4/29/05
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HFDM05 Test Summary

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1. Introduction

HFDM05 is a mirror magnet made from newly wound and cured Nb_3Sn cable (see construction report) which was made of RRP 0.7mm strand. The magnet was completed and shipped to MTF on April 20th, 2005. After it was installed into the VMTF dewar it was electrically checked out by April 21st , 2005. The VMTF dewar was filled with liquid helium on April 25th, 2005. This magnet went trough two test cycles. Between the test cycles the instrumentation of the magnet has changed: few more strain gauges were added and the preload of the coil was increased. The magnet test has been completed on May 28th. On July 6th 2005 the magnet was removed from the VMTF dewar.

2. Quench History and Quench Locations

The first quench of the magnet was at quite low current value (6890A) and it was about 42% of the critical current value calculated on the basis of witness strand sample critical current measurements. The magnet exhibited practically no training. Taking ten quenches was enough to confirm that the magnet quench current is limited so the magnet reached its quench plateau at 4.5K. We continued the test program with ramp rate dependence studies. In order to confirm that the magnet reached its plateau quench current value the magnet was cooled down to 2.2K. Quench behavior at 2.2 K was quite the same as it was at 4.5K with slightly increased quench current plateau. Taking a few quenches again at 4.5K we observed that the magnet quench current is in the same range than it was prior to 2.2 K quenching. After taking few more ramp rate dependence quenches we cooled down the magnet again to 2.2 K and performed special ramp rate dependent voltage spike studies. The magnet current was ramped three times up and down between 0A and 7000A with different ramp rates. Before we proceeded to the next ramp rate we initiated a quench with 150 A/s ramp rate.
After performing a thermal cycle and some adjustments on the magnet support pre-load values the magnet was re-tested. However the quench performance didn't improve. The quench current values remained at the same quench current range.
The quench summary is shown in Fig 1. and the details of the different current ramps are described in Table 1.

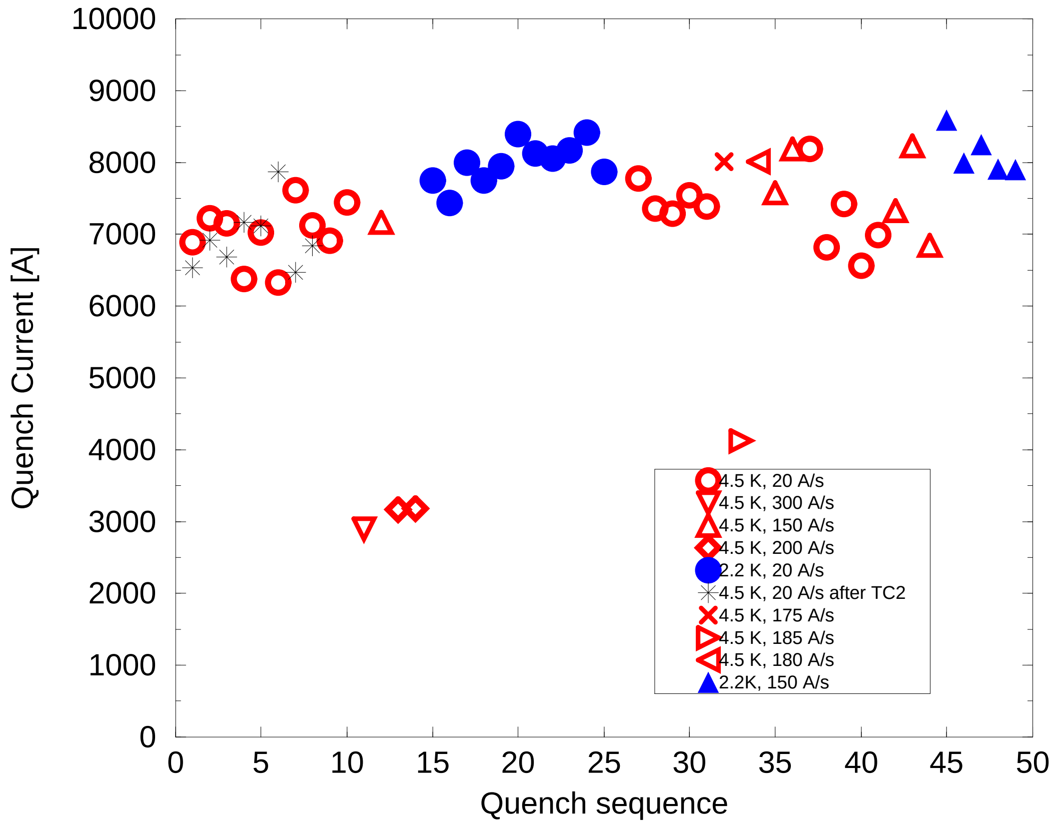


Fig. 1. Quench history of HFDM05 is shown.

Quench locations at 4.5K LHe bath temperatures and 20A/s ramp rates were in the outer coil. Higher ramp rate quenches started both in the inner and outer coils almost simultaneously. Almost all the time all of the inner coil segments quenched. The 2.2 K, 20A/s quench locations were alternating between the inner and outer coils.

Table 1. Quench summary details.

File	Current	dI/dt	t_{quench}	MIITs	QDC	1st Vtseg	t_{rise}	Mag Temp Bot L(1)	Comment
hfdm05.Quench.050425115822.690									
hfdm05.Quench.050425132332.427	0	0	0.0000	0.07		Q13au_QCC	-0.0001	4.4571	trip during balancing
hfdm05.Quench.050425134248.240	0	0	0.0000	1.08		Q13au_QCC	-0.0001	4.4566	1000A trip due to checking out the Copper leads
hfdm05.Quench.050425135151.180	0	0	0.0000	9.52		QIS31_Q5au	0.0001	4.4578	3000A, heater induced quench, SHFU=200V
hfdm05.Quench.050425142428.828	1004	0	0.0003	0.08	HcoilHcoil	Q13au_QCC	0.0024	4.4577	1000A manual trip
hfdm05.Quench.050425143801.151	**6890**	19	-0.0550	4.57	HcoilHcoil	QCC_QOS30	-0.0022	4.4606	1st quench, Iq=6890A, 4.45K, 20A/sec
hfdm05.Quench.050425145750.987	**7224**	20	-0.0568	5.10	HcoilHcoil	QCC_QOS30	-0.0120	4.4596	2nd, Iq=7224A, 20A/s, 4.45K
hfdm05.Quench.050425151747.033	**7150**	20	-0.0164	2.91	HcoilHcoil	QCC_QOS30	-0.0071	4.4594	3rd quench, 20A/s, Iq=7150A, 4.45K
hfdm05.Quench.050425153352.516	**6378**	20	-0.0842	5.14	HcoilHcoil	QCC_QOS30	0.0020	4.4588	4th quench, Iq=6378A, 20A/sec, 4.45K
hfdm05.Quench.050425155134.566	**7023**	20	-0.2113	12.48	HcoilHcoil	QCC_QOS30	-0.0015	4.4559	4th quench, 20a/sec, Iq=7023A, 4.45K
hfdm05.Quench.050425160935.026	**6330**	20	-0.0850	5.10	HcoilHcoil	QCC_QOS30	0.0015	4.4583	Quench #6, Iq=6330 A, ramp =20 A/s 4.45 K
hfdm05.Quench.050425163526.322	**7615**	20	-0.0160	3.24	HcoilHcoil	QCC_QOS30	-0.0046	4.4533	Quench #7, Iq = 7615 A, ramp = 20 A/s T = 4.45 K
hfdm05.Quench.050425165319.723	**7125**	20	-0.0778	6.04	HcoilHcoil	QCC_QOS30	-0.0053	4.4524	Quench #8, Iq = 7125 A, ramp = 20 A/s, T = 4.45 K
hfdm05.Quench.050425170933.007	**6912**	20	-0.0675	5.20	HcoilHcoil	QCC_QOS30	0.0007	4.4534	Ramp #9 Iq = 6912 A Ramp = 20 A/s T = 4.45 K
hfdm05.Quench.050425173200.487	**7447**	20	-0.0940	7.46	HcoilHcoil	QCC_QOS30	-0.0042	4.4527	Quench # 10 Iq = 7447 A ramp = 20 A/s T = 4.45 K
hfdm05.Quench.050425174728.061	**2899**	240	-0.0134	0.51	WcoilIdot	Q7au_Q13au	-0.0122	4.4508	Quench # 11 Iq = 2899 A Ramp = 300 A/s T = 4.45 K
hfdm05.Quench.050425180636.398	**7168**	151	-0.0031	2.17	HcoilHcoil	Q7au_Q13au	-0.0020	4.4472	Ramp #12 Iq = 7168 A Ramp = 150 A/s T = 4.45 K
hfdm05.Quench.050425183200.051	**3169**	192	-0.0122	0.59	WcoilIdot	Q7au_Q13au	-0.0102	4.4447	q#13, 200A/sec, Iq=3169A, 4.45K
hfdm05.Quench.050426091922.387	**3171**	192	-0.0162	0.64	WcoilGnd	Q7au_Q13au	-0.0088	4.3372	14th quench, 200A/sec, Iq=3000A, 4.3K
hfdm05.Quench.050426112252.729	**7748**	20	-0.0043	2.65	WcoilIdot	Q7au_Q13au	-0.0022	2.1705	Quench #15 Iq=7747.7 2.166K 20A/sec
hfdm05.Quench.050426115205.213	**7448**	20	-0.0557	5.35	HcoilHcoil	QCC_QOS30	0.0003	2.1743	Quench#16 Iq=7300A 20A/sec 2.174K
hfdm05.Quench.050426131714.171	**8000**	20	-0.0035	2.76	HcoilHcoil	Q7au_Q13au	-0.0025	2.1644	17th quench, 20A/s, 2.2K, Iq=8000A
hfdm05.Quench.050426133909.210	**7747**	20	-0.0137	3.23	HcoilHcoil	QCC_QOS30	-0.0066	2.1631	18th quench, 20A/sec, Iq=7747A, 2.2K
hfdm05.Quench.050426140334.523	**7947**	20	-0.0041	2.75	WcoilIdot	Q7au_Q13au	-0.0024	2.1635	19th quench, 20A/sec, 2.2K, Iq=7947A
hfdm05.Quench.050426142448.010	**8397**	20	-0.0027	2.91	HcoilHcoil	Q7au_Q13au	-0.0018	2.1636	20th qench, 20a/s, 2.2K, Iq=8397A
hfdm05.Quench.050426145035.788	**8125**	20	-0.0454	5.63	HcoilHcoil	QCC_QOS30	0.0008	2.1635	21st quench, 20A/sec, 2.2K, Iq=8125A
hfdm05.Quench.050426151806.759	**8058**	20	-0.0035	2.78	WcoilIdot	Q7au_Q13au	-0.0035	2.1622	22nd quench, 20A/s, 2.2K, Iq=8058A
hfdm05.Quench.050426154032.558	**8055**	0	-0.6171	42.71	HcoilHcoil	QCC_QOS30	-0.0038	2.1627	Quench #23 Iq = 8055 Ramp = 20 A/s T = 2.2 K
hfdm05.Quench.050426160828.029	**8166**	20	-0.0382	5.21	HcoilHcoil	QCC_QOS30	0.0000	2.1631	Quench # 24 Iq = 8166 A ramp = 20 A/s T = 2.2 K

hfdm05.Quench.050426163243.453	**8414**	20	-0.0028	2.95	WcoilIdot	Q7au_Q13au	-0.0015	2.1634	Quench # 25 Iq = 8414 A ramp = 20 A/s T = 2.2 K
hfdm05.Quench.050426165235.568	**7868**	20	-0.0500	5.60	HcoilHcoil	QCC_QOS30	-0.0083	2.1628	Quench # 26 Iq = 7868 A ramp = 20 A/s T = 2.2 K
hfdm05.Quench.050427093054.977	**7777**	20	-0.0133	3.22	HcoilHcoil	QCC_QOS30	-0.0042	4.4272	q27, 20A/sec, 4.45K, Iq=7777A
hfdm05.Quench.050427095408.848	**7361**	20	-0.0137	2.93	HcoilHcoil	QCC_QOS30	-0.0063	4.4301	q27, 4.45K, 20A/s, Iq=7361
hfdm05.Quench.050427102528.378	**7289**	20	-0.0147	2.93	HcoilHcoil	QCC_QOS30	-0.0067	4.4345	q29, 20A/sec, 4.5K, Iq=7289A
hfdm05.Quench.050427105148.977	**7541**	20	-0.0526	5.29	HcoilHcoil	QCC_QOS30	-0.0113	4.4345	q30, 20A/sec, 4.45K, Iq=7541A
hfdm05.Quench.050427111436.546	**7385**	20	-0.0134	2.94	HcoilHcoil	QIS31_Q5au	-0.0043	4.4354	31st quench, 4.45K, 20a/sec, Iq=7385A
hfdm05.Quench.050428074603.721	**8121**	176	-0.0041	2.69	HcoilHcoil	QIS31_Q5au	-0.0020	4.4610	32nd quench, 175A/sec, 4.45K, Iq=8121A
hfdm05.Quench.050428080246.888	**4123**	184	-0.2244	4.65	HcoilHcoil	Q13au_QCC	-0.0073	4.4569	33rd quench, 185A/s, Iq=4000A, 4.45K
hfdm05.Quench.050428081627.088	**8014**	0	-0.6218	41.91	HcoilHcoil	QIS31_Q5au	-0.0031	4.4575	q34, 180A/sec, 4.45K, Iq=8014A
hfdm05.Quench.050428103135.009	**7576**	150	-0.0109	2.89	HcoilHcoil	QIS31_Q5au	-0.0029	4.4446	q35, 4.45K, 150A/s, Iq=7576A
hfdm05.Quench.050428104627.841	**8191**	150	-0.0024	2.68	HcoilHcoil	QIS31_Q5au	0.0003	4.4486	36th quench, Iq=8191A, 150A/s, 4.45K
hfdm05.Quench.050428112833.065	**8187**	19	-0.0118	3.40	HcoilHcoil	QIS31_Q5au	-0.0032	4.4659	q37, 20A/sec, 4.45K, Iq=8187, special DC 4A on heaters which are parallel
hfdm05.Quench.050428114039.371	**6820**	20	-0.0445	3.98	HcoilHcoil	QIS31_Q5au	-0.0043	4.4809	38th quench, 20A/s, 4.45K, Iq=6820A, 6A applied to the heaters
hfdm05.Quench.050428115510.823	**7423**	20	-0.0305	3.90	HcoilHcoil	QIS31_Q5au	-0.0025	4.4791	Quench # 39 Iq= 7423 A ramp = 20 A/s T = 4.48 I = 4.5 A
hfdm05.Quench.050428121724.882	**6560**	20	-0.0710	4.86	HcoilHcoil	QIS31_Q5au	0.0013	4.4790	Quench #40 Iq= 6560 A ramp= 20 A/s T= 4.48K I=4 A
hfdm05.Quench.050428135451.299	**6989**	20	-0.0542	4.66	HcoilHcoil	QIS31_Q5au	-0.0013	4.4496	Quench #41 Iq= 6989 A ramp =20 A/s t = 4.45K I= 2 A
hfdm05.Quench.050428143913.259	**7329**	150	-0.0437	4.50	HcoilHcoil	QIS31_Q5au	-0.0035	4.4479	Quench 42 Iq=7328.8 150A/sec 4.44K
hfdm05.Quench.050428151247.594	**8230**	151	-0.0091	3.04	HcoilHcoil	QIS31_Q5au	-0.0031	4.4451	Iq=8230A, 150A/sec, 4.5K after cyclyng with 100A/sec
hfdm05.Quench.050428152524.772	**6847**	150	-0.0644	4.92	HcoilHcoil	QIS31_Q5au	-0.0025	4.4506	q44, 6847A, 150A/sec, 4.45K, after 150A/sec ramps
hfdm05.Quench.050428173646.802	4336	-50	0.0237	17.05	WcoilGnd	Q13au_QCC	1.0000	2.1580	Slow Ramp down while ramping up and down 50A/sec
hfdm05.Quench.050428180529.177	**8584**	150	-0.0206	4.24	HcoilHcoil	QIS31_Q5au	-0.0025	2.1667	Quench 45 Iq=8584 150A/sec 2.2K after ramp up and down 50A/sec
hfdm05.Quench.050428181607.599	**7993**	26	-0.0102	3.14	HcoilHcoil	Q13au_QCC	-0.0020	2.1684	Tripped 7993A 2.2K 150A/sec
hfdm05.Quench.050428182322.966	**8247**	150	-0.0032	2.76	WcoilIdot	QIS31_Q5au	-0.0021	2.1704	Quench 47 Iq=8247 150A/sec 2.2K
hfdm05.Quench.050428184259.648	**7909**	150	-0.3342	23.34	HcoilHcoil	QIS31_Q5au	-0.0041	2.1548	Quench 48 Iq=7909.7 150A/sec 2.2K after ramping up and down 100A/sec
hfdm05.Quench.050428185830.082	**7900**	150	-0.1504	12.05	HcoilHcoil	QIS31_Q5au	0.0010	2.1628	Quench 49 Iq=7900A 150A/sec 2.2K after ramping up and down at 150A/sec

File	Current (A)	dI/dt (A/sec)	t_{qnch} (sec)	MIITs	QDC	1st VTseg	Mag Temp Bot L (K)	Comment
hfdm05-1.Quench.050527115828.410	1006	0	0.0003	0.08	HcoilHcoil	QOS30_QOS31	4.4537	manual dqd coil trip at 1000A after balancing aqd and dqd signals, save data to check QD and QC signals. dump delayed by 20ms. no heater delay, heater at 100V.
hfdm05-1.Quench.050527122642.845	5022	0	-0.0566	2.49	HcoilHcoil	Q13au_QCC	4.4504	heater-induced quench at 5000A run plan did not indicate which voltage to use; 100V was too low, 200V worked (this was what hfdm05 test data showed for 3000A trip) dump delay of 25ms
hfdm05-1.Quench.050527134755.694	**6534**	20	-0.0718	4.88	HcoilHcoil	QIS31_Q5au	4.4393	ramp to quench at 20 A/s, quench at 6534 A. no heater protection, dump delay = 25ms. T=4.4K
hfdm05-1.Quench.050527142248.105	**6918**	20	-0.0633	5.04	HcoilHcoil	QIS31_Q5au	4.4513	Ramp to quench at 20A/s, quench at 6918A, T=4.4K, Spike ramp number 2
hfdm05-1.Quench.050527150529.403	**6686**	20	-0.0738	5.19	HcoilHcoil	Q13au_QCC	4.4432	Quench #3 20A/sec Iq=6686A T=4.4K
hfdm05-1.Quench.050527171632.278	**7167**	19	-0.0591	5.16	HcoilHcoil	Q13au_QCC	4.4418	Quench #4 20A/sec T=4.4K Iq=7167
hfdm05-1.Quench.050527173908.230	**7115**	20	-0.0493	4.60	HcoilHcoil	Q5au_Q6au	4.4398	quench #5 20A/sec Iq=7115A T=4.4K
hfdm05-1.Quench.050527175953.858	**7872**	19	-0.0090	3.04	HcoilHcoil	QIS31_Q5au	4.4406	Quench #6 Iq=7872 20A/sec T=4.4K
hfdm05-1.Quench.050527181302.581	**6469**	20	-0.0830	5.25	HcoilHcoil	Q5au_Q6au	4.4423	Quench #7 20A/sec T=4.4K Iq=6469A
hfdm05-1.Quench.050527184548.249	**6836**	20	-0.0206	2.92	HcoilHcoil	QIS31_Q5au	4.4455	quench #8 20A/sec to 6700A waited 10 min then ramp to quench 20A/sec T=4.4K Iq=6836A

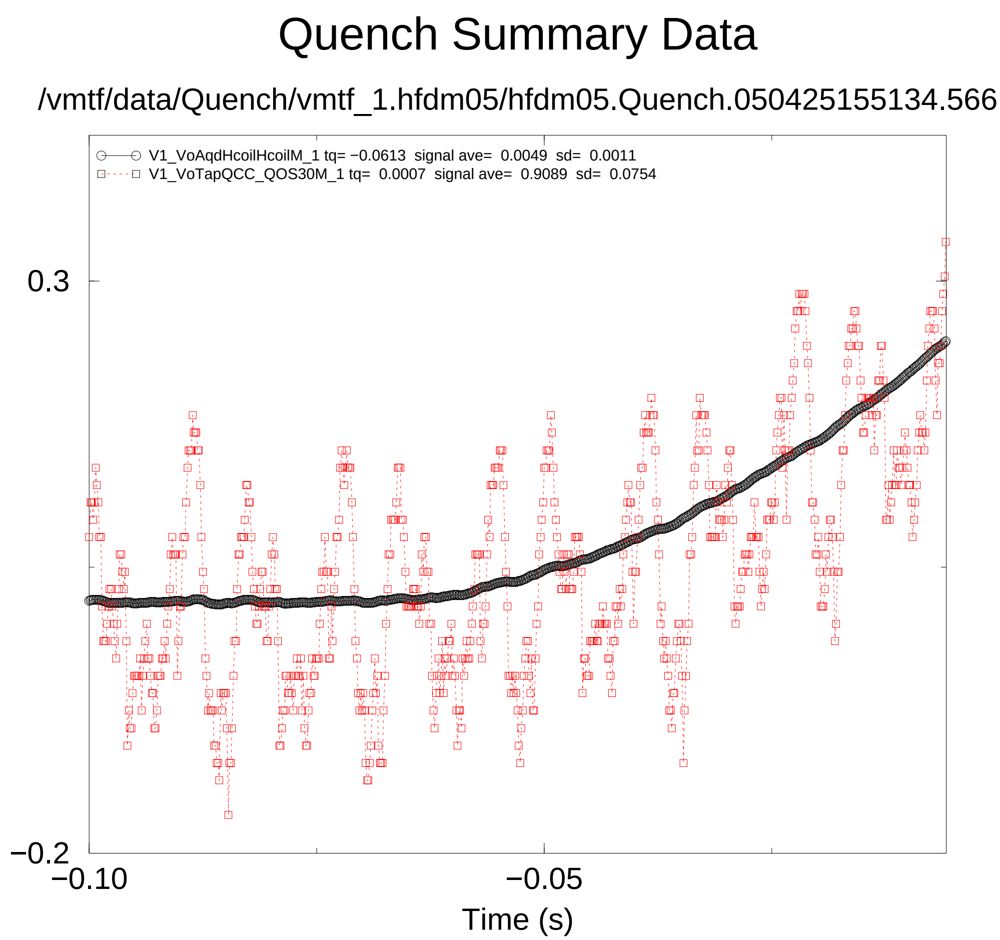


Fig 2. Voltage traces for quench number 5. Quench started in QCC_QOS30 segment.

3. Ramp Rate Dependence

Ramp rate dependence is shown in Fig 3. Quench current slightly increases with increasing ramp rate up to ~175 A/s than falls quite steep; about 4000 A quench current drop was observed within 10 A/s ramp rate change. This effect is likely to be related to cooling conditions of the magnet.

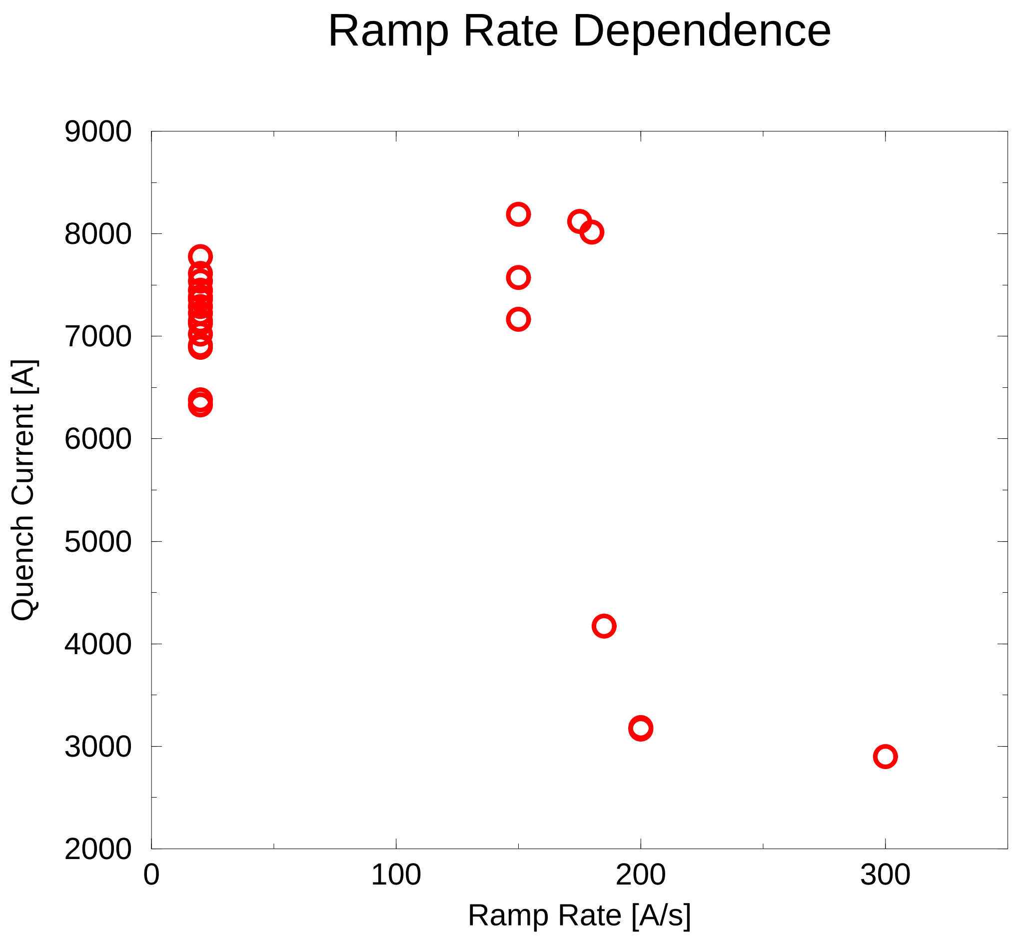


Fig 3. Quench current ramp rate dependence.

4. RRR measurements

After the cold test was completed the magnet was gradually warmed up. We used this opportunity to measure the magnet voltages under small current (± 10A) values as a function of the magnet temperature. The obtained RRR value for the whole coil is 39. For the inner coil RRR=55 and for the outer coil RRR=30.

5. Strain gauge results

This magnet was instrumented with several strain gauges. The summary of the gauges are summarized in Table 2. The warm measurement results of these strain gauges are presented in the production summary report.

Table 2. Strain gauge naming and locations.

HFDM05 Instrumentation Summary

Strain Gauges (resistive) on Spacers

Label	Type	Location
SPARG27	Active	RE top (coil pole)
SPARG28	Active	RE midplane right
SPCRG14	Temp Comp	RE midplane left
SPARG23	Active	LE top (coil pole)
SPARG24	Active	LE (splice) midplane right
SPCRG12	Temp Comp	LE midplane left

Note: "Left" and "Right" refer to magnet as viewed from the lead end looking toward non-lead end.

Strain Gauges (resistive) on skin

Label	Type	Location
SKUARG-30	Active	Upper skin
SKUARG-60	Active	Upper skin
SKUARG-90	Active	Upper skin
SKUCRG-60	Temp Comp	Upper skin
SKLARG-30	Active	Lower skin
SKLARG-60	Active	Lower skin
SKLARG-90	Active	Lower skin
SKLCRG-60	Temp Comp	Lower skin

Strain Gauges (resistive) on coil IR near pole

Label	Type	Location
1a	Active	on coil RE
1c	Temp Comp	on coil RE
2a	Active	on coil RE
2c	Temp Comp	on coil RE
3a	Active	on coil SS
3c	Temp Comp	on coil SS
4a	Active	on coil SS
4c	Temp Comp	on coil SS

Beam Gauges

Label	Type	Location
64InLE	Active	LE (splice) midplane inner

62InSS	Active	SS midplane inner layer
67outSS	Active	SS midplane outer layer
63outLE	Active	LE (splice) midplane outer
61InSS	Active	SS midplane inner layer
65OutSS	Active	SS midplane outer layer

Only gauges which were mounted directly onto the inner surface of the coil and the beam gauges located in the body part of the magnet showed change under Lorentz forces. Individual strain gauge results are summarized in Fig. 4 – Fig. 25. All the plots correspond to current ramps at 4K helium bath temperature.

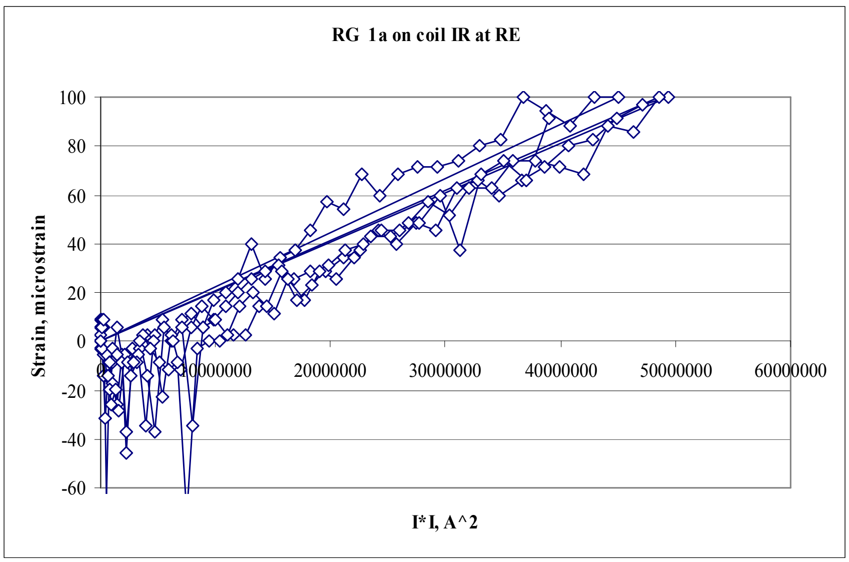


Fig. 4 Resistive gauge mounted inside coil surface showed clear strain dependence as a function of the Lorentz force.

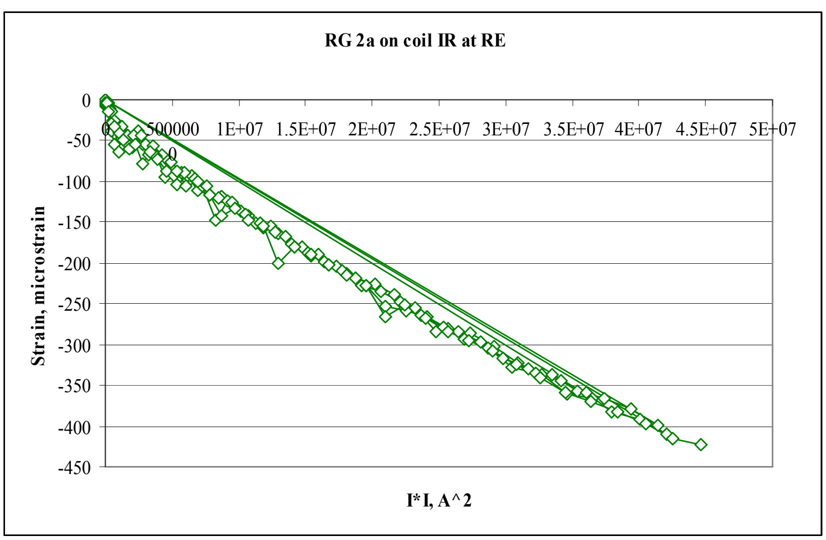


Fig. 5 Resistive gauge mounted inside coil surface showed clear strain dependence as a function of the Lorentz force.

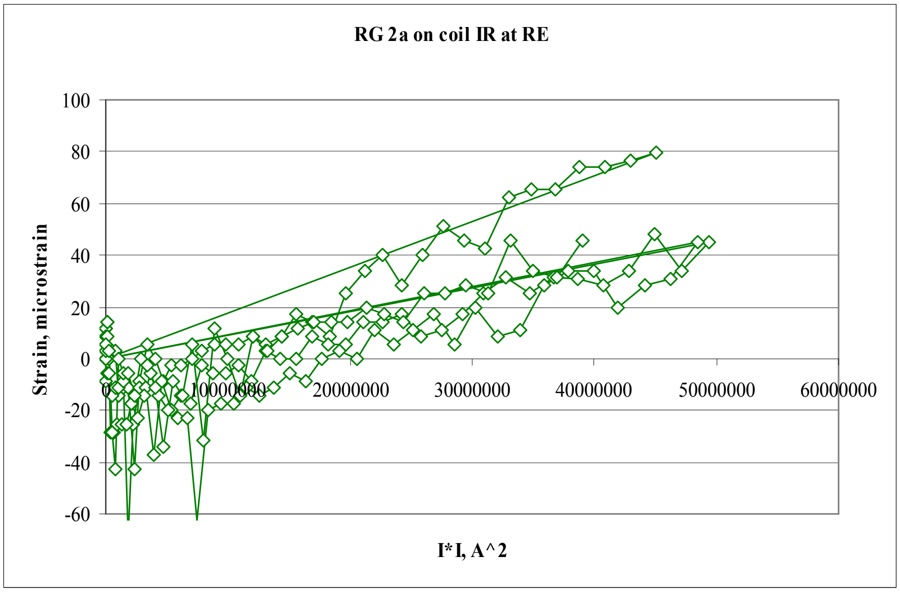


Fig. 6 Resistive gauge mounted inside coil surface showed clear strain dependence as a function of the Lorentz force.

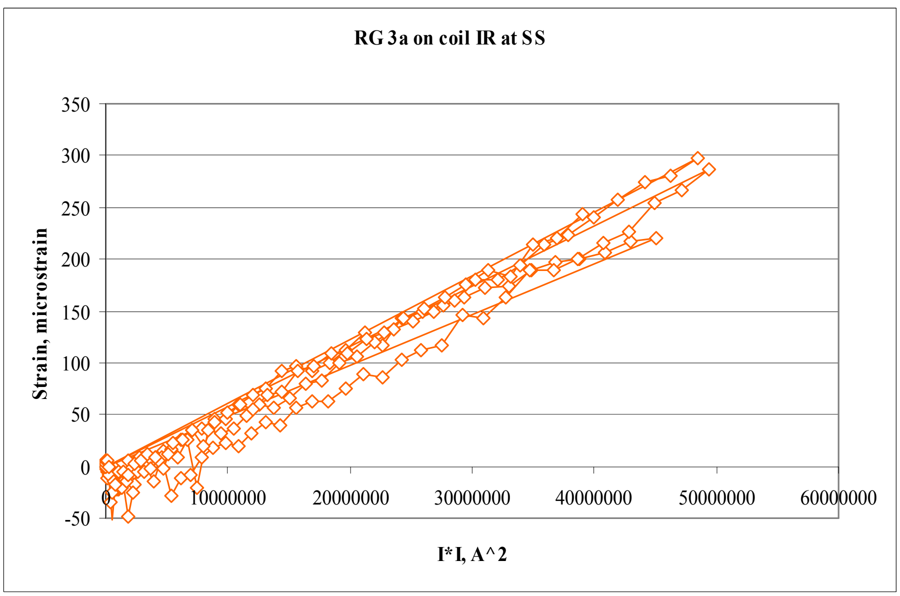


Fig. 7 Resistive gauge mounted inside coil surface showed clear strain dependence as a function of the Lorentz force.

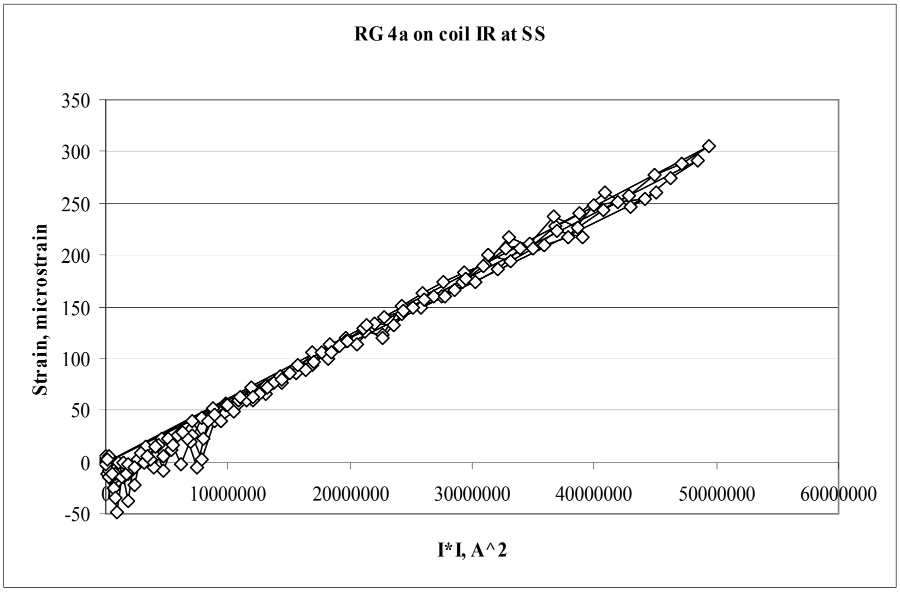


Fig. 8 Resistive gauge mounted inside coil surface showed clear strain dependence as a function of the Lorentz force.

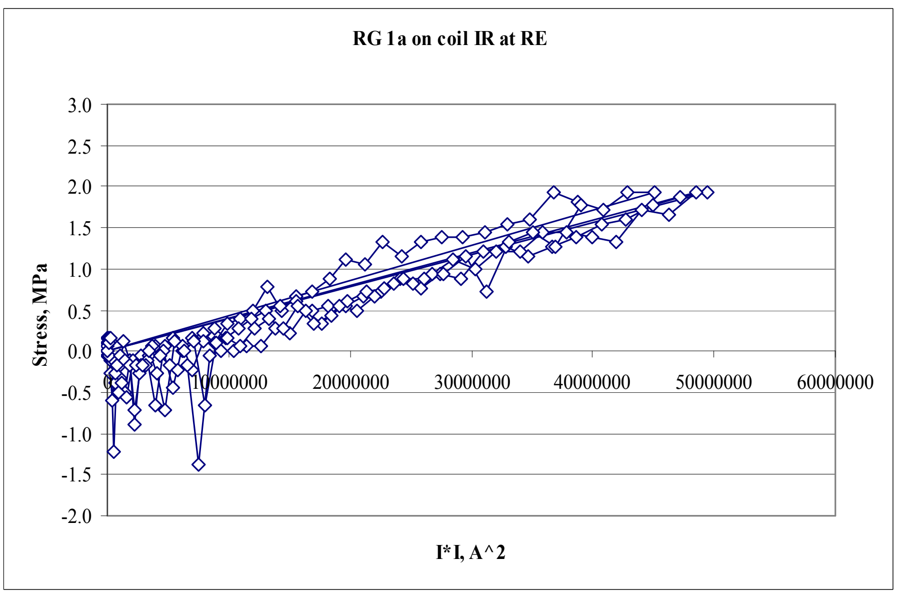


Fig. 9 Resistive gauge mounted inside coil surface showed clear strain dependence as a function of the Lorentz force.

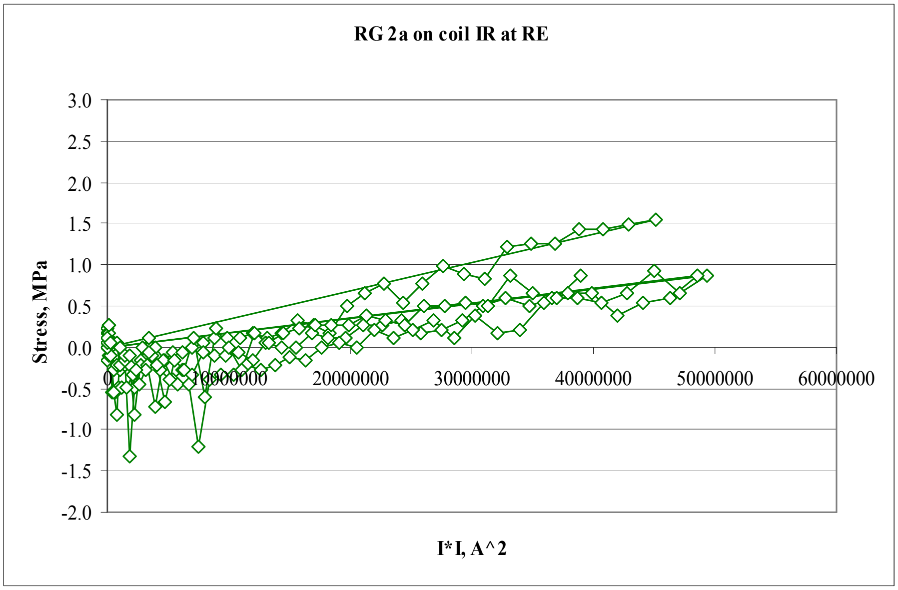


Fig. 10 Resistive gauge mounted inside coil surface showed clear strain dependence as a function of the Lorentz force.

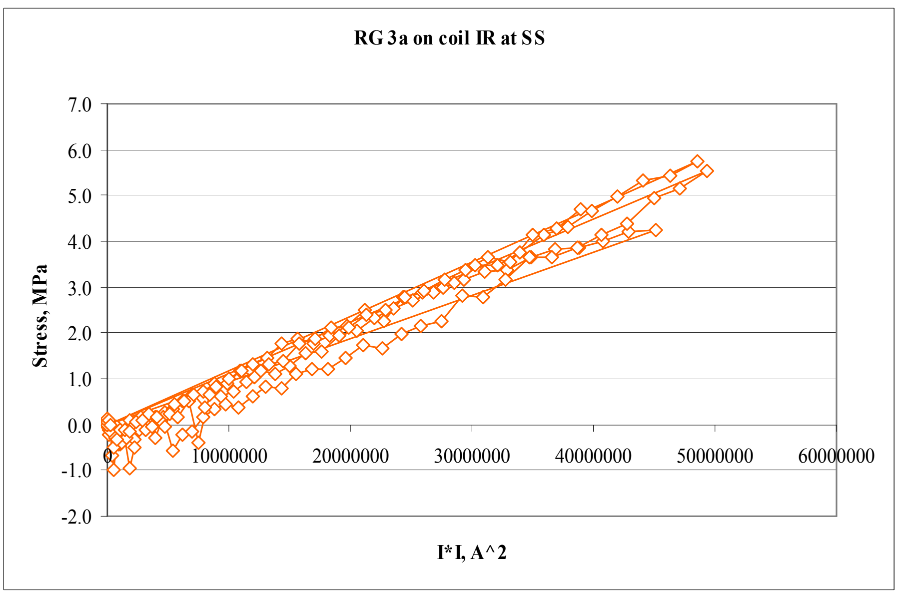


Fig. 11 Resistive gauge mounted inside coil surface showed clear strain dependence as a function of the Lorentz force.

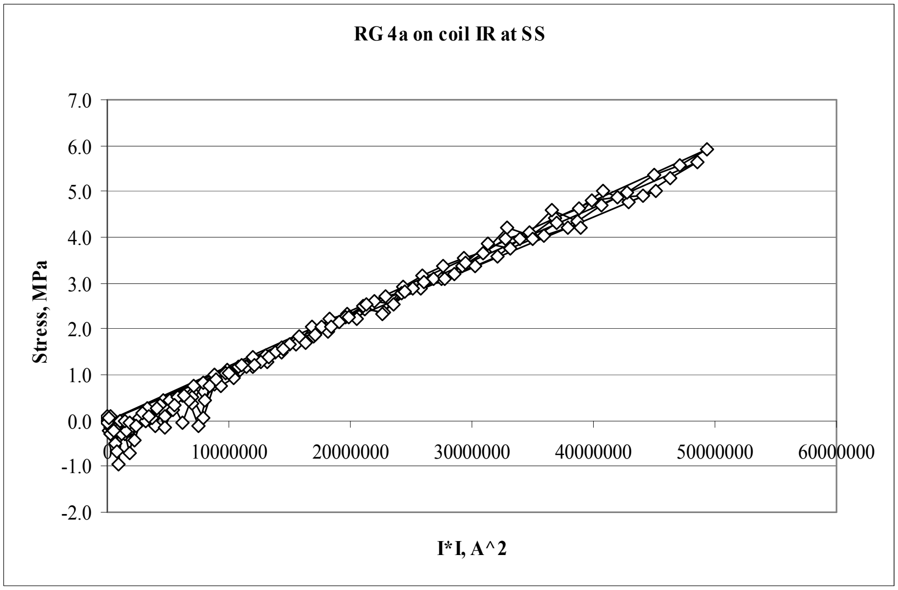


Fig. 12 Resistive gauge mounted inside coil surface showed clear strain dependence as a function of the Lorentz force.

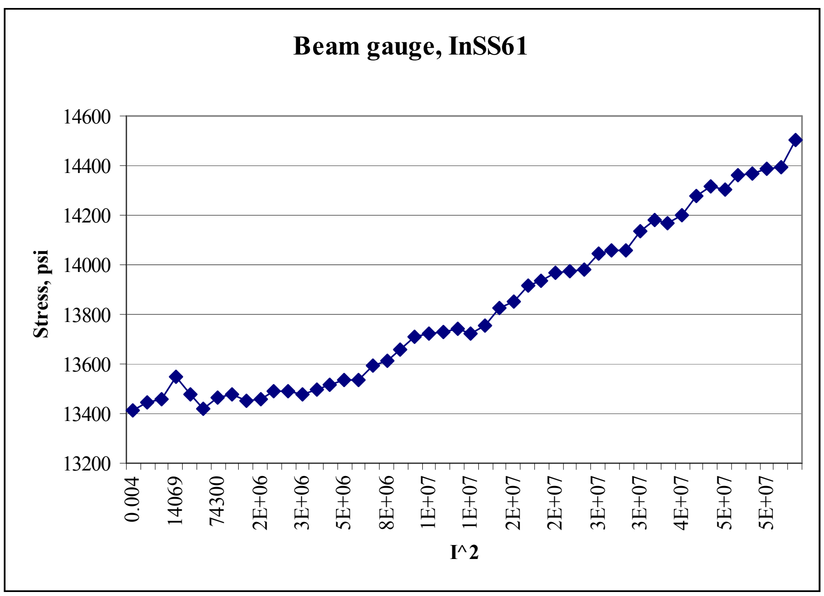


Fig. 13. Resistive beam gauge mounted at the surface of the mid-plane in the body region of the coil showed a clear change of the load as a function of the Lorentz force.

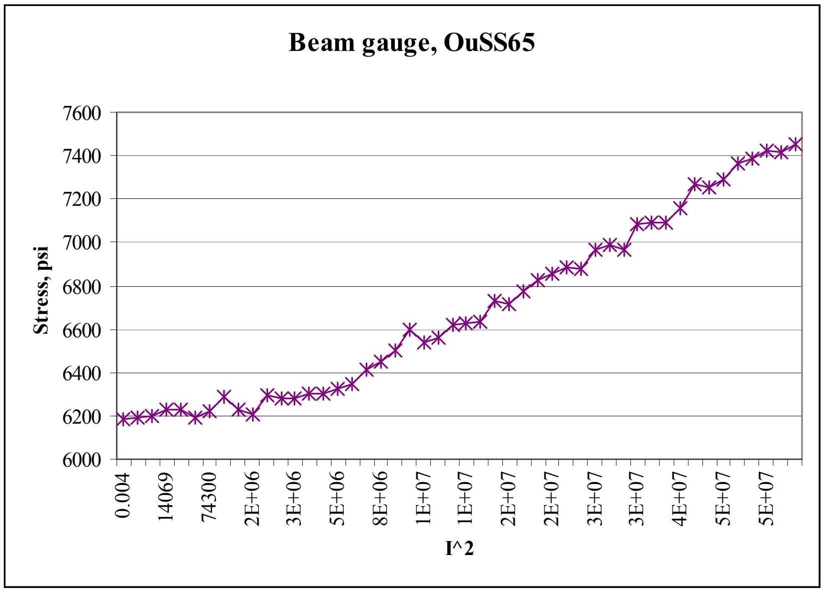


Fig. 14. Resistive beam gauge mounted at the surface of the mid-plane in the body region of the coil showed a clear change of the load as a function of the Lorentz force.

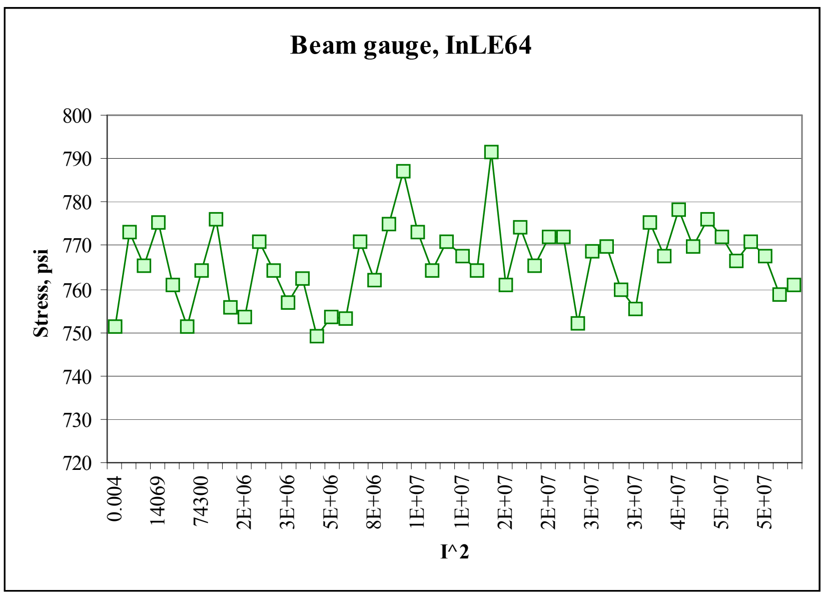


Fig. 15. Resistive beam gauge mounted at the surface of the mid-plane close to the splice region showed no clear sign of loading.

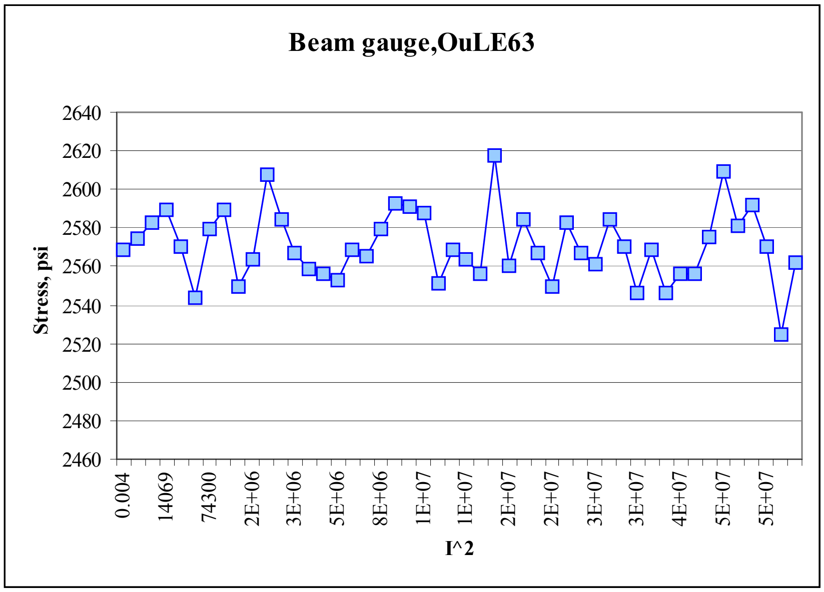


Fig. 16. Resistive beam gauge mounted at the surface of the mid-plane close to the splice region showed no clear sign of loading.

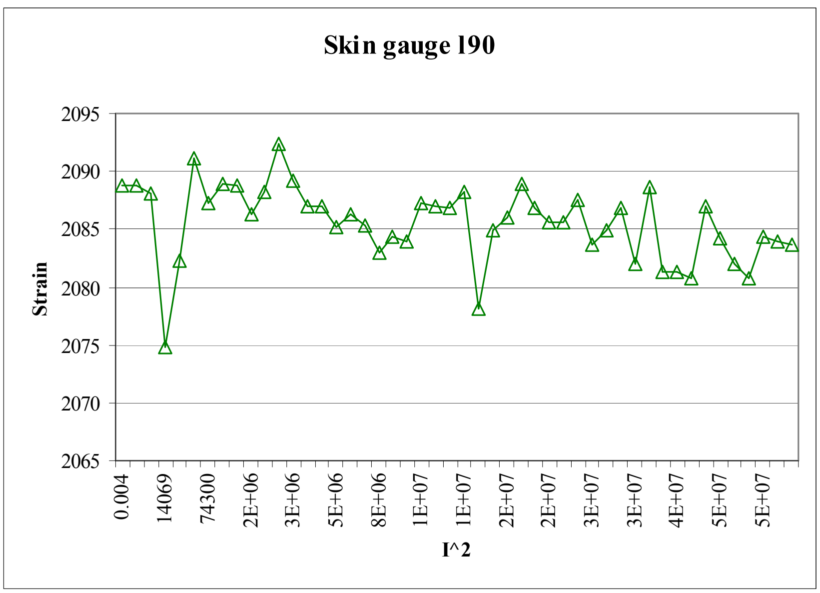


Fig. 17. Resistive skin gauge showed no clear change of the load as a function of the Lorentz force.

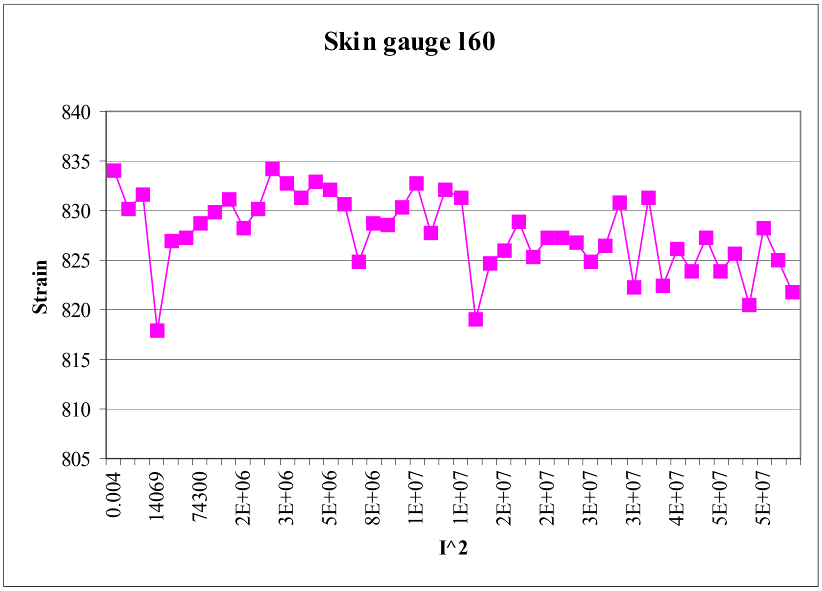


Fig. 18. Resistive skin gauge showed no clear change of the load as a function of the Lorentz force.

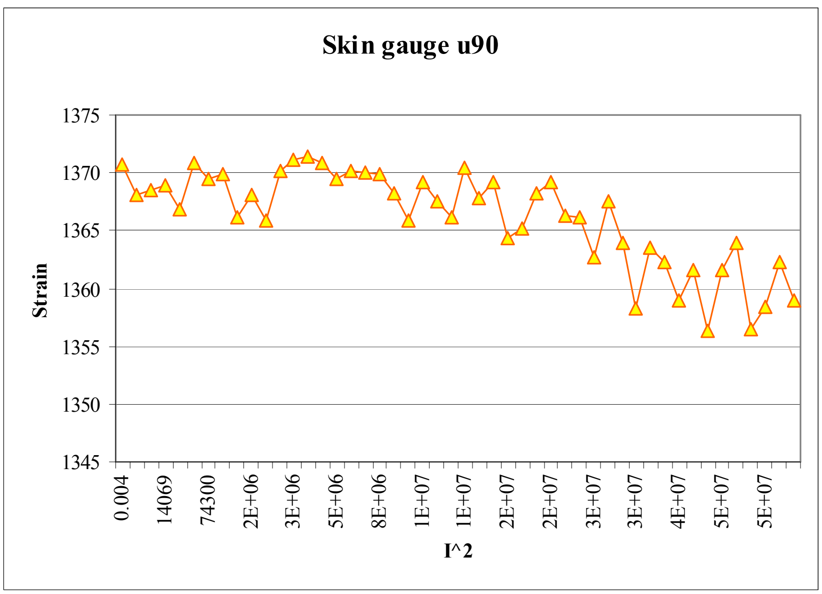


Fig. 19. Resistive skin gauge showed no clear change of the load as a function of the Lorentz force.

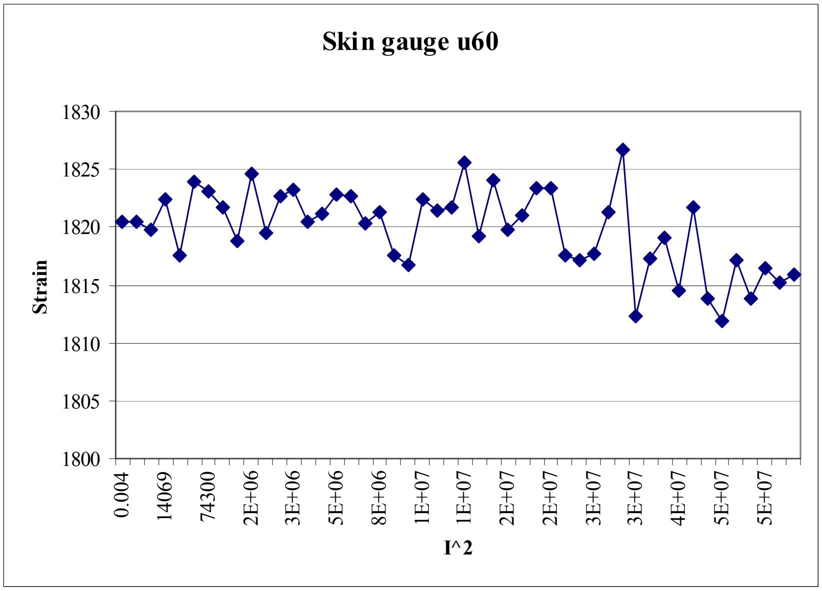


Fig. 20. Resistive skin gauge showed no clear change of the load as a function of the Lorentz force.

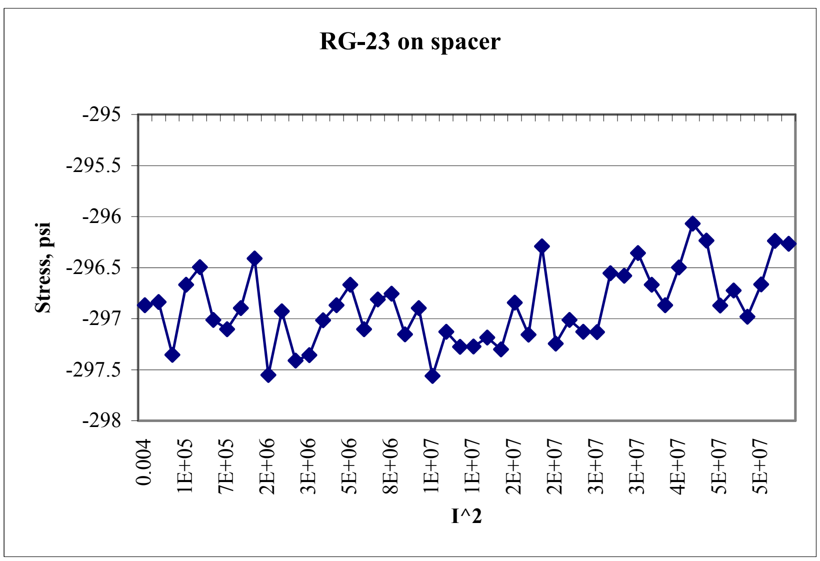


Fig. 21. Resistive gauge mounted onto the surface of the spacer showed no clear change of the load as a function of the Lorentz force.

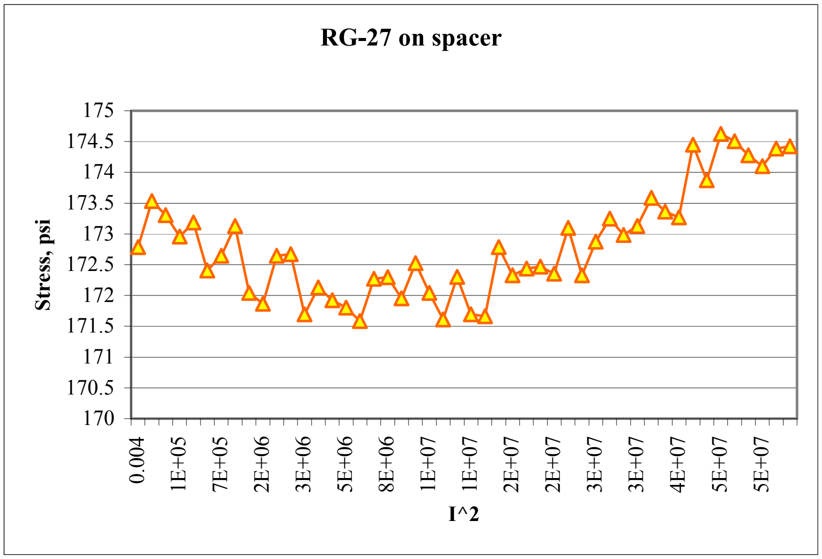


Fig. 22. Resistive gauge mounted onto the surface of the spacer showed no clear change of the load as a function of the Lorentz force.

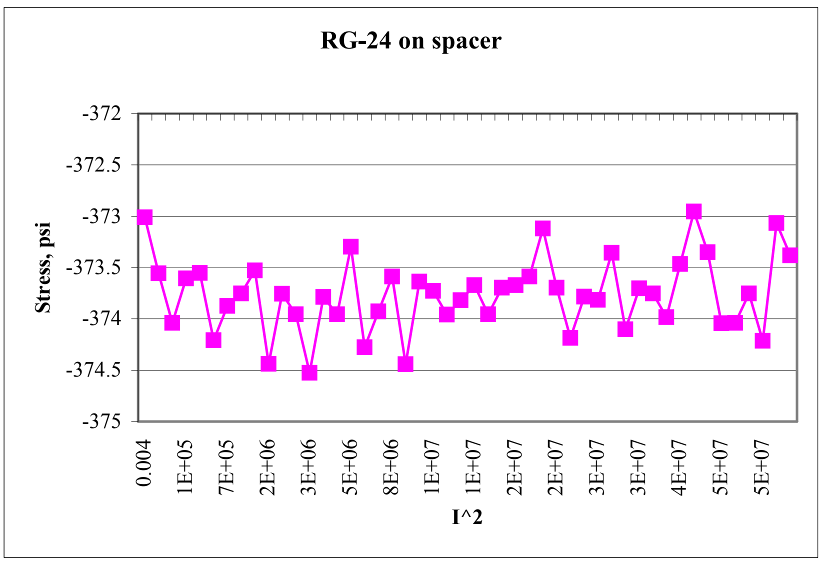


Fig. 23. Resistive gauge mounted onto the surface of the spacer showed no clear change of the load as a function of the Lorentz force.

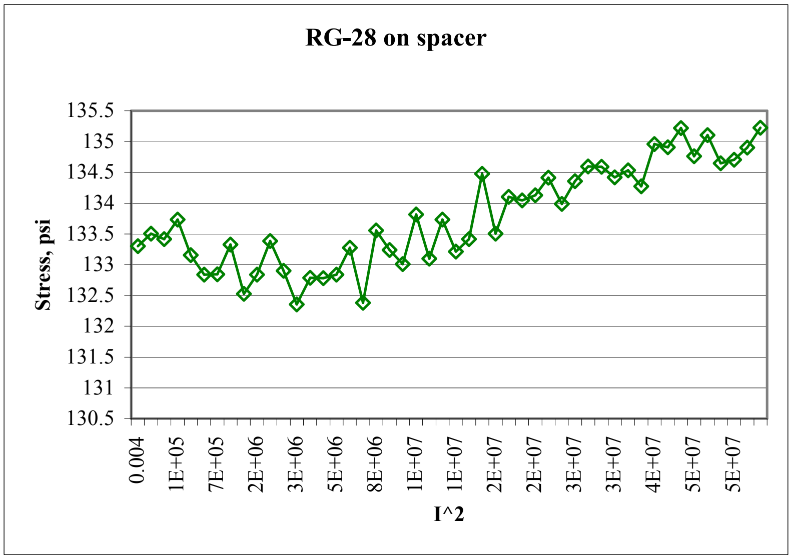


Fig. 24. Resistive gauge mounted onto the surface of the spacer showed no clear change of the load as a function of the Lorentz force.

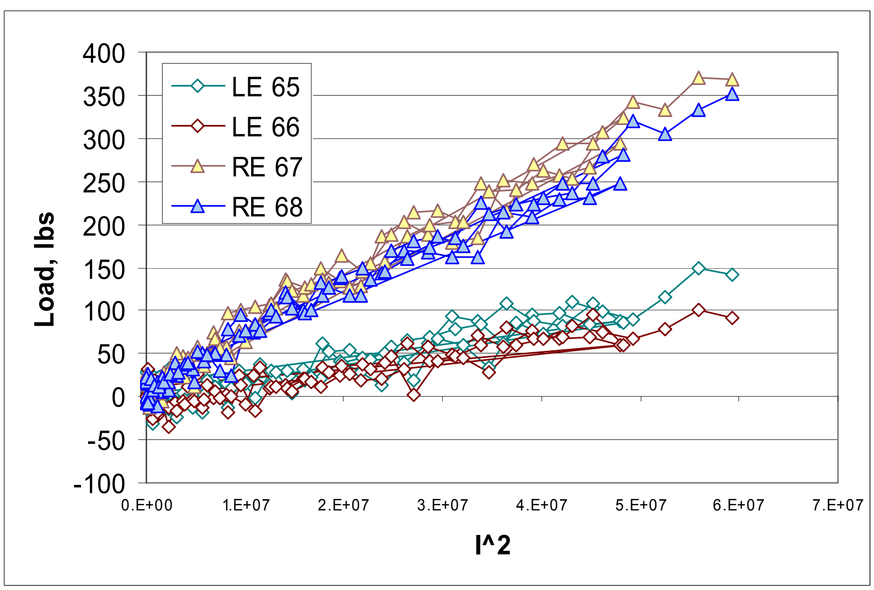


Fig. 25. Resistive gauge mounted onto the surface of the bullets showed clear change of the load as a function of the Lorentz force.

6. Splice measurements

We performed splice measurements. The current was increased up to 6000 A and the voltage drops across the splices were recorded. Figure 26. shows the measurement results. One of the resistances was quite large or it is possible that data recording was not done properly. In any case the magnet performance was not limited due to splice heating.

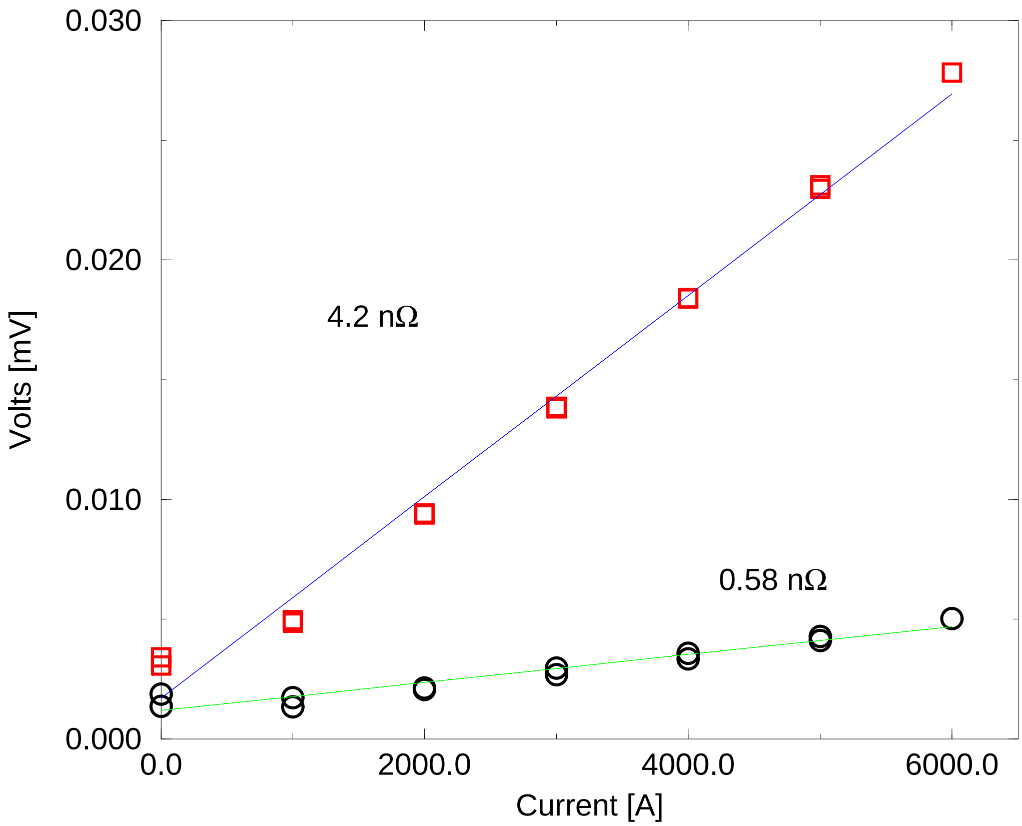
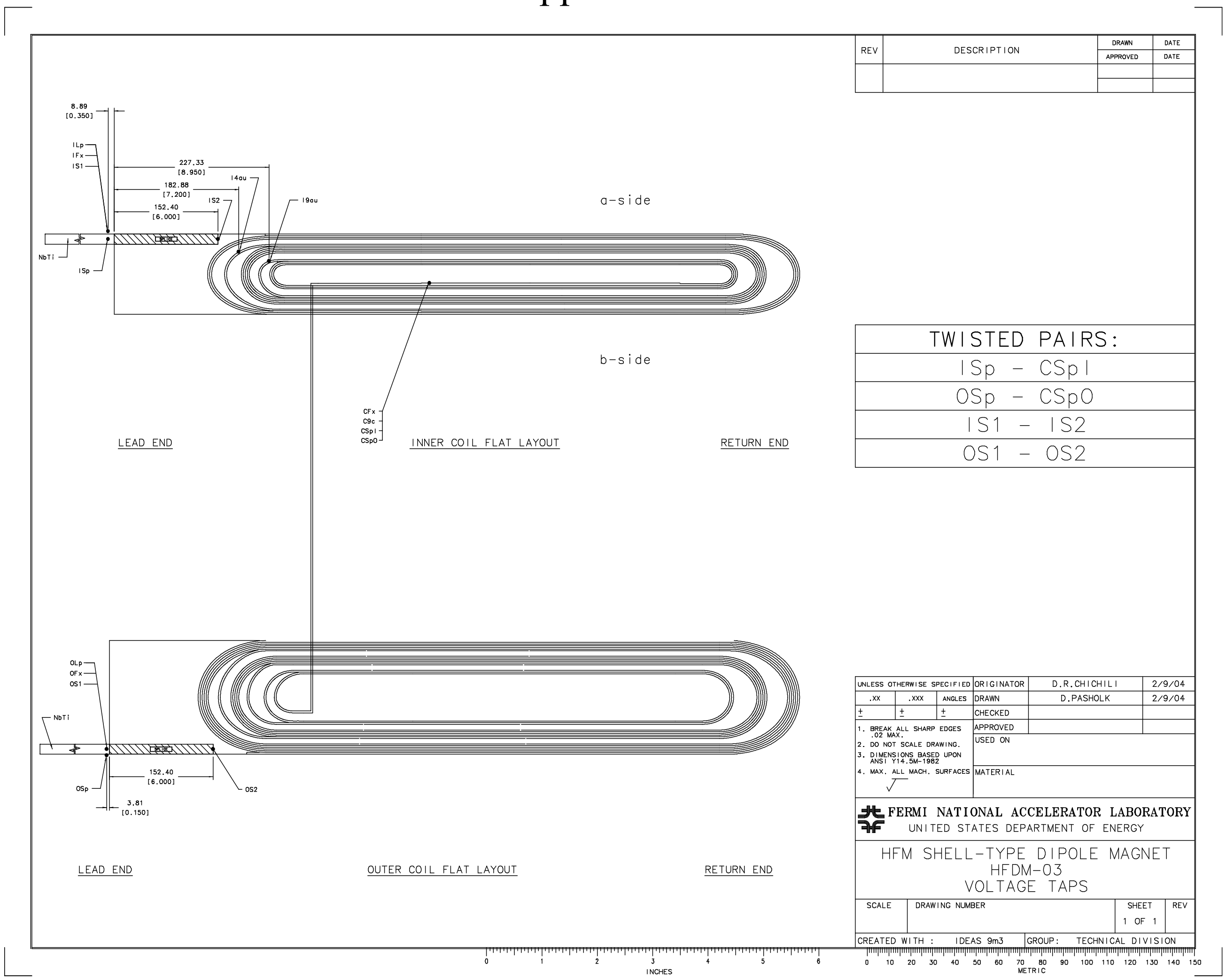


Fig. 26 Splice measurement results.

7. Appendix



Voltage tap layout