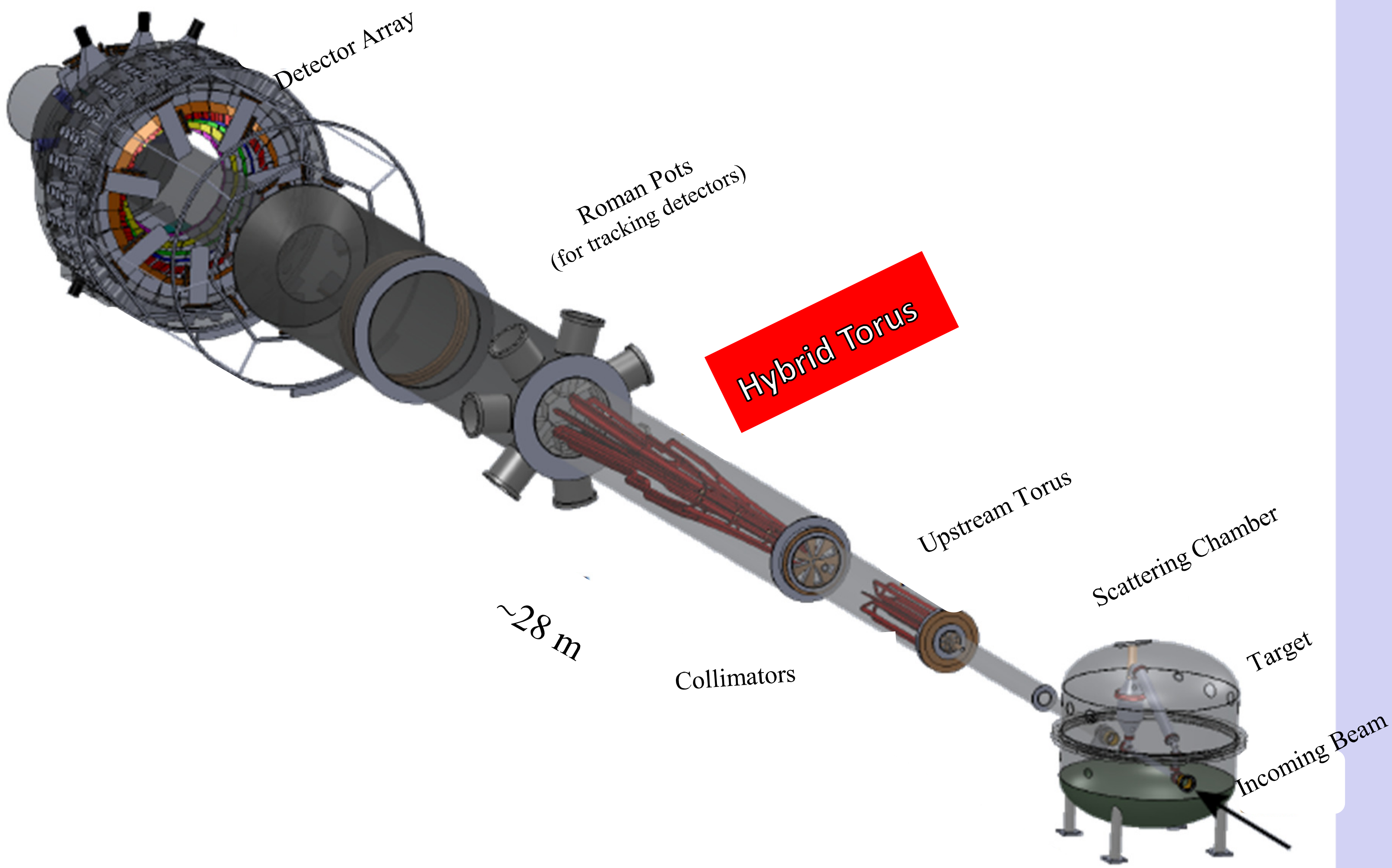
MOLLER Hybrid Toroid Internal Magnet Review

Presented by Jason Bessuille, Ernie Ihloff, and James Kelsey (MIT-Bates)

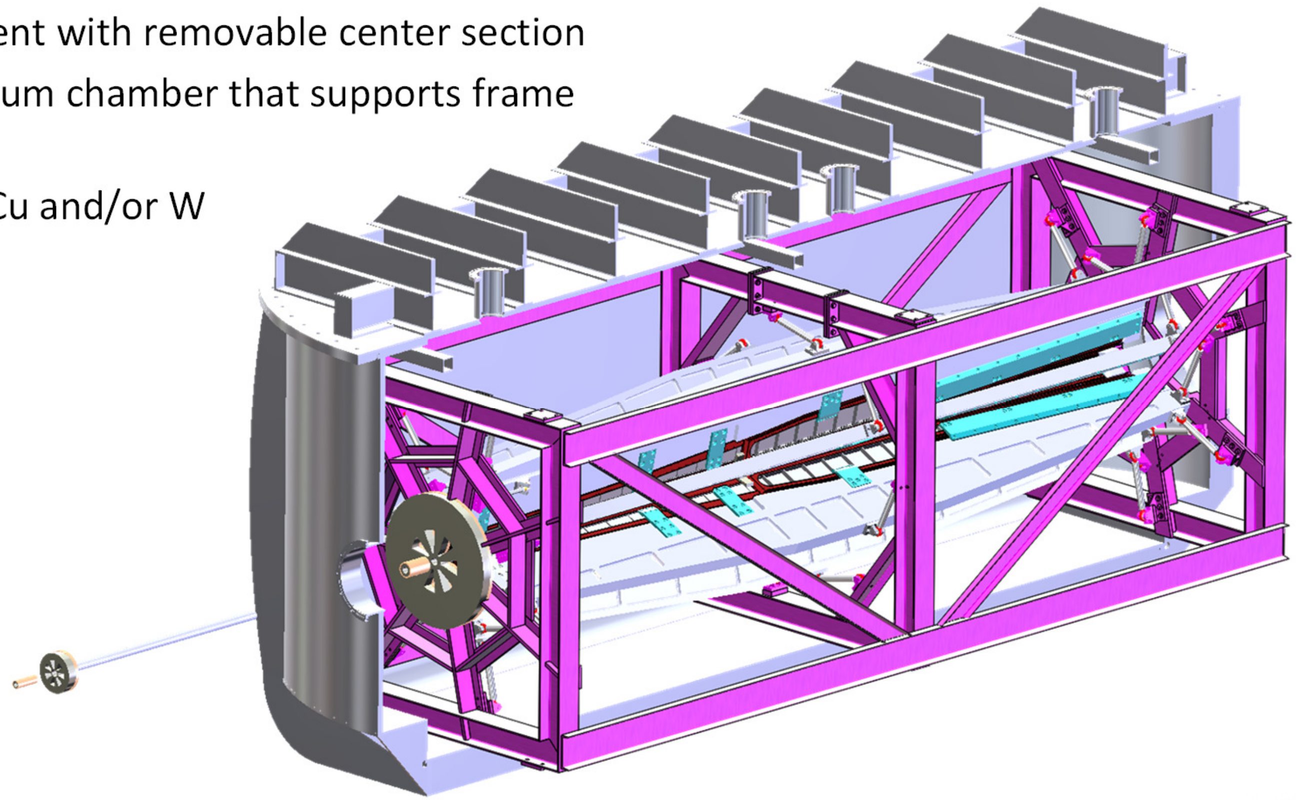
Presented to MOLLER Internal Magnet Advisory Group

Wednesday, 15th July, 2015

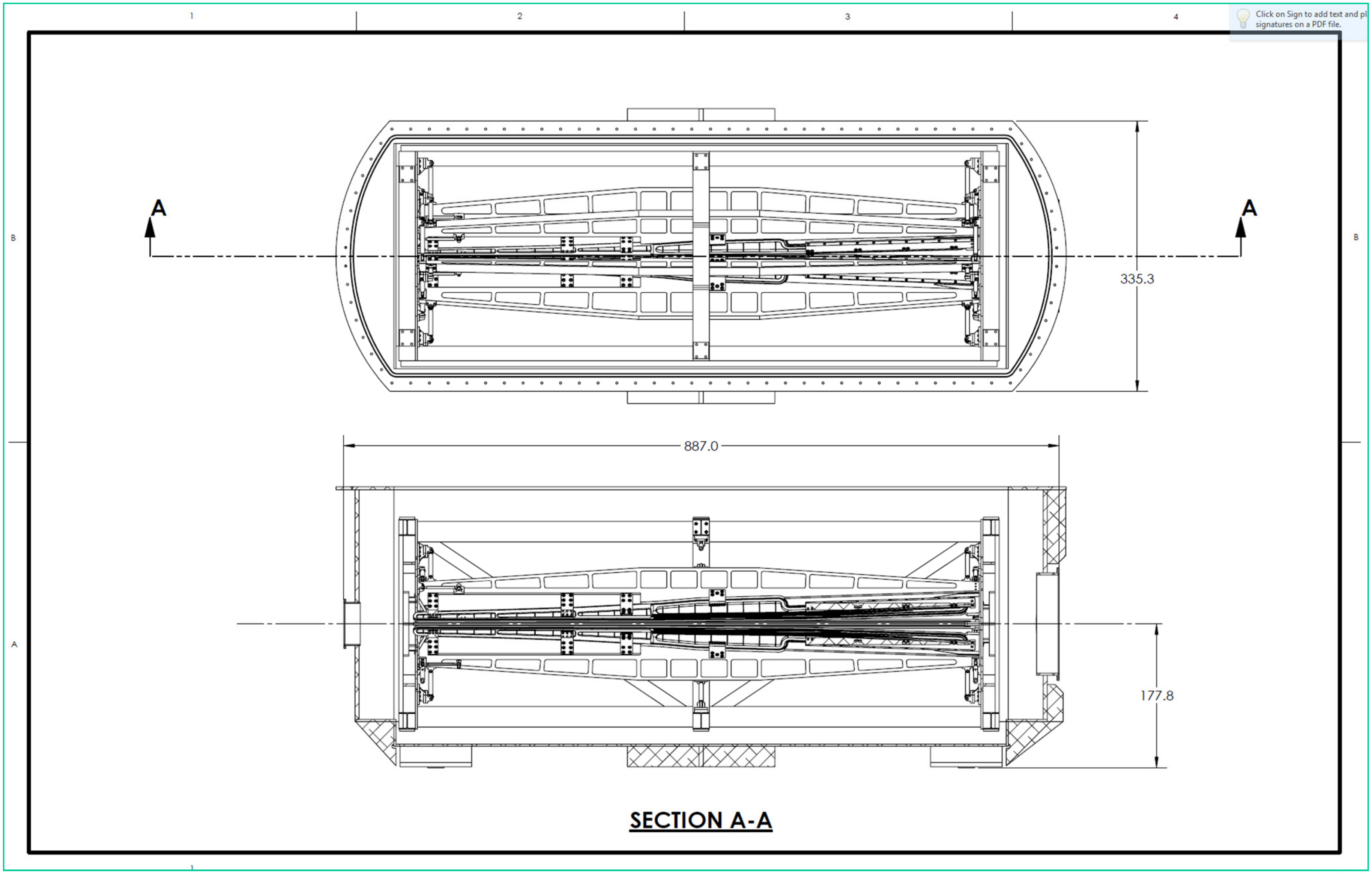

Detector Array
Roman Pots
(for tracking detectors)
Hybrid Torus
Upstream Torus
Scattering Chamber
Target
Incoming Beam
~28 m
Collimators

Overview

- **"Moller Hybrid":** A 7-sector toroidal magnet for focusing scattered moller and ep electrons
- **Coils:** pancake-wound, water-cooled copper with multiple current return loops. They are supported on aluminum strongbacks (or "coil carriers") which themselves mount to the frame via kinematic 6-strut linkage
- **Frame:** Aluminum weldment with removable center section
- **Chamber:** Aluminum vacuum chamber that supports frame hanging on removable lid
- **Collimators:** 6 elements, Cu and/or W



Overview



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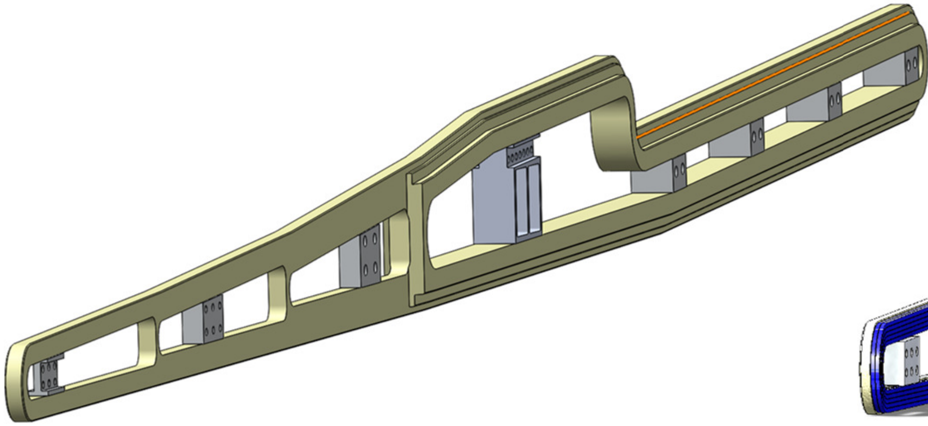
SECTION A-A

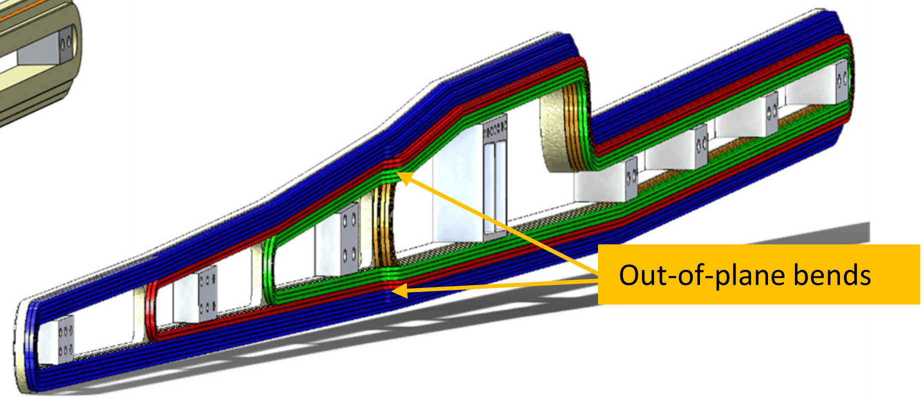
Extra Issues

- Site Infrastucture
- Magnet Cabling / Services
- Collimators
- Upstream toroid
- Coil Inserts and Wrapping scheme
- Comparison Slide

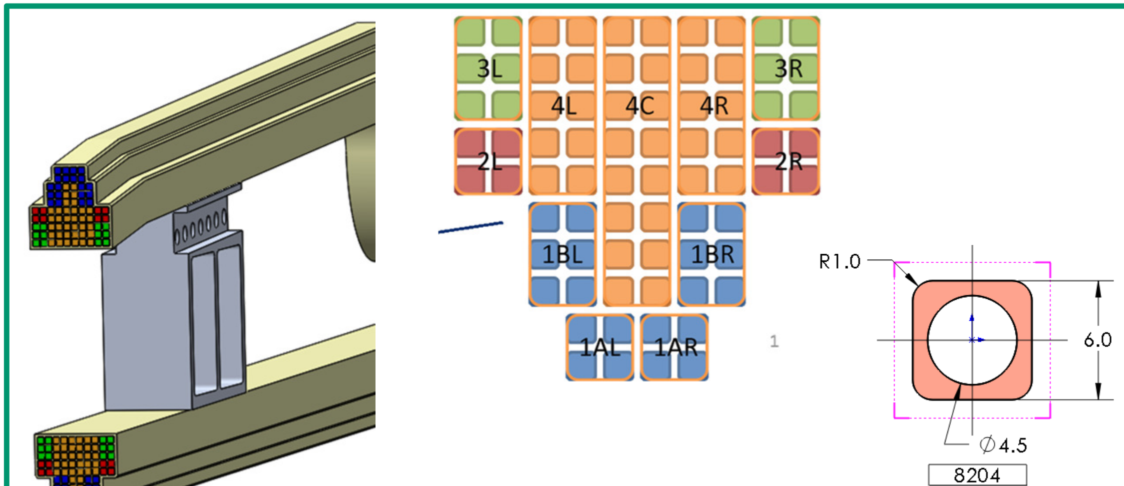
Coils Overview



Encapsulated coil shown with aluminum inserts. These inserts will be over-wrapped with the coil ground wrap and cured with the encapsulant



With ½ of the encapsulant removed, you can see the out-of-plane bends on pancakes 3R, 2R, and 1BR.

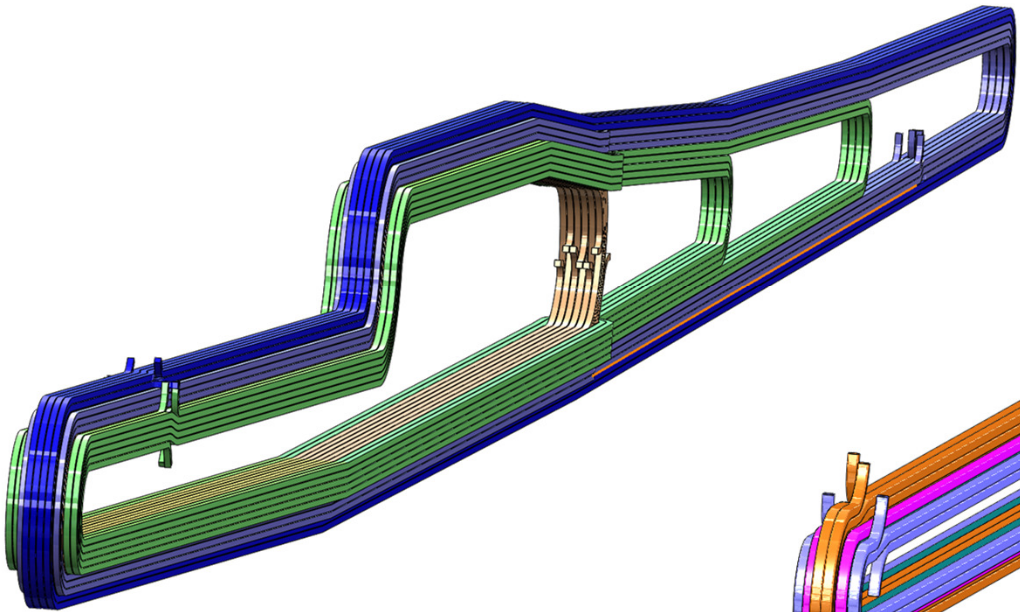


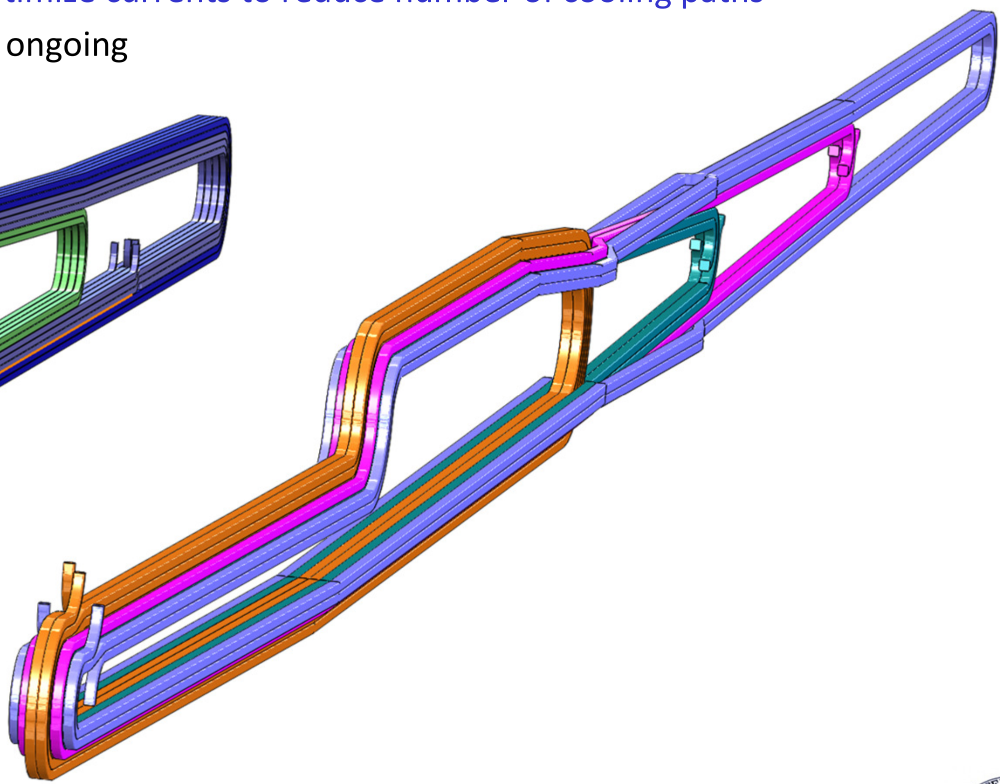
Coil cross section showing all 76 turns, 11 pancake shapes, and tentatively chosen conductor

Coil Mass	186	kg
Carrier Mass	1039	kg
Centering Force	3000 1361	lbf kgf
Current	384	A
Coil Voltage Drop	<300	V
Conductor Length / coil	775	m
Number of Turns	76	"turns"
Cooling Circuits / Coil:	17	"paths"
Water Flow / Coil:	39.72	lpm
	10.5	gpm
Water Flow / Toroid:	278.03	lpm
	73.4	gpm
Maximum Pressure:	16.7	atm
	245.2	psi
Water Temp in / out	20 / 60	°C

Coils

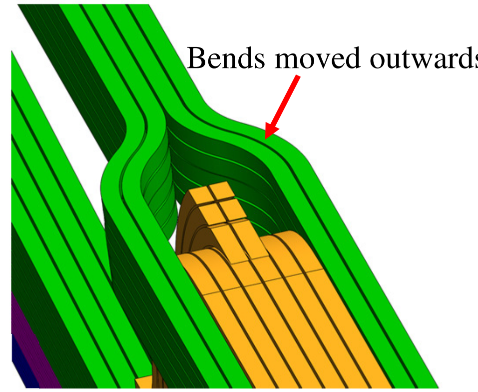
- The original design specified very long, narrow conductors. This was optimized for scattered beam optics: physics, not engineering challenges.
  - Needs many cooling paths to keep temperatures and pressure drops down
  - Predicated on the assumption that all coils will be driven by a single power supply
  - Maximum conductor length 84 m
- Now investigating alternative design that uses larger conductors driven by 4 separate power supplies
  - Multiple power supply option will also be investigated for small-conductor version – will result in lower voltages and improved tunability. Could potentially optimize currents to reduce number of cooling paths
- Design using original conductor placement still ongoing

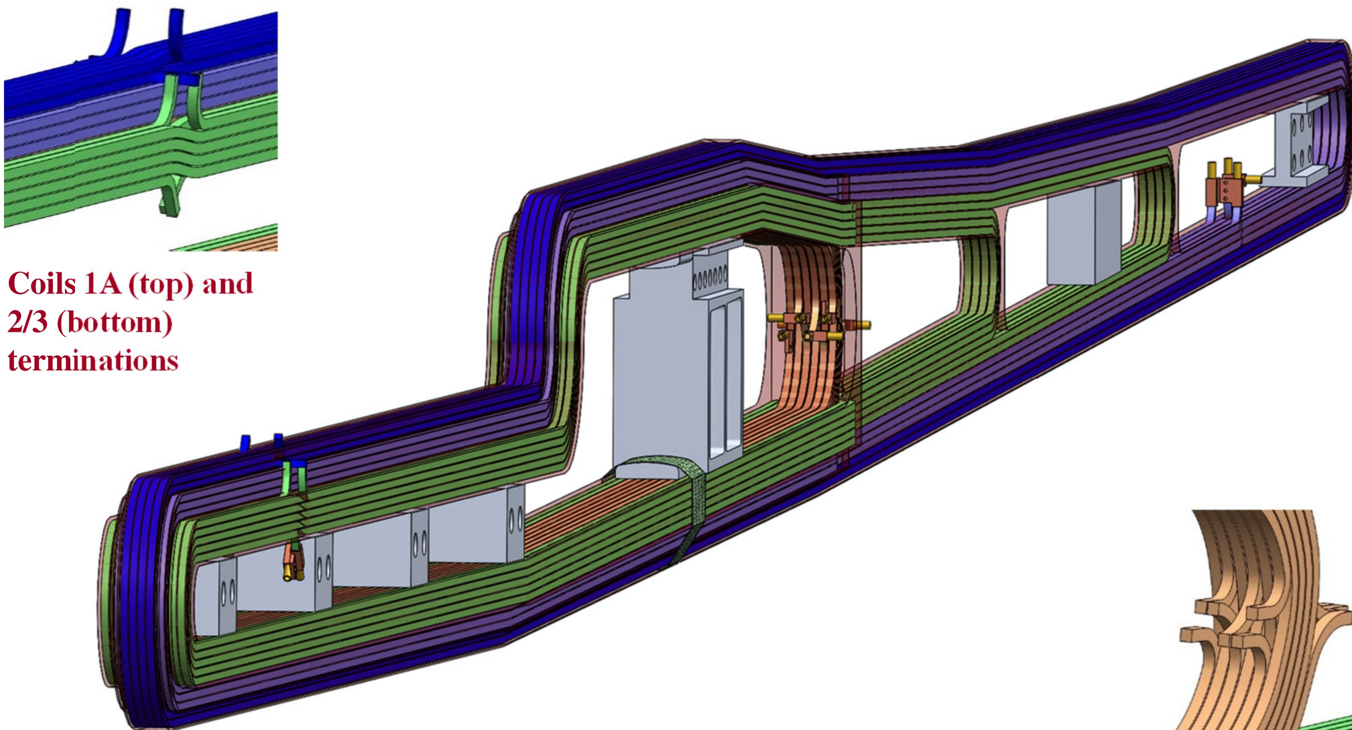




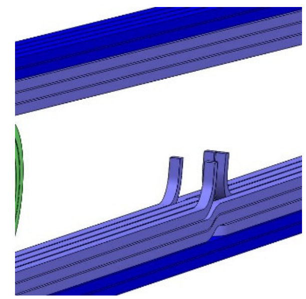
Baseline Design

- All pancakes wound using 6.0 mm conductor
- Pancakes #2 and 3 are now combined (in green; had to align their out of plane bends)
- Starting to model power and water connections
- Further work will include CFD analysis to optimize cooling path directions to minimize internal thermal gradients

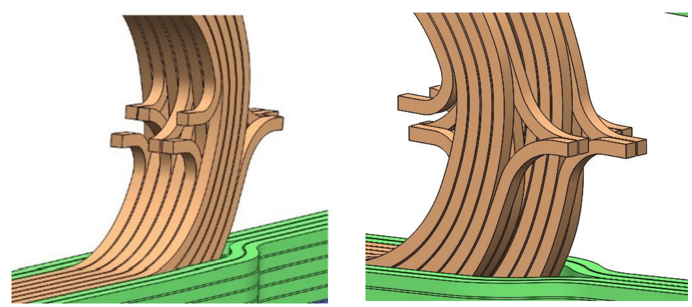




Coils 1A (top) and 2/3 (bottom) terminations

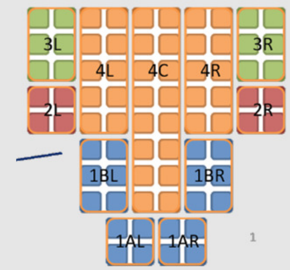


Coil 1B terminations

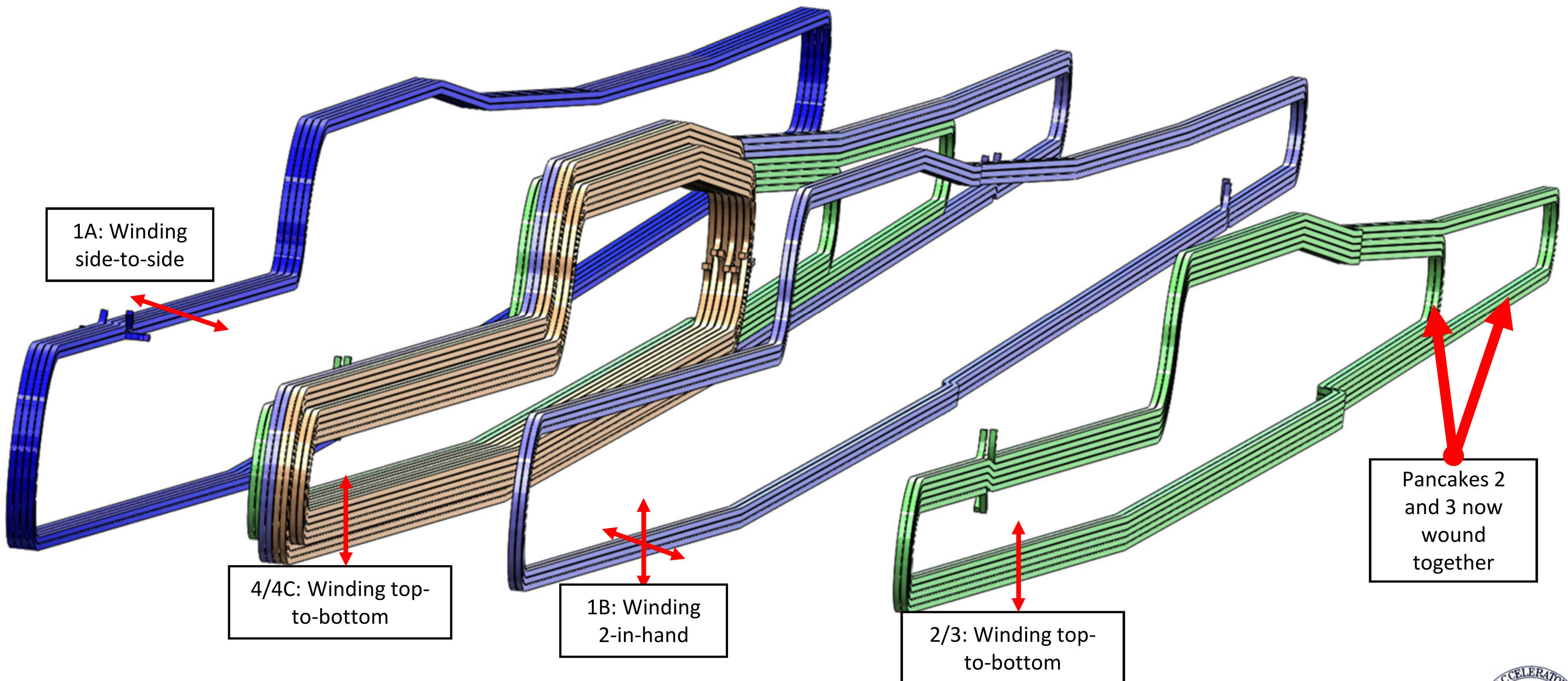


Coils 4 and 4C terminations

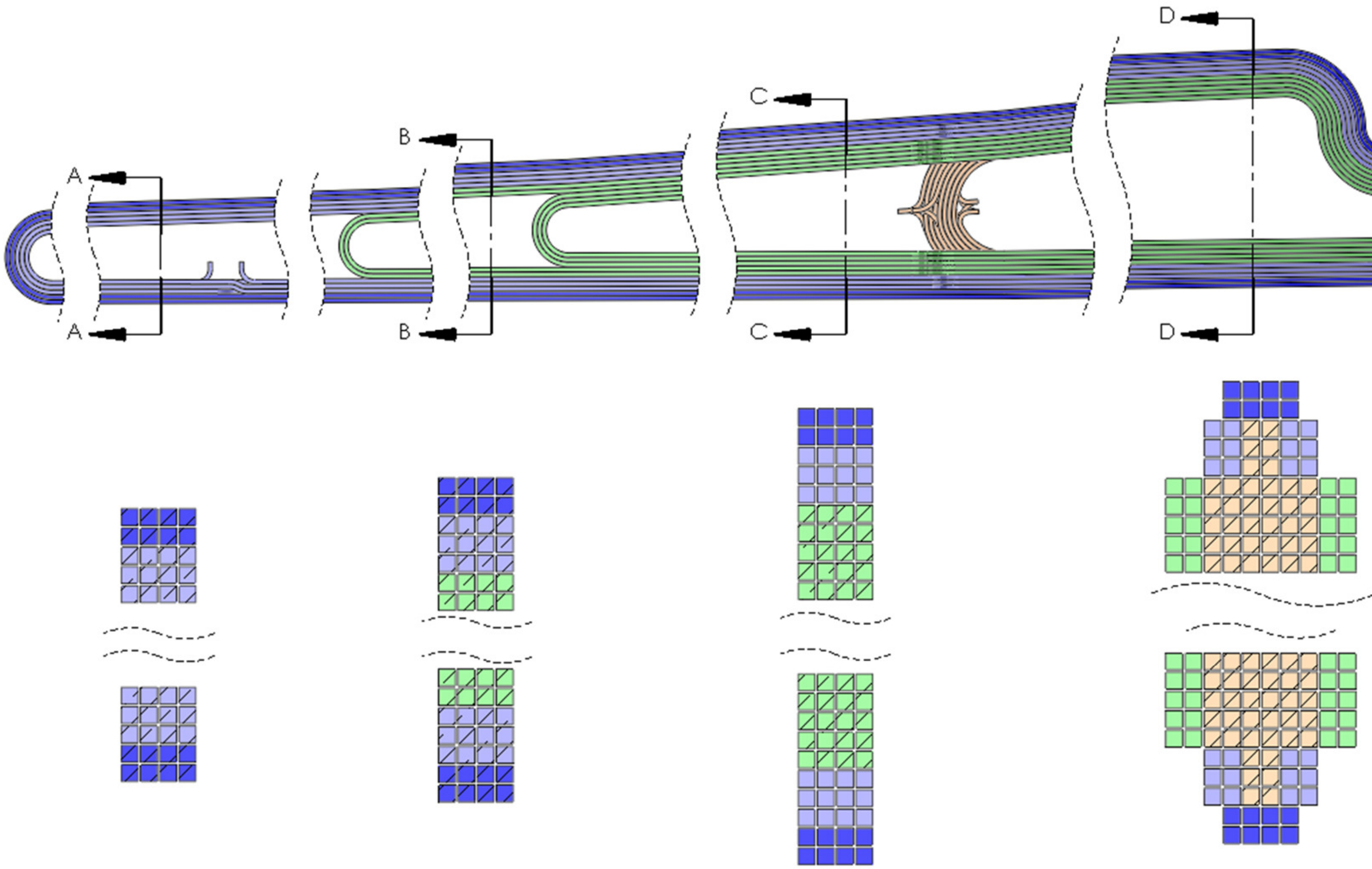
Baseline Design

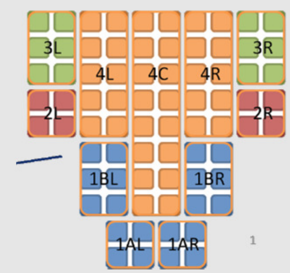


Reference Coil Layout
(not to scale)

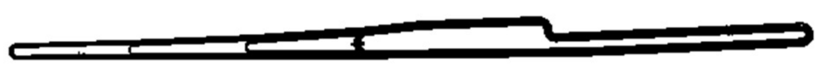


Baseline Design



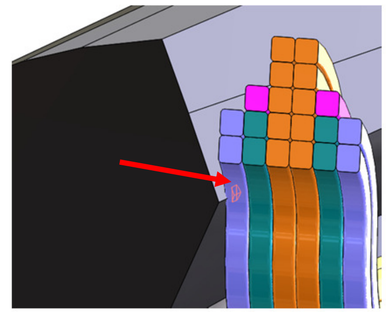


Reference Coil Layout
(not to scale)

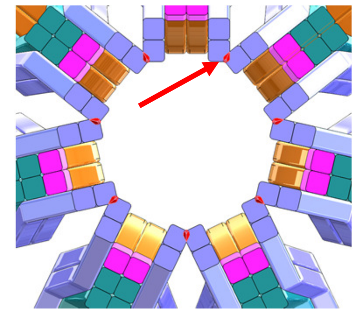


Alternative Design

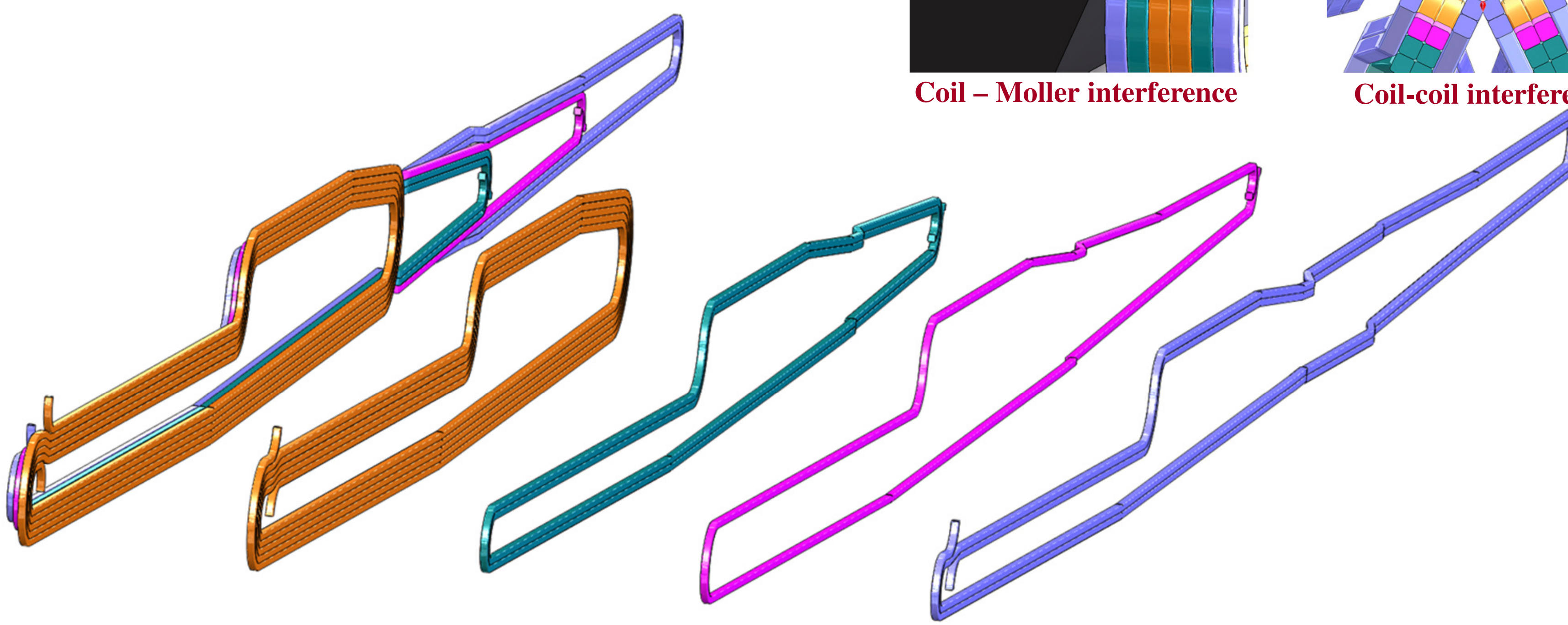
- Larger conductor (11.7 mm square with 6.5 mm hole) uses less power and can be cooled with fewer water paths
- NI for each of the 4 loops is the same as baseline
- Ratios of conductors in each loop have been changed → 4 separate power supplies needed
  - Same conductor throughout, so current densities are different for each loop
  - *Currents range from 1,230 A to 1,940 A*
- Still needs work to eliminate interferences
- Optics need to be checked with more detailed EM model



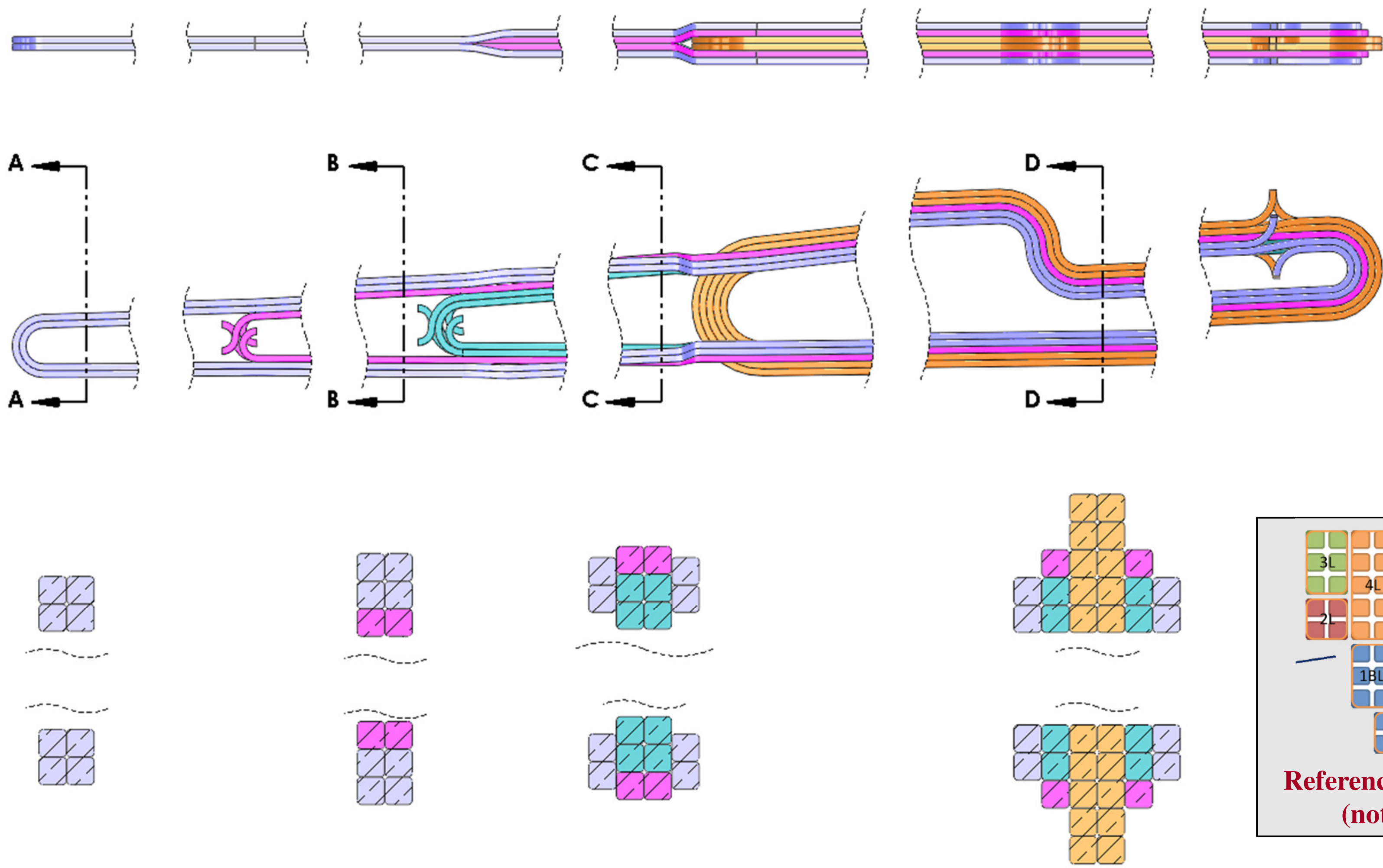
Coil – Moller interference

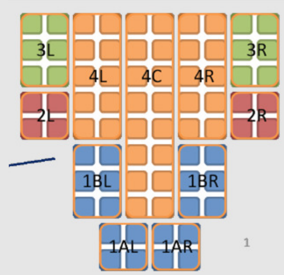


Coil-coil interference



Alternative Design

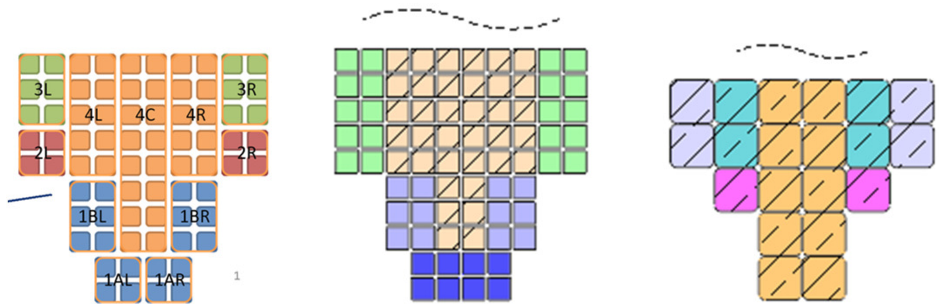




**Reference Coil Layout
(not to scale)**

Comparison of two Designs

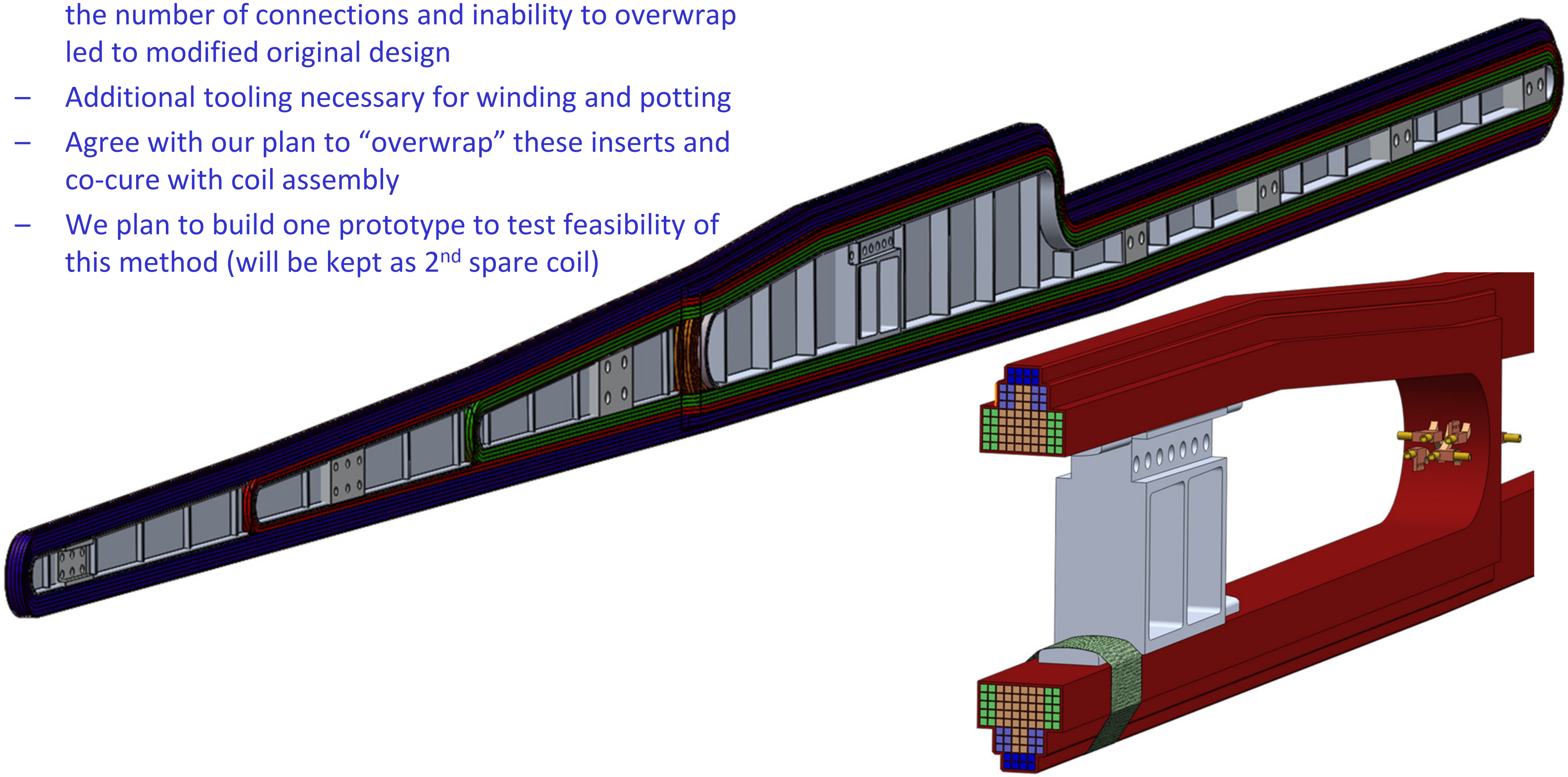
*note: Values are for individual coils unless otherwise indicated



<table>
<tr><th colspan="2"></th><th>Proposal</th><th>2013 Version</th><th>2015 Version</th><th>2015 MkII</th><th>Unit</th></tr>
<tr><td colspan="2">Conductor</td><td>5.8 sq</td><td>6.0 sq</td><td>6.0 sq</td><td>11.7 sq</td><td>mm</td></tr>
<tr><td colspan="2">Cooling Hole</td><td>3.125</td><td>4.5</td><td>4.5</td><td>6.5</td><td>mm Dia.</td></tr>
<tr><td colspan="2">Number of Turns</td><td>78</td><td>78</td><td>78</td><td>20</td><td>-</td></tr>
<tr><td colspan="2">Current Density</td><td>1553</td><td>1965</td><td>1965</td><td>1960 (max)</td><td>A/cm2</td></tr>
<tr><td colspan="2">Power Supply Voltage (7 coils)</td><td>1600</td><td>2000</td><td>2000</td><td>60-180</td><td>V</td></tr>
<tr><td colspan="2">Power</td><td>86</td><td>138</td><td>138</td><td>94.6</td><td>kW</td></tr>
<tr><td rowspan="6">Pressure Drop</td><td>1A</td><td>196</td><td>212</td><td>201</td><td rowspan="2">243</td><td>psi</td></tr>
<tr><td>1B</td><td>192</td><td>93</td><td>246</td><td>psi</td></tr>
<tr><td>2</td><td>227</td><td>132</td><td rowspan="2">175</td><td>48</td><td>psi</td></tr>
<tr><td>3</td><td>227</td><td>245</td><td>80</td><td>psi</td></tr>
<tr><td>4</td><td>126</td><td>82</td><td>78</td><td rowspan="2">150</td><td>psi</td></tr>
<tr><td>4C</td><td>128</td><td>138</td><td>237</td><td>psi</td></tr>
<tr><td colspan="2">Water Flow</td><td>17.3</td><td>10.5</td><td>11.9</td><td>13.0</td><td>GPM</td></tr>
<tr><td colspan="2">Water Channels</td><td>24</td><td>17</td><td>14</td><td>8</td><td>-</td></tr>
</table>

Coils Fabrication

- Vendors offered some advice on the bonded coil inserts
  - Would prefer these to completely fill the holes but the number of connections and inability to overwrap led to modified original design
  - Additional tooling necessary for winding and potting
  - Agree with our plan to "overwrap" these inserts and co-cure with coil assembly
  - We plan to build one prototype to test feasibility of this method (will be kept as 2^{nd} spare coil)



Shown above: coil model with Block inserts as well as full coverage. Inset: Current design with blocky inserts and "ears" to allow fiberglass overwrap

Coils Fabrication

- We conducted 2 site visits to Everson-Tesla in Nazareth, PA
- General impressions:
  - Clean, professional shop
  - Does excellent work on major projects → demonstrates relevant expertise
    - Cyclotrons
    - Beam optics for industry and academia.
    - BLAST toroid coils
- Feedback:
  - 250 psi water pressure is no problem
  - Suggest to use bisphenol-A-based epoxy, rather than cyanate-based.
    - Current estimates of radiation dose are 0.3 – 3.0 e10 rad over 3-year lifetime → Needs to be more precise.
    - Example epoxy is CTV-101k for good working properties, however CTD-403 and CTD-425 may provide better radiation tolerance at the expense of cost.
  - Ruled out our plan to use Double-Dacron Glass (DDG) as conductor insulation
    - Need to use 2x 0.007" fiberglass due to radiation damage tolerance
  - Provided some capability tolerances
    - 3mm planarity over entire coil
    - Coil position +/- 1.5 mm everywhere
    - Potting thickness tolerance +/- 1.5 mm → for minimum 1.5 mm epoxy thickness, need to design for 3.0 mm nominal.
  - They expect this project will take ~1 year from order placement to completion.

Hall A Infrastructure

- Hall A LCW Water System:
  - 500 GPM
  - 250 psi
  - 85 °F (29 °C) supply / 110 °F (43 °C) return
- Magnet cooling → A separate Moller magnet cooling system with refrigeration is required
  - Must isolate local water from site water to prevent activated water getting topside
  - Will include chiller to reduce LCW supply to 15-20 C and maintain to within a few degrees
    - Heat dumped to site water at 60 C
  - Will supply cooling to upstream torus, downstream torus (hybrid), and collimators.
- Hall A Power
  - Currently 0.86 MVA available
    - Estimate Hybrid alone will use **1 MW**
    - Additional substation and power drops being installed for 2 MVA
- Hall A Crane
  - 20 Ton capacity
  - Sufficient for assembling coils into support structure and loading into vacuum vessel
  - Combined toroid + vacuum vessel might be above 20t, but no plans to move them together with crane

Moller Hybrid Vacuum Chamber

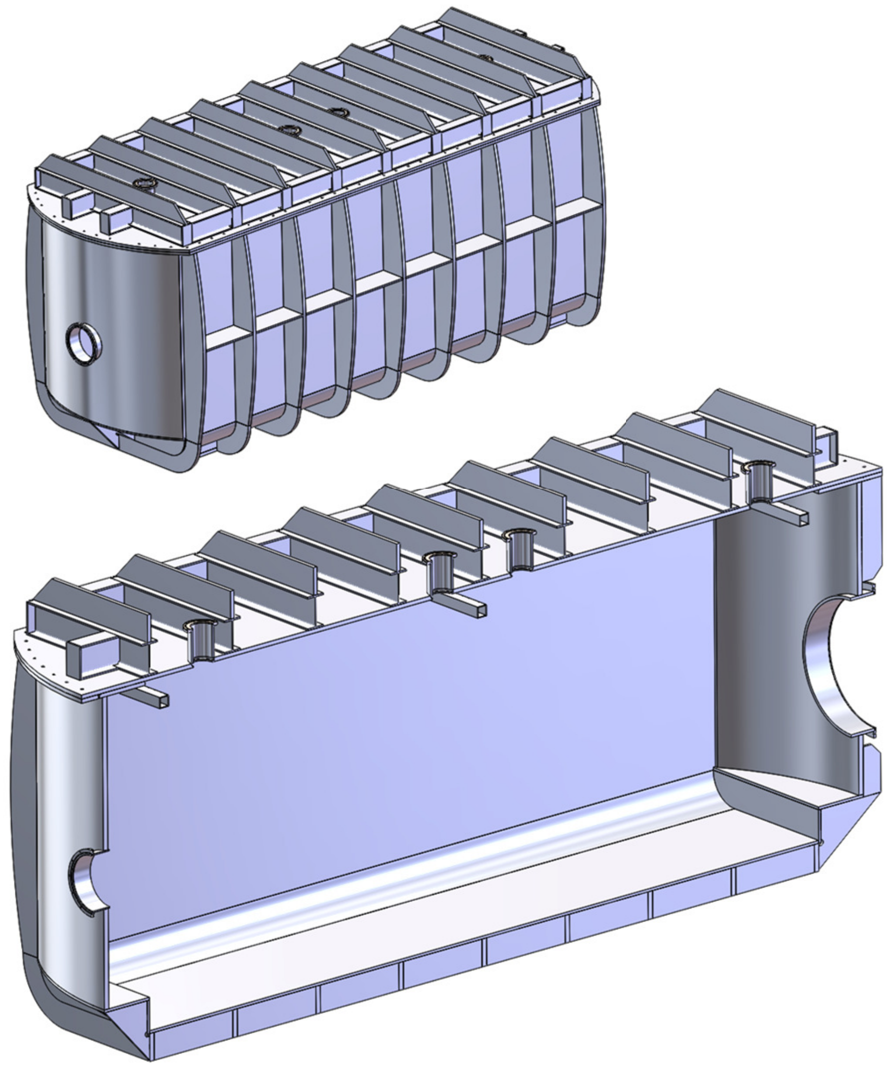
The MOLLER experiment design of the Hybrid magnet along with physics considerations has presented challenges for the vacuum system design. Several solutions were considered to minimize scattering in this region. One solution included vacuum chambers between the magnets with the appropriate windows. This was considered too complicated and also difficult to implement without compromising the physics. Another solution that is still an alternative is to use helium bags in this region. This still has the potential to compromise the physics due to scattering issues.

The baseline we are pursuing is a large vacuum chamber that encloses the entire Hybrid Toroid that then connects to the rest of the vacuum system for the experiment. This eliminates any scattering issues and maximizes the acceptance between the coils. The vacuum chamber design includes the feature of all of the magnet services attaching through the top flange. The coil support also attaches to the top flange thus allowing maintenance and alignment of the Hybrid Coil system by removing the top flange of the vacuum chamber. The following slides describe the current status of this design.

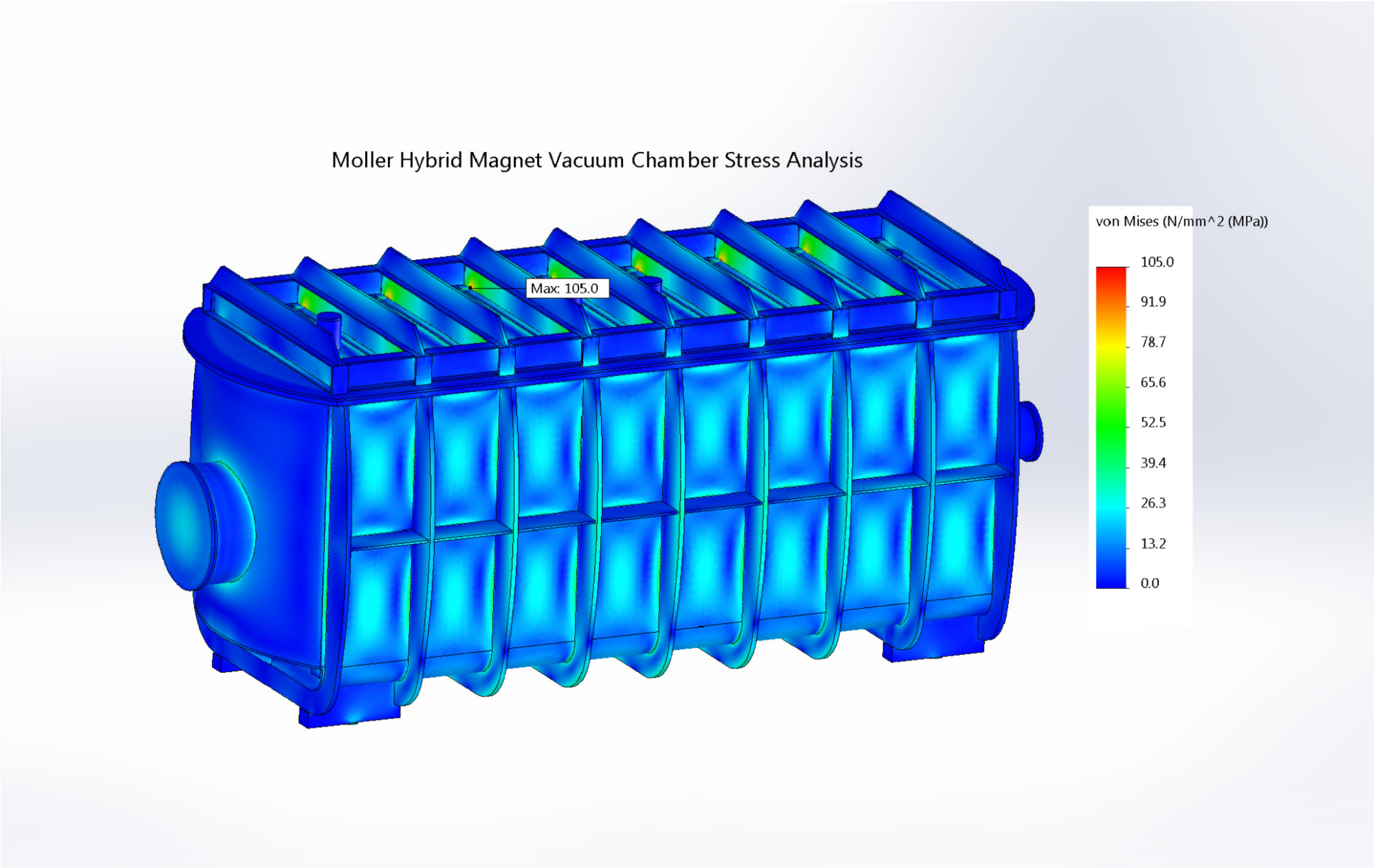
MOLLER Hybrid Vacuum Chamber

- Substantial optimization of Hybrid Vacuum Chamber for manufacturability based on vendor feedback.
- Full set of manufacturing drawings for budgetary bids of preliminary design.
  - Two manufacturers have been contacted. First bid is $600K, waiting for second bid.

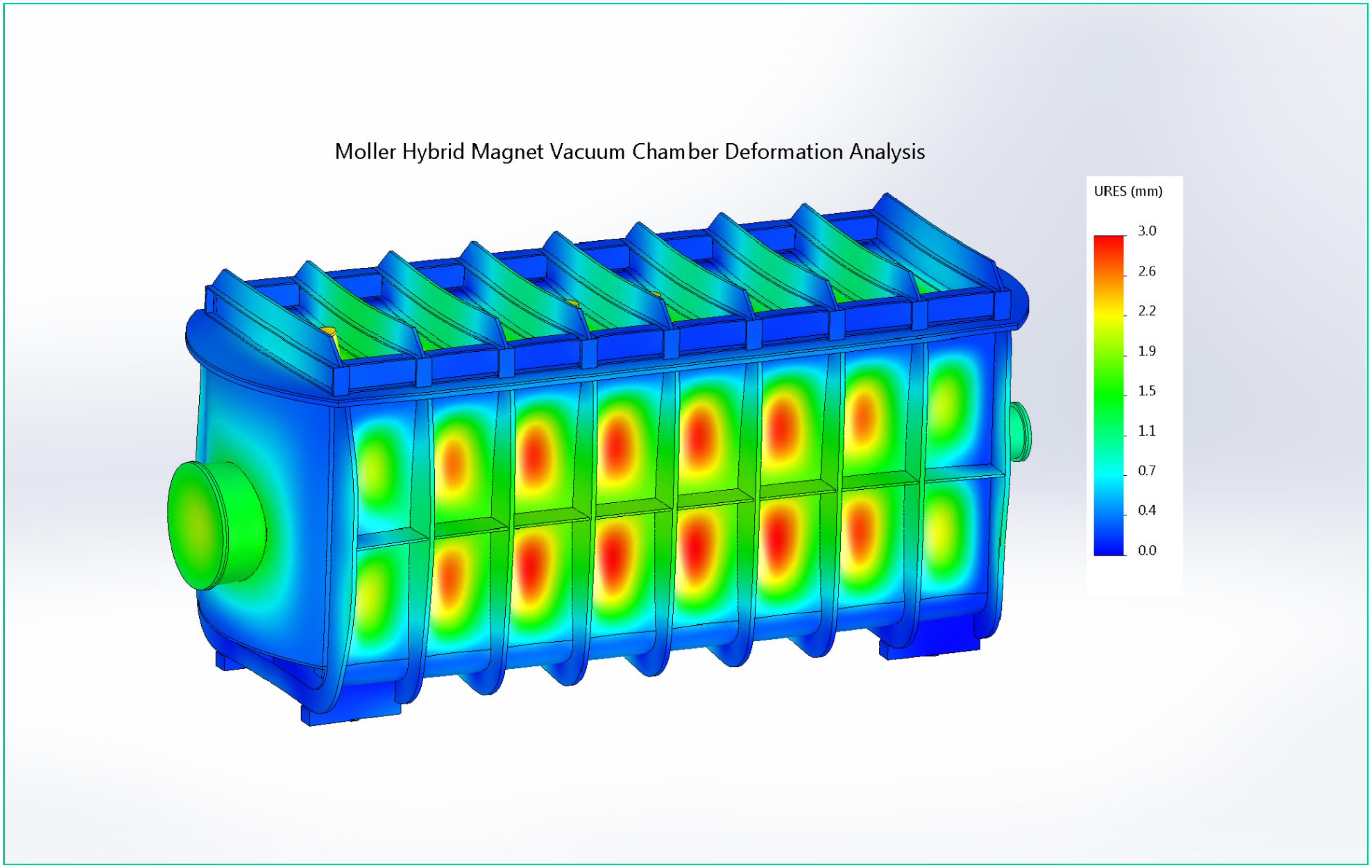
Overall Size	9.0 m x 3.3 m x 4.0 m (height)
Mass	38 000 lb
Pumping	Primary pumping via cryo-pumps Additional pumping via 77 K cryo panel on floor (supplied with house LN2). Offers up to 11 litre/s/cm2 pumping speed for H20
Seals	Differentially-pumped double o-ring on top flange
Loads	20 000 lbf weight of magnet + 1.0 atm pressure
Stress	120 MPa in bulk, 60 MPa near welds (FOS of 2 or greater)
Deflections	<3 mm on sides, <1.5 mm on top



MOLLER Hybrid Vacuum Chamber Stress Results

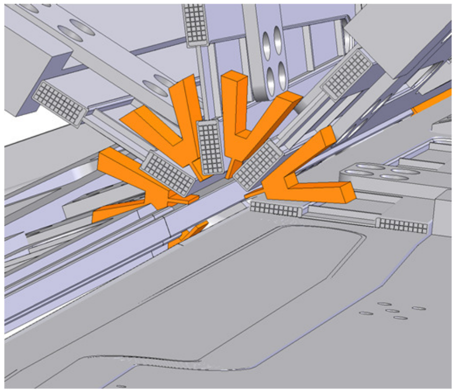


MOLLER Hybrid Vacuum Chamber Deformation Results

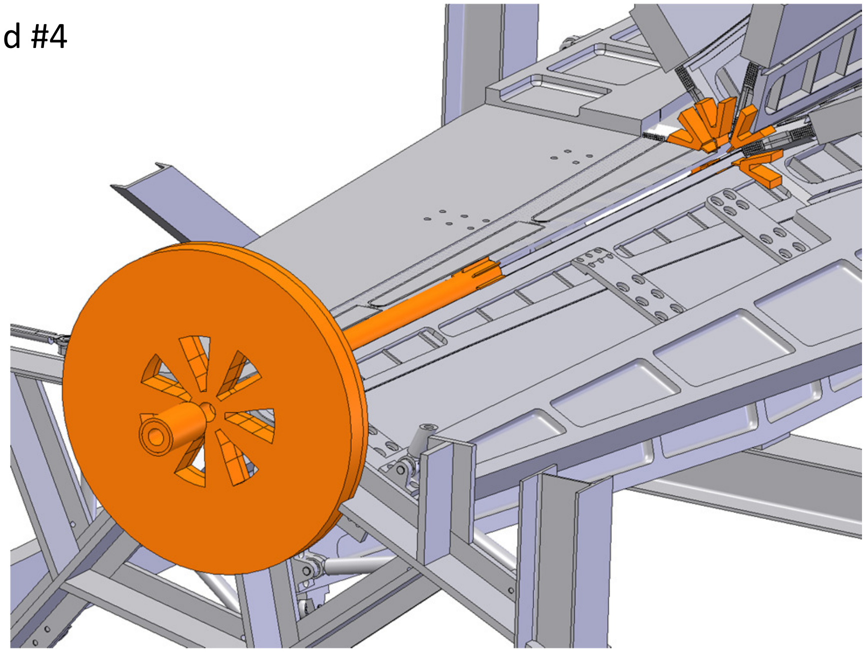


Collimators

- Collimators being integrated into assembly
- Collimator #5 lives completely inside the hybrid – consists of 2 parts
  - Split "beampipe" collimators in toroid
    - Absorbs 1kW photon flux
    - Current prediction of 3mm high-z material sufficient to absorb photons
    - Does not need to be complete cylinder. We could split the shape into 7 plates that nest. They only need to shield the gaps between the coils.
  - 7 separate Wedge collimators
- Both parts will be supported on coils
- Toroid frame being modified to support Collimators #3 and #4

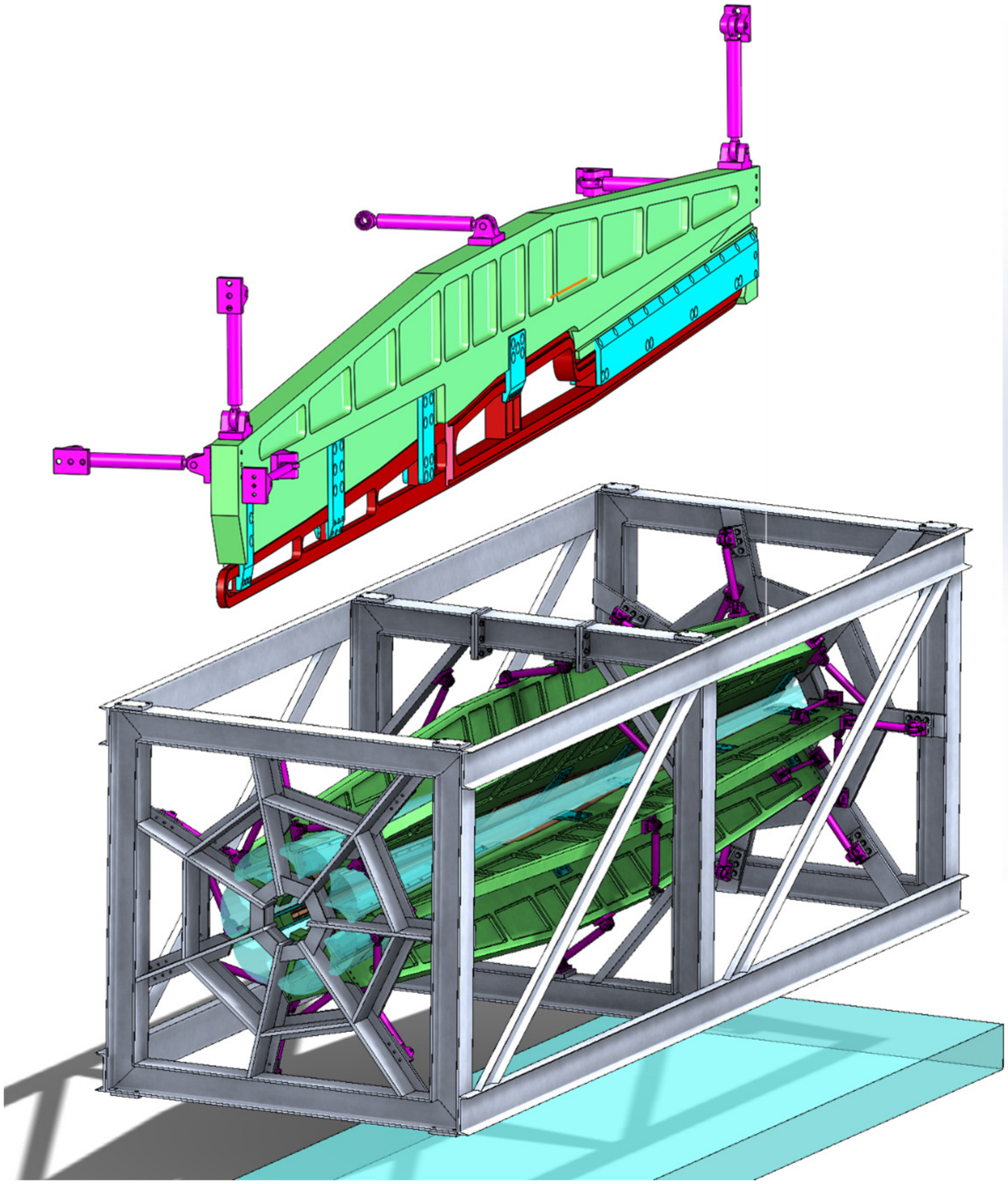


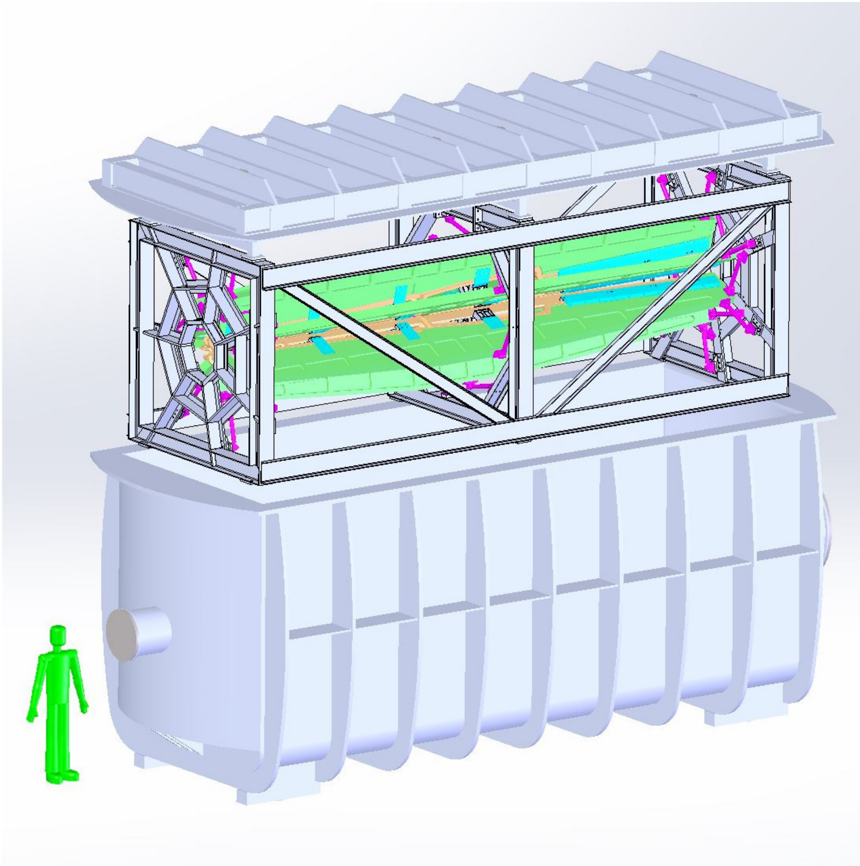
7 wedge segments of collimator 5



Collimators #3 through #5 (left to right)

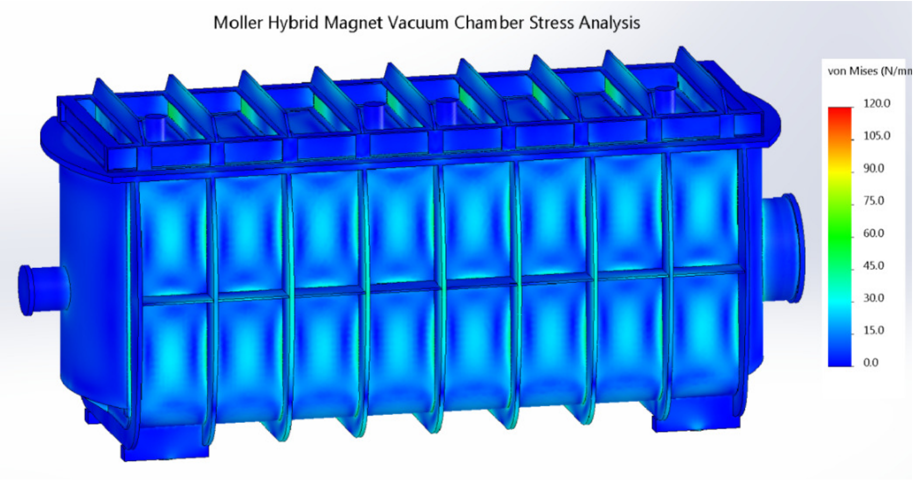
Latest Frame and Carriers

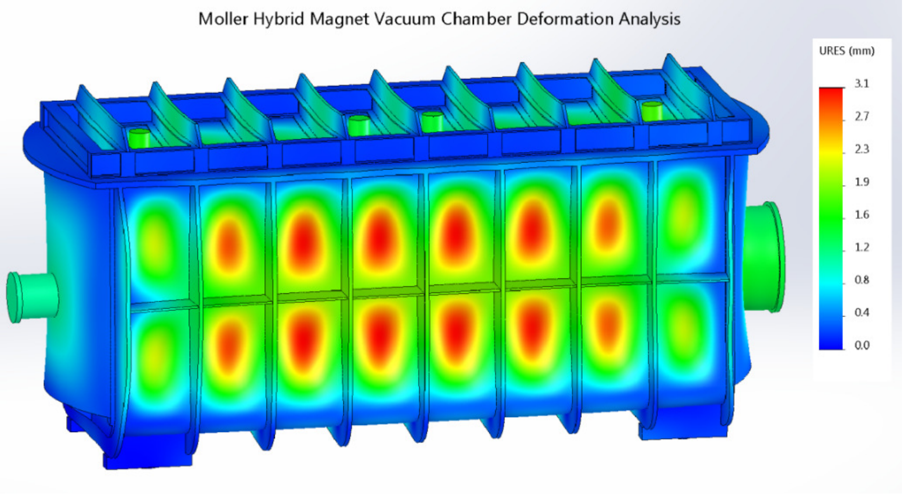




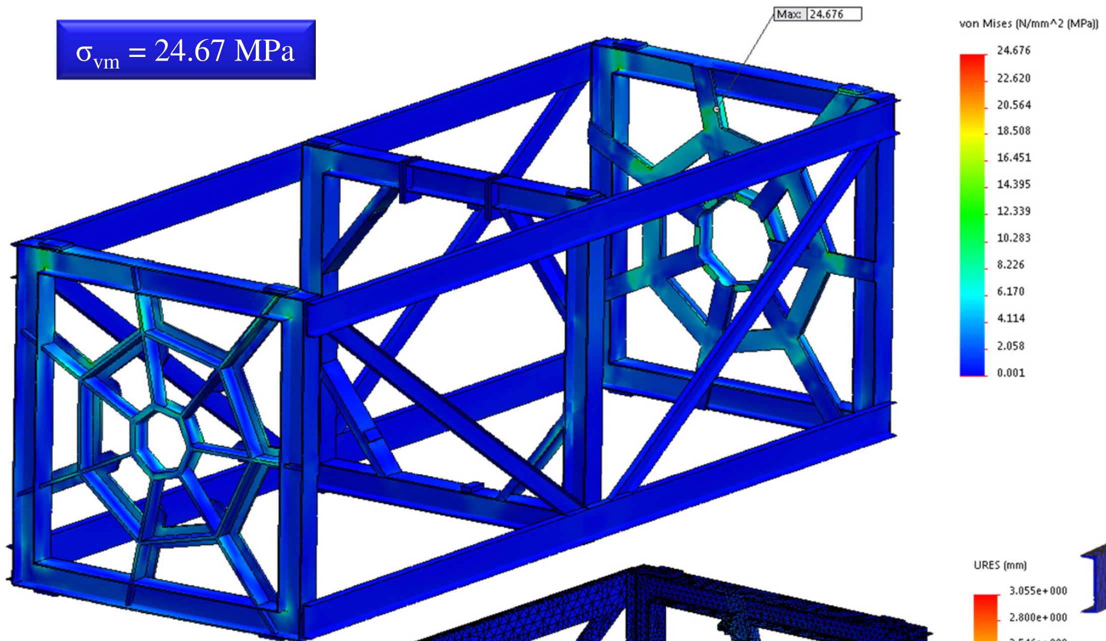
Chamber FEA

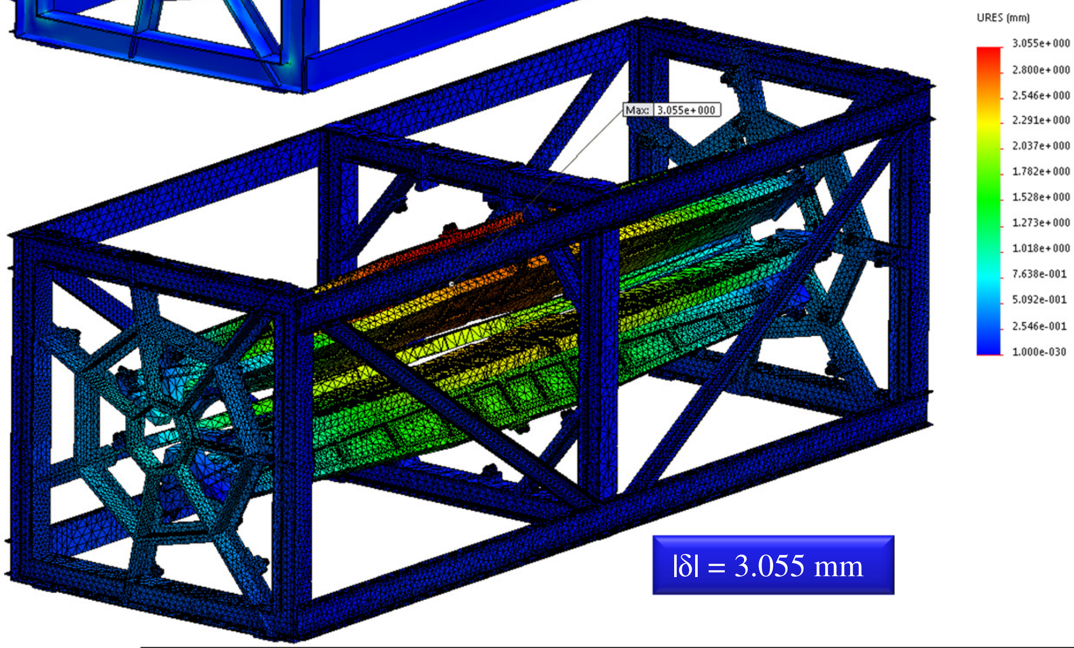
- Applied loads include self-weight of chamber (~19,000 lbf), external pressure (1.0 atm) and weight of toroid assembly supported on top plate (20,000 lbf)
  - End blankoff flanges included for analysis
    - These add to overall pressure load but must be used for initial testing.
- Maximum deflection on top plate is .059" (1.5 mm)
- Maximum global deflection is 3 mm on side plates
- Stress has a safety factor of 2 against yield (6061-T6 aluminum)
  - The yield stress limit is 240 MPa and 105 MPa across welds. Stress obtained from finite element analysis indicates maximum stress levels at 120 MPa and stress levels of 60 MPa near the welded sections.



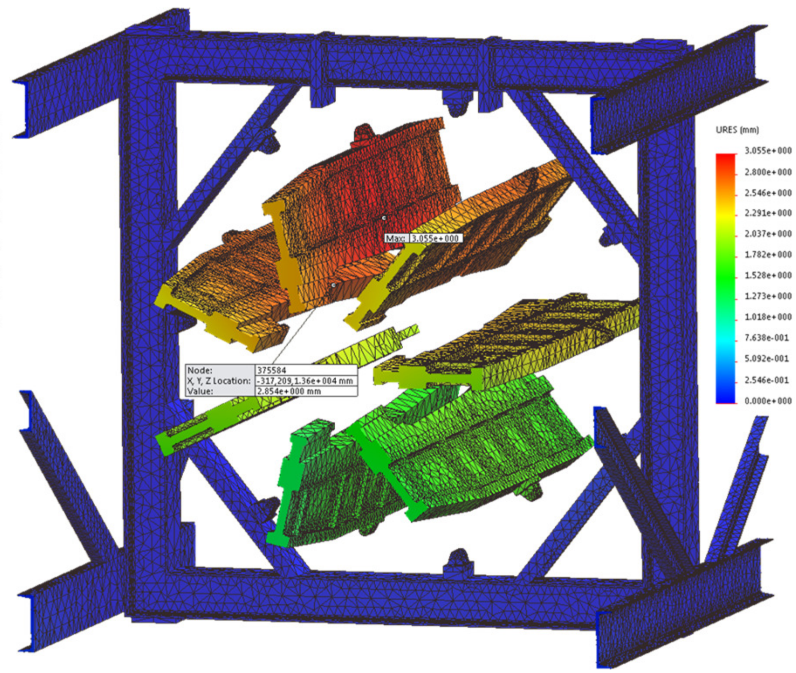


Frame Analysis



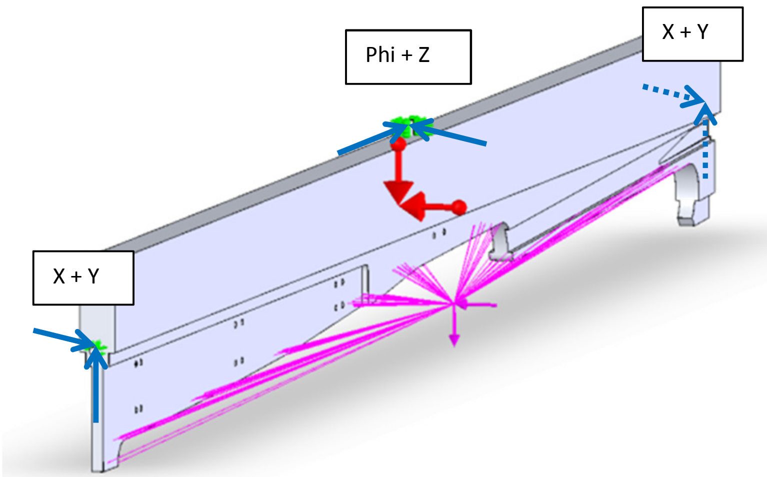


23Jan2014 – New model using commercially available aluminum members. Bolts not included, but link connectors are. Forces include gravity, magnetic forces (3000 lbf) and coil weight.

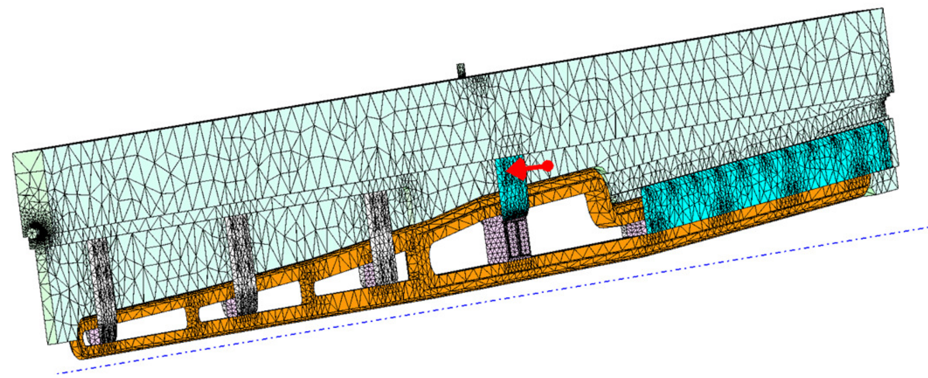


Carrier Analysis

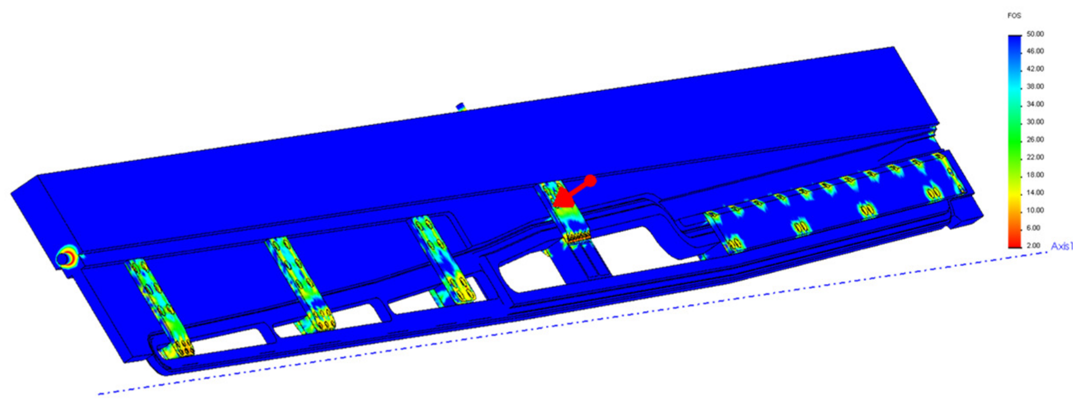
- Both vertical and horizontal orientations are considered
- Loads include gravity (approx. 1100 kgf for carrier and 250 kgf for coils) and magnetic centering force (3000 lbf)
- Boundary conditions based on 6-strut kinematic support



Boundary conditions for carrier analysis. Blue arrows denote fixed translational degrees of freedom from struts. Red arrows indicate components of gravity vector. Note: Both end pins are co-axial. All 3 pin axes intersect predicted CG of coil+carrier assembly.

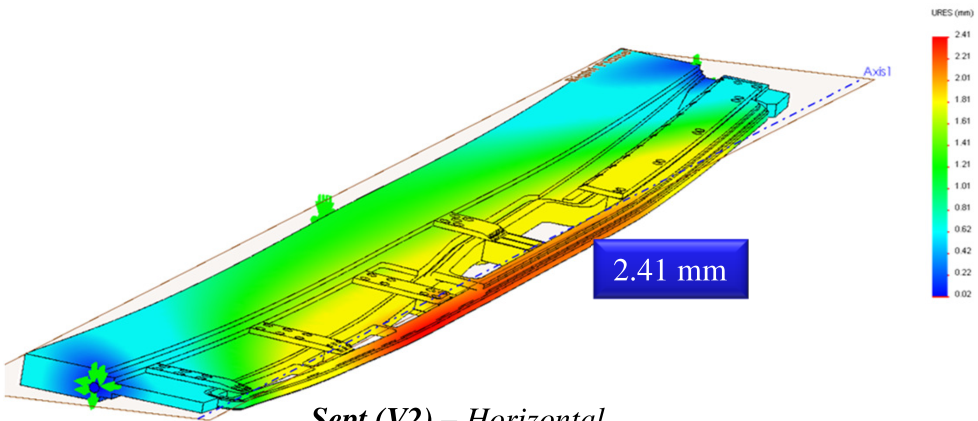


Solid mesh for study that incorporates carrier assembly + coils

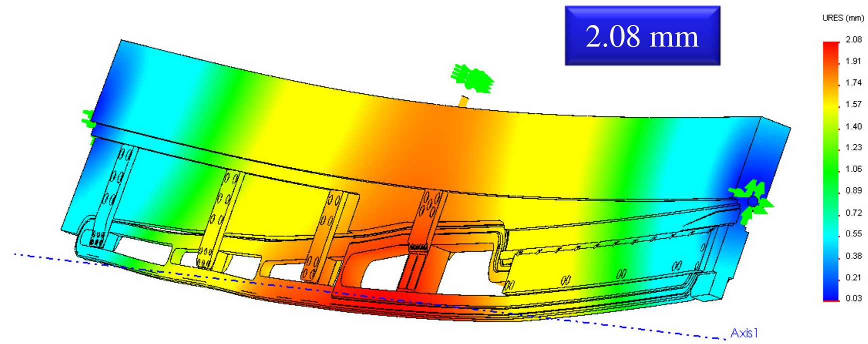


Stress analysis in which bolted joints are modeled. Horizontal orientation, showing Factor of Safety (areas between FoS = 2 and FoS = 50)

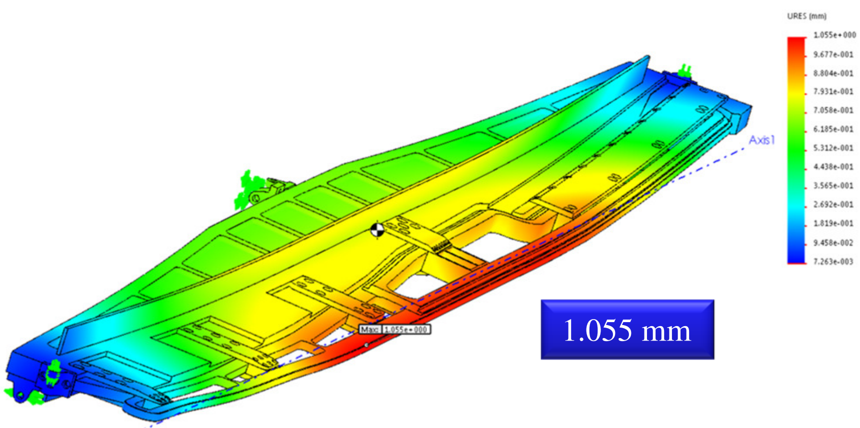
Carrier Analysis – Selected Deflections



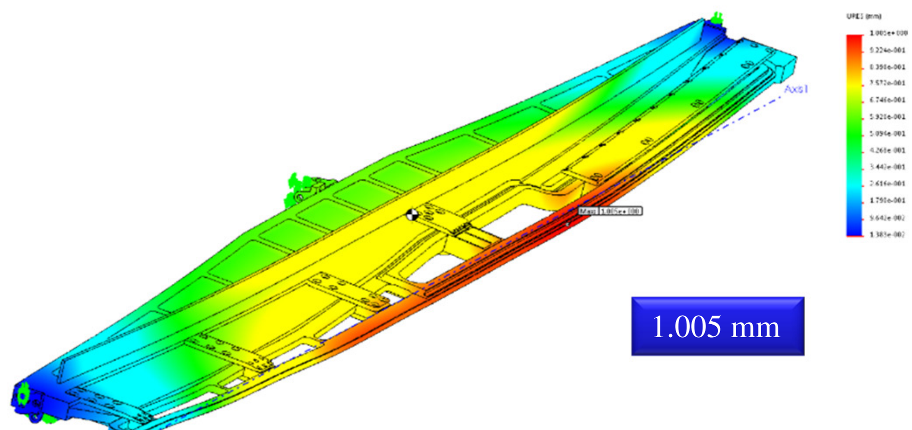
Sept (V2) – *Horizontal*



Sept (V2) – *25.8 deg ("vertical")*



Nov 7 (R9) – *includes upstream added material and side rib*

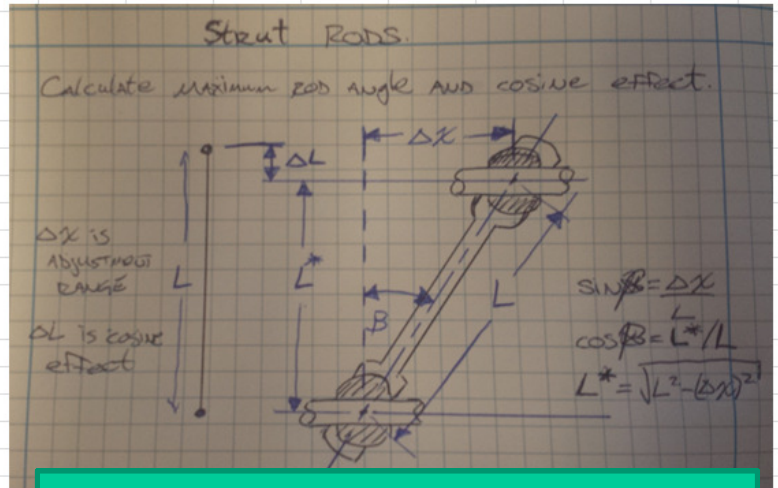


Nov 7 (R10) *Moved R supports outwards, moved end phi supports inwards*

6-Strut Support Links

	Cosine Effect (mm)					
Adjustment Range (mm) -->	5	10	15	20	25	30
200	0.06	0.25	0.56	1.00	1.57	2.26
300	0.04	0.17	0.38	0.67	1.04	1.50
400	0.03	0.13	0.28	0.50	0.78	1.13
500	0.03	0.10	0.23	0.40	0.63	0.90
600	0.02	0.08	0.19	0.33	0.52	0.75

	Ball Angle (deg)					
Adjustment Range (mm) -->	5	10	15	20	25	30
200	1.43	2.87	4.30	5.74	7.18	8.63
300	0.95	1.91	2.87	3.82	4.78	5.74
400	0.72	1.43	2.15	2.87	3.58	4.30
500	0.57	1.15	1.72	2.29	2.87	3.44
600	0.48	0.95	1.43	1.91	2.39	2.87



Strut Links Current Design Length: **450 mm**