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HGQ03A Test Summary Report

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Chapter 1

General Overview

1.1 Test Summary Report Outline

This report presents preliminary results of HGQ03A testing at the FNAL Vertical Magnet Test Facility. HGQ03A is the rebuilt version of HGQ003 which was the third 70 mm-aperture, short R&D model LHC quadrupole built at FNAL.

The cold testing overview is presented in chapter 1.

Chapter 2 is devoted to quench performance tests. An overview of quench history followed by quench start locations summary is presented. Relevant test conditions and results are given in summary tables.

Chapter 3 summarizes strain gauge (SG) runs performed throughout the first test cycle. Included here are summary sheets of all SG runs, and representative plots of coil stress and end force vs. I^2 (where I is the magnet excitation current) to the highest attainable current at each test temperature. Also included are tables summarizing SG readings at 0 A magnet excitation current (warm, before and after cool down), and plots of stress and end forces vs. time (summarizing SG history for the entire first test cycle).

Chapter 4 presents the results of splice resistance measurements.

1.2 Test Overview

HGQ03A was tested according to the runplan attached as an Appendix to this note. The magnet was placed into the VMTF dewar and room temperature magnetic measurements were performed on December 2. HGQ003 was first cooled down on December 3, 1998 and cold testing began on December 5. The test ended on December 11, 1998.

After warm magnetic measurements the initial cooldown was to 4.25K without restriction on the differences between any of the temperature sensors located in the VMTF dewar. The first spontaneous quench of the magnet occurred at 7438 A. Four additional quenches were made at the same 20A/sec ramp rate. Since the highest quench current was well below the sort sample limit the magnet was cooled to 1.9 K. Strain gauge runs were performed, and the first quench at 1.9K occurred at 11228 A. The magnet was quenched 18 additional times. The magnet exhibited very shallow training curve so we closed the the quench test with quench current temperature dependence studies. The magnet was quenched at 8 different temperatures ranging from 1.8K to 4.25K. At 4.25 K we performed EIEO measuremnets and the magnet was warmed up.

Chapter 2

Quench behavior

This chapter summarizes the quench behavior of the magnet. Instrumentation settings for the HGQ03A test are summarized in Table 2.1 and Table 2.2; a detailed description of the instrumentation and its configuration is presented elsewhere.

Quench data acquisition was performed using the VMTF (pentek) readout system with binary quench data stored on a UNIX workstation. The location of the files are on MTF UNIX cluster:

/vmtf/data/Quench/vmtf.hgq003_1/

The names of the quench files are summarized in Table 2.4. The data were analyzed using the quenchXmgr utility. HGQ003 had about 96 voltage taps, primarily instrumenting the pole turns and wedges on the four inner and outer coil quadrants and inner/outer coil splice regions.

2.1 Quench history

HGQ03A was tested according to the run plan attached as an Appendix to this note. The quench history is summarized in Table 2.3 and in Figure 2.1. Quench testing began at 4.25K at a ramp rate of 20A/s. The first spontaneous quench current was at 7438A, and the four additional quenches at 20A/s successively increased in quench current; the fifth quench reached 9245A. Since the predicted short sample limit of the superconducting cable used in this magnet is 11000A, the quench current obtained is about 15% below that expected. We cooled the magnet to 1.9K. At 1.9K the magnet was quenched 19 times (quench number 6 - 24) with 20A/sec ramp rates. The 6^{th} (first 1.9K quench of the second test cycle) was at 11228A, which is about 25% below the short sample limit of the cable, but much higher that any other HGQ model magnet's first 1.9K quench. The magnet exhibited very slow training behavior. The 24th quench current was still pretty low relative to the short sample limit (12133A). No significant improvement of the quench current was observed so we stoped training the magnet.

At the end of the test, 8 additional quenches were taken at temperatures ranging from 1.9K to 4.15K to study quench current dependence on temperature. In these studies, the magnet was ramped to quench at 20A/sec. The result of this study is summarized in Figure reffig:qtemp. As one can conclude from the plot the quench current doesn't depend on the the temperature up to 3.4 K. As the temperure increases above 3.4 K the magnet quench current seems to follow the prediction.

2.2 Quench locations

Voltage taps that instrumented HGQ03A allowed for localization of most quenches, however about 14% of the taps were bad and few quench locations were hard to localize. The locations of each spontaneous quenches are summarized in Table 2.3. Some of the location were ambiguous due to the lack of voltage taps and to obtain approximate locations quench antenna information was used.

Table 2.1: Instrumentation settings - spontaneous quenches

Dump Resistor	Resistance	$60 m\Omega$
	Time Delay	$25 msec$
Power Supply	Time Constant	$0.5 sec$
HFU	Capacitance	$14.4 mF$
	Time Delay	$0 - 20 msec$
	Voltage	$300V@4.3K$
		$350V@1.9K$
Data Logger	Sampling frequency	$7.4 kHz$
	Pre-quench window	50%
Current read back	Hollec	

Table 2.2: QDC settings

AQDC name	Threshold settings	Threshold values
Whole coil	1.0	10 V
Whole coil - Idot	0.4	4.0 V
Bucked Half coils	0.15	0.48 V
SC Leads	0.73	0.03 V
Cu Leads	0.76	0.03 V
Ground	1.26	0.1 V

Table 2.3: Quench history.

Quench num	T [K]	dI/dt [A/s]	I_q [A]	Quench location
1	4.25	20	7438	Q4O15a_Q4O16b Le.end Next to Vtap 15a
2	4.25	20	8910	Q4O15a_Q4O16b Le.end Next to Vtap 15a
3	4.25	20	9003	Q2I13b_Q2I14c (Le.end from Quench Antenna)
4	4.25	20	9076	Q3I12b_Q3I14a Le.end 1.4 msec from 14a
5	4.25	20	9245	Q4IOrs_Q4I14d Le.end - close to Vtap 14b
6	1.9	20	11228	Q4IOrs_Q4I14d Le.end - close to Vtap 14b
7	1.9	20	11440	Q4I14c_Q4I14d Re.end - 47% from 14c
8	1.9	20	11533	Q1I14c_Q1I14d Re.end - 46% from 14c
9	1.9	20	11583	Q2I14b_Q2I14c St.sec - 4.5 msec (~14 cm) from 14b
10	1.9	20	11606	Q4IOrs_Q4I14d Le.end - close to Vtap 14b
11	1.9	20	11744	Q2I13b_Q2I14c (Le.end from QA)
12	1.9	20	11828	Q1I14c_Q1I14d Re.end - 40% from Vtap 14c
13	1.9	20	11853	Q4IOrs_Q4I14d Le.end - close to Vtap 14b
14	1.9	20	11887	Q2I13b_Q2I14c (Le.end QA)
15	1.9	20	11905	Q4I14c_Q4I14d Re.end - 37% from 14d
16	1.9	20	11914	Q3I12b_Q3I14a Le.end 1.8 msec from 14a
17	1.9	20	11929	Q2I14b_Q2I14c (Re.end from QA)
18	1.9	20	12015	Q2I13b_Q2I14c (Le.end from QA)
19	1.9	20	12075	Q4IOrs_Q4I14d Le.end - close to Vtap 14b
20	1.9	20	12105	Q3I11a_Q3I11c St.sec 4.6 msec (~12 cm) from 11c
21	1.9	20	12121	Q2I14b_Q2I14c (Re.end from QA)
22	1.9	20	12126	Q2I13b_Q2I14c (Le.end from QA)
23	1.9	20	12133	Q1I14c_Q1I14d Re.end - 39% from 14c
24	1.9	20	12133	Q1I14d_Q1I14b St.sec 10 msec (~35 cm) from 14b
25	1.99	20	12182	Q3I12b_Q3I14a Le.end 1.4 msec from 14a
26	2.10	20	12174	Q2I11c_Q2I11a St.sec 9.7 msec from 11a
27	2.16	20	12170	Q4I11b_Q4I11d St.sec 1.7 msec from 11d
28	2.46	20	12176	Q4I14c_Q4I14d Re.end - 37% from 14d
29	2.66	20	12232	Q3I14c_Q3I14b (Re.end from QA)
30	3.46	20	12040	Q2O16d_Q2O16a (Le.end from QA)
31	3.95	20	11327	Q4O16d_Q4O16a 5.5 msec from 16d (Le.end from QA)
32	4.15	20	11111	Q1O16a_Q1O16c (Le.end from QA)

Table 2.4: Quench files

Quench num	File name
1	hgq003.Quench.980829110619.947
2	hgq003.Quench.980829114552.733
3	hgq003.Quench.980829121202.786
4	hgq003.Quench.980829133400.360
5	hgq003.Quench.980829150808.274
6	hgq003.Quench.980901143203.748
7	hgq003.Quench.980901153002.796
8	hgq003.Quench.980908203413.389
9	hgq003.Quench.980908212705.283
10	hgq003.Quench.980909141839.422
11	hgq003.Quench.980909153034.742
12	hgq003.Quench.980909162456.445
13	hgq003.Quench.980909171659.658
14	hgq003.Quench.980909180252.684
15	hgq003.Quench.980909190809.804
16	hgq003.Quench.980909201505.136
17	hgq003.Quench.980910101026.327
18	hgq003.Quench.980910110609.488
19	hgq003.Quench.980910121101.531
20	hgq003.Quench.980911133313.440
21	hgq003.Quench.980911141521.763
22	hgq003.Quench.980911151227.248
23	hgq003.Quench.980911171518.936
24	hgq003.Quench.980911175000.366
25	hgq003.Quench.980914160606.748
26	hgq003.Quench.980914182705.973
27	hgq003.Quench.980914210513.919
28	hgq003.Quench.980914223100.526
29	hgq003.Quench.980918205718.218
30	hgq003.Quench.980918220311.413
31	hgq003.Quench.980918233257.371
32	hgq003.Quench.980919004427.607

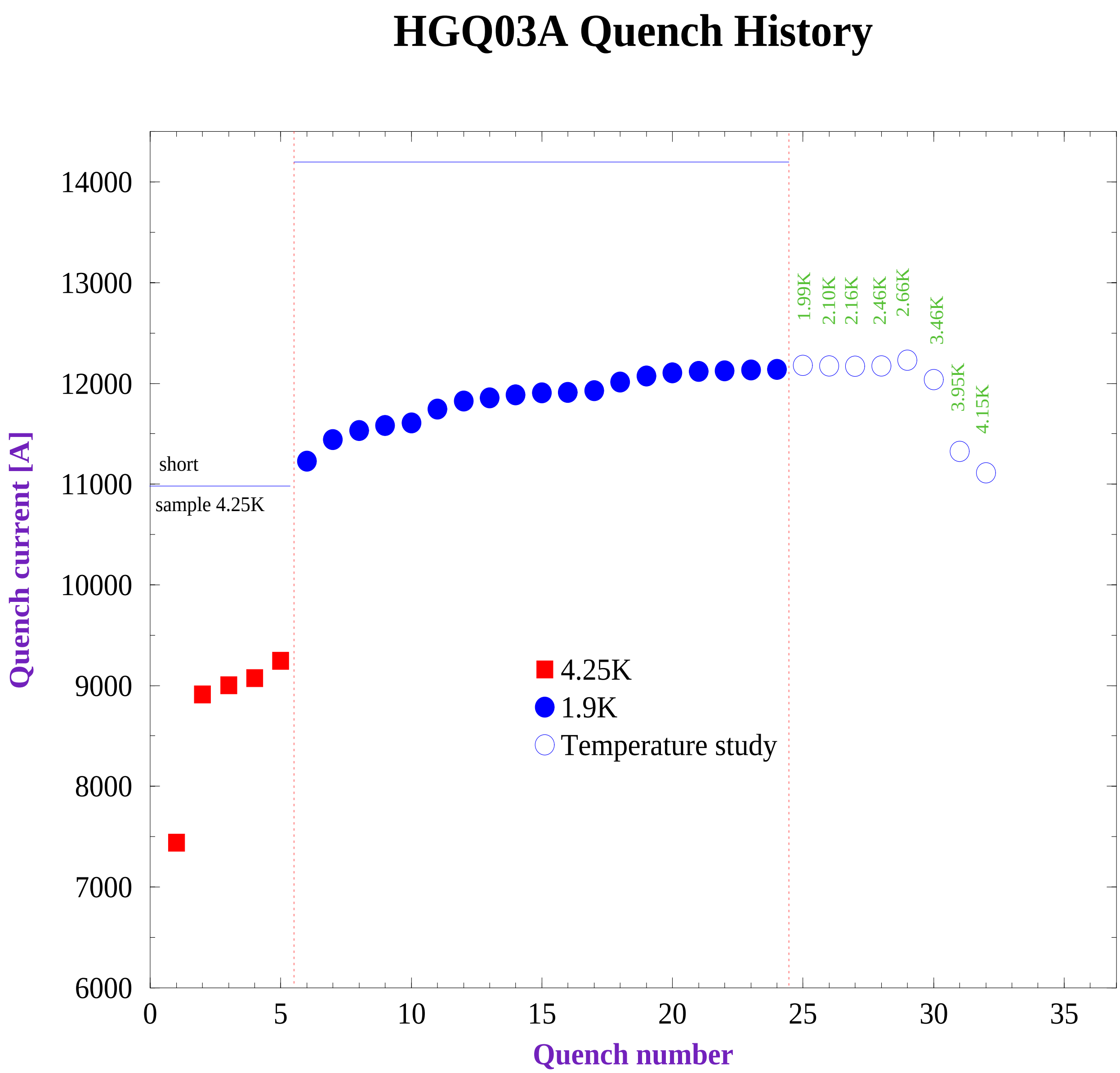

Figure 2.1: Quench history

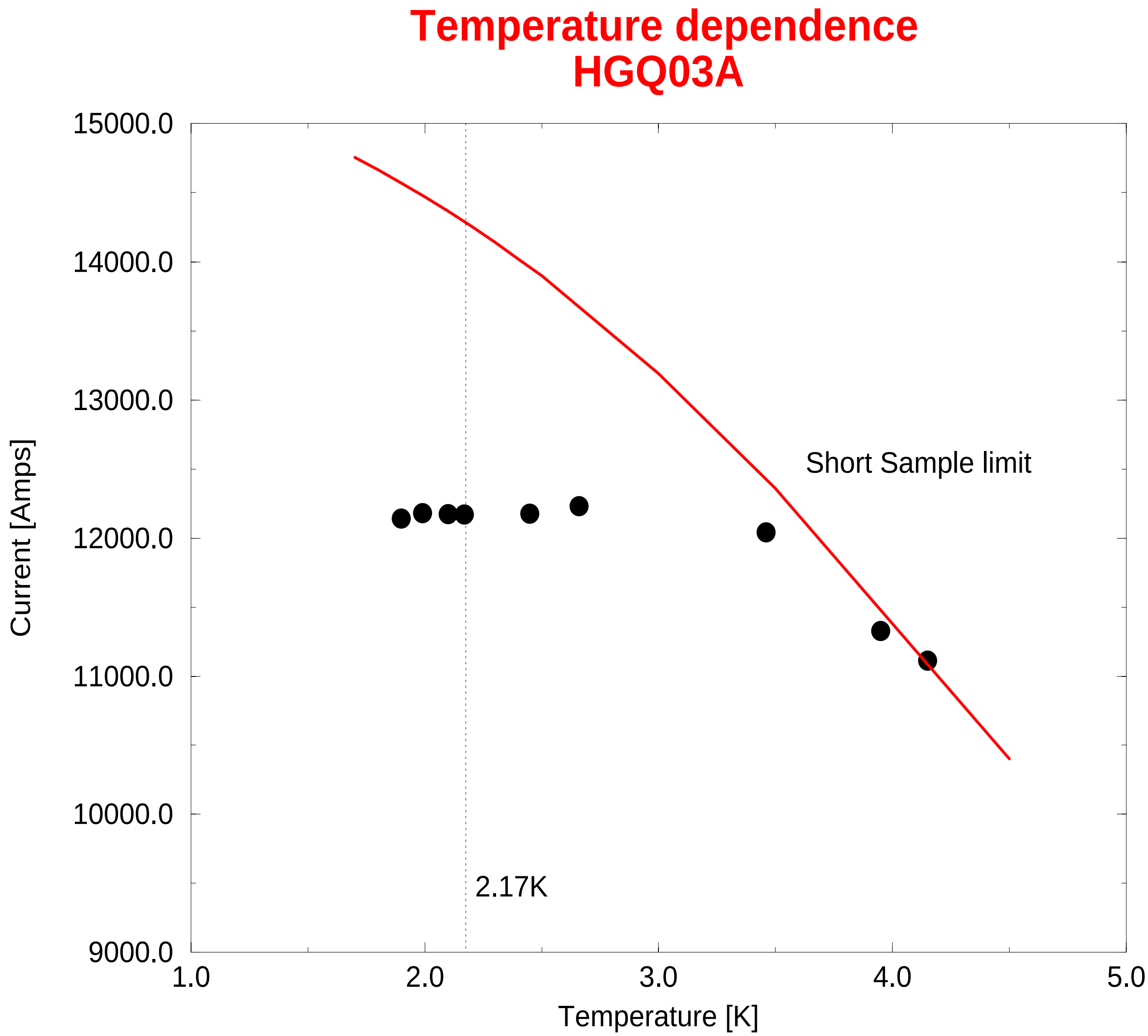

Figure 2.2: Quench current temperature dependence

Chapter 3

Strain Gauge Results

3.1 Instrumentation Details

Magnet HGQ03A is instrumented with an assortment of strain gauges to measure azimuthal coil stresses, coil end forces, and shell strains. Except for the shell gauges, these strain gauges are calibrated at room temperature and at liquid Helium temperature. All are read out during various phases of the magnet construction process, and during cryogenic testing.

A total of eight beam-type strain gauges are used to measure azimuthal stresses in the straight section of the coils, four mounted at the inner coils, four mounted at the outer coils. Each active strain gauge has a compensating gauge associated with it, whose purpose is to provide an independent measure of the apparent strains induced in the active gauges due to thermal contraction and magneto-resistance effects.

Four capacitance-type strain gauges were also installed in the straight section of the inner and outer coils (2 for each) to measure azimuthal stress. Each of these gauges were installed in such a way that they were in the same collared coil cavity as one of the beam gauges.

A total of eight bullet-type gauges are used to measure the end forces associated with each inner/outer coil pair. Four bullet gauges are mounted at the return-end of the magnet, while four are mounted at the lead end. Each bullet gauge consists of two strain gauges whose readings are subsequently averaged to eliminate strains resulting from bending of the transducer structure. The resultant strain is then used to compute the force on the bullet.

Two compensating gauges are placed at each end of the magnet, whose readings are averaged in order to provide apparent strain data used in eliminating apparent strains from the active gauges.

Skin gauges were mounted in both azimuthal and longitudinal orientations. Seven active gauges were mounted along the longitudinal axis of the cold mass, in a longitudinal orientation. They were equally spaced along the length, and oriented to be co-linear with the centerline of quadrant 1. Four additional gauges were mounted in an azimuthal orientation at the longitudinal center of the magnet, at different azimuthal locations (0, 30, 60, and about 90 degrees from the centerline of quadrant 1). Two compensating gauges, oriented azimuthally, were placed at the longitudinal center of the magnet, at the 0 and 90 degree azimuthal positions. These compensating gauges later failed (400 Ω short to ground, perhaps via the Cu HX shell). Therefore, apparent strains from magneto-resistive effects have been corrected using compensating gauge data from magnet HG003.

Table I gives the list of coil azimuthal beam strain gauges, names, and locations for magnet HGQ03A, while Table II lists the same information for the bullet gauges, Table III lists this information for capacitance strain gauges, and Table IIII lists the shell gauges.

3.2 Measurement Schedule

Strain gauge readings are performed several times during the magnet construction and testing cycles. Azimuthal coil stresses, measured with beam-type and capacitance strain gauges, are measured during the collaring and yoking/skinning assembly procedures. After the end plates are installed onto the magnet cold mass, the bullet gauges are then installed and the end loading screws torqued to achieve the desired end loads, while the bullet gauges are monitored.

Once cold mass fabrication has been completed, the magnet is moved to the magnet test facility, and prepared for cryogenic testing. At this time, the magnet's return end bullets were re-torqued while monitoring the bullet readings, in order to equalize the return and lead end longitudinal loads. Before, during, and after cryogenic testing all strain gauges are monitored. In particular, strain gauge data is acquired while ramping the magnet before and during quench training at 4.5K and 1.9K. Finally, the strain gauges are read out once the cold mass has been warmed back up to room temperature, so that comparisons with pre-cold test data can be made.

3.3 Results

The azimuthal coil stresses as measured by beam gauges are summarized in Table V, which shows the coil stresses (measured in psi) during various fabrication and operational conditions. Also presented is the average coil stress change during cooldown from 300K to 4.5K (or 1.9K) and also the dynamic change in coil stress as a function of the square of the excitation current. Figure 3.1 shows the azimuthal coil stress history of HGQ003 and HGQ03A during fabrication, through yoking/skinning in ICB, and at various cryogenic conditions.

The bullet gauge data, indicating longitudinal coil load conditions, are presented in Table III Figure 3.2 shows the end load history durng construction, bullet loading, and cryogenic operations. Figures 3.3– 3.6 show the results of strain gauge, bullet gauge, azimuthal and longitudinal skin gauge measurements as a function of I2 for a quench run to 12141A at 1.9K. Note that the azimuthal coil stresses remain non-zero for all values of excitation current. There is no evidence of coil unloading at even the highest current level reached. Furthermore, extrapolation indicates that the lowest pre-loaded coil would only reach zero azimuthal stress at currents above 15 kA, well above the designed operating current and short sample limit. This behavior is essentially identical to that observed for magnet HGQ003.

The plots shown in Figures 3.3– 3.6 are typical of all of the quench runs at 4.5K and 1.9K. No anomalous behavior was observed during cryogenic testing. Additional data/plots can be found at http://mdtf20.fnal.gov/~ozelis/HGQ03A/hgq03A_sum.html. The dynamic mechanical behavior of magnet HGQ03A is summarized in Table VII, along with the previous model magnets in the series. In general, one may conclude the following :

- Additional collar/yoke shimming provided marginal azimuthal prestress increase for the coils.

- Residual collar/yoke shimming appears to have reduced end loading cooldown loss, by restraining shrinkage of coils somewhat.

- Some longitudinal Lorentz loading was reacted by the skin/yoke, and not solely by the end plates.

- Coil azimuthal dynamic behavior was unchanged.

- Quench performance not affected - ends/transitions still a problem. Perhaps a more localized solution (as opposed to a global one) is required.

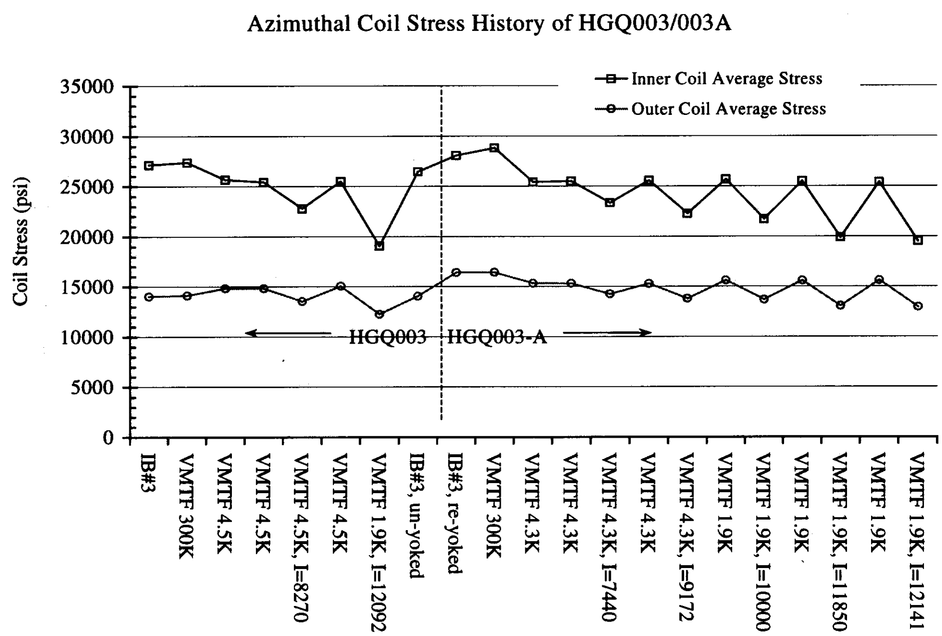

Figure 3.1: Summary of azmiuthal coil stress as measured by beam gauges.

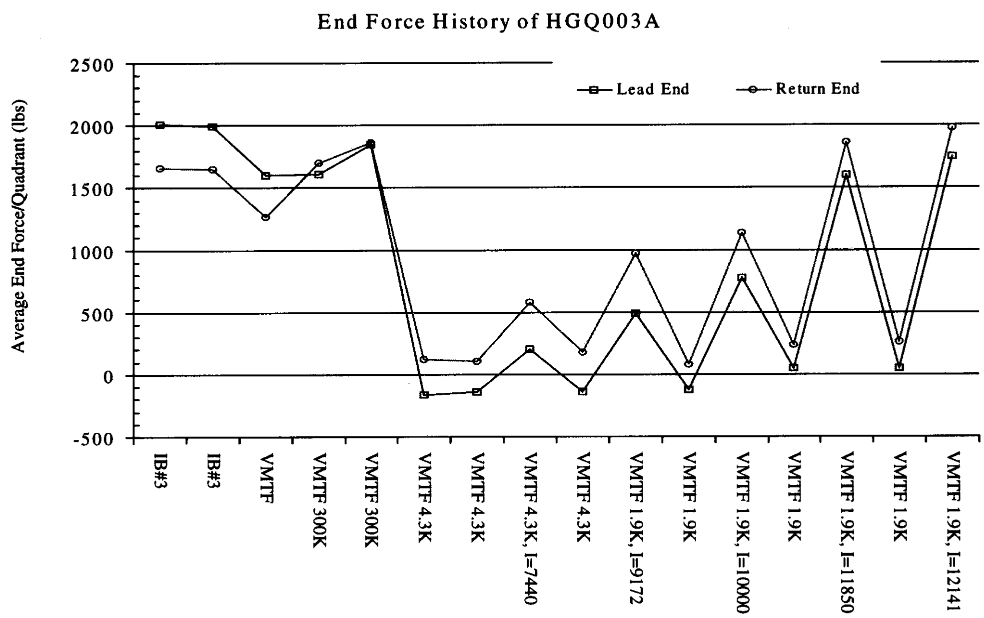

Figure 3.2: Average lead and return end longitudinal coil force during construction and cryogenic operations.

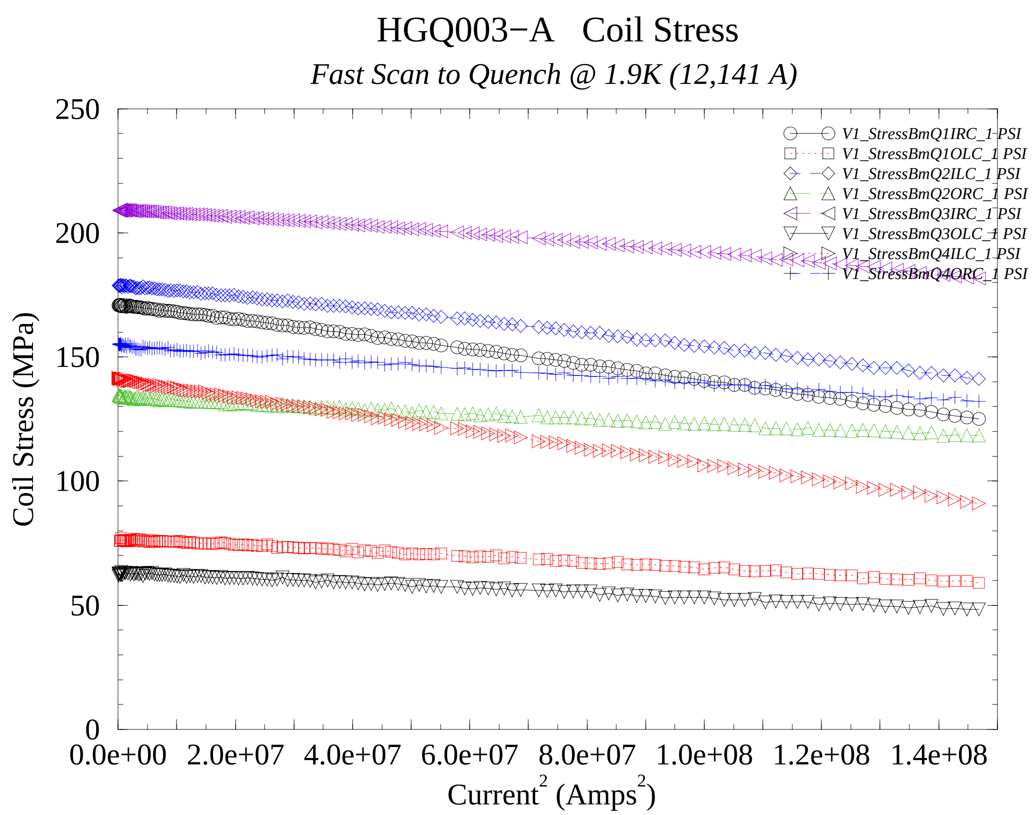

Figure 3.3: Azimuthal coil stress measured by beam gauges for a run to quench (12092A) at 1.9K

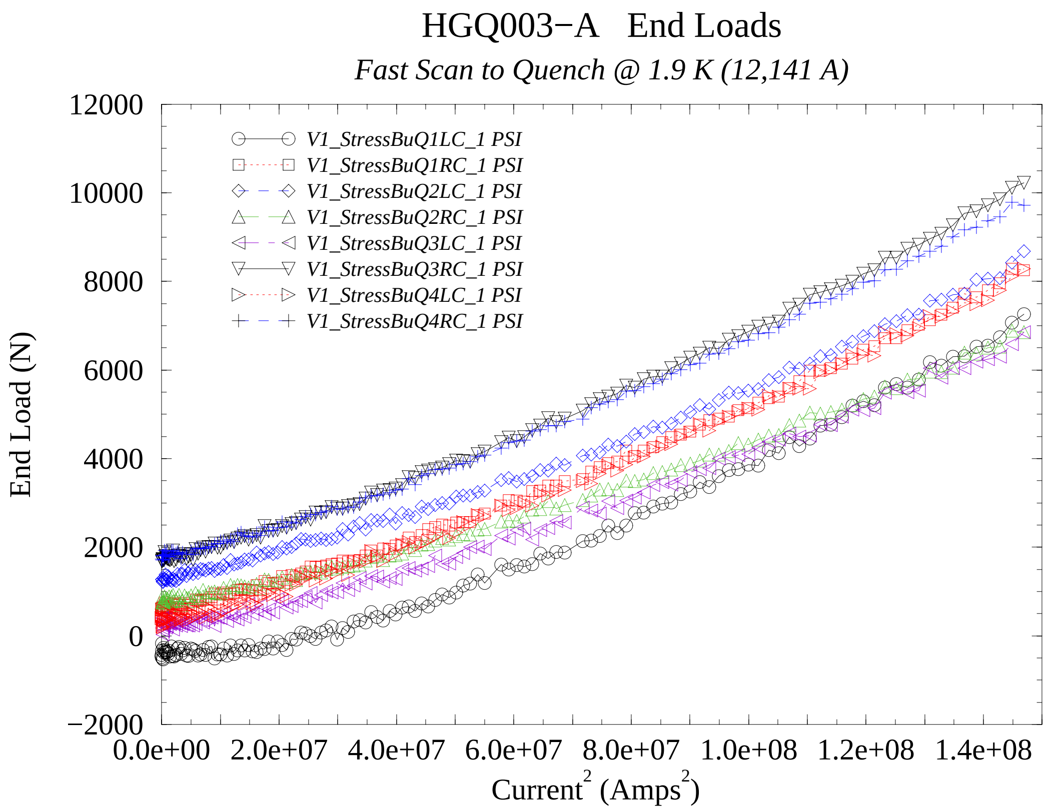

Figure 3.4: Longitudinal coil force measured by bullet gauges for a run to quench (12141A) at 1.9K

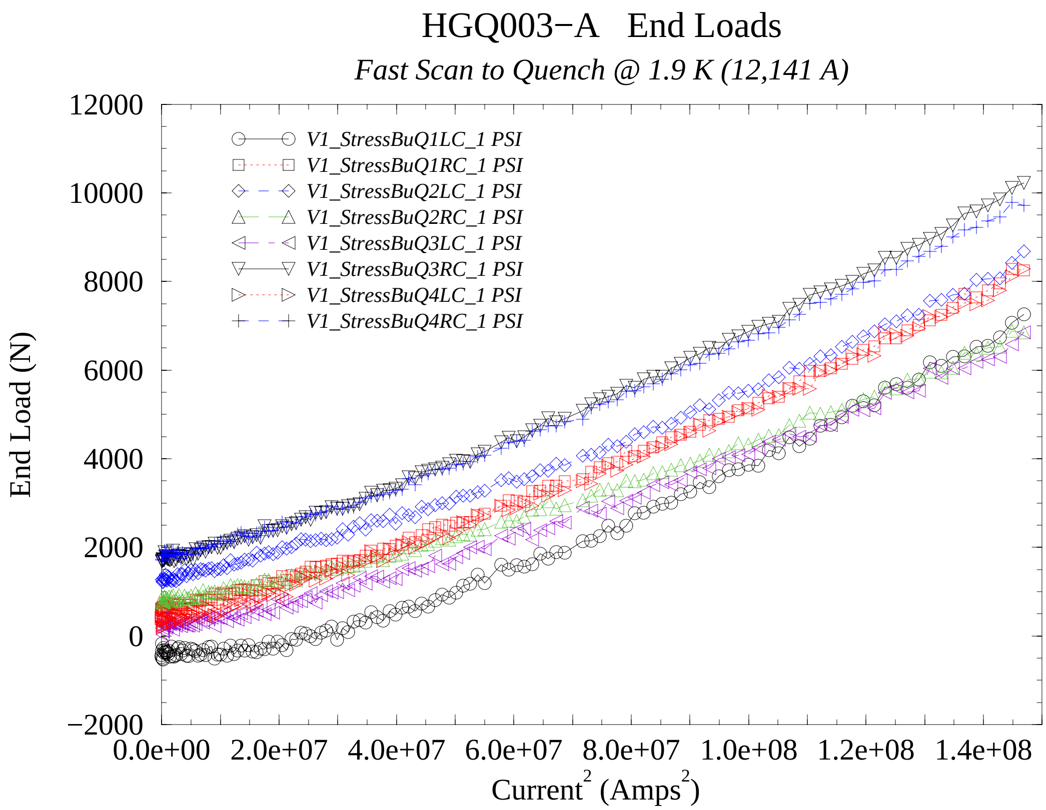

Figure 3.5: Azimuthal skin strains for a run to quench (12092A) at 1.9K

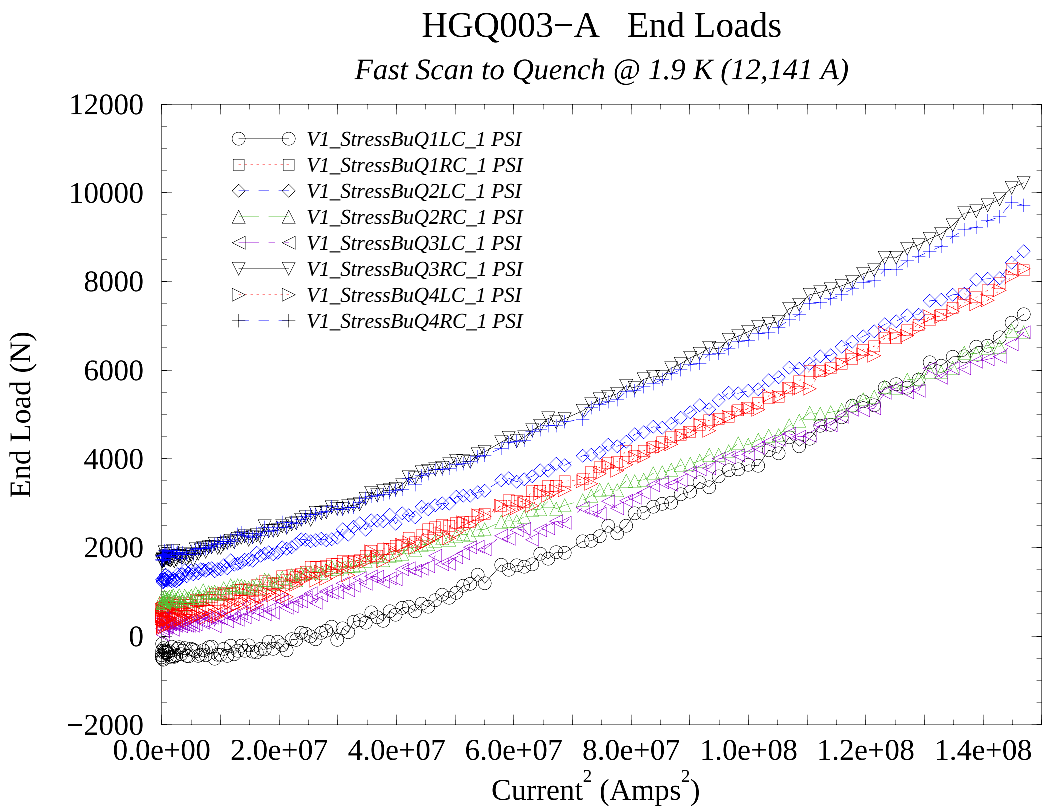

Figure 3.6: Longitudinal skin strains for a run to quench (12092A) at 1.9K

Table I - HGQ03A Beam Gauges

Gauge ID	Type	Coil	Function	Quadrant	End	VMTF Name
LHCI011	Beam	Inner	Active	Quad 1	RE	BmAcQ1IR
LHCI012	Beam	Inner	Active	Quad 3	RE	BmAcQ3IR
LHCI018	Beam	Inner	Active	Quad 2	LE	BmAcQ2IL
LHCI019	Beam	Inner	Active	Quad 4	LE	BmAcQ4IL
LHCTC15	Beam	Inner	Comp	Quad 1	RE	BmCoQ1IR
LHCTC6	Beam	Inner	Comp	Quad 3	RE	BmCoQ3IR
LHCTC9	Beam	Inner	Comp	Quad 2	LE	BmCoQ2IL
LHCTC46	Beam	Inner	Comp	Quad 4	LE	BmCoQ4IL
LHCO009	Beam	Outer	Active	Quad 2	RE	BmAcQ2OR
LHCO010	Beam	Outer	Active	Quad 4	RE	BmAcQ4OR
LHCO013	Beam	Outer	Active	Quad 1	LE	BmAcQ1OL
LHCO016	Beam	Outer	Active	Quad 3	LE	BmAcQ3OL
LHCTC17	Beam	Outer	Comp	Quad 2	RE	BmCoQ2OR
LHCTC8	Beam	Outer	Comp	Quad 4	RE	BmCoQ4OR
LHCTC47	Beam	Outer	Comp	Quad 1	LE	BmCoQ1OL
LHCTC48	Beam	Outer	Comp	Quad 3	LE	BmCoQ3OL

Table II - HGQ03A Bullet Gauges

Production Gauge Name	VMTF Gauge Name	Gauge Type	Gauge Location	Remarks
BL17A/B	BuQ1R	Bullet, active	Quad 1, RE	
BL18A/B	BuQ2R	Bullet, active	Quad 2, RE	
BL19A/B	BuQ3R	Bullet, active	Quad 3, RE	
BL20A/B	BuQ4R	Bullet, active	Quad 4, RE	
BL21A/B	BuQ1L	Bullet, active	Quad 1, LE	
BL22A/B	BuQ2L	Bullet, active	Quad 2, LE	
BL23A/B	BuQ3L	Bullet, active	Quad 3, LE	
BL24A/B	BuQ4L	Bullet, active	Quad 4, LE	
BT31	BuCoR_1	Bullet, comp.	RE	Comp. for RE bullets
BT32	BuCoR_2	Bullet, comp.	RE	"
BT33	BuCoL_1	Bullet, comp.	LE	Comp. for LE bullets
BT34	BuCoL_2	Bullet, comp.	LE	"

Table III - HGQ03A Capacitance Gauges

Gauge ID	Coil	Function	Quadrant	End	VMTF Name
HQCGI44	Outer	Active	Quad 4	LE	CgAcQ4OL
HQCGI41	Inner	Active	Quad 2	RE	CgAcQ2IR
HQCGI42	Inner	Active	Quad 4	RE	CgAcQ4IR
HQCGI43	Outer	Active	Quad 2	LE	CgAcQ2OL

Table IIII - HGQ03A Shell Gauges

Gauge ID	Orientation	Function	Location	VMTF Name
SKAL40	Longitudinal	Active	10 cm from RE	SkAcL010
SKAL41	Longitudinal	Active	44 cm from RE	SkAcL044
SKAL42	Longitudinal	Active	74 cm from RE	SkAcL074
SKAL43	Longitudinal	Active	104 cm from RE	SkAcL104
SKAL44	Longitudinal	Active	134 cm from RE	SkAcL134
SKAL45	Longitudinal	Active	164 cm from RE	SkAcL164
SKAL46	Longitudinal	Active	194 cm from RE	SkAcL194
SKAA47	Azimuthal	Active	At center, 30 degrees	SkAcA030
SKAA48	Azimuthal	Active	At center, 60 degrees	SkAcA060
SKAA49	Azimuthal	Active	At center, 90 degrees	SkAcA090
SKAA50	Azimuthal	Active	At center, 0 degrees	SkAcA104
SKAA47	Azimuthal	Active	At center, 30 degrees	SkAcA030
SKCL35	Longitudinal	Comp.	At center, 0 degrees	SkCoL101
SKCA36	Azimuthal	Comp.	At center, 90 degrees	SkCoA090

Table V - Coil Stresses (in psi)

Stress (comp.)	Stress (comp.)	Stress (comp.)	Stress (comp.)	Stress (comp.)	Stress (comp.)	Stress (comp.)	Stress (comp.)
IB#3	IB#3	VMTF 300K	VMTF 4.3K	VMTF 4.3K	VMTF 4.3K	VMTF 4.3K	VMTF 4.3K
21764	23000	23862	24968	25127	22639	25234	21442
33100	35275	35829	30222	30288	29036	30332	28248
29678	31189	30621	26308	26359	24437	26288	23331
21249	22773	24976	20172	20293	17299	20376	16093
26448	28059	28822	25418	25517	23353	25558	22279
182	194	199	175	176	161	176	154
			-3405 Cooldown Δσ		3.91E-05 $\Delta\sigma/\Delta I^2$	-3265 Cooldown Δσ	3.90E-05 $\Delta\sigma/\Delta I^2$
19946	22486	21769	18927	18847	17859	18750	17361
15128	18509	18609	22861	22762	21416	22772	20857
11266	13368	13838	10802	10886	9852	10870	9451
9825	11250	11493	8731	8764	7857	8725	7488
14041	16403	16427	15330	15315	14246	15279	13789
97	113	113	106	106	98	105	95
10/23/98 IB#3, un-yoked	11/12/98 IB#3, re-yoked	12/3/98 VMTF 300K	12/5/98 VMTF 4.3K	12/5/98 VMTF 4.3K	12/5/98 MTF 4.3K, I=74	12/5/98 VMTF 4.3K	12/5/98 MTF 4.3K, I=91
			-1097 Cooldown Δσ		1.93E-05 $\Delta\sigma/\Delta I^2$	-1148 Cooldown Δσ	1.77E-05 $\Delta\sigma/\Delta I^2$
Before re-yoking	After re-yoking	At VMTF	Before 1st SG Cycle	Before 1st quench	At 1st quench	Before last 4.3K quench	At last 4.3K quench

Stress (comp.)	Stress (comp.)	Stress (comp.)	Stress (comp.)	Stress (comp.)	Stress (comp.)	VMTF Name
VMTF 1.9K	VMTF 1.9K	VMTF 1.9K	VMTF 1.9K	VMTF 1.9K	VMTF 1.9K	
25196	20695	24857	18591	24805	18121	BmAcQ1IR
30468	28019	30363	26605	25954	20455	BmAcQ3IR
26363	22721	26226	20783	30365	26350	BmAcQ2IL
20686	15474	20611	13626	20517	13194	BmAcQ4IL
25678	21727	25514	19901	25410	19530	
177	150	176	137	175	135	
-3144 Cooldown Δσ	3.95E-05 $\Delta\sigma/\Delta I^2$	-3308 Cooldown Δσ	4.00E-05 $\Delta\sigma/\Delta I^2$	-3412 Cooldown Δσ	3.99E-05 $\Delta\sigma/\Delta I^2$	
19657	17783	19492	17242	11168	8567	BmAcQ2OR
22760	20161	22630	19310	19510	17130	BmAcQ4OR
11042	9288	11126	8656	9203	6994	BmAcQ1OL
9047	7532	9161	7057	22557	19144	BmAcQ3OL
15627	13691	15602	13066	15610	12959	
108	94	108	90	108	89	
12/5/94 VMTF 1.9K	12/5/94 ATF 1.9K, I=100	12/6/94 VMTF 1.9K	12/6/94 ATF 1.9K, I=118	12/6/94 VMTF 1.9K	12/6/94 ATF 1.9K, I=121	Date Condition
-801 Cooldown Δσ	1.94E-05 $\Delta\sigma/\Delta I^2$	-825 Cooldown Δσ	1.81E-05 $\Delta\sigma/\Delta I^2$	-818 Cooldown Δσ	1.80E-05 $\Delta\sigma/\Delta I^2$	
Before 1st 1.9K quench	At peak of 1st SG cycle	Before 9th quench	At 9th 1.9K quench	Before 24th quench	At 24th quench	Comments

Table VI - End Loads (in lbs)

Sensor name	Load (lbs) IB#3	Load (lbs) IB#3	Load (lbs) VMTF 300K	Load (lbs) VMTF 300K	Load (lbs) VMTF 300K	Load (lbs) VMTF 4.3K	Load (lbs) VMTF 4.3K	Load (lbs) VMTF 4.3K
LE Q1	1989	1974	1568	1585	1839	-196	-180	-86
LE Q2	2217	2211	1807	1831	2055	-50	10	533
LE Q3	1831	1818	1429	1439	1650	-192	-173	63
LE Q4	2001	1977	1583	1581	1842	-232	-212	318
Avg.	2010	1995	1597	1609	1847	-168	-139	207
Total	8038	7980	6387	6436	7386	-670	-555	828
Avg.(kN)	8.9	8.9	7.1	7.2	8.2	-0.7	-0.6	0.9
Total (kN)	35.8	35.5	28.4	28.6	32.9	-3.0	-2.5	3.7
					Quad. Avg.	-2014 Cooldown ΔF	-1985 Cooldown ΔF	6.25E-06 $\Delta F/\Delta I^2$
RE Q1	1506	1500	1073	1634	1759	-180	-208	139
RE Q2	1604	1590	1221	1598	1773	66	38	476
RE Q3	1529	1526	1152	1601	1774	225	200	700
RE Q4	1980	1987	1620	1967	2157	374	388	1015
Avg.	1655	1651	1267	1700	1866	121	105	583
Total	6619	6603	5066	6800	7463	485	418	2330
Avg.(kN)	7.4	7.3	5.6	7.6	8.3	0.5	0.5	2.6
Total (kN)	29.4	29.4	22.5	30.2	33.2	2.2	1.9	10.4
	11/18/98 IB#3	11/19/98 IB#3	11/25/98 VMTF	11/30/98 VMTF 300K	12/3/98 VMTF 300K	12/5/98 VMTF 4.3K	12/5/98 VMTF 4.3K	12/5/98 MTF 4.3K, I=74
					Quad. Avg.	-1745 Cooldown ΔF	-1761 Cooldown ΔF	8.64E-06 $\Delta F/\Delta I^2$
	After Quad Splices	After V-Taps on Quad Spl.	At VMTF	At VMTF RE torqued up	At VMTF in dewar	Before 1st SG cycle	Before 1st quench	At first quench

Load (lbs) VMTF 1.9K	Load (lbs) VMTF 1.9K	Load (lbs) VMTF 1.9K	Load (lbs) VMTF 1.9K	Load (lbs) VMTF 1.9K	Load (lbs) VMTF 1.9K	Load (lbs) VMTF 1.9K	Load (lbs) VMTF 1.9K	VMTF Name
-208	143	-153	517	-106	1465	-119	1632	BIAcQ1L
60	817	73	1058	327	1858	272	1951	BIAcQ2L
-226	298	-161	624	-21	1374	5	1540	BIAcQ3L
-173	707	-266	901	2	1695	42	1864	BIAcQ4L
-137	491	-127	775	51	1598	50	1747	
-547	1965	-507	3100	202	6392	200	6987	
-0.6	2.2	-0.6	3.4	0.2	7.1	0.2	7.8	
-2.4	8.7	-2.3	13.8	0.9	28.4	0.9	31.1	
-1983 Cooldown ΔF	7.47E-06 $\Delta F/\Delta I^2$	-1973 Cooldown ΔF	9.02E-06 $\Delta F/\Delta I^2$	-1796 Cooldown ΔF	1.10E-05 $\Delta F/\Delta I^2$	-1797 Cooldown ΔF	1.15E-05 $\Delta F/\Delta I^2$	
-172	563	-228	776	89	1755	127	1862	BIAcQ1R
151	785	97	955	150	1459	157	1549	BIAcQ2R
320	1179	236	1372	345	2174	377	2299	BIAcQ3R
404	1365	210	1425	355	2073	385	2201	BIAcQ4R
176	973	79	1132	235	1865	262	1978	
703	3892	315	4528	939	7461	1046	7911	
0.8	4.3	0.4	5.0	1.0	8.3	1.2	8.8	
3.1	17.3	1.4	20.1	4.2	33.2	4.7	35.2	
12/5/98 VMTF 4.3K	12/5/98 MTF 1.9K, I=91	12/6/98 VMTF 1.9K	12/6/98 MTF 1.9K, I=100	12/7/98 VMTF 1.9K	12/7/98 MTF 1.9K, I=118	12/7/98 VMTF 1.9K	12/7/98 MTF 1.9K, I=121	Date Condition
-1690 Cooldown ΔF	9.48E-06 $\Delta F/\Delta I^2$	-1787 Cooldown ΔF	1.05E-05 $\Delta F/\Delta I^2$	-1631 Cooldown ΔF	1.16E-05 $\Delta F/\Delta I^2$	-1604 Cooldown ΔF	1.16E-05 $\Delta F/\Delta I^2$	
Before last 4.3K quench	At last 4.3K quench	Before 1st 1.9K quench	At peak of 1st SG cycle	Before 9th quench	At 9th 1.9K quench	Before 24th quench	At 24th quench	Comments

Table VII - Mechanical Performance Summary

	Unit	Design	HGQ01	HGQ02	HGQ03	HGQ03-
Azimuthal Stress 300K						
- inner layer	MPa	81	67	73	187	199
- outer layer	MPa	81	72	94	97	113
Cooldown Loss						
- inner layer	MPa	-7	-29	+3	-14	-24
- outer layer	MPa	-15	-14	-10	+5	-8
Azimuthal Lorentz Force						
- inner layer	MPa/kA^2	-0.3	-0.28	-0.31	-0.29	-0.27
- outer layer	MPa/kA^2	-0.2	-0.13	-0.15	-0.13	-0.13
Longitudinal End Force						
- lead end	kN		0.8/14.3	7.5	----------	8.2
- return end	kN		0.8/22.4	11.4	----------	8.3
Cooldown Loss						
- lead end	kN		----/13.4	> 7.5	----------	9.0
- return end	kN		----/19.2	> 11.4	----------	7.8
Longitudinal Lorentz force						
- lead end	kN/kA^2	0.36	0.09	0.08	----------	0.06
- return end	kN/kA^2	0.36	0.09	0.07	----------	0.06

Chapter 4

Splice resistance measurement

This chapter summarizes the splice meaurement results. HGQ03A is the first HGQ model magnet with internal splices. The new splice design was optimized to get minimal heating at both AC and DC operations. To verify whether the the actual splicing technique provided the relevant resistance it was neccessary to measure the resistance of the splice.

During the magnet fabrication, voltage taps were placed directly on either side of each splice between coils, specifically to measure the voltage drops across the splices. A splice resistance is given by the ratio of measured voltage drop across the splice to the measured magnet current (by Ohm's Law).

4.1 Experimental setup

Measurement of the magnet current was made via a calibrated Holec transductor located on the negative bus of the power supply which is connected directly to the magnet. The estimated absolute error on the current is about 1 part in 10000.

The voltage was measured with an HP 3458 DMM sampling at 40 Hz and integrating over one line cycle to reduce 60 Hz noise. The data was recorded in the logbook by an operator. The error on the volatage reading was in the order of $1\mu V$.

4.2 Analysis and results

Plots of Splice Voltage versus current were created and least-squares fits were made using the program XMGR. The fitted slopes give the splice resistance directly. The VI curve and the straight line fits are summarized in Figure 4.1 – Figure 4.5. The splice resistance values are summarized in table 4.1. We were not able to measure two out of the seven splices due to broken voltage taps.

Table 4.1: Splice resistance summary

Splice	R @ 1.9K [nΩ]
Q1I-Q1O	.45 $\pm$ .03
Q2O-Q4I	.44 $\pm$ .03
Q3I-Q1O	.43 $\pm$ .015
Q3I-Q3O	.35 $\pm$ .02
Q4I-Q4O	.58 $\pm$ .03

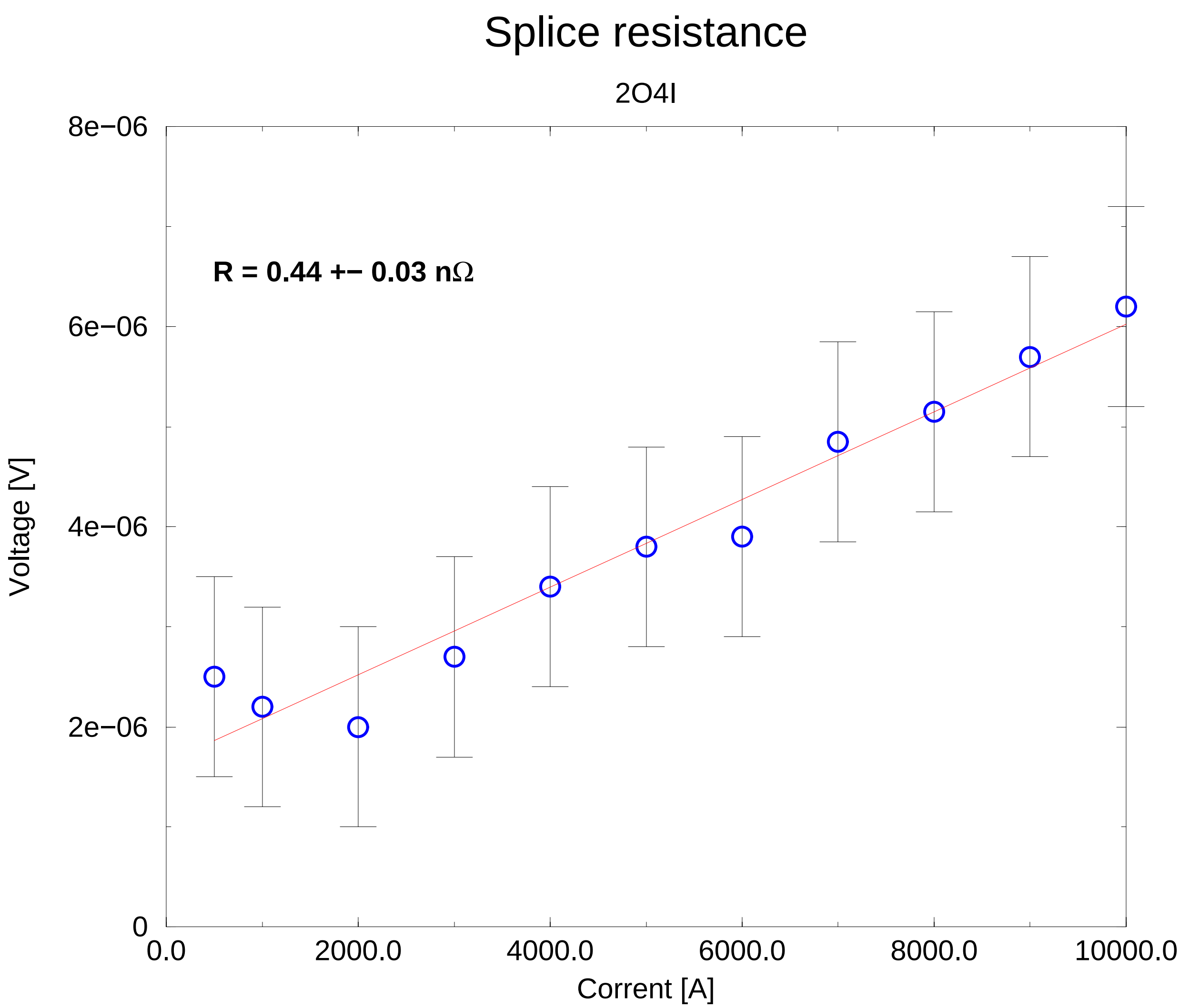

Figure 4.1: Quadrant 2 outer to quadrant 4 inner splice

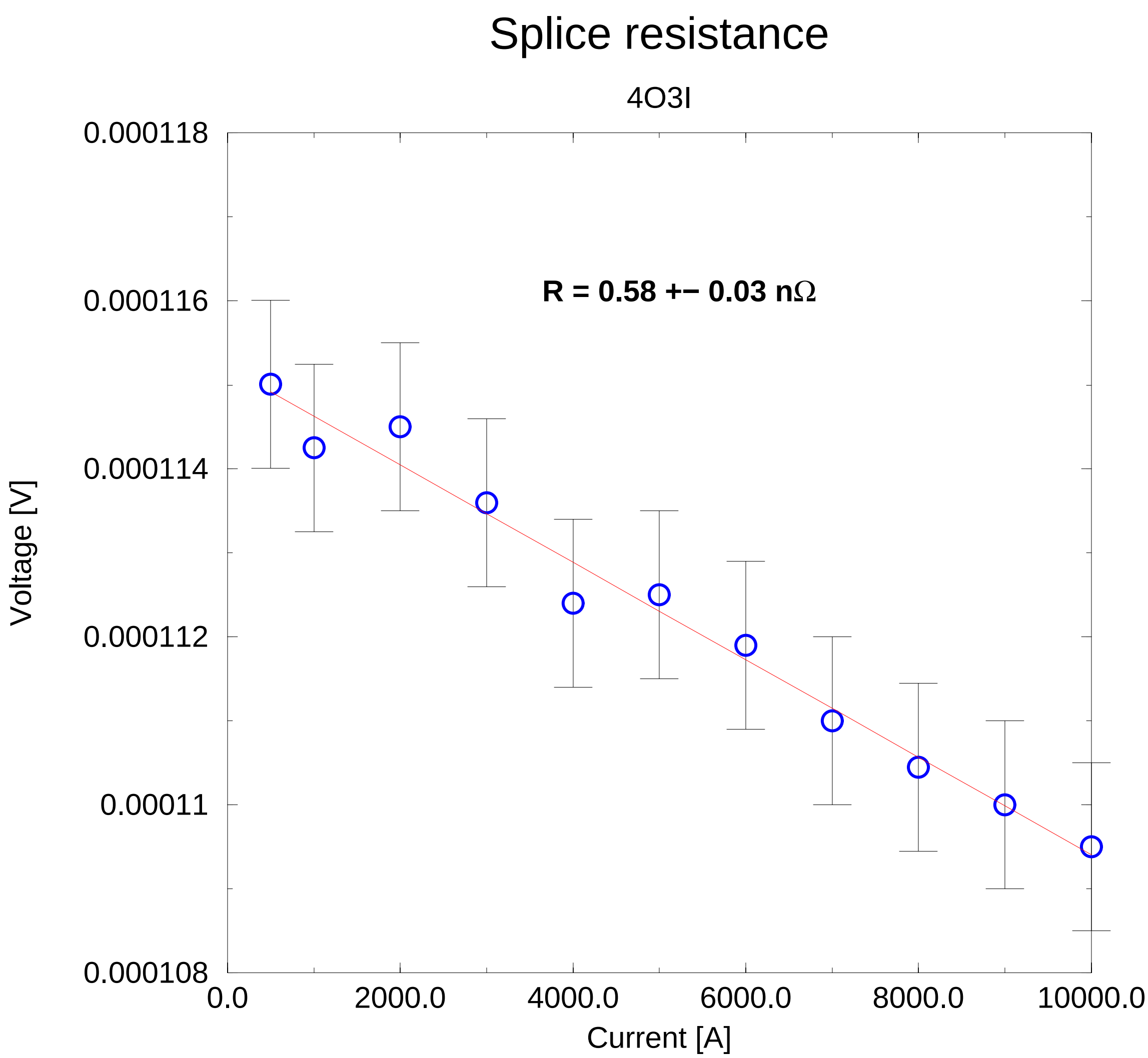

Figure 4.2: Quadrant 4 outer to quadrant 3 inner splice

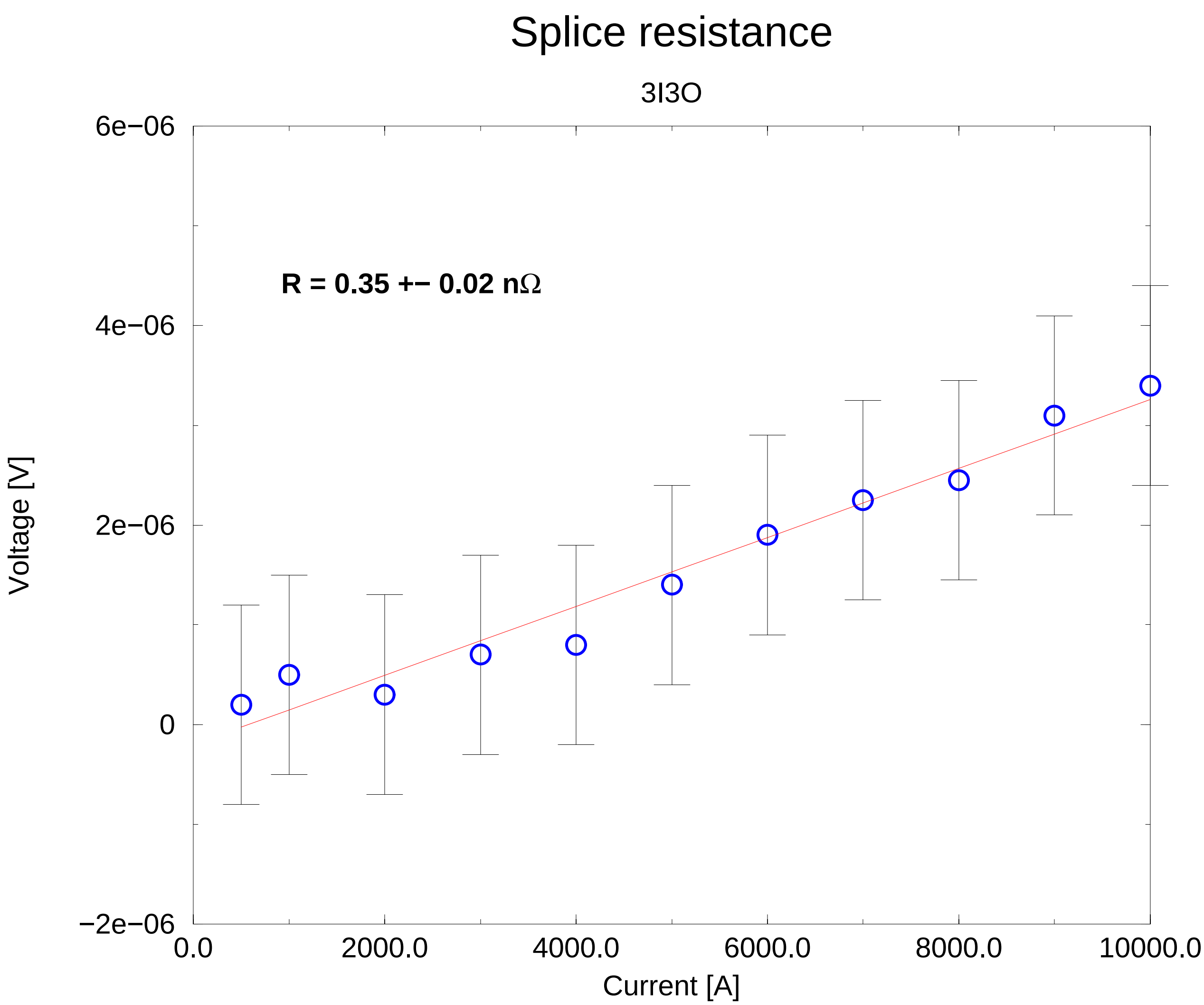

Figure 4.3: Quadrant 3 inner to quadrant 3 outer splice

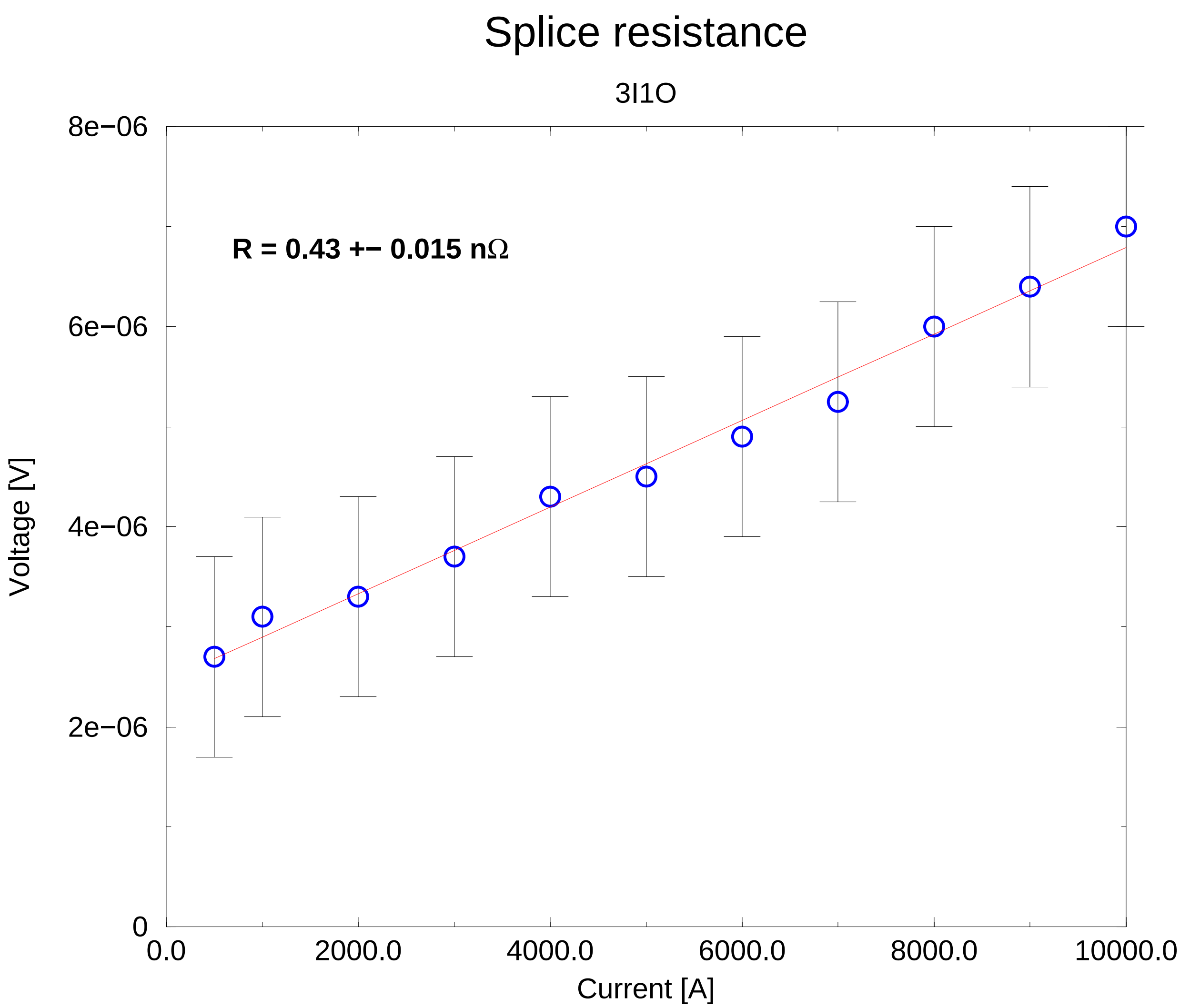

Figure 4.4: Quadrant 3 inner to quadrant 1 outer splice

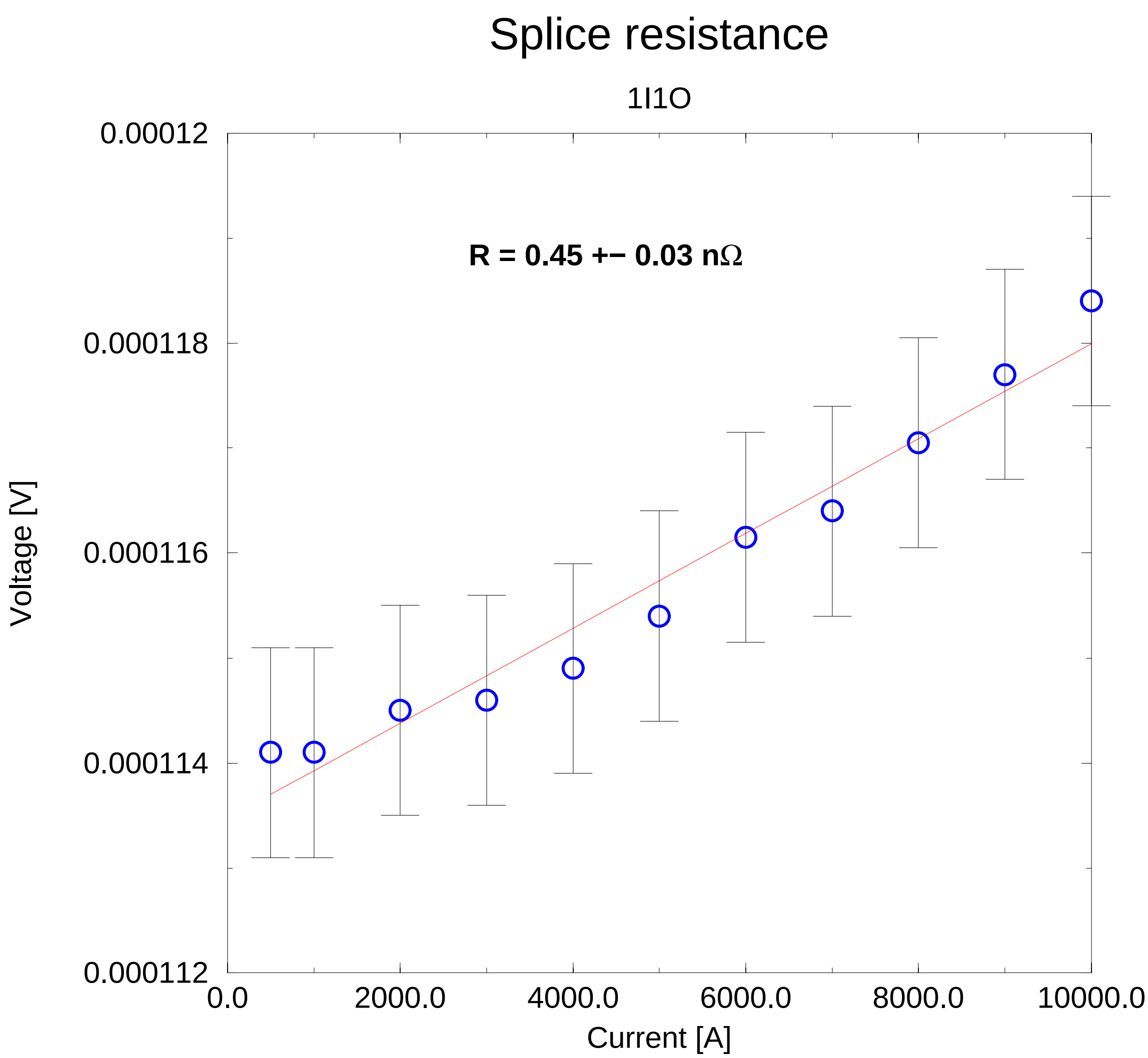

Figure 4.5: Quadrant 1 inner to quadrant 1 outer splice

Appendix A

HGQ003 TEST PLAN

A.1 Outline

Test Cycle I

- Magnetic measurements
- Room Temperature Pretest and Cool down
- At 4.5K Operation

  Pre-Current excitation Checkout

  2500 amp Heater test

  Strain gauge runs

  Quench Plateau (max. 5 quenches)

  Ramp Rate Studies
- At 1.9K Operation

  Pre-current excitation Checkout

  3000 amp Heater tests

  Strain gauge runs

  Quench Plateau

  Ramp rate studies

Magnetic measurements

Quench Current vs. temperature

Energy loss measurement

A.2 Test cycle I

A.2.1 Magnetic measurements

1. Warm measurement

2. In the dewar

   (a) Locate magnetic center by scanning ends

   (b) Apply ±10 A. Take measurements at 8 different z locations: 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.0 m. At each z step make 25 rotations. Take these readings with "amplifiers in".

3. Remove the measurement rig and install the quench antenna

A.2.2 Room Temperature Pretest/Cooldown

1. Follow present procedures for strain gauge, voltage taps, thermometer, and heater validation. Procedures include:

   (a) Hi pot the magnet in gaseous He environment. Maximum volts should not exceed V_{max} value (to be determined).

   (b) 4 wire measurement of all strain gages

   (c) 5 amps across magnet, measure voltage across taps Measure magnet resistance and compare it to the value measured at IB3. Verify that there are no shorts in the magnet

   (d) 4 wire heater resistance, system resistance for all four heaters.

2. Record at least 10 strain gage readings at room temperature, check values with post assembly readings.

3. Set strain gage and thermometer readings to 10 minute intervals

4. Place 5 amps through magnet, measure voltage across magnet (each eigth coils separately).
5. Cool down to 80K, then change strain gage and thermometer readings to 1 minute intervals. Cool to 4.5 K , 1.1 ATM with unrestricted cooldown following VMTF cool-down procedure.

A.2.3 At 4.5 K Operation

1. Cold electrical tests prior to magnet testing
   (a) Check magnet resistance to ground
   (b) Hi pot (1.1 ATM helium). Maximum volts should not exceed V_{max} value (to be determined).
   (c) Make sure that strain gauge readings are recorded
   (d) Protect magnet with a 60 mΩ dump resistor. $I_{max} * R_{dump} \leq 1000V$
   (e) Heater Pretests
      i. Configure QLM to fire heater with 1 sec dump firing delay
      ii. Check outer and inter-layer heater and heater system resistance using 4 wire techniques. System capacitance should be set to approximately 14.4 mF.
      iii. Verify that inter-layer and outer heaters are wired in parallel check system continuity
      iv. Fire inter-layer heaters from VMTF prgram. Verify RC, V heaters, I heaters from data logger plots
   (f) Disable Digital QDC (or set to high tresholds)
   (g) Balance quench detection circuitry for analog QDC
      i. Set dump delay to 0 sec
      ii. sawtooth ramps between 50 A and 200 A at 100 A/sec.
      iii. Establish thresholds based on observed noise versus anticipated signals.
   (h) Balance quench detection circuit for DQDC

(i) Set dump delay to 20 msec and the heater delay to 0msec. Manual trip at 1000 A. **Every single analog QDC platform has to be checked separately. Power supply, dump switch, heater and interlock respond should follow the proper quench logic.** Delay heater firing to 1 sec dump delay = 0 sec. Do another manual trip and check L/R, look at all data logger voltage signals; compare V_{max} to $I * R_{dump}$

2. Quench Heater Protection test
   (a) Set dump resistor delay to 0 ms, no heater delay, no power supply phase off delay
   (b) At 2500A magnet current, determine voltage required to quench heaters with $t_{fn} < 200$ ms
   (c) If MIITS o.k dump delay to 20 ms, delay heater firing to 0 ms
   (d) Check quench logic signal for proper quench timing sequence

3. Strain gauge run
   (a) Dump resistor set to 60 mΩ, 20 ms delay , delay heater to 20 ms, heater value as perr 0.2.3 2.b
   (b) At Ramp rate = 20 A /sec. :
   Measure the inductance of the magnet.Make sure to run "snapshot" script. Take strain gauge runs, one file per current loop, using the sequences of currents below.
      i. Run 1: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 7100 A and from 7100 A to 0 A. Disable "fast strain gauge" script.
      ii. Run 2: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 8400 A and from 8400 A to 0 A. Disable "fast strain gauge" script.
      iii. Run 3: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 9000 A and from 9000 A to 0 A. Disable "fast strain gauge" script. 9000 A
      iv. Run 4: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 9500 A and from 9500 A to 0 A. Disable "fast strain gauge" script. 9500 A

v. Run 5: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 10000 A and from 10000 A to 0 A. Disable “fast strain gauge” script. 10000 A

vi. Run 4: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 10500 A and from 10500 A to 0 A. Disable “fast strain gauge” script. Note: After Run 1, expect quench during strain gage run

4. Quench plateau.

   Before each quench measure the inductance of the magnet. Make sure that the inductance remain unchanged. With ramp rate = 20 A/sec, train the magnet. Do not do more than 5 quenches. The predicted short sample limit currents (inner coil) is 10340 A. Make sure to run “fast strain gauge” and “snap-shot” scripts.

5. RAMP RATE dependence studies.

   Ramp to quench at 300 a/s, 150 a/s,

A.2.4 At 1.9K Operation

1. Cold Electrical tests prior to current excitation Repeat section 0.2.3 1.c,d,e

2. Quench Heater Protection Test Repeat Section 0.2.3 2.a,b,c,d with 3000A applied current.

3. Strain gauge run

   (a) Repeat Section 0.2.2 4.a

   (b) At Ramp rate = 20 A /sec. :

   Measure the inductance of the magnet.Make sure to run “snap-shot” script. Take strain gauge runs, one file per current loop, using the sequences of currents below.

   i. Run 1: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 10000 A and from 10000 A to 0 A. Disable “fast strain gauge” script.

ii. Run 2: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 11000 A and from 11000 A to 0 A. Disable "fast strain gauge" script.
iii. Run 3: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 11800 A and from 11800 A to 0 A. Disable "fast strain gauge" script.
iv. Run 4: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 12700 A and from 12700 A to 0 A. Disable "fast strain gauge" script.
v. Run 5: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 13400 A and from 13400 A to 0 A. Disable "fast strain gauge" script.
vi. Run 4: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 14200 A and from 14200 A to 0 A. Disable "fast strain gauge" script. Note: After Run 1, expect quench during strain gage run

4. Quench plateau.

   With ramp rate = 20 A/sec, train the magnet until 4 plateau quenches have occurred. Do not do more than 15 quenches (only if magnet shows interesting behavior). The predicted short sample limit currents (inner coil) is 13900 A. Make sure to run "fast strain gauge" and "snap-shot" scripts.

5. RAMP RATE dependence studies.

   Ramp to quench at 300 A/sec, 200 A/sec, 150 A/sec, 100 A/sec, 75 A/sec, 50 A/sec

6. Magnetic measurements

   The default ramp rate is 20 A/sec.

   The nominal data set is 25 rotations of the coil.

   All measurement sequences should begin with a "cleansing" quench at $\sim$ 10000A. A cleansing quench is done by firing the magnet heaters with magnet current high enough to produce a small remnant field.

   (a) Remove the quench antenna and install the measurement rig.

(b) Set the heater delay to 20 sec, dump delay to 20 msec, and dump resistance to 60 mΩ.

(c) Determine the minimum magnet current for a cleansing quench: check the effect of a cleansing quench at 10000 A by checking the remnant magnetic field. If the remnant field is substantial increase the current and quench the magnet again. Repeat this proceedure until the minimum current is found. Use this value of the current for all cleasing quenches needed for this test plan.

(d) Remove pre-amplifiers used for warm measurement if this has not already been done.

(e) Set magnet measurement coordinate system as per TD-98-xxx. File the completed note with this run plan.

(f) Make a "hysteresis loop" measurement at magnet center (z =0.819 m): make three consecutive loops from I_{min} to $I_{quench} - 500$ A with continuous measurement. We define I_{min} as a current near to the injection current; I_{quench} is the quench plateau current reached following training .

(g) Make a standardization cycle measurement: ramp to flattop current, $I_{plateau} = I_{quench} - 500$ A, dwell at $I_{plateau}$ for t_{dwell} ramp down to 50 A, dwell for 2 sec, ramp to 800 A; wait $t_{injection}$, then ramp to $I_{quench} - 500$ A at 20 A/sec.

Default parameters are $I_{plateau} = I_{quench} - 500$ A; $t_{dwell} = 30$ min.; $t_{injection} = 30$ min.

(h) Remove the measurement rig and install the quench antenna

7. Quench Current vs. temperature

Ramp magnet to quench at 20 a/s at the following temperatures

1.8K, 2.1K, 2.7K, 3.2K, 3.7K, 4.2K

should not be exact value (± 0.2 K)