Fermilab

Fermi National Accelerator Laboratory
P.O. Box 500 • Batavia, Illinois • 60510

TD-97-011

Author	:	G. Sabbi
Date	:	April 2, 1997
Title	:	Load lines and short sample limits for HGQ model #1
Keywords	:	Magnetic design, short sample performance
Distribution	:	TD notes file S. Caspi R. Gupta J. Kerby F. Nobrega J. Strait S. Zlobin

Location of latex/eps source:
/afs/fnal.gov/files/code/hgq/notes/TD-97-011
Location of the referenced files:
/afs/fnal.gov/files/code/hgq/magdes/0397 (Unix server)
tsnt1.fnal.gov/TD_Libry/HGQ_Notes/TD-97-011 (NT server)

1 Introduction

This note reports calculations of gradient and field load lines for the first HGQ model. Both the magnet body and the end regions are considered. The short sample parameters for model #1 are then computed based on SSC conductor critical parameters.

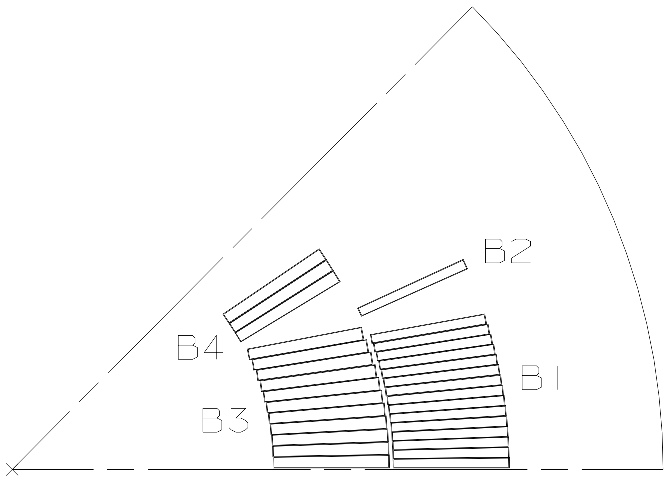

Figure 1: Coil cross-section [6].

2 Gradient and field load lines

2.1 Magnet body

Fig. 1 shows the coil cross section for one octant. In what follows, the four blocks of the reference octant will be labelled as follows: block 1 (15 turns) for outer layer, midplane side; block 2 (1 turn) for outer layer, pole side; block 3 (11 turns) for inner layer, mid-plane side; block 4 (3 turns) for inner layer, pole side. Within each layer, the conductors are numbered from the mid-plane side to the pole side.

Table 1 reports the field load line coefficients for each block computed using ROXIE [1]. The following cases are considered:

1. No iron yoke (file ssp/hgq45_noyok).

2. Circular yoke with a linear B-H characteristic (μ_i=3000) inner radius of 92.564 mm and outer radius r_{outer}=∞ (file ssp/hgq45_yok).

These calculations are based on Biot-Savart law. The transport current in the cable is modelled by defining a current filament at the position of each strand (2x19 filaments for the inner cable, 2x23 filaments for the outer cable). The coil geometry has not been described in terms of blocks (groups of conductors), as it is usually done with ROXIE: in order to have an exact matching between the ROXIE model and the original design [6], each conductor has been positioned, independently of the others, according to the design specifications.

Case	G	B_1	B_2	B_3	B_4
1	16.669	0.532	0.525	0.587	0.639
2	18.221	0.588	0.589	0.643	0.699

Table 1: Gradient (T/m/kA) and field (T/kA) load line coefficients in each block (analytical calculation based on Biot-Savart law, linear B-H characteristic).

The peak field for the inner layer is obtained in the pole turn (conductor 14). For the outer layer depending on the yoke configuration, the peak field is obtained either in conductor 16 (pole turn, block B2) or in conductor 15 (pole turn, block B1). The gradient load line coefficients are 16.669 T/m/kA for case 1, 18.221 T/m/kA for case 2. The relative contribution of the iron yoke to the gradient is about 9%.

Table 2 reports the field and gradient load lines, computed using POISOPT [2, 3, 4] using the yoke lamination design in [5] and a nonlinear B-H characteristic as in table 10 (file mat/DWG45). A packing factor of 98% has been assumed for the yoke laminations. Based on this result, the operating current for a nominal gradient of 235 T/m would be 13.14 kA.

I (kA)	G (T/m)	B_1^{max} (T)	B_2^{max} (T)	B_3^{max} (T)	B_4^{max} (T)
1	18.34	0.596	0.588	0.649	0.707
6	109.36	3.551	3.500	3.869	4.212
8	145.15	4.709	4.639	5.135	5.590
10	180.64	5.854	5.764	6.391	6.957
12	215.61	6.980	6.868	7.627	8.303
14	249.75	8.072	7.936	8.834	9.618
16	283.40	9.145	8.984	10.024	10.914

Table 2: Gradient and field load lines (real iron calculation). Yoke geometry as in [5].

2.2 End region

The field in the end region has been computed using ROXIE. Since the BEND-ROXIE interface is not yet fully tested, the end geometry has been defined using the standard modelling features in ROXIE. The contribution of the iron yoke to the field in the end region is not taken into account. However, previous results [6] indicate that for the present design the contribution of the iron yoke to the peak field in the ends is negligible. The linear coefficients for the maximum field in each block as function of current are reported in table 3 (file pke/fdend).

Block	B_1	B_2	B_3	B_4
B^{max}/I	0.611	0.540	0.598	0.656

Table 3: Field load line coefficients in the end region (T/kA). Analytical calculation based on Biot-Savart law. The contribution of the iron yoke to the field in the end region is neglected.

3 HGQ model #1 performance parameters

3.1 Conductor parameters

The cable which is presently being produced to build the first short model uses SSC NbTi s-trand, with a nominal critical current density Jc of 2.75 kA/mm^2 at 5 T and 4.2 K. The following parametrization has been assumed for the extrapolation of the critical current density J_c as function of temperature and field :

$$J_c(B,T) = J_c(B_0,T_0)\left(1-\frac{B-B_0}{B_c(T)-B_0}\right)\left(1-\frac{T^2-T_0^2}{2T_0(T_c(B_0)-T_0)}\right)$$

where $B_c(T)$ is calculated according to:

$$B_c(T) = B_{c_0}\left[1-\left(\frac{T}{T_{c_0}}\right)^{1.7}\right]$$

and with the following notations:

B_{c_0}	Critical field at zero temperature (14.1T)
T_{c_0}	Critical temperature at zero field (9.2 K)
B_0	Reference field (5T)
T_0	Reference temperature (4.2 K)
$T_c(B_0)$	Critical temperature at the reference field (7.1 K)

Using the above parametrization, the predicted critical current density at 7 T and 4.2 K is 1.73 kA/mm^2. Recent measurements carried out at LBL [7] found critical current densities at 7 T and 4.2 K between 1.70 and 1.74 kA/mm^2.

Note that for a given temperature, the model assumes a linear dependence of the critical current density on field: table 4 reports the resulting coefficients at 1.9 K. The other relevant strand parameters are reported in table 5. The total number of strands is 38 for the inner layer cable, 46 for the outer layer cable.

J_c(5T,4.2 K) kA/mm^2	J_c(5T,1.9 K) kA/mm^2	dJ_c/dB(1.9 K) kA/mm^2/T
2.75	4.334	-0.533

Table 4: SSC strand parameters.

Parameter	Unit	Inner layer	Outer layer
Strand diameter	mm	0.808	0.648
Cu/Sc ratio		1.3/1	1.8/1
Area SC	mm^2	0.223	0.118

Table 5: Strand parameters relevant to critical current calculation.

The critical current for each cable at 1.9 K as function of field can be obtained from the above data as:

$$\begin{aligned} J'_c(B,T) &= \gamma J_c(B,T) \\ I_c(B,T) &= N_s A_{sc} J'_c(B,T) \end{aligned}$$

where J'_c is the critical current density, γ is the degradation factor, N_s is the number of strands, A_{sc} is the superconductor area in the cross-section of each strand. Based on the results in [7], no cable degradation (γ=1) will be assumed here: the resulting coefficients for $I_c(B)$ are shown in table 6.

Conductor	Inner cable		Outer cable	
J_c(5T,4.2 K) kA/mm^2	I_c(5T,1.9 K) kA	dI_c/dB(1.9 K) kA/T	I_c(5T,1.9 K) kA	dI_c/dB(1.9 K) kA/T
2.75 (SSC)	36.71	-4.51	23.48	-2.89

Table 6: Parameters for SSC strand based cable.

3.2 Short sample limits

For what concerns the magnet body, table 7 reports the maximum gradient, current, and the corresponding peak field in the inner and outer layer, calculated on the basis of the assumptions and results discussed in the previous sections, for the following cases:

1. Collared coil without iron yoke.

2. Circular yoke with a linear B-H characteristic (μ_i=3000) inner radius of 92.564 mm and outer radius r_{outer}=∞.

3. Real iron calculation using the nonlinear B-H characteristic from table 10 and a yoke lamination design as in [5].

The limit field and the current in each layer are reported in table 8.

Case	I_{ss} (A)	G_{ss} (T/m)
1	14.95	249.2
2	14.04	255.8
3	14.24	253.8

Table 7: Maximum gradient and current in the magnet body.

Case	I_{ss} (kA)		B_{ss} (T)		Critical
	Inner	Outer	Inner	Outer	block/conductor
1	15.26	14.95	9.75	7.95	B_2/C_{16}
2	14.26	14.04	9.97	8.27	B_2/C_{16}
3	14.47	14.24	9.92	8.20	B_1/C_{15}

Table 8: Peak field, critical current, critical block/conductor (magnet body).

The short sample limits for the return end are reported in table 9. The contribution of the iron yoke to the end field is neglected. The limitation comes from the outer layer: the critical point is in conductor 15 of block B_1, which reaches a peak field B_{ss}=8.38 T.

Parameter	Unit	Value
I_{ss}	A	13.71
G_{ss}	T/m	244.9

Table 9: Short sample limits for the end region.

3.3 Conclusion

The short sample limit for HGQ model #1 is 13.71 A, corresponding to a gradient of 244.9 T/m. The limitation comes from the end region, block B_2, conductor 15. The short sample current limit for the magnet body is 14.24 A, corresponding to a gradient of 253.8 T/m.

A Iron magnetization curve

No experimental data is presently available for the B-H curve of the iron which will be used for the HGQ program. The B-H characteristic which had been assumed for the calculations is reported in table 10.

B (T)	**H** (A/m)	**B** (T)	**H** (A/m)
0.0	0.0	0.8944	178.25
1.2	294.43	1.4	501.33
1.5	796.56	1.55	1153.07
1.6	1795.26	1.65	2862.38
1.7	4383.1	1.75	6043.87
1.8	8121.63	1.85	10584.53
1.9	13607.67	1.95	17224.44
2.0	21167.48	2.05	26753.79
2.1	33756.56	2.12499	38216.85
2.15	43799.18	2.175	52443.63
2.2	66001.16	2.25	99470.45
2.27966	120939.53	2.30686	141210.18
2.3443	169592.91	2.39956	212166.6
2.4905	283123.03	2.56272	339890.08
2.6706	425036.67	2.84981	566947.93
3.20737	850768.05	3.56441	1134580.22
4.27824	1702247.52	4.81342	2127964.56
5.70517	2837501.76	6.41857	3405138.82
7.48872	4256638.18		

Table 10: B-H characteristic.

References

[1] S. Russenschuck, *"A Computer program for the design of superconducting accelerator magnets"*, CERN AT/95-39, September 1995.

[2] R. Holsinger, C. Iselin, *"The Cern-Poisson package user guide"*, Cern Program Library long writeup, August 1984.

[3] F. Rohner, *"User Guide of the Cern-Poisson program package"*, May 1992.

[4] S. Russenschuck, T. Tortschanoff, *"Mathematical optimization of superconducting accelerator magnets"*, CERN AT/93-37 (MA), May 1994.

[5] *"LHC IR Quadrupole magnet model yoke lamination"*, Drawing No. 5520-MD-344429, March 1997.

[6] S. Caspi, *"LHC IR Quad Magnetic Design"*, FNAL/LBL/CERN videoconference meeting, May 1st, 1996.

[7] R Scanlan et al, *"Design and Fabrication of a High Aspect Ratio Cable for a High Gradient Quadrupole Magnet"*, ASC '96, Pittsburgh, August 1996.