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CONSTRUCTION AND TEST OF 1.8M DIPOLE DSS014

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June 24, 1989

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SUMMARY.

This magnet was the second to be assembled with "line-to-line" fit of the yoke-collar assembly. Tapered keys were used in the collaring process, but the vertical pressure was made high enough so that the keys could be seated without horizontal pressure, as was done for square keys. The magnet quench performance was good. At 4.45K, it reached a plateau at 6.9T after one training quench. The magnet did not retrain after a thermal cycle. It reached 8T with little additional training. The multipoles were very good. The strain gauge data indicated that the coils were not unloaded at 8 kA. The results have been summarized in a conference paper (Appendix A). This note adds quench location and strain gauge data to that presented in the paper, and updates the multipole analysis.

QUENCH HISTORY AND LOCATION

With DSS014, as with previous 1.8 m SSC dipole magnets, the quench test procedure consisted of training by ramping up the magnet current at a rate of 16A/s until a quench was generated, and repeating this until the quench currents achieved had reached a four-quench plateau, within an allowable range of 30A. As for the DS0012 and DSS013 tests, the time between quenches was 1/2 hour. Training was performed at 4.35K (nominal), where the central magnetic field is 6.9T, then again at the subcooled temperatures of 3.85K and 3.35K, where the central field is about 7.6T and 8.1T, respectively. This schedule was then repeated after a warm-up to room temperature and recooling (thermal cycle). The training at subcooled temperatures is done to test the magnet to the limits of its mechanical performance under the stress of the higher magnetic fields possible at the lower temperatures. In addition, at the end of each set of plateau quenches, strain gauge measurements were made every 500A until the magnet quenched.

Figure 1 gives the quench history of the magnet and shows each of the training and conductor-limited (plateau) quenches by symbols which distinguish between upper and lower coil quenches. The quench history of DSS014 is the most consistent exhibited by any 1.8 m SSC dipole to be tested so far. Though, outwardly, it looks very similar to that for DSS013, there are some interesting differences in quench origin locations for both training and plateau quenches; these will be noted when appropriate. All quenches in DSS014 occurred in the inner coils, as in DSS013 and DSS012. Like DSS013, the training quenches were mostly in the ramp-splice section in the upper or

lower inner coils. All conductor- limited plateau quenches were in the upper inner coil in a long straight section of the pole turn. This was not always the case with DSS013, where most plateau quenches at 6.9T were in the ramp-splice region and in the same location as the training quenches.

Details of each quench as to temperature, current, and location are given in Table 1. As can be seen from the table, the conductor-limited quenches at 4.45K, 3.85K, and 3.35K were at average plateau values of 6856A, 7629A, and 8130A, respectively; and the corresponding calculated short sample limits at each temperature were exceeded by 1%, 3%, and 5%, respectively.

As can be seen from Fig. 1, there were only six training quenches during the testing schedule. This was slightly better in performance than DSS013, where the testing sequence was the same and eight training quenches were seen. All but one of the training quenches in DSS014 originated in the ramp-splice region, close to the tap 16G, which is situated on the straight section side of the ramp-splice section about 1/2 inch into the G10 box which houses the ramp-splice section. There were four such quenches, one of which happened in the lower coil and three in the upper coil. Calculation of the actual quench origin for these cases show that the position varies from being only about 1/4 inch from tap 16G, and therefore in the G10 box, to about 3/4 inch from 16G and outside the box. This last case was the lower coil quench while the former was located in the upper coil. The other two ramp-splice region cases were upper coil quenches and occurred at about 0.5 inch and 0.7 inch from 16G, so these were very close to the edge of the box; however, the accuracy of the calculations precludes a definite determination of whether they were actually inside the box or not. This prevalence for ramp-splice training quenches was also seen in DSS013, where there were at least four such quenches observed.

Table 2 summarizes these results for DSS014 and includes the locations for two strain gauge run quenches which also occurred in the ramp-splice section and looked like the above-mentioned training quenches. As discussed further on, the strain gauge runs resulted in quenches at currents slightly lower than plateau, so it was of interest to compare them to the training quenches which looked similar. As can be seen from the table, these occurred significantly farther from the 16G tap and were definitely out of the G10 box, though in other respects they did look like the training quenches. Two other strain gauge runs resulted in quenches in the long straight sections and looked more like plateau quenches.

The only training quench that did not occur in the ramp-splice region was at the return end in the pole turn (T16) of the lower inner coil. (During one training quench at 3.85K, the voltage tap data was lost.) Taking into consideration the time taken for the quench to reach each end tap of that

section, the origin was calculated to be 1 1/2 inches into the right hand straight part of the section outside of the curved end itself. This would put the origin about 2 inches closer to tap 16D on the right hand side than to tap 16C on the left side. This particular quench appeared at the end of an interesting series of training quenches at 3.35K which seemed to demonstrate that at 8.1T both the upper and lower coils trained separately, and in succession, since each showed an almost identical quench history symmetrically. This behavior can be seen by studying Fig. 1 and referring to Table 1. This type of training at 8.1T was also seen in DSS013, where the lower coil apparently trained after the upper coil had already done so. The upper coil first had a ramp-splice quench and reached plateau, as in DSS014, then exhibited a training quench in the lower coil in the turn 16 return end section straight section, again as in DSS014; but, unlike DSS014, it was not preceeded by a ramp-splice training quench. Also, though symmetrically similar to the T16RE quench in DSS014 described above, it was started on the left side at a spot heater and might be related to the presence of that device on the cable.

After the thermal cycle, training was seen only for one quench, at 8.1T, and it originated in the ramp-splice section of the upper coil as it did before the thermal cycle at 8.1T. No other training in the magnet was observed after the thermal cycle and all plateau quenches again originated in the pole turn straight sections of the upper inner coil. These results after the thermal cycle were more consistent than for DSS013.

One interesting effect occurred during the strain gauge runs. As mentioned before, quench currents after a strain gauge run were typically slightly lower (1% or less) than the previously established plateau. Both strain gauge quenches at 4.45K were located in the ramp-splice section like the training quenches, but the other two occurred in the pole turn straight section like a typical plateau quench. This behavior seems to indicate that the quench current is somewhat ramp rate dependent. This phenomenon has been seen sporadically in the previously tested 1.8 m dipoles, but was not observed in DSS013.

The quench data curves of DSS013 and DSS014 are very similar (cf. Appendix A Figs. 2 and 3, recalling that the "L" quenches in Fig. 2 were due to an error in the test stand connection). During assembly, the inner coils of DSS014 reached a pressure of 15 kpsi, while those of DSS013 reached 8 kpsi. The difference in these pressures did not significantly affect the training of these magnets.

STRAIN GAUGE DATA

The coil stress data at significant points in the history of the magnet are given in Table 3 and in Fig. 2. As can be seen in Fig. 2, the inner coil pressure during the

"square-key-like" assembly reached about 15 kpsi. (For comparison, the maximum inner coil pressure reached only 8 kpsi during the standard tapered key assembly of DSS13.) The coil stress versus current up to 8 kA is plotted in Fig. 3. As with DSS13, there is some gauge-to-gauge variation, but the prestress at 8 kA does appear to be greater than zero.

FIELD QUALITY DATA

A summary of the geometric multipole coefficients of the central 76cm of the magnet straight section is given in Table 4 for both cold and warm measurements. The results are given in the standard "units" (10**4/Bo at 1 cm radius). For the cold measurements, the geometric terms are obtained by averaging up-ramp and down-ramp data from 2 to 3 kA to eliminate the effect of magnetization currents. For the warm measurements, the geometric terms are obtained by averaging data at +10A and -10A to remove the effect of residual iron magnetization. For both cold and warm data, the unallowed 16-pole and 18-pole terms have been used to obtain the location of the measuring coil with respect to the magnet. (Thus, the values for b7, a7, b9, and a9 given in Table 4 are not meaningful. Upper limits for these terms can be obtained from the data before centering and are at most 0.02 units at 2.5 T.)

A plot of the sextupole versus current, which demonstrates the small effect of saturation, is given in Appendix A. More complete presentations of the multipole data are given in internal "prompt reports," TMG 396 (uncentered data) and TMG 399 (centered data).

At 1.8kA, the NMR measurement of the transfer function gave the result 1.0464 T/kA. However, in a number of places the field was not sufficiently uniform to permit the locking circuit to work. It was found that one of the strain gauge collar packs was located in the same axial region as the nonuniform field. The value given above excludes the data from this axial region.

TIME-DEPENDENT EFFECTS

A measurement of the change in sextupole with time at injection current is given in Fig. 4. The setup for this measurement was the same as for the last several magnets: spontaneous quench, AC cycle to 5.3kA, 8 minute wait at 25A idle current, ramp to 300A (3A overshoot), hold constant current, measure. Ramps were 16A/sec. The time dependence is close to that seen in DSS13 but larger than that observed in DSS6 and DSS11. DSS13 and DSS14 have cable from the same spools. The cable is has smaller filaments in both inner and outer coils than DSS6 and DSS11.

SPOT-HEATER DATA

A plot of MIITS versus quench current is given in Fig. 5 for spot heaters located in the magnet straight section at the pole turn (heater 4) and on the midplane (heater 3).

STRIP HEATERS

It was found in a recent magnet disassembly that the initial design of the strip heaters had concentrations of heating (as evidenced by discoloration). In this magnet, strip heaters of the new design were operated successfully.

YOKE CLOSING EXPERIMENT

To check whether the yoke was fully closed, a piece of indium wire slightly larger than the space for the yoke midplace key was placed in the keyway. Results of the experiment were made uncertain because of lamination-to-lamination offsets which occurred in the yoke blocks during magnet testing. In the analysis, the surface height of the indium and the blank 1/2 key that opposed it were measured relative to the midplane. This procedure yielded zero gap on one side and 0.002" gap on the other side. (Details are in SSC-MD-229.)

DSS 14

Note 4.45 K

Quench #	I_Q (A)	I	Temp (K)	start coil	date	File #	Comments B=UI	Lecroy Channel #	WDT
1	6422	16	4.45	UI	1/26	4	Ramp-splice (AG, very close to G)	512	
2	6863					5	Turn 16 SS, about middle axially, RHS	511	17.7
3	6859					6	Same as Q#2	511	to
4	6859					7	"	511	17.9
5	6852					8	"	511	
6	6800	0/16				9	same as Q#1	512	
7	7464		3.85	LI	1/31	15	Fast data lost		
8	7611			UI		16	T 16 SS, LHS, ≈ cntr axially	509	9.4
9	7636					17	"	509	to
10	7637					18	Turn 16 SS, ≈ 2/3 of way toward RE	509	9.6
11	7619					19	same as Q#10	509	
12	7605	0/16				20	Same as Q#8	509	
13	7912	16	3.35		2/1	21	Ramp-splice (AG, very close to G) "Same place"	512	5.4
14	8116					22	T16 LHS SS near RE except one is LI	509	5.35
15	8018			LI		23	Ramp-splice (AG, very close to G) & other is UI		5.3
16	8089			"		24	T16 RE (several turns close together)		5.35
17	8128			UI		25	T16 SS, ≈ 1/3 of the way from LE	509	5.20
18	8129					26	" , ≈ middle	509	
19	8146					27	" , closer to RE	509	
20	8146					28	" , ≈ center	509	
21	8105	0/16				29	" , closer to LE	509	
22	6859	16	4.45	UI	2/3	42	same as Q#2 Quench prior to b_2 vs. time	511	17.75
				THERMAL CYCLE					

$P = 17.8 \Rightarrow T = 4.44$

$P = 9.5 \Rightarrow T = 3.79$

$P = 5.3 \Rightarrow T = 3.30$

QUENCH DATA SUMMARY - MAGNET DSS14

BY PW DATE 2/1/89 PAGE 1

TABLE I (Page 1 of 2)

QUENCH DATA SUMMARY - MAGNET DSS14
BY PN DATE 2/21 PAGE 2

DSS 14

Quench #	I_Q (A)	I	Temp (K)	start coil	date	File #	Comments B=UI	Energy J	W&T
23	6849	16	4.415	UI	2/6	48	Same as QH2	511	17.7
24	6854					49	"	511	17.8
25	6854					50	"	511	
26	6855					51	"	511	
27	6834	0/16				52	Same as Q#1 Strain Gauge Run	512	
28	6850	16			2/7	71	Same as QH2	511	17.8
29	7626		3.85		2/8	72	Same as Q#8	509	9.6
30	7628					73	Same as Q#10	509	
31	7639					74	"	509	
32	7634					75	Same as Q#8	509	9.5
33	8016		3.35			76	Same as QH13	512	5.3
34	8110					77	Same as QH14	509	
35	8117					78	"	509	
36	8139					79	"	509	
37	8127					80	"	509	5.3
							END OF TEST		

TABLE I (page 2 of 2)

TABLE 2 DSS014 QUENCH LOCATION ANALYSIS RESULTS FOR RAMP-SPLICE REGION QUENCHES

QUENCH #	RUN #	DISTANCE FROM TAP 16G (in)	IN G10 BOX ?	TYPE OF QUENCH	DIFFERENCE FROM PLATEAU CURRENT (%)
1	4	0.7	?	training	6.3
6	9	1.9	no	strain gauge run	0.8
13	21	0.5	yes	training	2.7
15	23	0.8	no	training	1.4
27	52	2.3	no	strain gauge run	0.3
33	76	0.3	yes	training	1.4

Notes

1. One data sampling interval of 0.2 ms corresponds nominally to about 0.5 inch in distance travelled. This results in an error of approximately +/- 0.25 inches.

2. This quench occurred in the lower inner coil. All others listed were in the upper coil.

3. For the strain gauge runs that quenched in a straight section, the quench current differed by 0.3% from the plateau.

TABLE III
DSS013 & DSS014 COIL STRESS SUMMARIES
February 24, 1989

1. DSS013 SUMMARY

DATE	PACK1 - Straight Section Near Lead End	AVG. INNER	AVG. OUTER*	DELTA INNER	DELTA OUTER
10/ 5/88	After Collaring	7386	4777		
10/10/88	Before Shell Welding	6534	4373	-852	-404
10/18/88	After Shell Welding	6691	5601	158	1228
10/20/88	On Ass'y Floor	6619	5545	-72	-56
12/16/88	In Dewar at 4.3 deg K	4220	5143	-2399	-402
12/26/88	In Dewar at 298 deg K	6072	5360	1853	217
12/27/88	In Dewar at 4.3 deg K	3853	4950	-2219	-411

* - Average of Gauge #5&6

	PACK2 - Transition Section at Return end				
10/ 5/88	After Collaring	N/A	N/A		
10/10/88	Before Shell Welding	8144	4390	N/A	N/A
10/18/88	After Shell Welding	8202	5639	58	1248
10/20/88	On Ass'y Floor	8111	5601	-91	-38
12/16/88	In Dewar at 4.3 deg K	3508	3238	-4604	-2363
12/26/88	In Dewar at 298 deg K	7360	5543	3853	2305
12/27/88	In Dewar at 4.3 deg K	3319	3280	-4041	-2264

2.DSS014 SUMMARY

	Pack1 - Straight Section				
10/19/88	After Collaring	9390	6787		
1/19/89	On Ass'y Floor w/ Shell	9048	7927	-342	1139
1/25/89	In Dewar at 4.3 deg K	4820	4809	-4228	-3117
	Pack2 - Return End Transition				
10/19/88	After Collaring	11816	8005		
1/19/89	On Ass'y Floor w/ Shell	10345	8207	-1471	202
1/25/89	In Dewar at 4.3 deg K	7128	6054	-3217	-2153

16p/18p

Results of warm-cold comparison for magnet dss014 by program WARM run 5-JUN-89 at 13:30:17

dss014.201do is warm dsf
dss014.2376n is up ramp dsf
dss014.2387n is down ramp dsf

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Normal terms															
cold	1.00	0.61	-1.80	0.02	-0.81	-0.02	0.04	0.00	0.03	0.00	0.07	0.00	-0.01	0.00	0.00
warm	1.00	-0.10	-0.80	0.05	-0.98	0.03	0.05	0.01	0.03	0.00	0.07	0.00	-0.01	0.00	0.00
c-w	0.00	0.71	-1.00	-0.03	0.17	-0.06	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Skew terms															
cold	~~0.13~~	-2.60	-0.02	0.06	-0.01	-0.03	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
warm	~~[illegible]~~	-2.43	-0.38	0.29	0.04	0.00	0.01	-0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00
c-w	~~[illegible]~~	-0.17	0.36	-0.23	-0.05	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TABLE IV

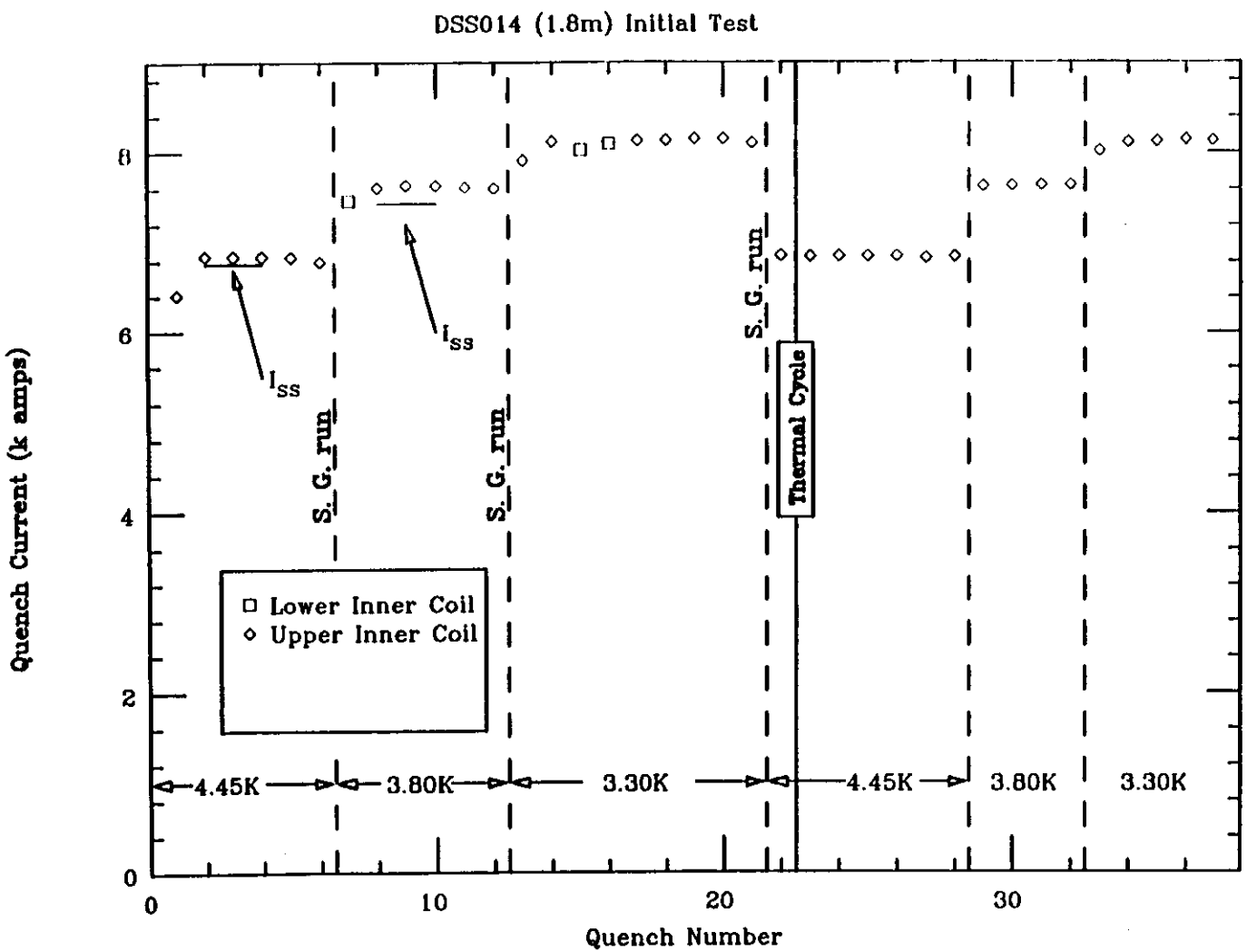
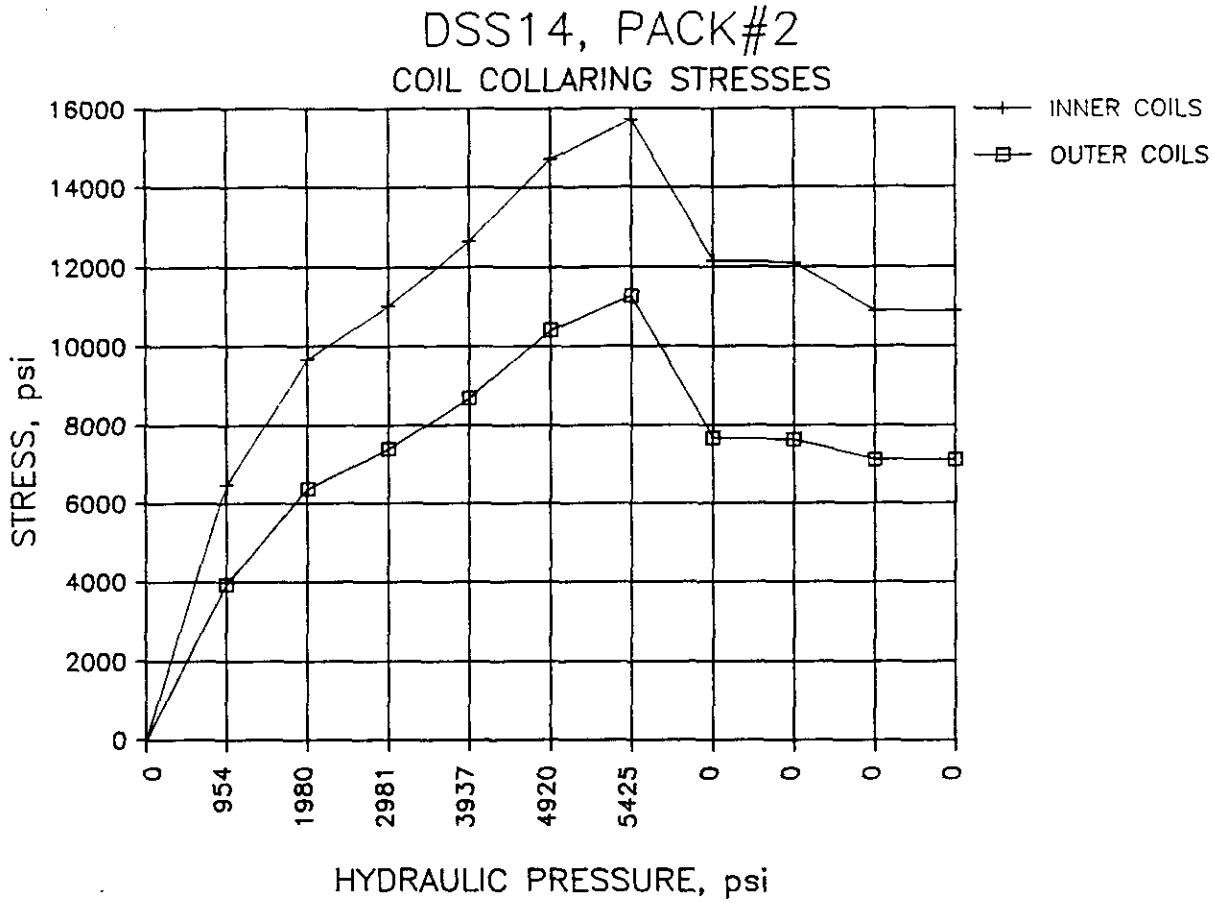

DSS014 (1.8m) Initial Test
Quench Current (k amps)
Quench Number
0
2
4
6
8
0
10
20
30
I_{ss}
I_{ss}
S. G. run
S. G. run
S. G. run
Thermal Cycle
Lower Inner Coil
Upper Inner Coil
4.45K
3.80K
3.30K
4.45K
3.80K
3.30K

Figure 1


DSS14, PACK#2
COIL COLLARING STRESSES
INNER COILS
OUTER COILS
STRESS, psi
16000
14000
12000
10000
8000
6000
4000
2000
0
0
954
1980
2981
3937
4920
5425
0
0
0
0
HYDRAULIC PRESSURE, psi

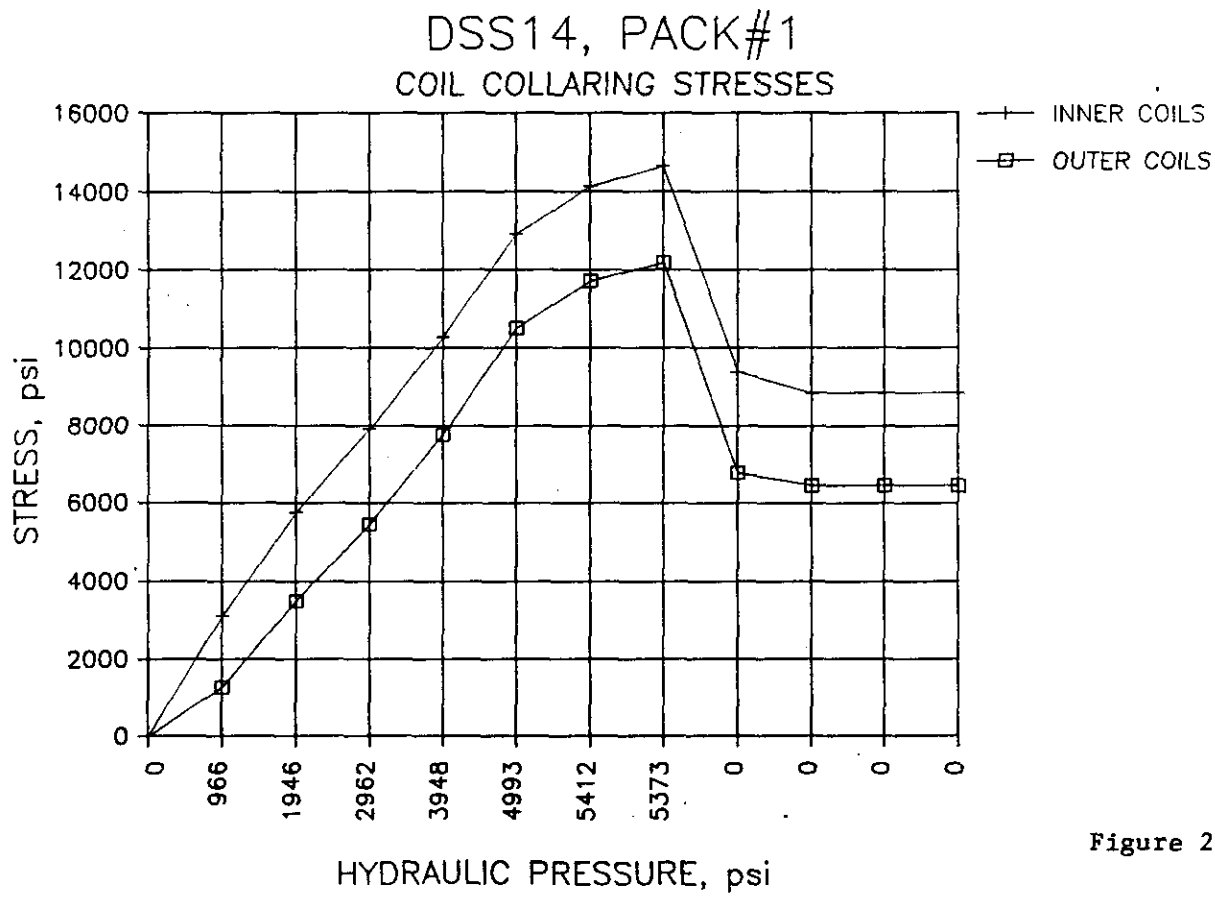
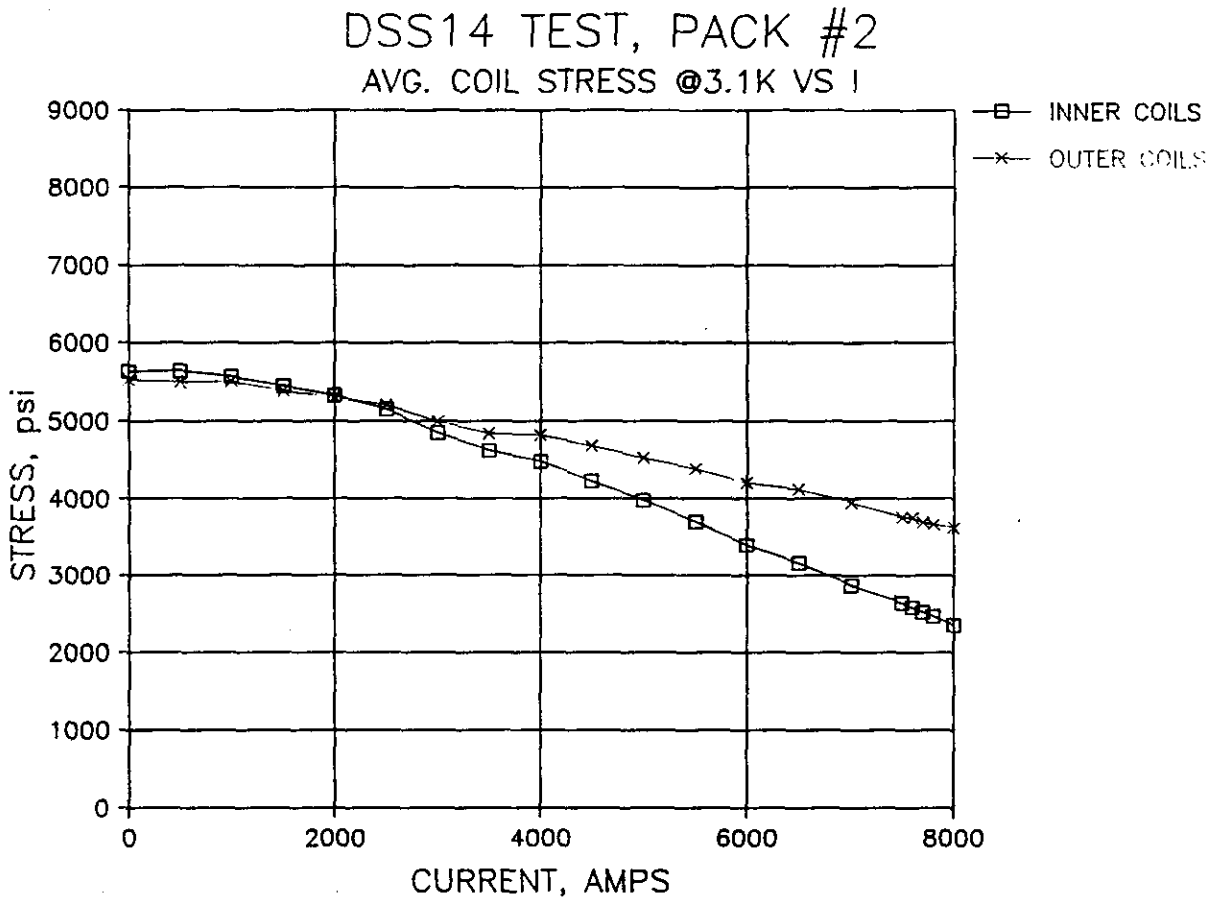

DSS14, PACK#1
COIL COLLARING STRESSES
INNER COILS
OUTER COILS
STRESS, psi
16000
14000
12000
10000
8000
6000
4000
2000
0
0
966
1946
2962
3948
4993
5412
5373
0
0
0
0
HYDRAULIC PRESSURE, psi

Figure 2


DSS14 TEST, PACK #2
AVG. COIL STRESS @3.1K VS I
INNER COILS
OUTER COILS
STRESS, psi
CURRENT, AMPS
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
2000
4000
6000
8000

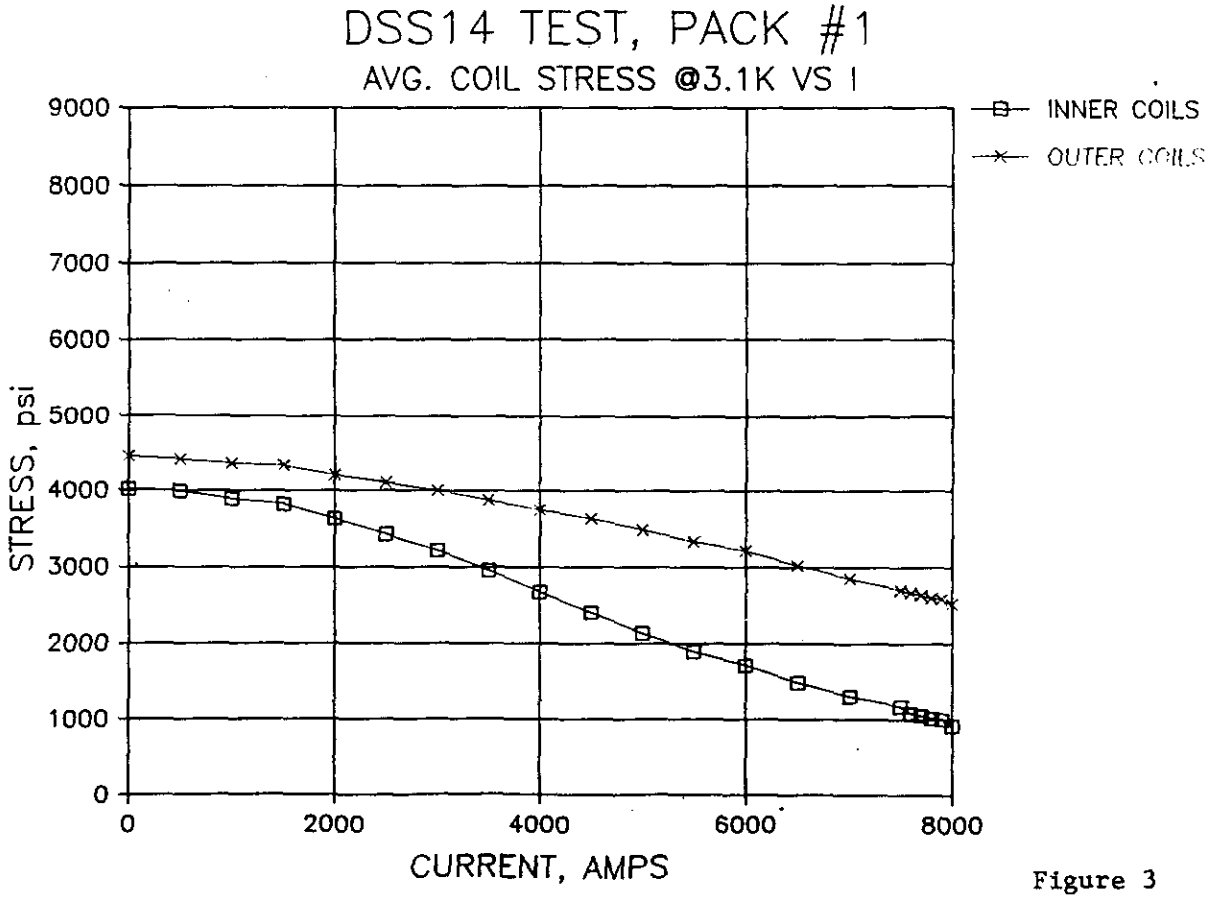

DSS14 TEST, PACK #1
AVG. COIL STRESS @3.1K VS I
INNER COILS
OUTER COILS
STRESS, psi
CURRENT, AMPS
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
2000
4000
6000
8000

Figure 3

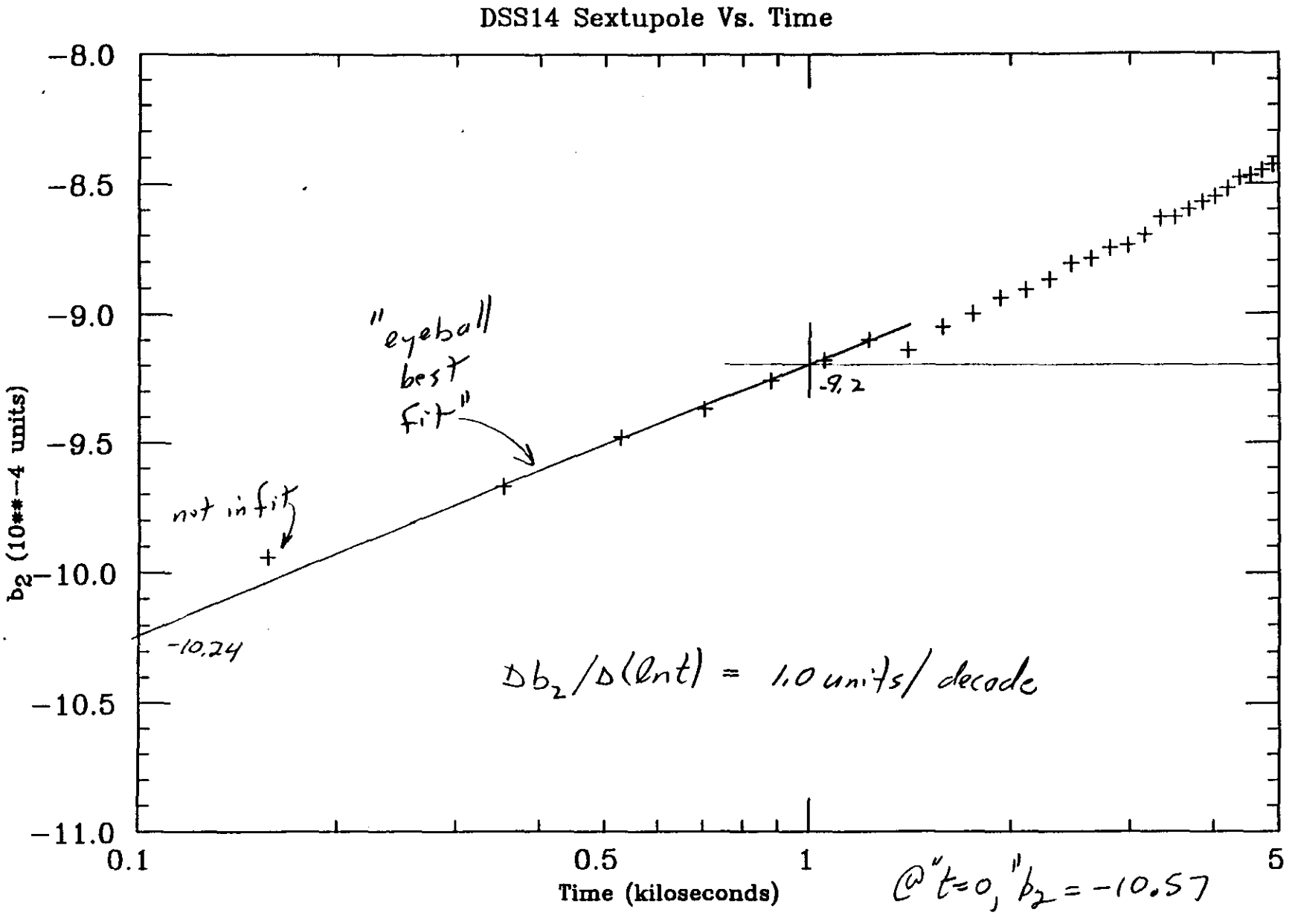

DSS14 Sextupole Vs. Time
-8.0
-8.5
-9.0
-9.5
-10.0
-10.5
-11.0
b2 (10**-4 units)
0.1
0.5
1
5
Time (kiloseconds)
"eyeball best fit"
not in fit
-9.2
-10.24
Db2/D(lnt) = 1.0 units/decade
@"t=0," b2 = -10.57

Figure 4

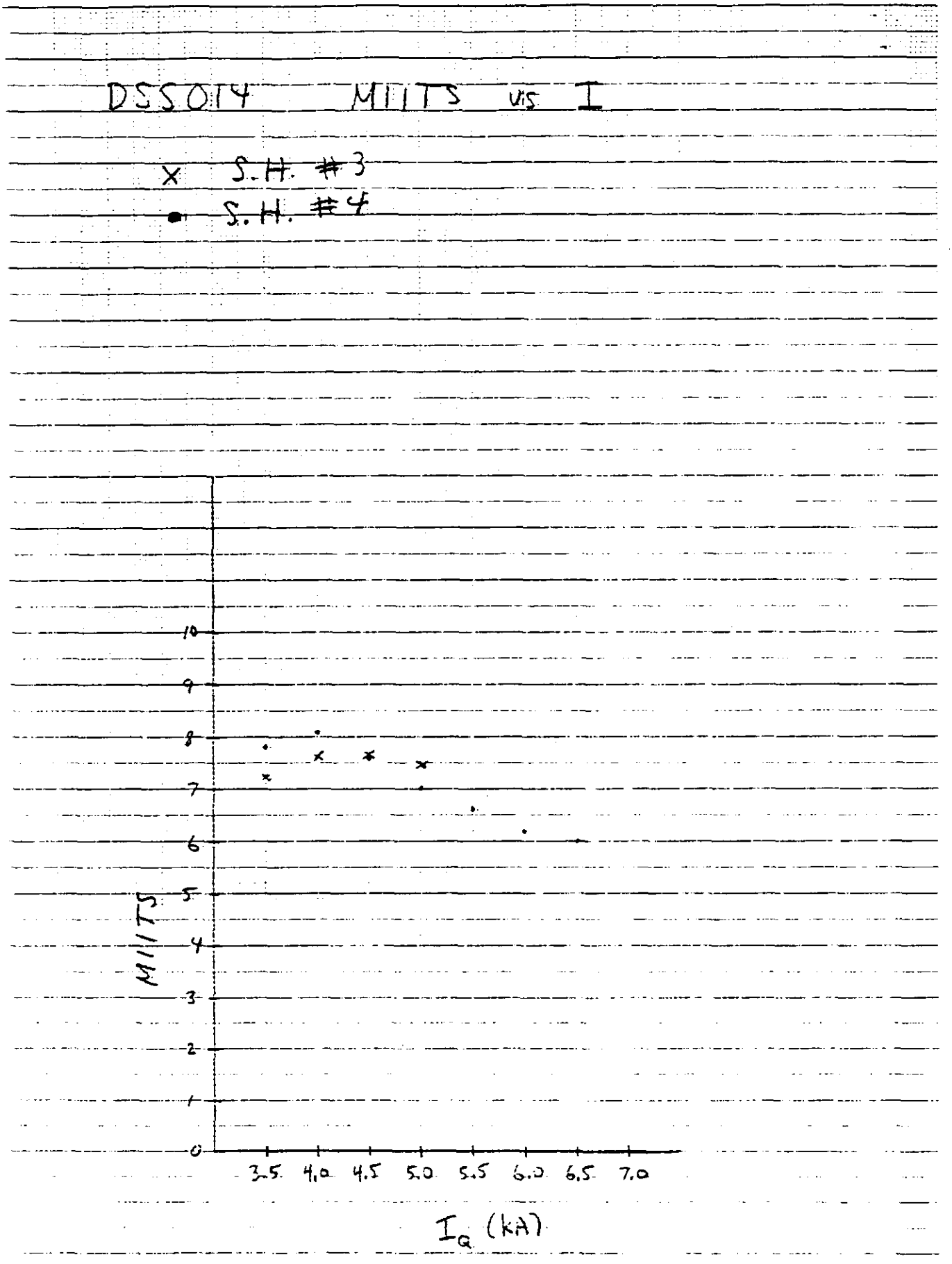

DSSO14 MIITS vs I
x S.H. #3
• S.H. #4
MIITS
10
9
8
7
6
5
4
3
2
1
0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
I_Q (kA)

Figure 5

APPENDIX A

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BNL-41898

TEST OF TWO 1.8 M SSC MODEL MAGNETS WITH ITERATED DESIGN*

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Abstract

We report results from two 1.8 m-long dipoles built as part of the Superconducting Super Collider (SSC) R&D program. These magnets contain design changes made on both the 1.8 m and the full-length 17 m dipoles to improve quench performance, magnetic field uniformity, and manufacturability. The magnets reach 8 T with little training.

Introduction

The good quench performance of two recent 17 m model dipoles [1] established the principles needed for producing magnets capable of reaching the conductor current-carrying limit with little training. Design changes have been made to implement these principles and other improvements in a more production-oriented way. Except for length, the 1.8 m magnet series [2,3] has the features of the SSC design, which is based on a two-layer cosine theta coil with 4 cm aperture. As compared to the 17 m design length SSC dipoles, these 1.8 m magnets are a faster and more economical way of testing design changes. To check magnet performance, these dipoles have been heavily instrumented with voltage taps, strain gauges and spot heaters. Existing tooling sets the magnet length at 1.8 m. The magnets are tested in liquid helium in a vertical dewar.

The design changes incorporated in these magnets are briefly summarized here. The coils were wound with a revised cross section which included asymmetric copper wedges and were molded in a single-cure procedure. In both magnets, the collars which compress the coils were locked with tapered keys. When one of the magnets was assembled, however, no pressure was applied to push the keys into the collars. The yoke inner diameter was reduced to obtain a line-to-line (zero clearance) fit to the collars. The yoke laminations were assembled to produce a monolithic yoke structure. The two yoke halves were keyed with respect to each other at the midplane.

Magnet Design and Construction

The coil aperture is 4 cm and the coil outer diameter is 8 cm. The yoke inner diameter is 11.1 cm; its outer diameter is 26.7 cm. The magnet is designed to operate at 6.6 T central field in 4.35 K helium with a current of 6.5 kA. Features of the magnet design which are not discussed in detail here are as described in the SSC Conceptual Design Report (CDR). [4]

Cable

The cable used in the inner (outer) quarter coils of both magnets came from a single reel. It had a critical current density of 2.77 (2.43) kA/mm^2 at 5 T, 4.22 K, a copper-to-superconductor ratio of 1.47 (1.74), a filament size of 6 (5)μm, and a relative resistance ratio between room temperature and 10 K of 63 (123).

Coil

A cross section of the collared coil in the yoke and helium vessel is shown in Fig. 1. The coil cross section (designated C358D) is a four-wedge non-radial block design. [5] The design differs only slightly from the previous design (C358A). The change was made to further reduce allowed multipoles.

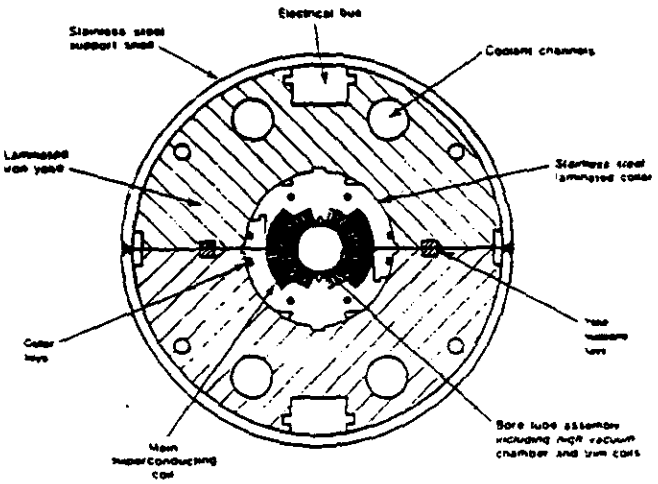

Fig. 1 Collared coil and yoke.

To eliminate the abrasion of wedge insulation during coil molding, the outer radius of the wedges was made with the same curvature as the coil. The result, in this non-radial design, was an "asymmetric" wedge.

To improve coil molding time, a "single size of the shim used in the curing fixture was determined from a size measurement made in the same fixture when the B-stage epoxy had become just warm enough to liquify. Also, further changes were made to the coil ends to make them stronger and more uniform in size.

Coil Assembly and Collaring

The G10 "ramp-splice" assembly was modified to better support and prestress the cable. This piece encapsulates the inner coil cable as the cable moves to the outer coil radius; it also encapsulates the splice between the inner and outer coils.

As in earlier models [2], the collars were punched from Nitronic 40 stainless steel and spot welded in pairs, with the pairs then left-right alternated to prevent twist in the collared coil. Tapered keys were used in the collaring. For DSS013, the usual procedure for tapered key assembly was followed, whereby the overall prestress on the magnet during collaring is minimized by using both vertical and horizontal force to seat the keys. As an experiment to test differences between this procedure and assembly with rectangular keys, DSS014 was assembled with tapered keys but with no significant horizontal force.

Yoke and Shell

The inner radius of the yoke laminations was 0.63 mm smaller than on previous magnets so that there would be a line-to-line (zero clearance) fit of yoke and unstressed collars at room temperature.

For the portion of the yoke which covered the straight section of the magnet, 15 cm-long stacks of standard iron laminations were alternated with single stainless steel laminations punched to provide channels for radial helium flow during quenches. All the laminations were stacked on rods and then compressed to a predetermined length to obtain a "monolithic" axial structure. The yoke end (including the last 5.2 cm of the inner coil straight section) contained only stainless steel laminations, bonded together.

To assure correct relative positioning, the two yoke halves were keyed together at the midplane with iron keys, as shown in Fig. 1. The stainless steel half shells were then welded around the

*Work performed under the auspices of the U.S. Department of Energy

yoke. The welding was done by hand, by two welders. The rods used to stack the yoke were withdrawn after the welding was completed and the end plates installed. A modest preload (a few hundred pounds) was applied to the coil ends via the one-piece 38.1-cm thick end plates.

Test Results

Quench Data

The initial quench program was carried out at temperatures close to those of SSC operation, 4.35 K. The helium temperature was then lowered in two 0.5 K steps to determine the mechanical limits of magnet performance. After a cycle to room temperature, these steps were repeated. As seen in Figs. 2 and 3, both magnets reached the conductor limit at fields above 8 T with little training and the training was retained after a thermal cycle. The maximum quench current in DSS013 was 8.11 kA; in DSS014 it was 8.14 kA. The current required to reach 8.0 T is approximately 8.07 kA.

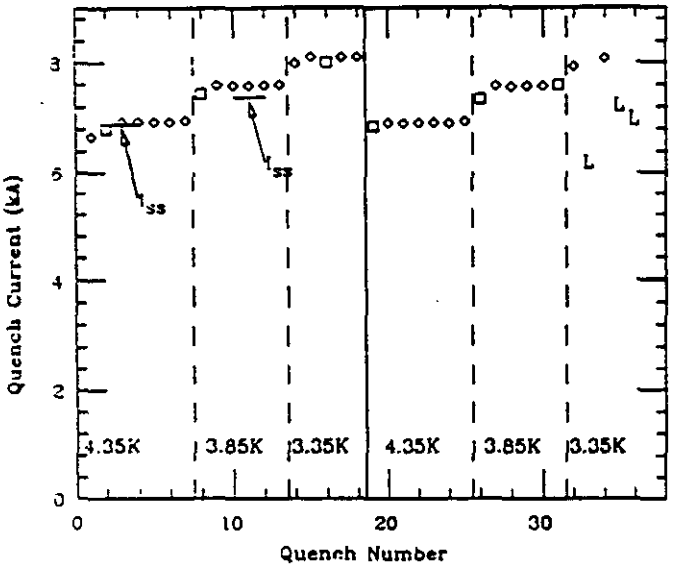

Fig. 2 Quench performance of DSS013. The solid line indicates a thermal cycle. Quenches originating in the lower (upper) inner coil are indicated by squares (diamonds). I_{SS} is the calculated quench current, based on measurements made on a short sample of the cable. Quenches designated L were due to a test stand fault.

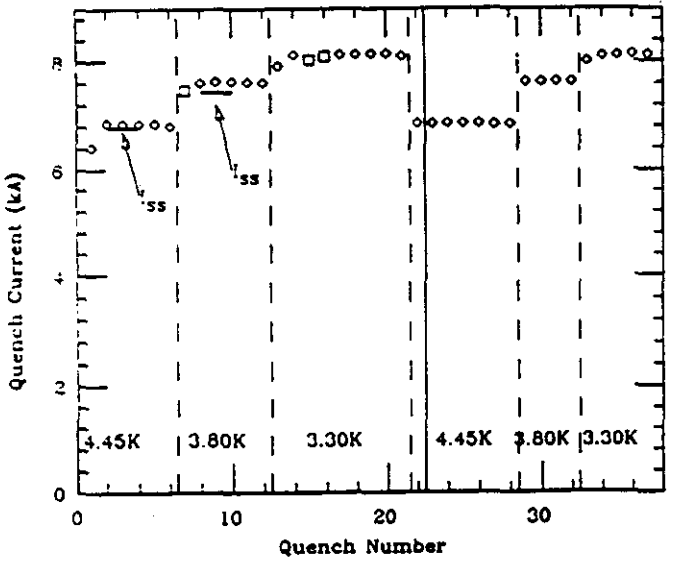

Fig. 3 Quench performance of DSS014. (Notation is the same as in the previous figure.)

Each magnet had more than 100 voltage taps, nearly all in the inner coils. Quenches which occurred when the magnet reached the current-carrying capacity of the conductor ("plateau" quenches) originated in the expected place, the pole turns of the inner coils. At 4.35 K, plateau quenches were at 6.93 kA, reproducible within about 0.01 kA.

Taking the locations of the non-plateau quenches of the two magnets as a group, the most common origin was the section of inner coil cable 5–10 cm beyond the G10 ramp-splice assembly. Other quenches also originated in the pole turn, in and near the non-lead end, and in the turn next to the largest wedge.

The longitudinal quench velocities generally agree with those in 17 m SSC dipoles. [6] These velocities are substantially higher than those measured in 4.5 m SSC dipoles [7] and in 1 m SSC models built at LBL [8]. These velocities are also faster than would be calculated in the adiabatic approximation. [6] The reason for this discrepancy is not understood at this time. Azimuthal quench velocities are about the same for all these magnets.

Stress Measurements

Each of the magnets was instrumented with two "beam-type" strain gauge packs. [9] One pack was located in the straight section, near the lead end. The other was the last pack in the straight section at the non-lead end. Each pack had four gauges for each coil, plus temperature compensating gauges. Average data from the gauge pack in the straight section of DSS013 are presented in Fig. 4. Gauge-to-gauge variations in stress make the average stress somewhat uncertain; however, the linear variation with I^2 does indicate that the coils do not become unloaded at the highest current measured, 7.5 kA.

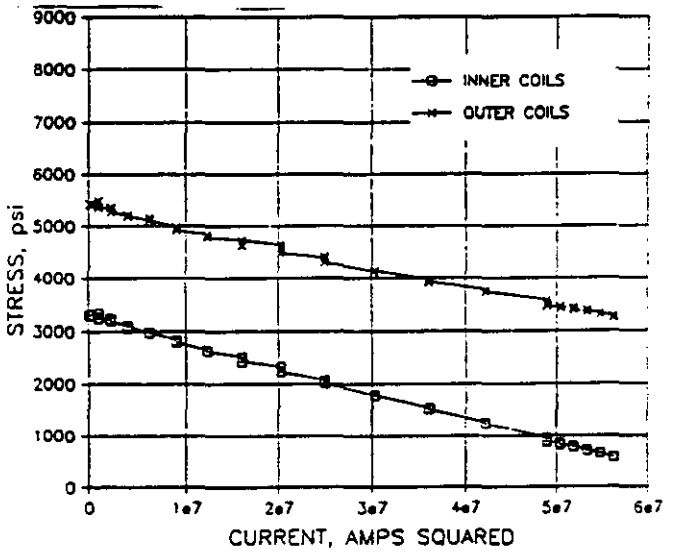

Fig. 4 Average inner coil stress vs. I^2, for strain gauge pack in DSS013 straight section.

Field Strength and Multipoles

The notation for multipoles is defined by the following equation:

$$B_y + iB_x = B_o \sum_{n=0}^{\infty} (b_n + ia_n)(x + iy)^n$$

where B_o is the dipole field, x and y are the horizontal and vertical coordinates measured from the magnet center. It is convenient to define a multipole "unit" as 10^{-4} of the dipole field, with the multipole evaluated at a radius of 1 cm.

Magnetic field measurements from the central section of the magnets are reported in Table I. The variation of the sextupole with current is shown in Fig. 5. The multipoles were measured with a

76-cm long rotating coil centered axially in the magnet. Measurements have been analyzed to remove feeddown and magnetization effects. [2]

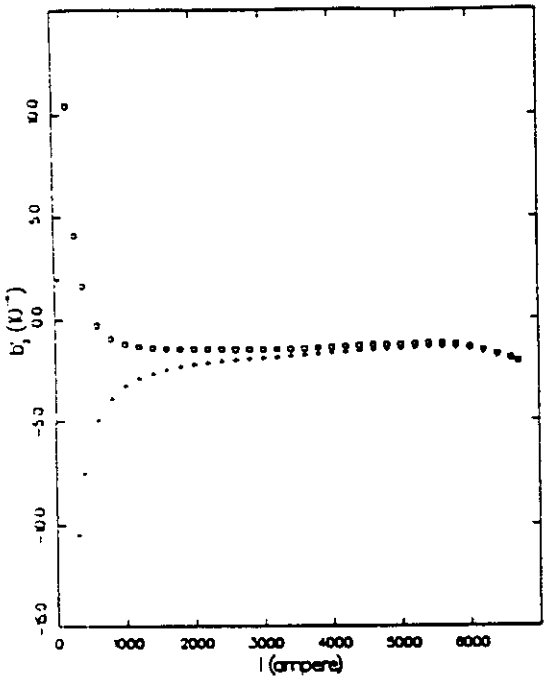

Fig. 5 Variation of sextupole with current in DSS014. The crosses are up-ramp data; the squares, down-ramp data.

Insofar as can be determined from two 1.8 m magnets, the higher order terms meet the SSC two-dimensional tolerances. [10] The low order terms deserve further comment. The quadrupole terms can be affected by the hand-welding involved in welding the shell around the yoke. Use of an automatic welding machine, to be introduced in the future, may reduce these terms. Allowed multipoles can be affected by changes in production procedures, such as the implementation of the line-to-line yoke-collar fit. It should be possible to compensate for these effects by making further small changes in the coil cross section.

Table I
Multipole Coefficients (1 "unit" = 10^{-4} B_0, r = 1 cm)

	Measured		SSC Tolerances (body)	
Coefficient	DSS013	DSS014	Random (rms)	Systematic
a_1	−.55	−2.53	0.7	0.2
a_2	−.65	−.01	0.6	0.1
a_3	.43	−.12	0.7	0.2
a_4	−.12	−.01	0.2	0.2
a_5	−.02	−.03	0.2	—
a_6	−.02	.01	0.1	—
a_7	−.01	−.01	0.2	—
a_8	.00	.00	0.1	—
b_1	−.55	.42	0.7	0.2
b_2	−2.80	−1.86	2.0	1.0
b_3	−.19	.01	0.3	0.1
b_4	−.59	−.82	0.7	0.2
b_5	.00	−.01	0.1	0.04
b_6	.02	.04	0.2	0.07
b_7	−.01	.01	0.2	0.1
b_8	.05	.03	0.1	0.2

The field strength was measured with an NMR probe at 1.8 T. The measured transfer functions were 1.0460 T/kA for DSS013 and 1.0463 T/kA for DSS014. The calculated value is 1.0439 T/kA, with design shims.

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[10] SSC Specification Number SSC-MAG-D-1010 (December 1988).

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