MOLLER Hybrid Toroid:
Small-Conductor vs Large-Conductor Design Comparison

For External Magnet Advisory Group

Ernie Ihloff, Jason Bessuille, Chris Vidal, Jim Kelsey

10/20/2016

Work done since July 2015 on Hybrid Magnet

- Had a contract engineer develop and vet large conductor design. The engineer was a modeling expert so he did CFD, thermal magnetics and solid models.
- Worked with a couple vendors to review design from a manufacturing standpoint
- Used ANSYS Maxwell to simulate magnetic fields and then compared to TOSCA
- Obtained actual quotes on conductors for project.

Issues with this work:

- We had a contractor take our original work and develop the coils. At some point a tangent was taken and the design was modified to the point it was not what was our base line large conductors. Returning to baseline and continue from there.
- Many if not all the conclusions made in this power point (most of this work was done before June 2016) are valid but the specific values need to be redone with the correct geometry.
- This is an Engineering management problem (Ihloff). The contractor is excellent and his work is precise but he deviated from the original design far enough to make it a problem when we continued his work. No way to get cooling lines out of this version. (Oct 2016)

Design as shown in July 2015 of Hybrid Magnet

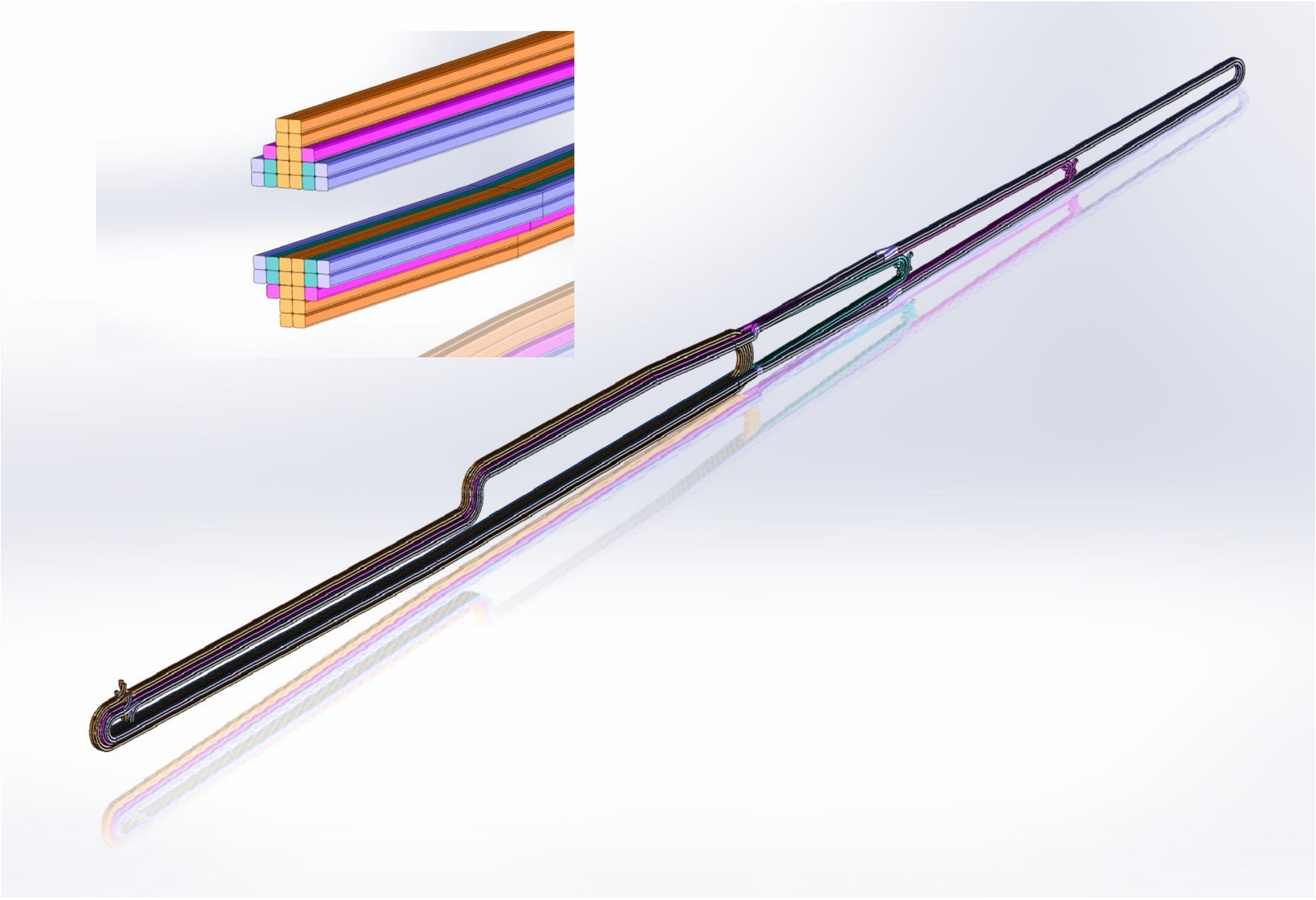
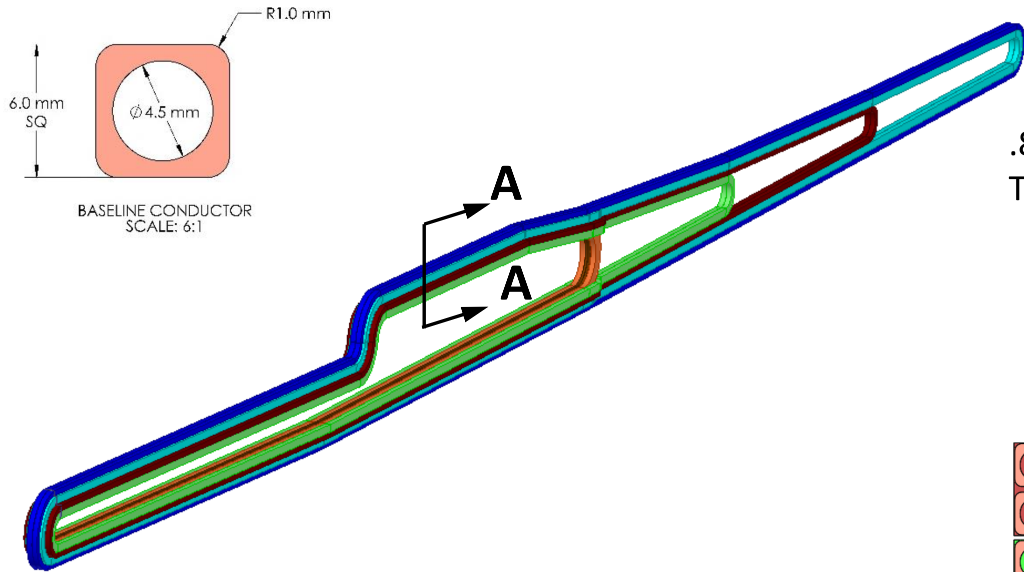
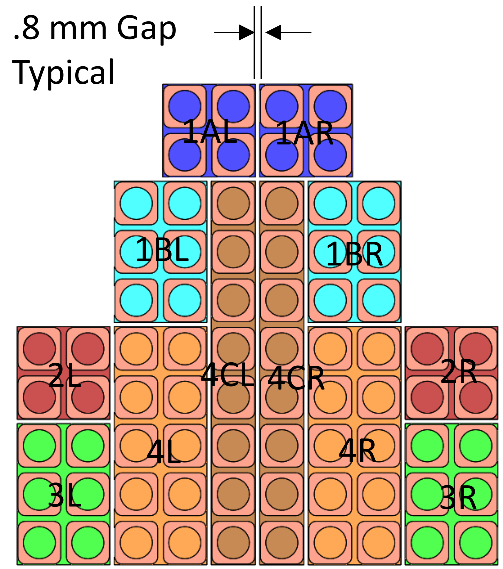


Table 1 - Small-Conductor vs Large-Conductor Design Comparison Summary

Category	Attribute	Small Conductor	Large Conductor	Comment
Physics	Meets all physics requirements	√	√	
	NI applied per ideal TOSCA conductor model	√	√	
Mechanical	Lowest maximum pressure drop		√	SC = 309 psi; LC = 46.5 psi
	Conductors stay within ideal encapsulant envelope	√	√	Due to the number of conductors, SC design may be more difficult to stay within ideal envelope
	Fewest cooling circuits		√	
	Uses existing insert designs	√	√	
	Lowest velocity		√	SC = 676 ft/min; LC = 437 ft/min
Electrical	Fewest number of power supplies	√		SC = 1; LC = 3
	Lowest maximum current/ smallest power cables	√		SC = 384 A; LC = 1536 A
	Lowest current density		√	SC =2000 A/ cm^2; LC = 1450 A/ cm^2
Manufacturing	Design is manufacturable as drawn	√	√	To validate design and manufacturability, vendor recommends building a full coil assembly for a prototype
	Shortest winding time		√	SC winding time ~3X as long as LC (1325/480 hours)
	Easiest to form reverse OOP bends	√		
	Lowest hollow conductor cost	√		SC ~25% less; LC requires 3 custom conductors
	Lowest winding tooling cost	√	√	Tooling costs same for both designs
	Lowest overall cost		√	LC 25%-50 % less expensive

Small-Conductor Design Model:
Coil Amp-Turns





Section A-A

Coil	# Turns	Amps	Amp-Turns
1A	4	384	1536
1B	6	384	2304
2	4	384	1536
3	6	384	2304
4C	8	384	3072
4	10	384	3840
		Half Coil	**14592**
		Full Coil 2X	**29184**
		Toroid 7X	**204288**

MOLLER Hybrid Small-Conductor Coil Design

Table 2 - Coil Length, Resistance, and Power Dissipation

Circuit	Circuit Qty	Area No Hole (mm^2)	Area w/ Hole (cm^2)	Length/ Circuit (m)	Current (A)	Current Density (A/cm^2)	Resistance/ Circuit (ohm)	Power/ Circuit (W)
Coil 1AI	1	36	0.192	55.85	384	2000.00	5.41E-02	7.98E+03
Coil 1AO	1			55.85			5.41E-02	7.98E+03
Coil 1BL	1			83.30			8.07E-02	1.19E+04
Coil 1BR	1			83.30			8.07E-02	1.19E+04
Coil (2+3)L	2			53.00			5.13E-02	7.57E+03
Coil (2+3)R	2			53.00			5.13E-02	7.57E+03
Coil 4L	2			39.40			3.55E-02	5.23E+03
Coil 4R	2			39.40			3.55E-02	5.23E+03
Coil 4CL	1			63.88			6.19E-02	9.13E+03
Coil 4CR	1			63.88			6.19E-02	9.13E+03
Coil Assy	**14**			**775.66**				**1.09E+05**

(292.5 lbs)

Table 3 - Coil Water Temp and GPM

Power/ Circuit (BTU/hr)	Temperature Change dT (F)	Volume Flow Rate q (GPM)
27228.88	72	0.76
27228.88		0.76
40611.74		1.13
40611.74		1.13
25839.40		0.72
25839.40		0.72
17866.35		0.50
17866.35		0.50
31143.79		0.87
31143.79		0.87
372791.81		**10.36**

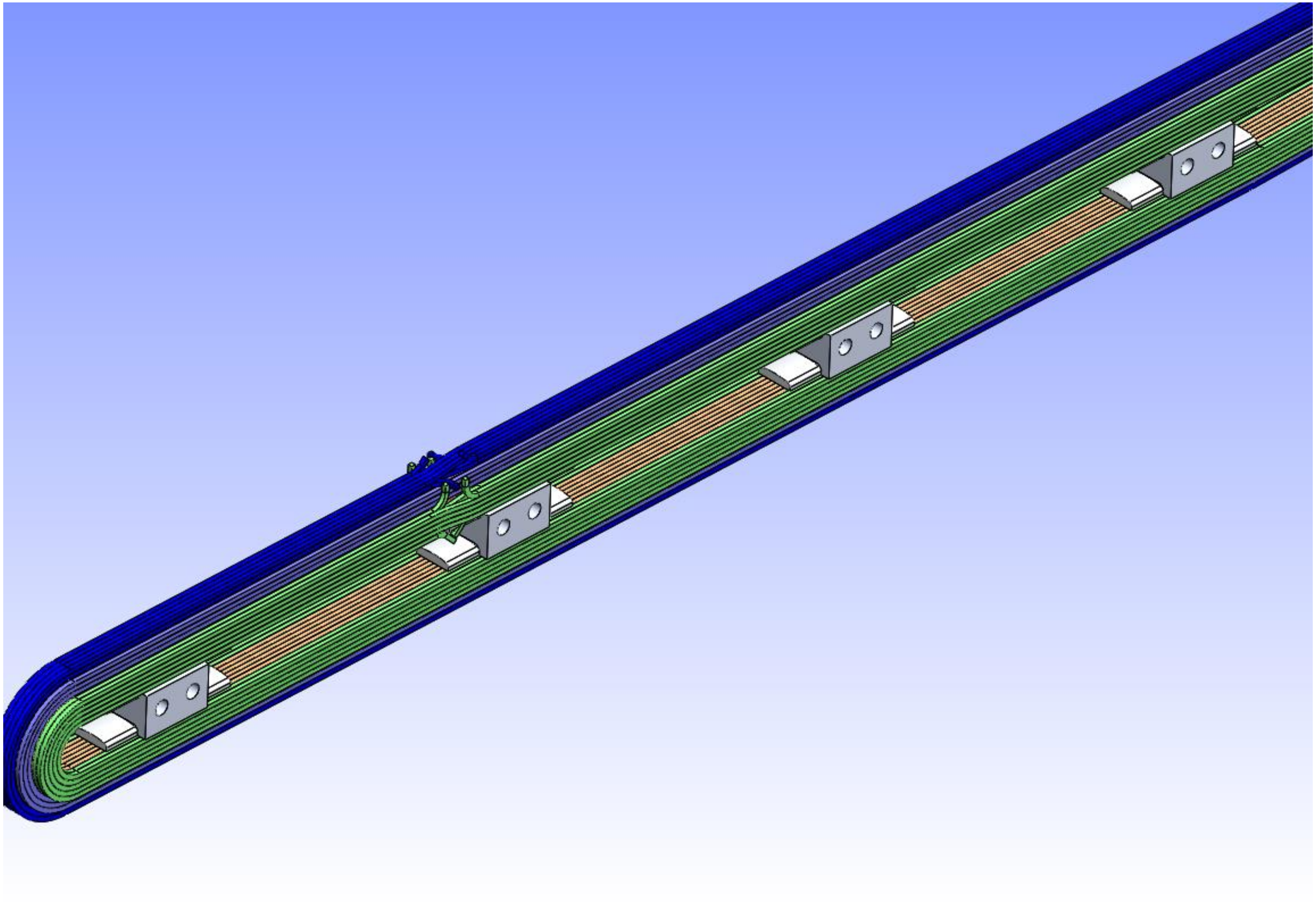
Table 4 - Coil Pressure Drop

Velocity (ft/min)	Hole Diameter (ft)	Flow Area (ft^2)	Reynolds Number	Friction Factor	Pressure Drop (psi)
5.91E+02	1.48E-02	1.71E-04	2.05E+04	2.64E-02	2.14E+02
5.91E+02			2.05E+04	2.64E-02	2.14E+02
8.81E+02			3.06E+04	2.39E-02	6.41E+02
8.81E+02			3.06E+04	2.39E-02	6.41E+02
5.61E+02			1.95E+04	2.67E-02	1.85E+02
5.61E+02			1.95E+04	2.67E-02	1.85E+02
3.88E+02			1.35E+04	2.93E-02	7.21E+01
3.88E+02			1.35E+04	2.93E-02	7.21E+01
6.76E+02			2.35E+04	2.55E-02	3.09E+02
6.76E+02			2.35E+04	2.55E-02	3.09E+02

Note: Cutting the length of any circuit in half will reduce the pressure drop by a factor of 8.

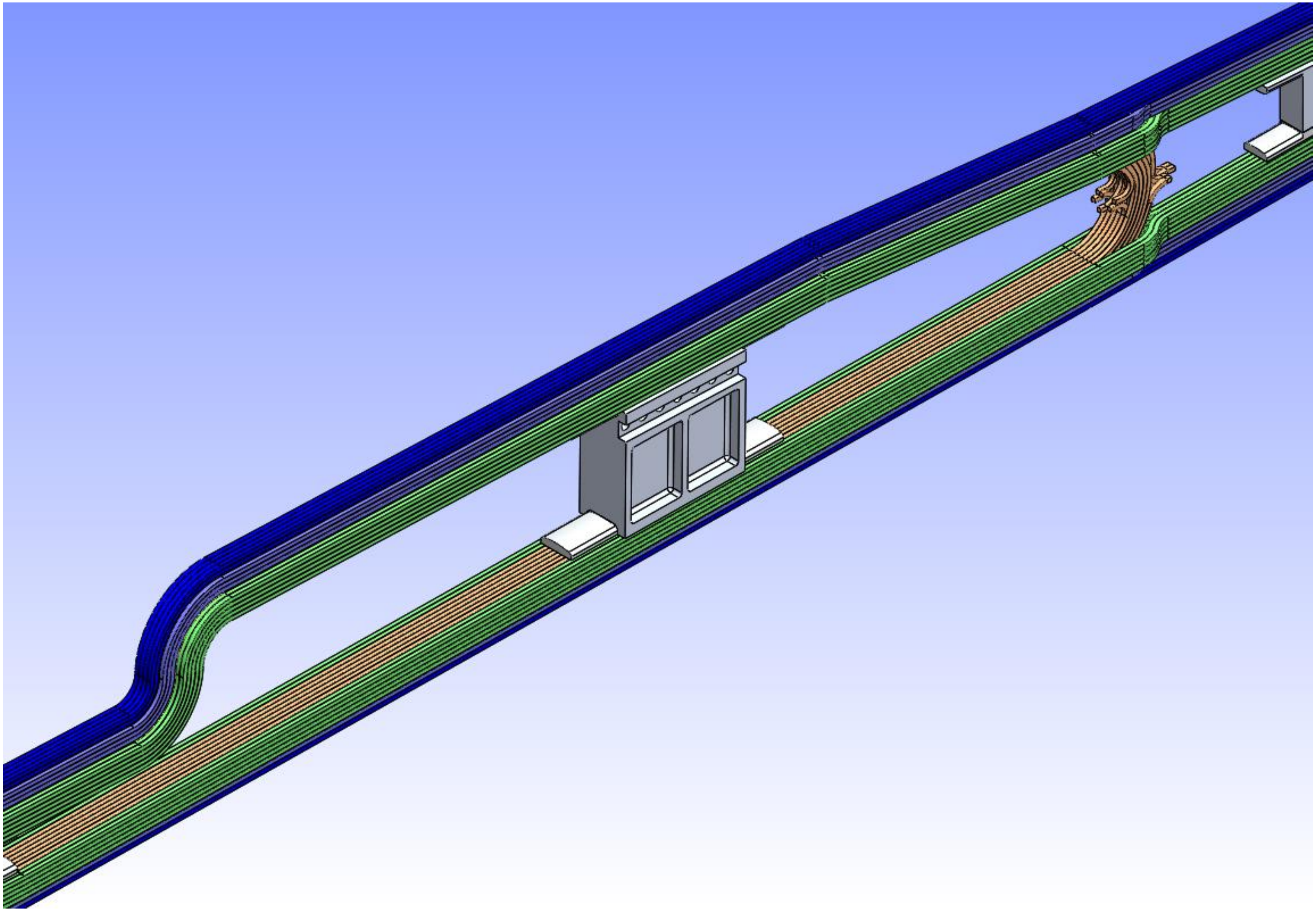
Small-Conductor Solid Model

With Inserts



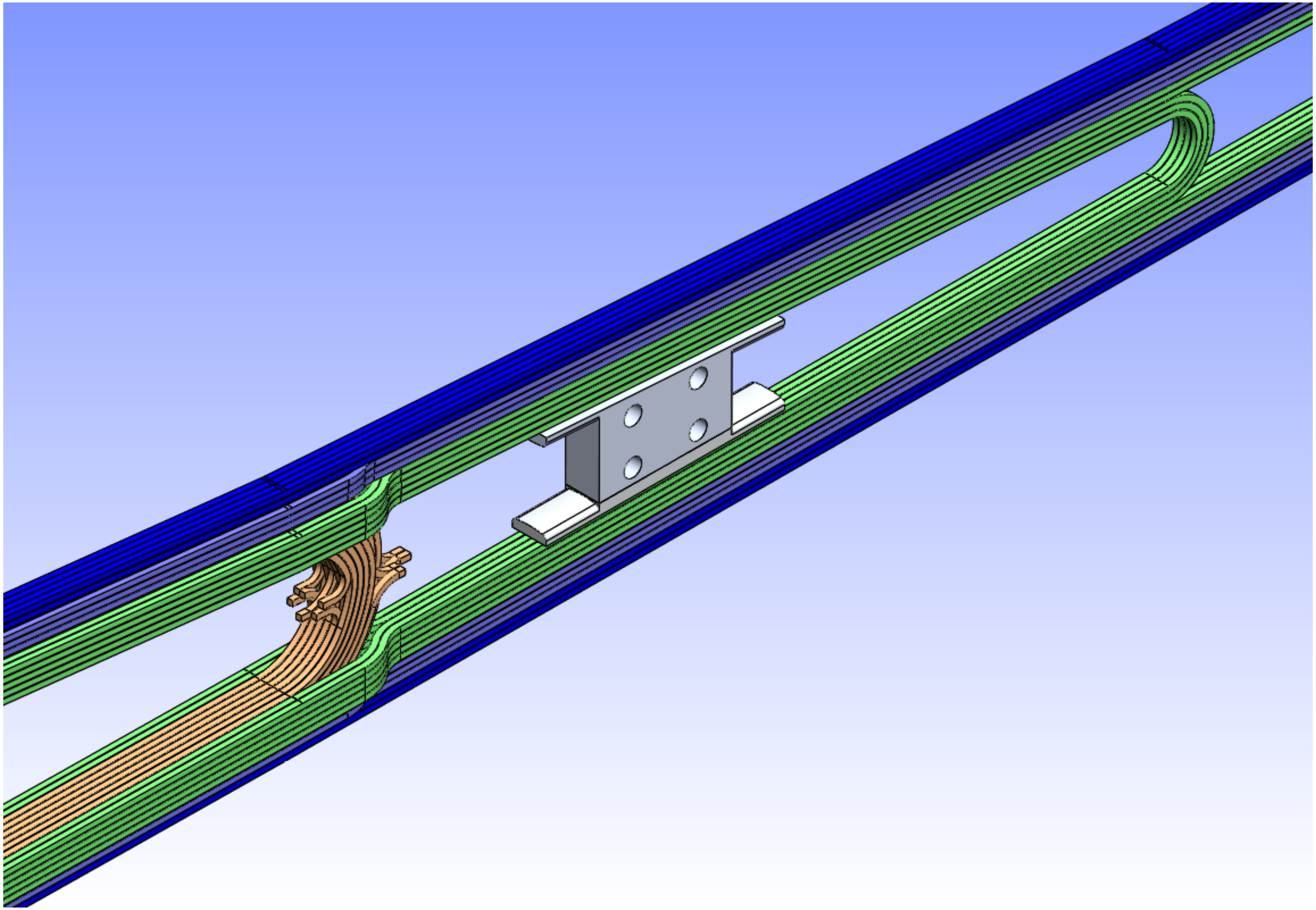
Small-Conductor Solid Model

With Inserts



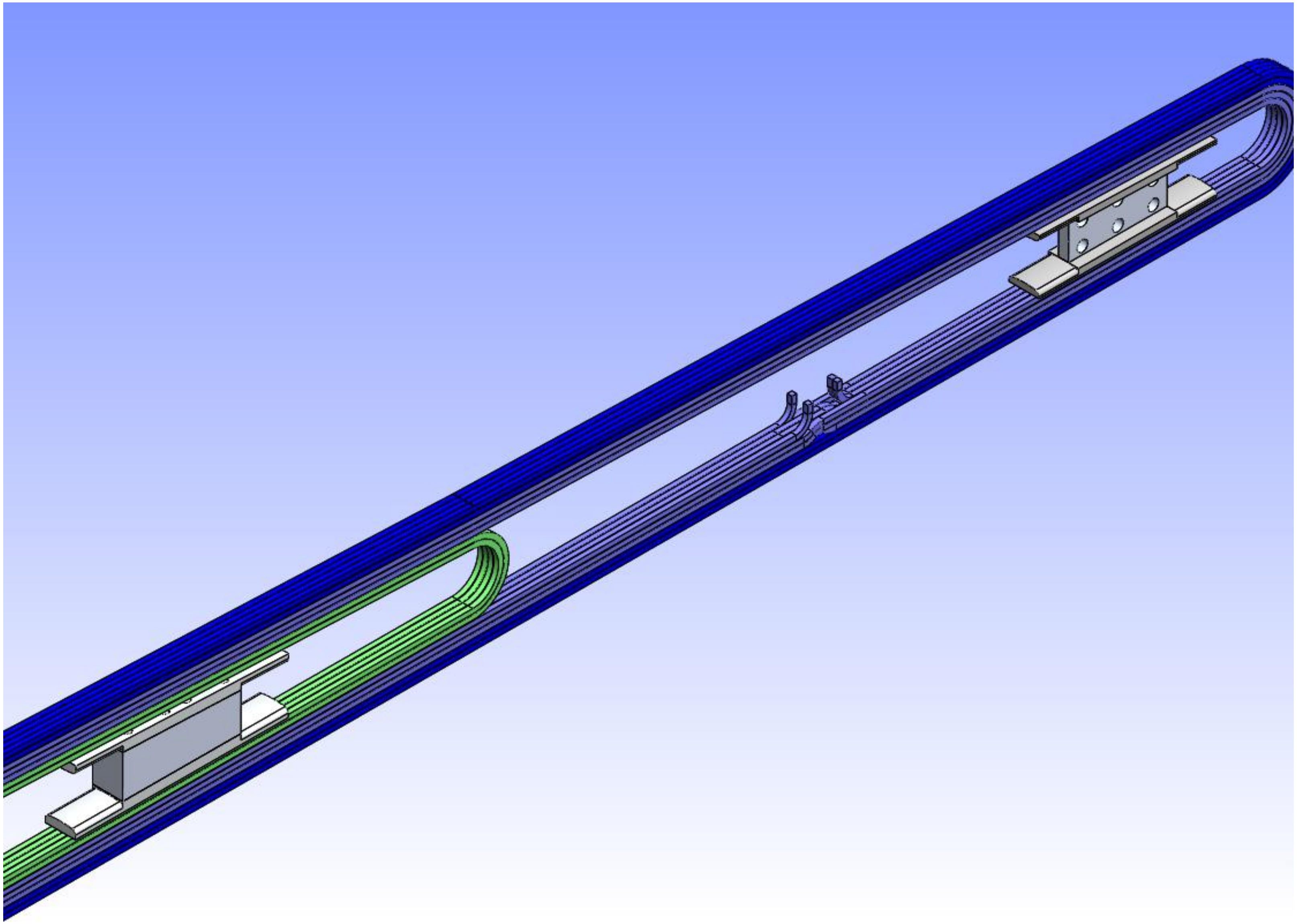
Small-Conductor Solid Model

With Inserts

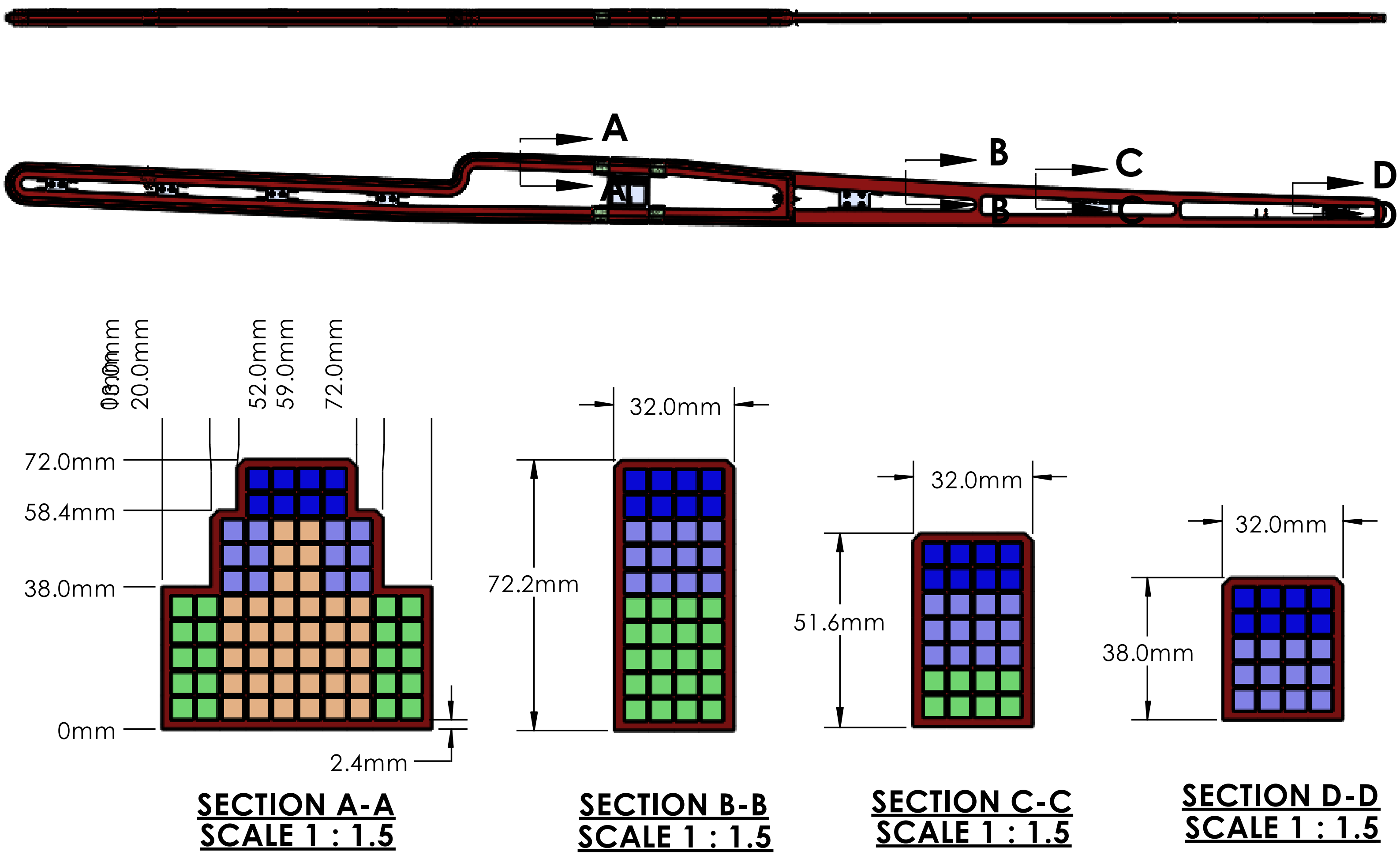


Small-Conductor Solid Model

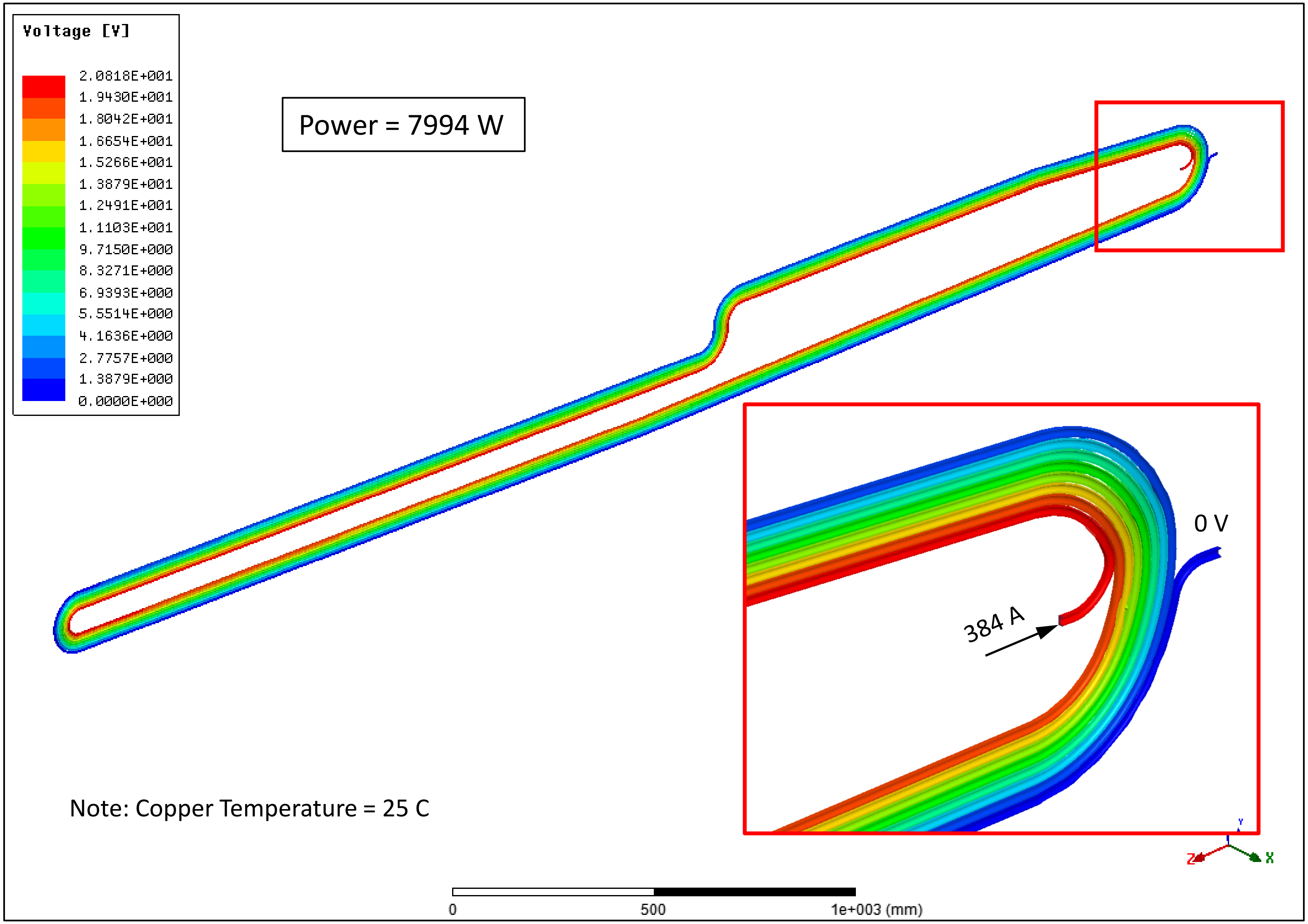
With Inserts



Small Conductor Model with Encapsulant: Cross Section Views

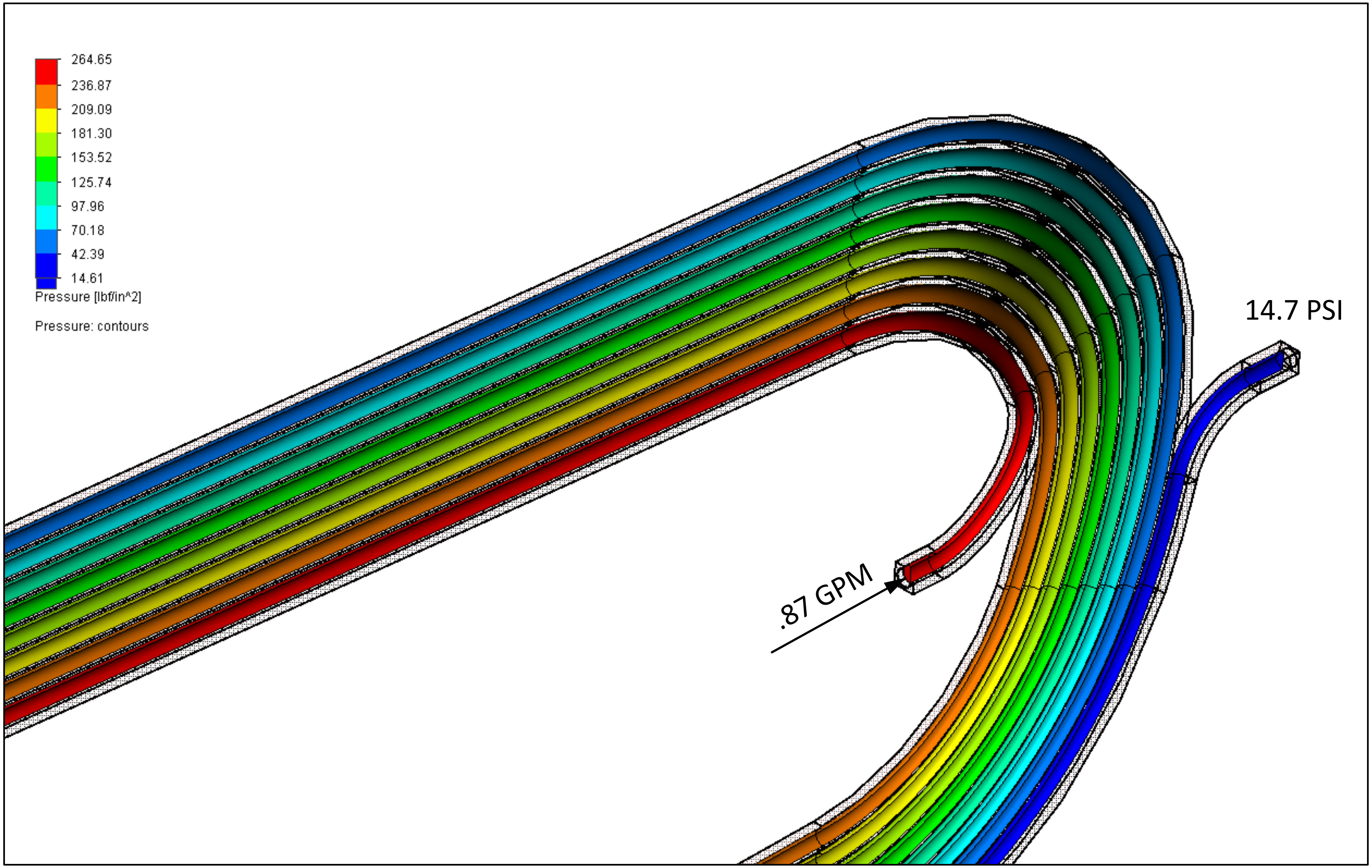


Maxwell Coil 4C Small-Conductor Design Results:
Voltage

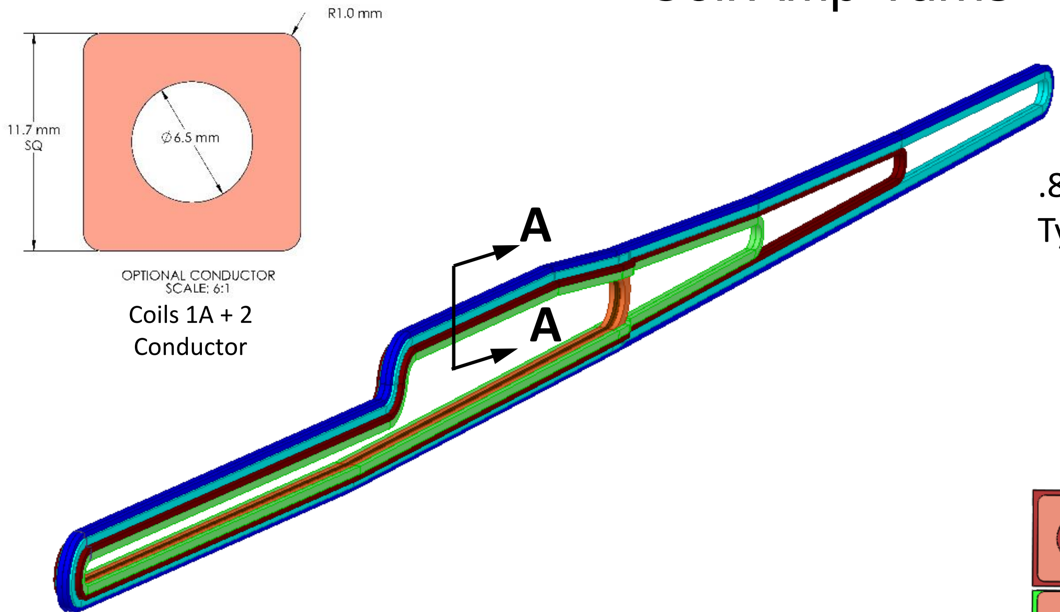


Flow Simulation Coil 4C Small-Conductor Design Results:

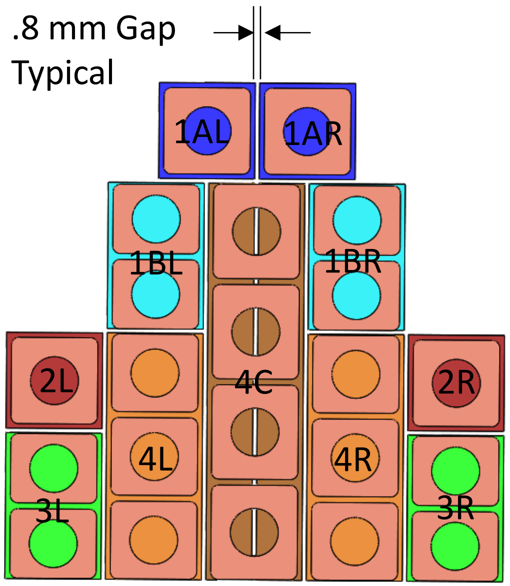
Pressure (Coarse Mesh)



Large-Conductor Design Model:
Coil Amp-Turns



Coils 1A + 2
Conductor



Section A-A

Requires 3 Custom
Conductor Sizes

Coil	# Turns	Amps	Amp-Turns
1A	1	1536	1536
1B	2	1152	2304
2	1	1536	1536
3	2	1152	2304
4C	4	1536	6144
4	3	1280	3840
		Full Coil	**29184**
		Toroid 7X	**204288**

MOLLER Hybrid Large-Conductor Coil Design

Table 5 - Coil Length, Resistance, and Power Dissipation

Circuit	Circuit Qty	Area No Hole (mm^2)	Area w/ Hole (cm^2)	Length/ Circuit (m)	Current (A)	Current Density (A/cm^2)	Resistance/ Circuit (ohm)	Power/ Circuit (W)
Coil 1AL	1	136.9	1.03	14.00	1536	1491.26	2.53E-03	5.96E+03
Coil 1AR	1	136.9	1.03	14.00	1536	1491.26	2.53E-03	5.96E+03
Coil 1BL	1	110	0.76	15.78	1152	1515.79	3.86E-03	5.13E+03
Coil 1BR	1	110	0.76	15.78	1152	1515.79	3.86E-03	5.13E+03
Coil 2L	1	136.9	1.03	7.83	1536	1491.26	1.41E-03	3.34E+03
Coil 2R	1	136.9	1.03	7.83	1536	1491.26	1.41E-03	3.34E+03
Coil 3L	1	110	0.76	15.58	1152	1515.79	3.81E-03	5.06E+03
Coil 3R	1	110	0.76	15.58	1152	1515.79	3.81E-03	5.06E+03
Coil 4L	1	123.2	0.89	23.76	1280	1438.20	4.97E-03	8.14E+03
Coil 4R	1	123.2	0.89	23.76	1280	1438.20	4.97E-03	8.14E+03
Coil 4C	1	149.8	1.16	32.48	1536	1324.14	5.21E-03	1.23E+04
Coil Assy	**11**			**186.38**				**6.75E+04**

(335.8 lbs)

Table 6 - Coil Water Temp and GPM

Power/ Circuit (BTU/hr)	Temperature Change dT (F)	Volume Flow Rate q (GPM)
20357.22	72	0.57
20357.22		0.57
17492.17		0.49
17492.17		0.49
11385.50		0.32
11385.50		0.32
17270.47		0.48
17270.47		0.48
27766.54		0.77
27766.54		0.77
41935.88		1.16
230479.69		**6.40**

Table 7 - Coil Pressure Drop

Velocity (ft/min)	Hole Diameter (ft)	Flow Area (ft^2)	Reynolds Number	Friction Factor	Pressure Drop (psi)
2.12E+02	2.13E-02	3.56E-04	1.06E+04	3.11E-02	5.64E+00
2.12E+02			1.06E+04	3.11E-02	5.64E+00
1.82E+02			9.14E+03	3.23E-02	4.88E+00
1.82E+02			9.14E+03	3.23E-02	4.88E+00
1.19E+02			5.95E+03	3.60E-02	1.14E+00
1.19E+02			5.95E+03	3.60E-02	1.14E+00
1.80E+02			9.02E+03	3.24E-02	4.71E+00
1.80E+02			9.02E+03	3.24E-02	4.71E+00
2.89E+02			1.45E+04	2.88E-02	1.65E+01
2.89E+02			1.45E+04	2.88E-02	1.65E+01
4.37E+02			2.19E+04	2.60E-02	4.64E+01

Luvata Hollow Conductor Quote Summary

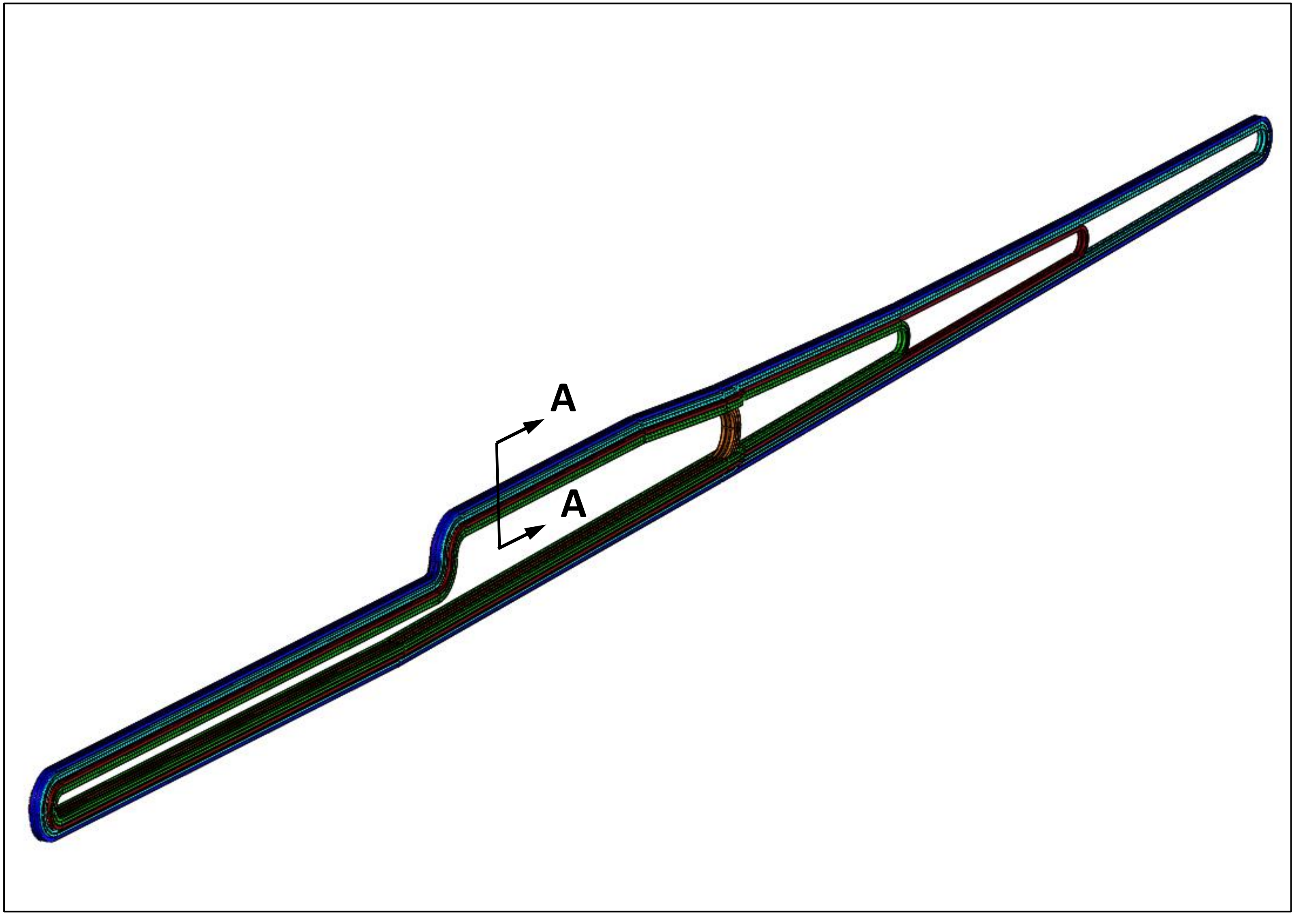
Table 8 - Luvata Hollow Conductor Sizes, Lengths, and Costs

Design	Coils	Size (mm)	Tool	Length/ Coil (m)	Total Length For 8 Coils (m)	Total Cost*
Small Conductor	All	6.0 x 6.0, Ø 4.5, R 1.0	8204	775.7	6205.6	15800USD
Large Conductor	1AL, 1AR, 2L, 2R	11.68 x 11.68, Ø 6.48, R 1.0	8345	43.7	349.6	4700 USD
	1BL, 1BR, 3L, 3R	11.7 x 9.4, Ø 6.5, R 1.0	Custom	62.7	501.6	5600 USD
	4L, 4R	11.7 x 10.53, Ø 6.5, R 1.0	Custom	47.5	380	5100 USD
	4C	11.7 x 12.8, Ø 6.5, R 1.0	Custom	32.5	260	4900 USD

*Note: Includes costs of metal, fabrication, tooling, and packaging

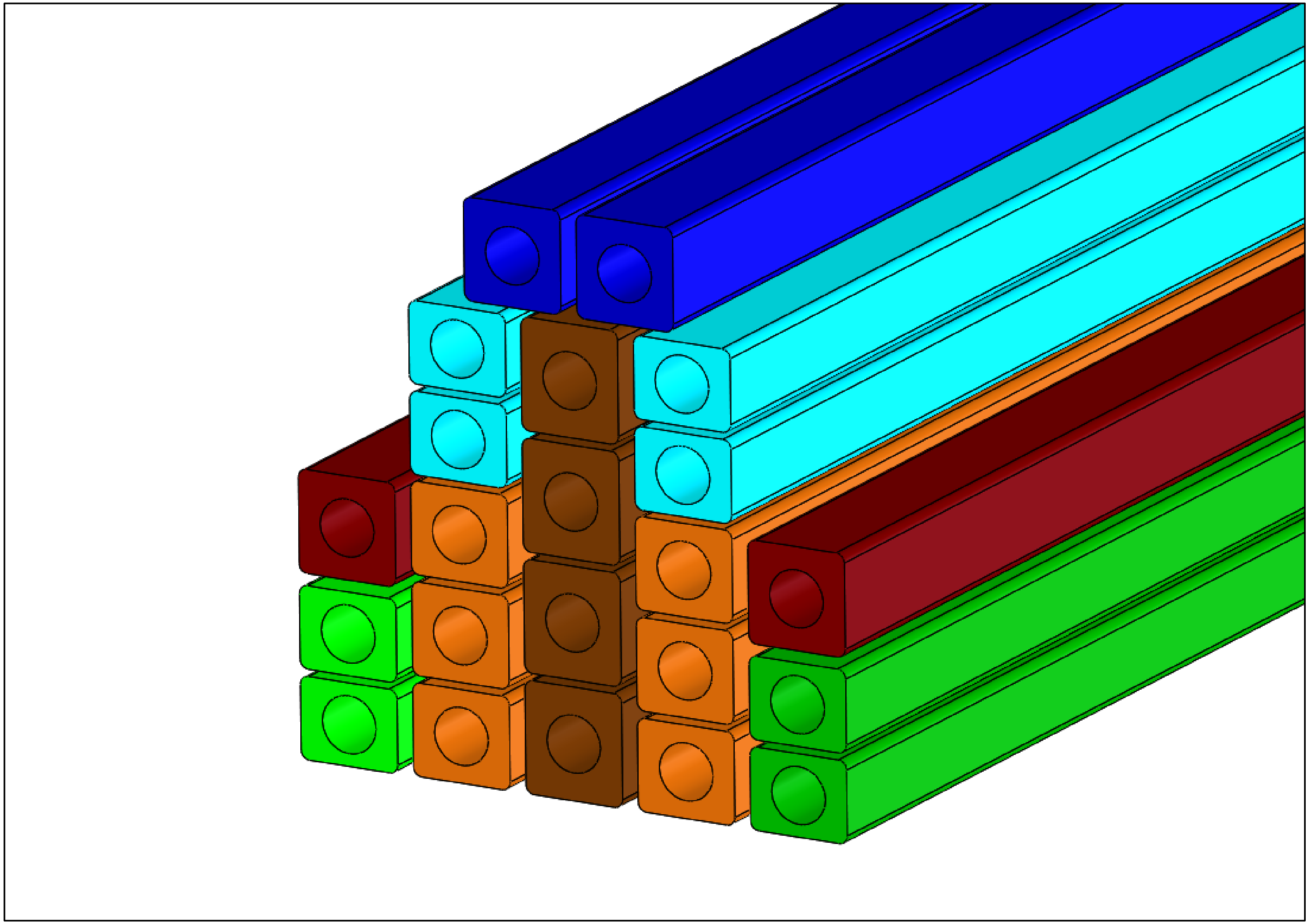
Large-Conductor Design Solid Model

Closed-Loop Models, Winding Ends Not Yet Detailed



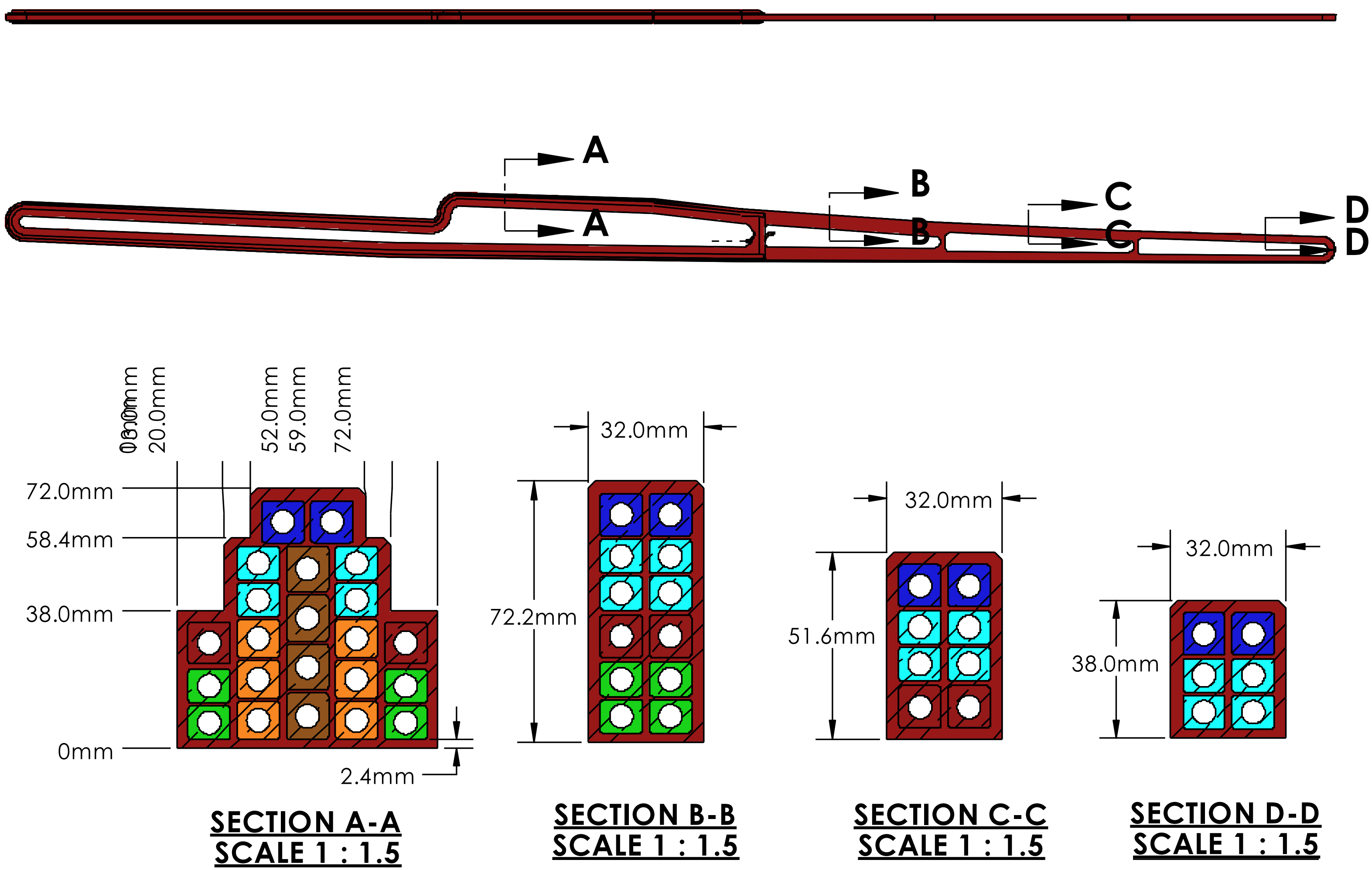
Large-Conductor Design Solid Model:

Coil Cross Section A-A

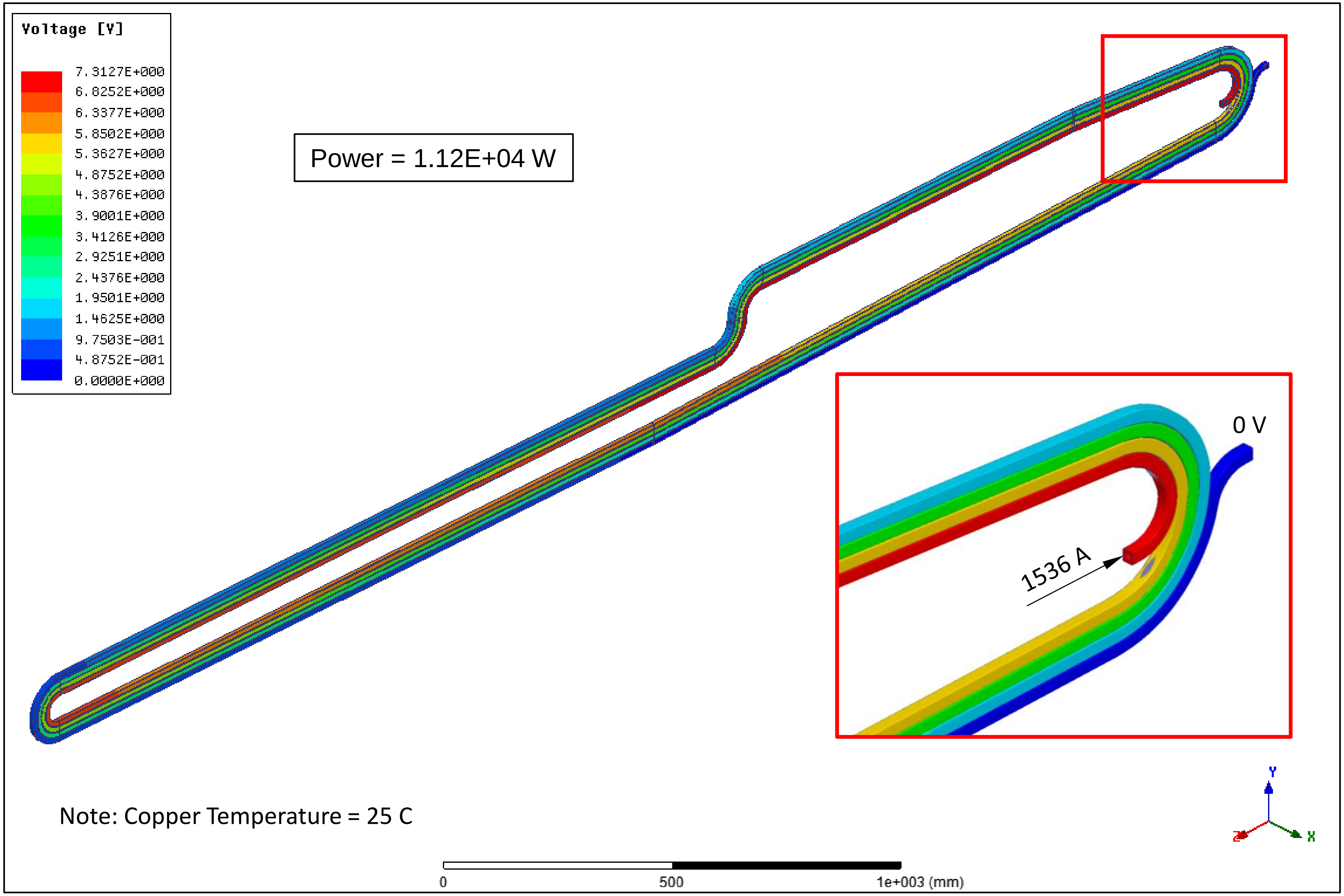


Large Conductor Model with Encapsulant: Cross Section Views

Encapsulant Envelope Same as for Small Conductor

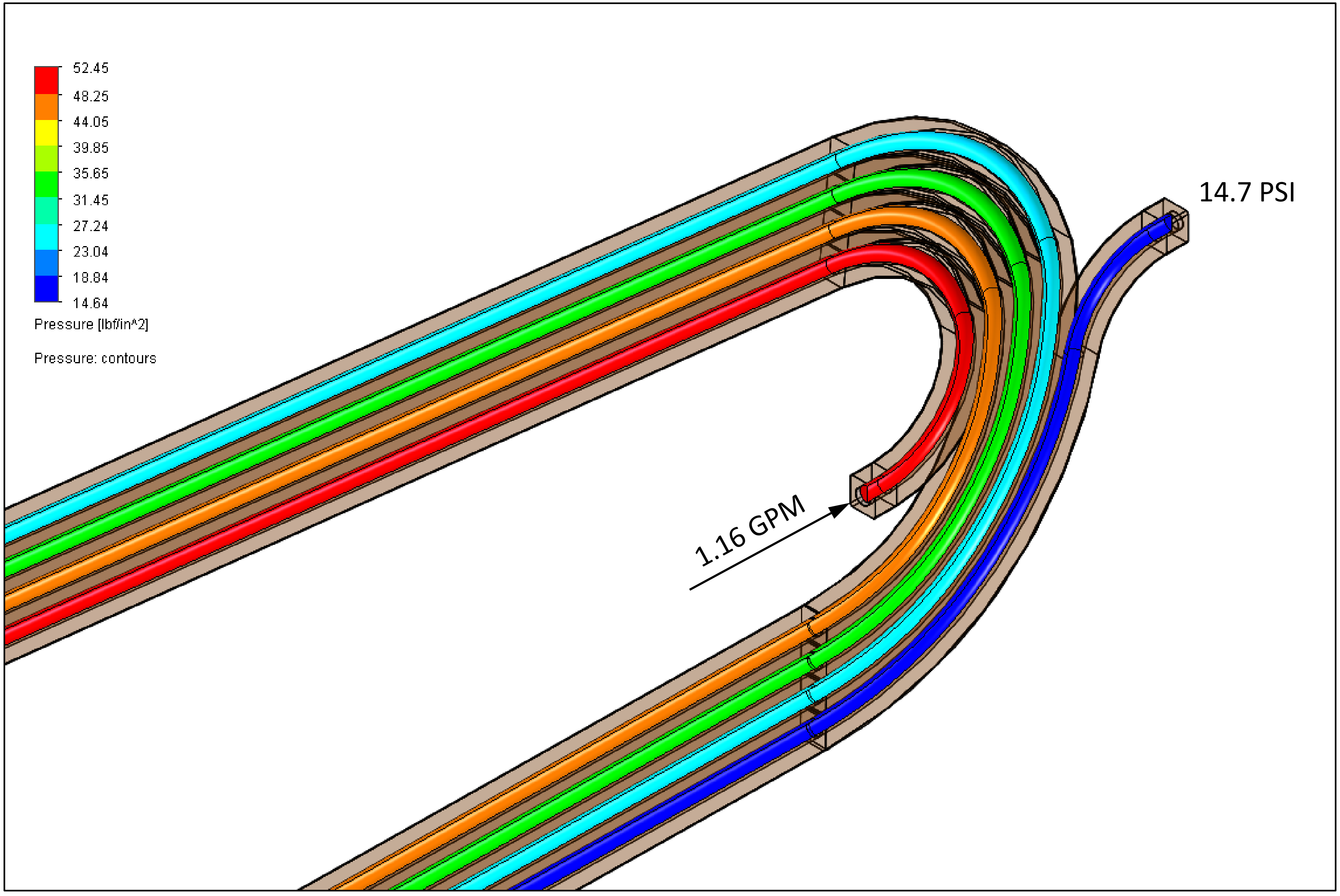


Maxwell Coil 4C Large-Conductor Design Results:
Voltage

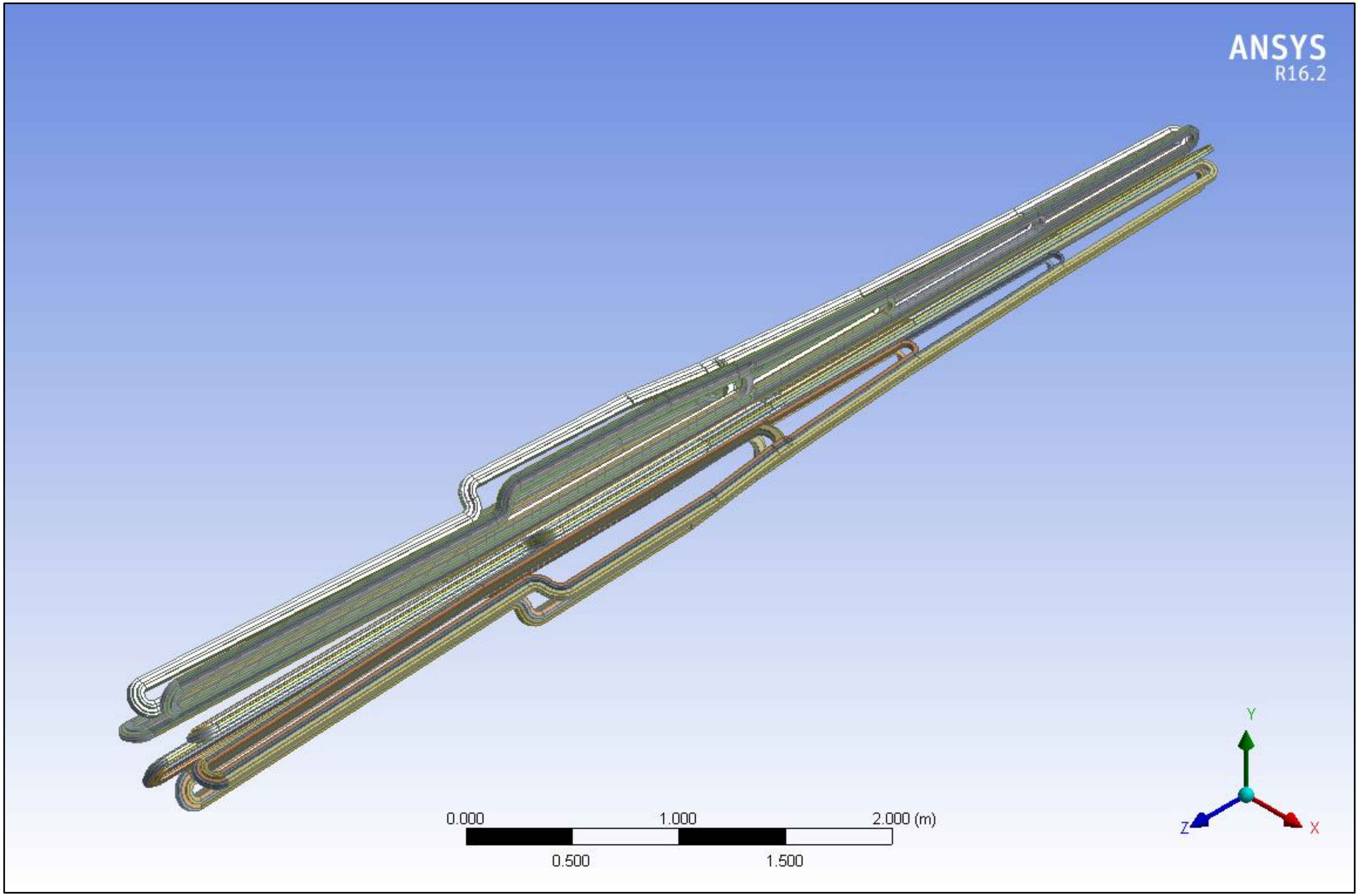


Flow Simulation Coil 4C Large-Conductor Design Results:

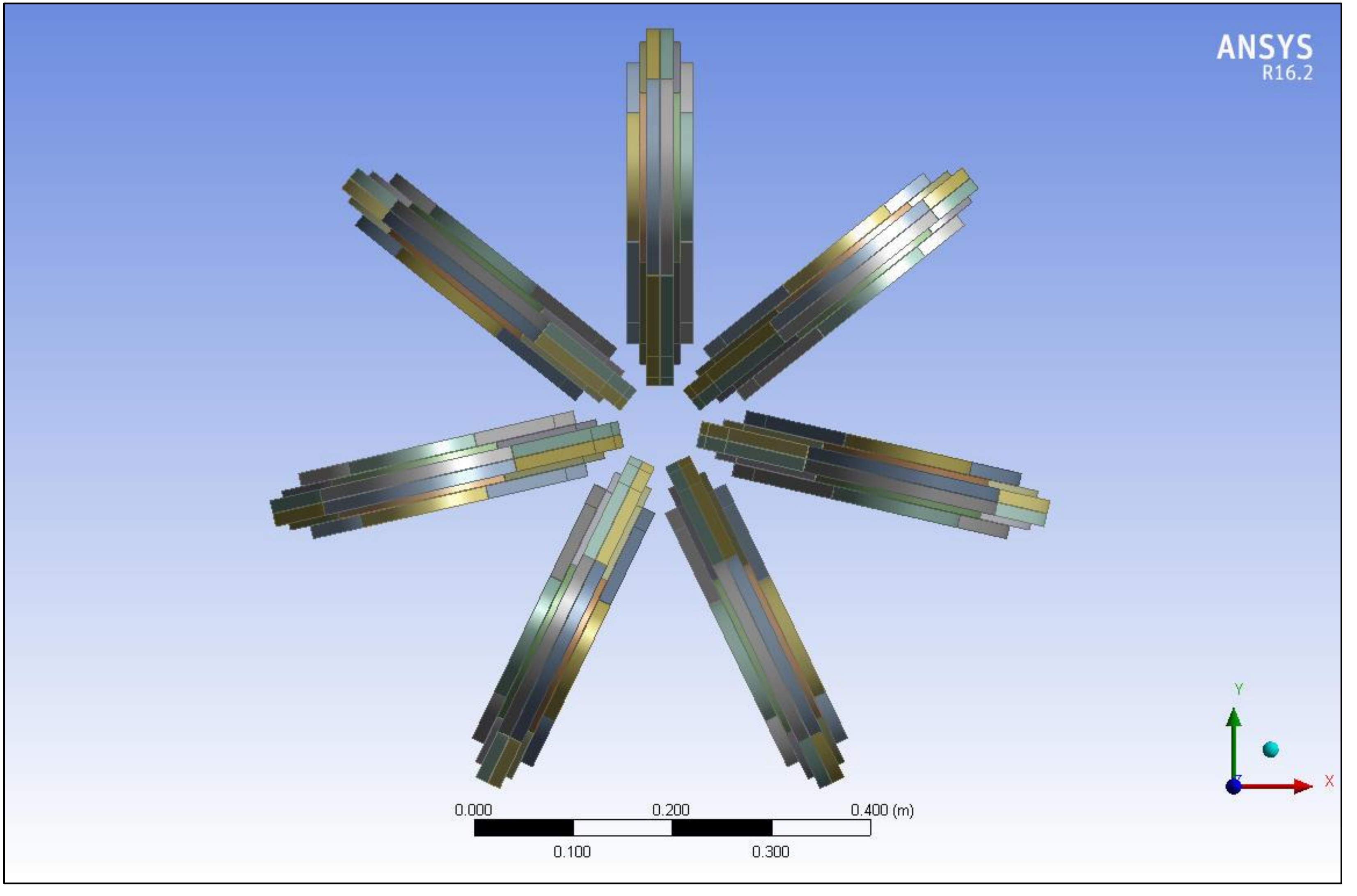
Pressure (Coarse Mesh)



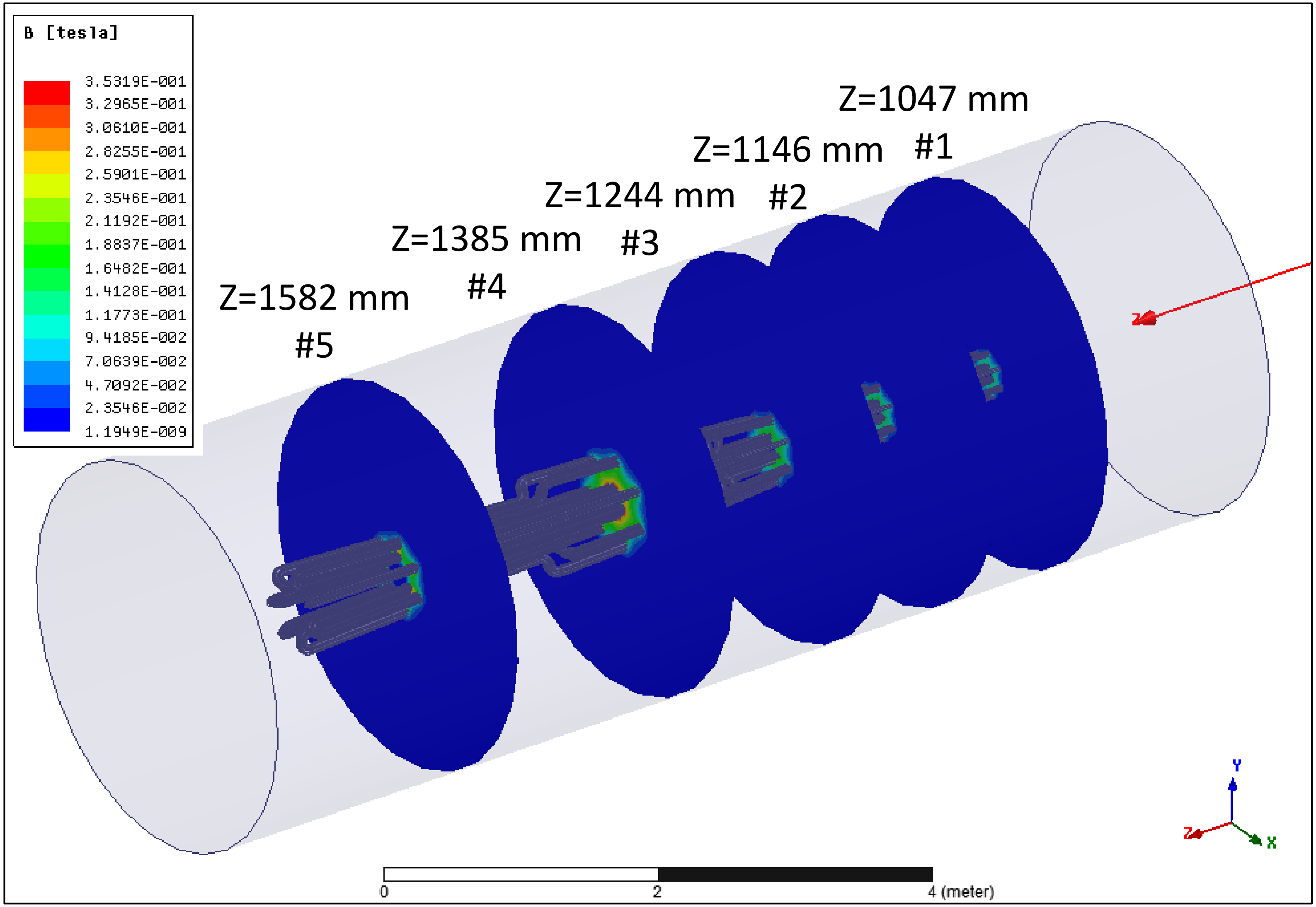
DesignModeler Solid Model: Iso View



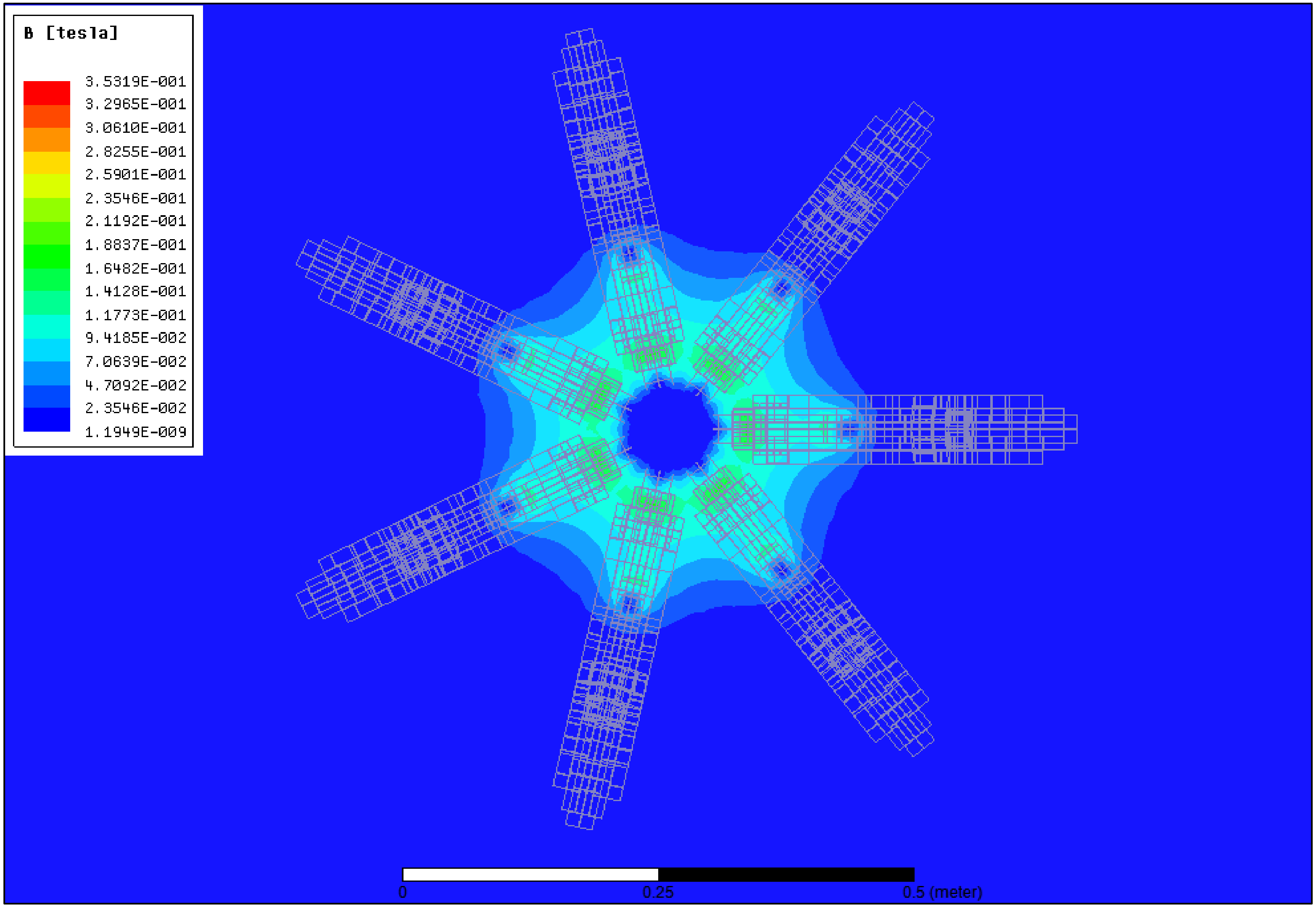
DesignModeler Solid Model: End View



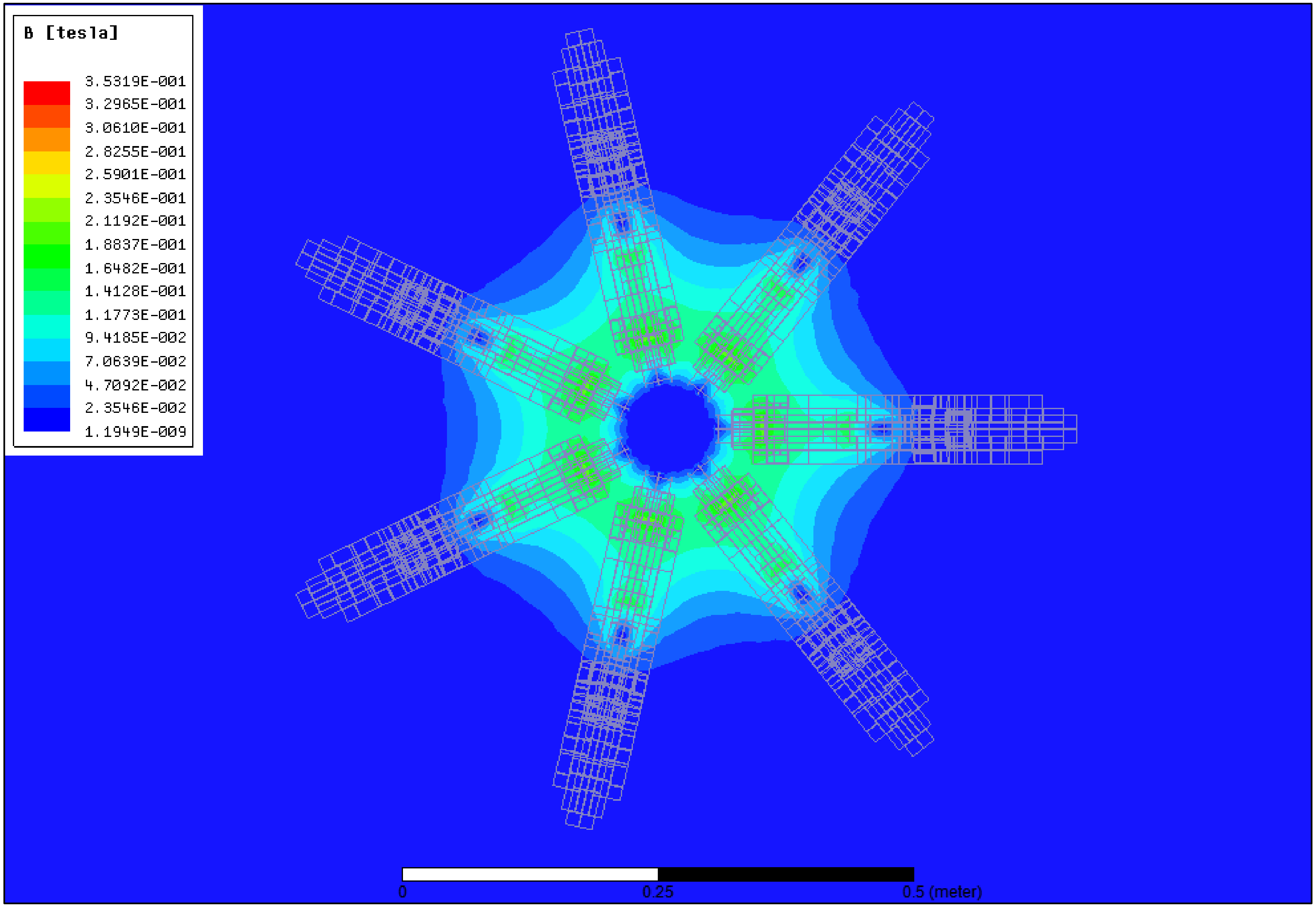
Maxwell Full 360 Model Results: Section B Fields



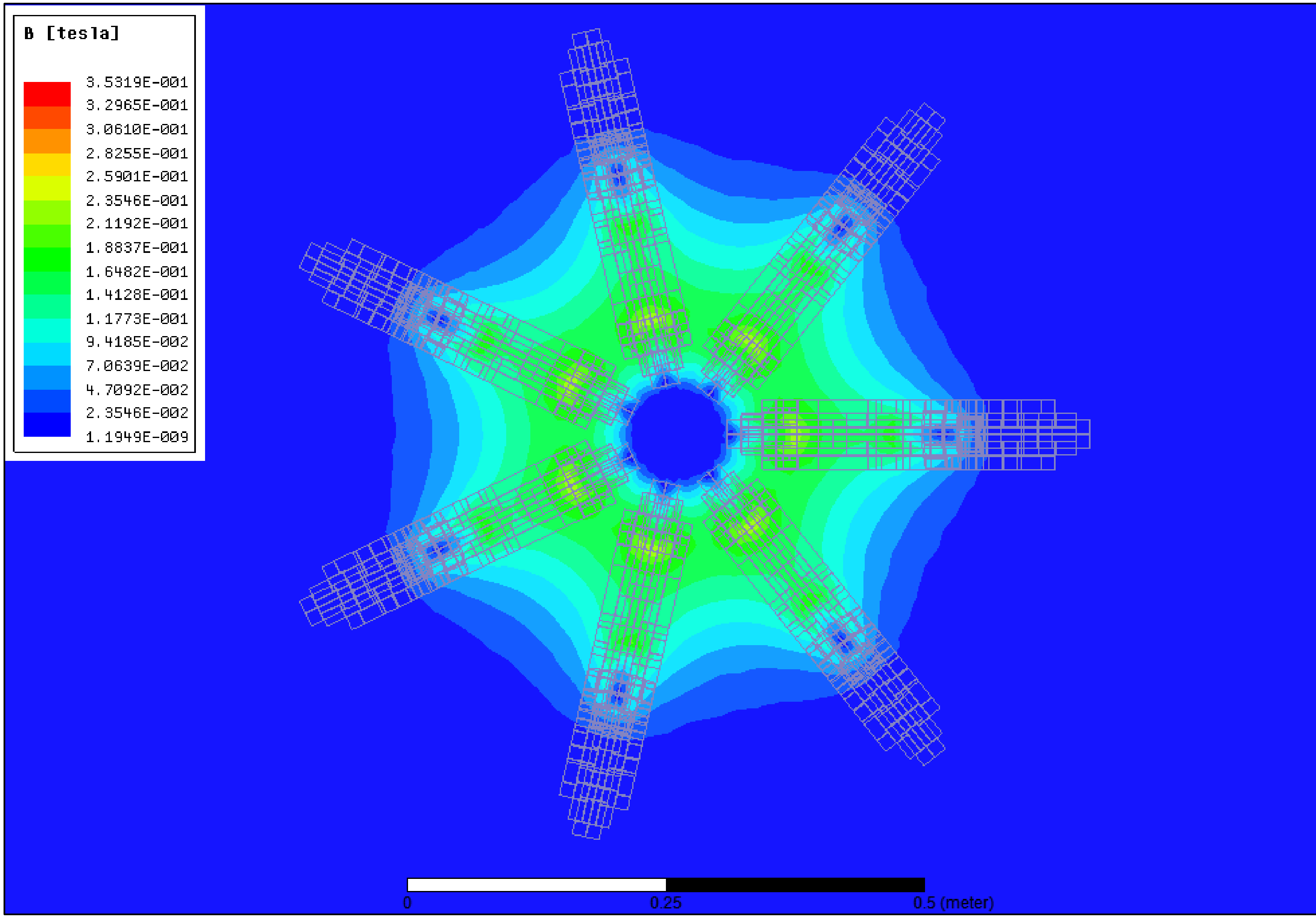
Maxwell Results: Section1 Magnetic Flux Density
Contour Plot



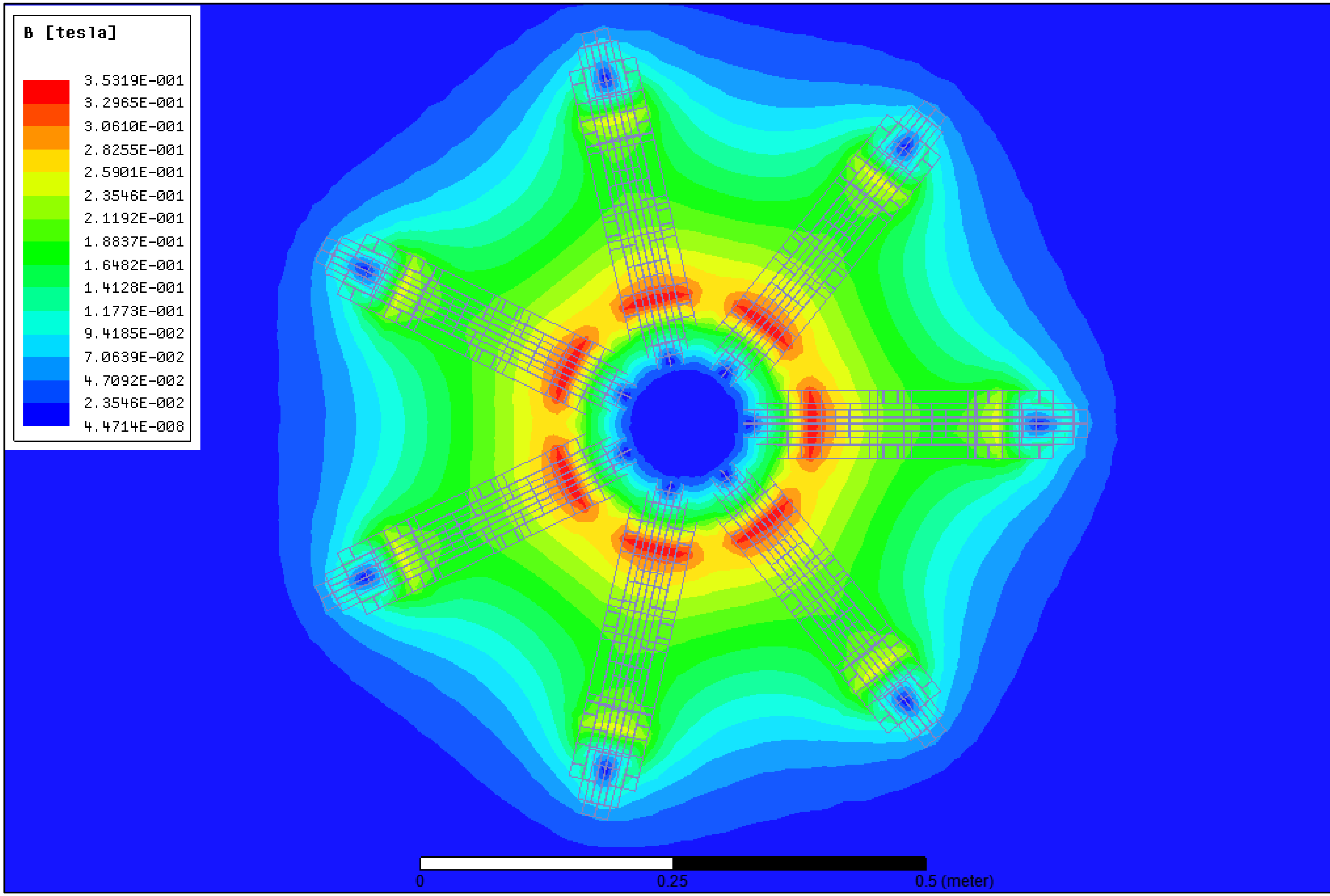
Maxwell Results: Section2 Magnetic Flux Density
Contour Plot



Maxwell Results: Section3 Magnetic Flux Density
Contour Plot



Maxwell Results: Section4 Magnetic Flux Density
Contour Plot



Maxwell Results: Section5 Magnetic Flux Density

Contour Plot