Analysis of Quench and Scenario of Magnet temperature Margin

Hall D Solenoid Magnet

Reference - JLab_HALL D

(Superconducting Magnet Solenoid)

May 21st 2013

Probir K Ghoshal & Renuka Rajput-Ghoshal

Engineering Division, Jlab

Distribution list:

William Schneider, Glenn Young, Claus Rode, George Biallas, Timothy Whitlatch, Jonathan Creel, Rolf Ent, Ahmed Sidi-Yekhlef, Venkatarao (Rao) Ganni, Eugene Chudakov, Patrizia Rossi, David Kashy, Will Oren

Table of revisions

Version	Subject of the modifications	Date
A	First Report	May 21 2013

Contents

Background

Hall D solenoid Quench - the magnet during operation, an occurrence of quench that lead to revisit the risk analysis on the magnet. This is undertaken to look into the possible scenarios of quench and mitigate them before energizing the magnet back to full operating current or to a restricted operating current.

The magnetic field profile obtained using Ansys/Maxwell™ (FEA tool) shows a discrepancy compared with Vector field (Opera™). This has been experienced a number of times in the past and Ansys/Maxwell converges nicely with fine meshing. Field analysis employing Opera™ provides with better results because the conductors are assumed to be a Biot Savart Conductor and not a meshed conductor. Secondly, analyzing the field over the conductor that needed to be evaluated should be based on the Nodal Integration over the volume/cross section of the conductor employing any FEA tool to have a nice convergence of the evaluating parameter. With Opera analysis with FEA and Bio Savart conductor, the differences are experienced as shown in the Coil only configuration for Hall D magnet in Figure 1 & Figure 2. The field data from Vector field (Opera™) agrees reasonably well (<7%) with the field profile in the SLAC calculation in 1971 (Alcron et al, using program NUTCRACKER).

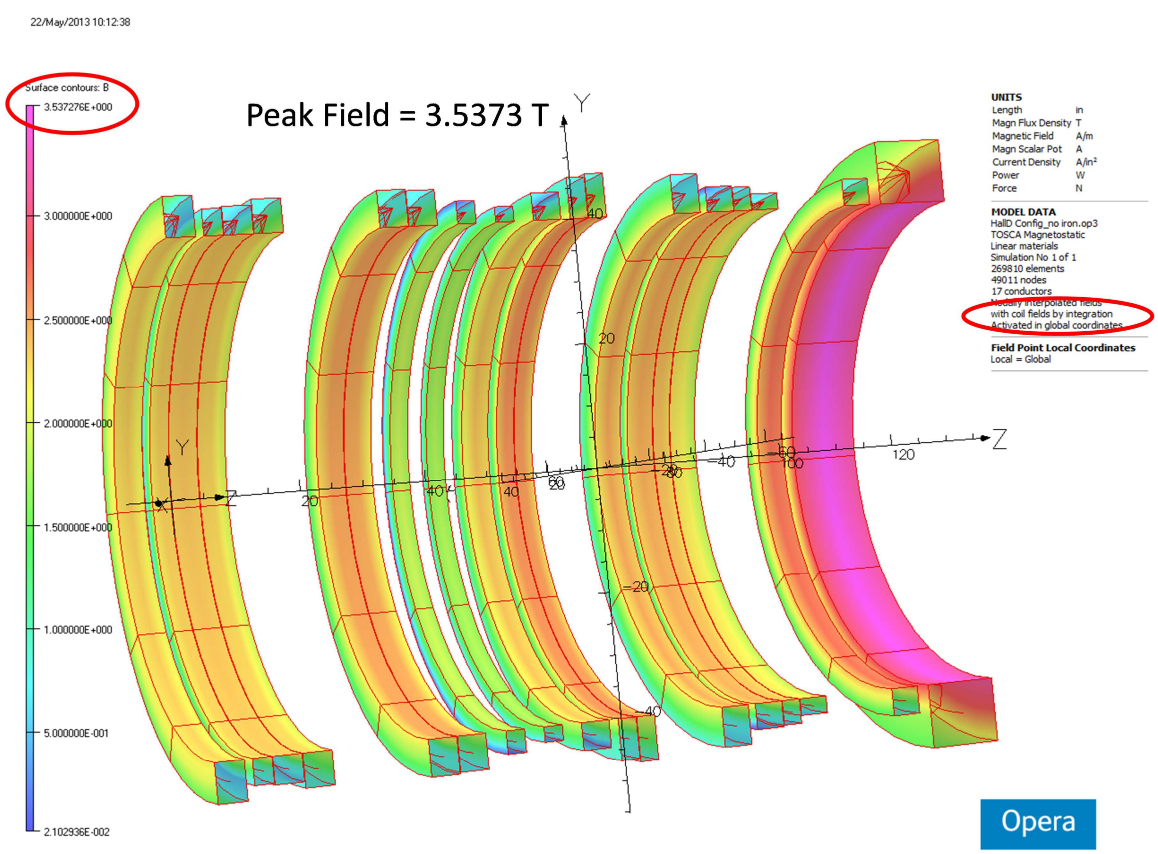

Figure 1- VF (Opera™) using field integral value

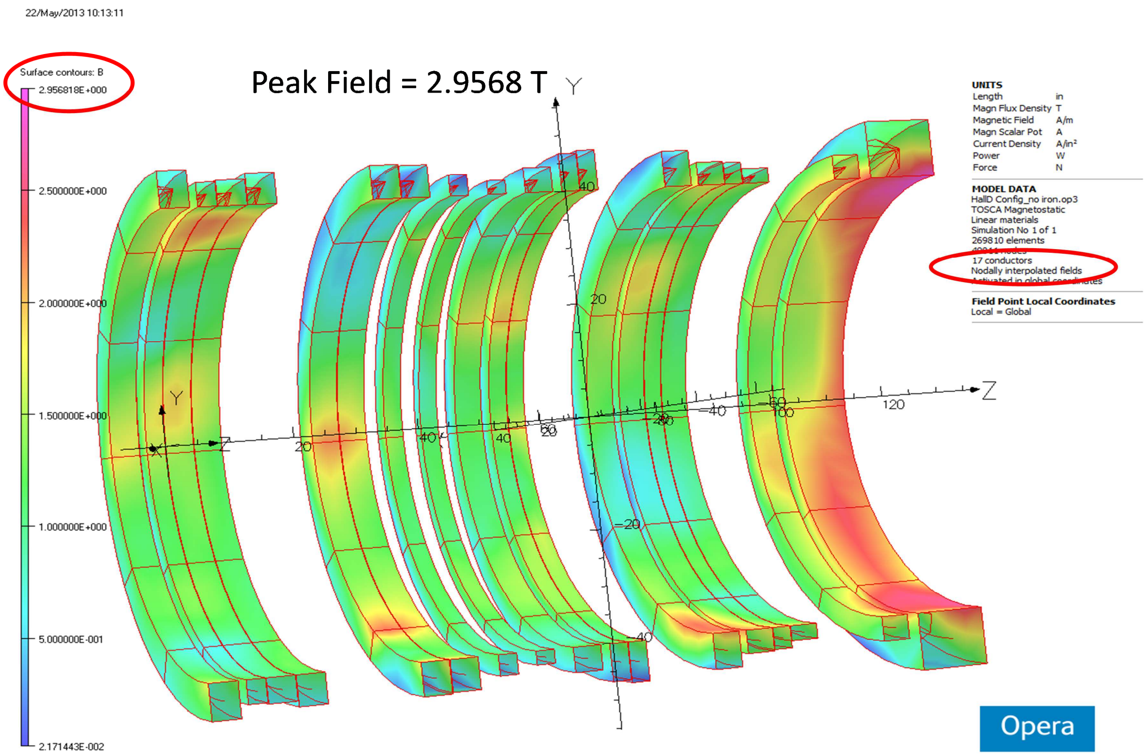

Figure 2- VF (Opera™) using Nodal interpolated field value

Motivation

The magnet was run to full field as defined to 1500 A in steps and parked. Following the success the magnet was ramped down to 0 A, subsequently ramped up to 1460 A in steps (intermittently parked the magnet at 800A holding on the Power supply) before the magnet quenched in coil 1A and Coil 1B.

Discussions

The possible reasons for the magnet to quench could be many but we can retire a few significant risks for the magnet performance upon looking into the magnet that was built and successfully run in the past at SLAC at 1600 A (from the system run log) back in 1970's and 80's. The comparisons are made with respect to the SLAC magnet configuration (Present Hall D magnet configuration is been modified from SLAC configuration by repositioning Coil 1-set). The quench plots obtained are shown in Figure 3& Figure 4. The distinctly shows the coil 1A and Coil 1B section of the Coil#1 have voltage across. Therefor the focus is primarily on Coil 1A and 1B.

1. The maximum operating current
2. The operating temperature and stability
3. Operating pressure and stability
4. The temperature margin
5. The forces and supports
6. The Conductor/splice support and connections with other sections
7. MQE
8. The quench/stability in other sections of the magnet

9. Any variation to the conductor performance (in terms of % degradation)

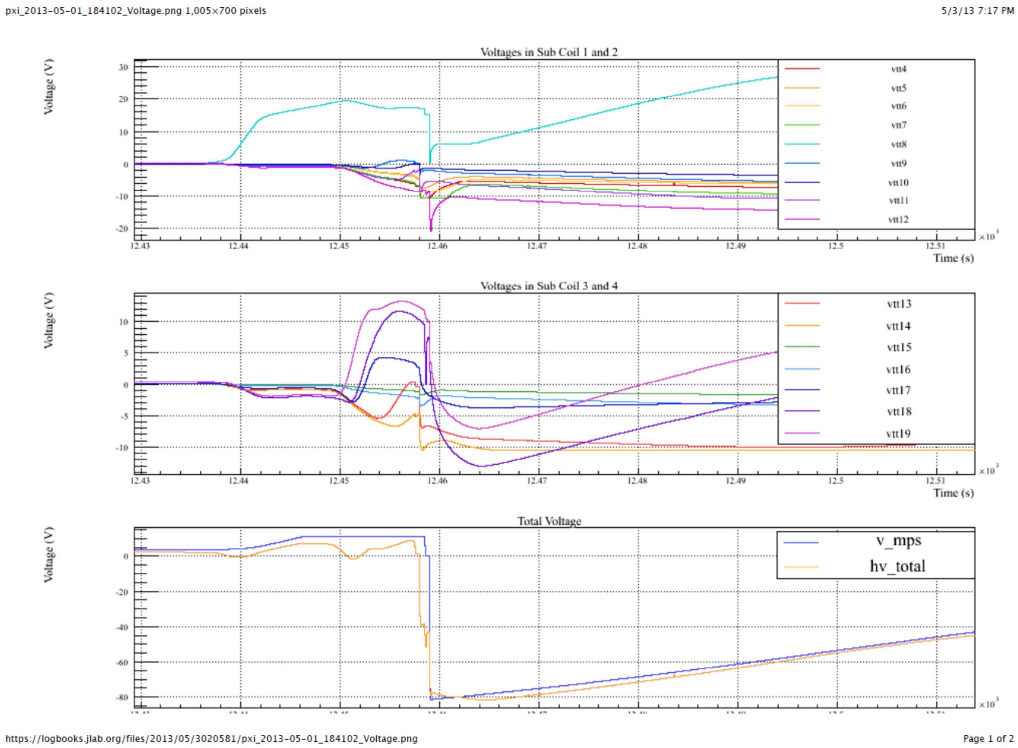

Figure 3- Plots showing the voltage across coils (blue line is the one seems to have taken off first Coil 1A+Coil1B)

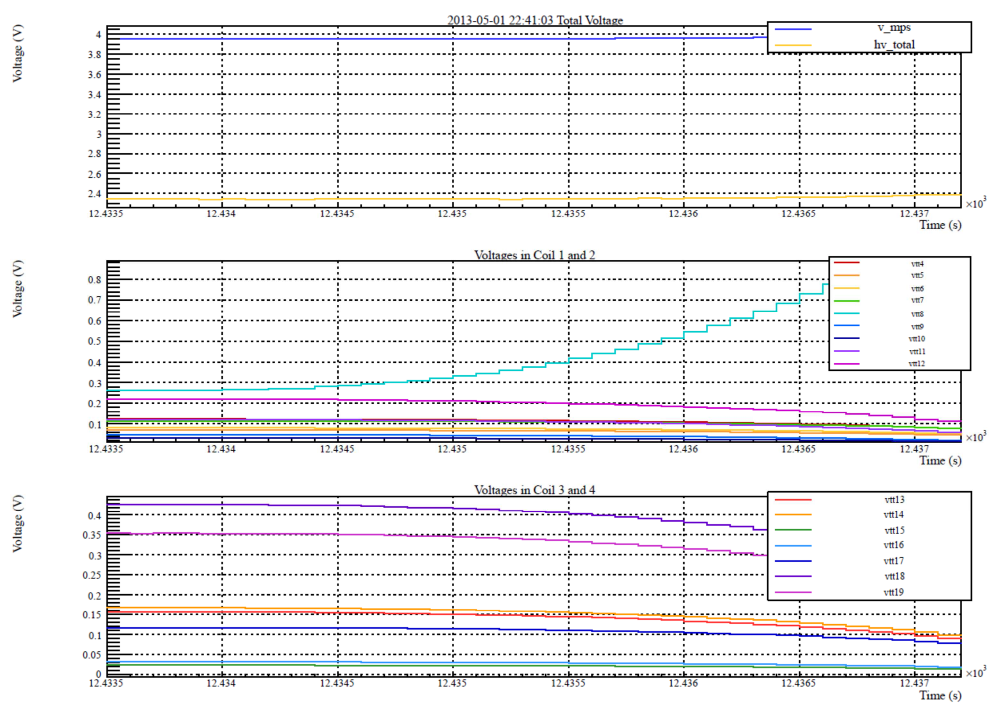

Figure 4- Plots Zoomed in view of the plot in Figure 3 (Section Coil #1)

Revisiting the conductor used in 1970-80, SLAC magnet [1] –
Primarily two type of copper backed NbTi conductor was used as shown in **Figure 5**.

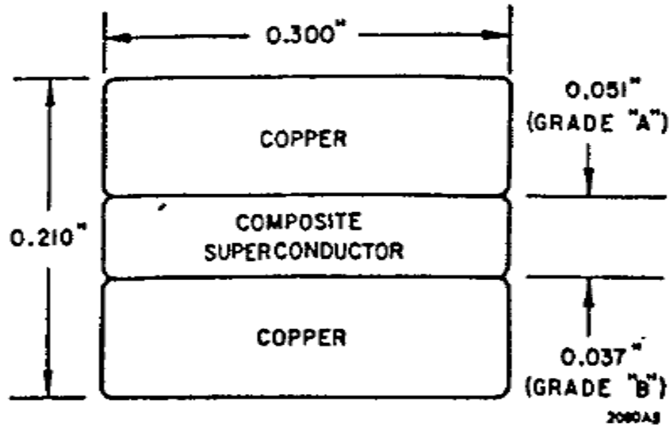

Figure 5- Conductor configuration from Alcorn et al, SLAC

The B-I characteristic for both Grade A and Grade B conductors are required to the following specifications-

Grade A - at 4.2 K and 5 T (50 kG), I_c=2.0 kA
Grade B - at 4.2 K and 4 T (40 kG), I_c=1.6 k

The measured data for the above conductors varied with reasonable success (40 years back) between the specs and the best of the samples as shown in Table 1 and Figure 6.

[1] The SLAC Two meter diameter, 25 kG, Superconducting solenoid – UAMH BINN, Alcorn et al (Communication from George Biallas).

Table 1

Leith 2-meter dia × 25 kG Solenoid (UAMH BINN)
MAGNET PARAMETERS

Basic Magnet Type: Segmented coil superconducting solenoid, segmented iron flux return path.

Inside diameter of coils	80 in (2.08 m)
Clear bore diameter	73 in (1.85 m)
Overall length (iron)	183 in
Central field	25 kG
Total ampere-turns	8.30×10^6
Conductor current	1800 A
Total stored energy	36 MJ
Total inductance	22 Henrys
Total helium volume (including reservoir)	5000 liters
Operating heat load (estimated)	30 liters/hr, ℓ He (4.2° K) + 30 liters/hr, ℓ N_2 (79° K)
Total cooldown time	30 hours
Charging time	8 hours
Protection circuit limiting voltage	500 V
Inside iron diameter	116 in (294.6 cm)
Outside iron diameter	148 in (375.9 cm)
Total iron weight	200 tons
Number of coils	4
Coil-to-coil separation	11 in (28 cm)
Vactank-to-vactank axial separation	6 in (15 cm)
Coil cooling scheme	Helium bath, interlayer cooling
Winding configuration	Pancake (layer-wound coils; 0.0937-in interlayer spacing; 0.020-in interturn support (SSt strip))
Conductor:	
Basic type	Cryostatically stabilized composite, multifilament wire
Configuration	Multicomponent: built up as three-layer "sandwich" from copper-composite superconductor-copper strips soldered together
Overall cross section	0.300 in wide × 0.210 in high
Composite superconductor strip:	
Width	0.300 in
Thickness	0.051 in (Grade A); 0.037 in (Grade B)
Superconducting filaments:	
Material	Nb_xTi
Number of filaments	87
Approximate filament diameter	0.007 in (Grade A); 0.005 in (Grade B)
Substrate material	Copper
Substrate-to-filament ratio	4:1
Twist	2/foot
Backing strip	High-conductivity copper
Interstrip bonding	50 - 50 Pb-Sn solder
Overall copper-to-superconductor ratio	20:1 (Grade A); 28:1 (Grade B)
Filament current density	0.91×10^5 A/cm^2 (Grade A) 1.26×10^5 A/cm^2 (Grade B)
Conductor average current density	4420 A/cm^2
Coil overall average current density	3000 A/cm^2
Total conductor length	117,600 ft
Total conductor weight	29,000 lbs

Table 1: Broad specification of the conductors (GrA and GrB)

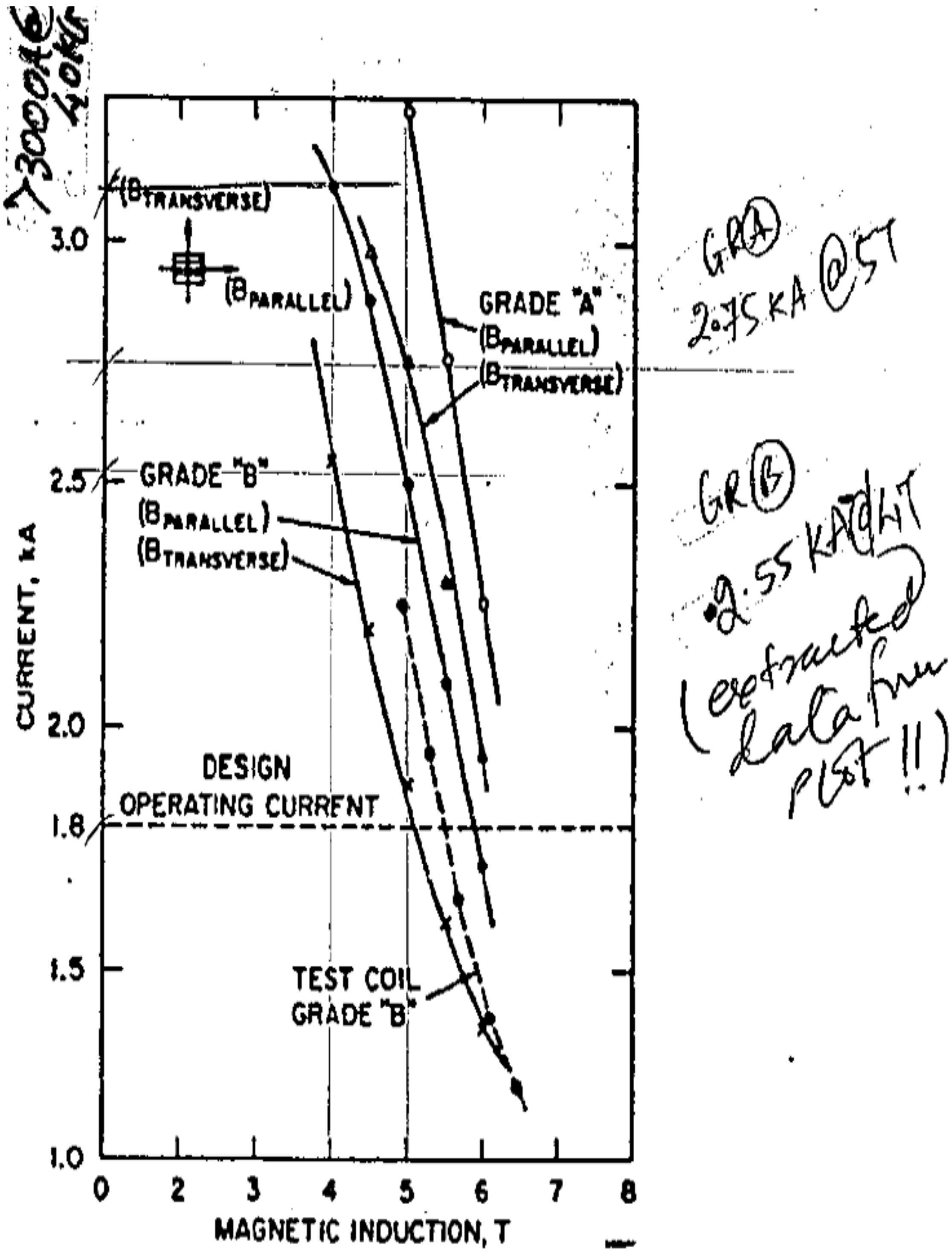

Figure 6: Preliminary data plots for the Short Sample Performance (SSP), SLAC Alcorn et al.

In reality, the measured data have a large variation in SSP and the conductors were selected and manufacturing was engineered selecting the conductors that were assigned to individual pancakes within a coil and a coil block (seems primarily based on the expected field peak during operation). The design was made to carry 1800 A but was only run to a field equivalent to 1600A (data log as suggested).

Following the design trend and looking through the built details and selection criteria of the SLAC configuration to the conductors, focus on this report is based only towards coil 1A and 1B. The conductors that are used in coils 1A and 1B are shown in Figure 7. A set of measured B-Ic is (a typical shown in Figure 8) been extracted and plotted to see the trend in order to compare the same between as reported in the Figure 6 and specification. The comparison is made with the average values and suggests that this is close to the specification and far from preliminary measured SSP. The extracted data from a number of conductors employed within Coil 1 is been averaged and suggests 2.2 kA at 4T and 4.2K.

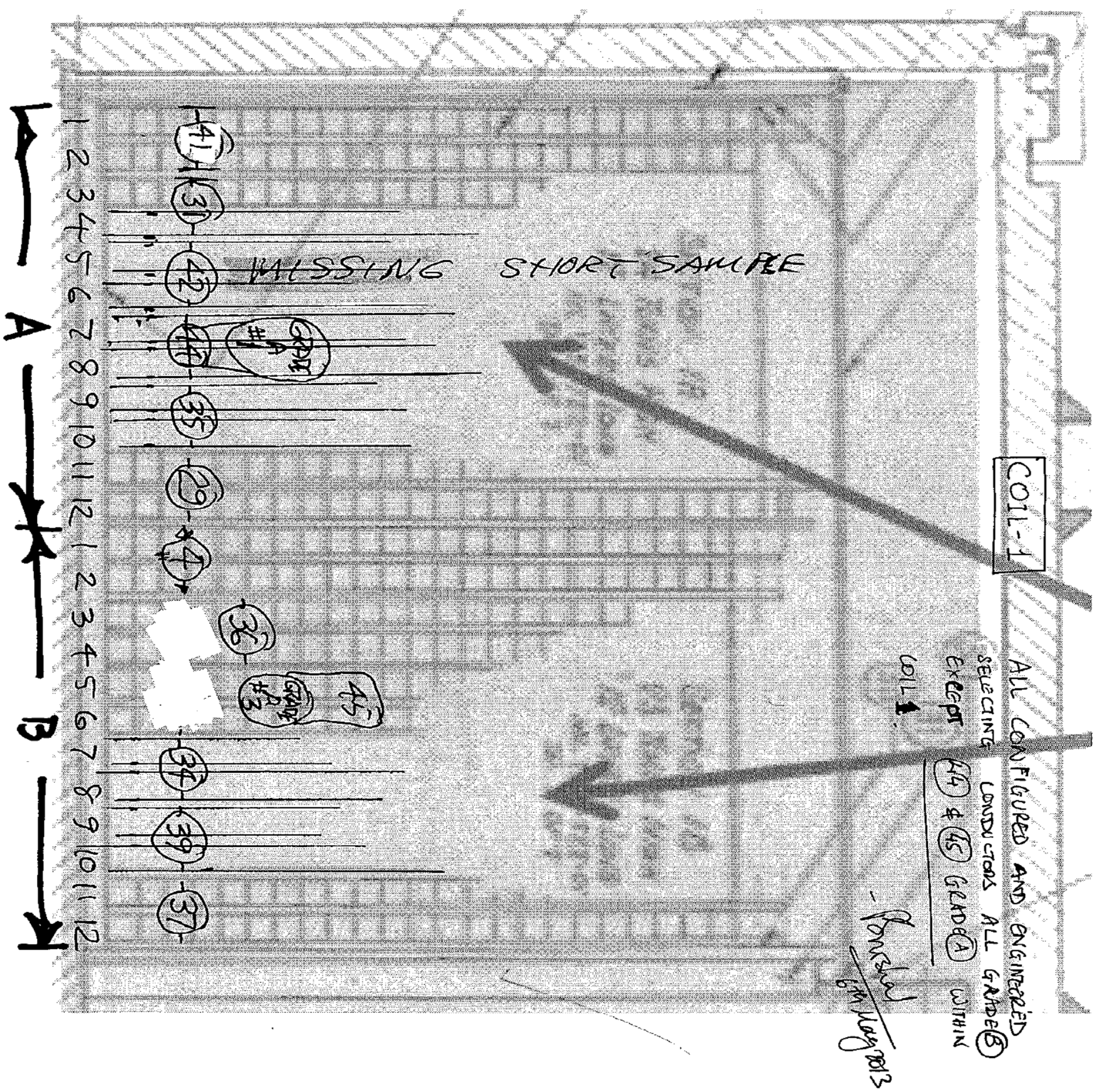

Figure 7: The layout / architecture of coil 1A and 1B, that is assigned a conductor based on the measured B-Ic value at 4.2 K

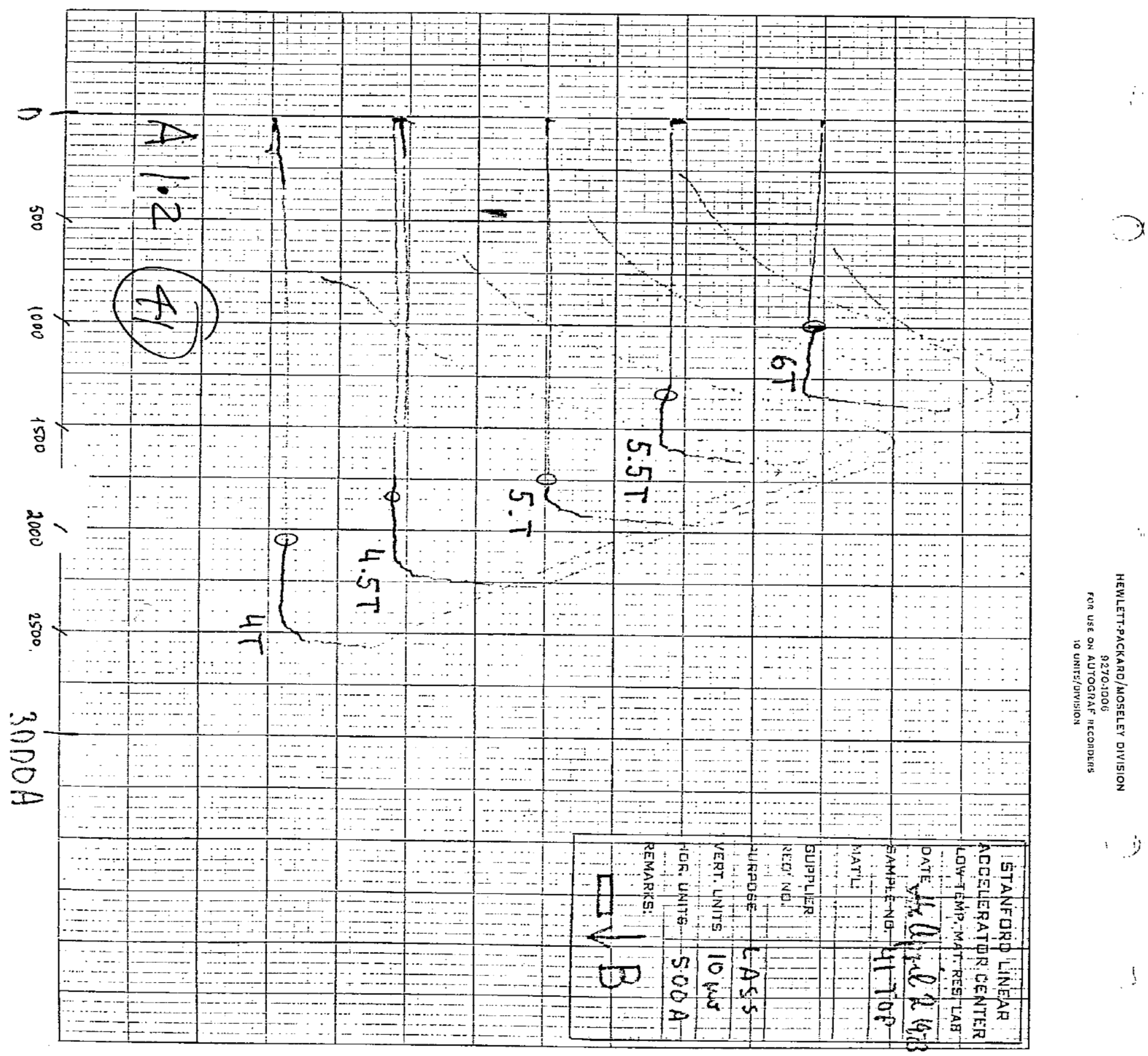

Figure 8: A typical of measured data for B-Ic, Grade B conductor

Analysis

With the above data for the conductors based on specification, Jlab Hall D magnet in Iron is examined for the peak magnetic flux density within coil 1 through to coil 4. The coil layout for Hall D configuration is shown in Figure 9 & Figure 10. The peak magnetic field is realized as 4.54 T in coil 4. The analysis is carried out using Vector Field (Opera) software for field analysis. A detailed analysis carried out in order to evaluate the performance of individual coil with respect to the following parameters-

i. Peak field in coils
ii. %SSP
iii. Critical temperature at the peak field
iv. Generation temperature at peak field
v. Temperature margin
vi. MQE (Minimum Quench Energy)

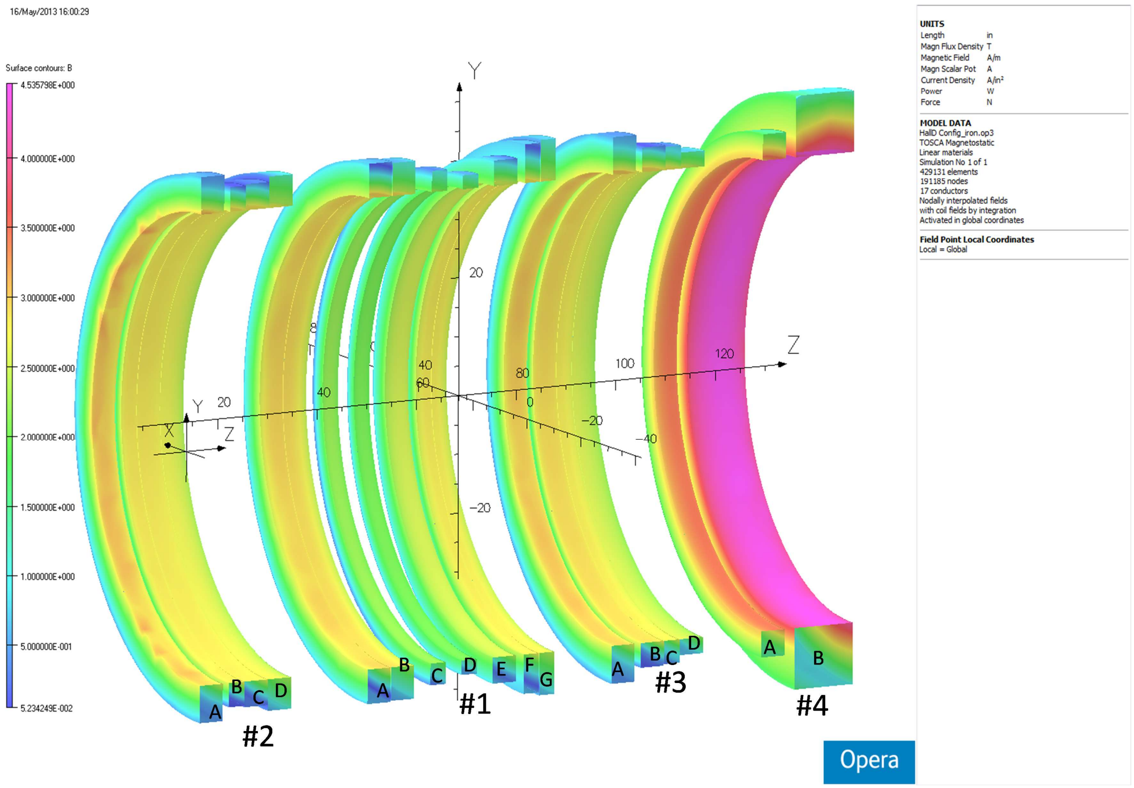

Figure 9 Hall D coil layout

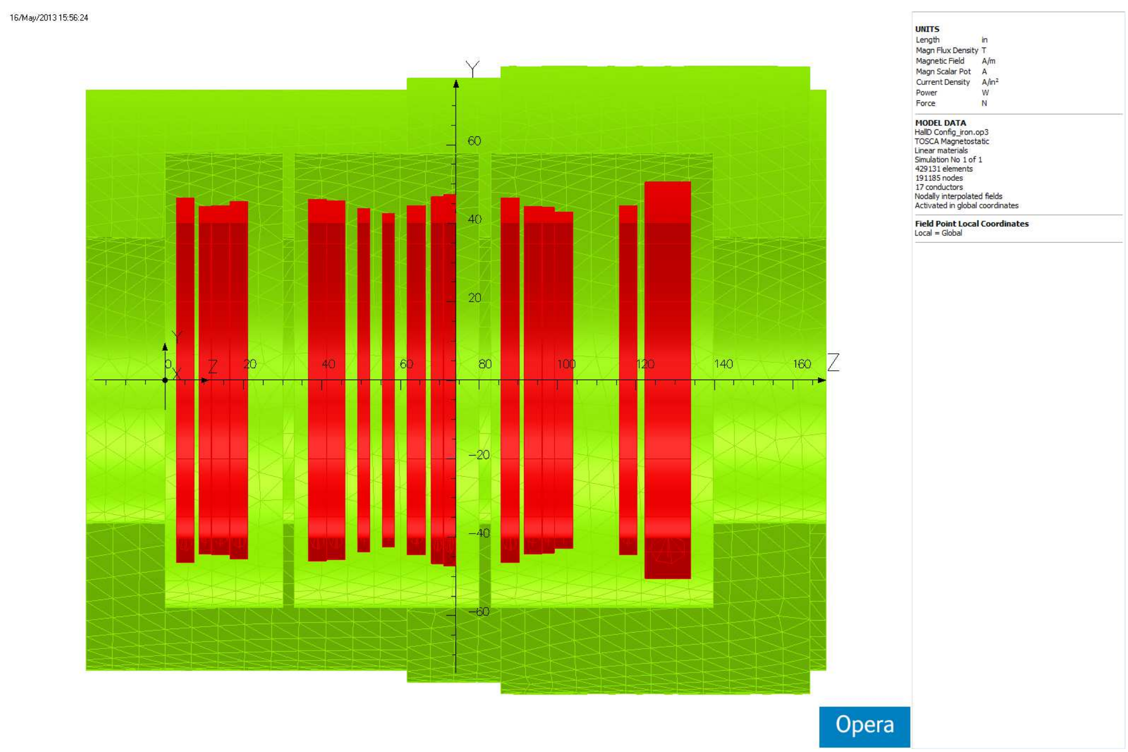

Figure 10 Hall D coil layout in an Iron shroud

Table 2: Coil information as Hall D magnet configuration[2] and design evaluation parameters -

Coil Number	Width(in)	Height(in)	Downstream Dim(in)	Radial Center (in)	# Turns	AT (amps)
1A	4.61165	5.93348	38.84240	43.07743	288	432000
1B	4.61165	5.68459	43.55700	42.95299	276	414000
1C	3.04329	3.69349	50.71960	41.95744	120	180000
1D	3.04329	2.44905	56.97921	41.33522	80	120000
1E	4.61165	4.44015	64.02299	42.33077	216	324000
1F	3.04329	6.68014	69.40255	43.45076	216	324000
1G	3.04329	7.17791	72.53926	43.69965	232	348000
2A	4.61165	6.43125	5.15800	43.32632	312	468000
2B	3.04329	4.19126	10.23244	42.20632	136	204000
2C	4.61165	4.44015	14.15333	42.33077	216	324000
2D	4.61165	5.43570	18.85841	42.82854	264	396000
3A	4.61165	6.43125	87.90800	43.32632	312	468000
3B	4.61165	4.19126	93.76662	42.20632	204	306000
3C	3.04329	3.94238	97.68751	42.08188	128	192000
3D	4.61165	2.69794	101.60841	41.45966	132	198000
4A/B	4.61165	4.44015	118.02141	42.33077	216	324000
4C/D	11.66926	10.41345	128.16156	45.31742	1260	1890000

Ic data based on Information in Paper from John S. Alcorn et al, April 1985
GrA 5T, 4.2K_2kA and GrB 4T, 4.2K_1.6kA

Operating temperature=4.5 K

Coil Name	Coil	Bmax (T) @1500 A	4.2K_Ic (at Bmax) (A)	4.5 K_Ic (at Bmax) (A)	% of SSP	Tc (K)	Tg (K)	Temp. margin (K)
1A	1	2.97	1864	1725	86.96	8.13	4.97	0.47
1B	2	2.91	1879	1740	86.21	8.15	5	0.5
1C	3	2.25	2046	1904	78.78	8.43	5.33	0.83
1D	4	2.07	2092	1949	76.96	8.51	5.42	0.92
1E	5	2.58	1963	1822	82.33	8.29	5.17	0.67
1F	6	2.8	1907	1767	84.89	8.2	5.06	0.56
1G	7	2.79	1910	1770	84.75	8.21	5.07	0.57
2A	8	3.3	1781	1643	91.3	7.98	4.8	0.3
2B	9	2.85	1895	1755	85.47	8.18	5.03	0.53
2C	10	2.83	1900	1760	85.23	8.19	5.04	0.54
2D	11	2.73	1925	1785	84.03	8.23	5.1	0.6
3A	12	3.07	1839	1700	88.24	8.08	4.92	0.42
3B	13	2.9	1882	1743	86.06	8.16	5.01	0.51
3C	14	2.8	1907	1767	84.89	8.2	5.06	0.56
3D	15	2.63	1950	1810	82.87	8.27	5.15	0.65
4AB	16	3.46	2579	2376	63.13	7.91	5.76	1.26
4CD	17	4.53	2178	1983	75.64	7.43	5.21	0.71

[2] Information available from Mr. Floyd, HALL D Engineering

The parameters evaluated are shown in Table 2 based on the specification of the conductors as discussed earlier, shows a temperature margin of about 0.5K in Coil 1A and 1B. The section of coil 2 (2A) is having a lower margin when operated at 4.5 K (as seen in Table 2).

Upon carrying out a detailed analysis on the conductor and operating conditions, comparison is drawn between SLAC and Hall D magnet at the following operating conditions. The Ic values are scaled to correct for the operating temperature as shown in Figure 11 -
SLAC magnet – I = 1600 A, 4.506 K
Hall D magnet - I = 1500 A, 4.603 K

The parameters stated above for evaluation is calculated for both SLAC and Hall D configuration shown in Figure 9, Figure 10, Figure 12, and Figure 13 are reported in
Table 3 and Table 4.

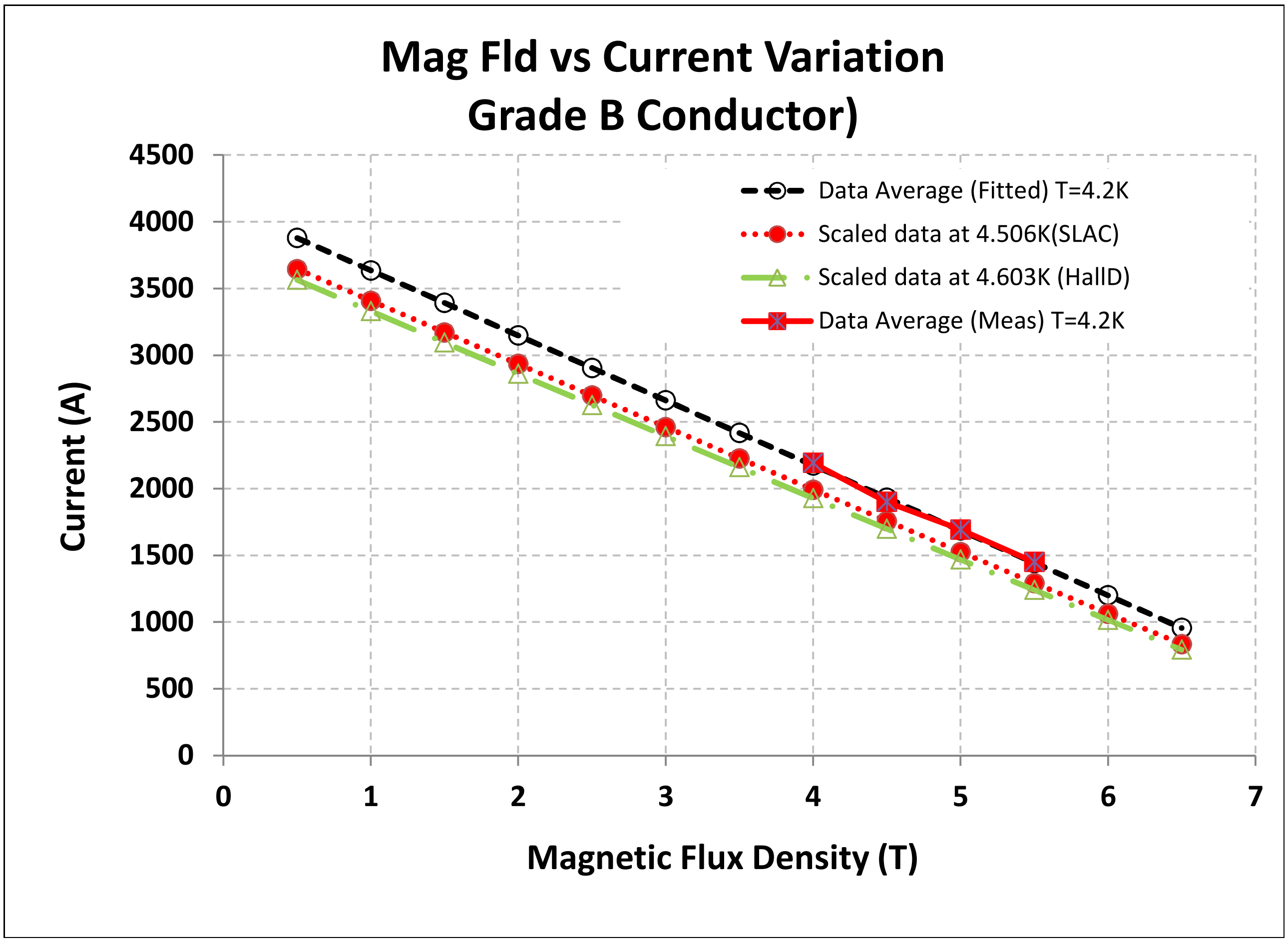

Figure 11: Current – Field plot at varying operating temperature (extrapolated) [1]

Table 3: SLAC Configuration[2] (with Coil and Iron in place)-

Coil Number	Width(in)	Height(in)	Downstream Dim(in)	Radial Center (in)	# Turns	AT (amps)
1A	4.6042	5.9335	8.8583	43.0774	288	518400
1B	4.6042	5.6846	13.5685	42.9530	276	496800
1C	3.0385	3.6935	20.7165	41.9574	120	216000
1D	3.0385	2.4490	26.9700	41.3352	80	144000
1E	4.6042	4.4402	34.0064	42.3308	216	388800
1F	3.0385	6.6801	39.3995	43.4508	216	388800
1G	3.0385	7.1779	42.5308	43.6996	232	417600
2A	4.6042	6.4313	57.9087	43.3263	312	561600
2B	3.0385	4.1913	62.9794	42.2063	136	244800
2C	4.6042	4.4402	66.8935	42.3308	216	388800
2D	4.6042	5.4357	71.5904	42.8285	264	475200
3A	4.60418	6.43125	87.90868	43.32632	312	561600
3B	4.60418	4.19126	93.76221	42.20632	204	367200
3C	3.03854	3.94238	97.67632	42.08188	128	230400
3D	4.60418	2.69794	101.59042	41.45966	132	237600
4A/B	4.60418	4.44015	118.02209	42.33077	216	388800
4C/D	11.64958	10.41345	128.15104	45.31742	1260	2268000

		SLAC	Operating temperature=4.506 K					
Coil Name	Coil	Bmax (T) @1600 A	4.2K_Ic (at Bmax) (A)	4.506K_Ic (at Bmax) (A)	% of SSP	Tc (K)	Tg (K)	Margin@4.506K
1A	1	2.94	2690.71	2494.41	64.14	8.14	5.81	1.30
1B	2	2.97	2676.09	2480.34	64.51	8.13	5.79	1.29
1C	3	2.37	2968.38	2761.75	57.93	8.38	6.14	1.63
1D	4	2.18	3060.93	2850.86	56.12	8.46	6.24	1.74
1E	5	2.71	2802.75	2602.28	61.48	8.24	5.94	1.44
1F	6	2.93	2695.58	2499.10	64.02	8.14	5.82	1.31
1G	7	2.92	2700.45	2503.79	63.90	8.15	5.82	1.32
2A	8	2.83	2744.29	2546.00	62.84	8.19	5.87	1.37
2B	9	2.88	2719.94	2522.55	63.43	8.17	5.84	1.34
2C	10	2.93	2695.58	2499.10	64.02	8.14	5.82	1.31
2D	11	2.90	2710.19	2513.17	63.66	8.16	5.83	1.33
3A	12	2.77	2773.52	2574.14	62.16	8.21	5.91	1.40
3B	13	2.77	2773.52	2574.14	62.16	8.21	5.91	1.40
3C	14	2.70	2807.62	2606.97	61.37	8.24	5.95	1.44
3D	15	2.54	2885.56	2682.01	59.66	8.31	6.04	1.54
4AB	16	3.35	3279.58	3024.82	52.90	8.06	6.18	1.67
4CD	17	4.33	2820.17	2573.54	62.17	7.77	5.74	1.23

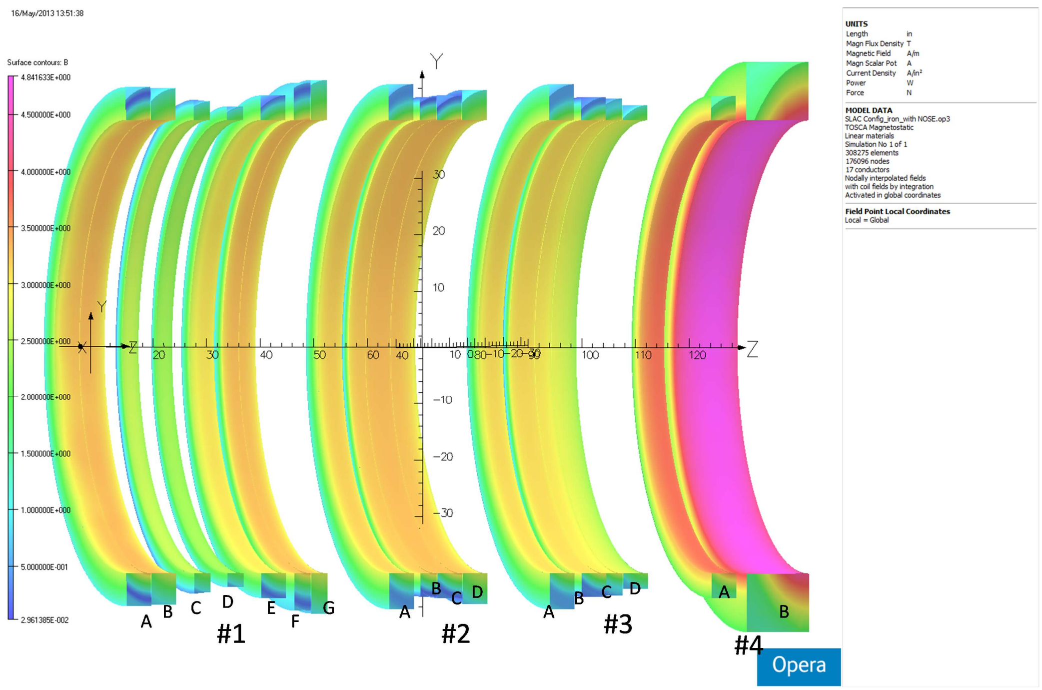

Figure 12: SLAC coil layout

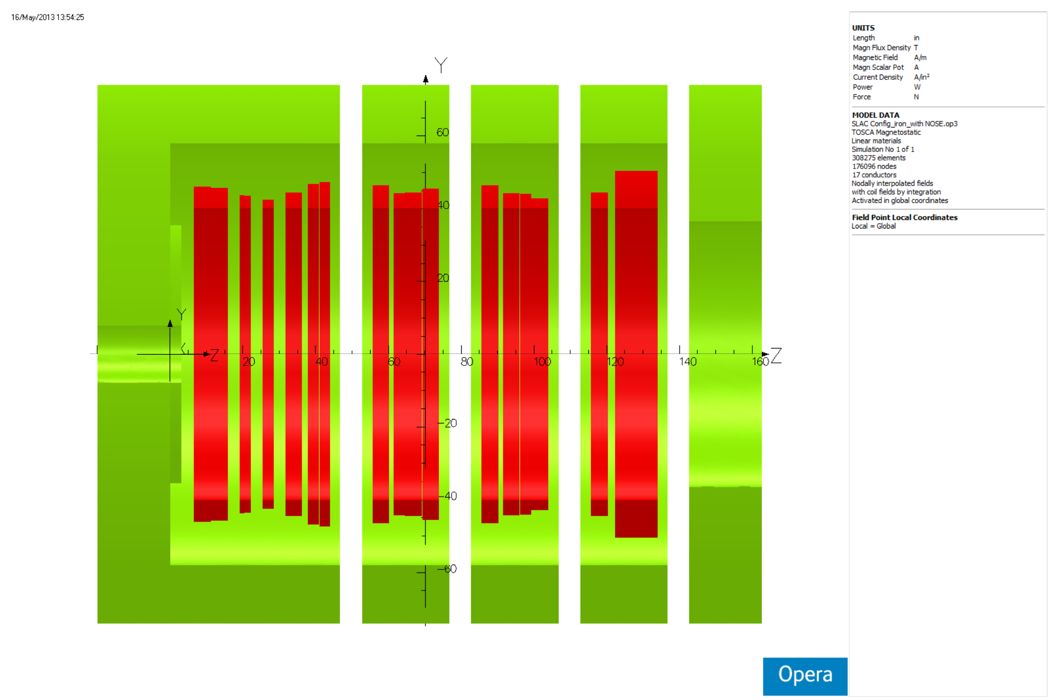

Figure 13: SLAC coil layout in an Iron shroud

Table 4: Temperature Margin HALL D Configuration

		HALL D	Operating temperature=4.603 K					
Coil Name	Coil	Bmax (T) @1500 A	4.2K_Ic (at Bmax) (A)	4.603K_Ic (at Bmax) (A)	% of SSP	Tc (K)	Tg (K)	Margin@4.603K
1A	1	2.97	2676.09	2413.02	62.16	8.13	5.94	1.33
1B	2	2.93	2695.58	2431.54	61.69	8.14	5.96	1.36
1C	3	2.26	3021.96	2741.63	54.71	8.43	6.34	1.73
1D	4	2.07	3114.52	2829.56	53.01	8.51	6.44	1.84
1E	5	2.59	2861.21	2588.90	57.94	8.29	6.15	1.55
1F	6	2.80	2758.91	2491.70	60.20	8.20	6.03	1.43
1G	7	2.79	2763.78	2496.33	60.09	8.21	6.04	1.44
2A	8	3.30	2515.34	2260.29	66.36	7.98	5.74	1.14
2B	9	2.85	2734.55	2468.56	60.76	8.18	6.01	1.40
2C	10	2.83	2744.29	2477.82	60.54	8.19	6.02	1.41
2D	11	2.74	2788.14	2519.47	59.54	8.23	6.07	1.47
3A	12	3.08	2622.51	2362.11	63.50	8.08	5.87	1.27
3B	13	2.90	2710.19	2445.42	61.34	8.16	5.98	1.37
3C	14	2.81	2754.04	2487.08	60.31	8.20	6.03	1.43
3D	15	2.63	2841.72	2570.38	58.36	8.27	6.13	1.53
4AB	16	3.46	3228.90	2887.65	51.95	8.02	6.24	1.64
4CD	17	4.54	2721.73	2392.45	62.70	7.68	5.75	1.15

A few important parameters are compared in order to analyze for major discrepancy between the two that might lead to a Q-scenario is given in Table 5 & Table 6. The inductance measured in Hall D configuration is in good agreement with the model. Similar analysis might be helpful to analyze the coil section[3] #4.

Table 5: Hall D and SLAC configuration (Inductance and Axial forces) modeled and calculated

Parameter	**Coil and iron model (Hall D) at 1500A**	**Coil and iron model (SLAC)_1600A**
Peak field in the coils (T)	4.53	4.33
Stored energy (MJ)	32.3	34.81
Inductance (H)	28.71	27.2

Iron	**Coil Forces (Hall D 1500A)**			**Coil Forces (SLAC 1600A)**		
Coil No.	**Fx(kN)**	**Fy(kN)**	**Fz(kN)**	**Fx(kN)**	**Fy(kN)**	**Fz(kN)**
1	-2	2	1546	-5	4	1541
2	-4	-3	-1280	-4	-1	-1737

[3] Suggested to have detailed analysis for coil#4 in terms of Margin and MQE with respect to the measured data

3	0	0	-302	0	0	-435
4	0	0	102	0	0	62
5	1	0	978	0	0	974
6	0	0	511	-1	0	482
7	0	0	-1600	-1	-1	-1870
8	-5	-8	1397	0	0	1708
9	-4	0	335	0	0	367
10	-1	-1	-219	0	0	-190
11	0	0	-2081	0	1	-2096
12	-4	1	873	0	1	1570
13	1	-4	-3	0	0	102
14	0	-1	-426	0	0	-471
15	0	0	-652	0	0	-766
16	-2	2	2684	1	0	2819
17	10	20	473	-1	7	-2932
All Coils	**-10**	**8**	**2333**	**-11**	**11**	**-871**

Table 6: Characteristic parameters been evaluated MQE for 3 configuration for a single coil Quench

Description Coil 1A			
Magnet Configuration	Hall D (Spec wire data)	**Hall D**	**SLAC**
Operating Temperature (K)	4.5	**4.603**	**4.506**
Number of turns/coil [ ]	288	288	288
Bmax (T)	2.97	2.97	**2.94**
Normal Operating current - Iop (A)	1500	**1500**	**1600**
Total Inductance (H)	28.71	**28.71**	**27.20**
Ic (A) Jlab cals based on measured (avg) Ic/Bc/Tc @ 2200A/4T/4.2K)	1600	**2200**	**2200**
%SSP	87	**62**	**64**
Tc (K)	8.13	8.13	8.14
Tg (K)	4.97	5.94	5.81
Margin	0.47	**1.33**	**1.30**
MQE (mJ)	33	**127 [2]**	**114**
Peak Temp (K)	182	182	189
Internal Peak voltage in the coil (V)	277	277	310
Coil Resistance (Ω)	0.115	0.118	0.118
Max Terminal voltage (No dump resistor) (V)	173	178	189

Summary and conclusion

1. The inductance calculation is in very good agreement with the measured inductance in Hall D configuration.
2. The temperature margin based on the averaged B-Ic of the individual conductor is better than the values estimated based on the conductor specification.
3. The margin in over 1.3 K in all cases employing Grade B conductor
4. The comparison made with SLAC original configuration is very close in terms of temperature margin and peak field experienced in Hall D
5. Uncertainty in the temperature in HALL D operating condition will change the scenario.
6. The MQE in both cases are comparable and estimated to be about 120mJ.

Steps forward

1. Look carefully into the Quench operating condition scenario, particularly with the helium temperature
2. Revisit the splice / joint support in the magnetic field, night be experiencing large Lorentz forces.
3. Evaluate mechanical and EM stability of the unsupported conductor or a part of conductor that could move.
4. Need to evaluate the Burst disc rupture scenario with all energy dumped into the coil and helium boiling off.

References

[1] Fermi Lab Tech Note - TD Note 00-041

[2] MQE calculations for the Coil 1A - Single coil quench analysis Hall D_4.6K_rev

Single coil_HALL D