Status of Non-Axisymmetric Coils Study

- Requirements
- Fabrication Concepts
- Design Issues
- Tools Development

General Design Criteria / Parameters

Parameter	Value	Units	Comments
Major Radius	1.5	m	
Plasma Radius	45	cm	34-cm to VV wall
Aspect Ratio	3 - 4		
Plasma Current	< 400	kA	
Toroidal Field	1 - 2	T	2.35T @ 1.49m
Pulse Length	3 - 5	s	
NBI/ICRF	12	MW	

Inboard NA Coil Design Parameters (2-d9e)

Parameter	Value	Units	Comments
Number of Coils	24		12 x 2
Current per Coil	68-72	kAT	
Coil Size	3.7 x 8.7	cm	4-6 kA/cm2
Coil Length	1.6 - 10	m	
Coil Weight	30 - 180	kg	
Winding Accuracy	0.02	%	Equiv to 0.2-mm / m

Features:

- Coils are wound in place using flexible copper conductor
- Coils are placed in vacuum can for potting and vacuum compatibility
- Coils are supported from radial ribs
- Structure must have insulating breaks to avoid toroidal current path

Outboard NA Coil Design Parameters

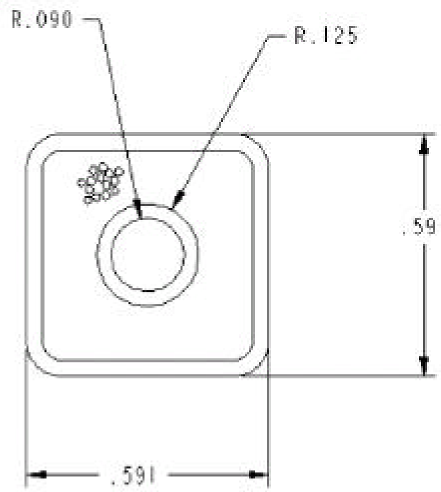
Parameter	Value	Units	Comments
Number of Coils	14		2 x 2 Saddle 1 x 10 Shear
Current per Coil	72 - 90	kAT	
Coil Size	3.7 x 8.7	cm	4-6 kA/cm2
Coil Length	6.1 – 8.4	m	
Coil Weight	~ 150	kg	
Winding Accuracy	0.02	%	Equiv to 0.2-mm / m

Coil Fabrication Options

Variations in conductor type and winding configuration have been studied:

Conductor Type

- Copper wires around solid tube
- Spring type flexible tube
- Braided copper, no tube

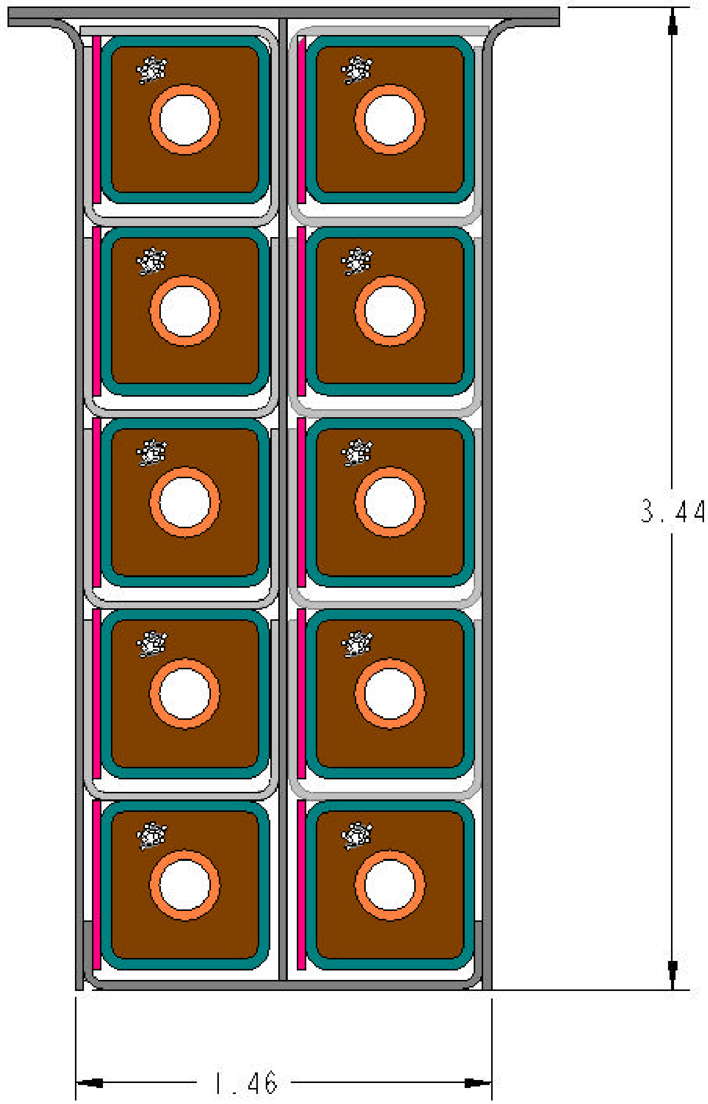


Leads and Crossover Configuration

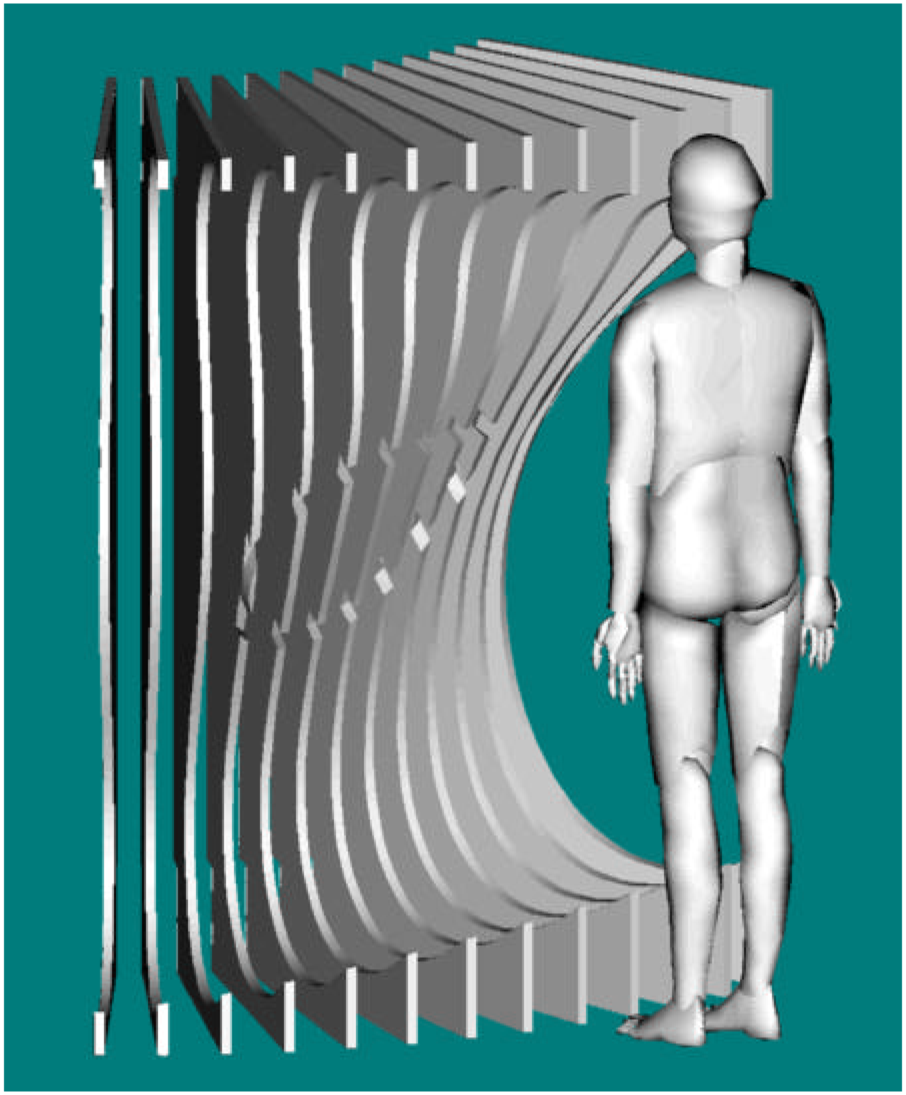
- Pancake winding, crossover block, parallel leads
- Layer winding, in-vessel joint, coaxial leads
- Pancake winding, continuous conductor, parallel leads
- Layer winding, continuous conductor, parallel leads

Reference Cross-Section

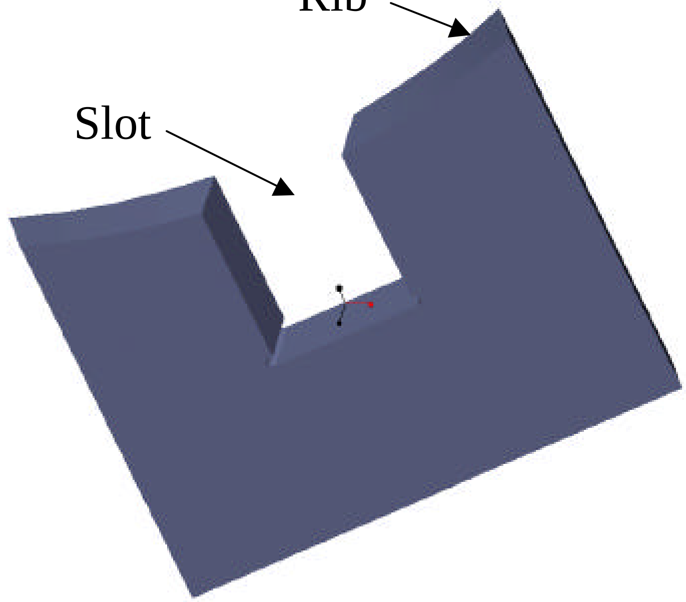
- Nominal conductor size is 15-mm square
- Cooling tube is 0.25-in x 0.035-in wall
- Thin metal clips between turns
- Typical plate thickness is .030-.063 inch
- Compliant layer for thermal expansion
- Envelope dimensions of 1.46 x 3.44-in are larger than original (0.98 x 3.15-in)



Saddle Coil Fabrication Concept

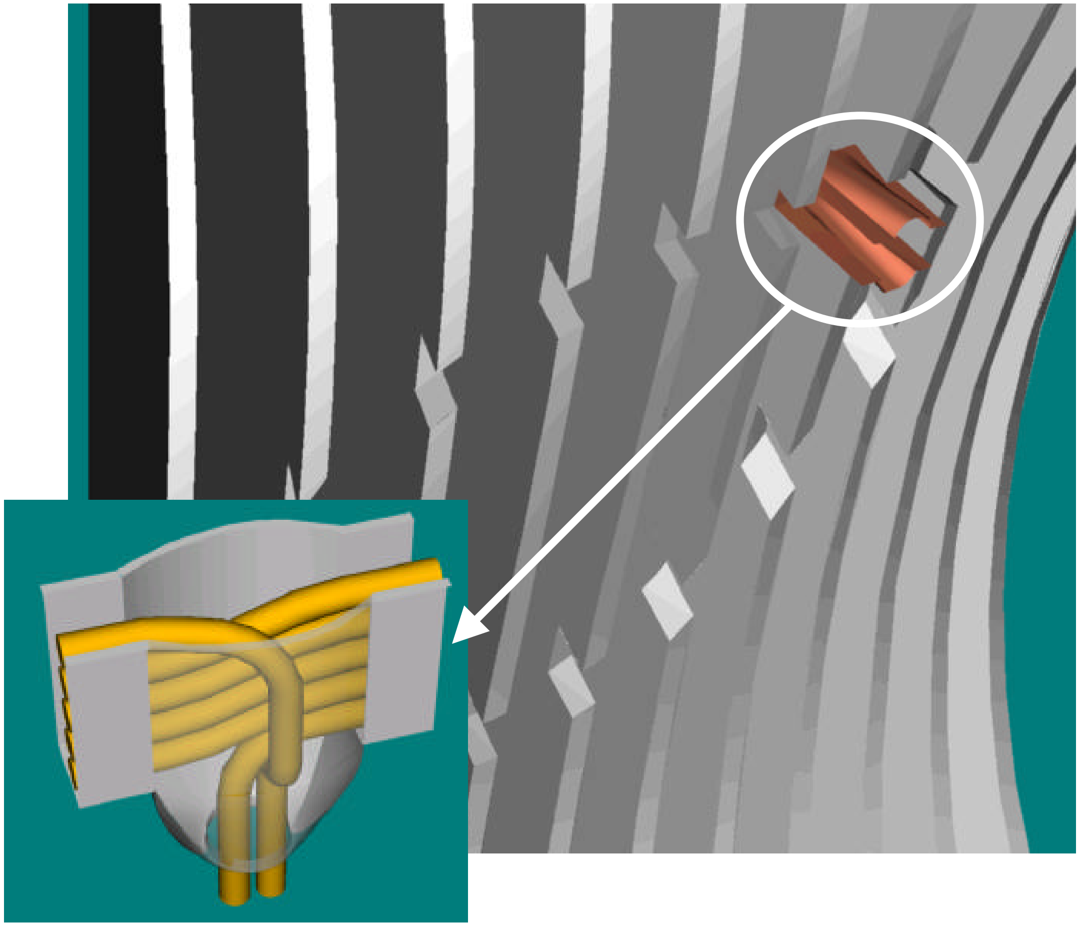


Prepare slots in radial rib structure



Saddle Coil Fabrication Concept

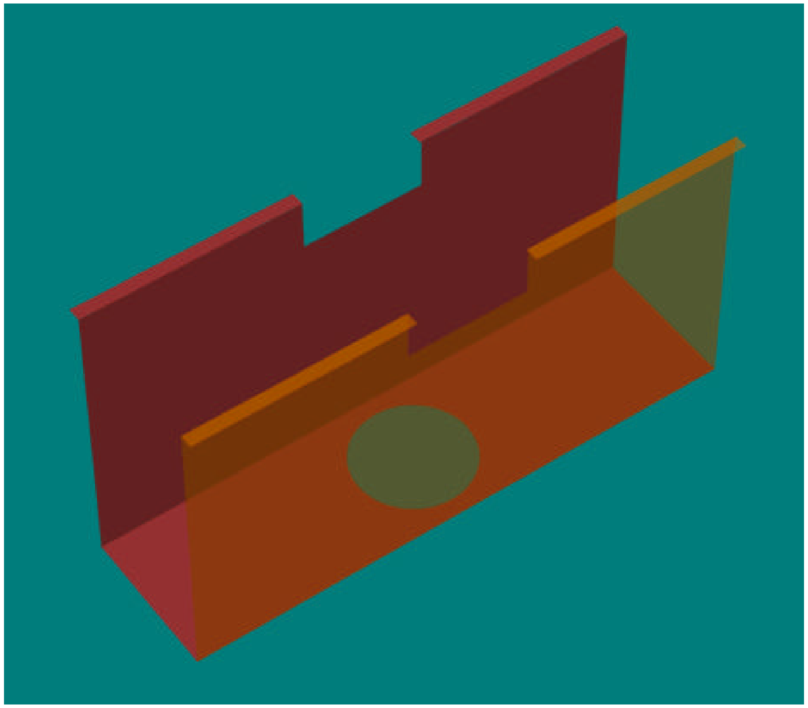
Install formed trough section for leads and crossover block

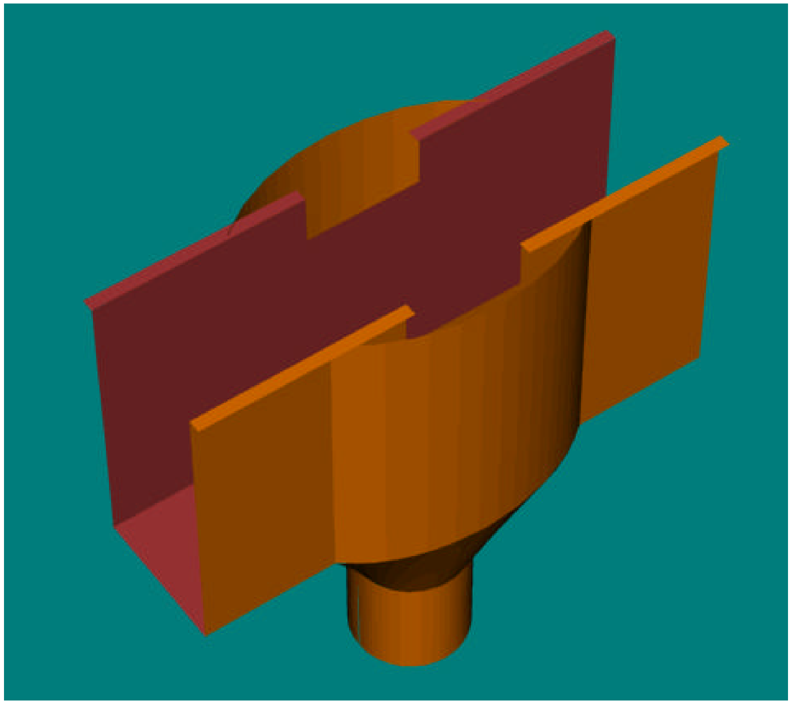


Saddle Coil Fabrication Concept

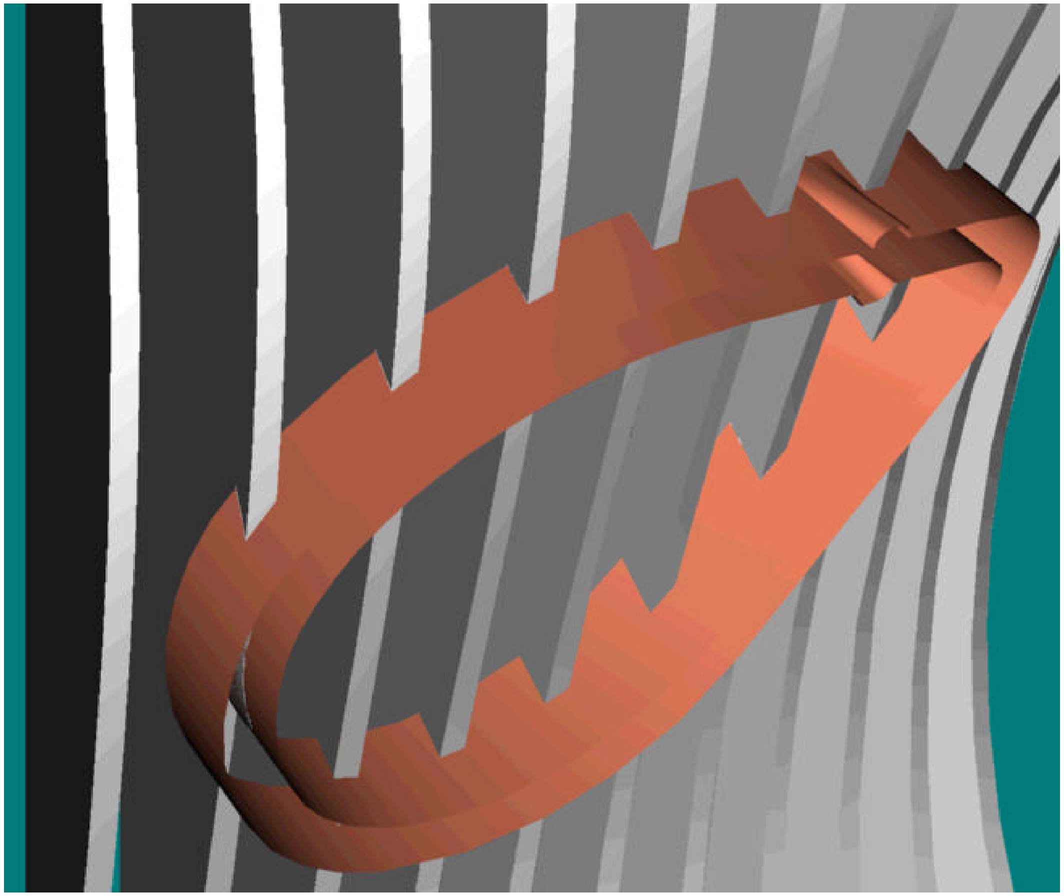
Alternate Concept for Lead/Crossover Trough Region -

- Cutouts in flat developments at leads/crossover
- Add additional structure to outside of trough

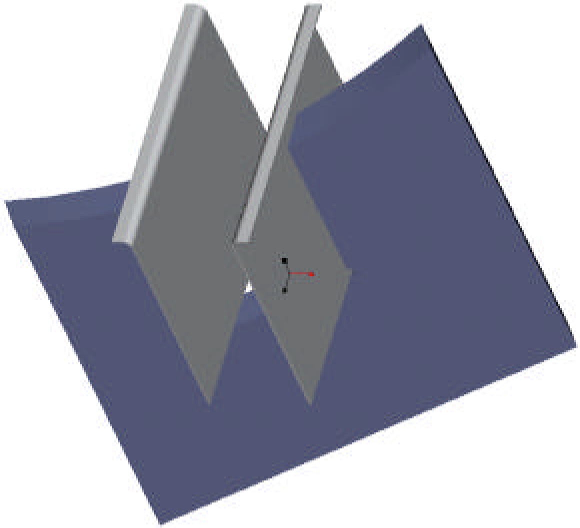




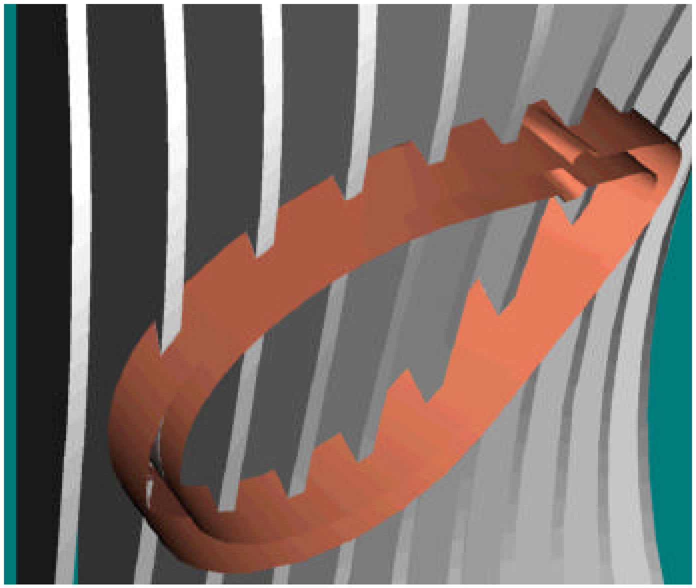
Saddle Coil Fabrication Concept



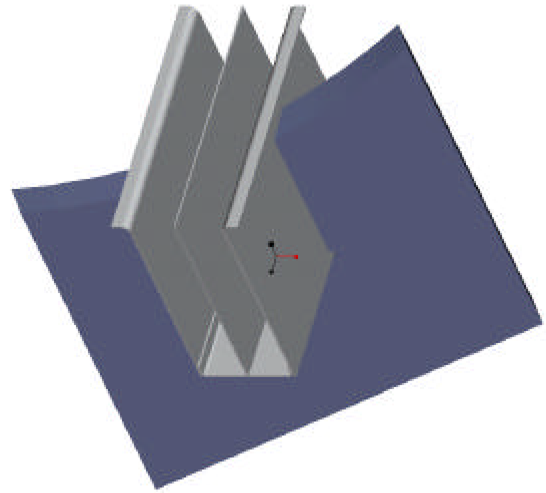
Insert trough side plates into slot and secure



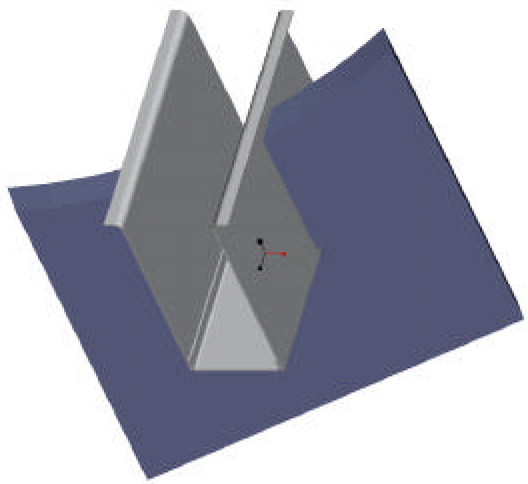
Saddle Coil Fabrication Concept



Weld septum to bottom

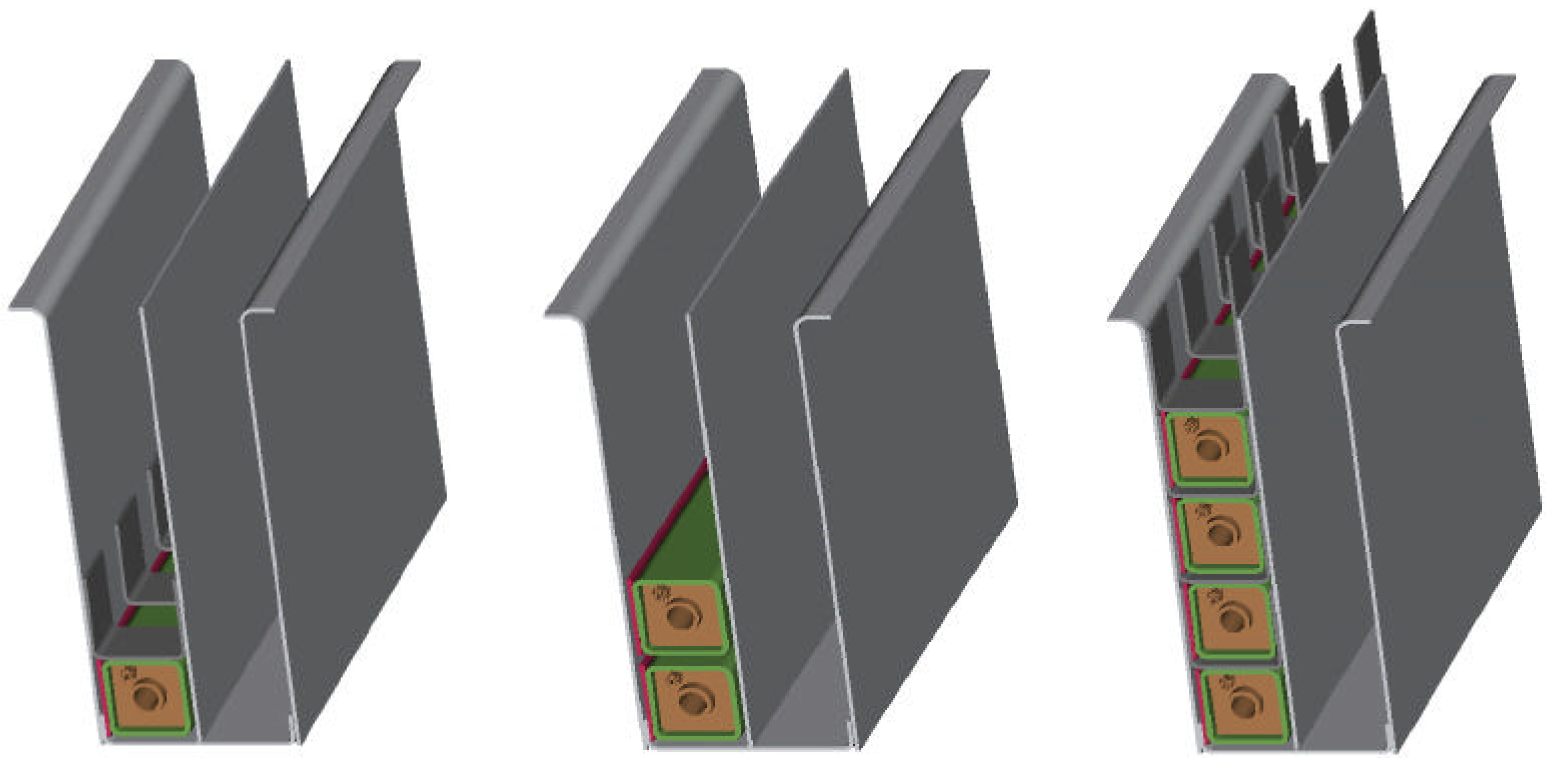


Insert trough bottom plate and seam weld



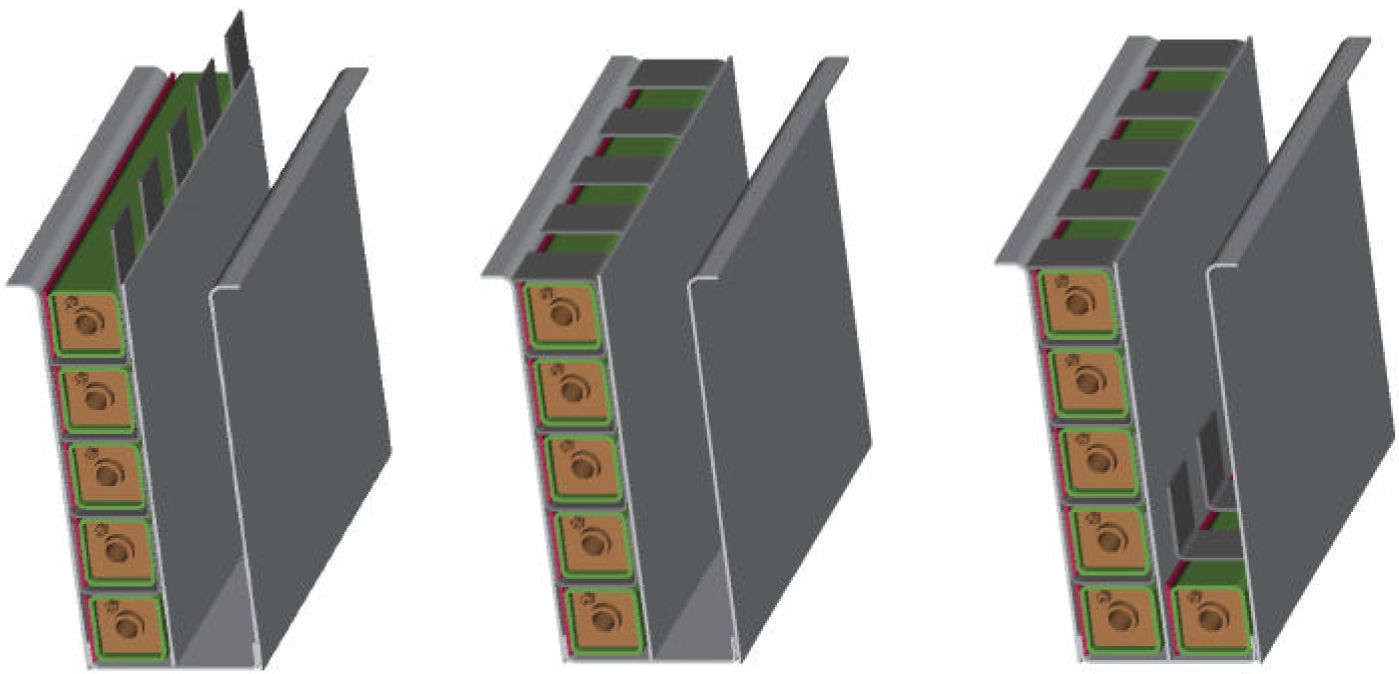
Saddle Coil Fabrication Concept

- First conductor layer is placed in trough and fixed by spot-welded clips
- Use extended clips on next-to-last conductor layer



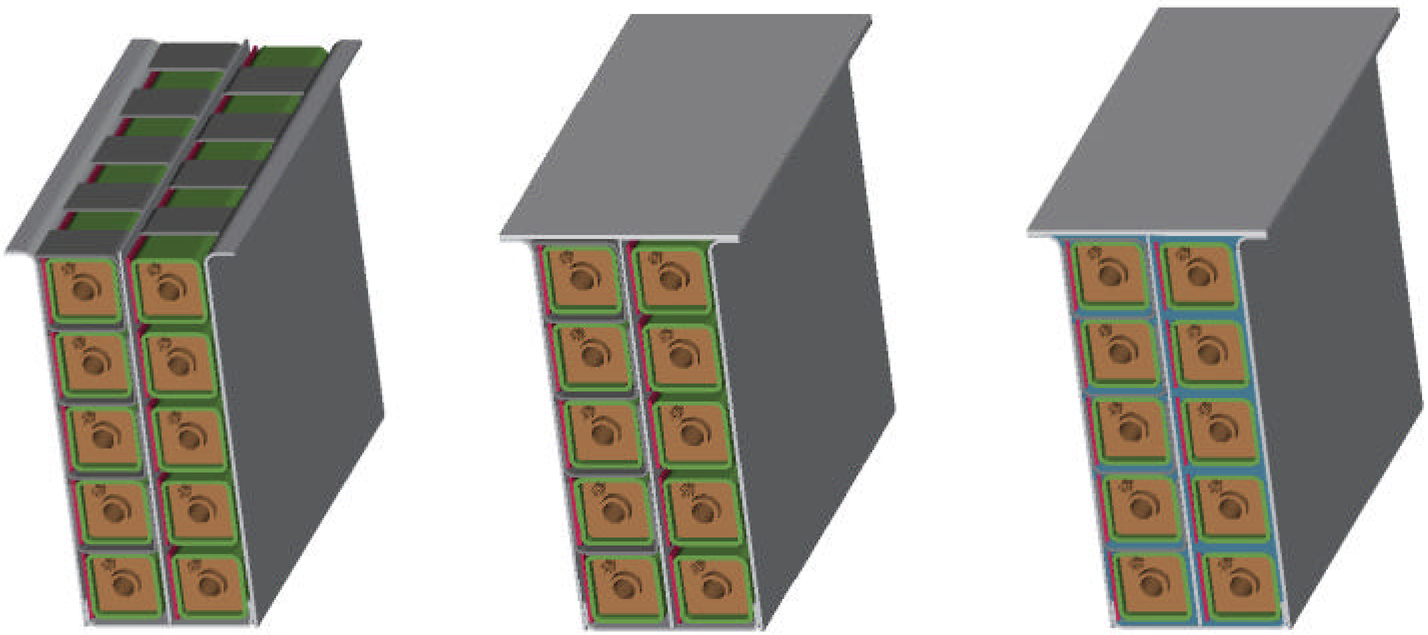
Saddle Coil Fabrication Concept

- Add last conductor layer, bend clips and spot weld
- Lay in conductor layer for second pancake

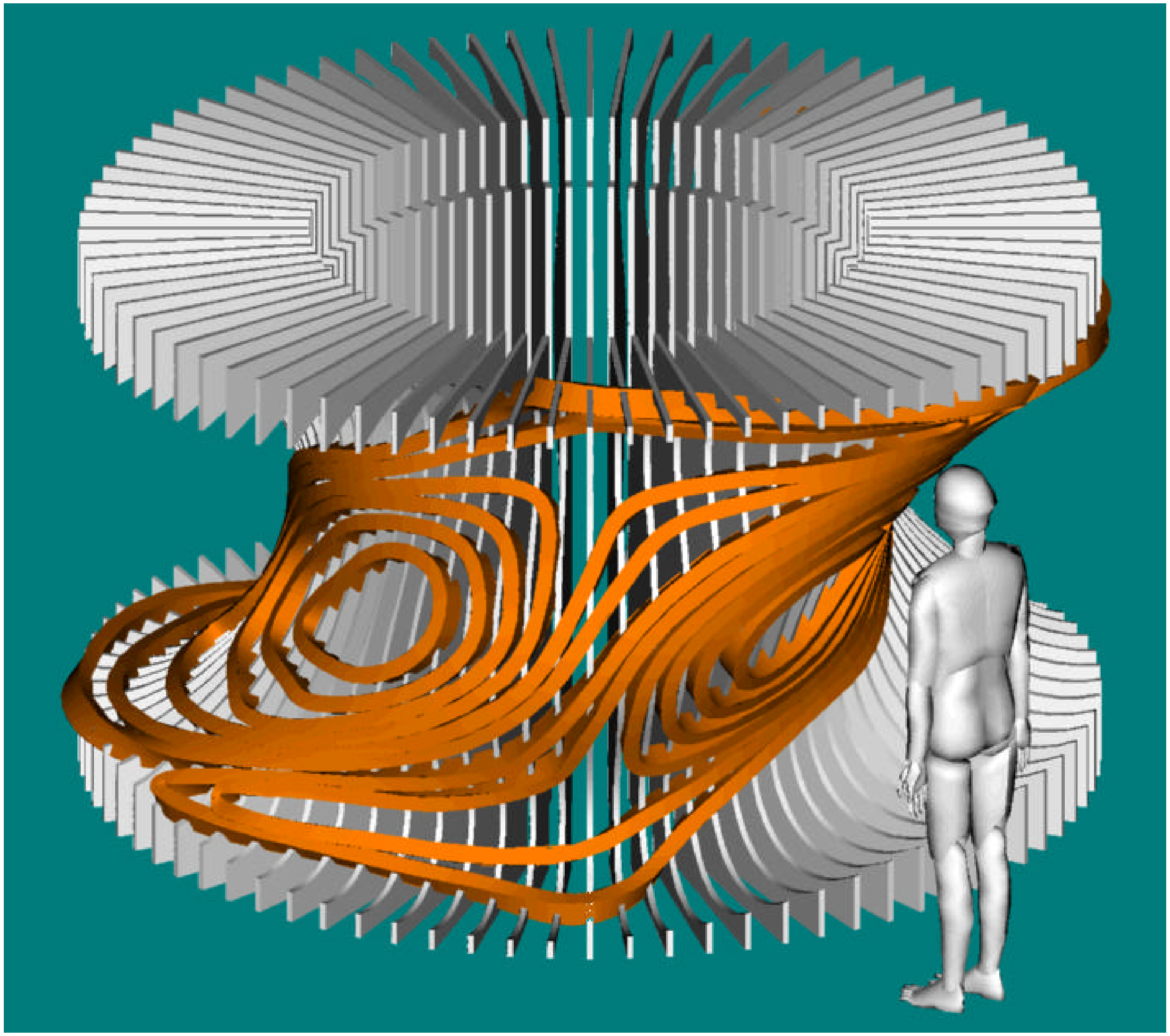


Saddle Coil Fabrication Concept

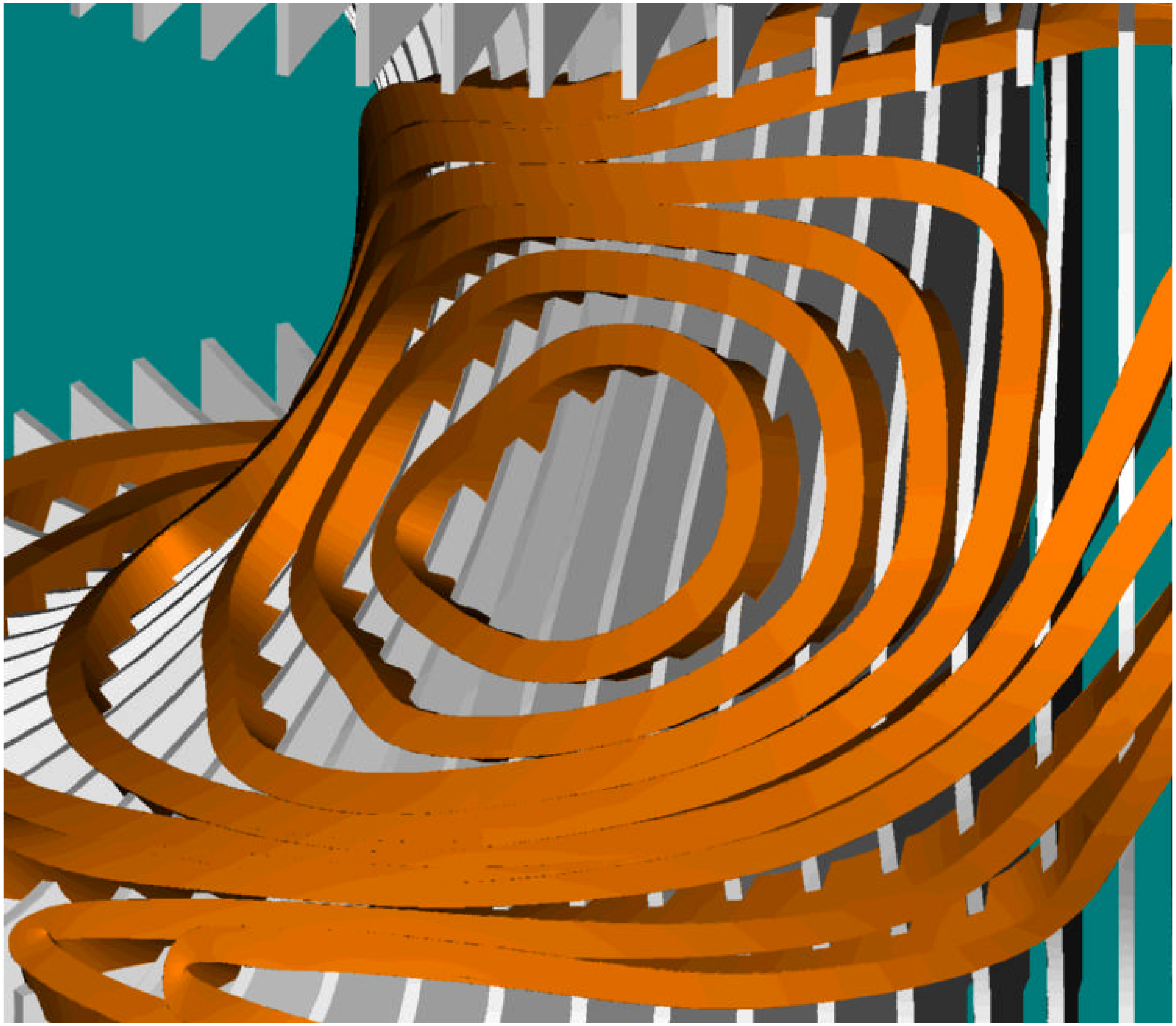
- Complete winding, bend clips and spot weld to secure
- Seam weld cover to can, forming vacuum tight enclosure
- Vacuum impregnate can and conductor with epoxy



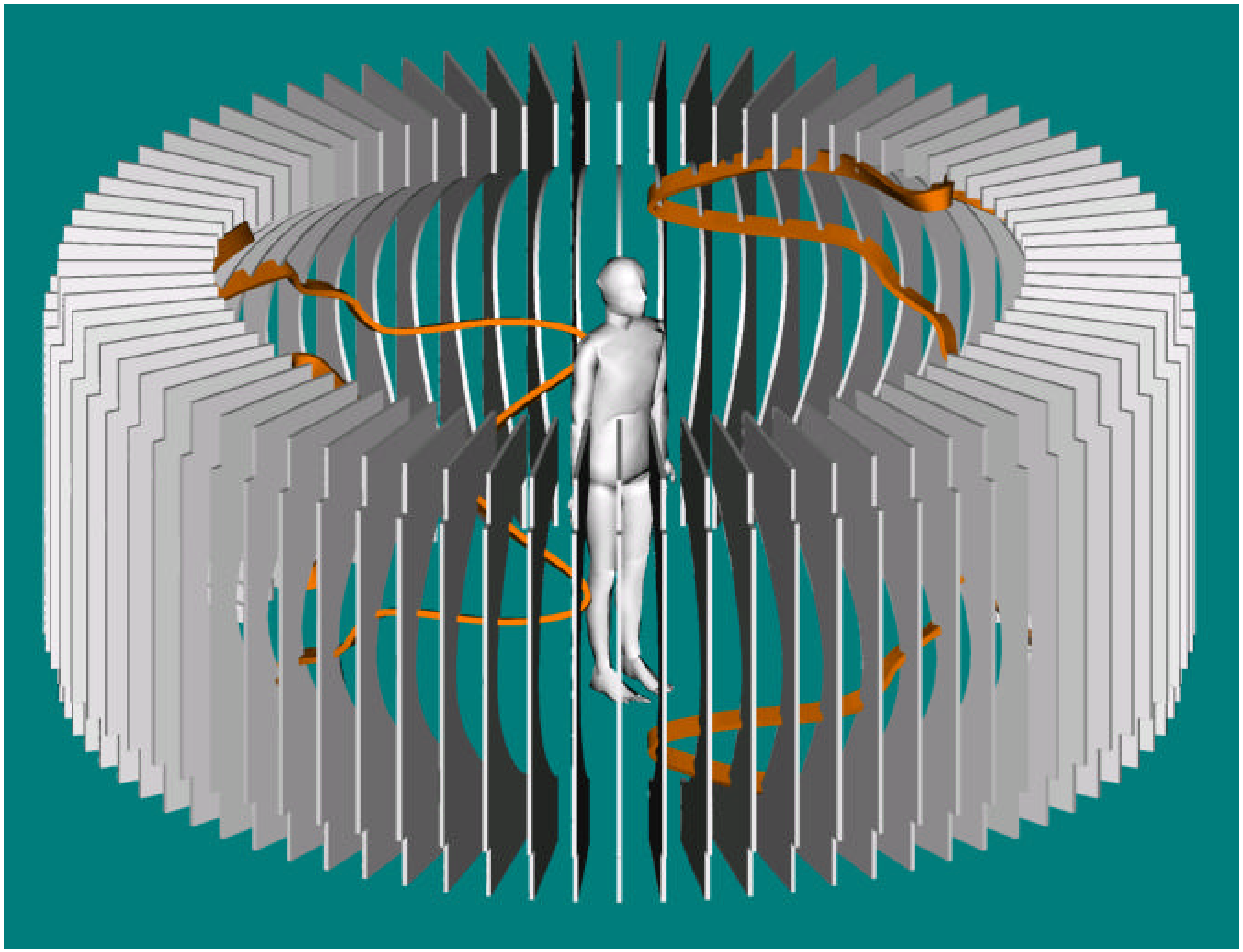
Inboard Saddle Coil Assembly



Inboard Saddle Coil Assembly



Outboard Saddle Coil Assembly



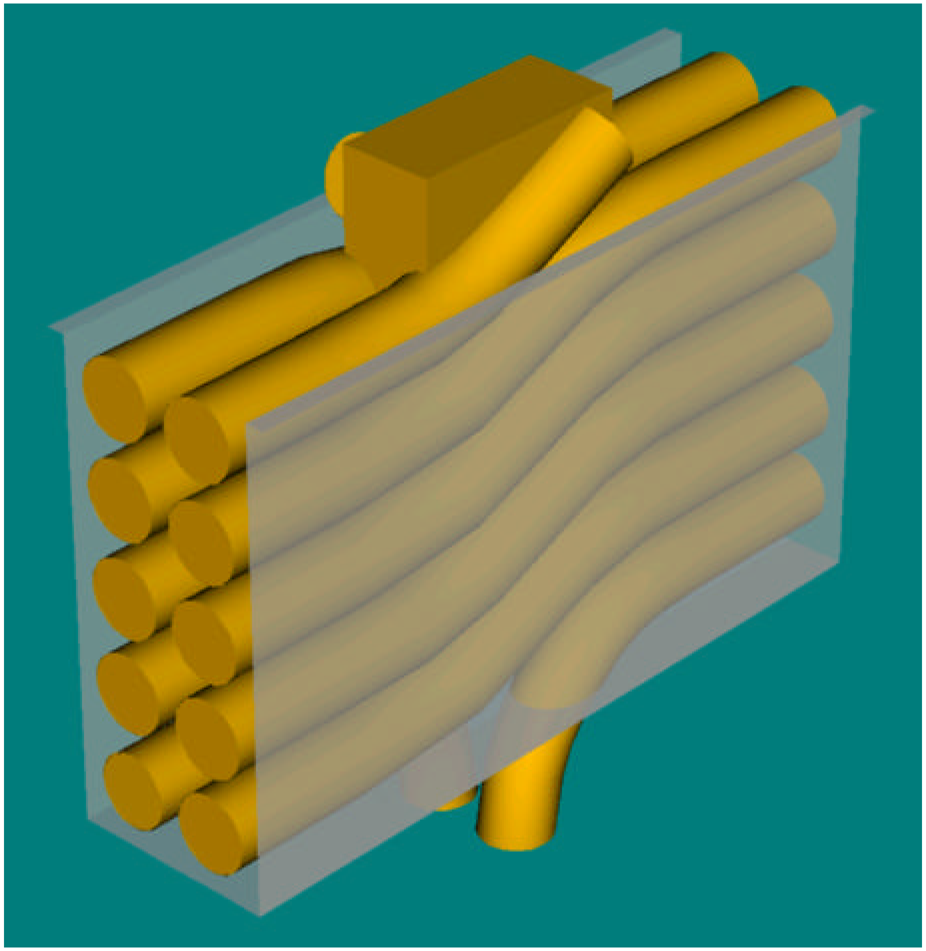
Leads and Crossover Option #1

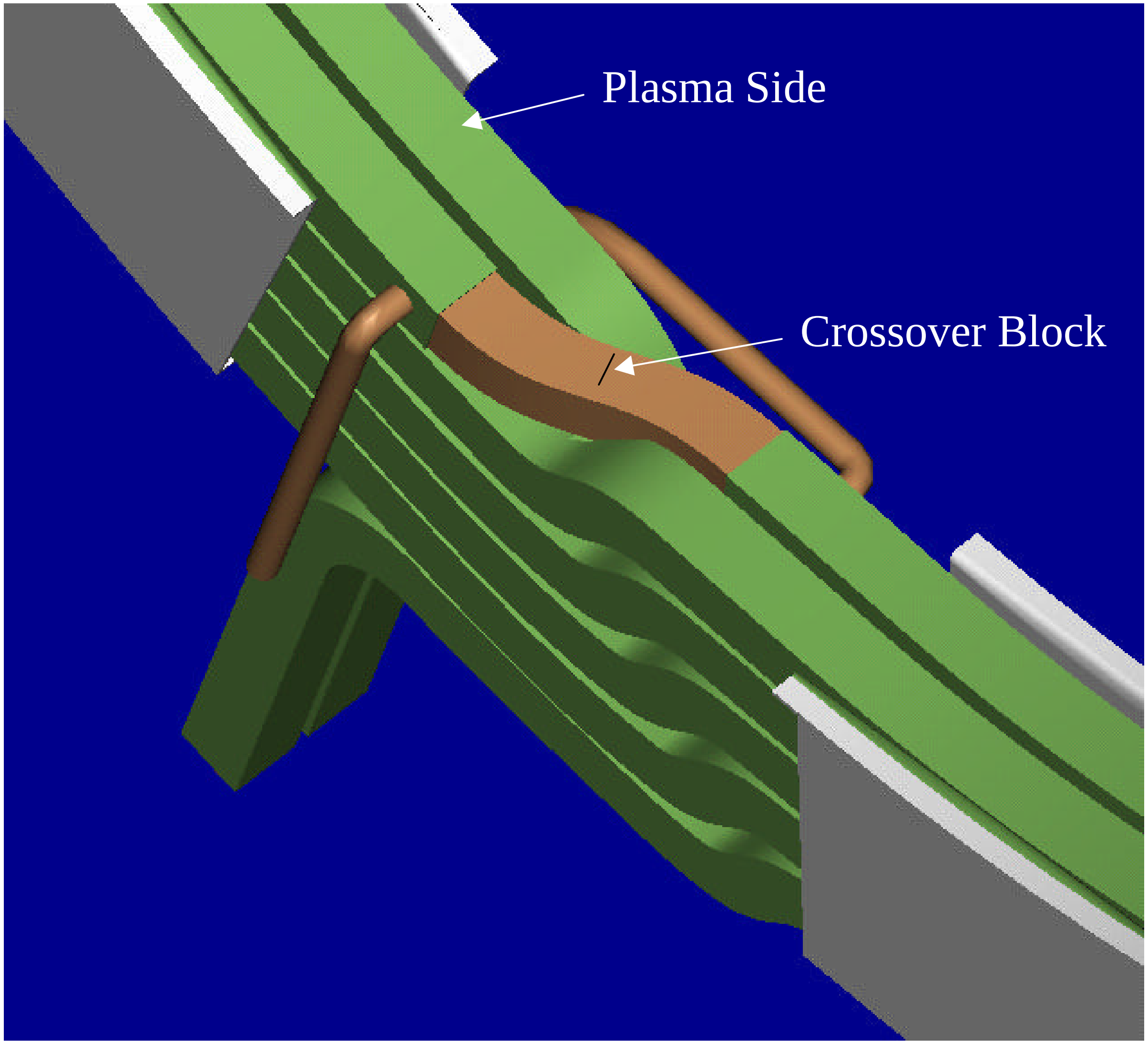
- Two pancakes wound from bottom of trough in opposite directions

- Plasma-side ends are connected to a crossover block

- Water may exit at crossover

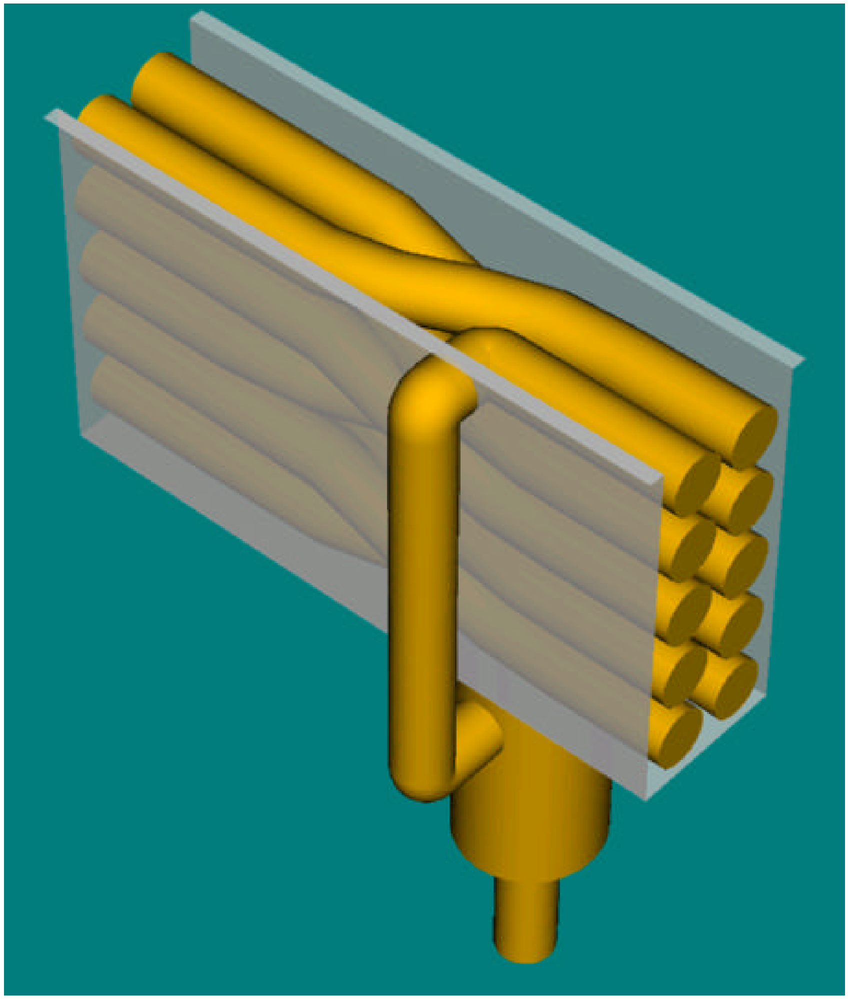
- Two parallel leads




Plasma Side
Crossover Block

Leads and Crossover Option #2

- Single layer wound from bottom of trough
- Plasma-side end is routed around winding pack and out to buswork
- Single coaxial lead

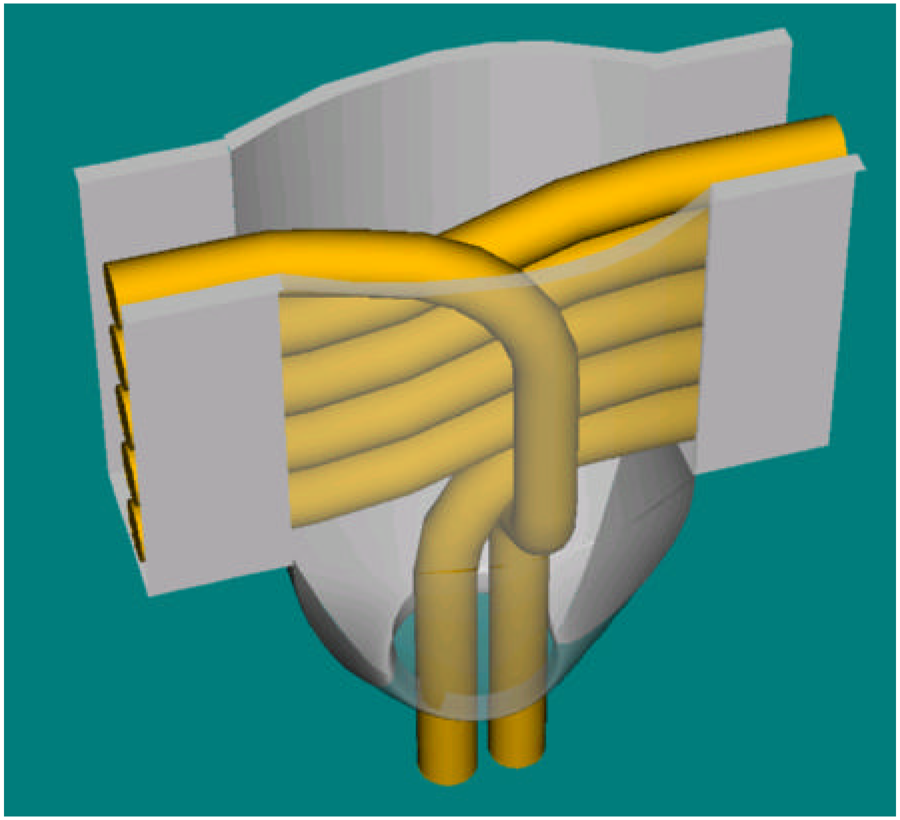


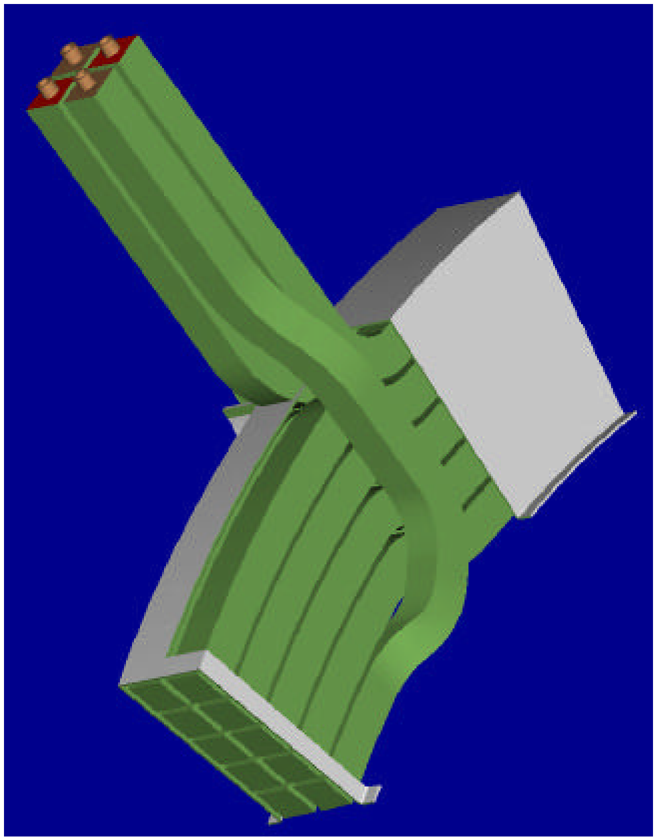
Leads and Crossover Option #3

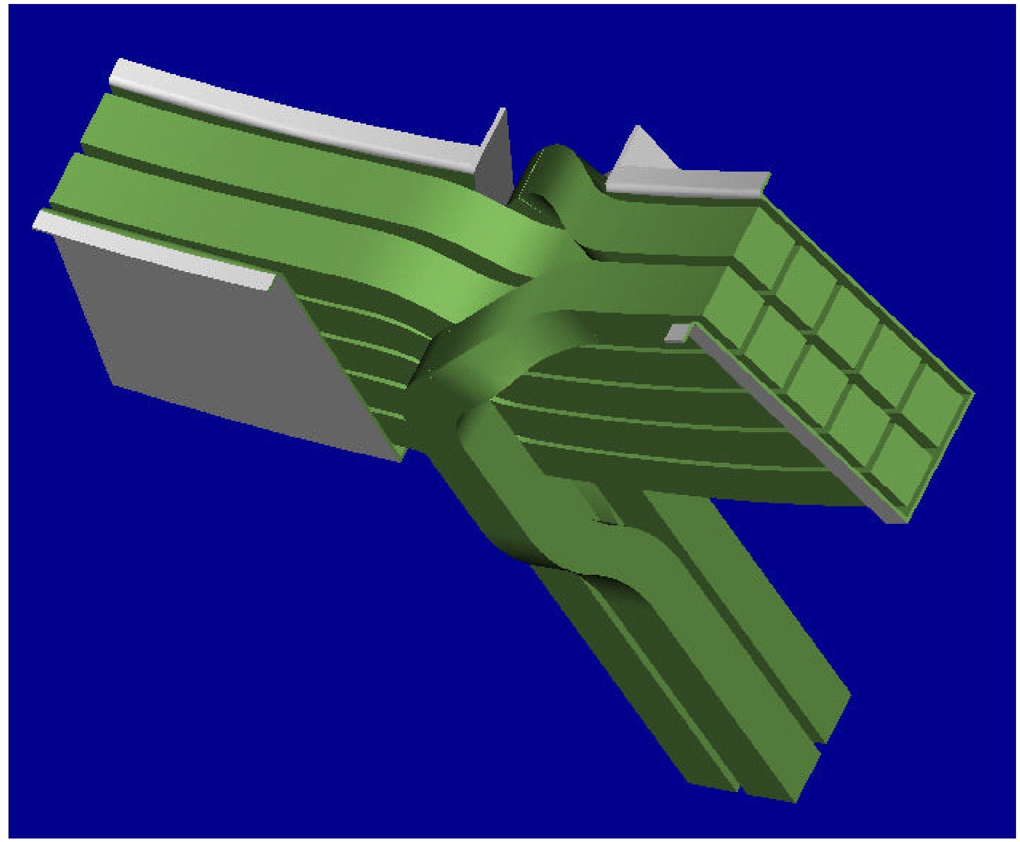
• Two pancakes wound from bottom of trough in opposite directions

• Ends are routed around winding pack and out beside starting lead

• Four parallel leads, continuous conductor

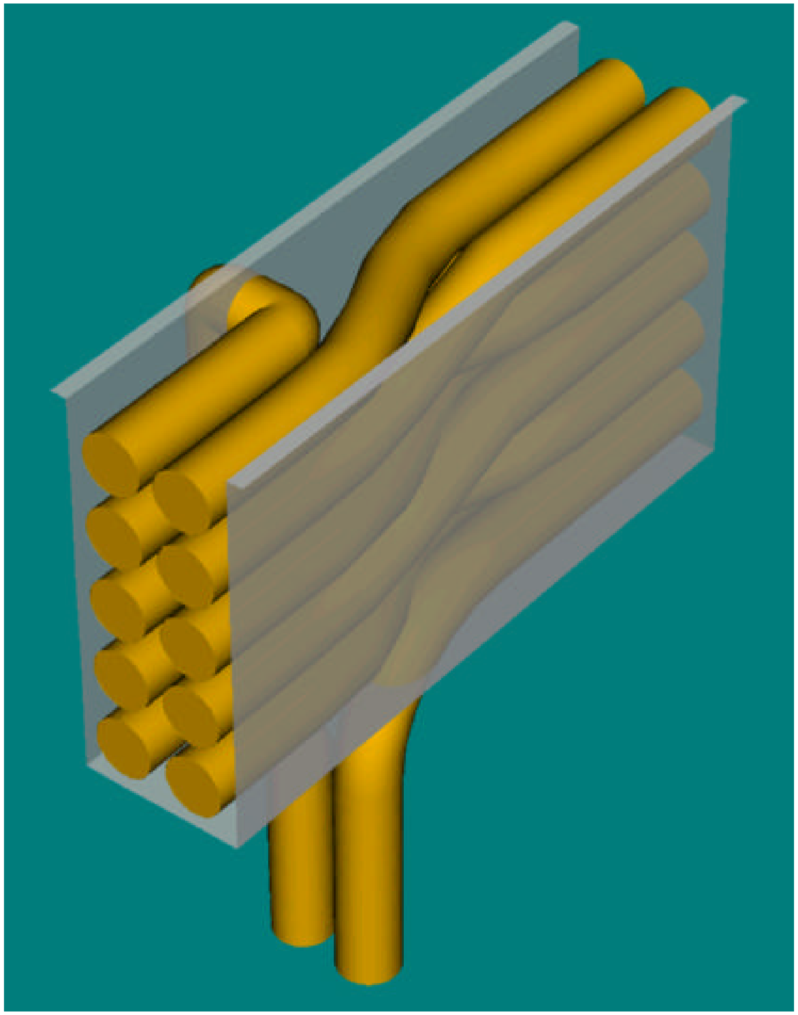






Leads and Crossover Option #4

- Single layer wound from bottom of trough
- Plasma-side end is routed around coil pack and out beside starting lead
- Two parallel leads, continuous conductor



Coil Fabrication Options

Option	Winding	Crossover	Leads	Cooling	Insulation	Structure
1	Pancake	Block at plasma side	Two in parallel	Solid Tube	Glass/epoxy throughout	Thin can / radial ribs
2	Pancake	Block at plasma side	Two in parallel	Spring Tube	Glass/epoxy between turns	Thick can / radial ribs
3	Pancake	Block at plasma side	Two in parallel	No Tube	Glass/epoxy between turns	Thick can / radial ribs
4	Layer	Join to buswork	Coaxial	Solid Tube	Glass/epoxy throughout	Thin can / radial ribs
5	Layer	Join to buswork	Coaxial	Spring Tube	Glass/epoxy between turns	Thick can / radial ribs
6	Layer	Join to buswork	Coaxial	No Tube	Glass/epoxy between turns	Thick can / radial ribs
7	Pancake	Continuous conductor	Four in parallel	Solid Tube	Glass/epoxy throughout	Thin can / radial ribs
8	Pancake	Continuous conductor	Four in parallel	Spring Tube	Glass/epoxy between turns	Thick can / radial ribs
9	Pancake	Continuous conductor	Four in parallel	No Tube	Glass/epoxy between turns	Thick can / radial ribs
10	Layer	Continuous conductor	Two in parallel	Solid Tube	Glass/epoxy throughout	Thin can / radial ribs
11	Layer	Continuous conductor	Two in parallel	Spring Tube	Glass/epoxy between turns	Thick can / radial ribs
12	Layer	Continuous conductor	Two in parallel	No Tube	Glass/epoxy between turns	Thick can / radial ribs

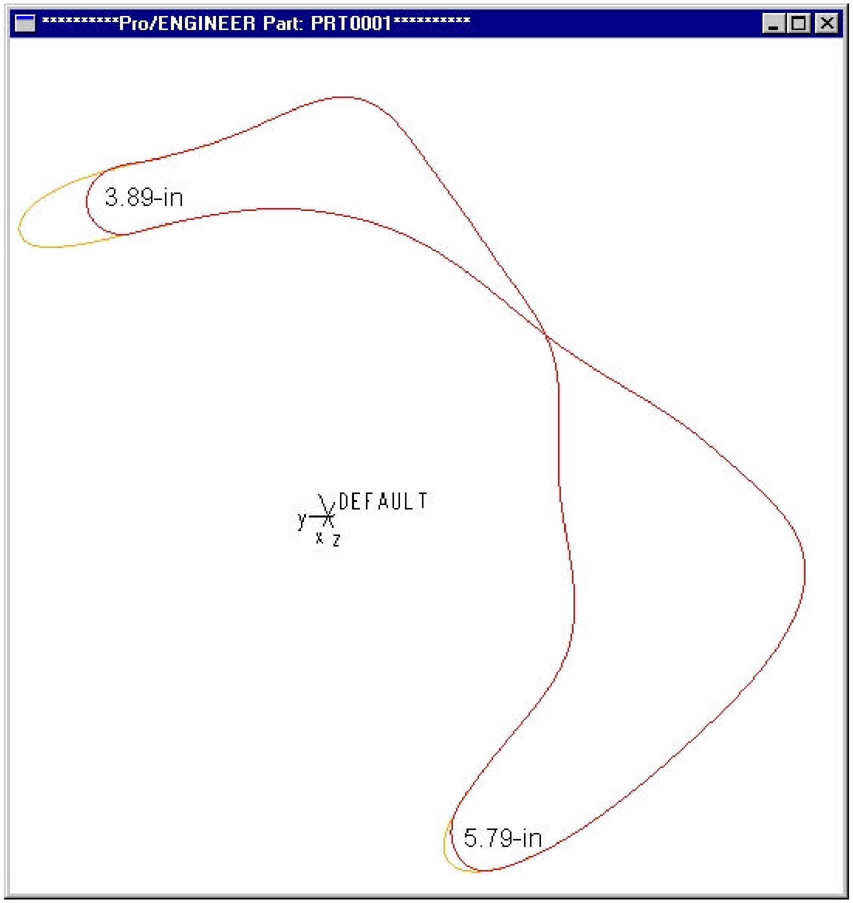
Non-Axisymmetric Coil Issues

- Coil Winding Center Geometry
- Conductor Design
- Current Density / Pulse Length
- Location of Leads / Field Error
- Coil Support / Can Thickness
- Thermal Stress

Issue: Coil Winding Center Geometry

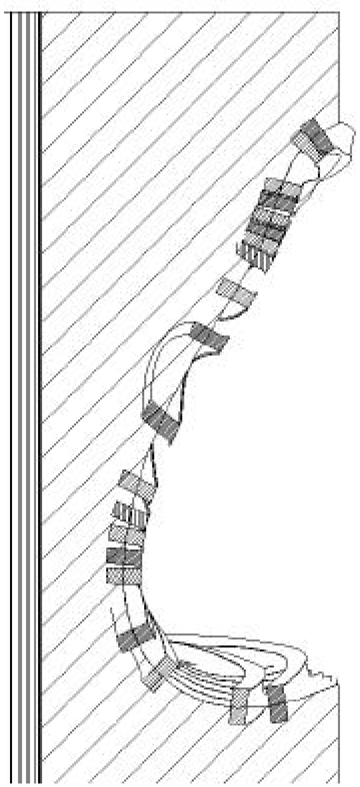
- Larger saddle coils may require change of coil path to increase radius of curvature

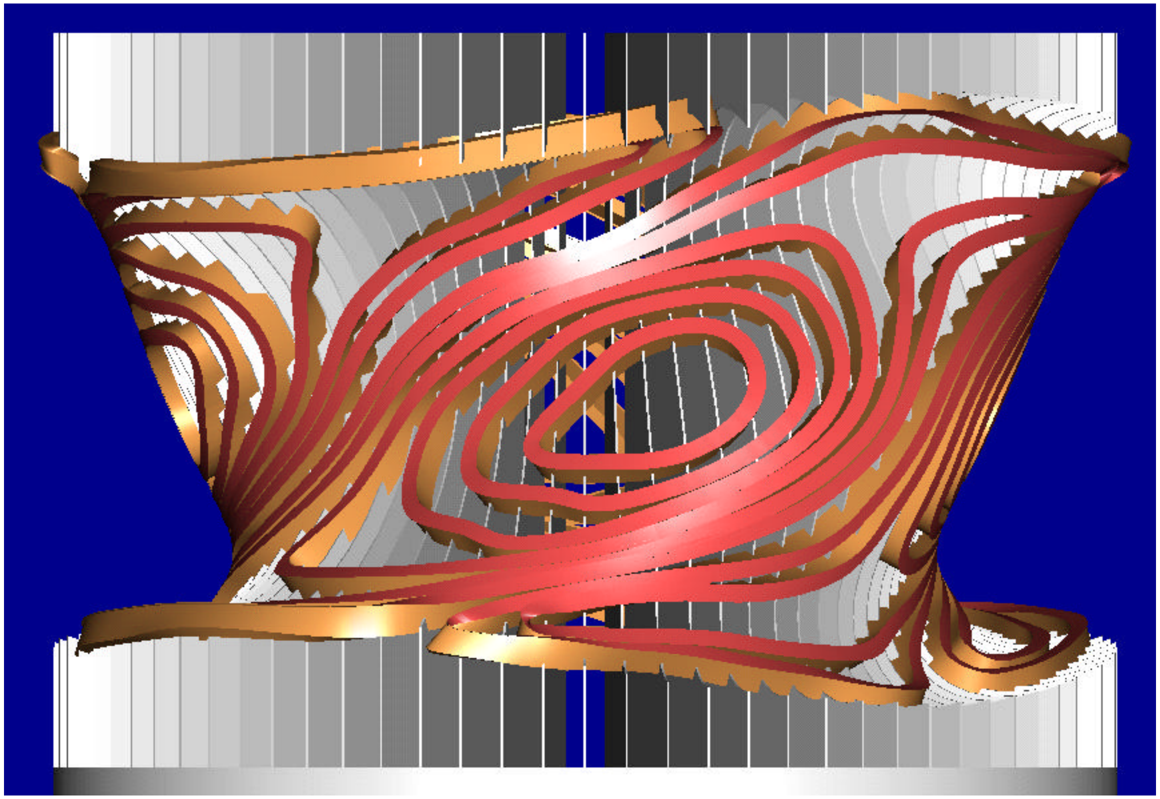
- Can be accomplished graphically using PATRAN and Pro/ENGINEER



Issue: Coil Winding Center Geometry

- Finite cross-section causes interference
- No room for support ribs in places
- Include coil spacing considerations in NESCOIL





Issue: Conductor Design

It may be difficult to wind conductor with solid tube

Option: Spring tube or braided cable

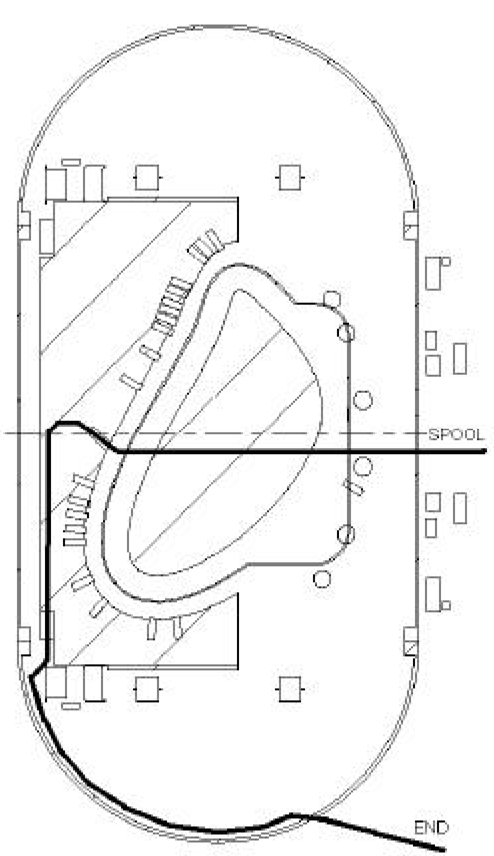
Two companies have expressed interest:
- Nu-Core
- Electro-Max

No problem with small cable size

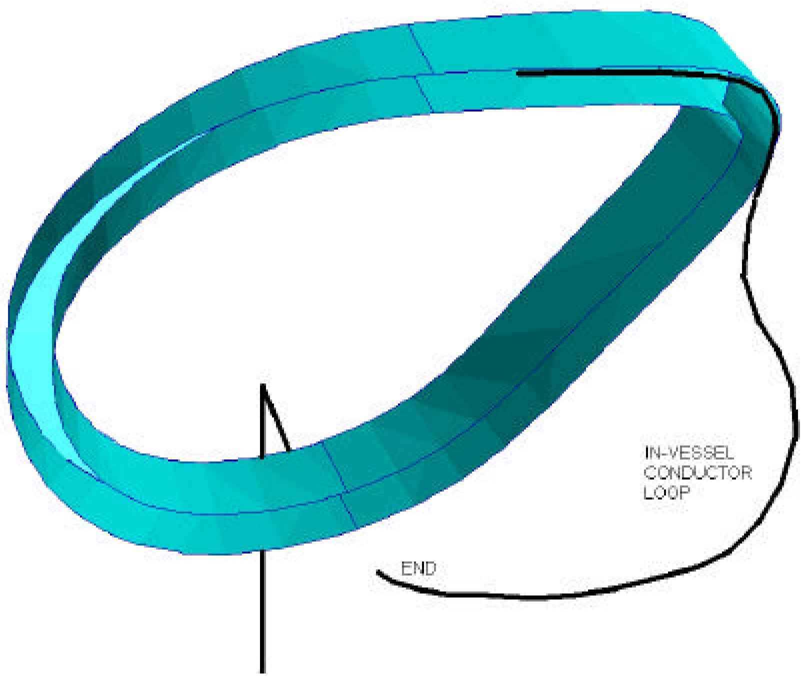
Issues appear to be
- Net copper current density
- Water jacket material and thickness
- Square vs round cross-section
- Terminations

Issue: Conductor Design

Continuous flexible conductor presents winding challenges



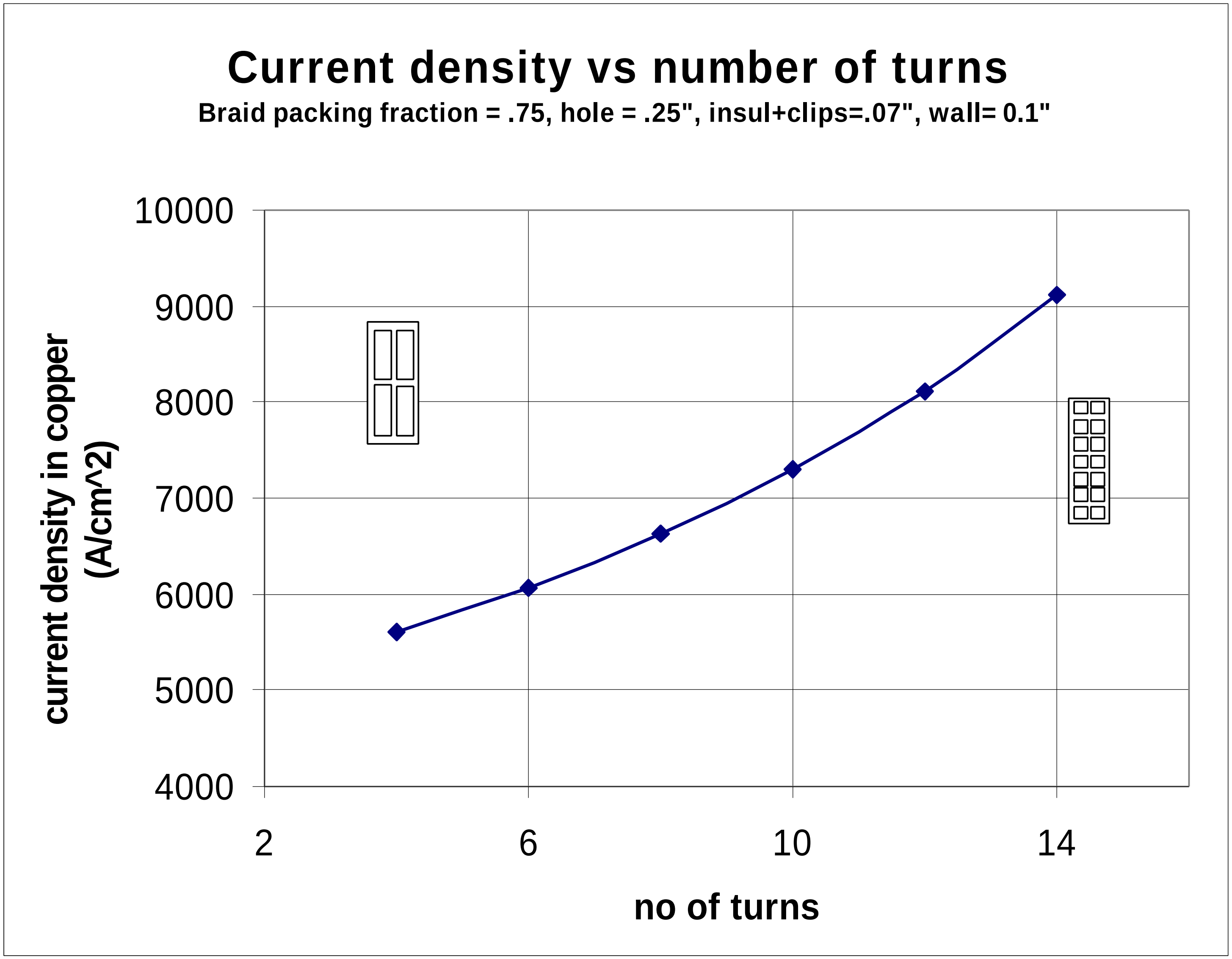
Start

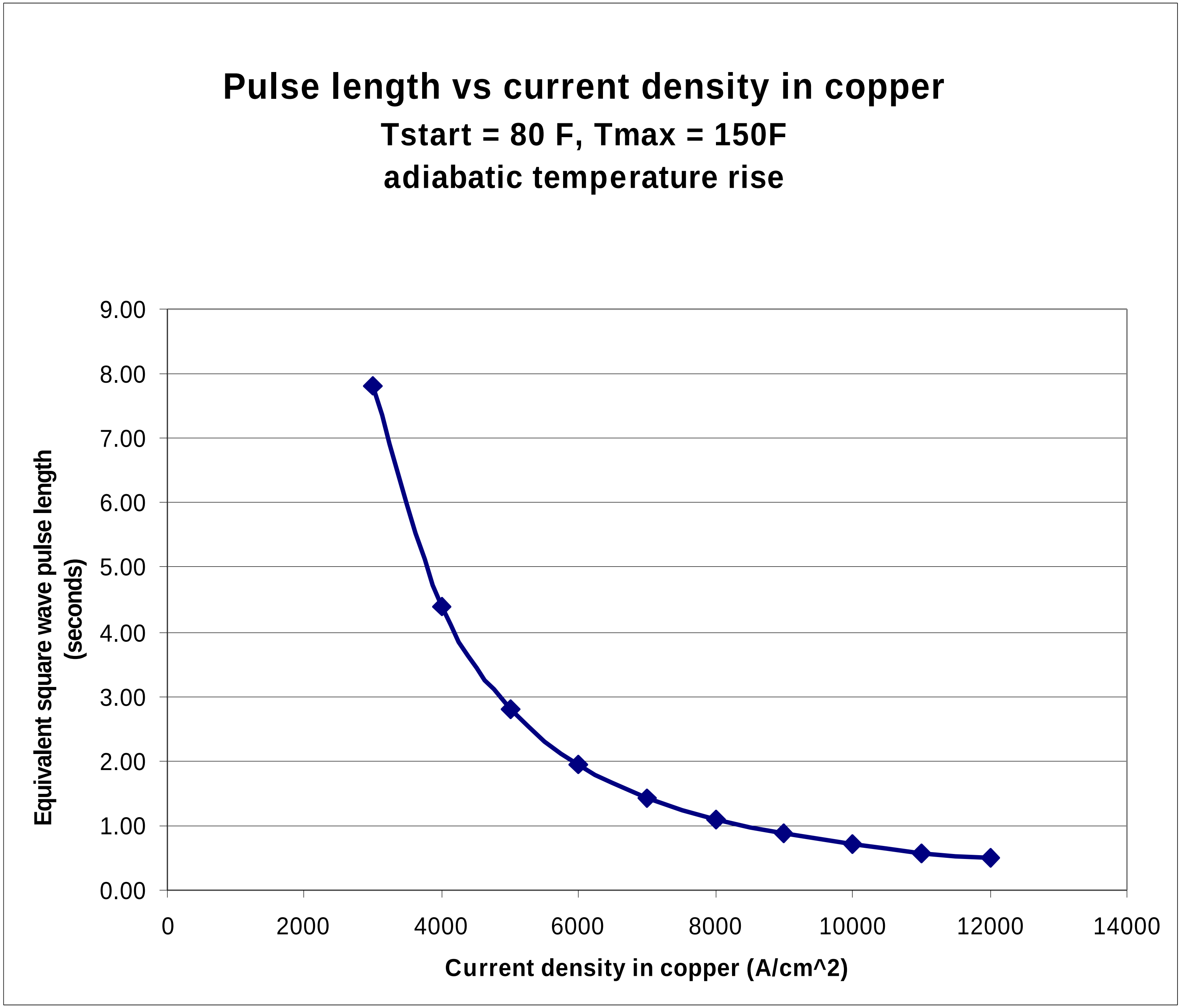


End

Issue: Current Density and Pulse Length

- Coil geometry pushes design to higher current density
  - -Winding centers can be closer to plasma surface
  - Adjacent windings can be closer to each other
- Current density determines pulse length for adiabababatic heating
- Current density is a function of number of turns, packing fraction in braided conductor
- Baseline design
  - Number of turns = 10
  - Current density in copper **~7 kA/cm^2**
  - Pulse length for 80 to 150 F rise = **1.4 seconds** (equivalent square wave)

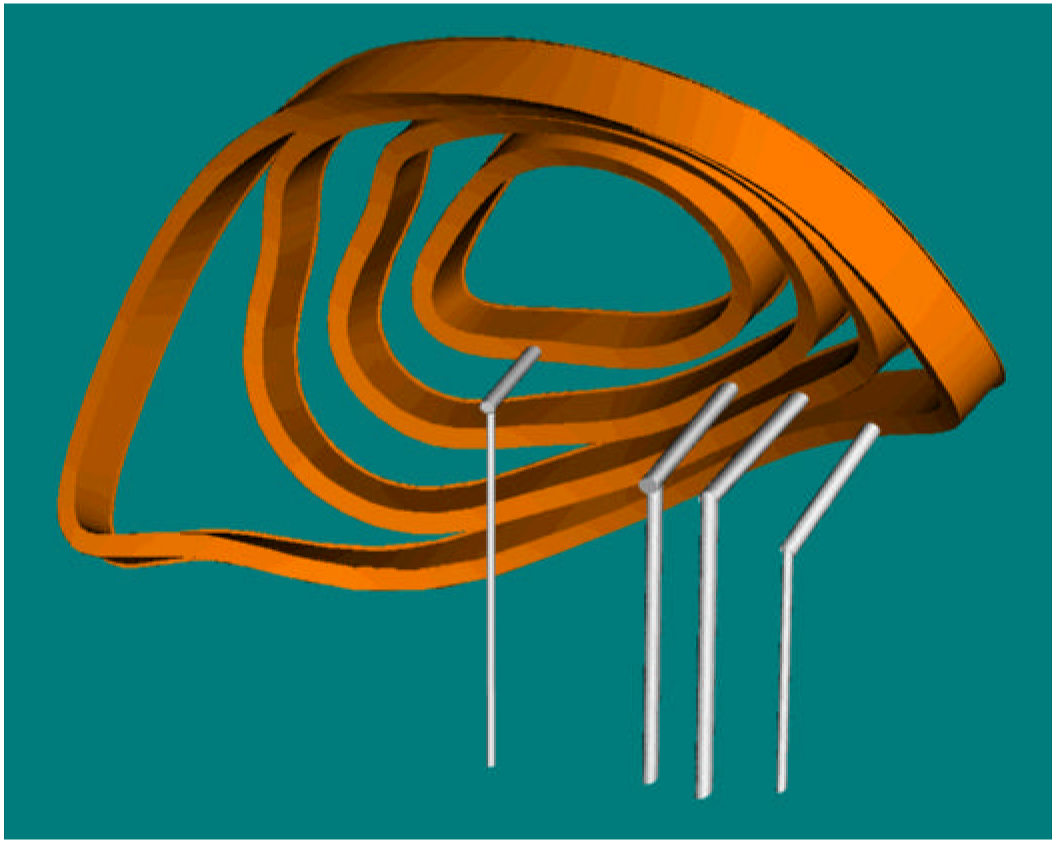

Current density vs number of turns
Braid packing fraction = .75, hole = .25", insul+clips=.07", wall= 0.1"
current density in copper (A/cm^2)
10000
9000
8000
7000
6000
5000
4000
2
6
10
14
no of turns


Pulse length vs current density in copper
Tstart = 80 F, Tmax = 150F
adiabatic temperature rise
Equivalent square wave pulse length (seconds)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
2000
4000
6000
8000
10000
12000
14000
Current density in copper (A/cm^2)

Issue: Location of Leads and Field Errors

Position of leads constrained by:

- Coil Geometry (straight sections)
- Space for winding pack bulge
- Other coil leads (clocking)



Options:

- Develop lead schematics early in design for space allocation

- Calculate field errors

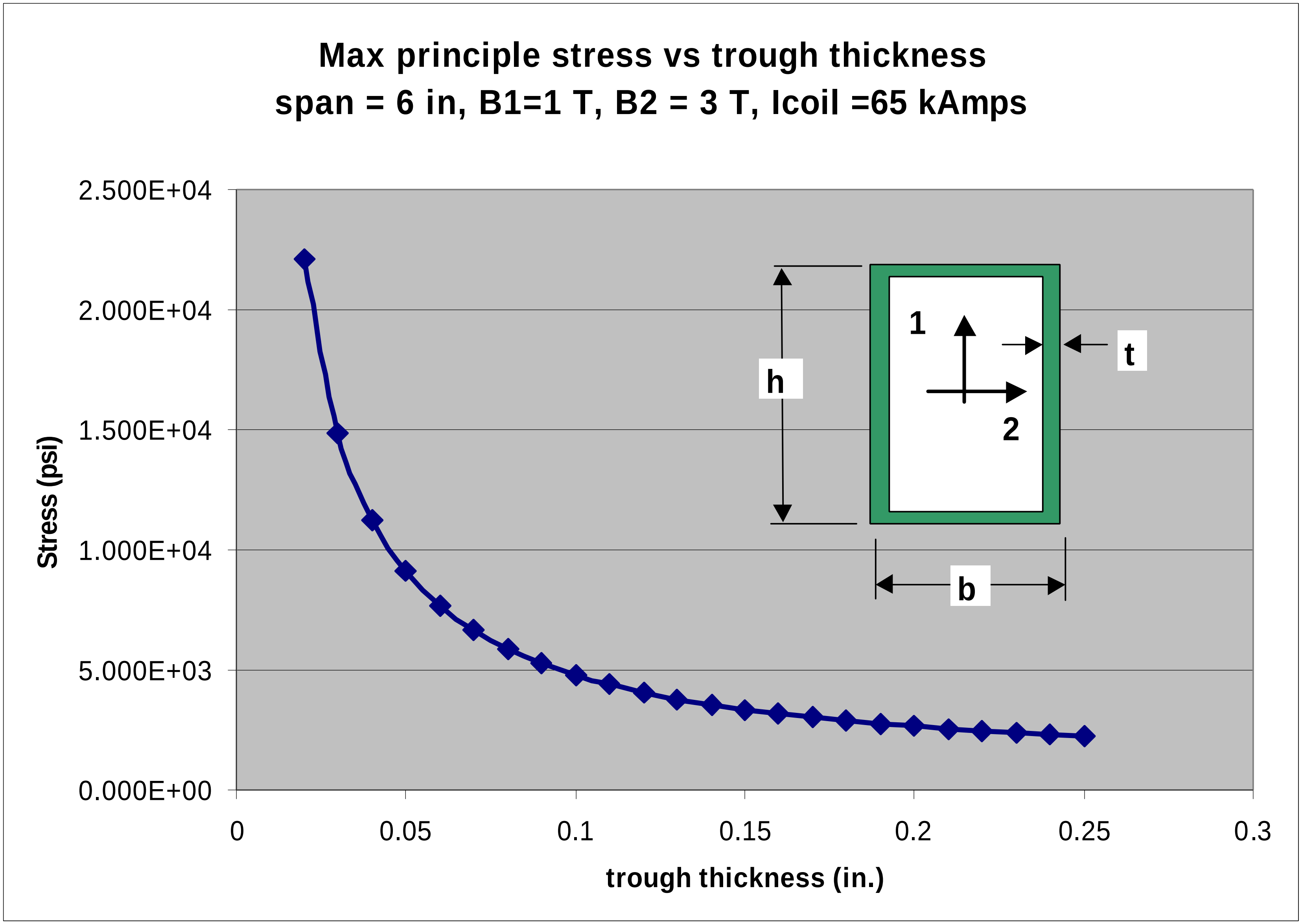
ISSUE: Is coil trough too stiff to fabricate in place?

Coil trough must be on the order of 0.1 inches thick, based on simple calculations, which is too thick to form in place, (we think)

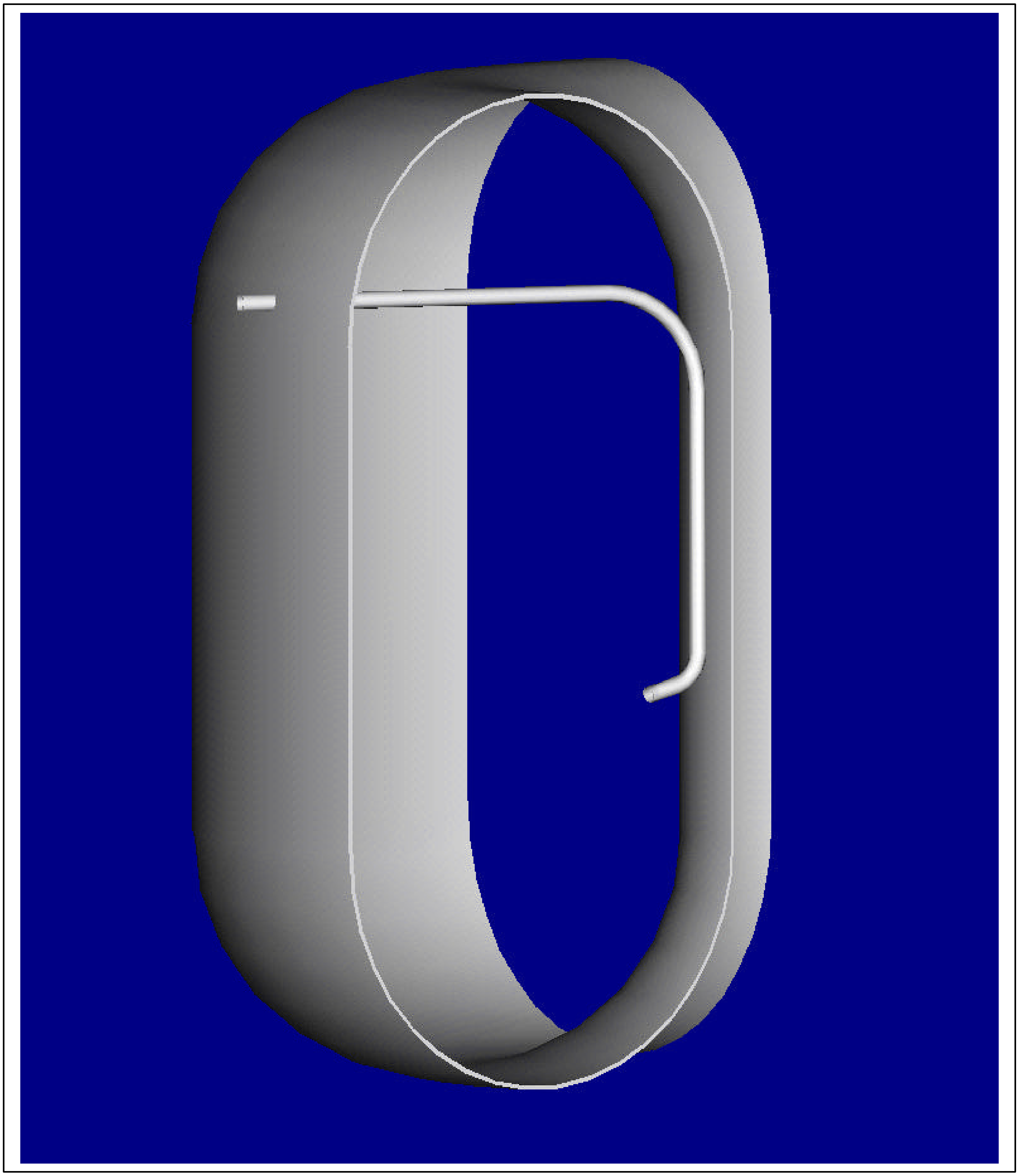
Options:

1. ***Weld trough inside vessel*** (Preform trough bottom, sides and top outside, weld together inside using slots in radial ribs as guides)
   - Maximizes welding inside vessel, all operations is series
   - Double tooling (forming fixtures and structural ribs)

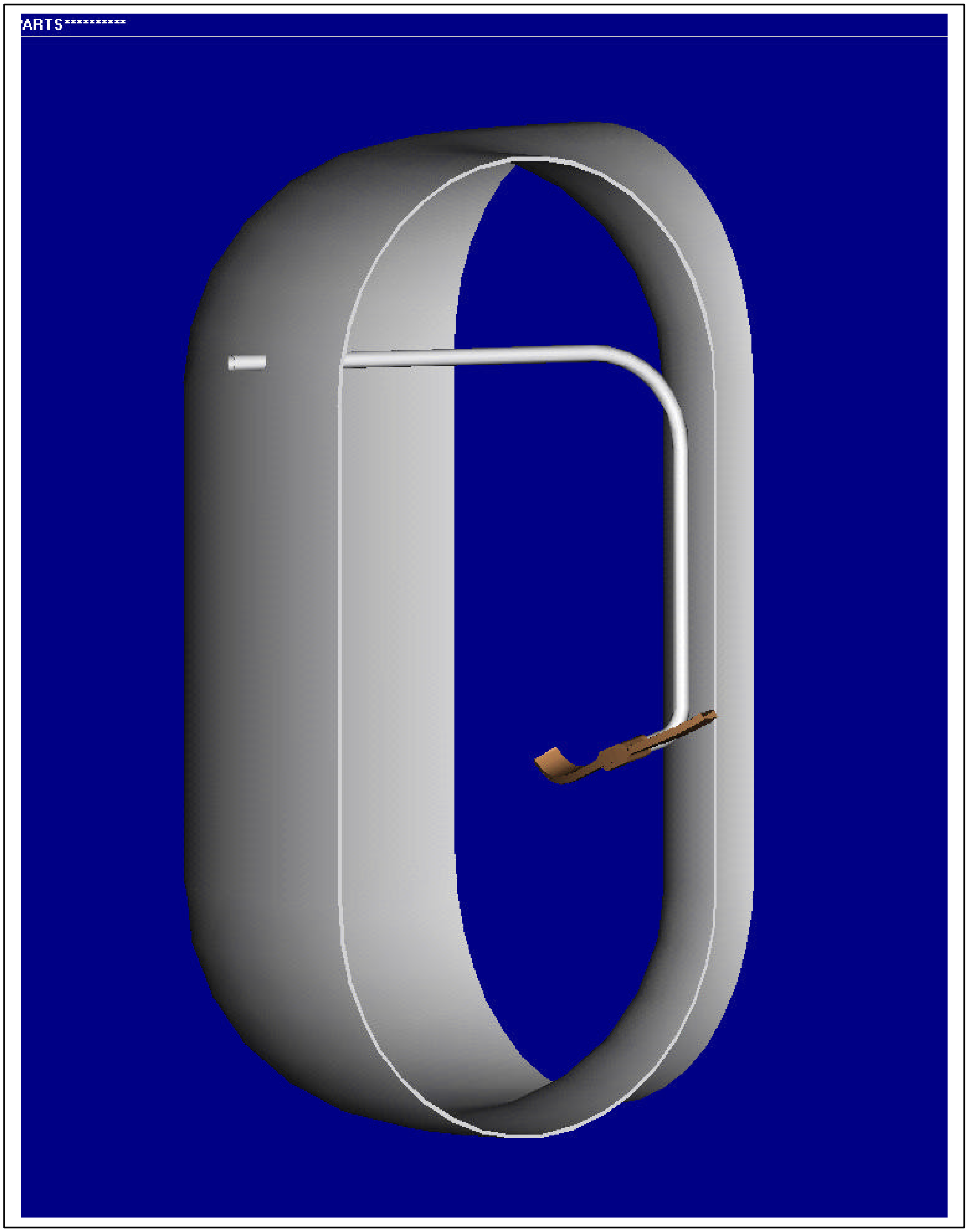
2. ***Weld trough sections outside vessel*** (Preform trough bottom, sides and top outside, and weld bottom and sides together outside. Eliminate slots in radial ribs, substitute pins or clips to locate and attach trough to ribs)
   - Less welding inside vessel, more operations in parallel
   - Still requires double tooling, but ribs are more simple
   - Coil-to-coil spacing is less critical


Max principle stress vs trough thickness
span = 6 in, B1=1 T, B2 = 3 T, Icoil =65 kAmps
Stress (psi)
2.500E+04
2.000E+04
1.500E+04
1.000E+04
5.000E+03
0.000E+00
0
0.05
0.1
0.15
0.2
0.25
0.3
trough thickness (in.)
h
1
2
t
b

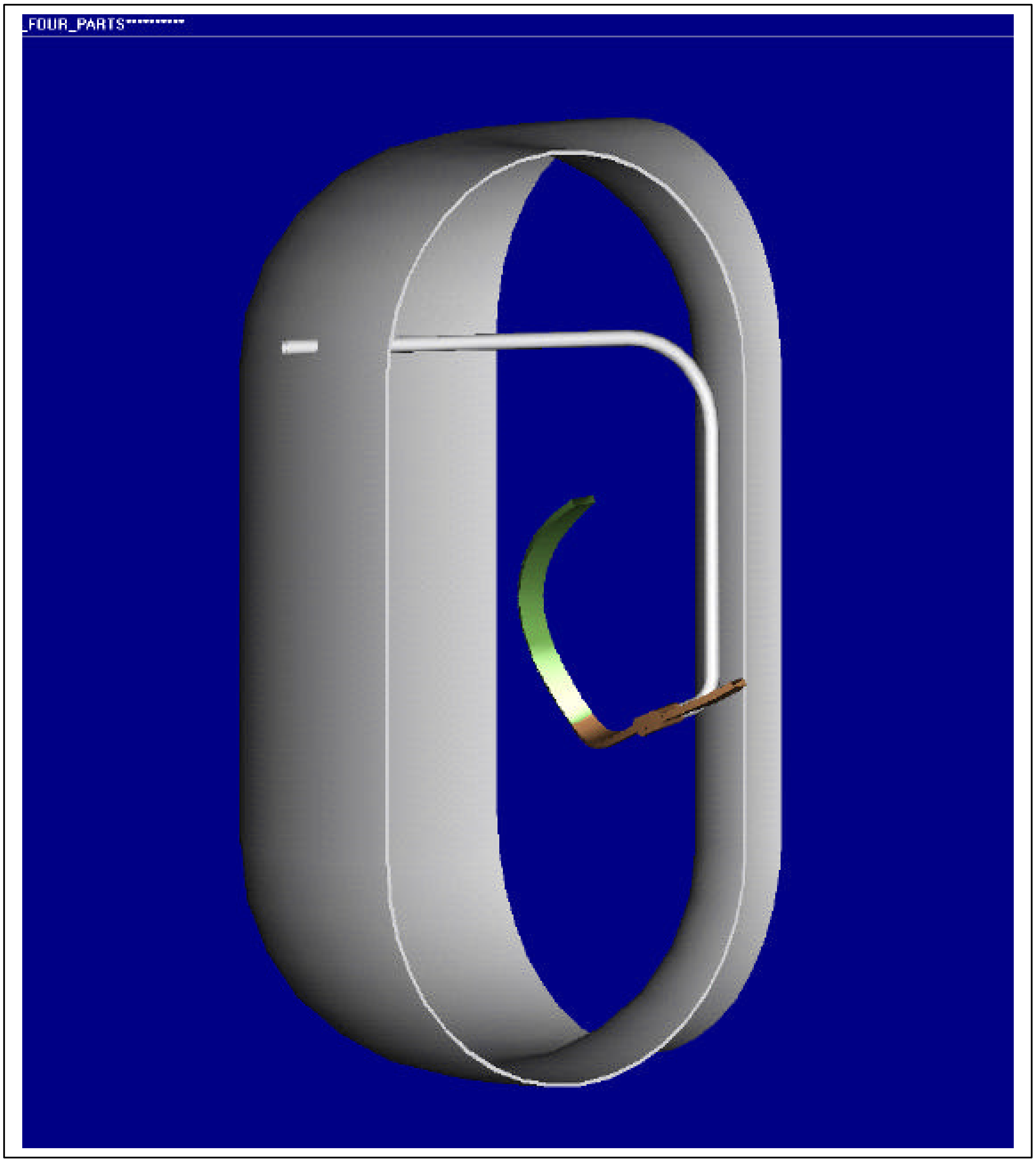
Install Conduit



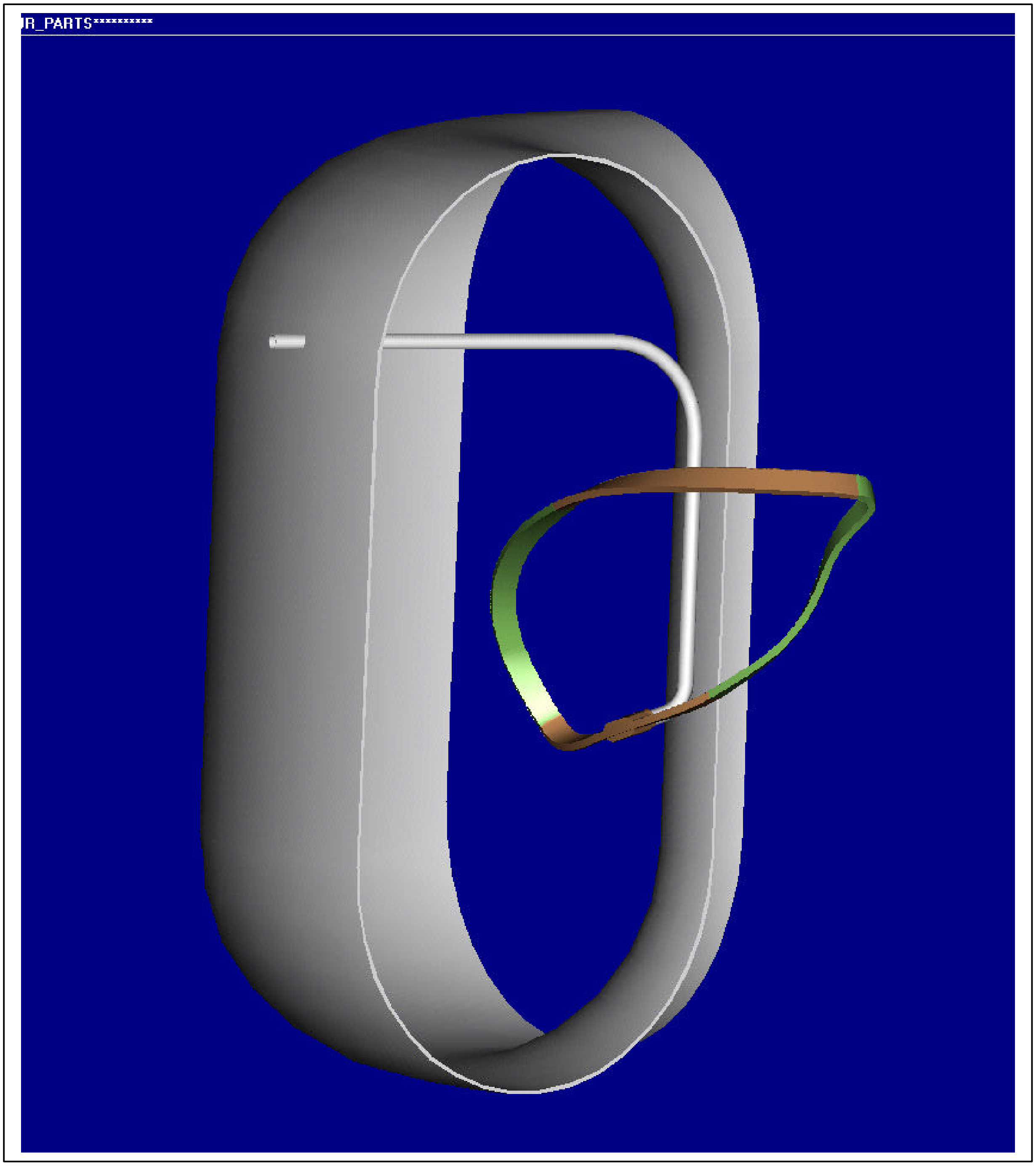
Add first section of coil trough



Add second section of coil trough



Add third and fourth sections of coil trough



Issue: Thermal Stress in Copper

- High Current Density results in rapid temperature rise in copper

- Structure temperature will lag copper

Option 1 ***Wind conductor with closed cell sponge on outer perimeter to allow expansion***

- Conductor will move every shot
- Sponge thickness is around 0.04 inches for larger coils

Option 2 ***Use standard water cooled ("wet") braided cable***

- Conductor consists of braided cable in conduit
- Conduit contains coolant, or coolant is contained in separate tube
- No reliable connections can be made inside machine, leads must be continuation of wound conductor to outside of vacuum vessel
- -Conductor is relatively free to expand inside conduit

Design Tools Development

- Developed code to calculate cross-section based on winding filament and plasma surface coefficient data

- Developed coil leads geometry using CAD (tedious)

- Procedure for generating multi-filament geometry for physics

- Developed surface models and flat developments for mock-up