NCSX

Design Basis Analysis

Stress Analysis of the NCSX Trim Coils

NCSX-CALC-133-001-00

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I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct. I concur with analysis methodology and inputs and with the reasonableness of the results and their interpretation.

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1.0 Executive Summary

This documents the results of the stress analysis of the NCSX Trim Coils in support of the Final Design Review. It includes the coil conductor and encasing structure up to but not including the support brackets which tie them to the MCWF/TF/PF support structures.

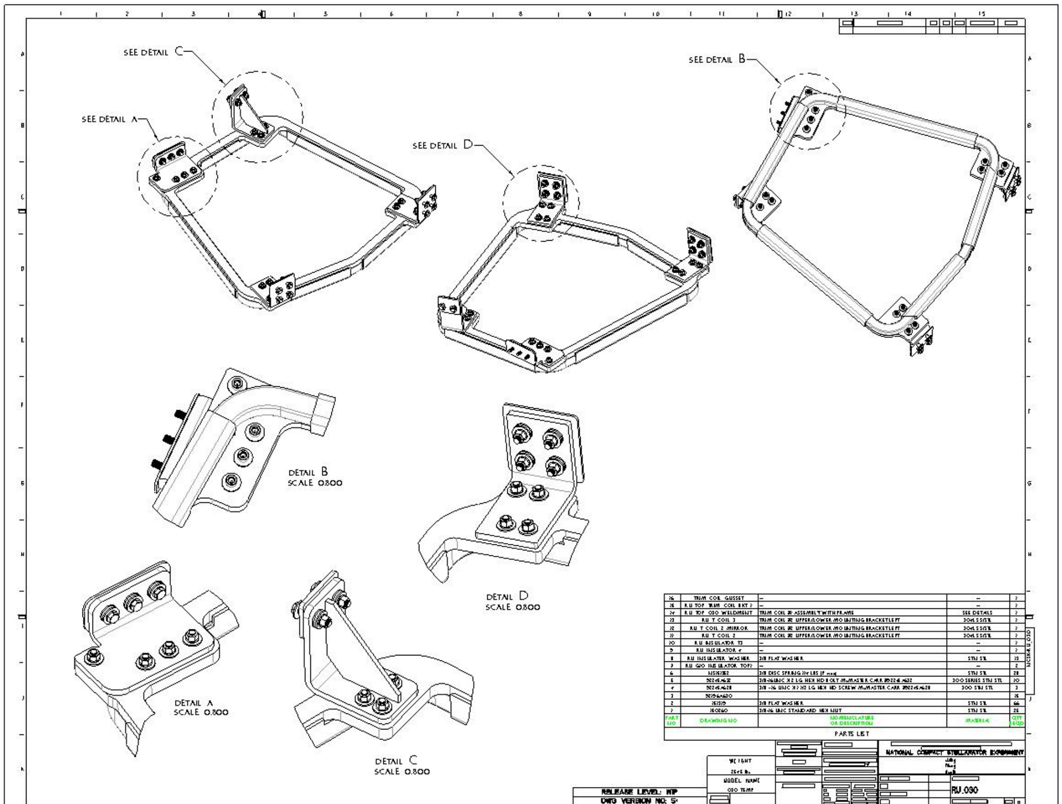
Worse case running load were found to be 80 lb/in for the inner coils and 60#/in for the outer coils. This is driven by the TF field since the trim coils lie just inside the TF coils. All of the GRD scenarios resulted in running loads of 50#/in or less as a result partially of lower TF levels.

The analysis results show the current design to be acceptable. Conservative estimates of the reaction loads are provided as input to the bracket design and for MCWF/TF/PF interface evaluation.

2.0 Assumptions and Notable Concerns

The design is based on a 120 turn copper winding wrapped with CTD -101K insulation turn to turn insulation and groundwrap. The conductor is partially encased by mounting it to a ¾" 304SS base plate and capturing it with a 3/16" wall 304SS formed U-Channel along the straight legs of the coil and attached to the base plate with a 1/8" weld. The coils are supported off the MCWF/TF/PF supported structure with brackets attached to the base plate. Where the brackets attachments are made, welding of the U-Channels is not accessible and assumed free. There are 4 attachment points per inner trim coil, at or near the corners along the toroidal running legs and unsupported along the radial running legs. The outer trim coils are supported along each of the 4 legs at 2-3 locations each. The conductor is assumed to be free to slide within the case. Analysis was done with and without friction. The conductor is free to lift off along the unsupported corners.

Analysis includes the impact of thermal stresses due to the cool down based on a difference in CTE of 2.e-6 m/m-K over the temperature change of 220 K (300K-80K). It is assumed that cool-down is slow enough such that large thermal gradients are not generated between the coils and the MCWF/TF/PF supported structure. An allowable gradient between the structures has not been established.



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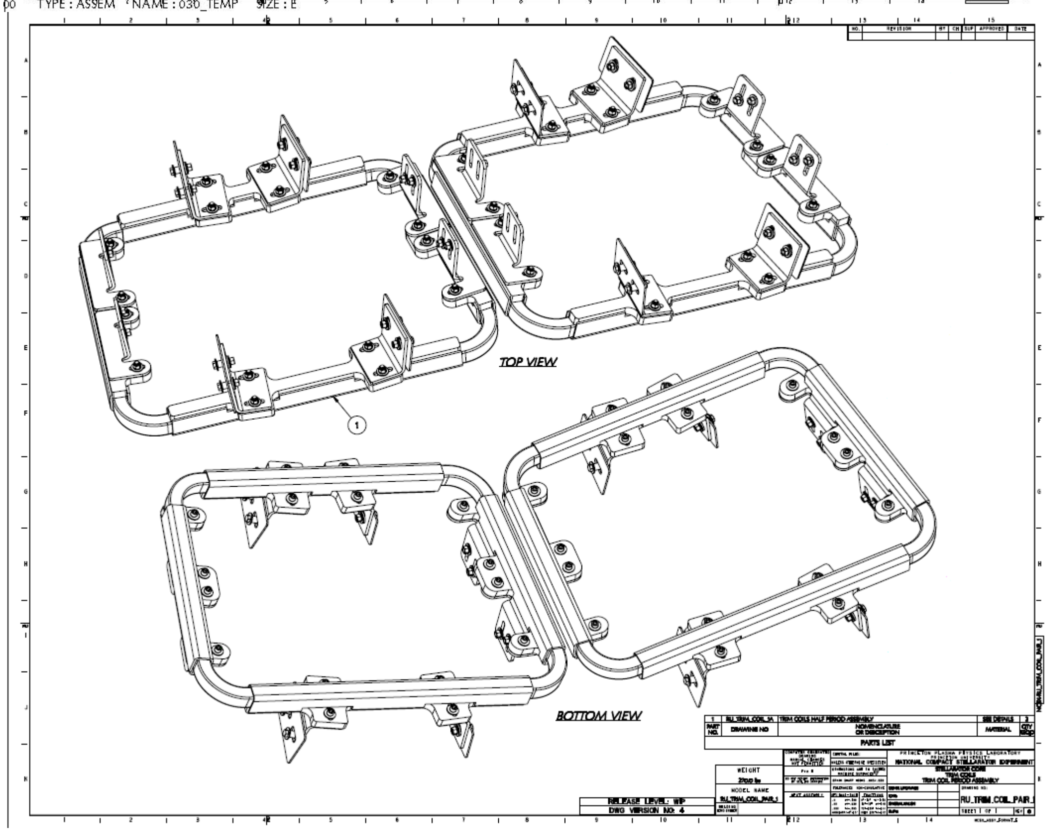
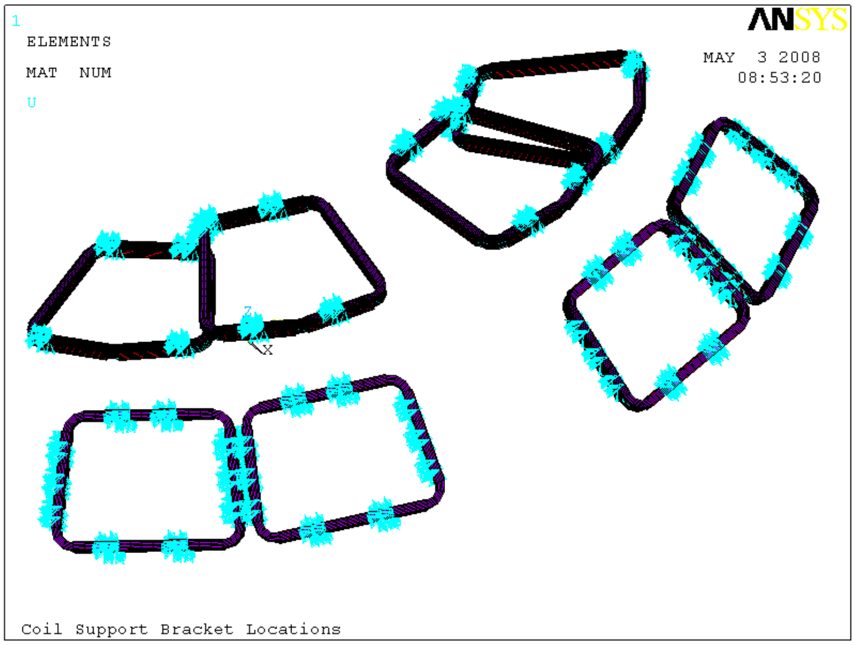
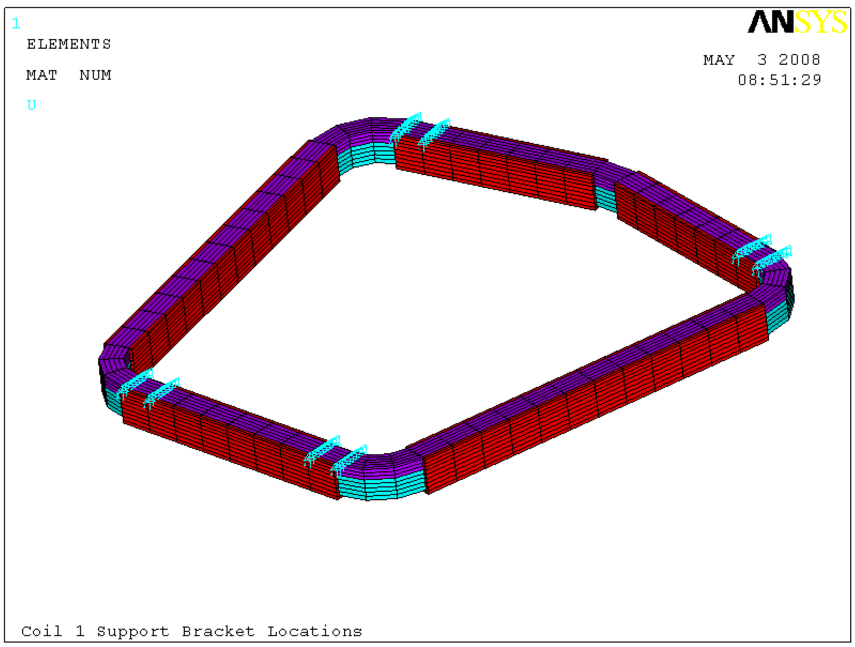


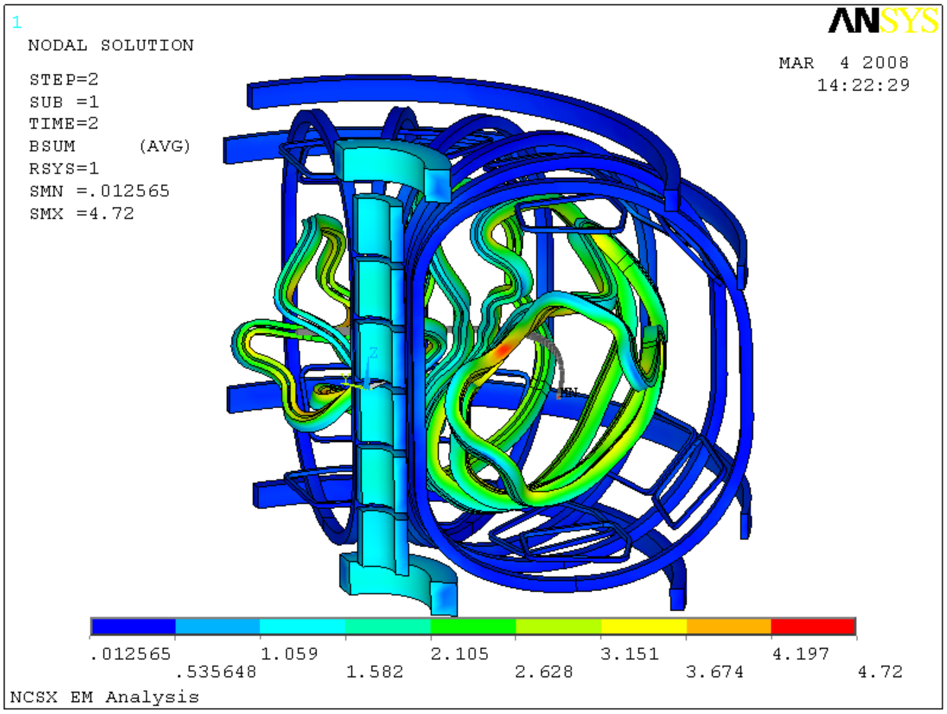
3.0 Analysis

An ANSYS model was created using the basic geometry defined by the ProE models but simplified to capture significant features. Only the coil centerline geometry from the ProE model was imported into ANSYS. The cross section geometry was modeled parametrically in ANSYS and extruded for each coil. Welds are modeled as coupling between welded interfaces at the top of the U-Channel and base (top) plate. The conductor-case interface was modeled with contact elements. Coefficients of friction of 0 and 0.3 were assumed during the initial analysis to assess impact. The conductor is fully captured by the u-channels along the straight legs but only supported by the plate in the corners where it is free to lift off. The supports are not modeled explicated; only the location of the supports are captured with constraints in the model as shown in the figures below. Reaction loads at the constraints are supplied for use in support bracket and hardware calculations being done outside the scope of this report.





An electromagnetics model was augmented with field sources from the Modular, TF and PF coils taken from an existing model of the Integrated Structure generated by HM Fan. The EM model represents a full period and assumes cyclic symmetry. While this is not true in all cases since the trim coils will be used to correct non stellarator symmetric field errors so will have current distributions that are not stellarator or cyclic symmetric, the main coil fields are symmetric. The forces on the trim coils are dominated by the field from the Modular, TF and PF coils while the self fields from the trim coils are comparatively small. The trim coils were assumed to carry their design current of 20 kA-turns in all scenarios analyzed. The plot below shows the resultant field from all the coils for the 2T High Beta scenario at t=0.197s.



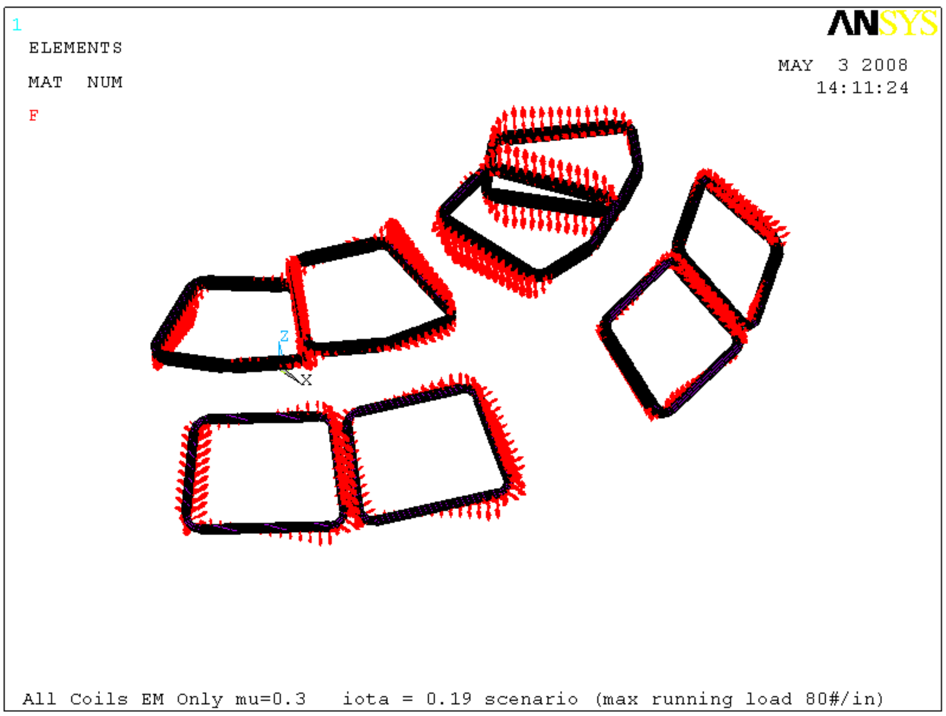
The running load on the trim coils was considered to be the best metric for identifying worse case scenarios to consider for detailed analysis since the response is driven by flexure of the coils between their supports. Alternatively the net force on the coils could have been used but this was not considered representative since there are large opposing forces in the coils. A scan of the expected operating scenarios given in the GRD and several additional flexibility requirements provided identified the worse case running load on the trim coils at their design current of 20 kA-t to be 80 lb/in for the inner coils and 60#/in for the outer coils. This is driven by the TF field since the trim coils lie just inside the TF coils. All of the GRD scenarios resulted in running loads of 50#/in or less as a result partially of lower TF levels.

The loads were checked with an independent FORTRAN code called forces5.f which was then used to scan thru all the GRD scenarios and time points plus additional physics flexibility cases. The results are tabulated below.

Scenario	Time	Running Load N/m	lb/in
1.2T_Long_Pulse	0	5783	33
	0.1	5783	33
	0.128	3869	22
	0.228	5467	31
	1.728	5464	31
1.7_Ohmic	0	8285	47
	0.1	8285	47
	0.14	4990	28
	0.24	4951	28
	0.44	4877	28
1.7T_High_beta	0	8283	47
	0.1	8283	47
	0.14	4893	28
	0.24	7531	43
	0.44	7531	43

Scenario	Time	Running Load N/m	lb/in
2T_High_Beta	0	6595	38
	0.05	6595	38
	0.097	5783	33
	0.192	8773	50
	0.197	8773	50
320KA_Ohmic	0	5573	32
	0.1	5573	32
	0.206	6692	38
	0.306	6687	38
	0.506	6679	38
0.5T_TF		13944	80
iota/shear scan	-0.10	6882	39
	0.19	13752	80
	0.20	6178	35
	0.65	10040	57

The forces on the coil are shown below for the iota=0.19 case which gave rise to the largest running load of 80 lb/in on the inner coils. The outer coils see a lesser value of 60 lb/in. The loads are greatest on the radial legs which cross the TF field and show the characteristic 1/r drop in magnitude.



Material properties for the coils and support are taken from the NCSX Online Material Database:

Trim Coils Material Properties

			Epoxy - CTD-101K RT	80K	Copper RT	80K	SS 304 RT	80K
Modulus	E	Gpa	12.9	16.7	125	137	200	
Poisson's Ratio	mu			*0.27*	0.34	0.34	0.29	
Thermal Coef of Expansion	alp	1e-6/K			16.70	8.30	16.60	
Average from RT		1e-6/K		10.00	16.7	14	16.6	12.3
Yield Strength		Mpa			240 (10% Cold Work)	270	240	485
Utimate Strength	Ut	Mpa					620	1585
Compressive Strength	Uc	Mpa						
Shear Strength		MPa		108				
References			CTD Technology Development, Inc		NIST Monograph 177 Prop of Cu … at Cryo Temps		Allegheny Ludlum Tech Data Blue Sheet	

Thermal Mismatch		
Cu_alp-SS_alp	2.E-06	1/K
strain, e	0.00044	
eE	60.3	Mpa
	8.7	Ksi

The conductor was modeled using equivalent properties calculated from a detailed flexural model of (previously) 121 turns with groundwrap. The model was simply supported and the ends and a unit load applied at the center. The flexural modulus was calculated as it would be for a flexural test setup:

$$E_b = \frac{PL^3}{4bh^3 d_{max}}$$

where

P is the applied load
L is the length of the test specimen
b is the section width
h is the section height
dmax is the max deflection at load P

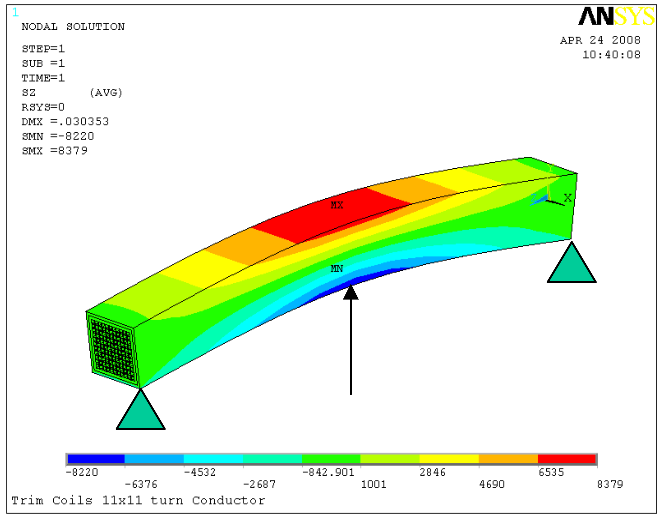
For verification, the model was rerun using the equivalent flexural modulus and displacements were checked to assure accurate stiffness representation.

Scaling factors for the copper and insulation stresses were determined by comparing max outer fiber stresses for the insulation in the initial model with the results achieved in the equivalent model. Similarly, max stresses at the copper were compared to their equivalent results. Unlike the insulation, the copper does not experience the extreme fiber stress in bending so its scale factor is further reduced based on distance from the neutral axis. Equivalently the copper stress can be normalize to the peak equivalent stress to determine the scale factor.

Equivalent Flexural Modulus and Stress Scaling for Trim Coils

	E, Mpsi	Sz, psi	E, Mpsi	Sz, psi	Sz/Sz	Sz/Sz_max
Cu Wire	17	18390	**5.85**	6620	2.78	**2.19**
Insulation	1.5	2111	**5.85**	8379	0.25	**0.25**
Composite (Flex Model)	**5.85**					

Detailed Model of 121 Turns



Results

The model was run initially with just a single coil to study the relative impact of EM loads and Cool down loads, separately and combined, and to see the effect of the assumed coefficient of friction on the results. They were iterations in the design and analysis until converging on the present configuration.

The results show some sensitivity to the coefficient of friction but there is adequate margin at both extremes. The actual design now calls for potting of the conductor with the case which will make the mu=0 less appropriate. However, we cannot assume a fully bonded coil (which earlier results suggested would have more robust) since the corners are not captured and the conductor will very likely separate from the plate.

While the trim coils are all of only two type (inner and outer), the loading differs from coil to coil as do the details of the supports. The structural model was run with 8 trim coils (half period) to capture the peak stresses in any coil. The results tabulated below are for the iota=0.19 case (largest running load of 80 lb/in in a ‘real’ scenario)

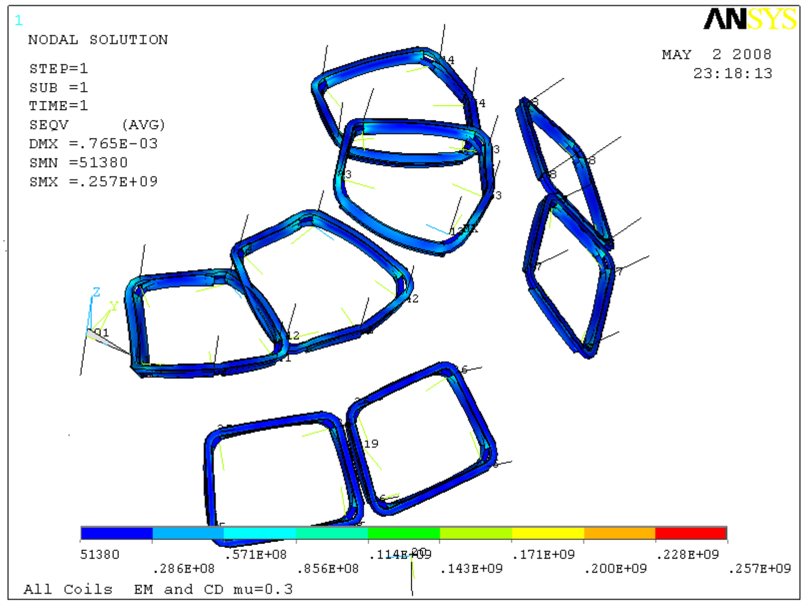
		Max Von Mises Stress					
		Cond Composite	Copper	Insulation Plate		U Channel	
No Friction	mu=0.0						
Coil1	CD+EM	32.5	71.5	8.1	113.0	186.0	Mpa
		4.6	10.2	1.2	16.1	26.6	ksi
	EM Only	19.9	43.8	5.0	44.2	34.1	Mpa
		2.8	6.3	0.7	6.3	4.9	ksi
	CD Only	25.0	55.0	6.3	106.0	198.0	Mpa
		3.6	7.9	0.9	15.1	28.3	ksi
Friction	mu=0.3						
Coil1	CD+EM	27.4	60.3	6.9	120.0	196.0	Mpa
		3.9	8.6	1.0	17.1	28.0	ksi
	EM Only	23.1	50.8	5.8	72.7	54.9	Mpa
		3.3	7.3	0.8	10.4	7.8	ksi
	CD Only	24.5	53.9	6.1	96.3	174.0	Mpa
		3.5	7.7	0.9	13.8	24.9	ksi
Friction	mu=0.3						
All Coils	CD+EM	33.9	74.6	8.5	166.0	257.0	Mpa
		4.8	10.7	1.2	23.7	36.7	ksi
	EM Only	22.9	50.4	5.7	79.2	116.0	Mpa
		3.3	7.2	0.8	11.3	16.6	ksi
	CD Only	25.5	56.1	6.4	117.0	188.0	Mpa
		3.6	8.0	0.9	16.7	26.9	ksi

The results above represent the peak stresses found in the model components. As the plots that follow will show, the primary stresses (ie averages thru sections) in the supporting structures (plate and U-Channel) are much smaller and are below the allowable of 140 MPa for 304 SS. For EM Only, the stresses are well within the limits for Local Primary and Primary plus bending of 210 MPa. For Cool down and Cooldown plus EM, the allowable is 420 MPa, governed by the Total primary plus secondary (thermal) stress limit. Once again the stresses are shown to be less than the allowable.

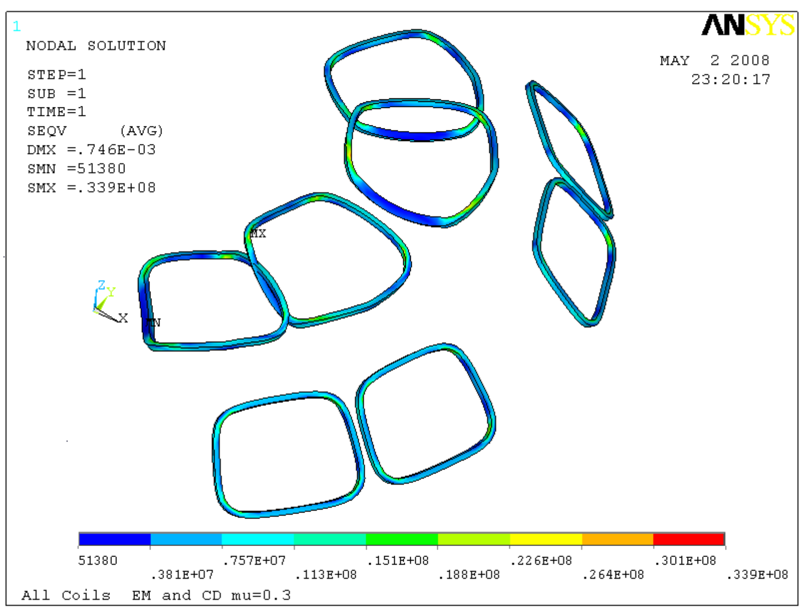
Metallic Structure Acceptance Criteria

Material	304 SS	
Minimum Yield Stress	30.0 ksi	210.0 MPa
Minimum Ultimate Tensile Strength	75.0 ksi	525.0 MPa
Sm (min 2/3 Sy or 1/2 Su)	20.0 ksi	140.0 MPa
Allowables		
Primary Membrane < 1.0 K Sm	20.0 ksi	140.0 MPa
Local Primary Membrane < 1.5 K Sm	30.0 ksi	210.0 MPa
Primary membrane plus bending < 1.5 K Sm	30.0 ksi	210.0 MPa
Total Primary plus Secondary < 3.0 K Sm	60.0 ksi	420.0 MPa
K Values		
Normal Operating Conditions	1.0	
Anticipated Conditions	1.1	
Unlikely Conditions	1.2	
Extremely Unlikely Conditions	1.35	

The figures below show stress distributions in the full set of coils. What is apparent is that the average stresses are fairly low (plots are very blue). The peaking is in the conductor corners and at the end of the welds that attach the u-channels to the support plate.

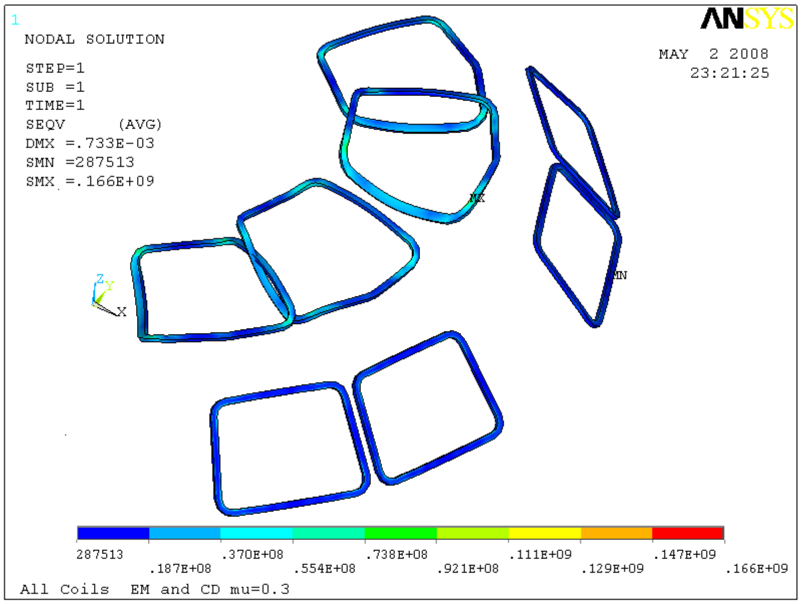


Plot of Coil Assembly Von Mises Stresses

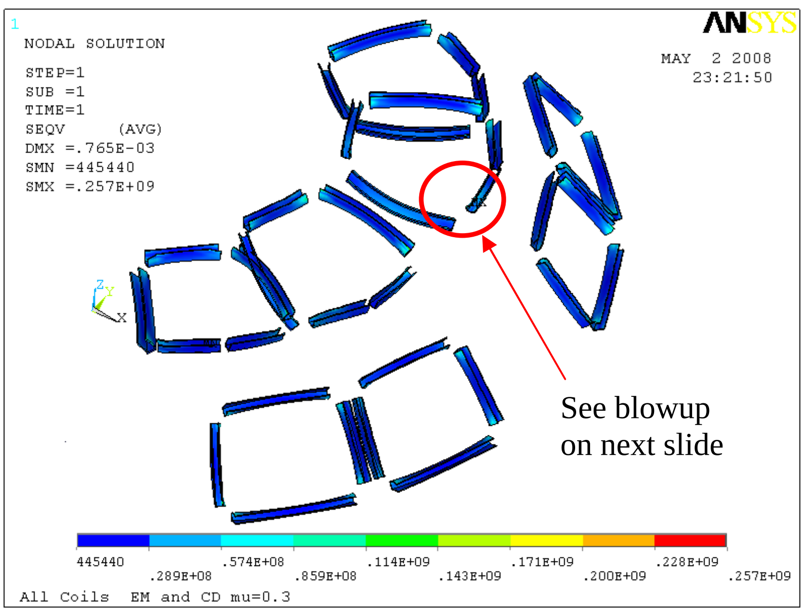


Plot of Conductor Von Mises Stresses (note: equivalent stresses)

The conductor plots show modest stresses where it is captured by the u-channel. At the corners where it is free, bending is greatest. The stresses are scaled by factors presented earlier to give the max insulation and copper stresses in the conductor tabulated above.



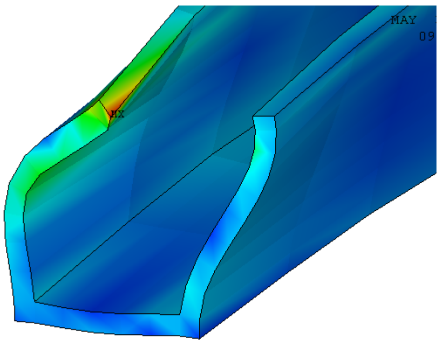
Plot of base (top) plate Von Mises Stresses



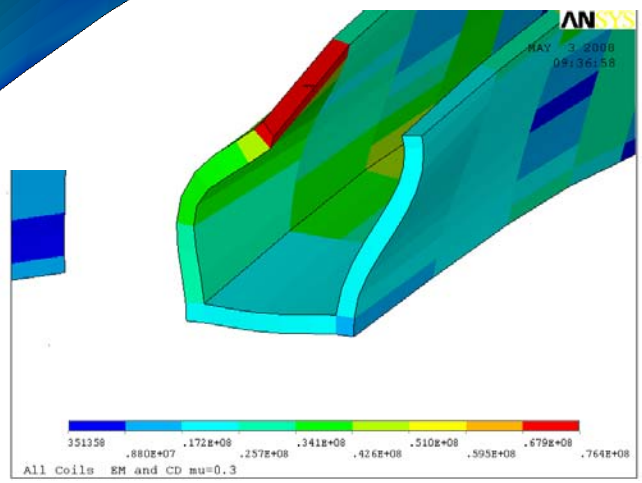
Plot of U-Channel Von-Mises Stresses

The ANSYS plots show high peak stresses at the end of the weld due to the geometric discontinuity there. Generally accepted practice is to look at averaged stresses over the local region to compare to allowable stress limits or for fatigue evaluation purposes.

Within ANSYS this is done by looking at element average stresses as opposed to the peak node stresses normally plotted. The plots below compare the differences. In the region of high stress the averaging makes a significant difference. In regions where the gradients are small, the averaging has little impact.



Peak Node Stress at
Weld
In Coil 3 U-Channel



Element Average
Stress Much
Lower

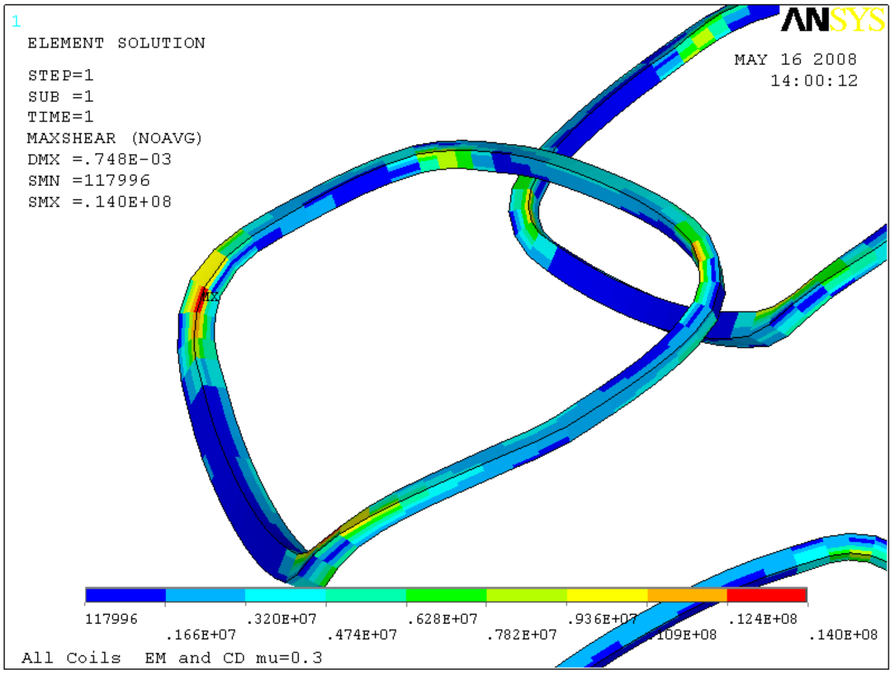
Plot of Peak Stress Region at Weld in U-Channel. Node stress still meets Acceptance critera

Two additional load cases were run thru the EM and Structural Analysis: the 0.5T TF only case which showed similarly high running loads of 80 lb/in and the 2T high beta scenario which has driven the design of the MCWF/TF/PF support structures. The node stress results are tabulated below:

Friction	mu=0.3	Max Von Mises Stress					
All Coils	EM Only	Cond Composite	Copper	Insulation	Plate	U Channel	
iota=0.19		22.9	50.4	5.7	79.2	116.0	Mpa
		3.3	7.2	0.8	11.3	16.6	ksi
0.5T TF		24.1	53.0	6.0	103.0	152.0	Mpa
		3.4	7.6	0.9	14.7	21.7	ksi
2T HB t=0.197s		13.4	29.5	3.4	46.3	38.9	Mpa
		1.9	4.2	0.5	6.6	5.6	ksi

While not shown here, the peak stresses found above occur in similar locations as the earlier case – at the end of welds of the u-channel to the base plate. An examination of the average element stresses for the 0.5T TF case shows the peak stress drops from 21.7 ksi to 8.2 ksi. Also the actual channel geometry show the U extending beyond the plate which will further reduce the node stresses show. Regardless, the node stress is still with the allowable for 304 SS (1.5 K Sm=30 ksi for local primary or primary plus bending).

The maximum shear stress in the insulation was extracted from the model by first tabulating the principle stresses (s1, s2, s3) and computing the max shear stress as the max(abs(s1-s2)/2, abs(s2-s3)/2, abs (s3-s1)/2). From the detailed model of the conductor the scaling factors for shear stress were found to be equal to the scale factor for bending (ie 0.25). The max shear for the worse case scenario below is 0.25*14 = 3.5 MPa (0.5 ksi) well within the capability of the insulation.



The reaction loads were extracted for the iota=0.19 scenario for use in bracket analysis. The table below provides the detailed results for each bracket location. Results are given in the global coordinate system (z vertical) for the four corner supports on the inner trim coils and along the four legs of the outer coils. The results show that the initial assumptions of designing the brackets to carry 80 lb/in over 1 leg of the coil (~28" long) gave a reason approximation the max load encountered. While the EM component is actually smaller, the cool down does add a fair amount of load.

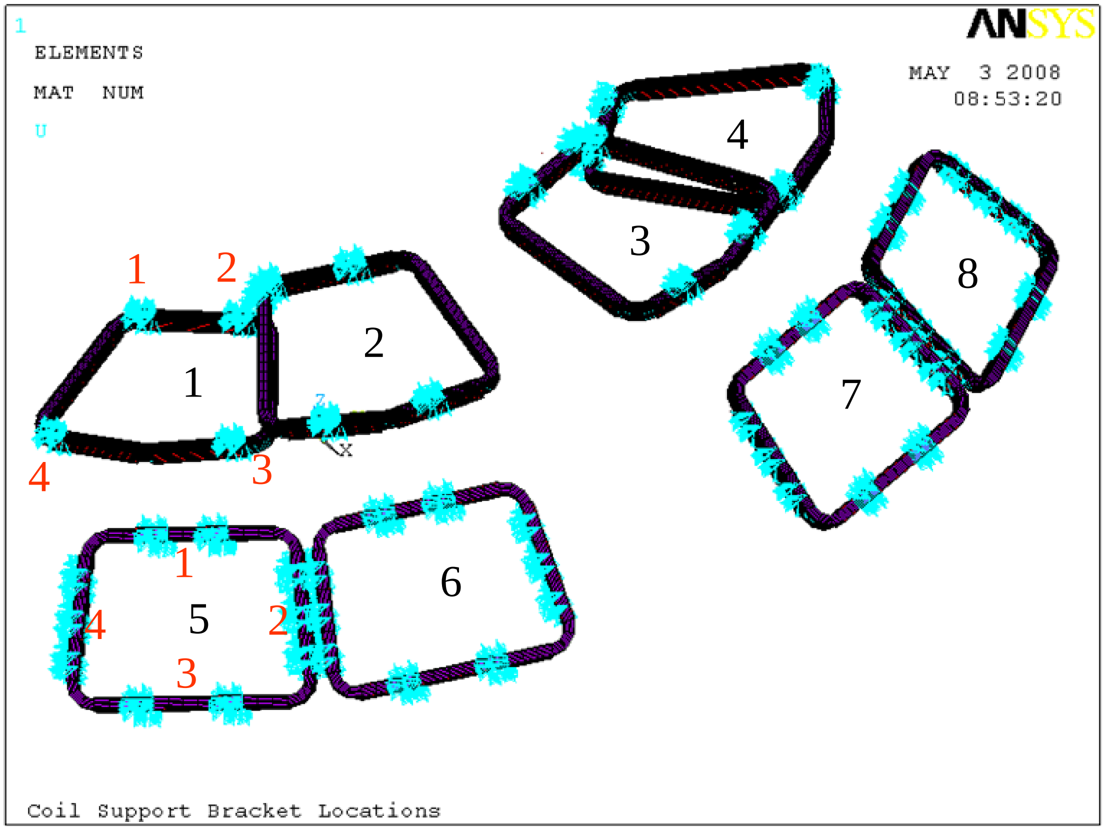
Reaction Forces at Trim Coil Support Brackets

iota=0.19 scenario (with max running load of 80#/in)

		CD				EM				EM+CD			
Inner Coil	Support	Fx, N	Fy, N	Fz, N	Fnet, N	Fx, N	Fy, N	Fz, N	Fnet, N	Fx, N	Fy, N	Fz, N	Fnet, N
1	1	-1652	-1709	-16	2377	-90	-67	3436	3438	-2201	-2229	3426	4642
	2	1738	1622	-16	2377	-712	-986	-4802	4953	1221	1211	-4846	5142
	3	1821	1876	16	2614	-1088	-937	-3996	4246	1150	912	-3968	4231
	4	-375	-3366	-177	3392	1061	-256	3802	3956	604	-4102	3640	5517
2	1	-1869	-3020	76	3552	-490	-1790	5860	6147	-2559	-5137	5840	8188
	2	534	3390	127	3434	1325	2789	-4284	5281	2014	6512	-4082	7945
	3	1710	2996	-27	3450	-1732	1134	-3343	3932	104	4604	-3362	5702
	4	-375	-3366	-177	3392	1061	-256	3802	3956	604	-4102	3640	5517
3	1	535	-3395	126	3439	-1311	4401	4790	6636	-855	722	4912	5038
	2	-1871	3025	76	3557	956	-2243	-4832	5412	-927	1054	-4769	4972
	3	-374	3363	-177	3388	-1048	-563	-2806	3048	-1593	3097	-2956	4568
	4	1709	-2993	-26	3446	1699	2115	4265	5054	3671	-1163	4231	5721
4	1	1751	-1626	-17	2389	-1088	-42	3043	3232	961	-2049	3034	3785
	2	-1662	1716	-17	2389	706	1310	-3748	4033	-1360	3228	-3784	5157
	3	-1903	1773	18	2601	-935	-1211	-2785	3177	-2878	869	-2772	4089
	4	1815	-1862	16	2600	466	857	2988	3143	2426	-1133	3021	4036
Outer Coil													
5	1	-1107	928	1630	2178	-119	-1065	-223	1095	-1197	-33	1502	1921
	2	2329	2802	40	3644	-3074	927	-2842	4288	-752	3749	-2876	4784
	3	1132	-950	-1711	2261	-1004	-321	682	1255	268	-1171	-1051	1595
	4	-2354	-2780	40	3643	2295	-2814	3245	4870	-222	-5818	3287	6686
6	1	-1358	494	1630	2178	892	-1044	-899	1642	-518	-442	841	1082
	2	1231	3429	40	3643	-2900	-1279	-2232	3877	-1662	2171	-2270	3553
	3	1388	-505	-1710	2259	-612	-949	1221	1663	916	-1263	-530	1647
	4	-1261	-3418	40	3643	3221	-1384	2611	4371	1866	-5123	2658	6065
7	1	-1355	-500	1631	2179	-599	-568	-369	904	-1972	-1072	1285	2587
	2	-1242	3385	34	3606	-2815	-958	-2562	3925	-4089	2472	-2599	5439
	3	1353	649	-1708	2273	771	-373	-609	1050	2159	251	-2278	3149
	4	1245	-3534	43	3747	2205	316	1599	2742	3464	-3234	1651	5018
8	1	-1107	-929	1630	2178	-187	-928	-152	959	-1325	-1846	1526	2737
	2	-2352	2779	40	3641	-2311	-2408	-2834	4379	-4676	365	-2883	5506
	3	1129	954	-1710	2260	948	-366	-639	1201	2046	665	-2299	3148
	4	2330	-2803	40	3645	2941	694	2321	3810	5347	-2193	2352	6239
	Max, N	2330	3429	1631	4455	3221	4401	5860	8005	5347	6512	5840	10252
	Min, N	-2354	-3534	-1711	4578	-3074	-2814	-4832	6381	-4676	-5818	-4846	8899
	Max, lbs	524	771	367	1001	724	989	1317	**1800** lb	1202	1464	1313	**2305** lb
	Min, lbs	-529	-794	-385	1029	-691	-633	-1086	1434 lb	-1051	-1308	-1089	2001 lb

Previous estimate based on
80#/in over ~28" **2240** lb

The location of the supports tabulated above is shown in the figure below:



Additional results and information can be found in the attached presentation material prepared in support of the Trim Coil Final Design Review.

4.0 Summary & Commentary

The analysis herein will be used to finalize the selection of materials and welds (base plate to U-channel and the connections to the TF brackets) for the trim coils. Based on the results, it appears that 304 SS is acceptable for both the plate and the U-channel. The stresses in trim coils conductor, insulation and encasing structure are shown to be within their allowables. The reaction loads provided will be applied to the global structural model as part of a separate analysis.

Trim Coils Final Design Review
Supporting Stress Analysis

Art Brooks
5 May 2008

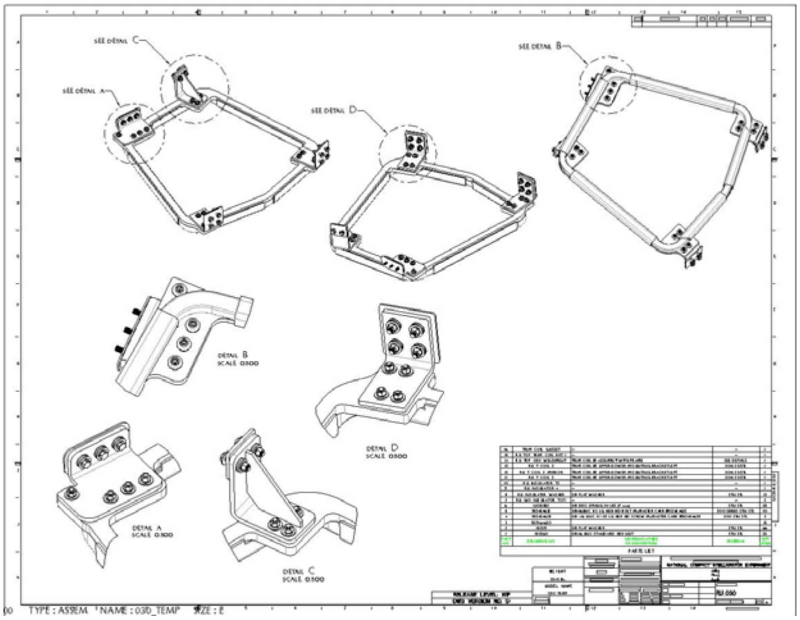
1

Trim Coil Stress Analysis Overview

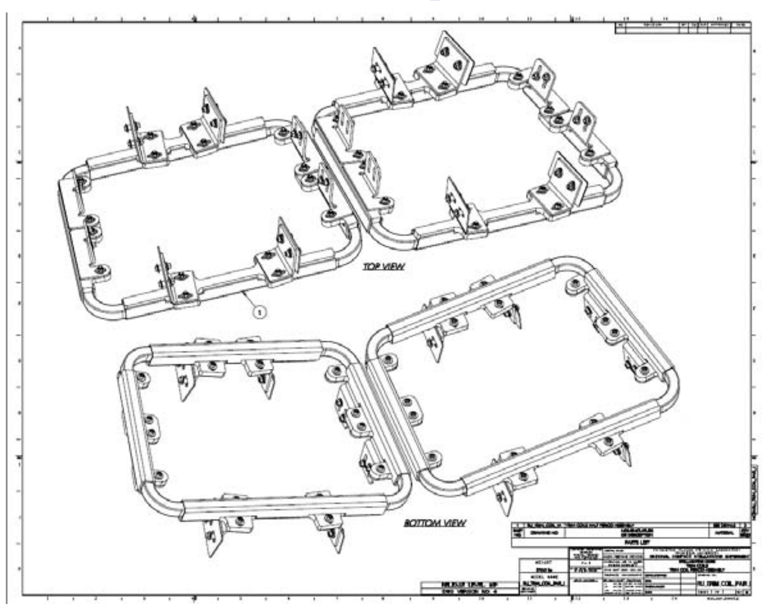
- ProE Geometry
- Finite Element Modeling Features
- Force Scan of Many Load Cases
  - Establish running load of 80#/in as worse case
- Local Model of Conductor Copper/Insulation to establish equivalent flexural properties and stress scale factors
- ANSYS Detailed Stress Plots
- Summary Stress Table

2

Inner Trim Coil



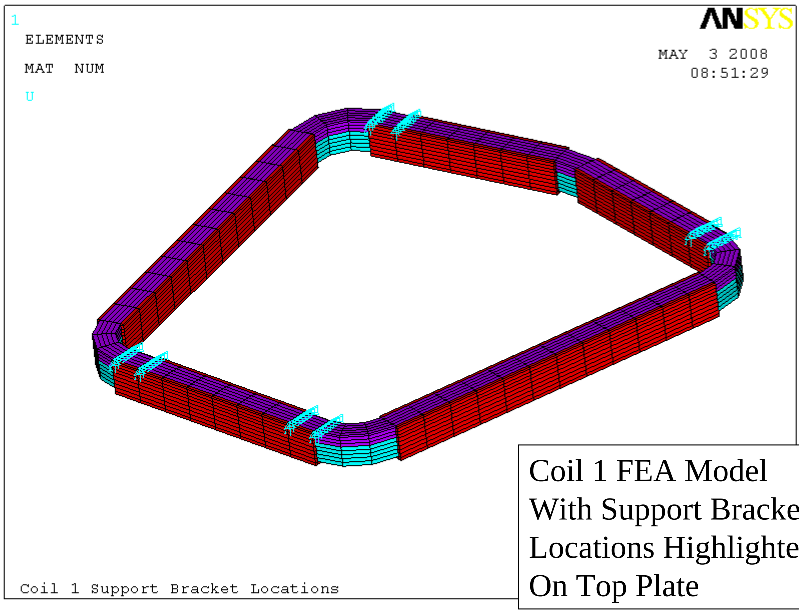
Outer Trim Coils (Top and Bottom)



Finite Element Model Features

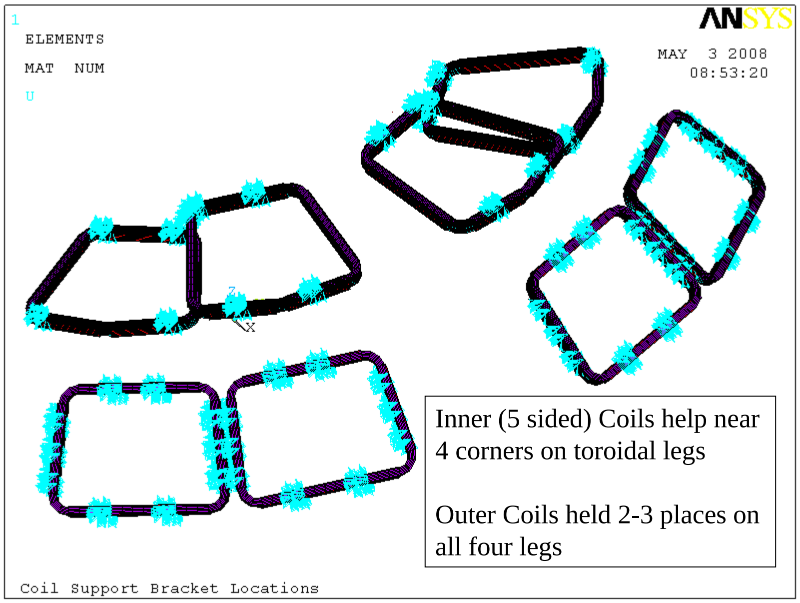
- Coil Modeled with Composite Properties for Copper and Insulation to minimize model size
  - Resultant plotted stress values must be scaled accordingly (~x2.2 for Cu, x0.25 for Insulation based on flexure)
- U Channels and Base (Top) Plate welded to form partial case
- Conductor free in corners
- Coil – Case contact assumes coefficient of friction of 0.3
- Supports model with simple fixed constraints at support locations
- Loading includes EM and Thermal Cool down
  - Since case is mounted to MCWF/TF/PF Structure, Only differential thermal contraction assumed

5



Coil 1 FEA Model With Support Bracket Locations Highlighted On Top Plate

6



Load Cases Investigated for EM Forces

- All GRD Load Cases at Multiple (5) time points
- Additional Flexibility Cases Identified by Physics
  - Iota Scan (2)
  - Shear Scan (2)
- Max Running Loads Found
  - 80 lb/in Inner Coils
  - 60 lb/in Outer Coils

- 2T High Beta
- 1.7T High beta
- 1.2T Long Pulse
- 1.7T Ohmic
- 320KA Ohmic
- 0.5 T TF
- Iota/Shear Scan
  - iota -0.10
  - iota 0.19 (High TF Field)
  - iota +0.20
  - iota 0.65

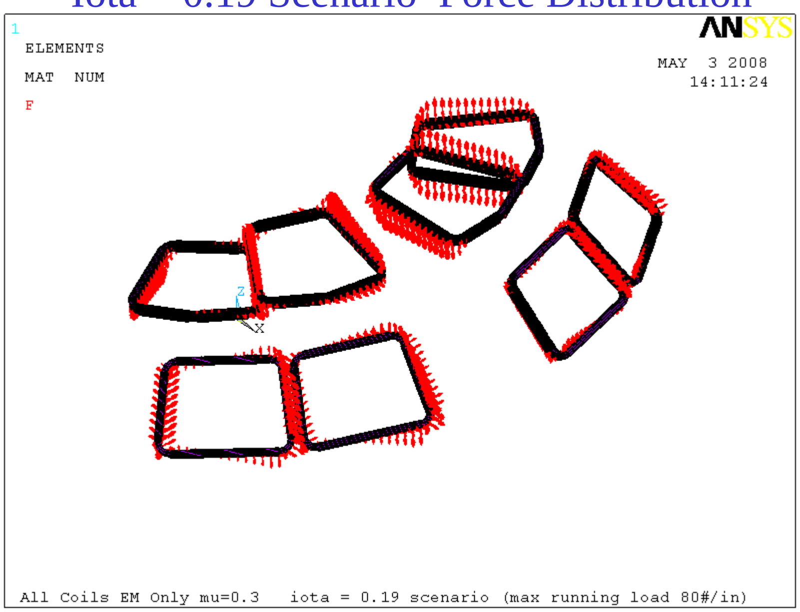
Running Load Comparison

Scenario	Time	Running Load N/m	Running Load lb/in
1.2T_Long_Pulse	0	5783	33
	0.1	5783	33
	0.128	3869	22
	0.228	5467	31
	1.728	5464	31
1.7_Ohmic	0	8285	47
	0.1	8285	47
	0.14	4990	28
	0.24	4951	28
	0.44	4877	28
1.7T_High_beta	0	8283	47
	0.1	8283	47
	0.14	4893	28
	0.24	7531	43
	0.44	7531	43

Scenario	Time	Running Load N/m	Running Load lb/in
2T_High_Beta	0	6595	38
	0.05	6595	38
	0.097	5783	33
	0.192	8773	50
	0.197	8773	50
320KA_Ohmic	0	5573	32
	0.1	5573	32
	0.206	6692	38
	0.306	6687	38
	0.506	6679	38
0.5T_TF		13944	80
iota/shear scan	-0.10	6882	39
	0.19	13752	80
	0.20	6178	35
	0.65	10040	57

9

Iota = 0.19 Scenario Force Distribution



Force Scan Done with FORTRAN Code Benchmarked with ANYS

Benchmark of Trim Coil Forces - Filament Model vs ANSYS Model
Net Force On Trim Coils for Worse Case Scenario (2T HB t=0.197s)

		Coil 1	Coil 2	Coil 3	Coil 4	Coil 5	Coil6	Coil 7	Coil 8
ANSYS	FX	-2096.4	-831.7	567.4	-422.2	-1155.9	2626.5	-1147.6	-322.6
	FY	-1817.0	993.9	4403.7	315.5	-3447.5	-3114.4	-268.2	-1124.0
	FZ	-3853.4	4882.3	2764.3	-1755.4	2100.1	1884.8	-2130.1	-1132.7
	Fnet	4748.1	5051.3	5230.3	1832.8	4199.0	4488.9	2434.4	1628.0
Forces5.f	FX	-2101.1	-837.3	554.6	-422.4	-1168.0	2602.4	-1171.4	-334.2
	FY	-1827.6	985.4	4410.9	300.2	-3440.6	-3112.0	-271.5	-1135.8
	FZ	-3853.1	4940.3	2777.2	-1762.7	2088.0	1861.9	-2160.0	-1163.7
	Fnet	4754.1	5106.7	5241.8	1837.3	4190.7	4463.6	2472.2	1660.1
Ratio	FX	1.00	0.99	1.02	1.00	0.99	1.01	0.98	0.97
	FY	0.99	1.01	1.00	1.05	1.00	1.00	0.99	0.99
	FZ	1.00	0.99	1.00	1.00	1.01	1.01	0.99	0.97
	Fnet	1.00	0.99	1.00	1.00	1.00	1.01	0.98	0.98

Forces in Newtons

11

Material Properties taken from NCSX Online Materials Database

Trim Coils Material Properties

			Epoxy - CTD-101K		Copper		SS 304	
			RT	80K	RT	80K	RT	80K
Modulus	E	Gpa	12.9	16.7	125	137	200	
Poisson's Ratio	mu			*0.27*	0.34	0.34	0.29	
Thermal Coef of Expansion	alp	1e-6/K			16.70	8.30	16.60	
Average from RT		1e-6/K		10.00	16.7	14	16.6	12.3
Yield Strength		Mpa			240 (10% Cold Work)	270	240	485
Utimate Strength	Ut	Mpa					620	1585
Compressive Strength	Uc	Mpa						
Shear Strength		MPa		108				
References			CTD Technology Development, Inc		NIST Monograph 177 Prop of Cu … at Cryo Temps		Allegheny Ludlum Tech Data Blue Sheet	

Thermal Mismatch		
Cu_alp-SS_alp	2	1e-6/K
strain, e	0.00044	
eE	60.3	Mpa
	8.7	Ksi

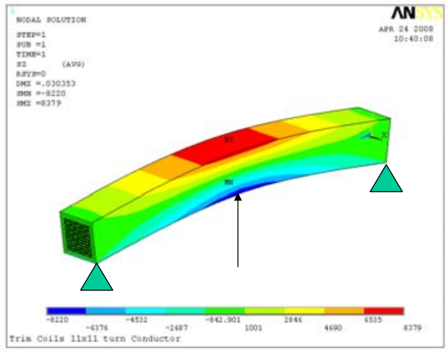
12

Conductor Modeled with Equivalent Properties calculated from Flexural Modulus Simulation

Equivalent Flexural Modulus and Stress Scaling for Trim Coils

	E, Mpsi	Sz, psi	E, Mpsi	Sz, psi	Sz/Sz	Sz/Sz_max
Cu Wire	17	18390	**5.85**	6620	2.78	**2.19**
Insulation	1.5	2111	**5.85**	8379	0.25	**0.25**
Composite (Flex Model)	**5.85**					

Detailed Model of 121 Turns



ANSYS Results Plots
Worse Case Running Load of 80#/in

- Coil 1 EM + CD mu = 0
- Coil 1 EM Only mu = 0
- Coil 1 CD Only mu = 0

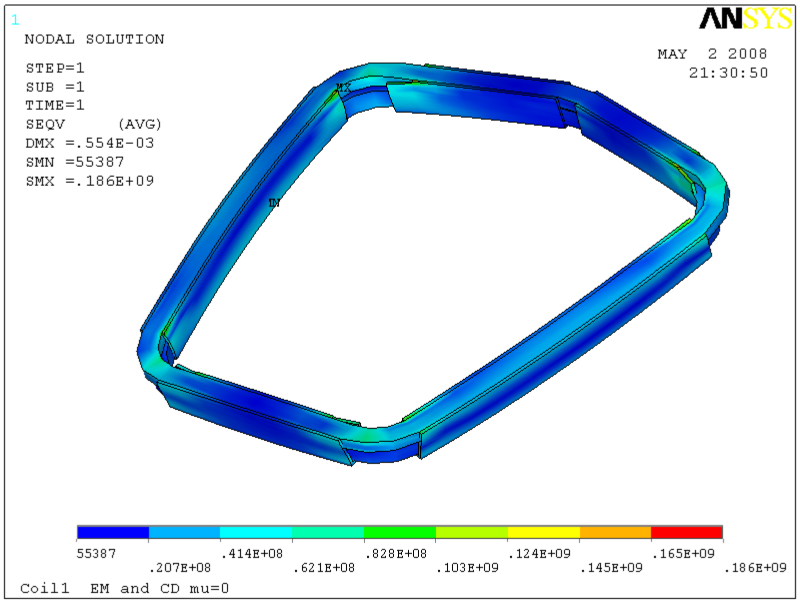
- Coil 1 EM + CD mu = 0.3
- Coil 1 EM Only mu = 0.3
- Coil 1 CD Only mu = 0.3

- All Coils EM + CD mu = 0.3
- All Coils EM Only mu = 0.3
- All Coils CD Only mu = 0.3

- 4 Plots per Case Shown
  - All
  - Conductor Only
  - Top Plate Only
  - U Channels Only
  - + Other Details in some cases

Coil 1 EM + CD mu = 0

15



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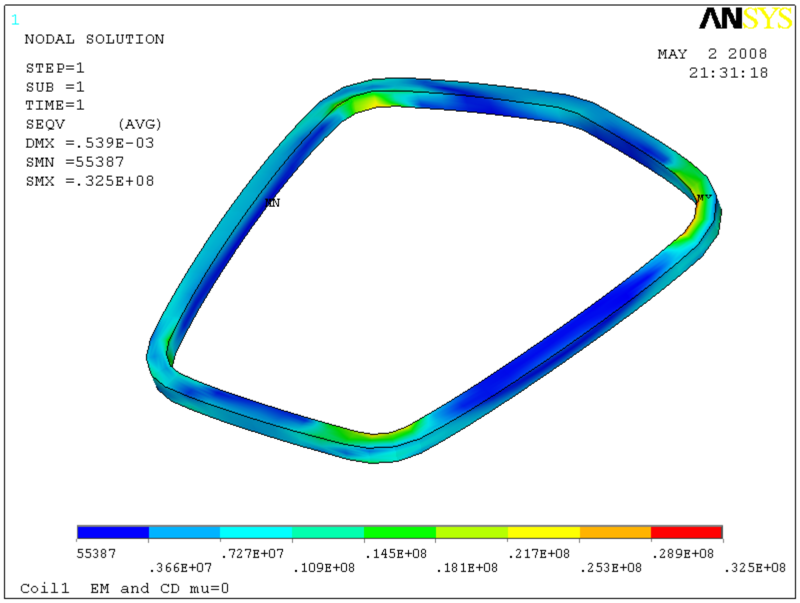
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MN
MX
55387
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.727E+07
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.253E+08
.289E+08
.325E+08
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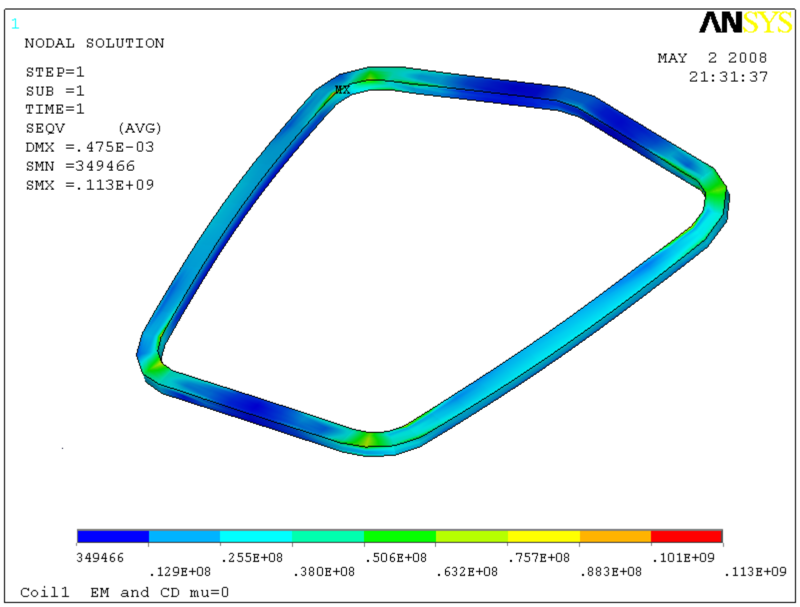
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MAY 2 2008
21:31:37
MX
349466
.129E+08
.255E+08
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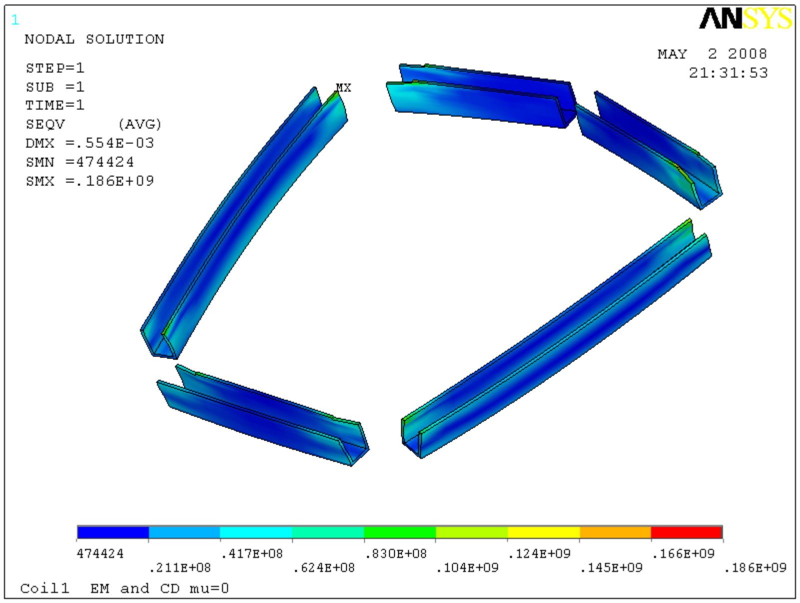
.506E+08
.632E+08
.757E+08
.883E+08
.101E+09
.113E+09
Coil1 EM and CD mu=0

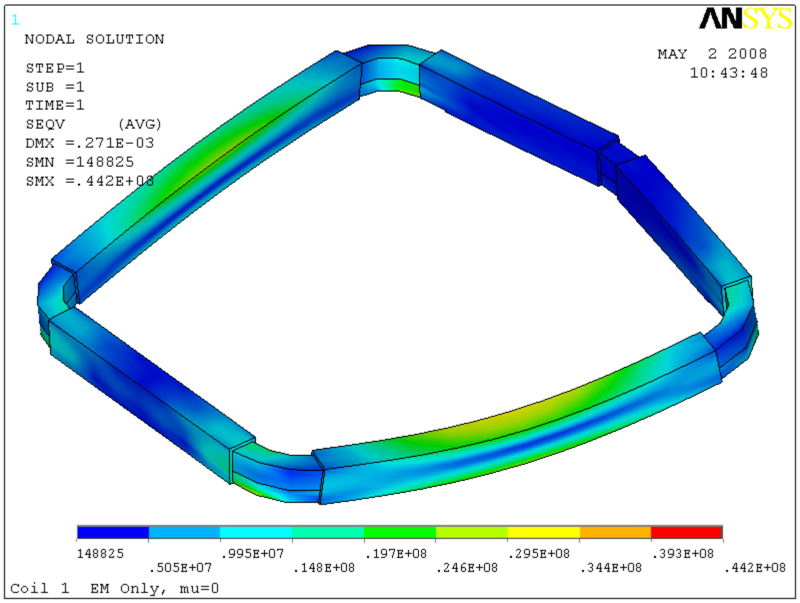
18



19

Coil 1 EM Only mu = 0

20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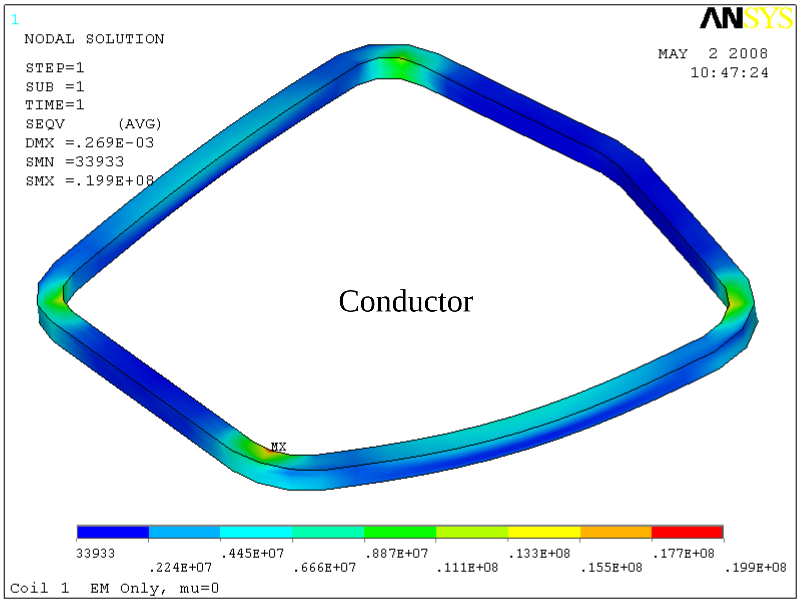
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10:47:24
Conductor
MX
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.445E+07
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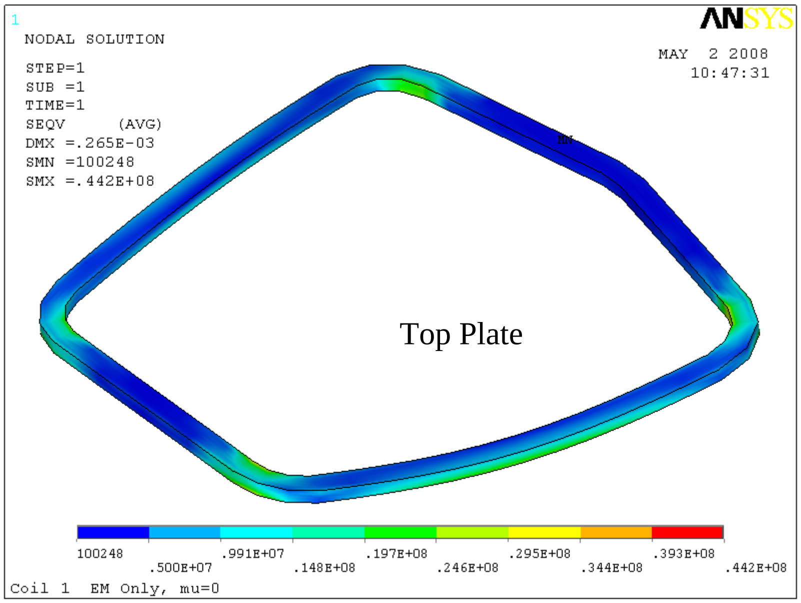

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10:47:31
Top Plate
100248
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.991E+07
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.246E+08
.295E+08
.344E+08
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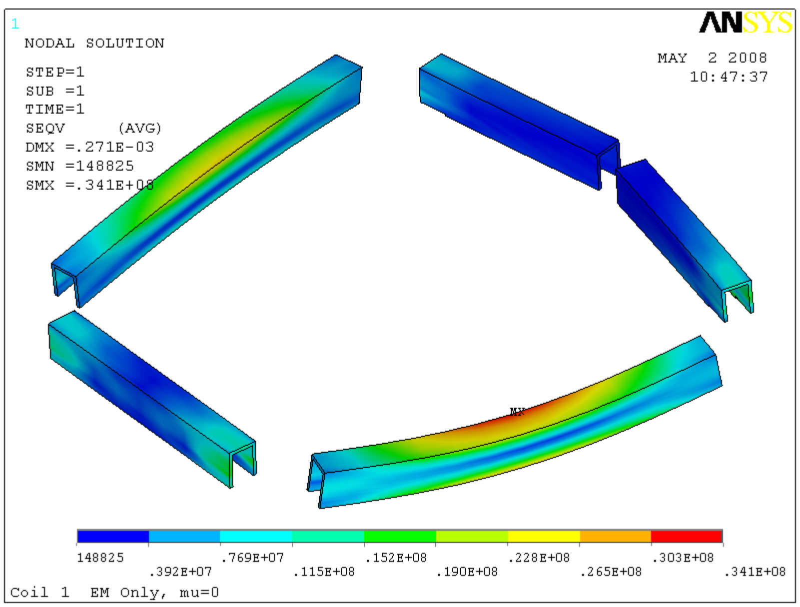
Coil 1 EM Only, mu=0



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10:47:37
148825
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.115E+08
.152E+08
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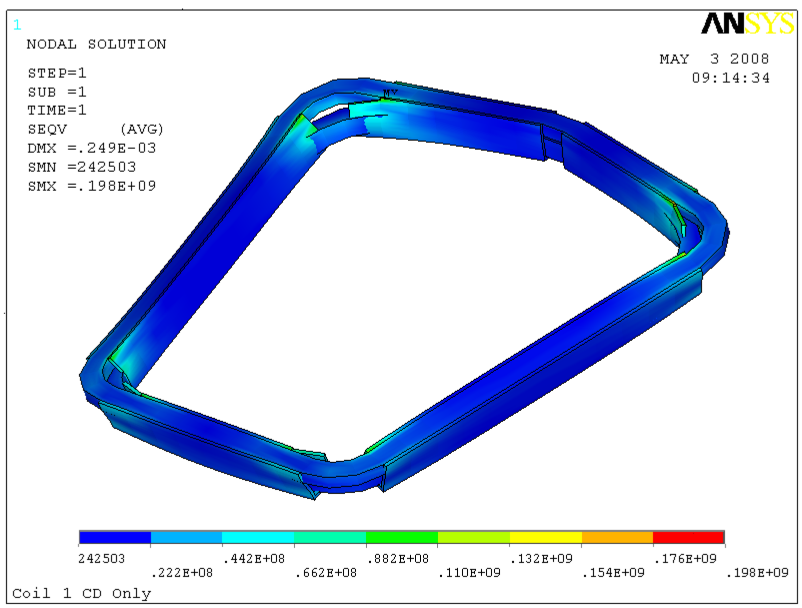
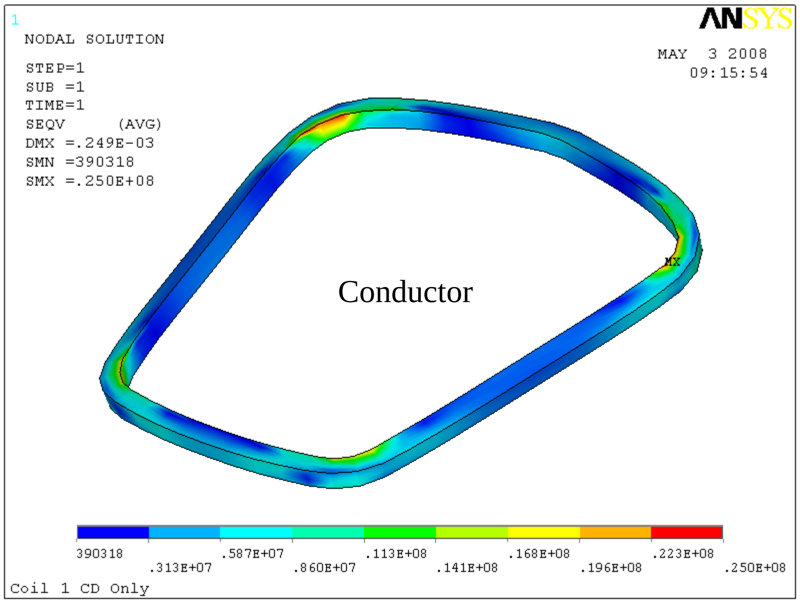
Coil 1 EM Only, mu=0

24

Coil 1 CD Only mu = 0

25

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MAY 3 2008
09:15:54
MX
Conductor
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.313E+07
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.113E+08
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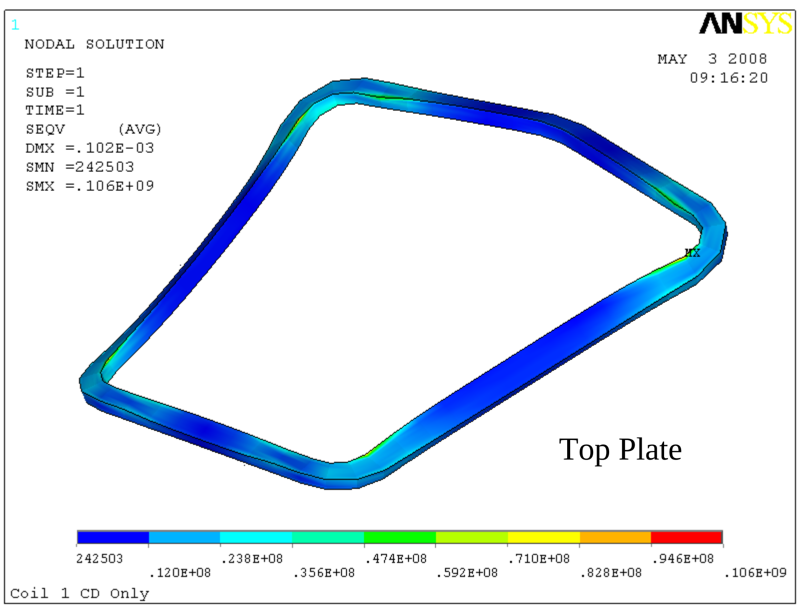
Coil 1 CD Only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09:16:20
MX
Top Plate
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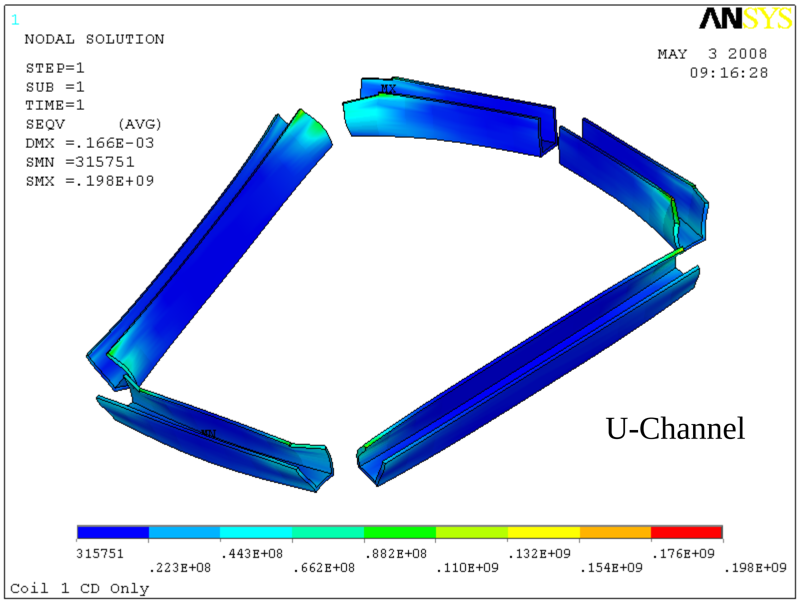
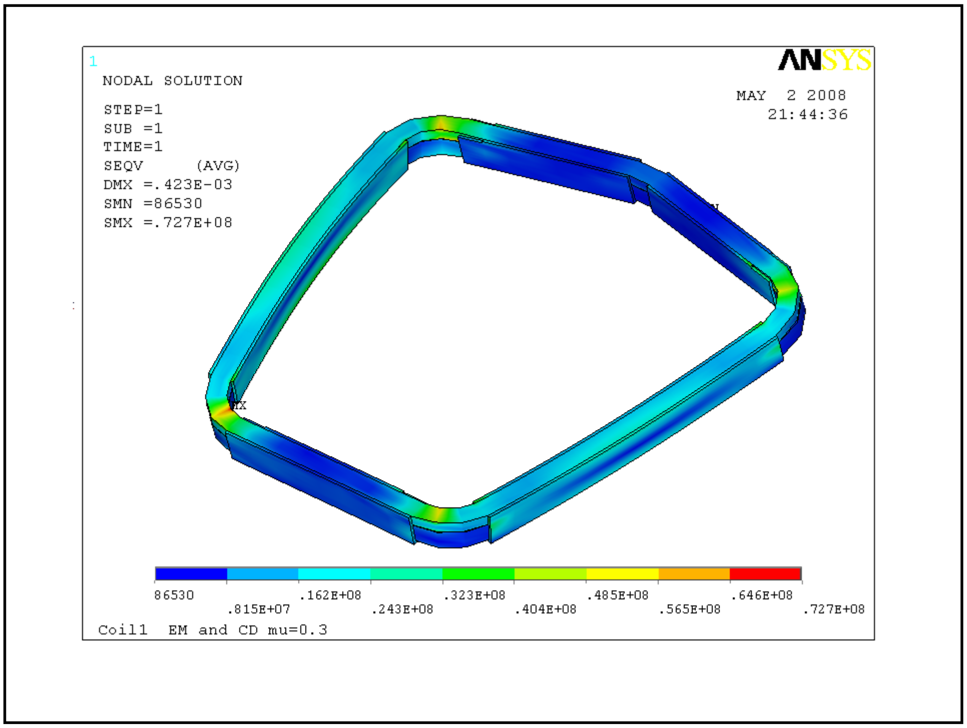
Coil 1 CD Only



29

Coil 1 EM + CD mu = 0.3

30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MAY 2 2008
21:44:36
86530
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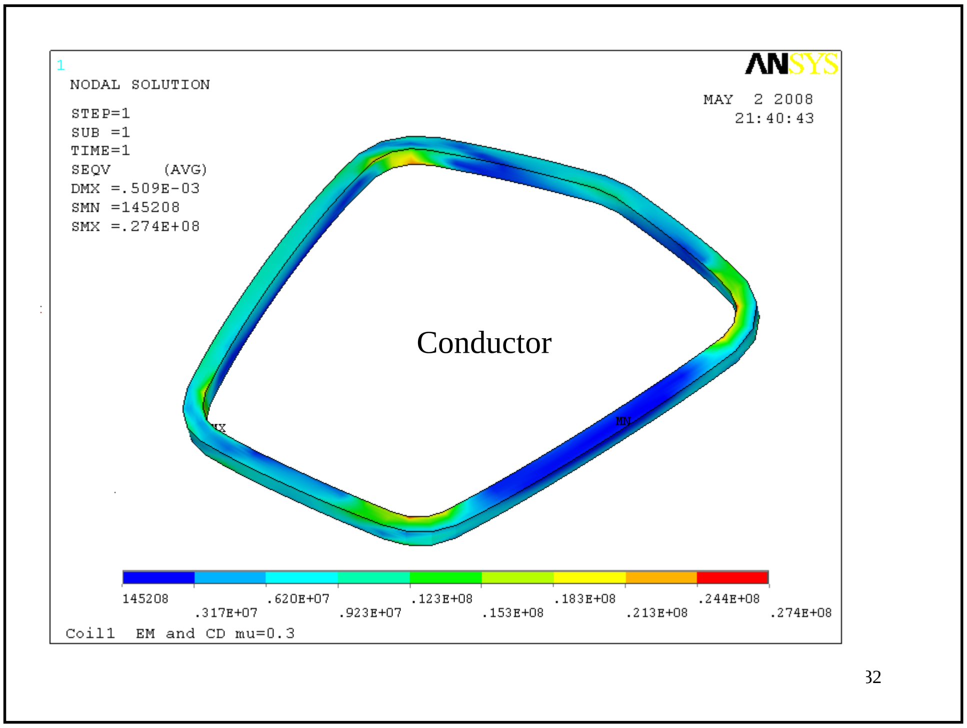
Coil1 EM and CD mu=0.3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MAY 2 2008
21:40:43
Conductor
145208
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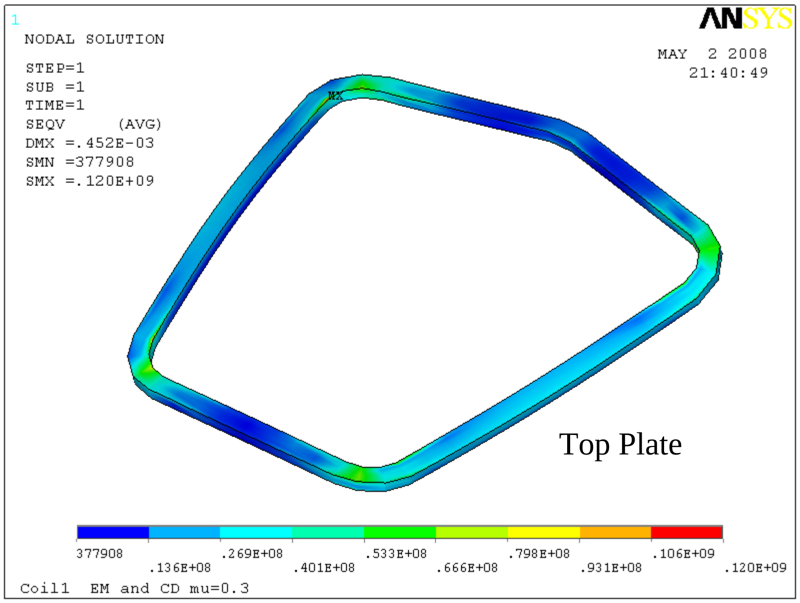
Coil1 EM and CD mu=0.3
32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MAY 2 2008
21:40:49
MX
Top Plate
377908
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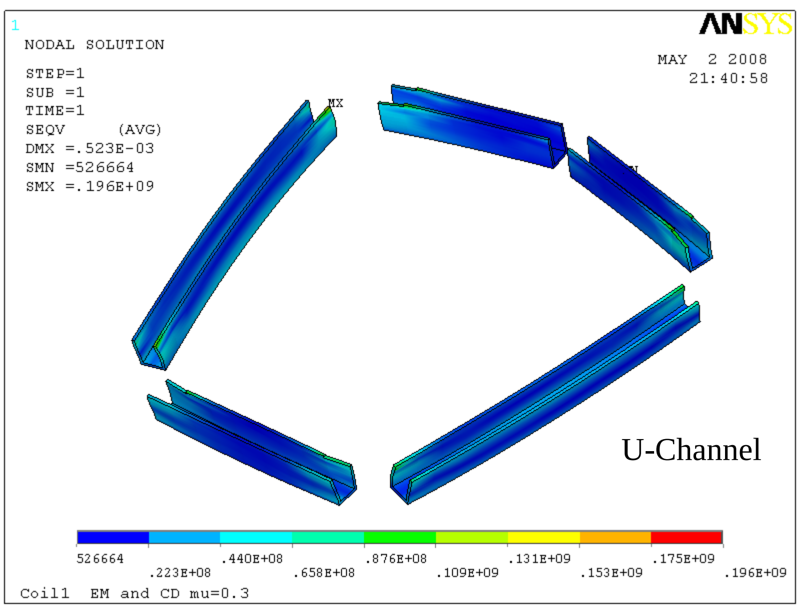
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21:40:58
MX
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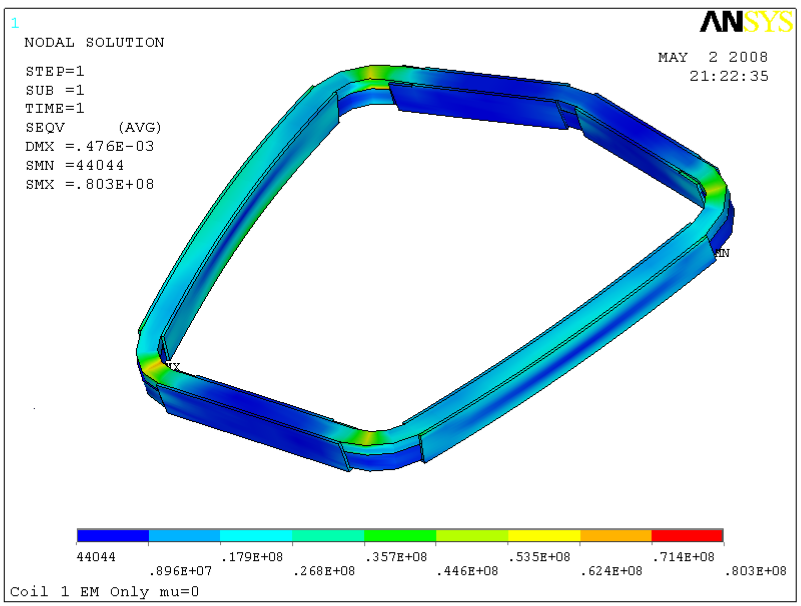
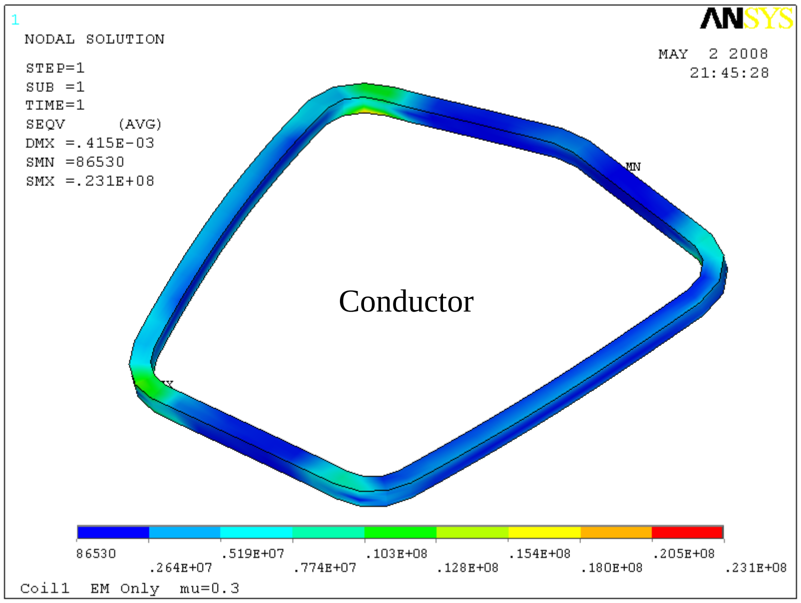
34

Coil 1 EM Only mu = 0.3

35

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MAY 2 2008
21:45:28
MN
Conductor
86530
.264E+07
.519E+07
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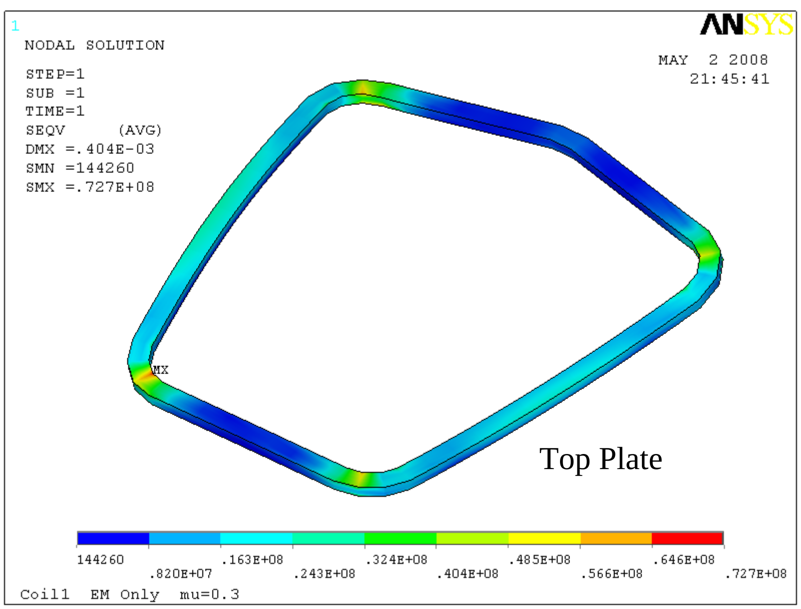
Coil1 EM Only mu=0.3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SMX =.727E+08
ANSYS
MAY 2 2008
21:45:41
MX
Top Plate
144260
.820E+07
.163E+08
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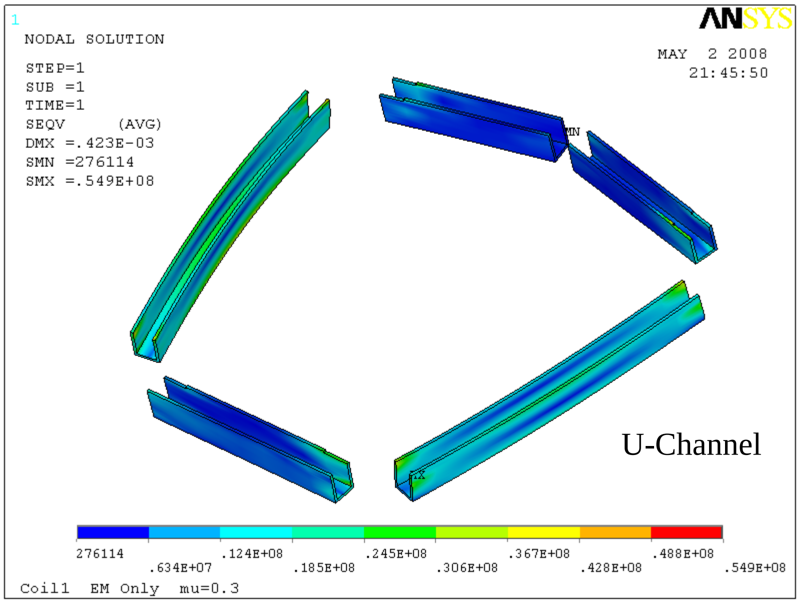
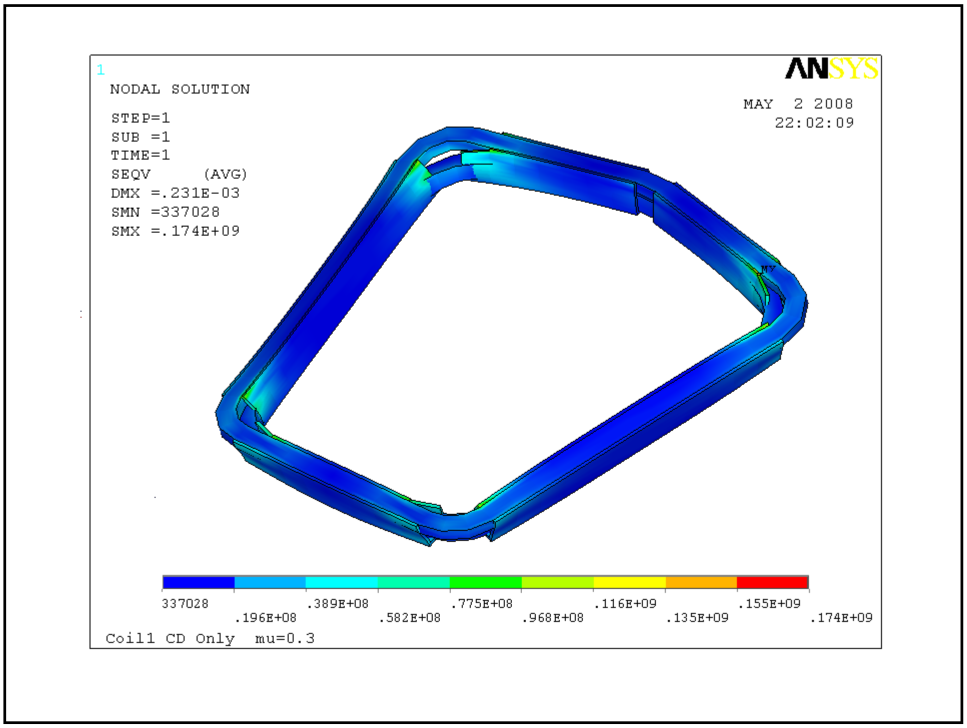
Coil1 EM Only mu=0.3



39

Coil 1 CD Only mu = 0.3

40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MAY 2 2008
22:02:09
337028
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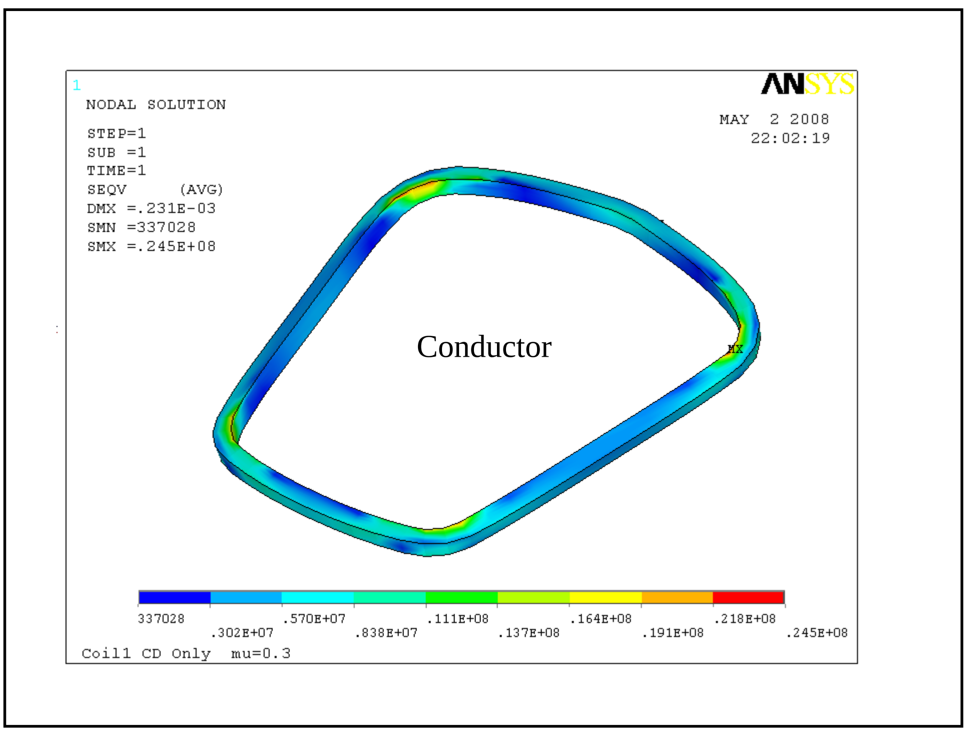
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MAY 2 2008
22:02:19
Conductor
MX
337028
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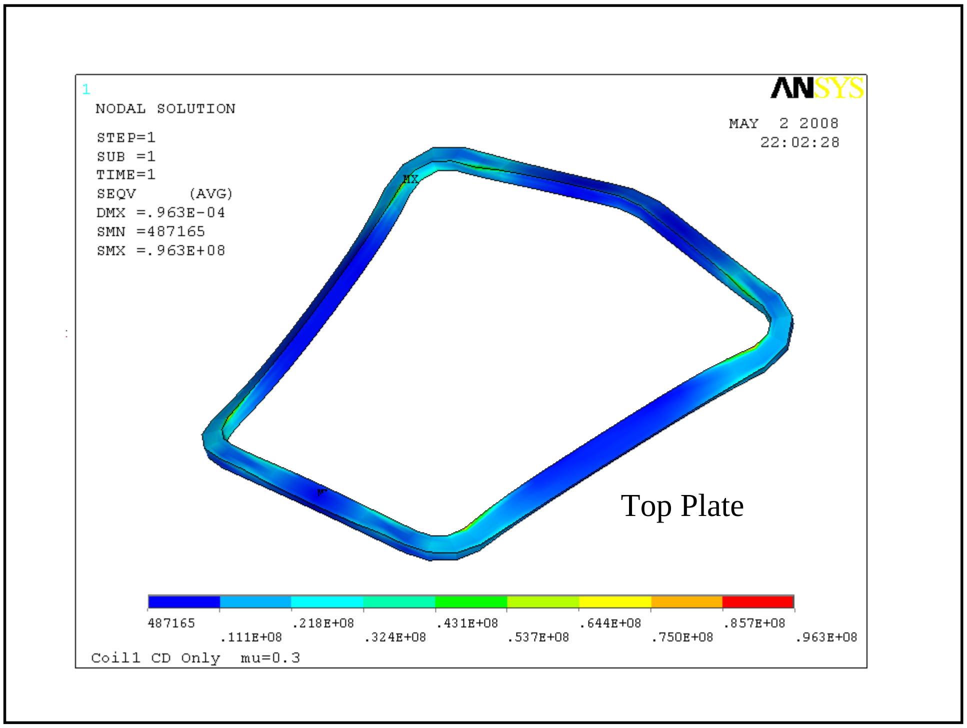
Coil1 CD Only mu=0.3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MAY 2 2008
22:02:28
MX
MN
Top Plate
487165
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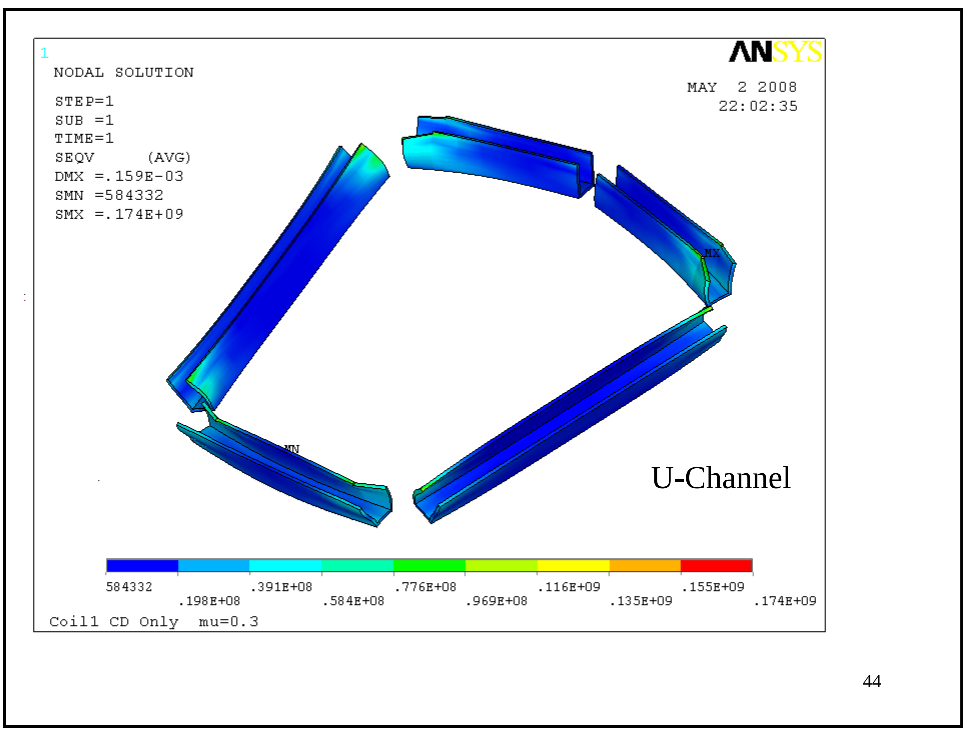
Coil1 CD Only mu=0.3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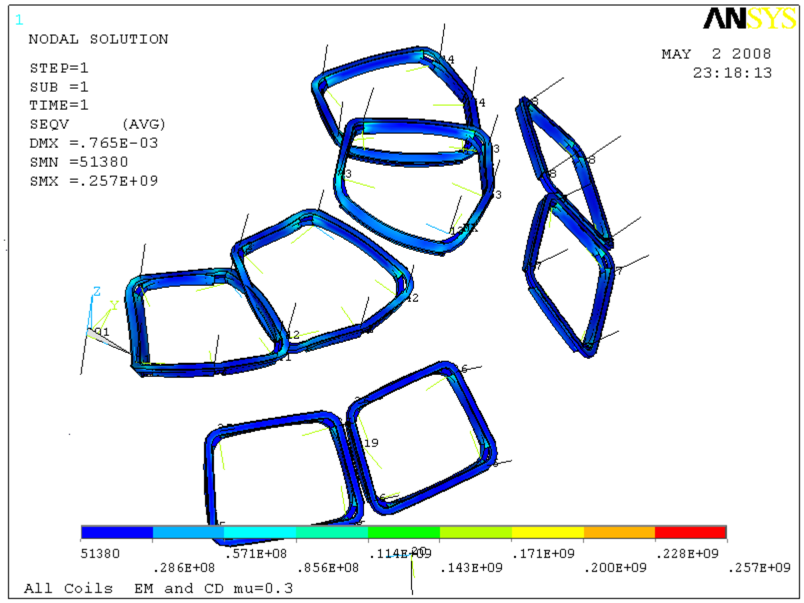
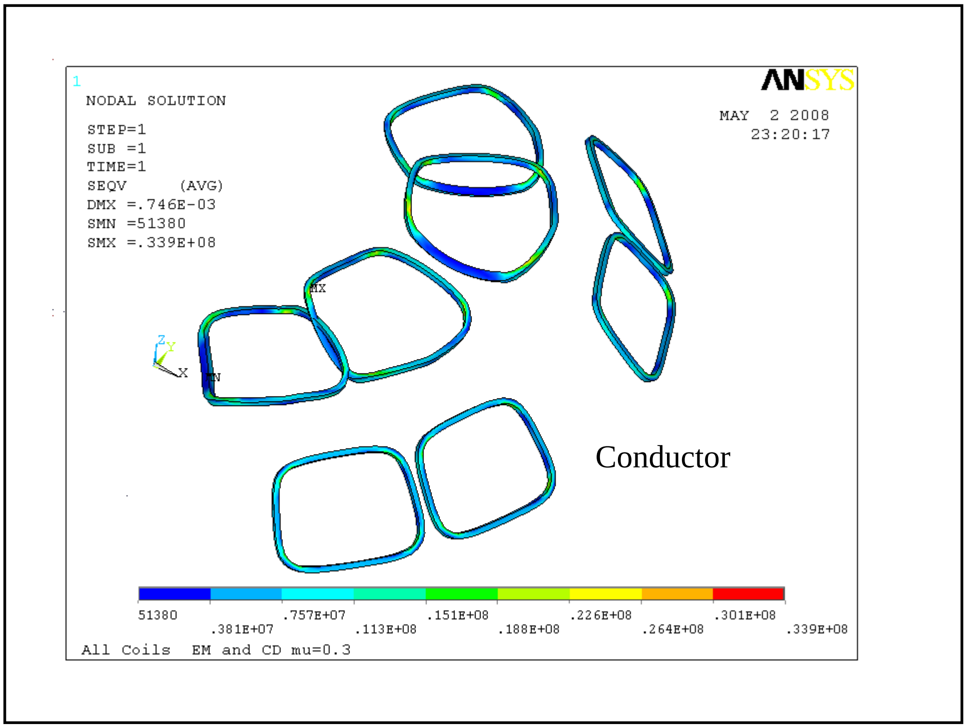
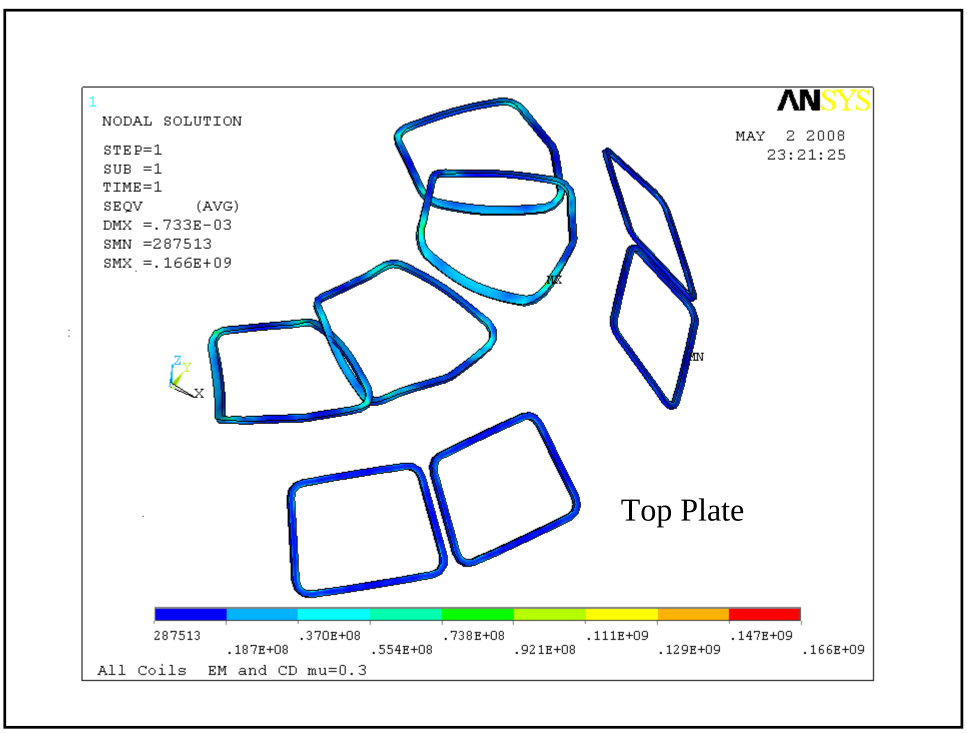
SMX =.174E+09
ANSYS
MAY 2 2008
22:02:35
MX
MN
U-Channel
584332
.198E+08
.391E+08
.584E+08
.776E+08
.969E+08
.116E+09
.135E+09
.155E+09
.174E+09
Coil1 CD Only mu=0.3
44

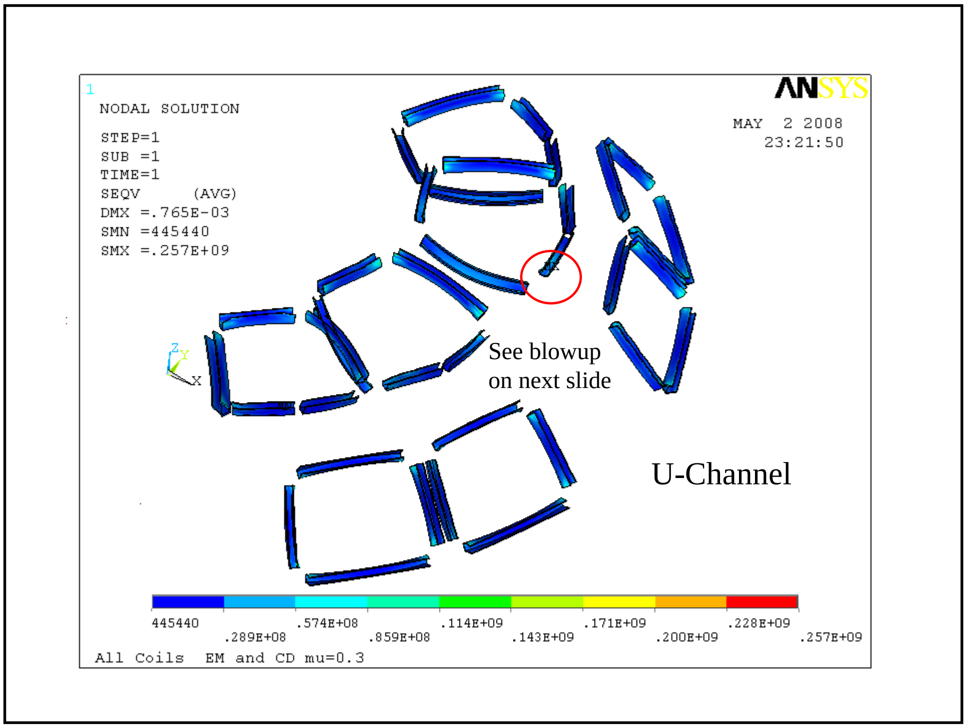
All Coils EM + CD mu = 0.3

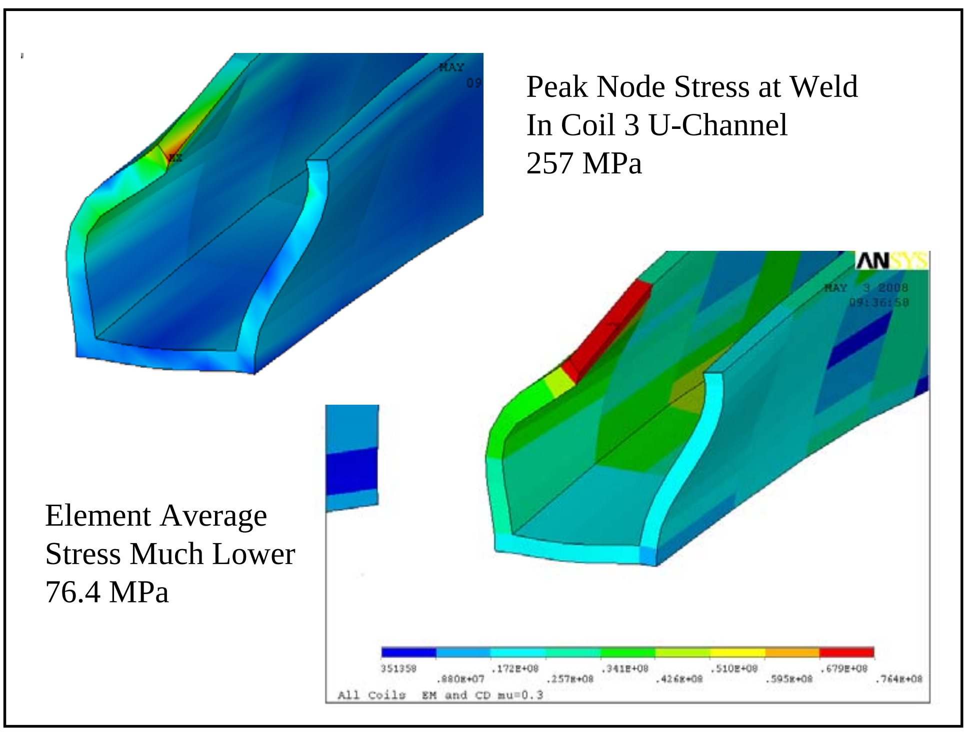
45




1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.746E-03
SMN =51380
SMX =.339E+08
ANSYS
MAY 2 2008
23:20:17
MX
MN
Conductor
51380
.381E+07
.757E+07
.113E+08
.151E+08
.188E+08
.226E+08
.264E+08
.301E+08
.339E+08
All Coils EM and CD mu=0.3

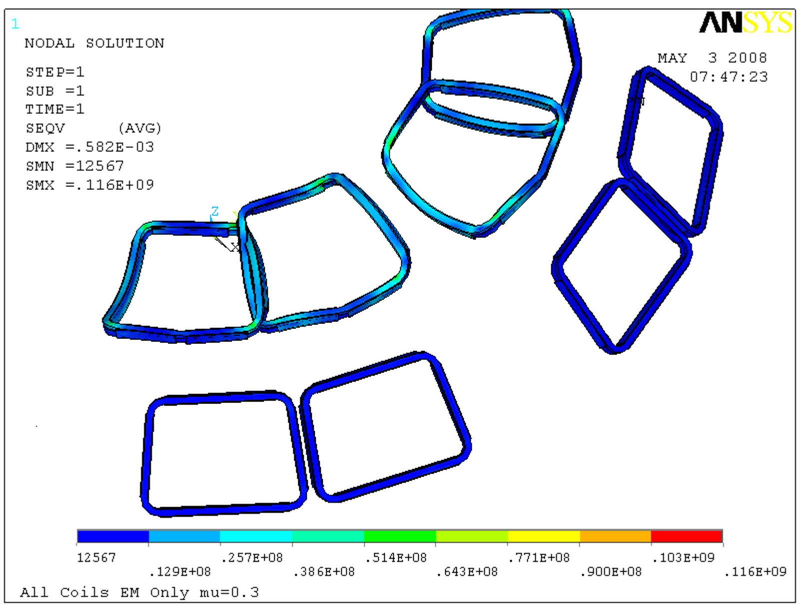

1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.733E-03
SMN =287513
SMX =.166E+09
ANSYS
MAY 2 2008
23:21:25
MX
MN
Top Plate
287513
.187E+08
.370E+08
.554E+08
.738E+08
.921E+08
.111E+09
.129E+09
.147E+09
.166E+09
All Coils EM and CD mu=0.3


NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.765E-03
SMN =445440
SMX =.257E+09
ANSYS
MAY 2 2008
23:21:50
See blowup
on next slide
U-Channel
445440
.289E+08
.574E+08
.859E+08
.114E+09
.143E+09
.171E+09
.200E+09
.228E+09
.257E+09
All Coils EM and CD mu=0.3

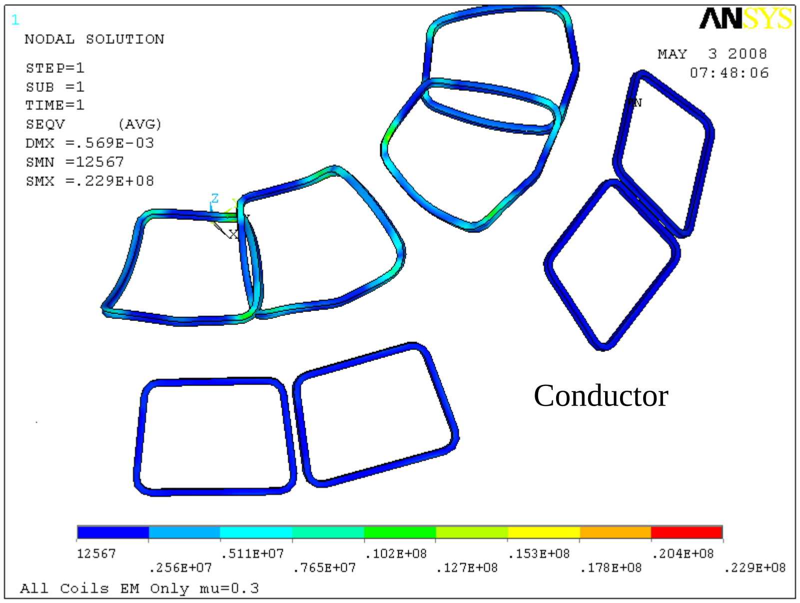

Peak Node Stress at Weld
In Coil 3 U-Channel
257 MPa
Element Average
Stress Much Lower
76.4 MPa
ANSYS
351358
.880E+07
.172E+08
.257E+08
.341E+08
.426E+08
.510E+08
.595E+08
.679E+08
.764E+08
All Coils EM and CD mu=0.3

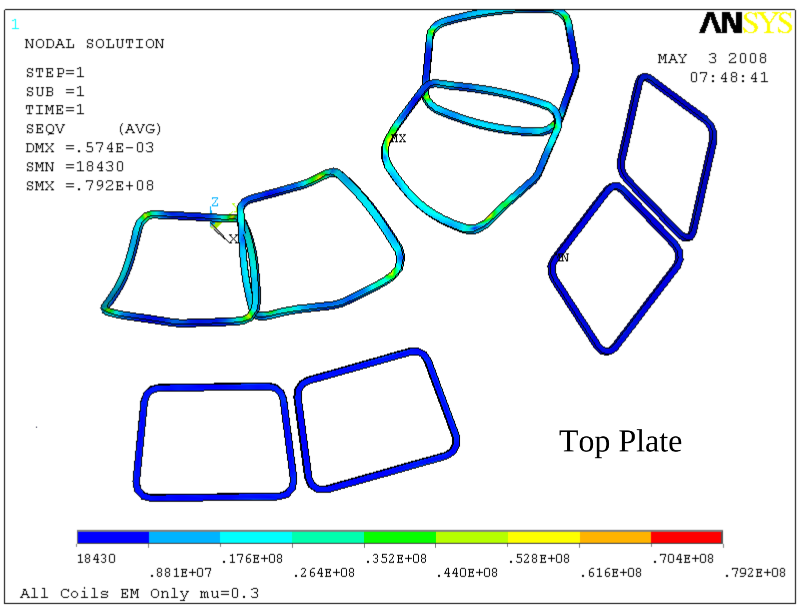
All Coils EM Only mu = 0.3

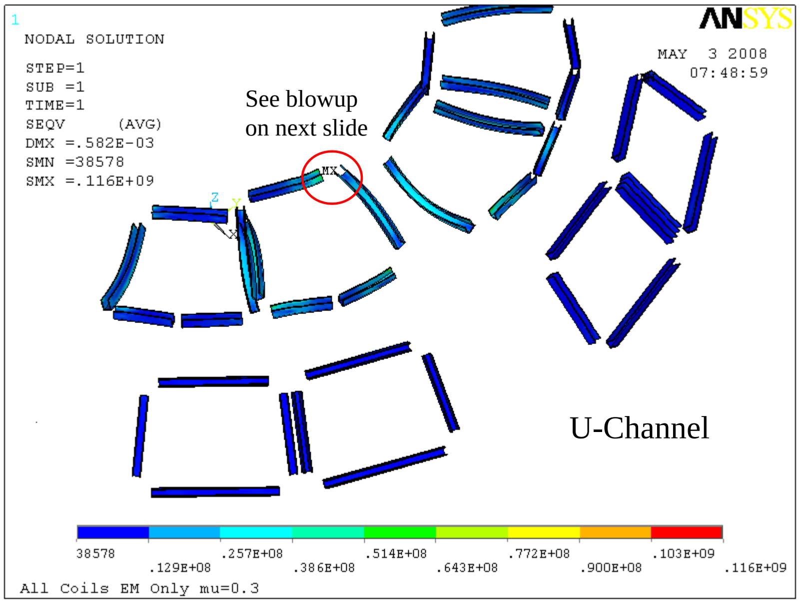
51

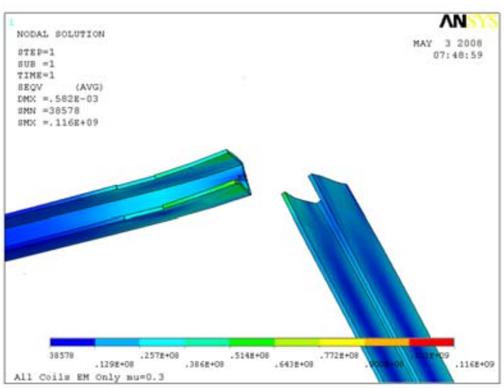


52

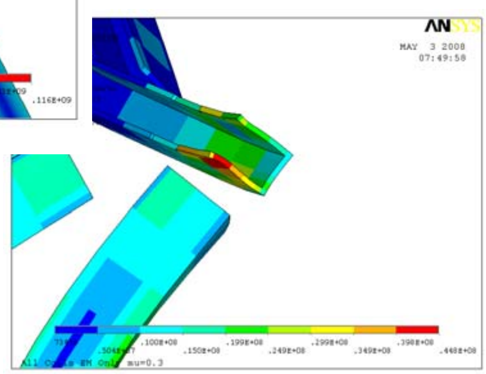

1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.569E-03
SMN =12567
SMX =.229E+08
ANSYS
MAY 3 2008
07:48:06
Conductor
12567
.256E+07
.511E+07
.765E+07
.102E+08
.127E+08
.153E+08
.178E+08
.204E+08
.229E+08
All Coils EM Only mu=0.3


1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.574E-03
SMN =18430
SMX =.792E+08
ANSYS
MAY 3 2008
07:48:41
Top Plate
18430
.881E+07
.176E+08
.264E+08
.352E+08
.440E+08
.528E+08
.616E+08
.704E+08
.792E+08
All Coils EM Only mu=0.3



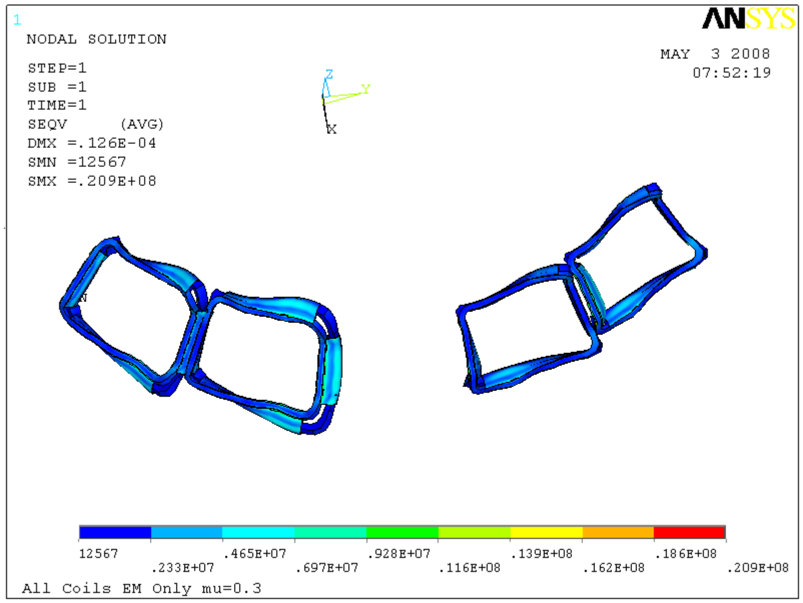


Peak Node Stress at Weld
In Coil 2 U-Channel
116 MPa



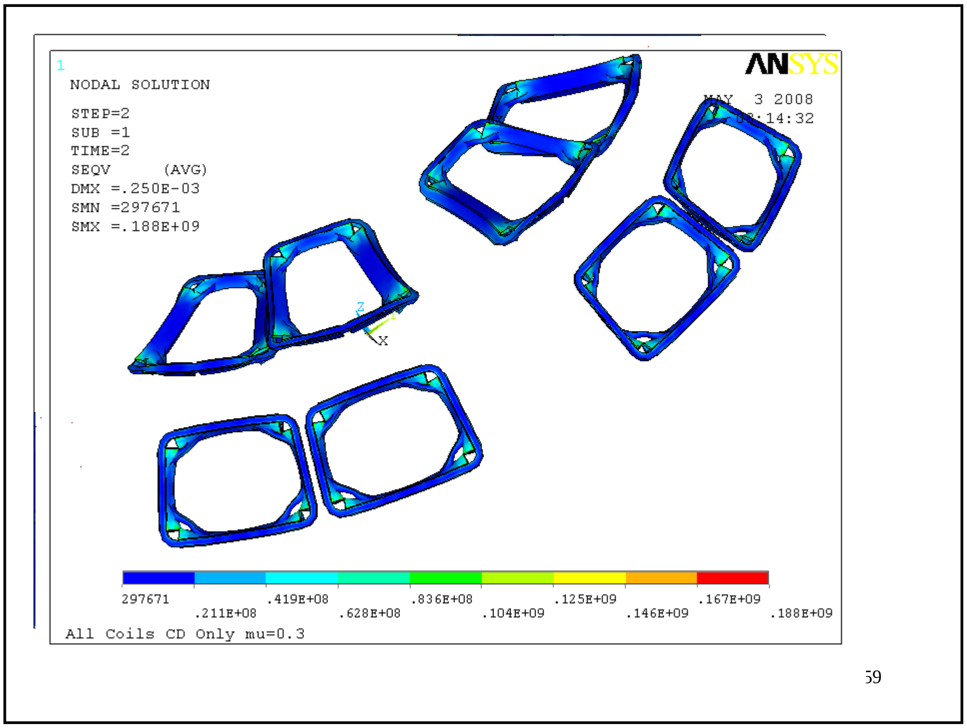
Element Average
Stresses
Much Lower 44.8 Mpa
(Same Location, Different View)

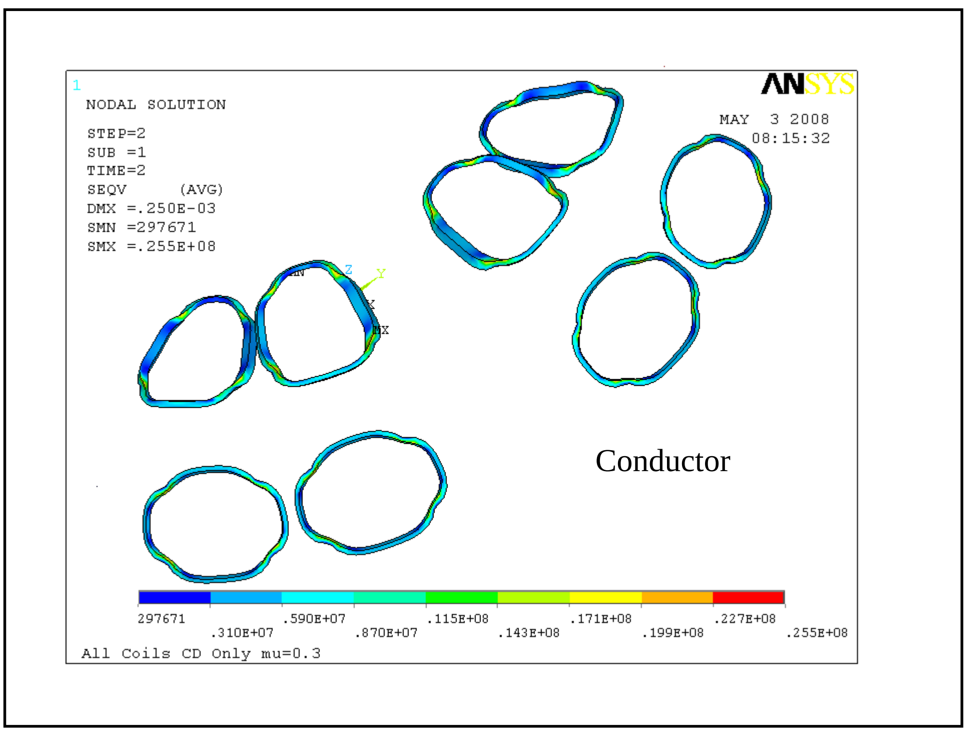
Outboard Coils EM Stresses Much Lower

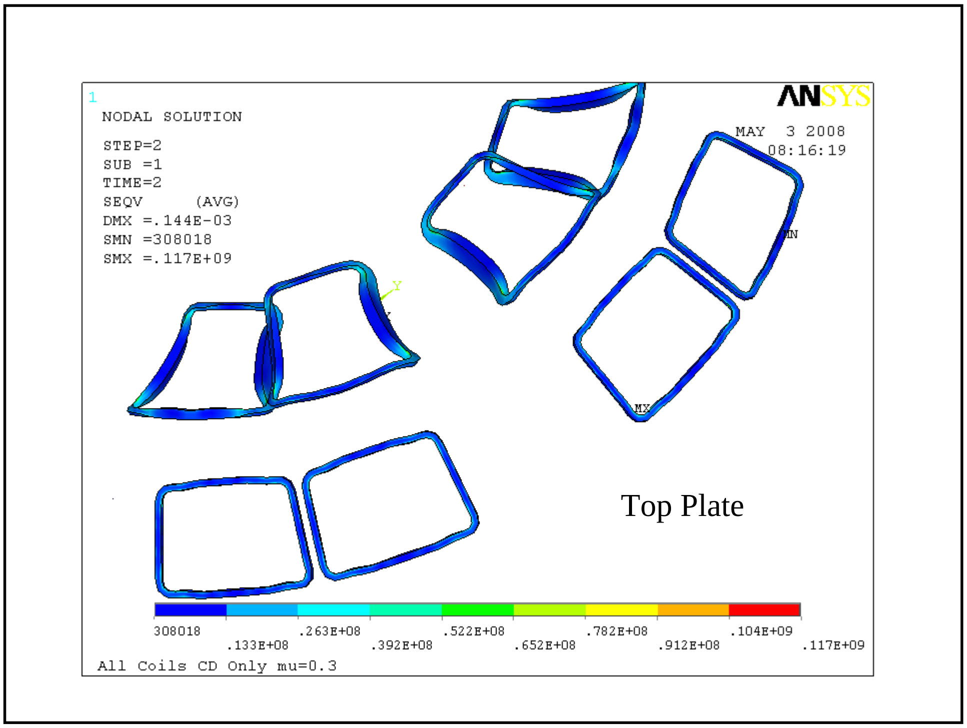


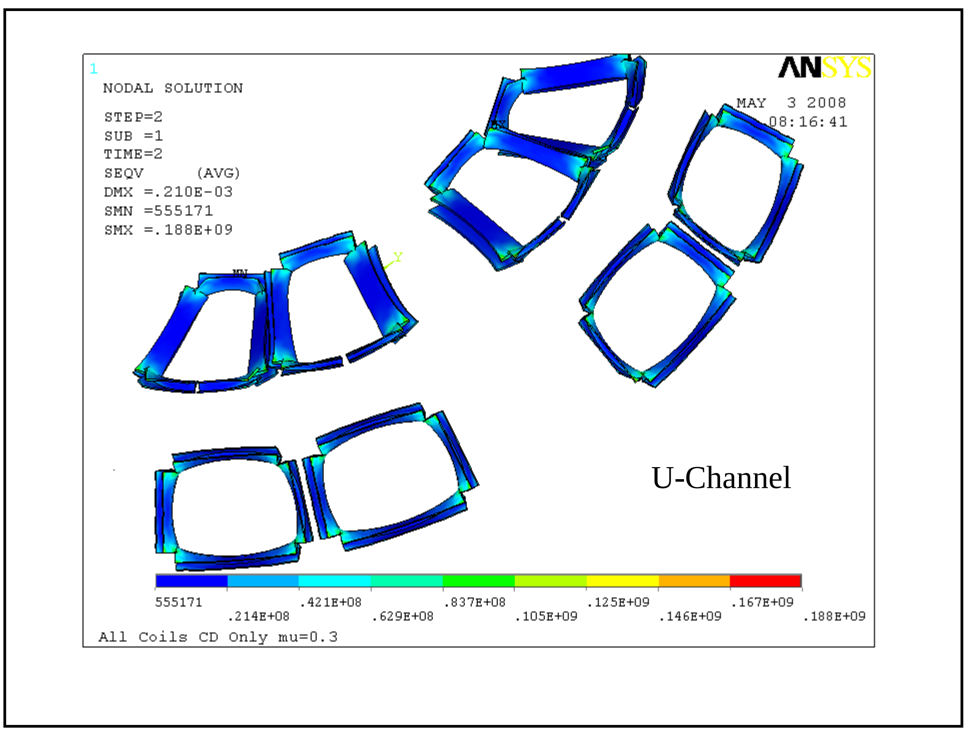
All Coils CD Only mu = 0.3

58


1
NODAL SOLUTION
STEP=2
SUB =1
TIME=2
SEQV (AVG)
DMX =.250E-03
SMN =297671
SMX =.188E+09
ANSYS
MAY 3 2008
08:14:32
297671
.211E+08
.419E+08
.628E+08
.836E+08
.104E+09
.125E+09
.146E+09
.167E+09
.188E+09
All Coils CD Only mu=0.3
59


1
NODAL SOLUTION
STEP=2
SUB =1
TIME=2
SEQV (AVG)
DMX =.250E-03
SMN =297671
SMX =.255E+08
ANSYS
MAY 3 2008
08:15:32
Conductor
297671
.310E+07
.590E+07
.870E+07
.115E+08
.143E+08
.171E+08
.199E+08
.227E+08
.255E+08
All Coils CD Only mu=0.3


1
NODAL SOLUTION
STEP=2
SUB =1
TIME=2
SEQV (AVG)
DMX =.144E-03
SMN =308018
SMX =.117E+09
ANSYS
MAY 3 2008
08:16:19
Top Plate
308018
.133E+08
.263E+08
.392E+08
.522E+08
.652E+08
.782E+08
.912E+08
.104E+09
.117E+09
All Coils CD Only mu=0.3


1
NODAL SOLUTION
STEP=2
SUB =1
TIME=2
SEQV (AVG)
DMX =.210E-03
SMN =555171
SMX =.188E+09
ANSYS
MAY 3 2008
08:16:41
U-Channel
555171
.214E+08
.421E+08
.629E+08
.837E+08
.105E+09
.125E+09
.146E+09
.167E+09
.188E+09
All Coils CD Only mu=0.3

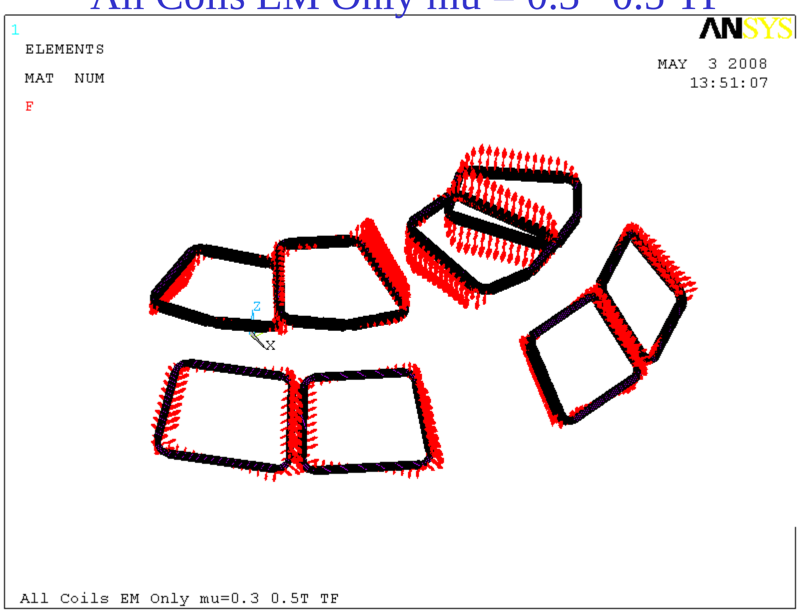
(Node) Stress Summary

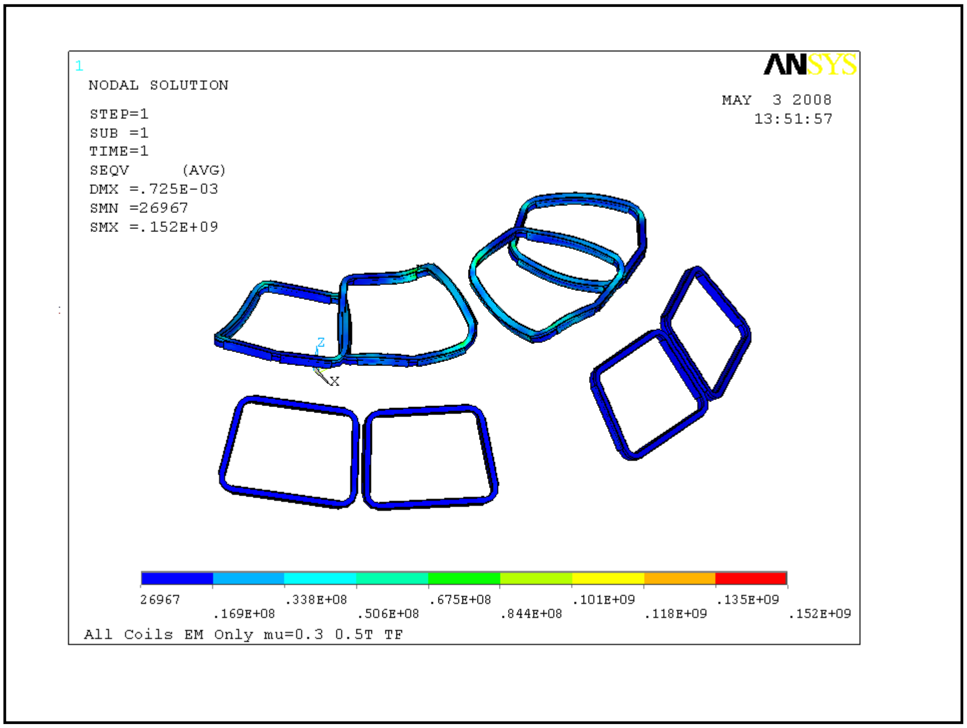
		Max Von Mises Stress Cond Composite	Copper	Insulation Plate		U Channel	
No Friction	mu=0.0						
Coil1	CD+EM	32.5	71.5	8.1	113.0	186.0	Mpa
		4.6	10.2	1.2	16.1	26.6	ksi
	EM Only	19.9	43.8	5.0	44.2	34.1	Mpa
		2.8	6.3	0.7	6.3	4.9	ksi
	CD Only	25.0	55.0	6.3	106.0	198.0	Mpa
		3.6	7.9	0.9	15.1	28.3	ksi
Friction	mu=0.3						
Coil1	CD+EM	27.4	60.3	6.9	120.0	196.0	Mpa
		3.9	8.6	1.0	17.1	28.0	ksi
	EM Only	23.1	50.8	5.8	72.7	54.9	Mpa
		3.3	7.3	0.8	10.4	7.8	ksi
	CD Only	24.5	53.9	6.1	96.3	174.0	Mpa
		3.5	7.7	0.9	13.8	24.9	ksi
Friction	mu=0.3						
All Coils	CD+EM	33.9	74.6	8.5	166.0	257.0	Mpa
		4.8	10.7	1.2	23.7	36.7	ksi
	EM Only	22.9	50.4	5.7	79.2	116.0	Mpa
		3.3	7.2	0.8	11.3	16.6	ksi
	CD Only	25.5	56.1	6.4	117.0	188.0	Mpa
		3.6	8.0	0.9	16.7	26.9	ksi

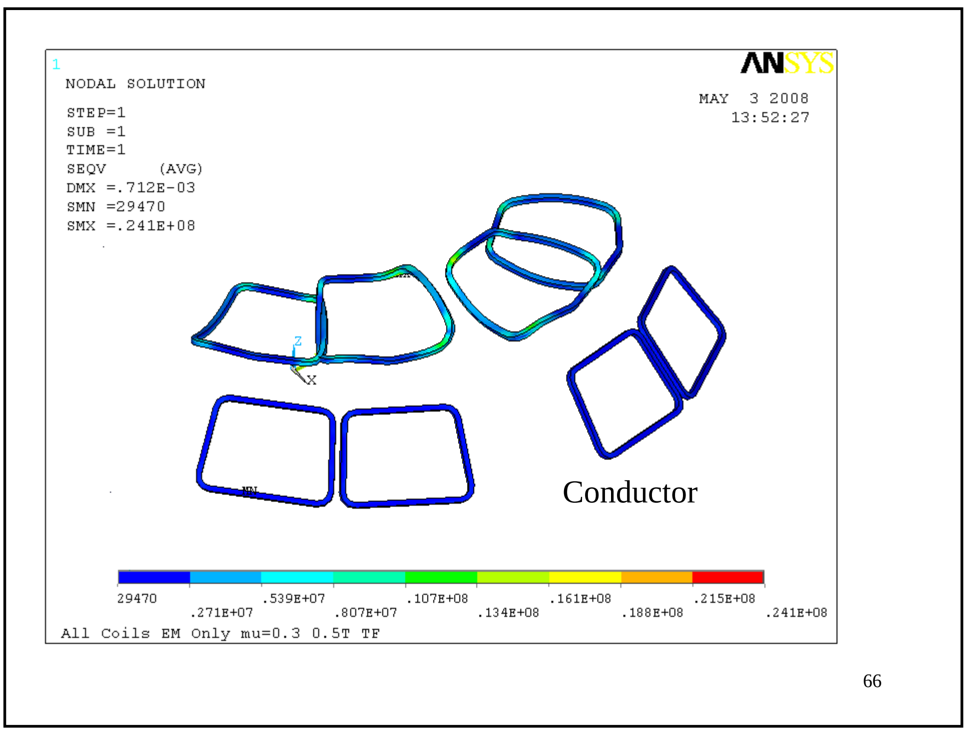
Element Average Stress at Max Location drops from 257 to **76.4 MPa**

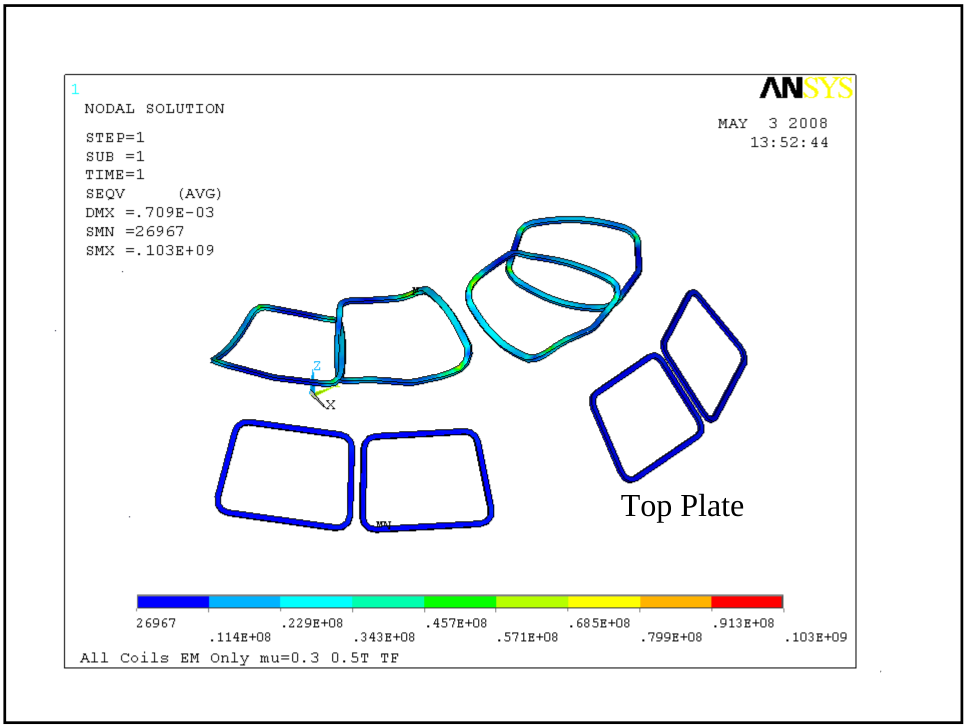
63

All Coils EM Only mu = 0.3   0.5 TF

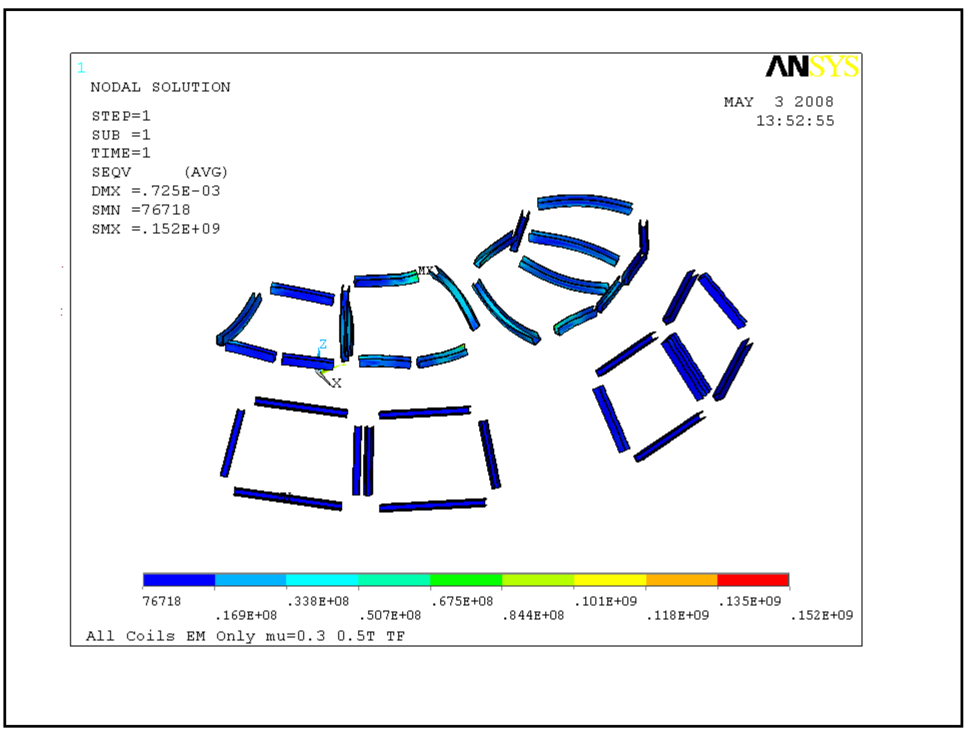



1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.725E-03
SMN =26967
SMX =.152E+09
ANSYS
MAY 3 2008
13:51:57
Z
X
26967
.169E+08
.338E+08
.506E+08
.675E+08
.844E+08
.101E+09
.118E+09
.135E+09
.152E+09
All Coils EM Only mu=0.3 0.5T TF


1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.712E-03
SMN =29470
SMX =.241E+08
ANSYS
MAY 3 2008
13:52:27
Z
X
Conductor
29470
.271E+07
.539E+07
.807E+07
.107E+08
.134E+08
.161E+08
.188E+08
.215E+08
.241E+08
All Coils EM Only mu=0.3 0.5T TF
66

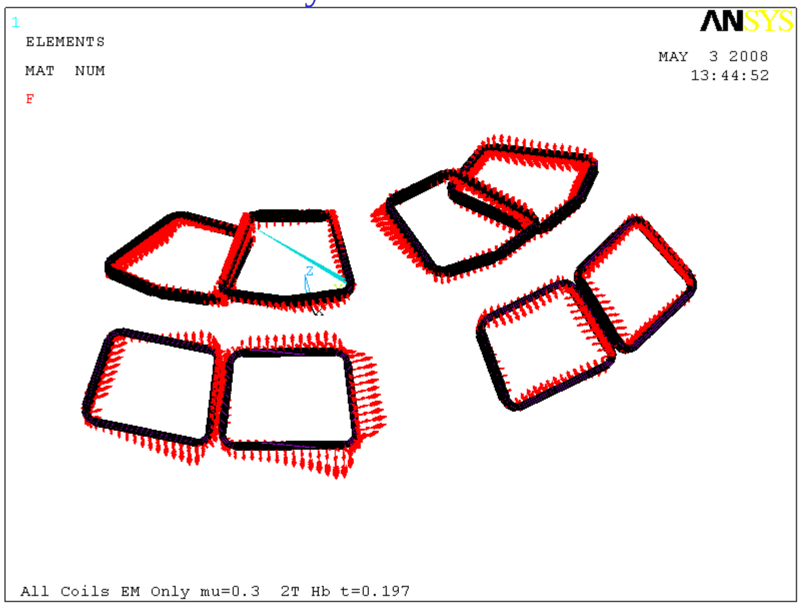


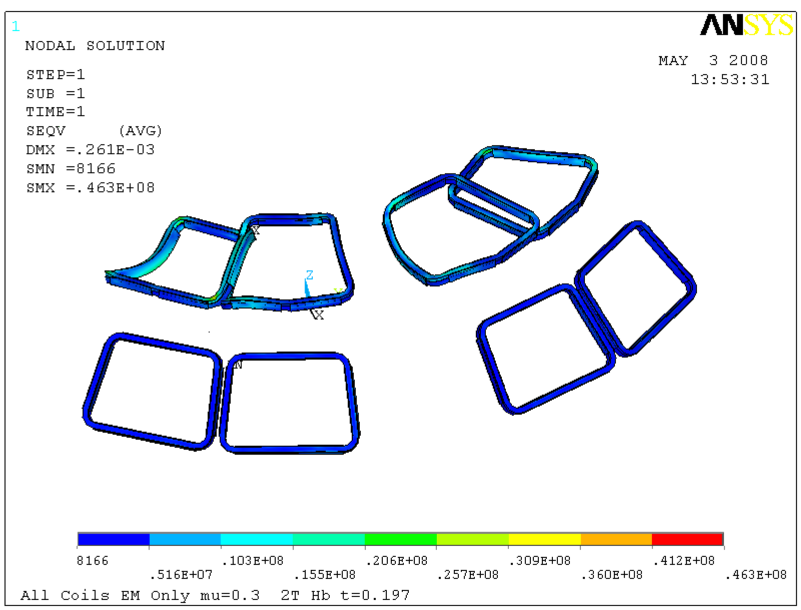
1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.709E-03
SMN =26967
SMX =.103E+09
ANSYS
MAY 3 2008
13:52:44
Z
X
Top Plate
26967
.114E+08
.229E+08
.343E+08
.457E+08
.571E+08
.685E+08
.799E+08
.913E+08
.103E+09
All Coils EM Only mu=0.3 0.5T TF

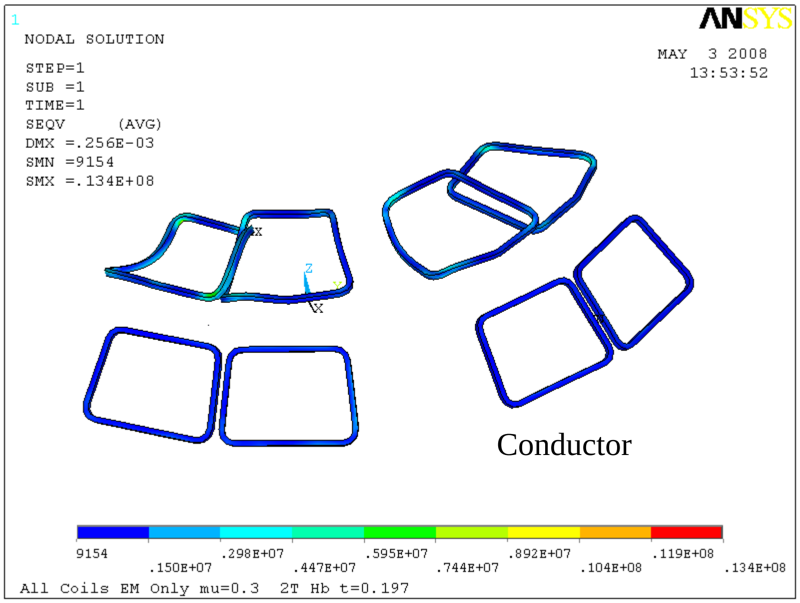


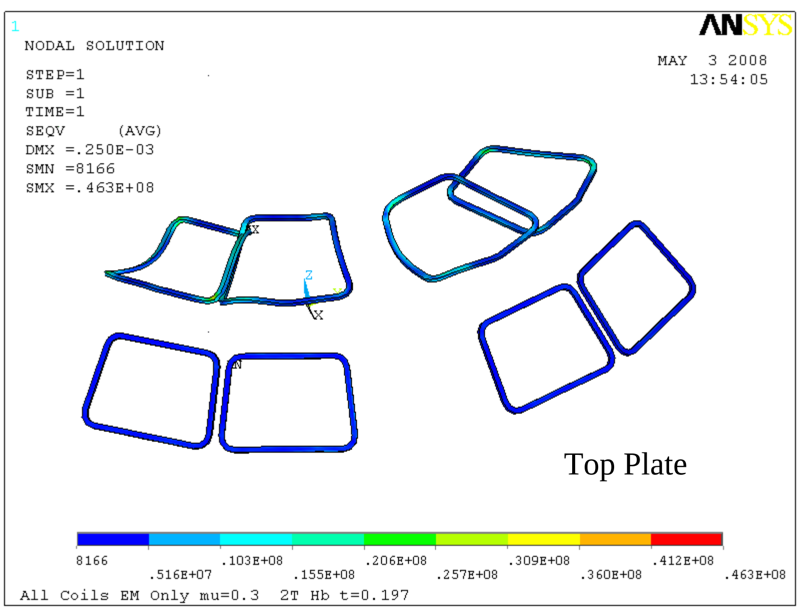
1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.725E-03
SMN =76718
SMX =.152E+09
ANSYS
MAY 3 2008
13:52:55
MX
Z
X
76718
.169E+08
.338E+08
.507E+08
.675E+08
.844E+08
.101E+09
.118E+09
.135E+09
.152E+09
All Coils EM Only mu=0.3 0.5T TF

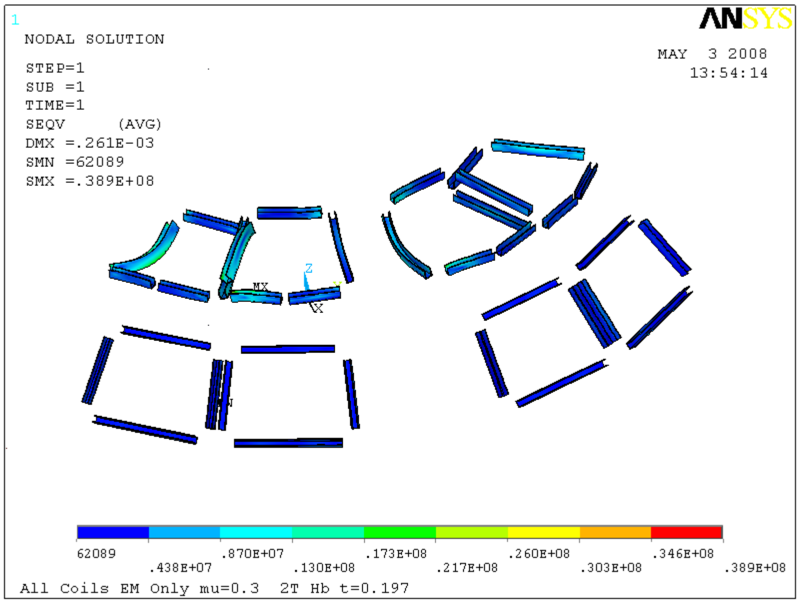
All Coils EM Only mu = 0.3   2T HB t=0.197s






NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.256E-03
SMN =9154
SMX =.134E+08
MAY 3 2008
13:53:52
Conductor
9154
.150E+07
.298E+07
.447E+07
.595E+07
.744E+07
.892E+07
.104E+08
.119E+08
.134E+08
All Coils EM Only mu=0.3 2T Hb t=0.197


NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.250E-03
SMN =8166
SMX =.463E+08
MAY 3 2008
13:54:05
Top Plate
8166
.516E+07
.103E+08
.155E+08
.206E+08
.257E+08
.309E+08
.360E+08
.412E+08
.463E+08
All Coils EM Only mu=0.3 2T Hb t=0.197



Comparison of EM Scenarios

Friction	mu=0.3	Max Von Mises Stress									
All Coils	EM Only	Cond Composite		Copper		Insulation Plate			U Channel		
iota=0.19		22.9		50.4		5.7		79.2		116.0	Mpa
			3.3		7.2		0.8		11.3	16.6	ksi
0.5T TF		24.1		53.0		6.0		103.0		152.0	Mpa
			3.4		7.6		0.9		14.7	21.7	ksi
2T HB t=0.197s		13.4		29.5		3.4		46.3		38.9	Mpa
			1.9		4.2		0.5		6.6	5.6	ksi

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