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SR04 Test Summary Report

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1. Introduction

The small racetrack magnet SR04 was the first high field magnet built using Nb3Al conductor manufactured by the Japanese National Institute for Material Science (NIMS). The magnet construction and instrumentation plan were otherwise identical to previous small racetracks in the series. It was fabricated in June 2006 and tested in September 2006 at the Fermilab vertical magnet test facility (VMTF) where it was mounted to the 30 kA "HFM" top plate assembly. Data acquisition scans were started following electrical checkout and warm measurements on Friday September 8; pre-cooling with liquid Nitrogen began on 9/9. The VMTF dewar was filled with helium early on Monday 9/11, followed by cold electrical checkout and quench/power system checks. The test plan was essentially performed twice, first with large amplitude (300A p-p) 180 Hz current ripple (as with previous magnets), and then again with the ripple amplitude reduced by a factor of 5 to 6 (by using a different power supply regulator module). The repeated elements included quench performance at 4.5 K and 2.2 K, ramp rate and temperature dependence, and energy loss. The quench performance was very strongly influenced by the ripple amplitude, and the error in energy loss measurements was greatly reduced by having smaller amplitude ripple. The magnet was put through an unplanned thermal cycle early in the test (on 9/15), because of a heat exchanger contamination problem that prevented temperature dependence studies. At the end of the test, on 9/23, splice resistances were measured, and some additional power supply regulator studies performed. Warm up was started on 9/24 and RRR data were captured at that time.

2. Quench Performance

a) Quench History

The quench performance program started with magnet training at 4.45K. Because of the low magnet inductance of about 30 μH, problems were again encountered with power supply regulation (as in previous small racetrack tests); analog quench detection (AQD) thresholds were initially set low, and this resulted in a number of low current trips because of rapid power supply current fluctuations that induced magnet voltage excursions which exceeded AQD thresholds. It took two days of adjusting the power supply regulator settings and quench detection thresholds (raising them high enough) to reach a point in which convincing magnet quenches were seen (as opposed to power supply induced trips). It should be noted that throughout the test, quenches were observed at "low" current in which one or both coils showed slow resistive voltage growth during a quench, but the origin – power supply induced, versus conductor instability – is not known. In many, but not all, cases there are glitches on the magnet current signal corresponding to coil voltage glitches, but it is not known whether this is a response of the power supply (regulator) to a magnet voltage spike, or vice-versa.

After the first real high current was observed on 9/14, four additional successive quenches indicated the magnet was not training to higher current. The actual quench current (about 15800 A), due to the large ripple amplitude, is not well captured by the system; we performed a visual average from the current trace to specify a quench current (although integration over a power line cycle would give a more precise value, it isn't clearly worth the extra effort involved to do this). Ramp rate studies at 4.45 K were then conducted, for ramp rates up to 1000 A/s. (Some of the higher ramp rates were not as high as requested, due to setting up the ramps with insufficiently high acceleration parameter).

The attempt to study temperature dependence failed due to heat exchanger contamination problems. Therefore energy loss measurements were taken before thermal cycling the magnet and VMTF test dewar to eliminate contamination. Upon resuming cold testing, the cool down to 2.2 K was begun immediately; a protection system test at 5000 A was made, followed by one ramp to quench at 3.5 K, then 2.16 K quench training. Again the magnet did not show training – it quenched consistently at about 16300 A. After 2.2 K quenching, the temperature was raised and quenches were performed as a function of temperature, up to 4.1 K.

The test plan was then interrupted by a day of power supply noise reduction studies, which resulted in greatly reduced current ripple amplitude. Two attempts to ramp to quench were made (at a reduced temperature of 3.6 K, due to some confusion in the test coordination) that resulted in system trips (due to AQD_LEADS) at quite high current, above 17000 A. The energy loss measurements were again made at 4.45 K before cooling the magnet down again to 2.16 K (under the assumption that training would be better conducted at lower temperature). Surprisingly, the magnet quenched at a much lower current at 2.16 K than it had done previously (ranging from about 12 to 14 kA). Ramp rate dependence at 2.16 K was explored, and it was found that the quench current improved substantially – to nearly the same 16 kA level achieved earlier at 2.16 with large amplitude ripple - with ramp rates in the 300 to 350 A/s range, then declined with higher ramp rates. (Discussion: This suggests that thermal conditions from eddy current heating at 20 A/s augmented by large amplitude ripple may correspond closely to those set up by heating from 300 A/s ramping with low amplitude ripple. Also: CERN Cable test data – ref TD note? - at 4.5 K and 1.9 K are not consistent with these magnet test data). Temperature dependence was repeated with the low amplitude ripple, and the highest quench current, 21764 A, was reached at 3.95 K. The 4.45 K 20 A/s quenching was then repeated and the quench current was somewhat lower, at 21350 A. Finally, ramp rate dependence was repeated, up to 600 A/s. After this, the system and magnet were again made available for power supply regulation tests, which resulted in a few additional 4.45 K quenches at 20 and 50 A/s.

The full list of quench data files is presented in Table 1. The quench current history is plotted in Figure 1.

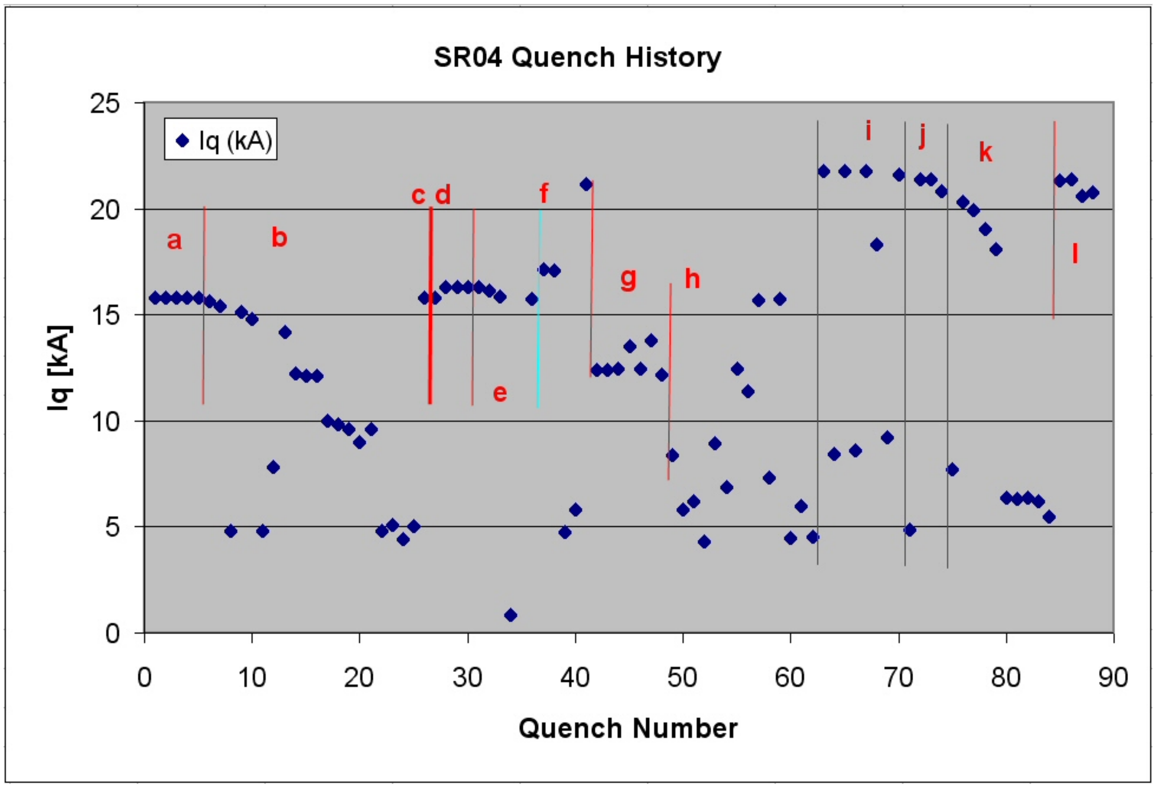


Figure 1. Quench history, starting from first “real quench” on 9/14. History followed the sequence: a) 4.5K 20A/s training, b) 4.5K ramp rate dependence, c) energy loss, d) thermal cycle, then 2.2K 20A/s training, e) temperature dependence, f) power system noise studies, then 3.5K 20 A/s (trips) and 4.5K 20A/s quenches, g) 2.2K 20A/s repeated, h) 2.2K ramp rate dependence, i) temperature dependence repeated, j) 4.5K 20A/s repeated, k) 4.5K ramp rate dependence repeated, l) more power supply regulator studies.

Table 1. Quench Data File Summary for SR04

	File	Current	dIdt	tquench	MIITs	QDC	Comment
1	sr04.Quench.060911152544.627	5254	13	0.0004	0.05	GndRef	saving data to see why QD system tripped off
2	sr04.Quench.060911164141.579	1305	-10	0.0001	0.06	WcoilIdot	quench current on this trip was "-399" so I want to look at this in the data.
3	sr04.Quench.060911172654.500	312	276	-0.0045	0.09	WcoilGnd	AQD leads trip while balancing the AQDs
4	sr04.Quench.060911181700.697	634	21	0.0024	0.07	SlWcoil	trip at 333.5 A... investigating
5	sr04.Quench.060911182419.375	712	22	0.0035	0.07	SlWcoil	at about 800 A (recall the need to "double" the reported quench manager quench current)
6	sr04.Quench.060911183310.249	933	16	-0.0162	0.08	WcoilIdot	we will check cu lead balance on next ramp at 500A. Don't understand why the quench current is "zero"
7	sr04.Quench.060911185037.625	1022	8	0.0000	0.07	WcoilGnd	once again the quench current is small - have to understand this, as well as why we are tripping
8	sr04.Quench.060911190007.260	990	1	0.0014	0.08	SlWcoil	successfully got to 1000A by setting the bandwidth to 2Hz (down from 5Hz).
9	sr04.Quench.060911191337.885	4536	20	-0.0010	0.56	SlWcoil	1st ramp to quench at 20A/s, VSDS ramp003 (80mV thresh lowered to 20mV above 3kA)
10	sr04.Quench.060911192753.052	4370	200	-0.2342	5.02	WcoilGnd	Ryuji was anxious to jump ahead with higher ramp rate. Therefore this was a 200 A/s ramp to quench... performance did not improve from 20A/s VSDS ramp004 for this ramp, with 80mV threshold.
11	sr04.Quench.060912135611.326	976	1	0.0024	0.16	WcoilIdot	after messing around with the cabling and thresholds thought it would be useful to check signals again.
12	sr04.Quench.060912141025.913	4632	21	-0.0055	0.66	WcoilIdot	ramp to quench at 20A/s; spike studies ramp006. this is probably another system trip at about 4616A.
13	sr04.Quench.060912144252.395	4373	18	-0.0041	0.21	WcoilIdot	Alex is going to look at the master PEI regulator, which was replaced recently.
14	sr04.Quench.060912151448.637	572	20	0.0000	0.07	WcoilGnd	
15	sr04.Quench.060912152102.973	389	18	0.0001	0.07	WcoilIdot	6 PEIs on, bandwith set to 2Hz, trip at 450A. Although these say "AQD_LEADS", the PS ripple is bad enough to cause all of the coil and Sclead aqds to trip at the same time.
16	sr04.Quench.060912153111.358	3358	20	-0.0181	0.51	HcoilHcoil	not a good day...
17	sr04.Quench.060912154845.755	822	18	0.0000	0.07	WcoilGnd	this was 1 Hz with PEIs 1-4, but the Wcoil-Idot AQD had Idot replaced by a 50 Ohm terminator.
18	sr04.Quench.060912155850.858	487	21	0.0000	0.06	WcoilIdot	trp at AQD_LEADS Ramp with 20A/s
19	sr04.Quench.060912172420.369	4726	20	-0.0020	0.65	HcoilHcoil	trip at 4725 A. Increase of bandwidth didn't solve the problem.
20	sr04.Quench.060912173320.342	793	19	0.0001	0.07	WcoilIdot	we tried the 0.5 mOhm setting, and it has tripped again

21	sr04.Quench.060912175845.440	3441	19	-0.0125	0.47	GndRef	another ramp with .5 mOhm and 20 Hz settings.
22	sr04.Quench.060912182729.019	9827	21	0.0000	0.33	WcoilGnd	Quench manager current is wrong, probably due to oscillation power gui was reading almost 10000A Possibly tripped due to Cu-I - we have not balanced this since 500 A... Whole coil thresholds were raised to 4 V. This has gotten us through the trouble region and power supply learches.ibeLa
23	sr04.Quench.060913113312.069	992	0	0.0010	0.15	SlWcoil	only master PS is on, regulator settings 20 Hz, .5 mOhm, .05 mH
24	sr04.Quench.060913114056.874	999	0	0.0014	0.08	SlWcoil	master only powered on, trip at 1000 A to compare regulation
25	sr04.Quench.060913114857.256	970	0	0.0014	0.08	SlWcoil	other parameters are the same.
26	sr04.Quench.060913115710.108	1032	0	-0.0003	0.08	SlWcoil	other parameters left the same
27	sr04.Quench.060913121559.247	15668	15	-0.0029	1.38	WcoilIdot	trip at 15070 A; dqd_leads tripped (not a real quench)
28	sr04.Quench.060913133555.854	4233	16166	-0.6346	12.18	HcoilHcoil	but it tripped just over 4kA.
29	sr04.Quench.060913135842.565	2529	-200	0.0000	0.10	WcoilIdot	Cu-I aqd balance pot doesn't want to turn in the direction I need to go !
30	sr04.Quench.060913142853.556	15463	25	0.0000	0.57	WcoilIdot	was not able to change the dqd cu-I balance
31	sr04.Quench.060913145208.079	1	0	-0.0160	857.49	GndRef	pwr_gui was unable to start the ramp
32	sr04.Quench.060913151559.447	15356	18	-0.2018	47.33	WcoilGnd	this appears to be a ScLead - Wcoil trip at 15500 A
33	sr04.Quench.060913154451.076	3353	21	-0.0123	0.45	WcoilIdot	Trip DQD coil at 3600 amp 4.5 K 20 A/sec regulator bandwidth 2 Hz
34	sr04.Quench.060913162737.747	16054	18	-0.0125	8.02	WcoilGnd	16000 A 4.5 K 20A/sec QDQ_COIL trip??
35	sr04.Quench.060913171633.711	5337	0	-0.5305	15.64	WcoilIdot	Trip AQD coil 5000 A 20a/sec 4.5 K
36	sr04.Quench.060913174412.812	15821	18	-0.0111	7.51	HcoilHcoil	Quench-Trip by DQD_HalfCoil at 16000A 20A/s
37	sr04.Quench.060914095117.249	15726	19	-0.2310	62.23	WcoilIdot	ramp to quench at 20 A/s VSDS ramp23
38	sr04.Quench.060914101832.335	15920	25	-0.0172	9.11	HcoilHcoil	ramp to quench at 20 A/s VSDS ram24
39	sr04.Quench.060914105331.256	15723	18	-0.2306	62.17	WcoilIdot	ramp to quench at 20 A/s VSDS ramp25
40	sr04.Quench.060914112345.562	15759	19	-0.3643	96.08	WcoilIdot	ramp to quench at 20 A/s VSDS ramp26
41	sr04.Quench.060914114545.709	15626	48	-0.0141	8.11	HcoilHcoil	After 5 training quenches with no change in quench current, we decided to proceed with ramp rate dependence. This was 50 A/s ramp to quench. VSDS ramp27
42	sr04.Quench.060914120106.538	15636	81	-0.0167	8.57	WcoilGnd	forgot to start VSDS system - no spikes this time ramp to quench at 75 A/s; quench current went down a little.
43	sr04.Quench.060914121000.821	4707	38	-0.3785	8.92	WcoilGnd	VSDS ramp 29 ramp to quench at 100 A/s quench at about 5000 A - this may be a power supply-induced quench
44	sr04.Quench.060914122101.039	15083	98	-0.0148	7.85	HcoilHcoil	VSDS ramp30 ramp to quench at 100 A/s - this time it quenched much higher, as expected.
45	sr04.Quench.060914134306.437	14698	151	-0.0281	10.26	HcoilHcoil	VSDS ramp30 ramp to quench at 150 A/s
46	sr04.Quench.060914141026.028	5231	0	-0.6372	18.45	WcoilGnd	VSDS ramp32 may be power supply induced quench. Ramp to

							quench at 200 A/s
47	sr04.Quench.060914141548.190	7877	200	-0.4213	27.63	HcoilHcoil	VSDS ramp 33, 200A/sec again, quenched higher than 1st attempt (about 7800 A)
48	sr04.Quench.060914142856.905	14353	200	-0.0252	9.06	WcoilGnd	VSDS ramp34 ramp to quench at 200 A/s again - quench current improved quite a lot (the first two tries were probably power supply induced quenches)
49	sr04.Quench.060914145236.545	12429	300	-0.0364	8.98	HcoilHcoil	VSDS ramp35, 300A/sec, Quenched current 12.2kA
50	sr04.Quench.060914150316.112	12264	302	-0.0263	7.28	HcoilHcoil	VSDS ramp36, 300A/sec, quenched current 12.1kA
51	sr04.Quench.060914152113.558	12299	303	-0.0262	7.27	HcoilHcoil	VSDS ramp 300A/sec, quenched current 12.1kA
52	sr04.Quench.060914153405.071	10339	443	-0.0536	8.23	WcoilIdot	VSDS ramp38, 500A/sec, quenched current 10kA
53	sr04.Quench.060914154131.150	9809	441	-0.0794	9.94	WcoilIdot	VSDS ramp 500A/sec. quenched current 9.8kA
54	sr04.Quench.060914154839.437	9833	442	-0.0654	8.57	WcoilIdot	VSDS ramp 800A/sec, quenched current 9.6kA
55	sr04.Quench.060914155524.474	9833	442	-0.0767	9.69	WcoilIdot	VSDS ramp 800A/sec, quenched current 9kA
56	sr04.Quench.060914160217.842	9976	444	-0.0629	8.66	HcoilHcoil	VSDS ramp 42, 1000A/sec, quenched current 9.6kA, ramping acceleration 10A/sec
57	sr04.Quench.060914161003.292	4591	0	-0.6385	15.57	HcoilHcoil	VSDS ramp 800A/sec, ramping acceleration 100A/s2, quenched current 4.8kA
58	sr04.Quench.060914161533.966	4639	0	-0.6561	16.32	WcoilIdot	VSDS ramp 43, 800A/sec, ramping acceleration 100A/s2, quenched current 4.5kA
59	sr04.Quench.060914162543.331	4540	0	-0.6320	15.49	HcoilHcoil	ramp to quench at 1000 A/s (need to check this in the data) VSDS ramp44
60	sr04.Quench.060914164145.483	5106	0	-0.5651	16.47	WcoilIdot	VSDS ramp45, 600A/sec, ramping acceleration 100A/s2, quenched current 5kA
61	sr04.Quench.060914170126.592	15686	16	-0.0113	7.47	HcoilHcoil	VSDS ramp46, 20A/sec, ramping acceleration 100A/s2, quenched current 15.8kA, no trainning
62	sr04.Quench.060919144201.599	5008	1	0.0027	0.69	HcoilHcoil	temperature is about 3.5 K. VSDS ramp47 with high pass filter on, threshold =40mV. Trip to check signals.
63	sr04.Quench.060919150238.533	15797	18	-0.0109	7.44	HcoilHcoil	first temperature dependence quench at about 3.5 K ramp to quench at 20 A/s VSDS ramp47
64	sr04.Quench.060919164239.286	16315	18	-0.0111	7.98	HcoilHcoil	quench current went up slightly from the 4.5K value to just above 16000 A VSDS ramp49
65	sr04.Quench.060919170737.349	16383	25	-0.0164	9.36	HcoilHcoil	approximately 16300 A, same as previous event VSDS ramp50
66	sr04.Quench.060919173006.506	16375	25	-0.0160	9.30	HcoilHcoil	same current, about 16300 A VSDS ramp 50
67	sr04.Quench.060919174929.145	16282	17	-0.0014	1.02	HcoilHcoil	possibly a bit lower current VSDS ramp51
68	sr04.Quench.060919183102.181	16163	25	-0.0165	9.15	HcoilHcoil	quench at about 16100A VSDS ramp53
69	sr04.Quench.060919185550.174	15839	17	-0.0106	7.42	HcoilHcoil	VSDS ramp54

70	sr04.Quench.060919191322.828	8141	18	-0.2933	20.66	GndRef	VSDS ramp 55
71	sr04.Quench.060919193158.385	5200	5	-0.4546	12.99	HcoilHcoil	VSDS ramp56 will have to look at this tomorrow to see what's going on, perhaps do additional temperature dependence studies
72	sr04.Quench.060920101011.951	15746	15	-0.0108	7.42	HcoilHcoil	Quench 36 3.6 K 20A/s, ,quench at about 16kA
73	sr04.Quench.060920104348.326	9987	0	-0.1252	14.25	HcoilHcoil	10kA trip for power system performance test. Ramp rate is 20A/s, acceleration rate is 100A/s2
74	sr04.Quench.060920121105.571	4406	25	0.0000	0.18	WcoilIdot	
75	sr04.Quench.060920122413.063	7600	28	-0.1766	11.09	WcoilGnd	during ramp up at 30 A/s for PS studies
76	sr04.Quench.060920124337.553	7767	22	-0.2971	17.09	WcoilIdot	tripped at same current ...
77	sr04.Quench.060920135116.415	7856	19	-0.1992	13.65	HcoilHcoil	tripped at around 8kA by DQD_Coil
78	sr04.Quench.060920191649.448	7004	0	0.0008	1.17	HcoilHcoil	Swapped another voltage regulator. Bandwidth=20Hz, ramp rate=20A/s, manual trip at 7000A
79	sr04.Quench.060921115911.134	17198	18	-0.0014	1.11	HcoilHcoil	VSDS ramp58 quench current is WAY UP from the corresponding measurement with large ripple taken several days ago !
80	sr04.Quench.060921123548.959	17068	19	-0.0014	1.01	HcoilHcoil	again a quench/trip above 17000 A, but AQD_LEADS initiated the trip VSDS ramp59
81	sr04.Quench.060921140230.017						File corrupted; comment from eLog: quench or trip while beginning eieo measurement
82	sr04.Quench.060921142033.634						File corrupted; comment from eLog: Quench at about 6100 A at 100 A/sec ramp during EIEO measurement.
83	sr04.Quench.060922093923.502	997	-1	-0.0048	0.17	SlWcoil	manual trip at 1000A
84	sr04.Quench.060922100315.539	4749	-21	-0.4910	11.55	WcoilGnd	VSDS ramp 60; one of the VSDS signals disappeared during the ramp system tripped at low current; not yet sure if this is a real quench or something else... AQD_COIL is indicated.r
85	sr04.Quench.060922101835.288	5704	20	-0.4222	14.03	HcoilHcoil	VSDS has lost "coil A", so we stopped taking spike data. trip or quench (AQD_COIL) at about 5500 A.
86	sr04.Quench.060922105838.309	21113	20	-0.0098	11.46	HcoilHcoil	no VSDS ramp data, still fixing the connector. PEI number 2 turned off, due to suspicious PS regulation earlier ramps. temperature 4.46 K
87	sr04.Quench.060922113608.671	989	0	0.0018	0.07	SlWcoil	manual coil trip at 1000A
88	sr04.Quench.060922115109.348	952	0	0.0000	0.07	WcoilIdot	Lead manual trip at 1000A
89	sr04.Quench.060922120800.230	755	-314	1.0000	0.00	GndRef	trip at 0A
90	sr04.Quench.060922121411.006	1006	-11	0.1480	0.67	HcoilHcoil	slow ramp down from 1000A
91	sr04.Quench.060922122823.243	747	-314	1.0000	0.00	GndRef	
92	sr04.Quench.060922133423.739	988	0	0.0014	0.08	WcoilIdot	coil trip at 1000A
93	sr04.Quench.060922134337.891	765	-312	1.0000	0.00	GndRef	slow ramp down
94	sr04.Quench.060922135345.786	1015	-1	-0.2454	0.31	HcoilHcoil	

95	sr04.Quench.060922140001.013	660	-337	-0.1603	0.13	HcoilHcoil	slow ramp down followed by a coil trip
96	sr04.Quench.060922144823.275	999	-16	-0.1648	0.25	HcoilHcoil	
97	sr04.Quench.060922161940.220	12396	20	-0.0466	10.52	WcoilIdot	just above 12000 A VSDS ramp62
98	sr04.Quench.060922164715.346	12409	20	-0.0494	10.96	HcoilHcoil	VSDS ramp64 2nd 2.2K quench just above 12000 A
99	sr04.Quench.060922170624.099	12448	20	-0.0368	9.12	WcoilIdot	VSDS ramp64 (previous quench 43 was ramp63 - incorrently entered earlier) quench just about the same current as before, 12400+ A
100	sr04.Quench.060922172640.755	13488	20	-0.0283	8.98	WcoilIdot	VSDS ramp65 substantially higher quench current this time - training ?? (but why??)tribute
101	sr04.Quench.060922174350.171	12464	19	-0.0431	10.09	WcoilIdot	VSDS ramp 66
102	sr04.Quench.060922181636.602	13783	18	-0.0522	12.94	GndRef	VSDS ramp 67 quench current went up again
103	sr04.Quench.060922183445.421	12146	20	-0.0528	10.90	WcoilIdot	VSDS ramp 68 another 12kA quench
104	sr04.Quench.060922184224.993	8402	493	-0.1906	14.86	WcoilIdot	VSDS ramp69 fast ramp to see what happens
105	sr04.Quench.060922185018.743	5680	0	-0.5477	15.96	WcoilGnd	VSDS ramp 70 low current quench, about 6kA
106	sr04.Quench.060922185733.904	6330	0	-0.5872	20.93	WcoilIdot	vsds ramp 71 another low current quench, just above 6kA
107	sr04.Quench.060922190326.339	4333	348	-0.4663	8.59	HcoilHcoil	vsds ramp72 quench about 4kA
108	sr04.Quench.060922191044.829	8941	98	-0.1539	13.74	WcoilGnd	vsds ramp 73 quench/trip at about 9kA
109	sr04.Quench.060922192009.895	6870	150	-0.3076	14.97	WcoilIdot	vsds ramp 74 trip/quench around 7kA
110	sr04.Quench.060922193810.265	12455	20	-0.0608	12.81	WcoilGnd	vsds ramp 75 repeat 20A/s and it repeated it's quench current around 12.4kA
111	sr04.Quench.060922194616.536	11381	50	-0.0777	12.82	WcoilGnd	vsds ramp 76 quench about 11500A
112	sr04.Quench.060922195103.759	15675	302	-0.0543	17.60	WcoilIdot	vsds ramp 77 quench current went up a lot, to about 15500A
113	sr04.Quench.060922195643.315	7340	254	-0.2842	15.74	WcoilGnd	vsds ramp 77 quench about 7kA
114	sr04.Quench.060922200507.487	15723	350	-0.0626	19.93	WcoilIdot	no vsds data - pxicontroller died quench current just under 16kA
115	sr04.Quench.060922201029.042	4475	245	-0.4205	8.74	WcoilGnd	no vsds data quench about 4kA
116	sr04.Quench.060922201918.686	5906	25648	-0.5728	20.28	HcoilHcoil	no vsds data quench just below 6kA
117	sr04.Quench.060922202450.091	4721	228	-0.3636	8.26	WcoilGnd	no vsds data quench about 4500A
118	sr04.Quench.060922210040.569	21762	20	-0.0077	11.21	HcoilHcoil	quenched above 22kA
119	sr04.Quench.060922211258.273	8349	20	-0.2999	20.98	WcoilIdot	quench at about 8kA
120	sr04.Quench.060922213756.752	21764	20	-0.0069	10.78	SlWcoil	this time the quench was close to 22kA (ramped through the 8kA ps glitches which were visible on the pwr_gui)
121	sr04.Quench.060923092329.579	8637	19	-0.1955	15.86	HcoilHcoil	no vsds data trip around 8400 A
122	sr04.Quench.060923095159.086	21748	19	-0.0084	11.41	HcoilHcoil	good quench at about 22.7kA
123	sr04.Quench.060923102751.016	18280	19	-0.3069	103.31	SlWcoil	vsds ramp79 (alive again) quenched lower, around 18000 A
124	sr04.Quench.060923104348.170	9199	20	-0.1505	12.93	SlWcoil	trip at about 9kA (AQD_COIL) vsds ramp80
125	sr04.Quench.060923110859.148	21620	19	-0.0062	3.72	SlWcoil	indication is AQD LEADS ?? about 21.5kA spike system had an error, and stopped before the quench...

126	sr04.Quench.060923120256.756	4755	-184	-0.4847	11.20	WcoilGnd	vsds ramp 82 trip/quench at below 5kA
127	sr04.Quench.060923122727.823	21350	19	-0.0060	10.26	WcoilIdot	vsds ramp 83 quench above 21kA
128	sr04.Quench.060923125029.546	21369	19	-0.0057	10.06	WcoilIdot	vsds ramp 84 quench about 23500 A
129	sr04.Quench.060923130304.901	20841	49	-0.0066	10.07	WcoilIdot	vsds ramp 85 ramp rate dependence - above 20KA
130	sr04.Quench.060923130937.428	7420	74	-0.3029	17.50	HcoilHcoil	vsds ramp 86 quench/trip at 7kA
131	sr04.Quench.060923132214.604	20332	77	-0.0066	9.76	SlWcoil	vsds ramp 87 quenched above 20kA
132	sr04.Quench.060923133359.645	19930	100	-0.0076	9.83	SlWcoil	vsds ramp 88 quench about 20kA
133	sr04.Quench.060923134016.072	19026	150	-0.0085	9.40	WcoilIdot	vsds ramp 89 about 18.5kA
134	sr04.Quench.060923134548.269	18073	200	-0.0101	9.13	SlWcoil	vsds ramp 90 about 18kA
135	sr04.Quench.060923135025.921	6437	0	-0.6217	25.60	HcoilHcoil	vsds ramp 91
136	sr04.Quench.060923135736.680	6341	0	-0.6308	25.51	WcoilGnd	vsds ramp 92 again quench at 6kA
137	sr04.Quench.060923140233.073	6475	15925	-0.6085	25.32	HcoilHcoil	vsds ramp 93 same current
138	sr04.Quench.060923140737.536	6153	0	-0.6221	24.87	HcoilHcoil	vsds ramp 94 6kA quench
139	sr04.Quench.060923141131.267	5470	0	-0.5354	16.82	HcoilHcoil	vsds ramp 95
140	sr04.Quench.060923163633.043	21316	20	-0.0069	10.49	SlWcoil	Quench above 20kA. Regulator #3, 5Hz. There was a glitch in the current at about 200-300A; after that there was no obvious glitch or sudden jump etc.
141	sr04.Quench.060923171210.770	21369	19	-0.0064	10.35	SlWcoil	Regulator #3, 10Hz, quenched above 20kA. Looks there is no obvious glitch or sharp change in the current while ramping
142	sr04.Quench.060923181238.716	20581	50	-0.0071	10.21	WcoilIdot	Regulator #4, 50A/s, 5Hz, compared to quench #74 Current profile looks smooth all the way
143	sr04.Quench.060923182918.681	20754	49	-0.0066	10.02	SlWcoil	Regulator #4, 50A/s, 10Hz. Current profile looks smooth all the way ...
144	sr04.Quench.060923184148.335	19482	51	-0.0085	9.99	SlWcoil	Regulator #4, 50A/s ramping, 20Hz, current went smoothly

b) Power System Noise Studies and Improvements

Power systems engineer Alex Yuan investigated the situation with current ripple in small inductance magnets connected to the CPS-3 power system in a number of ways. First, measurements showed the ripple to be dominated by 180 Hz noise. Then, circuit modeling showed that the power supply LR filters, which were designed to be effective for higher inductance magnets (above XX mH), interact with the low inductance load to actually amplify the noise. Further testing showed that the source of the 180 Hz noise was the power supply Voltage Regulator module. It turns out that MTF has four such modules, two of which generate large 180 Hz noise and two of which have much lower levels. Figure 2 shows the ripple at the 16300 A quench current when a noisy regulator (number 2) was used; Figure 3 shows the current just before the AQD LEADS trip at 17 kA after the noise level was reduced. Studies of active noise cancellation, by providing fast feedback to the voltage regulator using a special national instruments/labview circuit, were made with this magnet by summer student Sasha Mamrashev, and gave promising results for future power supply regulation and control.

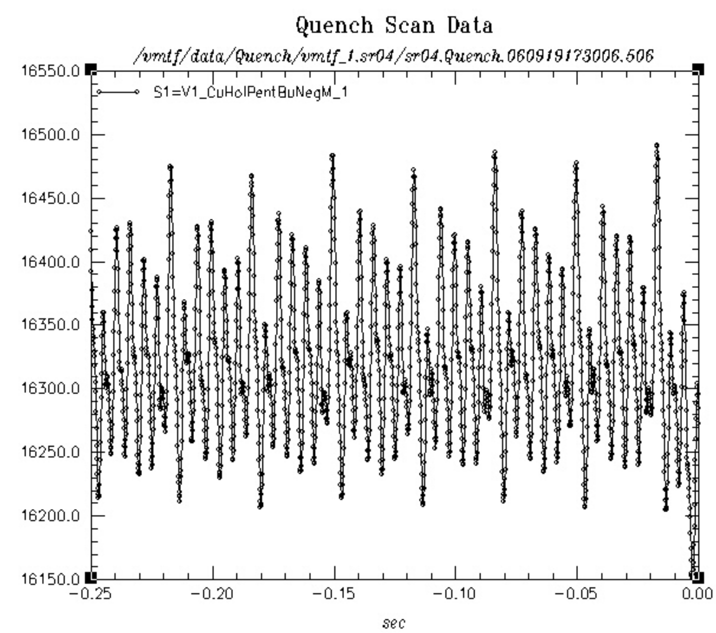


Figure 2. Large ripple current at start of the test.

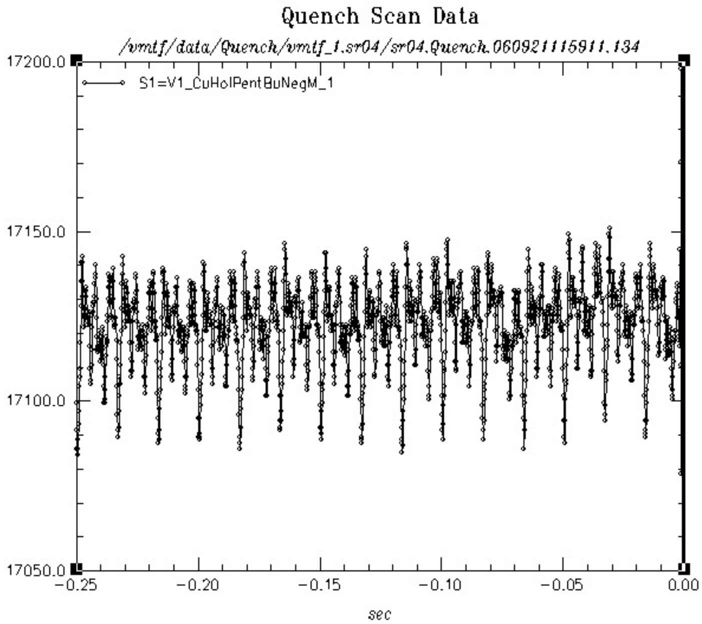


Figure 3. Ripple current reduced by factor of 5, from quench 37 onward.

c) Quench Locations

The small racetrack magnets have very few voltage taps for quench characterization. Figure 4 shows the schematic: basically there are splice segments, and (redundant) half coil segments for each coil. A very short segment between the splices and half coils exists, but is probably not meaningful. For many quenches voltage development is seen in both coils. For some of the low current quenches, development was so slow (more than one second) that the origin is not observed in the data logger quench window. The locations, insofar as they have been studied and identified, are listed in Table 2 below, which summarizes all of the known quenches (there are many more ramps and quench files, as seen in Table 1, due to the power supply noise causing confusion, and later, files produced during noise studies).

Table 2. Quench Locations

Date	Time	VSDS Ramp No.	Ramp Rate (A/sec)	Time	Quench No.	Iq (kA)	Quench Segment	Temp (K)
9/13/2006	-	22	20	-	1	15.8	Top coil	4.44
9/14/2006	0:40	23	20	9:52	2	15.8	Top coil	4.44
9/14/2006	10:08	24	20	10:19	3	15.8	Top coil	4.44
9/14/2006	10:40	25	20	10:54	4	15.8	Top coil	4.44
9/14/2006	11:11	26	20	11:24	5	15.8	Top coil	4.44
9/14/2006	11:40	27	50	11:46	6	15.6	top &	4.44

							bottom	
9/14/2006	11:58	28	75	12:01	7	15.4		4.44
9/14/2006	12:10	29	100	12:11	8	4.8	PS	4.44
9/14/2006	12:18	30	100	12:21	9	15.1		4.44
9/14/2006	13:40	31	150	13:43	10	14.8	top & bottom	4.44
9/14/2006	14:10	32	200	14:12	11	4.8	PS	4.44
9/14/2006	14:15	33	200	14:16	12	7.8	PS	4.44
9/14/2006	14:27	34	200	14:29	13	14.2	top & bottom	4.44
9/14/2006	14:51	35	300	14:52	14	12.2		4.44
9/14/2006	15:02	36	300	15:03	15	12.1		4.44
9/14/2006	15:20	37	300	15.21	16	12.1		4.44
9/14/2006	15:33	38	500	15:34	17	10		4.44
9/14/2006	15:40	39	500	15:41	18	9.8		4.44
9/14/2006	15:48	40	800		19	9.6		4.44
9/14/2006	15:54	41	800		20	9		4.44
9/14/2006	16:01	42	1000		21	9.6		4.44
9/14/2006	16:10		800		22	4.8		4.44
9/14/2006	16:15	43	800		23	5.1	Both coils	4.44
9/14/2006	16:25	44	1000		24	4.4		4.44
9/14/2006	16:43	45	600		25	5		4.44
9/14/2006	16:47	46	20		26	15.8		4.44
9/19/2006	14:35	47	20					
9/19/2006	14:48	48	20		27	15.8		3.57
9/19/2006	16:24	49	20		28	16.3		2.16
9/19/2006	16:53	50	20	17:07	29	16.3		2.15
9/19/2006	17:15	51	20	17:29	30	16.3		2.16
9/19/2006	17:35	52	20	17:50	31	16.3		2.16
9/19/2006	18:16	53	20	18:31	32	16.1		2.8
9/19/2006	18:41	54	20	18:55	33	15.85	Top coil	3.4
9/19/2006	19:05	55	20	19:13	34	0.814		4.1
9/19/2006	19:27	56	20	19:31	35			4
9/20/2006	9:56	57	20	10:11	36	15.74		3.61
9/21/2006	11:44	58	20	11:59	37	17.12		3.6
9/21/2006	12:16	59	20		38	17.068		3.61
9/22/2006	10:00	60	20		39	4.76	very slow quench	4.44
9/22/2006	10:13		20	10:18	40	5.8		4.44
9/22/2006		61	20	10:58	41	21.135	top &	4.46

							bottom	
9/22/2006	16:09	62	20	16:25	42	12.4	Top coil	2.16
9/22/2006	16:36	63	20	16:50	43	12.415	Top coil	2.16
9/22/2006	16:55	64	20	17:10	44	12.446	Top coil	2.165
9/22/2006	17:15	65	20	17:25	45	13.49	top & bottom	2.163
9/22/2006	17:33	66	20	17:50	46	12.463	Top coil	2.162
9/22/2006	18:04	67	20	18:17	47	13.78	top & bottom	2.161
9/22/2006	18:24	68	20	18:36	48	12.148	Bottom coil	2.162
9/22/2006	18:42	69	500	18:43	49	8.385	Top coil	2.161
9/22/2006	18:49	70	200	18:50	50	5.828	PS tripped	2.161
9/22/2006	18:56	71	200	18:57	51	6.213	PS tripped	2.163
9/22/2006	19:03	72	800	19:03	52	4.3	PS tripped	2.165
9/22/2006	19:09	73	100	19:10	53	8.94	Top coil	2.16
9/22/2006	19:19	74	150	19:20	54	6.863	Top coil	2.161
9/22/2006	19:27	75	20	19:38	55	12.449	Top coil	2.164
9/22/2006	19:42	76	50	19:46	56	11.376	Top coil	2.164
9/22/2006	19:50	77	300	19:51	57	15.67	top & bottom	2.161
9/22/2006	19:57	78	250	19:58	58	7.333	Top coil	2.162
9/22/2006	20:04		350	20:06	59	15.725	top & bottom	2.162
9/22/2006	20:10		400	20:11	60	4.45	bottom (PS tripped)	2.162
9/22/2006	20:19		600	20:19	61	5.959	Top coil	2.162
9/22/2006	20:24		1000	20:24	62	4.5	top & bottom	2.161
9/22/2006	20:42		20	21:02	63	21.754	top & bottom	3.18
9/22/2006	21:05		20	21:12	64	8.4	PS induced	3.93
9/22/2006	21:19		20	21.39	65	21.767	top & bottom	3.95
9/23/2006	9:15		20	9:16	66	8.6	trip	3.9
9/23/2006	9:33		20	9:52	67	21.743	top & bottom	3.9
9/23/2006	10:12	79	20	10:27	68	18.28	SC lead trip	4.173
9/23/2006	10:35	80	20	10:42	69	9.195	top & bottom	4.181
9/23/2006	10:50	81	20	11:09	70	21.607	top & bottom	4.21
9/23/2006	11:58	82	20	12:02	71	4.85	Bottom coil	4.455

9/23/2006	12:09	83	20	12:28	72	21.347	top & bottom	4.463
9/23/2006	12:32	84	20	12:52	73	21.371	top & bottom	4.463
9/23/2006	12:54	85	50	13:03	74	20.83	top & bottom	4.448
9/23/2006	13:07	86	75		75	7.714	Top coil	4.448
9/23/2006	13:15	87	75		76	20.32	top & bottom	4.448
9/23/2006	13:30	88	100		77	19.927	top & bottom	4.448
9/23/2006	13:38	89	150		78	19.015	top & bottom	4.448
9/23/2006	13:44	90	200	13:46	79	18.075	top & bottom	4.459
9/23/2006	13:49	91	300		80	6.364	top & bottom	4.448
9/23/2006	13:57	92	300		81	6.315	top & bottom	4.446
9/23/2006	14:02	93	300		82	6.378	top & bottom	4.446
9/23/2006	14:07	94	350		83	6.19		4.453
9/23/2006	14:11	95	600		84	5.474	Top coil	4.446
9/23/2006	16:36		20		85	21.316		4.45
9/23/2006	17:12		20		86	21.368		4.45
9/23/2006	18:12		50		87	20.581		4.45
9/23/2006	18:29		50		88	20.753		4.45

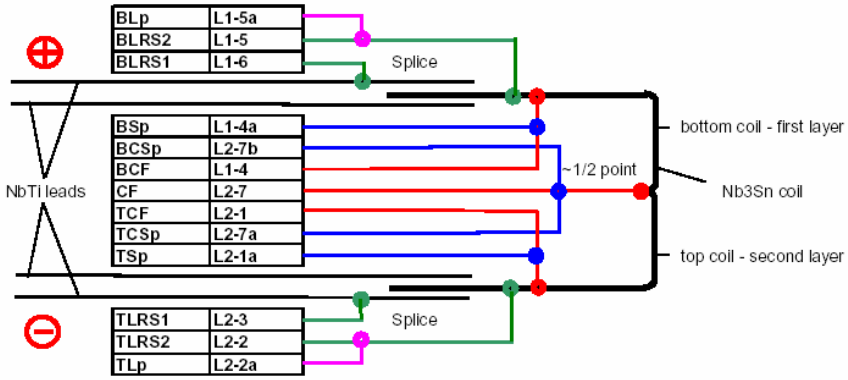


Figure 4. Voltage Tap positions and labels for SR04

d) Voltage Spike Detection System Results

The half coil voltage signals were digitized at 100MHz with the signals amplified by a factor of 5 and, since the wiring was inverted, reversing via software the polarity of one half coil signal. Within successive 500ms windows, the bucked half coil difference was calculated, and the half coil signals within a window were recorded if the bucked amplitude crossed threshold anywhere within that window (thus, there is no special meaning of t=0 in the figures below The substitution of the power supply current regulator (after quench no. 36) did not result in a significant reduction of trigger signal noise level at high currents: at ~16 kA the noise peak value of the bucked signal decreased from 40 mV to 30 mV. The magnet reached ~22 kA at 4.5 K after the regulator replacement; at this current level the noise peak value was about 40 mV.

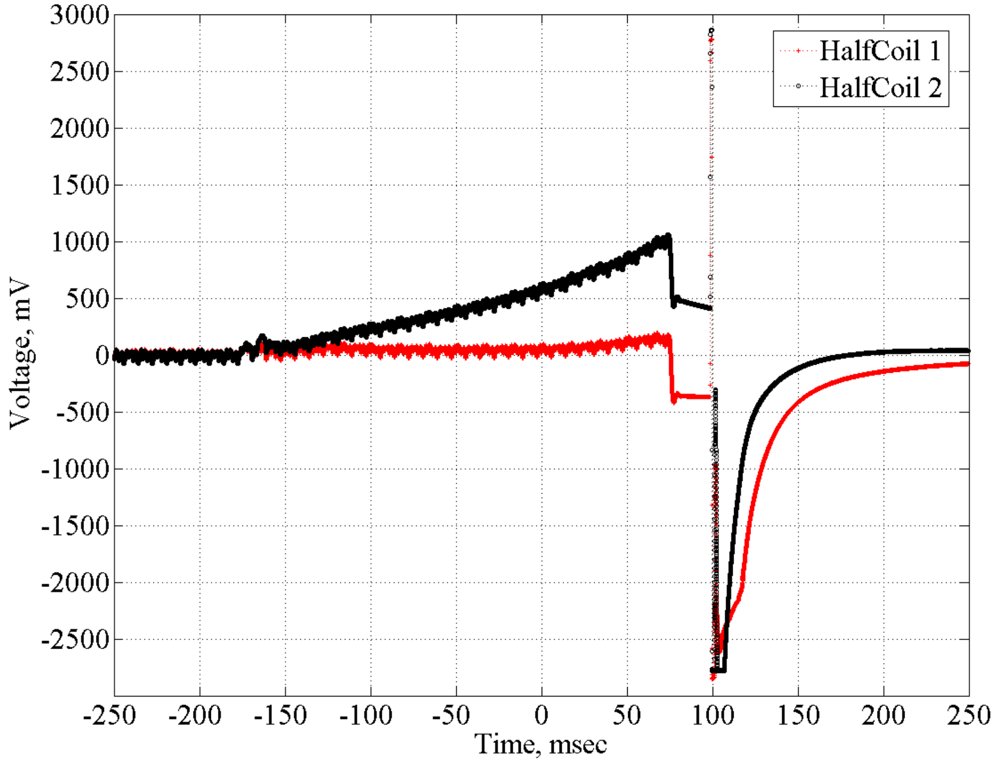
When the quenches occurred at low currents (below ~13 kA) and they did not start at the same time in both half coils, all the quench signals recorded by the VSDS showed a voltage spike initiating the quench. Table 3 shows for which quenches voltage spikes were detected initiating the quenches. For some ramps to quench we did not save the quench signals using the VSDS; these events are indicated by empty cells in the column 'VSDS quench signal' of Table 3. For other ramps to quench (in which there was no spike above trigger threshold) the VSDS was triggered too late and we lost the initial part of the quench development; in Table 3 these ramps are labeled 'Detected too late'.

An example of spike initiating the quenches is shown in figures 5, 6, and 7. Fig. 5*a* shows the half coil signals recorded by the VSDS (500 msec), in fig. 5*b* is the bucked signal in a smaller time window (100 msec) showing the voltage spikes that initiated the quench. The voltage spike can not be observed clearly in the raw half coil signals (fig. 6*a*) because of the high noise; nevertheless the spike is very clear once the half coil signals were cleaned by applying the matching filter technique (fig. 6*b*). Within the same time window that the voltage spike occurred, the current signal did not have any glitch (fig. 7). This means that these voltage spikes were not generated by the power supply; more likely they were produced by thermo-magnetic instabilities.

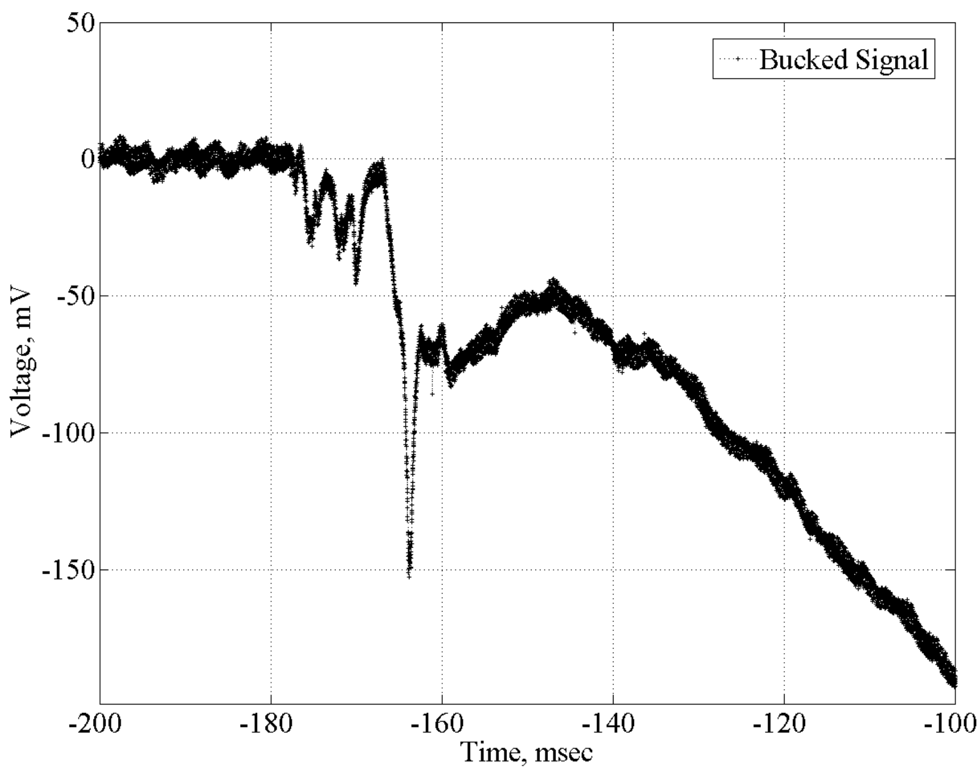
Fig. 8 shows an example of quench signals during a quench at high current: no spikes were found to have initiated the high current quenches.

Table 3. Quench information after repair of the current regulator

Temp [K]	Ramp Rate [A/sec]	Quench No.	VSDS Ramp No.	VSDS Quench Signal	Quench Current [kA]	Quench Segment
3.6	20	37	58	No Spike	17.12	
3.61	20	38	59	No Spike	17.068	
4.44	20	39	60		4.76	
4.44	20	40	61		5.8	
4.46	20	41			21.135	top & bottom
2.16	20	42	62	Detected too late	12.4	top coil
2.16	20	43	63	Spike	12.415	top coil
2.165	20	44	64	Spike	12.446	top coil
2.163	20	45	65	Not Clear	13.49	top & bottom
2.162	20	46	66	Spike	12.463	top coil
2.161	20	47	67	Not Clear	13.78	top & bottom
2.162	20	48	68	Spike	12.148	bottom coil
2.161	500	49	69	Detected too late	8.385	top coil
2.161	200	50	70	Detected too late	5.828	
2.163	200	51	71	Spike	6.213	
2.165	800	52	72	Detected too late	4.3	
2.16	100	53	73	Spike	8.94	top coil
2.161	150	54	74	Detected too late	6.863	top coil
2.164	20	55	75	Spike	12.449	top coil
2.164	50	56	76	Spike	11.376	top coil
2.161	300	57	77	Not Clear	15.67	top & bottom
2.162	250	58	78	Spike	7.333	top coil
2.162	350	59			15.725	top & bottom
2.162	400	60			4.45	bottom
2.162	600	61			5.959	top coil
2.161	1000	62			4.5	top & bottom
3.18	20	63			21.754	top & bottom
3.93	20	64			8.4	
3.95	20	65			21.767	top & bottom
3.9	20	66			8.6	
3.9	20	67			21.743	top & bottom
4.173	20	68	79	No quench	18.28	SC lead trip
4.181	20	69	80	Detected too late	9.195	top & bottom
4.21	20	70	81		21.607	top & bottom
4.455	20	71	82	Spike	4.85	bottom coil
4.463	20	72	83	No Spike	21.347	top & bottom
4.463	20	73	84	No Spike	21.371	top & bottom
4.448	50	74	85	No Spike	20.83	top & bottom
4.448	75	75	86	Spike	7.714	top coil
4.448	75	76	87	No Spike	20.32	top & bottom
4.448	100	77	88	No Spike	19.927	top & bottom
4.448	150	78	89	No Spike	19.015	top & bottom
4.459	200	79	90	No Spike	18.075	top & bottom
4.448	300	80	91	Spike	6.364	top & bottom
4.446	300	81	92	Spike	6.315	top & bottom
4.446	300	82	93	Spike	6.378	top & bottom
4.453	350	83	94	Detected too late	6.19	
4.446	600	84	95	Detected too late	5.474	top coil



(a)



(b)

Fig. 5. Quench signals during ramp no. 86 (quench no. 75): *a)* half coil signals; *b)* bucked signal

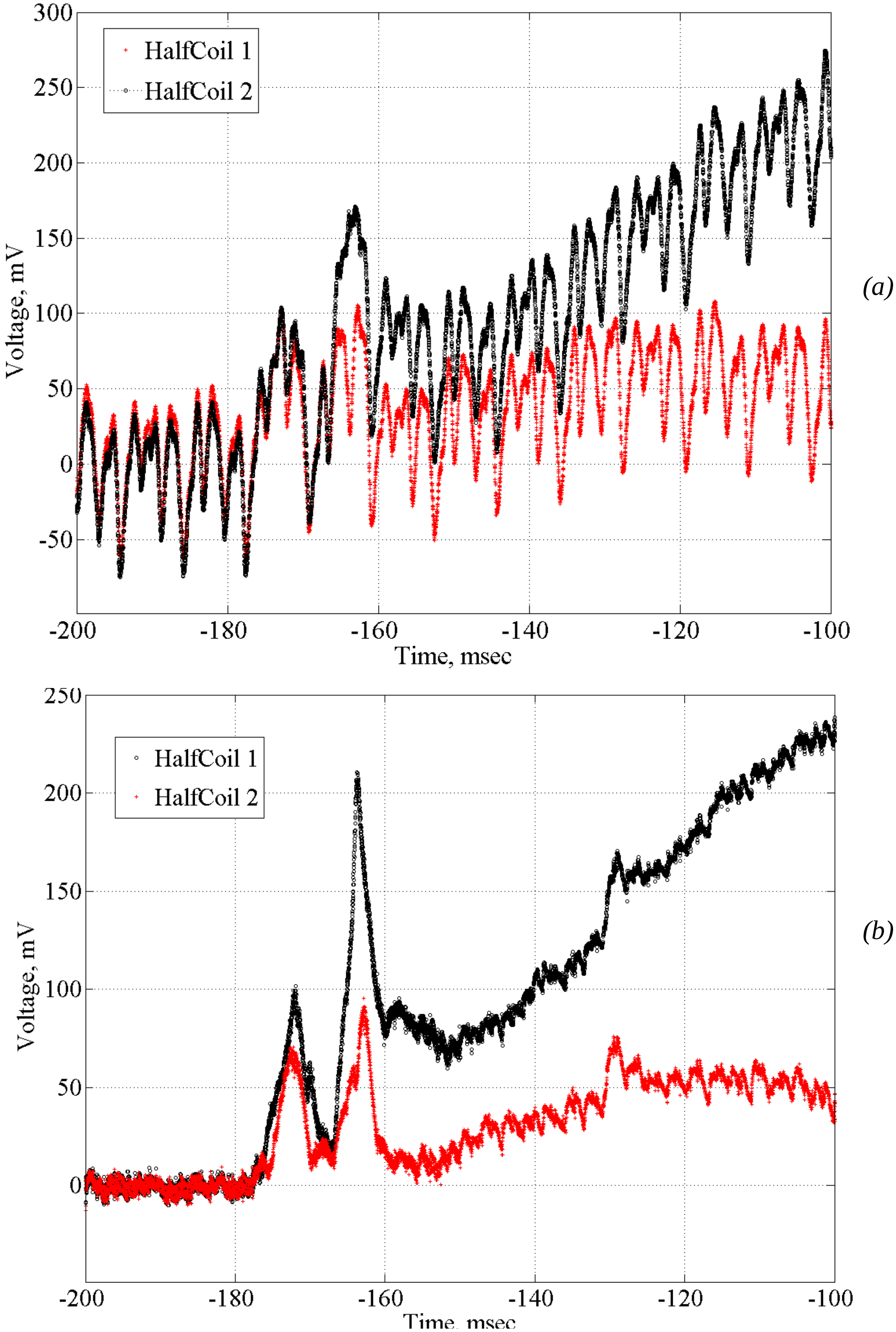


Figure 6. Voltage spike initiating the quench during ramp no. 86 (quench no. 75): *a)* half coil signals; *b)* half coil signals cleaned using the matching filtering

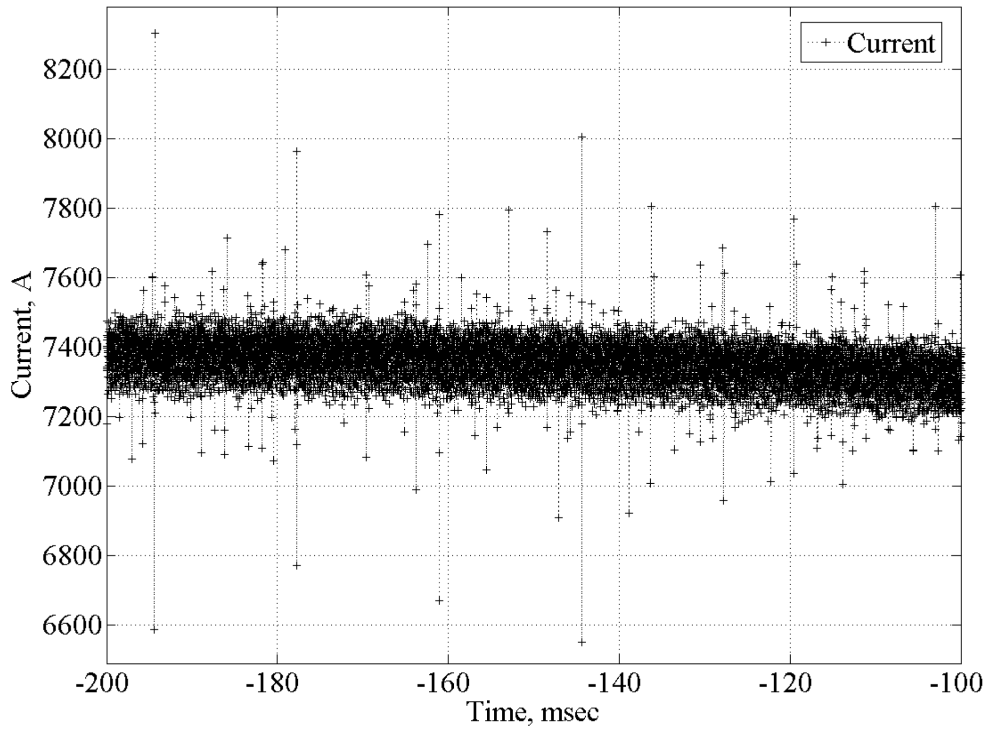
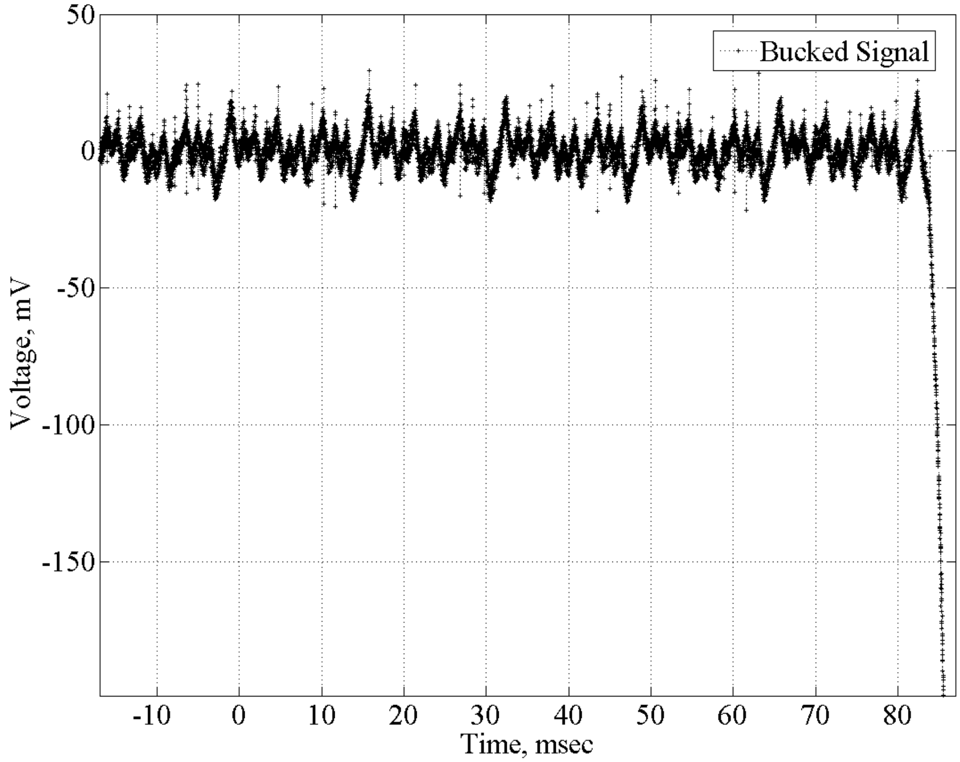
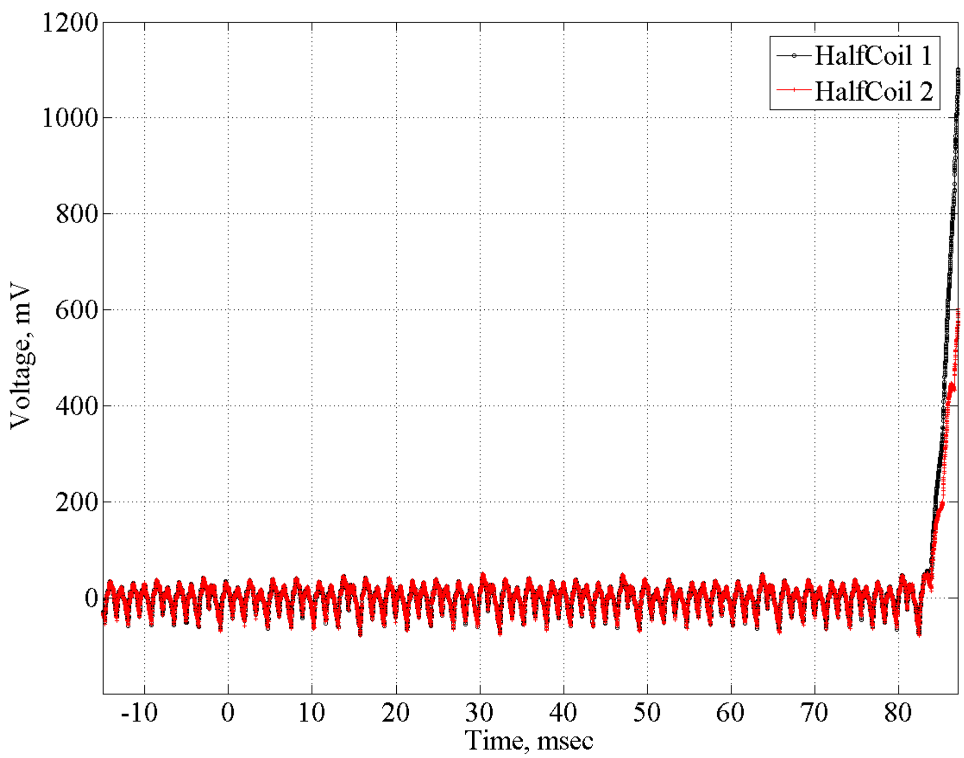


Figure 7. Current signal during the voltage spike initiating the quench in ramp no. 86 (quench no. 75)



(a)



(b)

Figure 8. Quench signal during ramp no. 83 (quench no. 72): *a)* bucked signal; *b)* half coil signals cleaned using the matching filtering technique

e) Ramp Rate Dependence

The default current ramp rate was 20 A/sec. Ramp rate dependence study at 4.5 K is summarized in Fig. 9 for the high amplitude ripple case, and in Fig. 10 for the low amplitude ripple case at 4.5 and and 2.2 K. With low ripple the performance drops dramatically above 200 A/s, whereas the drop occurred above 500 A/s with high ripple.

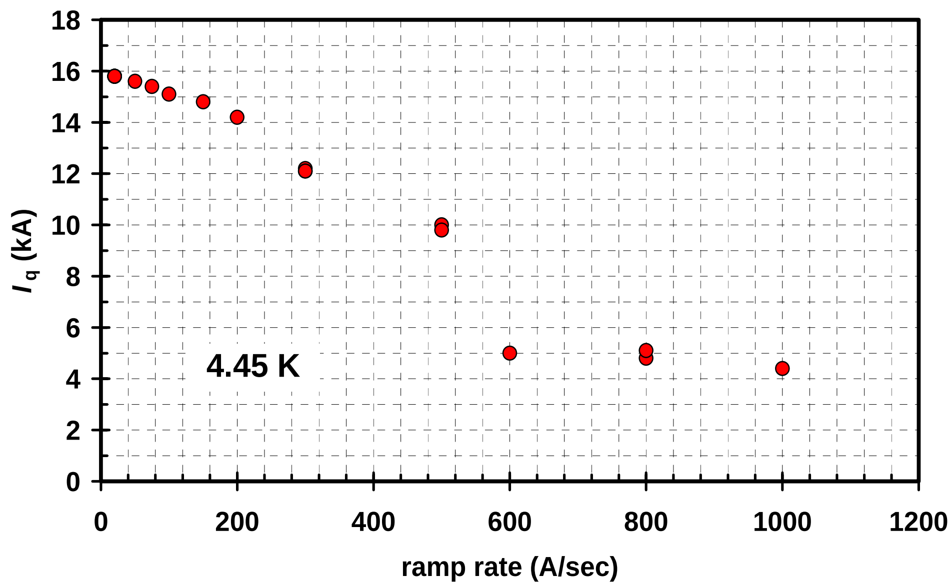


Figure 9. Current ramp rate dependence with high amplitude ripple at 4.5 K.

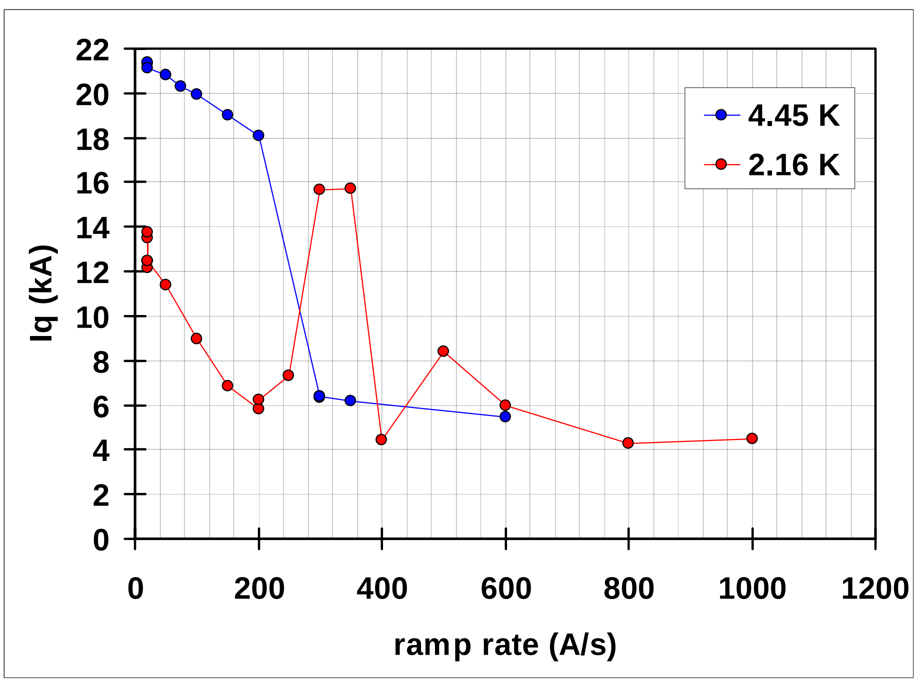


Figure 10. Current ramp rate dependence with low amplitude ripple at 2.2 K and 4.5 K.

f) Temperature Dependence

The temperature dependence is shown in Figure 11.

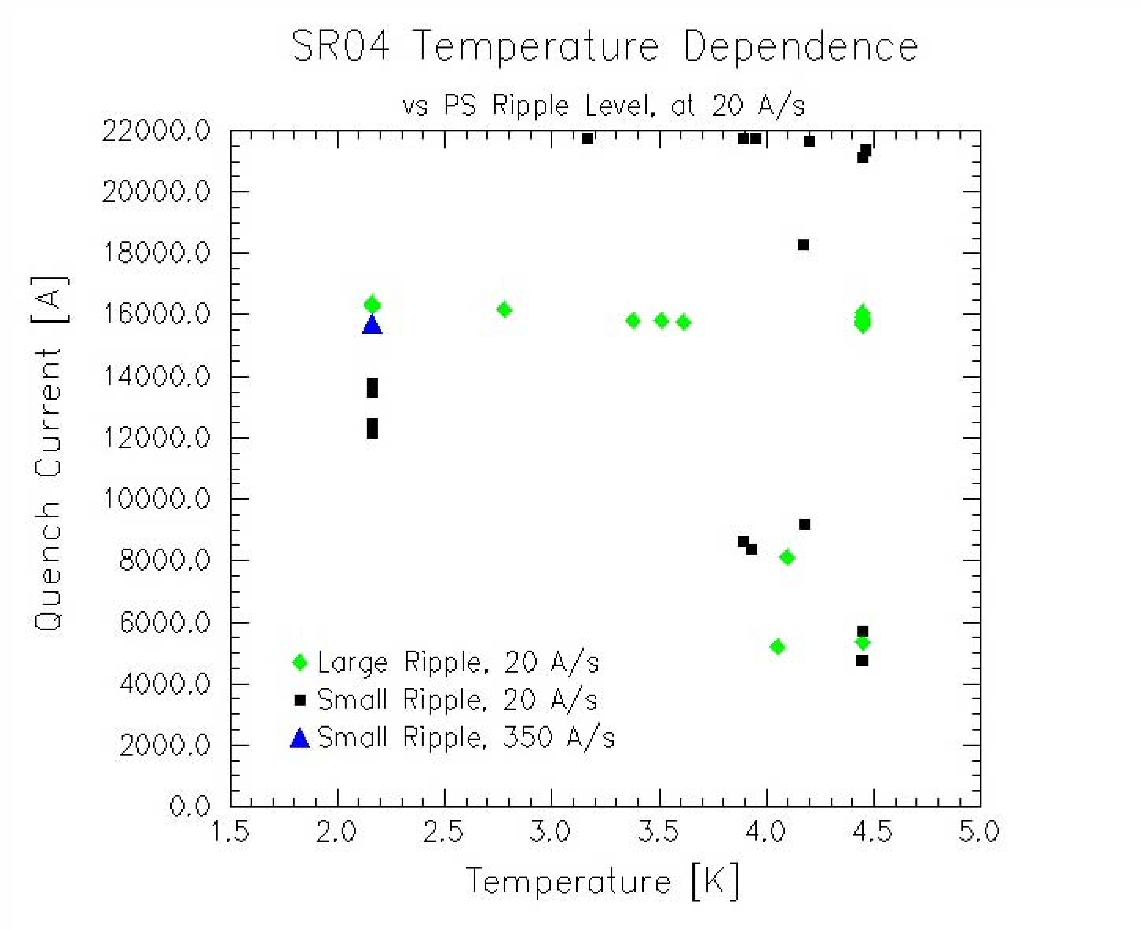


Figure 11. Temperature dependence for initial large ripple current data at 20 A/s is shown by black square data points; Green circles are quench current with reduced ripple at the same 20 A/s ramp rate. The blue triangle shows 350 A/s peak quench current at 2.2K.

3. Energy Loss measurements

Fig. 12 shows the overlay of average energy loss for both data sets, with large and small current ripple. The energy loss measurements and fits made after reducing ripple are shown in Figures 13 and 14.

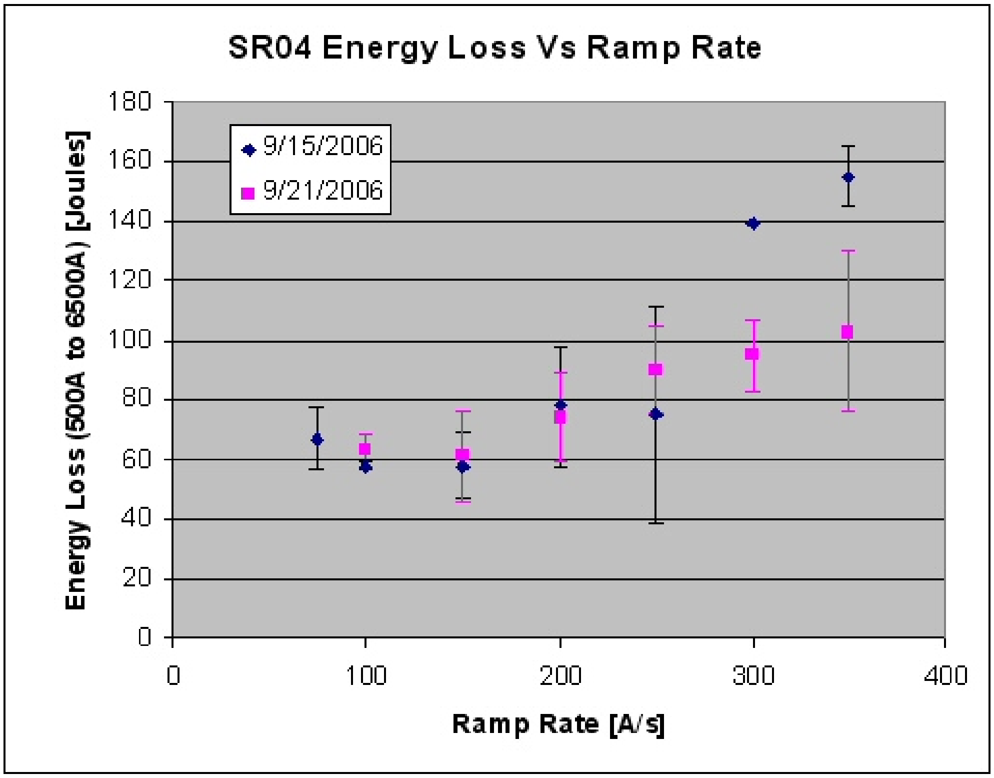


Figure 12. Average energy loss vs. ramp rate, measured with large (9/15) and small (9/21) ripple.

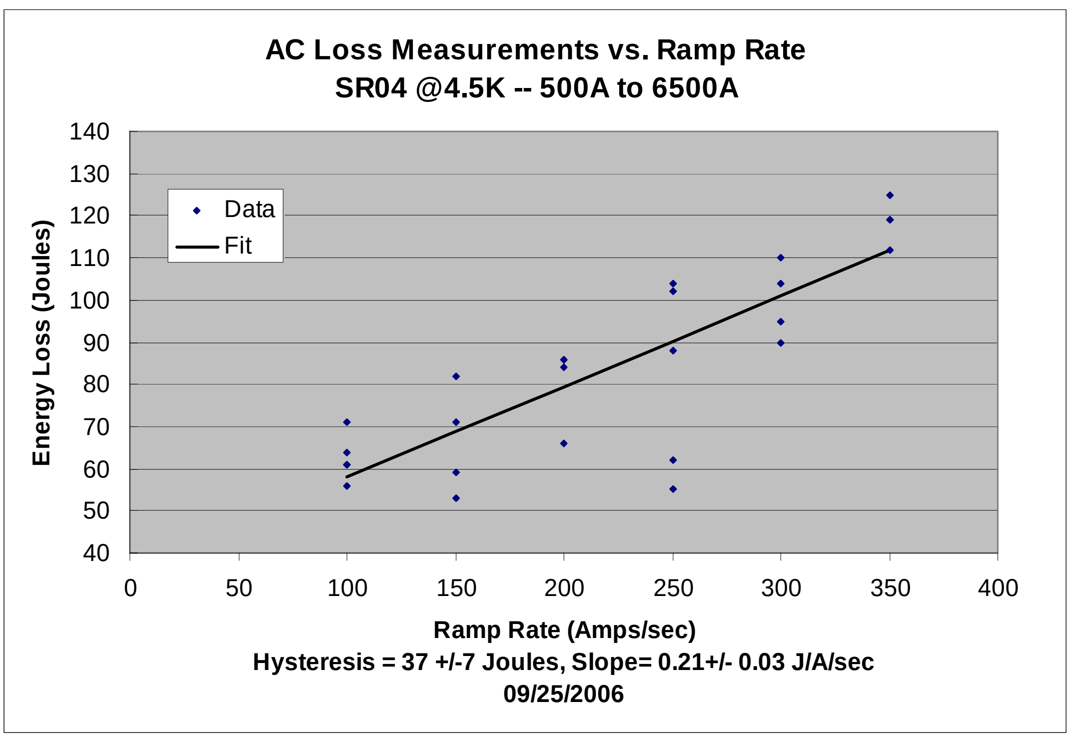


Figure 13. Hysteresis loss in 500 to 6500 A current loop, from small ripple data.

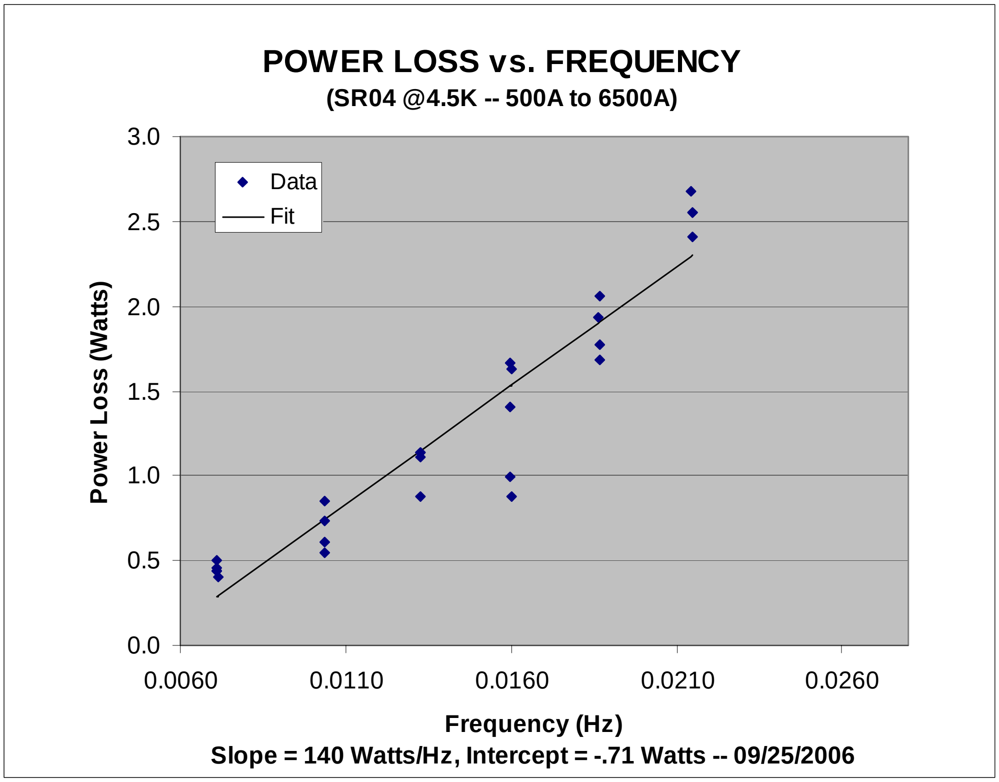


Figure 14. Power loss versus frequency, from small ripple data.

4. Strain Gauge measurements

The strain gauges haven't been studied, except to see that they were working, that the resistance values changed with temperature (Fig. 15), and (active gauges) showed some dependence on current-squared (Fig. 16).

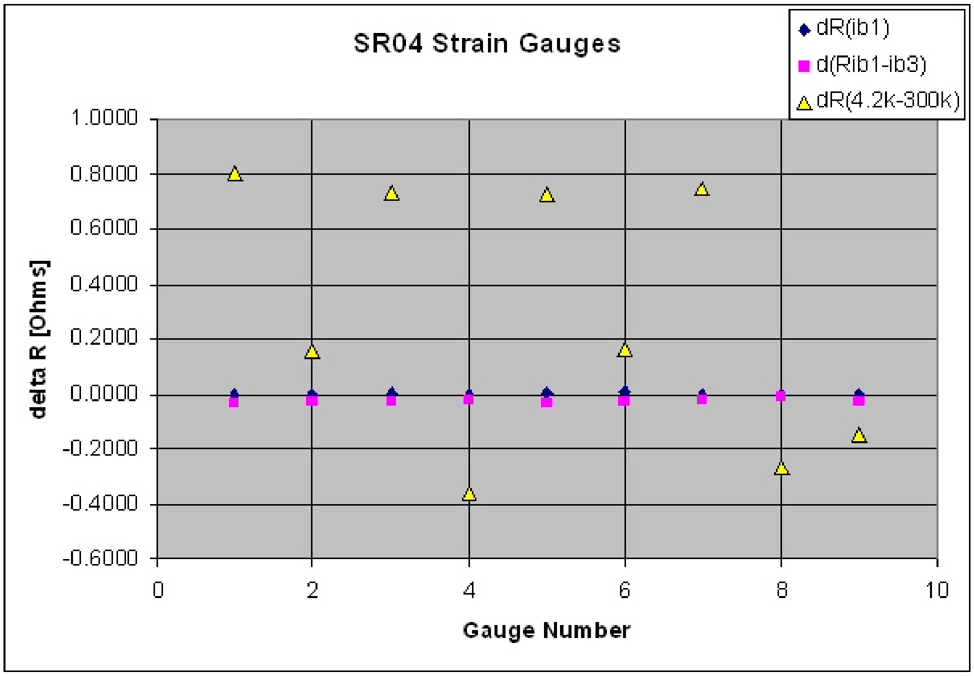


Figure 15. Change in gauge resistances from room temperature to 4.5 K Gauge 9 is the compensating gauge.

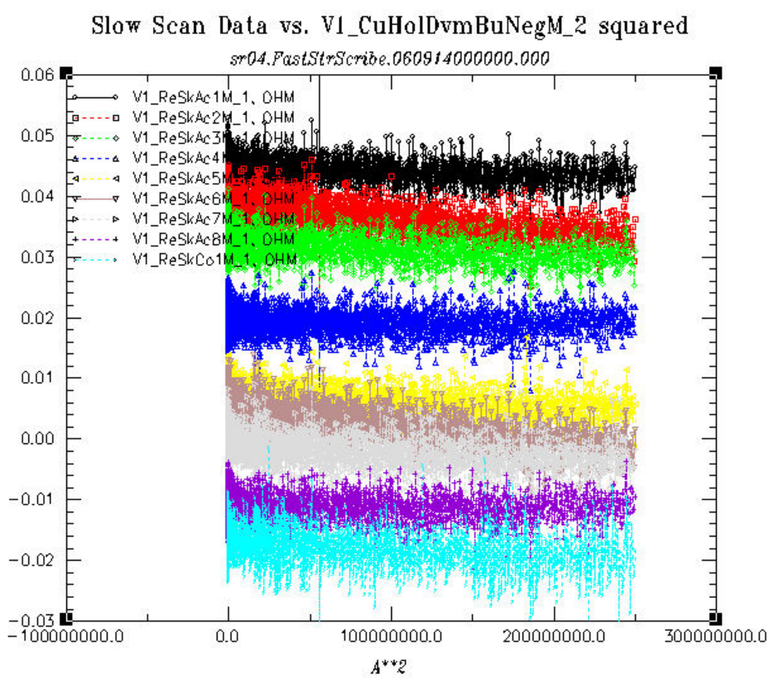


Figure 16. Change in gauge resistances versus current squared (offset for visibility)

5. Splice Resistance measurements

Following the quench performance and energy loss studies, the splice voltages were measured as a function of magnet current to determine their resistance. A calibrated Hewlet-Packard 3458 DVM was used to digitize the raw (unamplified) splice voltages; 60 Hz noise components were reduced by programming the DVM to integrate over 40 power line cycles. Both splices were measured at the same time by using the front and rear inputs to the device. Table 4 shows the current and raw voltage data (after subtraction of individual thermal voltage offsets), which are plotted in Figure 17. Both splices were found to have very nearly the same resistance value of about 0.38 nΩ.

Table 4. Splice Voltage (offsets subtracted) vs Magnet Current

Current (A)	V_front (Bottom)	V_rear (Top)	
0	0	0	PS_off
0	0	0	PS_on
500	0	0	
1000	0	0	
2000	1E-07	0	
5000	0.0000013	0.0000012	
7500	0.0000026	0.0000023	
10000	0.0000035	0.0000034	
12500	0.0000046	0.0000044	
15000	0.0000055	0.0000055	
17500	0.0000066	6.5E-06	
20000	0.0000077	7.5E-06	

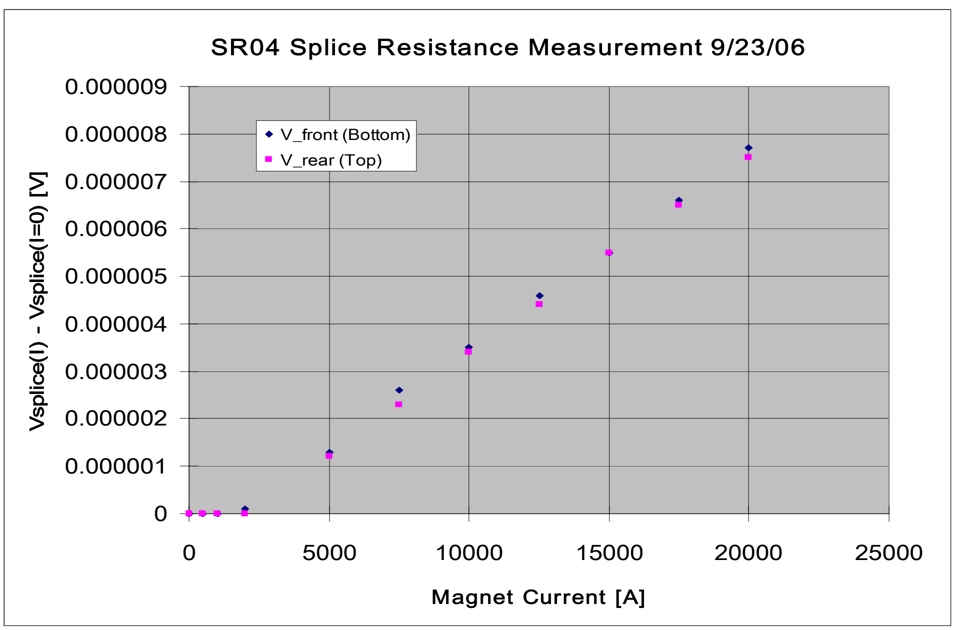


Figure 17. Splice Voltage versus Magnet Current

6. RRR measurement

The cold RRR measurement was performed on 9/24/06. The magnet was gradually warmed up and the coil voltages were recorded while applying ±10 A across the magnet. Warm measurements at 300 K were captured prior to the initial cool down, on 9/8/06. The coil made a transition to normal conducting at a temperature of 17 to 18 K, as predicted by Akihiro Kikuchi. In Fig. 18, the whole coil voltage is shown during the transition, and in Fig. 19 the warm whole coil voltage is shown. From these data, the RRR value is calculated to be 0.01815/0.0000745 = 244±20, where the estimated error is dominated by the uncertainty of the coil voltage at the transition temperature.

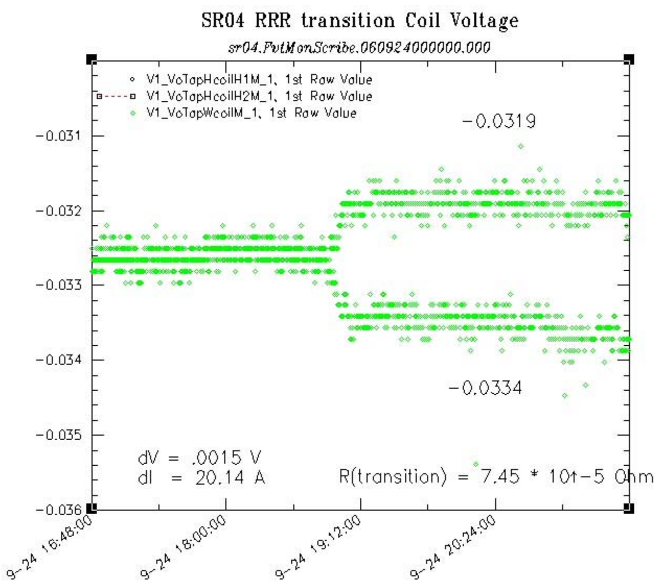


Figure 18. Transition temperature whole coil voltage and resistance values.

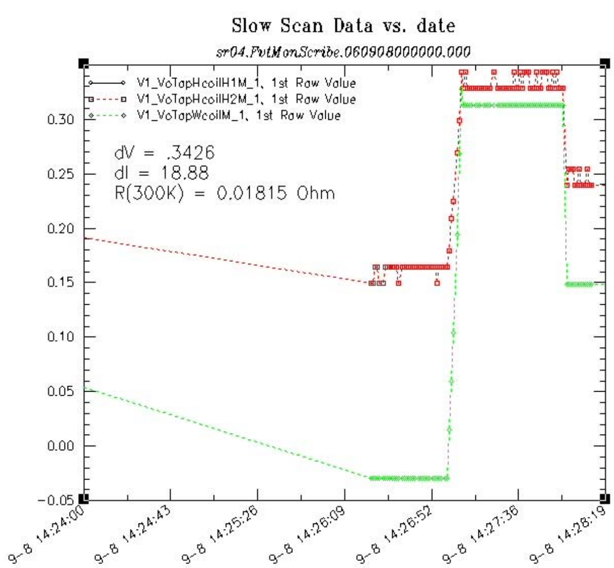


Figure 19. Room temperature whole coil voltage and resistance values.