Electro-Mechanical Analysis of the Coil Structure for the CLAS12 Torus for the JLab 12GeV Upgrade

P. K. Ghoshal, O. Pastor, D. Kashy, W. Schneider, M. Wiseman, M. Zarecky, G. Young, C. Rode, L. Elouadrhiri, V. Burkert

***Abstract*— The torus magnet for the CLAS12 spectrometer is a 3.6 T superconducting magnet being designed and built as part of the Jefferson Lab 12 GeV Upgrade. The magnet consists of six coil case assemblies mounted to a cold central hub. The coil case assembly consists of an aluminum case and cover enclosing an epoxy vacuum impregnated coil pack. The coil pack consists of a 117 turn double-pancake winding wrapped with 2 layers of 0.635 mm thick copper cooling sheets. The coil case assembly is cooled by supercritical helium at 4.6 K. This report details the structural analysis of the coil case assembly and the assessment of the coil pack stresses. For the normal operation of the torus magnet, the coil case assembly was analyzed for cool down to 4.6 K and the Lorentz forces at normal operating current. In addition to the normal operating configuration, the coil case assembly was analyzed for Lorentz forces arising from coil misalignment and current imbalances. The allowable stress criteria for the magnet followed the approach of the ASME codes. Primary stresses were limited to the lesser of 2/3 times the yield strength or 1/3 times the ultimate tensile strength. Primary plus secondary stresses were limited to 3 times the primary stress allowable. The analysis was performed using ANSYS Maxwell to calculate the magneto-static loads and ANSYS Mechanical to calculate the stresses.**

***Index Terms*— SSC Cable, coil structure, load, shorting coil, force imbalance, conduction cooled, superconducting magnet, magnet quench protection, double pancake, torus coil.**

I. INTRODUCTION

One of the main challenges with the Jefferson Lab 12 GeV upgrade is the size and complexity of the torus magnet system that needs to be accommodated as a part of the CLAS12 spectrometer in HALL B [1-2]. As part of the design and engineering associated with this torus; it is important to establish analytically that a magnet of this size (see Fig. 1 and Fig. 2) meets all of its basic design requirements [3] as tabulated in TABLE I and that it meets the electrical coil design parameters in TABLE II.

TABLE I: TORUS COIL BASIC DRIVERS

Parameters	Requirement	Requirement Driver
Angular coverage	$\Theta = 5^0 - 40^0$	Phase-space coverage from exclusive reactions
	$\Delta Ø$ = 50-90% of 2π	
∫B.dl @ nominal current	2.83 T.m@ $\Theta = 5^0$	Momentum resolution for charged particles $\Delta p/p < 1\%$
	0.6-1.0 T.m@ $\Theta = 40^0$	
No obstruction sideways	Open access to field volume	Access for maintenance and field measurement
Uniformity of B-field in Ø	Limit distortions from toroidal field	Asymmetry in acceptance for positive/negative tracks

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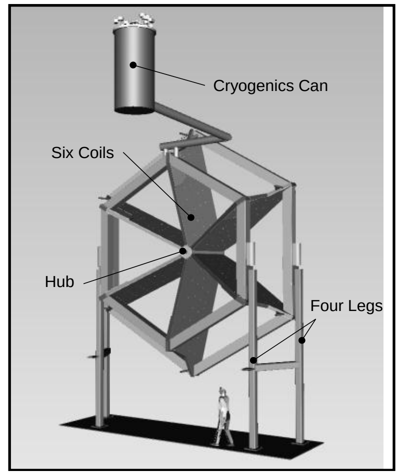

Fig. 1: CLAS12 torus magnet overview.

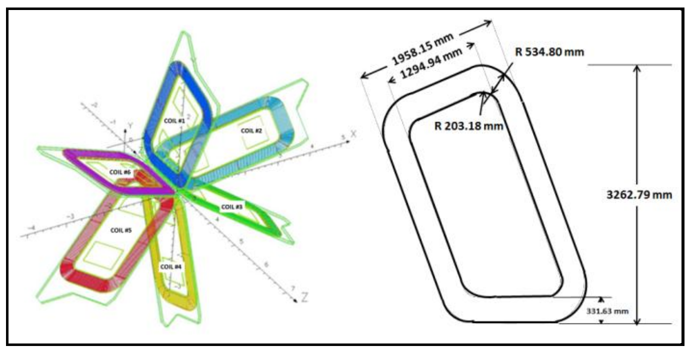

Fig. 2: Typical torus structure in FEA model and coil dimensions.

TABLE II: TORUS COIL PARAMETERS

Parameter	Unit	Value
Peak operating current	A	3770
Coil peak field	T	3.58
Operating temperature (nominal)	K	4.6
Number of coils	[ ]	6
Total number of turns/coil	[ ]	2 x 117
Superconducting cable dimensions	mm	2.5 x 20
NbTi strand bare diameter	mm	0.648
Number of strands in the cable	[ ]	36
Cu:Sc ratio (strand)	[ ]	1.8
Total stored energy	MJ	14.2
Inductance	H	2

The torus magnet for the CLAS12 spectrometer has features similar to the old torus magnet employed for the CLAS spectrometer. Both are indirectly cooled with supercritical helium and use aluminum coil cases in vacuum [4-5]. The CLAS12 magnet differs from earlier torus, first in that the conductor is copper stabilized versus aluminum and second in that the coils in the CLAS12 torus are mounted to a cold hub, whereas in the CLAS torus the coils were each independently connected to room temperature supports. The CLAS12 torus magnet consists of six superconducting coils forming the toroidal magnetic field, where the coils are mounted inside a common cryostat. These coils are made from double pancakes of 117 turns each and are vacuum impregnated with epoxy and placed into an aluminum case with indirect supercritical helium gas cooling to form the coil cold mass (CCM). The coil inside the CCM is in thermal communication with the cooling tubes through an OFHC shroud around the pancake at 4.6 K (nominal). Each CCM is surrounded by a nitrogen shield that is placed between the vacuum vessel walls and the coil cases. All six coils are electrically connected in series. The coils are built using already fabricated SSC cable (see parameters in TABLE III), which are based on a main dipole outer layer with 2x18 strands with keystone dimensions of 1.053 mm x 1.259 mm x 11.68 mm, and further stabilized with an extruded OFHC copper channel as shown in Fig. 3.

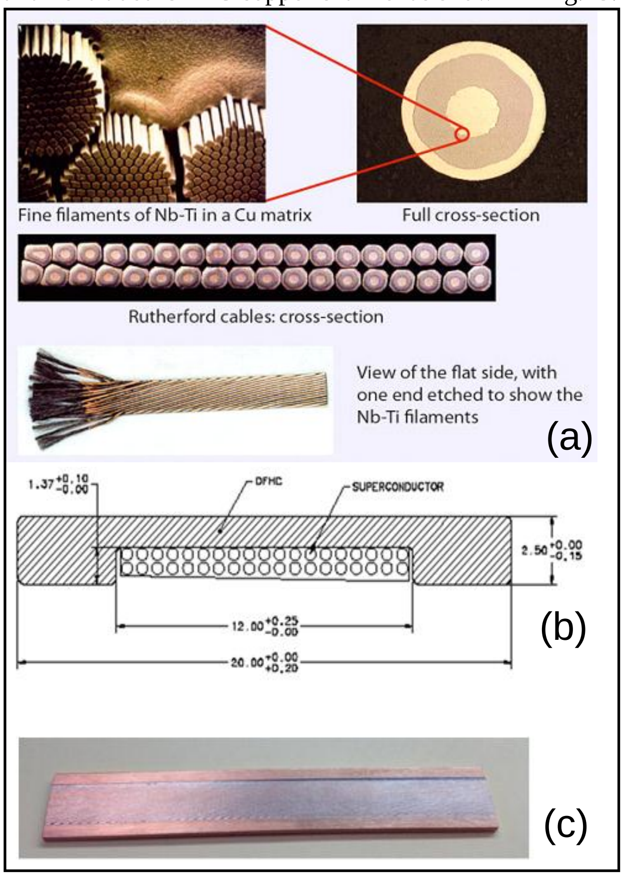

Fig. 3: (a) SSC outer cable, (b) conductor dimension for torus coil, (c) Soldered SSC cable in copper channel – torus conductor as manufactured.

TABLE III: TORUS CONDUCTOR SPECIFICATION

Parameter	**Details**
Rutherford type of cable (Superconductor)	NbTi
Conductor material (NbTi + Cu)	Cu-(NbTi) in Cu Channel
Number of strands in the cable	36
Number of NbTi filaments in each strand	4600
Strand bare diameter (mm)	0.648
Copper to non-Copper ratio	1.8
Twist pitch (mm)	**15**
Conductor size (bare) (mm x mm)	20 x 2.5
Conductor size (insulated) (mm x mm)	20.2 x 2.7
Short sample current at 4.22 K, 5 T (kA)	11
RRR Cu (Cu-NbTi) – Strand	100
RRR Cu Stabilizer (design purpose)	200 (70)

II. Design of Conductor Insulation and Stability

The 2.5 mm x 20 mm conductor design with OFHC stabilizer is insulated employing two layers of 0.076 mm thick E-glass, each having >40% overlap for the turn-to-turn insulation, with an additional 0.38 mm of G10 insulation between the two pancakes. For the turn to ground insulation between the turn to the copper cooling shroud, the following recipe is used – 2 layers of 0.076 mm E-Glass + 2 layers of 0.076 mm Kapton^{TM} + 2 layers of 0.178 mm E-glass cloth as shown in Fig. 4.

The breakdown voltage was calculated [6-8] and further scaled by applying a factor of safety [9] (a) turn to turn, (b) pancake to pancake, and (c) line (turn) to ground (GND), as shown in TABLE IV, in order to design the overall insulation breakdown voltage. This demonstrates the coil breakdown voltage is well within the expected voltages in the event of a quench.

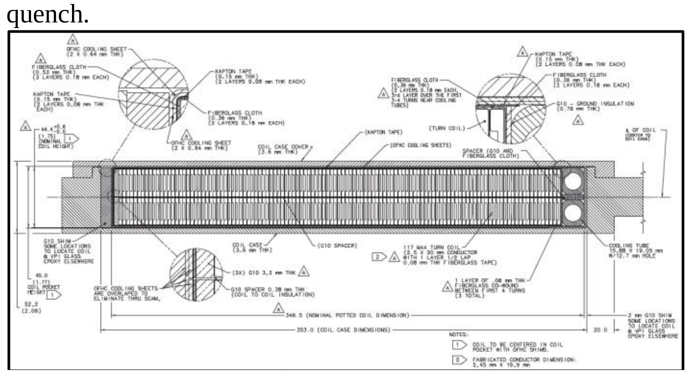

Fig. 4: Construction detail for the torus coils, showing the conduction cooling mechanism and the coil winding details.

With the above configuration of the magnet at full operating current, we estimated a torus conductor stability of 47 mJ of Minimum Quench Energy (MQE) at 4.9 K and 3770 A compared to ~56 mJ at 4.7 K and 3550 A under adiabatic conditions [10].

TABLE IV: TORUS COIL ELECTRICAL INSULATION BREAKDOWN VOLTAGE

Material	**E glass**		**Insulation G10**	**Kapton**		**E glass**	
Insulation Region	**# of layers**	**Thickness / layer (mm)**	**Thickness / layer (mm)**	**# of layers**	**Thickness / layer (mm)**	**# of layers**	**Thickness / layer (mm)**
Turn to Turn Insulation (T-T)	4	0.0762	0	0	0	0	0
Turn to Turn Insulation (P-P)	4	0.0762	0.38	0	0	0	0
Turn to GND	2	0.0762	0	2	0.0762	2	0.1778

Location	**Turn to Turn**	**P-P**	**Turn to GND**	**Remarks**
Breakdown Voltage (kV)	7.01	15.75 kV	21.74 kV	**Calculated**
Factor of safety	10	10	5	**Safety**
Breakdown voltage (kV)	***0.7***	***1.58***	***2.17***	**Designed**
Torus Magnet 12GeV (V)_expected	<10	<120	<250 (500*)	***Expected***

III. Electromagnetic Analysis

The magnet was analyzed operating at full current (3770 A). The electromagnetic (EM) design was made in order to achieve a temperature margin (relative to the generation temperature) of >1.5 K. The coil temperature distribution shown in Fig. 5 suggests that the expected temperature on the second pass of supercritical helium in the cooling tube is in thermal communication with the second pancake at about 4.9 K at the peak field region (compared to 4.7 K in the first pancake). Thermal analysis was performed on the coil pack with full contact on the inner and outer coil surfaces. Multiple cooling sheet thicknesses from 0.5 mm to 1.5 mm were analyzed. The thermal results shown in Fig. 5 are for a cooling sheet thickness of 1.0 mm. The thermal analysis assumes a heat input of 13 W, which is 3 times the calculated nominal heat input per coil. The results of this analysis indicate a temperature margin of 1.9 K at the peak field location.

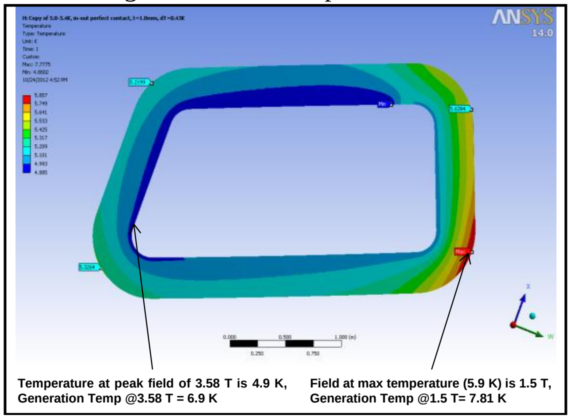

Fig. 5: Temperature distribution in the torus coil (second pancake).

The FMEA [11] suggests that the magnet operation be evaluated at an elevated temperature of about 0.40 mK, attributed to temperature perturbation in the peak field region, along with the following other failure modes:

Case #1: Operating temperature (T_{op}) 4.7 K (1st pancake), B_{max}
Case #2: T_{op}=4.9 K (2nd pancake), B_{max}
Case #3: T_{op} =5.3 K (2nd pancake), B_{max} (FMEA)
Case #4: T_{op} =5.3 K (2nd pancake), B_{max} (2 lost strands)
Case #5: T_{op} =5.9 K (2nd pancake), B = 1.5 T (lead exit)

The temperature margin and the short sample performance (SSP) for the cases studied are given in TABLE V meets the temperature margin of >1.5 K.

TABLE V: TORUS MAGNET MARGIN AND SSP

Case	B_{max} (T)	Ic (at B_{max}) (A) at T_{op}	I_{op} (A)	% SSP	T_{op} (K)	T_c (K)	T_g(K)	ΔT (K) = T_g(K)-T_{op}(K)
1	3.58	12076	3770	31.22	4.7	7.86	6.87	2.17
2	3.58	11332		33.27	4.9	7.86	6.88	1.98
3	3.58	9836		38.33	5.3	7.86	6.88	1.58
4	3.58	9285		40.6	5.3	7.86	6.82	1.52
5	1.5	11467		32.88	5.9	8.75	7.81	1.91

Where, T_C(K) *is the critical temperature of Superconductor at* B_{max} *in K and* T_g(K) *is the generation temperature in K.*

The selection of the conductor and the magnet design was evaluated under the stability criteria [10] given in TABLE VI (except the Stekly criteria, because this is not a wet magnet) before beginning the actual winding of torus magnet coils.

A comparison is also drawn with the old CLAS torus in evaluating the present torus magnet design. The results in TABLE VII show that RRR <120 significantly reduces the MQE at an elevated temperature under adiabatic conditions. The stability of the splice and the interconnecting leads are also carried out independently to make it quench tolerant.

Various quench scenarios were analyzed and in the worst case where one coil quenches and dumps its energy into the dump resistor, the magnet is self-protected, with a hot spot temperature < 60 K and < 75 K for the coil alone without the aluminum coil case and a maximum voltage across the magnet of <500 V.

TABLE VI: TORUS MAGNET STABILTY

Operating Scenario (Hall B Torus)		
Conductor temperature_T_{op} (K)	5.3	K
Maximum field in the coil_B_{max}(T)	3.58	T
Operating current_ I_{op} (A)	3770	A
Ic (at B_{max}) (A) at T_{op}	9836	
Summary		
Short sample performance (SSP)	< 40%	38.33%
Stable for T_{cs} value (Margin)	Yes	>1.5 K
Stable for Beta (Adiabatic stability)	Yes	
Adiabatic flux jump stability	Yes	
Dynamic stability	Yes	
Adiabatic self-field stability	Yes	
Stable in term of twist pitch	Yes	
Stable for finite element size	Yes	

TABLE VII: MQE COMPARISON

Parameters	Clas 6 Magnet	Reference Design (Wilson cals.)	JLab Design (12 GeV Torus)		
RRR	1200	200	120	120	70
Stabilizer material	Aluminum	Cu (OHFC)	Cu (OHFC)	Cu (OHFC)	Cu (OHFC)
Temperature (K)	4.7	4.7	4.7	4.9	5.3
MQE with NO cooling (mJ)	50	58	54	47	35

IV. Mechanical Analysis of Coil and Coil Case

The coil case integrated stress analysis was carried out with each coil epoxy vacuum impregnated inside an aluminum coil case. On the outside of the coil are two layers of 0.635 mm thick copper that provide cooling from the 4.6 K helium cooling tubes to the conductor and the coil case. The outer thickness of the coil case and cover is 3.6 mm thick aluminum. The 80 K thermal shield is 8 mm from the coil case surface. The stainless steel vacuum jacket is 12 mm from the heat shield. A cross section of the cryostat is shown in Fig. 3. The following load cases were studied:

a. *Cool Down* – The stresses in the coil and the case due to cooling from 395 K to 4 K were analyzed. By beginning the analysis at 395 K, the stresses due to epoxy curing at 122 C are also included. The results from this analysis suggest that the coils are preloaded (compression) at room temperature. All stresses due to cool down are secondary stresses (self-limiting).

b. *Normal Operation* – The analysis includes thermal stresses from cooling (395 K to 4 K), Lorentz forces due to the normal operating conditions, and 110% gravity loading - static (to include earthquake loads). The normal operation analysis assumes perfect coil symmetry with no out of plane forces due to EM. The stresses from this load case are both primary (EM and gravity) and secondary (cool down).

c. *Current Imbalance* – The analysis includes thermal stresses from cooling (395 K to 4 K), Lorentz forces due to a current imbalance condition, and 110% gravity loading. The current imbalance includes Lorentz forces from a 10% reduction of current (equivalent to losing ~12 turns in each pancake) in a single coil. This current imbalance generates a ~70 kN out of plane force on the coil. This analysis is also used to verify stresses due to out of plane EM forces resulting from imperfect coil locations. The maximum out of plane force due to imperfect coil locations is ~7 kN.

d. *Quench Fault Analysis* – The analysis includes thermal stresses from cooling (395 K to 4 K), Lorentz forces due to a quench resulting from a single coil to ground short, and 110% gravity loading. The out of plane load generated by this load case is ~129 kN.

The allowable stress criteria for the magnet cold mass followed the approach of the ASME codes. Primary stresses were limited to the lesser of 2/3 times the yield strength or 1/3 times the ultimate tensile strength. Primary stresses, such as Lorentz forces and gravity loads, include any normal stress or shear stress, and were imposed to satisfy the laws of equilibrium. Secondary stresses (e.g. thermal stress) are self-limiting and limited to local yielding and distortions not seen as a cause of failure.

A single coil analysis is performed to assess the stress in the aluminum case/cover and the coil with the coil case, cover, along with the cold beams, with no coil bonding to the coil case as represented in Fig. 6.

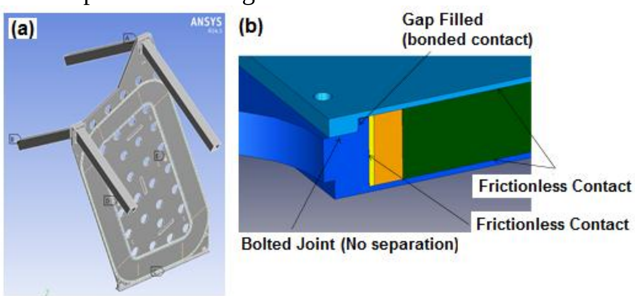

Fig. 6: Coil and coil case model (a) overall model and (b) case and cover

Coil pack hoop stresses are calculated as shown in Fig. 7 due to the following – (a) Cool down applies a compressive hoop stress of about 173 MPa, (b) EM forces load the coil pack with a tensile hoop stress of about 63 MPa, and (c) the energized magnet at 4 K remains in compression at 134 MPa.

A summary of the stresses from the analysis is shown in Table VIII. A local stress discontinuity exists in the case that exceeds that allowable for the quench fault case. The stress is below yield and is highly localized; therefore, it would not result in a structural failure of the case.

TABLE VIII: TORUS STRESS SUMMARY

Component	Cool Down		Normal Operation		Current Imbalance		Quench Fault		Stress Category (Limit)
	Peak	General	Peak	General	Peak	General	Peak	General	
Case									
EM + Gravity	-	-	110	50	140	70	350	30	Primary (Sa=184MPa)
Cool Down + EM + Gravity	340	250	370	290	380	300	374	250	Primary + Secondary (3*Sa=552MPa)
Cover									
EM + Gravity	-	-	130	35	130	45	60	30	Primary (Sa=184MPa)
Cool Down + EM + Gravity	410	300	430	350	430	270	410	200	Primary + Secondary (3*Sa=552MPa)

Coil Pack Component	Secondary Stress Allowable (MPa)	Max Secondary Stress	Primary Stress Allowable (MPa)	Max Primary Stress (MPa)	Max Primary + Secondary Stress Allowable (MPa)	Max Primary + Secondary Stress (MPa)
Epoxy/Glass/Conductor	+/-282	-117	+/-94	-30	+/-282	-120
Conductor Stress	+/-282	-186	+/-94	68	+/-282	-181
Bond Stress	45	22 (General) 37 (Local)	15	5 (General) 13 (Local)	45	20 (General) 40 (Local)

The eddy current analysis was also performed to mitigate the thermal shield stress and forces [12] taking into account the worst case discharge rate using ANSYS Maxwell [13] and subsequently applied to the structural model in ANSYS mechanical [14] to calculate stresses and deflections.

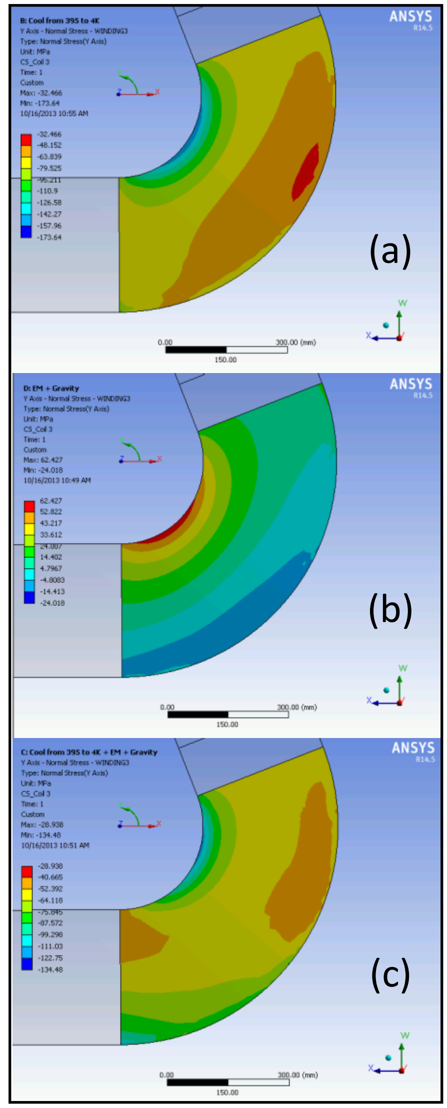

Fig. 7: Coil pack hoop stress in MPa – (a) Cool down, (b) Electromagnetic loading, and (c) magnet energized at 4K.

V. CONCLUSION

1. The CLAS12 torus magnet design has a comparable MQE with the old CLAS torus magnet.
2. The conductor in the magnet has a temperature margin of >1.5 K considering two lost strands in the SSC cable.
3. The electrical insulation recipe employed for the coil winding and the line to ground has an adequate margin of >4 times the peak voltage expected in an event of a quench.
4. The conductor used for the magnet is generally stable with respect to the criteria shown in TABLE VI.
5. The cold mass has been analyzed for cool down, normal operation, and two fault conditions. The results of the analysis show stresses that are below the allowable stresses as shown in TABLE VIII.

ACKNOWLEDGMENT

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