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# **Review of Twisted Racetrack Windings / Asm**

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G. Lovett, P. Miller, B. Nelson, D. Williamson  
16 April 2004

## Charge to reviewers:

- Does the twisted racetrack coil represent the desired features of the prototype and production modular coils?
- Does it meet requirements for measurement, diagnostics, testing?
- Are models/drawings of the clamps and chill plates ready for fabrication?
- Is the design consistent with coil winding and VPI plans?

## Outline of presentation:

- Requirements and test objectives
- Overview of design
- Performance evaluation
- Work to be done

- Twisted racetrack coil is one of four test articles (incl UT coil)
- First to demonstrate prototypical winding assembly and clamp design

### Coil Electrical Parameters

Calculated quantity		Flat Racetrack	Twisted Racetrack	Prototype (Coil type C)	Production Coil type A	Production Coil type B	Production Coil type C
Number of elec turns per winding pack		14	9	9	10	10	9
Number of electrical turns per coil		28	18	18	20	20	18
Number of physical turns per electrical turn		1	4	4	4	4	4
Conductor width, with serve	in	0.625	0.350	0.350	0.350	0.350	0.350
Conductor height, with serve	in	0.500	0.391	0.391	0.391	0.391	0.391
packing fraction		0.78	0.78	0.78	0.78	0.78	0.78
Winding resistance at RT	ohms	1.366E-02	7.201E-02	1.506E-02	1.848E-02	1.802E-02	1.506E-02
Winding resistance at 120K	ohms	1.772E-03	2.111E-02	5.136E-02	6.304E-02	6.146E-02	5.136E-02
Winding resistance at 80K	ohms	7.835E-04	1.081E-02	6.662E-03	8.177E-03	7.972E-03	6.662E-03
Inductance - windings only	Henries	6.63E-04	7.91E-03	7.90E-03	1.240E-02	9.230E-03	7.900E-03
Time constant - windings only, RT	seconds	4.85E-02	1.10E-01	5.25E-01	6.71E-01	5.12E-01	5.25E-01
Time constant - windings only, 120K	seconds	3.74E-01	3.75E-01	1.54E-01	1.97E-01	1.50E-01	1.54E-01
Time constant - windings only, 80K	seconds	8.46E-01	7.32E-01	1.19E+00	1.52E+00	1.16E+00	1.19E+00
Max operating current per elec turn	Amps	N/A	N/A	N/A	40908	41561	40598
Maximum test current	Amps						

# Goals for winding form fabrication

Objective	Metric
<b>11 Obtain first sample casting from EIO team</b>	
111 Pattern from Lawton	accurate translation of CAD data to pattern
112 pouring	riser design correctly predicted by flow solidification model?
113 distortion due to heat treat	part stays within machining allowance
115 radiography	buried defects within expected range
114 weld repairs	hours spent performing weld repairs
116 permeability of casting	permeability within 1.02 limit
<b>12 Obtain first sample machining of semi-prototypical casting</b>	
121 machining simulation and NC tape	Part can be machined
122 Fixturing	Part can be held and manipulated on machine
123 machining winding contour	winding contour within tolerance
124 Clamp features - pockets, tapped holes	clamp features within tolerance
125 potting groove	functional groove is provided
126 metrology datum targets	targets are useable and durable
127 permeability change due to surface work hardening	permeability within 1.02 limit
<b>13 Measurement of winding form at PPPL</b>	
131 Use of datum targets	targets are visible, useable and repeatable
132 Measurement of winding contour	contour measurements match 123 above
133 Measurement of clamp features	clamp features match 124 above
134 Best fit of as measured part to data	datum target locations can be redefined to optimize fit of selected features to theoretical part
<b>14 Preparation of first prototypical winding form for winding</b>	
141 mold release	Mold release prevents copper chill plate from sticking to winding form
142 kapton insulation	Maintains electrical isolation of chill plate
143 forming and attachment of internal copper chill plates	winding-side surface is accurate enough to place windings
144 weld studs	all studs welded to full structural integrity and geometric accuracy
145 winding start blocks at leads	start blocks attached with geometric accuracy of +/- 0.02 in.

# Goals for coil winding process

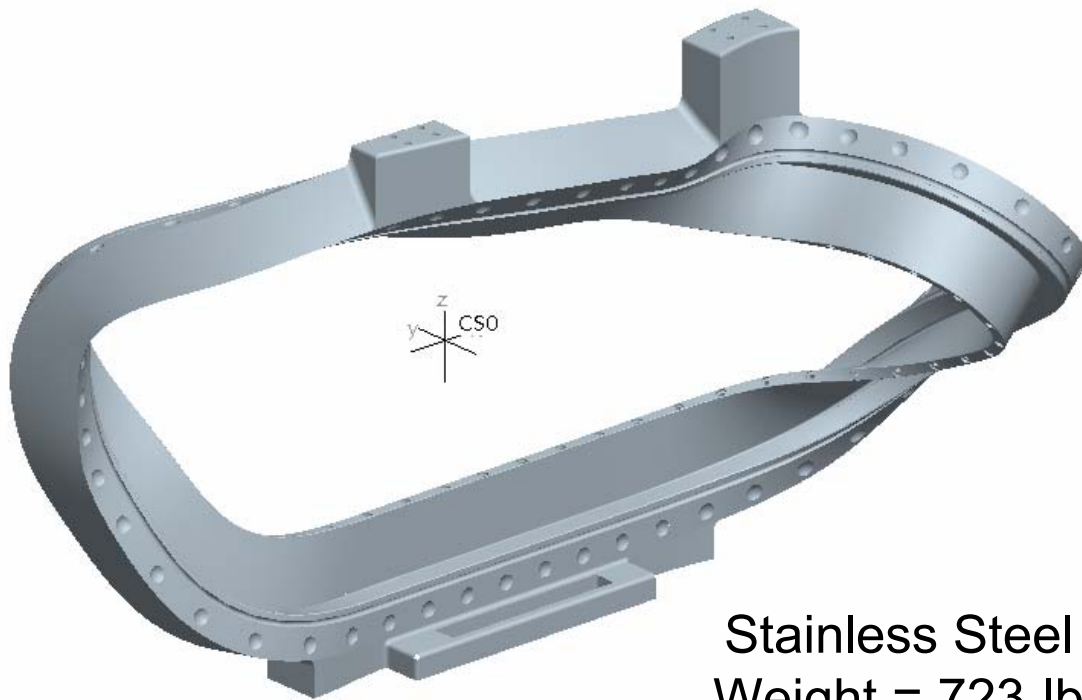
<b>21 Placing and "setting" conductor</b>	
211 Clamping conductor	winding clamps work as designed and are frequent enough to restrain winding within accuracy requirements
212 Measuring for shims	surface of as-wound layers can be measured and shim height calculated
213 Placing layer to layer shims	surface of layer after shimming meets or exceed tolerance requirements
214 Placing lateral shims between B and C rows	total winding width is within tolerance
225 Handling layer to layer joggles	joggles can be clamped and held with sufficient accuracy to keep lead geometry from wandering
<b>22 Leads</b>	
221 Initial placement and start of winding	placement in start blocks is within accuracy requirements
222 routing of 4 parallel turns at end of winding and interleaving with first turns	Lead arrangement can be clamped and held to required accuracy
223 dip soldering and re-insulating ends of leads	conductor ends can be trimmed to proper length and soldered into end lugs without damaging or contaminating rest of winding
224 conductor attachment to lead block	soldered end lugs match lead block properly
<b>23 Finishing winding pack stackup</b>	
231 forming of external chill plates	chill plates can be formed and fitted to winding pack
232 attachment of external chill plates to internal chill plates	thermal connection can be reliably made at both ends
233 forming and brazing of cooling tubes and pads	tube geometry is predictable and layout matches winding pack
234 attachment of cooling tubes to external chill plates	fastening system works without undue thermal isolation
235 attachment of G-11 pads at clamp locations	pads can be accurately fitted and held in place and extra glass roving used to fill gaps
<b>24 VPI</b>	
241 application of self-fusing tape, including juggling of winding clamps and sealing around leads	tape forms good seal, removing clamps one by one does not distort winding
242 application of "french toast" pressure shell over bag	shell can be applied between clamps and is contained without wicking into clamps or clamp springs
243 pump down	winding pack pumps down to required pressure
244 heating to reduce viscosity	coil can be heated in autoclave to proper temperature in controlled manner without distorting winding or losing vacuum seal
245 epoxy impregnation	epoxy is contained within bag system
246 pressure cycling	vacuum/pressure/"milking" is successful
247 heating for cure	temperature can be raised in the proper time period without causing temperature gradients in winding form that result in distortion of winding
248 controlled cooldown	cooldown accomplished in controlled manner without distorting winding
249 cure shrinkage	shrinkage of winding relative to winding form is within predicted limits
<b>25 winding pack completion</b>	
251 cleanup of coil	excess epoxy can be removed, as well as self fusing silicone tape under winding clamps
252 attachment of final clamps and "tuning" preload	winding clamps replaced with operational clamps and the clamp preload set successfully

# Goals for coil testing

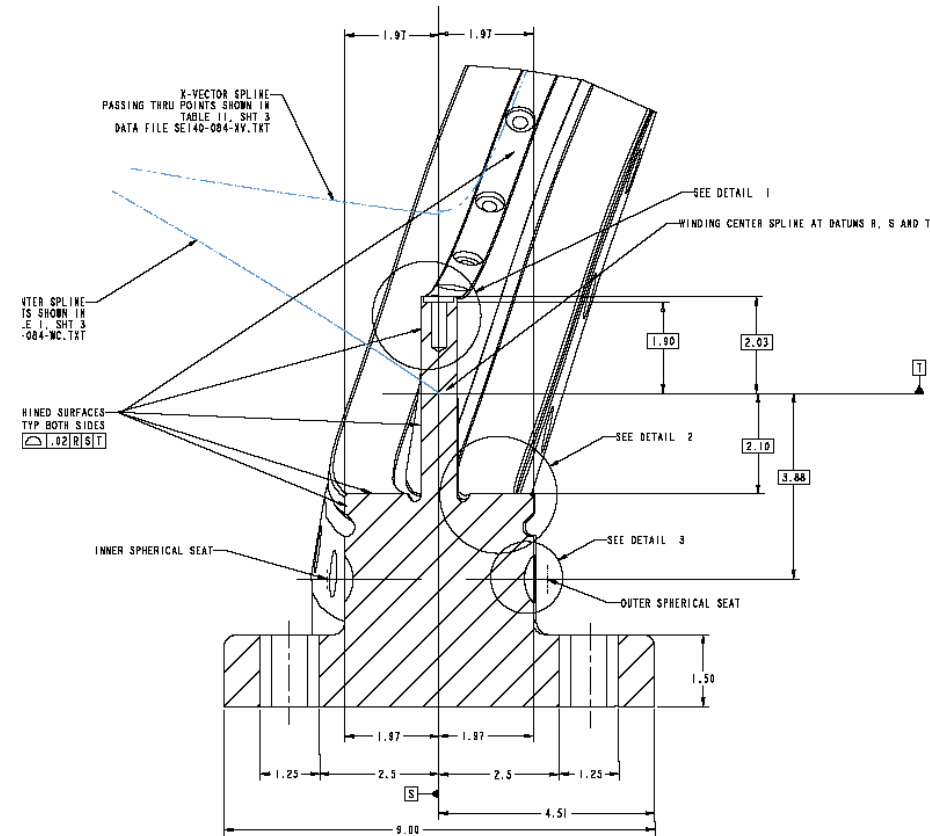
<b>31 Geometric tests</b>	
311 Gross winding pack shape relative to theoretical	as-measured winding pack geometry within acceptable tolerance
312 Winding form shape	as-measured winding winding form shape is the same as pre-potted shape
313 magnetic field measurement	field measurements consistent with geometric measurements
<b>32 electrical tests</b>	
321 resistance	Resistance at room temperature and LN2 temperature matches prediction
322 time constant / inductance	decay time matches prediction
<b>33 hydraulic tests</b>	
331 Flow rate	Required flow rate can be achieved
332 pressure drop of LN2	Pressure drop matches prediction for range of flow rates
<b>34 Thermal tests</b>	
341 cooldown from RT to LN2 temp	winding form and winding pack cool down as expected
342 heating during current pulse	temperature rise during current pulse matches prediction
343 cooldown between pulses	Winding returns to pre-shot temperature within 15 minutes
<b>35 Structural tests</b>	
351 Strain in winding form from cooldown to LN2 temp	Measured strain in winding form matches prediction within 20%
352 Strain in winding form from magnetic loads	Measured strain in winding form matches prediction within 20%
353 gaps between winding packs and tee before, during and after magnetic loading.	Distortion of winding pack relative to winding form matches prediction within 20%
<b>36 fatigue tests</b>	
361 change in resistance vs strain in winding pack, cycles	no detectable (< 5%) change for number of cycles tested
362 changes/increases in deflection vs number of cycles	no detectable (< 5%) change for number of cycles tested
363 degradation in cooling behavior vs cycles	no detectable (< 5%) change for number of cycles tested
364 degradation in clamps (wear in insulation, loss of preload, bending/breaking of studs, thread loosening) vs cycles	no detectable degradation for number of cycles tested
365 degradation in crossover and lead connections vs number of cycles	
<b>37 Instrumentation</b>	
371 temp instrumentation is reliable and accurate	Temperature signals have consistent response and accuracy
372 strain instrumentation is reliable and accurate	Strain signals do not drift
373 deflection instrumentation is accurate	deflection measurement technique is repeatable
374 voltage taps work	voltage tap system can be used as reliable signal for coil protection system
<b>38 Power feeds (coax leads)</b>	
381 Power feeds can be routed as needed and work at LN2 temp	bend radius consistent with specs
382 Power feeds work at LN2 temp	no degradation, voltage drop matches prediction
383 Power feeds do not introduce heat leak to coils	lead temperature matches coolant temperature during idle
384 Power feeds do not "kick" or put undo strain on coil lead terminations	no appreciable movement when energized
385 error fields within limits	error fields from coax power feeds negligible
386 Frost at warm end of power feed can be controlled	low power blower can eliminate frost at warm end

# Winding form geometry

- Winding path is composite of production coil “worst” regions
- Machined features identical to prototype modular coil
- Currently being machined, delivery by end of April

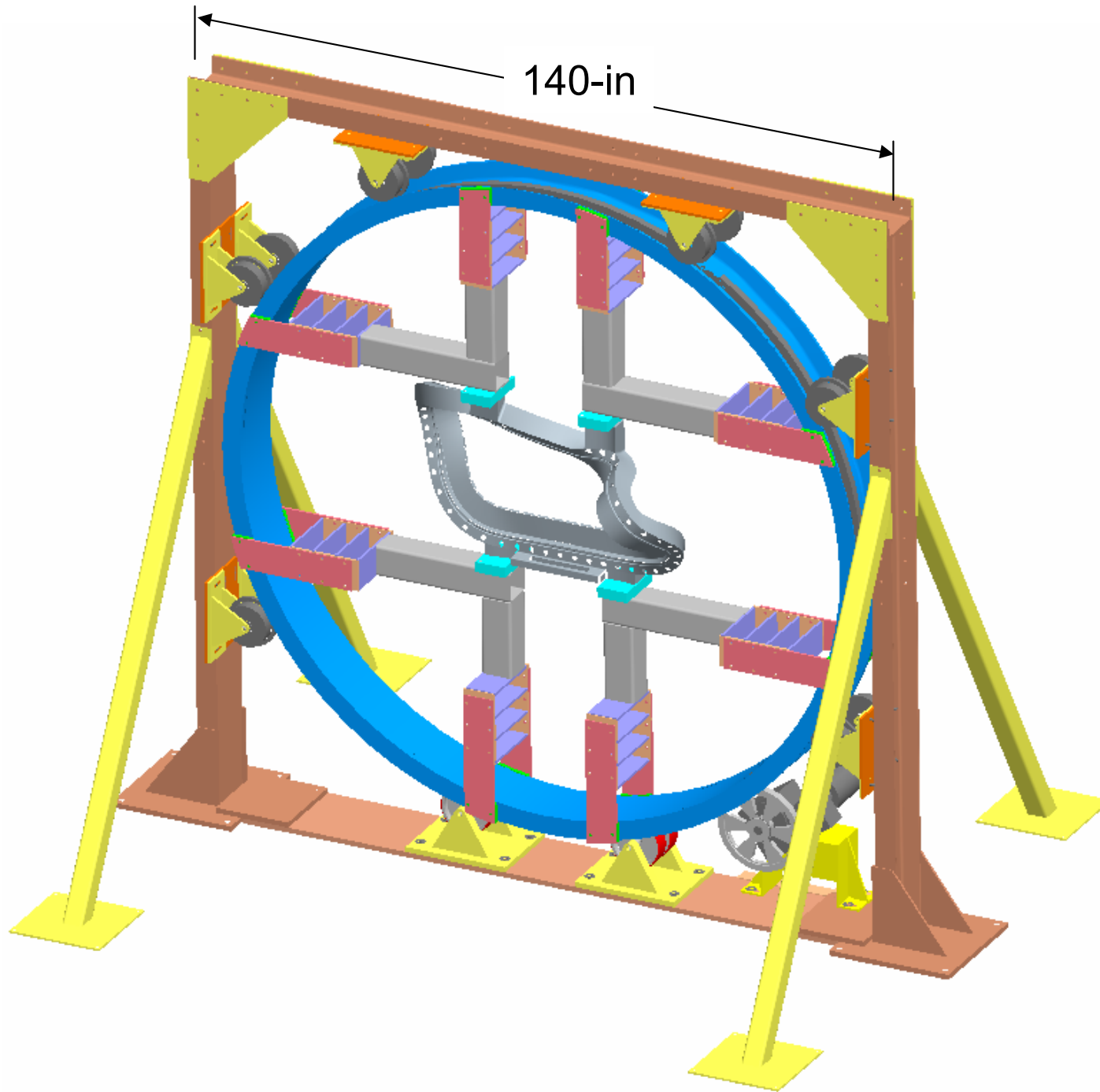


Stainless Steel  
Weight = 723-lb



SECTION R-R  
SCALE 1.0  
APPLIES AT ALL POINTS  
ALONG WINDING CENTER

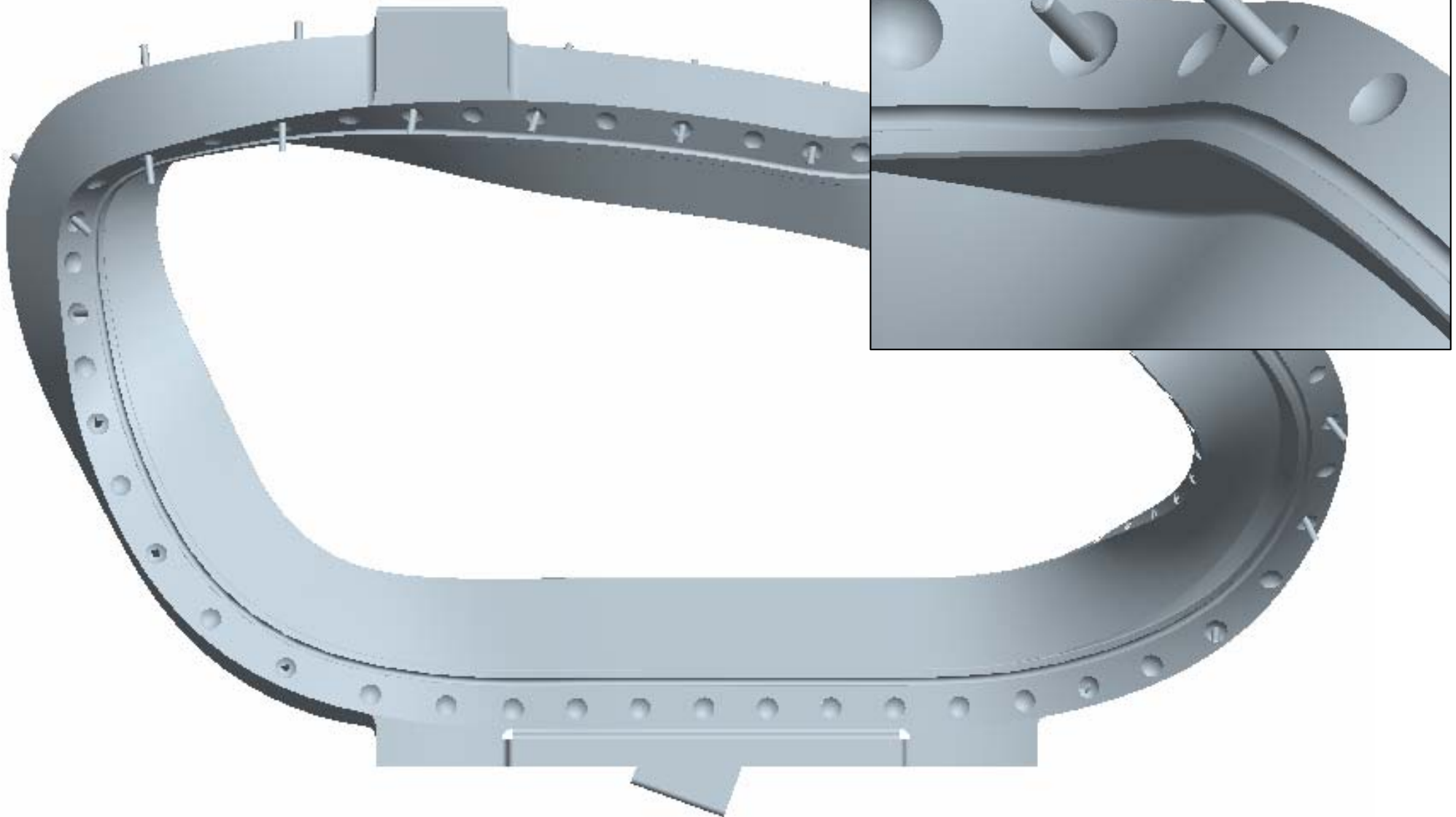
# Winding form in turning fixture





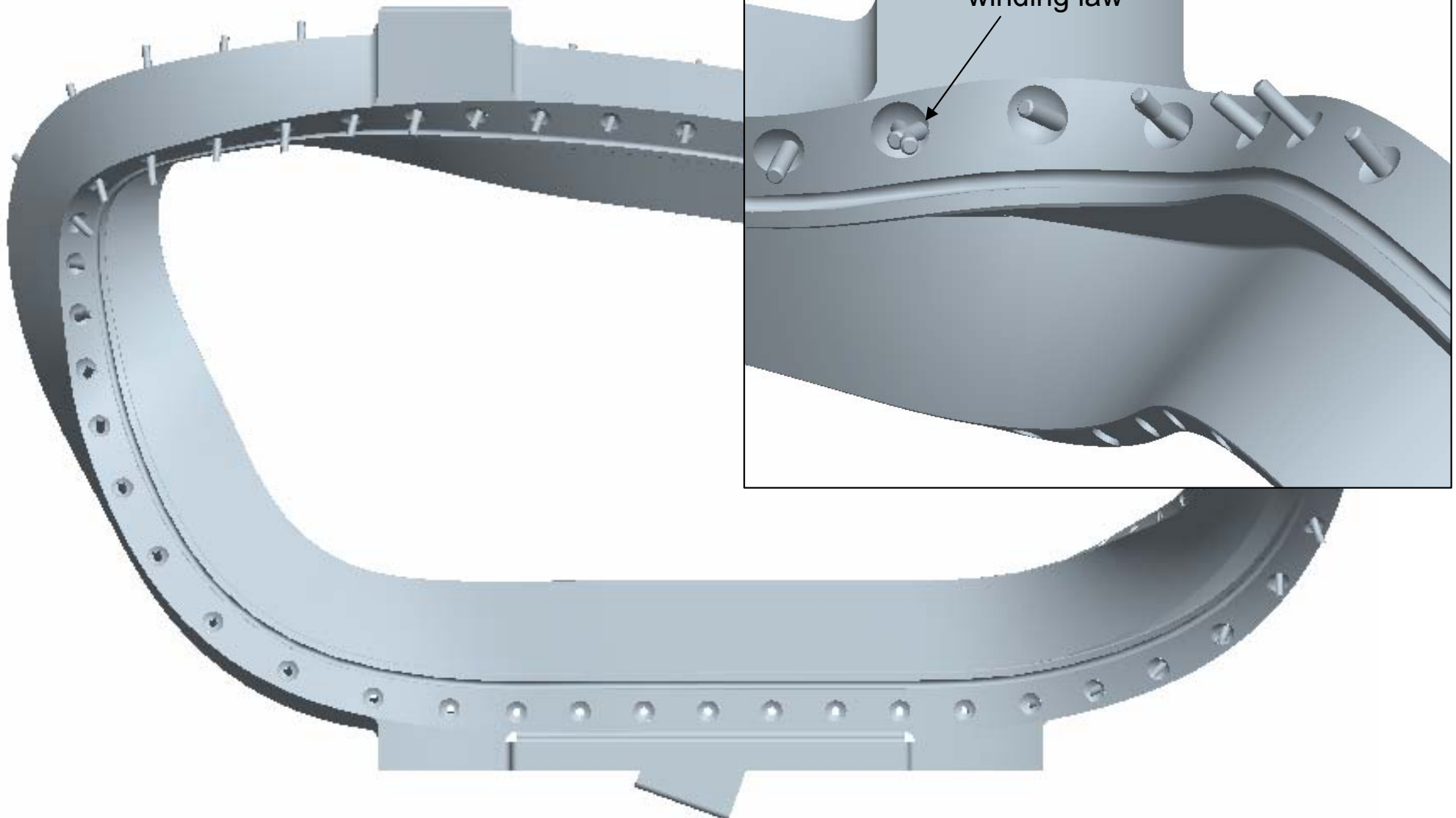
## Features to be added

- 3/8-dia x 1.5-in stud, located within spherical seat
- Alignment by fixture mounted to tee web
- Typical 100 places for winding, perm clamps



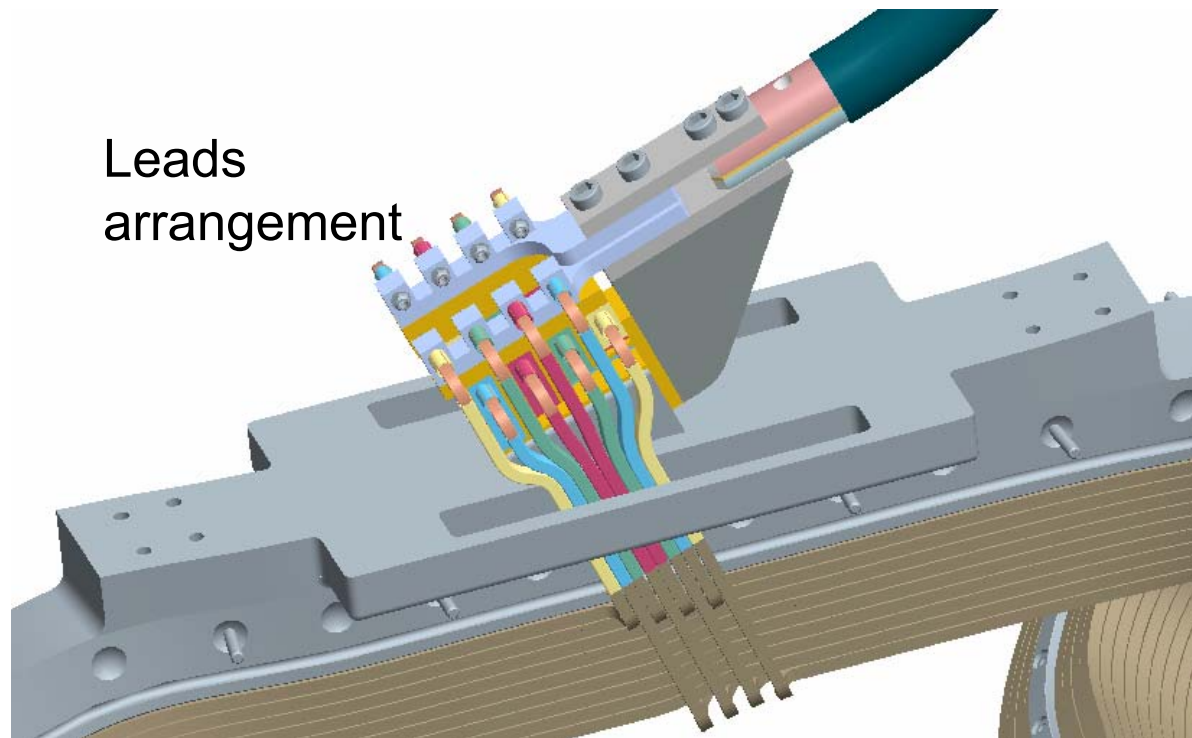
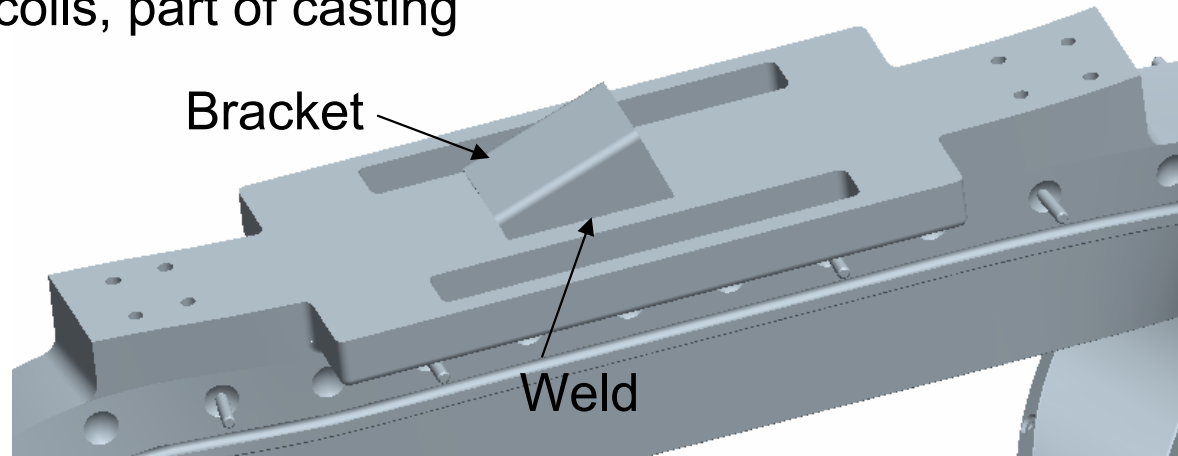
## Stud alignment varies

- In severely twisted regions, studs aligned to winding law fall outside spherical seat
- Accommodated by clamp design

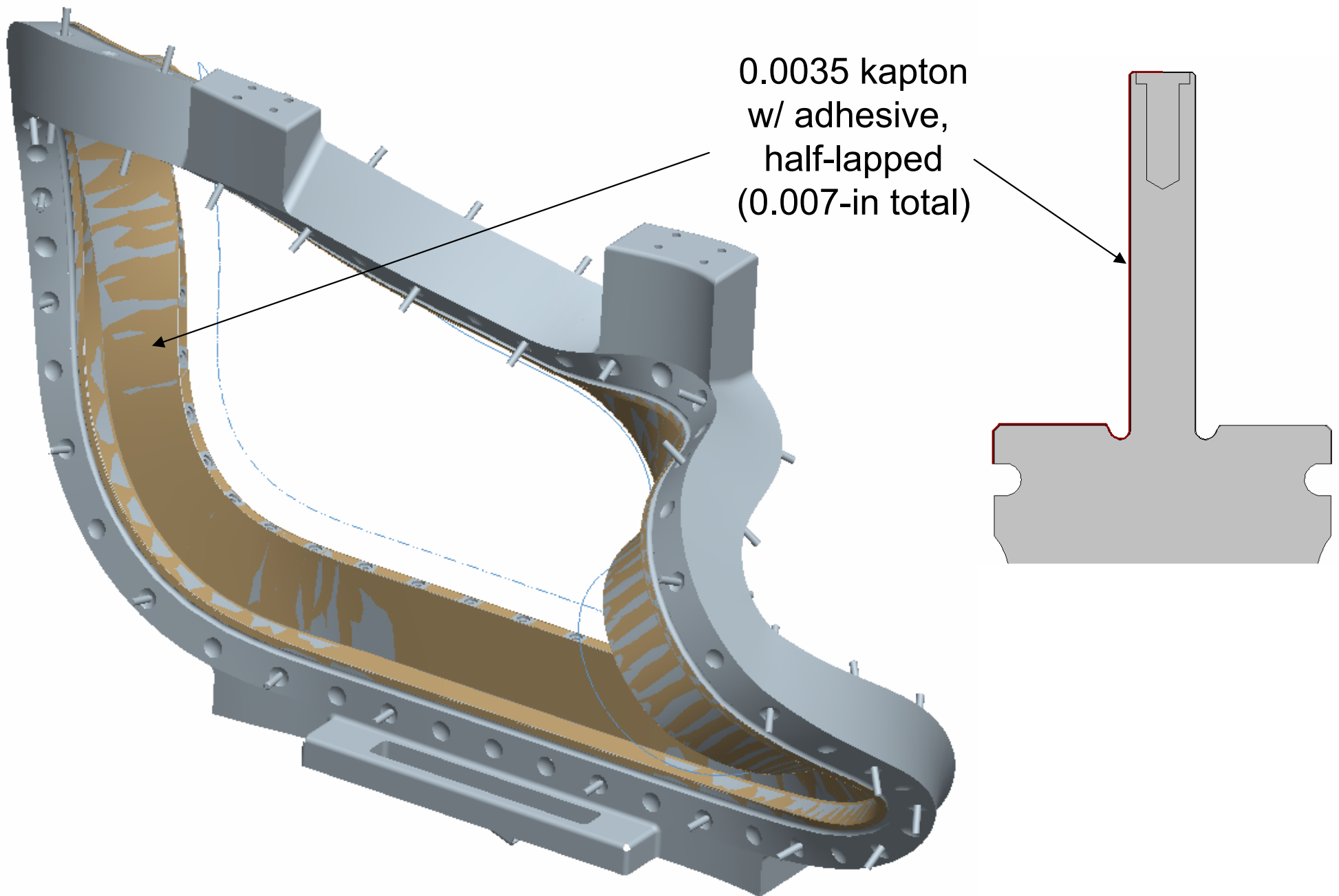


# Bracket to be added

- Bracket needed to mount prototypical terminal block
- In production coils, part of casting

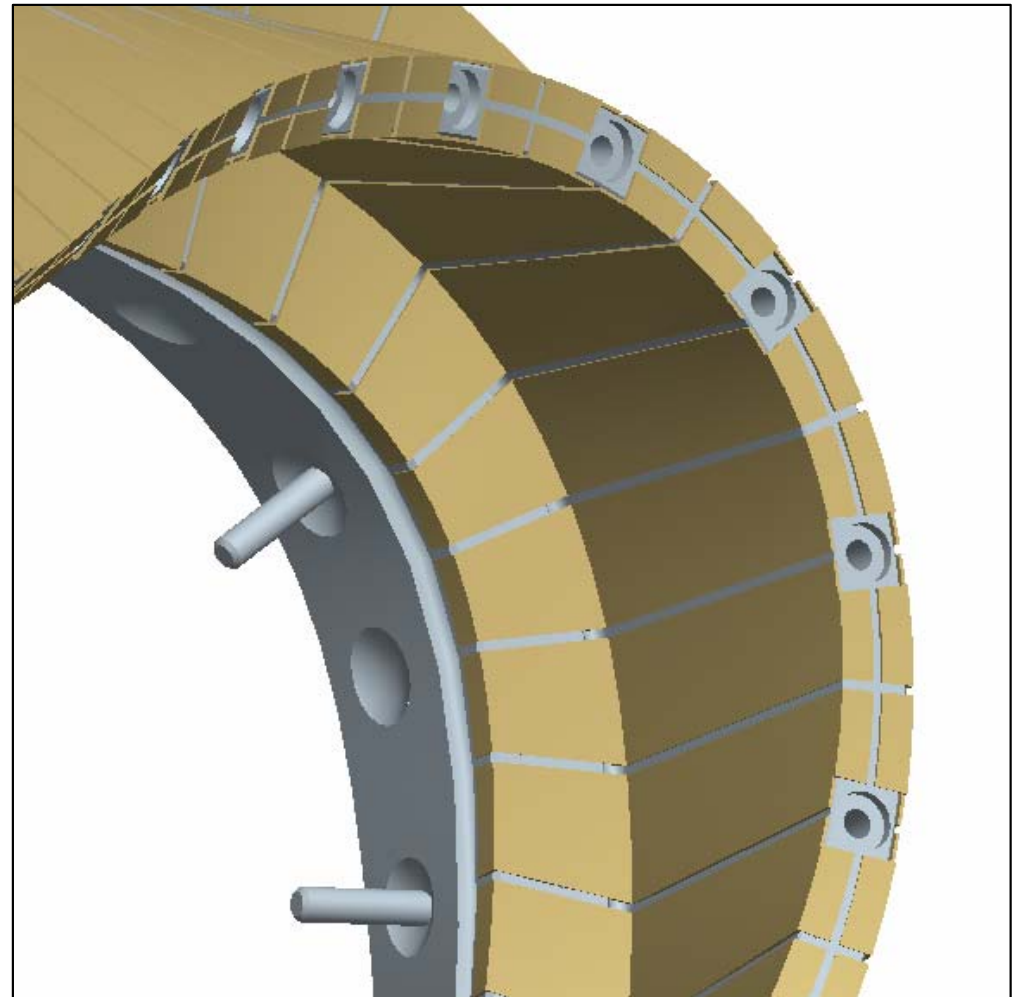
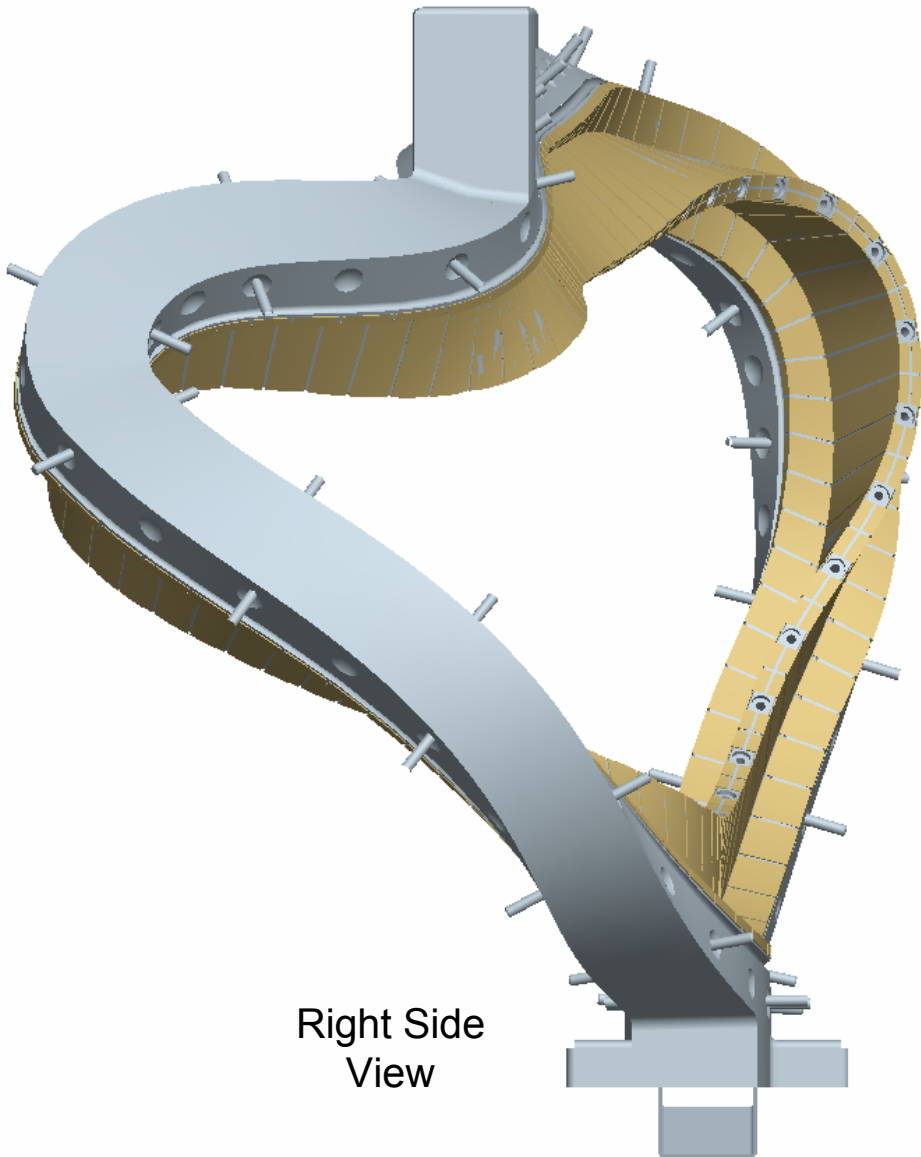


# First layer – electrical insulation

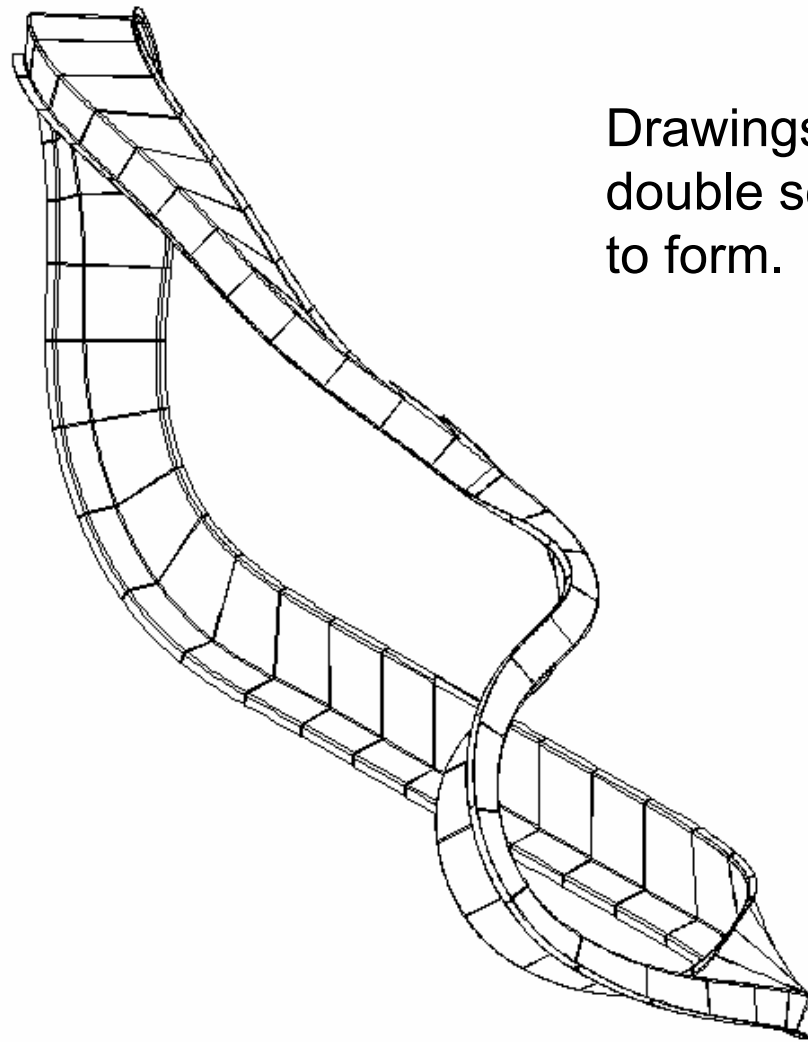


## Second layer – copper cladding

- Copper sheet, 0.040-in thick
- Approx dims = 1.4 x 6.1-in
- Qty = 200 parts



# Drawings based on 3-in segmentation



Drawings are being revised for double segmentation, easier to form.

SE140-164-SHELL-N-FLAT  
SIMPLIFIED REP: FLATS

QUANTITY	CODE	PART OR IDENTIFYING NO	QUANTITY OR DESCRIPTION	MATERIAL	SPECIFICATION	FIG NO
←		86 ASSEMBLY	←			
			PART'S LIST			

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN INCHES AND DECIMALS THEREOF. DIMENSIONS IN PARENTHESES INDICATE DIMENSIONS TO CENTER UNLESS OTHERWISE SPECIFIED. DIMENSIONS TO CENTER UNLESS OTHERWISE SPECIFIED. DIMENSIONS TO CENTER UNLESS OTHERWISE SPECIFIED. DIMENSIONS TO CENTER UNLESS OTHERWISE SPECIFIED.
   
 P THE DRAWING PRODUCED ON PROFORMER

NO.	DESCRIPTION	QTY	UNIT	SCALE	DATE

**SCALE**  
 1" = 1'-0"  
 1/4" = 1'-0"  
 1/2" = 1'-0"  
 3/4" = 1'-0"  
 1" = 1'-0"  
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 1 1/2" = 1'-0"  
 1 3/4" = 1'-0"  
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 8 1/2" = 1'-0"  
 8 3/4" = 1'-0"  
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 9 3/4" = 1'-0"  
 10" = 1'-0"

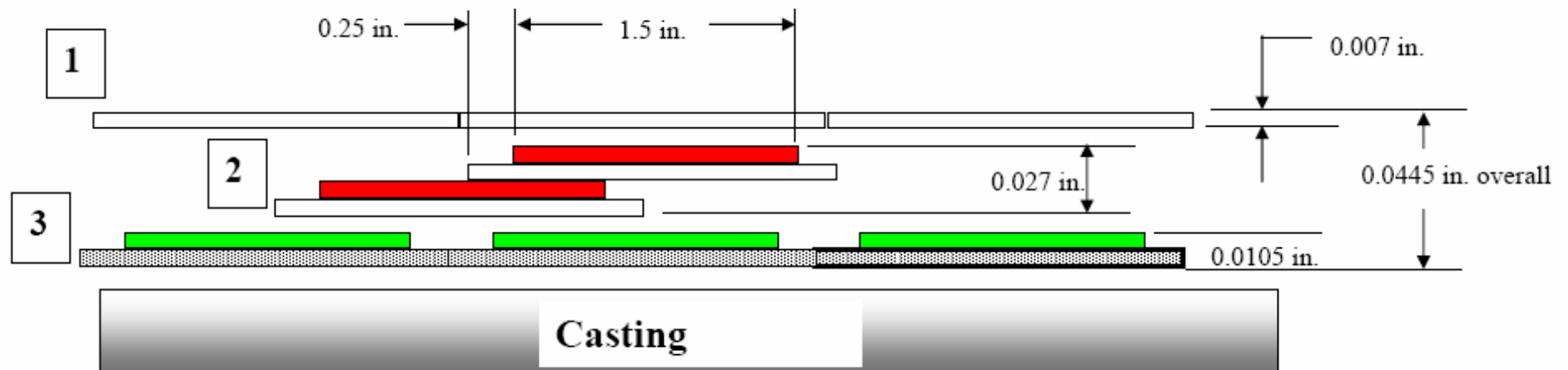
**UT-BATT-BALL**  
 D6 Shell and Libson  
 D6 SHELL AND LIBSON  
 D6 SHELL AND LIBSON  
 D6 SHELL AND LIBSON

# Developed shapes for 3-in segmentation



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<b>NATIONAL IMPACT STEEL LABORATORY</b>			
<small>1000 EAST 17TH AVENUE, DENVER, CO 80202</small>			
<small>DATE</small> 12/15/00	<small>REV</small> 1	<small>BY</small> J. J. ...	<small>APP</small> ...
SE140-184			

# Third layer – ground insulation



**1** (1) Butt lapped layer  
0.007 in. thick S-2 glass [2 inch nom. wide]

**2** (1) Half-lapped layer of composite:  
- 0.007 in. thick glass [2 inch nom. wide] & 0.0065(HN) Kapton [1.5 nom. wide] with adhesive  
- X 2 = 0.027 in. thick

**3** (1) Butt lapped layer of composite:  
- 0.007 in. thick glass [2 inch nom. wide] and 0.0035 (HN) Kapton [1.5 nom. wide] with adhesive

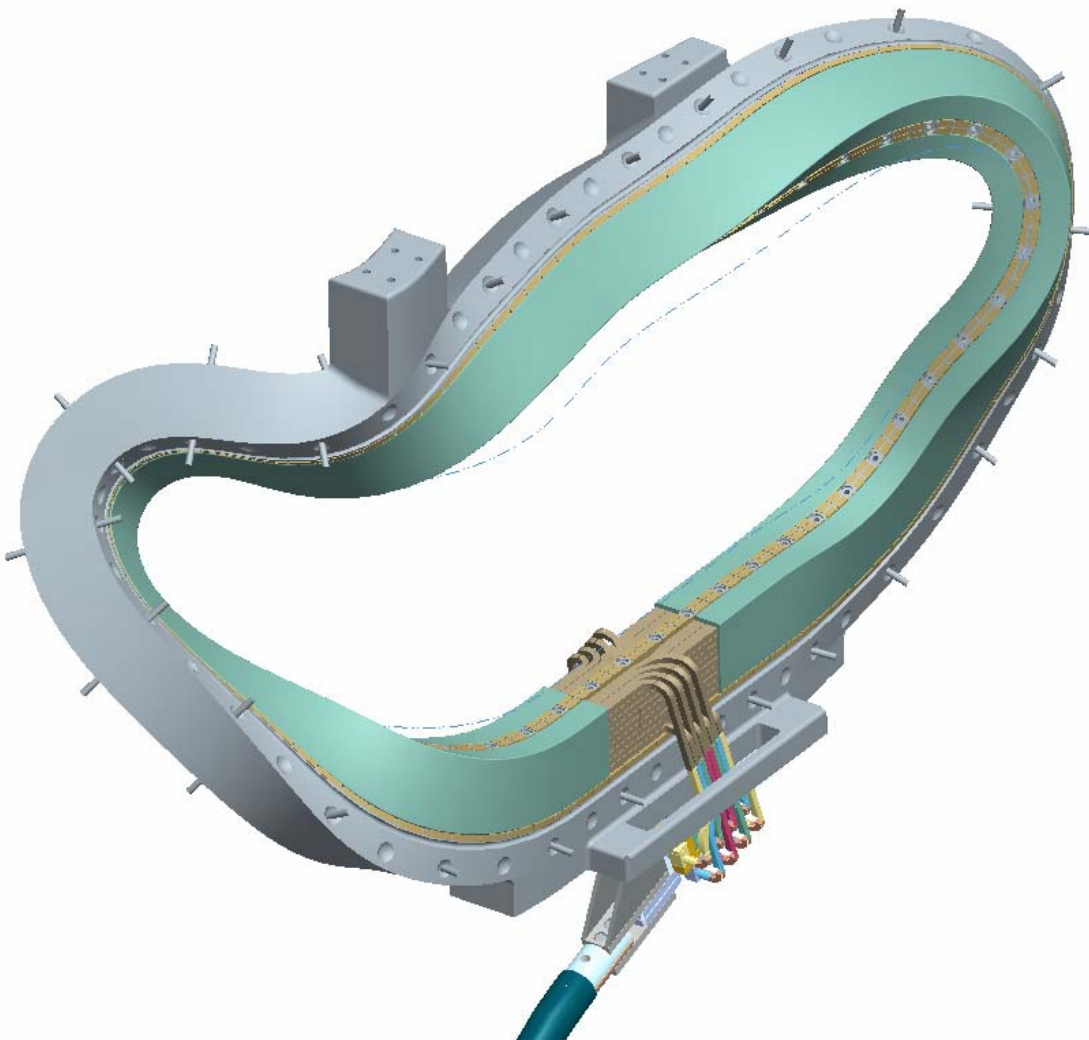
Tracking distance = 1.0 inches

March 24, 2004  
J.H. Chrzanowski



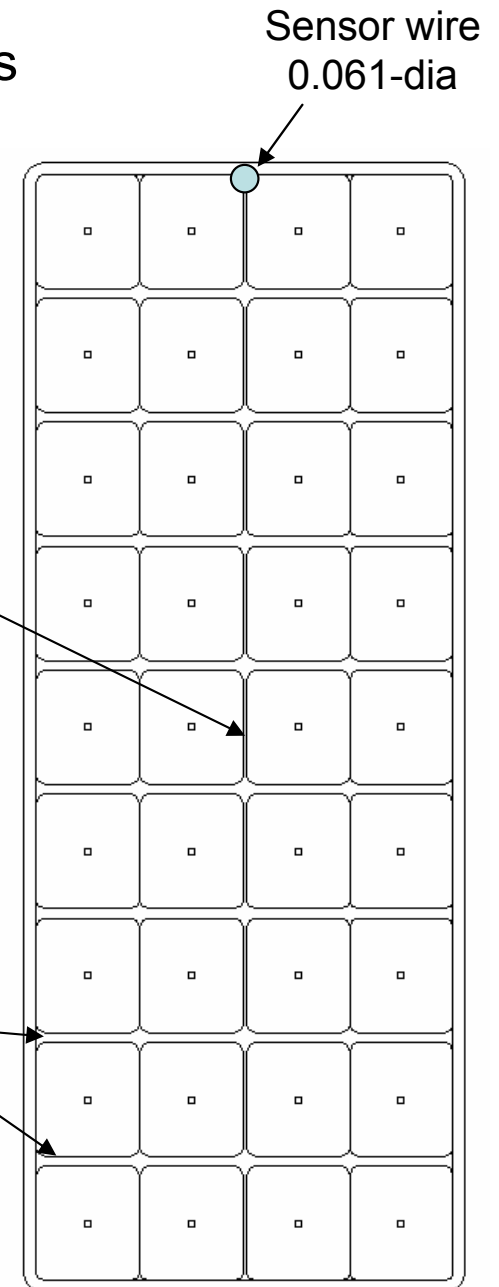
# Winding pack

- 4-in-hand, 9 turns / winding pack as in prototype
- Conductor is OFHC copper, 34-ga, 12x5/54/34, 3240 strands
- Conductor dims = 0.372w x 0.413h, incl insulation
- Insulation = 0.004-in nylon serve, 2 x 0.0055-in S-2 glass
- Total length = 432-ft, weight = 573-lb per winding pack



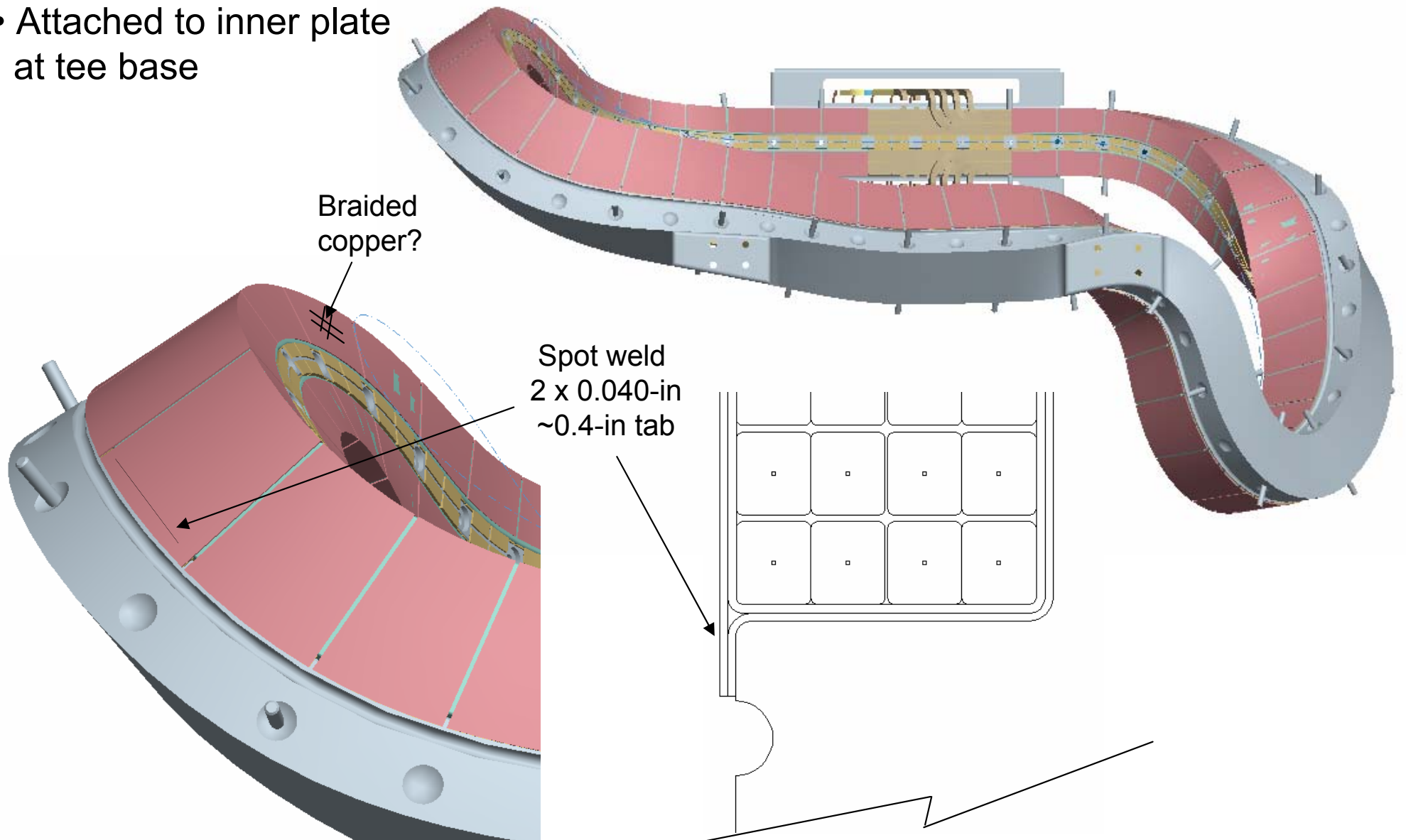
0.014-in  
nom shim

0.035-in  
nom shim  
between  
layers



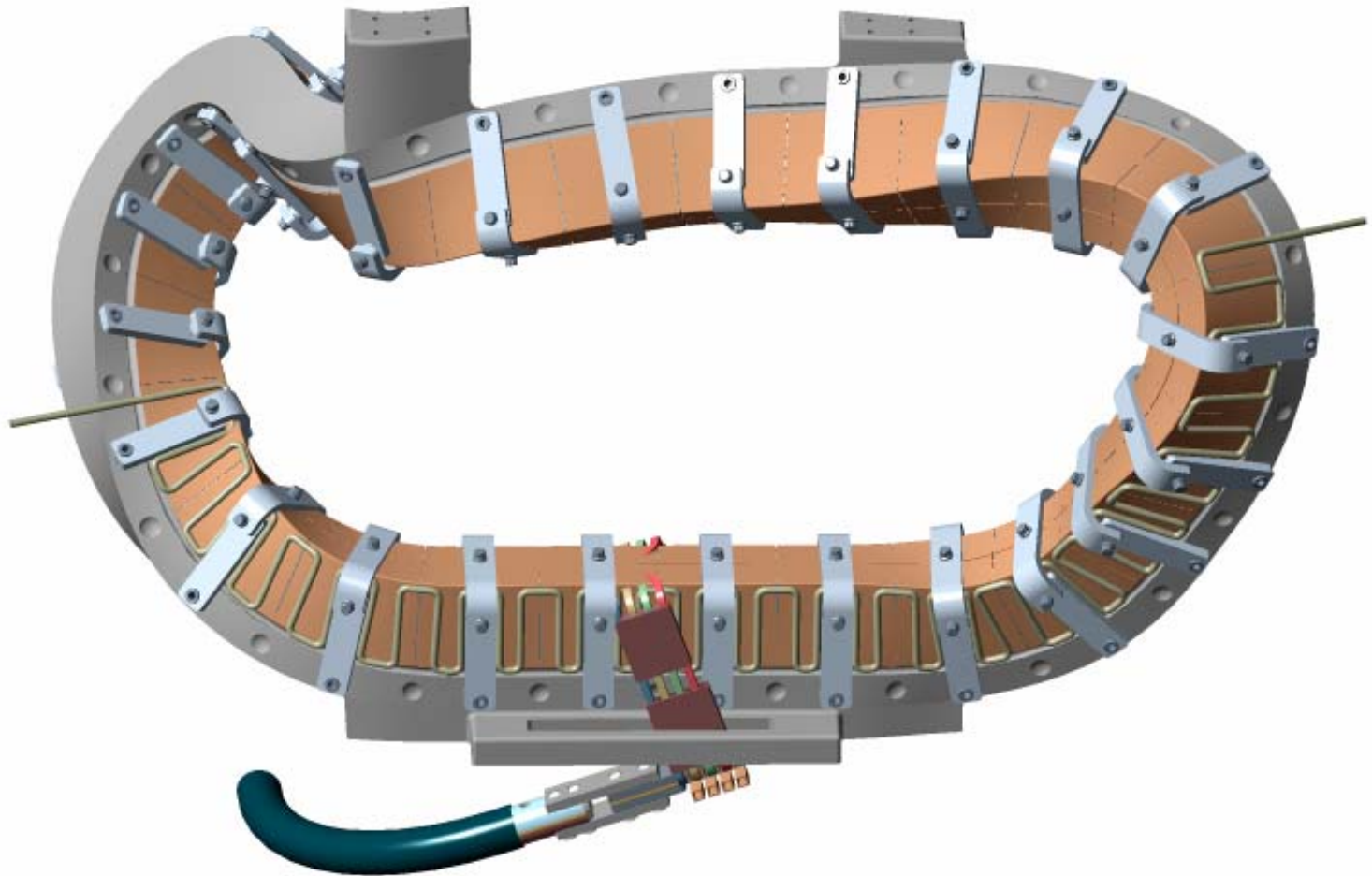
# Outer chill plate and cooling

- Copper sheet, 0.040-in thick
- Approx dims = 3 x 6-in
- Qty = 100 parts
- Attached to inner plate at tee base



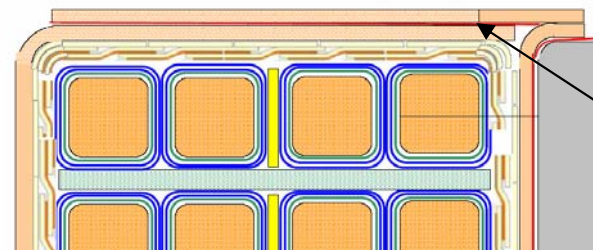
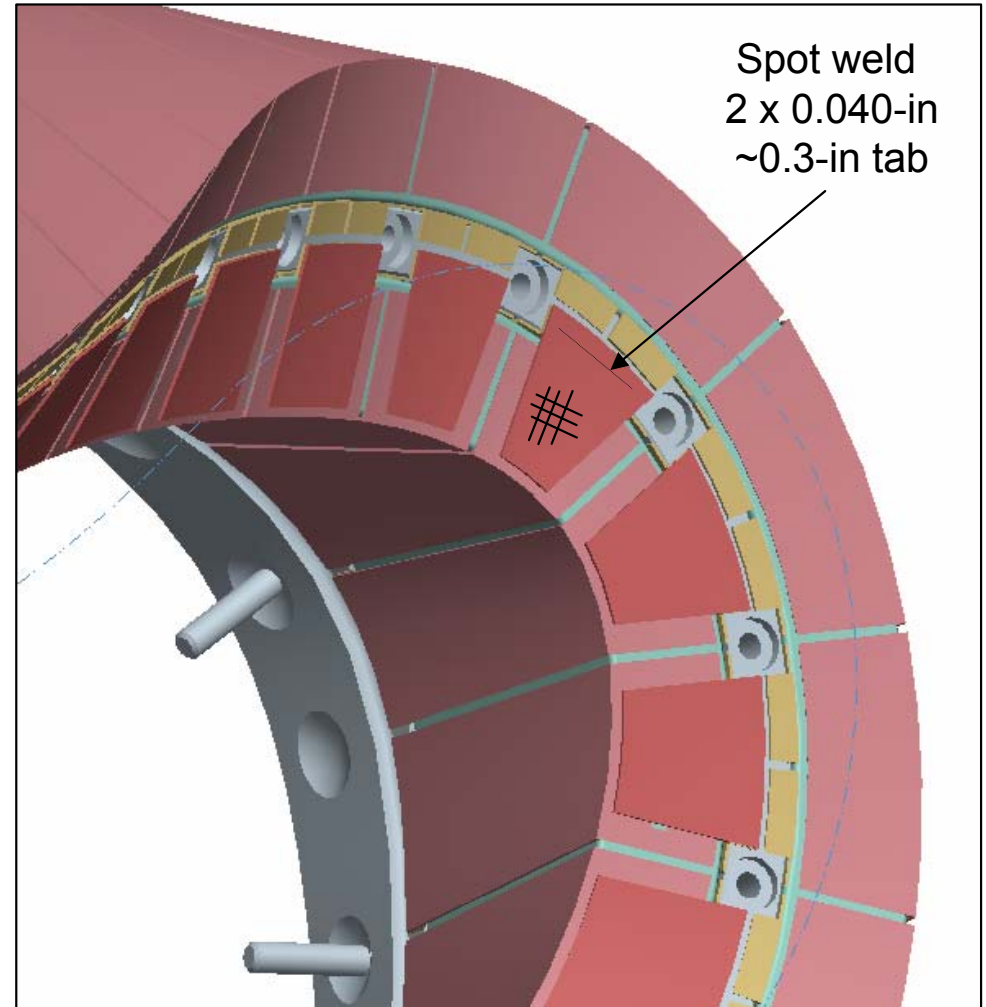
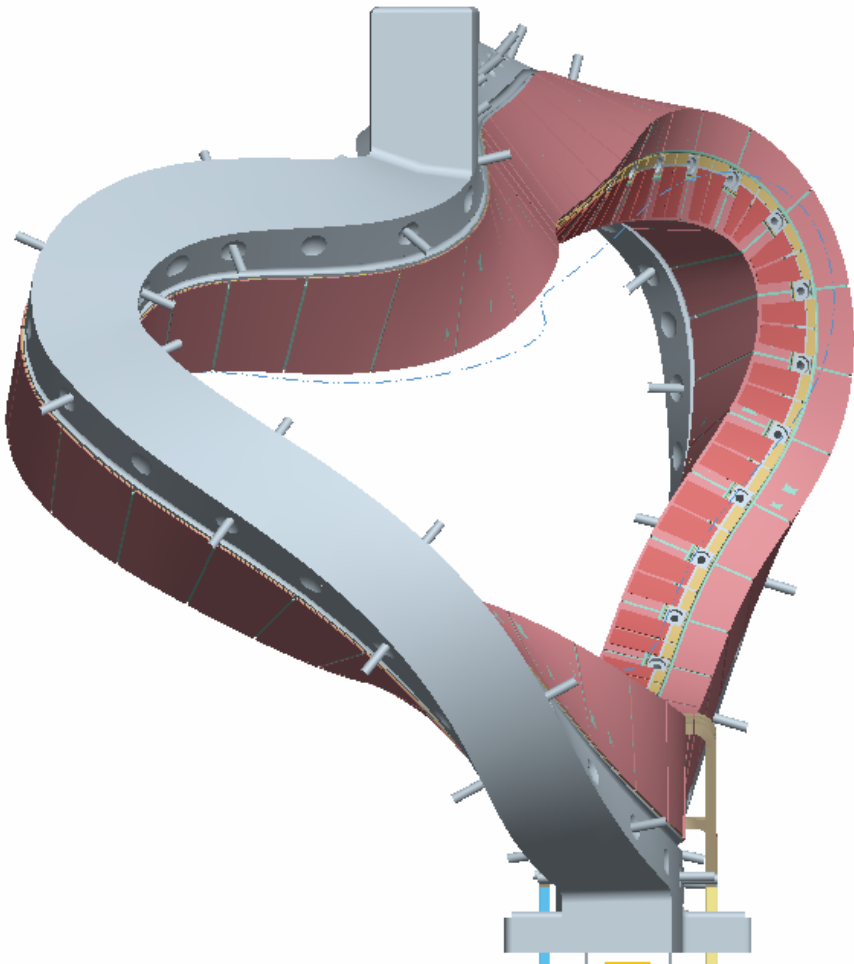
# Cooling tubes

- 3/8-dia copper tube, 4 circuits, ~25-ft ea
- Models / drawings not complete



## Outer chill plate (2)

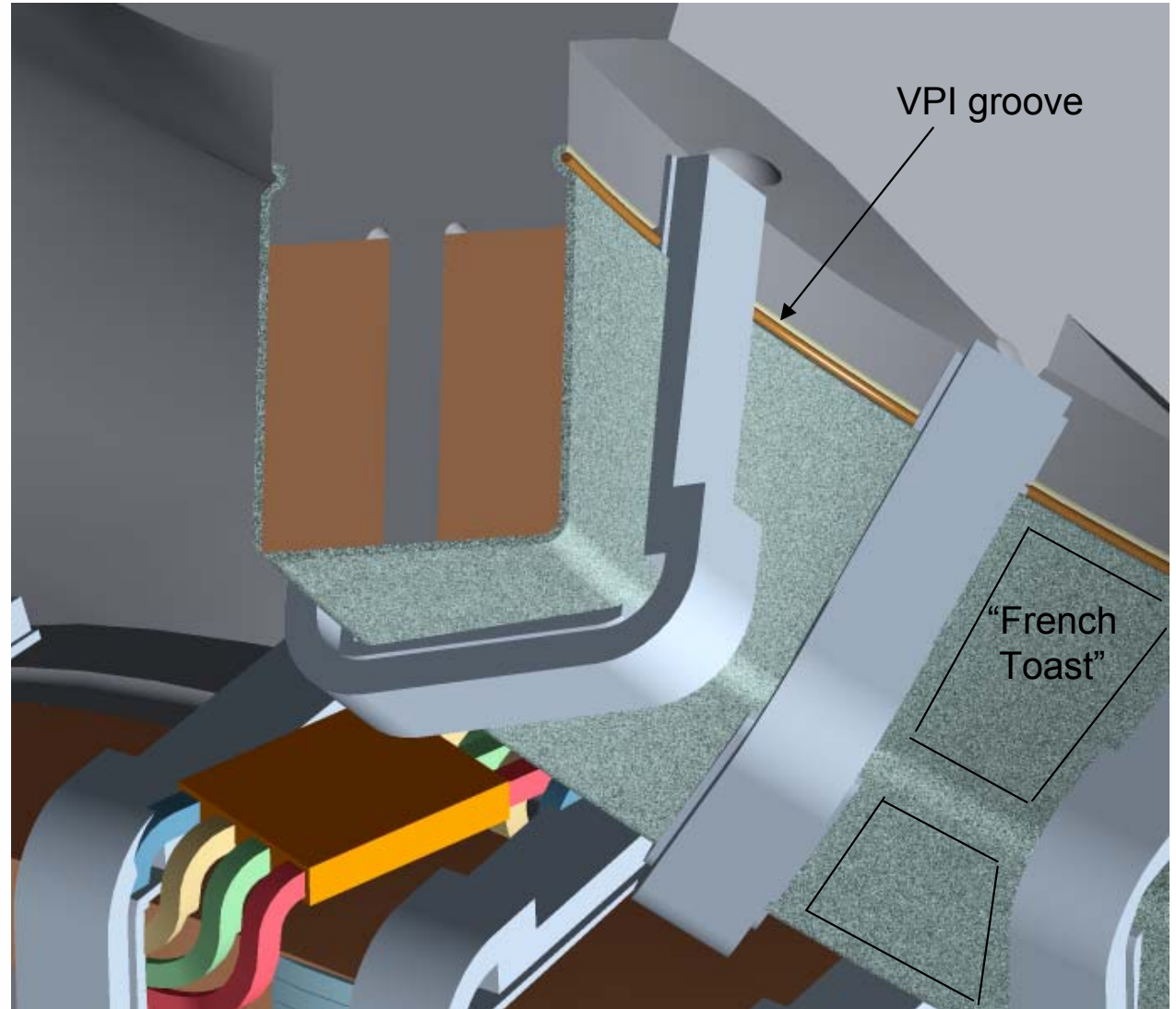
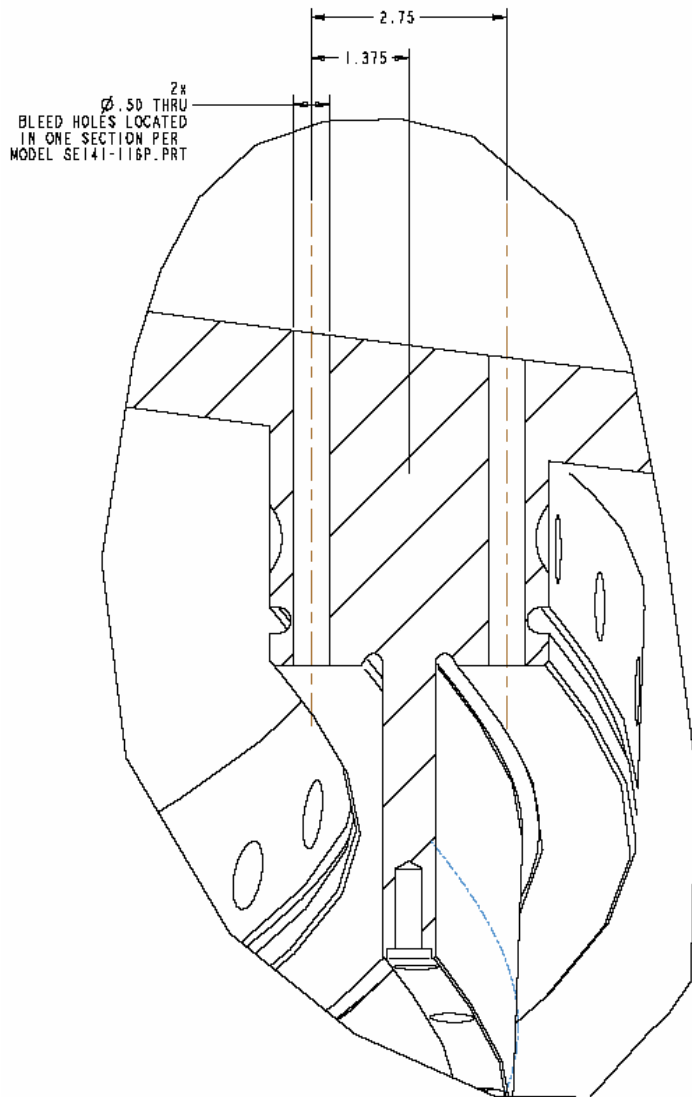
- Copper sheet, 0.040-in thick
- Approx dims = 2 x 3-in
- Qty = 100 parts
- Attached to inner plate at tee web



Insulation layer  
between chill  
plates

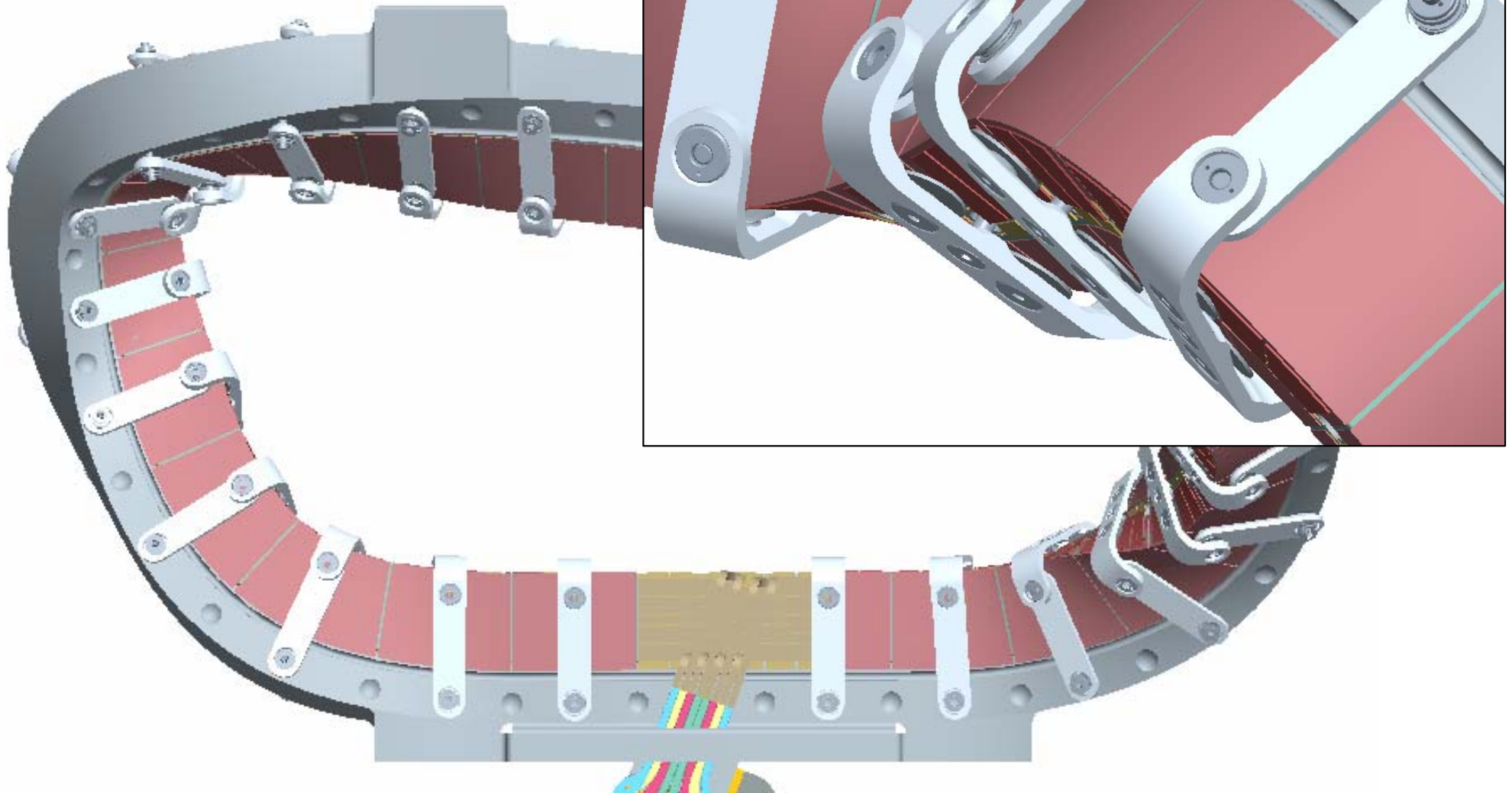
# VPI bag mold

- VPI mold composed of epoxy impregnated felt and silicon rubber tape
- Located between winding pack and clamps, sealed by base groove
- Bleed holes at “top” position

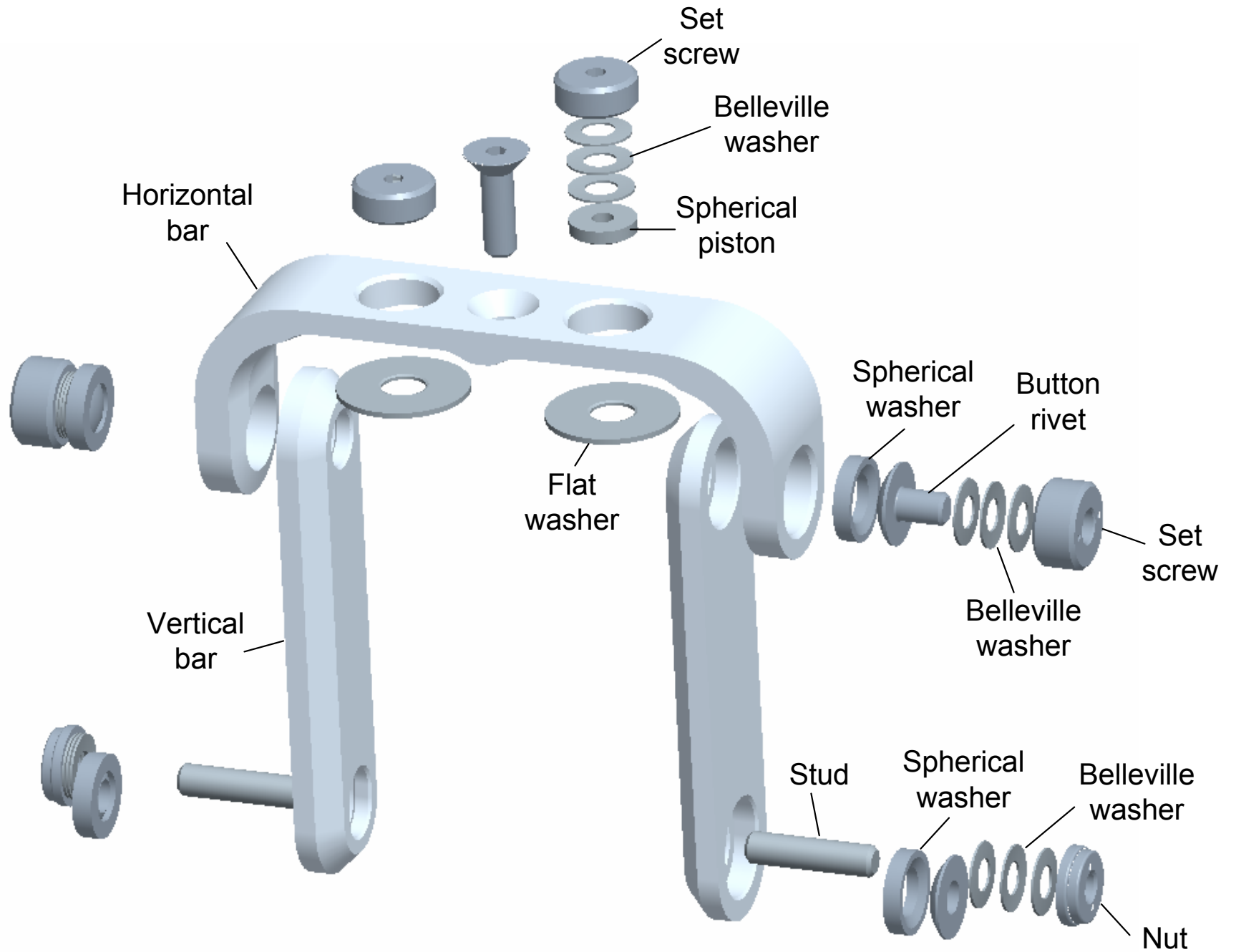


# Clamp assemblies

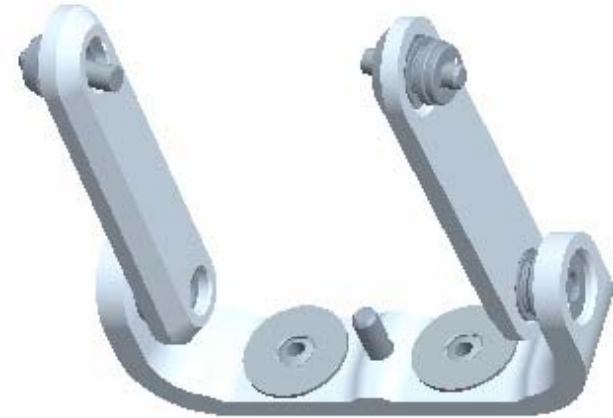
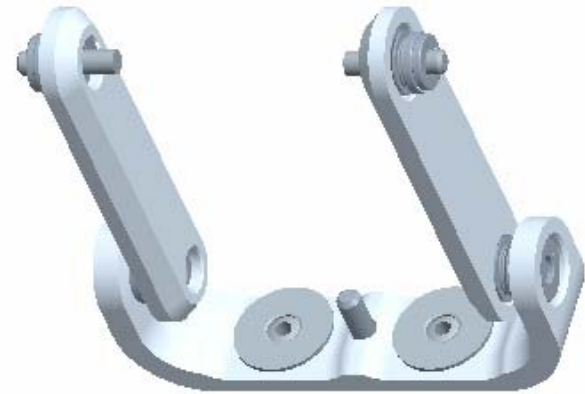
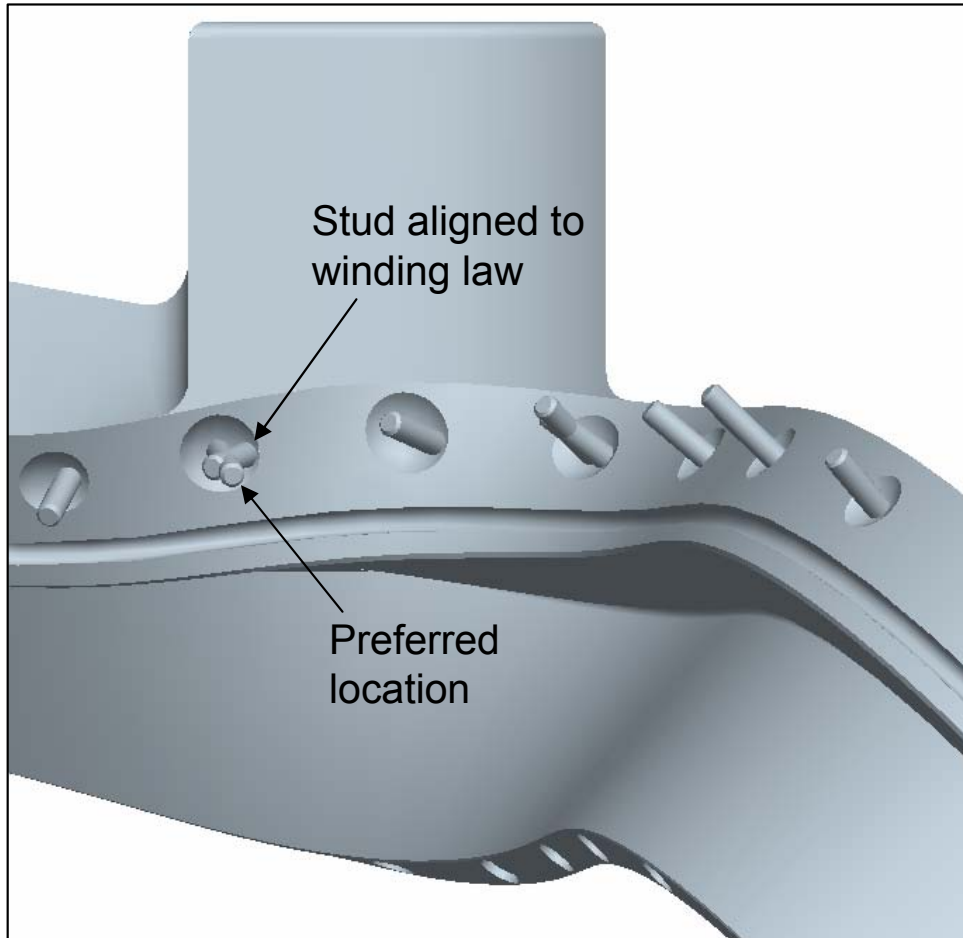
- 25 clamps, ~6-in spacing
- Material = 316SS, weight = 4.4-lb
- Hard spacer between chill plate and clamp not shown



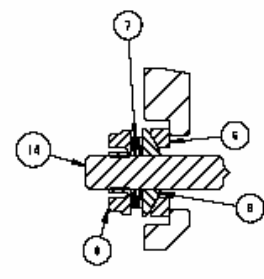
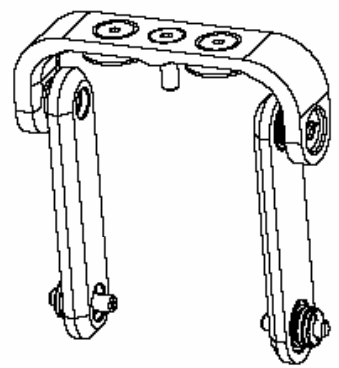
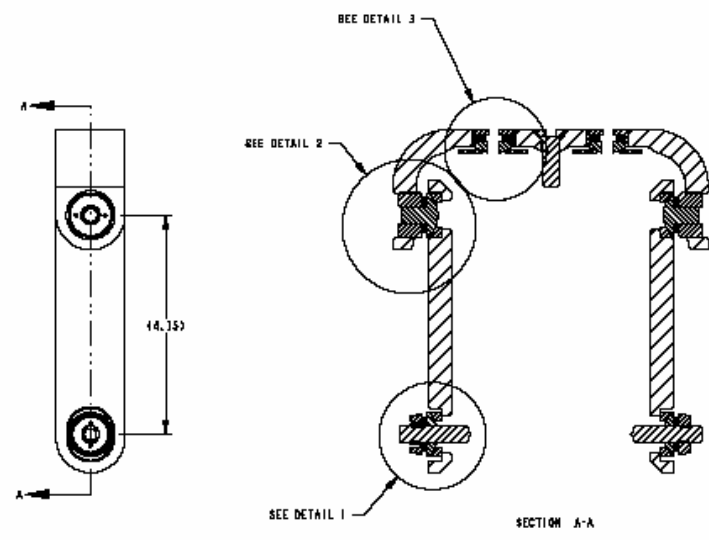
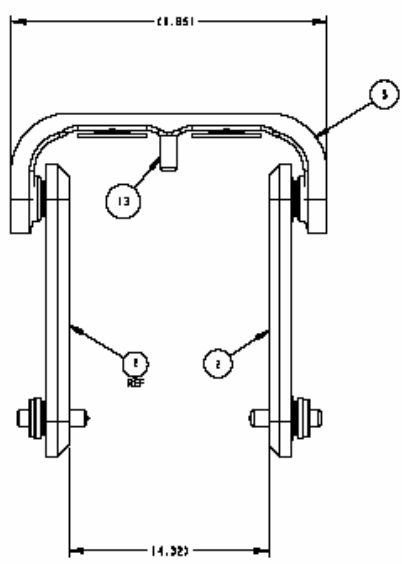
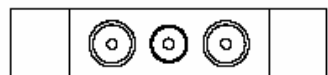
# Clamp exploded view



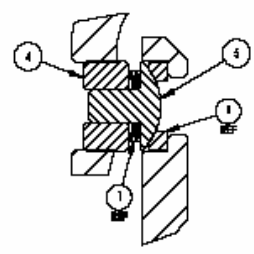
# Assembly positions



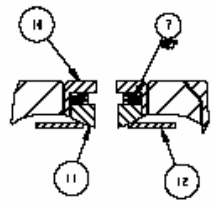




DETAIL 1  
SCALE 2.0



DETAIL 2  
SCALE 2.0



DETAIL 3  
SCALE 2.00

- NOTES:
1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.5M
  2. DIMENSIONS ARE IN INCHES
  3. DIMENSIONS APPLY AT ROOM TEMPERATURE, OPERATING TEMP 400 R
  4. GEOMETRY IS DEFINED IN PRO ENGINEER CAD MODEL(S)/FILE(S)
  5. DRAWINGS AND MODELS COMBINED DEFINE FINISHED MACHINED PART

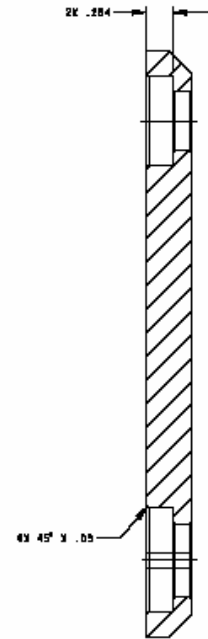
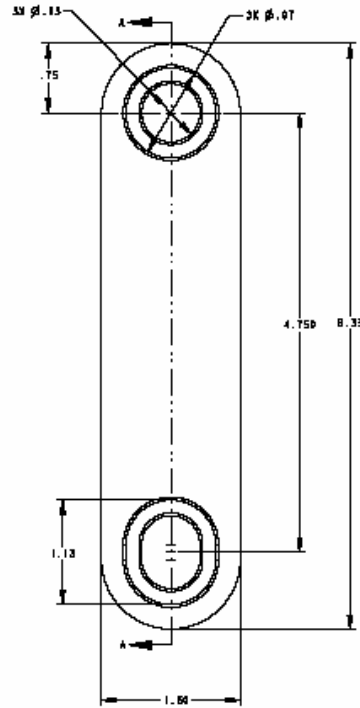
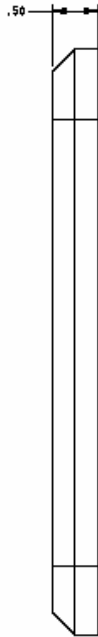
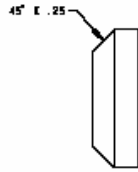
QTY	CAGE CODE	PART OR IDENTIFYING NO	DESCRIPTION OR IDENTIFICATION	MATERIAL	SPECIFICATION	FIG NO
2	SE1405-265	STUD, M6x1.0x1.0x0.50	316 STAINLESS STEEL	---	---	14
1	SE1405-264	WASHER, 3/16-18 UNC-2A x 1.00	316 STAINLESS STEEL	---	---	13
2	SE1405-263	WASHER, FLAT, 1/4-20, 3/16 TD	316 STAINLESS STEEL	---	---	12
2	SE1405-262	PIN, SPHERICAL, 3/16 DIA	316 STAINLESS STEEL	---	---	11
2	SE1405-261	SCREW, SET, 1/8-18 UNC-2A x 1.00	316 STAINLESS STEEL	---	---	10
2	SE1405-260	NUT, F16 NYTR, 3/16-18 UNC-2A	316 STAINLESS STEEL	---	---	9
2	SE1405-259	WASHER, SPHERICAL, TYPE C	316 STAINLESS STEEL	O.D. IN 3/16-18	---	8
10	SE1405-258	WASHER, WELDFILL, 3/16 DIA, 3/16 TD	316 STAINLESS STEEL	---	---	7
4	SE1405-257	WASHER, SPHERICAL, TYPE B	316 STAINLESS STEEL	O.D. IN 3/16-18	---	6
2	SE1405-256	WASHER, SPHERICAL, TYPE A	316 STAINLESS STEEL	---	---	5
2	SE1405-255	SCREW, SET, 1-18 UNC-2A x 1.125	316 STAINLESS STEEL	---	---	4
1	SE1405-254	NUT, 1/2-13, 3/8 HOLE	316 STAINLESS STEEL	---	---	3
2	SE1405-253	NUT, FLANG, 1/2-13	316 STAINLESS STEEL	---	---	2
1	SE1405-252	CLAMP ASSEMBLY, 40 TURN	---	---	---	1

THIS DRAWING PRODUCED ON PRO-ENGINEER

SCALE	NOTED	BY PAUL MILLER	DATE	16 APR 04
DATE	16 APR 04	BY PAUL MILLER	DATE	16 APR 04
FUNCTION	DESIGN	BY PAUL MILLER	DATE	16 APR 04
DESIGN	BY PAUL MILLER	DATE	16 APR 04	
APPROVAL	BY PAUL MILLER	DATE	16 APR 04	
FINISH	BY PAUL MILLER	DATE	16 APR 04	

UT-BATTELLE  
NATIONAL COMPACT STELLARATOR EXPERIMENT  
CLAMP ASSEMBLY, 40 TURN  
SE1405-252

- NOTES:
1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.5M
  2. DIMENSIONS ARE IN INCHES
  3. DIMENSIONS APPLY AT ROOM TEMPERATURE, OPERATING TEMP 40 K
  4. GEOMETRY IS DEFINED IN PRO ENGINEER CAD MODELS/FILES
  5. DRAWINGS AND MODELS COMBINED DEFINE FINISHED MACHINED PART



SECTION A-A



REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1					

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1					

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1					

THIS DRAWING PRODUCED ON PRO-ENGINEER

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
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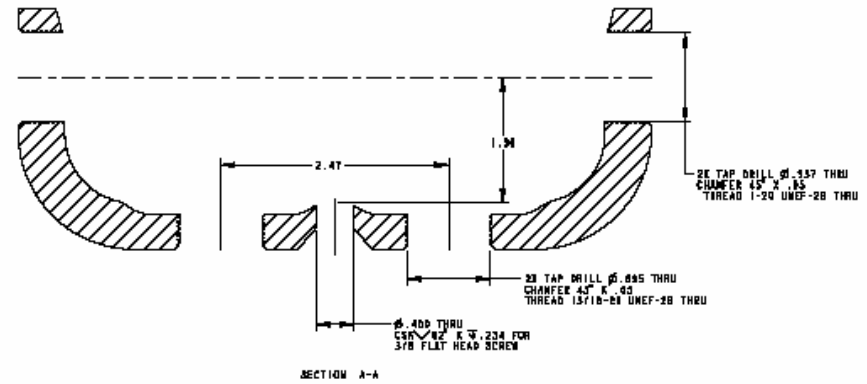
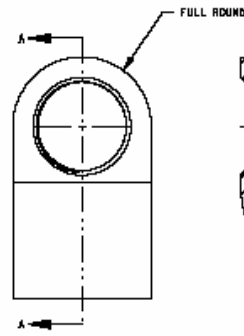
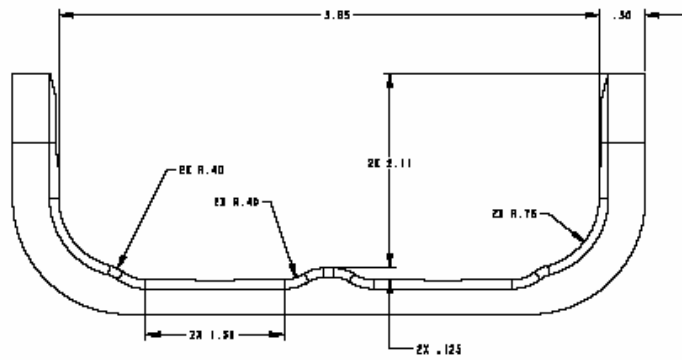
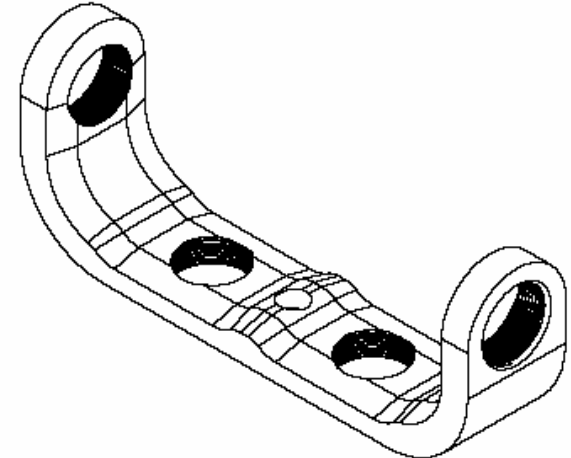
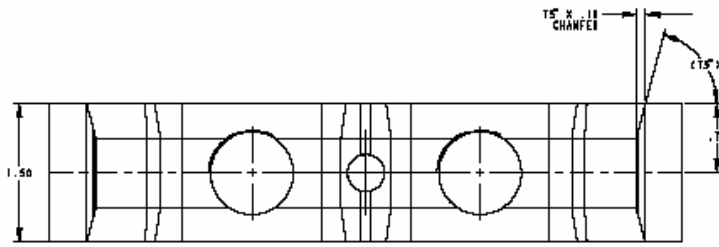
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1:1		1					

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1					

UT-BATTELLE  
NATIONAL COMPACT STELLARATOR EXPERIMENT  
BAR, CLAMP, VERTICAL  
SE1405-253

- NOTES:
1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.6M
  2. DIMENSIONS ARE IN INCHES
  3. DIMENSIONS APPLY AT ROOM TEMPERATURE, OPERATING TEMP 400 K
  4. GEOMETRY IS DEFINED IN PRO ENGINEER CAD MODELS/FILES
  5. DRAWING AND MODEL COMBINED DEFINE FINISHED MACHINED PART



SECTION A-A

REV	DATE	DESCRIPTION	PART OR IDENTIFYING NO	CONCISE DESCRIPTION OF DESCRIPTION	MATERIAL	SPECIFICATION	FINISH
1		SE1405-254	BAR, CLAMP, HORIZONTAL	316 STAINLESS STEEL			

← NEXT ASSEMBLY

PARTS LIST

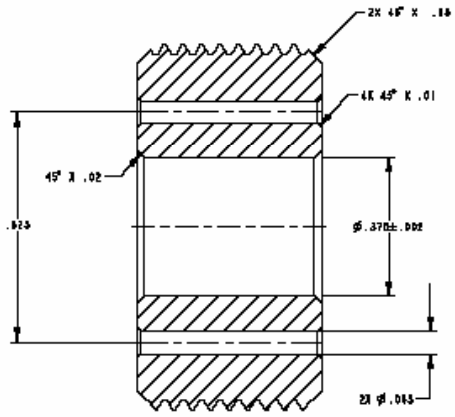
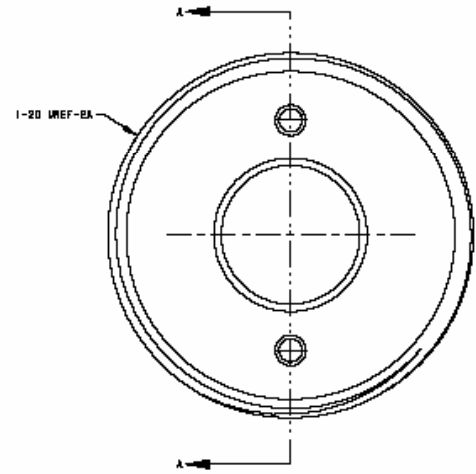
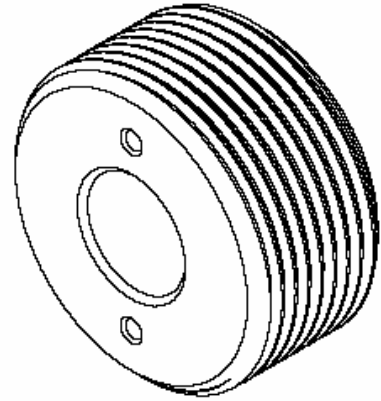
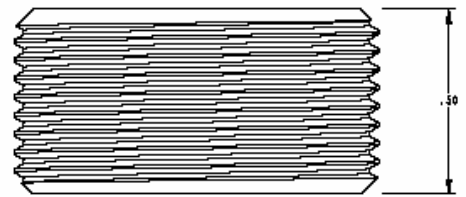
**P** THIS DRAWING PRODUCED ON PRO-ENGINEER

REV	DESCRIPTION	BY	DATE	APP'D	DATE	SCALE	NOTES

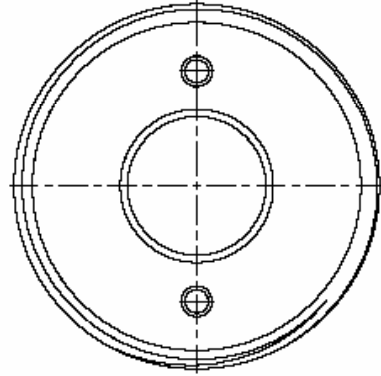
DESIGNED BY	PAUL MILLER	DATE	12/15/03
DRAWN BY	PAUL MILLER	DATE	12/15/03
CHECKED BY		DATE	
APPROVED BY		DATE	

PROJECT	SE1405-254
TITLE	BAR, CLAMP, HORIZONTAL
DATE	12/15/03
SCALE	AS SHOWN
DRAWING NO.	1
REV.	1
DATE	12/15/03

- NOTES:
1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.6M
  2. DIMENSIONS ARE IN INCHES
  3. DIMENSIONS APPLY AT 100H TEMPERATURE, OPERATING TEMP 400 K
  4. GEOMETRY IS DEFINED IN PRO ENGINEER CAD MODELS/FILES
  5. DRAWINGS AND MODELS COMBINED DEFINE FINISHED MACHINED PART



SECTION A-A

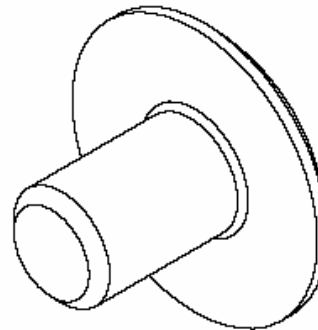
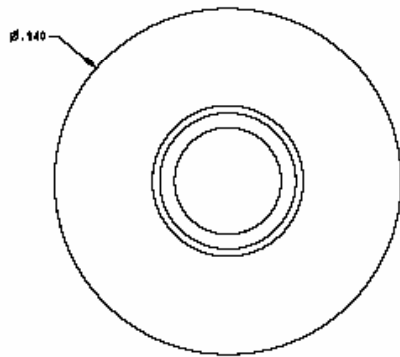
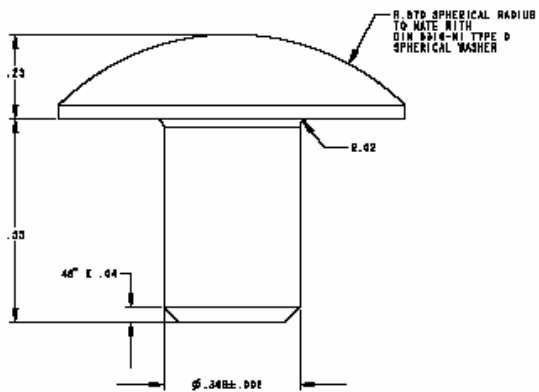


REV	DATE	DESCRIPTION	BY	CHKD	APP'D	DATE
1		SCREW SET, 1-20 UNEF-2A X 1/2				

SCALE	NOTED	DESIGNED BY	DATE	PROJECT	REV	DATE	BY	CHKD	APP'D	DATE
1:1		PAUL MILLER		UT-BATTELLE						
		PAUL MILLER		NATIONAL COMPACT STELLARATOR EXPERIMENT						
				SCREW SET, 1-20 UNEF-2A X 1/2						

THIS DRAWING PRODUCED ON PRO-ENGINEER

REV	DESCRIPTION	BY	DATE	CHKD	APP'D	DATE



- NOTES:
1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.6M
  2. DIMENSIONS ARE IN INCHES
  3. DIMENSIONS APPLY AT 100M TEMPERATURE, OPERATING TEMP 400 K
  4. GEOMETRY IS DEFINED IN PRO ENGINEER CAD MODELS/FILES
  5. DRAWINGS AND MODELS COMBINED DEFINE FINISHED MACHINED PART

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1		REVISED TO ADD DIMENSIONS			

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1		REVISED TO ADD DIMENSIONS			

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1		REVISED TO ADD DIMENSIONS			

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1		REVISED TO ADD DIMENSIONS			

THIS DRAWING PRODUCED ON PRO-ENGINEER

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
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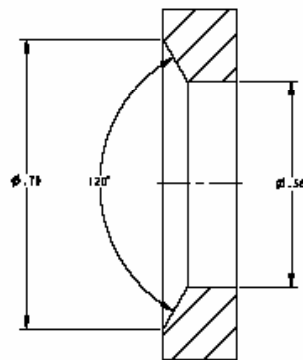
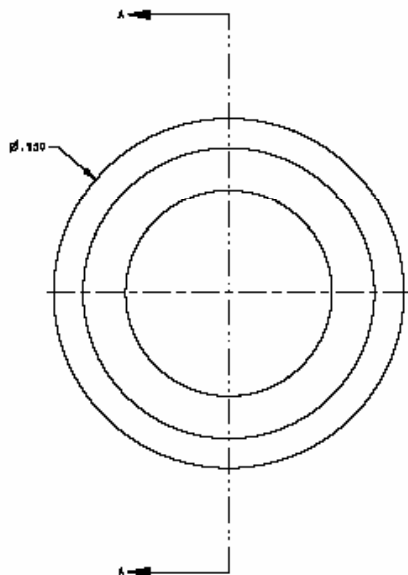
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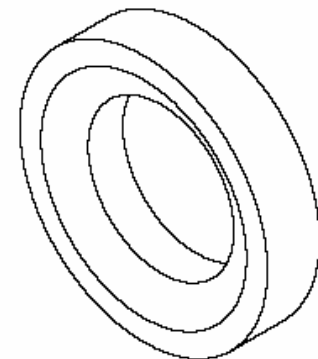
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1		REVISED TO ADD DIMENSIONS			

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1		REVISED TO ADD DIMENSIONS			

- NOTES:
1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.6M
  2. DIMENSIONS ARE IN INCHES
  3. DIMENSIONS APPLY AT ROOM TEMPERATURE, OPERATING TEMP 400 K
  4. GEOMETRY IS DEFINED IN PRO ENGINEER CAD MODELS/FILES
  5. DRAWING AND MODELS COMBINED DEFINE FINISHED MACHINED PART



SECTION A-A



REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1					

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1					

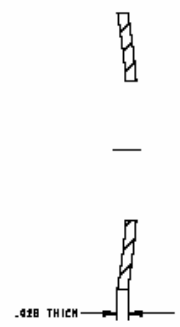
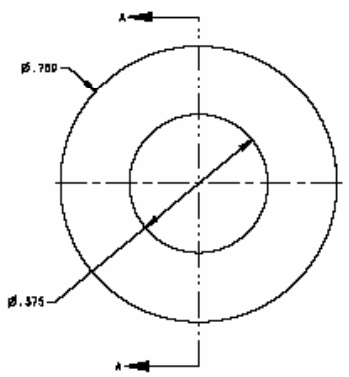
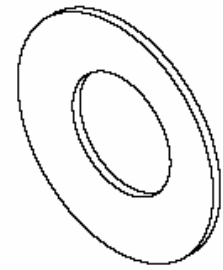
REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1					

**P** THIS DRAWING PRODUCED ON PRO-ENGINEER

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1					

SCALE	NOTED	REV PAUL MILLER	FINISH	UT-BATTELLE
TOLERANCE	±0.0005	REV PAUL MILLER	INTERNAL	NATIONAL COMPACT STELLARATOR EXPERIMENT
FRACCTIONS	1/16	REV	1	WASHER, SPHERICAL, TYPE D
DECIMALS	0.001	REV	1	REVISED BY: PAUL DENNIS MILLER
ANGLES	0.001	REV	1	DATE: 16-Apr-04
FINISH	AS SUPPLIED	REV	1	PROJECT: SE1405-257

- NOTES:
1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.6M
  2. DIMENSIONS ARE IN INCHES
  3. DIMENSIONS APPLY AT ROOM TEMPERATURE. OPERATING TEMP 400 K
  4. GEOMETRY IS DEFINED IN PRO ENGINEER CAD MODELS/FILES
  5. DRAWING AND MODEL COMBINED DEFINE FINISHED MACHINED PART
  6. SPRING CONSTANT K=7510 LBS/IN



SECTION A-A

REV	DATE	DESCRIPTION	BY	CHKD	APP'D	DATE
1						

REV	DATE	DESCRIPTION	BY	CHKD	APP'D	DATE
1						

REV	DATE	DESCRIPTION	BY	CHKD	APP'D	DATE
1						

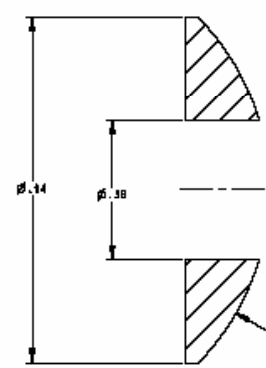
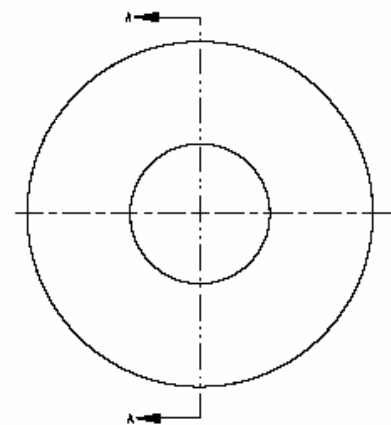
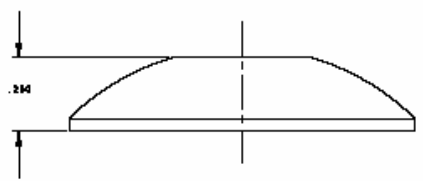
THIS DRAWING PRODUCED ON PRO-ENGINEER

REV	DATE	DESCRIPTION	BY	CHKD	APP'D	DATE
1						

REV	DATE	DESCRIPTION	BY	CHKD	APP'D	DATE
1						

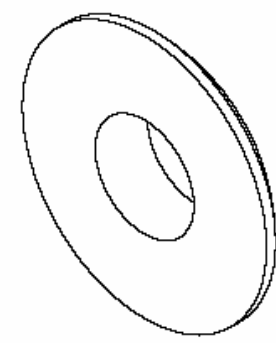
SE1405-258

A



R. STD SPHERICAL RADII  
TO MATE WITH  
DIM 8218-N1 TYPE D  
SPHERICAL WASHER

SECTION A-A



- NOTES:
1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.6M
  2. DIMENSIONS ARE IN INCHES
  3. DIMENSIONS APPLY AT ROOM TEMPERATURE, OPERATING TEMP 400 R
  4. GEOMETRY IS DEFINED IN PRO ENGINEER CAD MODELS/FILES
  5. DRAWINGS AND MODELS COMBINED DEFINE FINISHED MACHINED PART

DATE	REV	DESCRIPTION	BY	CHKD	APP'D	DATE
16-Apr-04	1	INITIAL DESIGN	PAUL MILLER			

QTY	PART OR IDENTIFYING NO	DESCRIPTION OR IDENTIFICATION	MATERIAL	SPECIFICATION	FINISH
1	SE1405-259	WASHER, SPHERICAL, TYPE C	316 STAINLESS STEEL	Q118	NI

← NEXT ASSEMBLY

PARTS LIST

THIS DRAWING PROVIDED ON PRO-ENGINEER

SCALE	NOTED	BY PAUL MILLER	CHKD PAUL MILLER	APP'D
TOLERANCES UNLESS OTHERWISE SPECIFIED				
FRACTIONS				
2ND DECIMALS				
3RD DECIMALS				
4TH DEC				
5TH DEC				
FINISH				

DATE	REV	DESCRIPTION	BY	CHKD	APP'D	DATE

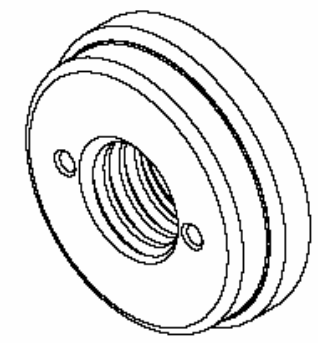
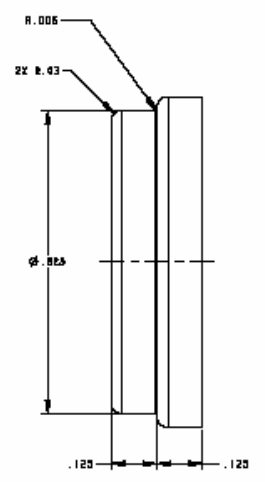
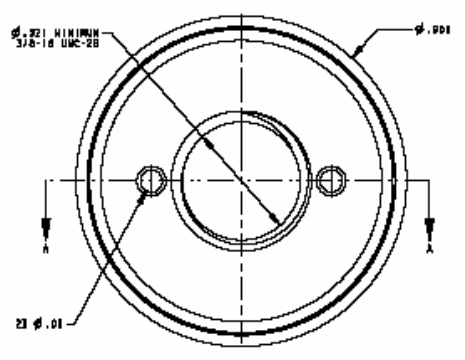
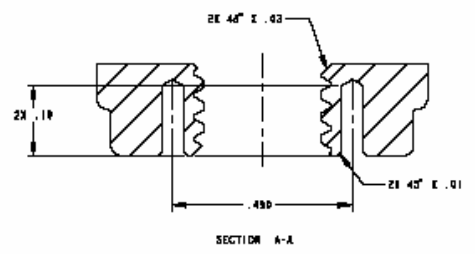
  

PROJECT NO.	REV	DATE	BY	CHKD	APP'D
458	X-10	3/2000			

UT-BATTELLE  
NATIONAL COMPACT STELLARATOR EXPERIMENT  
WASHER, SPHERICAL, TYPE C  
SEI 1405-259





- NOTES:
1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.6M
  2. DIMENSIONS ARE IN INCHES
  3. DIMENSIONS APPLY AT 100N TEMPERATURE, OPERATING TEMP 40 K
  4. GEOMETRY IS DEFINED IN PDM ENGINEER CAD MODELS/FILES
  5. DRAWING AND MODELS COMBINED DEFINE FINISHED MACHINED PART

REV	DATE	DESCRIPTION	BY	CHKD	APP'D	QTY	UNIT	TIME	DATE
1		NEXT ASSEMBLY							

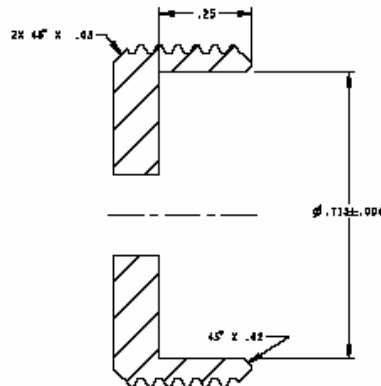
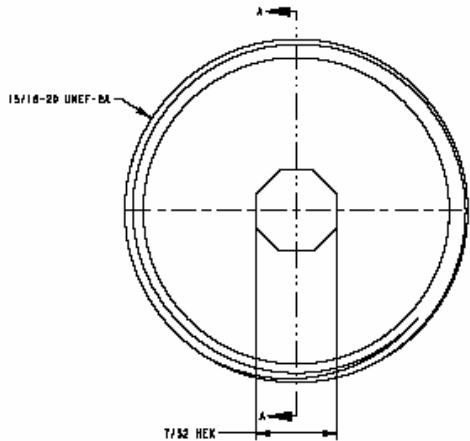
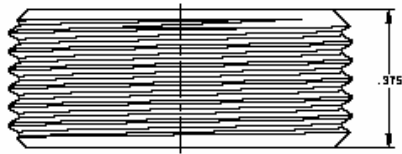
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2	CHANGES							
3	REVISIONS							
4	FRACTIONS							
5	2X DECIMALS							
6	3X DECIMALS							
7	4X DECIMALS							
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9	6X DECIMALS							
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THIS DRAWING PROVIDED ON PDM-ENGINEER

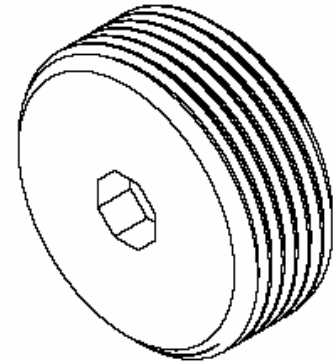
UT-BATTELLE  
 NATIONAL COMPACT STELLARATOR EXPERIMENT  
 NUT, PIN DRIVE, 3/8-16 UNC-2B  
 SE1405-260

NOTES:

1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.6M
2. DIMENSIONS ARE IN INCHES
3. DIMENSIONS APPLY AT ROOM TEMPERATURE, OPERATING TEMP 400 K
4. GEOMETRY IS DEFINED IN PRO ENGINEER CAD MODELS/FILES
5. DRAWING AND MODELS COMBINED DEFINE FINISHED MACHINED PART



SECTION A-A



REV	DATE	DESCRIPTION	BY	CHKD	APP'D	QTY	UNIT	REVISION
1		SCREW, SET, 15/16-20 UNEF-2A X 3/8						

REV	DATE	DESCRIPTION	BY	CHKD	APP'D	QTY	UNIT	REVISION
1		SCREW, SET, 15/16-20 UNEF-2A X 3/8						

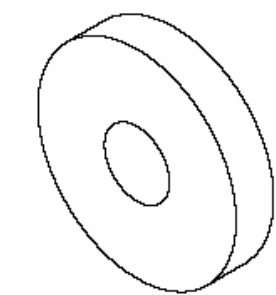
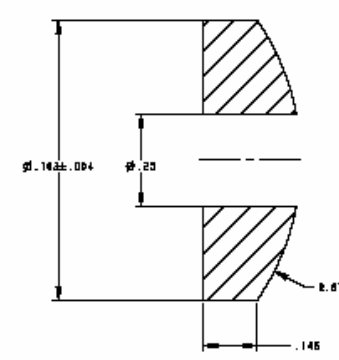
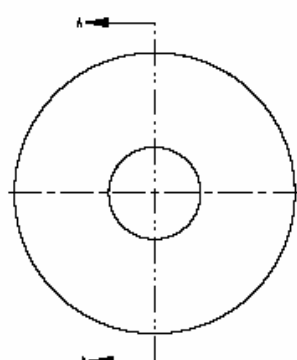
REV	DATE	DESCRIPTION	BY	CHKD	APP'D	QTY	UNIT	REVISION
1		SCREW, SET, 15/16-20 UNEF-2A X 3/8						

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**P** THIS DRAWING PRODUCED ON PRO-ENGINEER

SCALE: NOTED  
 DRAWN BY: PAUL MILLER  
 CHECKED BY: PAUL MILLER  
 NATIONAL COMPACT STELLARATOR EXPERIMENT  
 SCREW, SET, 15/16-20 UNEF-2A X 3/8  
 SEI 1405-261

- NOTES:
1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.6M
  2. DIMENSIONS ARE IN INCHES
  3. DIMENSIONS APPLY AT ROOM TEMPERATURE. OPERATING TEMP 800 K
  4. GEOMETRY IS DEFINED IN PRO-ENGINEER CAD MODELS/FILES
  5. DRAWING AND MODEL COMBINED DEFINE FINISHED MACHINED PART



SECTION A-A

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1		NET ASSEMBLY			

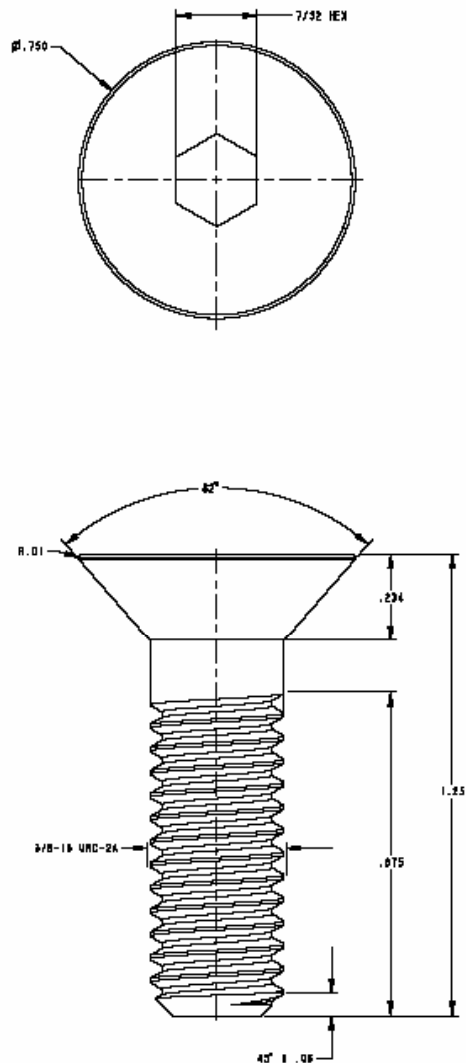
SEI405-262	PISTON, SPHERICAL, 3/4 OD	316 STAINLESS STEEL			
SEI405-262	PISTON, SPHERICAL, 3/4 OD	316 STAINLESS STEEL			

THIS DRAWING PRODUCED ON PRO-ENGINEER

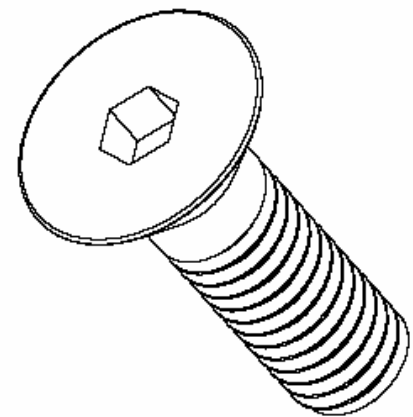
SCALE NOTED	BY PAUL MILLER	DATE	16-APR-04
BY PAUL MILLER	DATE	16-APR-04	
FRACCTIONS	2	DECIMALS	2
UNITS	IN	INCHES	
FINISH	AS SUPPLIED		

SEI405-262	PISTON, SPHERICAL, 3/4 OD	316 STAINLESS STEEL			
SEI405-262	PISTON, SPHERICAL, 3/4 OD	316 STAINLESS STEEL			





- NOTES:
1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.6M
  2. DIMENSIONS ARE IN INCHES
  3. DIMENSIONS APPLY AT ROOM TEMPERATURE, OPERATING TEMP 400 K
  4. GEOMETRY IS DEFINED IN PRO ENGINEER CAD MODELS/FILES
  5. DRAWING AND MODEL COMBINED DEFINE FINISHED MACHINED PART



REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1					

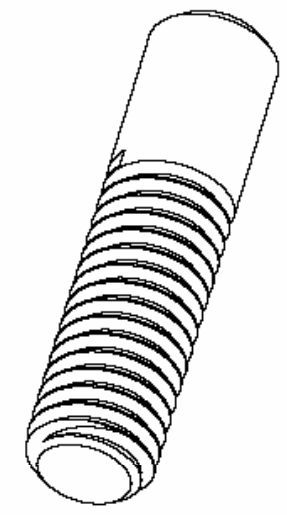
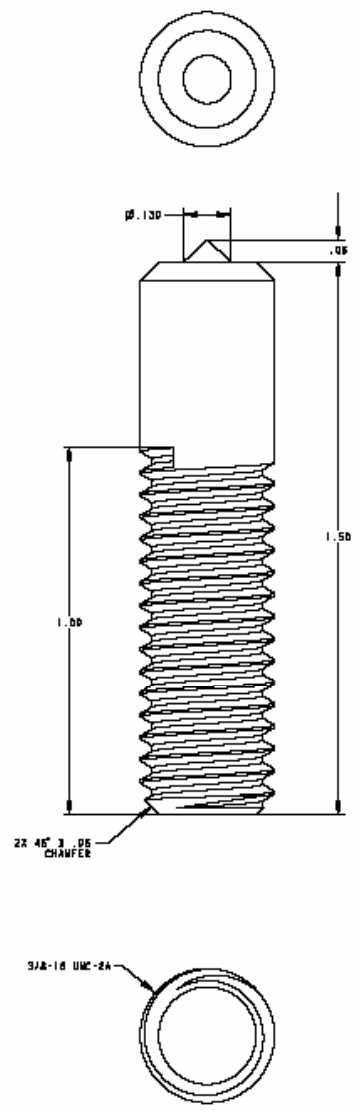
REV	DESCRIPTION	BY	CHKD	APP'D
1				

SCALE	NOTED	REV	PAUL MILLER	DATE	04-16-04
UNITS	INCHES	REV	PAUL MILLER	DATE	04-16-04
FUNCTIONS		REV		DATE	
2D DESIGNS	25.00	REV		DATE	
3D DESIGNS	0.00	REV		DATE	
ASSEMBLY	0.00	REV		DATE	
REV	DATE	BY	CHKD	APP'D	
1					

**P** THIS DRAWING PRODUCED ON PRO-ENGINEER

UT-BATTELLE  
 NATIONAL COMPACT STELLARATOR EXPERIMENT  
 SCREW, 3/8-16 UNC-2A X 1 1/4  
 SE1405-264

- NOTES:
1. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y14.6M
  2. DIMENSIONS ARE IN INCHES
  3. DIMENSIONS APPLY AT ROOM TEMPERATURE. OPERATING TEMP 40 K
  4. GEOMETRY IS DEFINED IN PRO ENGINEER CAD MODELS/FILES
  5. DRAWING AND MODEL COMBINED DEFINE FINISHED MACHINED PART



REV	DATE	DESCRIPTION	BY	CHK	APP	DATE
1						

REV	DATE	DESCRIPTION	BY	CHK	APP	DATE
1						

REV	DATE	DESCRIPTION	BY	CHK	APP	DATE
1						

REV	DATE	DESCRIPTION	BY	CHK	APP	DATE
1						

THIS DRAWING PROVIDED ON PRO-ENGINEER

REV	DATE	DESCRIPTION	BY	CHK	APP	DATE
1						

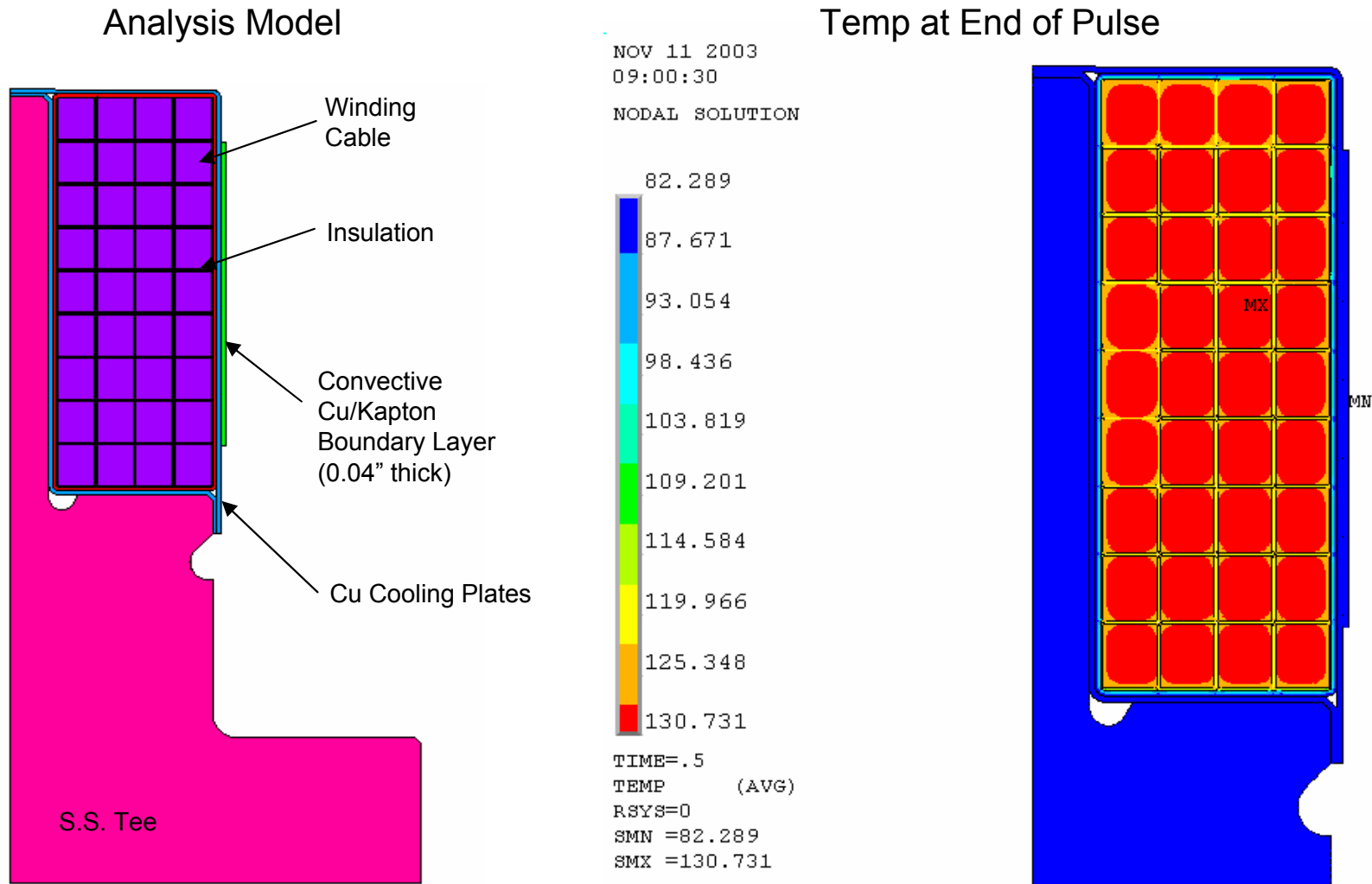
REV	DATE	DESCRIPTION	BY	CHK	APP	DATE
1						

SE1405-265

A

# Thermal Performance

- Transient conduction/convection model has been updated for four-in-hand winding



# Temperature During Cooldown

1

NOV 11 2003

09:41:50

NODAL SOLUTION

81.261

84.612

87.962

91.313

94.663

98.014

101.364

104.715

108.065

111.416

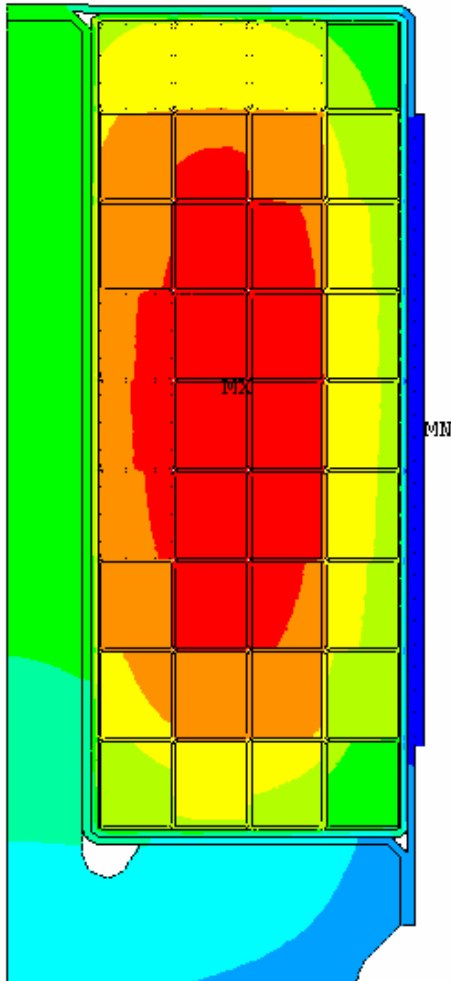
TIME=180

TEMP (AVG)

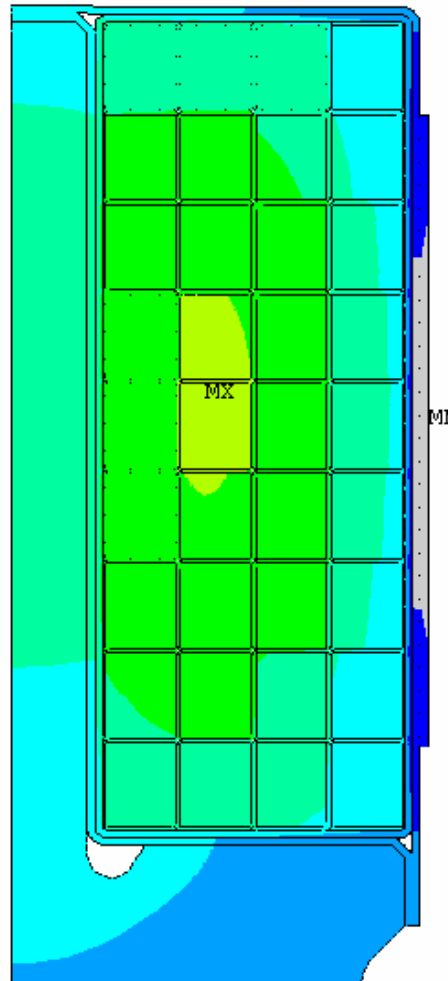
RSYS=0

SMN =81.261

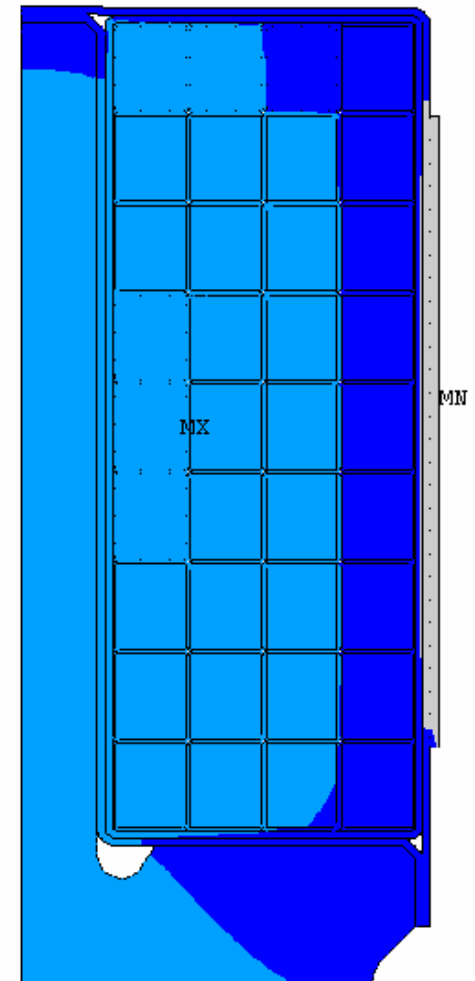
SMX =111.416



3 minutes



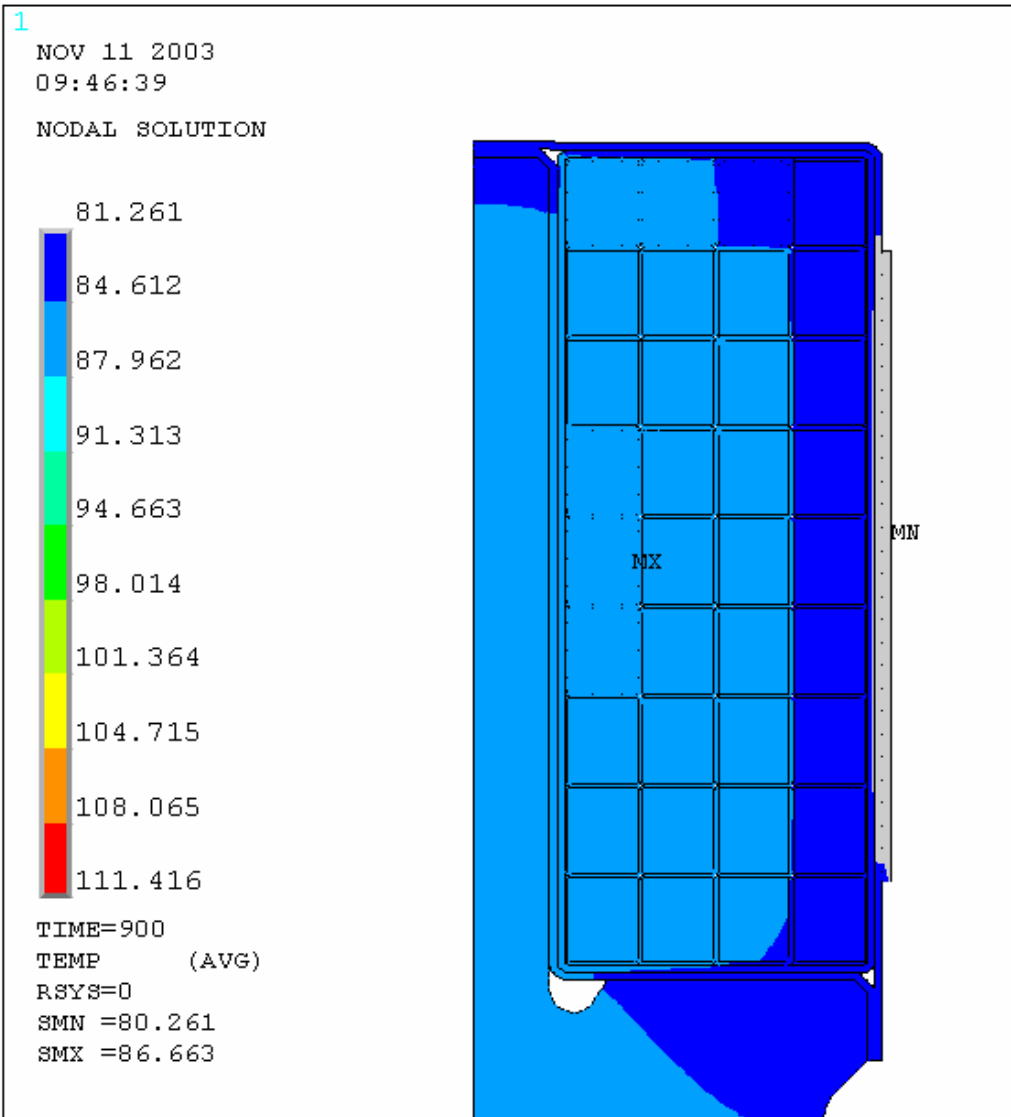
7 minutes



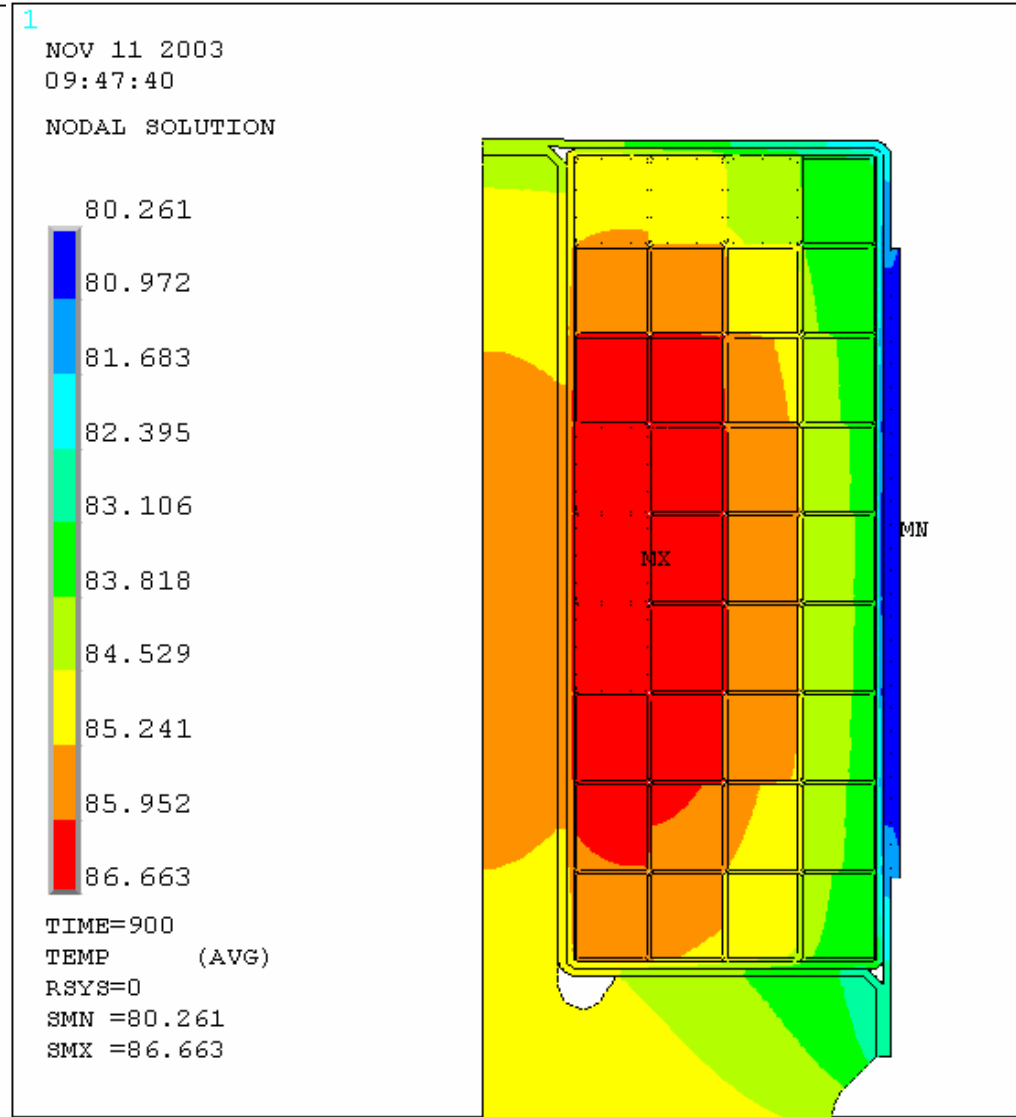
15 minutes



# Temperature At 15-Min



Same Scale as above cases at 15 mins



Automatic Scale at 15 mins

# Temperature After 10 Cycles

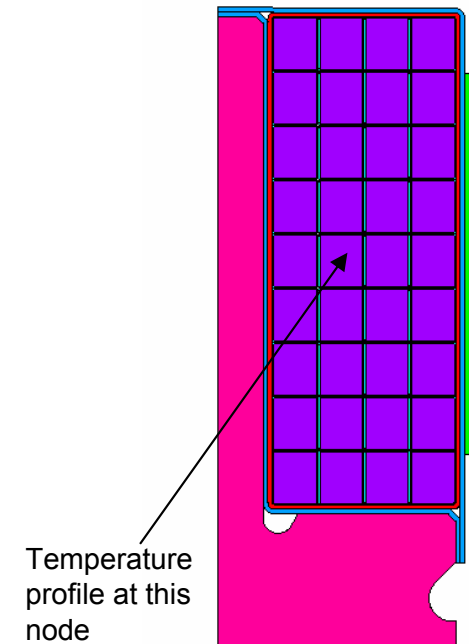
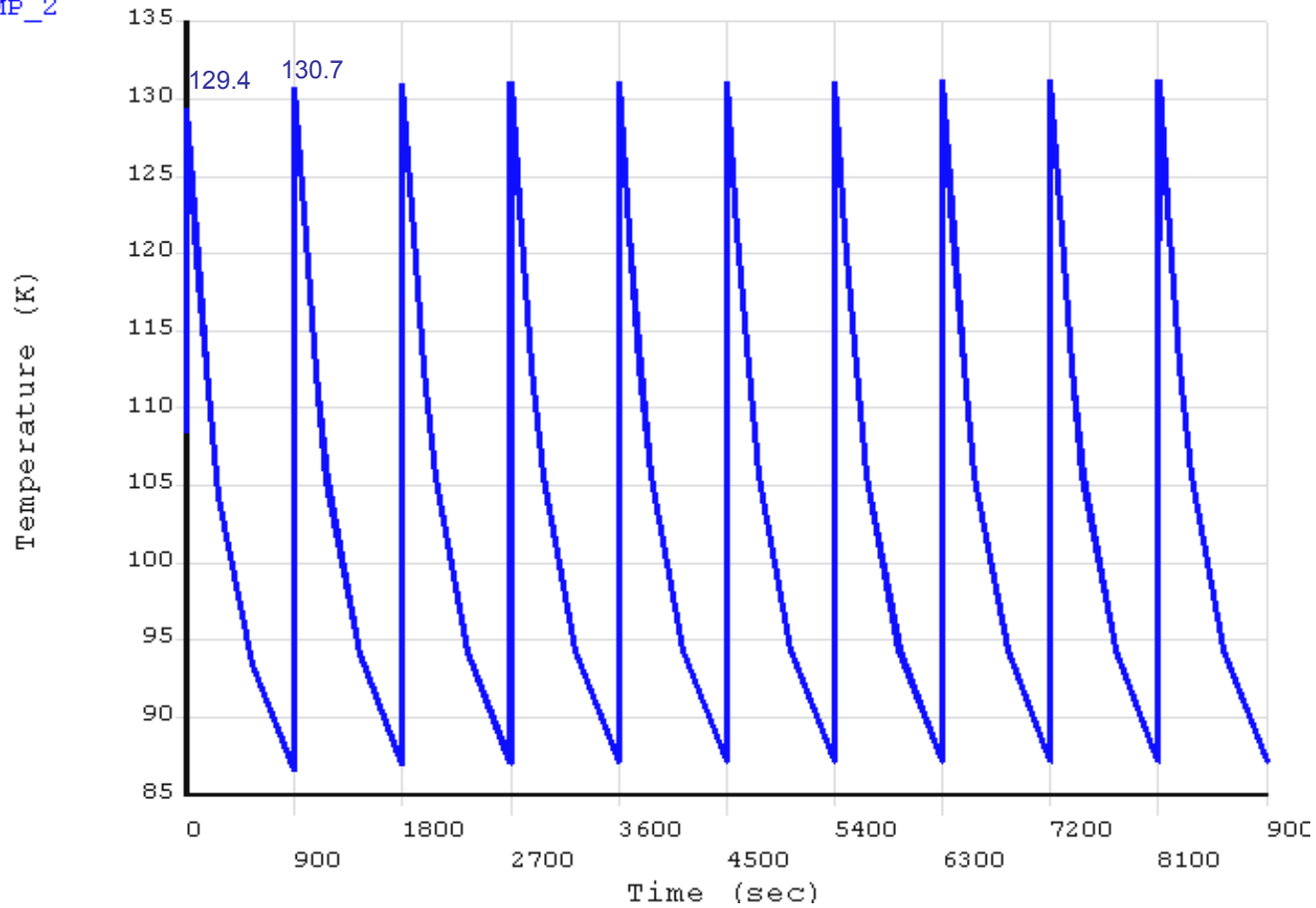
L

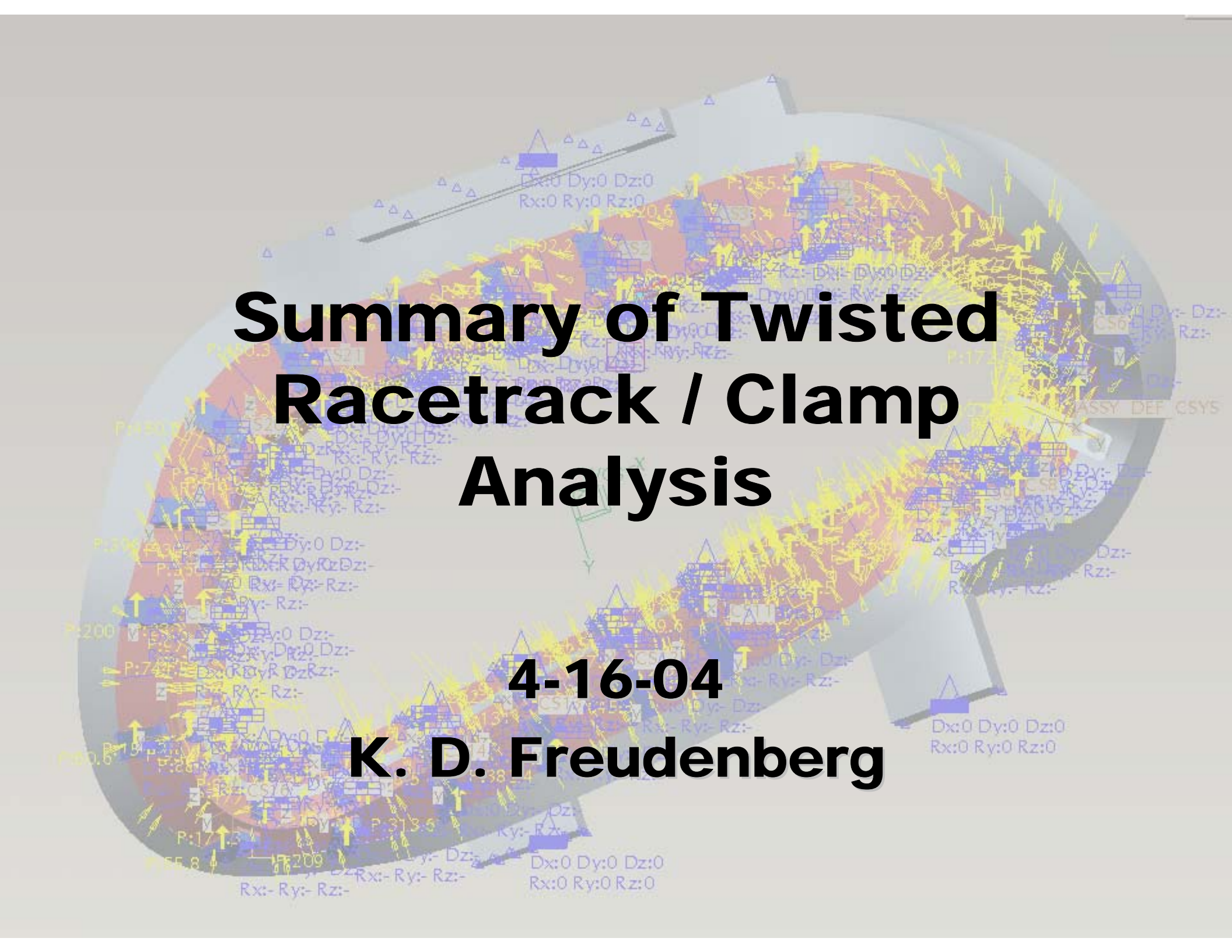
NOV 11 2003

10:56:46

POST26

TEMP\_2



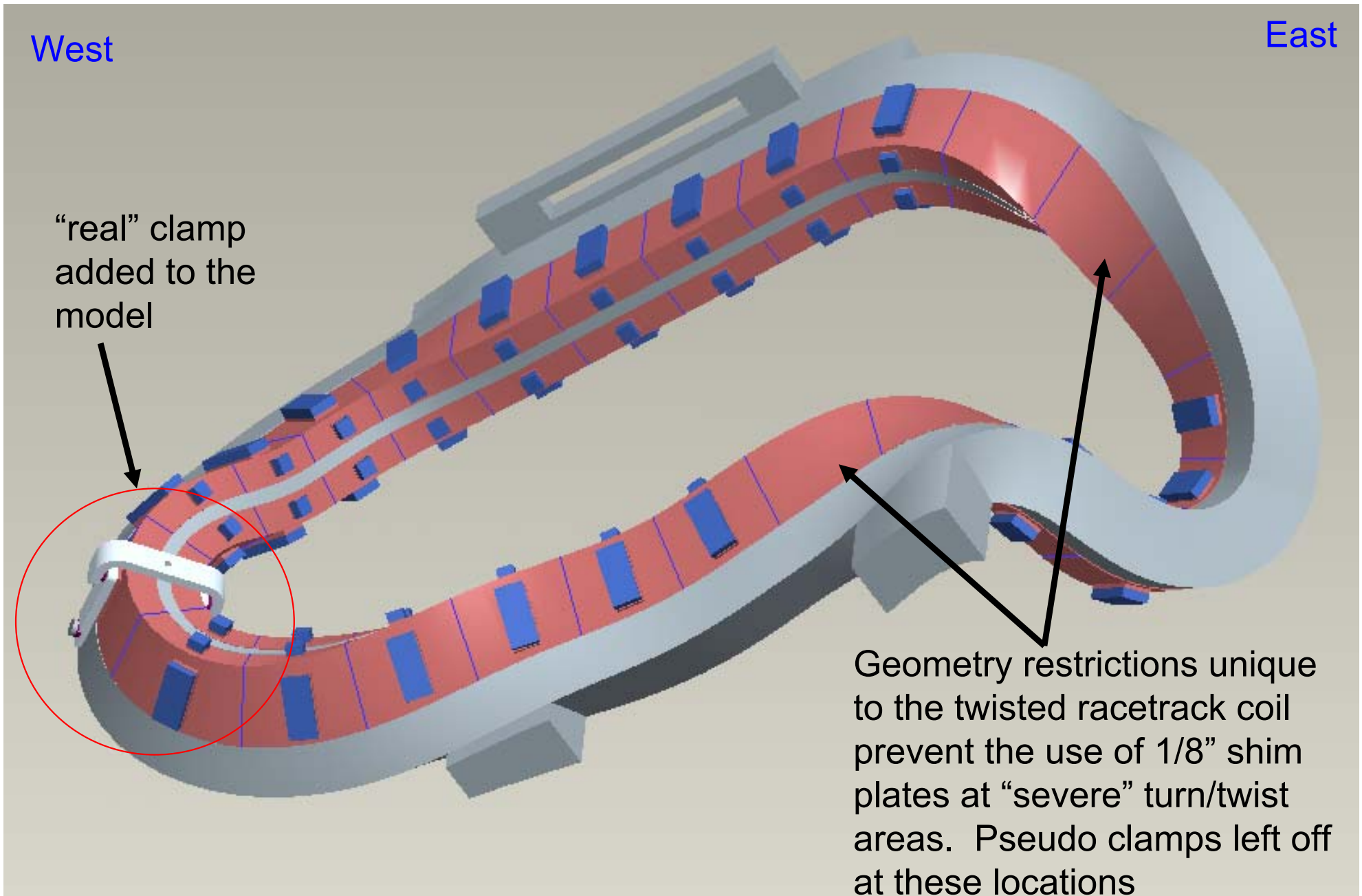


# Summary of Twisted Racetrack / Clamp Analysis

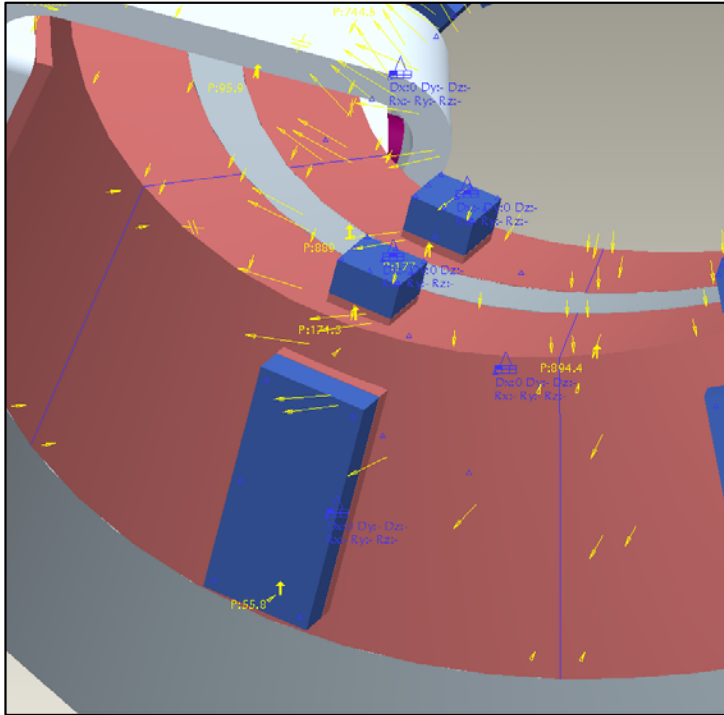
4-16-04

K. D. Freudenberg

# Twisted Racetrack FEA Mechanical Model



# Restraints and loads



- Winding is broken into regions (between blue lines) on which the magnetic pressure loads are applied, pressures correspond to  **$I=42\text{-kA/electrical turn}$** .
- Max EM Running Loads:  
**Radial: 1819 lb/in.**  
**Lateral: 3946 lb/in.**
- Pseudo clamps are restrained in their respective normal directions to simulate real clamp behavior.

- Contact surfaces are used between the clamp winding and the tee.
- Thermal growth is imposed on the winding by utilizing the cte property and by applying a known strain over a given temperature change.

*Example: strain =  $-800\mu\epsilon$  , arbitrary temp difference = 72 F. Therefore,*

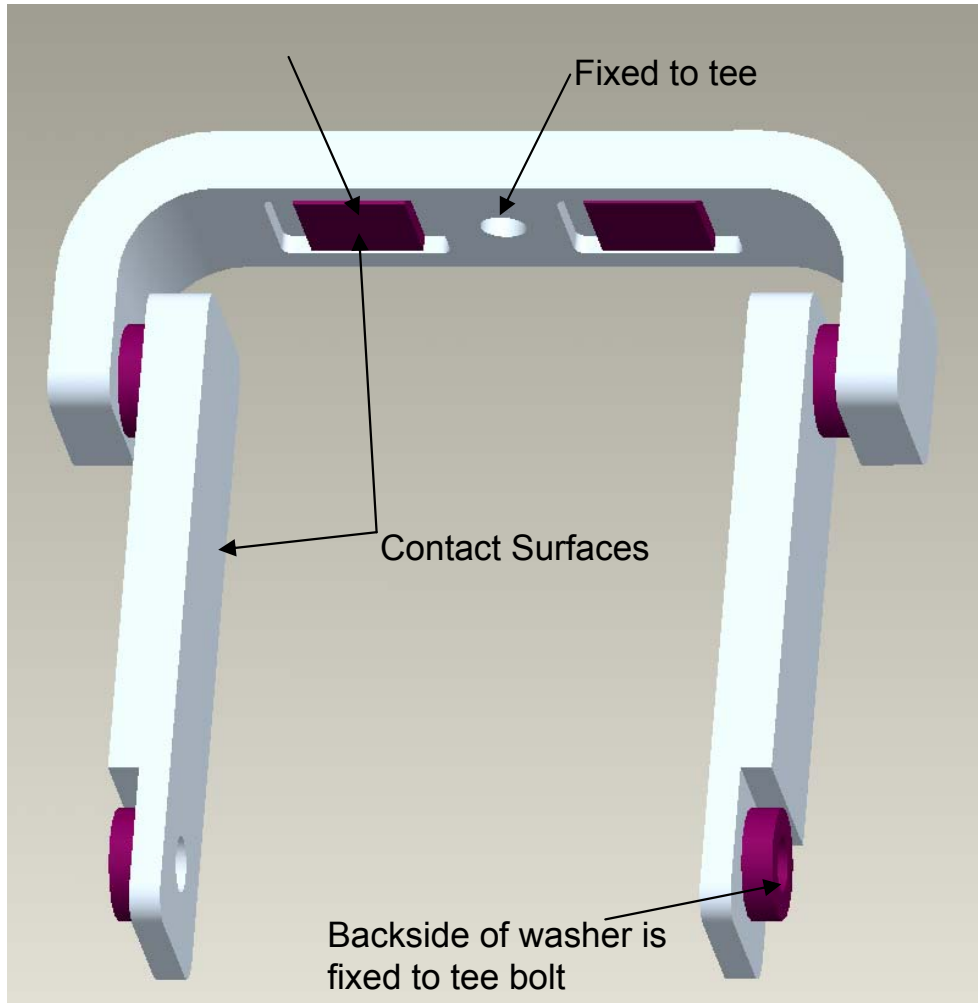
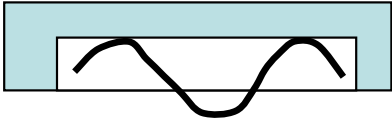
$$\text{Winding cte} = -800\mu\epsilon / 72 F = 1.11E-5 / F$$

$$\text{Tee cte} = 0$$

The latest data indicates essentially no cure shrinkage of the winding. Therefore, the  $-800\mu\epsilon$  used in this analysis should be tailored down to  $-400\mu\epsilon$  to account only for the cool-down shrinkage between the tee and winding (4-10-2004).

# Clamp modeling

Wave spring in clamp pocket



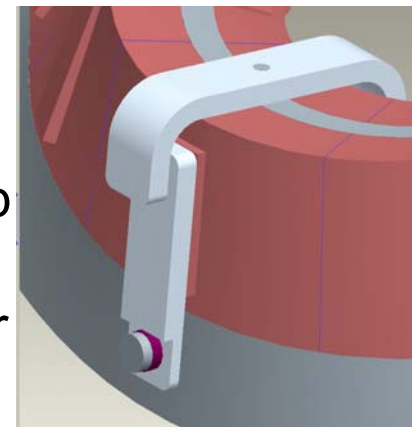
**Contact Surfaces are used between the clamp and the winding.**

-Modulus of washers is tailored to represent the spring constant of the belleville washers. Example:  $k = 26,000 \text{ lb/in}$ ,  $A_{\text{washer}} = 0.81 \text{ in}^2$ ,  $\text{Depth}_{\text{washer}} = 0.15 \text{ in}$ . Therefore:  $E = k \cdot \text{depth} / A = 4814 \text{ psi}$

- The cte of the washer is used to impose a preload on the clamp and winding. Assume  $0.1 \text{ in/in}$  strain  
Therefore:  $\text{cte} = 0.1 / -72 F = -0.00138 / F$   
and preload for "hard" springs is 2600 lbs, and 1000 for "soft" springs

- All washers have the same spring constant but have different modulus values.

-The clamp is fixed to the tee by a stud at the top of the clamp and a representative bolt head on the lower end.

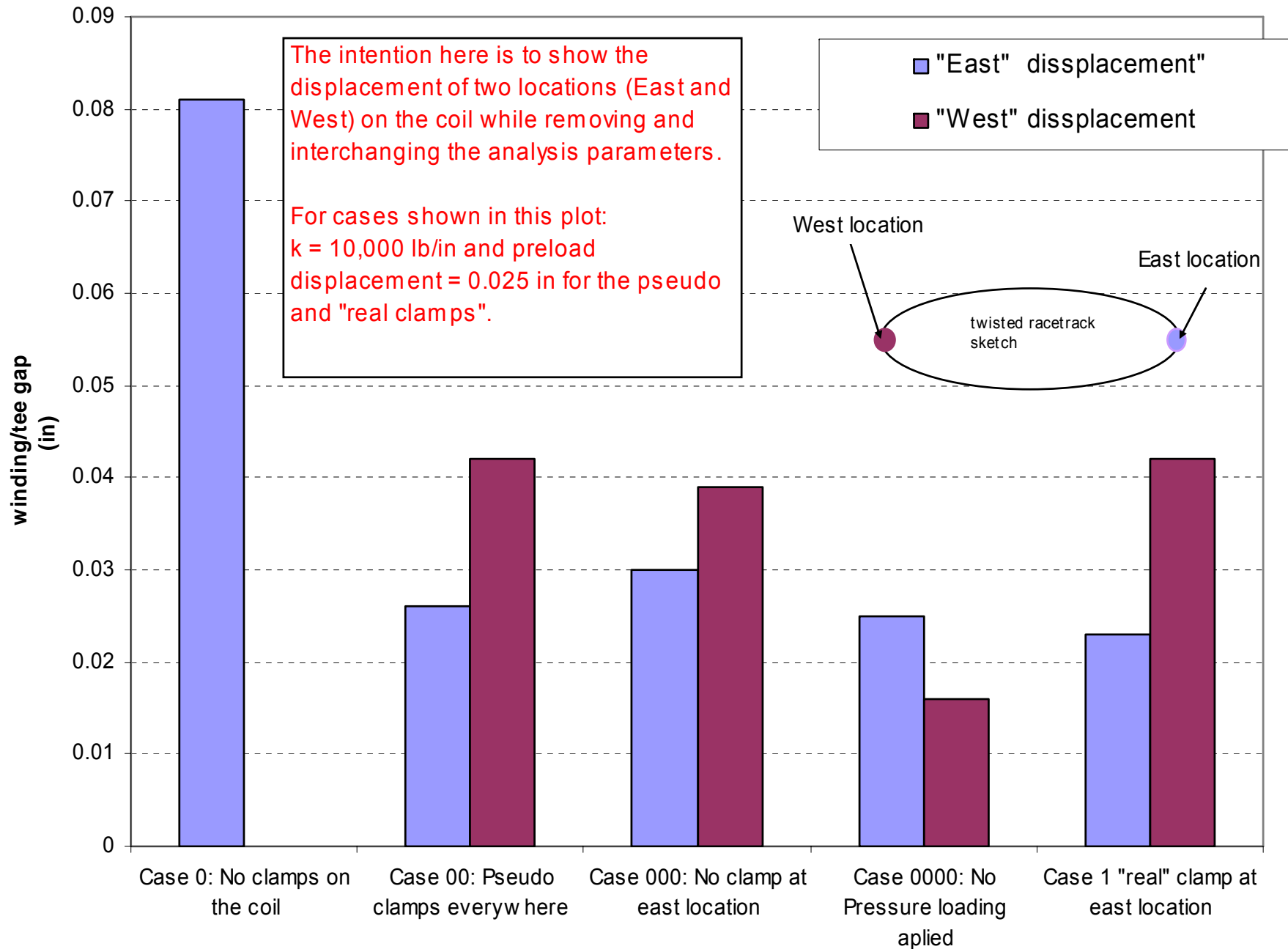


# Clamp Design Iterations

	<b>Case 0:</b> No clamps on the coil	<b>Case 00:</b> Faux clamps everywhere	<b>Case 000:</b> No Pressure loading applied	<b>Case 1</b>	<b>Case 2</b>	<b>Case 3</b>	<b>Case 4</b>	<b>Case 5</b>	<b>Case 6</b>	<b>Case 7</b>
<b>Washer k (lb/in)</b>	-	10,000	10,000	10,000	5,000	20,000	2,500	10,000	10,000	10,000
<b>Washer Preload (in)</b>	-	0.025	0.025	0.025	0.025	0.025	0.025	0.05	0.01	0
<b>Washer Preload (lb)</b>	-	250	250	250	125	500	62.5	500	100	0
<b>Winding E (psi)</b>	9.50E+06	9.50E+06	9.50E+06	9.50E+06	9.50E+06	9.50E+06	9.50E+06	9.50E+06	9.50E+06	9.50E+06
<b>Approximate Winding Displacement off Tee [west] (in)</b>	<b>0.081</b>	0.026	0.025	0.023	0.023	0.022	0.021	0.02	0.025	0.026
<b>Winding Displacement [East] (in)</b>	<b>0</b>	0.042	0.016	0.042	0.047	0.032	0.054	0.038	0.045	0.046
<b>Max Von Mises Stress in winding (psi)</b>	<b>22,000</b>	10,700	3,500	11,500	10,200	12,200	9,500	11,500	10,500	10,500
<b>Max Von Mises Stress Clamp (psi)</b>	-	-	63,000 (39,000)	48,000 (28,000)	29,000 (15,000)	78,000 (46,800)	6,600 (4,200)	91,000 (54,000)	31,800 (11,400)	24,000 (3,800)

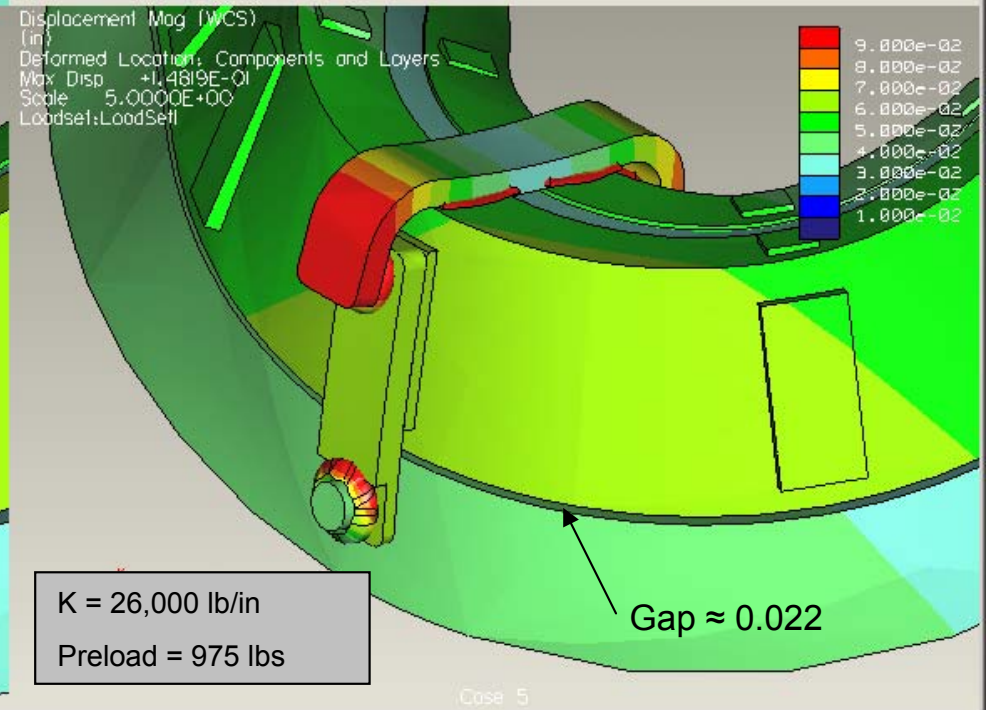
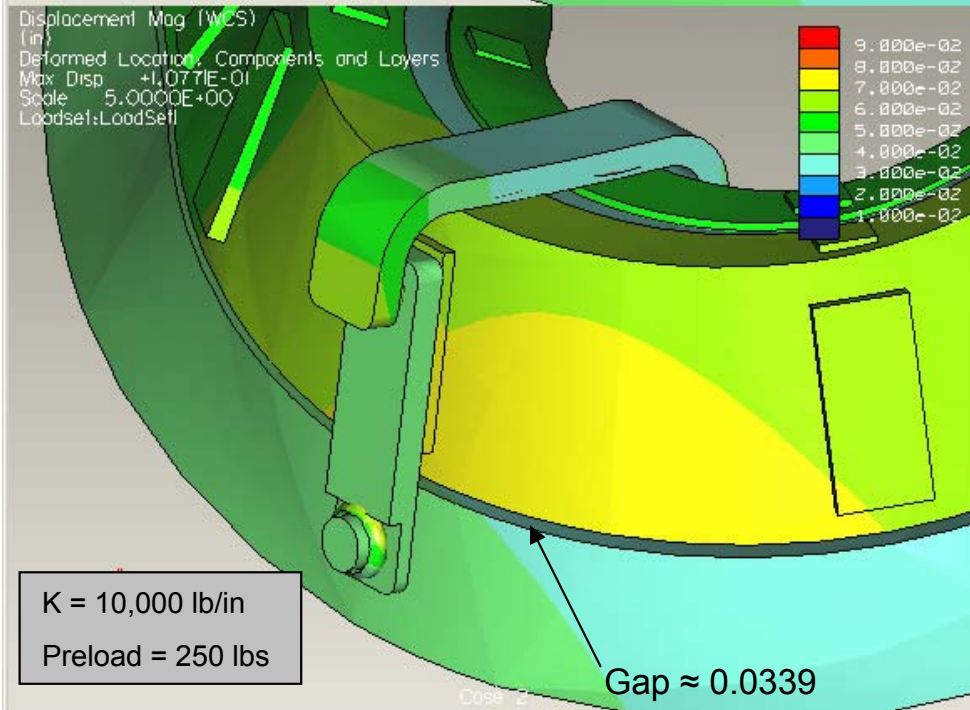
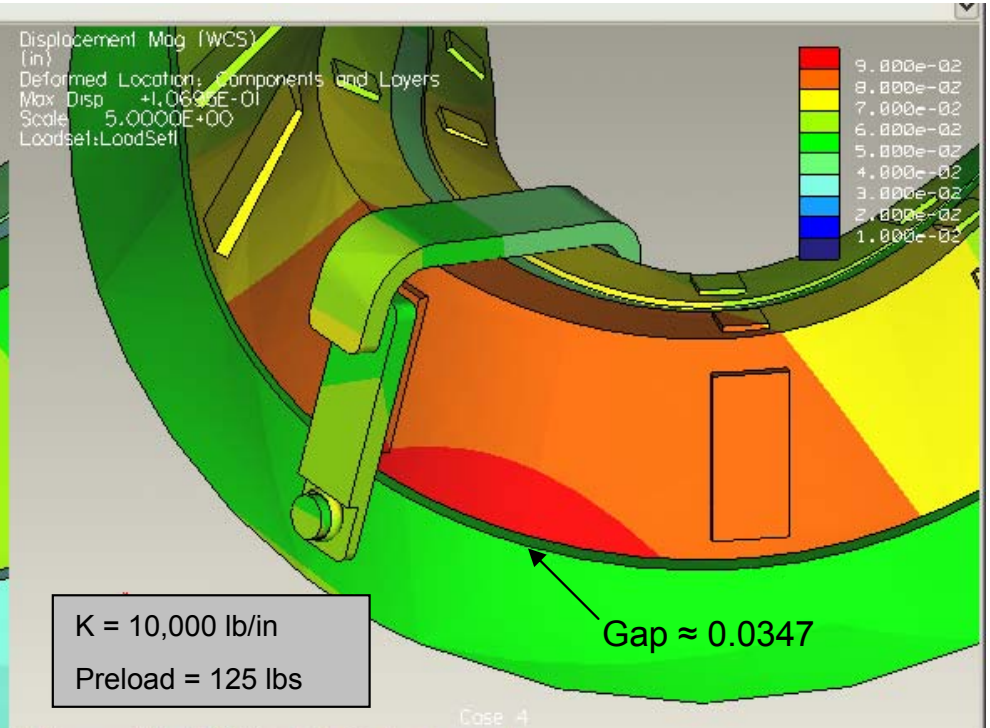
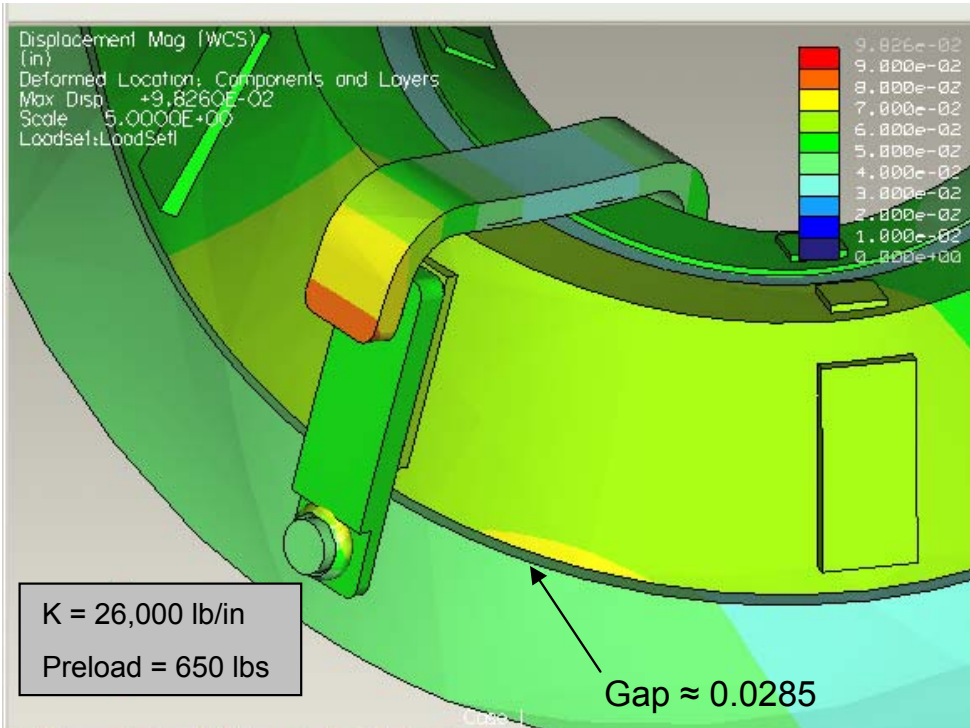
Multiple case have been run to determine what the correct design parameters should be for the clamps and corresponding Belleville washers. Cases 1–7 have one “real clamp” on board at west location and the rest are pseudo clamps.

# Displacement Comparison

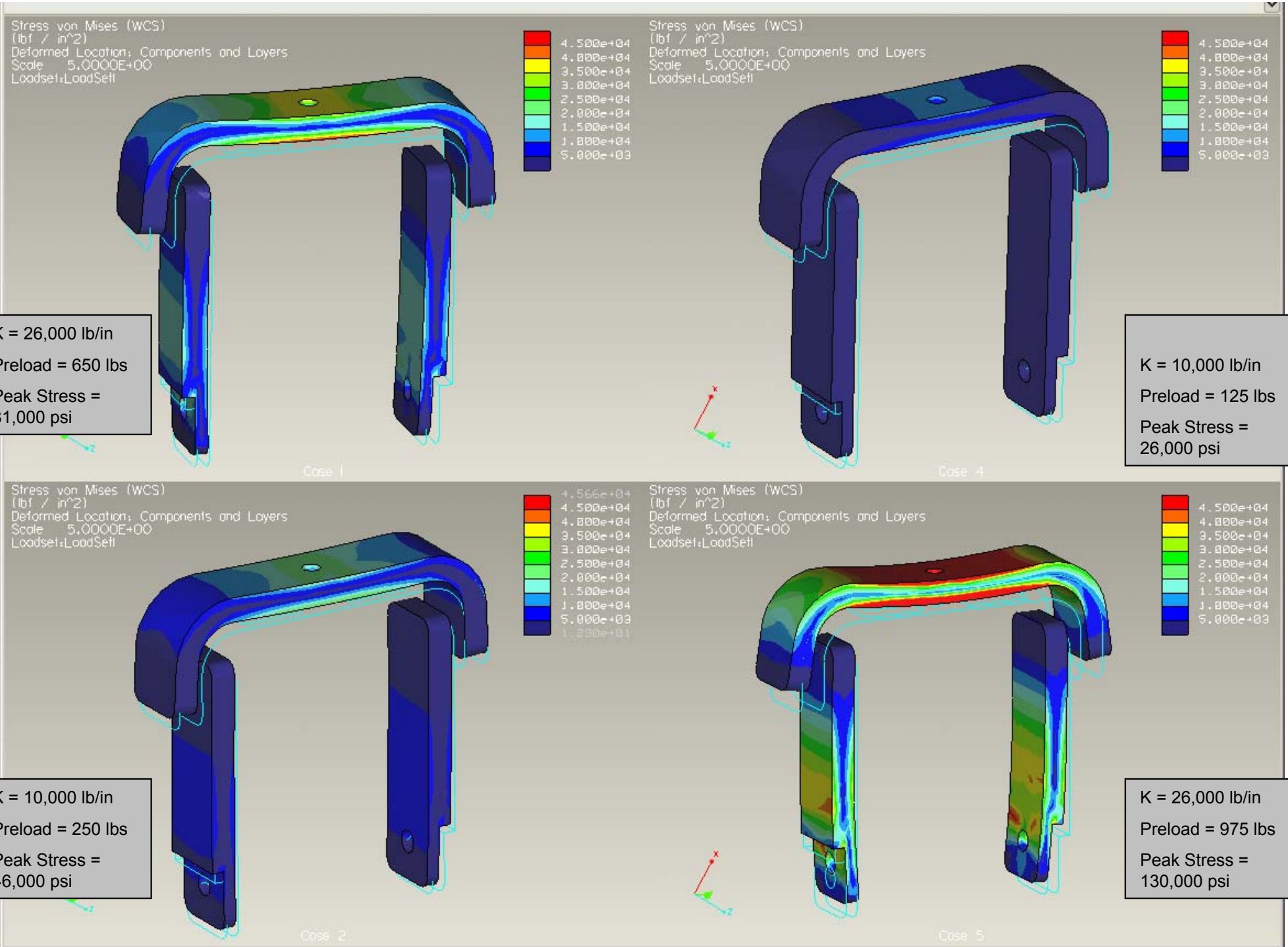




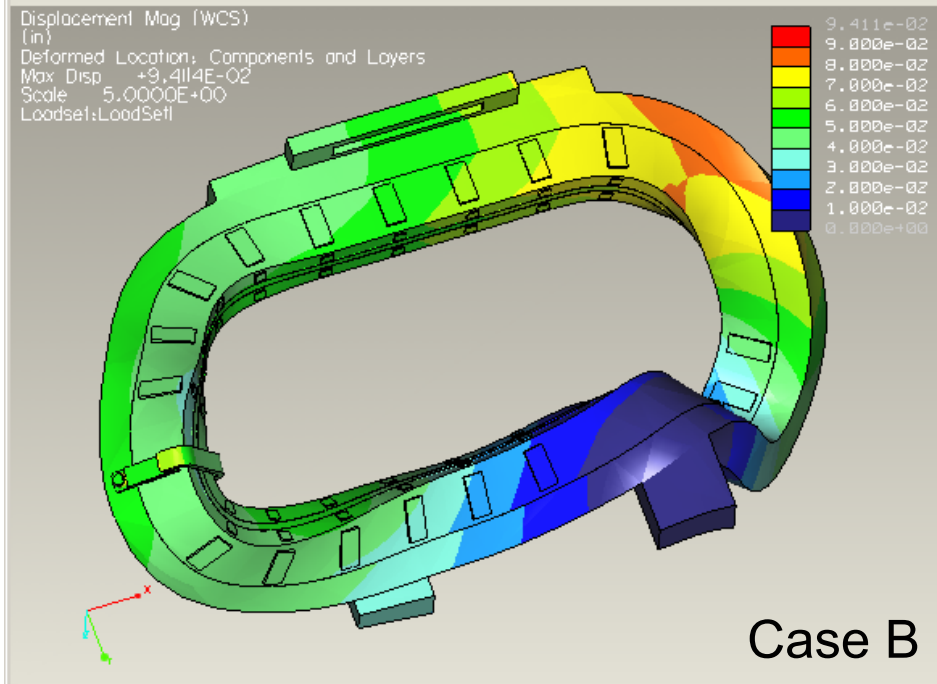
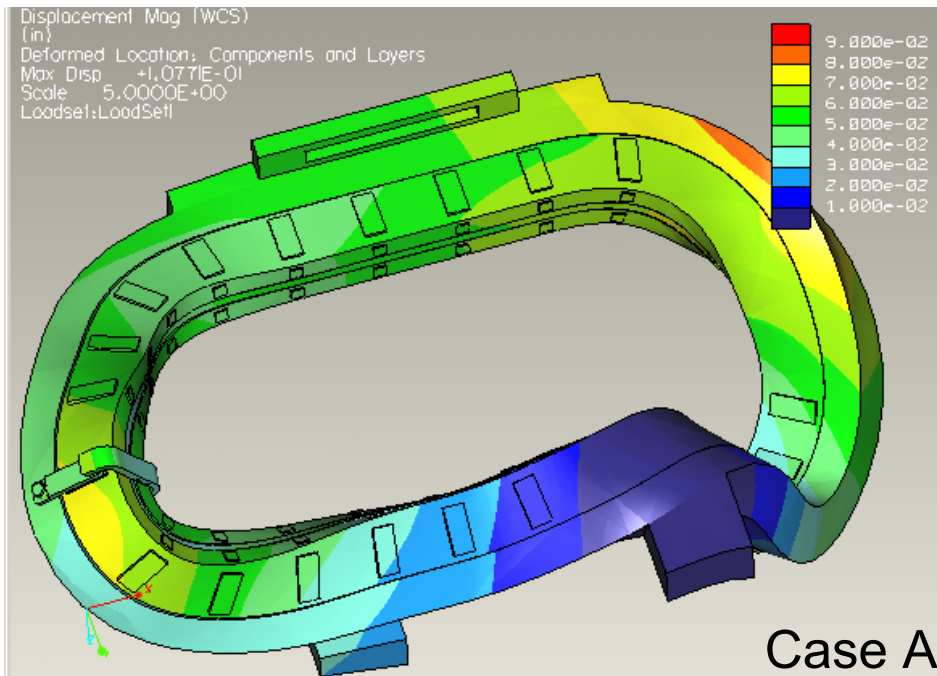
# How are Displacements from Tee Measured



# Clamp Stresses



# Winding Modulus Comparison Deformation

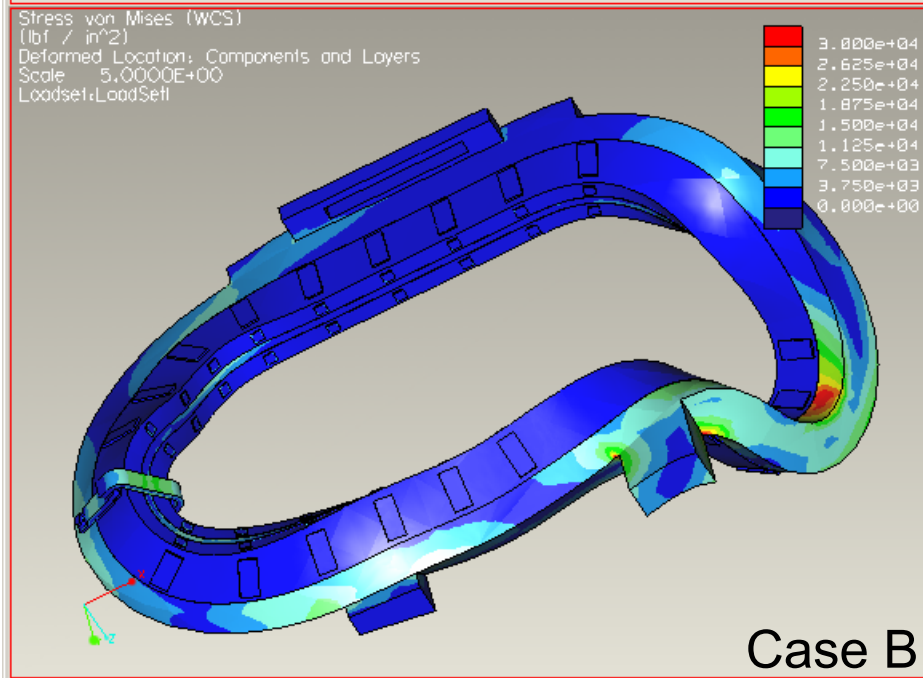
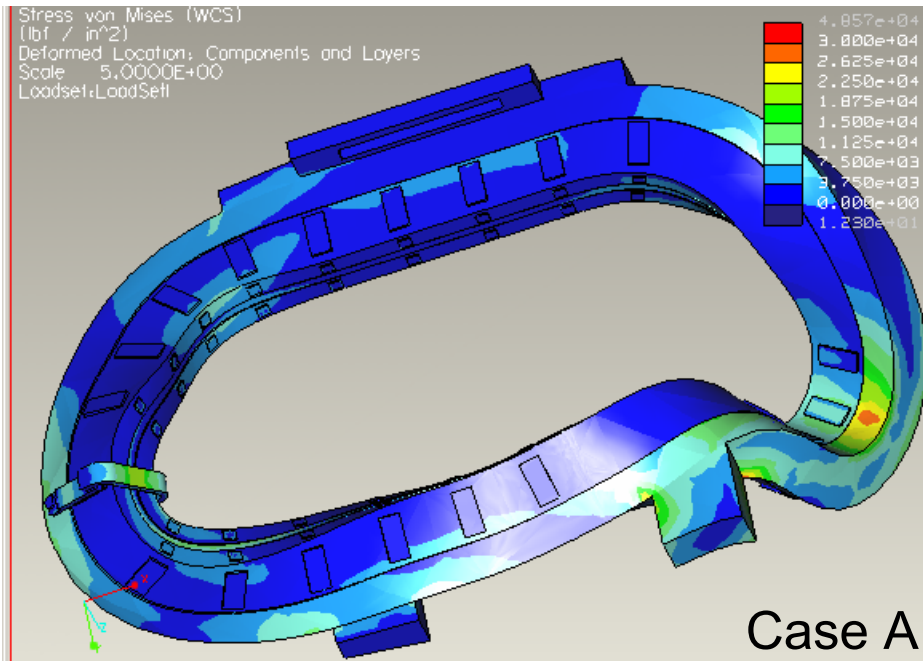


## Points:

- The modulus of the winding is a big player in determining the deflection of the coil.
- The deformation decreases with the lower modulus coil.

Parameter	CASE A	CASE B
Spring stiffness (lb/in)	10,000	10,000
Winding Modulus (psi)	9.50E+06	1.00E+06
Pre-load deflection (in)	0.1	0.1

# Winding Modulus Comparison Stress



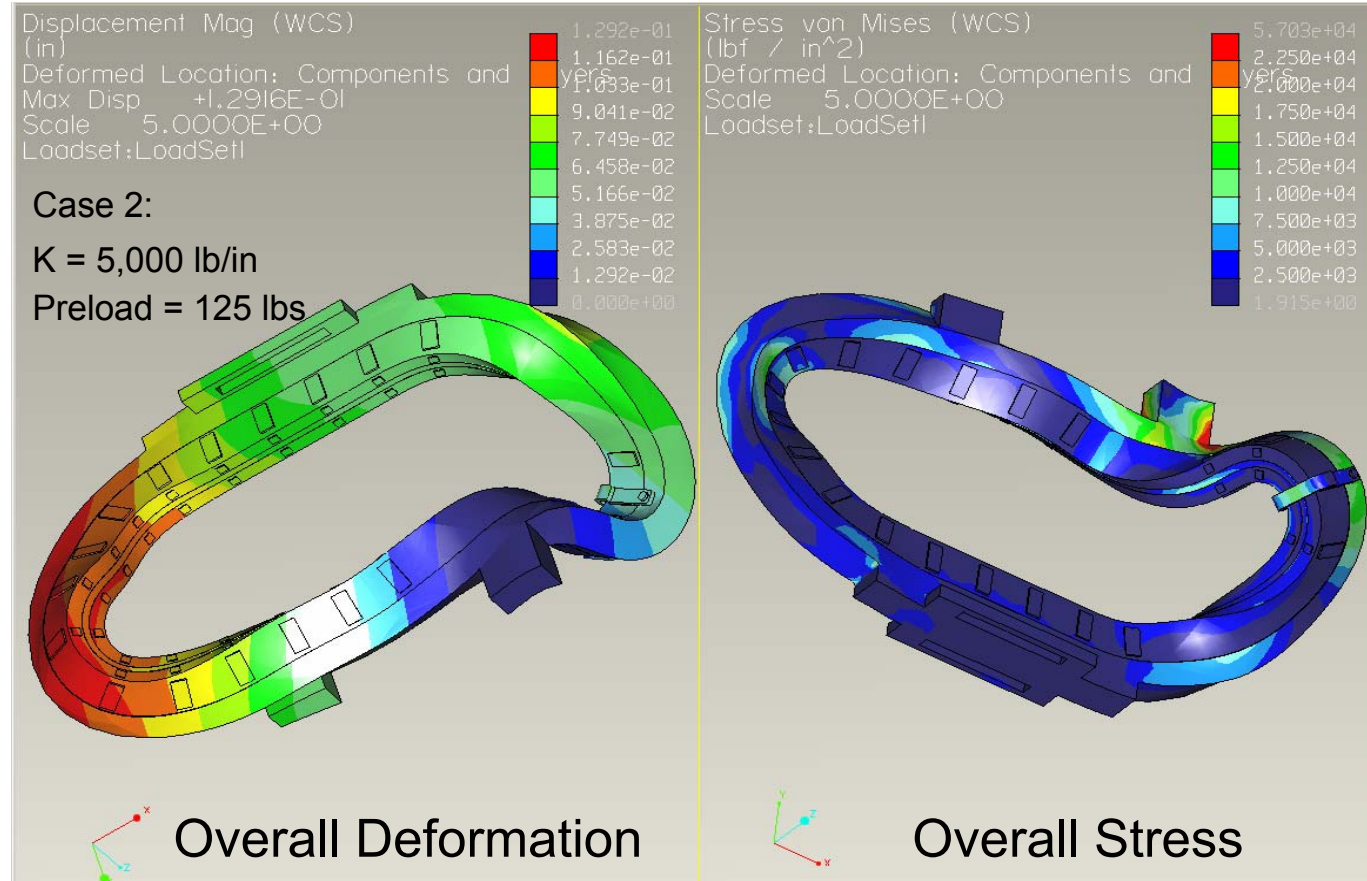
## Points:

- **Stress in tee is higher for the less stiff winding.**
- **Winding stress decreases as winding modulus is lowered.**
- **Clamp Stress is relatively the same. Clamp is dominated by preloaded springs**

Parameter	CASE A	CASE B
Spring stiffness (lb/in)	10,000	10,000
Winding Modulus (psi)	9.50E+06	1.00E+06
Pre-load deflection (in)	0.1	0.1

# Case 2 (Revisited 4-10-2004)

- Case 2 produced the best fit in terms of gap deflection, winding stress and clamp stress.
- Rerunning the case with the new cure shrinkage data produces the following results.



	Approximate Displacement Off Tee (in)	Faux Clamp Displacement (in)	Max Von Mises Stress in Winding (psi)	Max Von Mises Stress Clamp (psi)
0.04 % cure shrinkage (1-10-2004)	0.023	0.047	10,200	29,000 (15,000)
No Cure Shrinkage (4-12-2004)	0.007	0.019	8,400	25,000 (14,000)

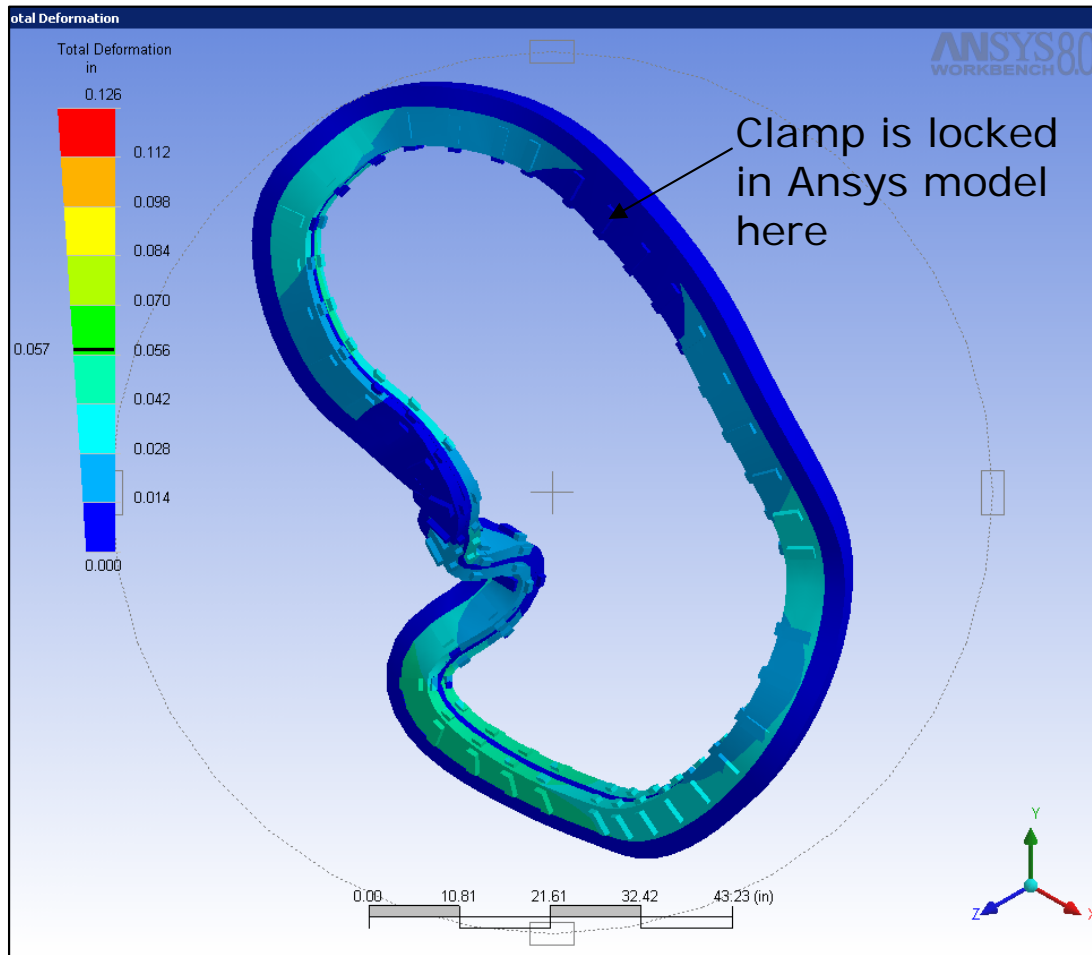
Obviously, the new data, if genuine, is encouraging.

# Considering the 4 Operating States (Case 2, No Cure Shrinkage)

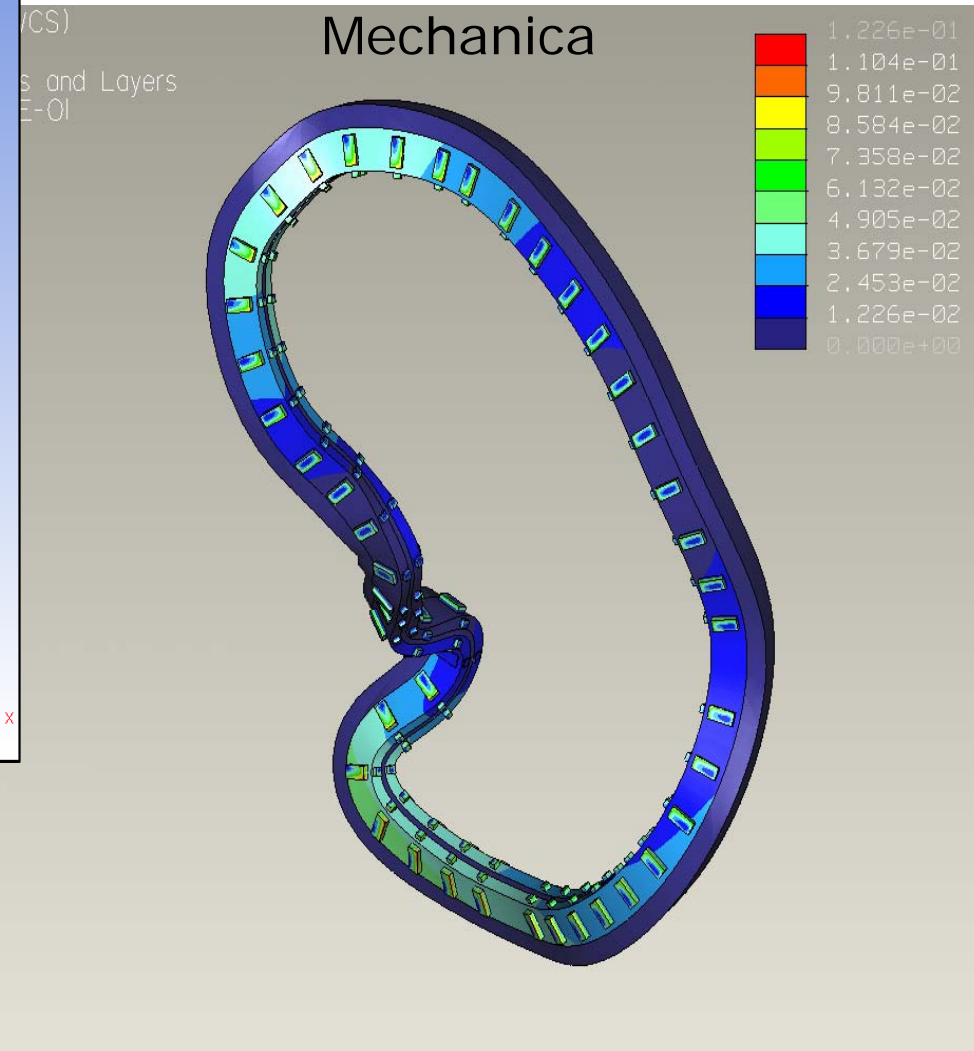
1. **Immediately after cool down.** -0.04 % relative strain between winding and tee due to thermal expansion.
2. **Beginning of Pulse.** Magnetic loading applied with thermal expansion.
3. **End of pulse.** Magnetic loading applied without thermal expansion, heating of coil has resulted in a relative +0.04 % strain difference between the winding and tee. (strain value is only coincidentally equal to the cool down strain difference).
4. **Post Pulse.** No magnetic loading, no thermal expansion (at rest state, coil will then cool back to state 1)

Operating State	Approximate Displacement Off Tee (in)	Faux Clamp Displacement (in)	Max Von Mises Stress in Winding (psi)	Max Von Mises Stress in Tee (psi)	Max Von Mises Stress Clamp (psi)
1	0.014	0.008	4,000	14,000	23,000 (12,000)
2	0.007	0.019	8,400	22,800	24,000 (14,000)
3	0	0.0002	7,350	35,285	23,000 (11,000)
4	-	-	-	-	24,000 (12,000)

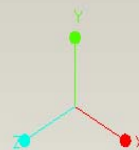
# Is Mechanics Accurate, Can It Be Trusted For Non-Linear Contact Analysis ?



A comparison study has been worked in Ansys for modular coil 2.



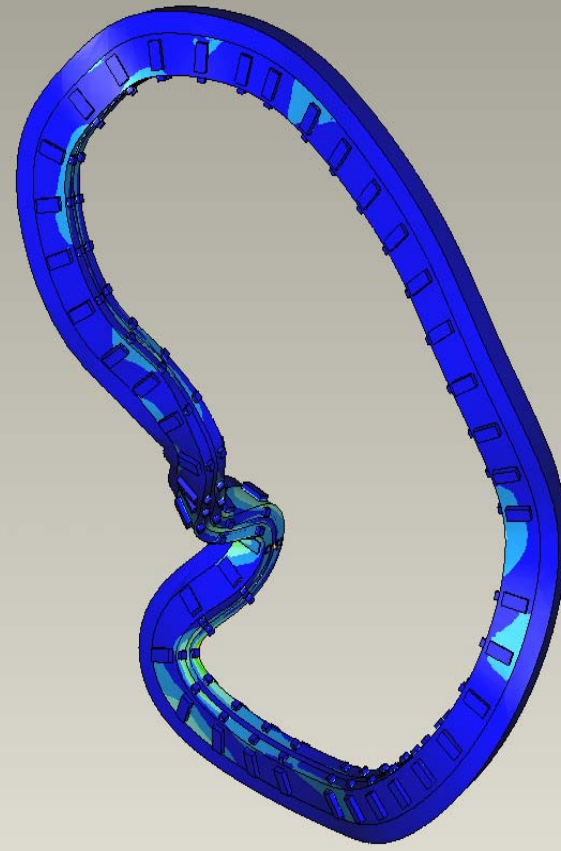
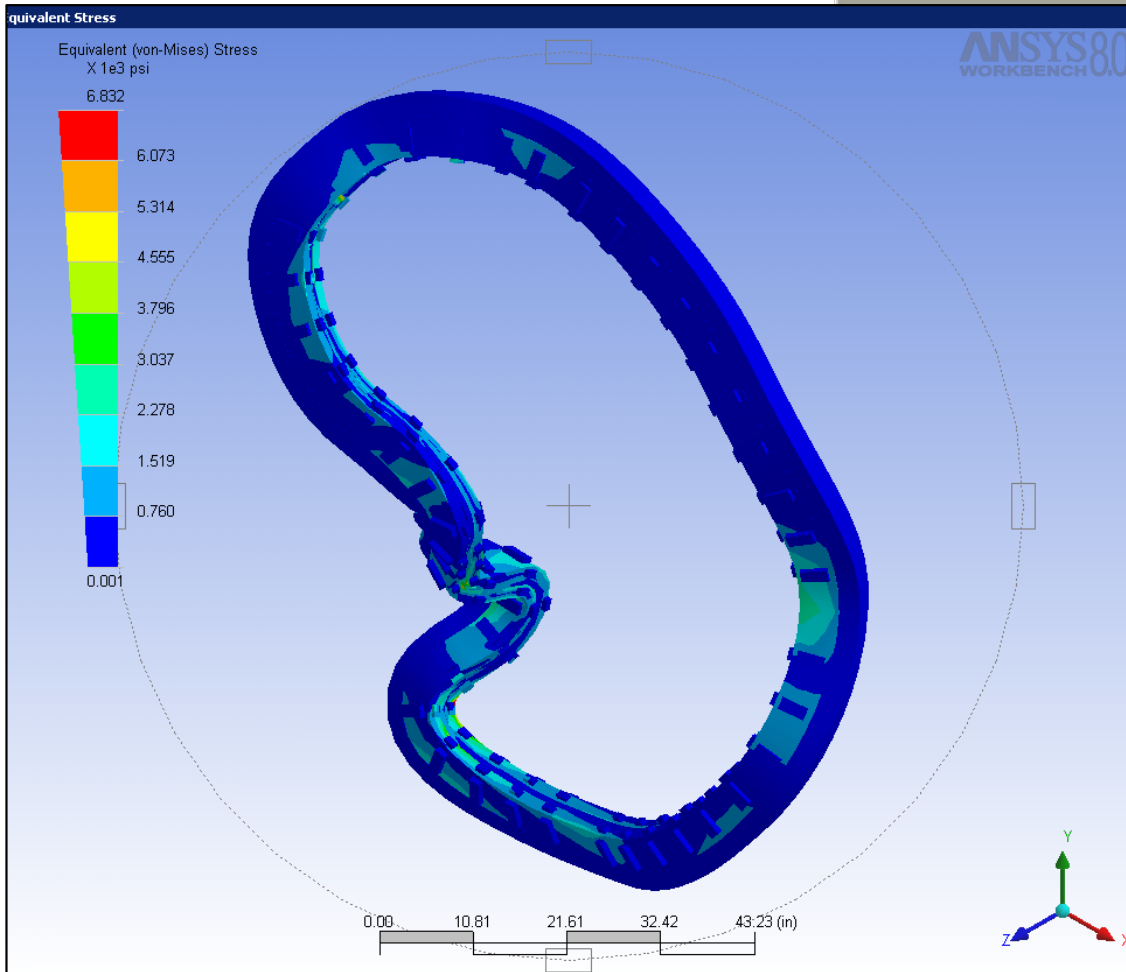
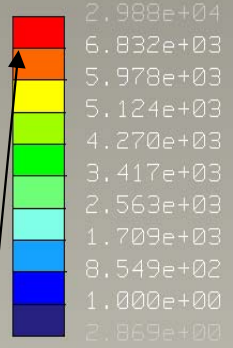
No Preload on clamp pads in Ansys version



# Comparison Between Mechanics and Ansys (Von Mises Stress)

Stress von Mises (WCS)  
(lbf / in<sup>2</sup>)  
Location: Components and Layers  
Loadset:LoadSet1

Mechanica



**Is Mechanics Accurate? Yes,  
It agrees well with Ansys**

The high stress is in the pin connecting the clamp which the Ansys model does not have.

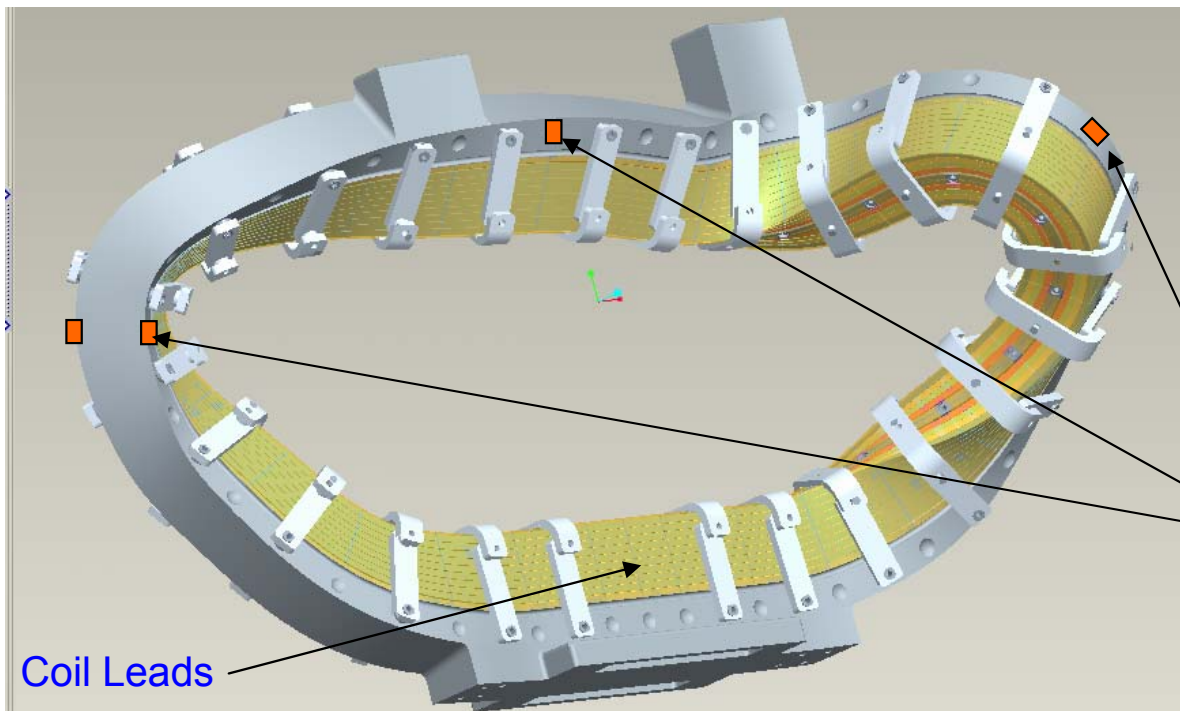


# Summary

- Iterations show that Belleville washers should be designed with a stiffness of 5,000 - 10,000 lb/in and a preload of 100 – 125 lbs. This corresponds to case 2 and case 6.
- Clamp Stresses depends mostly on preload.
- Soft windings stick to the tee better, but do raise stress in the tee.
- Using no clamps, results in larger displacements and gaps, but this effect is less for the stiff winding pack.
- Mechanica and Ansys give the same answers for non-linear contact analysis.

# Future Work

- Modify Winding Stiffness based on results of ongoing tension and compression tests at PPPL.
- Provide a table for predicted strain values at experimental strain gage locations for the four loading states.
- Perform a detailed analysis of the actual clamp design (with all features) based on the max deflections measured in this analysis.



“Actual” clamp design

Strain Gauge Locations  
(ends and middle of  
winding form) ?

# Work to be done

## Design tasks -

- Complete pattern drawings for inner plate (cladding)
- Issue clamp detail drawings for fabrication
- Finalize patterns for chill plate and cooling tubes, develop drawings

## Schedule -

	May				Jun				Jul				Aug				Sep							
Week #	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Issue cladding and clamp detail drawings	X																							
Issue chill plate / cooling detail drawings		X																						
Fabricate / procure hardware		X	X	X	X	X	X																	
Wind coil								X	X	X	X	X												
Mold and VPI													X	X	X									
Setup and test																X	X	X	X					

Begin winding  
prototype coil

The twisted racetrack coil is prototypical

- complex winding surface
- actual conductor and insulation
- prototypical clamps and chill plates
- utilizes production winding facility

Test objectives have been defined

All models / drawings are not final, but should be released in stages asap to improve schedule