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HFDM06 Test Summary Report

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1. Introduction

The Cosθ dipole mirror magnet HFDM06 was made in the “standard” mirror configuration, using a coil manufactured using the RRP 108/127 Nb_3Sn strand (exactly the same as was used in SR03). It was tested in November 2006 at the Fermilab vertical magnet test facility (VMTF) where it was mounted to the 30 kA “HFM” top plate assembly. Data acquisition scan configurations were prepared using new configuration and version control tools; thus the preparation took several days longer than usual, and led to some minor difficulties during the test. Scans were started following electrical checkout and warm measurements on Tuesday November 7; pre-cooling with liquid Nitrogen began on 11/8. The VMTF dewar was filled with helium early on Thursday 11/9, followed by cold electrical checkout, quench/power system checks, and the first training quench that day. Quench training and ramp rate studies were conducted at 4.5 K, 2.2 K, and 3.5 K. These were followed by heater protection tests, during which an SCR in the dump switch failed and the magnet absorbed the full quench energy, resulting in a quench integral of about 18.5 MIITS; several additional quenches demonstrated no performance degradation. Heater tests were then completed and splice resistances measured. Warm up was started on 11/22 and RRR data were captured at that time, and again when warm on 11/29. The magnet was removed from the VMTF top plate assembly on 11/30 and returned to IB3 for modification of the coil pre-load, in anticipation of a second test cycle.

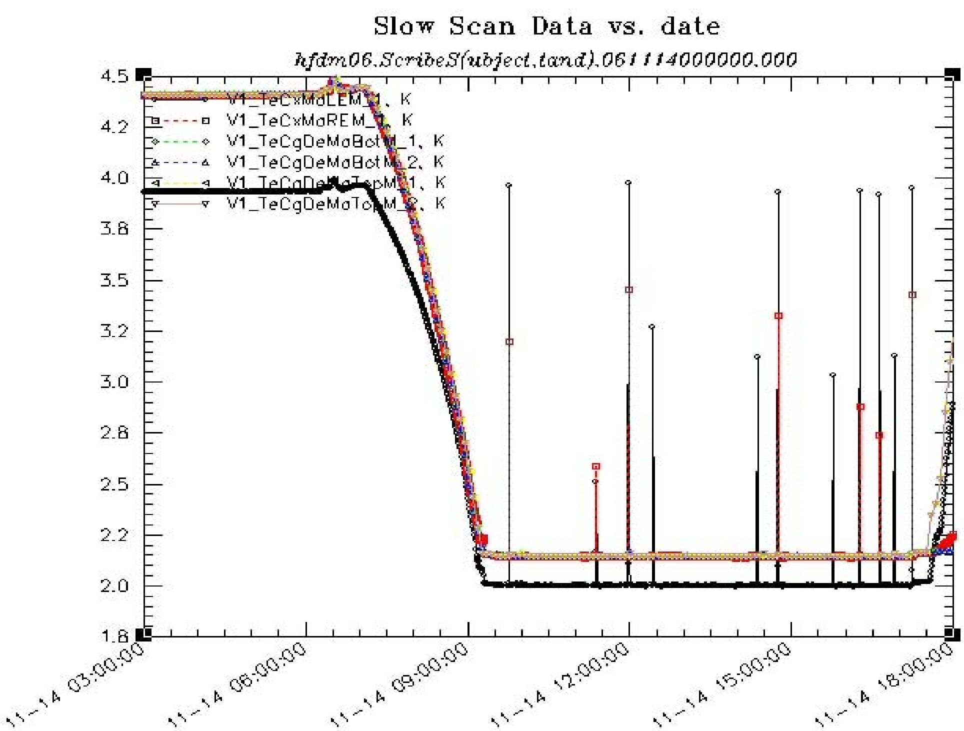

Figure 1. Temperatures in the magnet (black, red) and VMTF test dewar at 4.5K and 2.2K; the magnet LE RTD showed inaccurate readings at all temperatures.

The magnet contained an imbedded RTD at the Lead End and one at the Non-Lead end. Fig. 1 shows that the Lead End temperature sensor (CX22317) did not provide accurate temperature readings at any temperature, indicating that its calibration has changed, or that the wrong sensor was installed in this location. In addition there were many strain gauges, including several that were added specifically to gain more understanding of stress readings around the pole, and to apply this knowledge to measurements in the TQC magnet program. Configurable Voltage taps are shown in the coil map in Fig. 2.

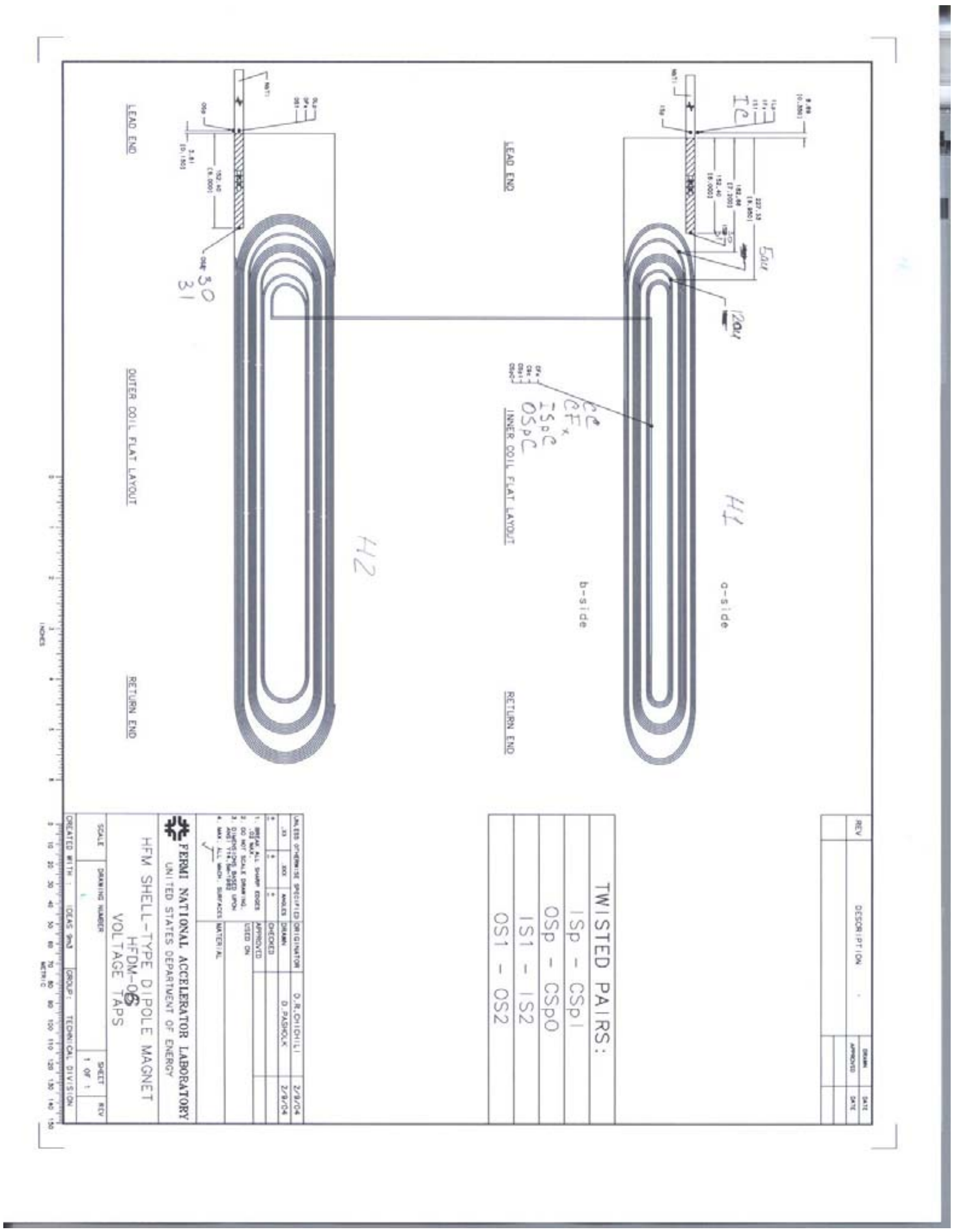

Figure 2. Coil Layout and configurable voltage tap locations for HFDM06.

2. Quench Performance

a) Quench History, Ramp Rate and Temperature Dependence

The quench performance program, illustrated in Fig. 3, started with magnet training at 4.45 K at 20 A/s, followed by 4.5 K ramp rate studies on 11/13. Training and ramp rate studies at 2.2 K followed on 11/14, and were to be continued on 11/15; however, the attempt to return to 2.2 K for additional temperature dependence studies failed due to heat exchanger contamination problems. An intermediate temperature of about 3.5 K was reached, however, and the training quenches there showed even better performance than at 2.2 K. Quench performance at 4.5 K was revisited on 11/16, at various ramp rates to explore conjectures about the apparently unstable quench currents. The full list of quench data files is presented in Table 1. Ramp rate dependence is shown in Fig. 4: The data suggest that the short sample limit (estimated from witness sample tests to be between 24.5 and 25.5 kA) was achieved at 4.5 K, but at lower temperatures was limited, presumably by either mechanical or thermo-magnetic instabilities.

A number of system trips occurred during the program, caused in part by incorrect DQD threshold settings (that were inadvertently re-established due to improper version control, or were set too low to begin with). At 3.5 K, two superconducting leads quenches occurred above 23kA; we relearned (SR03 test encountered the same issue) that the power leads require the liquid level to be raised to a higher set point (minimum of 24 cm) in order to prevent Joule heating from causing Sc Leads quenches.

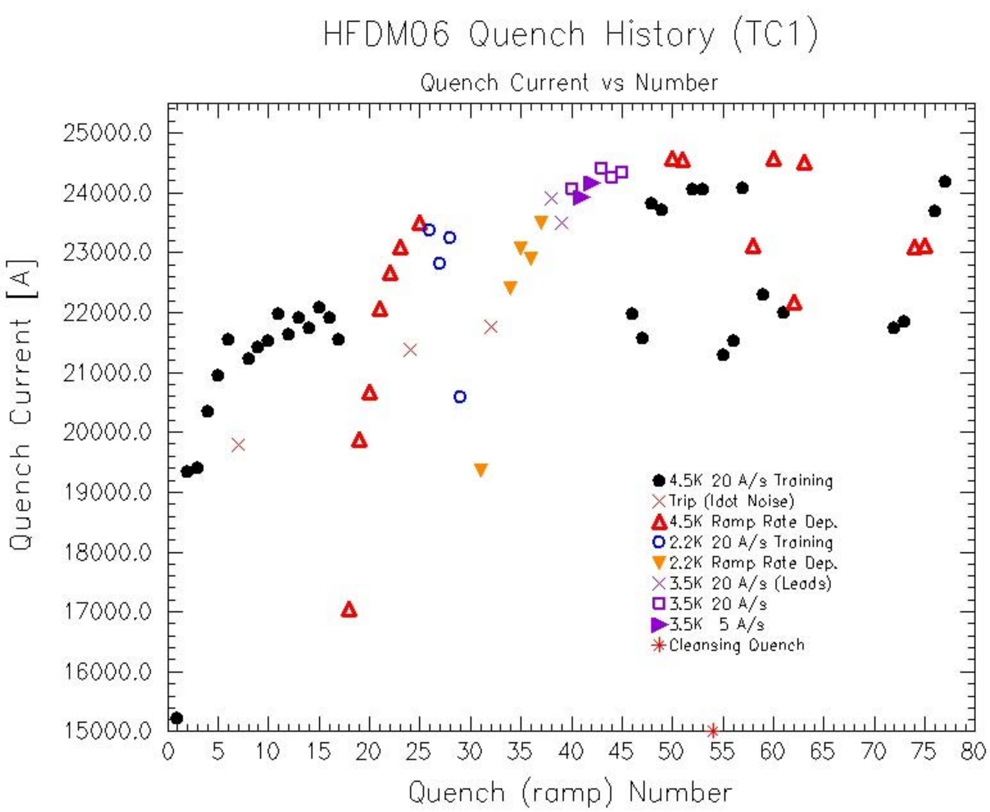

Figure 3. Quench history in the first thermal cycle of HFDM06.

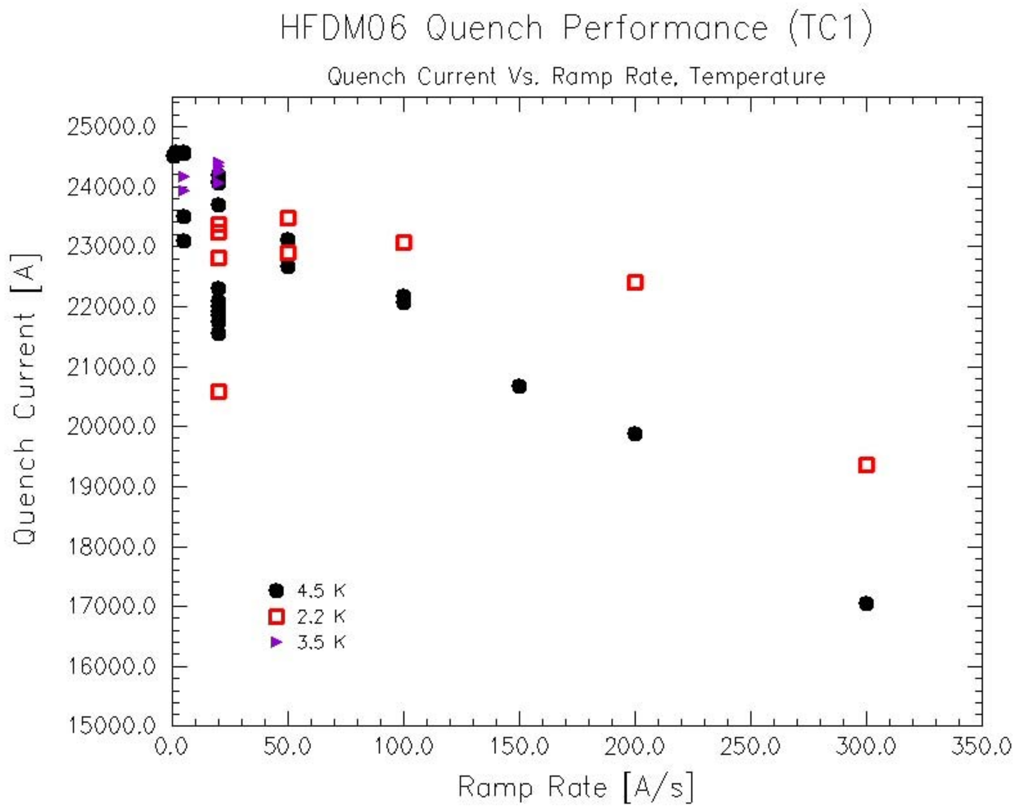

Figure 4. HFDM06 quench current versus ramp rate at various temperatures.

Table 1. Quench Data File Summary for HFDM06

Quench (Ramp)	Date	Time	Temp.	dI/dt	Iq	1st Half Coil 1=inner	1st CVT	tq	Comments
0	11/9/2006	17:21	4.42	0	5000	2			Htr 1 fired at 200 V; tfn = 0.188 - 0.088 = 0.10s
1	11/9/2006	18:25	4.44	20	15219	1	5au_12au	-0.0223	
2	11/10/2006	10:10	4.45	20	19354	1	12au_CC	-0.0093	
3	11/10/2006	11:12	4.44	20	19414	1	12au_CC	-0.007	
4	11/10/2006	12:02	4.45	20	20343	1	5au_12au, IS31_5au	-0.0045	
5	11/10/2006	14:40	4.45	20	20944	1	5au_12au	-0.006	
6	11/10/2006	15:48	4.45	20	21542			1	Lost Data due to vme/computer problem
7	11/10/2006	16:54	4.45	20	19790			1	DQD Trip due to noisy IDOT
8	11/10/2006	17:50	4.45	20	21218	1	12au_CC	-0.0048	
9	11/10/2006	18:40	4.45	20	21410	1	12au_CC, 5au_12au	-0.0046	
10	11/13/2006	9:07	4.45	20	21526	2	CC_OS30, IS31_5au	-0.01	
11	11/13/2006	10:02	4.45	20	21997	1	5au_12au, IS31_5au	-0.0046	
12	11/13/2006	10:48	4.45	20	21624	2	CC_OS30	-0.0065	
13	11/13/2006	11:32	4.45	20	21922	2	CC_OS30	-0.0061	
14	11/13/2006	12:20	4.45	20	21741	2	CC_OS30	-0.006	
15	11/13/2006	13:53	4.45	20	22078	2	CC_OS30	-0.0062	
16	11/13/2006	14:43	4.45	20	21902	2	CC_OS30	-0.0055	
17	11/13/2006	15:28	4.45	20	21540	1	5au_12au, IS31_5au	-0.0034	
18	11/13/2006	15:51	4.45	300	17041	1	5au_12au	-0.0048	12au_CC
19	11/13/2006	16:15	4.45	200	19884	1	5au_12au	-0.0035	12au_CC
20	11/13/2006	16:40	4.45	150	20660	1	5au_12au, IS31_5au	-0.0016	
21	11/13/2006	17:03	4.45	100	22057	1	5au_12au	-0.0034	12au_CC
22	11/13/2006	17:30	4.45	50	22652	1	can't tell origin	-0.0014	
23	11/13/2006	17:59	4.45	5	23093	1	5au_12au	-0.003	100 A/s to 20kA
24	11/13/2006	20:05	4.45	5	21366			1	DQD IDOT TRIP; 100 A/s to 21kA
25	11/13/2006	20:56	4.44	5	23486	2	can't tell	-0.0055	100 A/s to 21kA

							origin		
26	11/14/2006	9:45	2.15	20	23457	1	5au_12au	-0.0021	
27	11/14/2006	11:22	2.15	20	22819	1	5au_12au	-0.0031	12au_CC
28	11/14/2006	11:58	2.15	20	23245	1	5au_12au, 12au_CC	-0.0025	**H2, then H1; H2 starts at -.0048, but CVT signal doesn't show anything**
29	11/14/2006	12:25	2.15	20	20584	2	CC_OS30, IS31_5au, 5au_12au, 12au_CC	-0.003	
30	11/14/2006	13:01	2.15	5	7220			1	PLC Interlock trip
31	11/14/2006	14:21	2.15	300	19359	1	5au_12au	-0.0042	
32	11/14/2006	14:44	2.15	200	21766			1	DQD_LEADS trip due to low Cu-I threshold
33	11/14/2006				0			1	zero amp trip - PS won't ramp
34	11/14/2006	16:15	2.15	200	22402	1	5au_12au, 12au_CC, IS31_5au	-0.0017	
35	11/14/2006	16:37	2.15	100	23066	1	5au_12au, 12au_CC, IS31_5au	-0.0028	**H2, then H1**
36	11/14/2006	16:53	2.15	50	22896	1	5au_12au, 12au_CC, IS31_5au, CC_OS30	-0.001	very fast, hard to localize
37	11/14/2006	17:13	2.15	50	23485	1	5au_12au, 12au_CC, IS31_5au, CC_OS31	-0.0012	
38	11/15/2006	12:48	3.3	20	23913			1	AQD_LEADS quench (liquid level at 22cm is too low at this current!)
39	11/15/2006	13:23	3.3	20	23492			1	AQD_LEADS quench
40	11/15/2006	14:10	3.4	20	24061	1	5au_12au, 12au_CC, IS31_5au	-0.0042	**H2, then H1**
41	11/15/2006	14:40	3.4	5	23916	1	5au_12au, 12au_CC, IS31_5au	-0.0046	**H2, Then H1; 100 A/s to 21kA, 20 A/s to 23kA, 5 A/s to quench**
42	11/15/2006	17:41	3.7	5	24158	2	can't tell origin	-0.0001	
43	11/15/2006	18:37	3.7	20	24405	1	5au_12au	-0.0017	
44	11/15/2006	19:09	3.7	20	24239	1	5au_12au, 12au_CC	-0.0018	
45	11/15/2006	19:36	3.7	20	24325	1	5au_12au	-0.001	

46	11/16/2006	10:16	4.45	20	21967	2	CC_OS30	-0.0025	
47	11/16/2006	10:47	4.45	20	21562	2	CC_OS30	-0.003	
48	11/16/2006	11:08	4.45	20	23819	1	5au_12au	-0.002	100 A/s to 21kA, 20 A/s to quench
49	11/16/2006	11:29	4.45	20	23706	1	5au_12au	-0.003	100 A/s to 21kA, 20 A/s to quench
50	11/16/2006	11:57	4.45	5	24560	1	12au_CC	-0.002	100 A/s to 21kA, 5 A/s to quench
51	11/16/2006	12:22	4.45	5	24557	1	12au_CC	-0.0026	100 A/s to 21kA, 5 A/s to quench
52	11/16/2006	14:05	4.45	20	24063	1	5au_12au	-0.002	
53	11/16/2006	14:35	4.45	20	24058	1	5au_12au	-0.004	IS31_5au, 12au_CC
54	11/16/2006	14:56	4.45	0	15000	-2		1	cleansing quench
55	11/16/2006	15:31	4.45	20	21281	2		-0.0071	
56	11/16/2006	16:16	4.45	20	21520	2		-0.006	
57	11/16/2006	16:34	4.45	20	24067	1		-0.001	
58	11/16/2006	16:55	4.45	50	23107	1	5au_12au	-0.003	IS31_5au, 12au_CC
59	11/16/2006	17:13	4.45	20	22289	2	CC_OS30	-0.0047	
60	11/16/2006	18:24	4.45	2	24575	1	12au_CC	-0.0026	
61	11/16/2006	19:08	4.45	20	22005	2		-0.006	
62	11/20/2006	9:08	4.45	100	22177	1	5au_12au, 12au_CC, IS31_5au	-0.0019	
63	11/20/2006	10:17	4.45	1	24509	1	12au_CC	-0.0027	5au_12au

Heater Protection Studies		**Vhtr1 (min)**	Temp.	dI/dt	Iq	t(q)	tfn	
64	11/20/2006	**141**	4.45	0	**5000**	-0.117	**0.154**	
65	11/20/2006	**100**	4.45	0	**10000**	-0.034	**0.144**	
66	11/20/2006	**100**	4.45	0	**17500**	-0.0042	**0.0692**	Dump Switch SCR Failure !
67	11/21/2006	**100**	4.45	0	**22500**	-0.0014	**0.0439**	
		Vhtr2 (min)						
68	11/21/2006	**173**	4.45	0	**5000**	-0.385	**0.362**	
69	11/21/2006	**173**	4.45	0	**10000**	-0.026	**0.15**	
70	11/21/2006	**141**	4.45	0	**17500**	-0.0093	**0.1292**	
71	11/21/2006	**100**	4.45	0	**21000**	-0.008	**0.139**	
78	11/22/2006	**100**	4.45	0	**22500**	-0.0066	**0.1207**	

Repeat Some Quenches Following SCR OFF failure

Quench (Ramp)	Date	Time	Temp	dI/dt	Iq	Half Coil	1st CVT	tq	Comments
72	11/21/2006	11:53	4.45	20	21733	2		-0.0063	
73	11/21/2006	13:21	4.45	20	21854	2		-0.006	
74	11/21/2006	13:40	4.45	50	23090	1	5au_12au	-0.0033	
75	11/21/2006	13:57	4.45	50	23115	1	5au_12au	-0.0029	
76	11/21/2006	14:17	4.45	20	23699	1	5au_12au	-0.0015	100 A/s to 21kA, 20 A/s to quench
77	11/21/2006	15:24	4.45	20	24189	1	5au_12au	-0.0024	12au_CC, IS31_5au

b) Quench Locations

Quench locations, in so far as they could be determined, are included in Table 1. The assignment of Inner or Outer coil is straightforward, based upon the sign of the half coil AQD voltage signal. Quench locations from the configurable voltage tap data were somewhat difficult to determine, because the quenches develop very quickly in most cases, and the signals themselves were both small and noisy. In fact, there was some confusion about which AQD signal detected the quench, or whether some of these event were in fact system trips, because the "Change Of State" module (which captures the times for logic signal transitions, with 1ms resolution) showed multiple AQDs firing simultaneously. After quench 52, the dump was delayed by 1ms to allow slightly more time for signal identification (without introducing too many additional MIITS). The VSDS system, which operates at much higher sampling rate, identified the suspicious events as actual, but very rapidly developing, quenches. The AQD signal timing confusion was caused by the dump firing without delay (inducing coil and lead signals to trip the AQD modules), combined with the limited COS module resolution of 1ms.

The quench currents, locations and timing are correlated, as can be seen in Fig. 5: outer coil quenches generally (but not always) develop more slowly, and at lower current. A number of events, in two different classes, stand out as especially interesting (or unusual): first, in four events (28, 35, 40, 41) the Half Coil AQD signal shows development starting in the outer coil, which is then overwhelmed by a quench in the inner coil; for these the CC_OS30 (outer coil) CVT segment, strangely, does not show anything happening. Second, eight events (20, 22, 29, 36, 37, 42, 43, 45) – two in the outer coil - seem to have developed very quickly such that either all segments show voltage growth, or the origin could not be visually determined from the CVT segments.

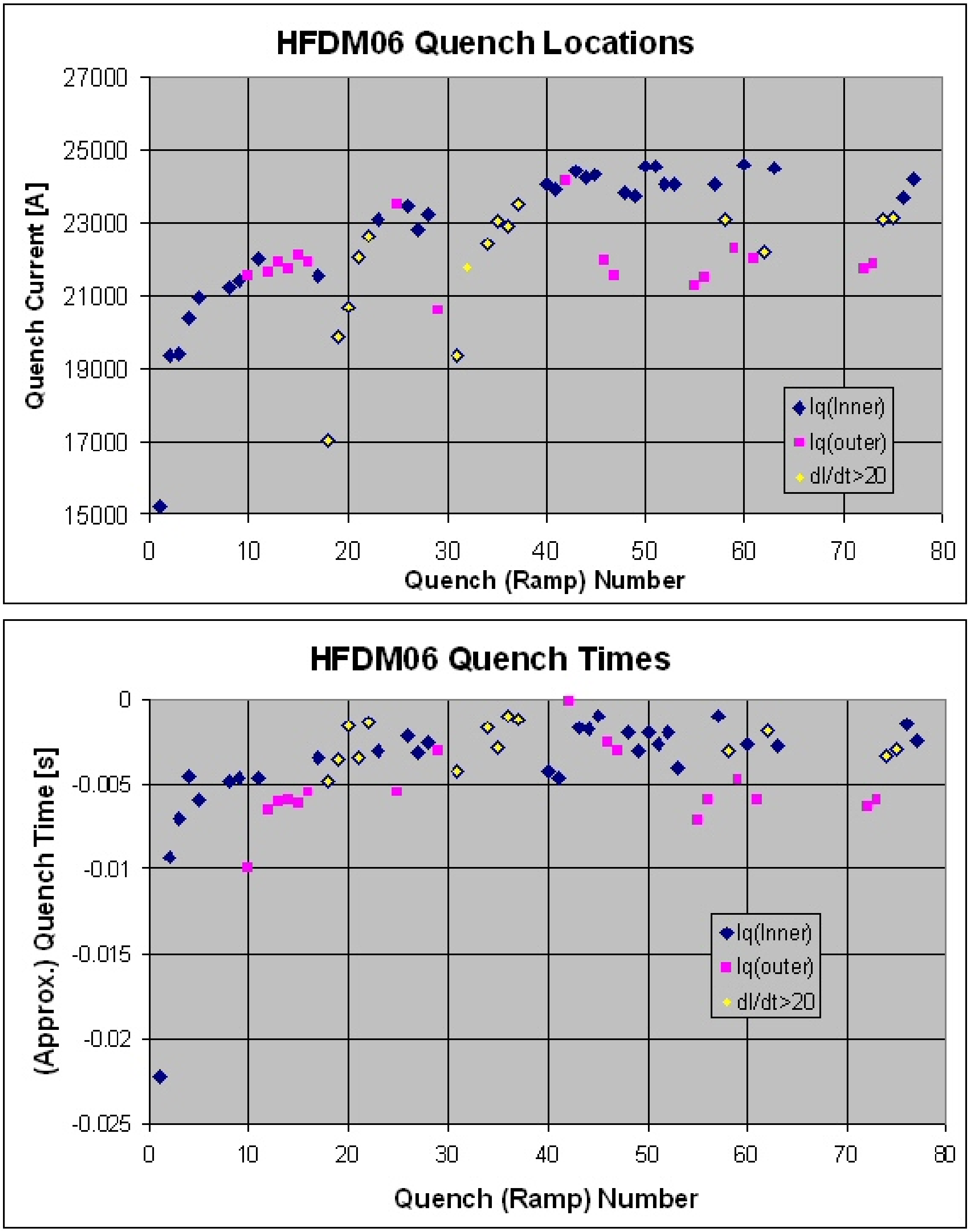

Figure 5. (a) Quench currents and (b) quench development time by location (inner, outer coil). High ramp rate quenches are separately identified.

d) Voltage Spike Detection System Results

The Voltage Spike Detection System (VSDS) captured spike data (individual half coil voltages, and magnet current) for all ramps at a threshold (on the half coil difference voltage) of from 15 to 17 mV, and it was quite clear that the **spikes associated with this conductor are not very numerous and are generally of small amplitude** (power supply noise triggered the capture of most "events" at this low threshold). Spikes for each ramp were studied "by hand" using simple MATLAB event display tools. For those that appear to be actual half coil voltage excursions (rather than just noise), the peak pulse height and some estimate of the pulse duration have been recorded. In most quench events, the quench development was also captured by the spike system: in almost all cases there is **no evidence for a voltage spike preceding the quench**, and in those few cases the "spikes" are small, narrow, and likely to be power supply (SCR) noise. Figure 6 shows the history of magnet currents at which data were triggered. Figure 7 shows the pulse duration versus amplitude for the "actual" spikes, and Figure 8 illustrates that the widest pulses all occur at relatively low magnet current.

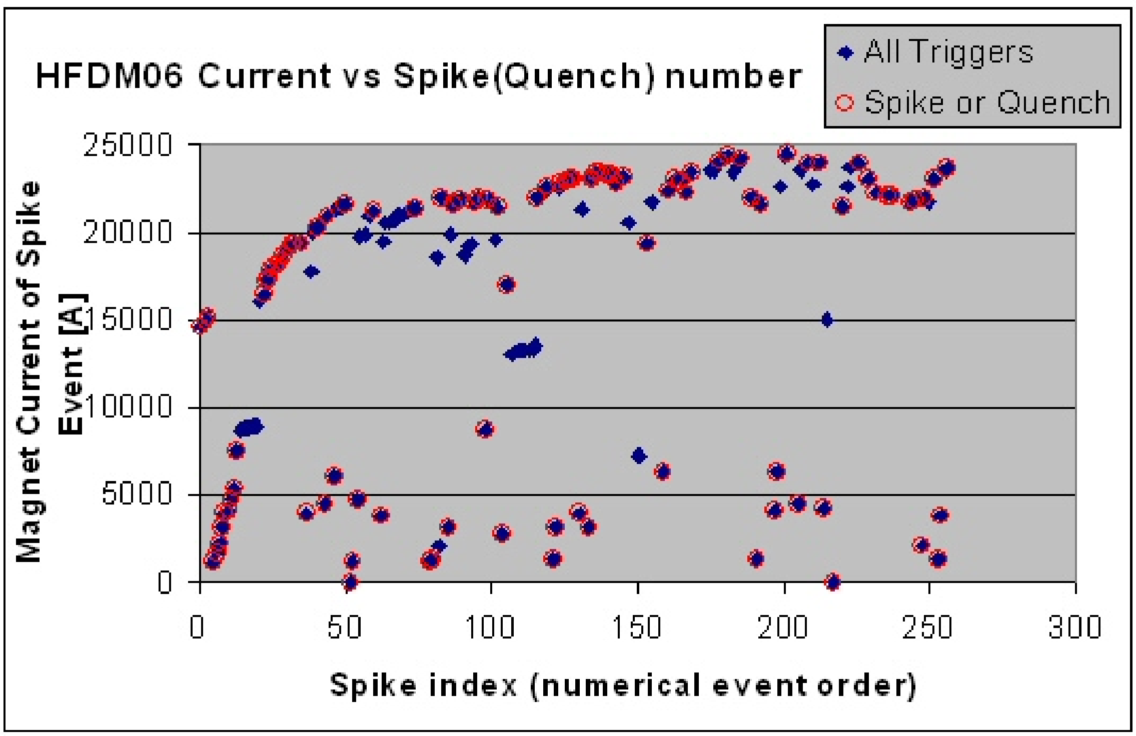

Figure 6. Current for spike system by event number, for "all" triggers(dark diamonds) and actual "spikes' or "quenches" (red circles); power supply noise is clearly exacerbated in middle and high current ranges.

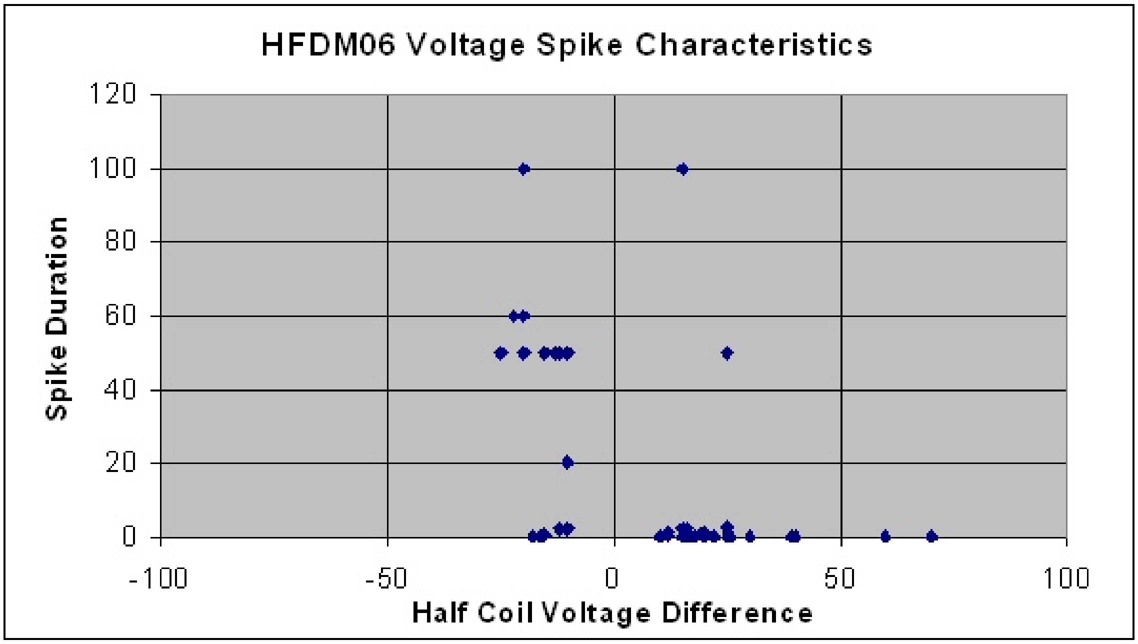

Figure 7. Duration versus peak amplitude for actual spikes

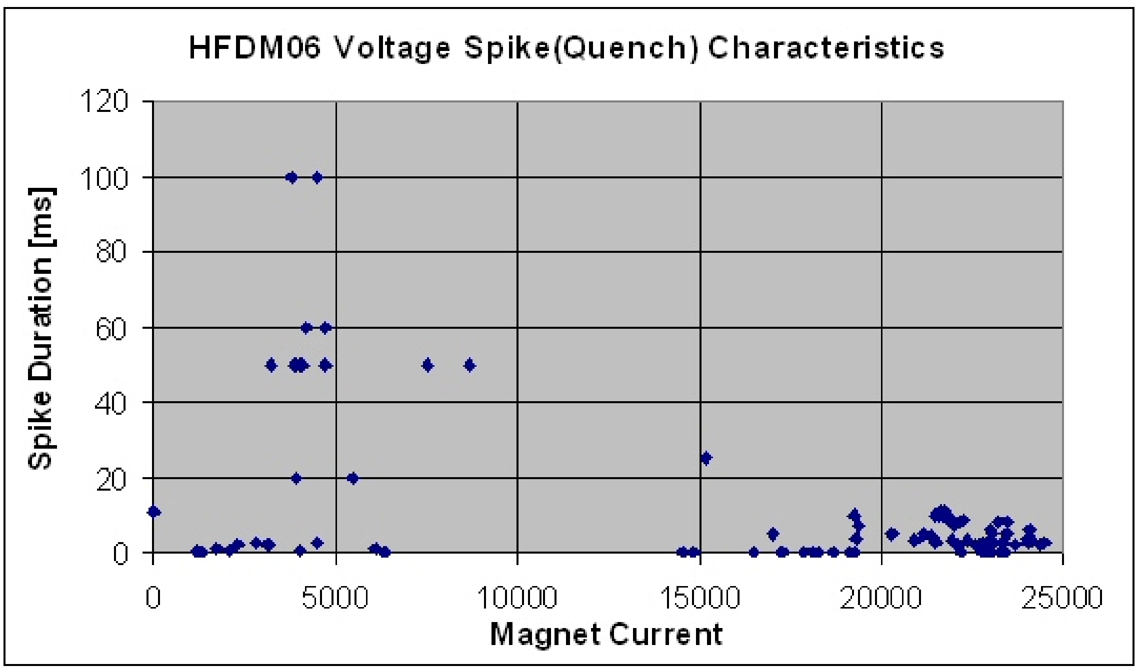

Figure 8. Spike duration versus magnet current for actual spikes (or quenches)

3. Heater Protection Studies

This magnet had two sets of strip heaters installed, both which spanned the full magnet length along both sides of the outer coil. As shown in the cross section view of Fig. 9, one heater set (Heater 1) covered the “pole” turn region, while the other (Heater 2) covered the “midplane” region. Heater parameters are included in Table 1 (quenches 64-71, 78): at each magnet current, corresponding to I/Ic={0.2, 0.4, 0.7, 0.9}, the minimum heater voltage required to induce a quench was determined separately for each heater (shown in Fig. 10); also the heater delay was measured, defined as the time between when the heater was fired and when resistive voltage began to appear (Fig. 11). In all cases, the quenches developed in the outer coil.

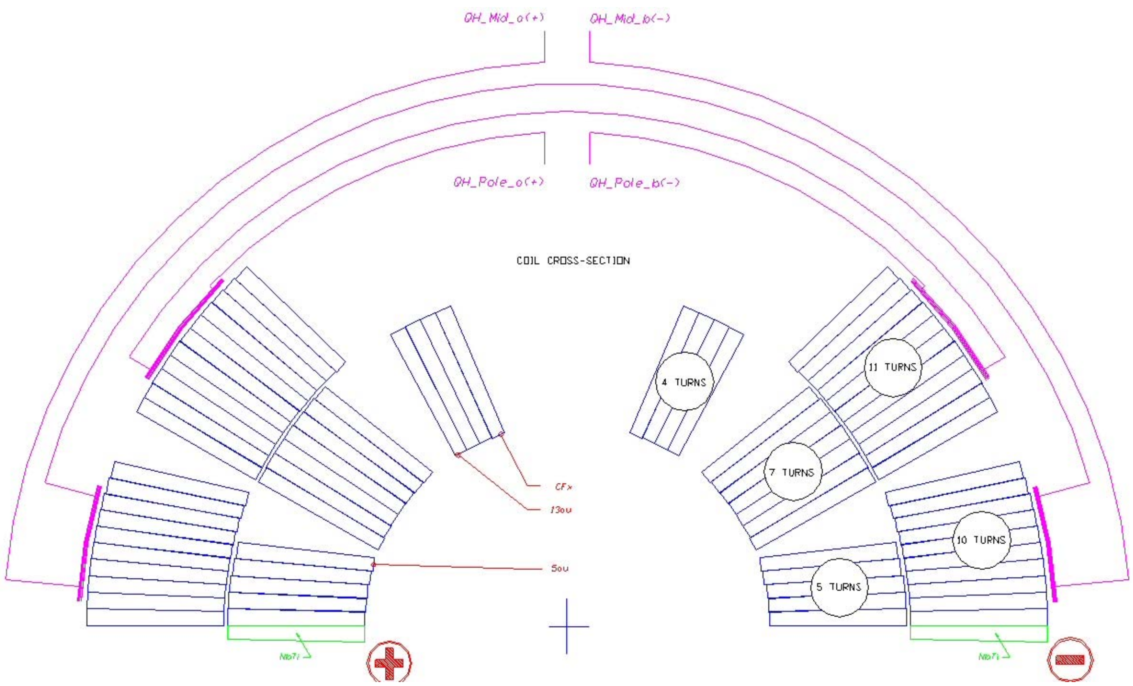

Figure 9. Coil cross section and strip heater positions.

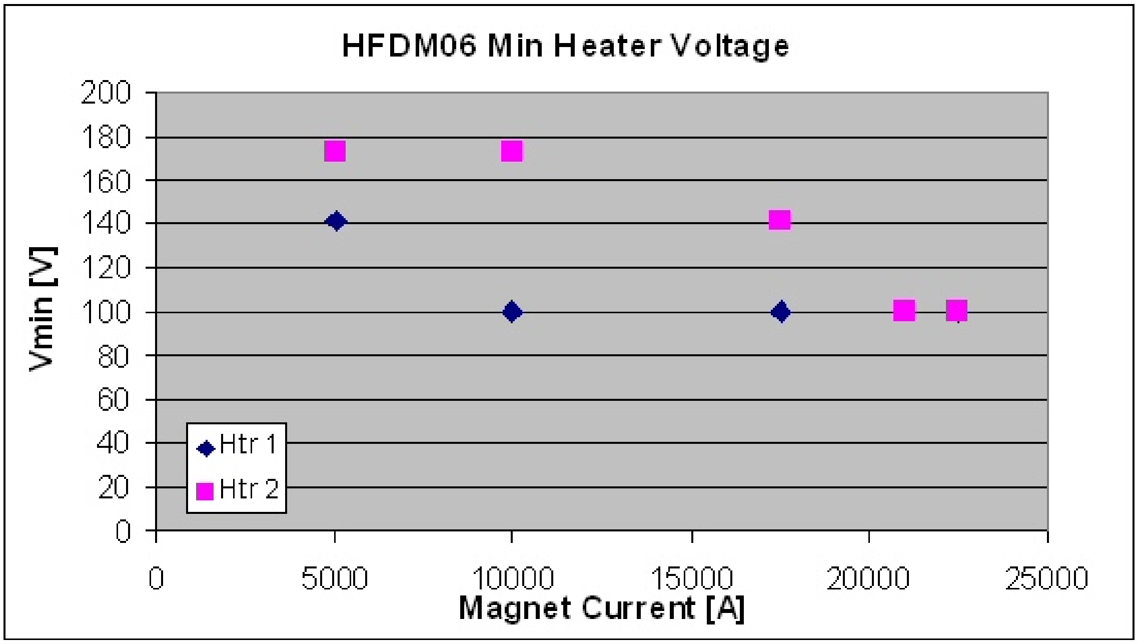

Figure 10. Minimum heater voltage required to induce a quench for HFDM06 strip heaters 1(pole) and 2(midplane), as a function of magnet current.

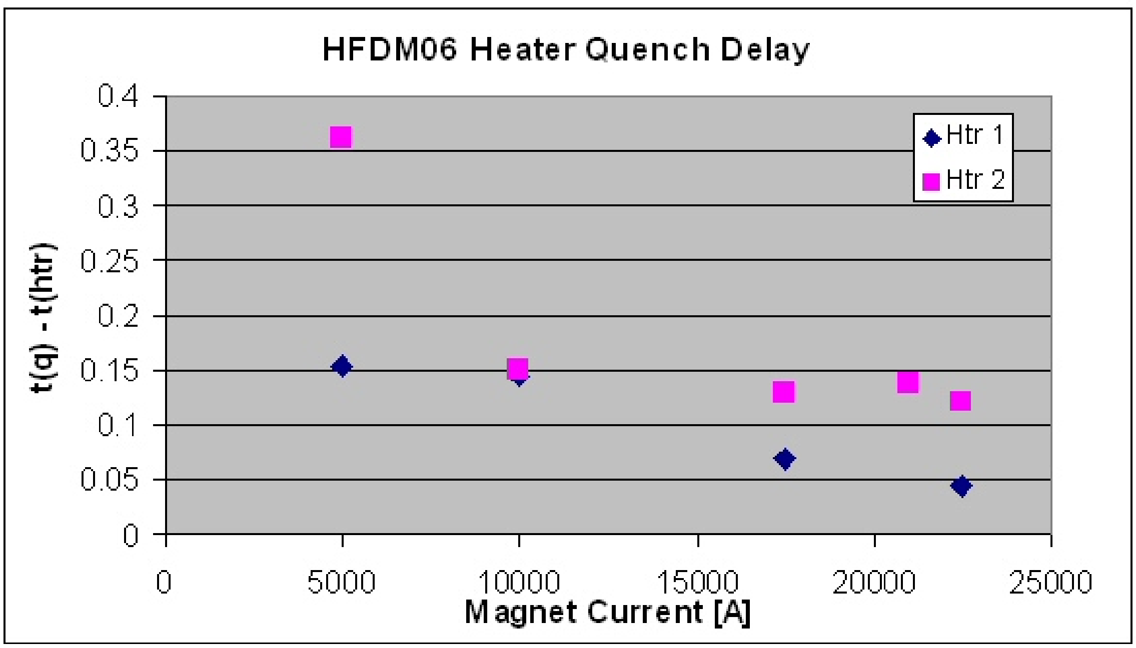

Figure 11. Time for quench to start for HFDM06 strip heaters 1(pole) and 2(midplane), as a function of magnet current.

4. Strain Gauge measurements

Remarkably, all of the strain gauges worked. They have been studied and results are presented in a separate companion note, TD-07-017.

5. Splice Resistance measurements

Following the quench performance and heater protection 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 12. Both splices were found to have very nearly the same resistance value of about 0.1 nΩ, which is unusually good.

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

			Vo=	0.0178	-0.0171
I	V(ICsplice) [mV]	V(OCsplice) [mV]		V(IC)+Vo	V(OC)+Vo
0	-0.0178	0.0171		0	0
1000	-0.0177	0.017		1E-04	-1E-04
2000	-0.0175	0.0172		0.0003	1E-04
4000	-0.0174	0.0178		0.0004	0.0007
6000	-0.0173	0.0178		0.0005	0.0007
8000	-0.0172	0.0182		0.0006	0.0011
14000	-0.0165	0.0187		0.0013	0.0016
18000	-0.0163	0.0191		0.0015	0.002
21000	-0.0159	0.0196		0.0019	0.0025
19000	-0.0163	0.0192		0.0015	0.0021
16000	-0.0168	0.0191		0.001	0.002
12000	-0.0171	0.0183		0.0007	0.0012
5000	-0.0179	0.0174		-1E-04	0.0003

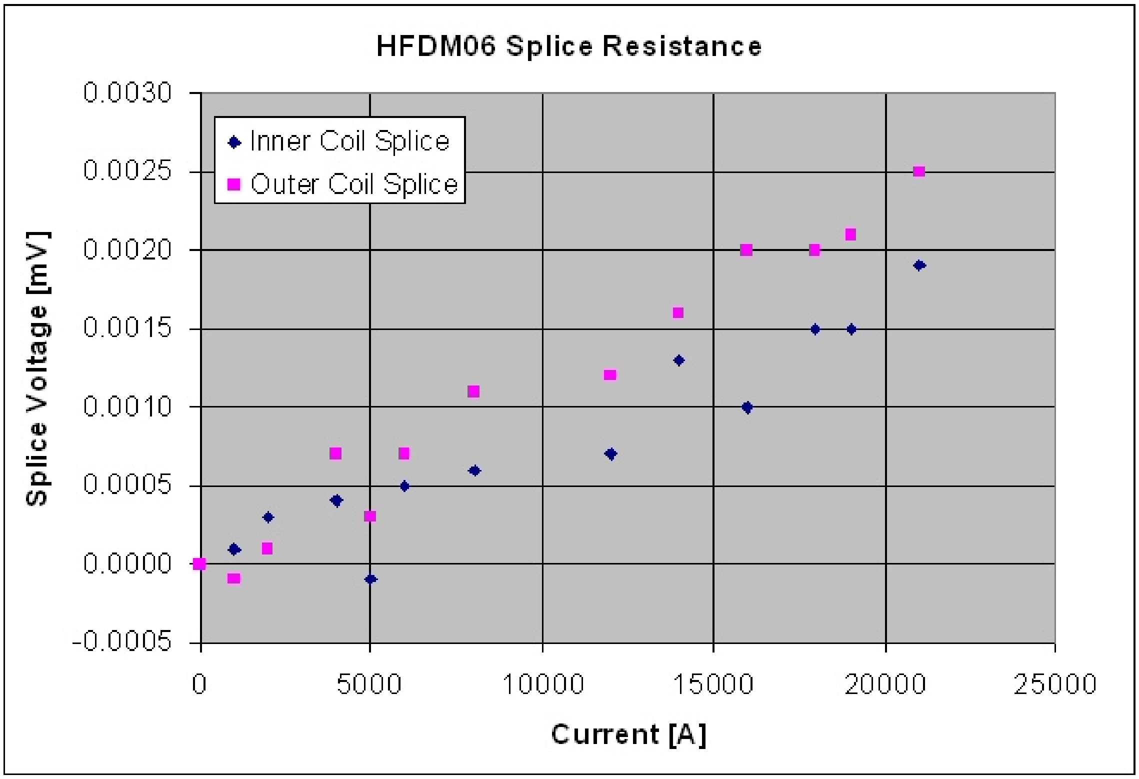

Figure 12. Splice Voltage versus Magnet Current

6. RRR measurement

The cold RRR measurement was performed on 11/23/06 with the transition to normal appearing complete at about 02:00. The magnet was gradually warmed up and the coil voltages were recorded while applying ±10 A across the magnet through transition. The coil made a transition to normal conducting at a temperature of 17 to 18 K (Figure 13). Warm measurements at 300 K were captured on 11/29/06. In Fig. 14, the whole and half coil voltages are shown during the transition, and in Fig. 15 the warm coil voltages are shown. From these data, reproduced in Table 5, the RRR of all segments are consistent with the value 172 +/- 3.

Table 5. RRR data for HFDM06

Segment	I+	I-	V+	V-	(I+ - I-)	(V+ - V-)	V/I	Rwarm/Rcold
WARM	10.265	-10.139			20.404			
Wcoil			0.631	-0.689		1.32	0.064693	**169.2308**
H1			0.291	-0.2833		0.5743	0.028146	**169.9112**
H2			0.389	-0.3509		0.7399	0.036262	**168.9269**
IS31_5au			0.08934	-0.08973		0.17907	0.008776	**172.5145**
5au_12au			0.1273	-0.1243		0.2516	0.012331	**175.9441**
12au_CC			0.0627	-0.0622		0.1249	0.006121	**175.9155**
CC_OS30			0.3682	-0.3547		0.7229	0.035429	**175.0363**
COLD	10.267	-10.132			20.399			
Wcoil			-0.0315	-0.0393		0.0078	0.000382	

H1	0.0029	-0.00048	0.00338	0.000166
H2	0.01758	0.0132	0.00438	0.000215
IS31_5au	0.00095	-0.000088	0.001038	5.09E-05
5au_12au	0.00345	0.00202	0.00143	7.01E-05
12au_CC	0.0012	0.00049	0.00071	3.48E-05
CC_OS30	0.01216	0.00803	0.00413	0.000202

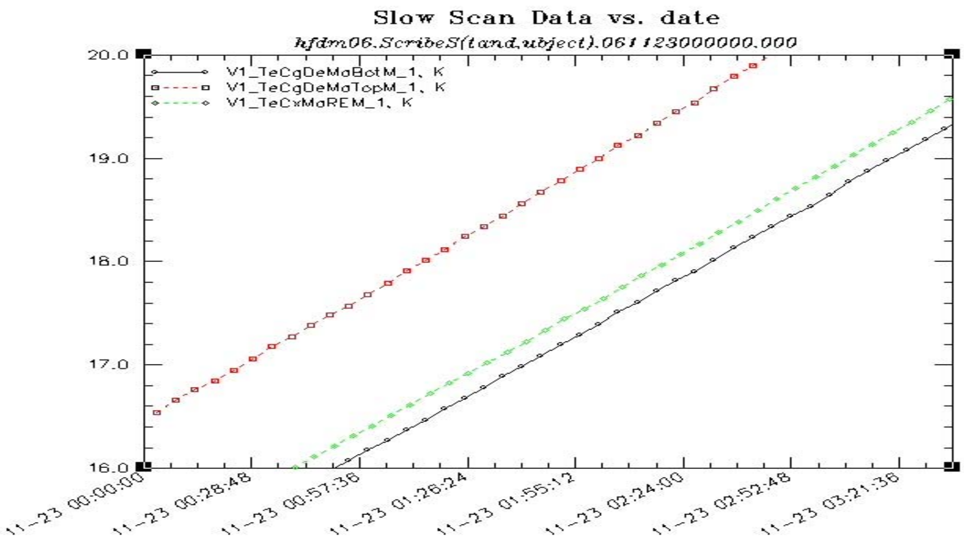

Figure 13. Temperature vs time during the cold transition to normal.

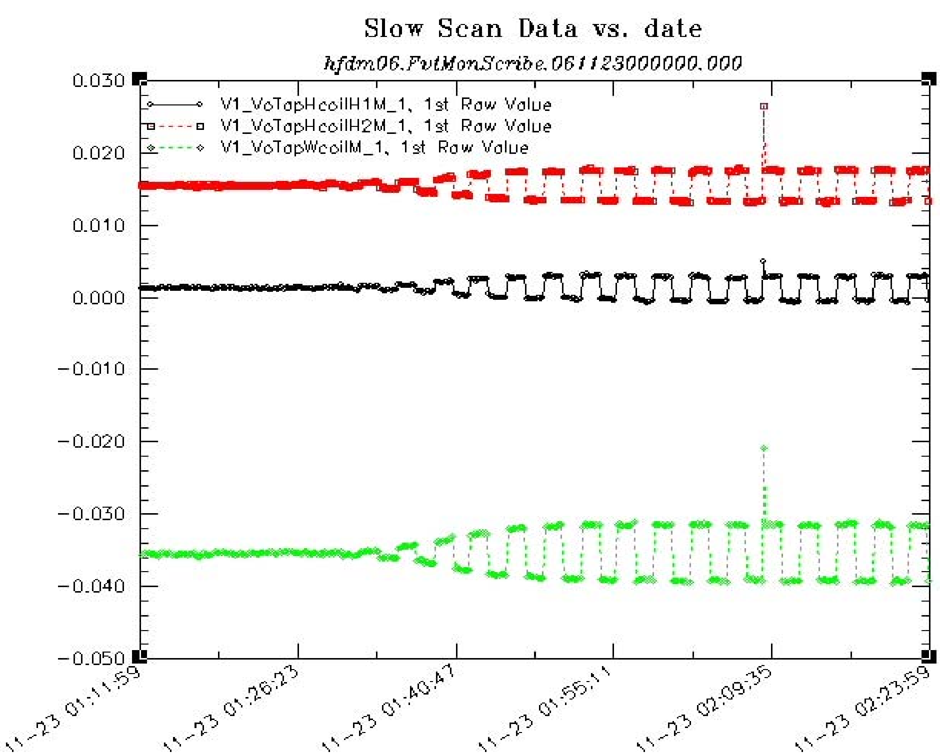

Figure 14. Transition temperature whole coil voltage and resistance values.

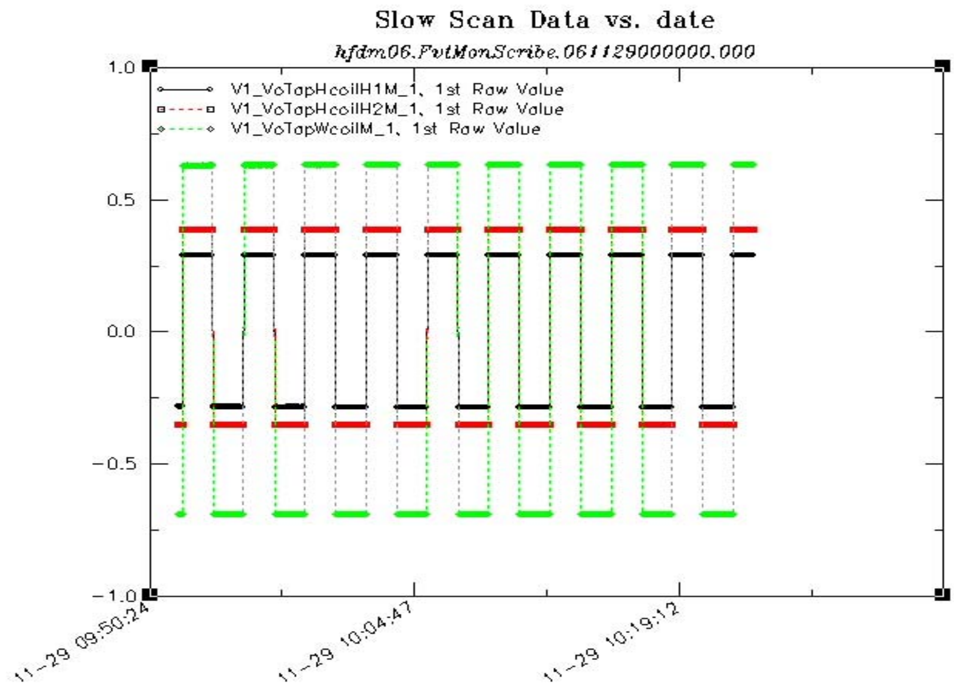

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Figure 15. Room temperature whole coil voltage and resistance values.