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TD-02-045

HFDA04 Test Summary

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1. Introduction

HFDA04 was completed on May 15, 2002. The magnet was installed into the VMTF dewar and it was electrically checked by the end of May 17th, 2002. We were also able to start LN2 cool down on the same day. The VMTF dewar was filled with liquid helium on May 20th. First thermal cycle of the magnet has been completed on May 23rd. The magnet was removed from the dewar and in order to improve quench performance several modifications were made in IB3. The magnet was installed into the VMTF dewar in June 14 and it was cold by the end of the day June 17. The second thermal cycle test was finished on June19th.

2. Quench History

After completing a short magnetic measurements the magnet current was ramped up to 10000A and down without observing a quench. The target current for the second high current ramp was 13000A. The first quench occurred at 10033A. After a short magnet training and ramp rate studies it was discovered that the magnet quench performance is erratic and all of the quenches occur at the outer coil splice regions, regardless of the current ramp rate applied. After thermal cycling the magnet the quench behavior didn't change. The quenches still appear at the same splice region. We even cooled the magnet down to 2.15 K. We've seen a little quench current increase but the same erratic behavior and the same quench locations.

The quench history plot is presented in Figure 1. and in Table 1. Special ramp profile was used for quench number 18 and 19. The ramp profile is shown in figure 2 and 3. Table 1 also contains the locations of the quenches. Voltage traces of voltage segments for a typical quench are plotted in Figure 4.

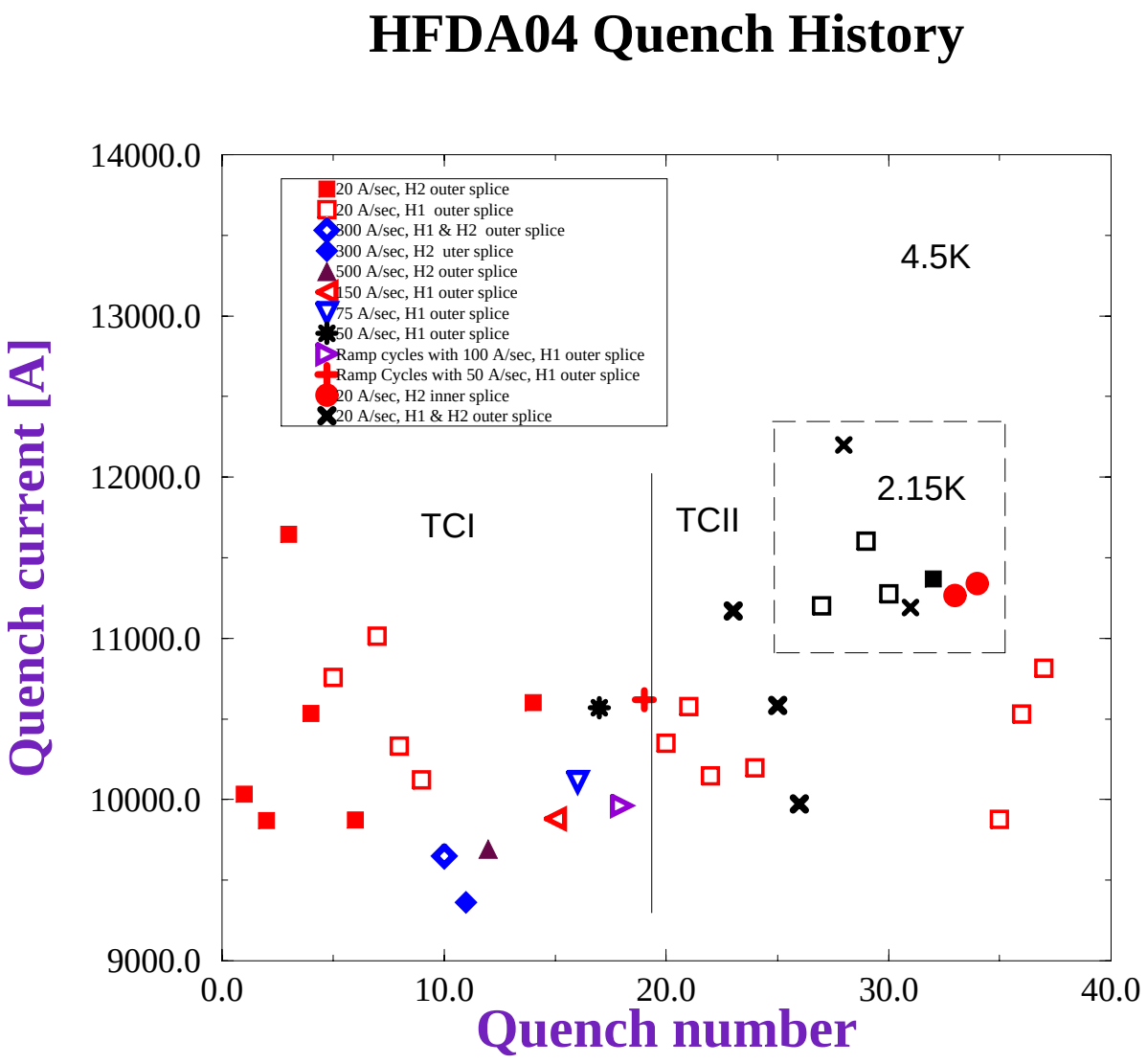

Figure 1. Quench history

Quench #	Quench File	Current, A	Ramp Rate, A/s	Temp, K	t_{quench}	MIITs	Quench Start Tap Segment
1	hfda04.Quench.020521121826.169	10032	20	4.5	-0.012		H2NbTi-H2Nb3Sn
2	hfda04.Quench.020521125322.131	9870	20	4.5	-0.012	6.5	H2NbTi-H2Nb3Sn
3	hfda04.Quench.020521132509.786	11647	20	4.5	-0.007	8.1	H2NbTi-H2Nb3Sn
4	hfda04.Quench.020521140411.515	10534	20	4.5	-0.01		H2NbTi-H2Nb3Sn
5	hfda04.Quench.020521145414.639	10756	20	4.5			H1NbTi-H1Nb3Sn
6	hfda04.Quench.020521154128.054	9874	20	4.5	-0.017	5.1	H2NbTi-H2Nb3Sn
7	hfda04.Quench.020521162424.269	11013	20	4.5	-0.007	5.4	H1NbTi-H1Nb3Sn
8	hfda04.Quench.020521170813.827	10331	20	4.5	-0.008	4.9	H1NbTi-H1Nb3Sn
9	hfda04.Quench.020521182732.501	10138	20	4.5	-0.014	5.3	H1NbTi-H1Nb3Sn
10	hfda04.Quench.020521185508.014	9661	300	4.5	-0.012	4.5	H2NbTi-H2Nb3Sn, H1NbTi-H1Nb3Sn
11	hfda04.Quench.020521192110.065	9360	300	4.5	-0.013		H1NbTi-H1Nb3Sn
12	hfda04.Quench.020521194622.932	9692	500	4.5	-0.01		H2NbTi-H2Nb3Sn
13	hfda04.Quench.020521201011.788	8882	500	4.5	-0.013	3.9	H2NbTi-H2Nb3Sn
14	hfda04.Quench.020522090434.197	10600	20	4.5	-0.007		H2NbTi-H2Nb3Sn
15	hfda04.Quench.020523182142.195	9879	150	4.5	-0.007		H1NbTi-H1Nb3Sn
16	hfda04.Quench.020523184600.570	10113	75	4.5	-0.011		H1NbTi-H1Nb3Sn
17	hfda04.Quench.020523191426.322	10571	50	4.5	-0.009		H1NbTi-H1Nb3Sn
18	hfda04.Quench.020523195254.315	9963	100	4.5			H1NbTi-H1Nb3Sn
19	hfda04.Quench.020523201616.579	10618	50	4.5	-0.01		H1NbTi-H1Nb3Sn
20	hfda04.Quench.020617164524.343	10348	20	4.5			H1NbTi-H1Nb3Sn
21	hfda04.Quench.020617172200.103	10575	20	4.5			H1NbTi-H1Nb3Sn
22	hfda04.Quench.020617181711.177	10147	20	4.5			H1NbTi-H1Nb3Sn
23	hfda04.Quench.020617192555.847	11171	20	4.5			H2NbTi-H2Nb3Sn, H1NbTi-H1Nb3Sn
24	hfda04.Quench.020617201814.924	10195	20	4.5			H1NbTi-H1Nb3Sn
25	hfda04.Quench.020618093845.651	10584	20	4.5			H2NbTi-H2Nb3Sn, H1NbTi-H1Nb3Sn
26	hfda04.Quench.020618101927.108	9973	20	4.5			H2NbTi-H2Nb3Sn, H1NbTi-H1Nb3Sn
27	hfda04.Quench.020618135104.167	11202	20	2.15			H1NbTi-H1Nb3Sn
28	hfda04.Quench.020618150409.027	12199	20	2.15			H1NbTi-H1Nb3Sn
29	hfda04.Quench.020618154424.798	11602	20	2.15			H1NbTi-H1Nb3Sn
30	hfda04.Quench.020618161745.748	11280	20	2.15			H1NbTi-H1Nb3Sn
31	hfda04.Quench.020618165558.598	11191	20	2.15			H2NbTi-H2Nb3Sn, H1NbTi-H1Nb3Sn
32	hfda04.Quench.020618174417.248	11367	20	2.15			H2NbTi-H2Nb3Sn
33	hfda04.Quench.020618191540.819	11264	20	2.15			H2LNbTi-H2LNb3Sn
34	hfda04.Quench.020618202812.304	11341	20	2.15			H2LNbTi-H2LNb3Sn
35	hfda04.Quench.020619091714.939	9877	20	4.5			H1NbTi-H1Nb3Sn
36	hfda04.Quench.020619101427.427	10530	20	4.5			H1NbTi-H1Nb3Sn
37	hfda04.Quench.020619105333.641	10816	20	4.5	-0.01		H1NbTi-H1Nb3Sn

Table 1. Quench history. Quench number 18 and 19 used a special ramp profile (see figure 2 and figure 3).

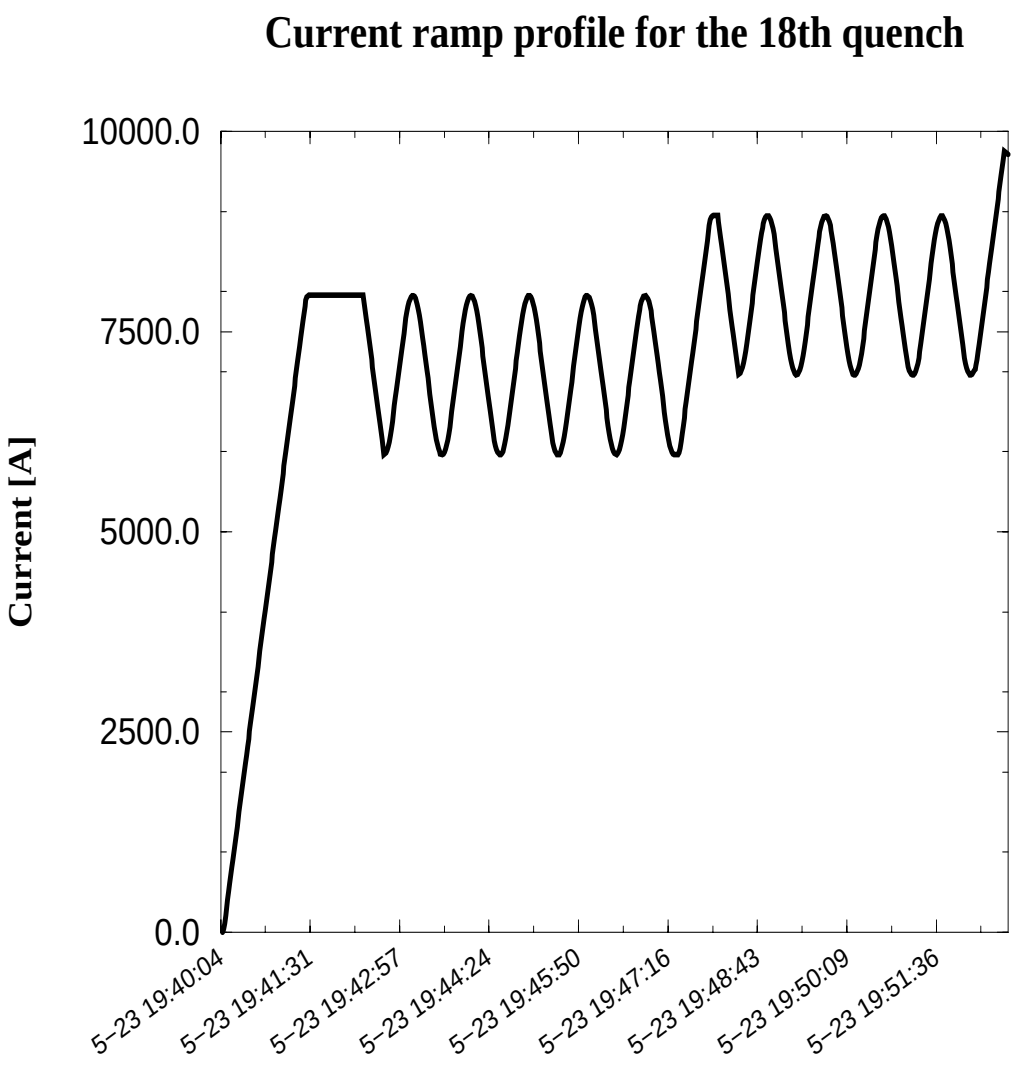

Figure 2. Current ramp profile used for quench number 18.

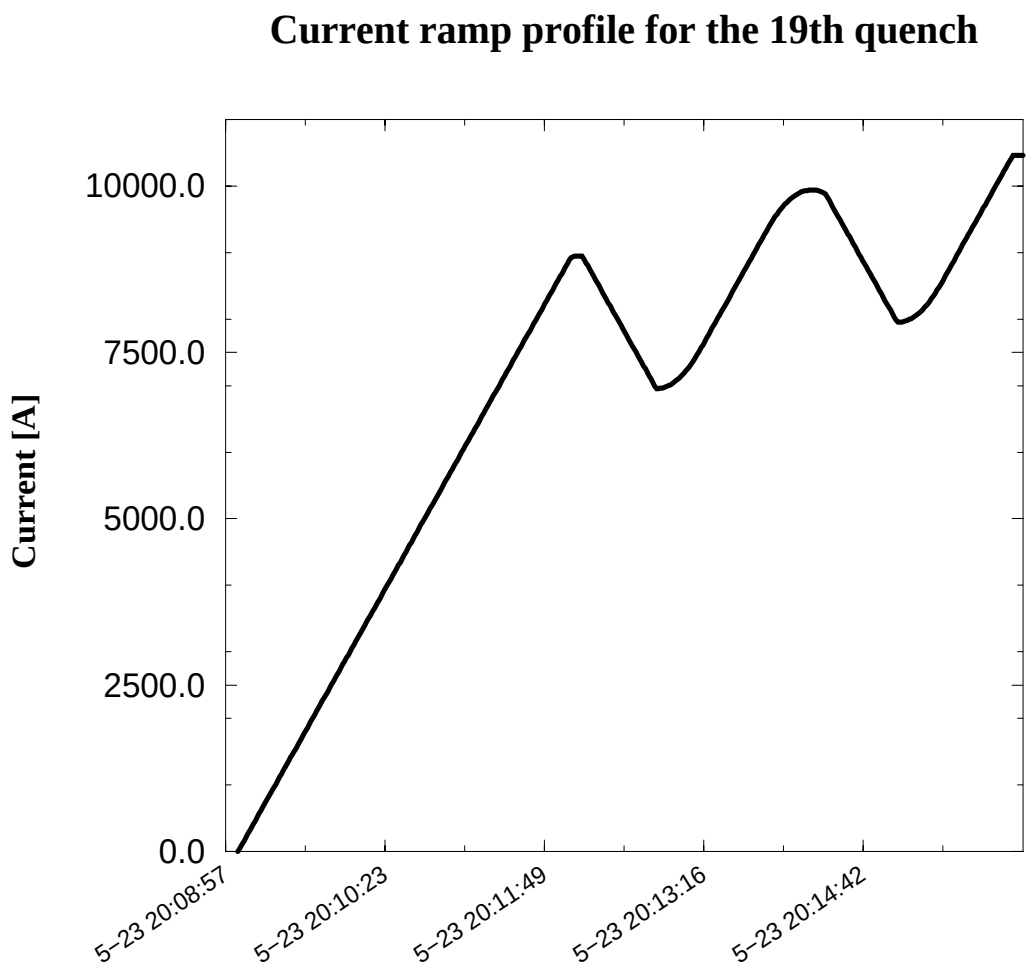

Figure 3. Current ramp profile used for quench number 19.

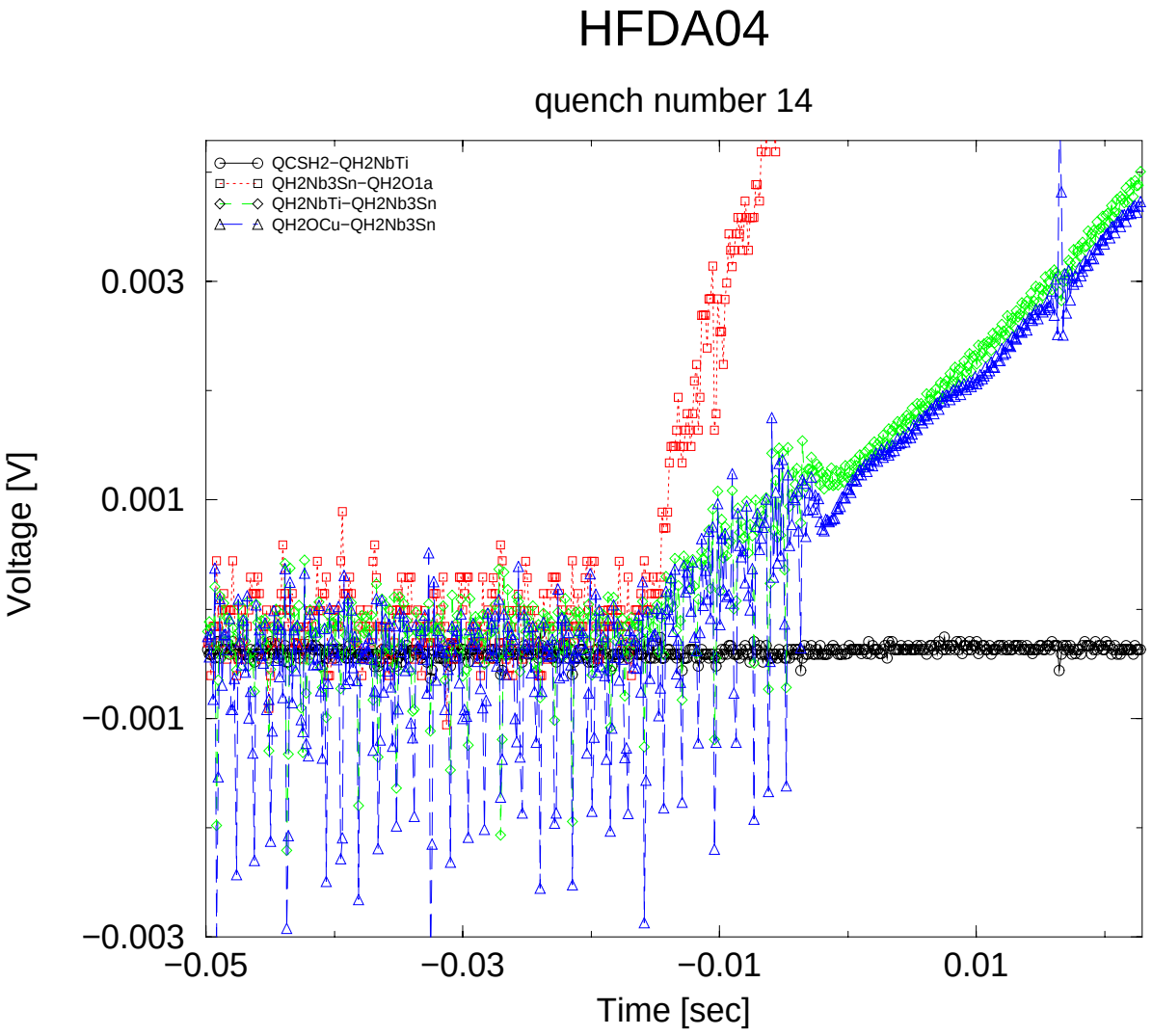

Figure 4. Quench number 14.

3. Ramp Rate Dependence

The default current ramp rate was 20 A/sec. Even if the magnet quench current exhibited erratic behavior we still performed ramp rate dependence study which is summarized in Figure 5.

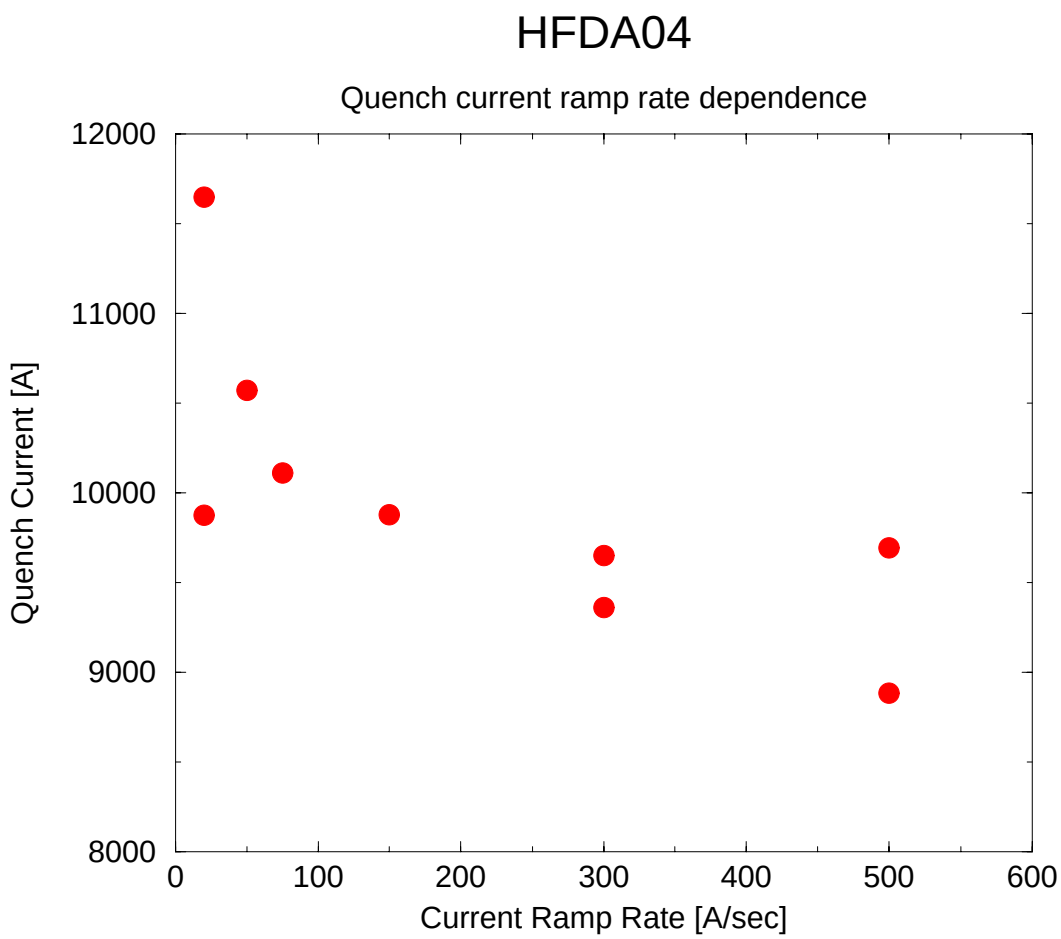

Figure 5. Current ramp rate dependence.

4. Strip Heater Study

Although the magnet hasn't been trained we still performed heater studies. The results are summarized in table 2 and the two most important plots are shown in Figure 6 and 7.

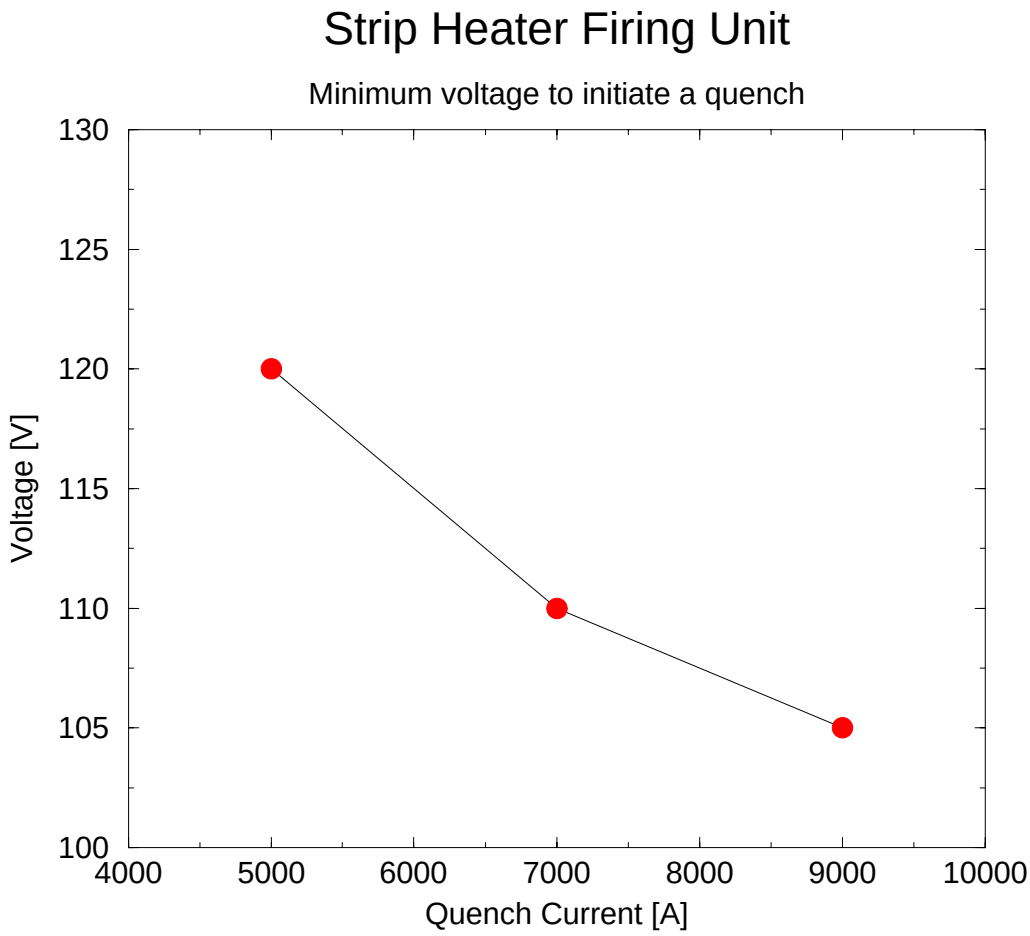

Figure 6. Minimum voltage study

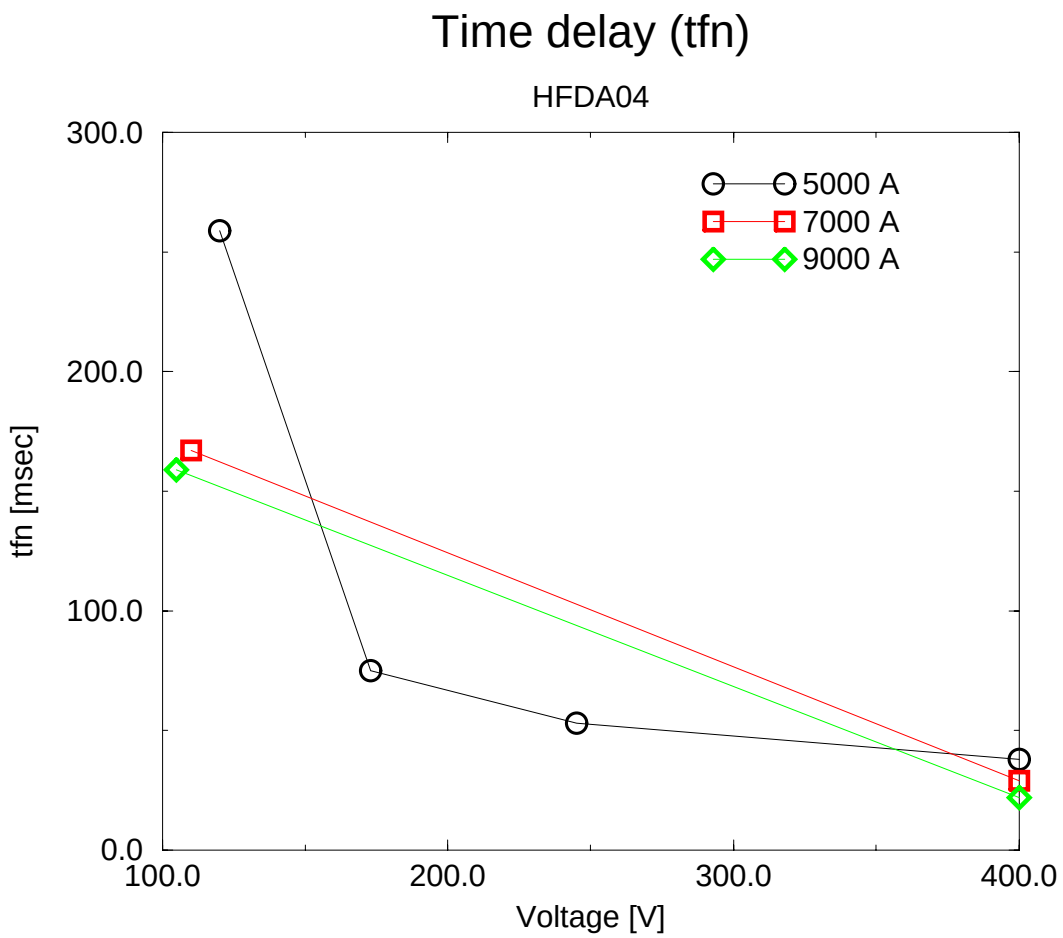

Figure 7. Time delay study

	Current [A]	SHFU Voltage [V]	Tfn [sec]	Comment
1	5000	120	0.259	Vmin
2	5000	173	0.075	
3	5000	245	0.053	
4	5000	400	0.038	
5	7000	110	0.167	Vmin
6	7000	400	0.029	
7	9000	105	0.159	Vmin
8	9000	400	0.022	

Table 2: Heater study data

5. Splice measurement

We performed splice measurements. The current was increased up to 9000 A and the voltage drops across the splices were recorded. Figure 8 shows a typical measurement and Table 3 summarizes the results.

Table 3

	Outer H1	Outer H2	Inner H1	Inner H2
Resistance nΩ	0.8	0.9	0.8	1.1

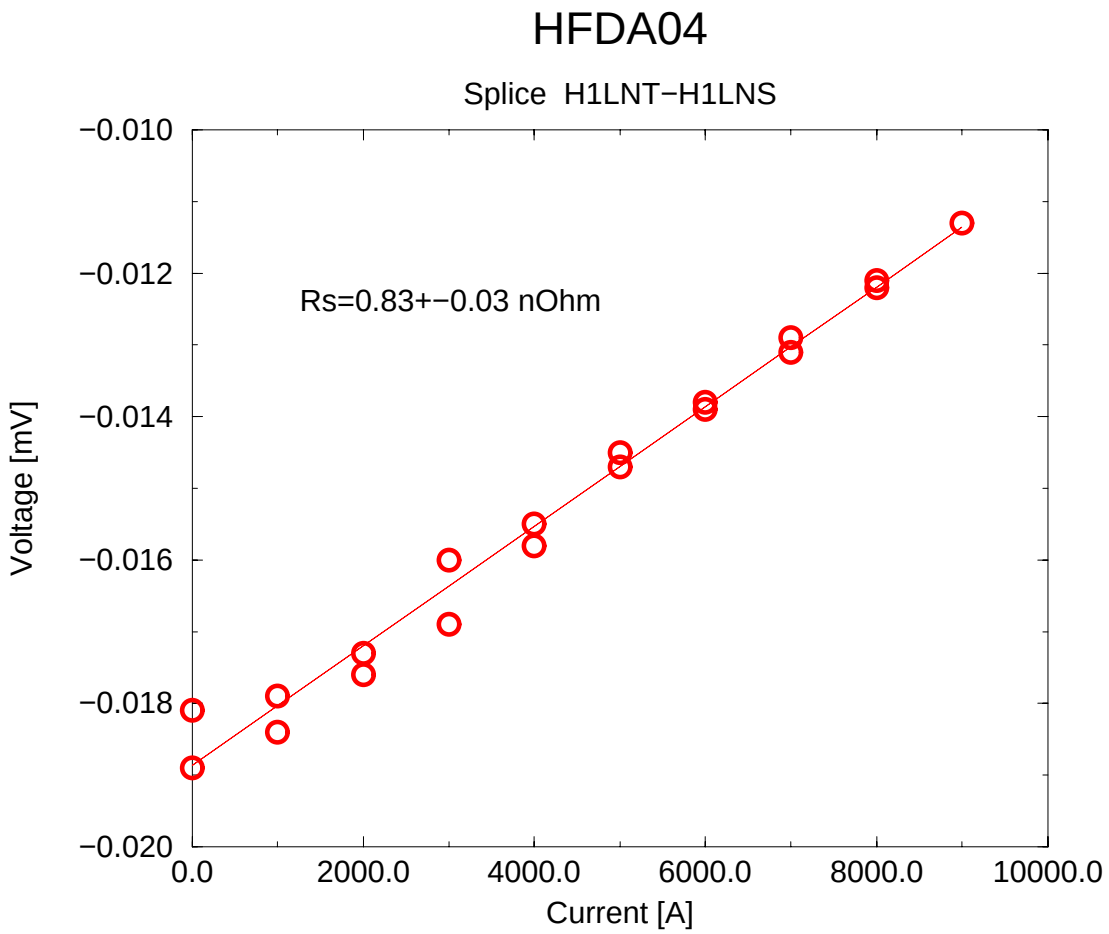

Figure 3. Typical voltage vs. current plot of a splice measurement.

6. Snappy event study

There were mysterious glitches what we were able to record using our snappy trigger. These glitches occurred quite randomly at almost any current. The current distribution of these glitches are summarized in Figure 9. Figure 10. shows a typical glitch signal.

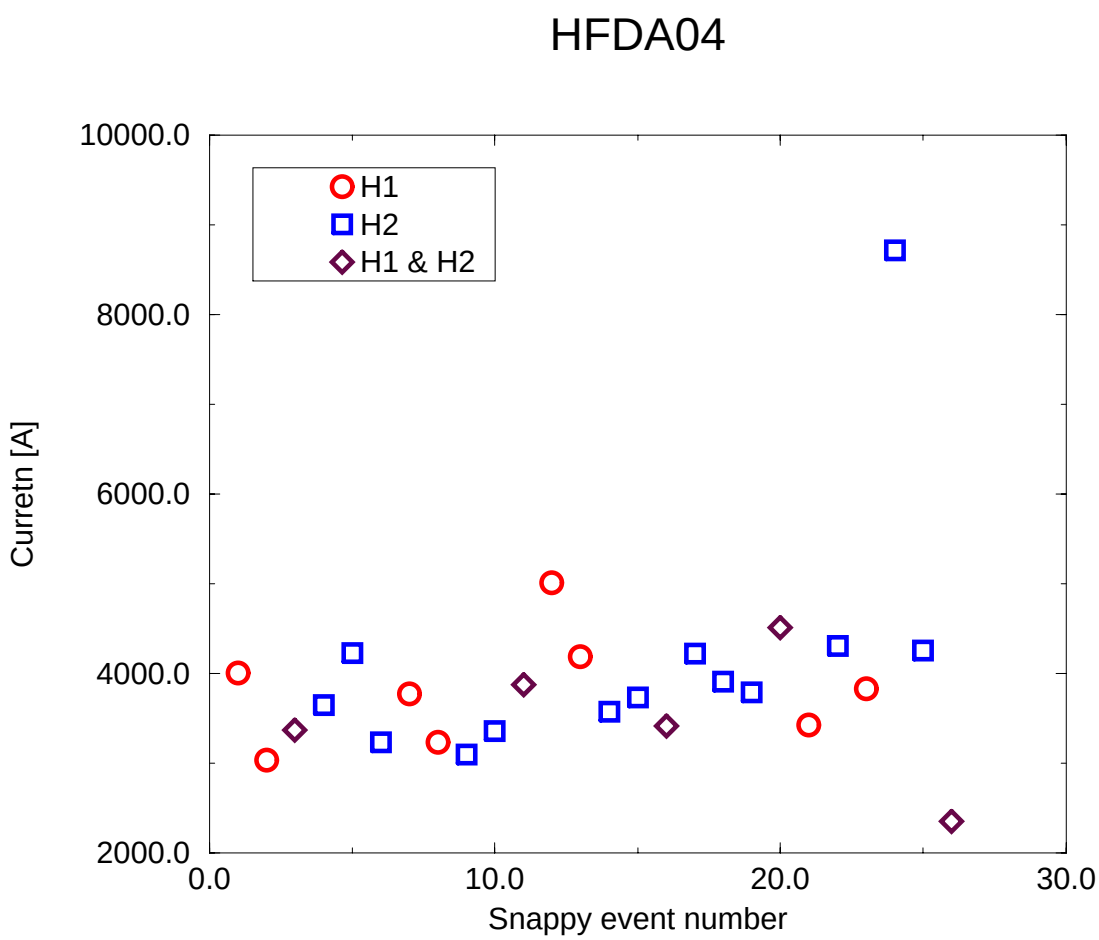

Figure 9. Snappy events occurrence

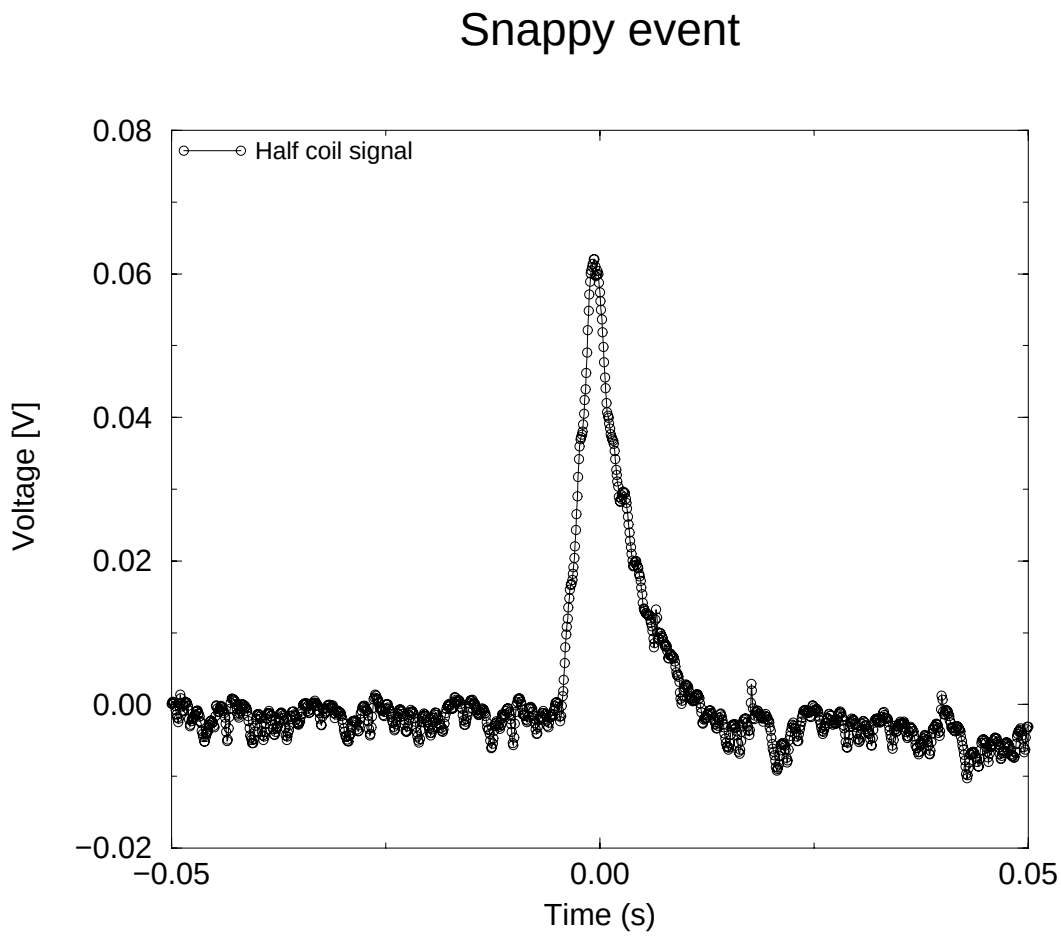

Figure 10. Typical snappy event signal

7. Magnetic measurements

Measurements of magnetic fields in the aperture were performed before and after cooling down. The measurement system utilized a 250 mm long probe (active length), 25 mm in diameter. The probe had a tangential winding for measurement of high order harmonics as well as dedicated dipole and quadrupole windings for measurement of low order harmonics and bucking.[1] Voltages generated in the windings during the probe rotation were sampled 128 times per rotation using HP3458 DVMs and read on the subsequent rotation during which no data is recorded. The probe rotation period was 3 s. An additional DVM was used to monitor the magnet current. DVMs were triggered simultaneously by an angular encoder on the probe shaft, synchronizing measurements of the field and current. A second order probe centering correction was performed assuming that the unallowed by the dipole symmetry a_8/a_{10} and b_8/b_{10} harmonics were zero. For data taken at constant current, centering is performed for each rotation. For data taken under changing current conditions (i.e. loops) the centering correction is determined using data taken between 2000 and 3000 A on both up and down ramps during the first cycle and applied throughout.[2] The main field was assumed to be pure normal (no skew dipole component) and a field angle was assigned.

During the warm measurements, the magnets were energized by a small (10 A) current that reversed sign at each probe position in order to cancel possible weak fields not related to the magnet current. Table 4 summarizes geometrical harmonics in the magnet body. Large harmonic deviations were observed.

The cold magnetic measurements were done in the first test cycle before and after quenching. Measurements after quenching included loop measurements up to 9000 A, "snap back" measurements at 1750 A and longitudinal scan measurements at 3000 A, 5000 A, and 9000 A on the up ramp. Measurements were then repeated at 5000 and 3000 A on the down ramp.

During loop measurements, the magnets were tested at ramp rates of 20 A/s and 80 A/s. No visible change in the hysteresis width was observed. Figure 11 shows the low order harmonics as a function of applied field. The measured harmonics were consistent with calculations for the relevant magnetization of superconductor.

The "snap back" measurement at a 1750 A current plateau was preceded with 0-5000-0-1750 A pre-cycle and followed by a current ramp at 40 A/s to 5000 A and back down.

[1] The quadrupole windings were not used.
[2] There is not a clear indication that the centering helps. We did it anyway.

Figure 12 presents low order harmonics at the plateau as function of time. The harmonics have wave-like shapes with the more high frequency content in some harmonic orders than in others. . Apart from that, there is virtually no visible decay in harmonics and therefore no “snap back” after the ramp resuming.

In order to obtain values of geometrical harmonics, measurements were averaged between up and down ramps for each longitudinal position. Cold harmonics were generally smaller than warm harmonics particularly for the low order harmonics.. Figure 13 shows low order harmonics at 3000 A during up and down ramps as a function of longitudinal position. Table 4 summarizes geometrical harmonics in the magnet center. A complete list of measurements is given in Table 5. The complete set of magnetic measurement data are in Q:\HFM\CosTheta_Dipole\Tests\hfda04\Magnetic folder.

Table 4. Geometrical harmonics.

n	**Warm, 10 A**		**Cold, 3000 A**	
	a_n	b_n	a_n	b_n
2	39.47	-7.39	12.56	0.75
3	3.32	-54.69	-0.25	8.28
4	-3.03	2.34	0.06	0.16
5	0.09	-3.08	0.11	-0.34
6	-0.10	-0.37	-0.01	0.02
7	-0.41	4.14	-0.03	0.49
9	0.02	-1.26	-0.07	-0.15

Table 5. List of measurements.

Type	**Imax (kA)**	**Ramp rate (A/s)**	**Comment**
warm			
scan	0.010	0	±10 A
cold, before quenching			
loop	6.5	20	
loop	5	20	“snapback” measurement, 1750 A, 30 min
cold, after quenching			
loop	9	20	
loop	9	80	
loop	5	40	“snapback” measurement, 1750 A, 30 min
scan	3	0	up ramp
scan	5	0	up ramp
scan	7	0	up ramp
scan	5	0	down ramp
scan	3	0	down ramp

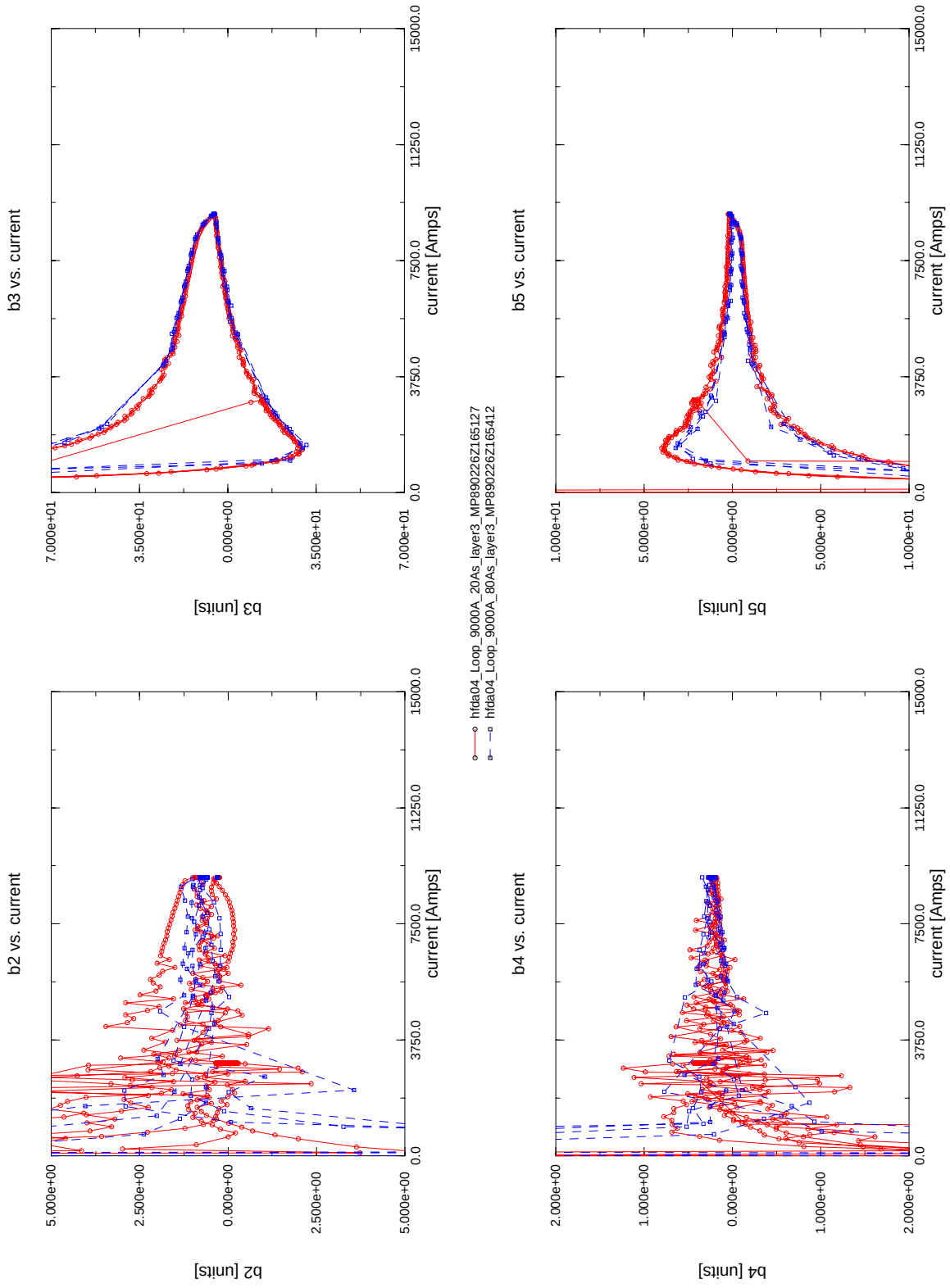

Figure 12. Loop measurements.

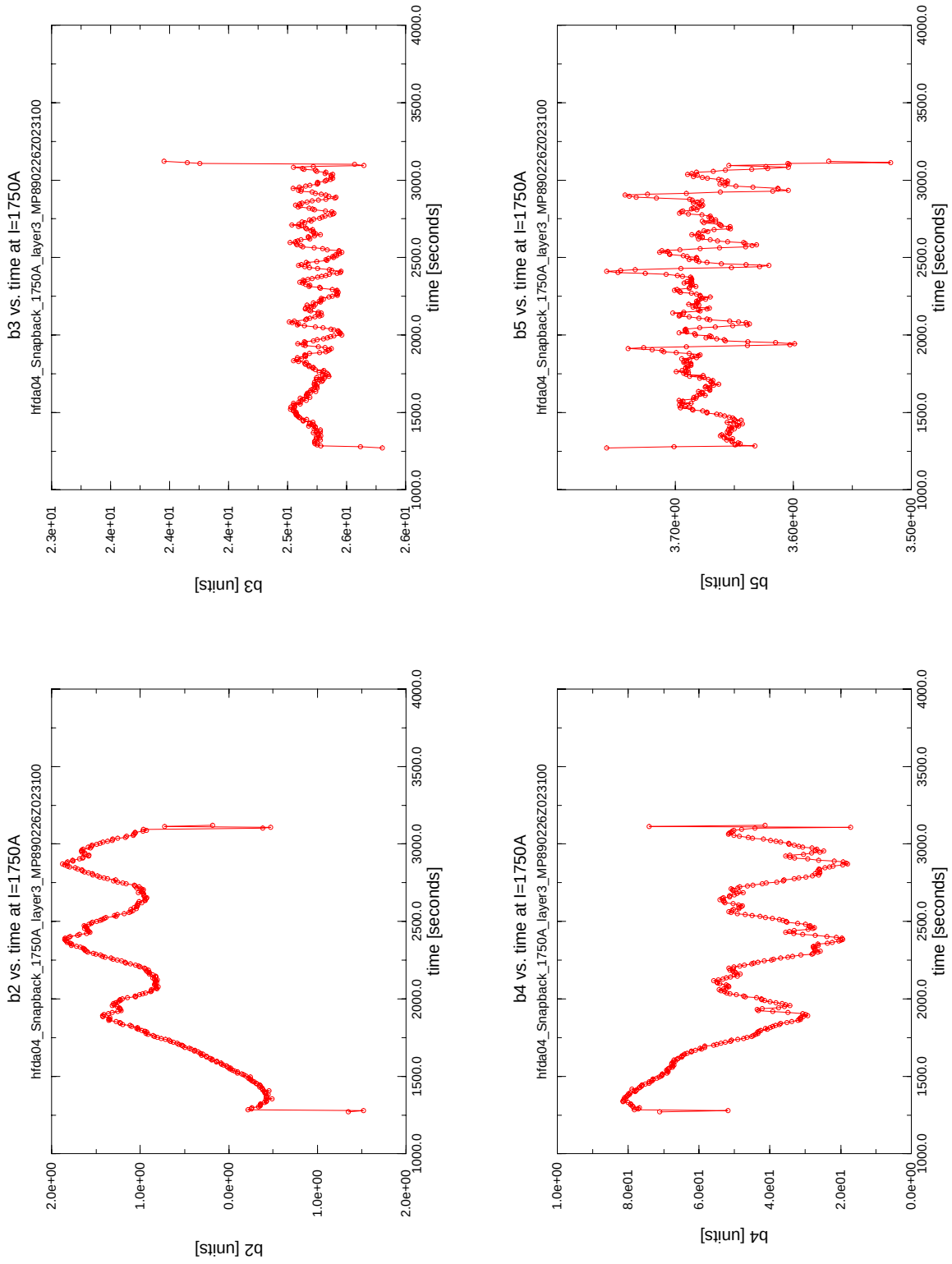

Figure 12. Snap back measurements.

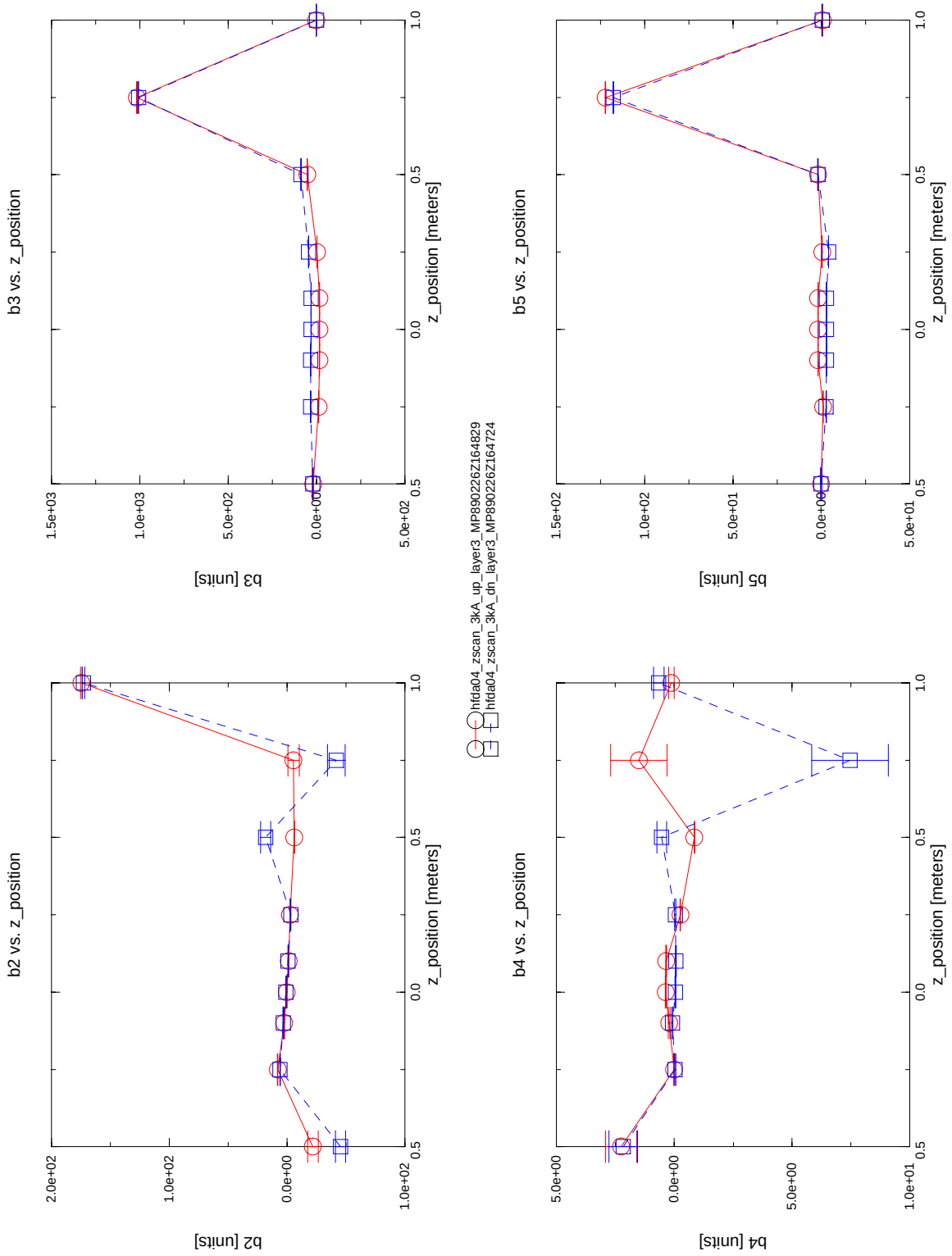

Figure 13. Z-scan measurements.

8. Strain gauge measurements

Capacitance Gauge Data:

Two capacitance gauges per half coil were installed. Note that all of them are on the outer pole region. The drop in coil azimuthal stress during excitation was about 8.5 MPa. Similar behavior was observed in both the thermal cycles and at both temperatures.

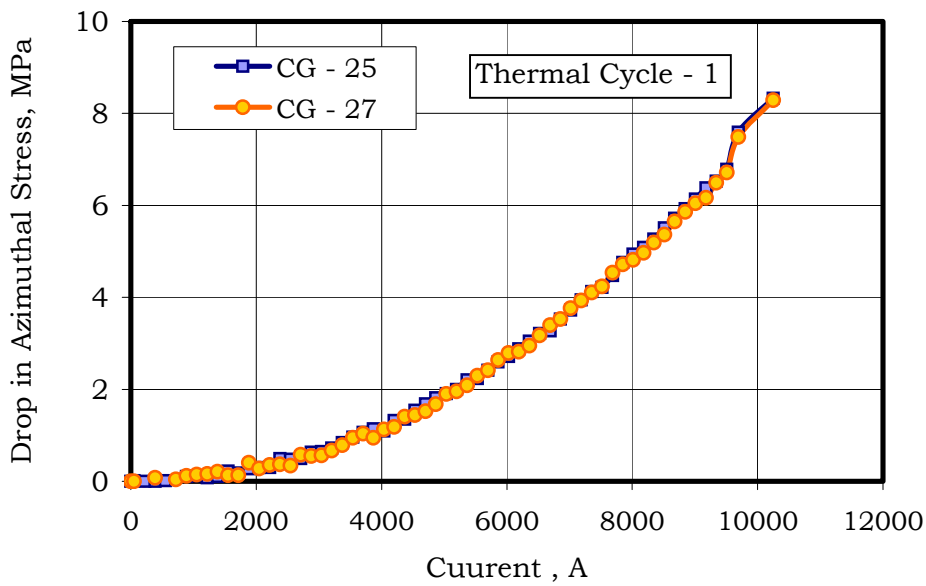

Fig. 14: Evolution of outer coil azimuthal stress with excitation.

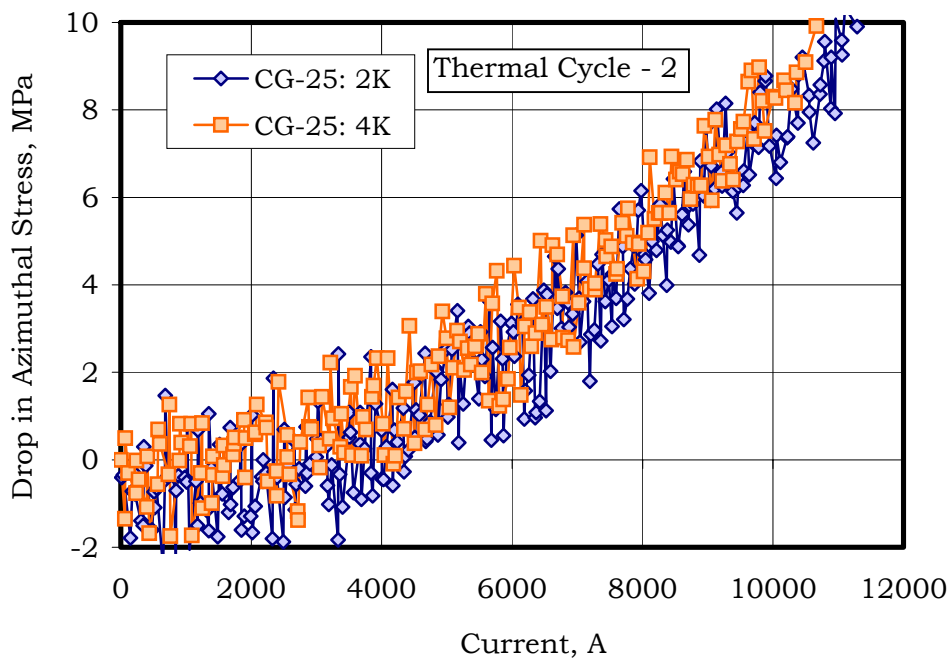

Fig. 15: Evolution of outer coil azimuthal stress with excitation thermal cycle-II.

Spacer Strain Gauge Data in the Magnet Straight Section:

Strain gauges were mounted on the aluminum spacers to measure azimuthal stress near the mid-plane and at pole region. Based on the measurements, the spacers are in compression at all stages of the magnet operation.

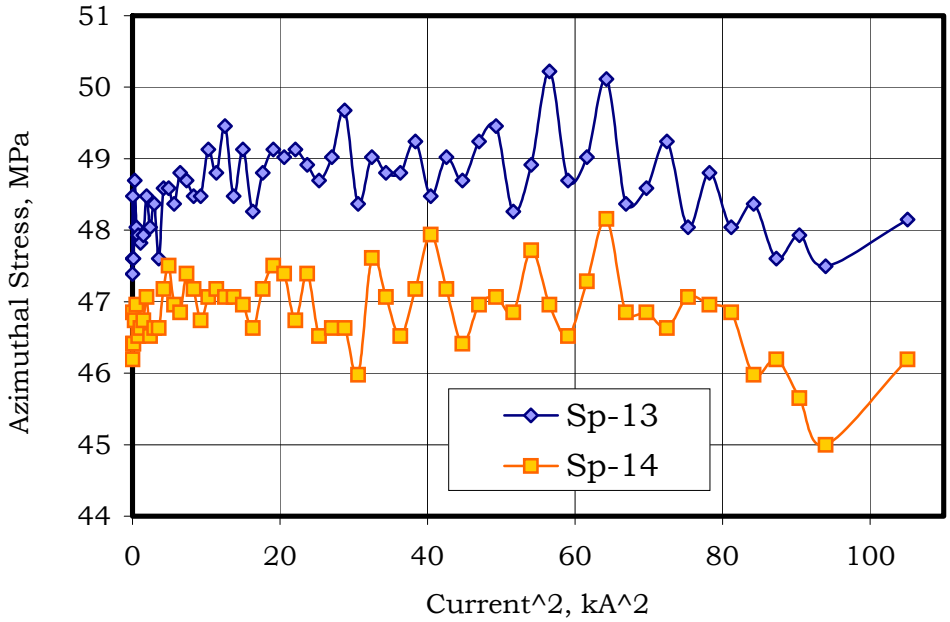

Fig. 16: Azimuthal stress variation with magnet excitation for top spacer.

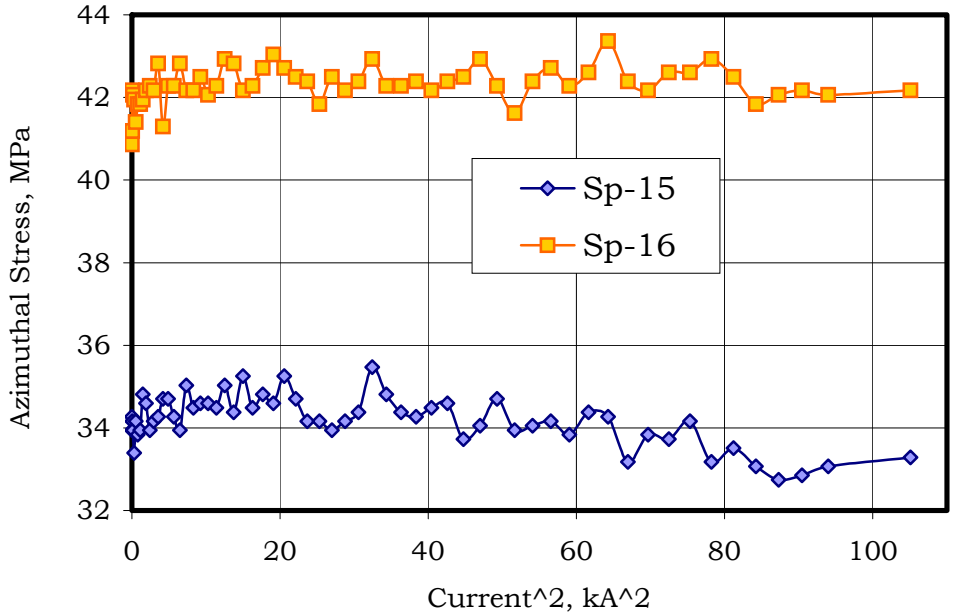

Fig. 17: Azimuthal stress variation with magnet excitation for bottom spacer.

Spacer Strain Gauge Data in the Magnet LE Section:

Strain gauges were mounted on the LE aluminum spacers to estimate the azimuthal stress in the splice region. Based on the measurements, the spacers are in compression at all stages of the magnet operation.

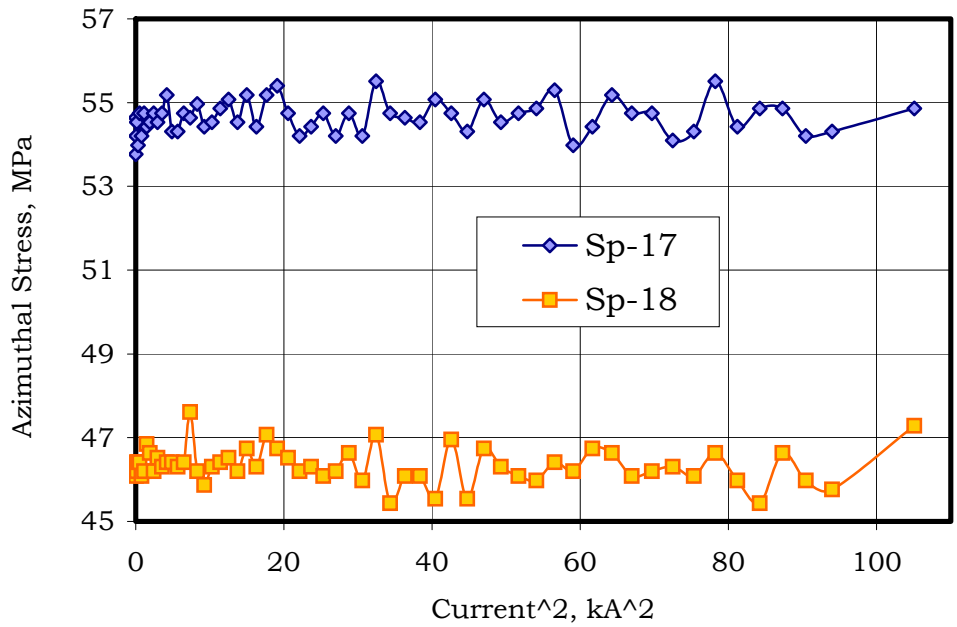

Fig. 18: Azimuthal stress variation with magnet excitation for top spacer in LE.

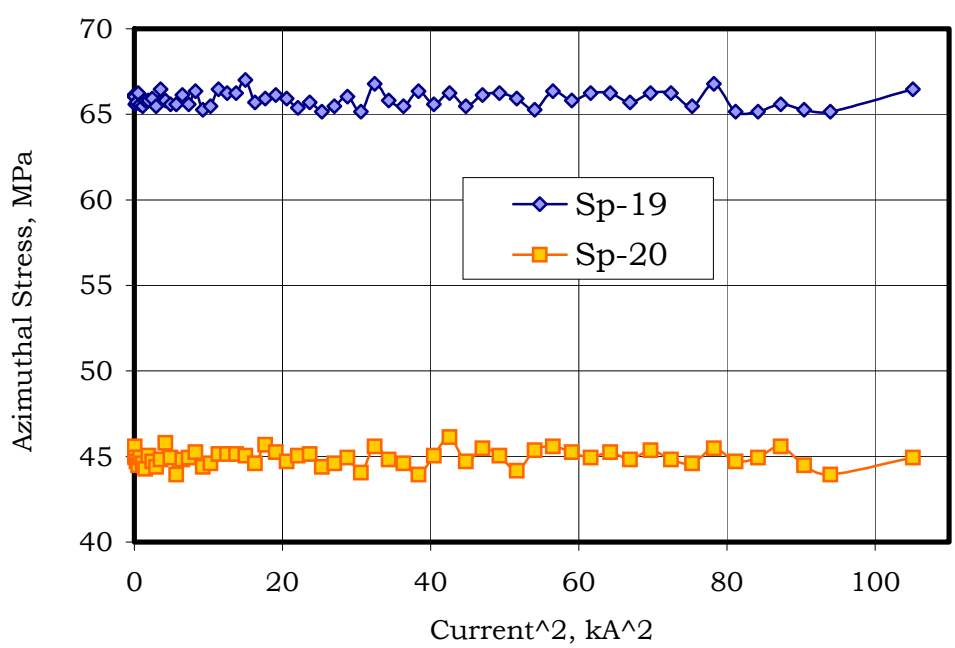

Fig. 19: Azimuthal stress variation with magnet excitation for bottom spacer in LE.

LE Bullet Gauge Data:

Four bullets were installed on LE, two per half coil. The data shows that the bullets were in contact with the coil after cool down. However we do not see any load transfer with excitation. The reasoning could be that the Lorentz forces were transferred to the skin through friction and not to the end bullets.

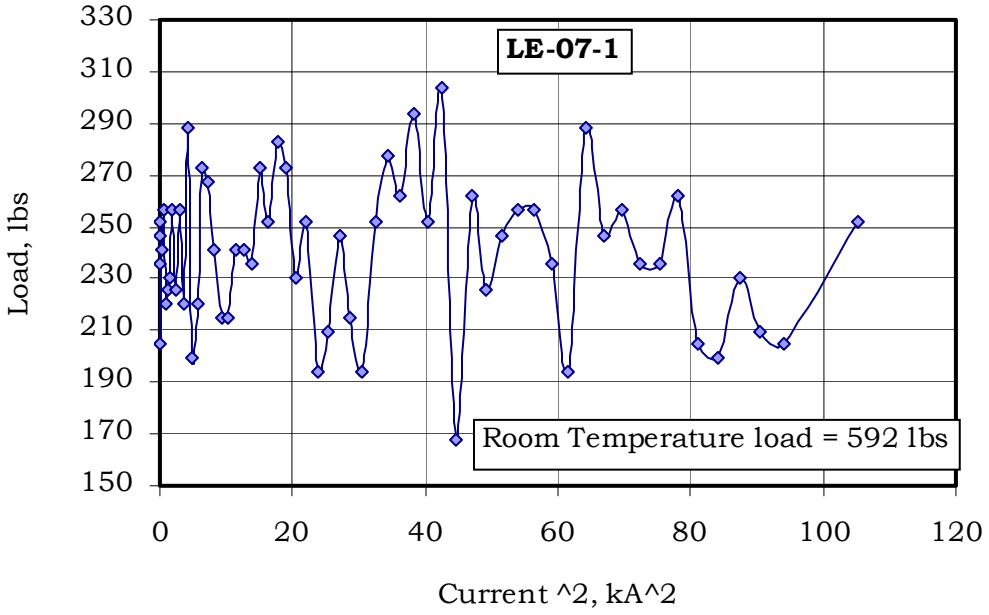

Fig. 20: Evolution of LE-07-1 bullet load with magnet excitation.

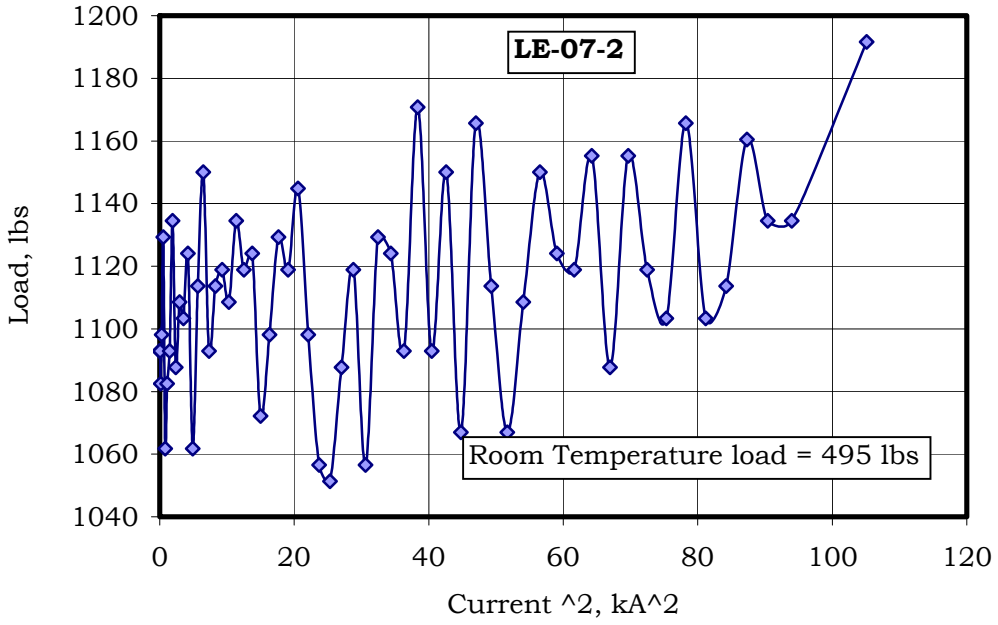

Fig. 21: Evolution of LE-07-2 bullet load with magnet excitation.

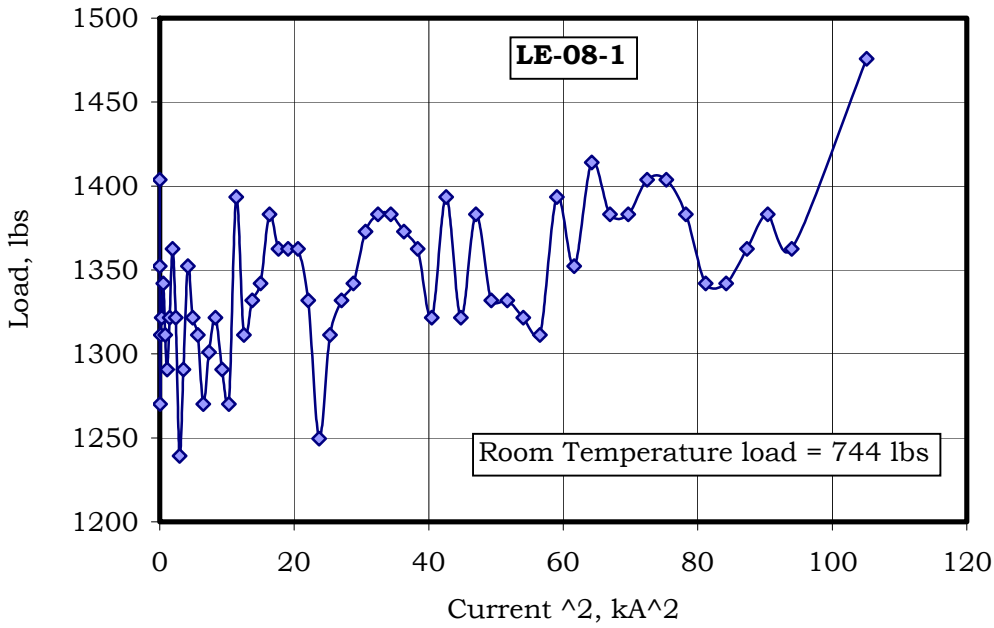

Fig. 22: Evolution of LE-08-1 bullet load with magnet excitation.

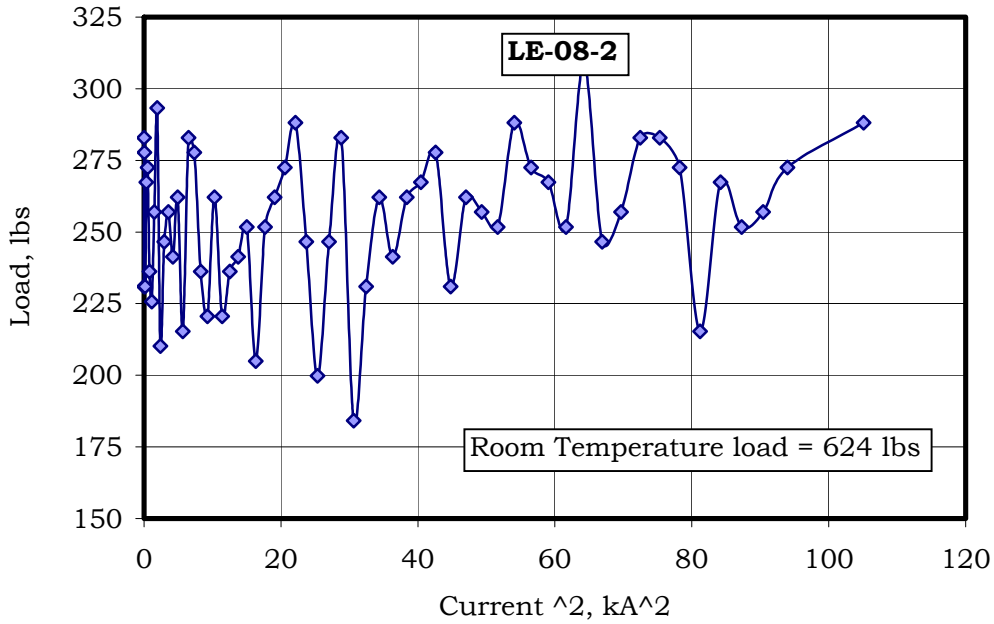

Fig. 23: Evolution of LE-08-2 bullet load with magnet excitation.

Note: Both LE-07-2 and LE-08-1 indicate loads at 4.2 K higher than that at room temperature, which is not realistic. This still needs to be understood.

RE Bullet Gauge Data:

Four bullets, two per half coil, were also installed on RE. The data shows the bullets were in contact with the coil after cool down and that there is load transfer from coils to the bullets on excitation.

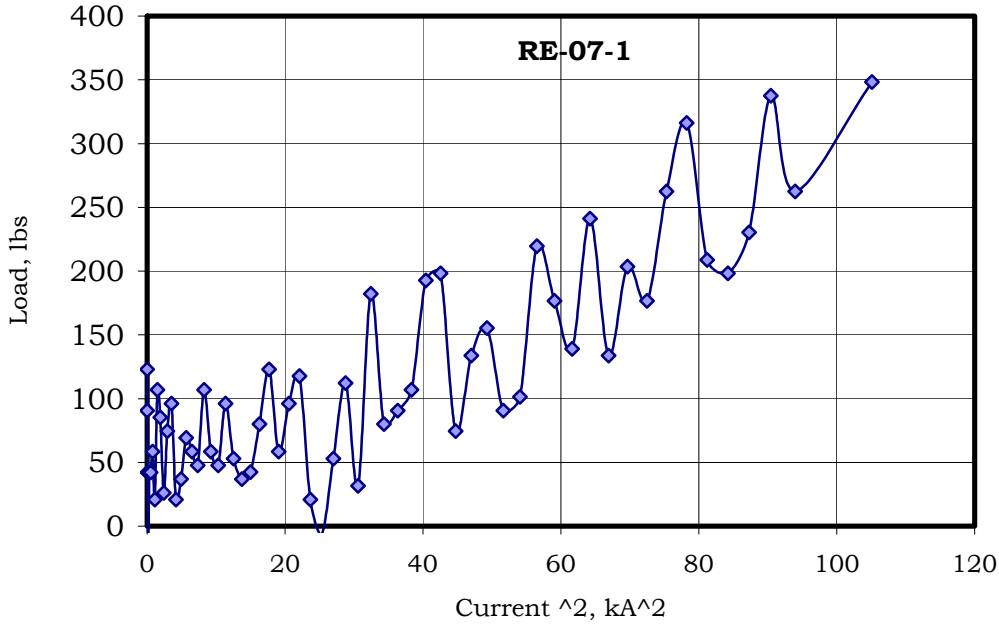

Fig. 24: Evolution of RE-07-1 bullet load with magnet excitation.

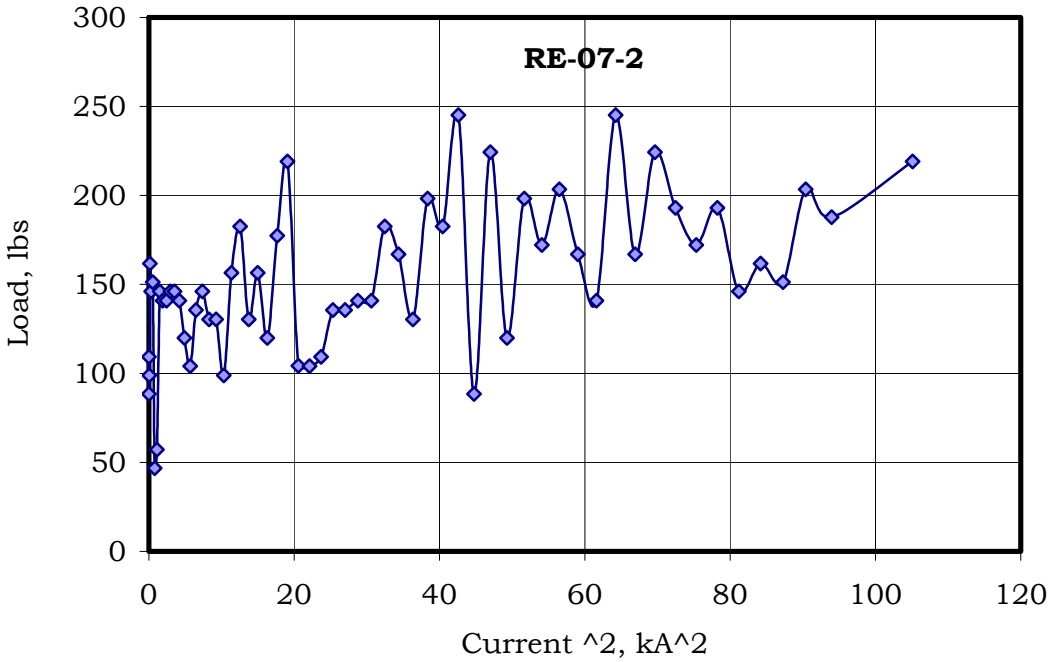

Fig. 25: Evolution of RE-07-2 bullet load with magnet excitation.

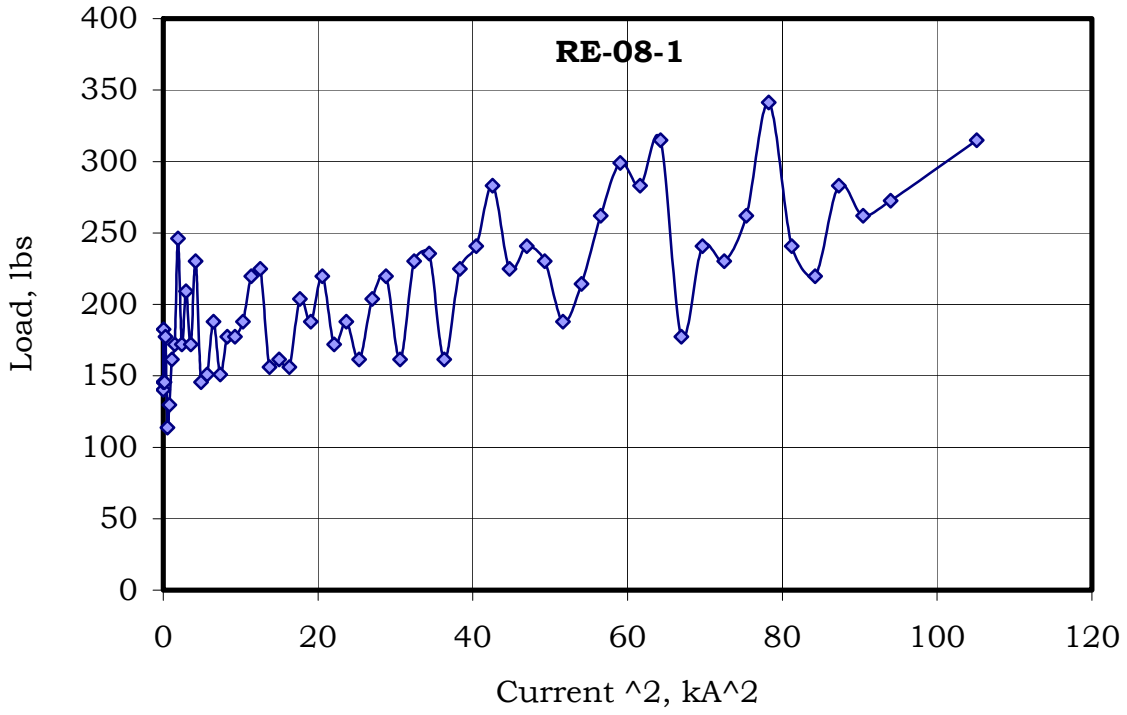

Fig. 26: Evolution of RE-08-1 bullet load with magnet excitation.

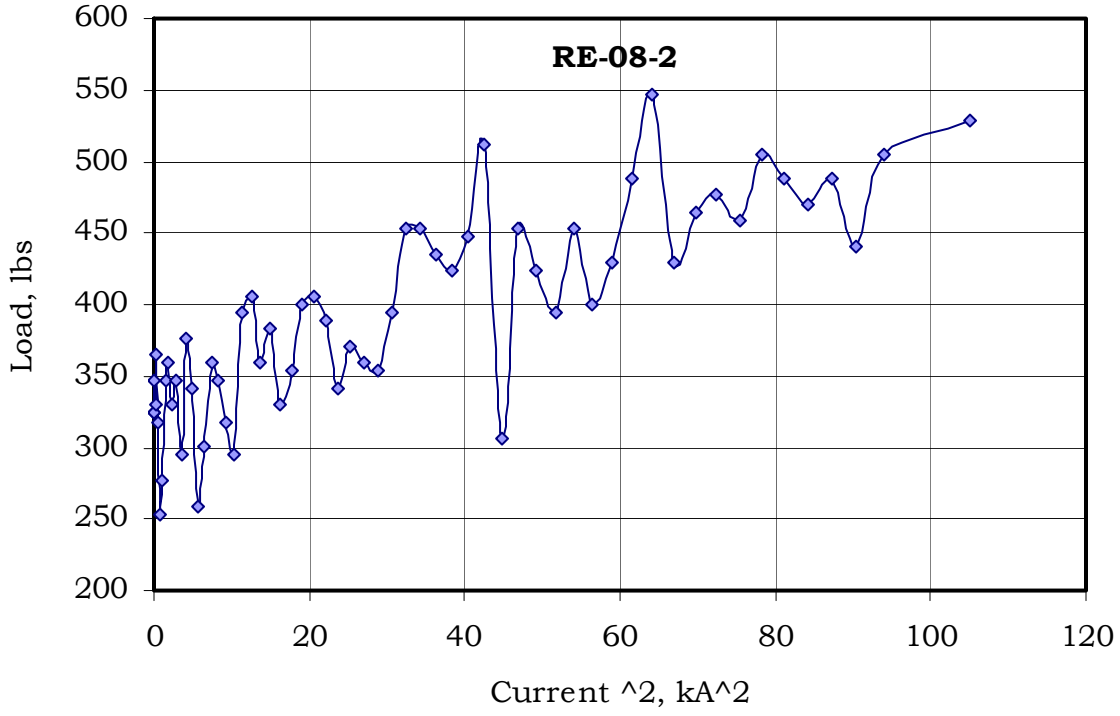

Fig. 27: Evolution of RE-08-2 bullet load with magnet excitation.

Behavior of Strain Gauges at 2 K:

We observed some peculiar behavior of strain gauges at 2 K when compared to at 4 K. However if we take into account the behavior of temperature compensators we would end up with similar behavior.

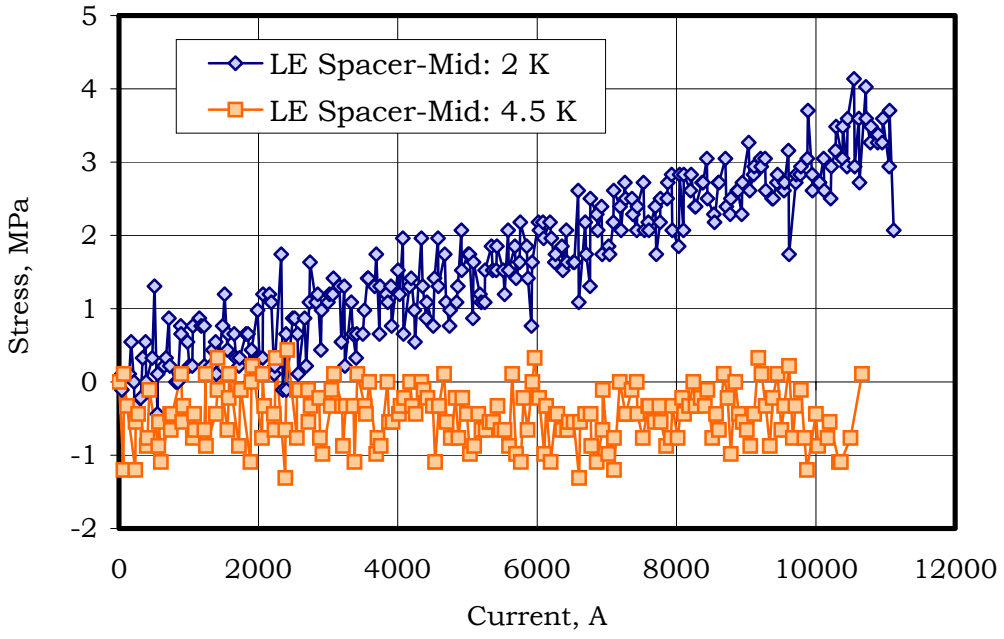

Fig. 28: Comparison of the behavior of active strain gauges at 4K and 2K.

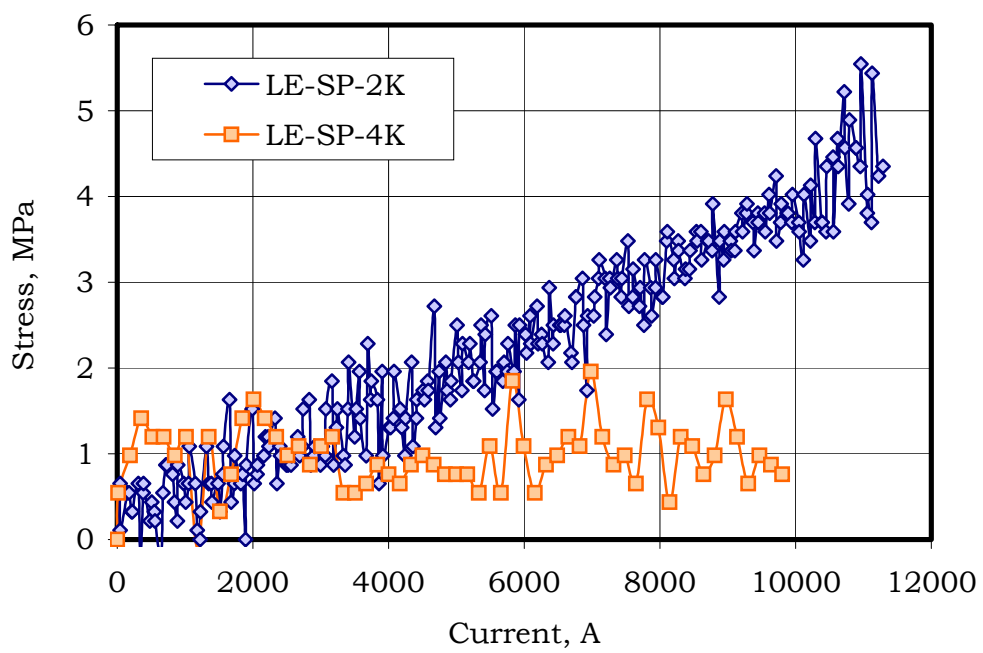

Fig. 29: Comparison of the behavior of temperature compensators at 4K and 2K.

9. AC loss measurements

Energy Loss measurements were performed on HFDA04 at 4.5K using two HP3458A Digital Multimeters (dmm) setup to integrate over 1 power line cycle and sample at 60Hz. One dmm measured the magnet voltage and the second dmm measured the magnet current via a 20KA Holec Transductor. The magnet was ramped between 500A and 6500A for all measurements. Five measurements were performed at each ramp rate of 75A/s, 100A/s, 150A/s, 200A/s, 250A/s, 300A/s, 350A/s, 400A/s, and 450A/s, and three pre-ramp cycles were performed before each new ramp rate.

The measured **Hysteresis = 905 Joules**
And the measured **Slope = 0.15J/A/s**

The following is a plot of the data (see previous page):

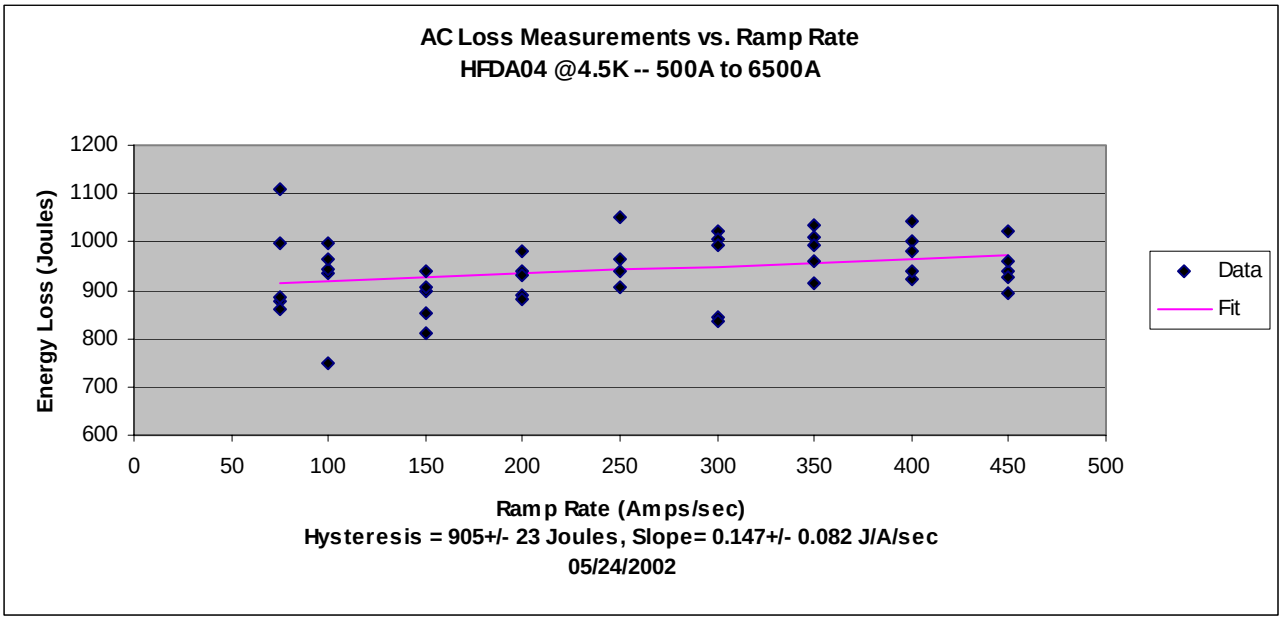

Figure 30. AC loss measurement plot as a function of current ramp rate.

Table 6.

HFDA04 Energy Loss Measurement Summery @4.5K -- 500Amps to 6500Amps

Ramp Rate(Amps/sec)	*Energy Loss(Joules)*	*Integral Volts*
75	1107.176147	0.063223
75	996.909485	0.044638
75	875.573425	0.018862
75	860.655579	0.002703
75	884.333557	0.024752
100	747.893127	-0.027094
100	998.393738	0.034318
100	936.061096	0.008606
100	943.597534	0.019422
100	965.332397	0.033037
150	898.283691	-0.000282
150	905.438904	-0.000197
150	850.598328	-0.007064
150	812.012512	-0.0094
150	937.874939	0.009952
200	979.402222	0.013979
200	887.690186	0.00684
200	881.996948	0.007321
200	937.244873	0.012719
200	932.020813	0.019707
250	965.204834	0.011586
250	940.396484	0.002972
250	906.051147	0.006207
250	1050.36731	0.036062
300	1024.002319	0.022701
300	845.991516	-0.02702
300	1006.232666	0.012397
300	834.462036	-0.026841
300	994.064453	0.018819
350	960.918213	-0.002183
350	1011.148254	0.003266
350	1033.030273	0.022861
350	914.489014	-0.004489
350	992.626038	0.007537
400	1001.880798	0.006441
400	1042.660156	0.023293
400	923.299255	-0.011717
400	978.636108	0.004845
400	937.301514	0.001538
450	941.30249	-0.010476
450	1021.904236	0.010771
450	925.848328	-0.011129
450	893.401245	-0.027093
450	961.054443	0.003346

10. RRR measurement

The RRR measurement was performed on 5/24. The magnet was gradually warming up and meanwhile we recorded the whole coil voltage value generated by 10 A across the magnet. The low temperature plot and the corresponding magnet voltage is shown in Figure 31 and 32, the magnet voltage at room temperature is shown in Figure 33. The measured RRR value is 4.9.

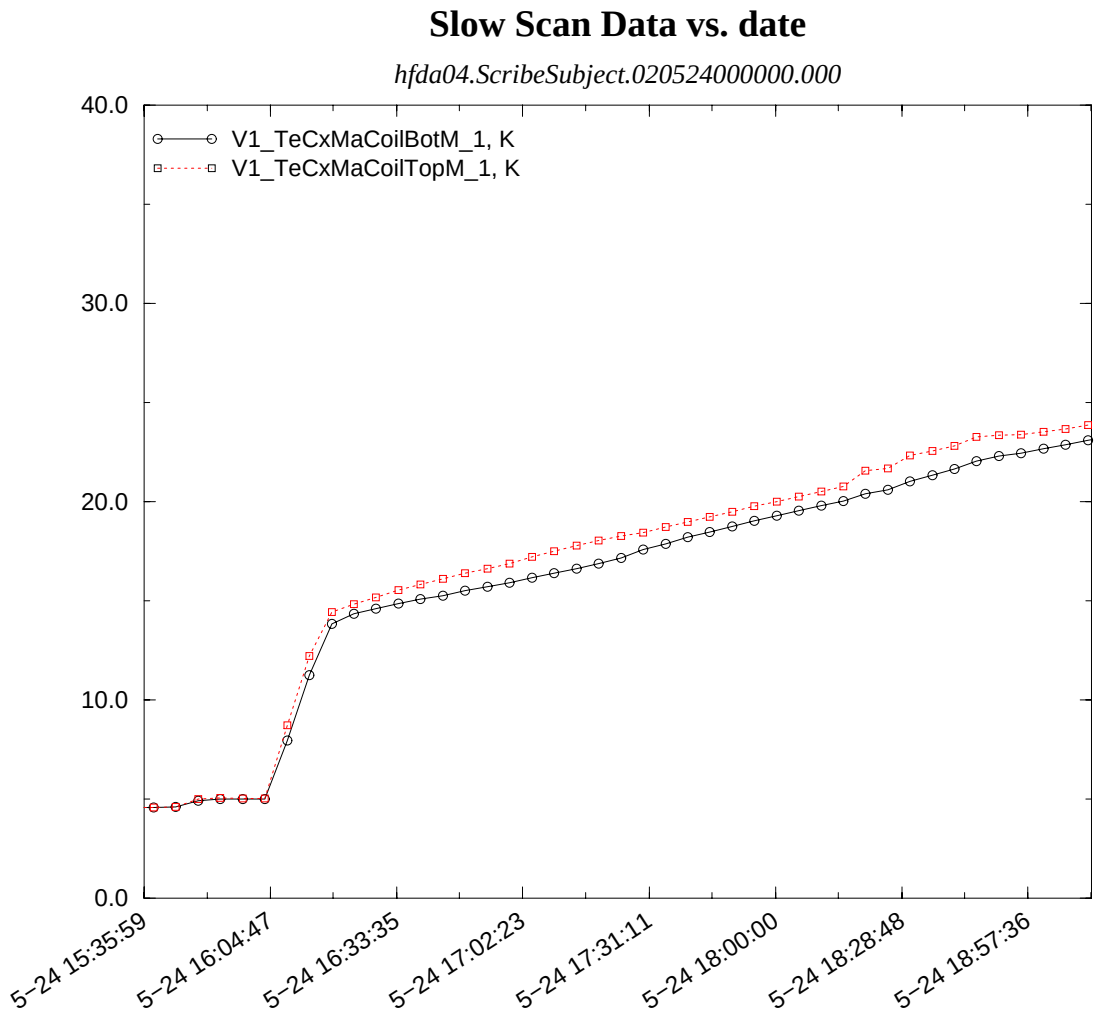

Figure 31. Magnet temperature when the low temperature rrr data was taken

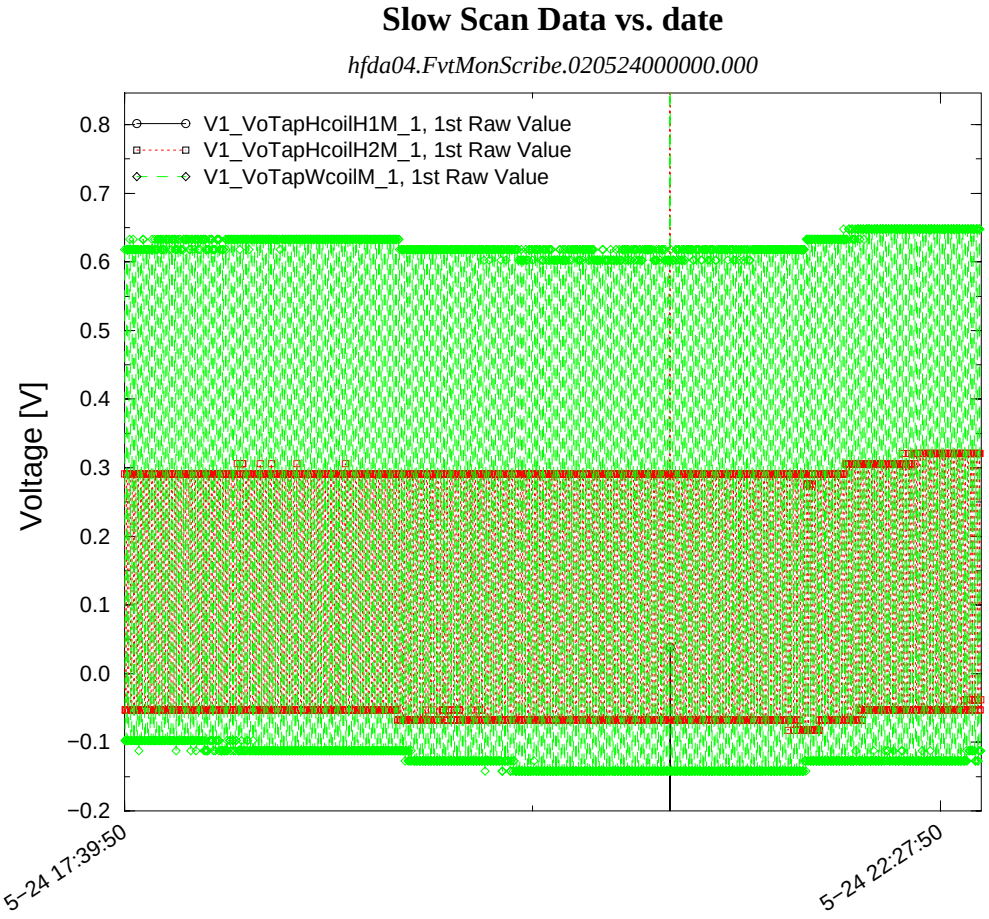

Figure 32. Magnet voltage at 10A applied current and at ~20K magnet temperature.

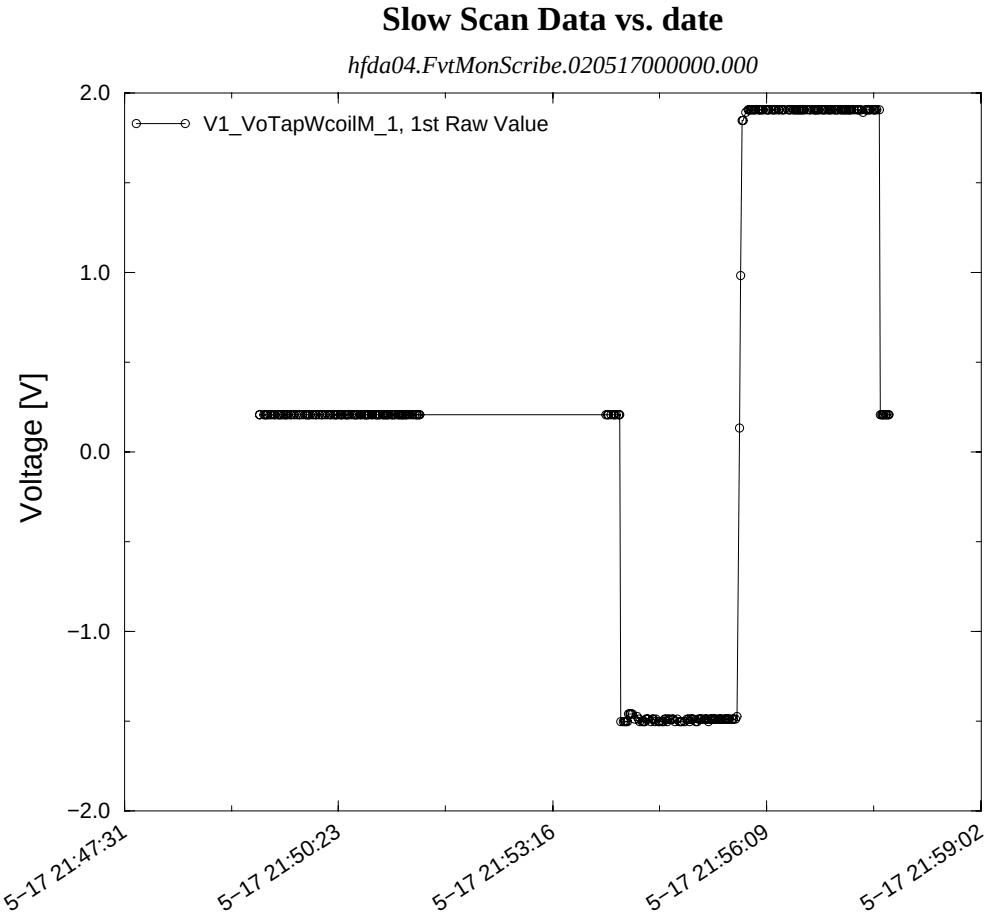

Figure 33. Magnet Voltage at 10A applied current and at 300K.