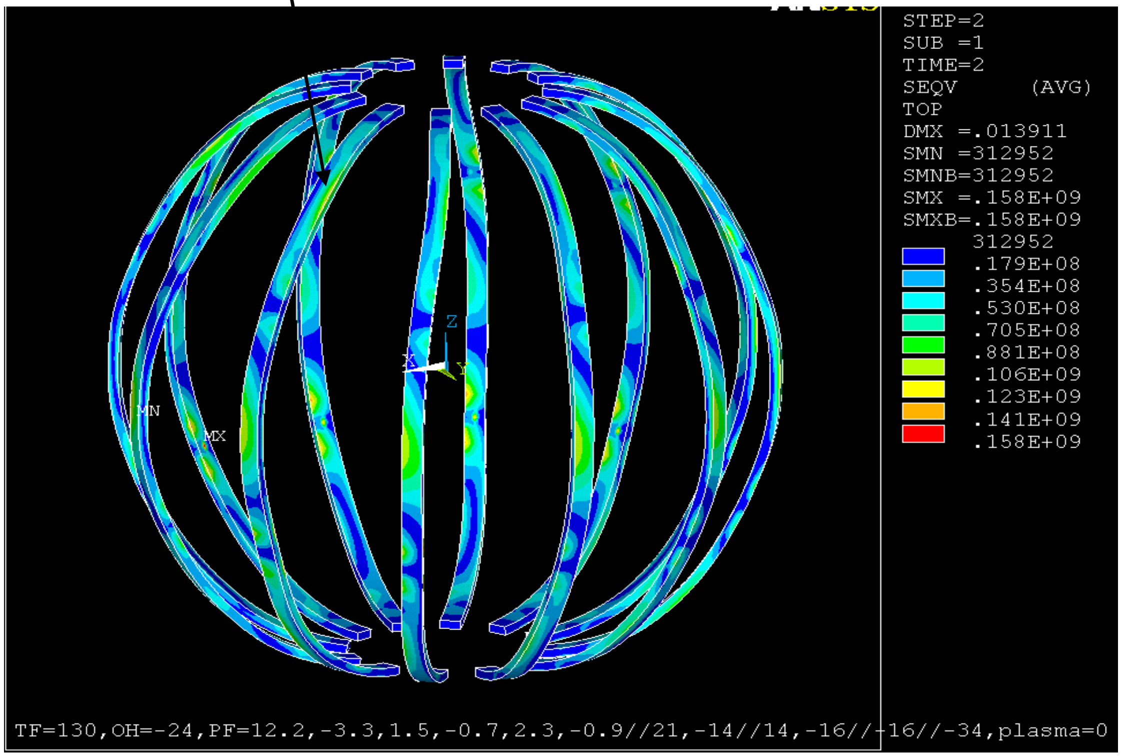


Tangential Radius Rod Concept Supports OOP Loads, Uses Territory That is Already Used By the TF Support Truss, and Allows Radial Growth During Bake-Out



Coil Bending Stress Asymmetric PF currents, H.Zhang Analysis of C. Neumeyer's "Worst Asymmetric Currents"

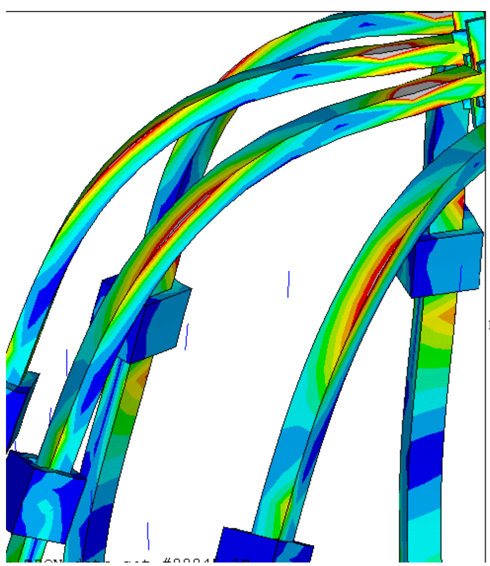
140 MPa



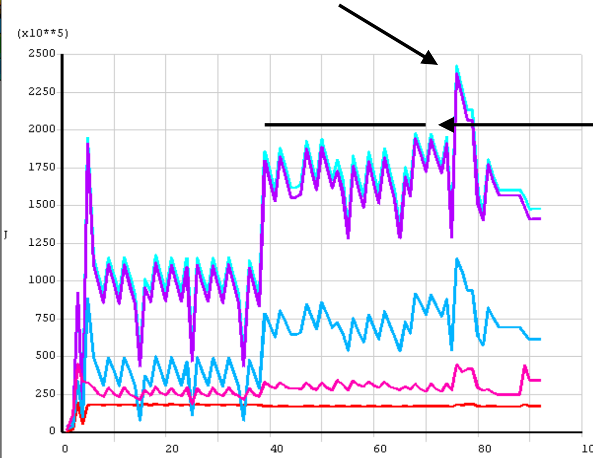
Global Model Upper Outer TF Leg SI

TF Copper

1.5*Sm = 233MPa



Charlies "Worst"



200 MPa

Vessel Stresses With Tangential Radius Rods

Arch Regions Needing Reinforcement

Positions of radius rod support (stress ~139MPa (20ksi)

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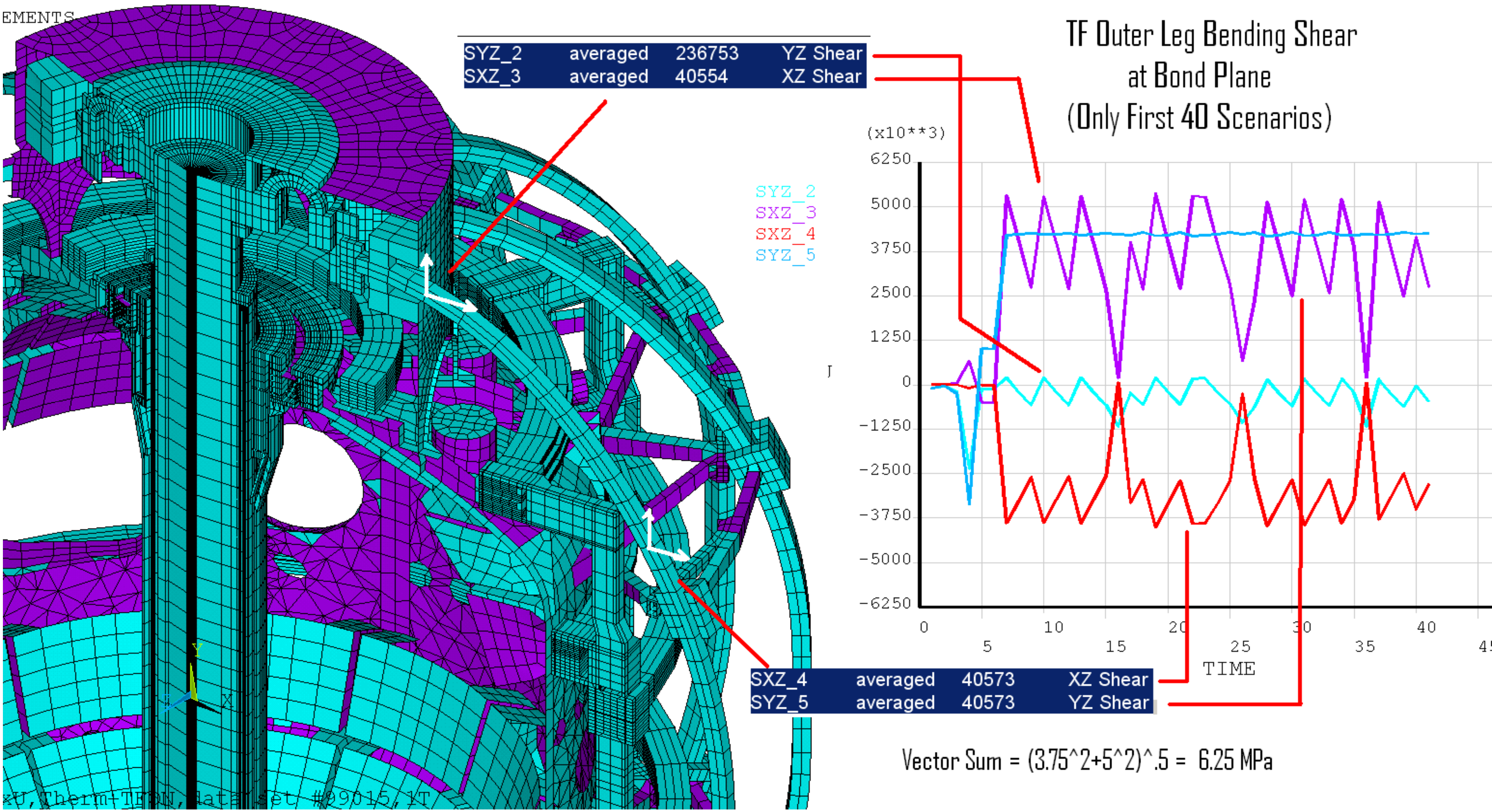
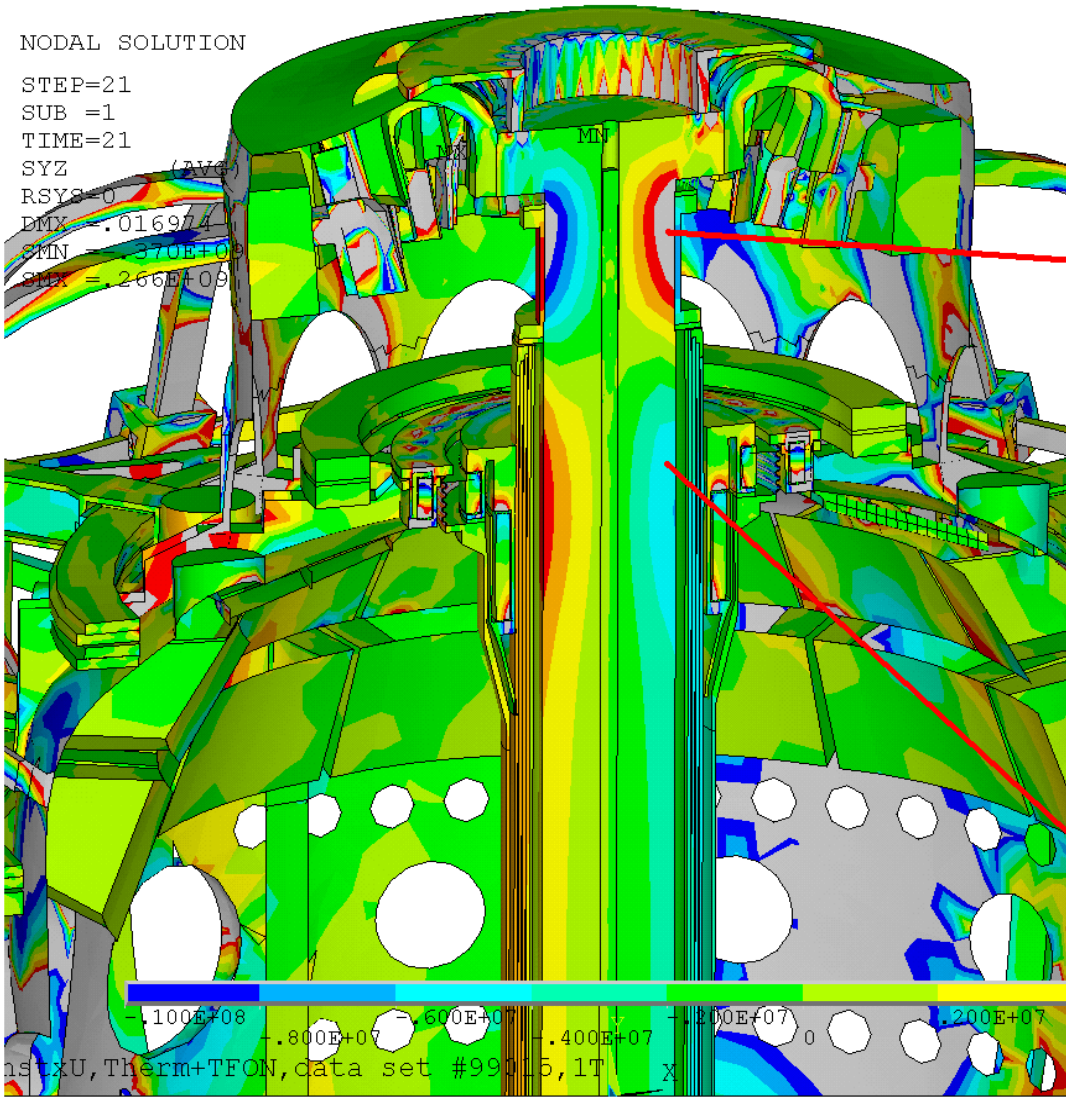
Outer Leg Turn to Turn Bond Shear

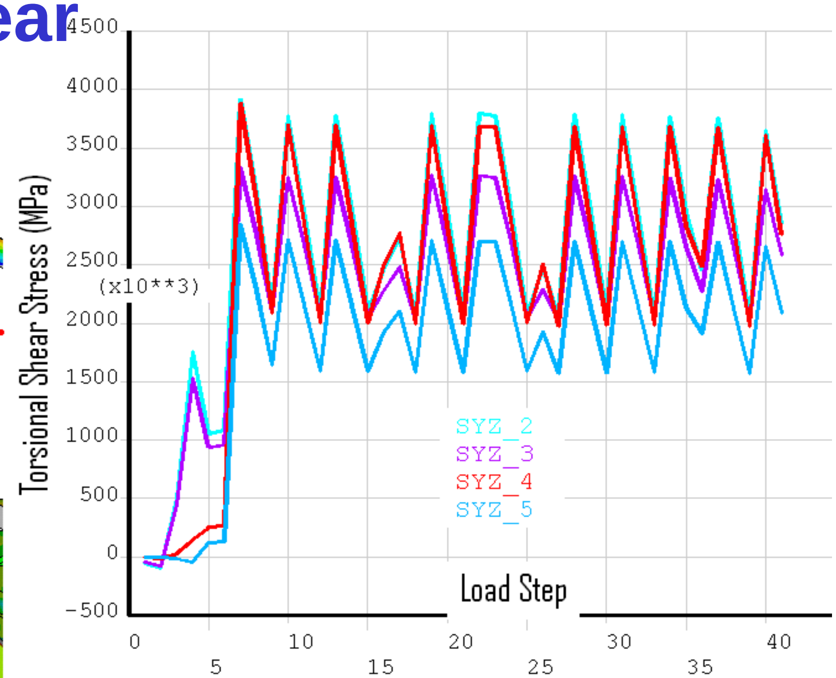
Insulation Shear Allowable= 2/3 of 32.5 MPa = 21.7 MPa

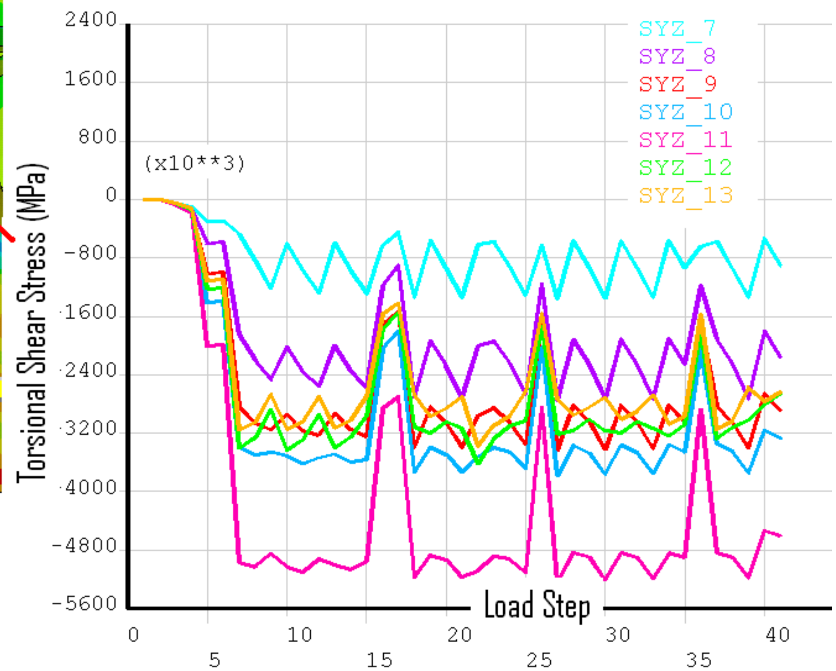


Vector Sum = (3.75^2+5^2)^.5 = 6.25 MPa

Normal Operating TF Inner Leg Torsional Shear

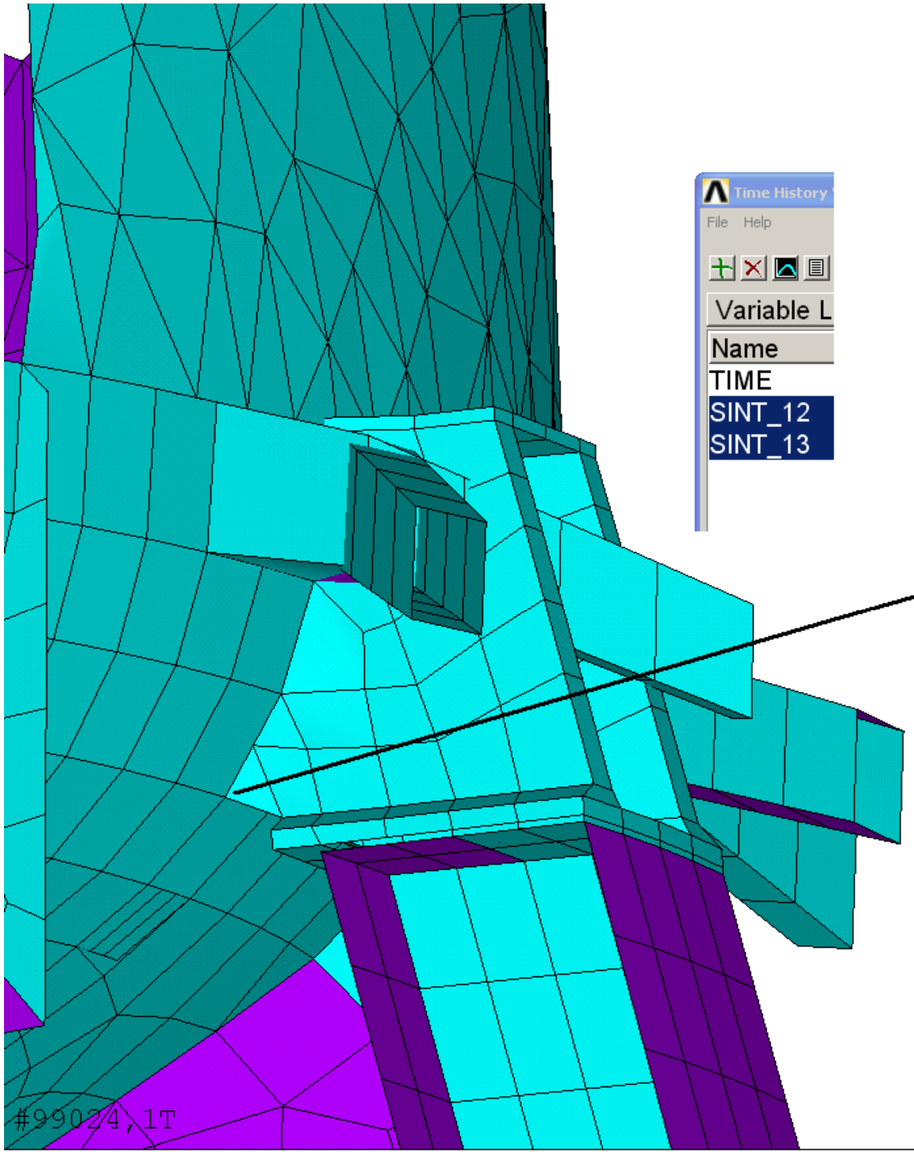


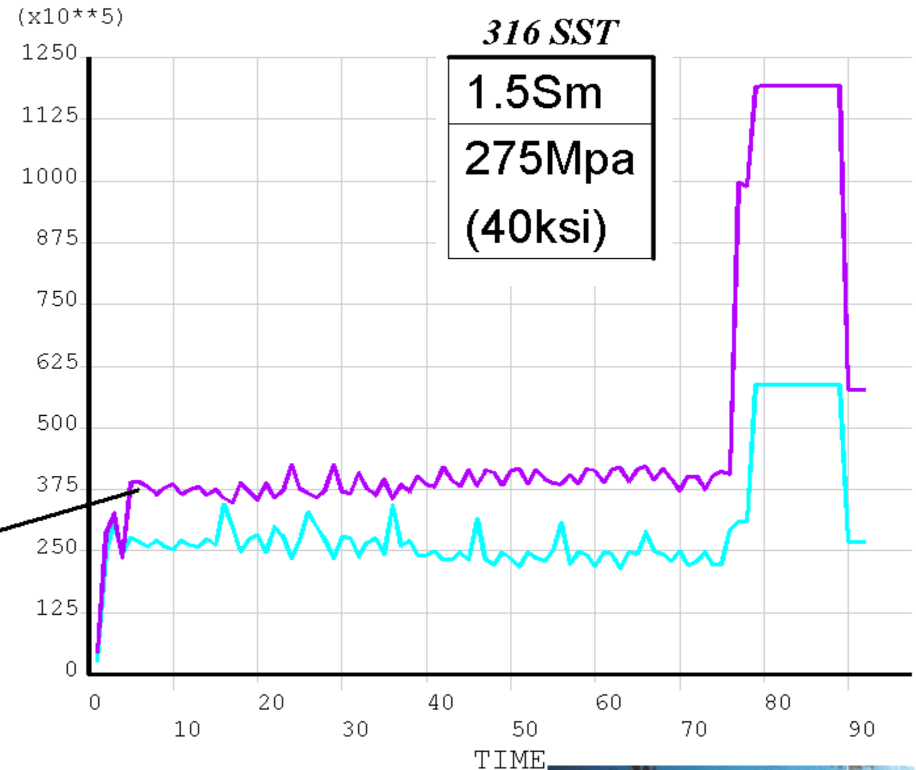




From the “worst” Currents, the worst torsional shear is 20.4 MPa with an allowable of ***21.7 MPa***

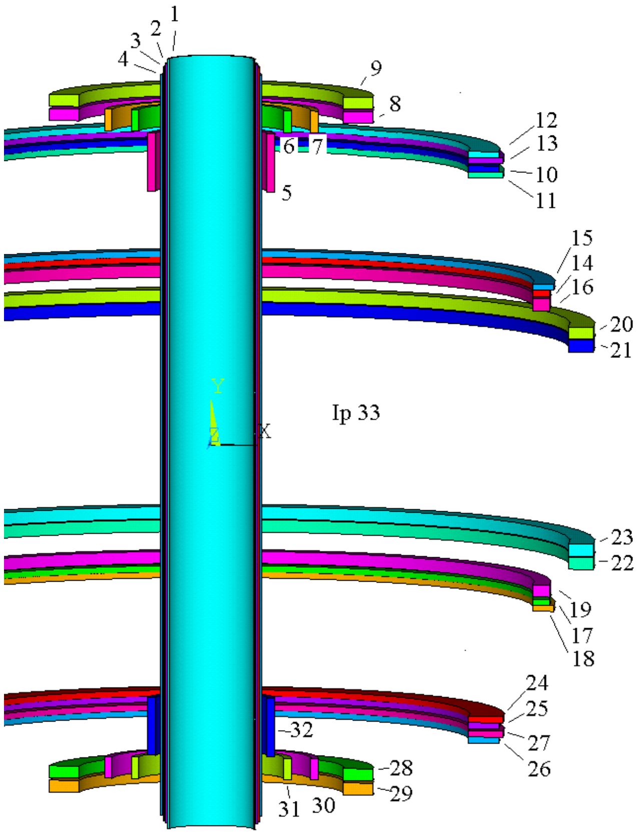
Support Leg-Vessel Intersection Stress

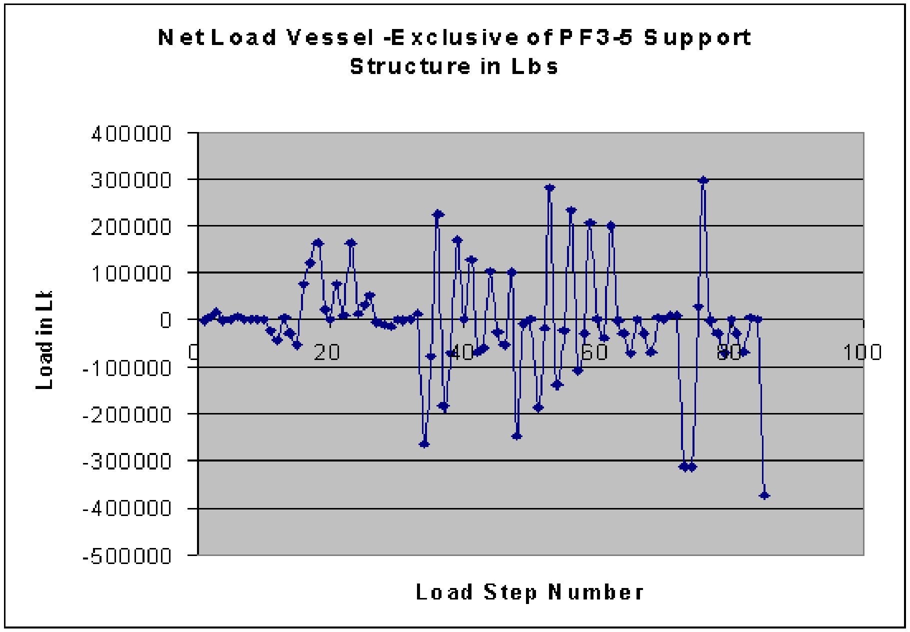


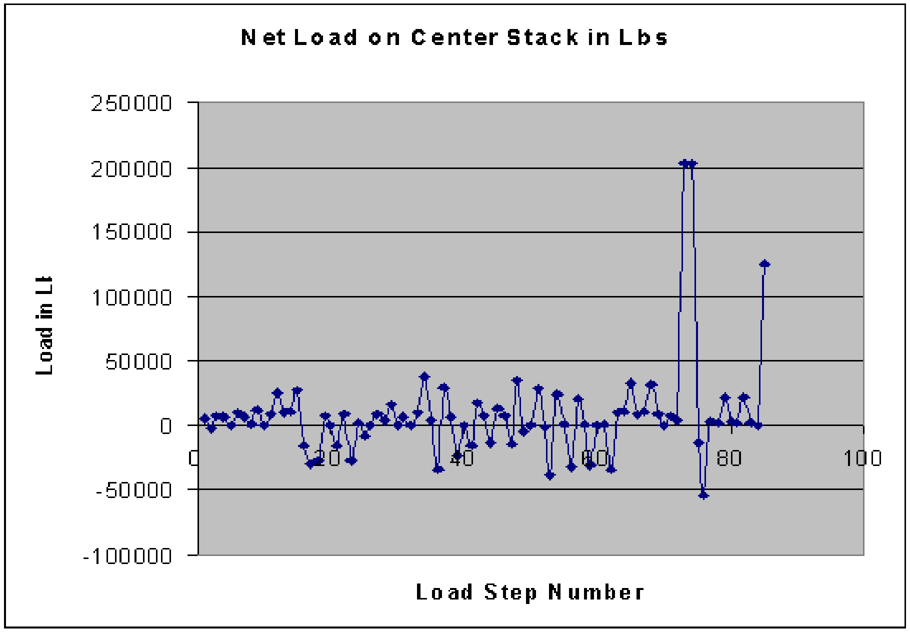


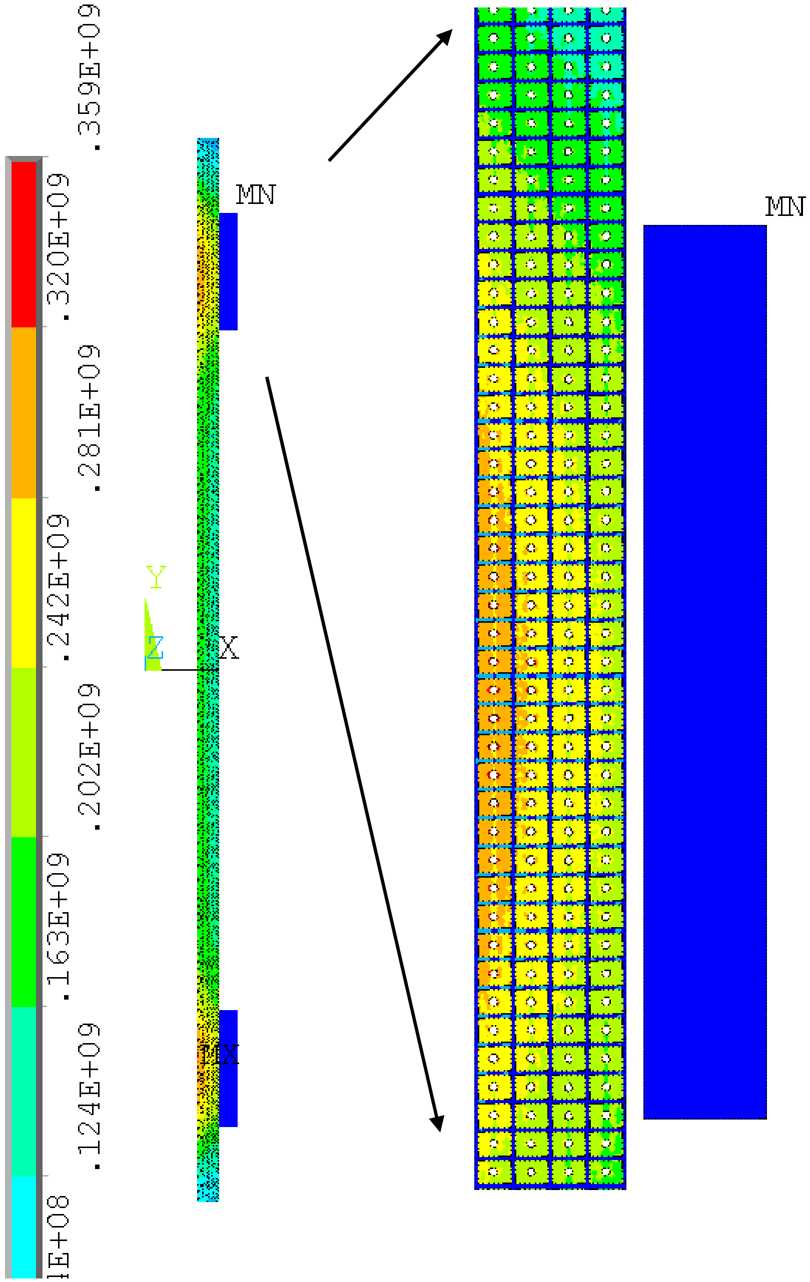
Net Load on Vessel (Global Model Load Files)

PF1c,2U&L Real Constants 7,8,9,28,29,30







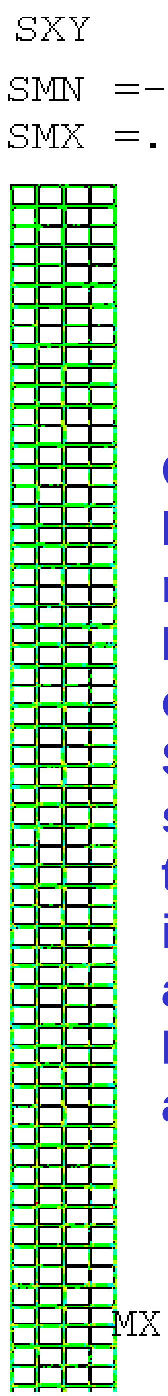


Influence of PF1A on the OH Coil

(A. Zolfaghari)

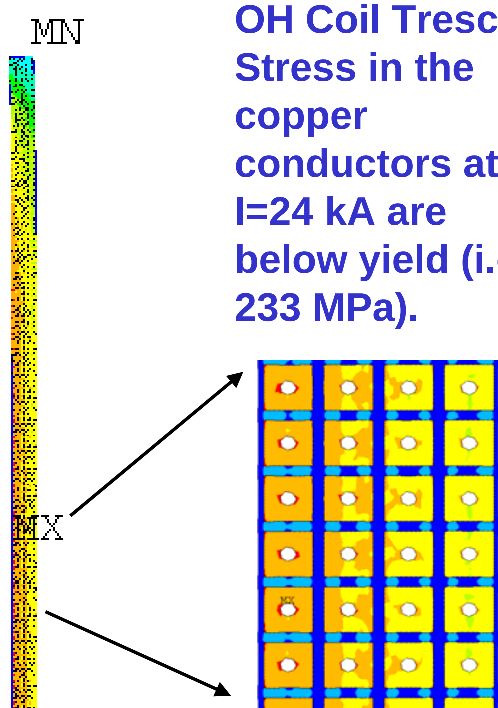
OH Coil at I=24 kA, PF1A at full current of 12.2 kA: The full current in PF1A coil causes stresses beyond yield (233 MPa) in the copper.

This led to a Limit on the OH swing from +24kA to -13kA

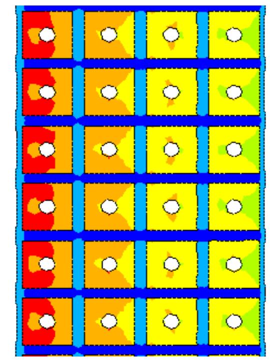


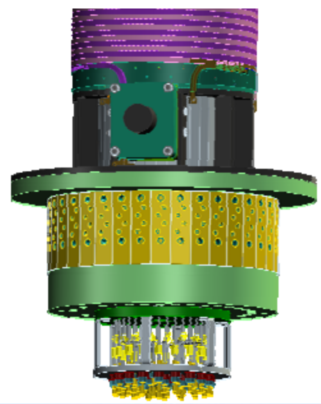
OH Coil at I=24 kA, with reduced PF1A current of 4.2 kA. Shear stresses in the insulation are below 22 MPa allowable.

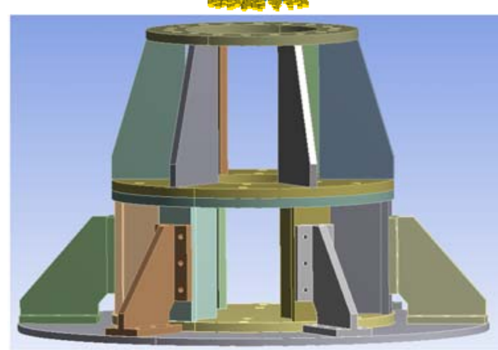
OH Coil Tresca Stress in the copper conductors at I=24 kA are below yield (i.e. 233 MPa).



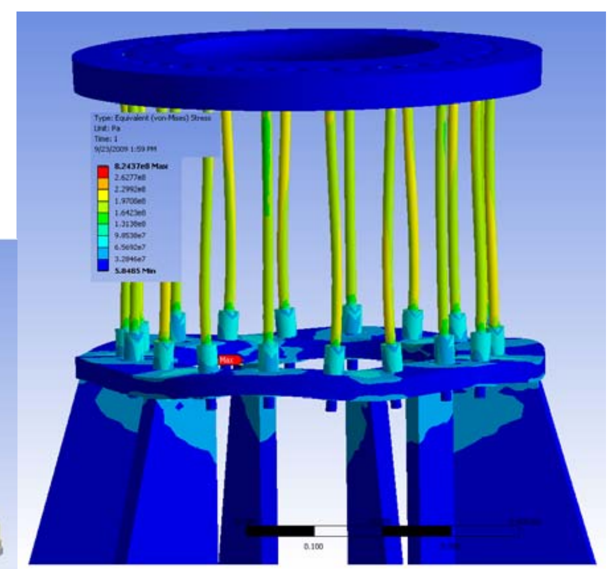
OH Coil Self Hoop Stress =157MPa at I=24 kA:







TF Tie Bolts and Pedistal OK for 130 kip Upward Load



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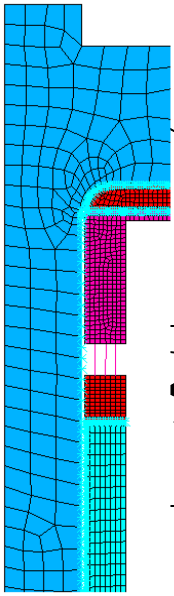
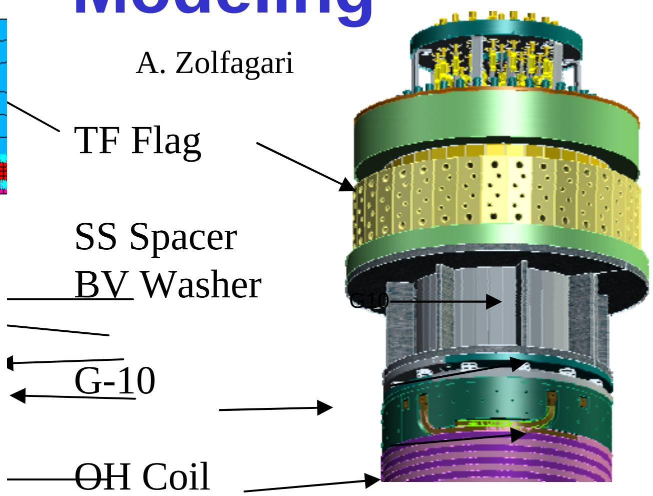
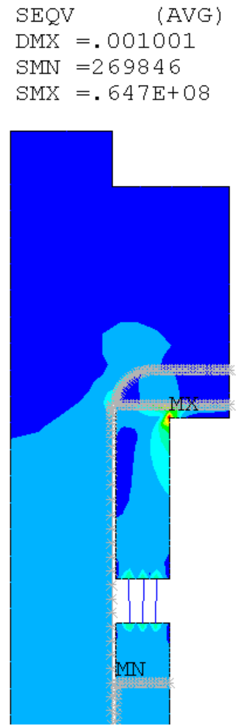
CS Structural/Emag Modeling

A. Zolfagari



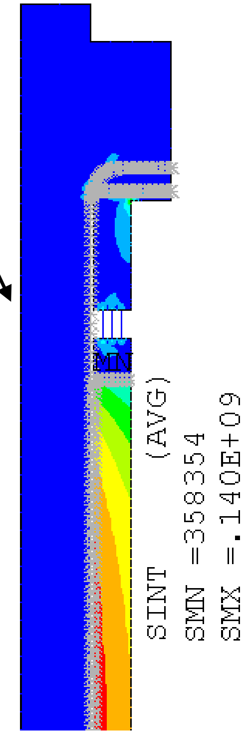




No currents, Cold TF, Cold OH

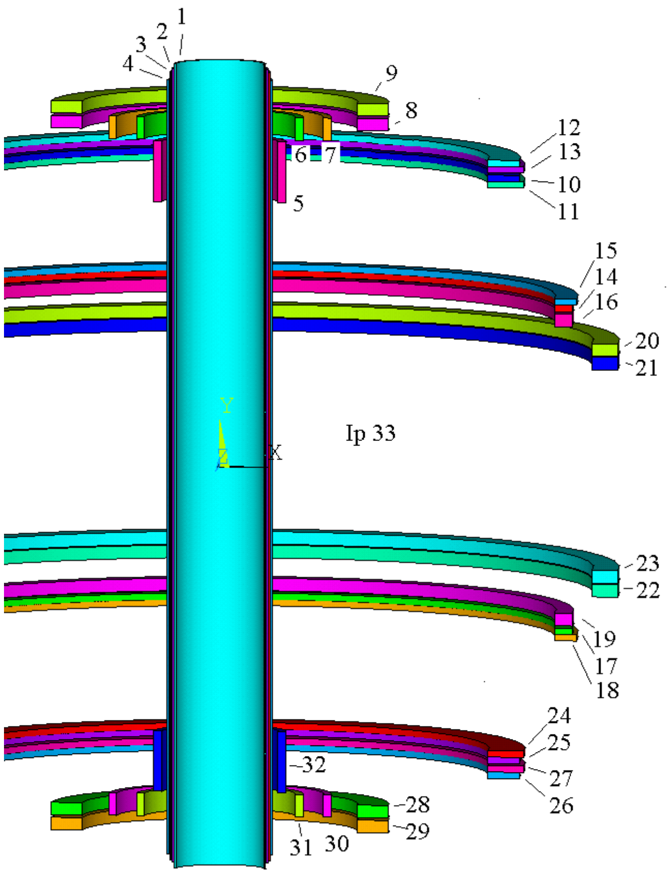
Bellville stack, 18 mm preload and 2.5e7 N/m spring constant

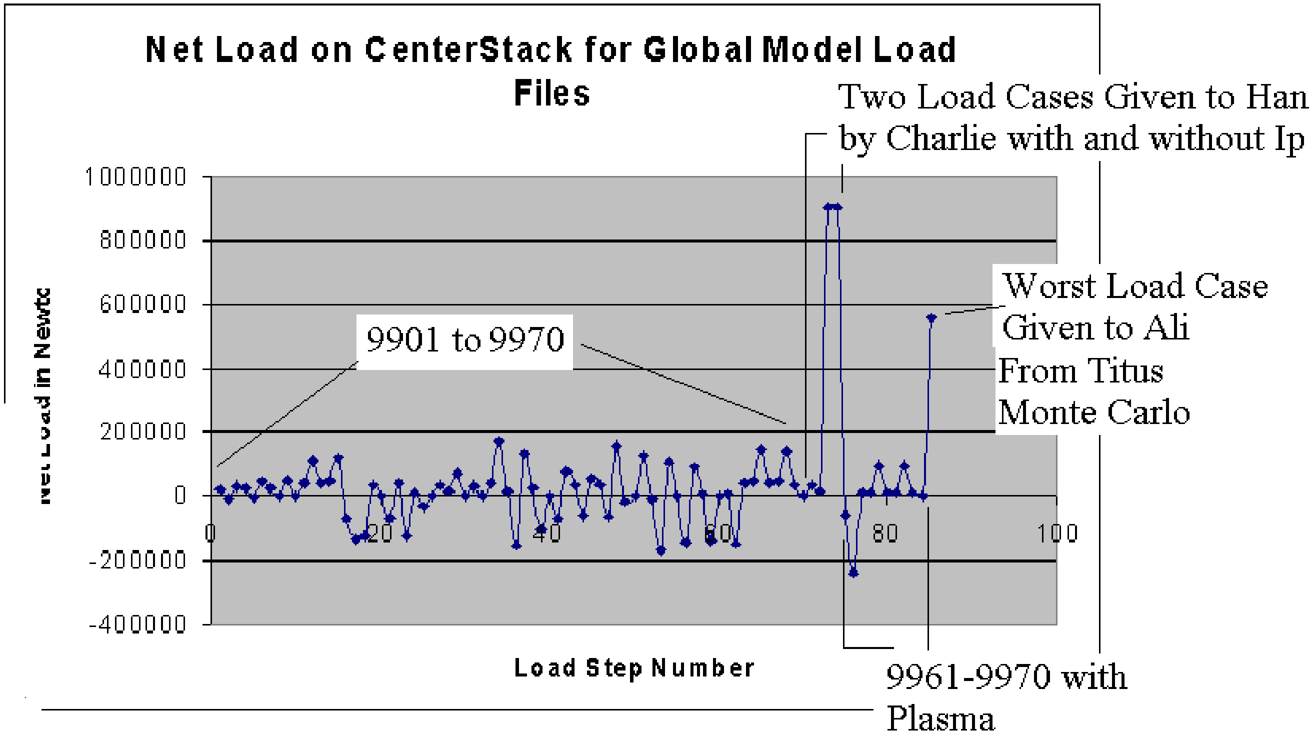
Hot OH, Cold TF, OH Self EM Load

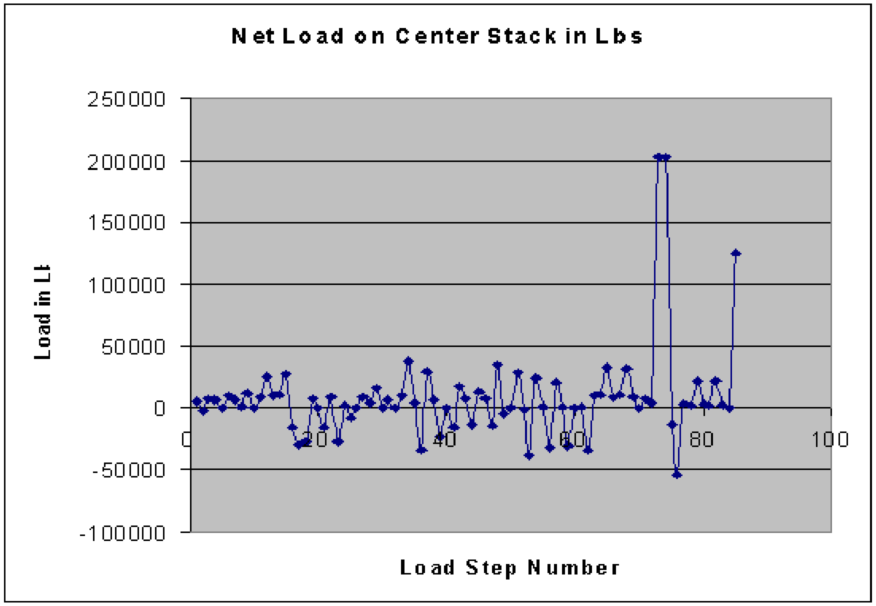


TF Temp.	OH Temp.	TF Current	OH Current	Launch Force	Peak OH Stress	Peak TF Stress	Peak Displacement	OH Lifted?	Case #	Notes
COLD	COLD	OFF	OFF	OFF	7-14 MPA	7-14 MPA	0.6 mm TF	NO	00000	Bellville staff force only
HOT	COLD	ON	OFF	OFF	102-115 MPA	38-51 MPA	8.8 mm TF	NO	10100	TF grows pushing OH laterally
COLD	HOT	OFF	OFF	OFF	10-19 MPA	19-29 MPA	4.6 mm OH	NO	01000	
COLD	HOT	OFF	ON	OFF	125-140 MPA	16-31 MPA	1.6 mm OH	NO	01010	TF was off and OH current was turned on with hoop stress only
COLD	HOT	OFF	ON	ON	123-138 MPA	16-31 MPA	1.9 mm OH	NO	01011	TF was off and OH current was turned on with hoop stress and launch force.
HOT	COLD	ON	ON	ON	117-132 MPA	15-29 MPA	8.2 mm TF	NO	10111	Just in case, OH getting current before heating up
HOT	HOT	ON	ON	ON	110-134 MPA	15-19 MPA	8.3 mm	NO	11111	

Net Load on CS Real Constants 1,2,3,4,5,6,31,32



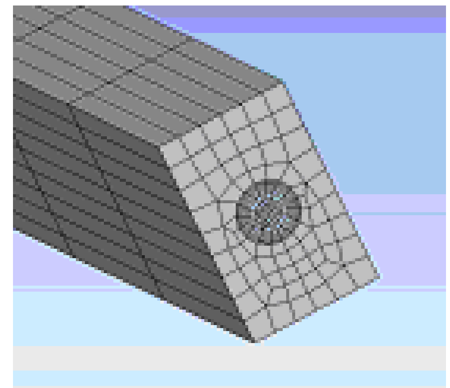




Center Stack
CS Coolant Hole Optimization, CFX, FCOOL –
(Ali Zolfaghari, Fred Dahlgren))

Optimizing the coolant channel diameter:

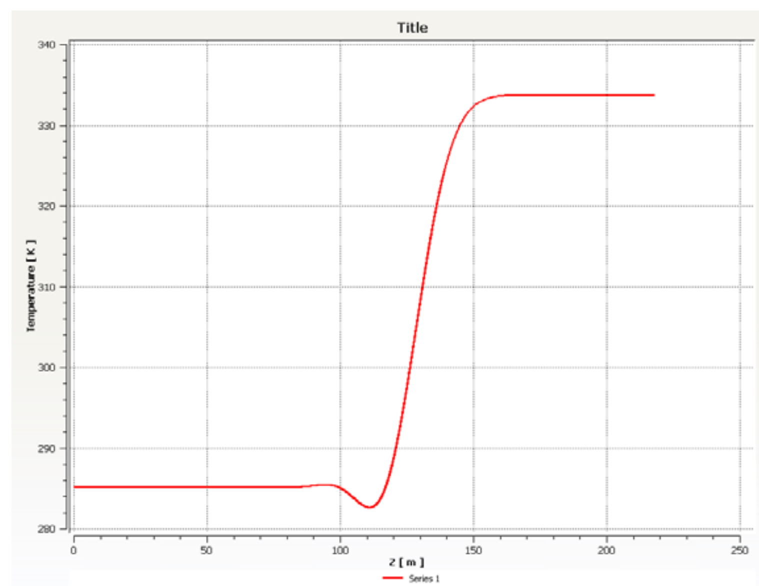
- Started from 0.188 in. diameter in existing NSTX OH coil. Analysis shows that increasing this diameter leads to coil temp above 100° C for I=24 kA and Tesw=0.8 s and higher.
- Decreasing the coolant channel diameter allows higher Tesw at the expense of cooling time.
- A diameter of 0.175 in. allows a Tesw of 0.85 sec. (I=24 kA) in the coil without exceeding 100° C.



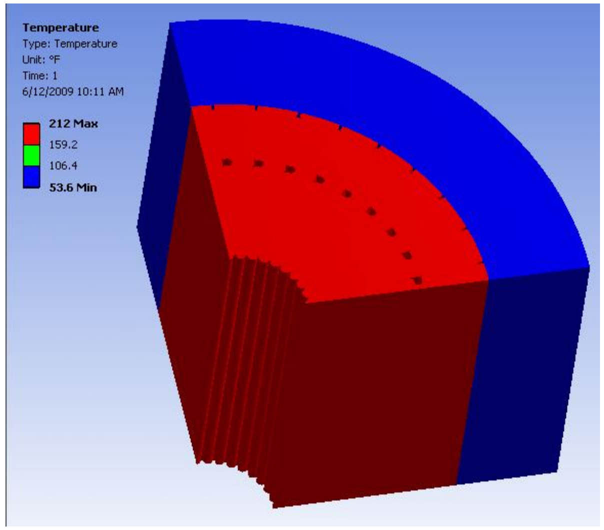
Conclusions:

- 0.175 in. coolant channel diameter is optimal. This value keeps the maximum conductor temperature below 100° C for I=24 kA and Tesw=0.85 s allowing scenarios with OH double swing.

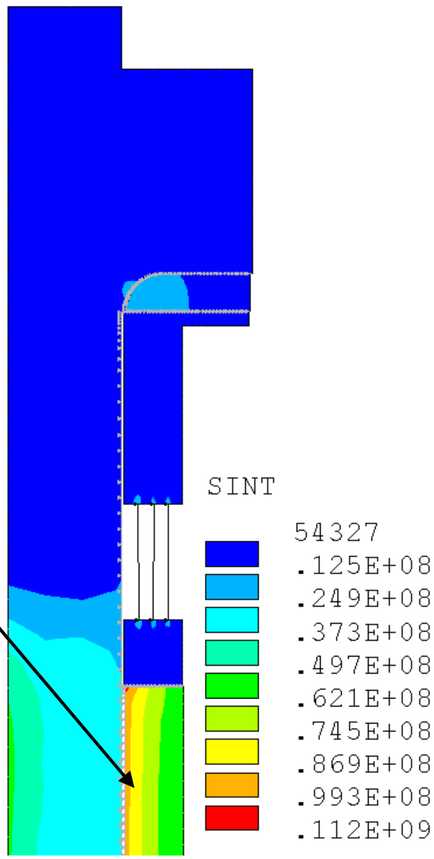
- Using 0.175 in. coolant channel diameter, an effective pressure drop of 500 PSI is needed to keep the coil cooling time below 20 minutes.



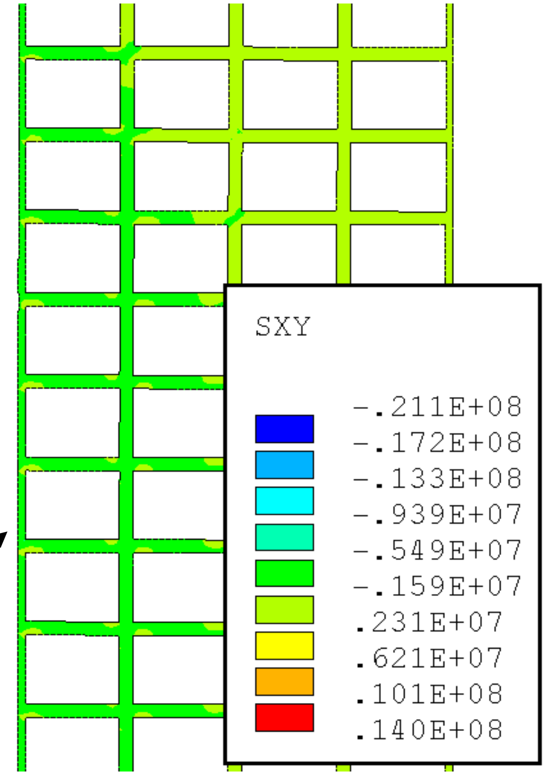
Winding the OH on the TF



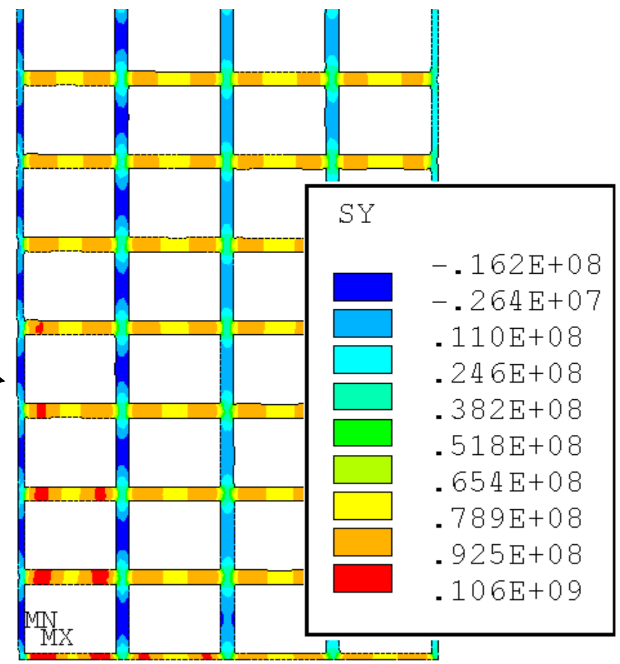
Hot TF Cold OH Produces Acceptable Hoop Stresses



But Frictional Shear Along the height of the interface Produces:



Unacceptable Axial (Vertical) Tension in the OH



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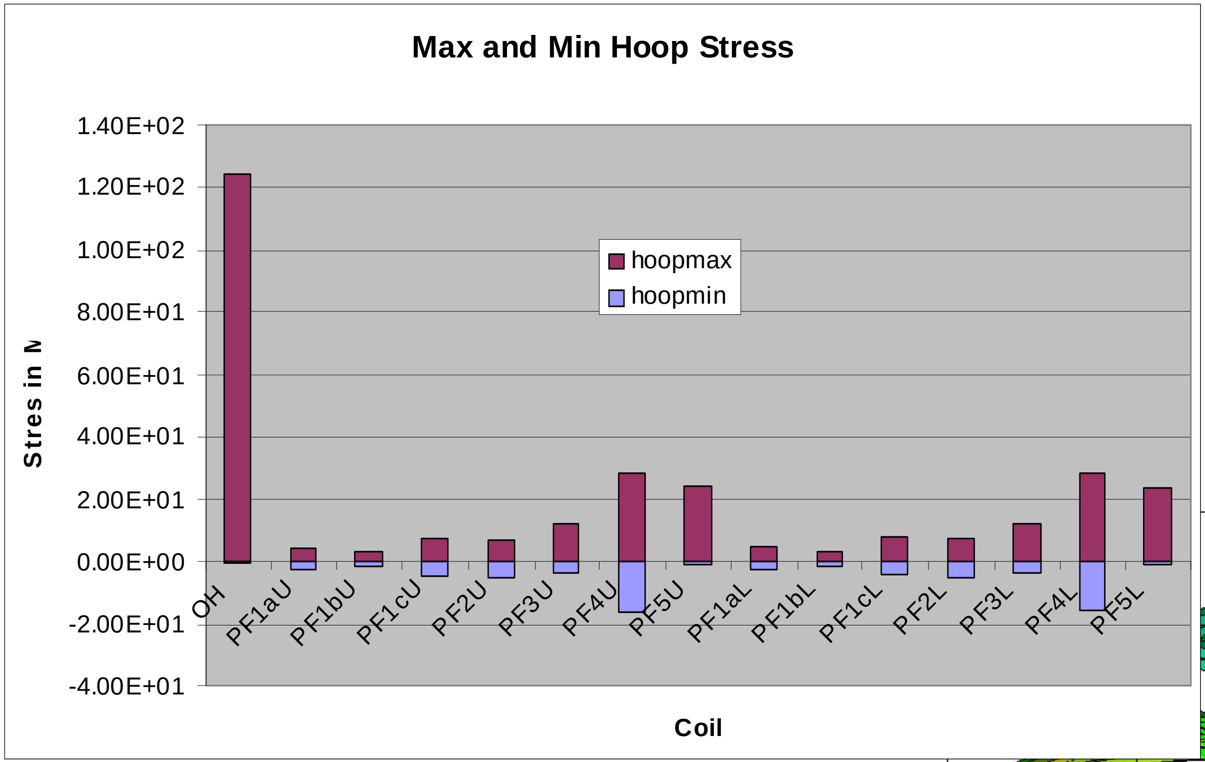
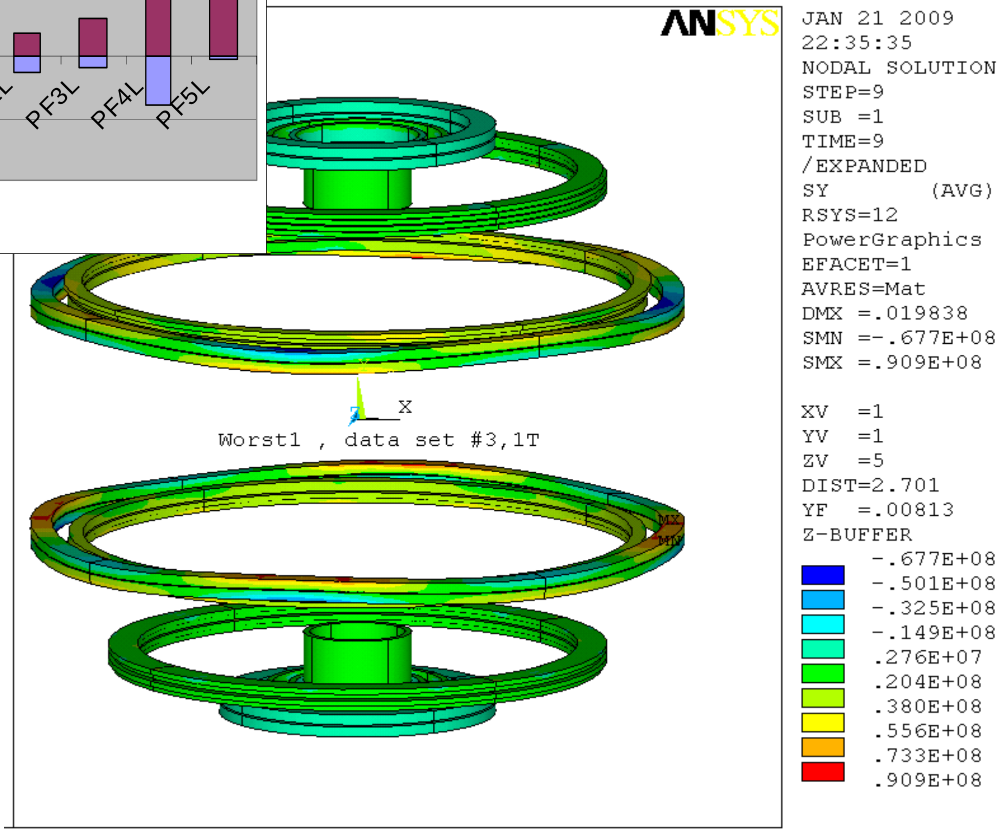
PF Hoop Stress





In all but the OH, the hoop stresses are small. Hoop strains are small allowing “non-flexible” supports to resist the vertical loads

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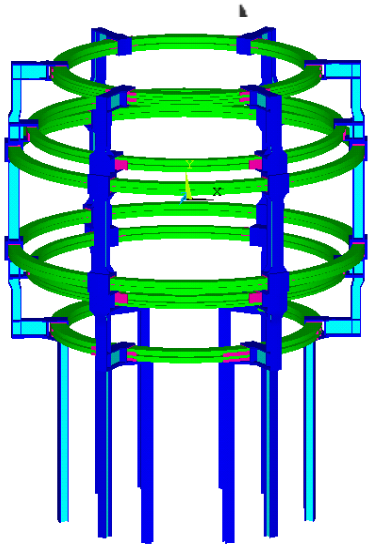
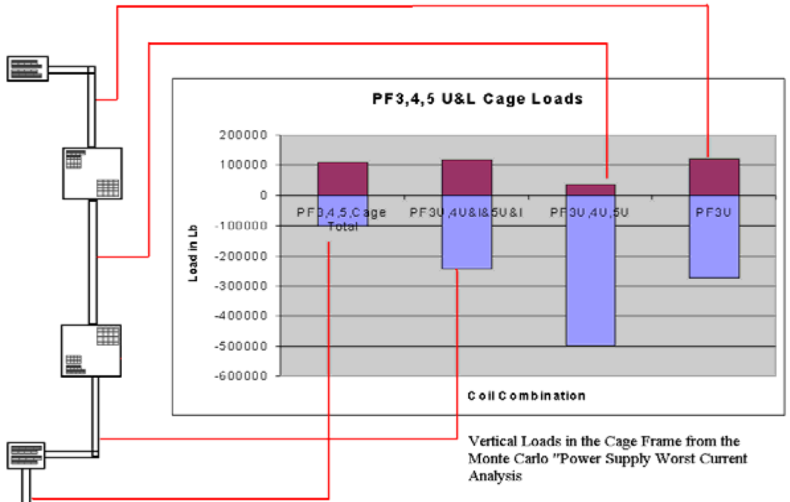
NSTX CSU

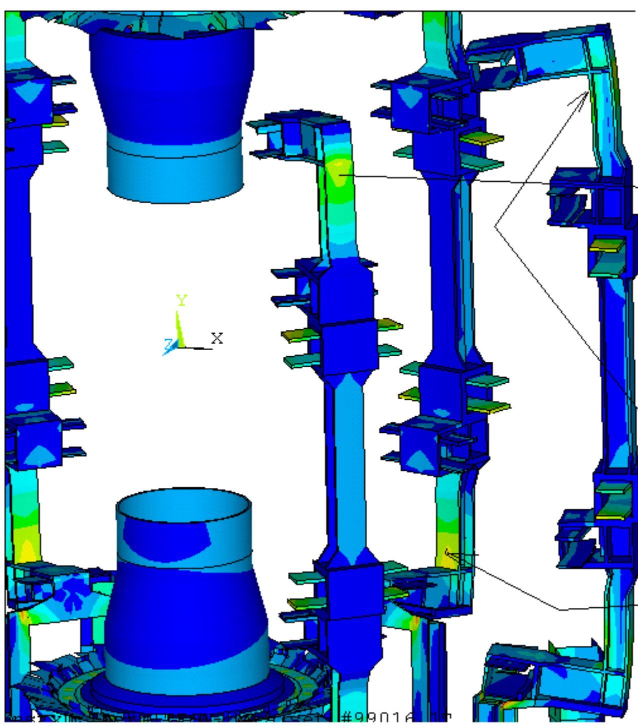
PF 3,4,5,U&L Support Cage – 6 Support Points Global Model Results

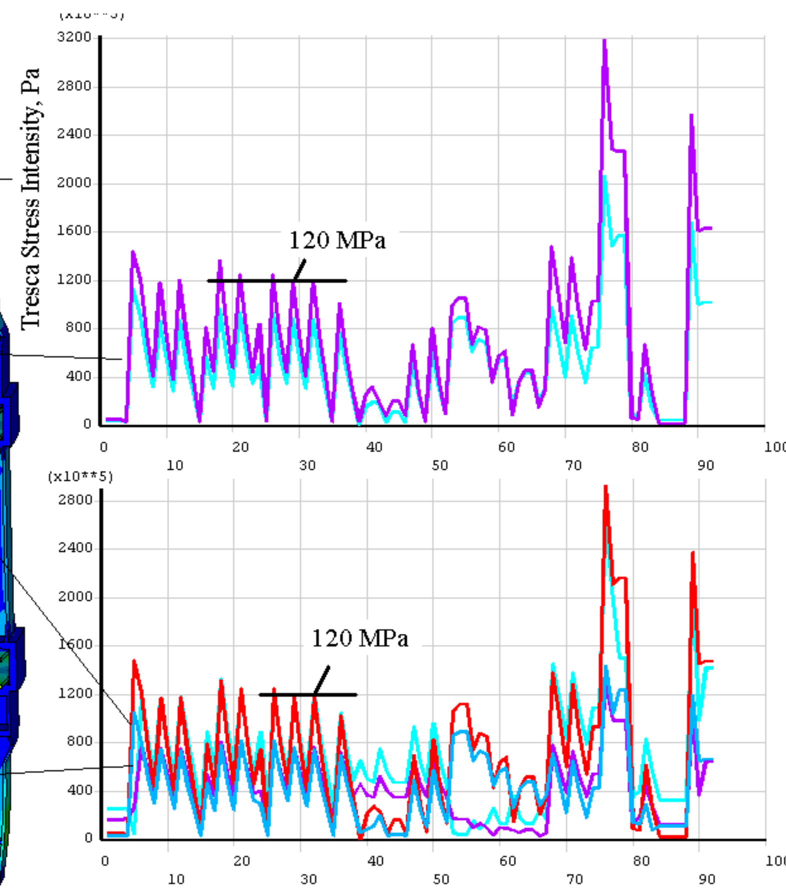




Vertical Loads in the Cage Frame from the Monte Carlo "Power Supply Worst Current Analysis

Stresses in PF 3,4,5U&L Support Cage
(Only 6 Supports)





316 SST
1.5Sm
275Mpa (40ksi)

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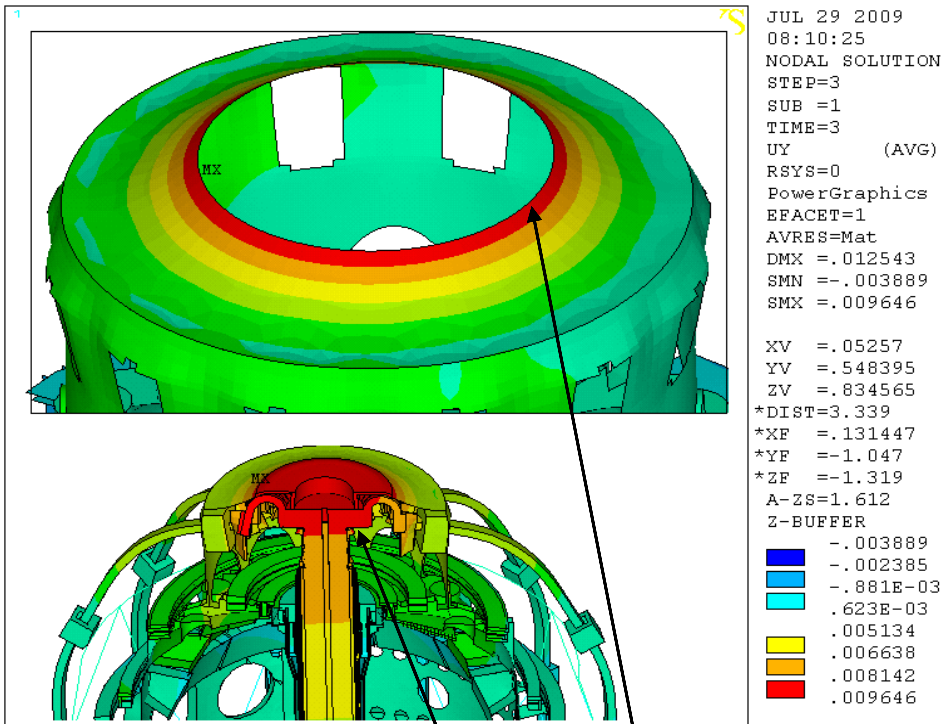
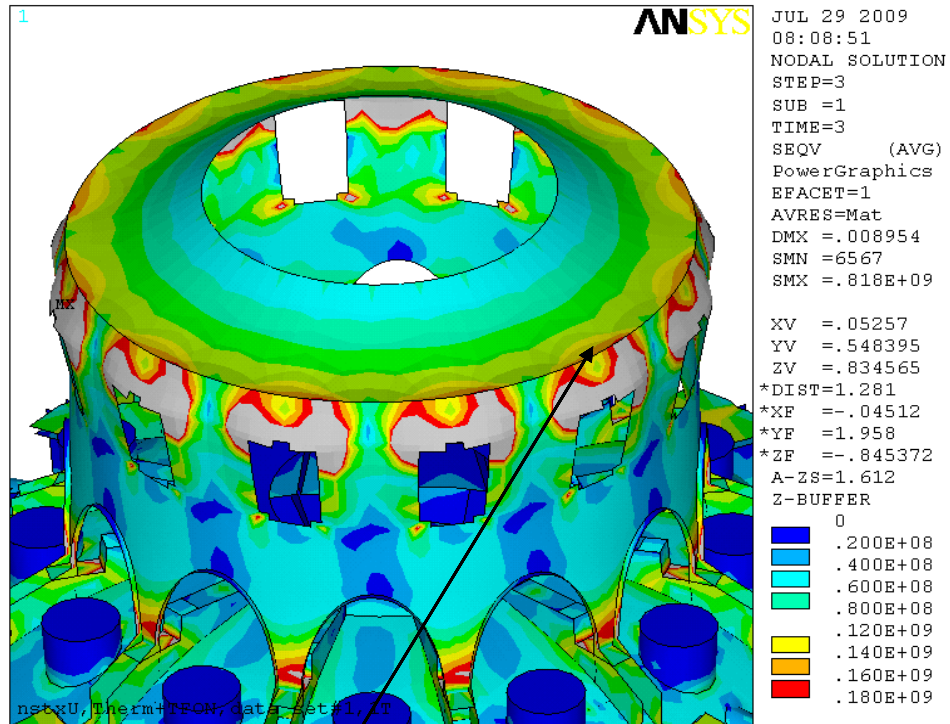
NSTX CSU

Upper Flex Plate/Diaphragm Replaces the Gear Tooth Connection

Hot Central Column, Cold Vessel



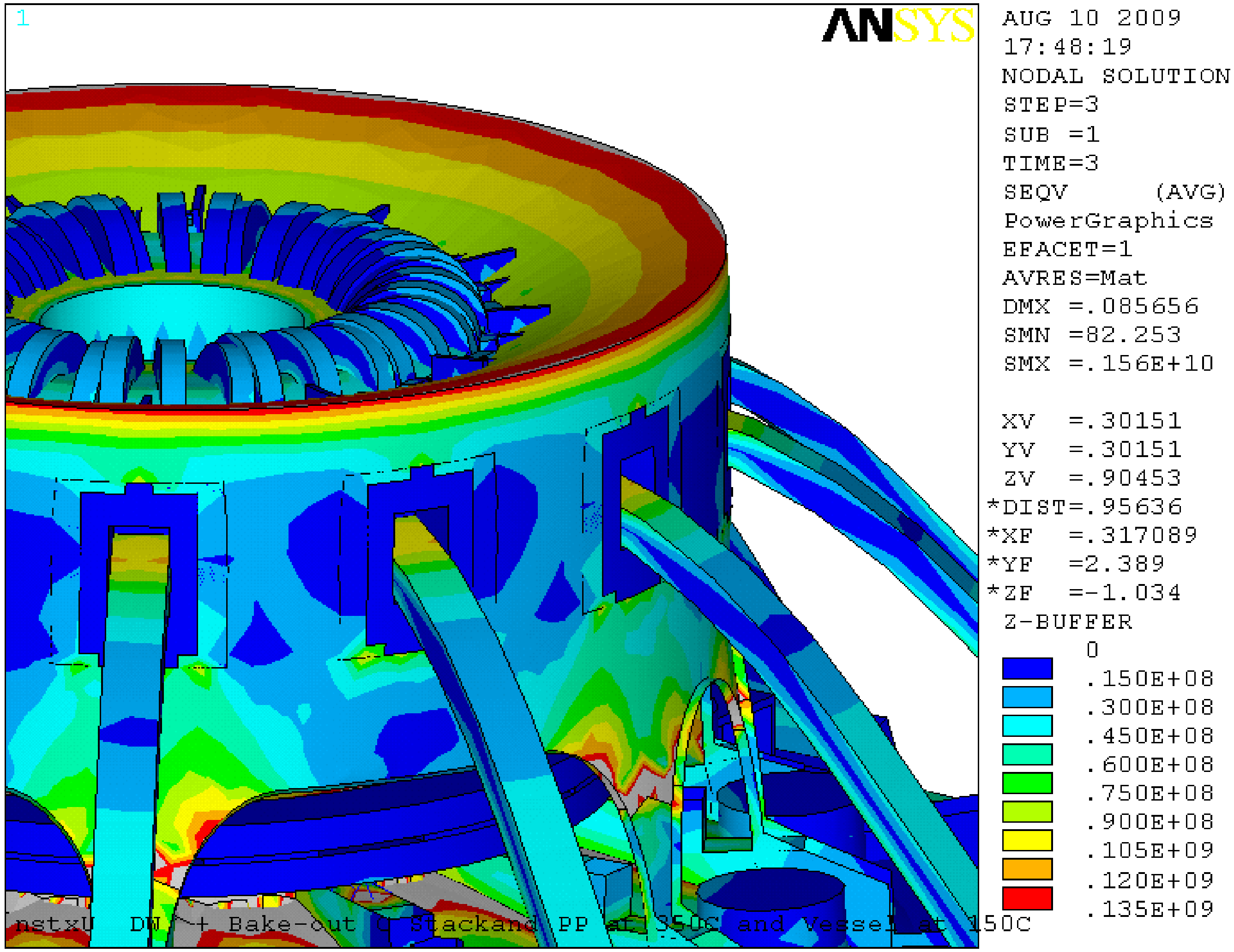


Central Column
Expands 9mm

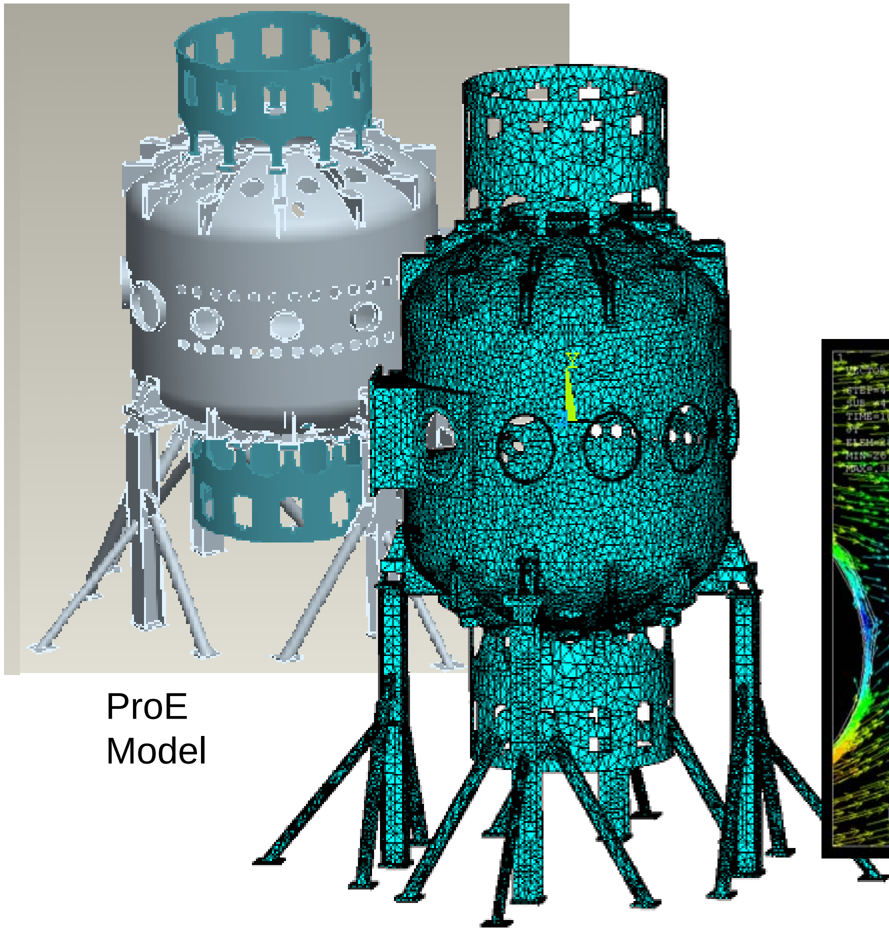
5/8” Flex/Diaphram, 150 MPa
Note Non-Uniform Stress when TF Expands

Upper Flex Plate/Diaphragm Replaces the Gear Tooth Connection

- Vessel at 150C during Bake-Out RT Central Column
- Vessel Expands +8mm
- Flex/Diaphram Stress is 135 MPa
- Note Uniform Stress at Edge



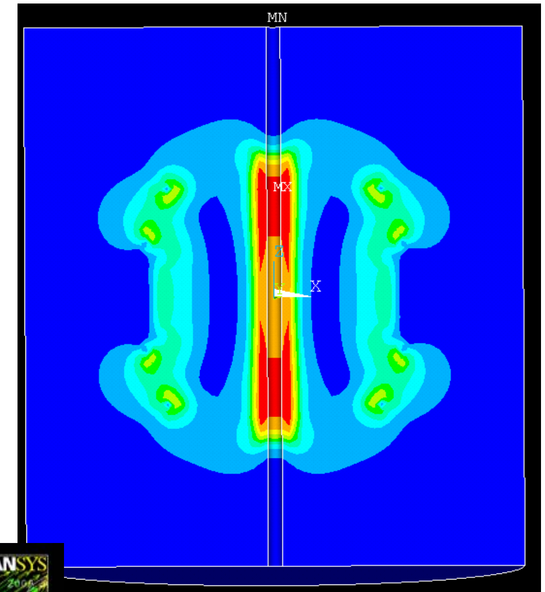
NSTX Disruption Analysis
Mid-Plane
2MA Ip Disruption

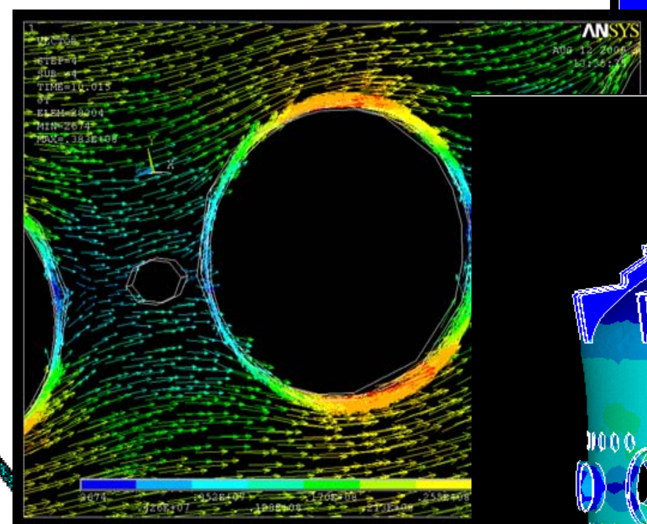


ProE
Model

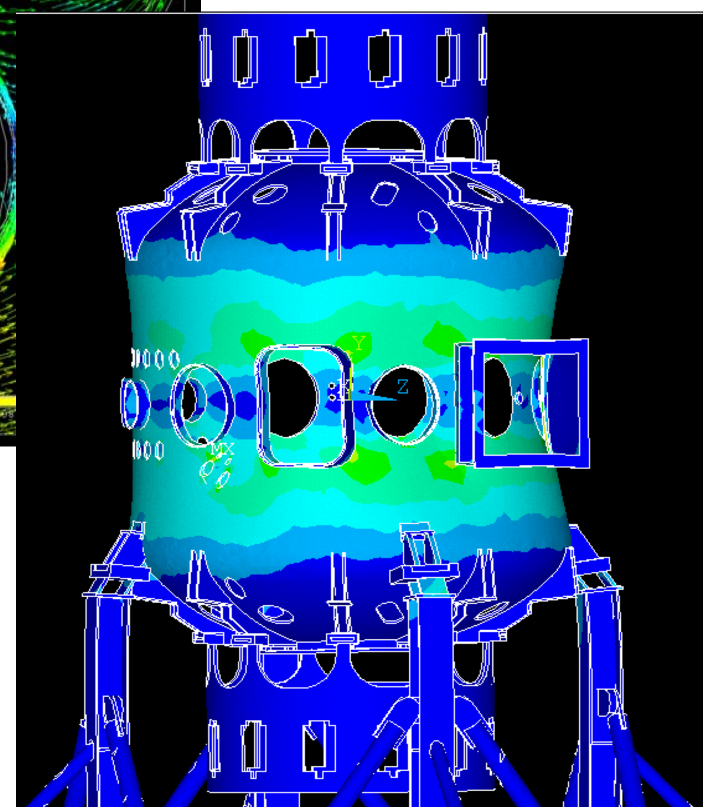
Meshed in
Classic
ANSYS

Axisymmetric
Opera Vector
Potential
Solution
Imposed on
ANSYS EM
Analysis





ANSYS EM Loads
Passed to ANSYS
Stress Analysis



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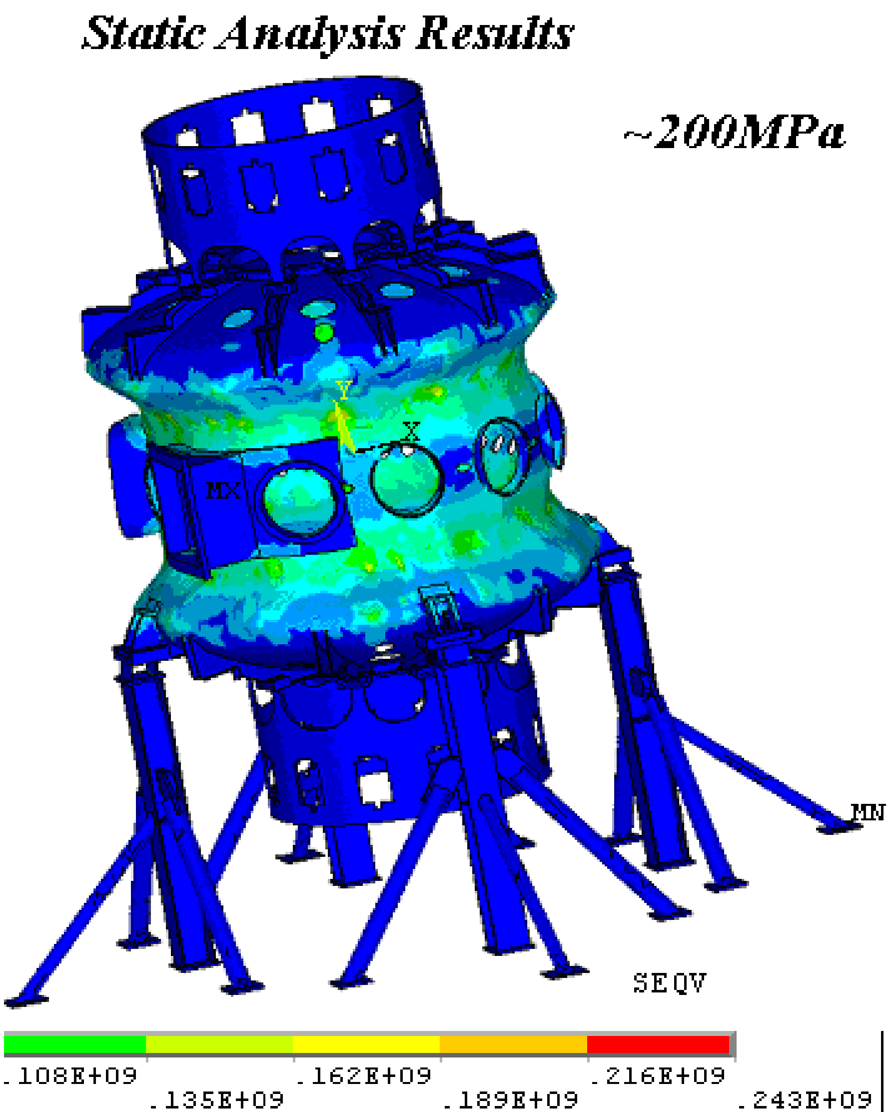
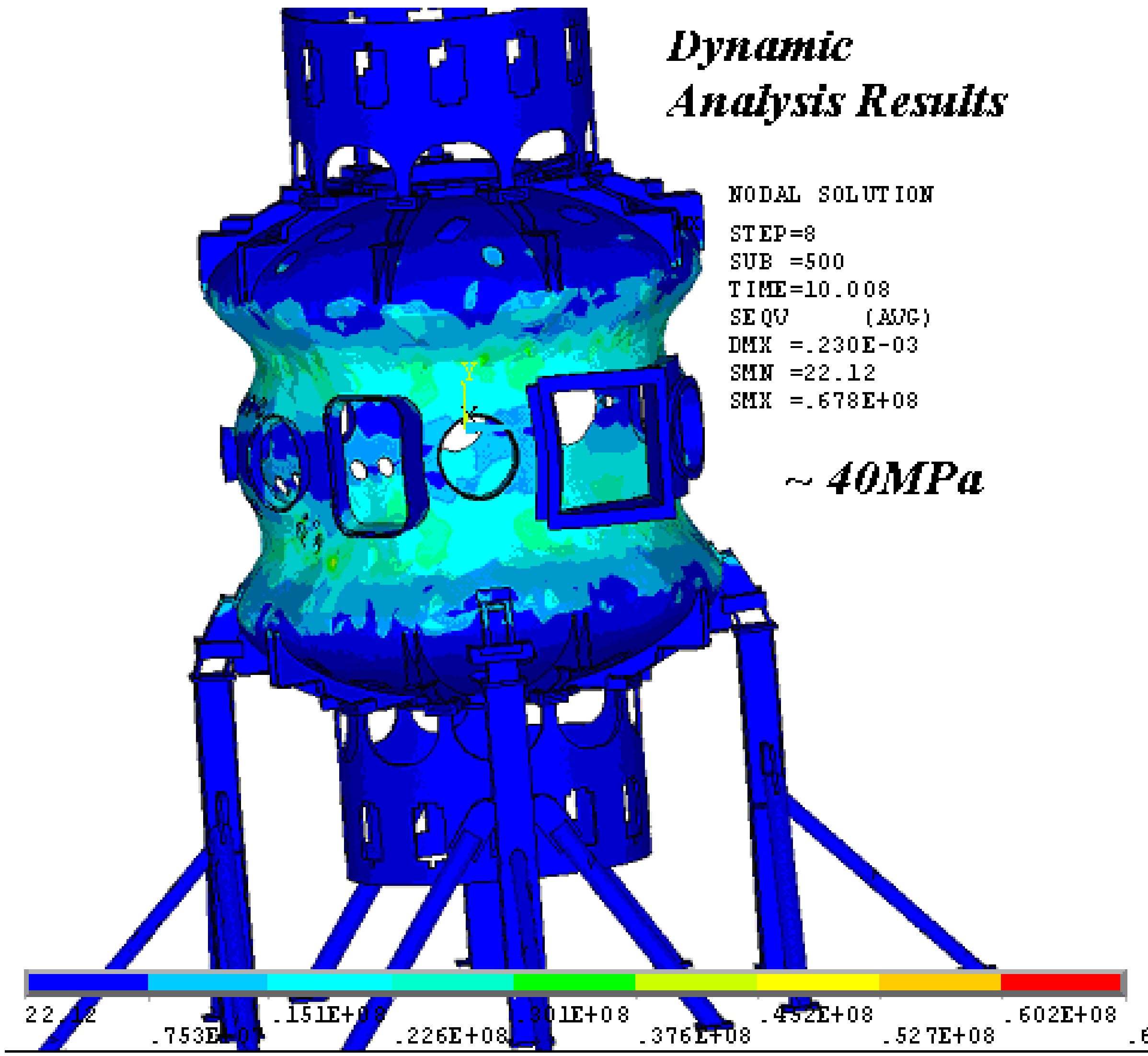
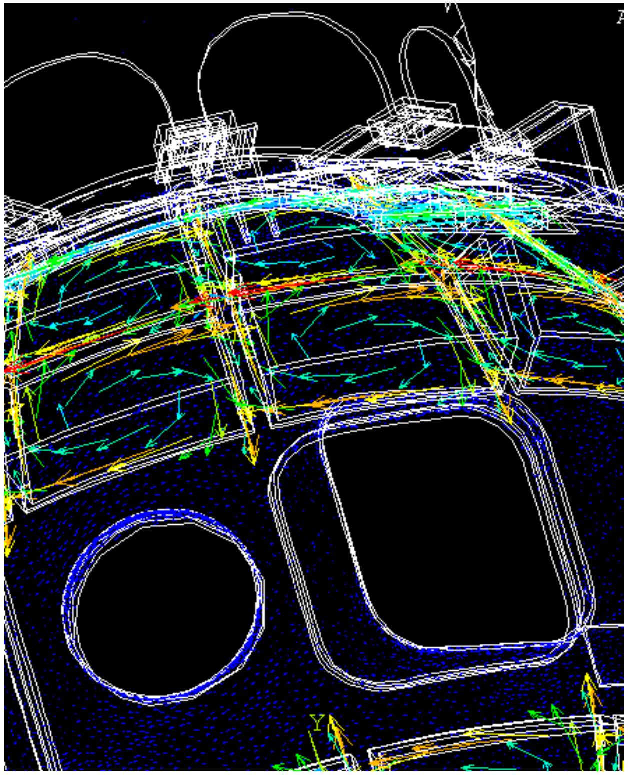
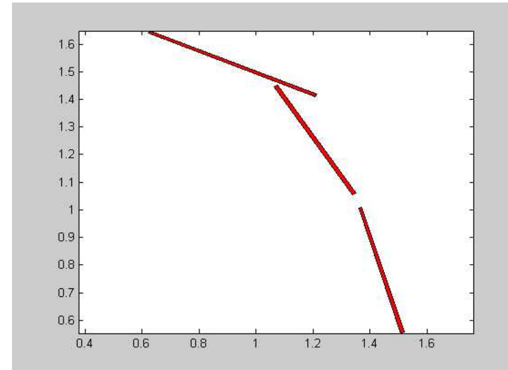
Vessel Stresses





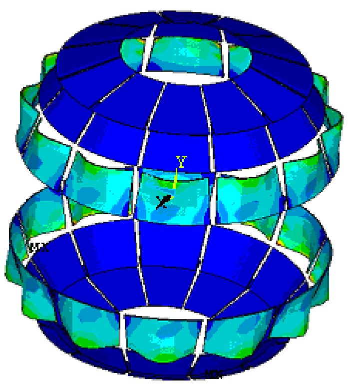
Passive Plate Disruption Eddy Currents and Stresses



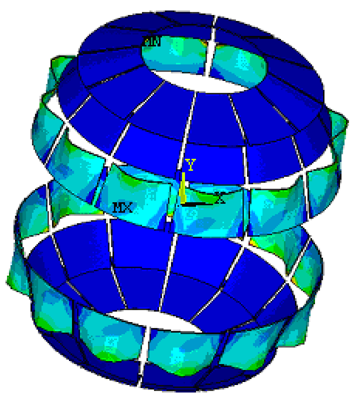


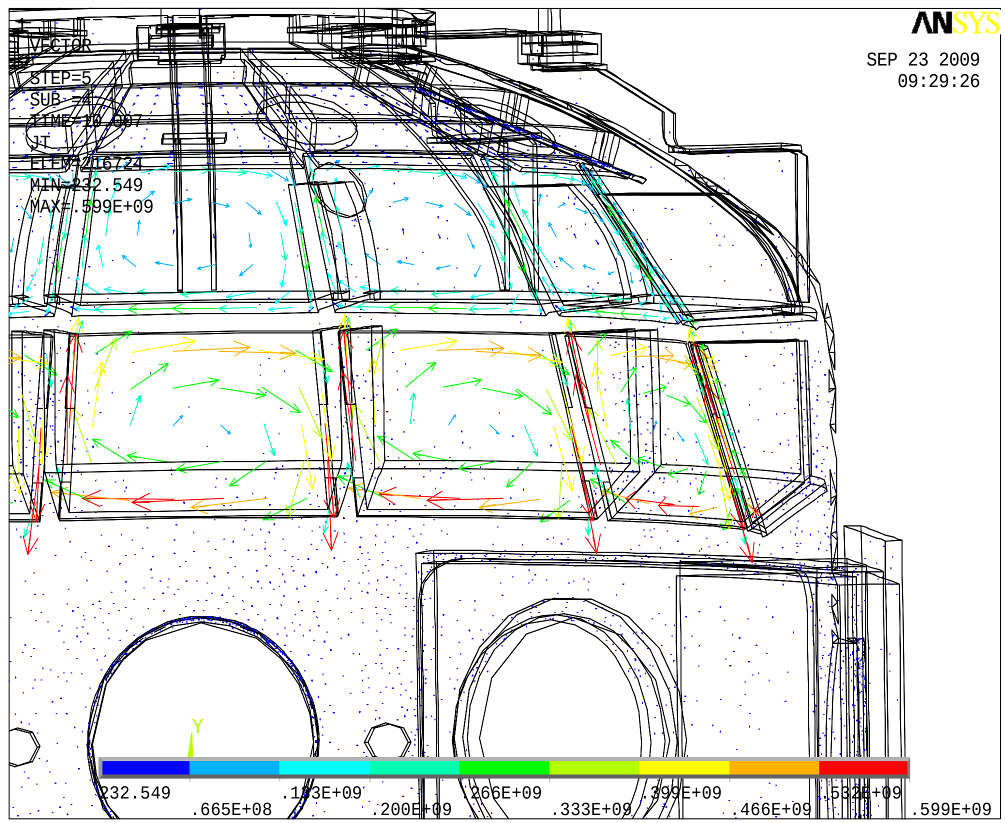
OPERA PP Geometry

2410 MPa from the Static Analysis



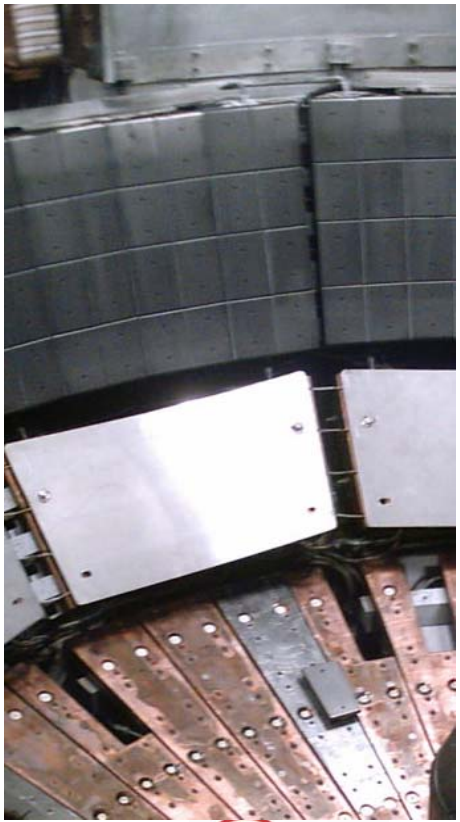
290 MPa from the Dynamic Analysis





Passive Plate/Vessel Disruption Analysis Conclusions:

- The Dynamic Load Factors are found to less than 0.25
- The stresses are under acceptable limit.
- Macros developed here could be used for other models to simulate disruption stresses.
- This method (of imposing Vector Potentials) circumvents the modeling of air and other complexities involving complex 3-D geometry.
- The disruption scenario studied here is just the Out Board Diverter disruption. The other two scenarios : Primary Passive Plate and Secondary Passive Plate should be studied.
- All the high stress modes of vibration might not have been picked up by the dynamic analysis because of memory limitations of PC
- CAD model of the Passive Plates is yet to be obtained and integrated into the model.



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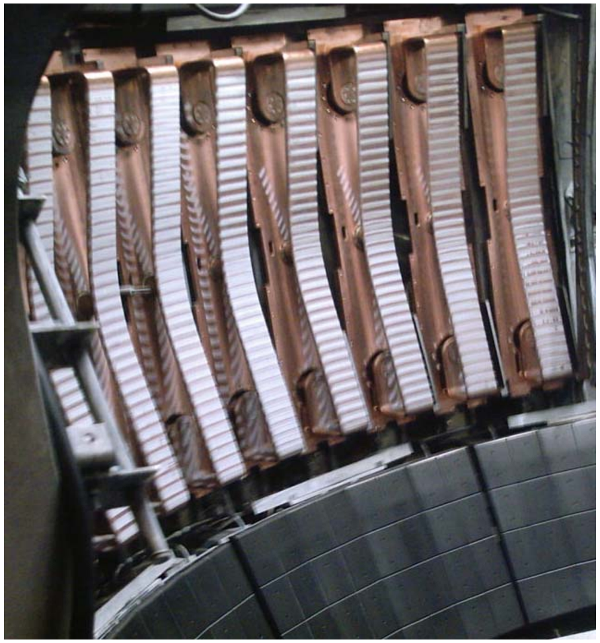
NSTX CSU

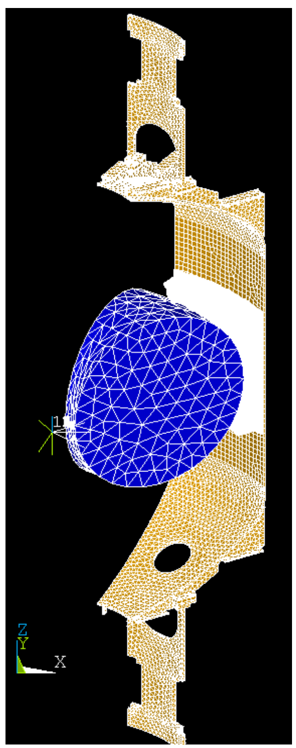
NSTX Disruption Analysis of the HHFW Antenna using ANSYS (by H.Zhang)

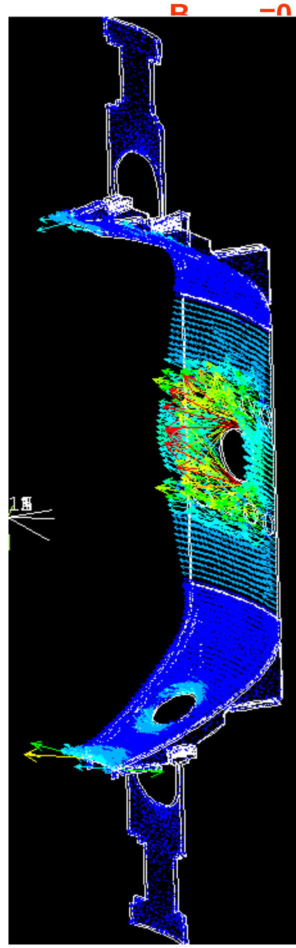


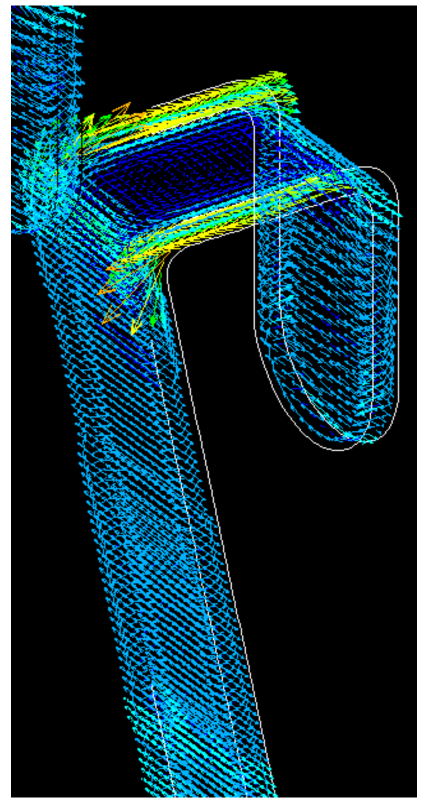
External B:
B_z=0.4T
B =0.4T

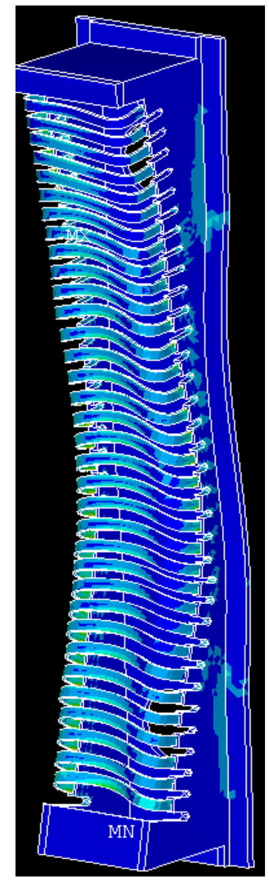
Antenna Strap Eddy Currents

Faraday Shield Stresses

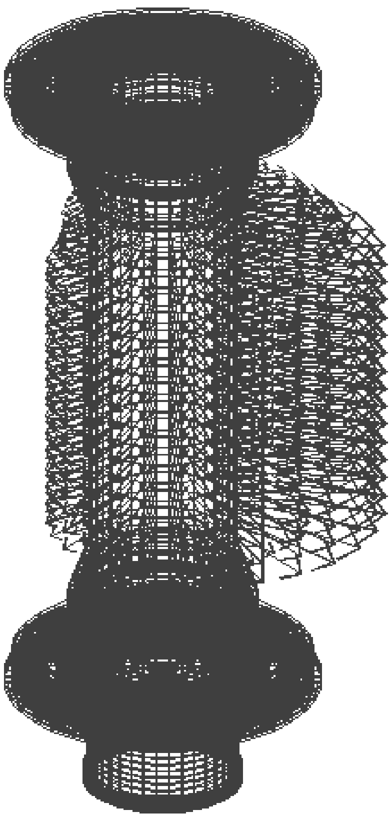






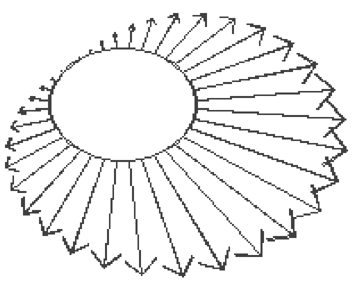


Center Stack Casing Disruption Results

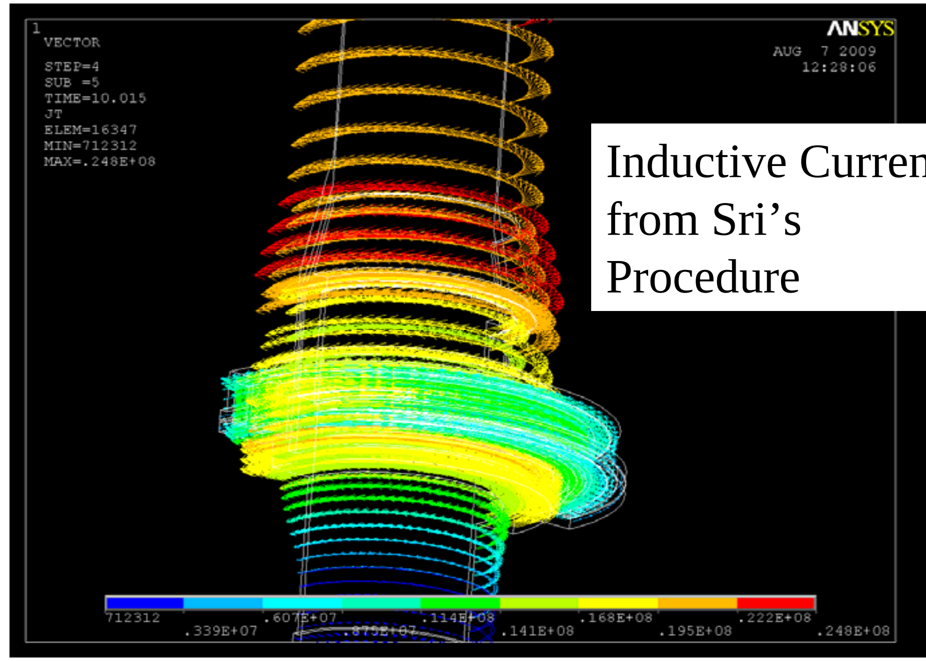


Halo Loads Based on GRD Table 700kA Central Region Entry and Exit

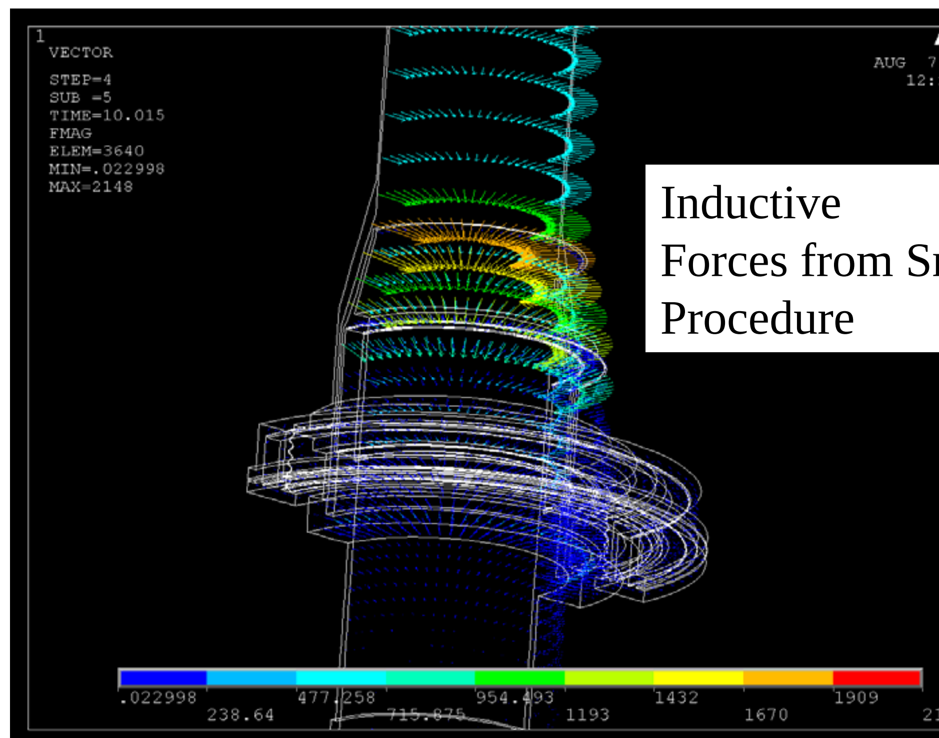
Halo Loads calculated outside ANSYS



Cosine Distribution, Peaking Factor of 2

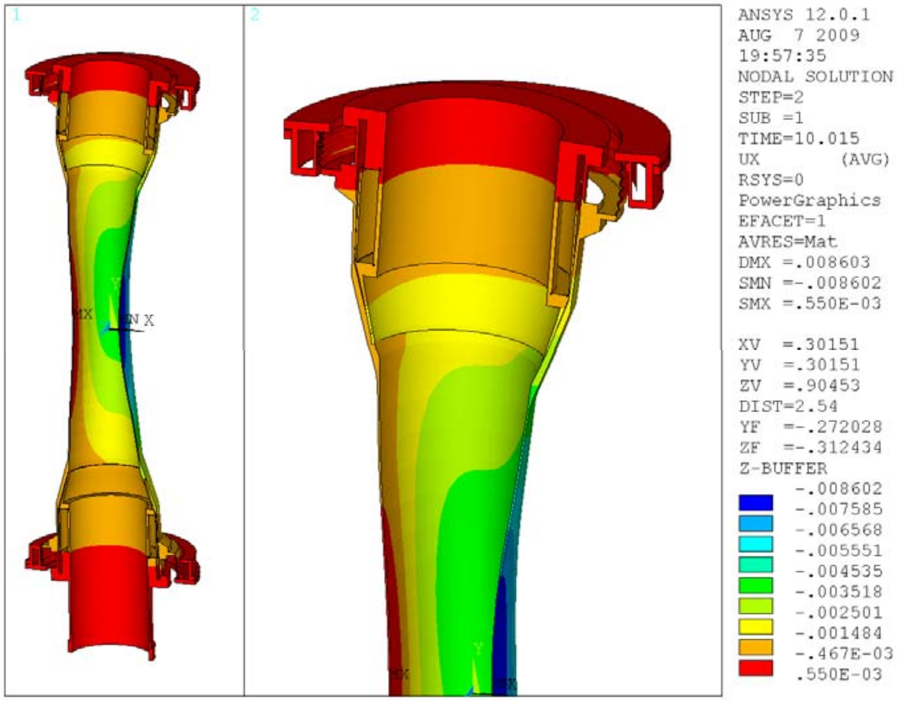


Inductive Currents from Sri's Procedure



Inductive Forces from Sri's Procedure

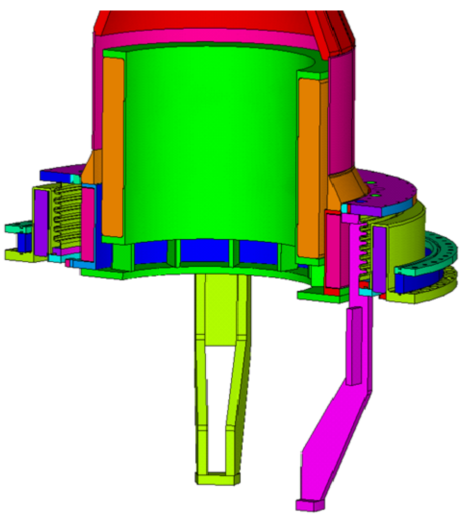
Center Stack Disruption Analysis Halo+Inductive



Dynamic Analysis

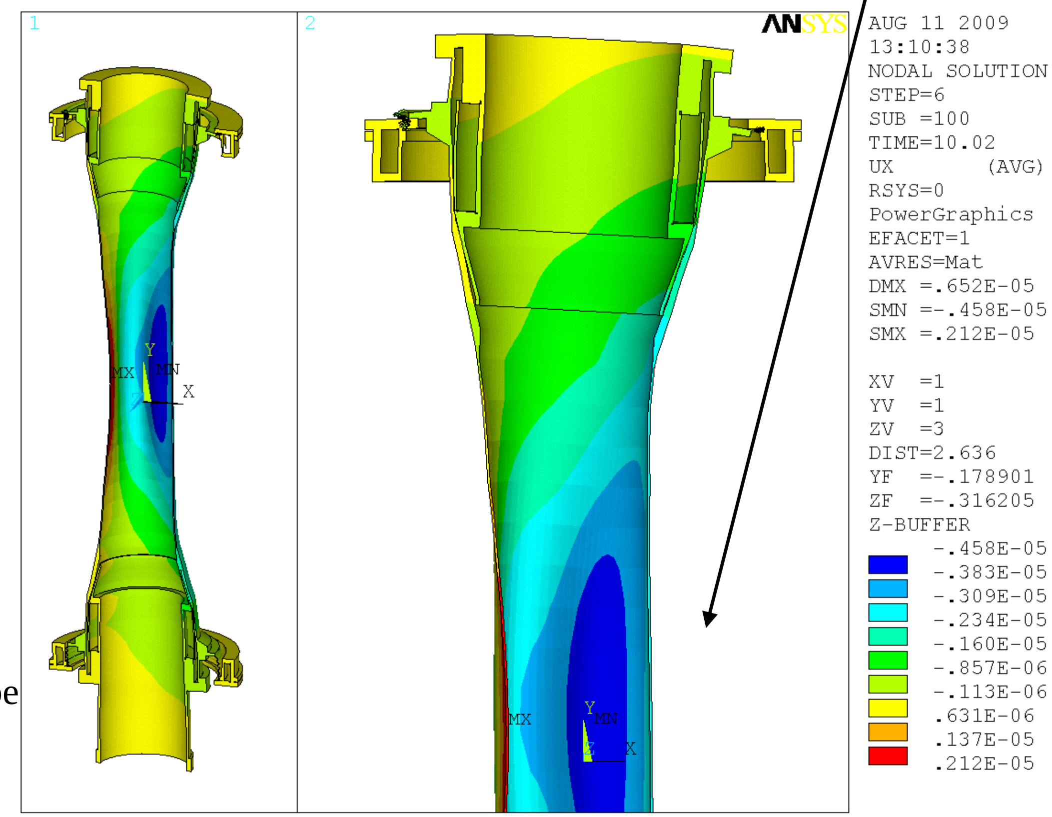
-.004mm 5% Damping

-.25mm 0% Damping

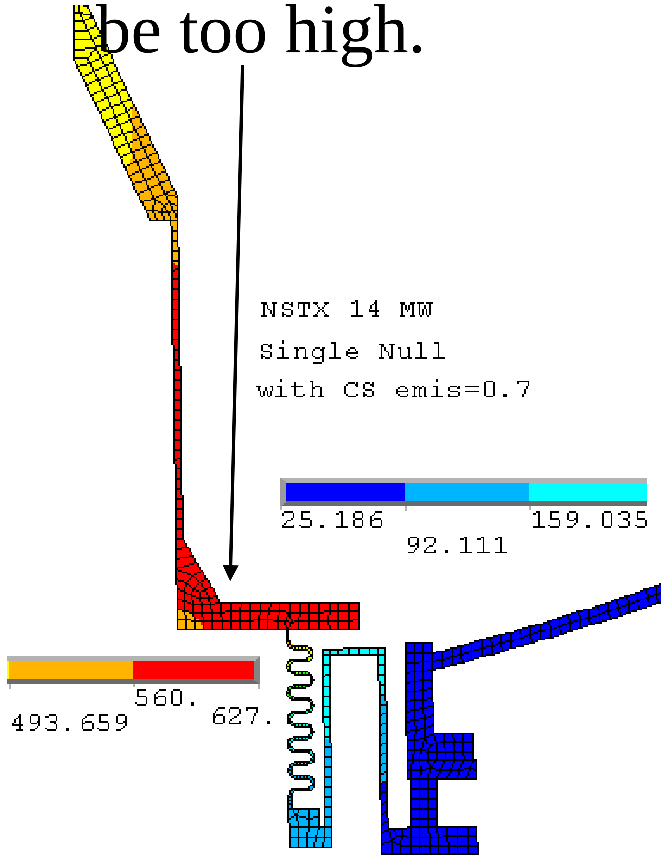


- Static Analysis
- -8mm

Net Side Loads from Halo Currents must be reacted by the center stack support legs



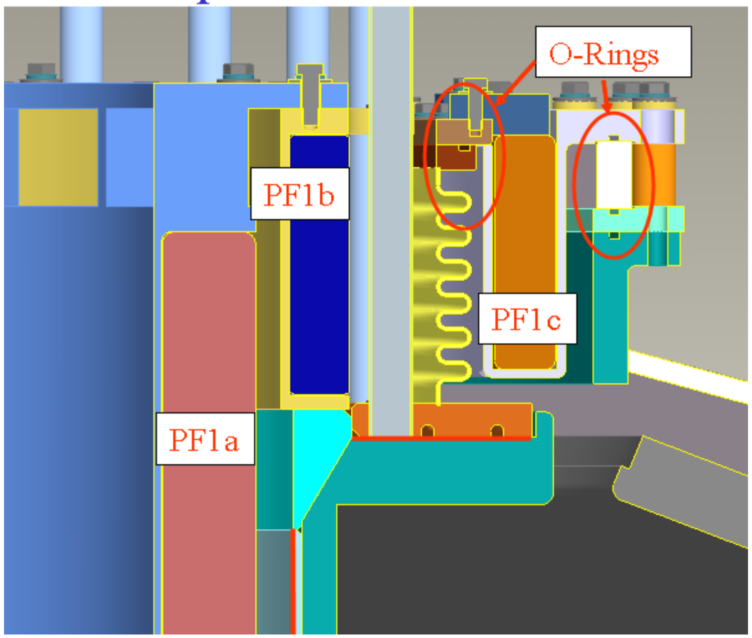
Based on existing cooling provisions (much of which is in-active), the CSU temperatures would be too high.

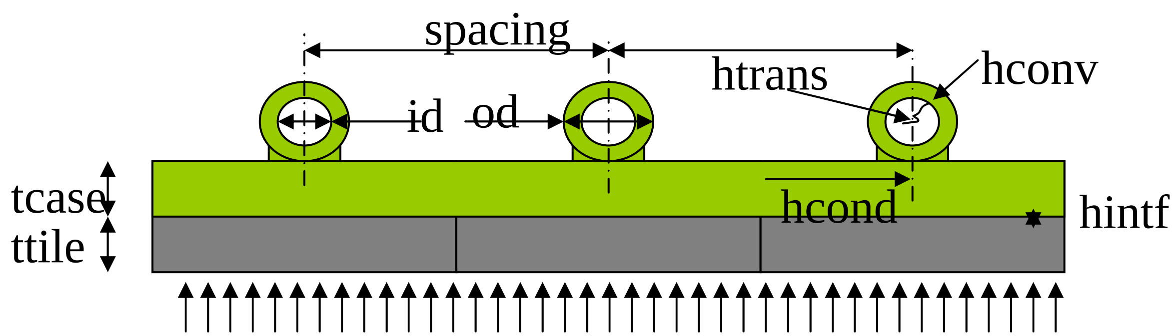


CS/Divertor/Passive Plate Thermal Analysis (A.Brooks)

- Concerns
  - Need to limit max temperature and thermal gradients in CS casing
    - Need to provide protection of CS Coils and O-Rings at joints
    - Desirable to avoid boiling of coolant
    - Potential Thermal Stress Issue
  - Desirable to limit cooling capacity demands by thermally buffering heat loads
- Mitigations
  - Increase effective cooling from Cooling tubes on CSas, IBDvs and IBDhs
  - Limit heat transfer from CS Tiles to CS Casing
    - Tile and Casing coupled via radiation only
    - Rely more on radiation to PP, OD and VV

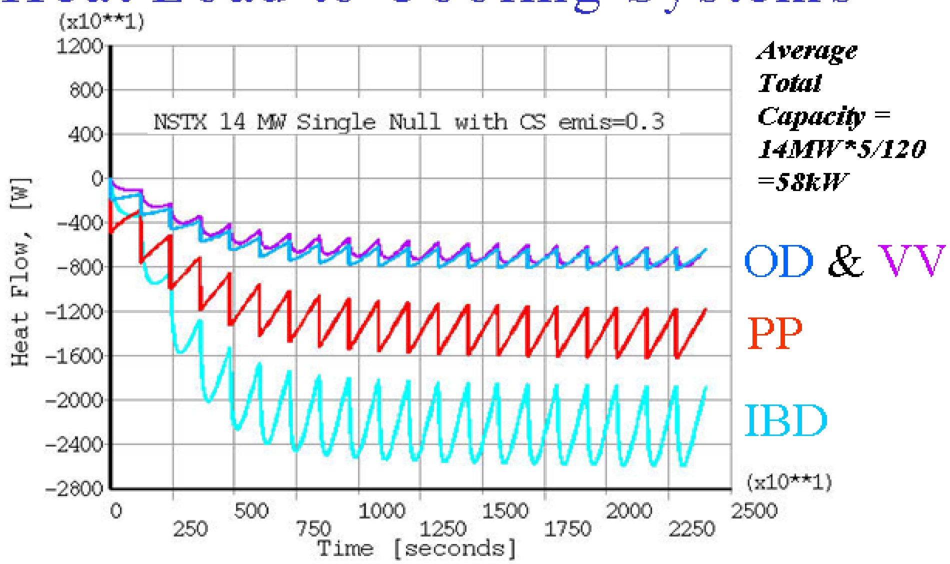
CS Coils and O-Ring Locations for Temperature Considerations



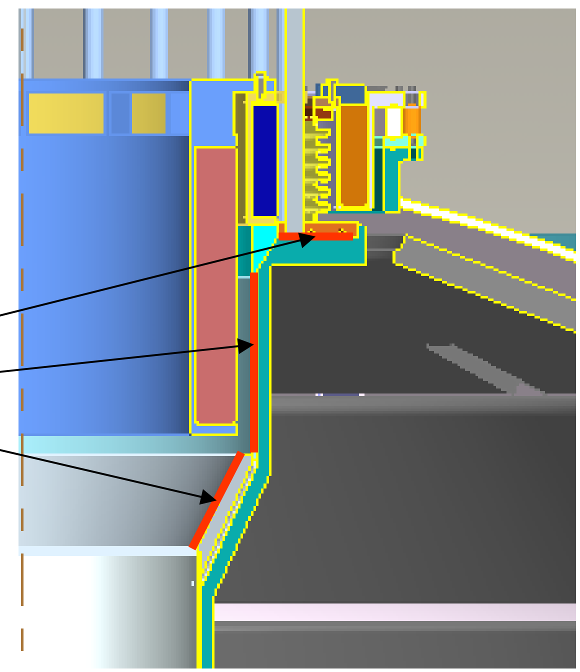


CS & IBD Cooling Tube Locations

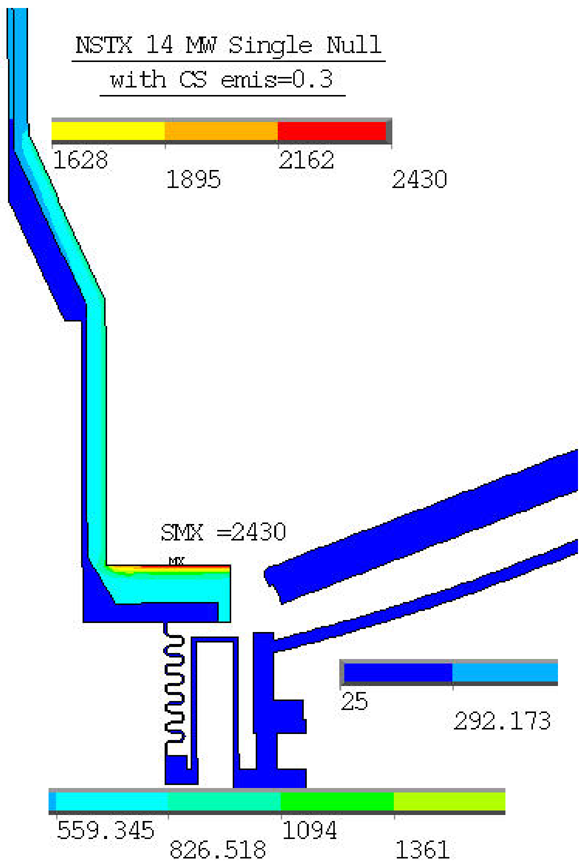
Heat Load to Cooling Systems



Added/Increased Effective Convection of 300 w/m2-C From cooling tubes along red surfaces



Summary

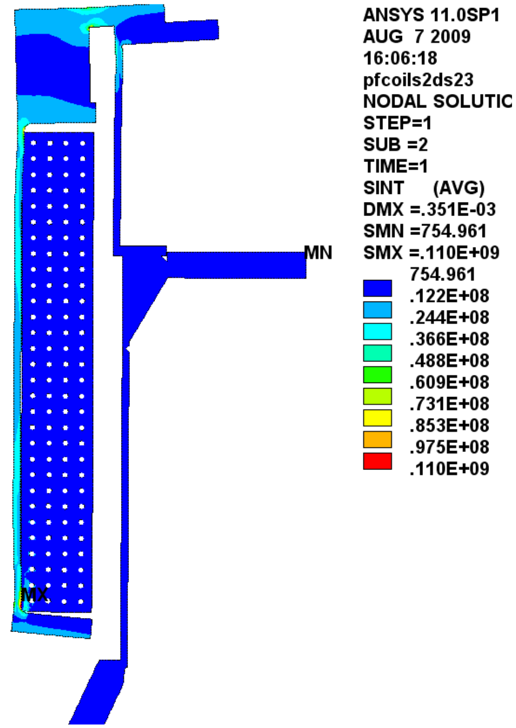


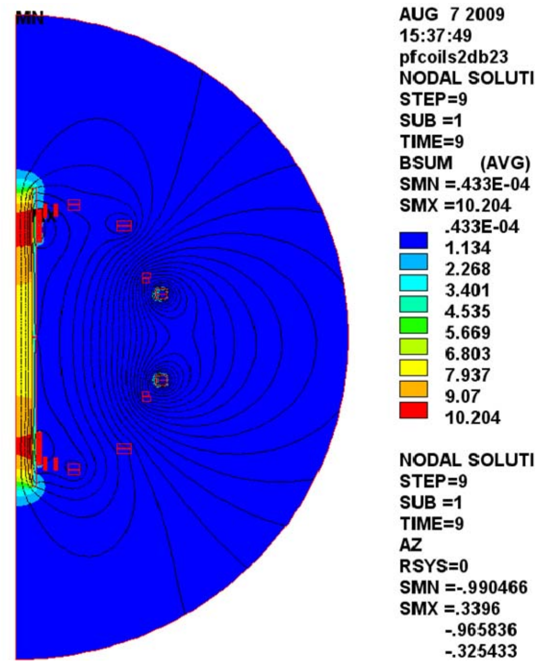
- Enhanced Cooling and Radiation Only Coupled Tiles-Casing Effective at addressing Concerns
  - Protection of CS Coils and O-Rings at joints appears adequate
  - With reasonable back pressure, water boiling can be avoided
  - Thermal Stresses have yet to be evaluated but temperatures and gradients are lowered
  - Cooling capacity demands are reasonable - heat loads have been thermally buffered
- Expected Tile Temperatures may influence choice of Graphite
  - ATJ appears adequate, but current operational Limit is only 1200C
  - Detailed thermal stress of actual tile geometry is being done

Inner PF Supports

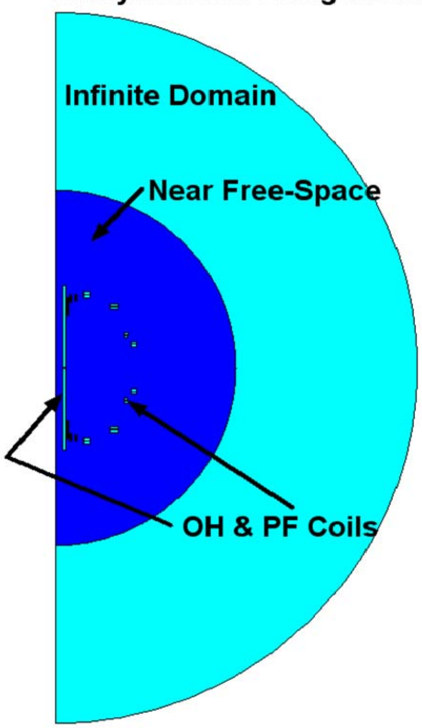
PF1a,b,U/L
Assembly

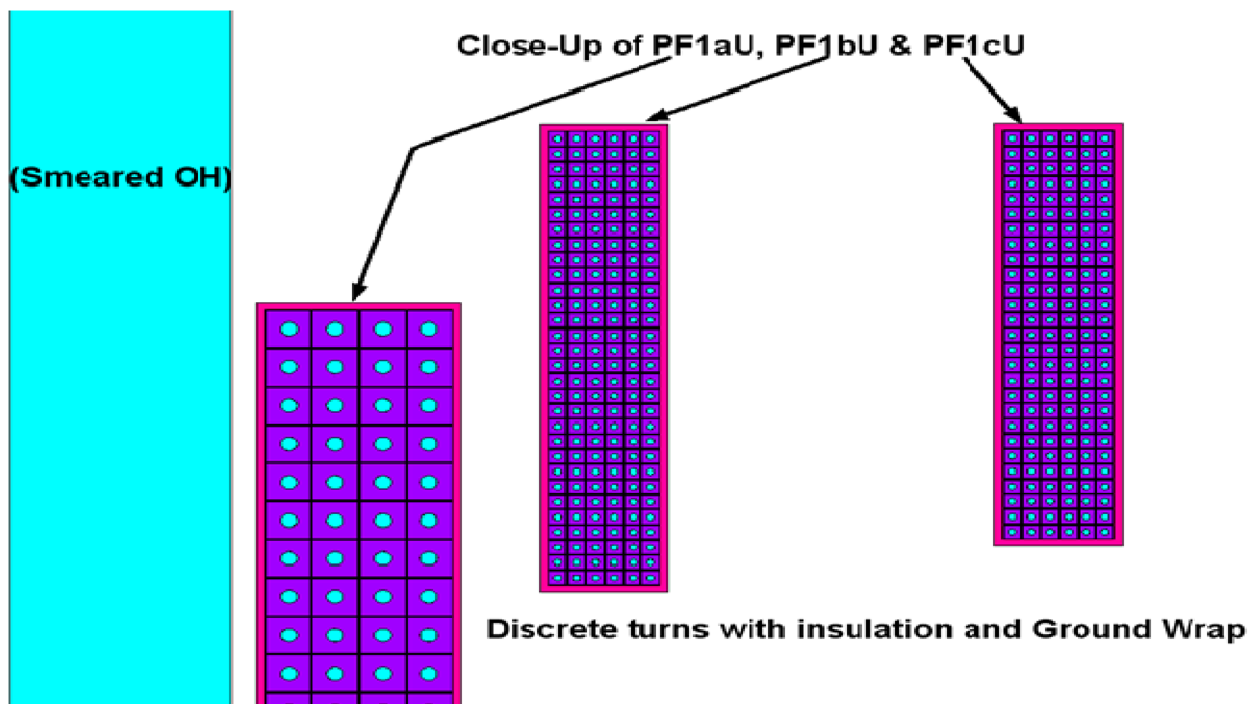
(Len Myatt)



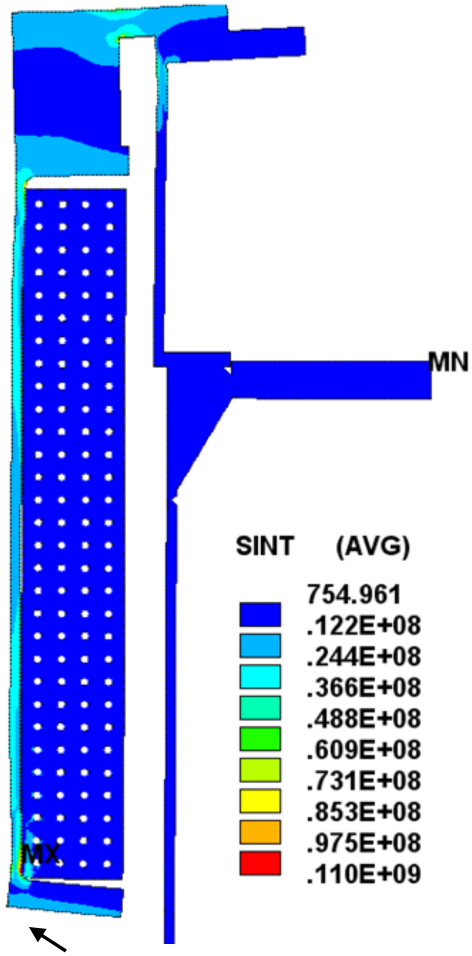


Axisymmetric EMag Model



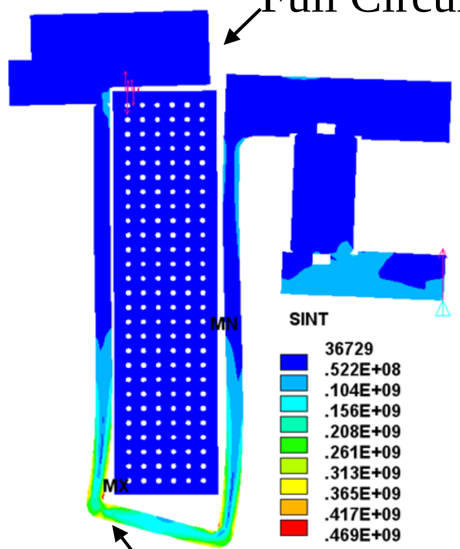


Inner PF Analysis Results

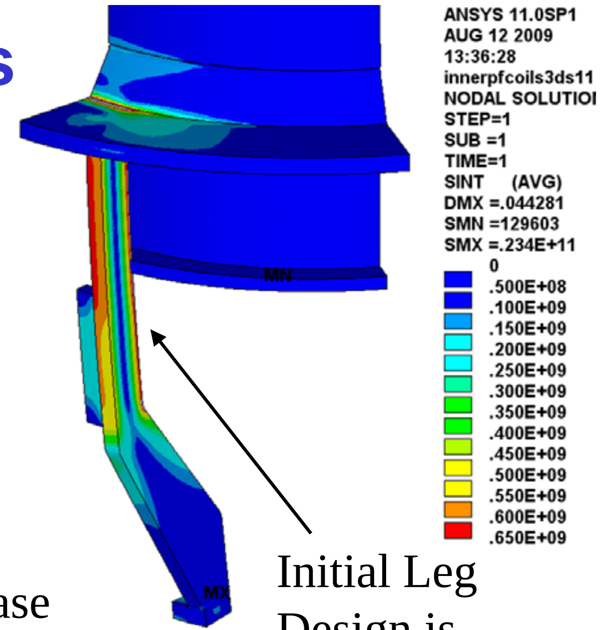


Flange Stiffener Added

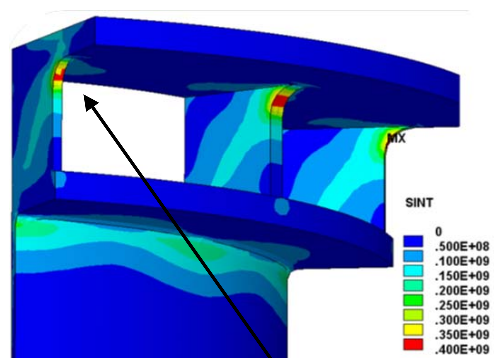
PF1c Cover Made Full Circumference



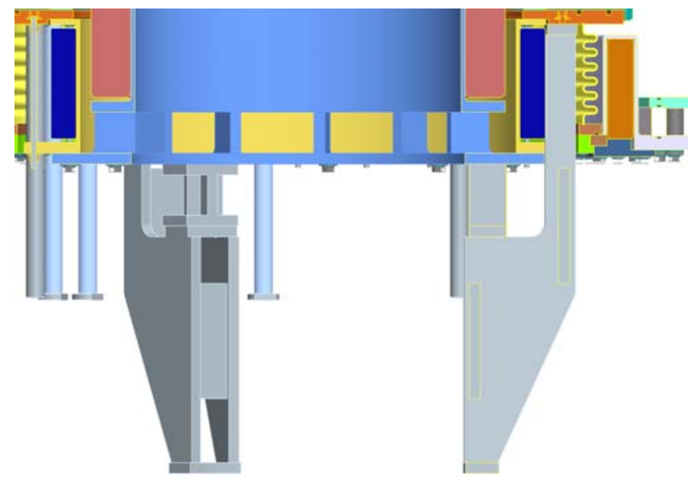
To Fix Case Bending



Initial Leg Design is Overstressed



Radius Added



Legs Reinforced (More needed for Halo Loads)

Conclusions

- Design basis loading is evolving because of GRD guidance on Worst Case vs Normal +Machine Protection System. Cost savings are likely as we remove extreme load scenarios via inclusion in MPS.
- TF Inner Joint Field and displacement boundary conditions have been passed to a detailed model of the joint (T. Willard's talk)
- TF reinforcements for in-plane and out-of plane loads have been designed to Worst Case loads and remain in the territory currently used by the present TF supports – Loosening or disassembly is not required for bake-out. Reinforcements of the umbrella structure are needed.
- Centerstack TF and OH assembly meets normal operational loads, Belleville support system maintains OH coil contact at lower support to eliminate motion at leads and coolant connections
- As of the CDR no modifications of the vessel or passive plates are needed for disruption loads. More disruption cases are being run, and more detailed models of the passive plate support hardware are being modeled.
- Active cooling being incorporated into the new centerstack divertor areas has been sized. Tile surface temperatures for long pulse full power operation are high and require further evaluation.
- Inner PF's and structure are undergoing improvements as a part of the normal design process to meet Normal and Haloi loads.
- Analysis work continues to complete treatment of all details of the design and optimize and economize the design concepts.