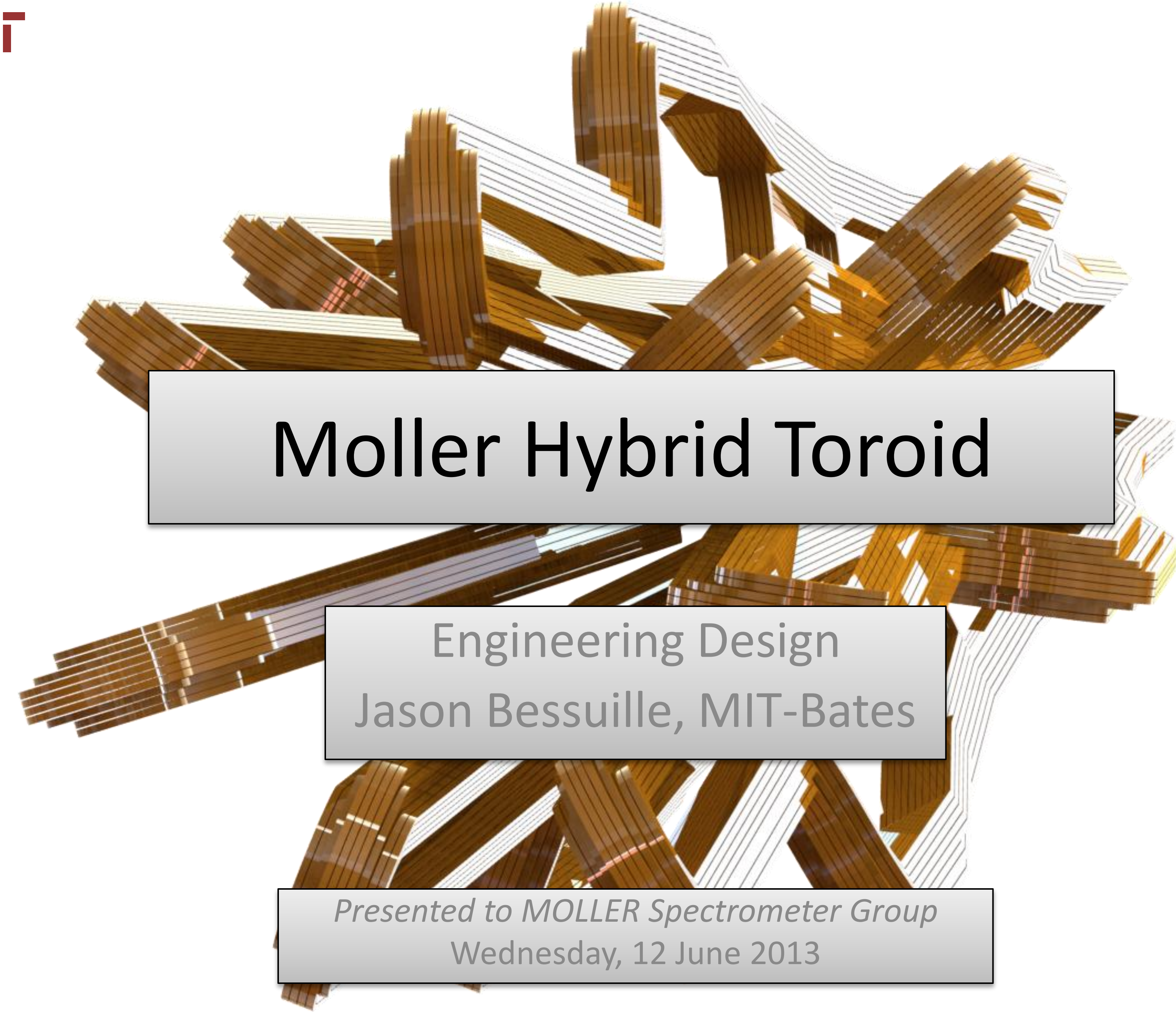


Moller Hybrid Toroid

Engineering Design

Jason Bessuille, MIT-Bates

Presented to MOLLER Spectrometer Group

Wednesday, 12 June 2013

Introduction

- MIT Bates Research and Engineering Center has been working with Krishna and Juliette on an engineering study of the MOLLER hybrid toroid spectrometer.
- Our lab has a great deal of experience with accelerator systems, including warm magnets and spectrometers
  - Designed and built toroids for BLAST (MIT-Bates) and QWEAK (JLAB/Hall C)
  - Hall C Compton Polarimeter
- People currently involved in this project at Bates:
  - Mechanical Engineers
    - Jim Kelsey
    - Ernie Ihloff
    - Jason Bessuille
  - Mechanical Designers
    - Cathy Moran
    - Chris Vidal

The BLAST spectrometer during disassembly

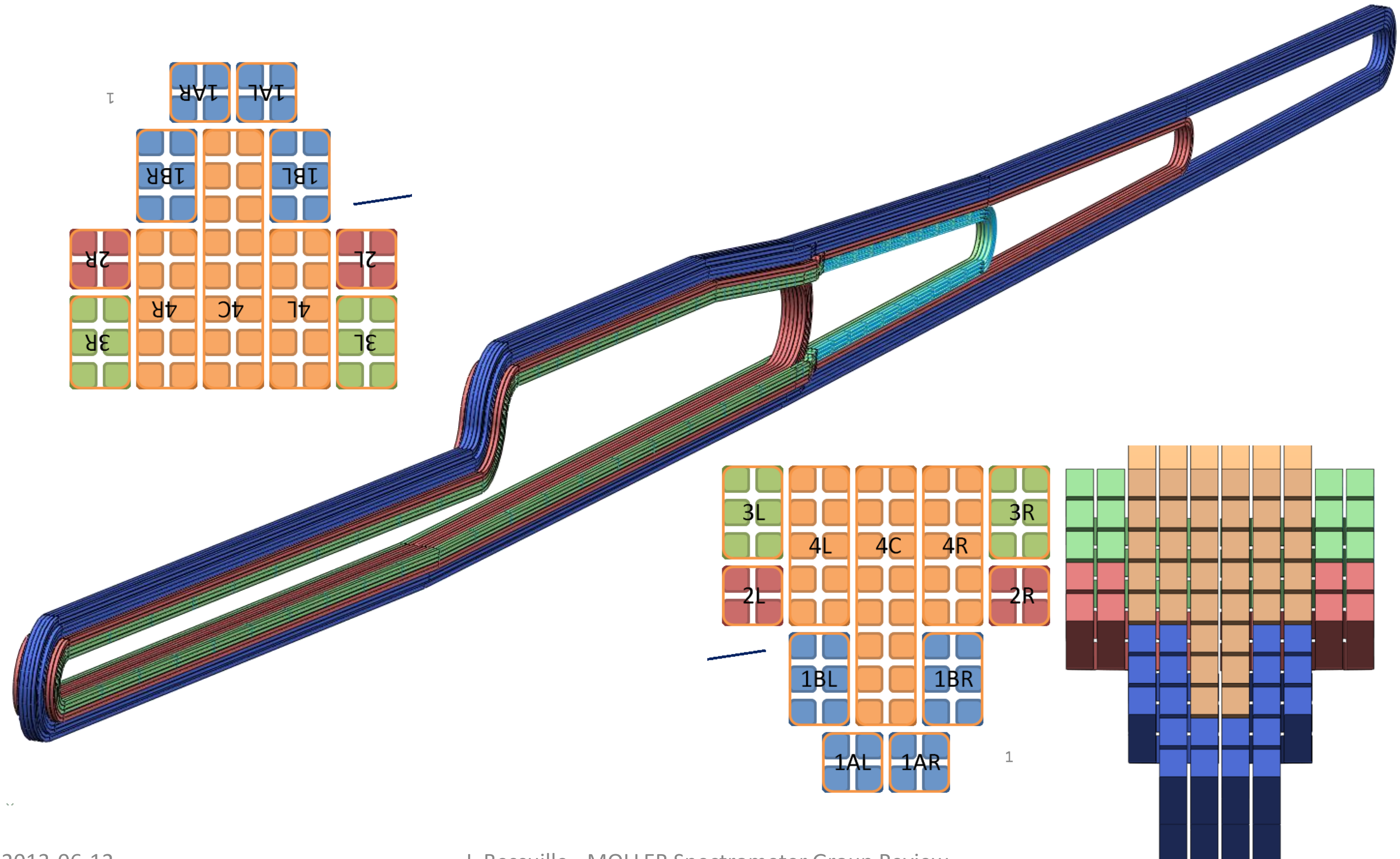
The QWeak spectrometer during testing

Overview

- Coil Models
- Thermal Calculations
- Assembly Configuration
  - In-air vs. in-vacuum designs
  - Support structures and vacuum enclosures
- Pressing Issues / Questions

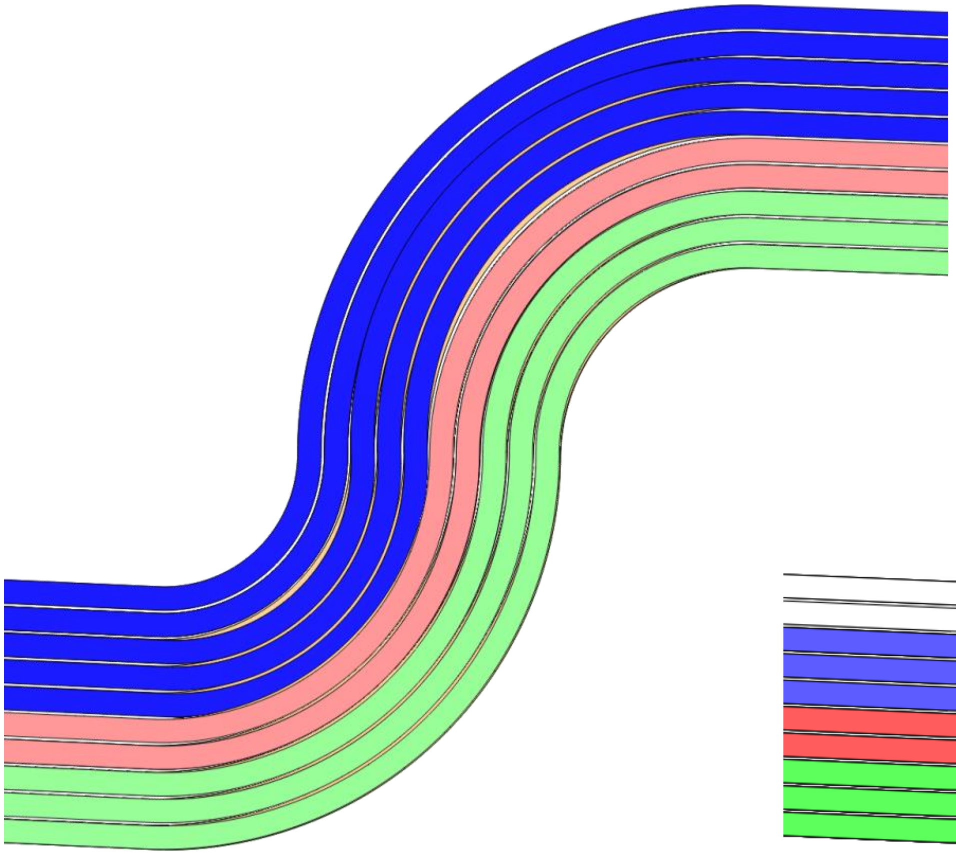
Coil Models

Imported from STEP into SWX, 18 July 2012

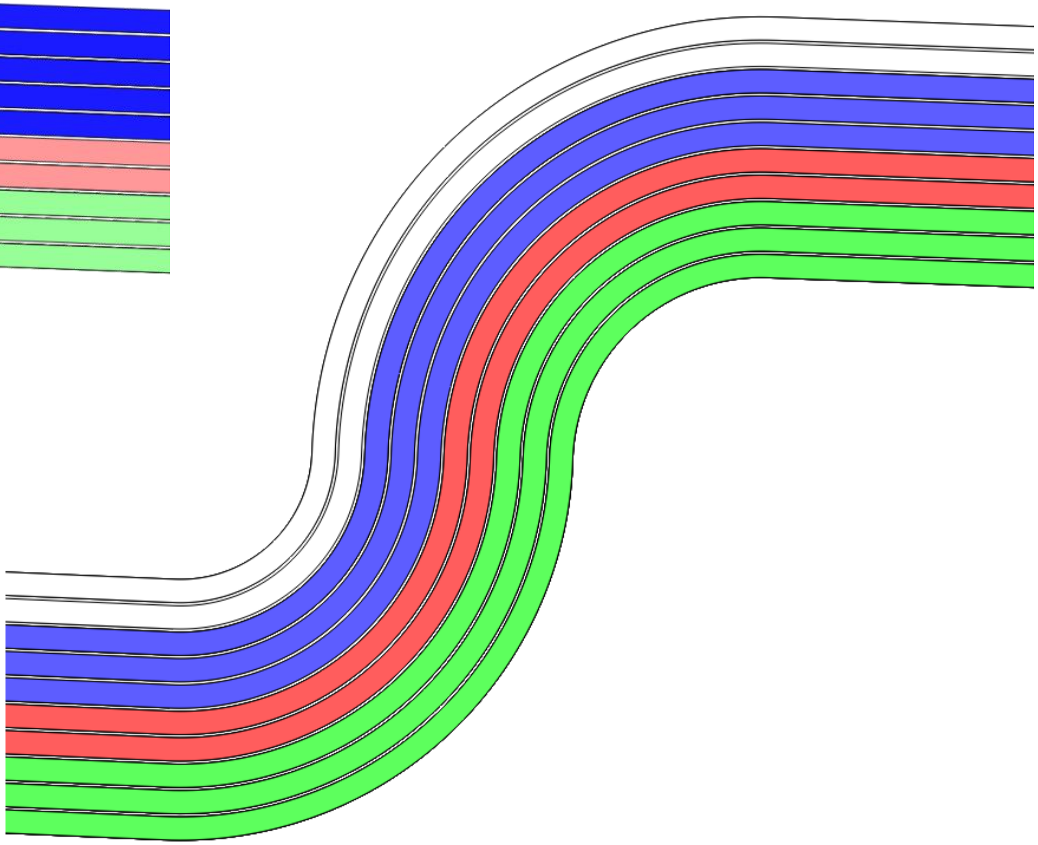


Solidworks Part Model -16 oct 2012

- I've created a new model as a multi-body part. It was done from scratch using Solidworks. Most of the dimensions are driven off a single sketch, the inner edge of the 1A sweep path.
- This results in a smaller file with more uniform geometry
  - Note below how all bend radii are now concentric.
- The current plan is to use this Solidworks model with explicitly defined dimensions that can be updated easily if the TOSCA models change



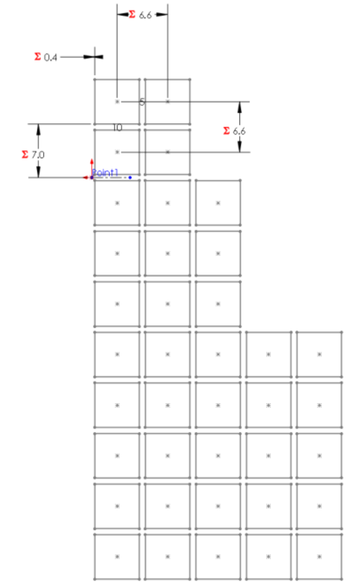
Imported TOSCA Geometry



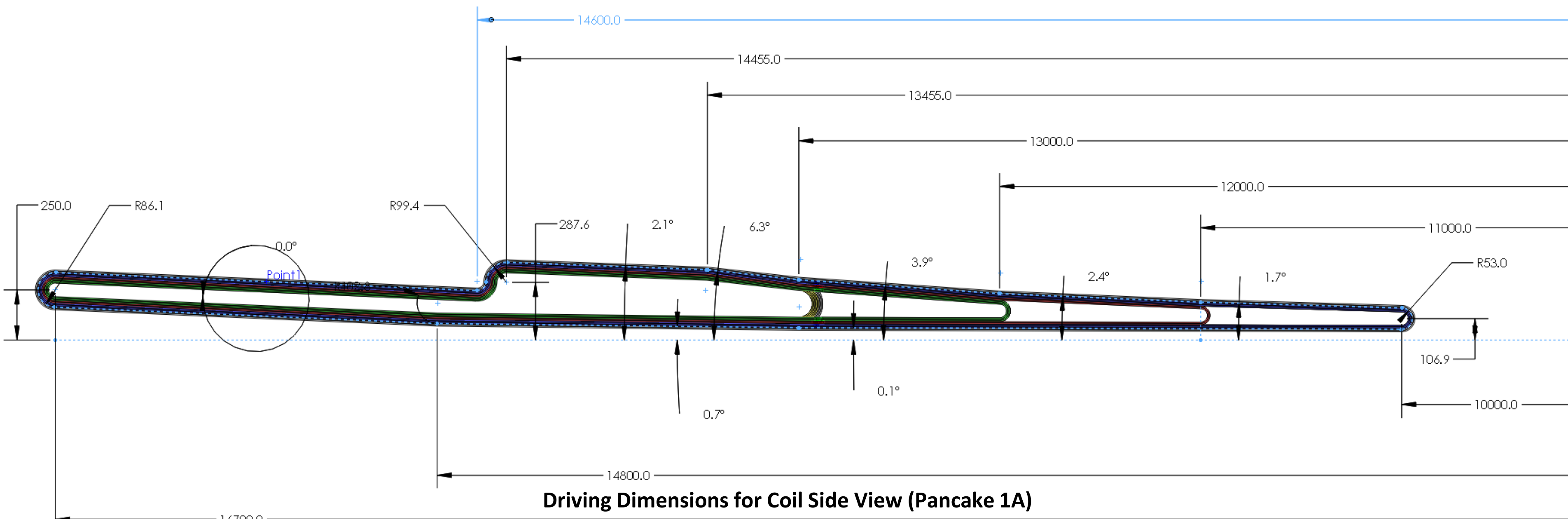
Native SW Geometry

Solidworks Part Model -16 oct 2012

- The coil package is modeled as a multi-body part: *Coil Assy_NativeSW.SLDPRT*
- The entire model is driven by 3 main features:
  - A sketch of the side-view of the inner edge of pancake 1A
  - A sketch of the conductor cross sections
  - A pair of parameters describing the square conductor side length and insulation thickness
- The remainder of the sweep paths are related to the 1A sketch by the conductor parameters
- Only the left side is modeled at this stage
- Each pancake consists of a number of solid bodies equal to the number of turns
- These groups of bodies are then saved as individual parts (e.g. *Coil Assy_NativeSW-1A.SLDPRT*) and recombined into an assembly, *Coil_Assy.SLDASM.* Mirrored parts are created at this level.



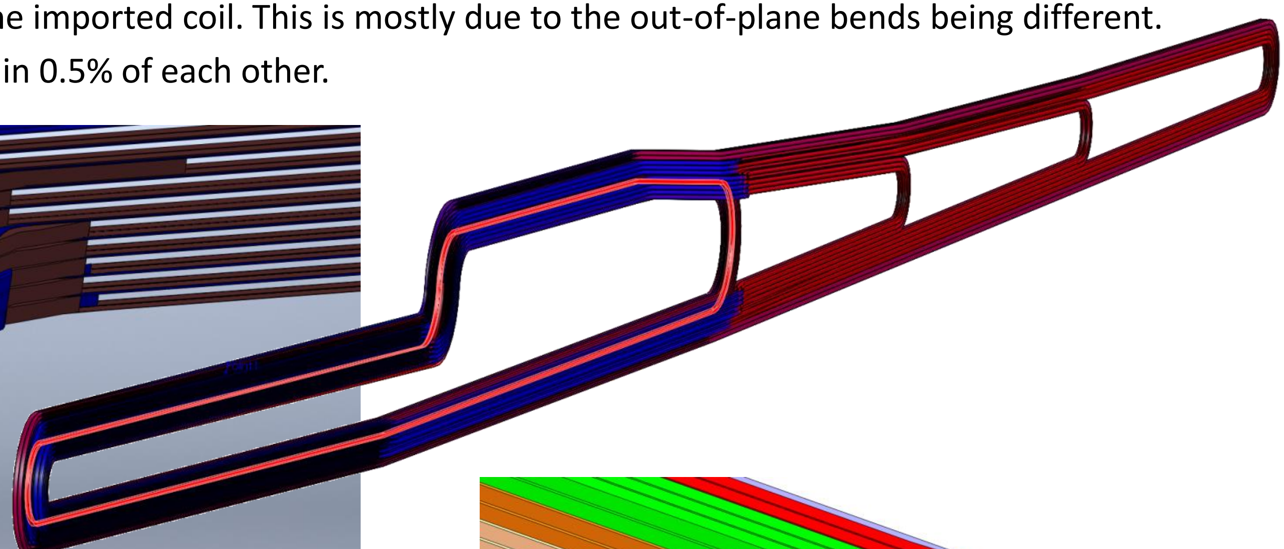
Driving Dimensions for Coil Cross Section

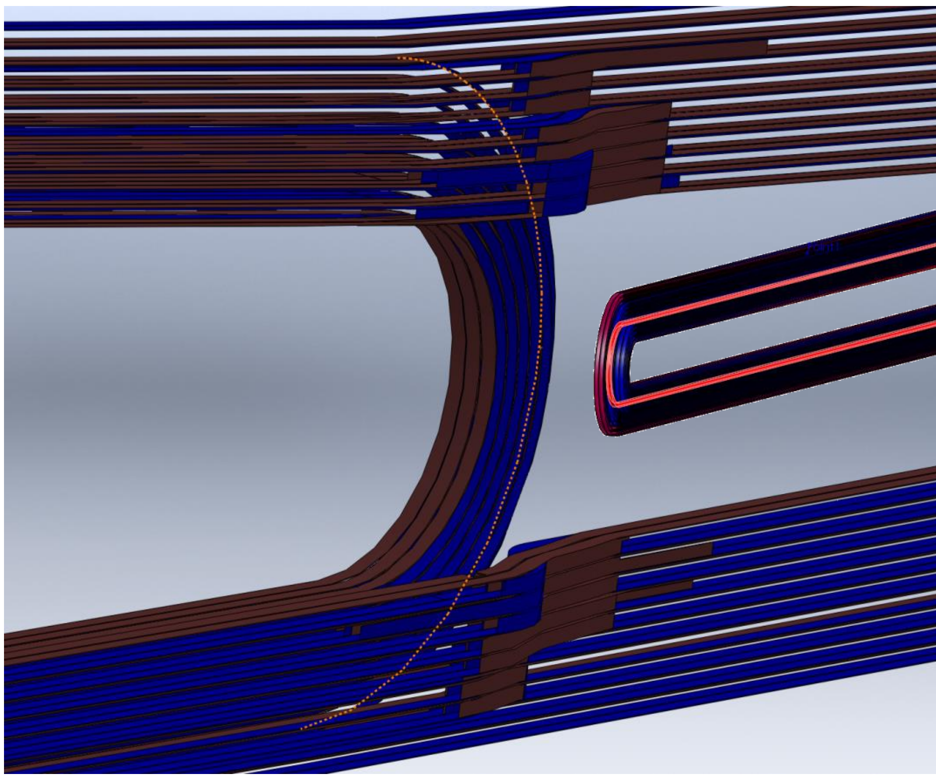


Driving Dimensions for Coil Side View (Pancake 1A)

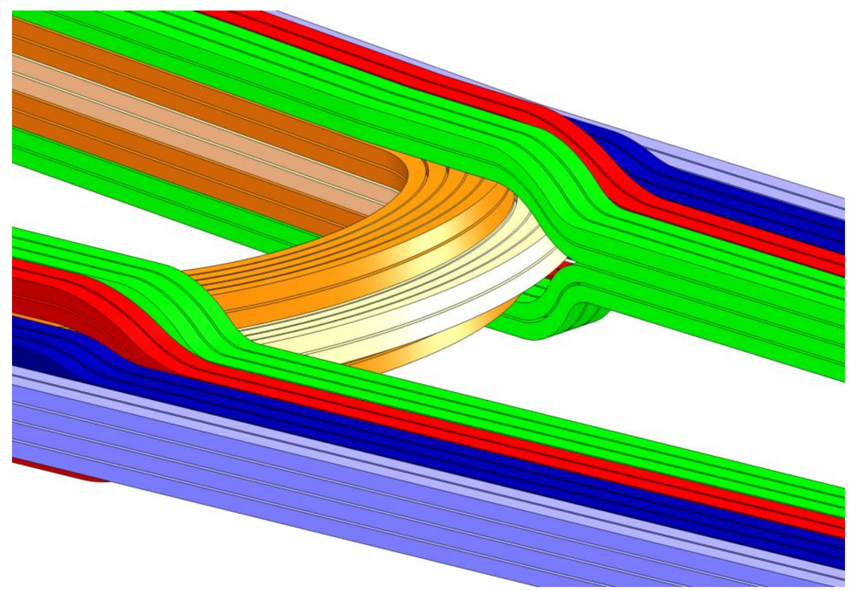
Solidworks Part Model -16 oct 2012

- Comparing the two coils (imported vs. native) has proven to be very difficult. Ideally, I'd like to know what is the proportion of shared volume between the two coils. There are various methods in SWX for doing this, but so far they all come up with errors. I've succeeded with one workaround, calculating the intersection between "Boolean NOT coil volumes") and get a variation of 5.1%. That is, the volume occupied by the Boolean AND of the two coils is 5.1% larger than the volume of just the imported coil. This is mostly due to the out-of-plane bends being different.
- The actual coil volumes are within 0.5% of each other.





Volume comparison of coils. Only the differences are shown.
Blue = native SWX model, brown = imported model
Note: Imported coils have dual s-bends; Native SWX coils are changed to single s-bends

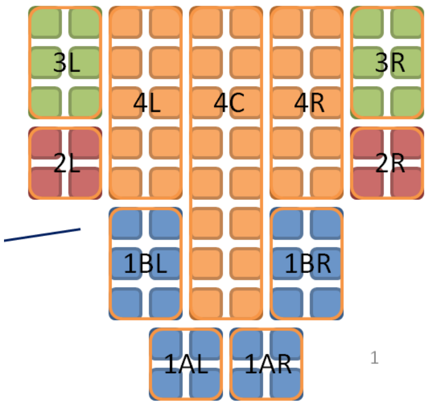


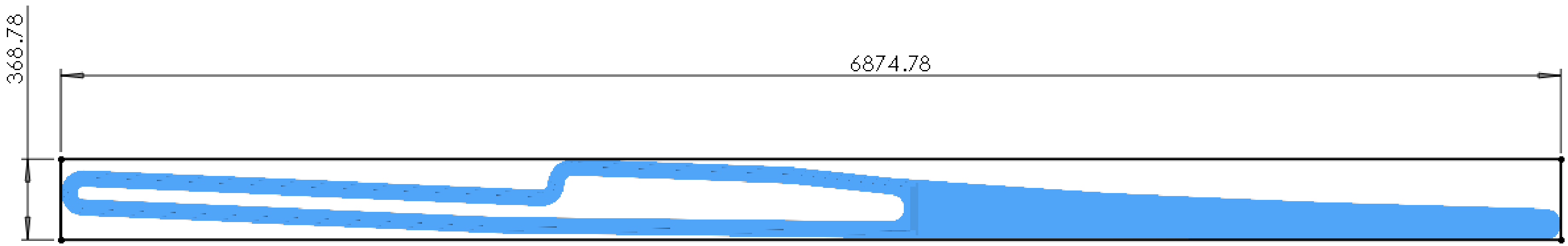
Coil Package with single out-of-plane bends

Cooling

Coil Cooling

- Each coil…
  - Is made up of 11 pancakes (6 different types; left and right are mirror images)
  - Has NI = 76 turns x 384 A
  - Has a total conductor length of 775 m
- The given conductor geometry was 5.8 x 5.8 mm^2, with a circular 3.18 mm cooling passage
- High current density (>1500 A/cm^2) requires that we use water cooling
- This is a very long and thin conductor for a water-cooled magnet.
  - The original design specified a square conductor with a 3.18 mm cooling hole. With an average turn length of 10.2 m, a single cooling loop per turn would have an aspect ratio >3200.
    - This is approximately equivalent to an 80' drinking straw, or a 6" human hair.





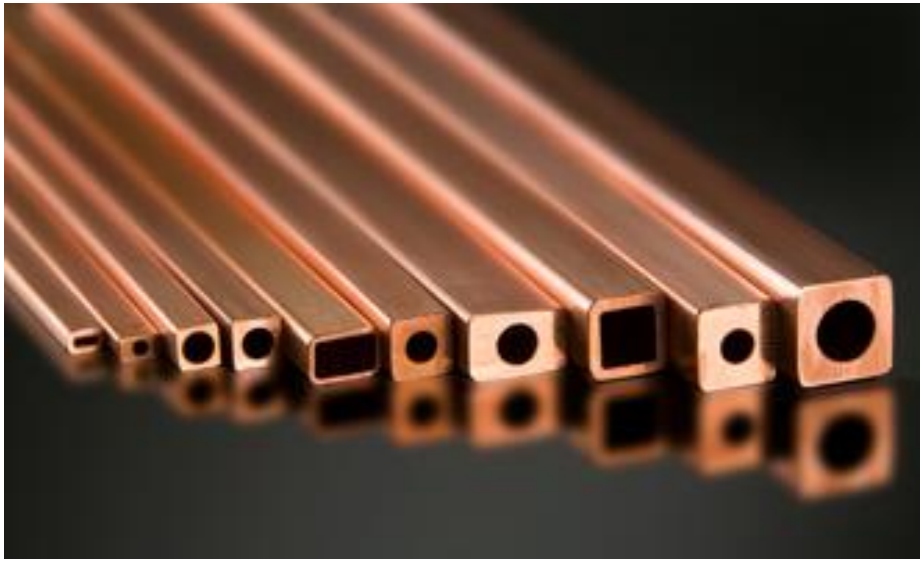
Bounding Box with 5mm encapsulant; dimensions in mm

Coil Cooling

- Assumptions for cooling analysis:
  - Pure water is used as cooling medium
  - Maximum water pressure will be limited to 17 atm (≈250 psi)
  - Inlet temperature 15 C, outlet temperatures from 50 – 80 C are explored
  - Fittings and bends not yet considered in pressure drop calculations

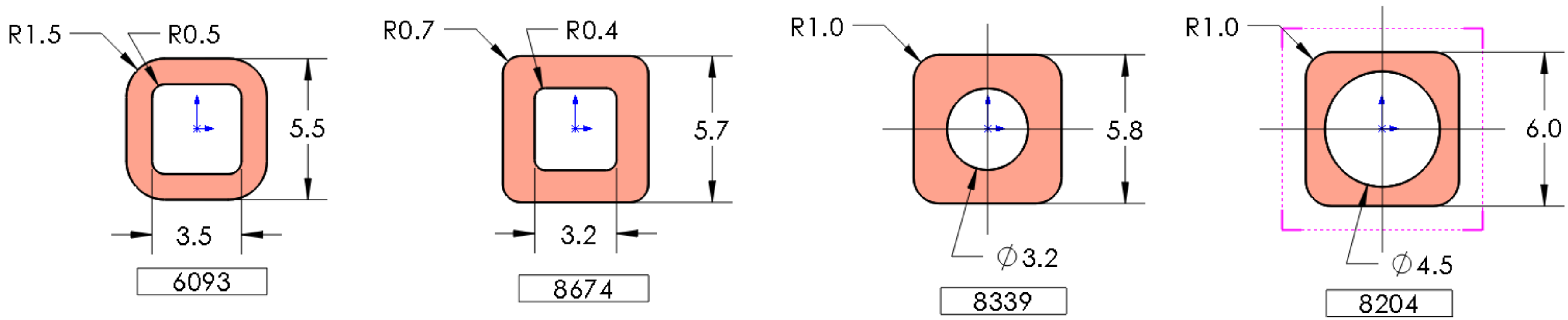
For reference…

140 ^{o}F = 60 ^{o}C
60 ^{o}F ≈ 15 ^{o}C
100 psi ≈ 7 atm
250 psi = 17 atm



Conductors

- Hollow Cu conductors are available in a variety of standard sizes. I'm using data from Luvata; http://www.luvata.com/en/Products--Markets/Products/Hollow-Conductors/

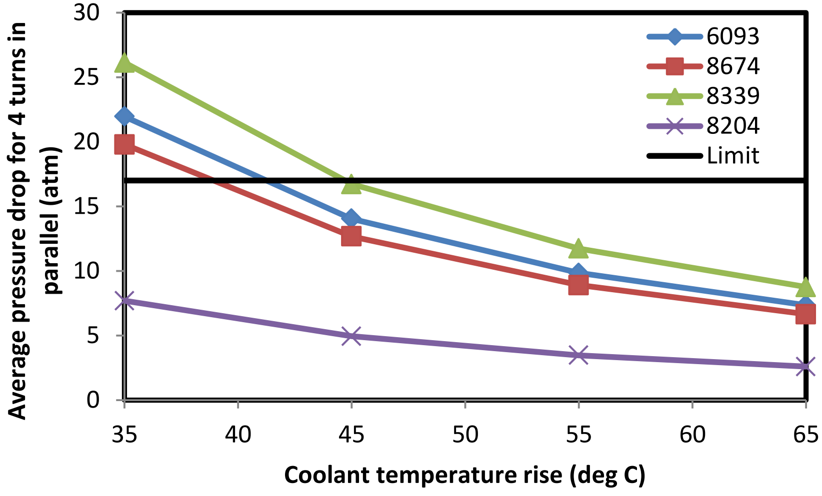


From original TOSCA design

Conductor Style and Resulting Power and Voltage for I=384 A				Flow Properties assuming 4 average-length turns / cooling circuit; 45 deg C deltaT	
Part #	Current Density [A/cm^2]	Toroid Voltage Drop [V]	Toroid power [kW]	Velocity (4 turns in parallel) [m/s]	Pressure Drop (avg) [atm]
6093	*2358*	*2377*	*913*	*3.04*	*14*
8674	*1748*	*1762*	*677*	*2.68*	*13*
8339	*1553*	*1566*	*601*	*3.03*	*17*
8204	*1996*	*2012*	*773*	*1.95*	*5*

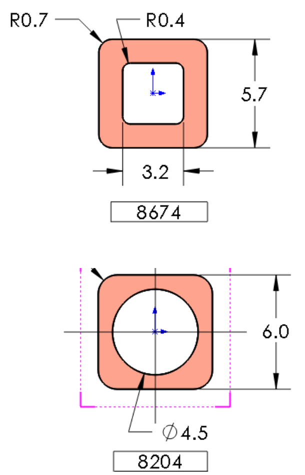
Cooling Circuits

- By setting an allowable temperature rise, we determine the required coolant flow rate. Each conductor has a different electrical and hydraulic resistance, both of which contribute to the pressure drop.



- For a given conductor and temperature rise, we can look at the pressure drops that are realized from splitting each pancake into different numbers of cooling paths. Setting a limit on the pressure allows to establish the optimal (minimum) number of cooling circuits for a given configuration.

Tmax	DeltaT	8674	8204
		Cooling Paths / coil	
50	35	**28**	**21**
60	45	**24**	**17**
70	55	**23**	**16**
80	65	**19**	**14**

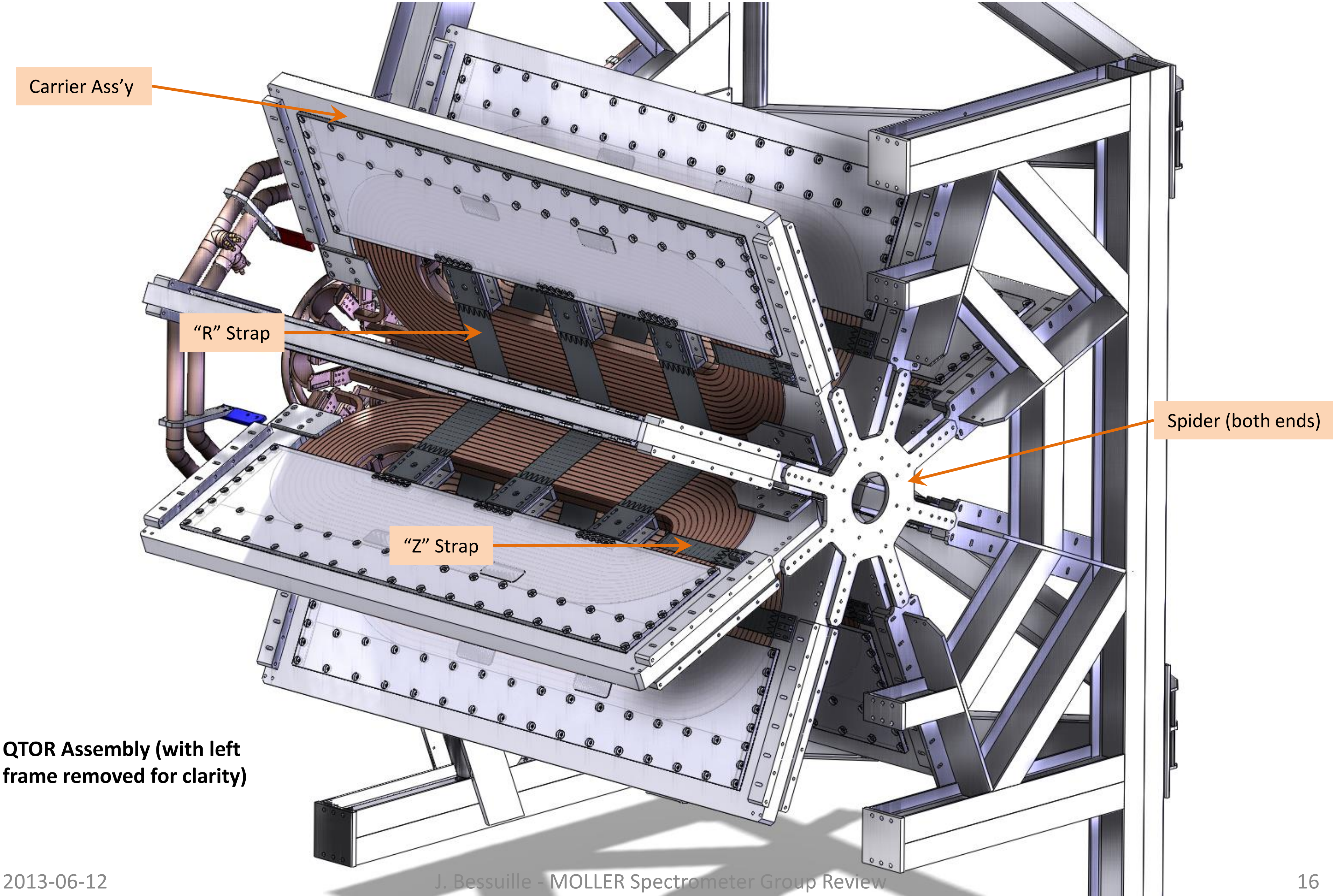


Cooling Summary

- I looked at several conductor types and have narrowed down the field to just 4 options
  - 8674: Fewest number of cooling channels for conductors that fit existing volume budget
  - 8339: Lowest power & voltage for conductors that fit the existing volume budget
  - **8204: Fewest number of cooling channels for conductors that are oversized @ 6.0 mm ← Recommended to use**
    - **Results in ~2000 A/cm^2 current density**
  - 8680: Lowest power & voltage for conductors that that are oversized @ 6.0 mm
- We need to decide if the 6.0 mm size is okay, and then determine the relative importance of power & voltage vs. number of cooling channels
- If the coils are run in series electrically, we can expect to see from **1500 to 2400 V** on the first coil.
  - Possible alternative would be to connect identical pancakes of each coil in series, with separate circuit for each pancake.
- Depending on conductor, the full toroid will draw between **0.6 and 0.9 MW**
- Depending on temperature limits and conductor cross section, the cooling load can be extracted with **140 - 350 lpm** (37 – 90 GPM) of total water flow
- In order to operate at less than **17 atm** (250 psi), We can expect to use anywhere from **14 to 28 parallel cooling circuits** per coil.
- Need JLab confirmation on maximum pressure and outlet temperature for the site.

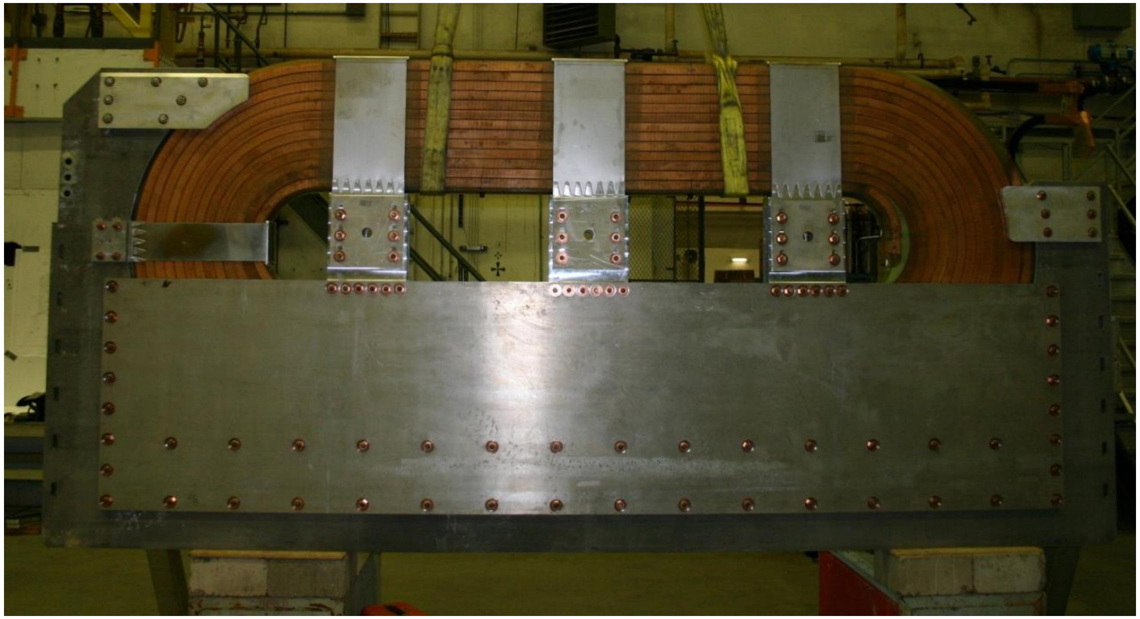
Assembly CAD

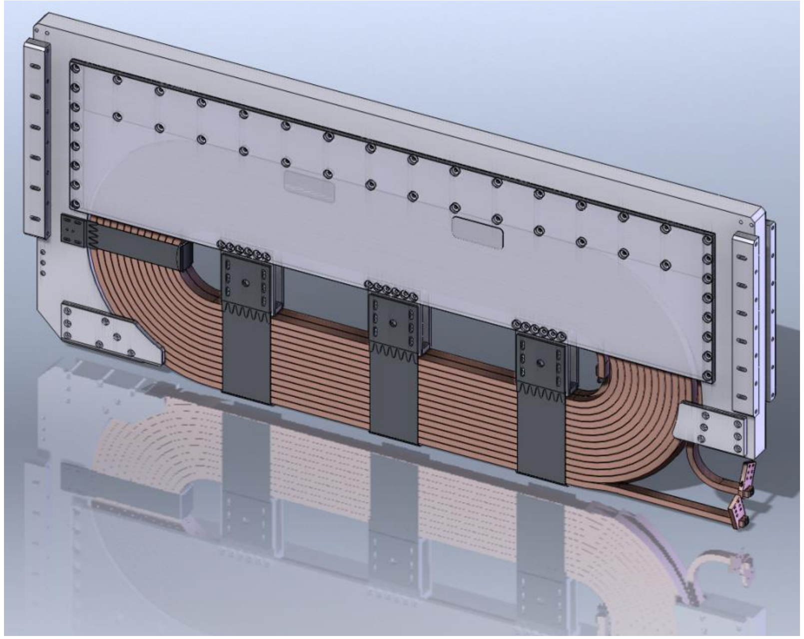
QWEAK Toroid Assembly

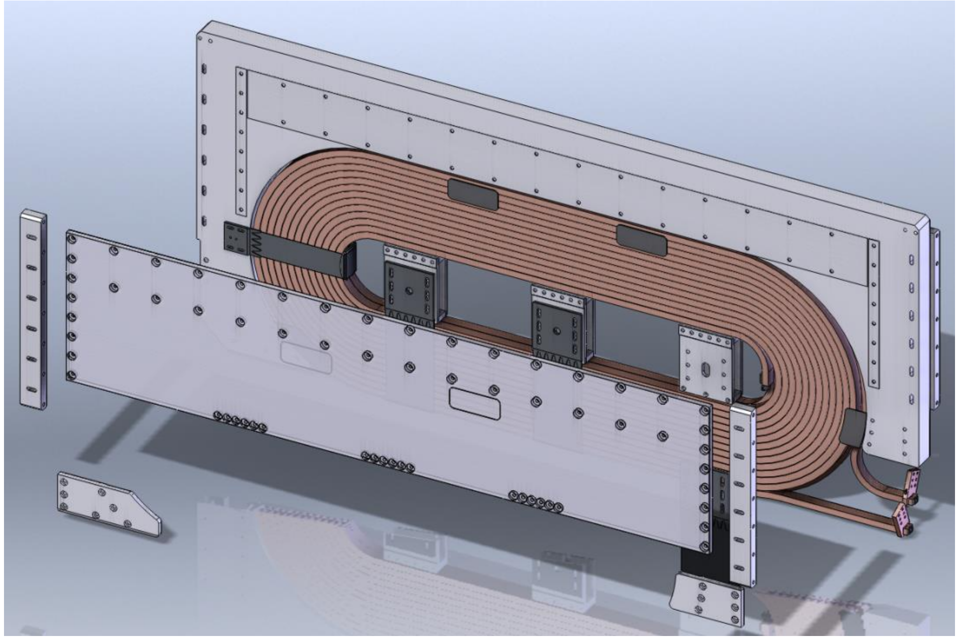


QTOR Assembly (with left frame removed for clarity)

Qweak Coil & Carrier

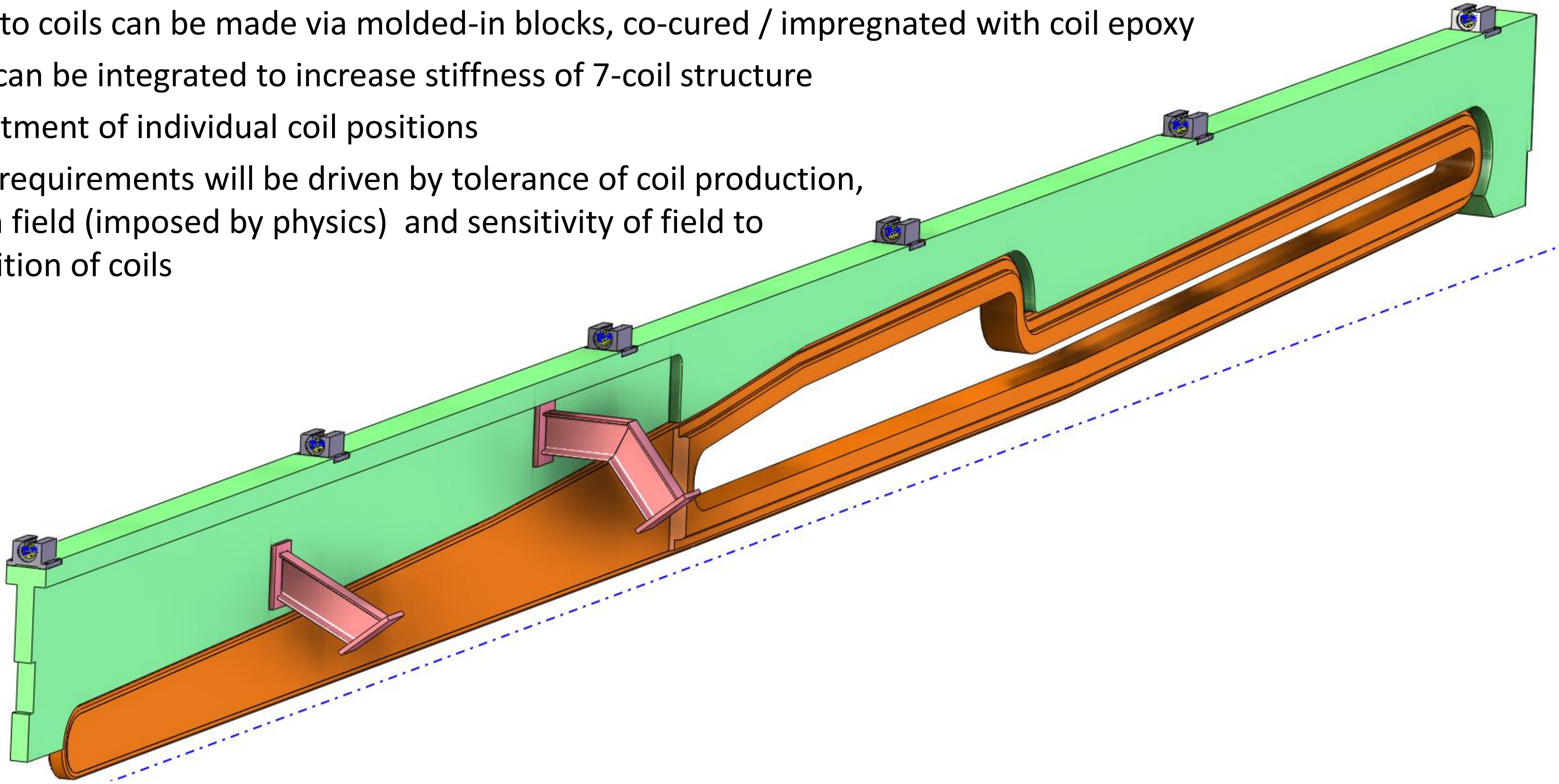


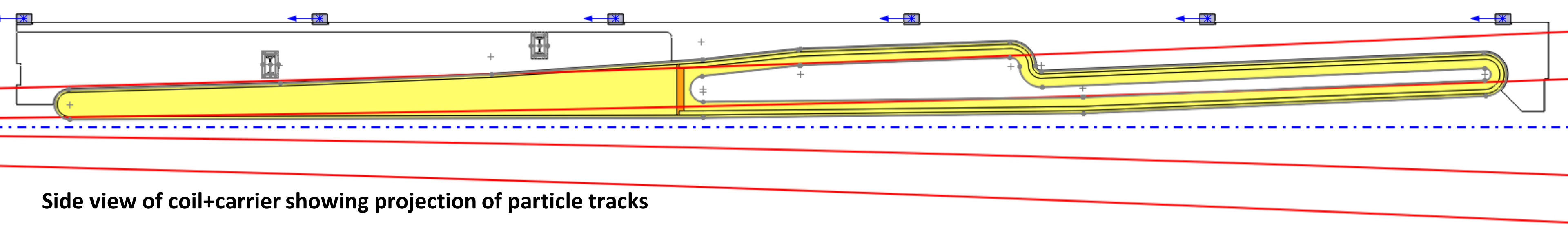




Moller Hybrid Coil Carriers

- Supports the coil against gravity and magnetic centering forces
- Maintains shape of the coil against "rounding" forces (those that tend to force the coil into a circular shape)
- Attachment to coils can be made via molded-in blocks, co-cured / impregnated with coil epoxy
- Collimators can be integrated to increase stiffness of 7-coil structure
- Allows adjustment of individual coil positions
- Adjustment requirements will be driven by tolerance of coil production, tolerance on field (imposed by physics) and sensitivity of field to physical position of coils

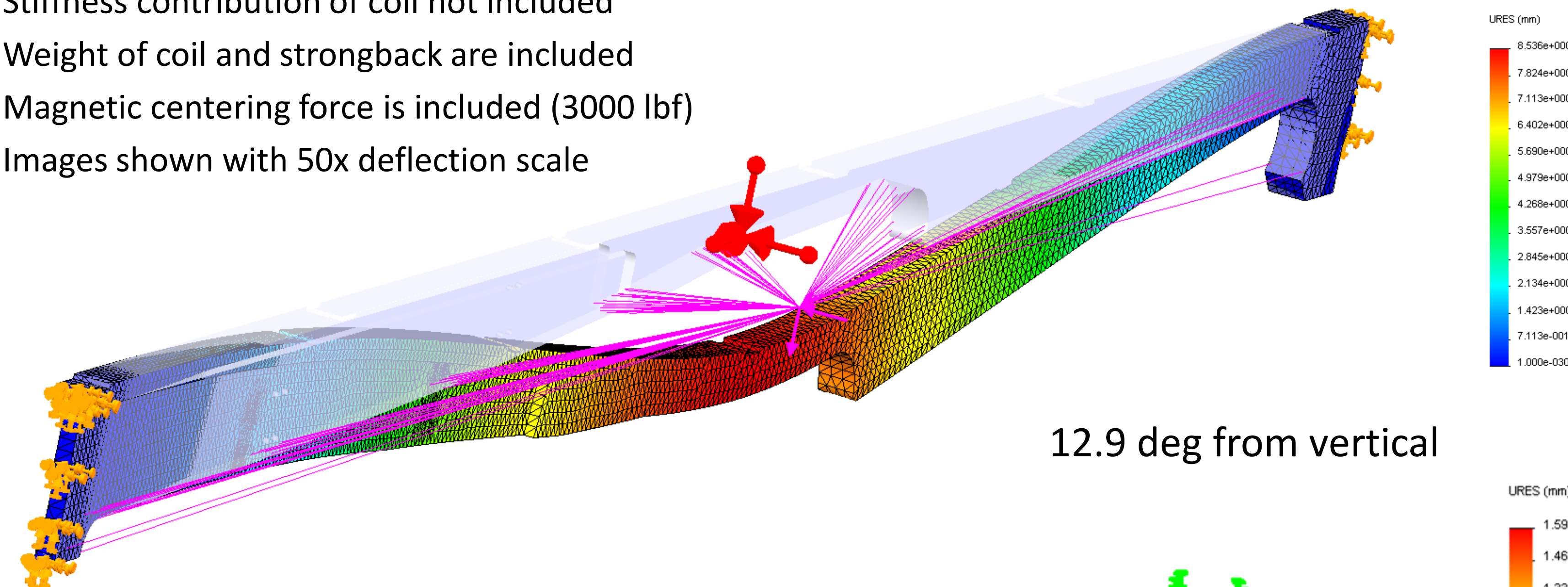




Side view of coil+carrier showing projection of particle tracks

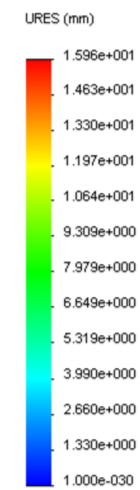
FEA of Coil Carrier

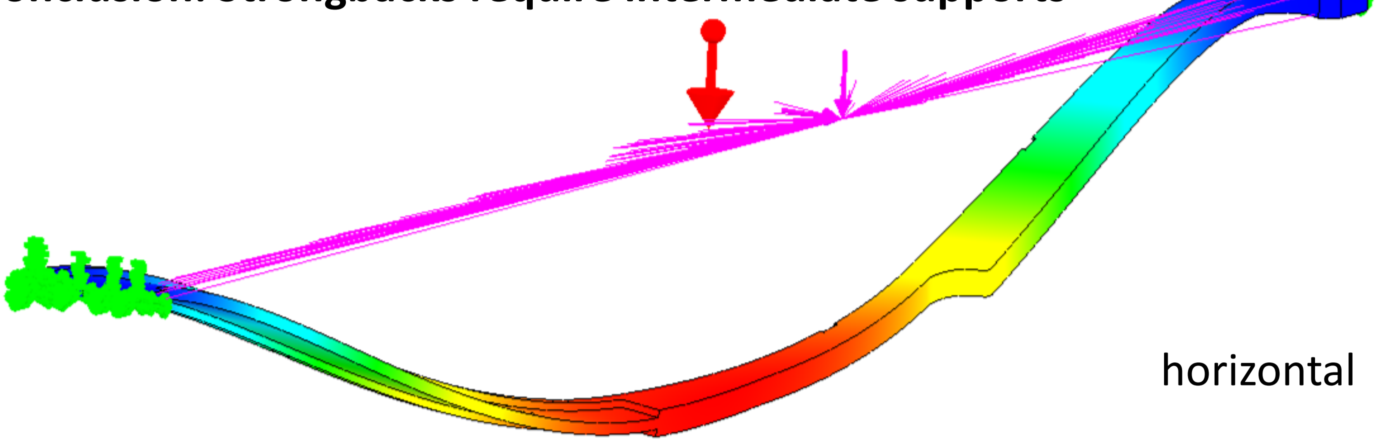
- Very basic first-pass deflection analysis on aluminum coil strongback
- Only supported at ends (clamped)
- Stiffness contribution of coil not included
- Weight of coil and strongback are included
- Magnetic centering force is included (3000 lbf)
- Images shown with 50x deflection scale



12.9 deg from vertical

Conclusion: Strongbacks require intermediate supports





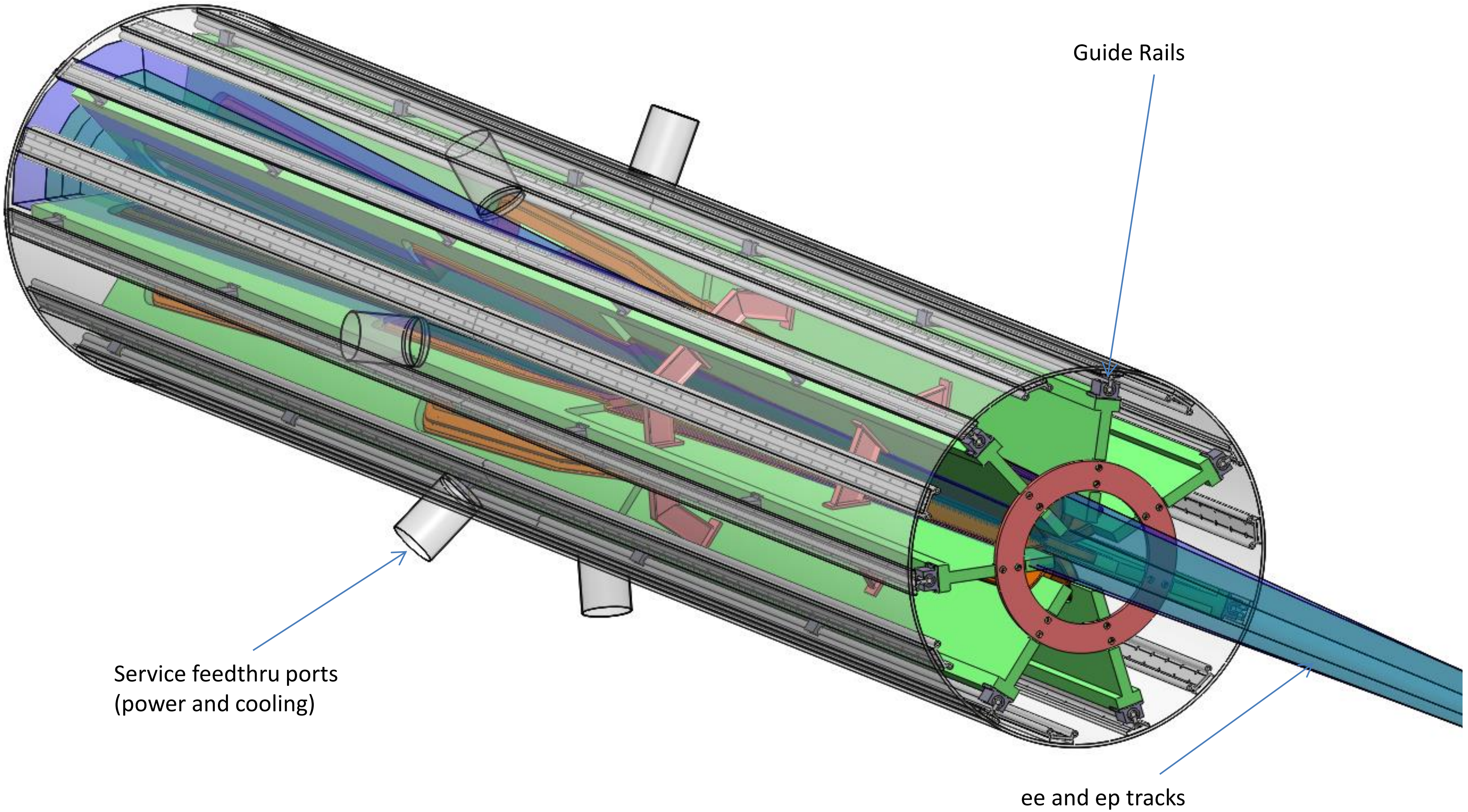
horizontal

In-Air vs. In-Vacuum

	Coils in Vacuum	Coils in Air
Beampipe / vacuum system	• Large vacuum chamber to hold all coils – could have issues with pressure vessel code @ JLab • Need water system interlocked to vacuum system	• Needs complex beampipe system, which could incur the wrath of pressure vessel inspectors. • Central beampipe needs to be capable of absorbing 1000 W of photon flux over 6 m.
Coil Support	• Inter-coil supports could be implemented easily, due to absence of beam pipe	• Inter-coil supports could be more difficult; would require tulip petal pipe with circumferential holes or as 8 separate pipes.
Physics Acceptance	• Only determined by coils	• Beampipe cuts into acceptance, figure at least 4 mm thick.
Attachment of services	• More difficult… would likely need to rout these all to one end or the other. • Would need flexible lines in vacuum – metal due to radiation → $$$	• Can access services directly at outer radius.
Maintenance	• More difficult	• Less difficult
Alignment	• Much more difficult, JLab laser tracking system would be used.	• Laser tracking system is easier to use for this configuration.

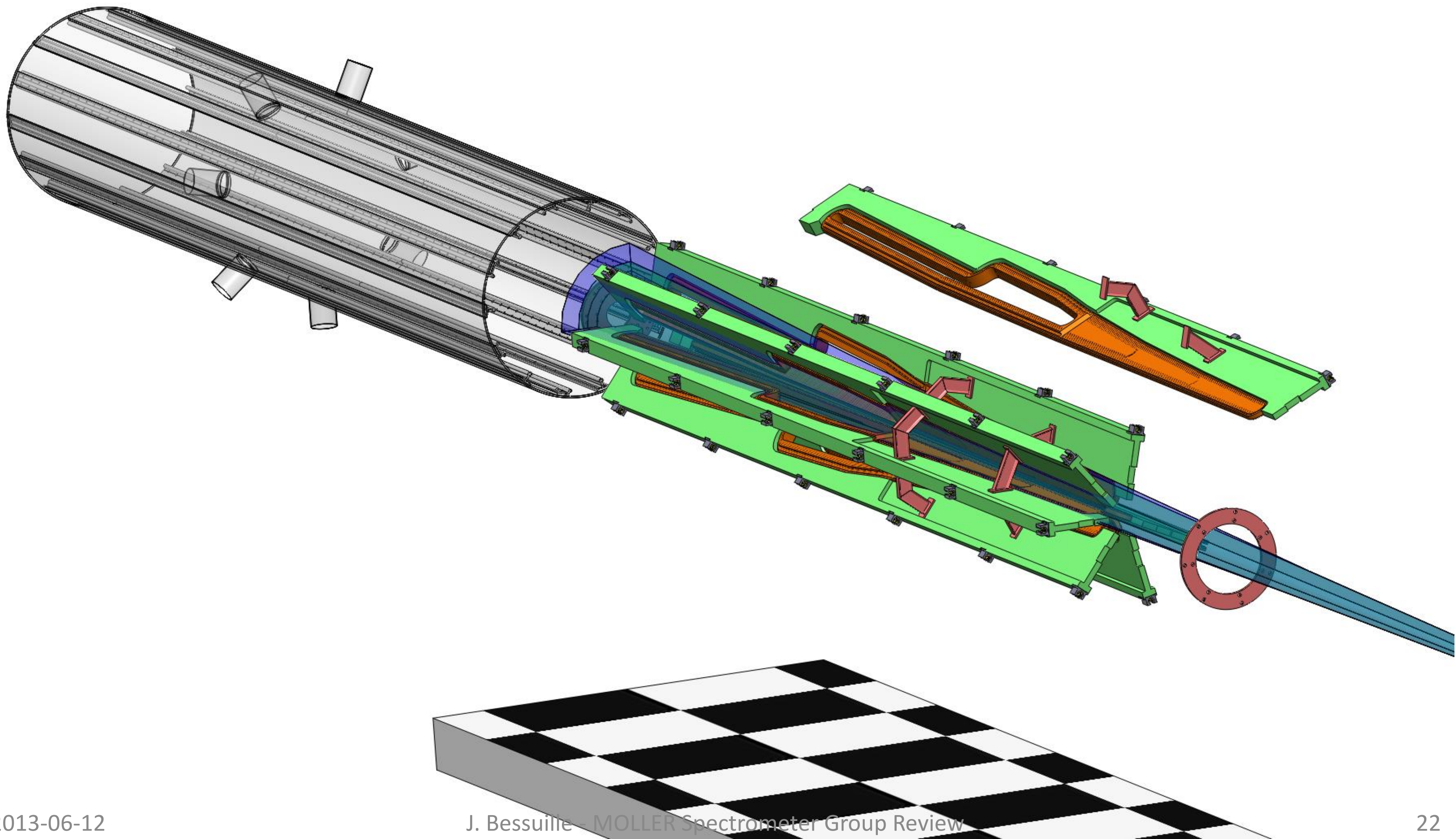
Coils In Vacuum

- Shown is standard 3/8 thk 46”diameter Stainless Steel Pipe
- Single module, crane-able assembly, allowing very limited access during runs



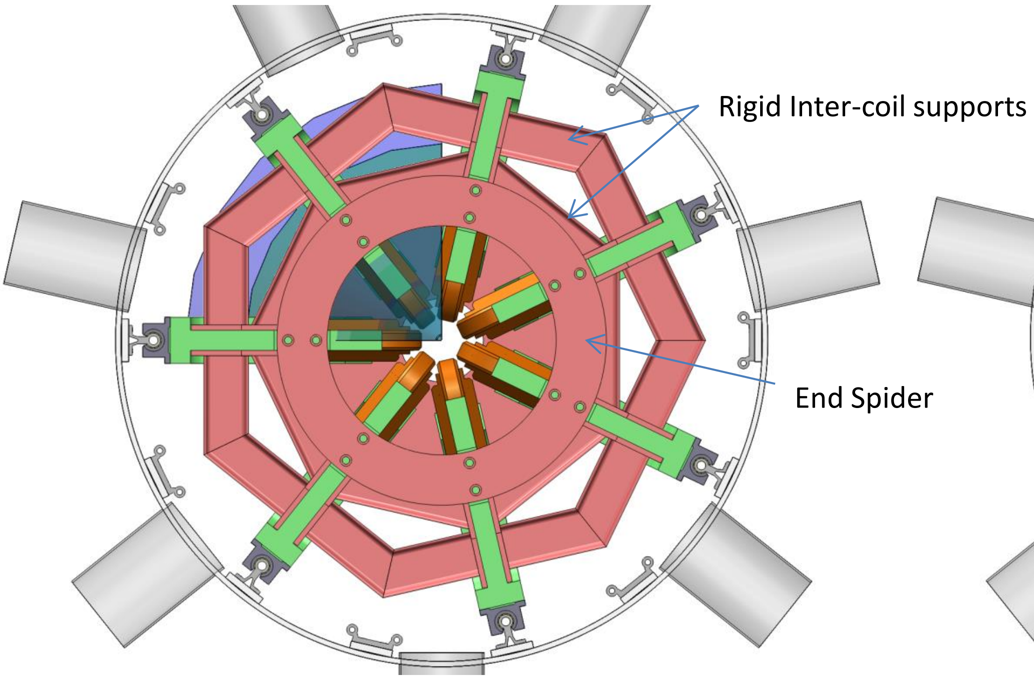
Coils in Vacuum

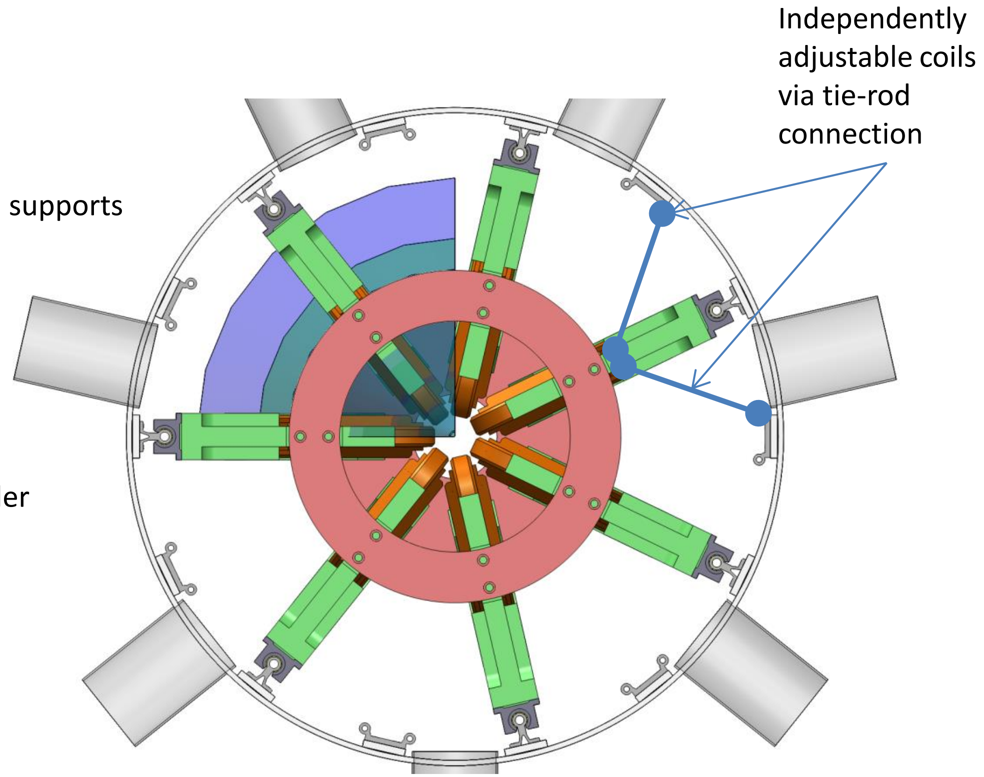
- Full assembly, Exploded



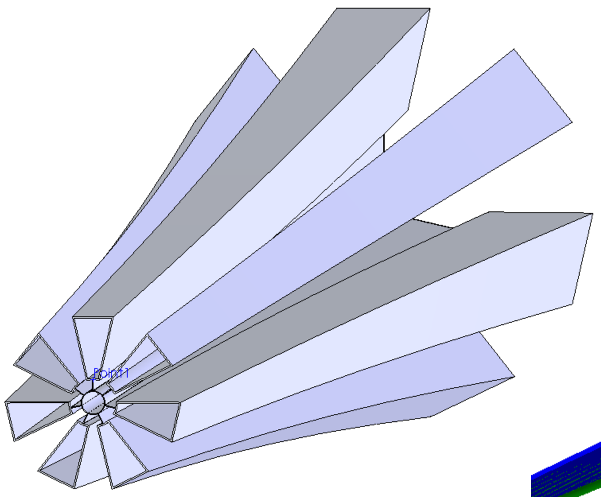
Toroid Assembly

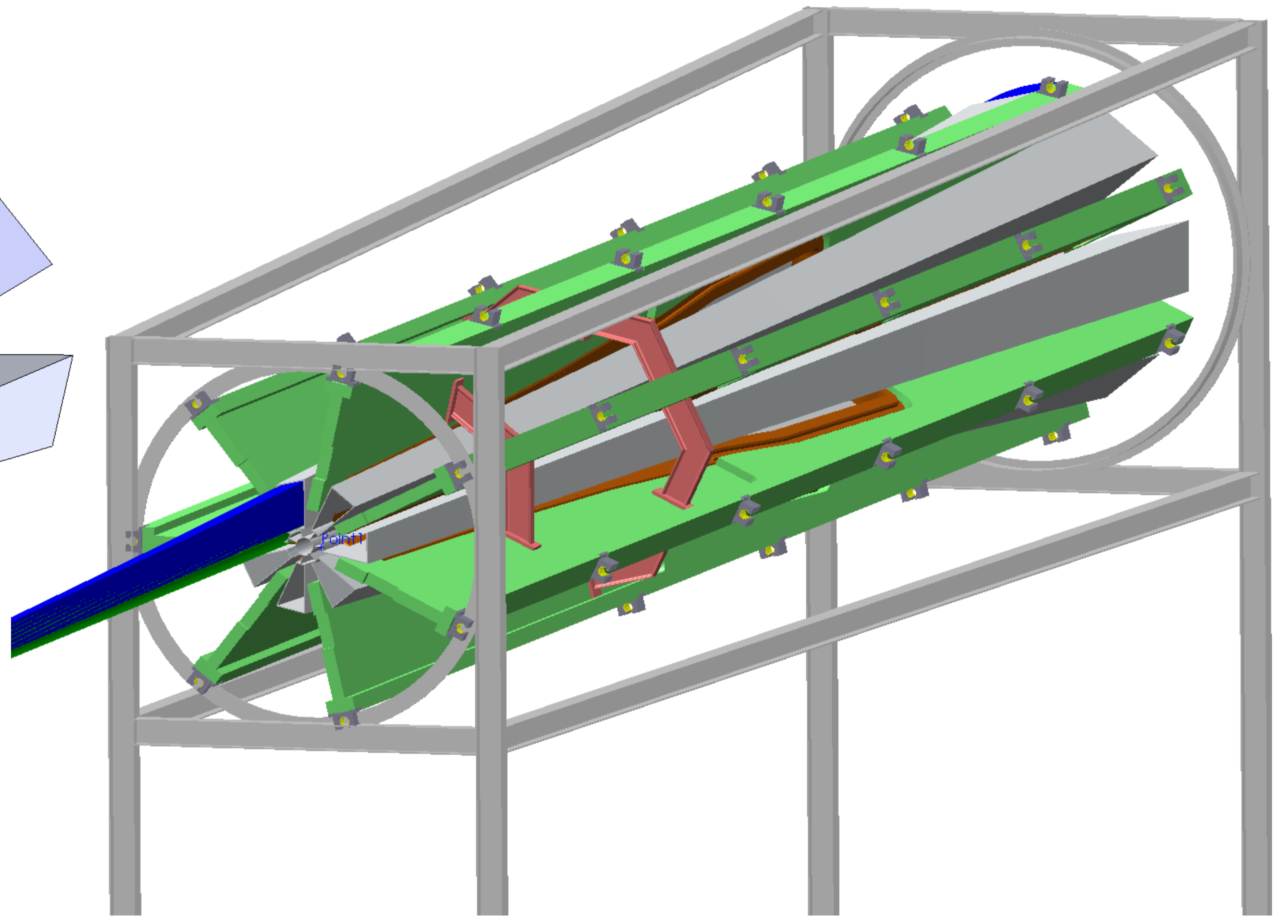
- Different options for inter-coil support.





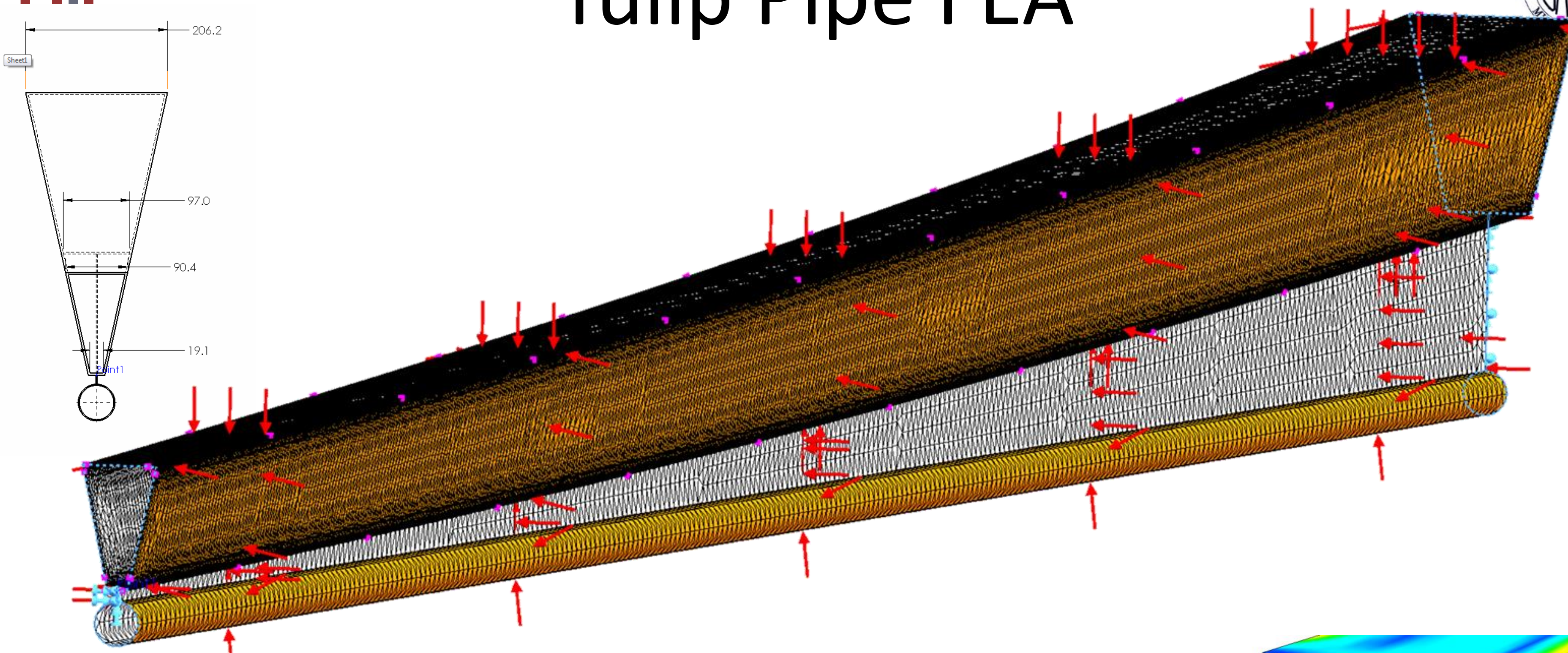
Coils in Air

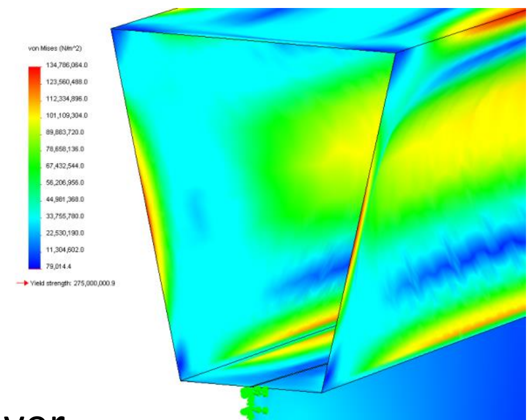




- Collimated beams pass through 8 distinct volumes, comprising the “Tulip Pipe”.

Tulip Pipe FEA





Material	Thickness (mm)	FoS	Deflection (mm)
316L	3.2	0.82	2.4
6061-T6	3.2	1.30	7.5
316L	4.0	1.27	1.2
6061-T6	4.0	2.05	3.6

- Reduced stiffness of aluminum gives larger deflections, however,
- Increased yield strength of aluminum results in higher factor of safety (FoS)

To-Do List and Questions

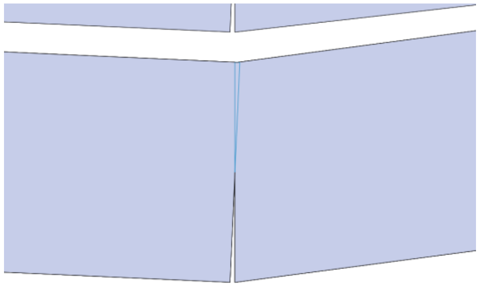
1. Decide on a conductor type – currently I think we're leaning towards the 6.0 mm version.
   a. Discuss Hall A infrastructure and develop conceptual system design including pumps, chillers, heat exchangers and power supply
2. Iterate between TOSCA and FEA simulations with the modified coils (single s-bends) and new choice of conductor.
   a. Involve potential coil vendors at this stage
3. Review in-vacuum vs. out-of-vacuum options, and 2-coil vs. 3-coil configurations
4. Once a mounting configuration is established, start designing support frame, coil package details, and coil carriers in parallel.
5. Questions for JLab / Moller group:
   - Need to know radiation levels for design of epoxy, o-rings
   - Need developed plan for how often these subsections will be moved… requirements for modularity.
   - Need to determine accurate pressure and power capabilities of cooling water

Backup Slides

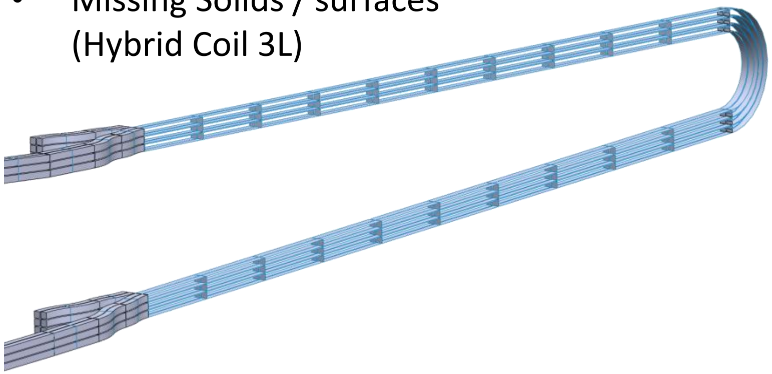
Issues Importing STEP Files

- All files came with surfaces and solid bodies
  - Between 4 and ~20 solid bodies per coil
  - Between 450 and ~1000 surface bodies.
    - Most of these I deleted, with one exception where the solids were not properly formed (3L)

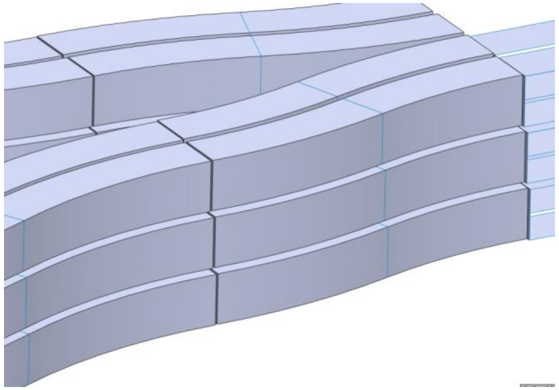
- Discontinuous transition from straight to curved section

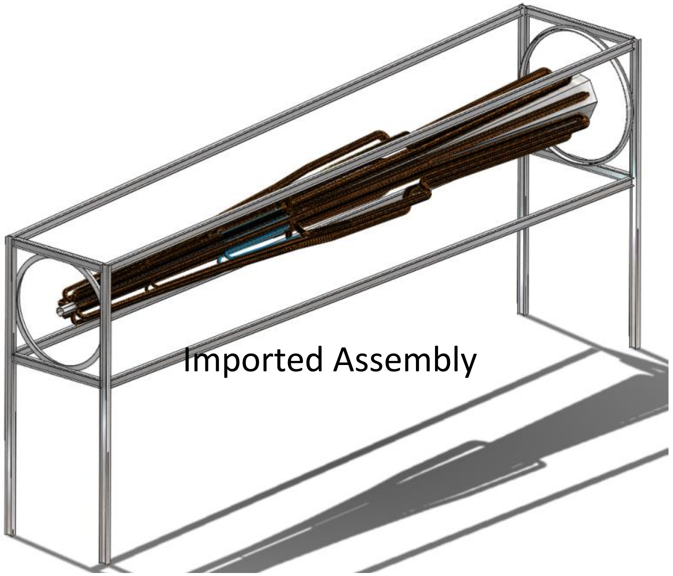


- Missing Solids / surfaces (Hybrid Coil 3L)



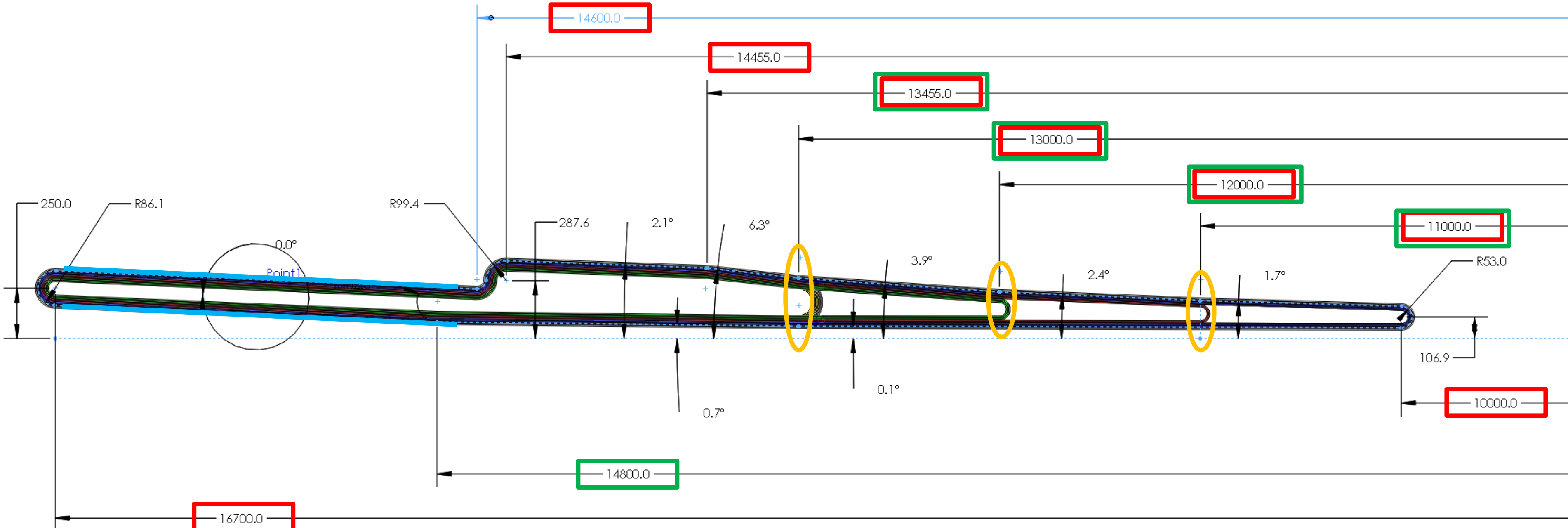
- Gaps and offsets
  - Here we see a gap of 0.03 mm, with offsets of 0.005 mm (y) and 0.015 mm (x)
  - 1BL, 1BR





Imported Assembly

Coil Definition -16 oct 2012

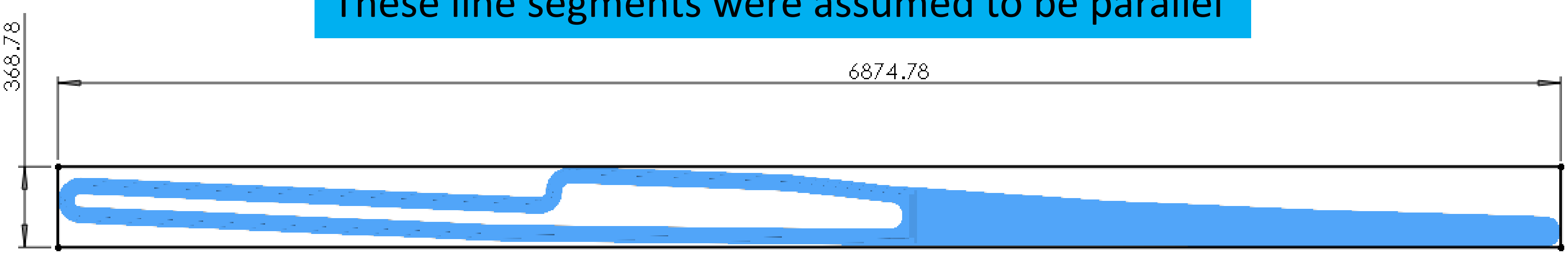


These dimensions establish the z-position of the bends

These dimensions locate the transitions between different angles

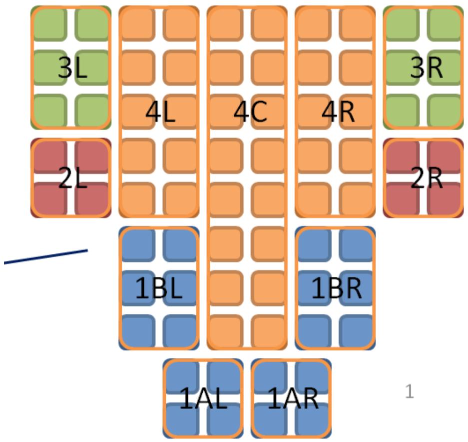
These groups of arc centers and angle transitions were assumed to have the same z

These line segments were assumed to be parallel



Bounding Box with 5mm encapsulant; dimensions in mm

Pancake Properties



Pancake	Length / Turn [m]	# Conductors / Pancake	Length / Pancake [m]	# Pancakes / Coil	Length / Coil [m]
1A	13.9	4	55.7	2	111.4
1B	13.8	6	82.9	2	165.7
2	11.7	4	46.9	2	93.8
3	9.8	6	58.7	2	117.4
4	7.9	10	79.2	2	158.4
4C	8.0	16	127.5	1	127.5
total conductor length	774.3 m				
total number of turns	76 turns				
average length / turn	10.2 m				

Conductor Properties

index	Part #	OD [mm]	ID[mm]	Outer R [mm]	Inner r [mm]	Cooling bore type	Toroid Voltage Drop [V]	Toroid power [W]	Toroid Power [kW]	required flowrate for coil [m3/s]	required flowrate for coil [lpm]	Velocity (4 turns in //) [m/s]	Reynold's Number	pressure drop (avg) [atm]	pressure drop (avg) [psi]	coil mass [kg]	Current Density [A/cm^2]
1	6093	5.50	3.50	1.50	0.50	sq	2377	912919	913	4.81E-04	28.88	2.10	11717	7	108	122	2358
2	8674	5.70	3.20	0.70	0.40	sq	1762	676716	677	3.57E-04	21.40	1.86	9423	7	98	160	1748
3	8339	5.79	3.18	1.00	-	cir	1566	601261	601	3.17E-04	19.02	2.10	10151	9	129	178	1553
4	8283	6.00	3.00	1.00	-	cir	1379	529520	530	2.79E-04	16.75	2.08	9477	9	136	200	1368
5	6881	5.60	3.60	1.00		cir	1905	731454	731	3.86E-04	23.14	1.99	10909	7	100	149	1890
6	8204	6.00	4.50	1.00		cir	2012	772730	773	4.07E-04	24.44	1.35	9219	3	38	146	1996
7	8680	6.00	3.50	0.80		cir	1499	575514	576	3.03E-04	18.20	1.66	8828	5	75	187	1487

Cooling Circuit Worksheet

Assumptions
System is isolated and radiation can (and will) be ignored
All heat is conducted radially only, thus heat flux thru tube is constant along length
Pressure losses in fittings and bends are not considered
Inlet flow is fully developed

Common Parameters (INPUT)			
Nominal Current	384	A	
Liquid inlet temperature	15	deg C	
Liquid Outlet temperature (max)	70	deg C	
Pressure Drop (max)	17	atm	17 atm = 250 psi
Tube Roughness	1.50E-03	mm	From Cengel, for drawn tubing
Solid Material	Copper	-	
Liquid Material	Water	-	

Input									
Coil Pancake	--	1a	1B	2	3	4	4C	4C	choose from pancakes worksheet
Conductor Length	*m*	*55.72*	*82.86*	*46.92*	*58.68*	*79.20*	*127.52*	*127.52*	
# Turns	*--*	*4*	*6*	*4*	*6*	*10*	*16*	*16*	
Power	*W*	*6957*	*10346*	*5858*	*7327*	*9889*	*15922*	*15922*	
Conductor	--	2	2	2	2	2	2	2	choose from 'conductors' worksheet
Cooling Channel Type	*--*	*3.2 mm, sq*	*3.2 mm, sq*	*3.2 mm, sq*	*3.2 mm, sq*	*3.2 mm, sq*	*3.2 mm, sq*	*3.2 mm, sq*	
Copper Area	*mm2*	*21.97*	*21.97*	*21.97*	*21.97*	*21.97*	*21.97*	*21.97*	
Water Area	*mm2*	*10.10*	*10.10*	*10.10*	*10.10*	*10.10*	*10.10*	*10.10*	
Hydraulic Diameter	*mm*	*3.34*	*3.34*	*3.34*	*3.34*	*3.34*	*3.34*	*3.34*	
Turns / Cooling Circuit	--	2	3	4	3	5	5	6	
Number of cooling circuits	*--*	*2*	*2*	*1*	*2*	*2*	*4*	*3*	*Separate parallel cooling circuits for pancake*

Summary									
Pressure Drop	***atm***	**3.1**	**9.3**	**13.1**	**3.6**	**8.2**	**8.4**	**13.8**	**depends on conductor / # channels**

Energy Balance									
Coolant Flow Rate	***l/min***	**1.82**	**2.71**	**1.53**	**1.92**	**2.59**	**4.17**	**4.17**	**Total for one pancake**
T_Water_Out	***deg C***	**70.00**	**70.00**	**70.00**	**70.00**	**70.00**	**70.00**	**70.00**	
T_Water_mean	***deg C***	**42.50**	**42.50**	**42.50**	**42.50**	**42.50**	**42.50**	**42.50**	

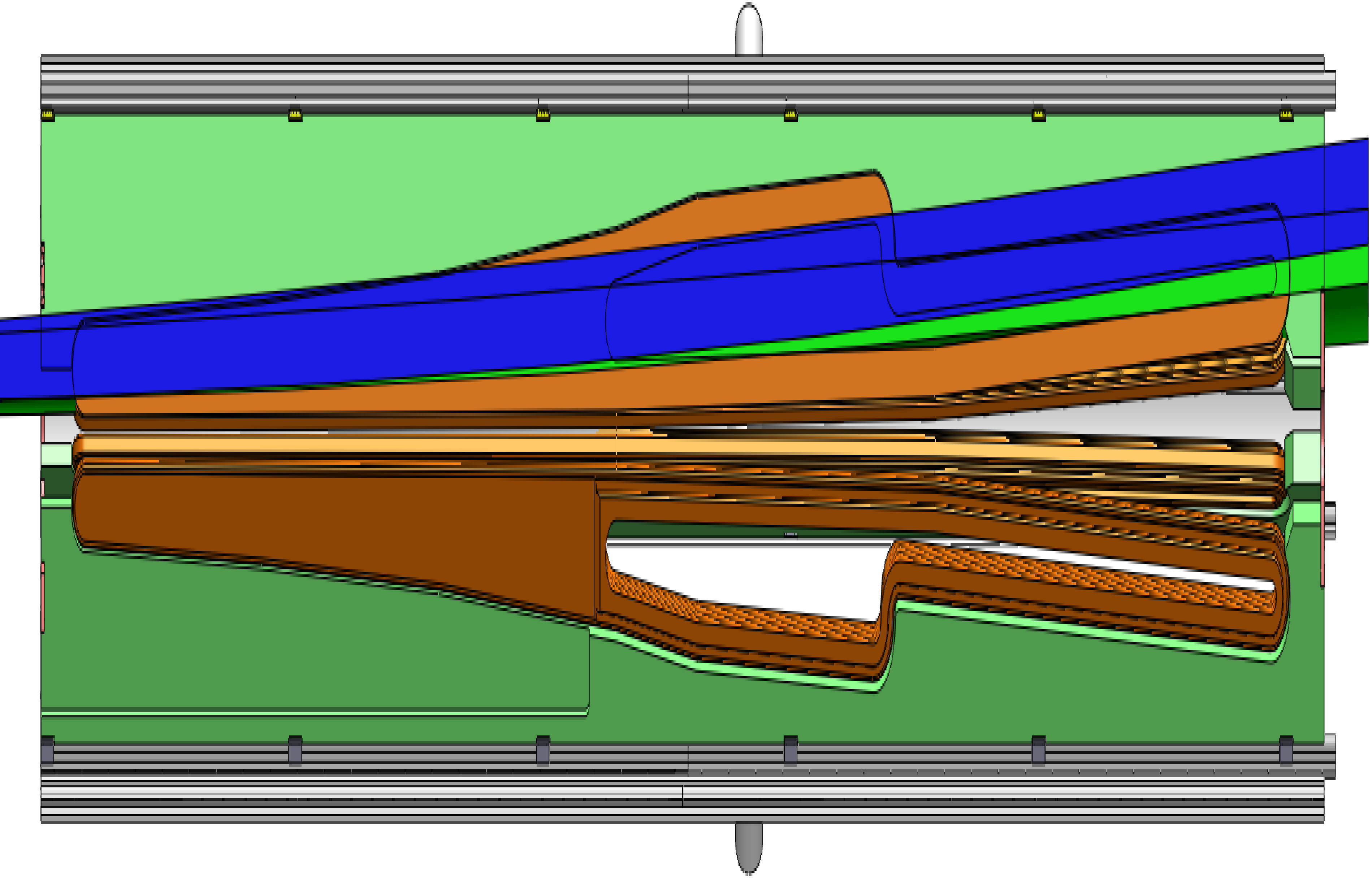
Bulk Medium Properties at average temperature									
v	***m2/s***	**6.58E-07**	**6.58E-07**	**6.58E-07**	**6.58E-07**	**6.58E-07**	**6.58E-07**	**6.58E-07**	**kinematic viscosity**
Pr	***-***	**4.34**	**4.34**	**4.34**	**4.34**	**4.34**	**4.34**	**4.34**	
k	***W/m-K***	**0.63**	**0.63**	**0.63**	**0.63**	**0.63**	**0.63**	**0.63**	
Re	***-***	**7.61E+03**	**1.13E+04**	**1.28E+04**	**8.02E+03**	**1.08E+04**	**1.09E+04**	**1.31E+04**	**this is turbulent**
Nusselt	***-***	**57**	**79**	**88**	**60**	**76**	**77**	**89**	**Using second Pethrikov equation**
h	***W/m2-K***	**10827**	**14977**	**16599**	**11292**	**14431**	**14505**	**16862**	

Flow Calculations									
L_circuit	***m***	**27.86**	**41.43**	**46.92**	**29.34**	**39.60**	**39.85**	**47.82**	
Velocity	***m/s***	**1.50**	**2.23**	**2.53**	**1.58**	**2.13**	**2.15**	**2.58**	**In each circuit**
f_factor_guess	***-***	**0.0338**	**0.0306**	**0.0297**	**0.0334**	**0.0310**	**0.0309**	**0.0296**	**Blasius Formula to start iteration.**
f_factor	***-***	**0.0338**	**0.0306**	**0.0297**	**0.0334**	**0.0310**	**0.0309**	**0.0296**	
deltaP_pipefriction	***Atm***	**3.13**	**9.32**	**13.13**	**3.61**	**8.22**	**8.37**	**13.84**	
deltaP	***Atm***	**3**	**9**	**13**	**4**	**8**	**8**	**14**	
	psi	**46**	**137**	**193**	**53**	**121**	**123**	**203**	

Heat Transfer Calculations									
deltaT_Tubesurface	**deg C**	**0.95**	**0.69**	**0.62**	**0.91**	**0.71**	**0.71**	**0.61**	**at any point along the tube's length**
T_Max_Tubesurface	**deg C**	**70.95**	**70.69**	**70.62**	**70.91**	**70.71**	**70.71**	**70.61**	**Maximum temperature inside the cooling tube**

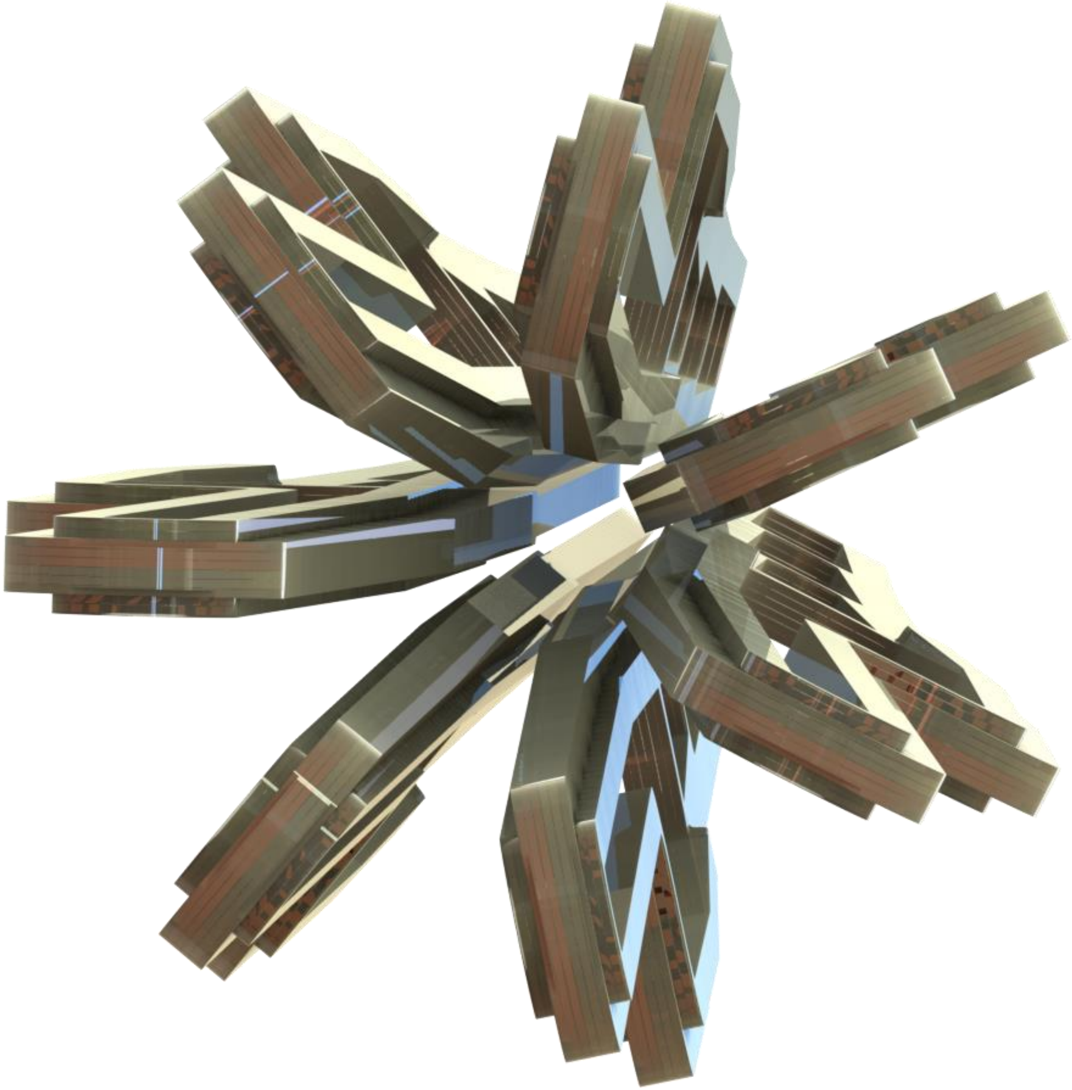
Toroid Assembly

- Stretched side-cut (inter-coil supports hidden)



7-Coil Package

- Encapsulated coils created in SWX.
  - Mass is about 200 kg each, including coolant and 5mm epoxy.



QWEAK Coil Package Specification

1. INSULATION NOTES:
    1.1 CONDUCTOR INSULATION: HEAT CLEANED FIBERGLASS TAPE .016 THK, SINGLE WOUND HALF-LAPPED.
    1.2 GROUND WRAP: HEAT CLEANED FIBERGLASS TAPE .016 THK, DOUBLE WOUND HALF-LAPPED.
2. VACUUM IMPREGNATED EPOXY CHARACTERISTICS:
    2.1 THERMAL CONDUCTIVITY: 0.01 BTU/in.-Hr-Degree F. Min.
    2.2 SHEER STRENGTH: 2000psi Shear Min.
    2.3 RADIATION RESISTENCE: 100 Rads per year for 20 years.
    2.4 ELECTRICAL RUPTURE STRENGTH: 300 Volts/mil Min.
    2.5 COLOR: CLEAR TRANSLUCENT.
    2.6 TEMPERATURE RATING: 80 C Max.
3. EPOXY UNIFORMITY:
    3.1 EPOXY THICKNESS SHOULD BE EQUAL IN ALL CONTACT AREAS. EPOXY THICKNESS VARIATION FROM AREA TO AREA MUST NOT EXCEED 0.063".
    3.2 VENDOR MUST MEASURE AND DOCUMENT THE ACTUAL THICKNESS IN THESE AREAS.
4. ALL EPOXY VOLUMES SHALL BE REINFORCED WITH FIBERGLASS. FILL VOIDS WITH FIBERGLASS ROVING TO AVOID RESIN-RICH AREAS.