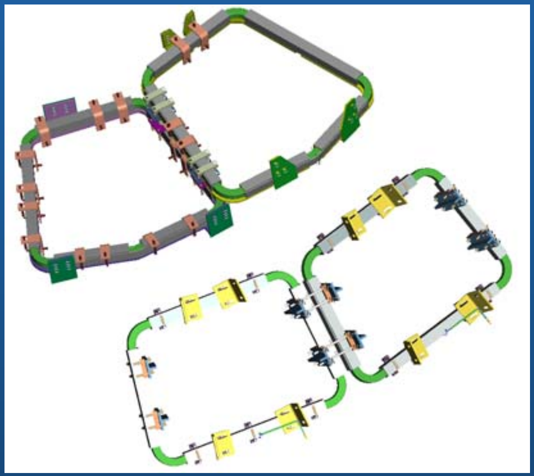
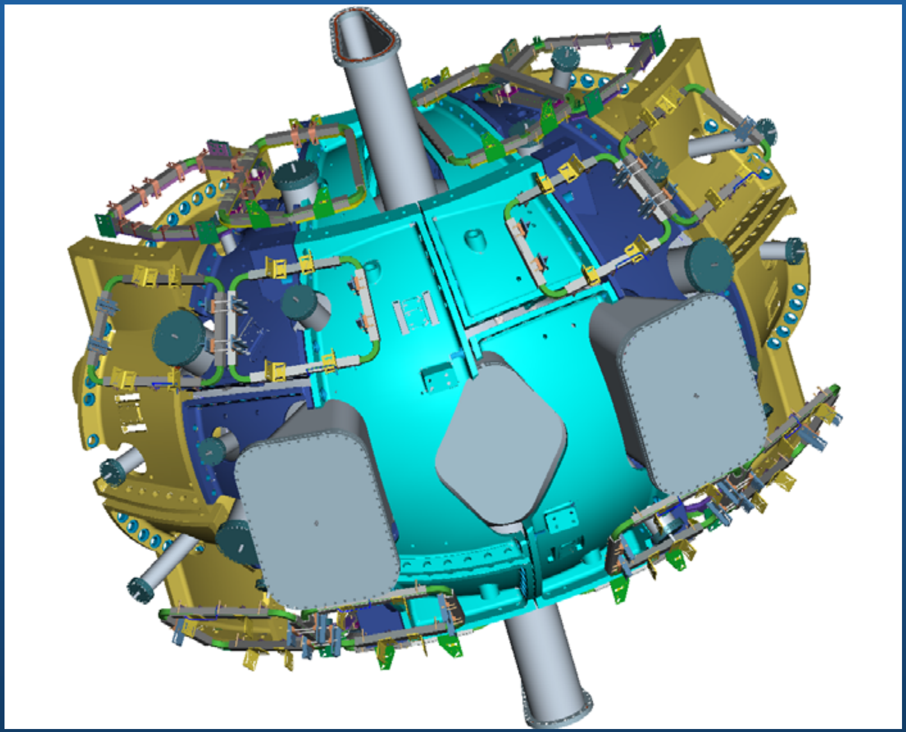
NCSX Trim Coil Preliminary Design Review

NCSX





Art Brooks

Joe Rushinski

Mike Kalish

Charge

1. **Is the Systems Requirements Document adequate and finalized? Are interfaces defined?**

2. **Is the design consistent with the requirements?**

3. **Are the design basis analyses and any supporting R&D documented and adequate?**

4. **Are the drawings and models at the PDR level?**

5. **Have chits from the Peer Review been addressed?**

Outline

- **Requirements**
- **Design Evolution**
  - Geometry and Qty to meet Physics Req.
  - Optimization of # of Turns
  - Insulation Design
  - Support Structure
  - Lead Locations
- **Analysis**
  - Structural
  - Thermal
- **Interfaces**
- **Peer Review Chits**
- **Summary**

Summary- Requirements

- **Meet Requirements when subjected to GRD reference scenarios**
- **Island Suppression 10%**
  - 20 kAmp Turns
  - 48 Coil Configuration
- **Thermal Excursions and Stress within limits**
  - 2 second pulse every 15 minutes
  - 165 amps
- **Withstand Operating Voltages**
  - Max Operating Voltage 1.0kV
  - Design Standoff Voltage to Ground of 6.7 kV
  - Design Standoff Voltage Turn to Turn of 1.0 kV
- **Winding Tolerances**
  - Installed tolerance +/-6mm
  - Fabrication tolerance +/- 3mm
  - Location measured to within 2mm
- **Achievable Response Time of 20ms**
- **Installation at Start of Station 5**

Magnetic Permeability Requirement

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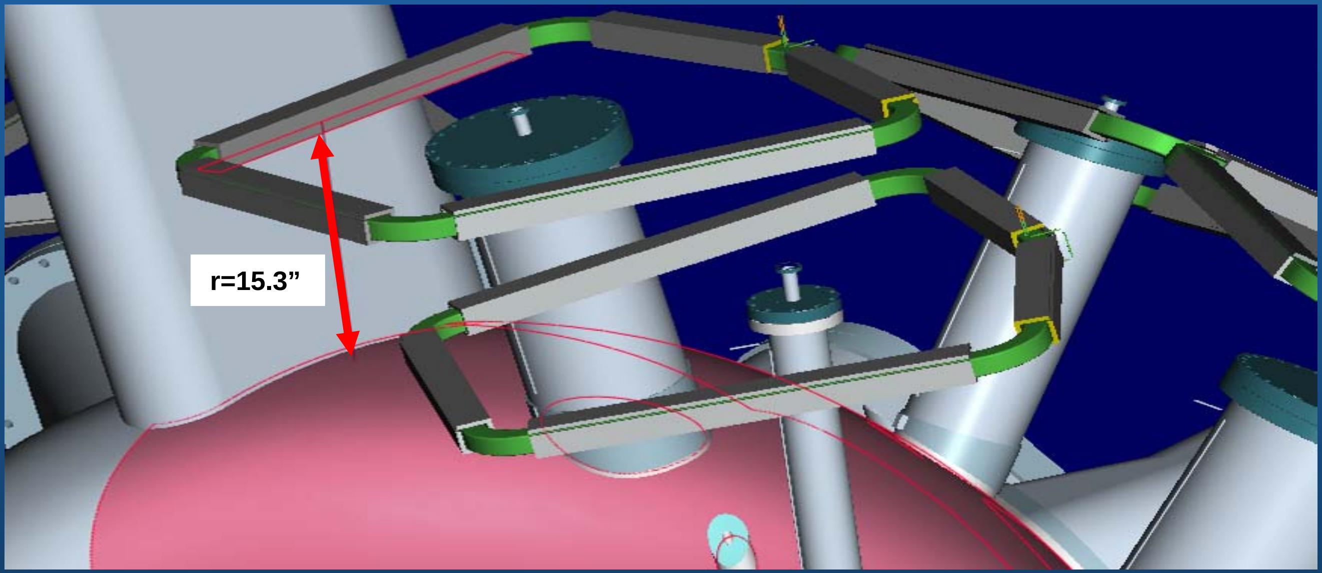
- **Magnetic Permeability Required is 1.02 without further relief**

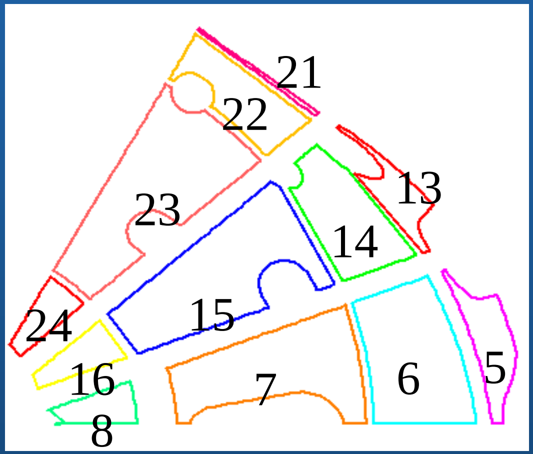
$$6 \cdot 10^{-5} > \frac{(\mu_r - 1) \cdot V_\mu}{r_\mu^{3}}$$



$$\frac{1}{50000} \cdot \frac{\left(3 \cdot r_\mu^{3} + 50000\, V_\mu\right)}{V_\mu} = 1.005$$

required magnetic permeability not to be less than 1.02

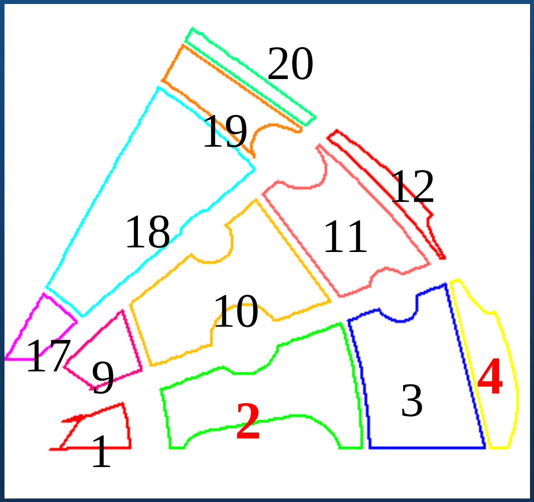
Evolution of Coil Set Configuration- 144 to 12



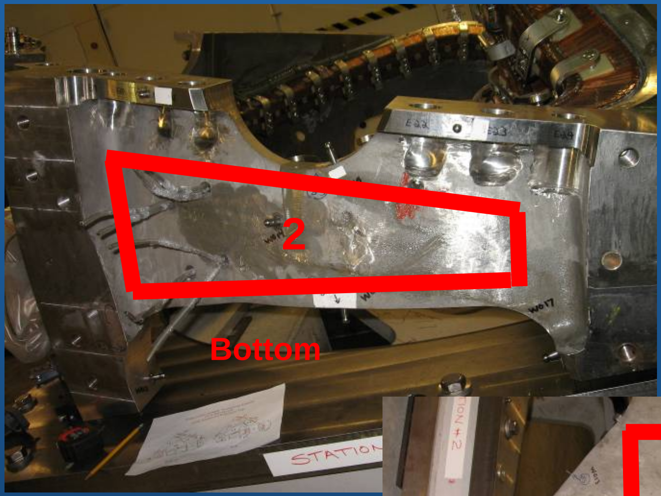
Top

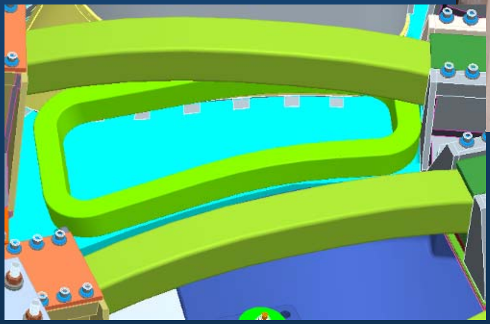
144 Coil Set

Analysis provided the optimum subset of 12 coils



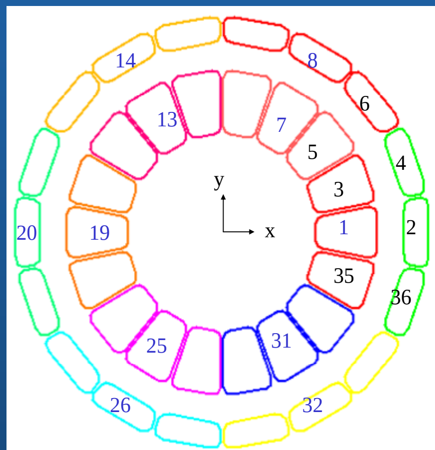
Bottom

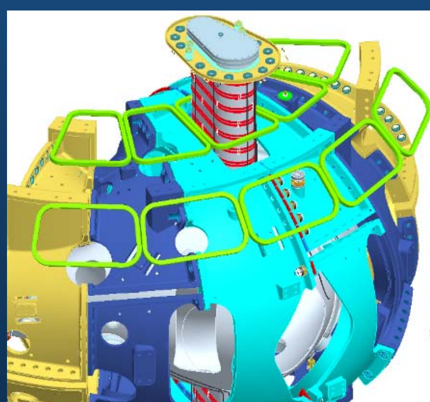




Actual Enclosed Area of Coil Les than %50 of Initial Layout Forced Increase in Amp-Turns

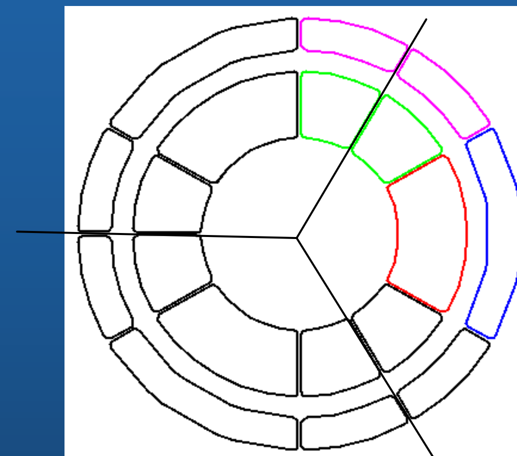
Evolution of Coil Set Configuration- 72 to 36

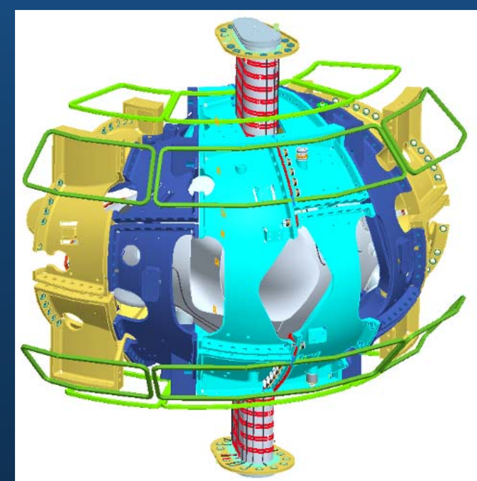




72 Coil Set

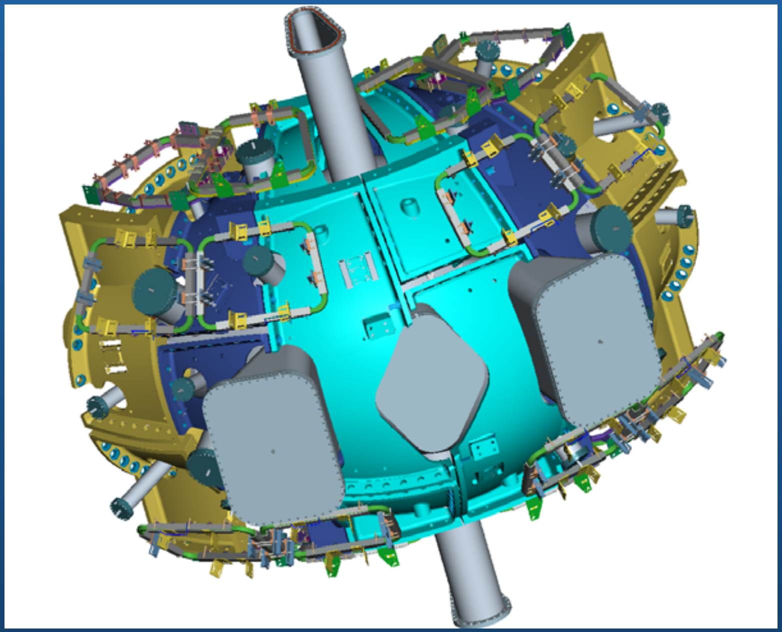
- Subsets of 72 Coil Set Explored
- Evolved into 36 Coil Set

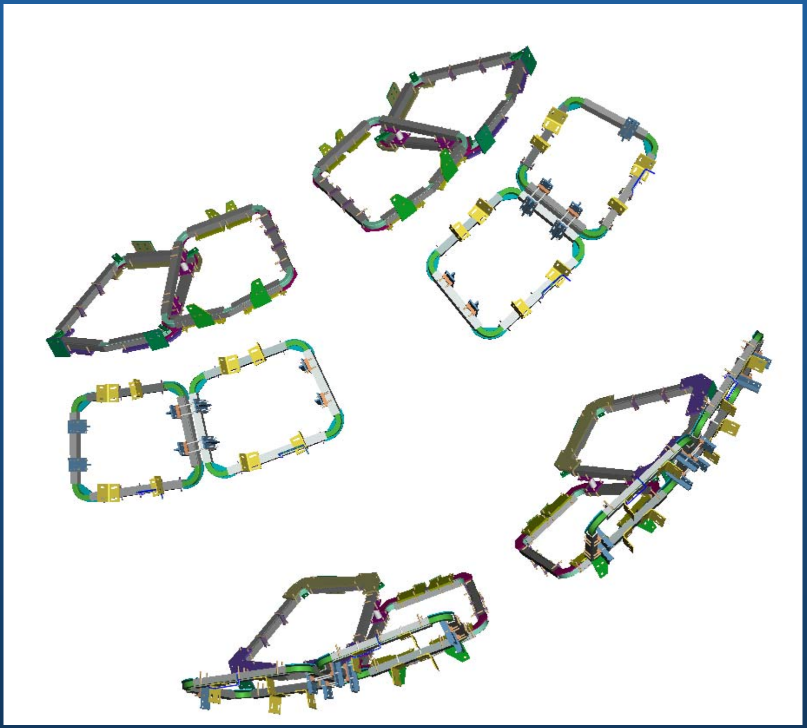




36 Coil Set

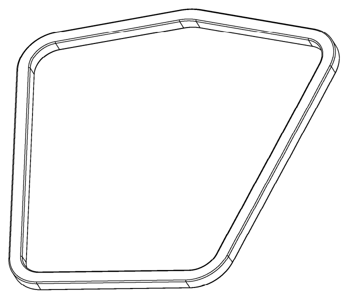
Final Trim Coil Configuration

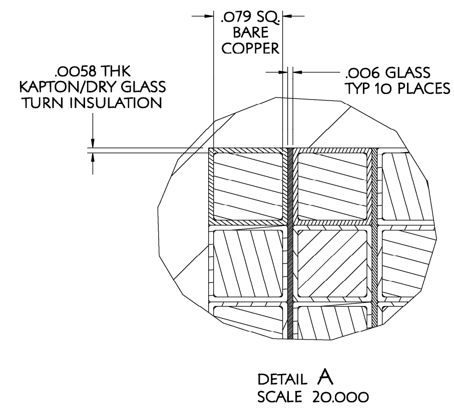




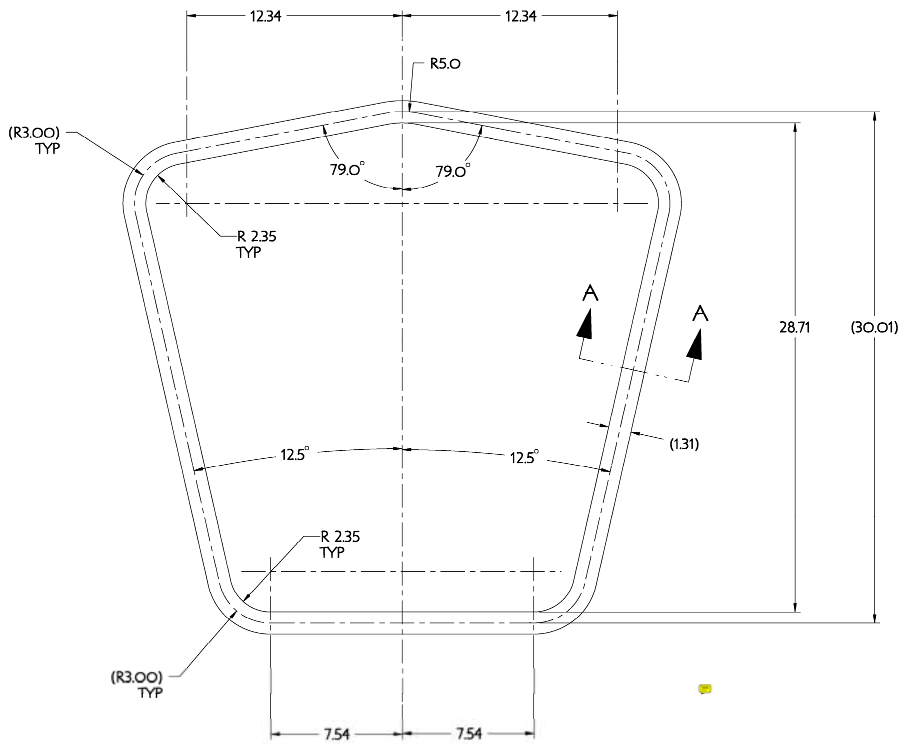
- **48 Coils**
- **Only two coil types**
- **All Coils Planar**
- **Top bottom symmetric half period patterns**

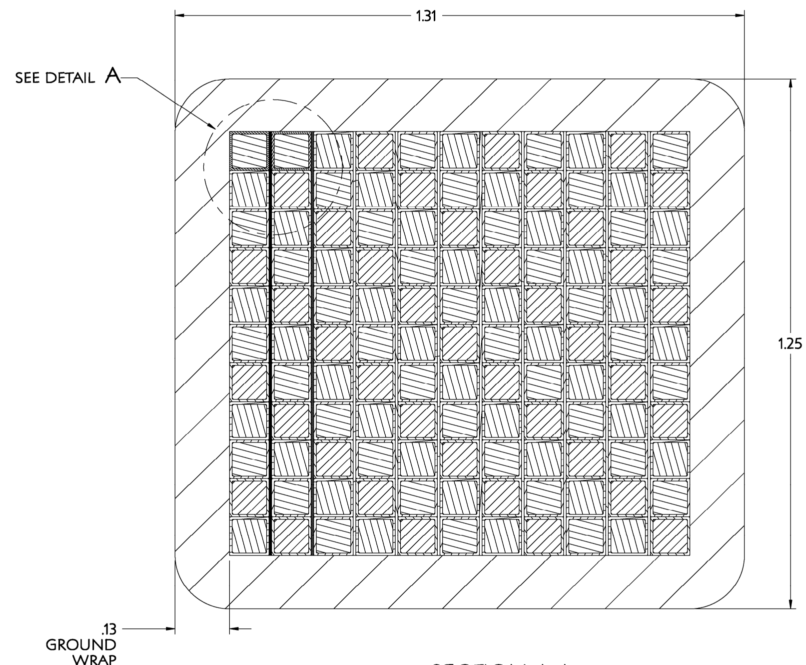
NO.	REVISION	BY	CH	SUP	APPROVED	DATE





1. DRAWINGS PREPARED IN ACCORDANCE WITH ASME Y14.100-2000
2. INTERPRET DIMENSIONS & TOLERANCES PER ASME Y14.5-1994.
3. DIMENSIONS ARE IN INCHES.
4. SEE SPECIFICATION NCSX-CSPEC-XXX-XX-XX FOR ADDITIONAL INFORMATION AND/OR MATERIAL REQUIREMENTS.





SECTION A-A

24 REQUIRED

NOT APPROVED
INFORMATION ONLY

PART NO.	DRAWING/MODEL NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	QTY REQD
1	TC133-031	--		--

PARTS LIST

COMPUTER GENERATED DRAWING MANUAL CHANGES NOT PERMITTED	CENTRAL FILES:
	UNLESS OTHERWISE SPECIFIED
Pro E	DIMENSIONS ARE IN INCHES MACHINE SURFACES
DO NOT VERIFY INFORMATION BY SCALING DRAWING	BREAK SHARP EDGES .005/.020
NEXT ASSEMBLY	TOLERANCES NON-CUMULATIVE

PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY
NATIONAL COMPACT STELLARATOR EXPERIMENT

STELLARATOR CORE
TRIM COILS
TRIM COIL 1 DETAIL

DSN: T. CRUICKSHANK
CHK:
ENGR: T. BROWN
SUPV:

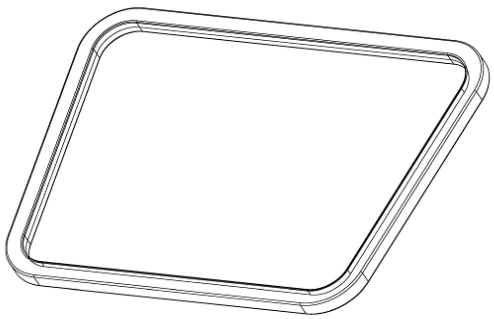
DRAWING NO: SE133-031
SHEET 1 OF 1 | REV 0

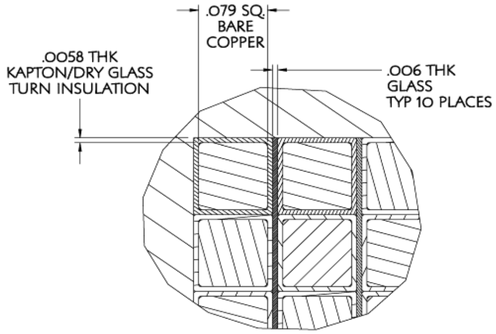
WEIGHT
MODEL NAME TC133-031
WELDING ENGINEER

RELEASE LEVEL: WIP
DWG VERSION NO: 0+

NCSX-SE133-031

NCSX_PART_FORMAT_E





DETAIL A
SCALE 20.000

1. DRAWINGS PREPARED IN ACCORDANCE WITH ASME Y14.100-2000
2. INTERPRET DIMENSIONS & TOLERANCES PER ASME Y14.5-1994.
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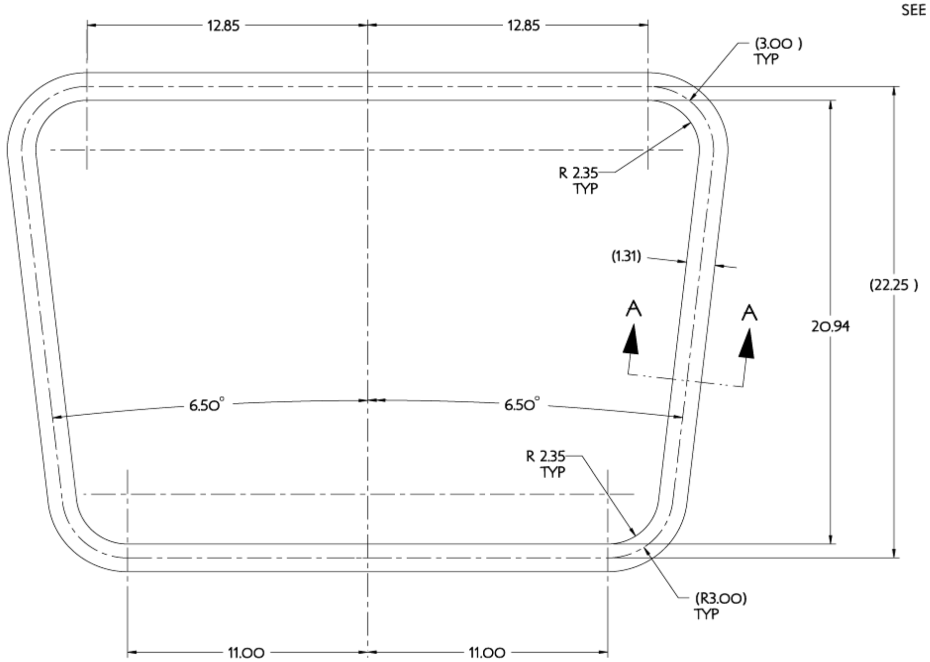

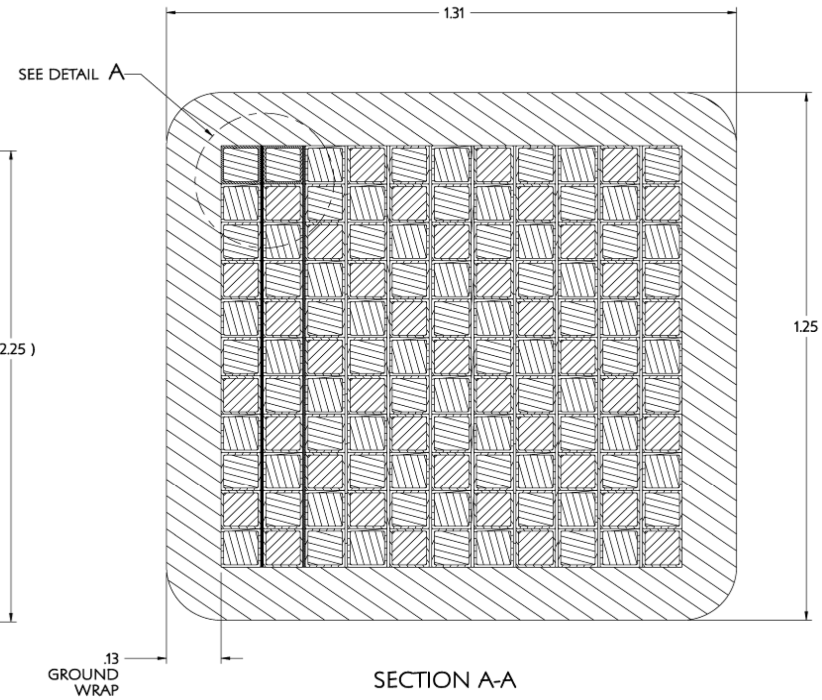

SECTION A-A

24 REQUIRED

NOT APPROVED

INFORMATION ONLY

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1	TC133-041	--	--	

PARTS LIST

COMPUTER GENERATED DRAWING MANUAL CHANGES NOT PERMITTED	CENTRAL FILES:	PRINCETON PLASMA PHYSICS LABORATORY PRINCETON UNIVERSITY **NATIONAL COMPACT STELLARATOR EXPERIMENT**
Pro E	UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES MACHINE SURFACES	STELLARATOR CORE TRIM COILS TRIM COIL TWO DETAIL
DO NOT VERIFY INFORMATION BY SCALING DRAWING	BREAK SHARP EDGES .005/.020	
NEXT ASSEMBLY	TOLERANCES NON-CUMULATIVE	DSN: T. CRUICKSHANK
	DECIMAL-INCH .X +/-.100 .XX +/-.030 .XXX +/-.005 ANGULAR+/-0°-15'	CHK:
	FRACTIONS 0"-12" +/-1/16 12"-72" +/-1/8 72"-120" +/-1/4 OVER 120"+/-1/2	ENGR: T. BROWN
		SUPV:

WEIGHT

MODEL NAME TRIM_COIL_WIRE_COPPER

WELDING ENGINEER

DRAWING NO: SE133-041

SHEET 1 OF 1 REV 0.0

RELEASE LEVEL: WIP

DWG VERSION NO: 0+

NCSX-SE133-041

NCSX_PART_FORMAT_E

48 Coil Trim Coil Configuration Meets Design Objective with Margin

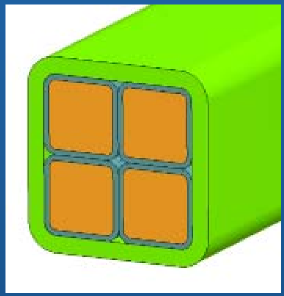
Design Point
< 10% Islands
< 20 kA-T

NCSX

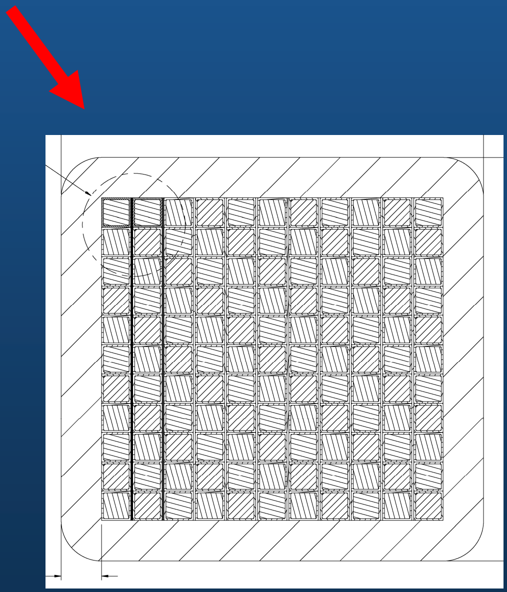
		Using SVD Solution		Using NLP Solution	
Trim Coil Configuration	Total Number Coils	Total Island Size %Total Flux	Max Current kA-T	Total Island Size %Total Flux	Max Current kA-T
Original 36 coils, 24 circuits	36	4.42	8.34	3.35	10.00
Original with 12 Midplane Coils	48	4.41	7.85	2.55	10.00
All Inner/Outer Coils Only (as Modified)	54	4.30	9.96	2.87	10.00
All Inner/Outer Coils Only (as Modified) (but without Outer AA)	48	4.29 6.95	11.36 10.00		
All Inner/Outer & Midplane Coils	66	4.26	9.21	2.17	10.00
All Inner/Outer & Midplane Coils (but without Outer AA)	60	4.25	9.56		
All Inner/Outer Coils (port12 split) (with Outer AA Coils)	**60**	4.47 4.21	10.00 10.30	2.89	10.00
All Inner/Outer Coils (port12 split) (without Outer AA Coils)	**54**	7.98 4.18	10.00 11.88	3.00	10.00
All Inner/Outer Coils (port12 split) (without Outer AA and CC Coils)	**48**	8.49 4.06	10.00 12.25	**3.12**	10.00
Above Plus Wings Distorted +40 mils (Stellarator Symmetric) -40 mils		- -	- -	**3.88** **3.88**	10.00 10.00
Above Plus Wings Distorted +40 mils (1 HP Only, Non Stellarator Sym)		-	-	**3.25**	10.00

Optimization of the # of Turns

NCSX



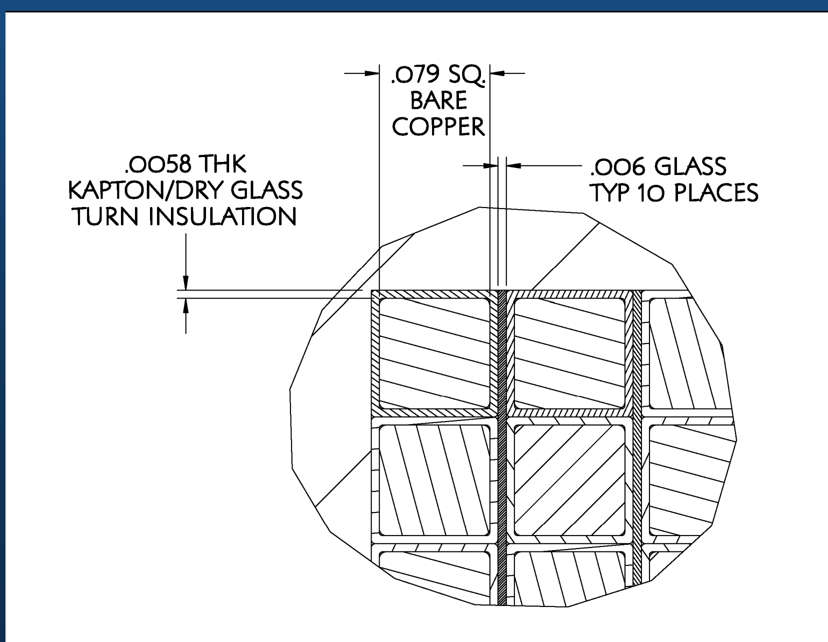
- **Optimized Design =121 Turns**
- **Large # of Turns has Advantages**
  - Higher Voltage Lower Current
    - Current Requirement only 165Amps
    - Equivalent RMS Current only 8Amps
    - Higher Voltage has no cost impact for MIE
  - Allows for 11x11 build with easy to wind 2mm conductor size
  - Conductor readily available in long lengths pre-insulated ($12 per lb)
  - Likely that four twisted 12AWG wires can be used for buss connections



Winding Pack Insulation Scheme

NCSX

- **Kapton Tape applied directly to conductor to enhance turn to turn dielectric standoff**
- **One half lap layer of glass to allow for epoxy impregnation**
- **Additional .006” thk by 1” wide glass between layers to wick epoxy**



Trim Ground Wrap					
1/2 Lap Layer Dry Glass	Glass	0.006		0.54	
	Glass	0.006		0.54	
1/2 Lap Layer Dry Glass	Glass	0.006		0.54	
	Glass	0.006		0.54	
1/2 Lap Layer Dry Glass	Glass	0.006		0.54	
	Glass	0.006		0.54	
1/2 Lap Layer Dry Glass	Glass	0.006		0.54	
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1/2 Lap Layer Dry Glass	Glass	0.006		0.54	
	Glass	0.006		0.54	
1/2 Lap Layer Dry Glass	Glass	0.006		0.54	
	Glass	0.006		0.54	
1/2 Lap Layer Dry Glass	Glass	0.006		0.54	
	Glass	0.006		0.54	
1/2 Lap Layer Dry Glass	Glass	0.006		0.54	
	Glass	0.006		0.54	
1/2 Lap Layer Dry Glass	Glass	0.006		0.54	
	Glass	0.006		0.54	
		0.12	**Inches**	**10.8**	**KV**
Trim Turn to Turn					
1/2 Lap Layer Dry Glass	Glass	0.005		0.45	
	Glass	0.005		0.45	
	Kapton	0.006		7.8	
	Kapton	0.006			
		0.022	**Inches**	**8.7**	**KV**

Turn To Turn Voltage Standoff Requirement

NCSX

- Calculated Turn to Turn Break Down Voltage exceeds requirement by a factor of 17

NCSX Coil Voltage Standoff Requirements Turn to Turn		
3/6/2008		
Operating Voltage (KV)	per coil for coils in series	1.00
For Turn to Turn Voltage Divide Total Voltage By #Layers-1	note: = #coils x #Boundaries	10.00
Turn to Turn (KV)		0.10
Design Requirement for Volatge Standoff (Turn to Turn x10) (KV)		**1.00**
Turn to Turn Glass Thickness		0.010
Calculated Coil Turn to Turn Long Term Break Down (90V/mil) Plus Kapton (KV)		1.80
Calculated Kapton Standoff (KV)		15.60
Calculated Total Turn to Turn Break Down Voltage (KV)		**17.40**
Safety Factor (Calculated Break Down Voltage / Design Requirement for Voltage Standoff)		**17.4**

Ground Plane Voltage Standoff Requirement

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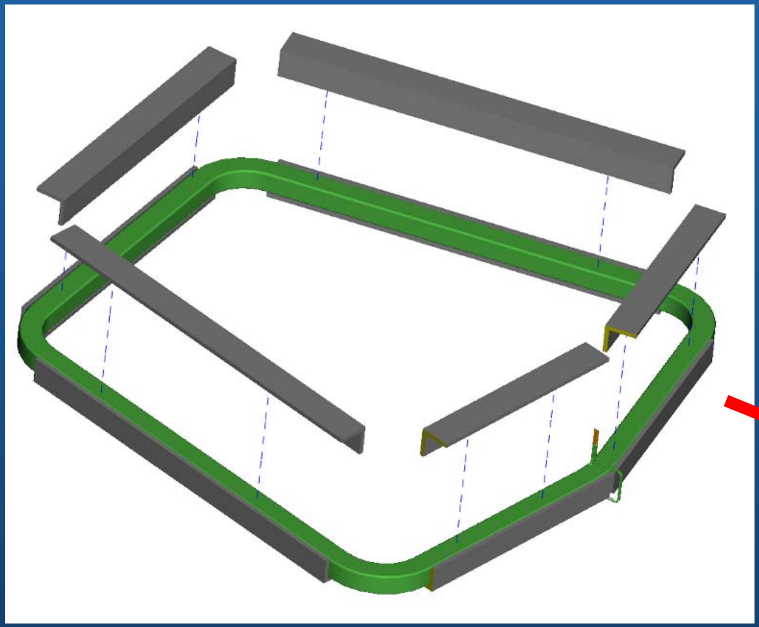
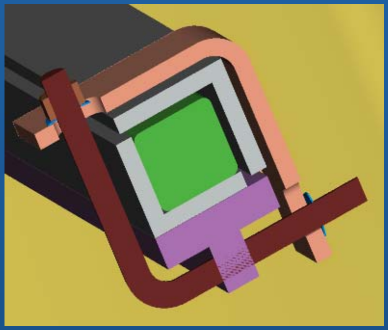
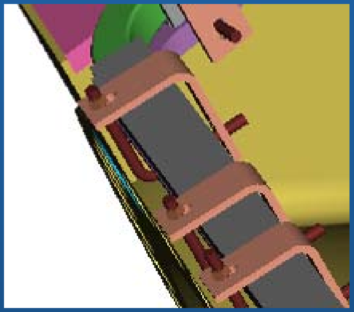
- Calculated Break Down Voltage to Ground exceeds design requirement by a factor of 2.9

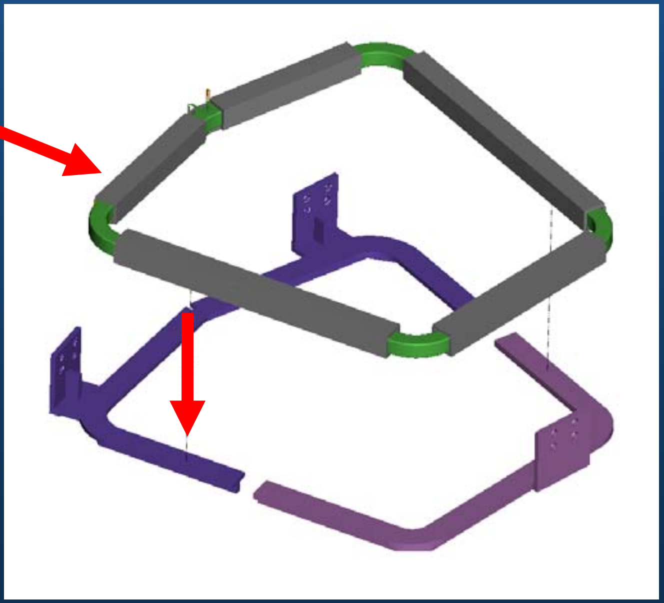
NCSX Coil Voltage Standoff Requirements Ground Plane		
3/6/2008		
		Trim
Max Operating Voltage (KV)		1.00
Maintenance Field Test Voltage (KV)	(Operating Volatage x 2) + 1	3.00
Manufacturing Test Voltage (KV)	Maintenance Test Voltage x 1.5	4.50
Design Volatge Standoff Requirement (KV)	Manufacturing Test Voltage x 1.5	**6.75**
Calculated Coil Turn Long Term Break Down (90V/mil+Kapton)		8.70
Calculated Ground Wrap Long Term Break Down		10.8
Calculated Standoff to Ground KV	Ground + Turn Insulation	**19.5**
Safety Factor to GND (Standoff to Ground / Design Voltage Standoff Requirement)		**2.9**

Structural Design









- Diagonal clamps transmit stiffness of angles to coil and fasten coil to base supports

Structural Design

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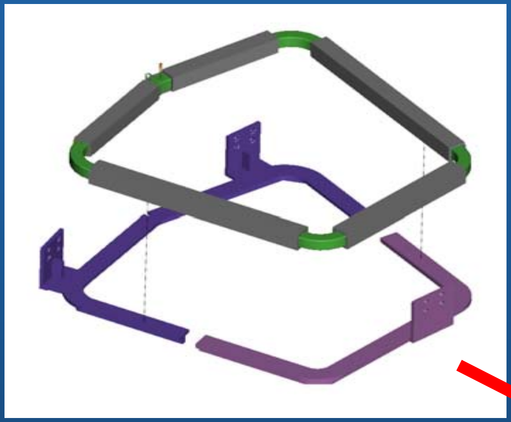
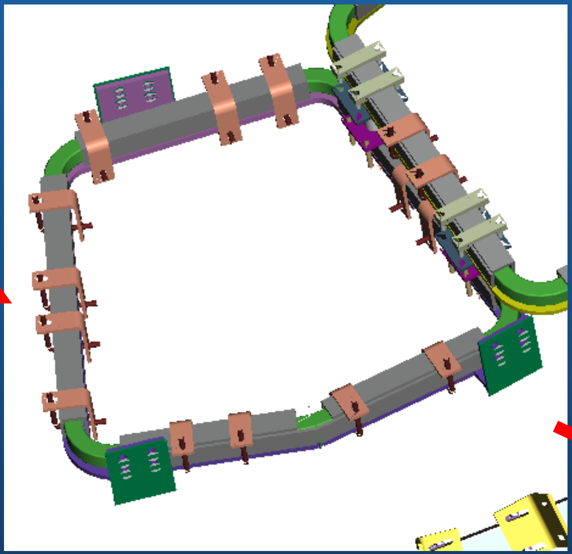
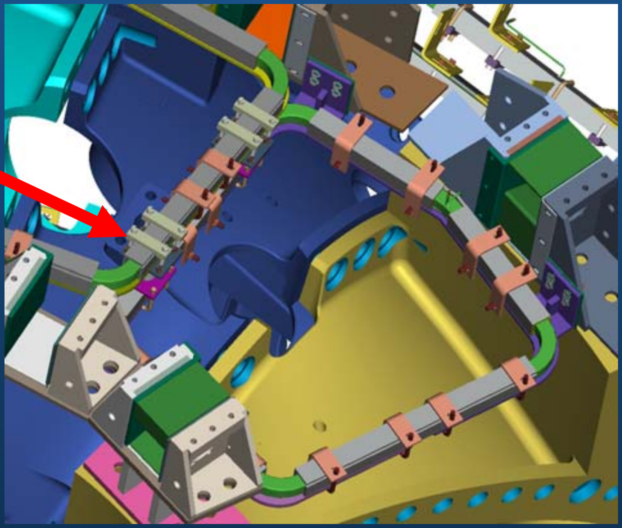
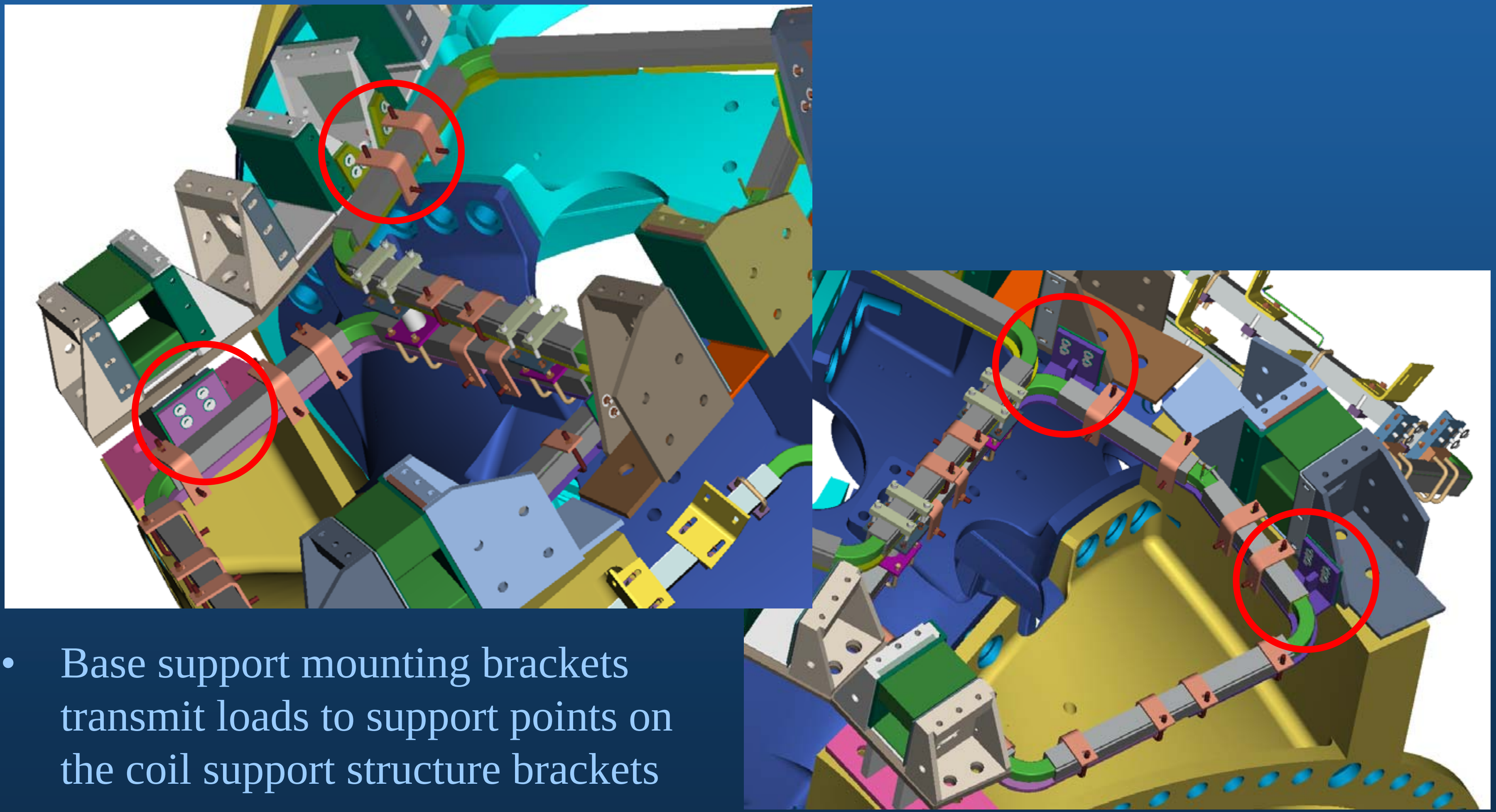






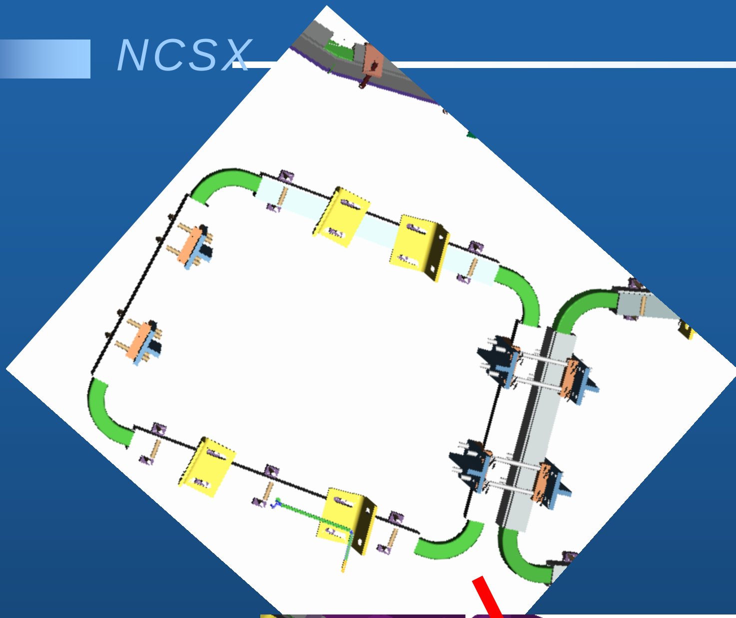
- Coil Assemblies assembled off line and then bolted to TF and PF Coils supports
- Custom shimming will be required

Structural, Design

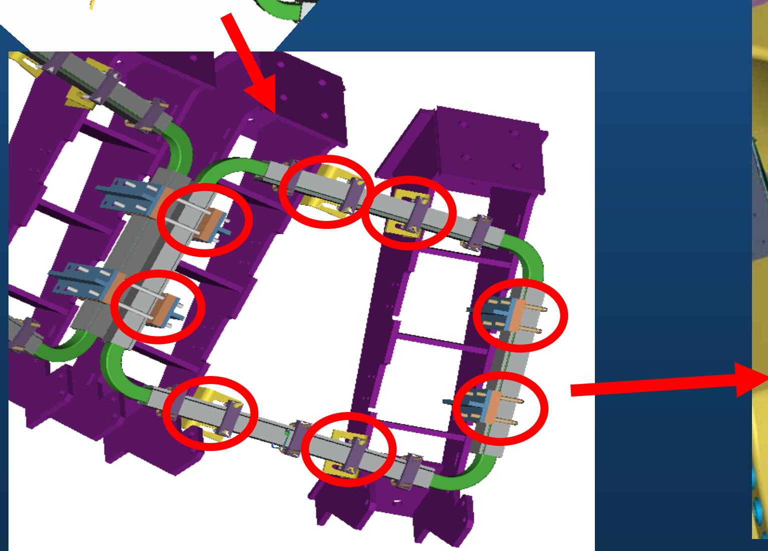


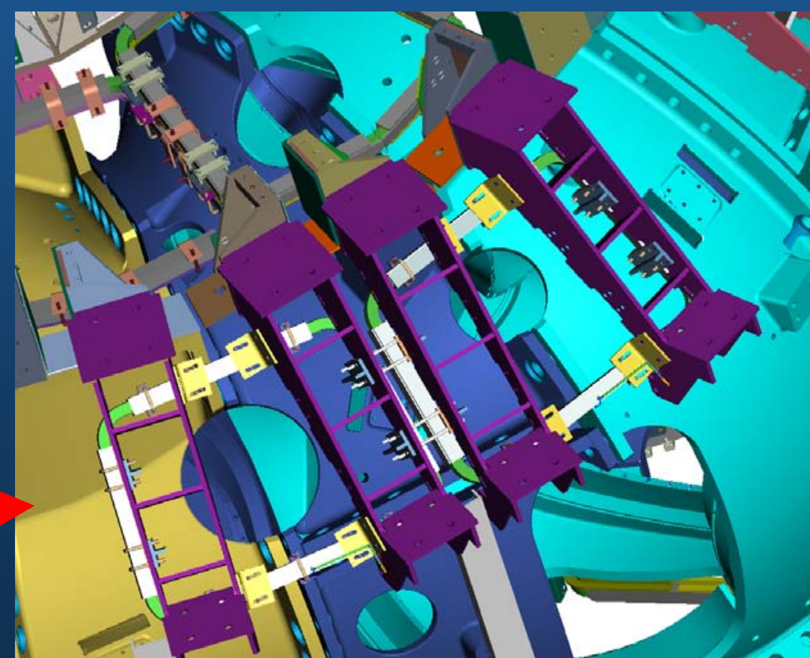
- Base support mounting brackets transmit loads to support points on the coil support structure brackets

Structural, Design



- **Rectangular coils only require local support brackets due to numerous mounting points**





Coil Leads

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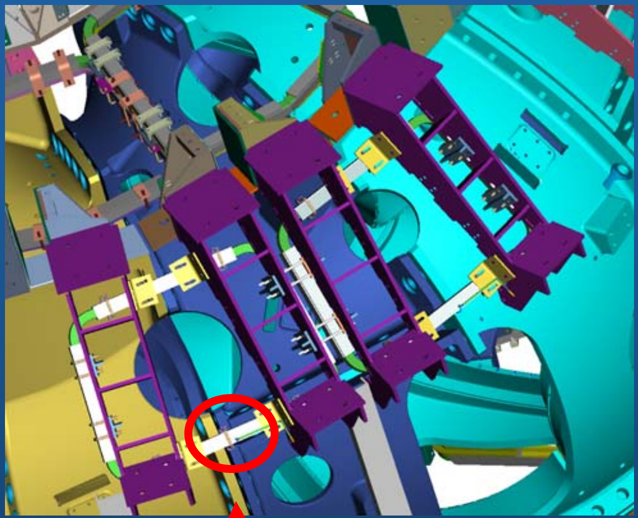
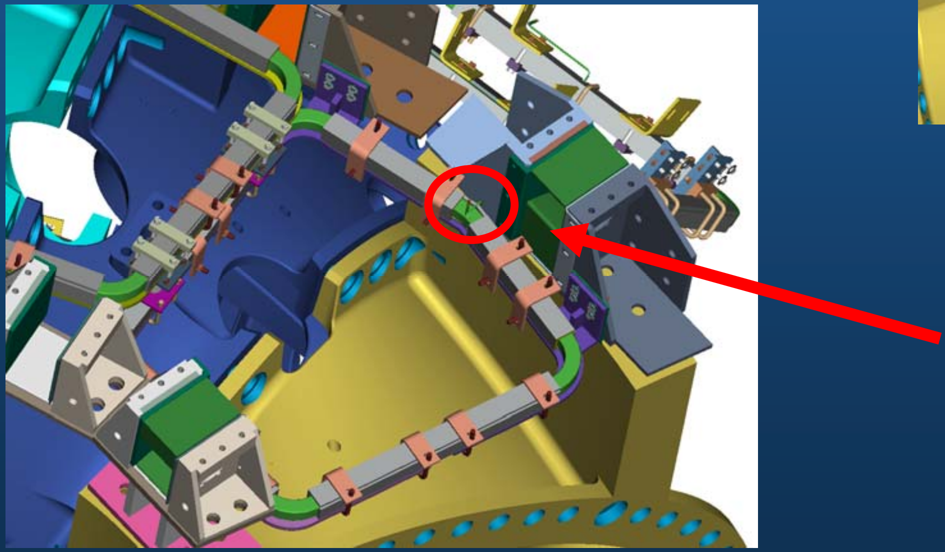
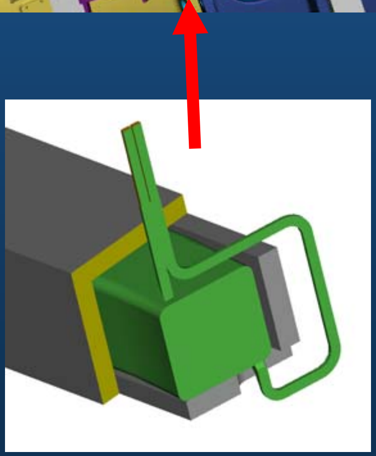
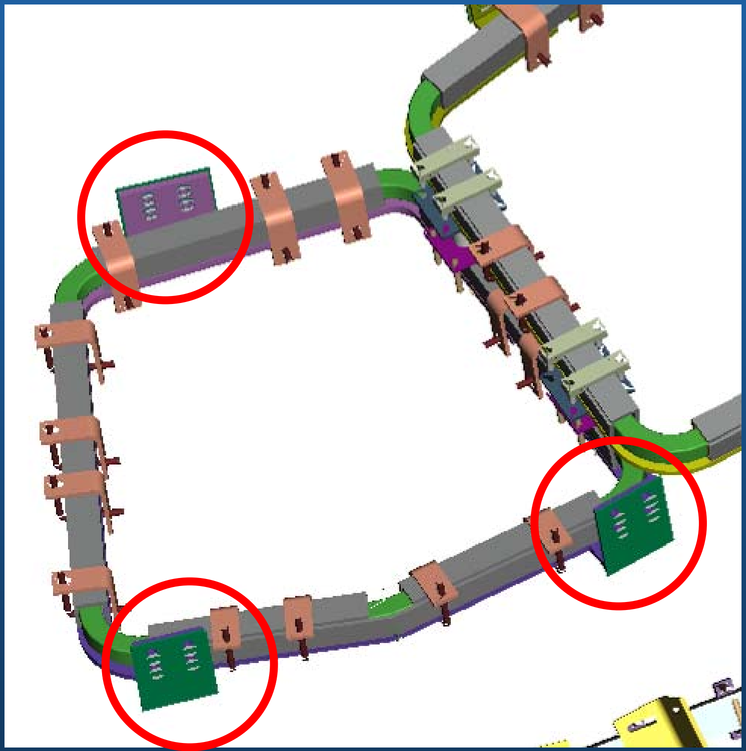
- **Leads protrude from a notch in the support angle**
- **G11 Support Bracket will be required**



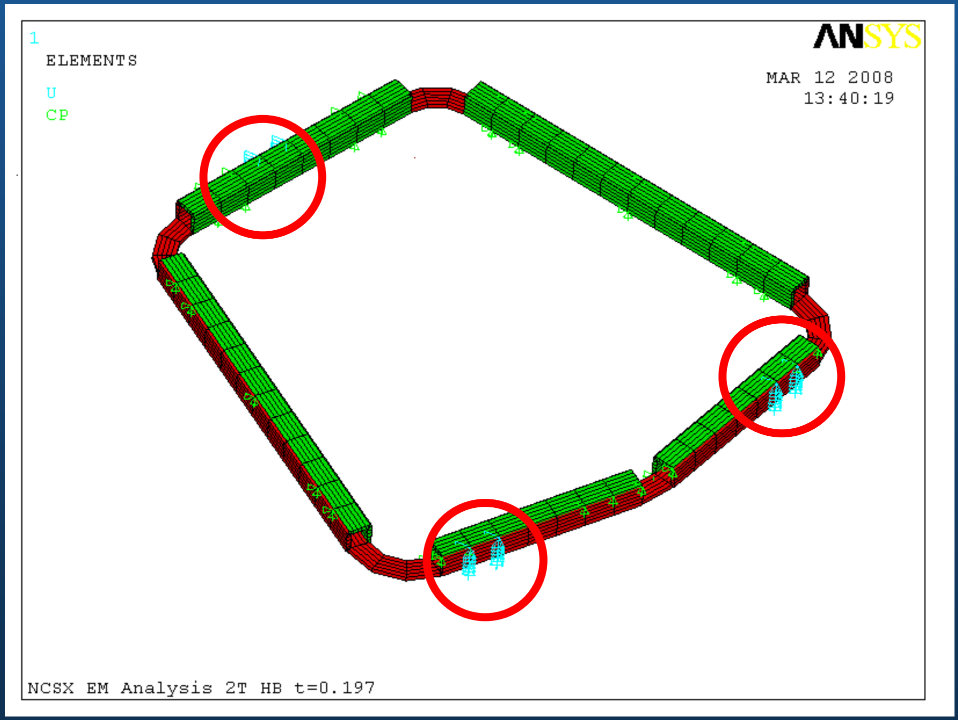




Preliminary Stress Analysis Model



- Simple model for preliminary analysis yields conservative (higher stress and deflection) results



Preliminary Stress Analysis
Results Coil and Structure

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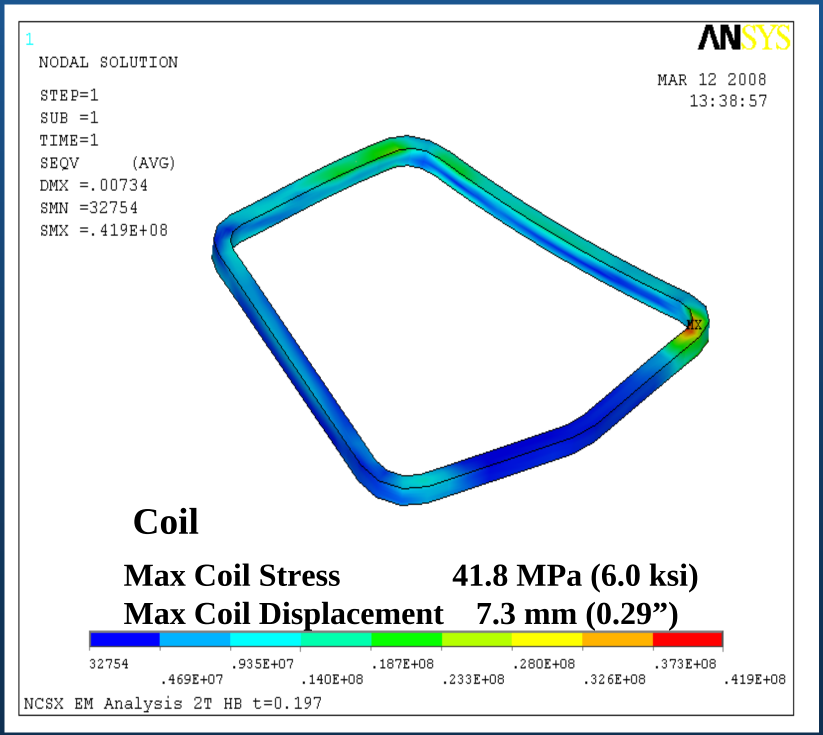
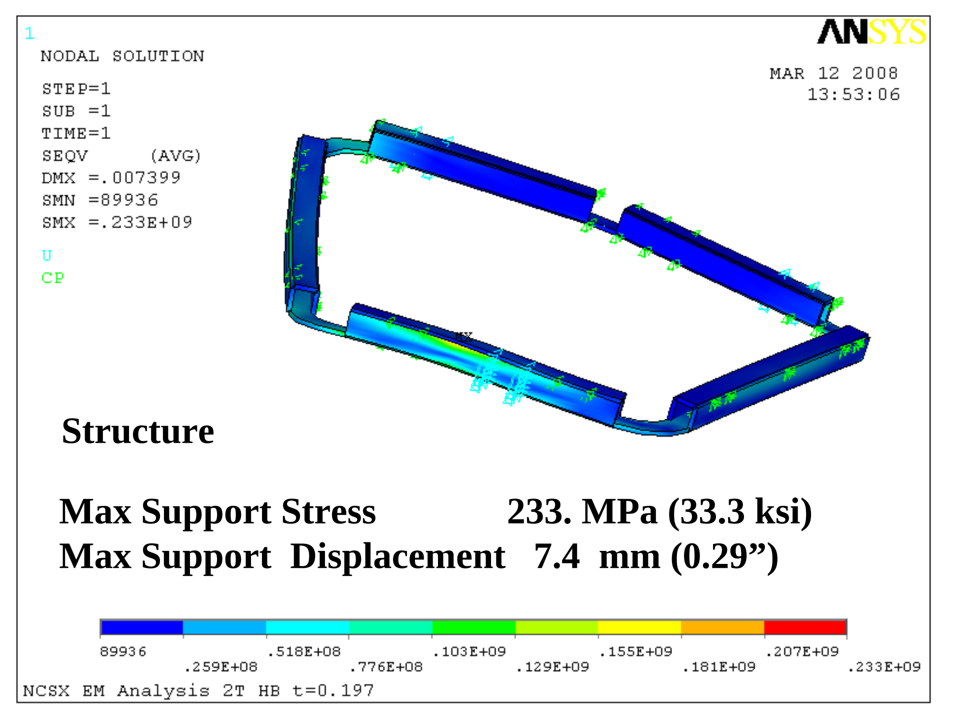
- **Results for 2Tesla High Beta t=0.197s Scenario (50 lb/in max)**
- **Analysis indicates stress & deflection high without support in corners**



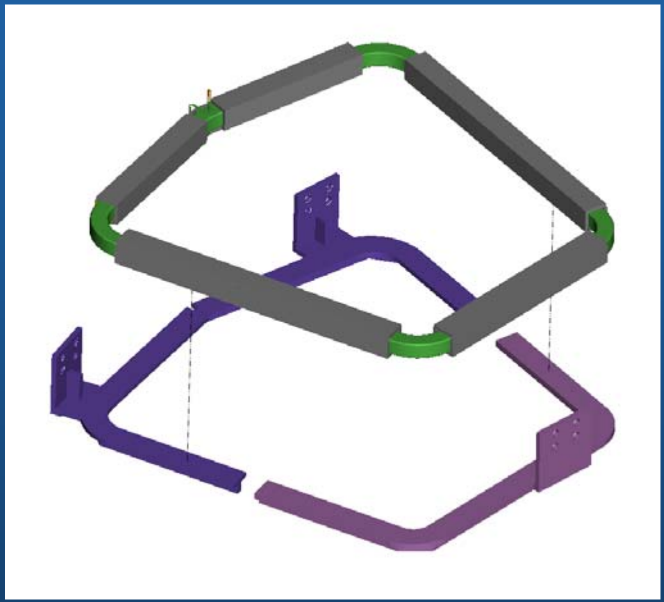


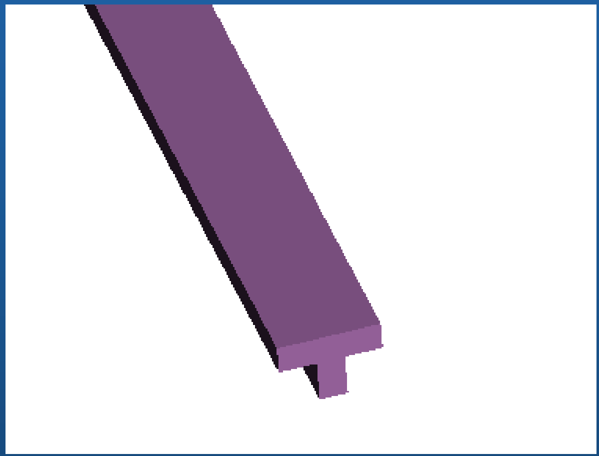
- **For the Conductor at 20C**

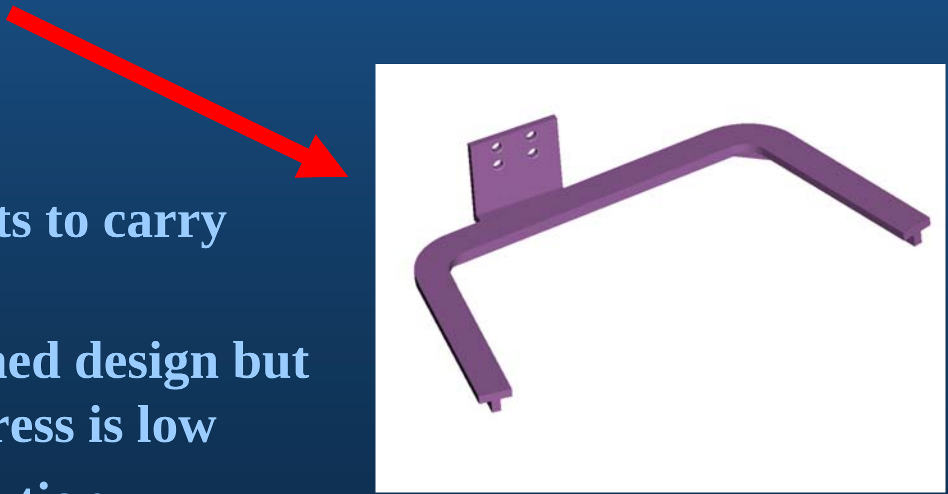
  S.m= 6 ksi
- **For 304 at LN temp**

  S.m= 39 ksi

Preliminary Stress Analysis
Corners Stiffened



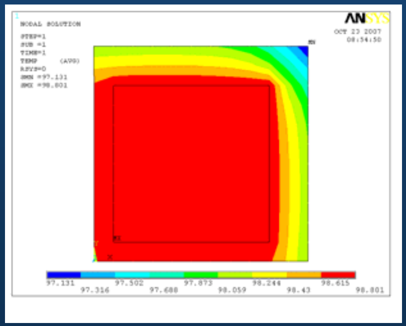




- Ribs added to supporting brackets to carry stiffness around corners
- Final analysis required for stiffened design but risk of further iteration due to stress is low
- Material issues still require resolution

Coil Cooling Analysis
Comfortable Design Margins With Convection Cooling

- **Requirement**
  - 2 second pulse every 15 minutes
  - 20 Kamp Turns
  - Equivalent average power of 27 watts
- **For 121 Turn Coil With 2mm Conductor (11X11)**
  - Convection cooling adequate
  - Temperature increase per pulse is only approx.= 2.6 C
  - Equilibrium reached with temperature rise approx.= 9.0C
- **Margin Available**
  - Doubling the current to 40 amp turns
  - Equivalent Average Power of 107 watts
  - Temperature increase per pulse is only approx.= 10.3 C
  - Equilibrium reached with temp. rise approx.= 35C



Interfaces

- **Modular Coils, PF and TF Coils**
  - EM loads from the Modular, PF and TF coils were calculated and incorporated into the preliminary stress analysis
- **Coil Support Structure**
  - Interfaces defined by Pro-E Model
- **Liquid Nitrogen System**
  - Coils are convection cooled
  - No pressurized LN2 flow required

Interfaces

- **Electrical Leads**
  - "Individual leads will be provided at the center of each Trim coil capable of handling an equivalent RMS current of 8 amps (165 amps for 2 seconds every 15 minutes)."
  - Interfacing Cables likely to be 4 twisted 12 awg wires
- **Coil Protection System and I&C**
  - One thermocouple will be provided on each Trim Coil to be used as necessary to monitor temperatures during operation
- **Magnetic Diagnostic Loops**
  - No diagnostic loops will be provided on the Trim Coils

Interfaces

Assembly

- Targets or other means of facilitating metrology are TBD
- It will be required that the location of each coil be measured after installation

- **Electrical Grounding**
  - Trim Coils will not have a ground plane but will provide a single point ground on each coil

Peer Review Chits

- **Seven Chits addressed exploring other possible coil geometries and orientations including splitting the large coil and applying coils to midplane**
  - Art Brooks analysis evaluated additional possibilities with improved methods
  - Large Coil is now split
  - Provisions to add midplane coils are being pursued but mid plane coils will not be installed for day one operation
  - After further analysis and several meetings were held. There is consensus between physics, engineering, and management on the existing configuration

Peer Review Chits (continued)

- **"Design Coils for 3kV if not cost prohibitive for the faster potential response time"**
- **Making coils faster up to a point comparable to wall time would be useful even if power supplies can not.**

  – Done, Designed for 1kV operating. 3kV Operating Test, and 4.5kV Manufacturing Test. Sufficient for possible future requirement of 20ms response time.

Peer Review Chits (continued)

- **“Set tolerance requirements economically, Physics probably doesn’t require better than +/-.25 in coil fab, +/- .5 in placement. But must be measured with accurate metrology”**
  - Done, however mechanical requirements will drive fabrication tolerances tighter than that
- **“Generate spec for Trim Coils clearly stipulating, a) response required, b) harmonics that can be accepted, c) tolerance acceptable, d) possibly induced voltages, e) mutual inductances”**
  - a and c included in SRD
  - b, d, and e have not been included, not seen as coil requirement ?
  - initial analysis shows voltages up to 400V may be induced, within coil design capability

Peer Review Chits (continued)

- **Try to find off the shelf power supply solution, then design coil voltage and # of turns around same**
  - Requirement for 121 turns agreed to based on the assumption that the lower current requirement will drive down costs. Also lower current requirement significantly drives down cost of cables while only marginally impacting the cost of the coils
- **"Determine effect of mutual coupling between modular and PF coils in terms of induced voltage which must be bucked by trim coil power supplies, and which will cause ripple in trim coil current."**
  - requirement for power supplies not coil?

Chits to Self – From Peer Review View Graph "Priorities Headed for PDR"

- **Areas of Design with lower maturity needing work up front**
  - Finalize layout – eliminate interferences
    - Complete (potential interferences for clamps still being investigated)
  - Modify layout so that coil is wound in tension
    - Complete
  - Determine best support plan to minimize complexity and cost
    - Several approaches considered and current design chosen
  - Structural Analysis
    - PDR level analysis complete
  - Determine assembly method
    - Smaller coils eliminate most significant challenges

Summary

- **Requirements Defined**
- **Field Error Suppression Capability Analyzed –Iterated- and Agreed Upon**
- **Dielectric Standoff to Ground and Turn To Turn Standoff has generous margins**
- **Preliminary Thermal Analysis Complete**
- **Preliminary Stress Analysis Complete**
  - Final analysis required for stiffened structure
- **Interfaces Defined**
- **Peer Review Chits Resolved**
- **Chits to Self**
  - Ground Isolation Needs Detail Design
  - Lead Support Concept Not Complete
  - Material Selection Required- Mag. Permeability Issues
  - Assembly Issues need to be fleshed out