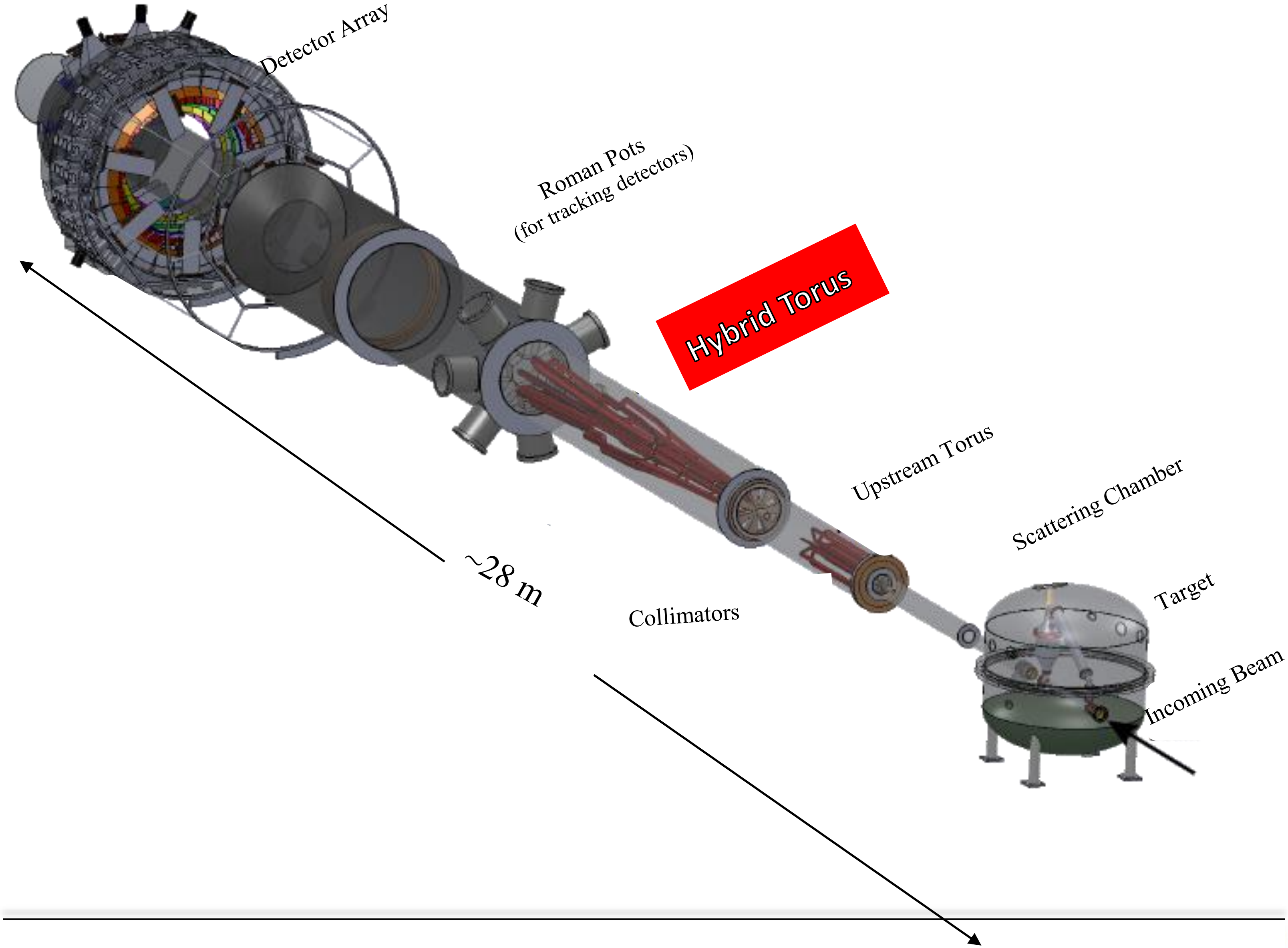
MOLLER Hybrid Toroid External Magnet Review

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

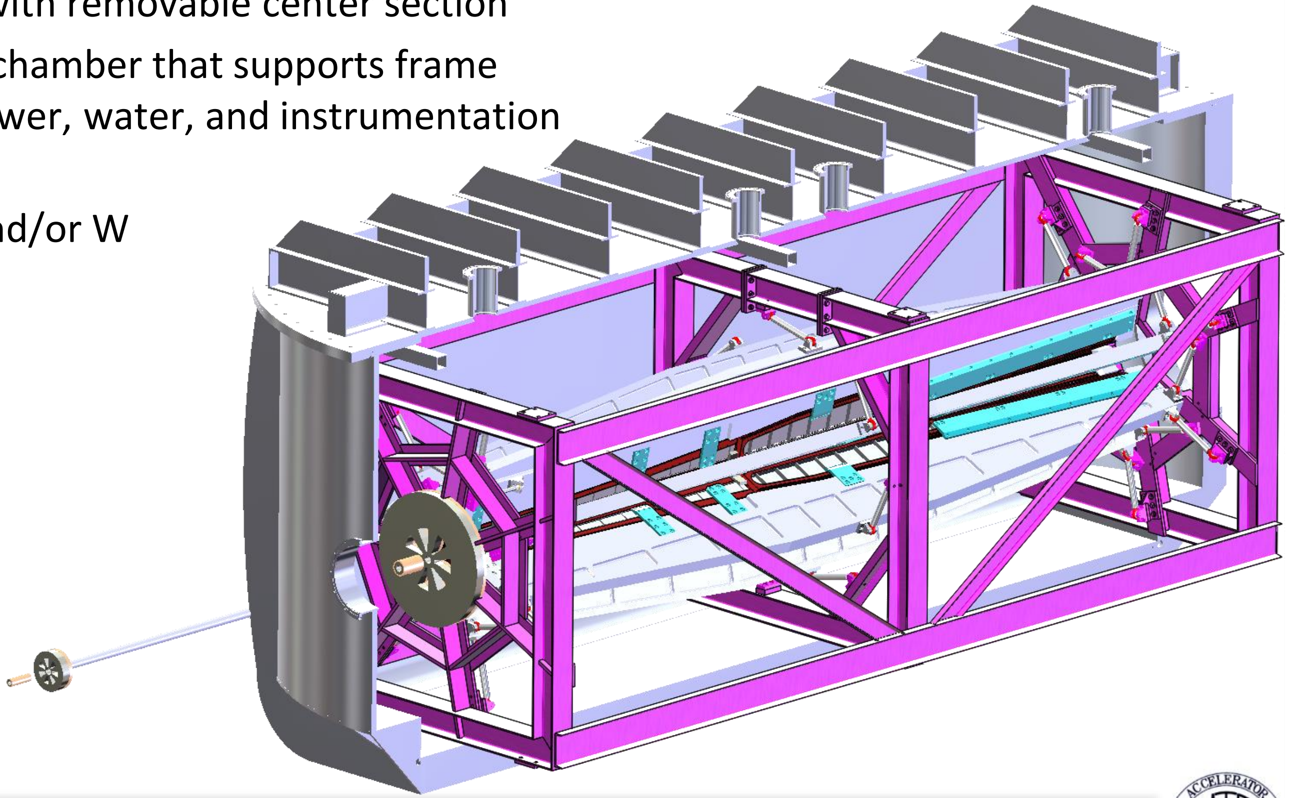
Presented to MOLLER Internal Magnet Advisory Group

Thursday, 23rd July, 2015

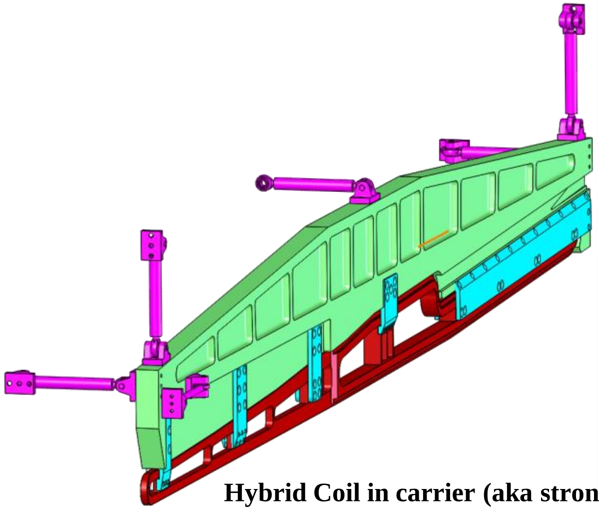

Detector Array
Roman Pots
(for tracking detectors)
Hybrid Torus
Upstream Torus
Scattering Chamber
Target
Incoming Beam
Collimators
~28 m

Overview

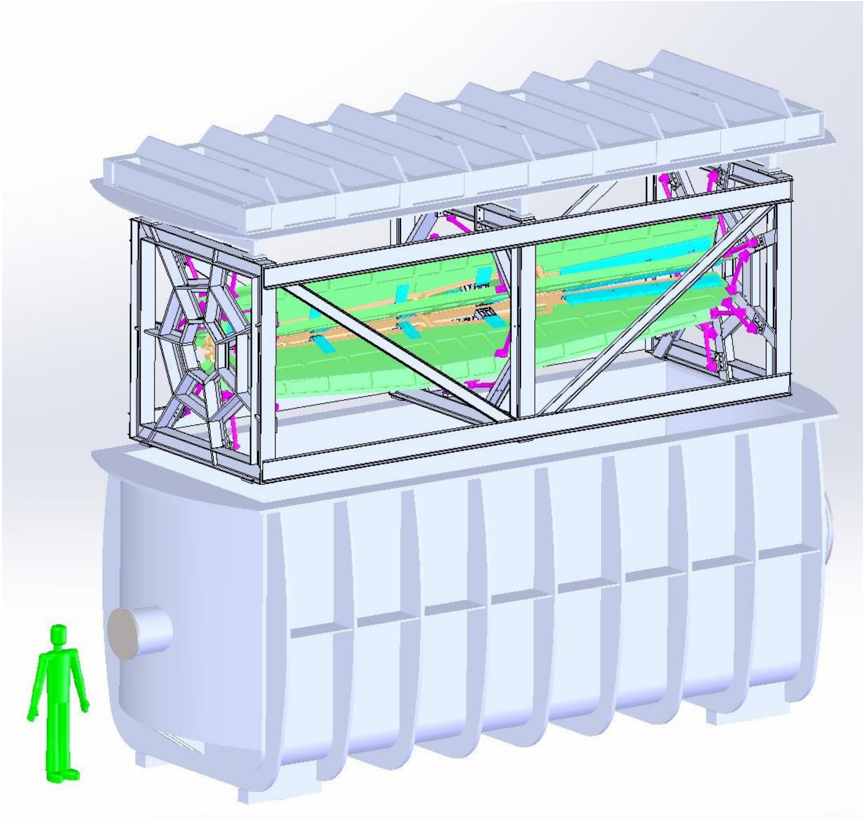
- **"Moller Hybrid":** A 7-sector toroidal magnet for focusing scattered Møller and ep electrons
- **Coils:** pancake-wound, water-cooled copper with multiple current return loops. They are supported on aluminum strongbacks (or "coil carriers") which themselves mount to the frame via kinematic 6-strut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



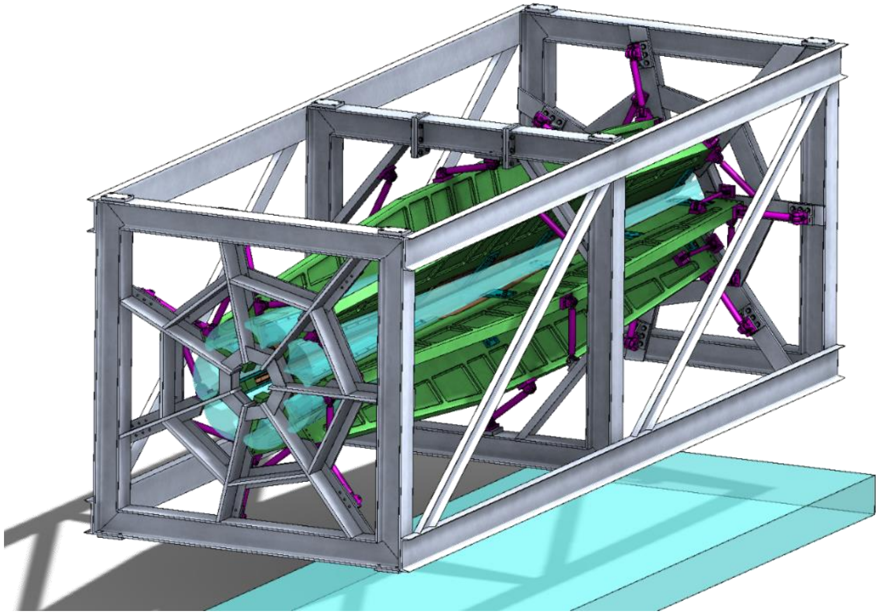
Overview



Hybrid Coil in carrier (aka strongback)

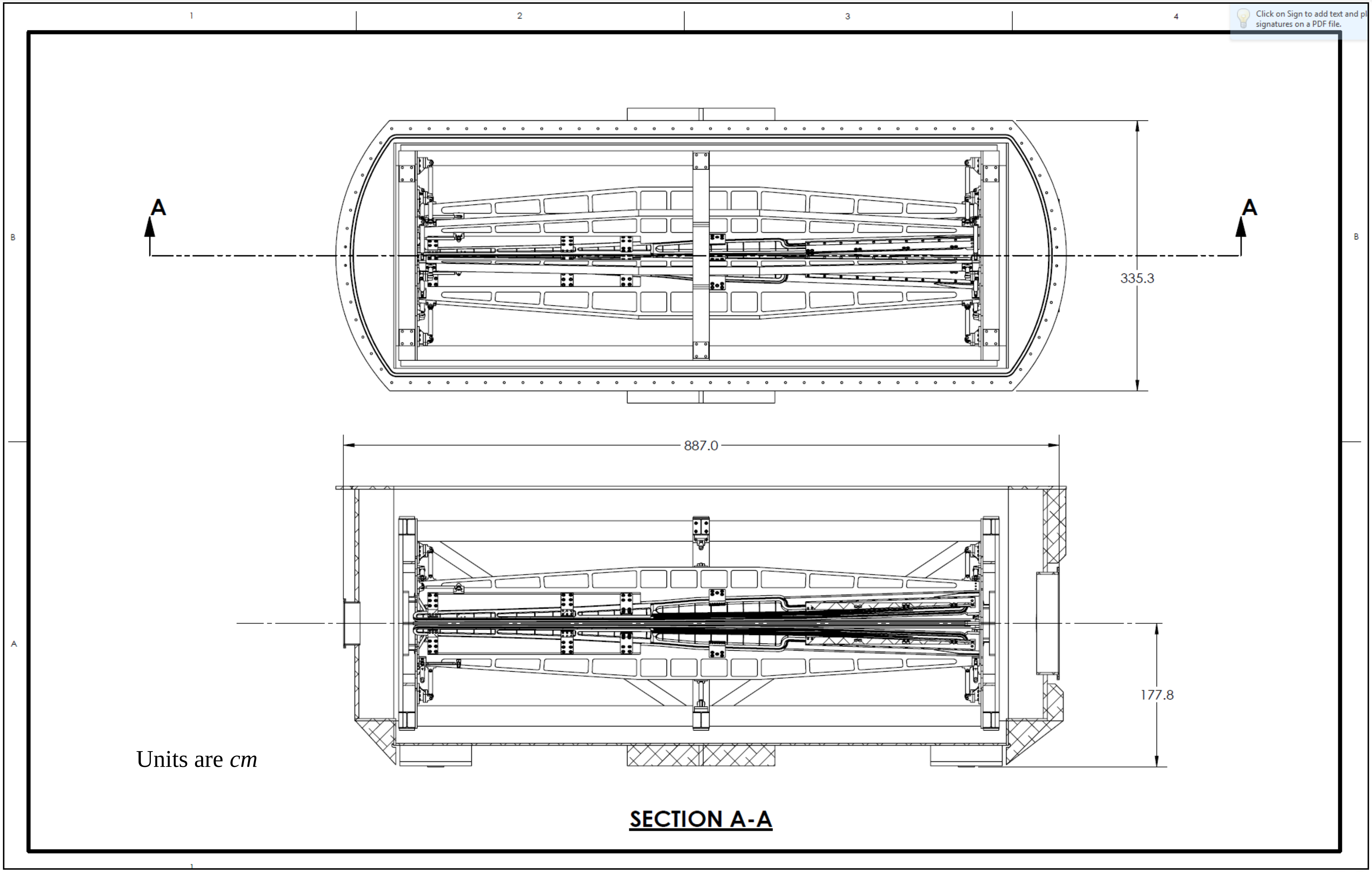


Hybrid Coil in frame, hanging from vacuum chamber lid



Hybrid Coil in frame, showing particle tracks in blue

Overview

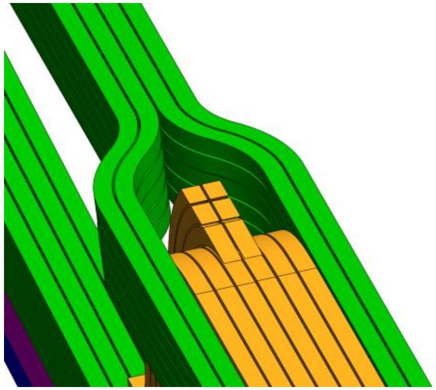


Units are *cm*

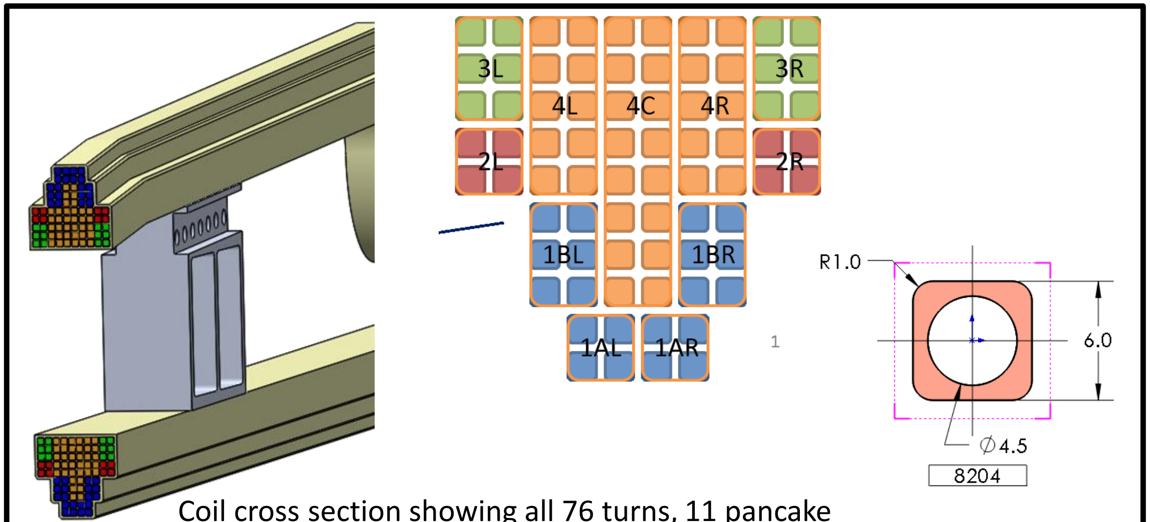
SECTION A-A

Coils Overview – 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



Bends moved outwards

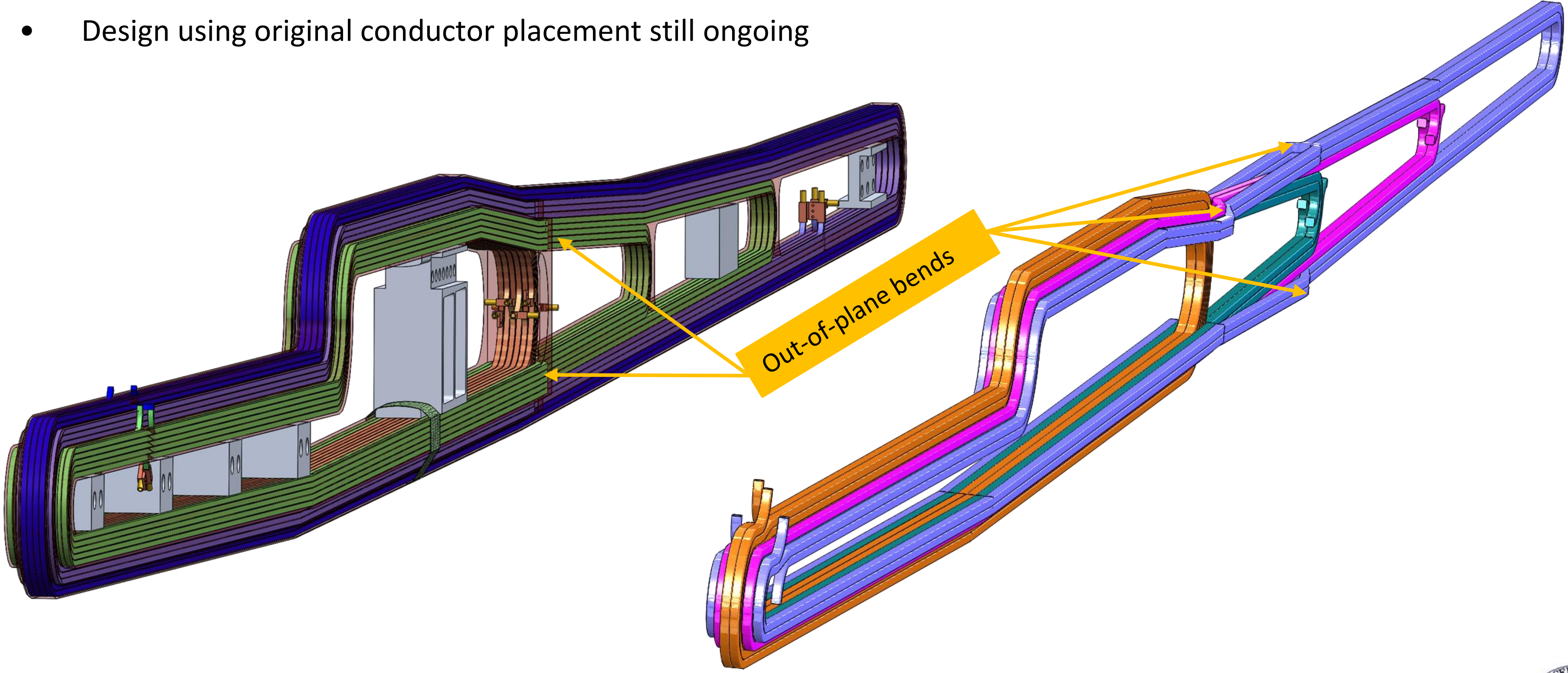


Coil cross section showing all 76 turns, 11 pancake shapes, and chosen conductor

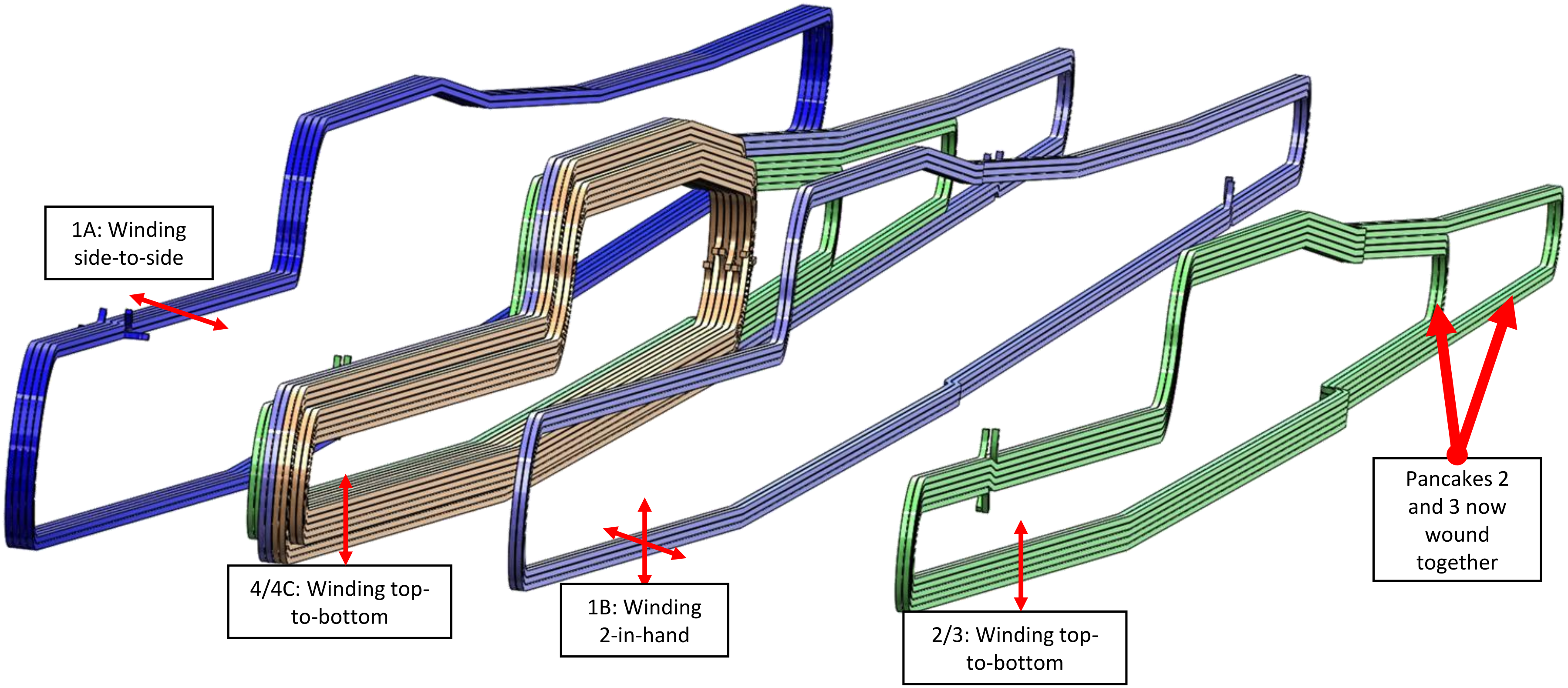
Coil Mass	186	kg
Carrier Mass	1039	kg
Centering Force	3000 1361	lbf kgf
Current	384	A
Coil Voltage Drop	<300	V
Conductor Length / coil	775	m
Number of Turns	76	“turns”
Cooling Circuits / Coil:	14	”paths”
Water Flow / Coil:	39.72	lpm
	10.5	gpm
Water Flow / Toroid:	278.03	lpm
	73.4	gpm
Maximum Pressure:	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 → no internal splices
- 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 tuneability. Could potentially optimize currents to reduce number of cooling paths
- Design using original conductor placement still ongoing



Baseline Design – Winding Details



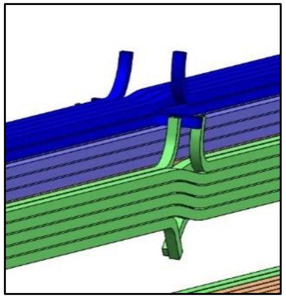
1A: Winding side-to-side

4/4C: Winding top-to-bottom

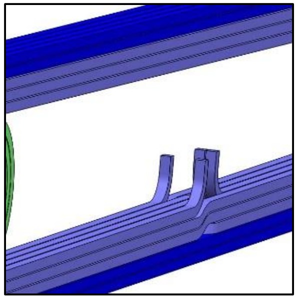
1B: Winding 2-in-hand

2/3: Winding top-to-bottom

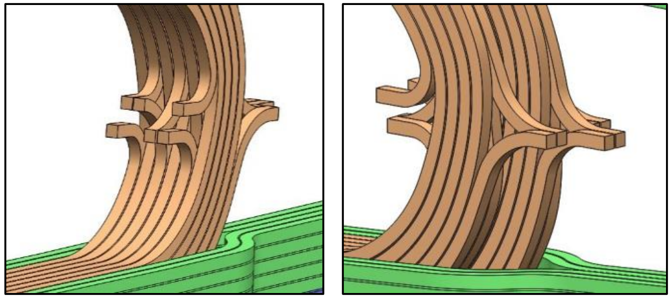
Pancakes 2 and 3 now wound together



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

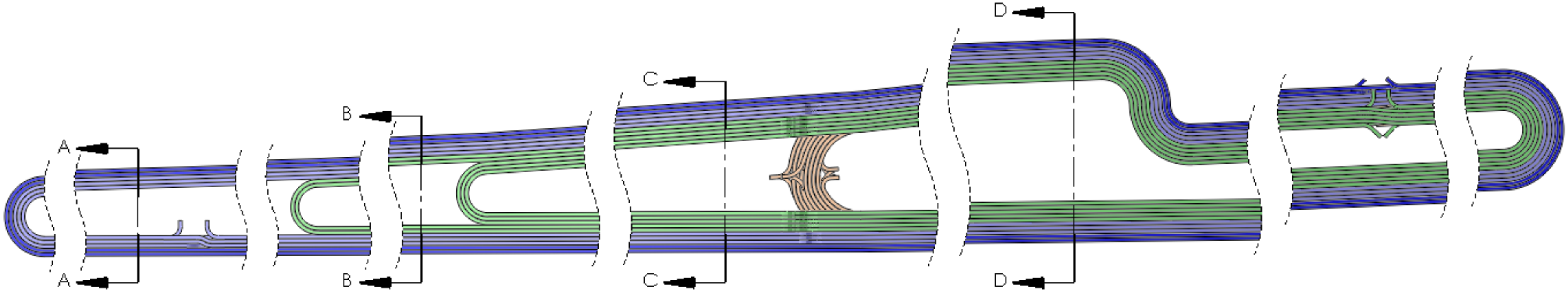


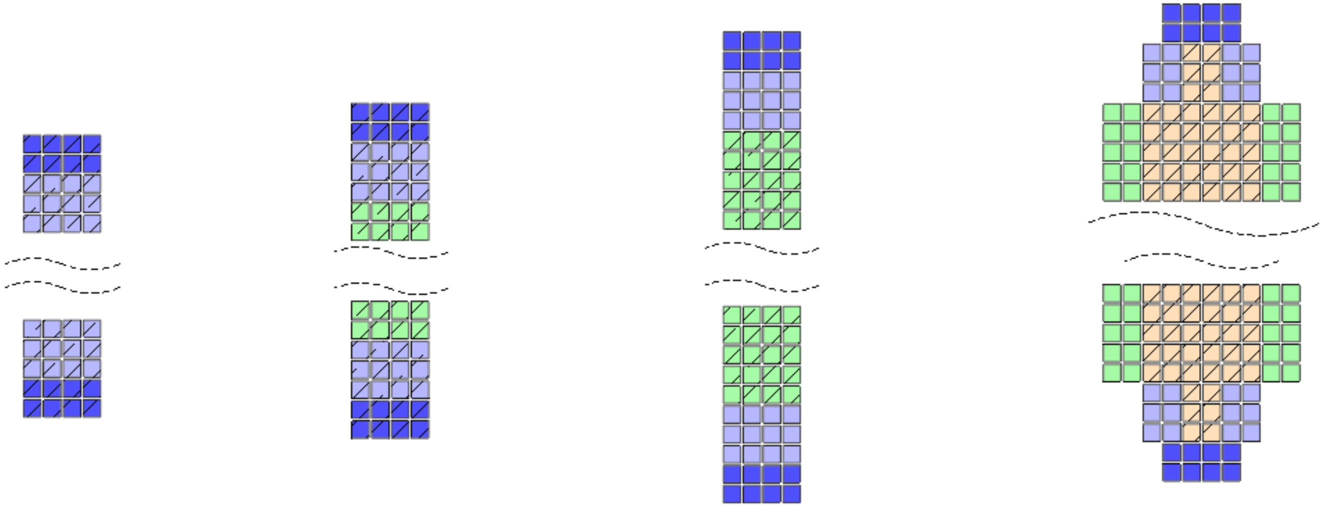
Coil 1B terminations

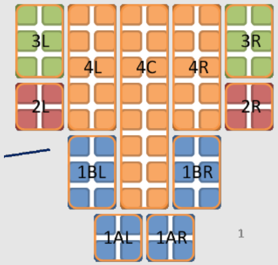


Coils 4 and 4C terminations

Baseline Design



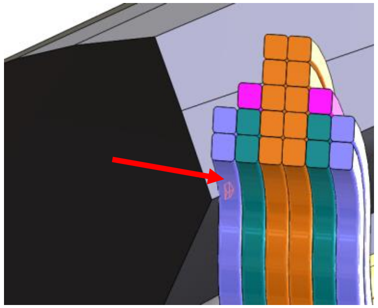




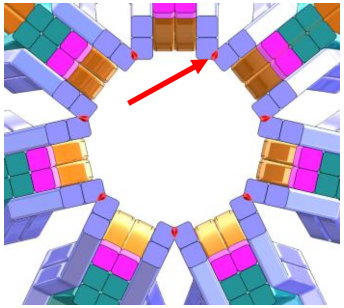
Reference Coil Layout (not to scale)

Alternative Design

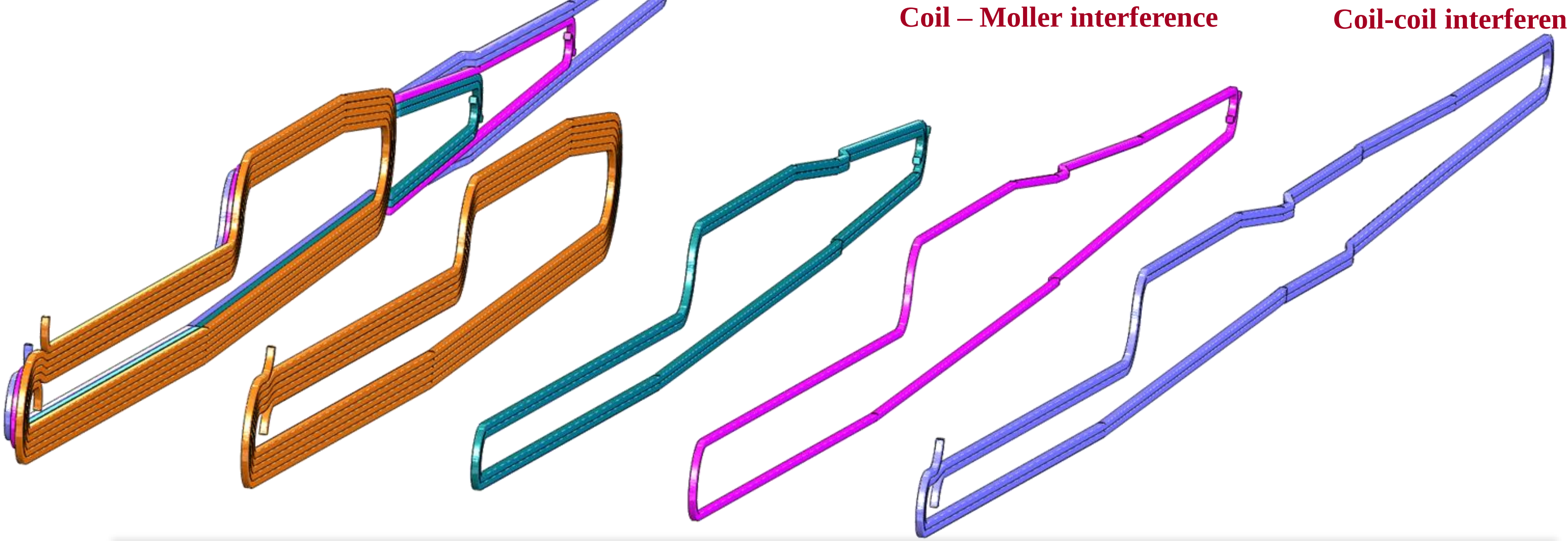
- Larger conductor (11.7 mm square with 6.5 mm hole) uses less power and can be cooled with fewer water paths
- NI for each of the 4 loops is the same as baseline
- Ratios of conductors in each loop have been changed → 4 separate power supplies needed
  - Same conductor throughout, so current densities 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



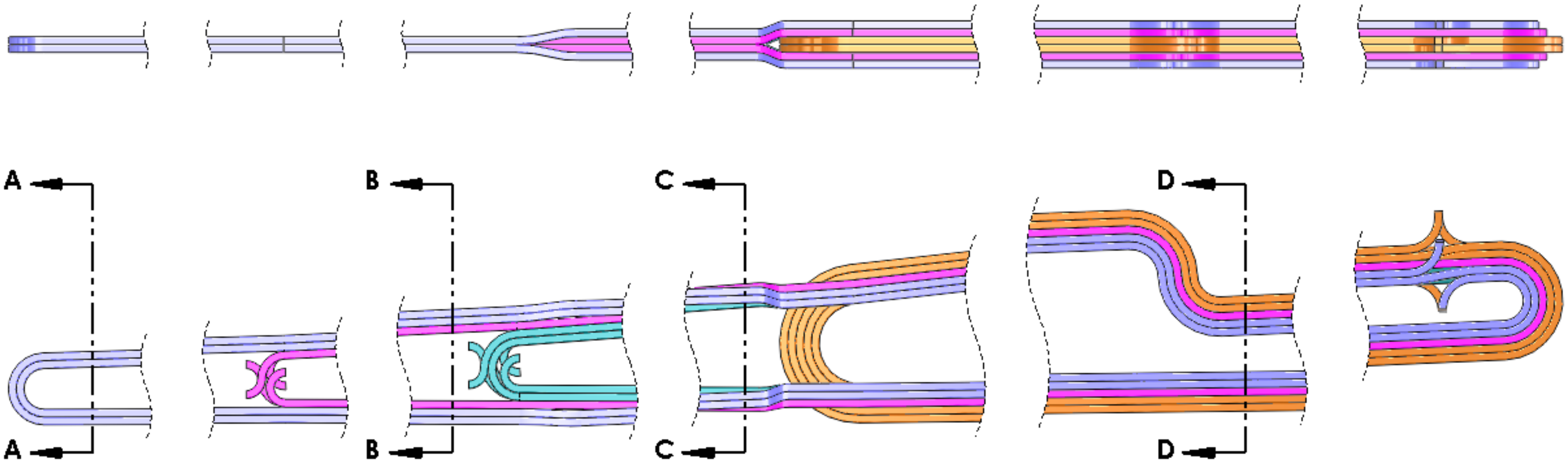
Coil – Moller interference

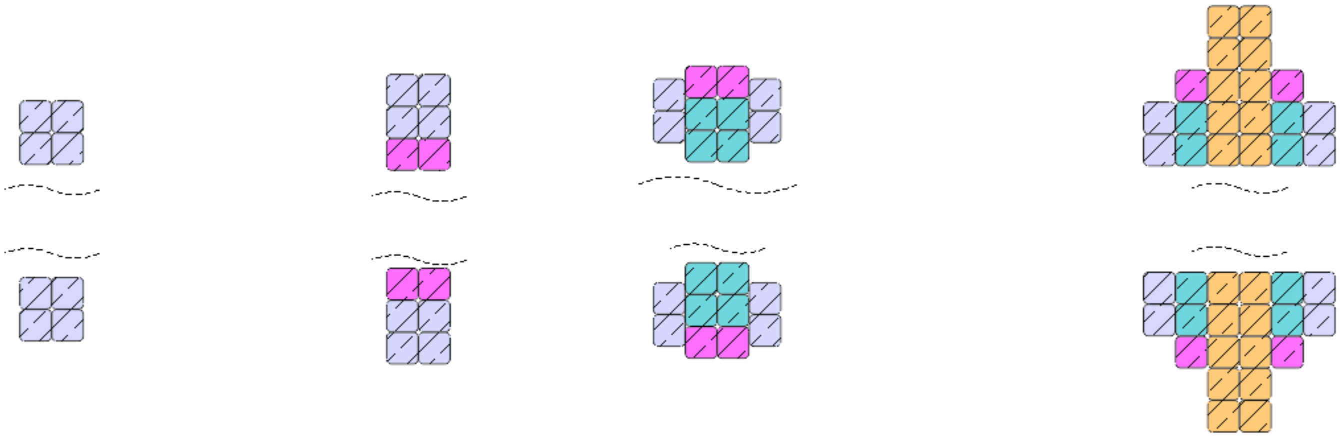


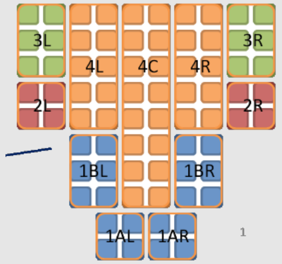
Coil-coil interference



Alternative (MkII) Design



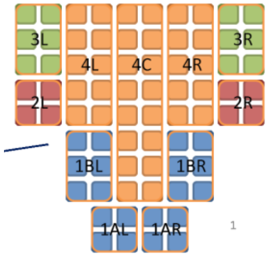


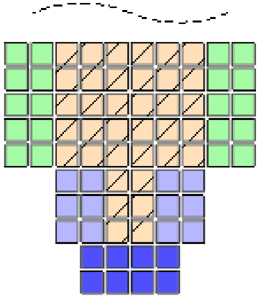


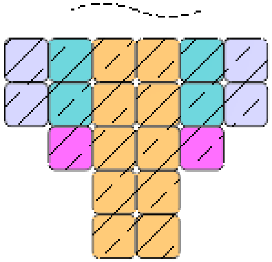
Reference Coil Layout (not to scale)

Comparison of two Designs

*note: Values are for individual coils unless otherwise indicated



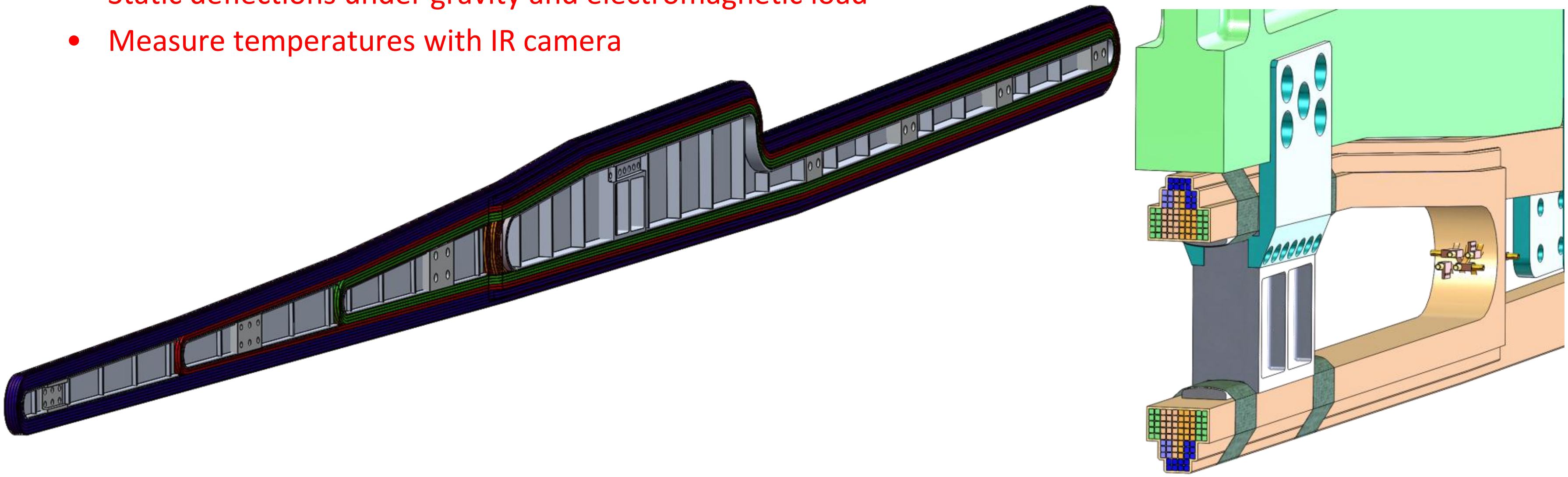




		Proposal	2015 Version	2015 MkII	Unit
Conductor		5.8 sq	6.0 sq	11.7 sq	mm
Cooling Hole		3.125	4.5	6.5	mm Dia.
Number of Turns		78	78	20	-
Current Density		1553	1965	1960 (max)	A/cm2
Power Supply Voltage (7 coils)		1600	2000	60-180	V
Power		86	138	94.6	kW
Pressure Drop	1A	196	201	243	psi
	1B	192	246		psi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

Coils Fabrication

- Vendors offered some advice on the bonded coil inserts
  - Would prefer these to completely fill the holes but the number of water/power 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 coil to test feasibility of this method (will be kept as 2nd spare coil)
    - Measure conductor placement accuracy
    - Pressure drops
    - Static deflections under gravity and electromagnetic load
    - Measure temperatures with IR camera



Shown above: coil model with individual block inserts superimposed with full coverage inserts. Inset: Existing design with blocky inserts and “wings” 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.
  - We expect this project will take ~2 years 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 magnet water from LCW supply temp (29 °C) 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

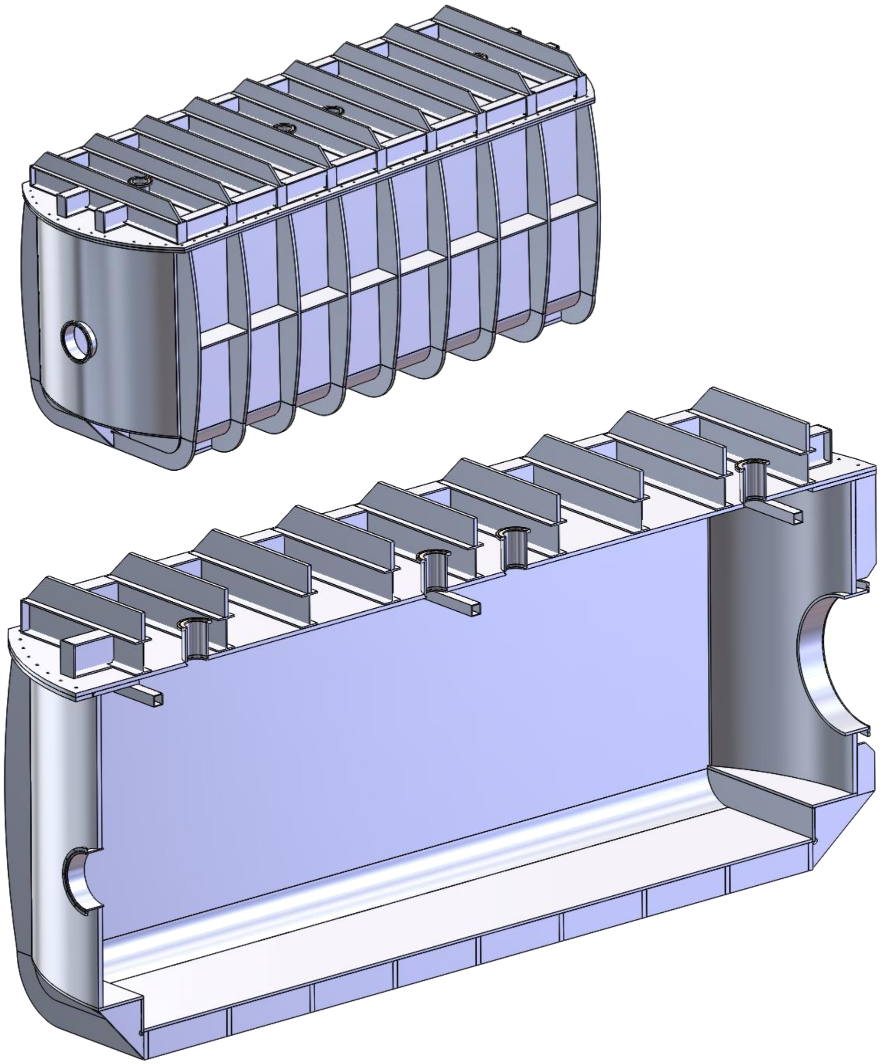
Hall A Integration

- Modularity
  - Experiment needs to be moved into and out of beamline 3 times over lifetime
    - Hall A crane has 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
  - Must repeat position to +/- 1mm
  - All water and power connections to hybrid are through the chamber top plate – allowing easy disconnection and removal of toroid from beamline.
- Alignment
  - Detector acceptance governed completely by collimator position → Collimators are primary element to be aligned w.r.t. beam and target.
  - Coils must be physically located in the shadow of collimators, regardless of actual conductor location, therefore, coils will be aligned relative to collimators.
    - This will be done with the frame outside the chamber, but optically checked once it has been installed and put under vacuum
  - The field shape will be the result of the position of the coils and of the conductors within each coil.
    - A field map will be produced once the coil positions are fixed

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



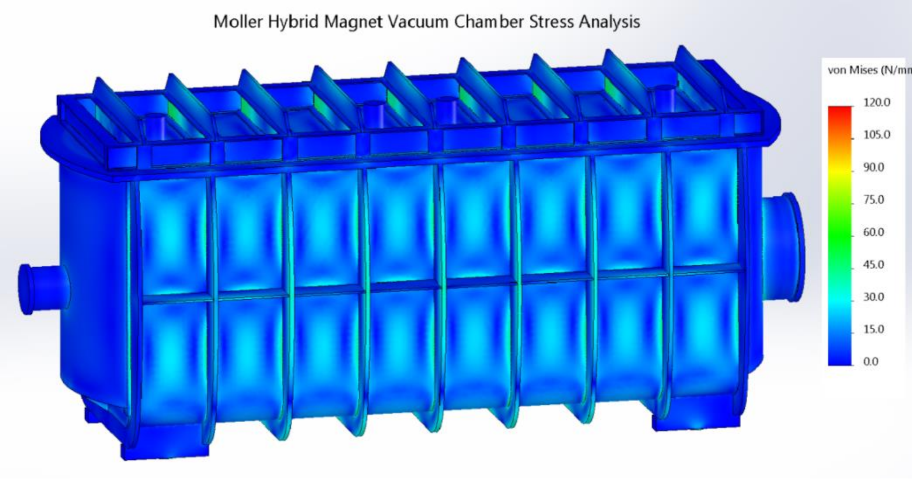
Backup

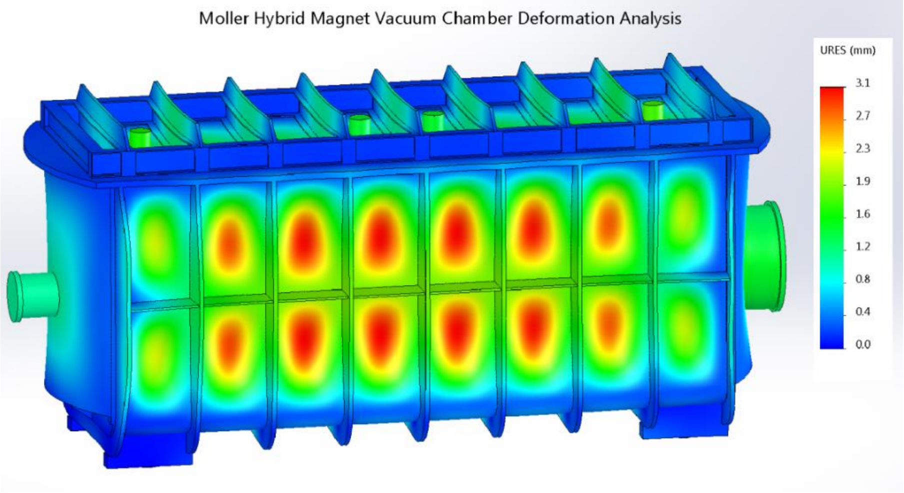
Contents:

1. Vacuum Chamber FEA
2. Frame FEA
3. Carrier FEA
4. Coils FEA
5. Coil CFD
6. Collimators Overview

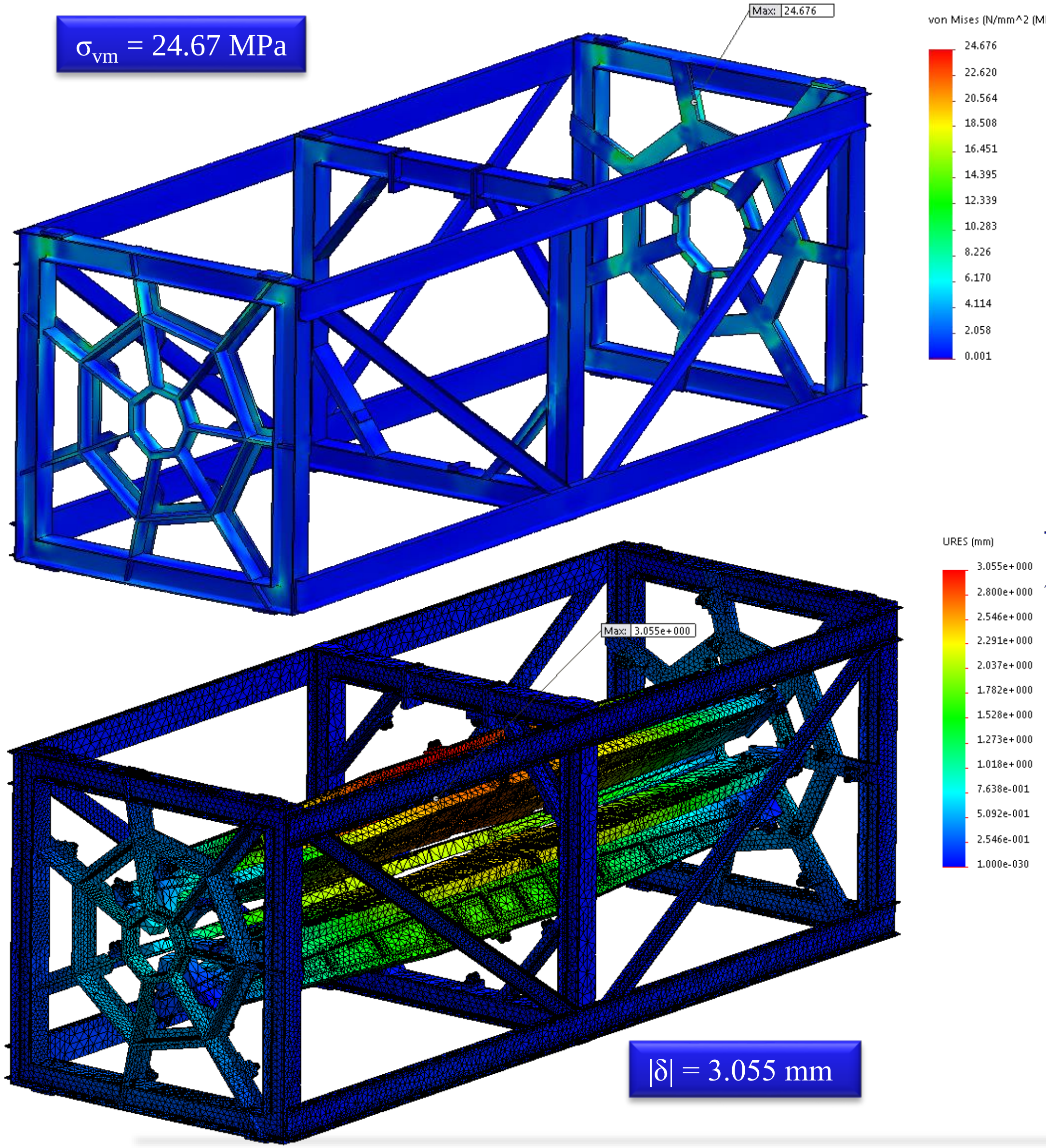
Chamber FEA

- 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.


Moller Hybrid Magnet Vacuum Chamber Stress Analysis


Moller Hybrid Magnet Vacuum Chamber Deformation Analysis

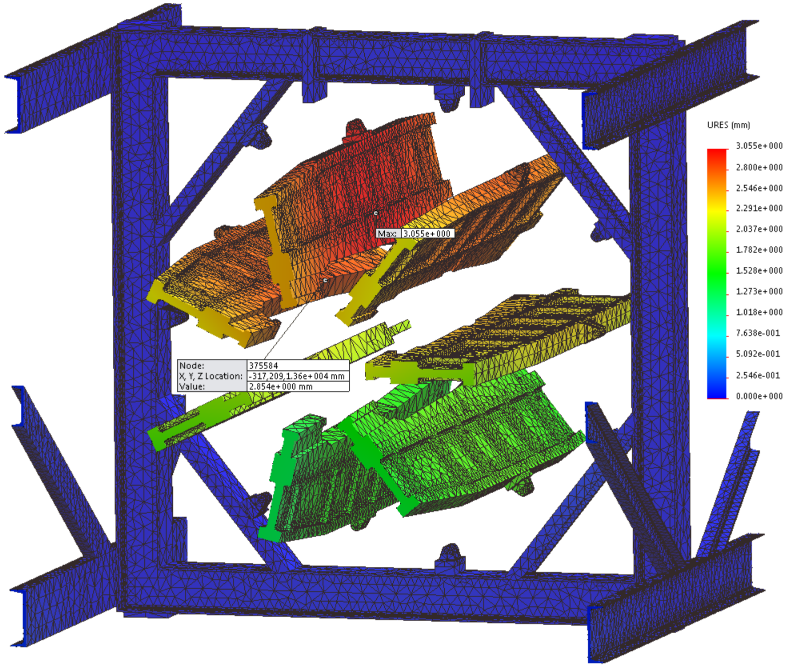
Frame Analysis



σ_{vm} = 24.67 MPa

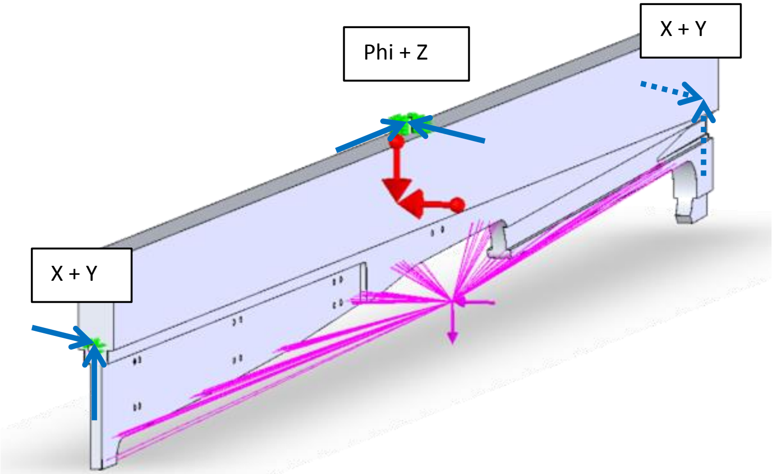
$|\delta|$ = 3.055 mm

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.

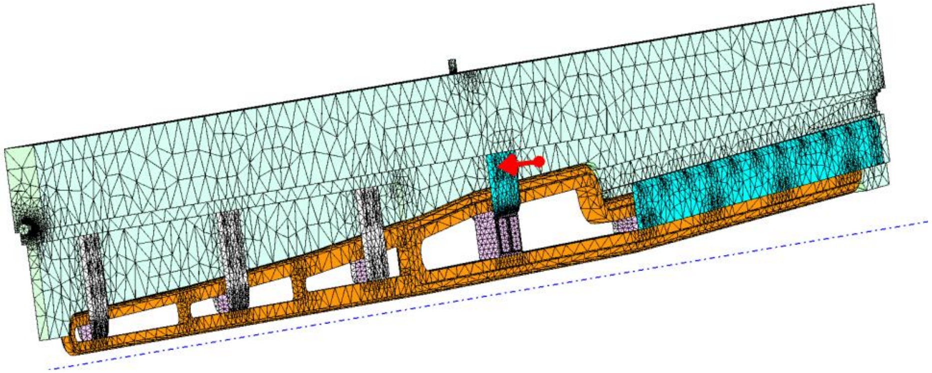


Carrier Analysis

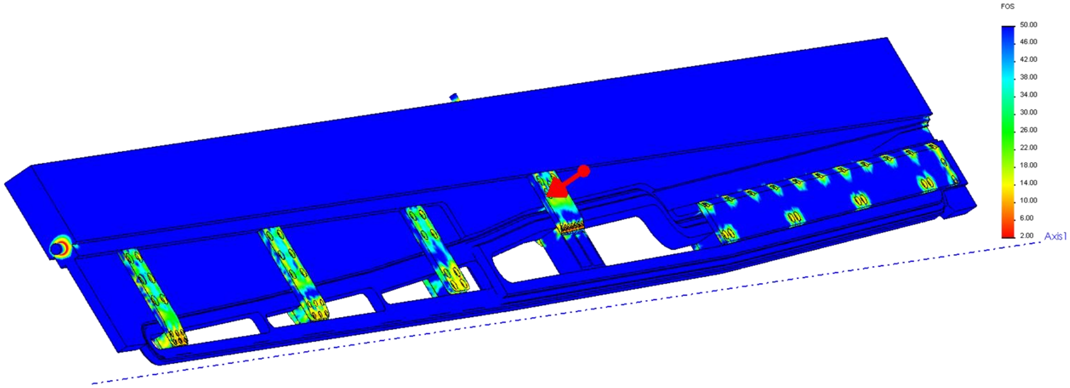
- Both vertical and horizontal orientations are considered
- Loads include gravity (approx. 1100 kgf for carrier and 250 kgf for coils) and magnetic centering force (3000 lbf)
- Boundary conditions based on 6-strut kinematic support



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.

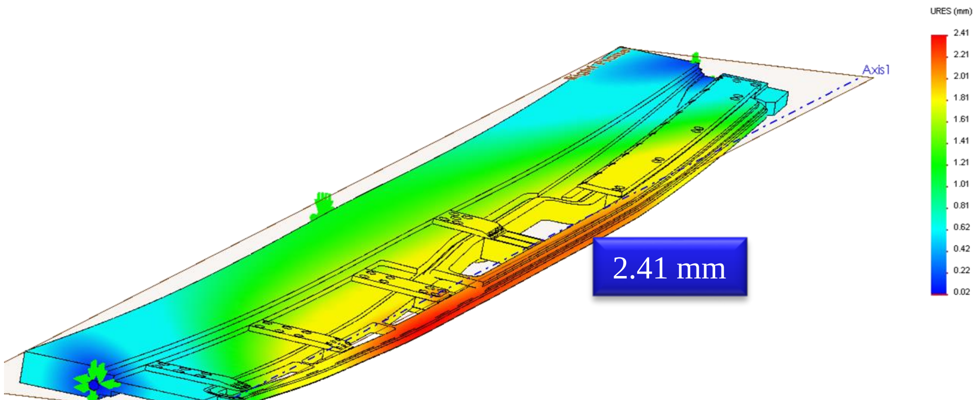


Solid mesh for study that incorporates carrier assembly + coils

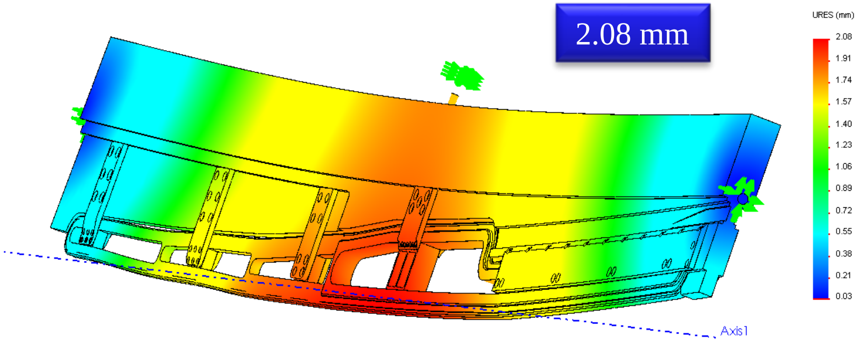


Stress analysis in which bolted joints are modeled. Horizontal orientation, showing Factor of Safety (areas between FoS = 2 and FoS = 50)

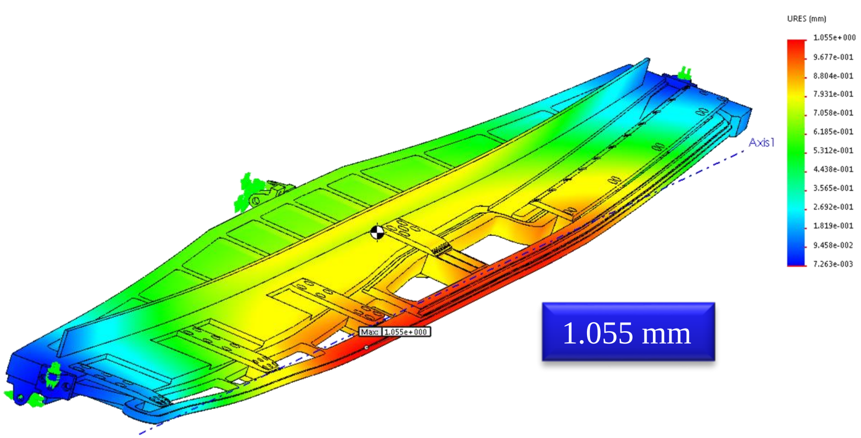
Carrier Analysis – Selected Deflections



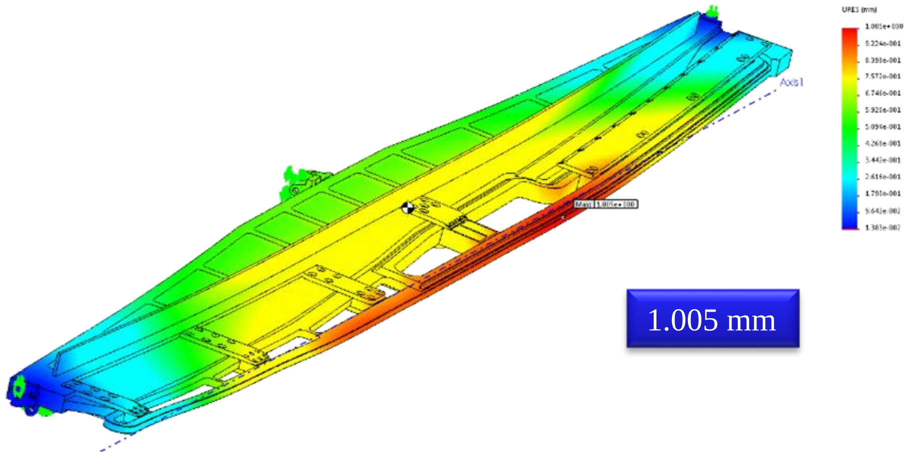
Sept (V2) *– Horizontal*



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*

Coil internal stresses

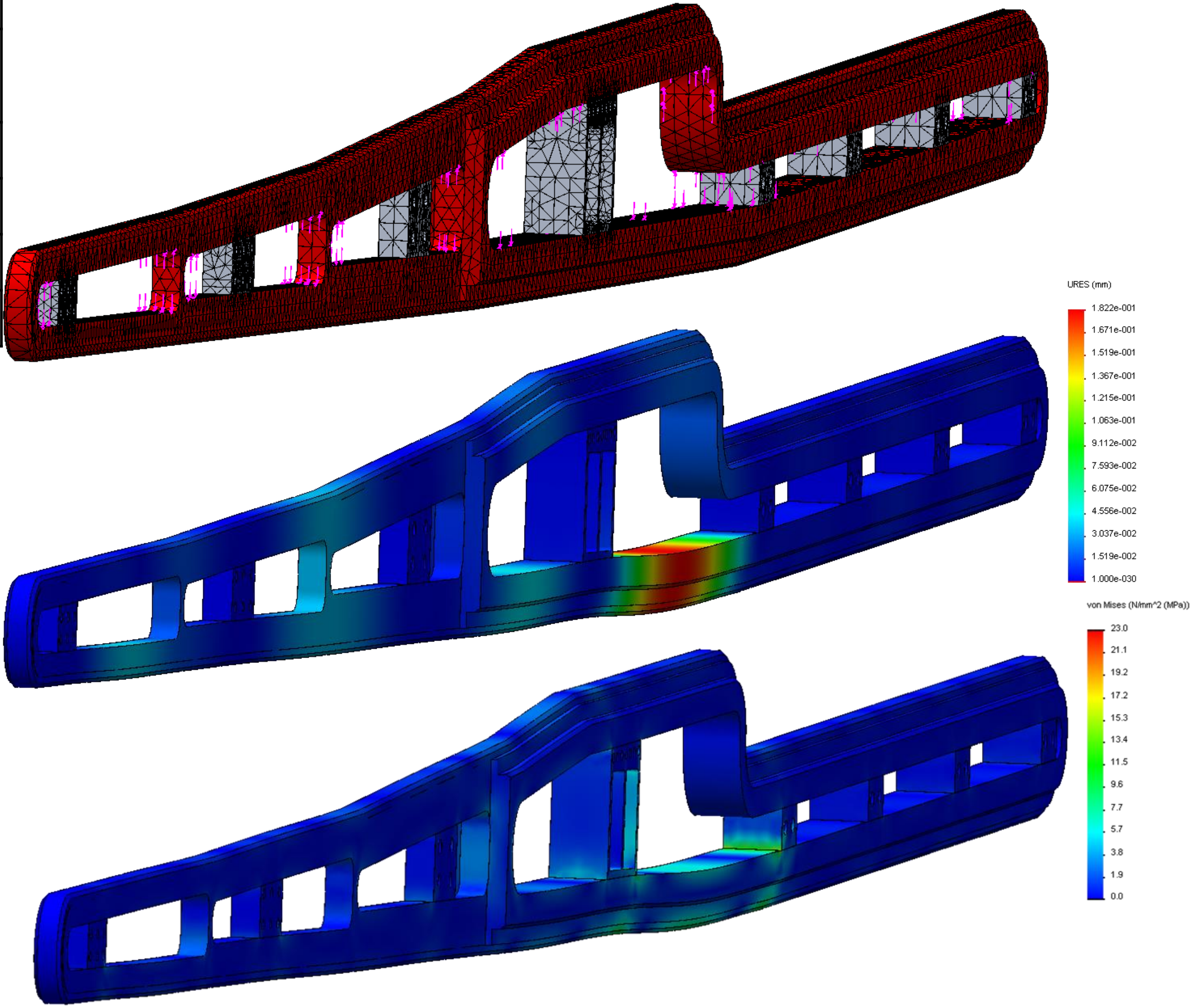
Coil Assy.SLDASM	
File Configuration	FEA2
Model Type	Solid, Static
Loads	Coil Rounding Force
Restraints	Fixed Bolt Holes
Contacts	Bonded

→ Deflection Plot (Max = 0.182 mm)

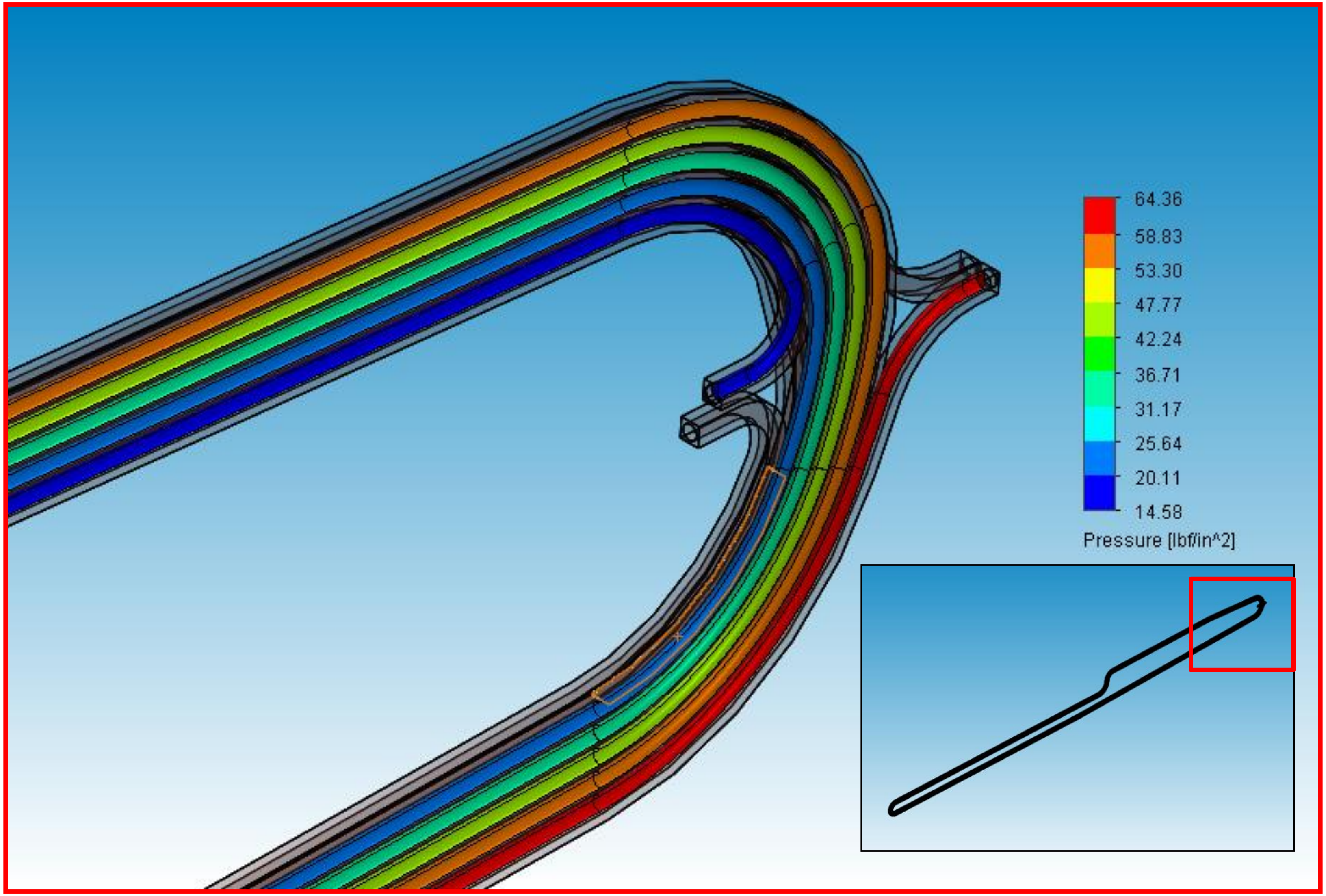
→ Stress Plot (Max = 23 MPa)

Yield strength depends on specifics of composite and type of stress

Most likely shear stress will need to be compared with delamination strength of gfrp or epoxy – copper bond

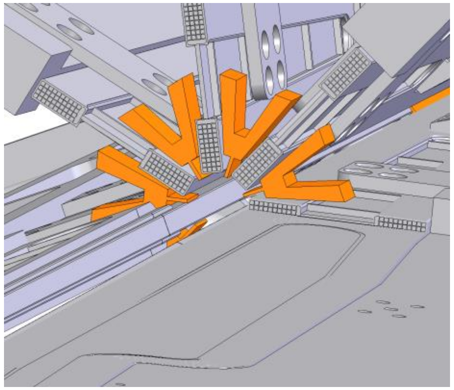


Coil CFD – Initial results

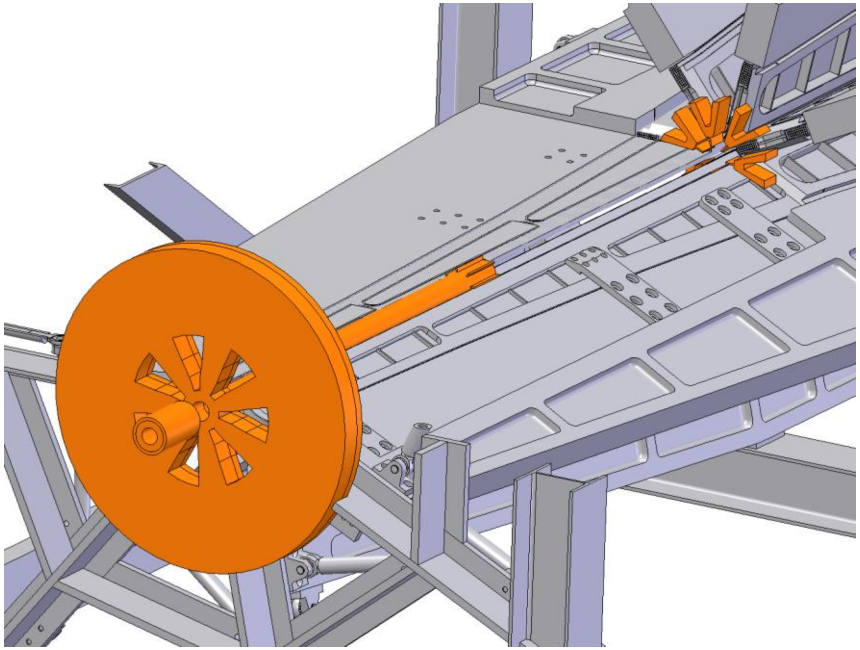


Collimators

- 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 modified to support Collimators #3 and #4



7 wedge segments of collimator 5



Collimators #3 through #5 (left to right)