ANSYS 2D Magnetostatic and Structural Analysis of sPHENIX Coil at Full Current

John Cozzolino

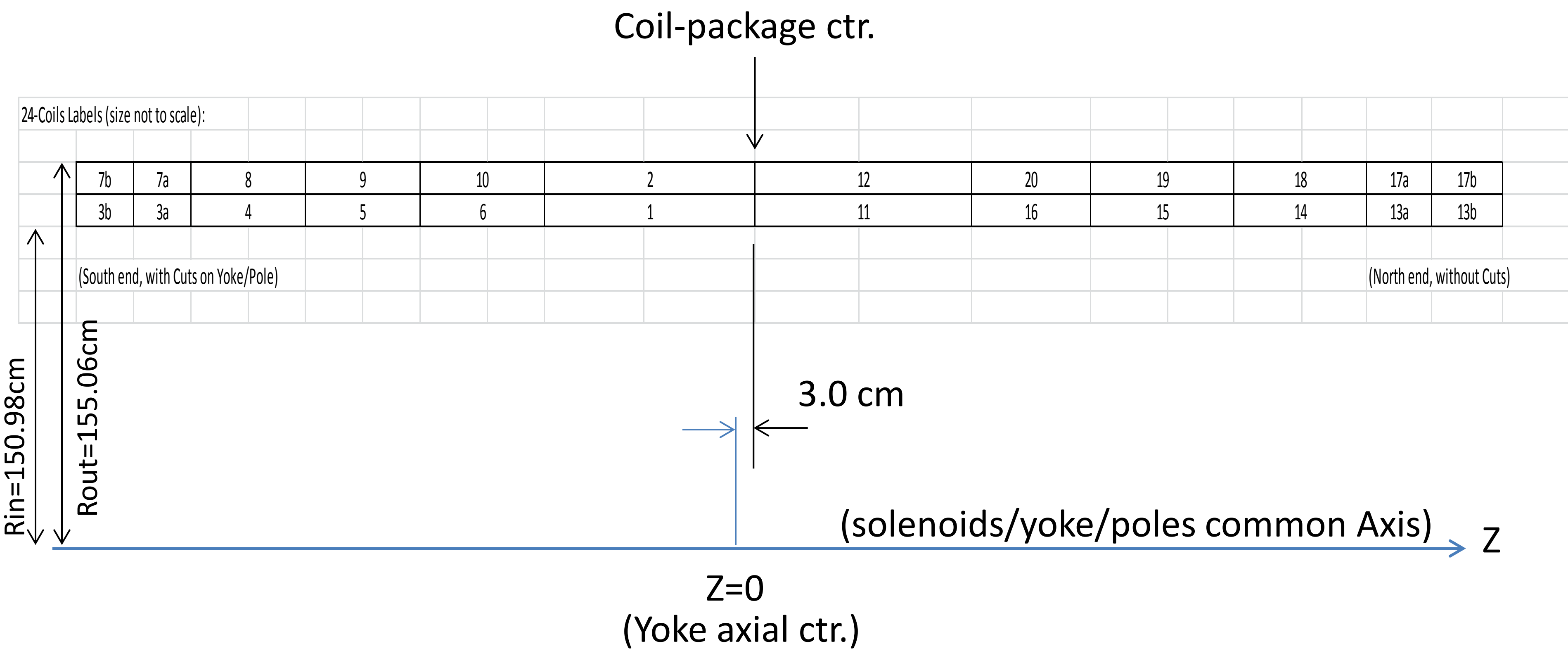
August 3, 2016

- ***ANSYS Maxwell Analysis of sPHENIX Coil***
  - 2D Magnetostatic FE analysis of complete coil
    - Geometry and current densities are taken from Wuzheng Meng's magnetic data – 6/17/2015.
      - Coil center is shifted 3cm north relative to the iron.
      - Coils are divided into 24 blocks, each with corresponding current densities at maximum power (4600 A).
    - Iron enclosure is approximated by an axisymmetric cylinder, capped at both ends.
      - » Cylinder weight is equal to the actual iron weight (approximately 1,323,000 lb).
      - » Pole iron thickness and axial distance from coil ends is the same as the actual.
      - » Iron cylinder I.D. is set to the sidewall radial distance closest to the coil.
    - Lorentz forces are calculated using ANSYS Maxwell and then exported to the mechanical model.

Labels on 24 Solenoid Coils

(Not to Scale)

W. Meng, 6/17/15



sPHENIX 24-Coils Information (W. Meng, 6/17/15)

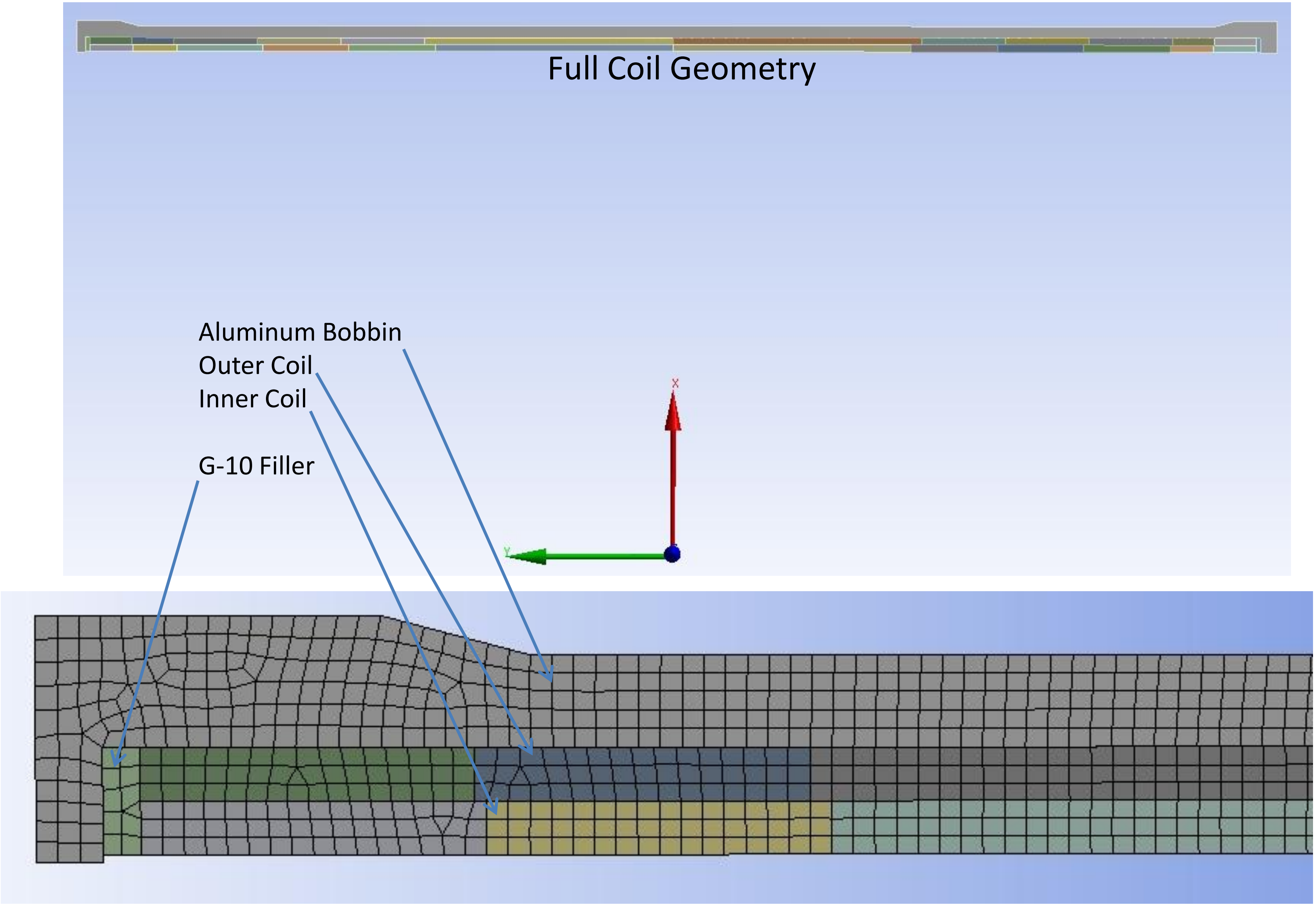
		Axial Center Zc (cm)		Coil Axial Length	**Current Density**
Coil No.	Rc (cm)	shift=0	shift=3cm	dz (cm)	**J (A/cm^2)**
1	152.00	-35.56	-32.56	71.12	**2502.564**
2	154.04	-37.12	-34.12	74.23	**2519.067**
3a	152.00	-155.12	-152.12	12.90	**4205.118**
3b	152.00	-168.02	-165.02	12.90	**4205.118**
4	152.00	-135.75	-132.75	25.81	**4205.118**
5	152.00	-109.90	-106.90	25.81	**4205.118**
6	152.00	-84.05	-81.05	25.81	**4205.118**
7a	154.04	-155.65	-152.65	12.53	**4204.423**
7b	154.04	-168.17	-165.17	12.53	**4204.423**
8	154.04	-136.86	-133.86	25.05	**4204.423**
9	154.04	-111.81	-108.81	25.05	**4204.423**
10	154.04	-86.76	-83.76	25.05	**4204.423**
11	152.00	35.56	38.56	71.12	**2502.564**
12	154.04	37.12	40.12	74.23	**2519.067**
13a	152.00	155.12	158.12	12.90	**4205.118**
13b	152.00	168.02	171.02	12.90	**4205.118**
14	152.00	135.75	138.75	25.81	**4205.118**
15	152.00	109.90	112.90	25.81	**4205.118**
16	152.00	84.05	87.05	25.81	**4205.118**
17a	154.04	155.65	158.65	12.53	**4204.423**
17b	154.04	168.17	171.17	12.53	**4204.423**
18	154.04	136.00	139.00	25.05	**4204.423**
19	154.04	111.81	114.81	25.05	**4204.423**
20	154.04	86.76	89.76	25.05	**4204.423**

System Origin is Located at Center of sPhenix Yoke
Coil thickness is about 2 cm (for inner or outer layer)

- ***ANSYS FE Structural Analysis of sPHENIX Coil***
  - 2d Axisymmetric Steady-State FE Analysis of Complete Coil
    - Includes external aluminum bobbin and G-10 end fillers
    - Lorentz forces are imported directly from the ANSYS Maxwell Magnetostatic FE model at 4600 A.
    - Thermal stresses during cool-down from RT to 4K are included.
    - Mechanical properties vs. temperature are included.
      - Coil properties E and CTE are adjusted for percentage of insulation vs. conductor (Ref Ansaldo Dwg# 620RM07142, pg. 1).
        - » Radial direction 2.0% insulation (all coils)
        - » Axial direction 4.7% (middle coils)
        - » Axial direction 8.1% (end coils)
    - All connections (contacts) are bonded.
    - Tensile and shear stresses are studied throughout the coil
      - Shear stress limit: 30 MPa (4350 psi)
      - Tensile stress limit: 30 MPa

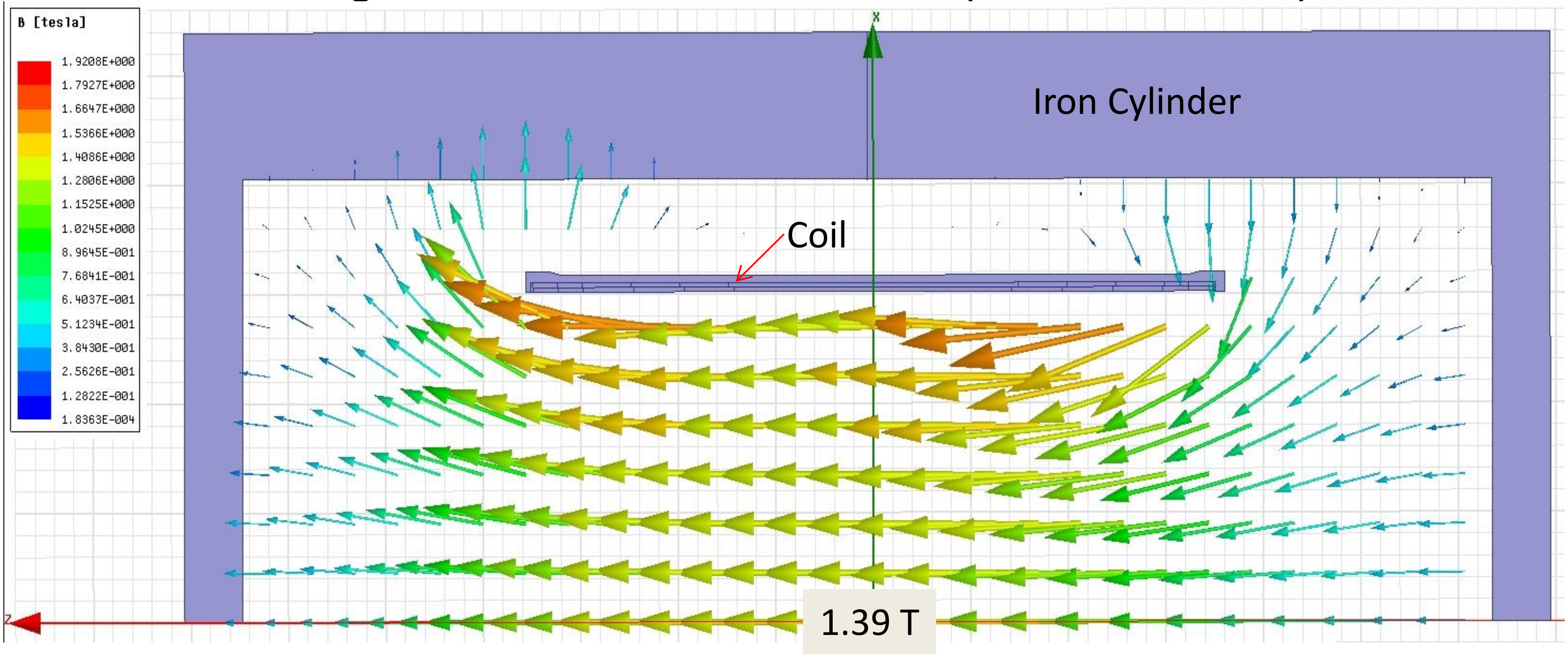
- ***ANSYS FE Structural Analysis of sPHENIX Coil (cont'd)***

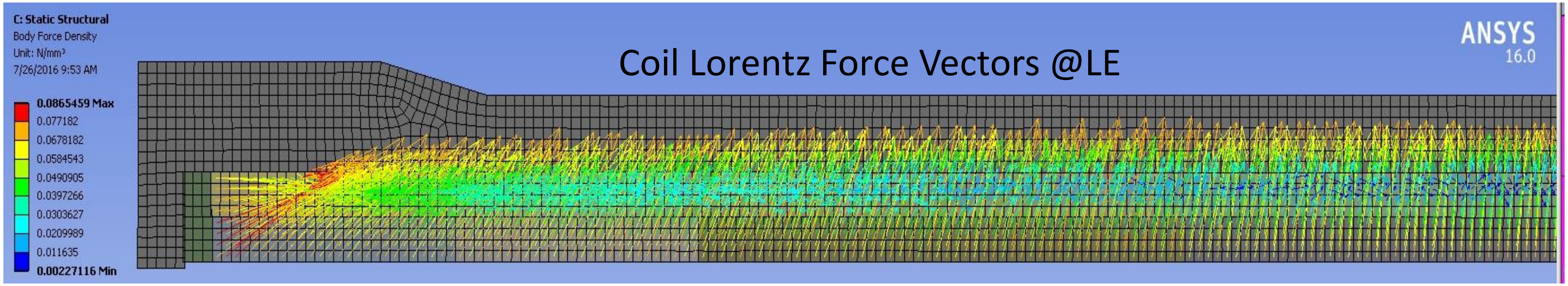
  - Stresses and deflections will be compared to those derived in the previous analysis from 7/16/15.
    - Lorentz forces were first calculated by W. Meng using Opera.
    - They were then input by hand as coil face pressures into an ANSYS static structural model.
    - Direct mapping of these forces from ANSYS Maxwell to a static structural model should provide more accurate results.
    - What follows is a side-by-side comparison of results from the two analyses.

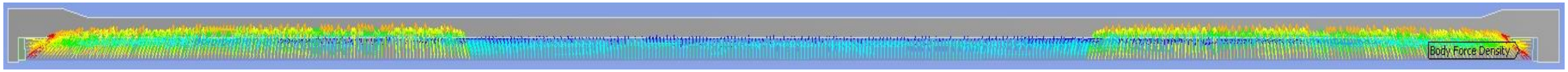


FE Mesh for Static Structural Model (Lead “South” End)

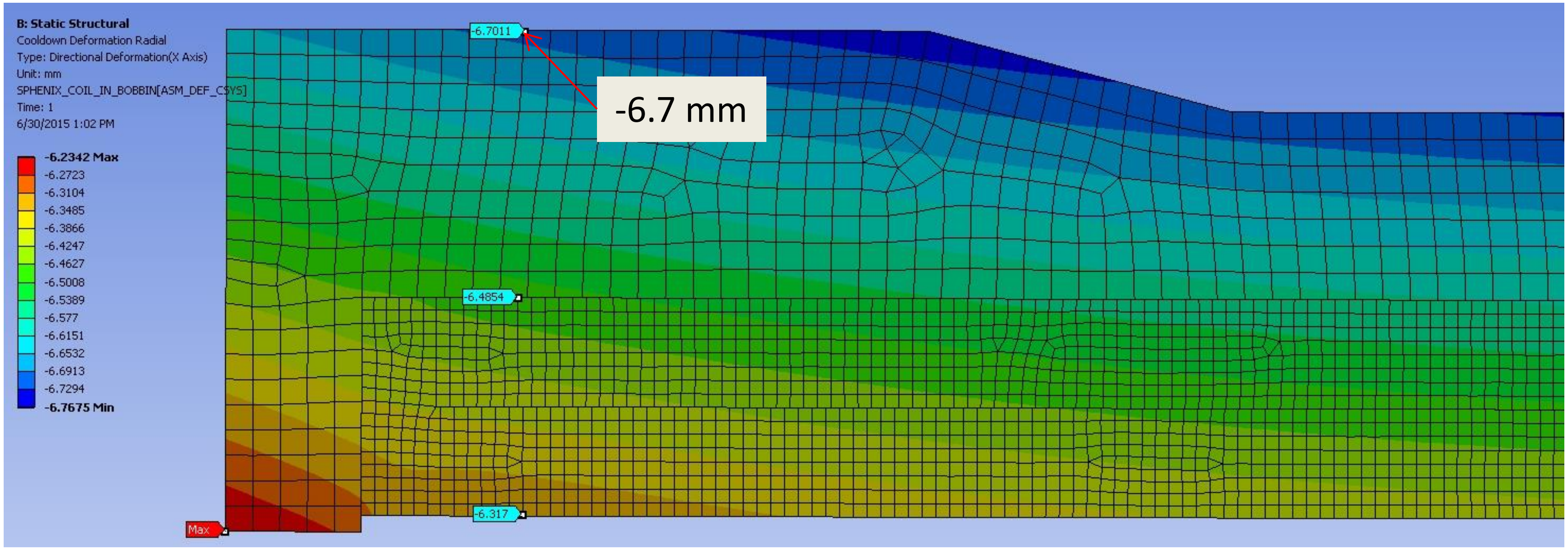
Magnetic Flux Vectors at 4600 A (ANSYS Maxwell)



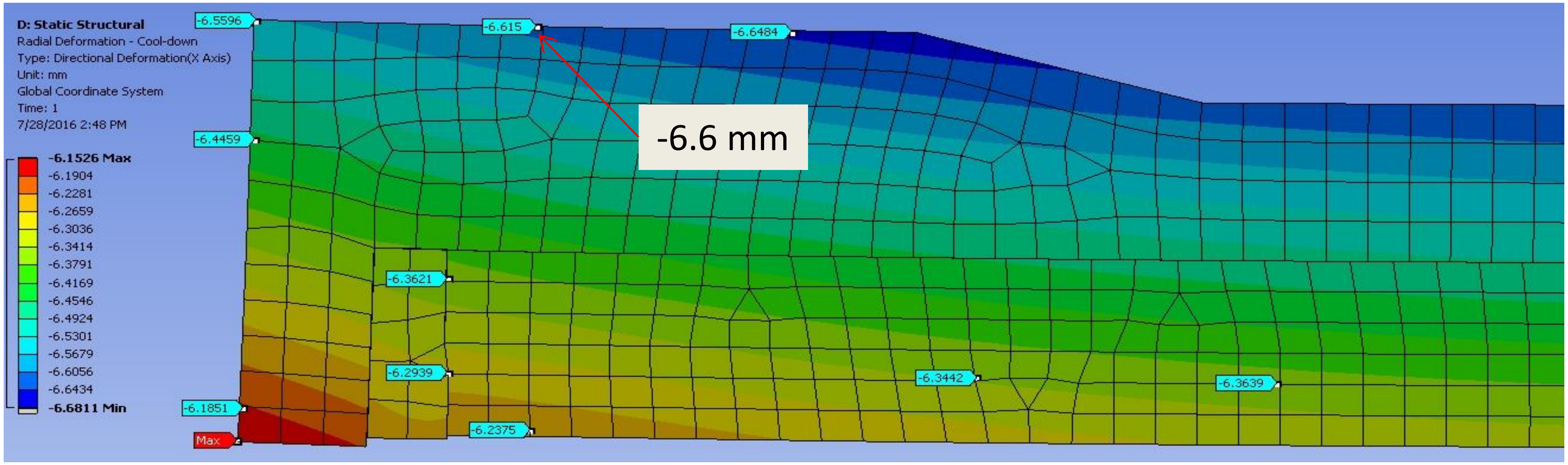




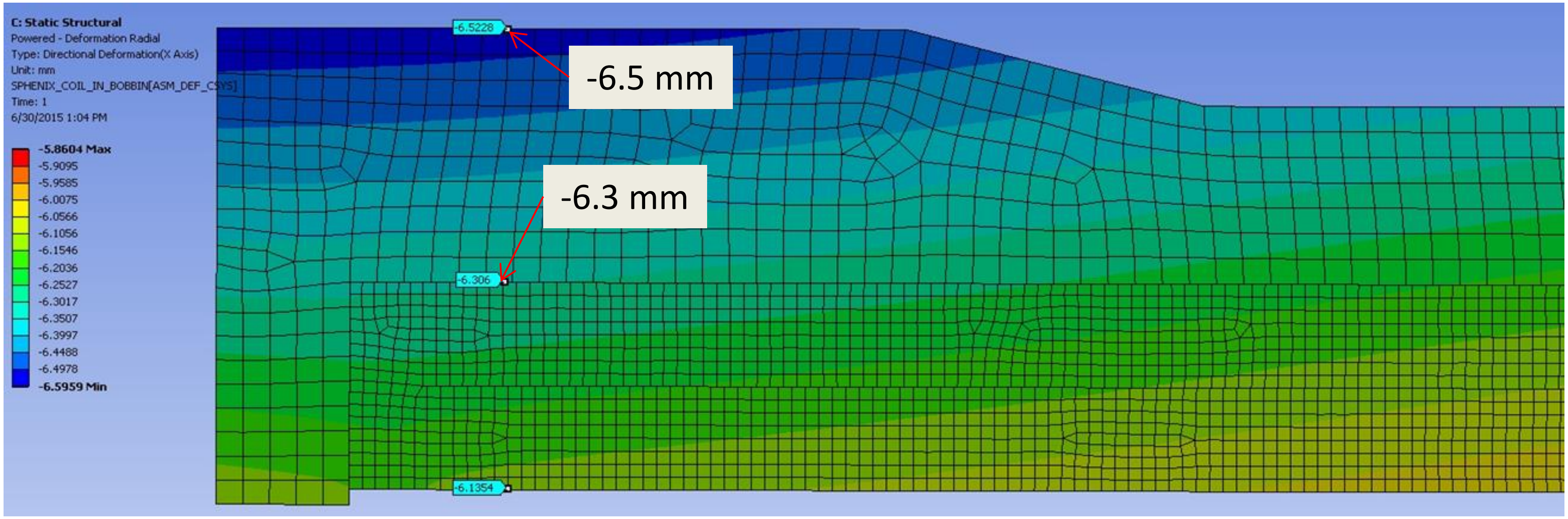
Radial Deflection @ Cool-down (LE view - mm) 7/16/2015



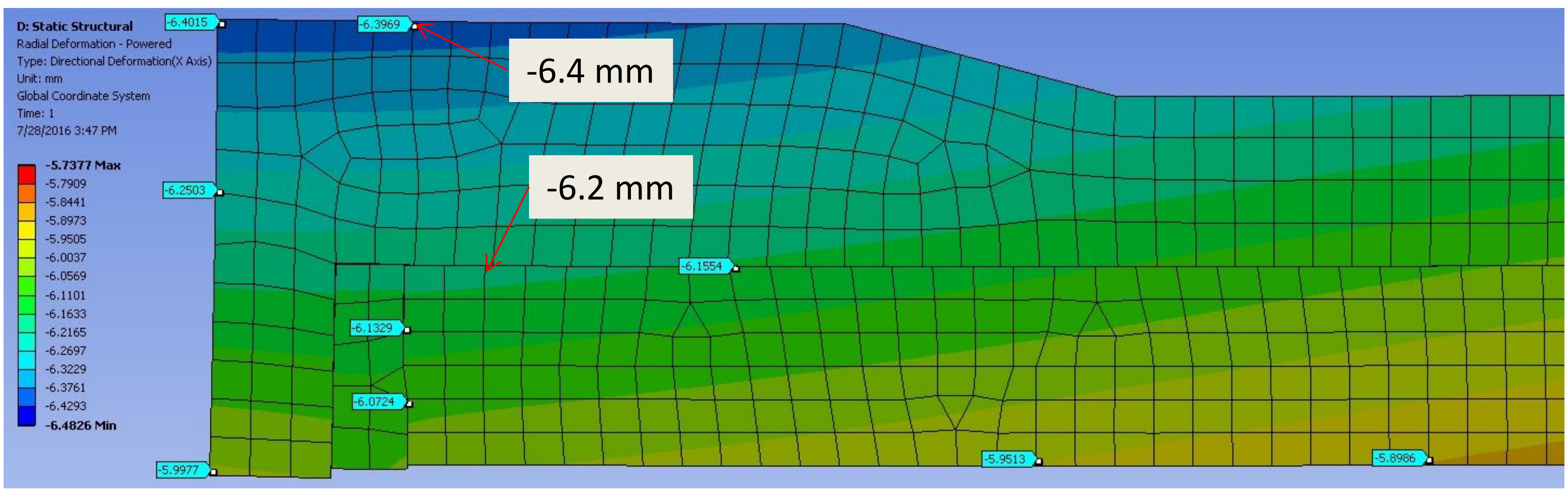
Radial Deflection @ Cool-down (LE view - mm) 7/28/2016



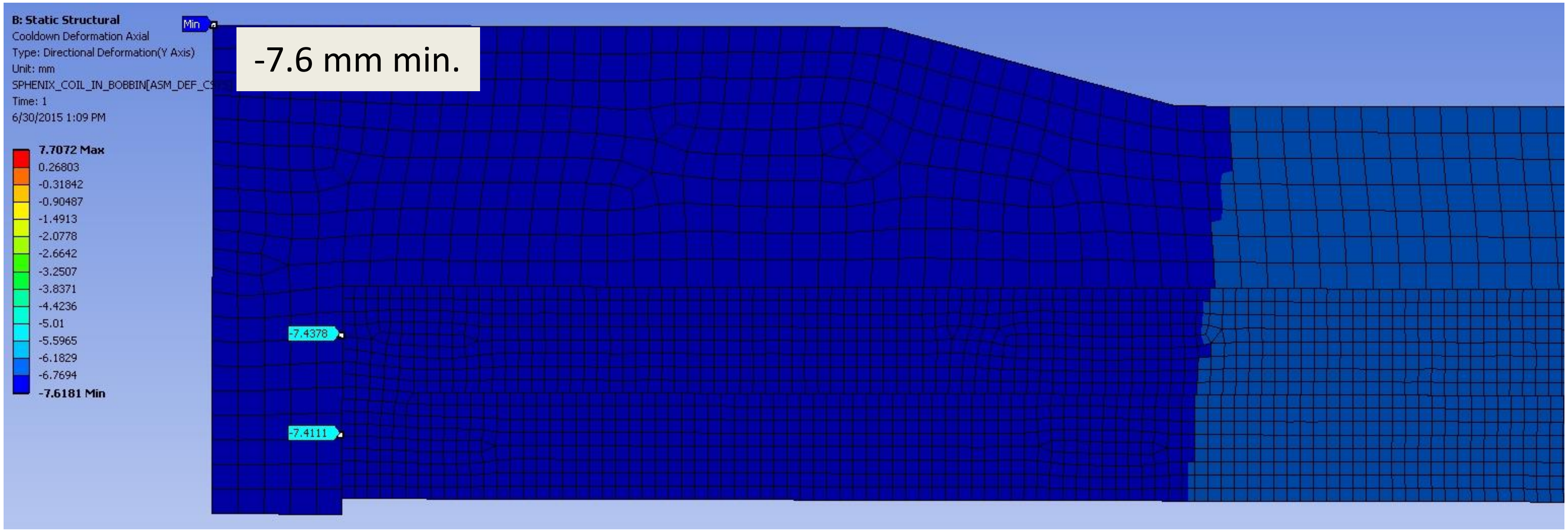
Radial Deflection @ Max Current (LE view - mm) 7/16/2015



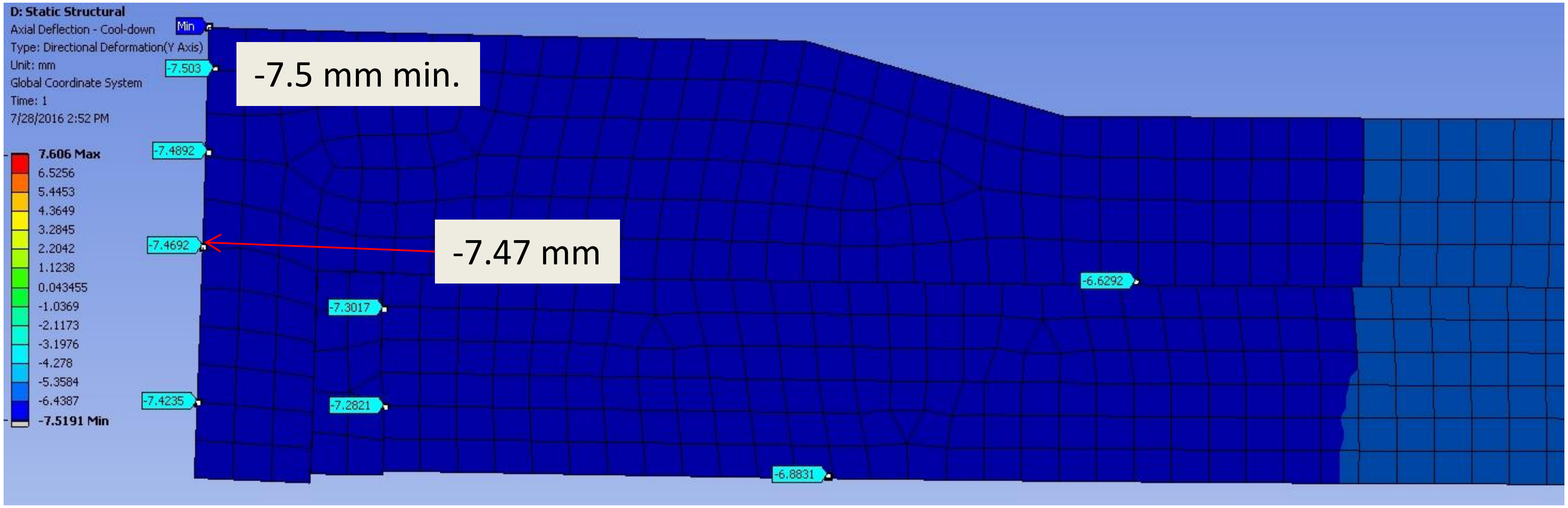
Radial Deflection @ Max Current using MAXWELL (LE view - mm) 7/28/2016



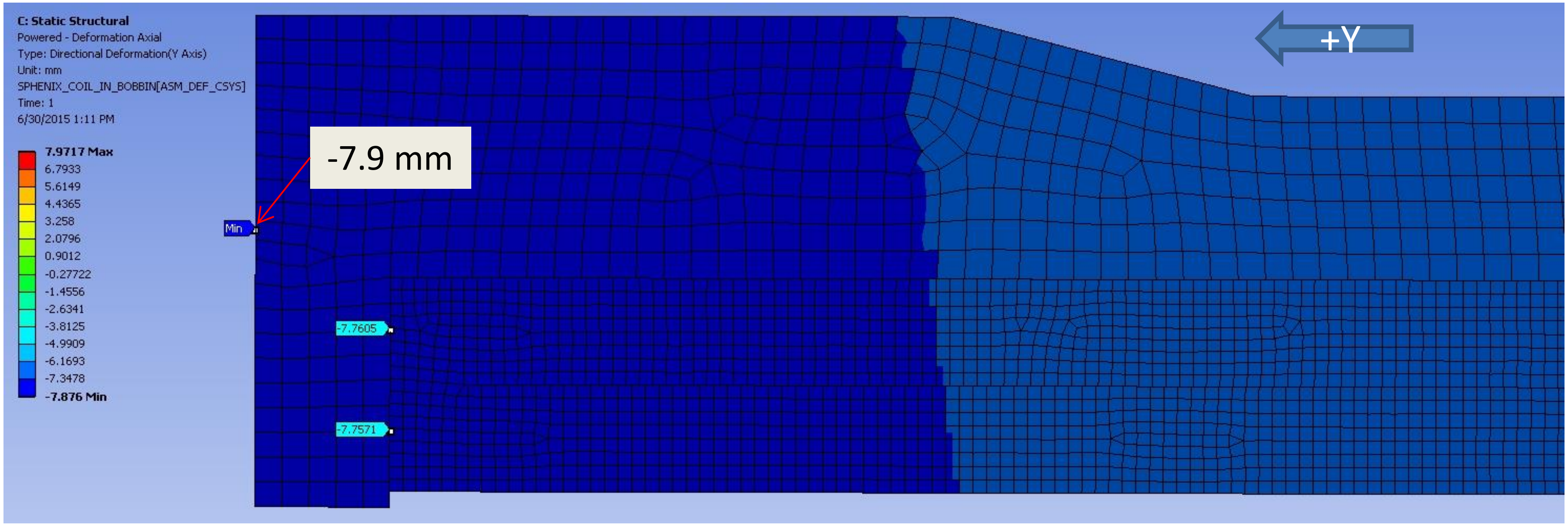
Axial Deflection @ Cool-down (LE view - mm) 7/16/2015



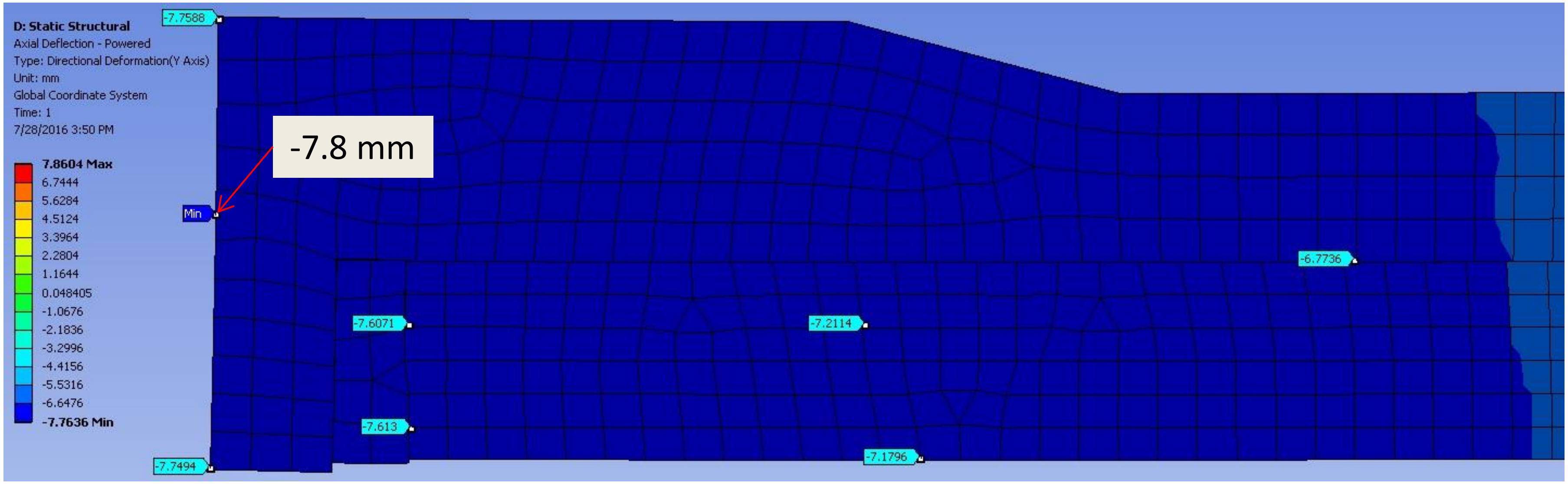
Axial Deflection @ Cool-down (LE view - mm) 7/28/2016



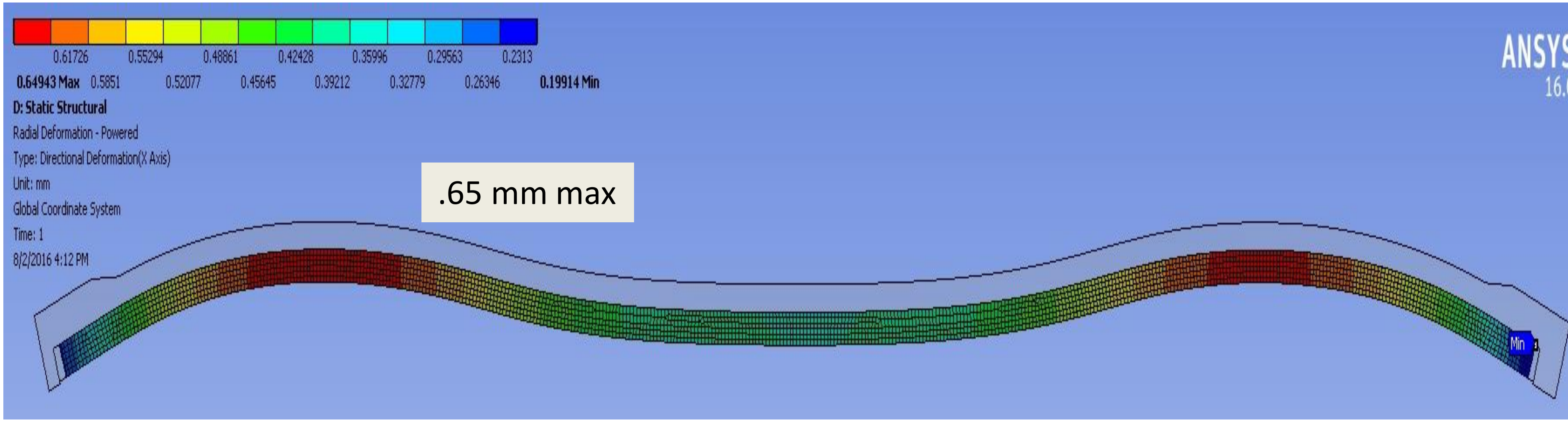
Axial Deflection @ Max Current (LE view - mm) 7/16/2015



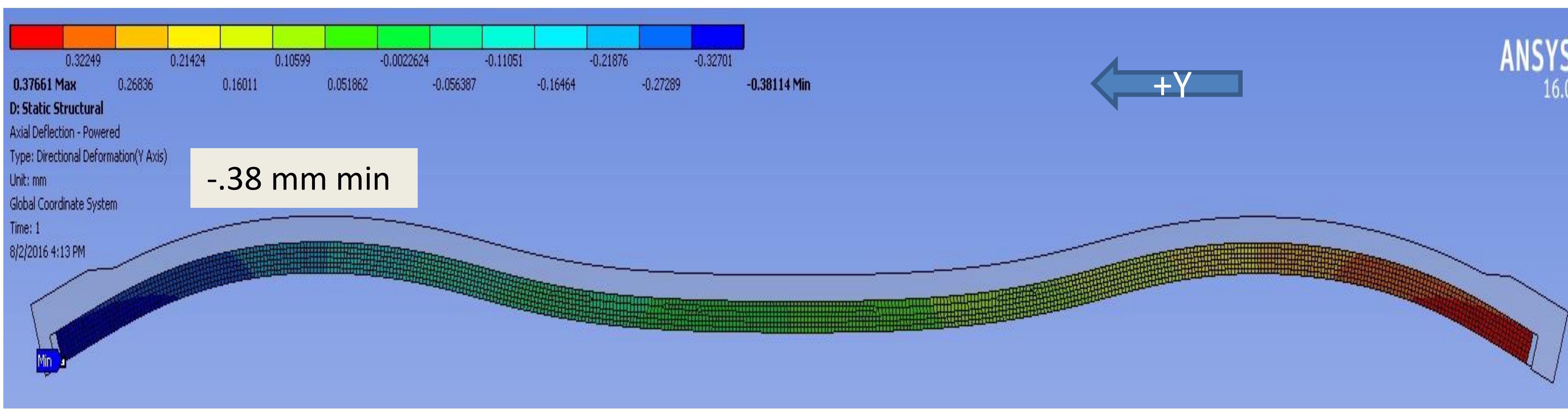
Axial Deflection @ Max Current using MAXWELL (LE view - mm) 7/28/2016



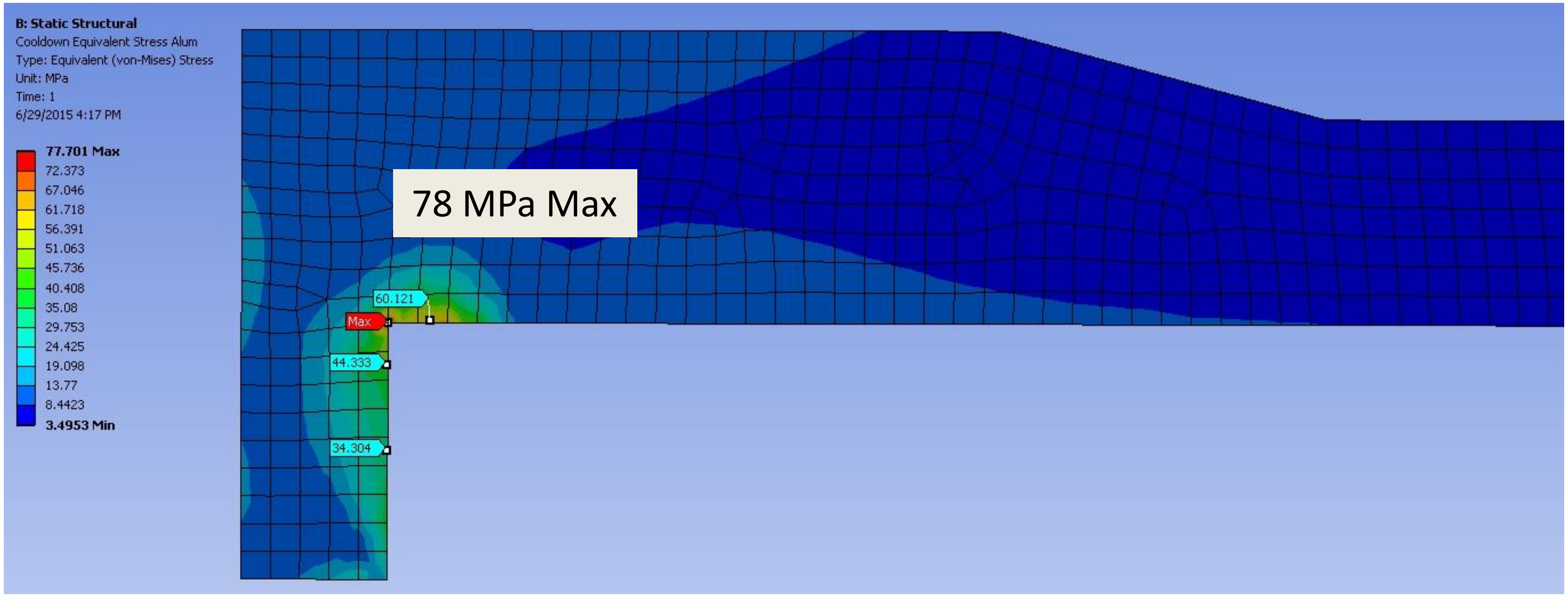
Radial Deflection @ Max Current w/o Cool-down Effects (LE view - mm) 7/28/2016



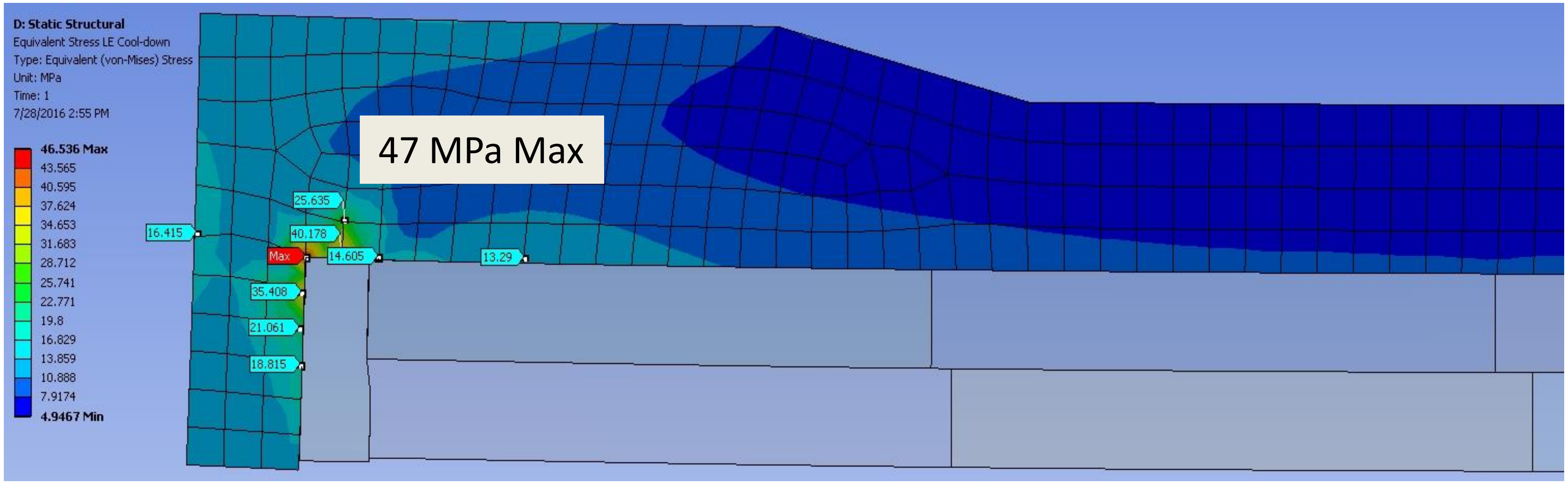
Axial Deflection @ Max Current w/o Cool-down Effects (LE view - mm) 7/28/2016



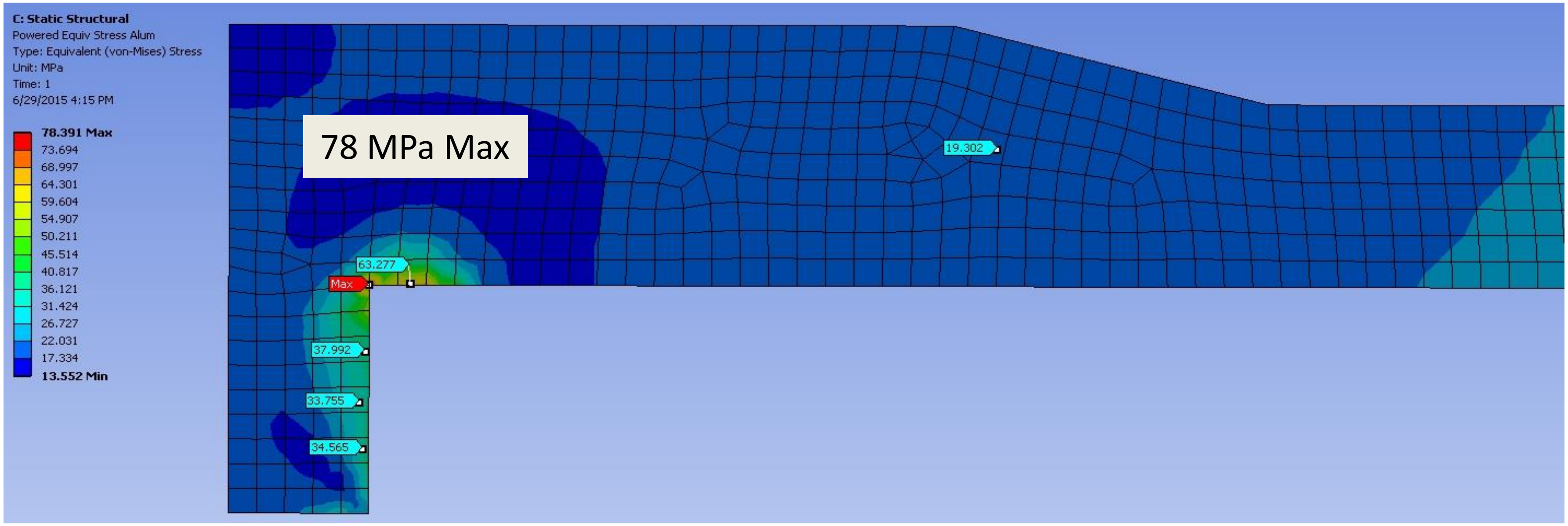
Equivalent Stress in Aluminum Bobbin @ Cool-down (LE view - MPa) 7/16/2015



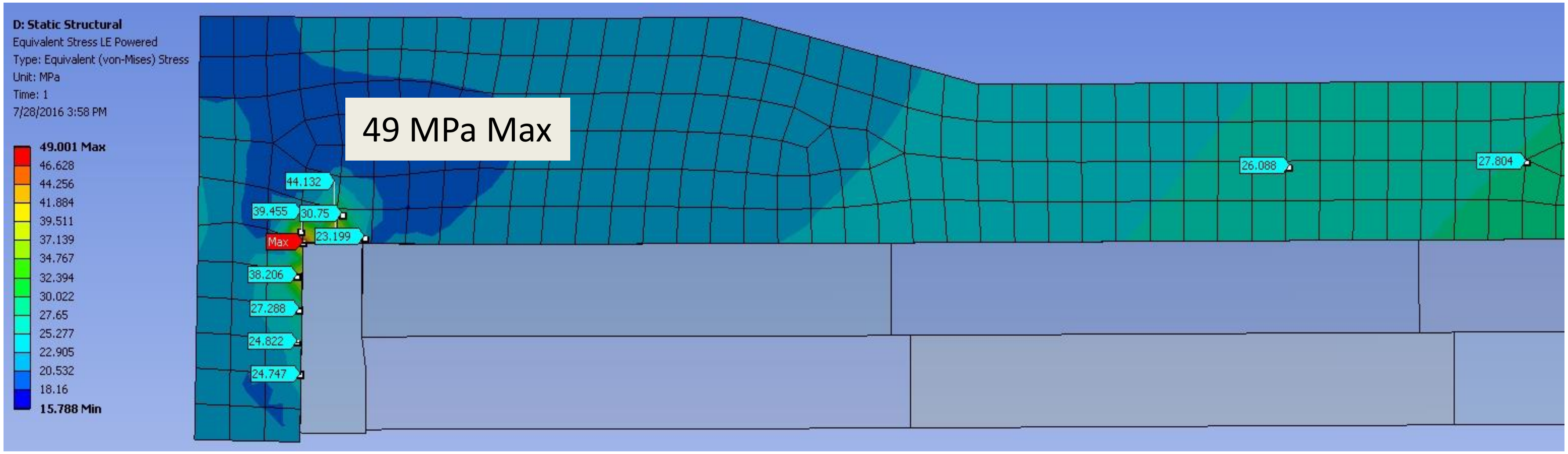
Equivalent Stress in Aluminum Bobbin @ Cool-down (LE view - MPa) 7/28/2016



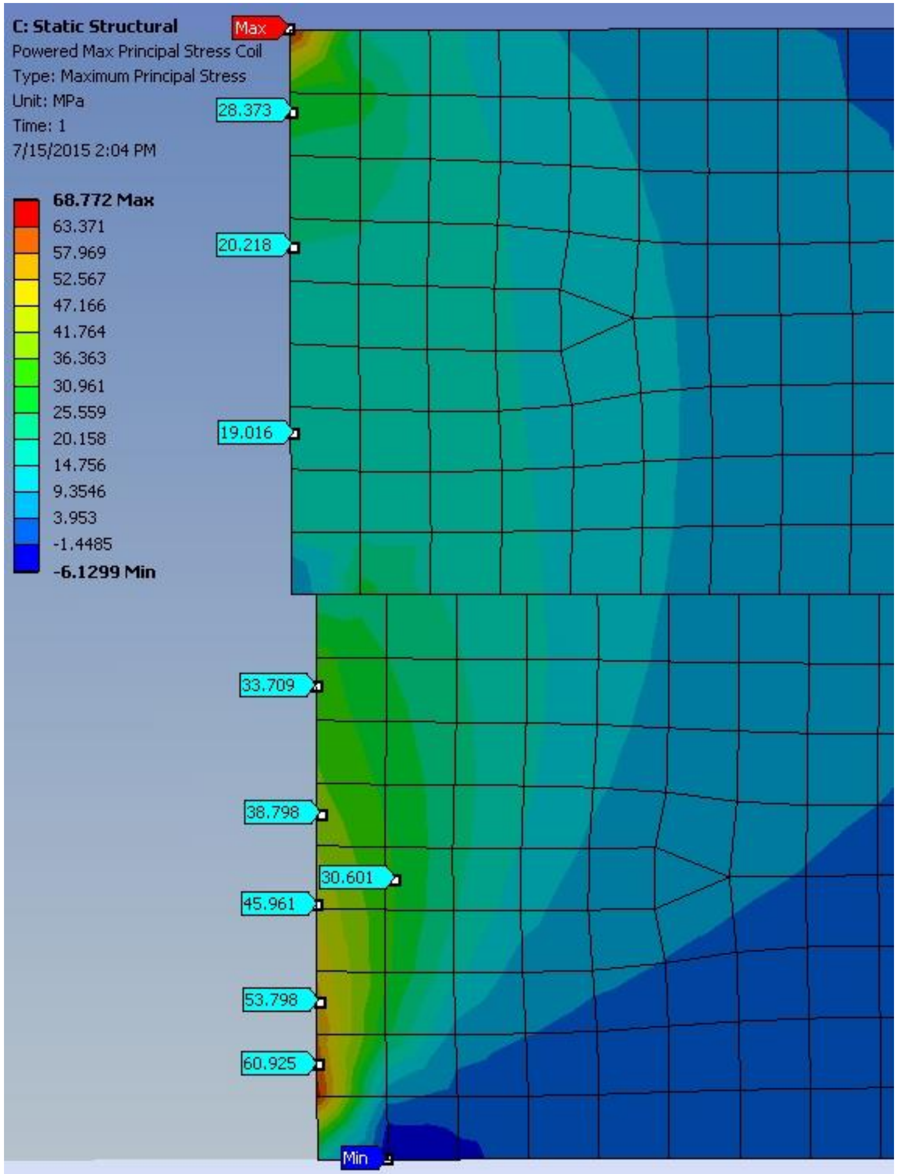
Equivalent Stress in Aluminum Bobbin @ Max Current (LE view - MPa) 7/16/2015



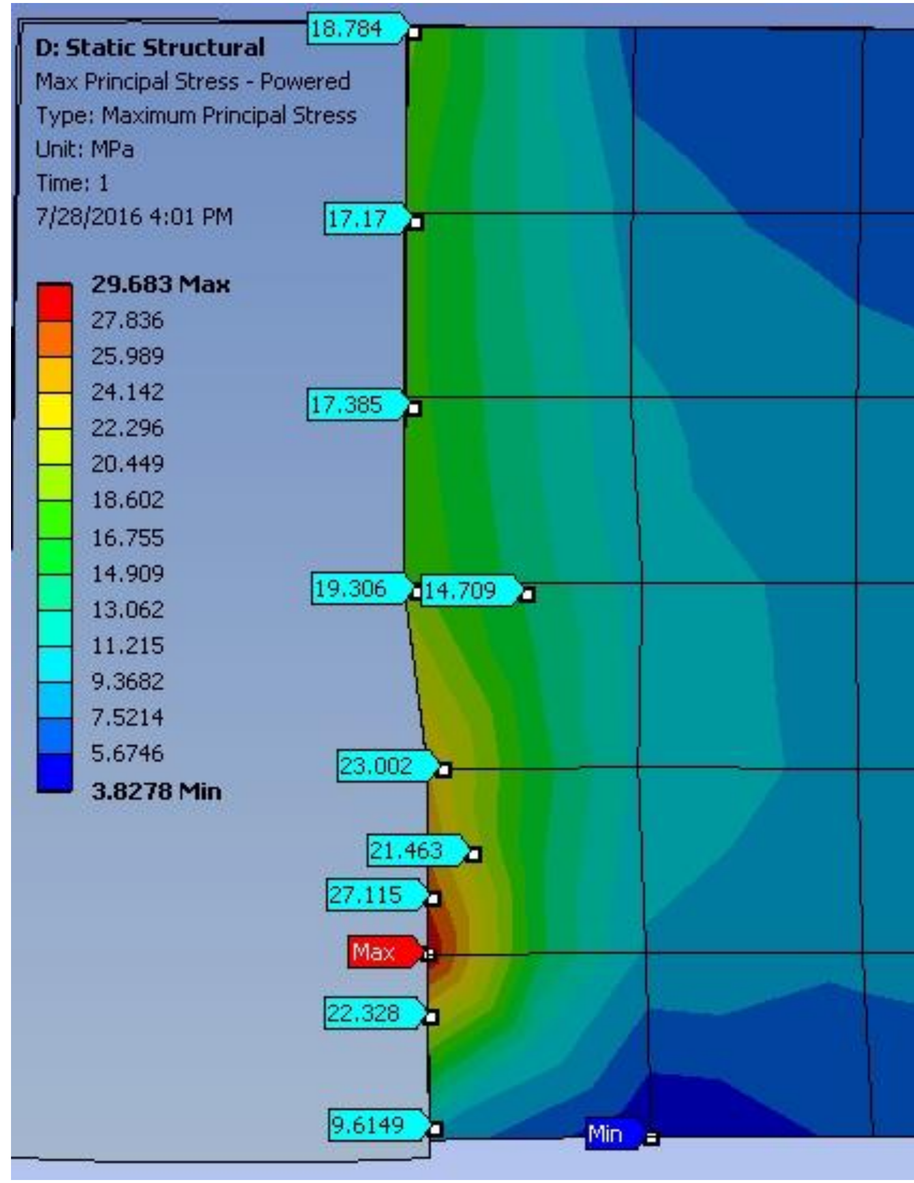
Equivalent Stress in Aluminum Bobbin @ Max Current (LE view - MPa) 7/28/2016



Coil Lead End Maximum Tensile Stress @ Full Power (MPa)

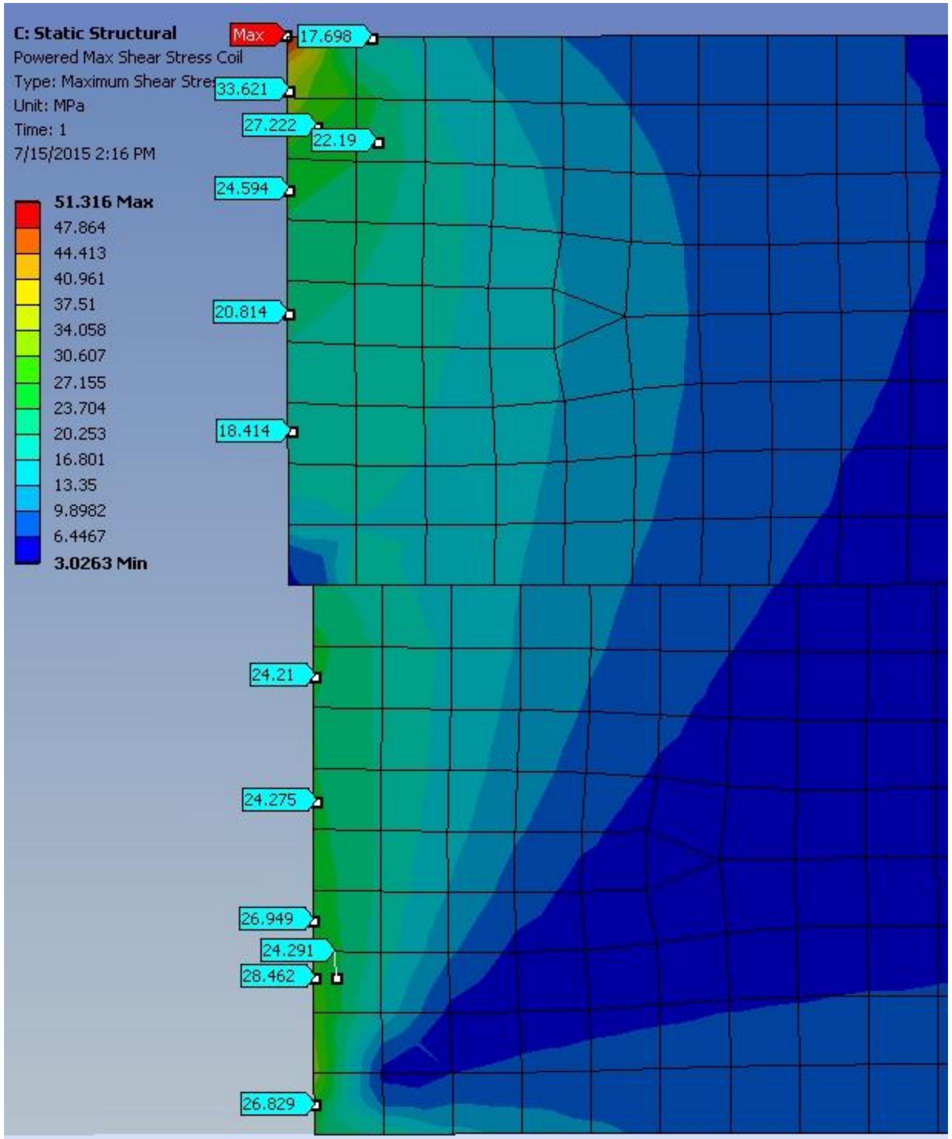


7/16/2015

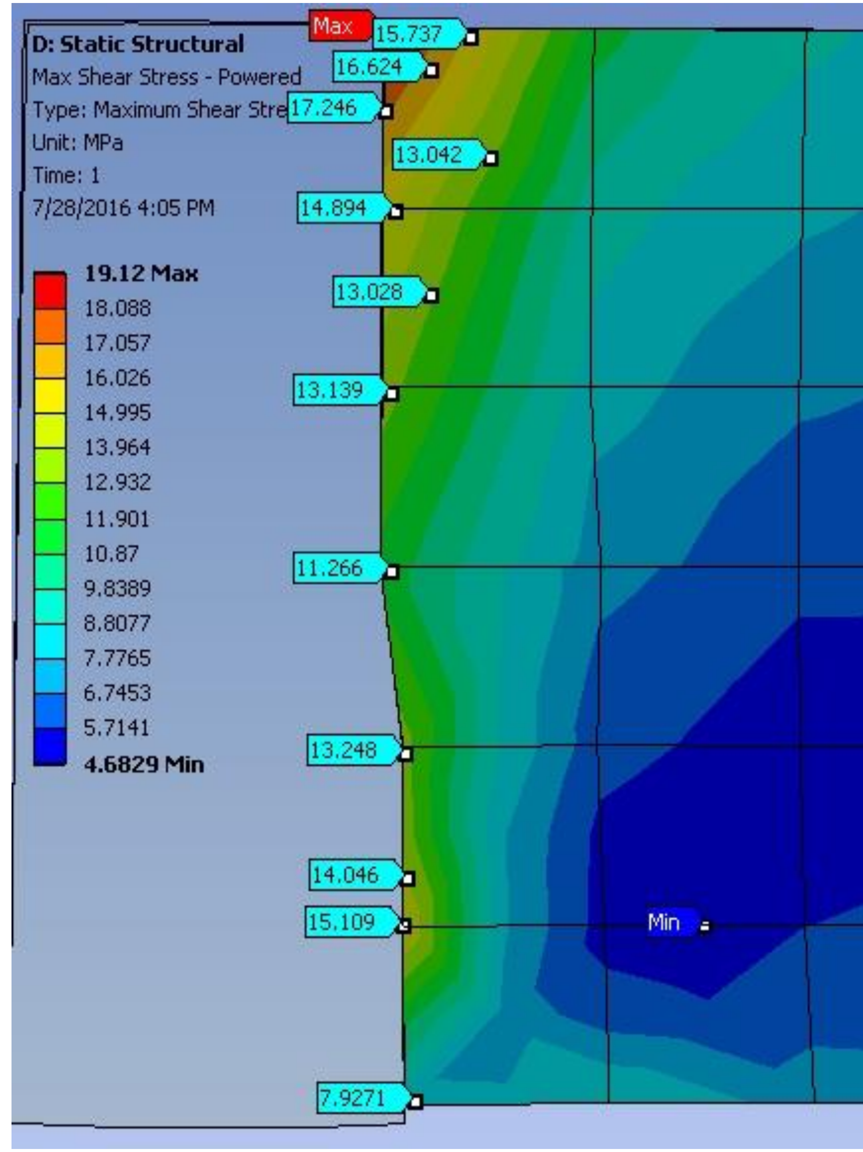


7/28/2016 (MAXWELL)

Coil Lead End Maximum Shear Stress @ Full Power (MPa)

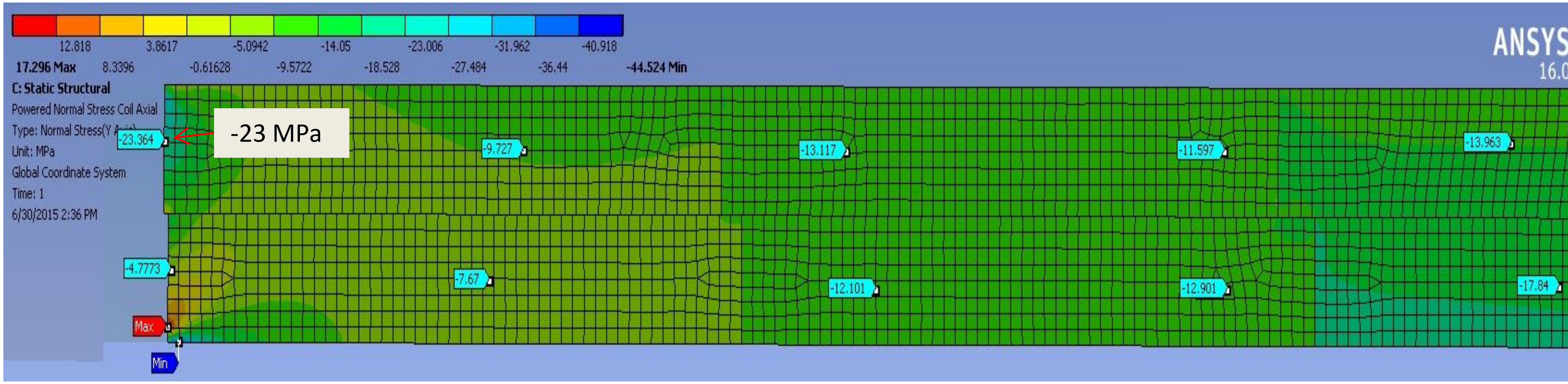


7/16/2015



7/28/2016 (MAXWELL)

Coil Lead End Axial Stress at Full Power (MPa) – 7/16/2015



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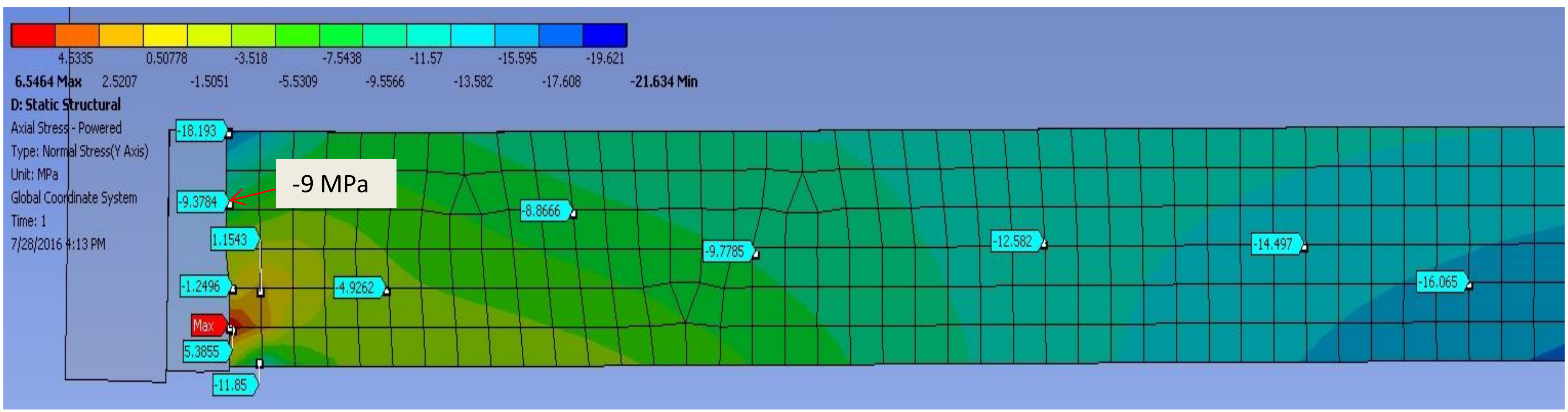
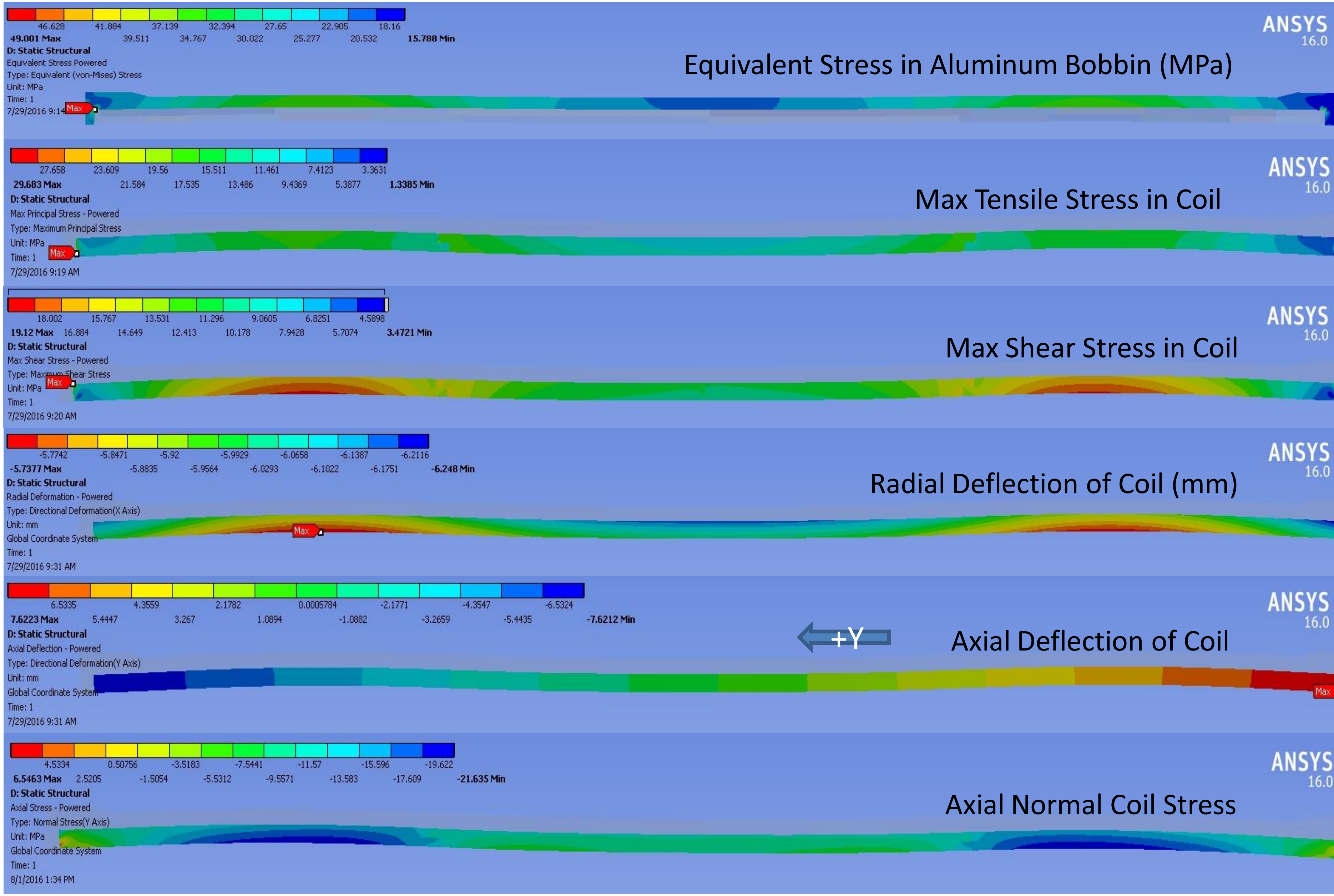
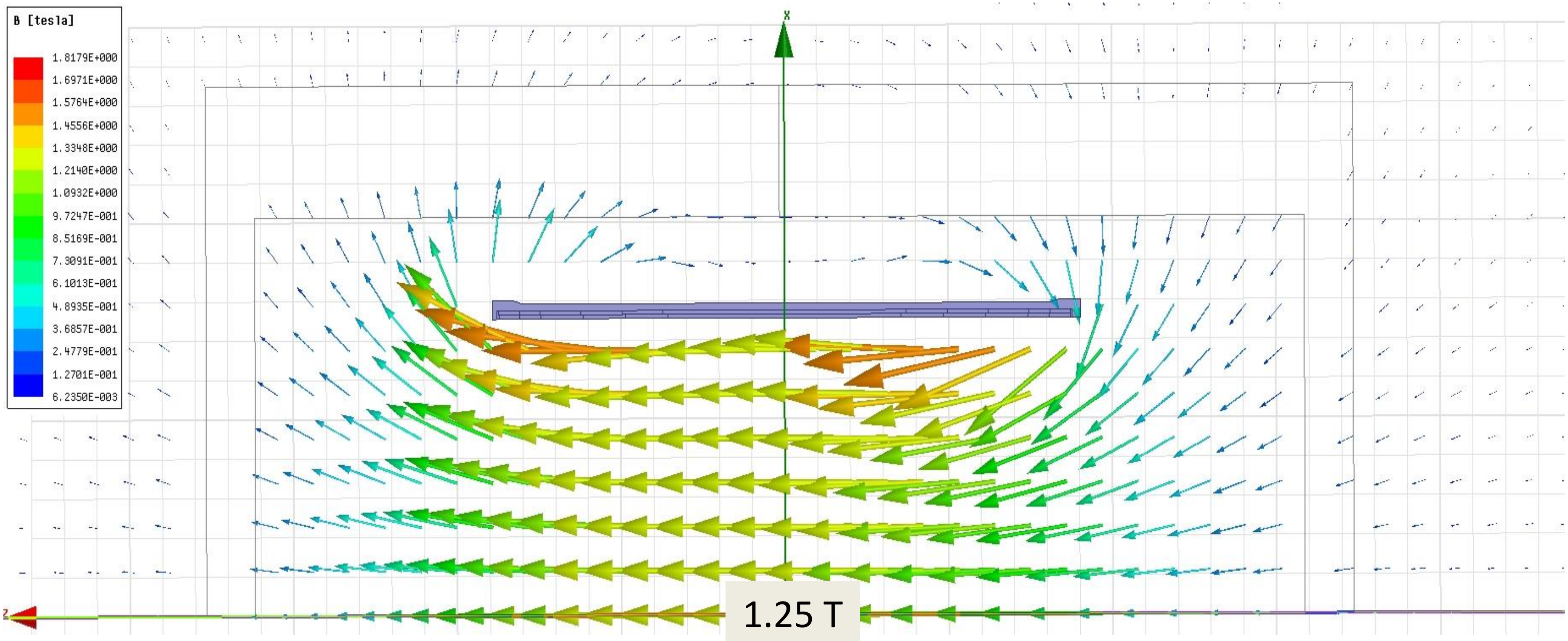
Lead End Axial Stress at Full Power (MPa) using MAXWELL – 7/28/2016



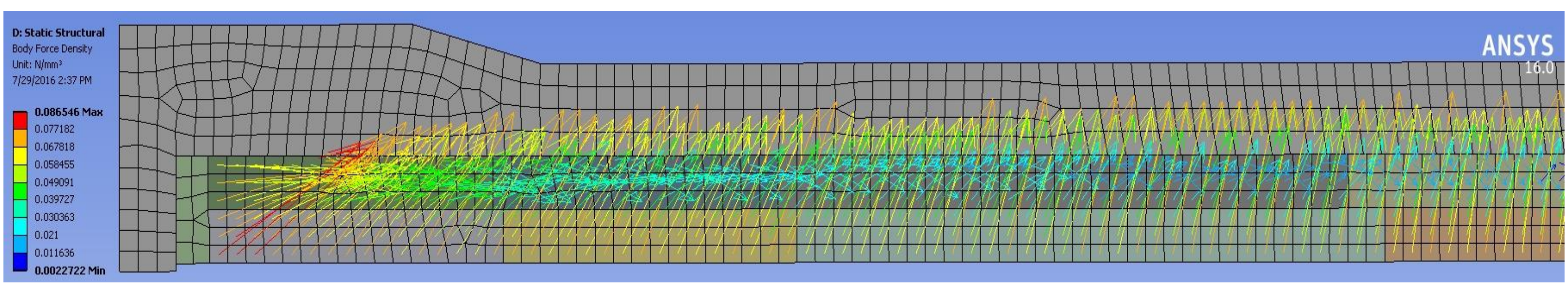
Coil Stresses and Deflections at Full Power using MAXWELL – 7/28/2016



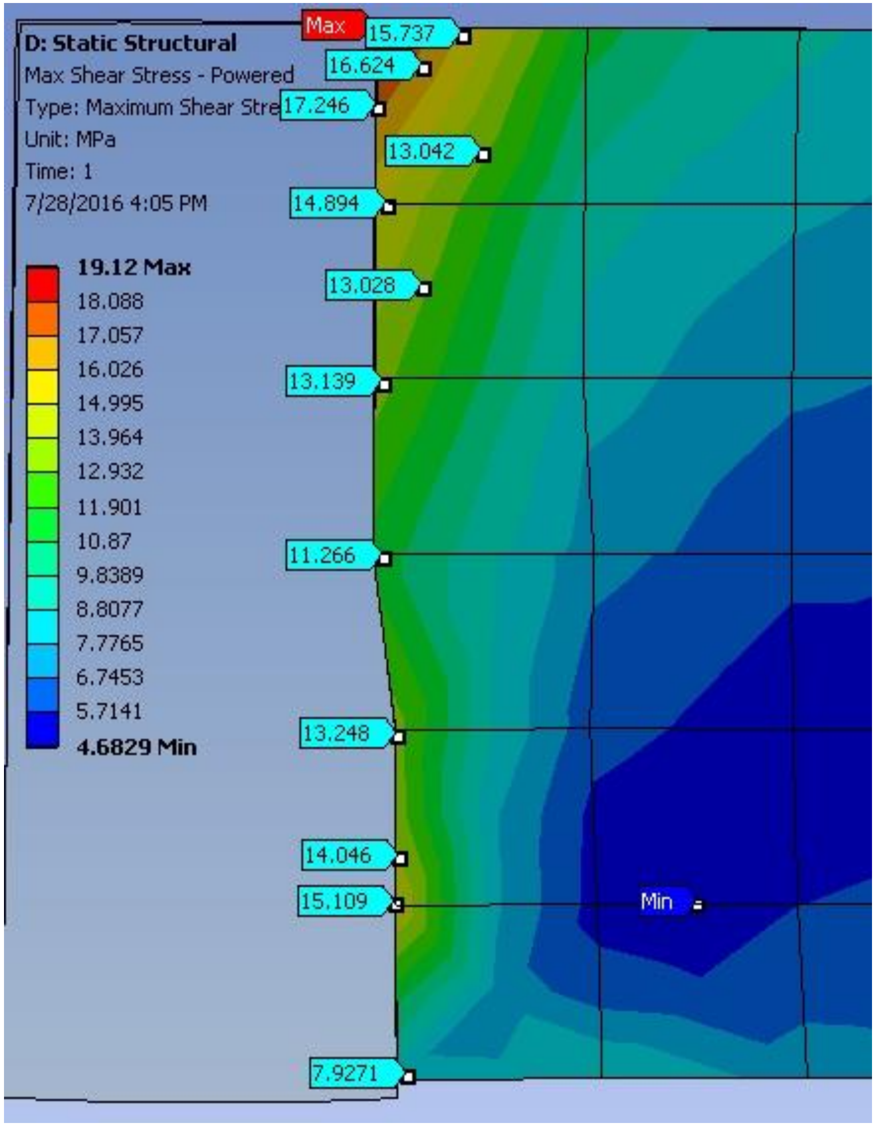
Magnetic Flux Vectors at 4600 A – No Iron



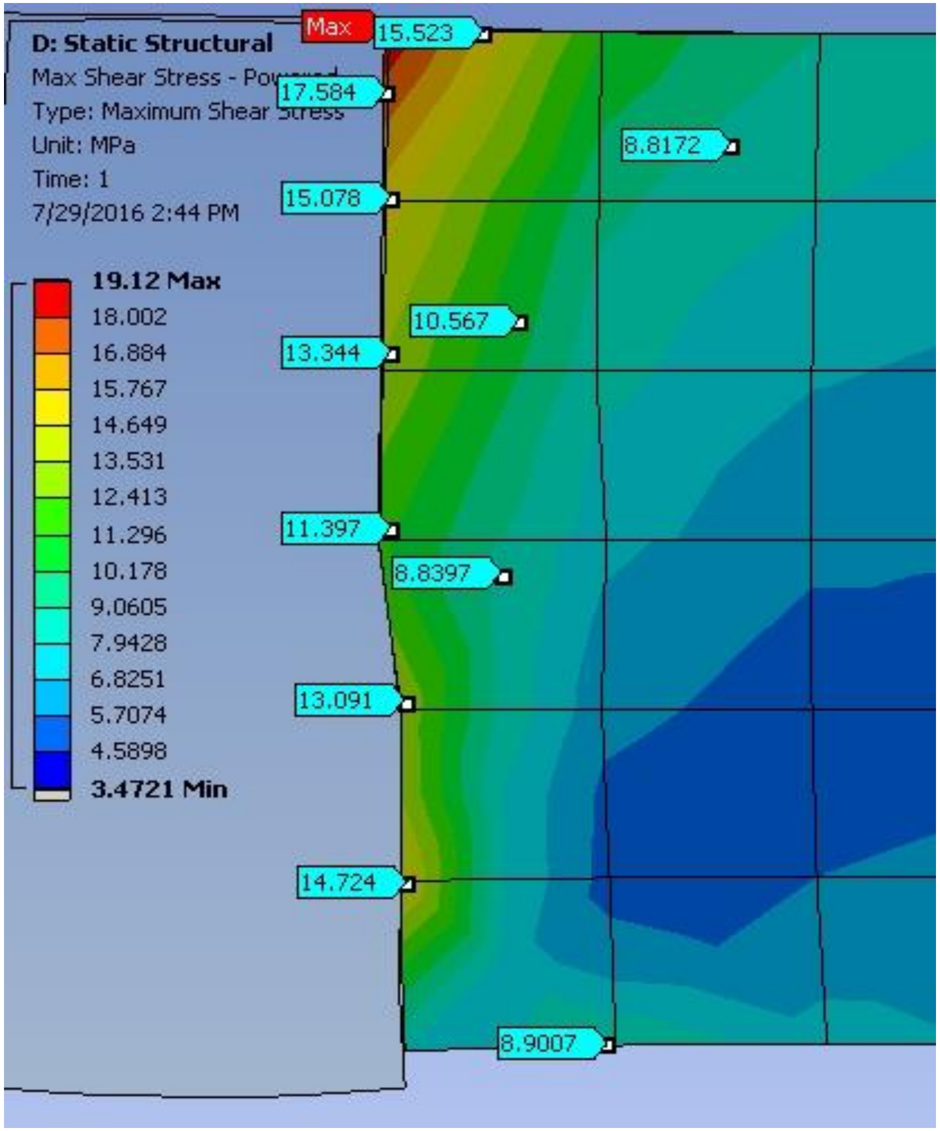
Coil Lorentz Force Vectors – No Iron



Coil Lead End Maximum Shear Stress @ Full Power (MPa) Iron vs. No Iron 7/28/2016



With Iron

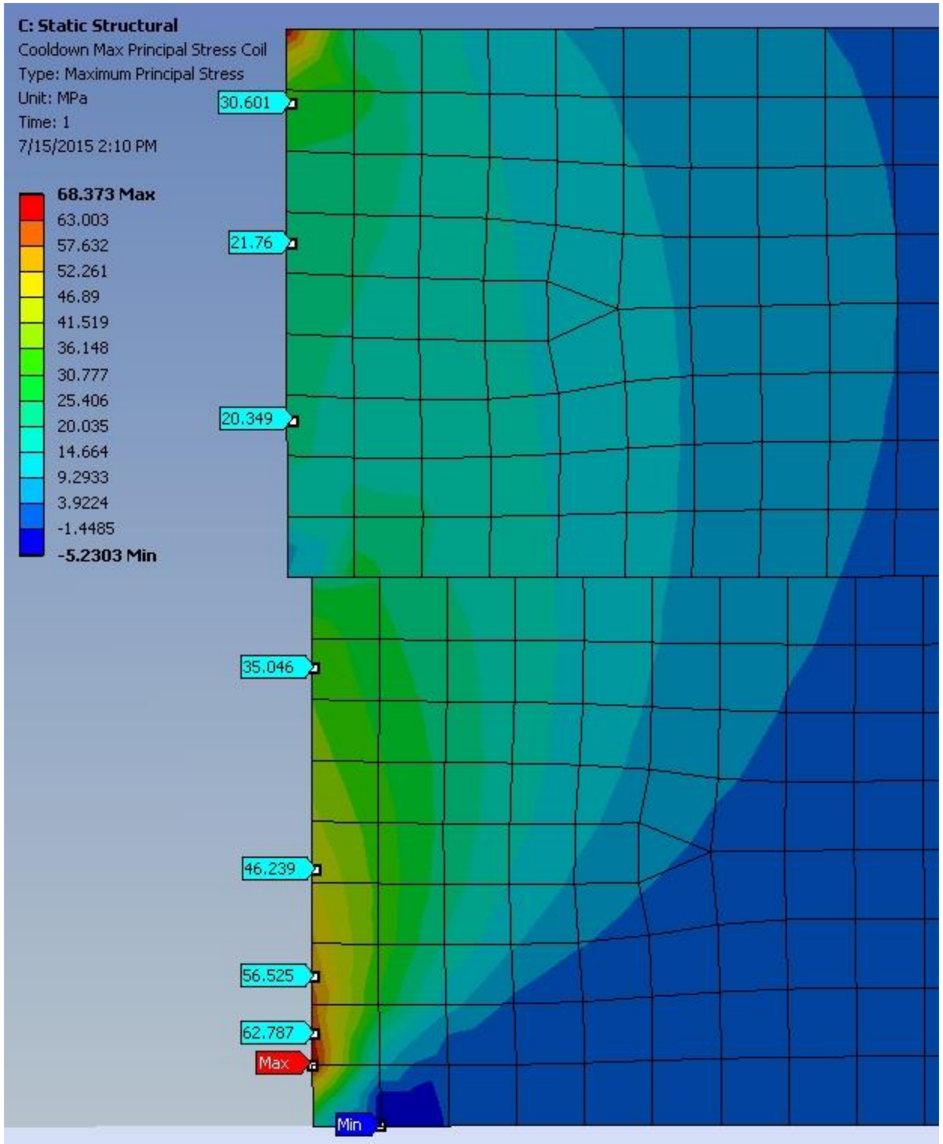


No Iron

- ***Summary & Conclusions***
  - ***Generally good agreement between both FE analyses***
  - ***Latest analysis calculates stresses that are lower than previous results***
    - Cool-down and Lorentz forces will not yield the aluminum bobbin.
      - Assuming 5083-0 (annealed) YP= 110 MPa (16 kpsi)
    - Tensile stress at the coil ends approaches the allowable limit (30 MPa) at maximum operating current (at the extreme end in a small area).
      - Based on the maximum principal stress (σ_1)
    - Shear stress at the coil ends is below the allowable limit (30 MPa) at maximum operating current.
    - Axial compressive stresses at the coil ends do not exceed the yield point of 99.5% pure aluminum (~30 MPa).
    - The completion of a 3D FE analysis may be the next logical step in this study.
      - Some 3D studies have already been successfully run to exhibit iron deflection.

Backup Slides

Lead End Max Tensile Stress @ Cool-down (MPa)



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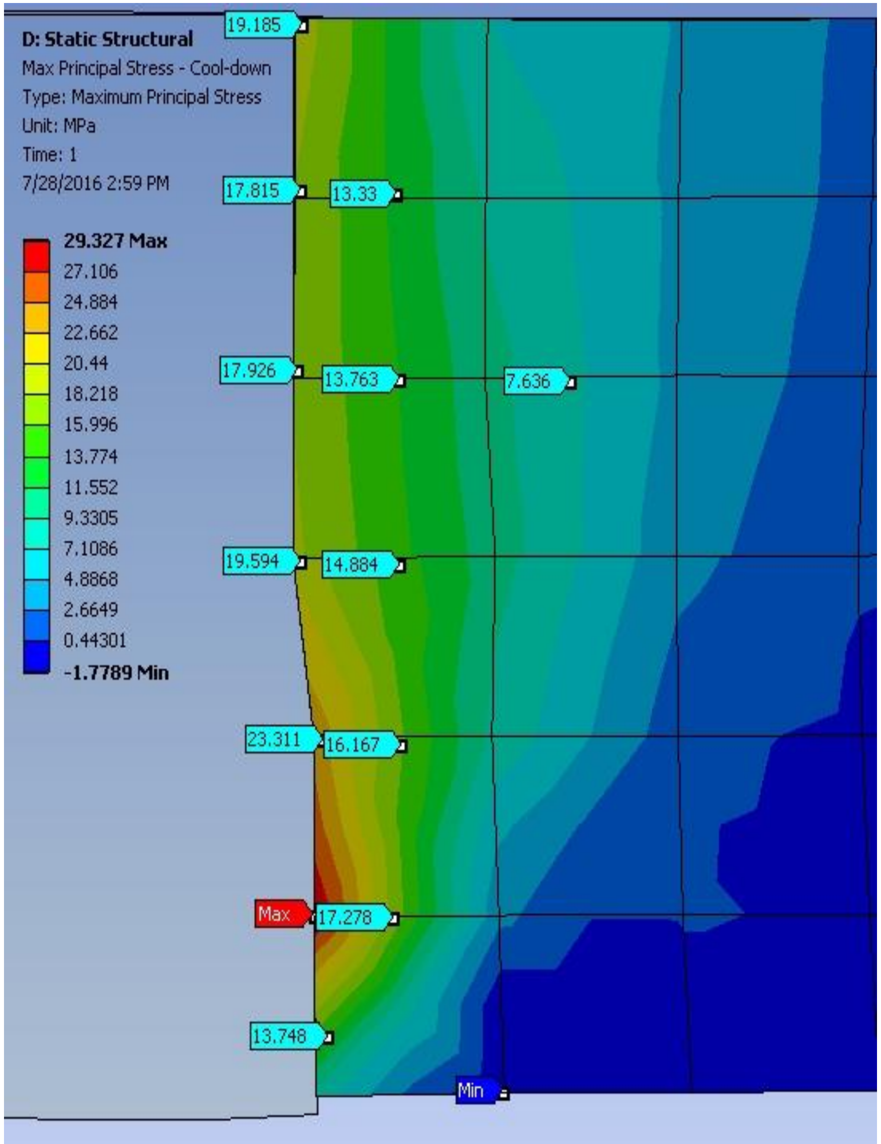

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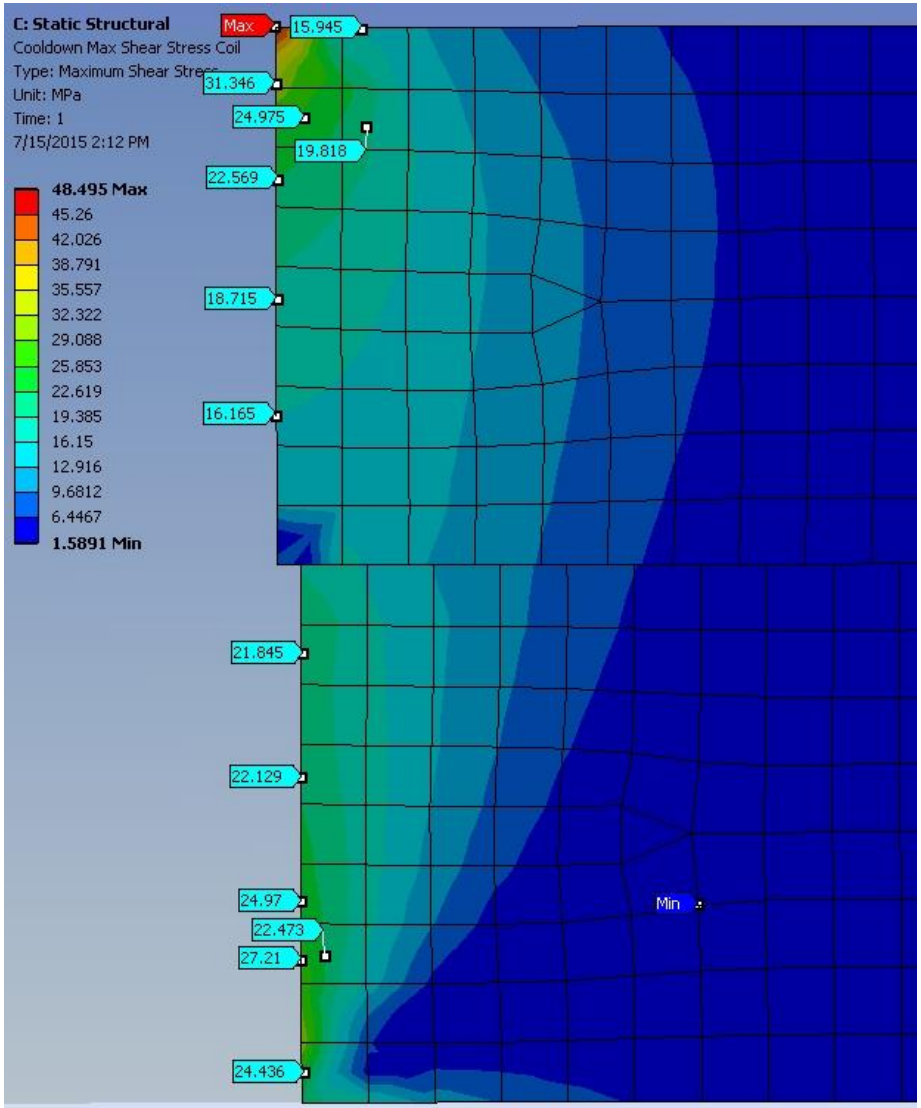
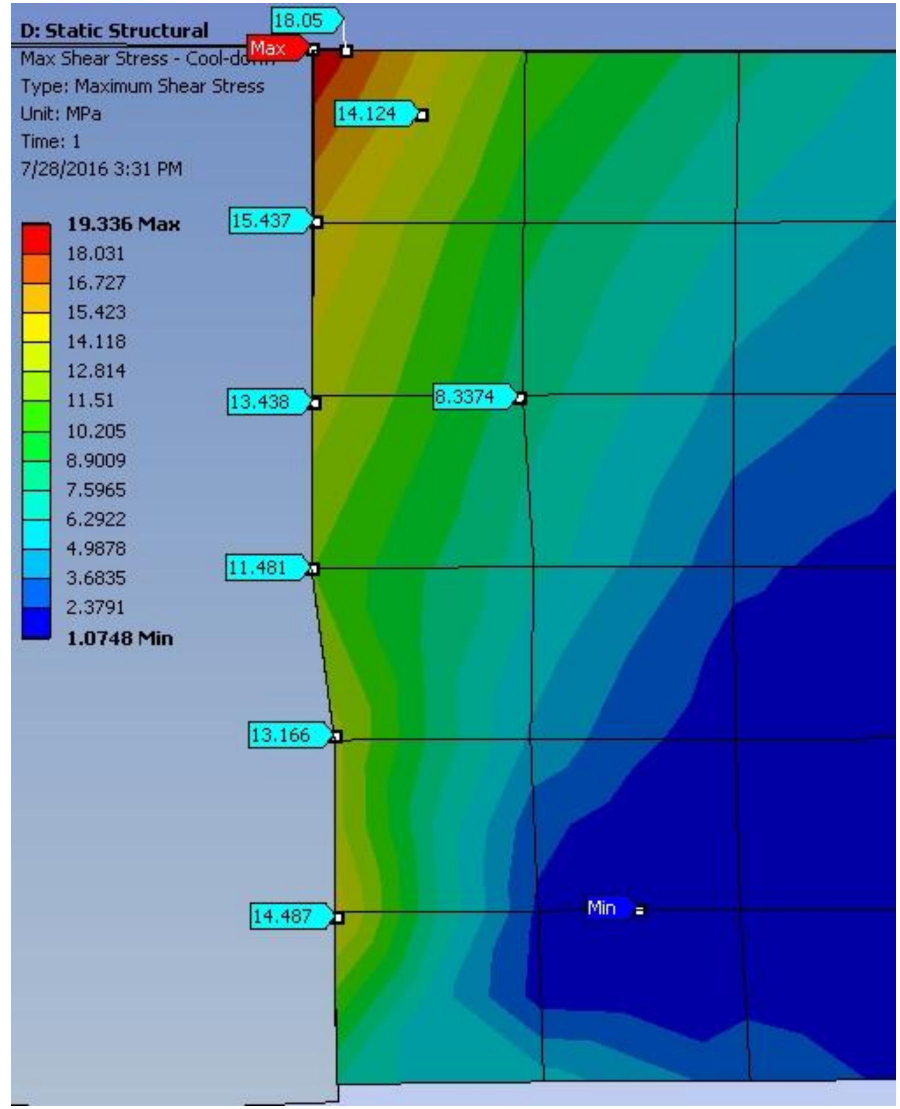
Lead End Maximum Shear Stress @ Cool-down (MPa)

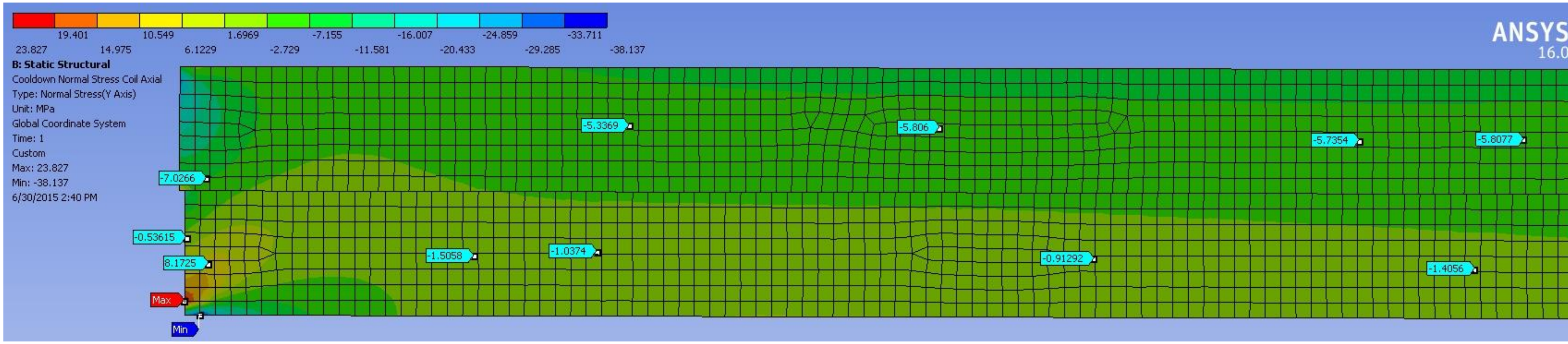


7/16/2015

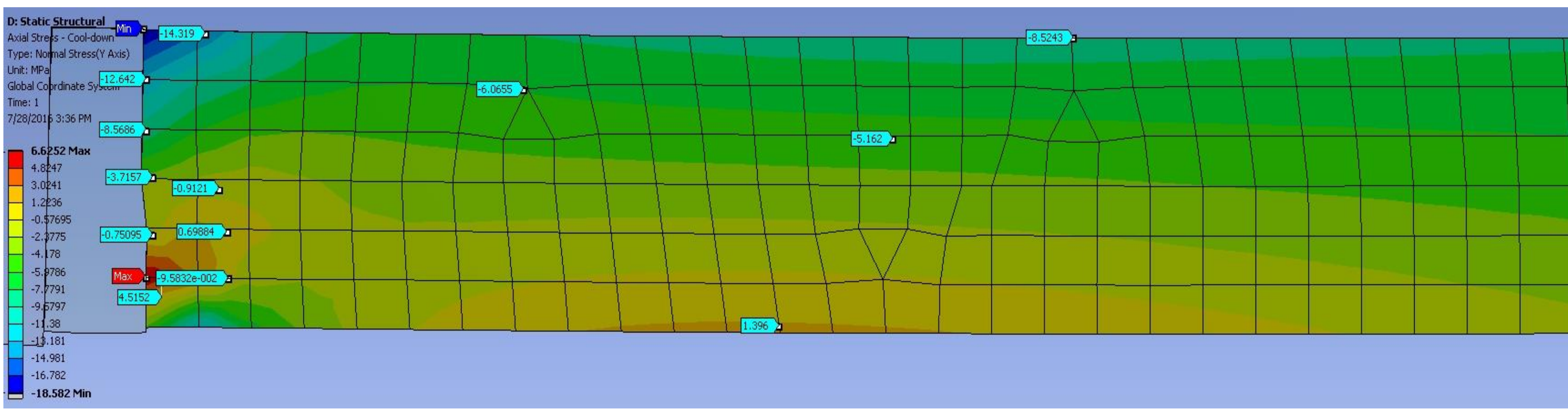


7/28/2016

Lead End Axial Stresses at Cool-down (MPa)



7/16/2015



7/28/2016

ANSYS Structural Analyses of sPHENIX Magnet Coil at Full Current

(superceded on 7/28/2016)

John Cozzolino

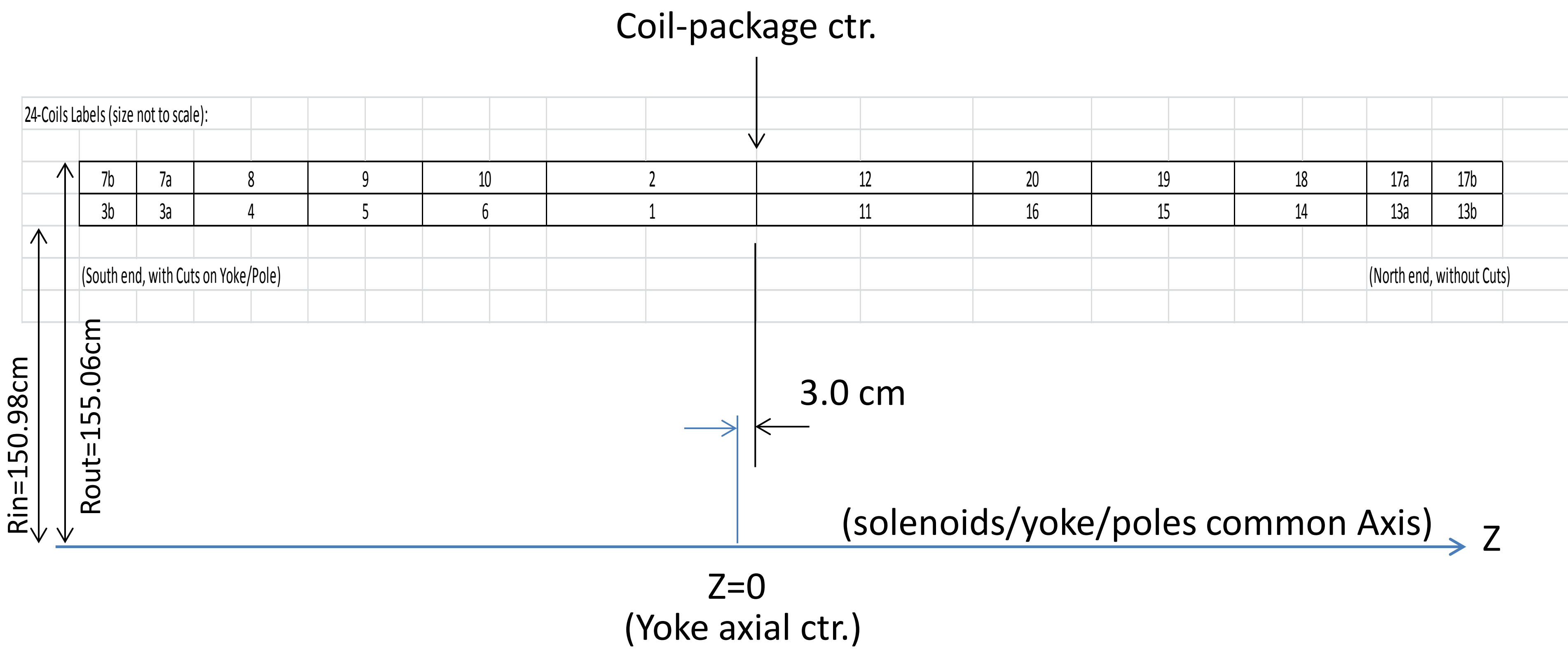
July 16, 2015

- ***ANSYS FE Structural Analysis of sPHENIX Coil***
  - 2d axisymmetric steady-state FE analysis of complete coil
    - Includes external aluminum bobbin and G-10 end fillers
    - Geometry and forces taken from Wuzheng Meng's magnetic model – 6/17/2015
      - Coil center is shifted 3cm north relative to iron
      - Coils divided into 24 blocks, each with corresponding radial and axial pressures due to the Lorentz forces at maximum current
    - Thermal stresses from cool-down to 4K included
    - Mechanical properties vs. temperature are included
      - Coil properties E and CTE adjusted for percentage of insulation vs. conductor (Ref Ansaldo Dwg# 620RM07142, pg. 1)
        - » Radial direction 2.0% insulation (all coils)
        - » Axial direction 4.7% (middle coils)
        - » Axial direction 8.1% (end coils)
    - All connections (contacts) are bonded
    - Tensile and shear stresses are studied throughout the coil
      - Shear stress limit: 30 MPa (4350 psi)
      - Tensile stress limit: 30 MPa

Labels on 24 Solenoid Coils

(Not to Scale)

W. Meng

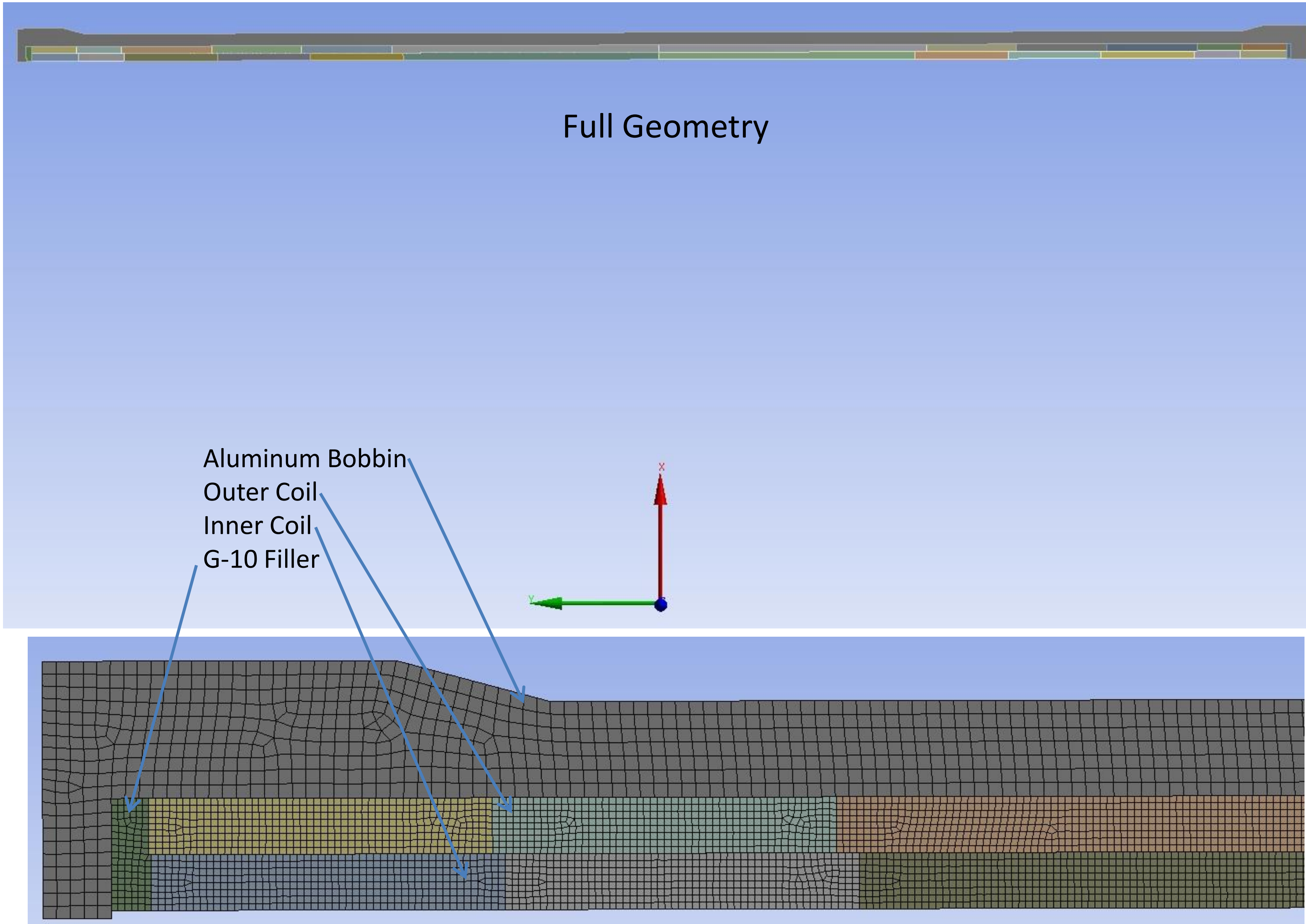


Radial Pressure (outward-force per unit area) Table (W. Meng):

	Coils Ave. Ctr.	(MPa)	(PSI)	(MPa)	(PSI)	(MPa)	(PSI)
	Zc (cm)	Inner	Inner	Outer	Outer	Inner+Outer	Inner+Outer
Coils 3b +7b	-165.10	0.7867	114.07	0.0032	0.46	0.7899	114.53
Coils 3a + 7a	-152.38	0.8978	130.19	0.0149	2.17	0.9128	132.35
Coils 4 + 8	-133.30	0.9708	140.77	0.0751	10.89	1.0459	151.66
Coils 5 + 9	-107.85	1.0461	151.68	0.1502	21.77	1.1962	173.45
Coils 6 + 10	-82.40	1.0286	149.15	0.1677	24.32	1.1964	173.47
Coils 1 + 2	-33.34	0.4864	70.53	0.1534	22.24	0.6398	92.76
Coils 11 + 12	39.34	0.4863	70.51	0.1532	22.22	0.6395	92.72
Coils 16 + 20	88.40	1.0275	148.98	0.1664	24.13	1.1939	173.12
Coils 15 + 19	113.85	1.0426	151.18	0.1463	21.21	1.1889	172.40
Coils 14 + 18	139.30	0.9004	130.55	0.0693	10.05	0.9697	140.61
Coils 13a + 17a	158.38	0.9004	130.55	0.0180	2.61	0.9184	133.16
Coils 13b +17b	171.10	0.7944	115.19	0.0095	1.38	0.8039	116.57

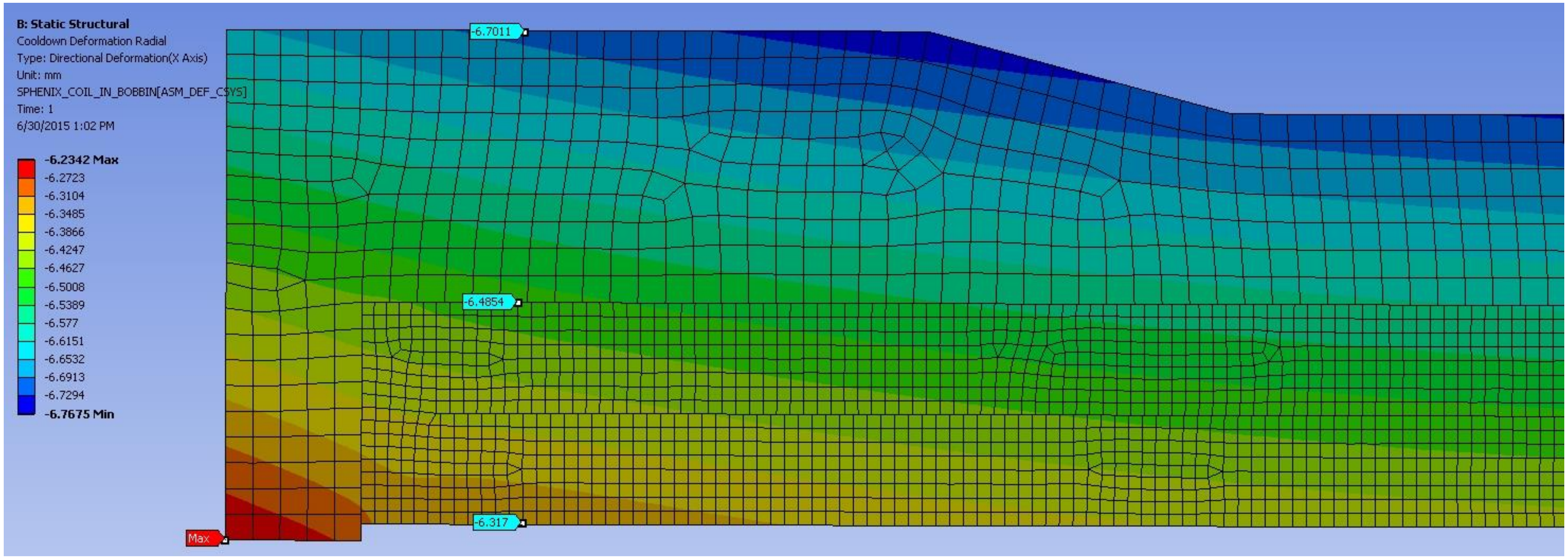
Axial Force Table (W. Meng):

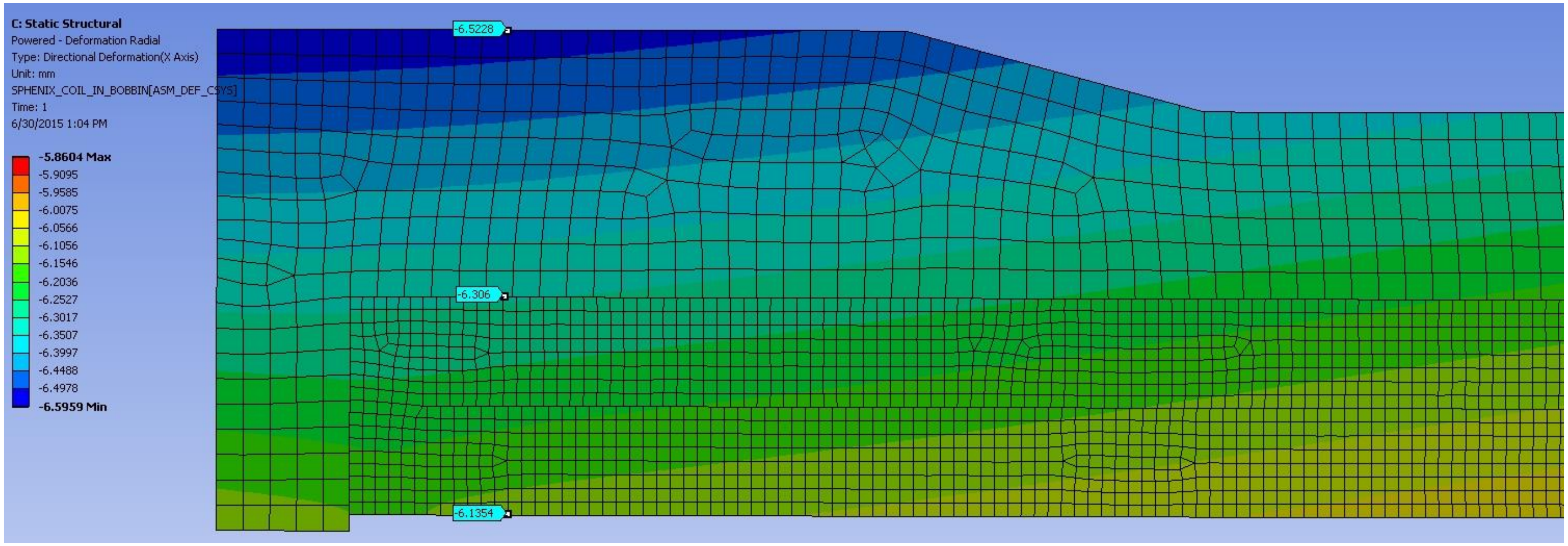
	Coils Ave. Ctr.	Fz (N)	Fz(Lb)	Fz (N)	Fz(Lb)	Fz (N)	Fz(Lb)		
	Zc (cm)	Inner	Inner	Outer	Outer	Inner+Outer	Inner+Outer		
Coils 3b + 7b	-165.10	1.23E+06	2.771E+05	1.22E+06	2.73E+05	2.45E+06	5.505E+05		
Coils 3a + 7a	-152.38	7.84E+05	1.761E+05	7.84E+05	1.76E+05	1.57E+06	3.520E+05		
Coils 4 + 8	-133.30	1.01E+06	2.258E+05	1.03E+06	2.30E+05	2.03E+06	4.560E+05		
Coils 5 + 9	-107.85	4.10E+05	9.196E+04	4.47E+05	1.00E+05	8.57E+05	1.924E+05		
Coils 6 + 10	-82.40	-2.97E+05	-6.675E+04	-1.96E+05	-4.41E+04	-4.94E+05	-1.108E+05		
Coils 1 + 2	-33.34	-3.33E+05	-7.479E+04	-3.98E+05	-8.93E+04	-7.31E+05	-1.641E+05		
Coils 11 + 12	39.34	3.32E+05	7.449E+04	3.96E+05	8.89E+04	7.28E+05	1.634E+05		
Coils 16 + 20	88.40	2.96E+05	6.638E+04	1.94E+05	4.36E+04	4.90E+05	1.100E+05		
Coils 15 + 19	113.85	-4.10E+05	-9.212E+04	-4.49E+05	-1.01E+05	-8.59E+05	-1.928E+05		
Coils 14 + 18	139.30	-9.91E+05	-2.225E+05	-1.01E+06	-2.27E+05	-2.00E+06	-4.490E+05		
Coils 13a + 17a	158.38	-7.71E+05	-1.730E+05	-7.69E+05	-1.73E+05	-1.54E+06	-3.457E+05		
Coils 13b + 17b	171.10	-1.22E+06	-2.749E+05	-1.21E+06	-2.71E+05	-2.43E+06	-5.462E+05		
					Total Fz =	7.00E+04	1.57E+04		(with 3 cm Shift)
						(N)	(Lb)		



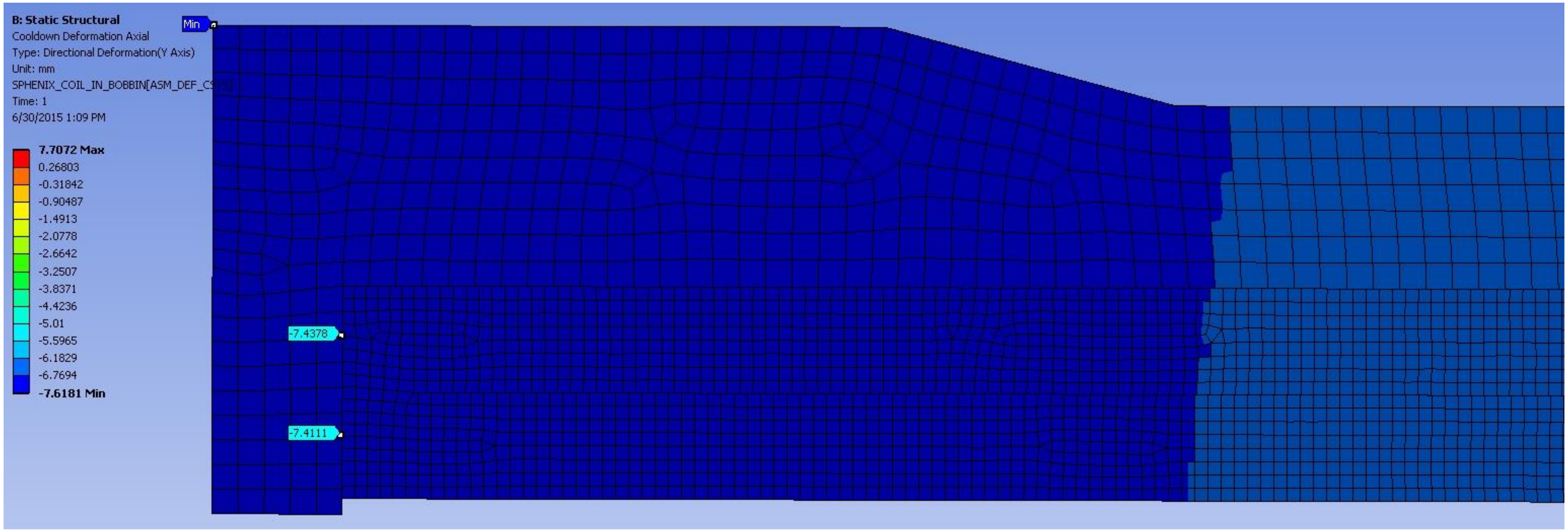
FE Mesh (Lead End)

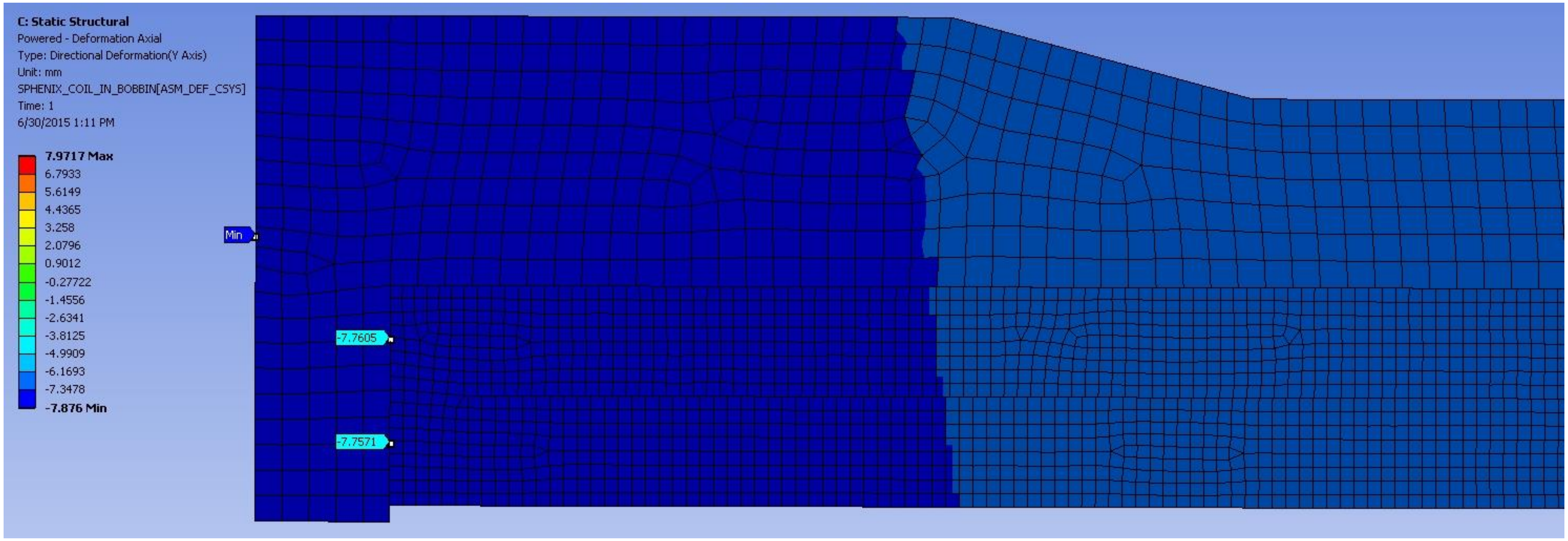
Radial Deflection @ Cool-down Followed by Max Current (LE View)



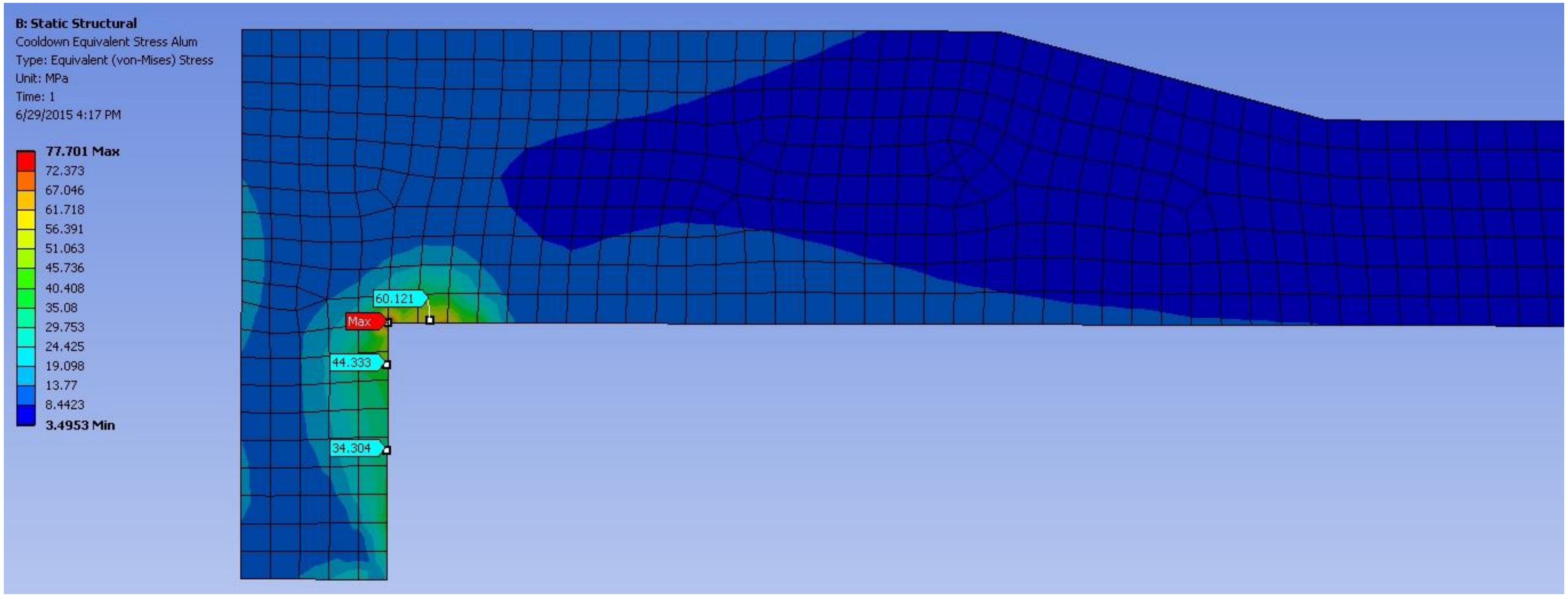


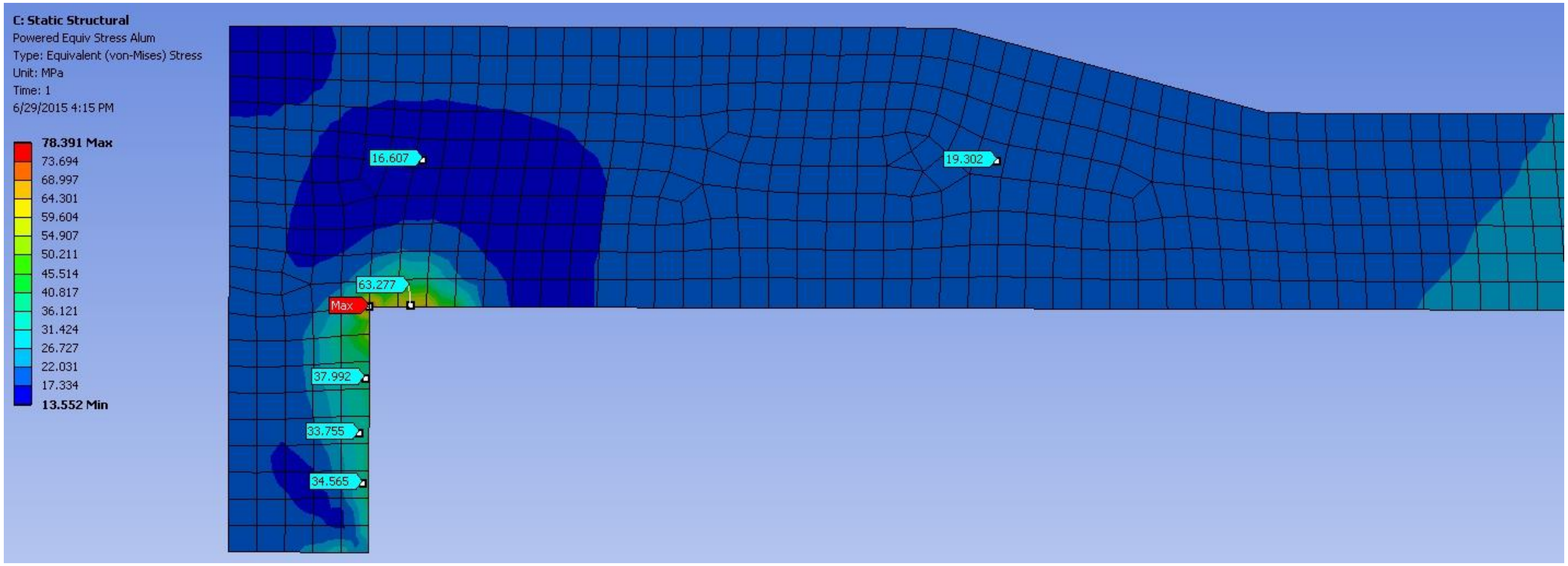
Axial Deflection @ Cool-down Followed by Max Current (LE View)



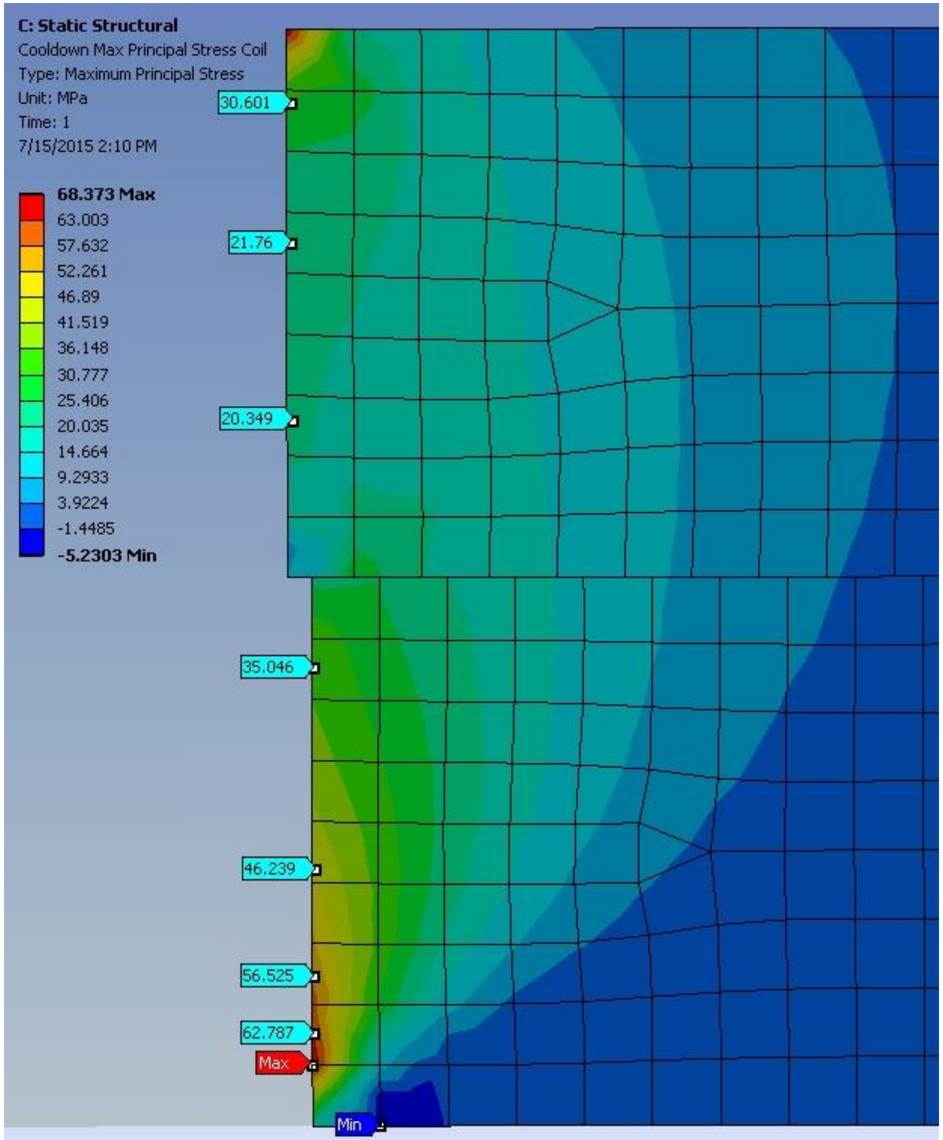


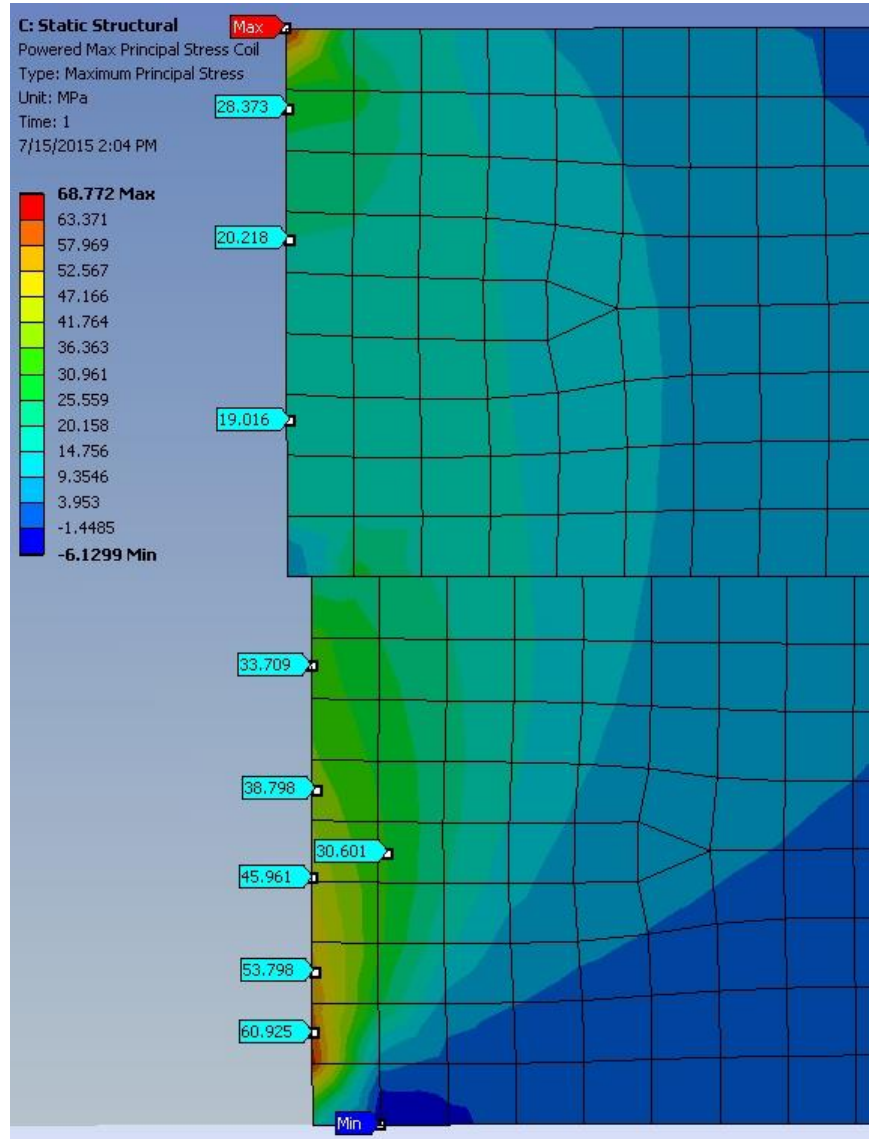
Equivalent Stress in Aluminum Bobbin @ Cool-down & Max Current (LE View)



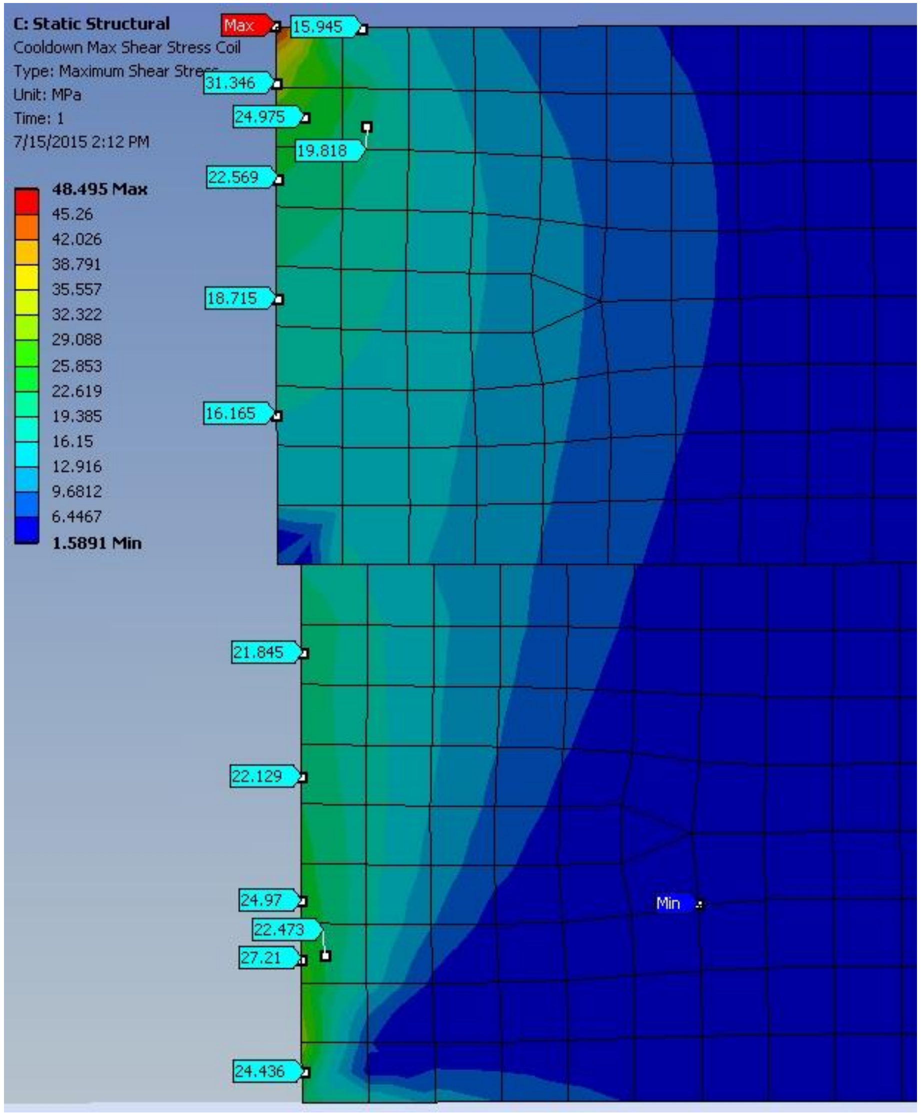


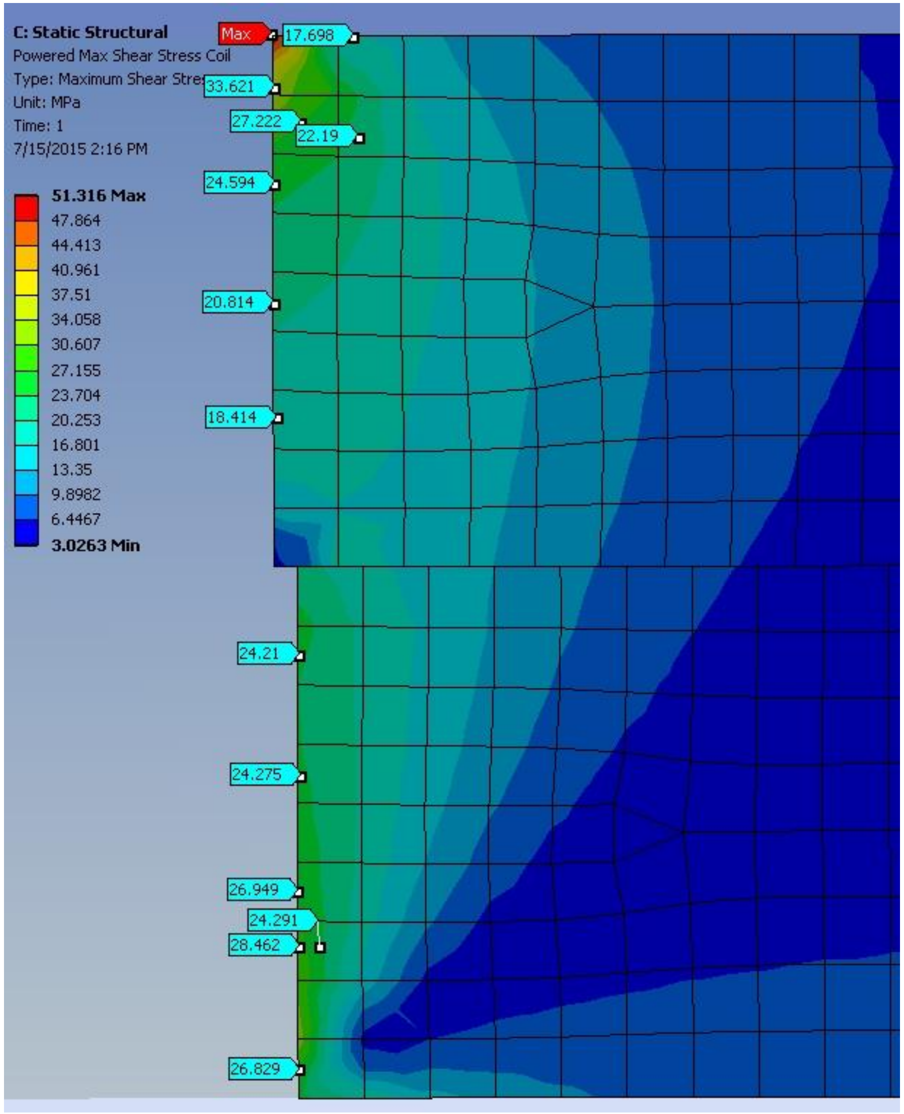
Lead End Max Tensile Stress @ Cool-down & Full Power



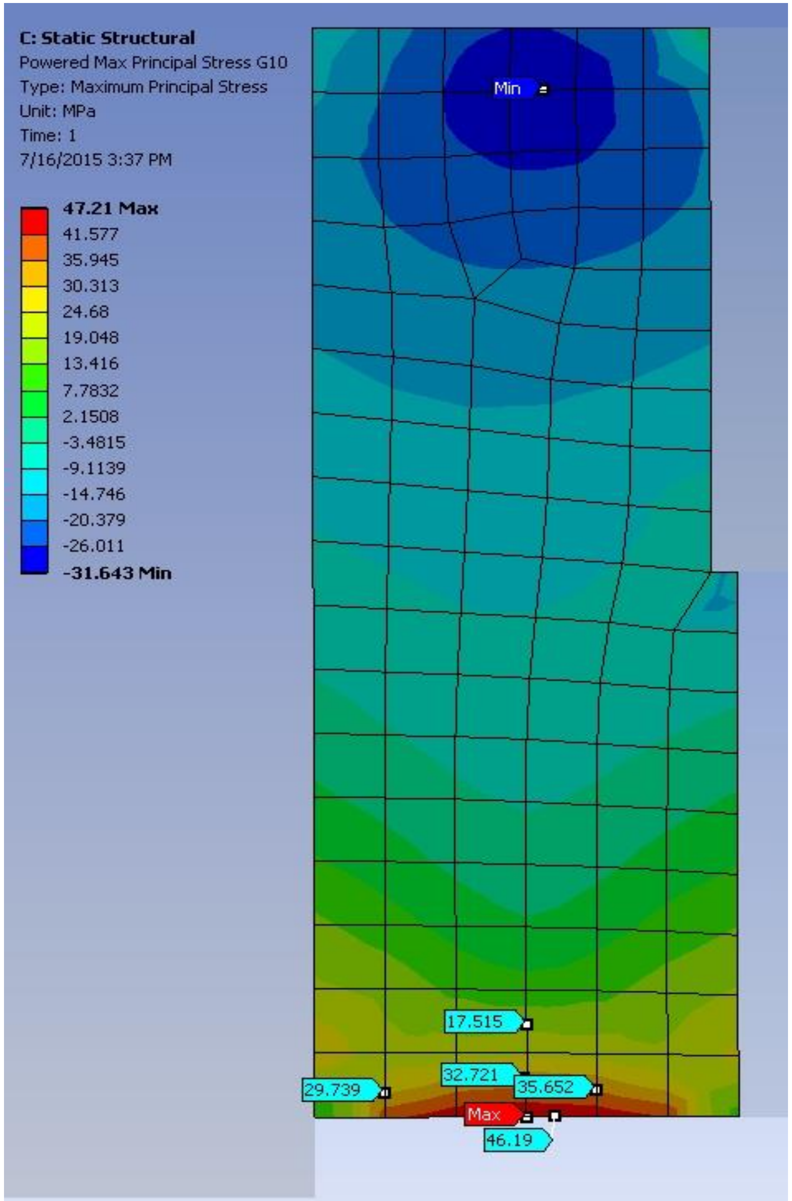


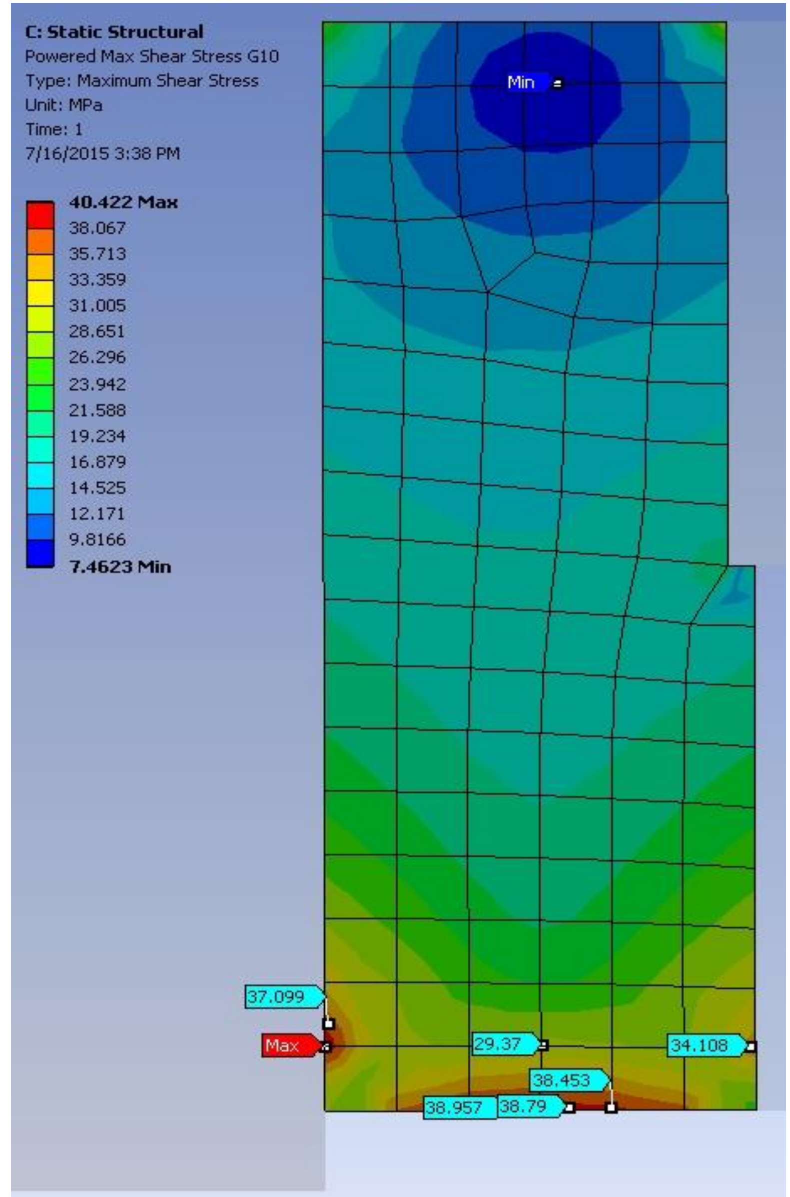
Lead End Max Shear Stress @ Cool-down & Full Power



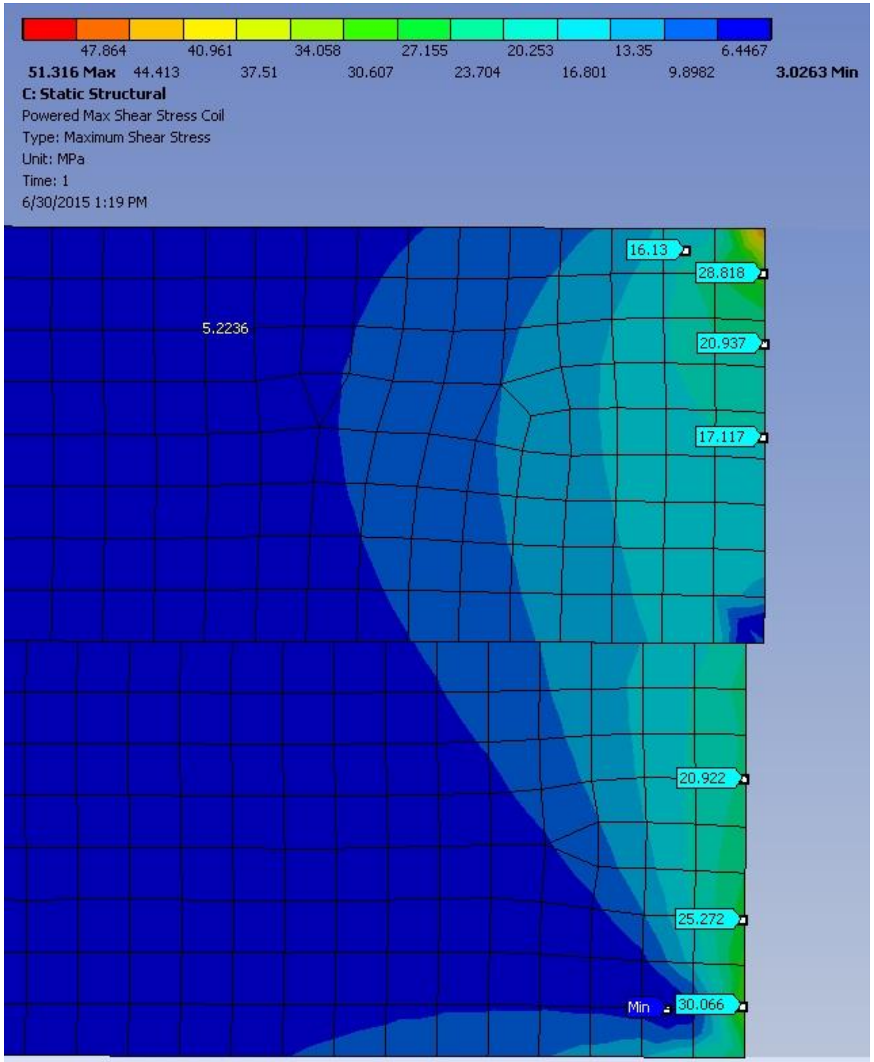


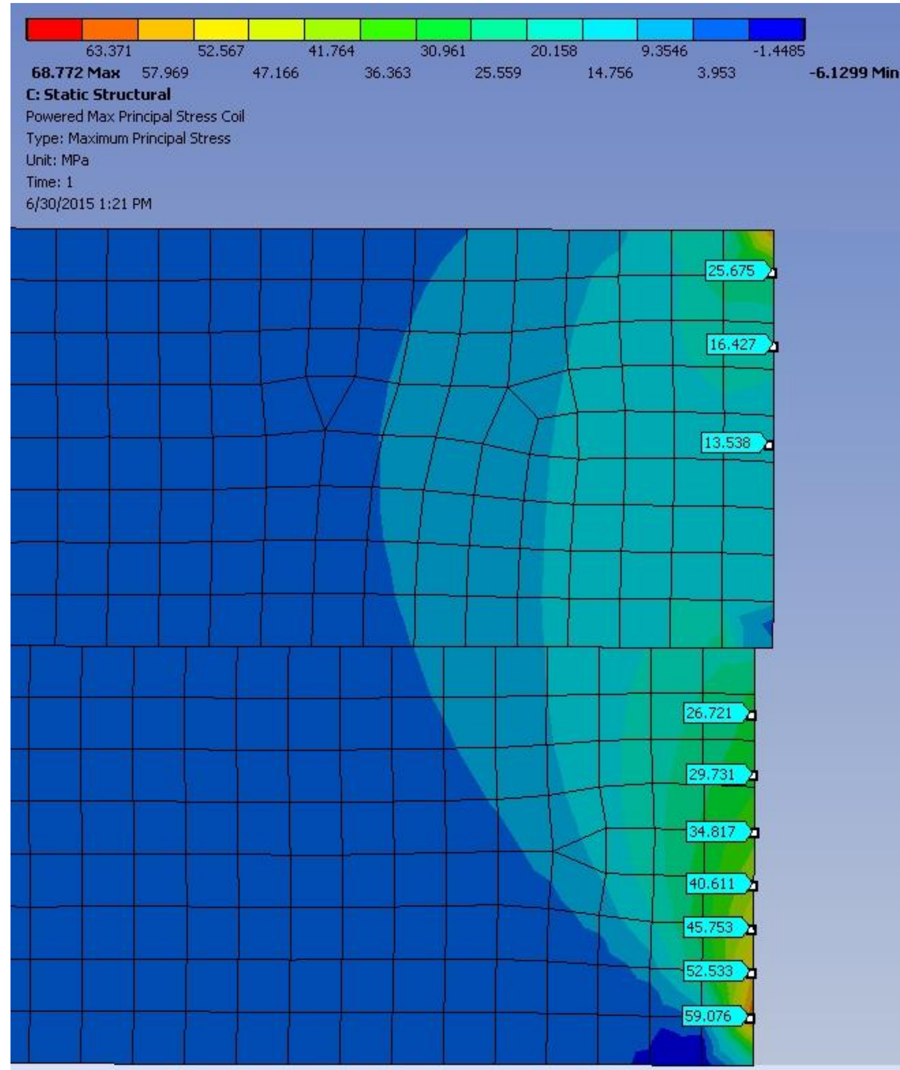
Lead End G-10 Max Tensile & Shear Stress @ Full Power



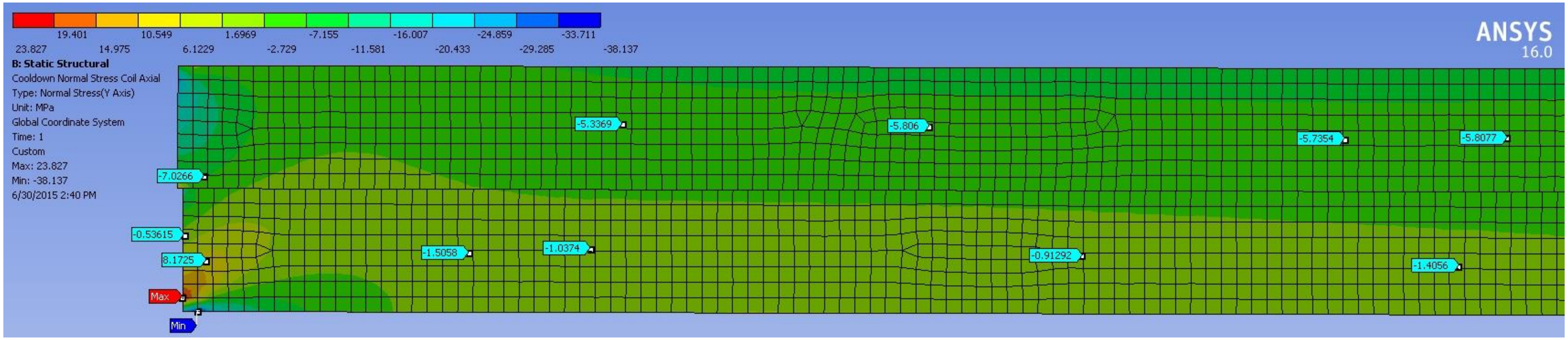


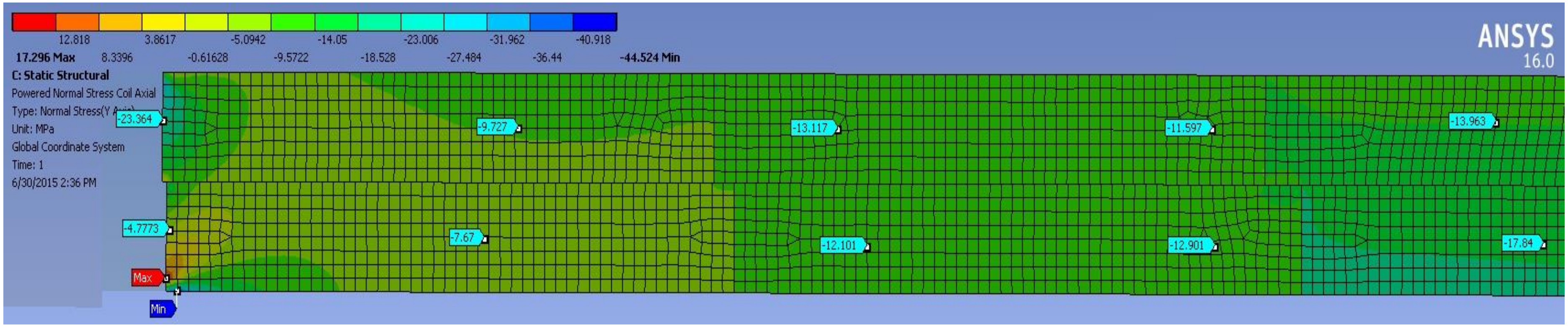
Non-Lead End Max Shear and Tensile Stresses @ Full Power



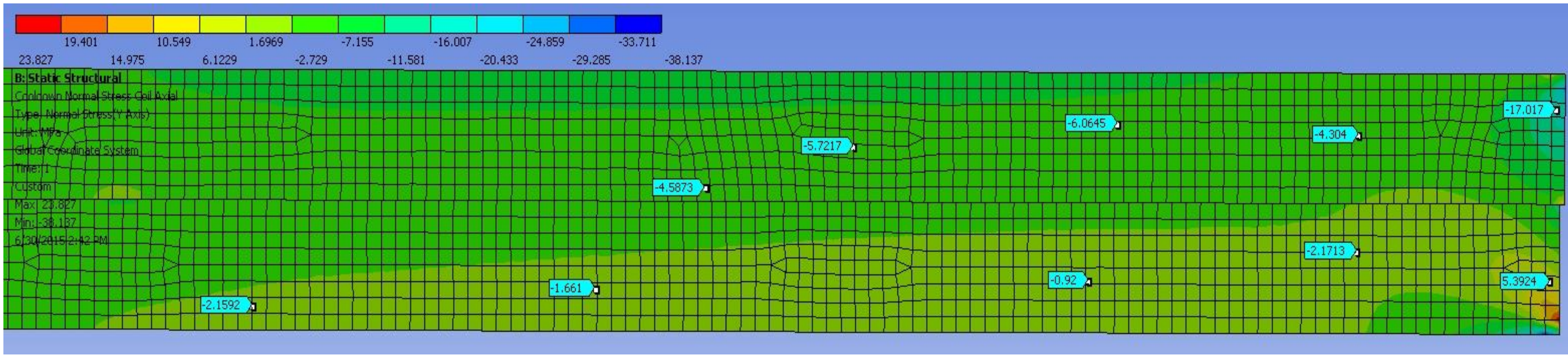


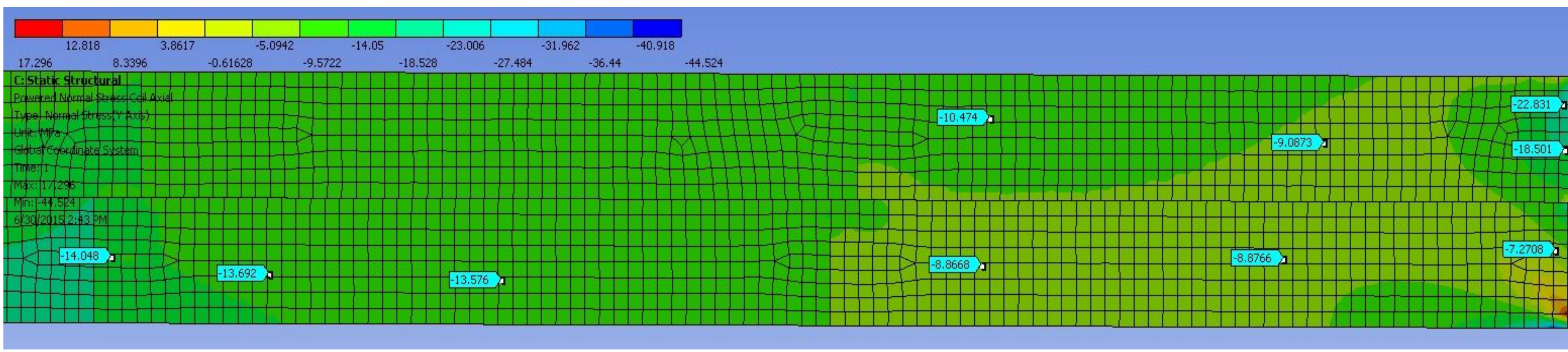
Lead End Axial Compressive Stresses at Cool-down & Full Power (MPa)





Non-Lead End Axial Compressive Stresses at Cool-down & Full Power (MPa)





- ***Summary & Conclusions*** (superceded on 7/28/2016)
  - Cool-down and Lorentz forces will not yield the aluminum bobbin.
    - Assuming 5083-0 (annealed) YP= 110 MPa (16 kpsi)
  - Tensile stresses at the coil ends exceed the allowable limit (30 MPa) at maximum operating current.
    - Based on the maximum principal stress (σ_1)
  - Shear stresses at the coil ends are at the allowable limit (30 MPa) at maximum operating current.
  - Axial compressive stresses at the coil ends do not exceed the yield point of 99.5% pure aluminum (~30 MPa).