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LARP TQS02a Test Summary

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Content:

1. Introduction

TQS02a is a 1m long quadrupole model assembled at LBNL as part of the LARP program. TQS02a uses the same support structure of TQS01 with new coils (made of 54/61 RRP strand). This report documents the test of TQS02a performed at Fermilab in the Vertical Magnet Test Facility (VMTF) at 4.5 and 1.9 K. According to a request by LBNL a slow cool down (maintaining $\Delta T<50$ K across the magnet) was executed, starting on the early morning of June 2 to the end of the day on June 3, during which strain gauges and coil segment resistances were continuously monitored. Magnet test started on June 4 and lasted until June 21. The VSDS (Voltage Spike Detection System) was used during the whole test. A detailed analysis of the data recorded by the VSDS is presented in [1].

2. Quench History

The cold test program started at 4.5 K with cold magnetic measurement followed by magnet training at 20 A/s ramp rate. At the beginning of the training the quench detection threshold was set to 500 mV. A series of trips induced by voltage spikes (flux jumps) caused the increase of the detection threshold to 700 mV, then to 1.5 V and finally to 3 V. Subsequently the threshold was lowered to 2V (because of concerns about possible high MIITs), but had to be increased again to 3 V to avoid trips induced by flux jumps. The first quench occurred at 9902 A. During training at 4.5 K, with 3 V detection threshold, two trips induced by very high voltage spikes occurred at 1737 and 1949 A.

After a series of quenches (from #8 to #16) in coil 20, with quench current varying between 11.1 and 11.8 kA, the quench onset moved to coil 21. Quench #18 started in the so called "pizza box" (a G10 structure containing all coil-to-coil junctions, located on the top of the lead end) close to the splice between coil 20 and coil 21 NbTi leads. This quench occurred at 12.274 A, the highest current reached at 4.5K during the whole test. This quench developed 10 MIITs because of the high quench detection threshold, and the slow propagation. However it didn't cause any damage to the NbTi cables. At lower temperatures TQS02 reached two times higher currents without quenhes in the "pizza box". The following quenches showed a fallback (11.4 kA in quench #19), a quick recovery, and a plateau with an average of 12123 A and a slightly negative slop of -22 A/quench.

Subsequently ramp rate studies at 4.5 K were performed, and then the magnet was cooled down to 1.9 K. Tests with 20 A/s ramp rate at 1.9K (from #34 to #45) showed the quench current fluctuating in the range 11.25 kA – 11.95 kA with the exception of quench # 42 that reached 12.39 kA (this quench occurred after magnetic measurement at 1.9K performed after a partial magnet warm-up). All quenches at 1.9K started in coil 21. Quenches from #46 to #48 were performed during magnet warm-up. Ramp #47 started with 40 A/s up to 10 kA, and then 10 A/s. This ramp reached the highest quench current of the whole test (12,467 A). A final series of quenches at 4.5 K with 20 A/s ramp showed a plateau of 11930 A +/- 10A.

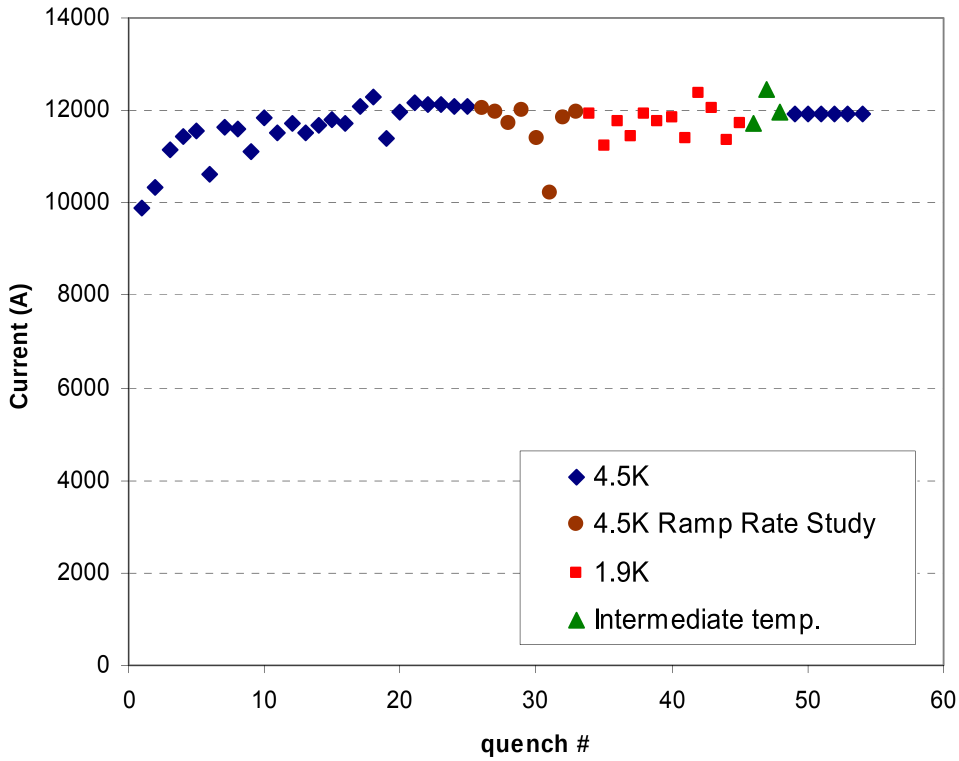


Figure 2.1. TQS02a quench history.

TQS02a Quench History table with comments

File	#	Current (A)	dI/dt (A/s)	t_{quench}	MIITs	Mag Temp Bot L (K)	Mag Temp Top L (K)	Comments
tqs02a.Quench.070604130438.013		1002	0	0.0017	0.17	4.424	4.421	darryl couldn't balance cu-i aqd, so the techs will have to look at this.
tqs02a.Quench.070604153926.160		1327	50	-0.4000	0.88	4.429	4.427	dqd_coil detected a signal - perhaps a spike-induced trip? we were ramping up at 50A/s to perform heater-induced quench.
tqs02a.Quench.070604155955.441		1727	20	-0.0027	0.30	4.426	4.422	20 A /s ramp to 5000A to perform heater-induced quench, with threshold raised to 1.5V. DQD coil detection.
tqs02a.Quench.070604162531.931		5003	20	-0.0238	2.55	4.427	4.425	HFU_1 fired at 300V to induce a quench and capture data at 5000A. We will check signals, which GV and JH conduct magnetic measurements. HFU_2 was in protection mode at 100V, HFU_3 spot heater was "offline" but should have fired from _2 contact closure, at 12V.
tqs02a.Quench.070605100858.753		1705	20	-0.0218	0.34	4.441	4.442	2V threshold appears to be unworkable... we tripped off on a voltage spike similar to yesterday's large spike at 1750A.
tqs02a.Quench.070605144544.801		8014	20	-0.0434	5.64	4.430	4.426	spot heaters in series at 9.6mF, 3.5Ohms resistance total hfu voltage 30V no dump delay; protection heaters at 400V, no p-heater delay
tqs02a.Quench.070605155126.832		8009	20	-0.0357	5.07	4.428	4.432	the first test at 30V induced a quench only in coil 23. So we raised the voltage to see if we could initiate quenches in all 4 coils.
tqs02a.Quench.070605162403.186		8006	20	-0.0365	5.12	4.432	4.433	raised the voltage from 50 to 70 V, fired spot heaters to induce quenches, hoping all coils will develop voltage.
tqs02a.Quench.070605183235.446		5004	20	-0.0325	2.24	4.433	4.430	repeated the heater-induced quench at 5000A, but with hfu_2 triggered at 400V; hfu_1 in protection mode at 400V; hfu_3 simultaneously triggered at 70V.
tqs02a.Quench.070605184714.684	1	9906	20	-0.0148	4.88	4.439	4.436	protection heaters at 400V, no delay dump 1ms delay spot heater fired at detection, 70V.
tqs02a.Quench.070606094913.966	2	10326	20	-0.0105	4.69	4.442	4.437	quenched at 10321A, ramp rate 20A/s, T=4.45K. HFU3 was off.
tqs02a.Quench.070606102106.918		1732	20	-0.0192	0.29	4.443	4.441	trip at 1700 A, ramp = 20 A/s, T = 4.5K

tqs02a.Quench.070606111444.461	3	11165	20	-0.0106	5.23	4.435	4.434	Ramp 4, rate 20 A/s, I = 11161 A, T = 4.5 K dump 3ms, PH 300V 7
tqs02a.Quench.070606115518.721	4	11441	20	-0.0085	5.07	4.436	4.436	ramp 5, I = 11440 A, rate = 20 A/s, T = 4.5 K
tqs02a.Quench.070606123347.247	5	11578	20	-0.0108	5.43	4.437	4.434	Ramp 6, I = 11575 A, ramp = 20 A/s, T = 4.5 K
tqs02a.Quench.070606140258.865	6	10634	20	-0.0155	5.55	4.430	4.427	VSDS system appears to be crashed, so we did not get spike data.
tqs02a.Quench.070606144702.183	7	11642	20	-0.0109	5.47	4.437	4.435	Ramp 8, I = 11637 A, rate = 20 A/s, T = 4.5 Kto
tqs02a.Quench.070606152746.043	8	11602	20	-0.0070	4.90	4.434	4.435	quench at 11599.2A, ramp rate 20A/s, T=4.45K. H□n□`□n□x
tqs02a.Quench.070606155359.065	9	11127	20	-0.0120	5.39	4.454	4.454	ramp 10, I = 11126 A, rate = 20 A/s, T = 4.5K
tqs02a.Quench.070606162133.230	10	11848	20	-0.0073	4.98	4.448	4.444	quench at 11845.6A ramp rate 20A/s T=4.45K
tqs02a.Quench.070606164135.111		1945	20	-0.0122	0.33	4.450	4.448	tripped at 1949A, ramp rate 20A/s. T=4.45K.
tqs02a.Quench.070606170223.671	11	11499	20	-0.0115	5.48	4.440	4.436	Ramp 13, I = 11495 A, rate = 20 A/s, T = 4.5K
tqs02a.Quench.070606173608.118	12	11706	20	-0.0053	4.66	4.446	4.445	Ramp 14, I = 11700 A, rate 20 A/s, T = 4.5K□ƒ÷
tqs02a.Quench.070606180247.881	13	11521	20	-0.0063	4.81	4.452	4.451	ramp 15, I = 11515, rate = 20 A/s, T = 4.5K
tqs02a.Quench.070606183249.640	14	11700	20	-0.0050	4.60	4.453	4.450	ramp 16, I = 11696 A, rate = 20 A/s, T = 4.5K
tqs02a.Quench.070606190519.154	15	11808	20	-0.0048	5.24	4.454	4.450	Ramp 17, I = 11802 A, rate = 20 A/s, T = 4.5K
tqs02a.Quench.070606193546.194	16	11712	20	-0.0046	5.20	4.457	4.455	Ramp 18, I = 11710 A, rate 20 A/s, T = 4.5 K
tqs02a.Quench.070607085819.744	17	12072	20	-0.0076	6.00	4.467	4.466	ramp 19, I = 12069 A, rate = 20 A/s, T = 4.5 K
tqs02a.Quench.070607093814.124	18	12274	20	-0.0339	10.07	4.452	4.455	ramp 20, I = 12269 A, rate = 20 A/s, T = 4.5K
tqs02a.Quench.070607104128.088	19	11380	20	-0.0098	4.92	4.432	4.433	ramp 21, I = 11378 A, rate = 20 A/s, T = 4.5K
tqs02a.Quench.070607112015.464	20	11974	20	-0.0109	6.38	4.439	4.434	Ramp 22, I = 11970 A, rate 20 A/s, T = 4.5K
tqs02a.Quench.070607114524.375	21	12165	20	-0.0050	5.6	4.472	4.465	Ramp 23, I = 12162 A, rate 20 A/s, T = 4.5K
tqs02a.Quench.070607121514.882	22	12153	20	-0.0052	5.61	4.459	4.457	ramp 24, I = 12146 A, rate = 20 A/s, T = 4.5K
tqs02a.Quench.070607135538.210	23	12139	20	-0.0055	5.7	4.320	4.383	cool down to 1.9K was aborted because Kinney pump developed a problem, but temperature is slightly cooler than it was earlier.
tqs02a.Quench.070607163339.026	24	12110	20	-0.0046	5.61	4.410	4.410	several gains were changed to prevent saturation, 21B04_12B05, 21B03_21B04, 21B05_21B06
tqs02a.Quench.070607172917.427	25	12074	20	-0.0050	5.88	4.421	4.421	quench at 12070.5A, ramp rate 20A/s, T=4.42K. Dump delay 18 msec (was 13 msec)
tqs02a.Quench.070608101421.572	26	12050	5	-0.0055	5.83	4.429	4.427	Ramp to 11kAmps at 20Amps/sec then ramp to quench at 5Amps/sece
tqs02a.Quench.070608110141.397	27	11964	40	-0.0070	6	4.438	4.437	Ramp to quench at 40A/sec
tqs02a.Quench.070608112453.473	28	11717	80	-0.0090	6.1	4.442	4.445	quench at 11714.4A, ramp rate was 80A/s, T=4.45K.
tqs02a.Quench.070608121122.767	29	12011	10	-0.0056	5.82	4.452	4.446	quench at I=12008A, ramp rate = 10A/s, T=4.45K.
tqs02a.Quench.070608140958.401	30	11407	100	-0.0028	4.78	4.426	4.423	ramped at 5A/s to 7500A, then 100A/s to quench (not realizing that 5A/s had already been done).
tqs02a.Quench.070609135925.713	31	10217	120	-0.0048	4.68	4.421	4.421	Ramp 33, I = 10217 A, rate = 120 A/s, T = 4.5 K
tqs02a.Quench.070609143013.717	32	11844	60	-0.0087	6.15	4.429	4.433	Ramp 34, I = 11839 A, Rate = 60 A/s, T = 4.5K

tqs02a.Quench.070611162130.884	33	11963	5	-0.0046	4.53	4.410	4.408	quench at 11956A, ramp rate was 20A/s upto 10kA and then 5A/s till the quench. HFU1/2 both were charged to 200V, delay 0ms. Dump delay 1ms.
tqs02a.Quench.070612140759.260	34	11937	20	-0.0057	4.83	1.853	1.853	heaters at 200V to keep noise low. ramp rate 20 A/s
tqs02a.Quench.070612152045.937	35	11252	20	-0.0084	4.93	1.881	1.882	quench current is rather low! appears to be AQD_COIL
tqs02a.Quench.070612172710.819	36	11777	20	-0.0063	4.83	1.815	1.813	spike system threshold at 150mV. This will be the last quench today, as the gas storage tank pressure is now 150 psi and we need to make liquid.
tqs02a.Quench.070618140753.334		1516	20	0.0003	0.16	1.818	1.819	We did a manual trip in order to check that everything is OK after the work done Friday/Monday.
tqs02a.Quench.070618143844.917	37	11446	20	-0.0070	4.85	1.820	1.820	quench at 11439A, T=1.82K, ramp rate 20A/s. HFU1/2=200V, 0ms delay, dump delay 1ms.
tqs02a.Quench.070618155056.289	38	11947	20	-0.0053	4.74	1.895	1.906	quench at I=11941A, T=1.9K, ramp rate 20A/s. Ç
tqs02a.Quench.070618171826.086	39	11757	20	-0.0057	4.77	1.900	1.901	quench at 11731A, T=1.91K, ramp rate 20A/s, many paramet. were tuned for VSDS (Conor knows details).
tqs02a.Quench.070618185329.392	40	11850	20	-0.0059	4.78	1.886	1.887	quench at 11844A, T=1.89K, ramp rate 20A/s.
tqs02a.Quench.070618204435.298	41	11417	20	-0.0122	5.48	1.866	1.867	quench at 11411A, T=1.9K, ramp rate 20A/s.
tqs02a.Quench.070619162136.084	42	12391	20	-0.0050	4.84	1.854	1.859	quench at 12383A, T=1.86K, ramp rate 20A/s.
tqs02a.Quench.070619173320.354	43	12051	20	-0.0053	4.75	1.931	1.932	quench at 12045A, T=1.94K, ramp rate 20A/s.
tqs02a.Quench.070619185157.071	44	11384	20	-0.0083	4.96	1.911	1.913	quench at 11374A, T=1.92K, ramp rate=20A/s.
tqs02a.Quench.070619202645.177	45	11751	20	-0.0070	4.92	1.891	1.891	Quench 45, I = 11741 A, ramp = 20 A/s, T = 1.9K, after sawtooth 0-10.5kA-0 3 times at 80 A/s
tqs02a.Quench.070619205921.684	46	11727	20	-0.0063	4.79	2.069	2.068	quench at 11716A, T=2.08K, ramp rate 20A/s.
tqs02a.Quench.070619212304.332	47	12467	10	-0.0045	4.67	2.173	2.180	quench at 12462.5A, T=2.17K, ramp rate 40A/s (upto 10kA) and then 10A/s.
tqs02a.Quench.070619220625.464	48	11966	20	-0.0069	4.9	2.949	3.077	quench at 11957A, T=2.95K, ramp rate 20A/s.
tqs02a.Quench.070620081502.510	49	11939	20	-0.0069	4.88	4.440	4.437	Quenching again at 4.5K. I_q=11932.8A, T=4.42K, ramp rate 20A/s.
tqs02a.Quench.070620085746.697	50	11941	20	-0.0066	4.77	4.445	4.441	quench at 11935.3A, T=4.44K, ramp rate 20 A/s.
tqs02a.Quench.070620094054.329	51	11940	20	-0.0069	4.81	4.441	4.437	quench at 11933.8A, T=4.44K, ramp rate 20A/s.
tqs02a.Quench.070620104514.523	52	11929	20	-0.0073	4.89	4.448	4.444	quench at 11924.5A, T=4.44K, ramp rate 20A/s
tqs02a.Quench.070620120733.533		1001	20	-0.6323	0.75	4.458	4.458	Manual trip at 1000A for Darryl's test.
tqs02a.Quench.070620122618.997	53	11921	20	-0.0067	4.78	4.451	4.452	quench at 11916.7A, T=4.45K, ramp rate 20A/s.
tqs02a.Quench.070620152411.289		1005	20	0.0021	0.13	4.456	4.453	manual trip at 1000A to test noise reduction.
tqs02a.Quench.070620171503.734		11410	20	-0.0024	3.83	4.522	4.536	Trip at 11400A, T=4.49K. HFU1 fired at 400V. HFU2 in protection mode.
tqs02a.Quench.070620182836.832		8006	20	-0.0130	3.48	4.447	4.505	manual trip at 8000A, T=4.46K, ramp rate 20A. HFU1 in test mode, HFU2 in protect. mode (400V for both).
tqs02a.Quench.070620190124.970		5007	20	-0.0372	2.32	4.440	4.460	PHeater study, I = 5000A HFU#1, 400V

tqs02a.Quench.070620193005.259		3007	20	-0.1187	1.64	4.435	4.448	PHeater study, I = 3000 A, HFU#1 400V
tqs02a.Quench.070620200206.825		11414	20	-0.0064	4.38	4.427	4.453	PHeater study, I = 11400A, HFU#1 300V
tqs02a.Quench.070621075902.153		8004	20	-0.0171	3.8	4.426	4.427	Heater study: HFU1/2 capacitor voltage=300V. Ramp to 8000A. HFU1 fired.
tqs02a.Quench.070621082344.072		5002	20	-0.0441	2.48	4.423	4.418	Heater studies: ramp to 5000A. HfU1 fired (300V), HFU2 (400V) in protection mode.
tqs02a.Quench.070621084451.523		3004	20	-0.1334	1.77	4.432	4.444	Heater studies: ramp to 3000A, HFU1 (300V) fired, HFU2 (400V) in a protection mode. T=4.43K. Ramp rate 20A/s.
tqs02a.Quench.070621093553.536		10009	20	-0.0193	5.31	4.416	4.413	Spot heater study: trip induced by spot heater. HFU1/2 (200V) in protection mode, all delays 0ms. HFU3 - 40V.
tqs02a.Quench.070621100130.437		8008	20	-0.0507	5.98	4.430	4.426	Spot heater study: ramp to 8000A (w ramp rate 20A/s). HFU1/2 (200V) in protection mode, HFU3 (50V) in testing mode. T=4.43K.
tqs02a.Quench.070621102520.937	54	11930	20	-0.0083	4.87	4.425	4.424	Ramp 68 - quench 54 I = 11927 A, 20 A/s, T = 4.45K

TQS02a Quench History table with first quenching segments

File	#	Current (A)	dI/dt (A/s)	t_{quench}	QDC	1st VTseg	t_{rise}	2nd VTseg	t_{rise}	Mag Temp		VSDS run
										Bot	Top	
tqs02a.Quench.070604130438.013		1002	0	0.0017	WcoilGnd	V1_TrigCvtB1	-0.0003	23A05_23A06	0.0022	4.424	4.421	
tqs02a.Quench.070604153926.160		1327	50	-0.4000	HcoilHcoil	22A08_22A09	-0.0245	20B05_20B06	-0.0055	4.429	4.427	
tqs02a.Quench.070604155955.441		1727	20	-0.0027	HcoilHcoil	21A06_21A05	-0.0046	21A08_21A07	-0.0046	4.426	4.422	
tqs02a.Quench.070604162531.931		5003	20	-0.0238	HcoilHcoil	21B01_21B02	-0.0207	21B03_21B04	-0.0206	4.427	4.425	
tqs02a.Quench.070605100858.753		1705	20	-0.0218	HcoilHcoil	22B04_22B03	-0.0213	22A02_22A03	-0.0210	4.441	4.442	
tqs02a.Quench.070605144544.801		8014	20	-0.0434	HcoilHcoil	23A09_23A10	-0.0448	23A07_23A08	-0.0402	4.430	4.426	
tqs02a.Quench.070605155126.832		8009	20	-0.0357	HcoilHcoil	23A09_23A10	-0.0382	23A07_23A08	-0.0339	4.428	4.432	
tqs02a.Quench.070605162403.186		8006	20	-0.0365	HcoilHcoil	23A09_23A10	-0.0382	23A07_23A08	-0.0336	4.432	4.433	
tqs02a.Quench.070605183235.446		5004	20	-0.0325	WcoilGnd	23A05_23A06	-0.0315	HP_HN	-0.0291	4.433	4.430	
tqs02a.Quench.070605184714.684	1	9906	20	-0.0148	HcoilHcoil	21A08_21A07	-0.0160	21A06_21A05	-0.0139	4.439	4.436	1

tqs02a.Quench.070606094913.966	2	10326	20	-0.0105	HcoilHcoil	21B05_21B06	-0.0095	21B01_21B02	-0.0091	4.442	4.437	2
tqs02a.Quench.070606102106.918		1732	20	-0.0192	HcoilHcoil	22B04_22B03	-0.0098	22A02_22A03	-0.0097	4.443	4.441	3
tqs02a.Quench.070606111444.461	3	11165	20	-0.0106	HcoilHcoil	20B01_20B02	-0.0106	Q24P_Q24N	-0.0106	4.435	4.434	4
tqs02a.Quench.070606115518.721	4	11441	20	-0.0085	HcoilHcoil	20A10_20A09	-0.0091	20A08_20A07	-0.0077	4.436	4.436	5
tqs02a.Quench.070606123347.247	5	11578	20	-0.0108	HcoilHcoil	21B03_21B04	-0.0105	21B01_21B02	-0.0098	4.437	4.434	6
tqs02a.Quench.070606140258.865	6	10634	20	-0.0155	HcoilHcoil	21B03_21B04	-0.0171	21B01_21B02	-0.0132	4.430	4.427	
tqs02a.Quench.070606144702.183	7	11642	20	-0.0109	HcoilHcoil	22A08_22A09	-0.0119	22A06_22A07	-0.0113	4.437	4.435	8
tqs02a.Quench.070606152746.043	8	11602	20	-0.0070	HcoilHcoil	20A08_20A07	-0.0081	Q24P_Q24N	-0.0063	4.434	4.435	9
tqs02a.Quench.070606155359.065	9	11127	20	-0.0120	HcoilHcoil	20A08_20A07	-0.0127	20A10_20A09	-0.0105	4.454	4.454	10
tqs02a.Quench.070606162133.230	10	11848	20	-0.0073	HcoilHcoil	20A08_20A07	-0.0081	Q24P_Q24N	-0.0053	4.448	4.444	11
tqs02a.Quench.070606164135.111		1945	20	-0.0122	HcoilHcoil	20A08_20A07	-0.0122	20A10_20A09	-0.0122	4.450	4.448	12
tqs02a.Quench.070606170223.671	11	11499	20	-0.0115	HcoilHcoil	20A08_20A07	-0.0102	Q24P_Q24N	-0.0071	4.440	4.436	13
tqs02a.Quench.070606173608.118	12	11706	20	-0.0053	HcoilHcoil	20A08_20A07	-0.0053	20A06_20A05	-0.0048	4.446	4.445	
tqs02a.Quench.070606180247.881	13	11521	20	-0.0063	HcoilHcoil	20A08_20A07	-0.0077	20A06_20A05	-0.0073	4.452	4.451	15
tqs02a.Quench.070606183249.640	14	11700	20	-0.0050	HcoilHcoil	20A08_20A07	-0.0052	20A06_20A05	-0.0046	4.453	4.450	16
tqs02a.Quench.070606190519.154	15	11808	20	-0.0048	HcoilHcoil	20A08_20A07	-0.0048	20A06_20A05	-0.0042	4.454	4.450	17
tqs02a.Quench.070606193546.194	16	11712	20	-0.0046	HcoilHcoil	20A08_20A07	-0.0050	20A06_20A05	-0.0045	4.457	4.455	18
tqs02a.Quench.070607085819.744	17	12072	20	-0.0076	HcoilHcoil	21B03_21B04	-0.0073	21B01_21B02	-0.0071	4.467	4.466	19
tqs02a.Quench.070607093814.124	18	12274	20	-0.0339	HcoilHcoil	20A02_20A01	-0.0309	21A01_22A01	-0.0115	4.452	4.455	
tqs02a.Quench.070607104128.088	19	11380	20	-0.0098	HcoilHcoil	21B03_21B04	-0.0111	21B01_21B02	-0.0087	4.432	4.433	21
tqs02a.Quench.070607112015.464	20	11974	20	-0.0109	HcoilHcoil	21B03_21B04	-0.0085	21B01_21B02	-0.0074	4.439	4.434	22
tqs02a.Quench.070607114524.375	21	12165	20	-0.0050	HcoilHcoil	21B03_21B04	-0.0055	21B01_21B02	-0.0043	4.472	4.465	23
tqs02a.Quench.070607121514.882	22	12153	20	-0.0052	HcoilHcoil	21B03_21B04	-0.0056	21B01_21B02	-0.0046	4.459	4.457	24
tqs02a.Quench.070607135538.210	23	12139	20	-0.0055	HcoilHcoil	21B03_21B04	-0.0059	21B01_21B02	-0.0052	4.320	4.383	25
tqs02a.Quench.070607163339.026	24	12110	20	-0.0046	HcoilHcoil	21B03_21B04	-0.0049	21B01_21B02	-0.0041	4.410	4.410	26
tqs02a.Quench.070607172917.427	25	12074	20	-0.0050	HcoilHcoil	21B03_21B04	-0.0053	21A01_22A01	-0.0043	4.421	4.421	27
tqs02a.Quench.070608101421.572	26	12050	5	-0.0055	HcoilHcoil	21B03_21B04	-0.0056	21B01_21B02	-0.0052	4.429	4.427	
tqs02a.Quench.070608110141.397	27	11964	40	-0.0070	HcoilHcoil	21B03_21B04	-0.0077	21A04_21A03	-0.0069	4.438	4.437	29
tqs02a.Quench.070608112453.473	28	11717	80	-0.0090	HcoilHcoil	21B03_21B04	-0.0094	21A04_21A03	-0.0080	4.442	4.445	30
tqs02a.Quench.070608121122.767	29	12011	10	-0.0056	HcoilHcoil	21B03_21B04	-0.0055	21B01_21B02	-0.0045	4.452	4.446	31
tqs02a.Quench.070608140958.401	30	11407	100	-0.0028	HcoilHcoil	21B01_21B02	-0.0032	23A07_23A08	-0.0032	4.426	4.423	32
tqs02a.Quench.070609135925.713	31	10217	120	-0.0048	HcoilHcoil	21A01_22A01	-0.0043	23A07_23A08	-0.0034	4.421	4.421	33
tqs02a.Quench.070609143013.717	32	11844	60	-0.0087	HcoilHcoil	21B03_21B04	-0.0095	21A04_21A03	-0.0084	4.429	4.433	
tqs02a.Quench.070611162130.884	33	11963	5	-0.0046	HcoilHcoil	21B03_21B04	-0.0049	21B01_21B02	-0.0046	4.410	4.408	35
tqs02a.Quench.070612140759.260	34	11937	20	-0.0057	HcoilHcoil	21B03_21B04	-0.0064	21B01_21B02	-0.0048	1.853	1.853	36
tqs02a.Quench.070612152045.937	35	11252	20	-0.0084	HcoilHcoil	21B03_21B04	-0.0092	21B01_21B02	-0.0069	1.881	1.882	37

tqs02a.Quench.070612172710.819	36	11777	20	-0.0063	HcoilHcoil	21B03_21B04	-0.0073	21B01_21B02	-0.0056	1.815	1.813	38
tqs02a.Quench.070618140753.334		1516	20	0.0003	WcoilGnd	V1_TrigCvtB1	-0.0003	20A02_20A01	0.0004	1.818	1.819	
tqs02a.Quench.070618143844.917	37	11446	20	-0.0070	HcoilHcoil	21B03_21B04	-0.0080	21B01_21B02	-0.0053	1.820	1.820	39
tqs02a.Quench.070618155056.289	38	11947	20	-0.0053	HcoilHcoil	21B03_21B04	-0.0062	21B01_21B02	-0.0043	1.895	1.906	40
tqs02a.Quench.070618171826.086	39	11757	20	-0.0057	HcoilHcoil	21B03_21B04	-0.0066	21B01_21B02	-0.0045	1.900	1.901	41
tqs02a.Quench.070618185329.392	40	11850	20	-0.0059	HcoilHcoil	21B03_21B04	-0.0069	21B01_21B02	-0.0049	1.886	1.887	42
tqs02a.Quench.070618204435.298	41	11417	20	-0.0122	HcoilHcoil	21B03_21B04	-0.0091	21B01_21B02	-0.0077	1.866	1.867	43
tqs02a.Quench.070619162136.084	42	12391	20	-0.0050	HcoilHcoil	21B03_21B04	-0.0056	21B01_21B02	-0.0046	1.854	1.859	44
tqs02a.Quench.070619173320.354	43	12051	20	-0.0053	HcoilHcoil	21B03_21B04	-0.0060	21B01_21B02	-0.0043	1.931	1.932	45
tqs02a.Quench.070619185157.071	44	11384	20	-0.0083	HcoilHcoil	21B03_21B04	-0.0092	21B01_21B02	-0.0066	1.911	1.913	46
tqs02a.Quench.070619202645.177	45	11751	20	-0.0070	HcoilHcoil	21B03_21B04	-0.0078	21B01_21B02	-0.0056	1.891	1.891	48
tqs02a.Quench.070619205921.684	46	11727	20	-0.0063	HcoilHcoil	21B03_21B04	-0.0070	21B01_21B02	-0.0055	2.069	2.068	49
tqs02a.Quench.070619212304.332	47	12467	10	-0.0045	HcoilHcoil	20A08_20A07	-0.0074	20A06_20A05	-0.0073	2.173	2.180	50
tqs02a.Quench.070619220625.464	48	11966	20	-0.0069	HcoilHcoil	20A08_20A07	-0.0071	20A06_20A05	-0.0066	2.949	3.077	51
tqs02a.Quench.070620081502.510	49	11939	20	-0.0069	HcoilHcoil	21B03_21B04	-0.0073	21B01_21B02	-0.0066	4.440	4.437	52
tqs02a.Quench.070620085746.697	50	11941	20	-0.0066	HcoilHcoil	21B03_21B04	-0.0073	21B01_21B02	-0.0056	4.445	4.441	53
tqs02a.Quench.070620094054.329	51	11940	20	-0.0069	HcoilHcoil	21B03_21B04	-0.0074	21B01_21B02	-0.0056	4.441	4.437	54
tqs02a.Quench.070620104514.523	52	11929	20	-0.0073	HcoilHcoil	21B03_21B04	-0.0077	21B01_21B02	-0.0074	4.448	4.444	55
tqs02a.Quench.070620120733.533		1001	20	-0.6323	HcoilHcoil	V1_TrigCvtB1	-0.0034	21A08_21A07	-0.0020	4.458	4.458	56
tqs02a.Quench.070620122618.997	53	11921	20	-0.0067	HcoilHcoil	21B03_21B04	-0.0073	21B01_21B02	-0.0059	4.451	4.452	57
tqs02a.Quench.070620152411.289		1005	20	0.0021	WcoilGnd	V1_TrigCvtB1	-0.0003	23A05_23A06	0.0010	4.456	4.453	
tqs02a.Quench.070620171503.734		11410	20	-0.0024	HcoilHcoil	21A10_21A09	-0.0036	22B02_22B01	-0.0024	4.522	4.536	58
tqs02a.Quench.070620182836.832		8006	20	-0.0130	HcoilHcoil	21A08_21A07	-0.0112	20A08_20A07	-0.0111	4.447	4.505	59
tqs02a.Quench.070620190124.970		5007	20	-0.0372	HcoilHcoil	20A06_20A05	-0.0393	23B03_23B02	-0.0385	4.440	4.460	60
tqs02a.Quench.070620193005.259		3007	20	-0.1187	HcoilHcoil	20A06_20A05	-0.1179	20A08_20A07	-0.1179	4.435	4.448	61
tqs02a.Quench.070620200206.825		11414	20	-0.0064	HcoilHcoil	20B03_20B04	-0.0031	20B01_20B02	-0.0029	4.427	4.453	62
tqs02a.Quench.070621075902.153		8004	20	-0.0171	HcoilHcoil	20A06_20A05	-0.0150	20A08_20A07	-0.0150	4.426	4.427	63
tqs02a.Quench.070621082344.072		5002	20	-0.0441	HcoilHcoil	21A06_21A05	-0.0435	23B03_23B02	-0.0428	4.423	4.418	64
tqs02a.Quench.070621084451.523		3004	20	-0.1334	HcoilHcoil	22A02_22A03	-0.1260	23B03_23B02	-0.1259	4.432	4.444	65
tqs02a.Quench.070621093553.536		10009	20	-0.0193	HcoilHcoil	23A09_23A10	-0.0195	23A07_23A08	-0.0169	4.416	4.413	66
tqs02a.Quench.070621100130.437		8008	20	-0.0507	HcoilHcoil	23A09_23A10	-0.0463	23A07_23A08	-0.0417	4.430	4.426	67
tqs02a.Quench.070621102520.937	54	11930	20	-0.0083	HcoilHcoil	21B03_21B04	-0.0084	21B01_21B02	-0.0074	4.425	4.424	68

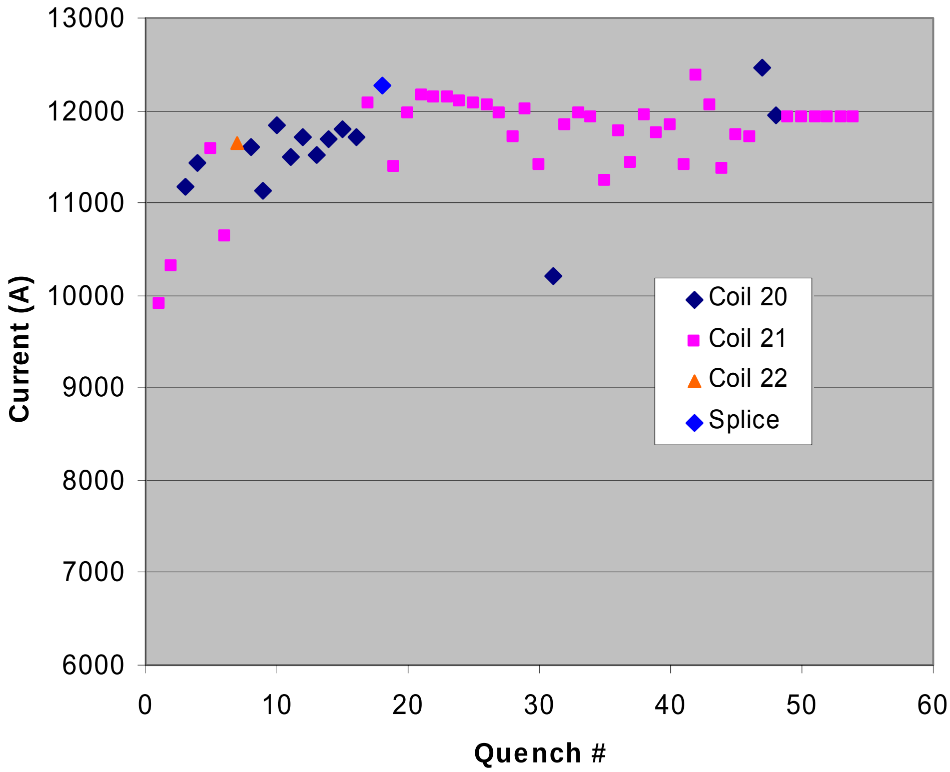


Figure 2.2. Quench history during training at 4.5K, at 1.9K, and during temperature dependence study. The marker of each quench shows the coil where it started.

3. Quenches at temperature between 1.9 and 4.5K

Three quenches (#46 to #48) were performed during magnet warm up from 1.9K to 4.5K. It should be noted that the magnet temperature was not very uniform when these quenches were performed. Quenches 47 and 48 occurred in coil 20. Ramp 47 started at 40 A/s up to10000 A and continued up to quench at 10 A/s. The quench current (12467 A) was the highest ever reached over the whole test.

4. Ramp Rate Dependence

Ramp rate dependence studies at 4.5K were performed on June 8th and 9th. Current ramp rate was varied from 5A/s to 120A/s. Results are shown in Figure A. Quench current decreases with increasing ramp rate. There were two ramps done at 5A/s rate, at the beginning and at the end of ramp rate study. During this study we did not reproduce the highest quench current (12270A) previously reached with regular ramp rate (20A/s) at 4.5K.

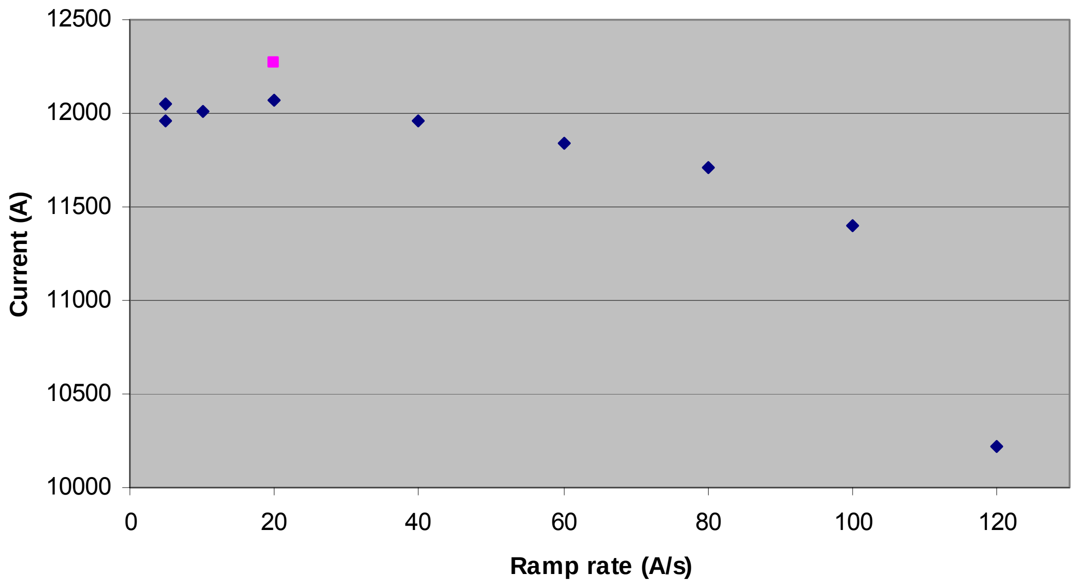


Fig.4.1. Ramp rate dependence of magnet quench current at 4.5K. The highest quench current previously reached at 4.5K is also shown (square marker).

5. Protection Heater studies

Protection heater studies were performed at 4.5K after the magnet training was completed at 1.9K temperature. In the TQS02a magnet 2 strip heaters, connected in series, were mounted on the outer layer of each coil (each heater covered one side of the outer layer). Two Heater Firing Units (HFU) were configured for 4.8mF capacitance, each connected to two coil strip heaters in parallel. One HFU was manually fired with the magnet at a constant current to initiate a quench, while second HFU was discharged as a protection heater by the system when the quench was detected. HFUs delay was set to 0ms. HFU1 in a test mode was connected to the strip heaters on coils 20 and 21. Heater studies were performed at 300V and 400V HFU capacitor voltages. Protection heater delays are shown in Figures 5.1 and 5.2. Full markers show the delay to quench start (= |firing time – quench onset time|). Open markers show the delay to quench detection (= |firing time|). The delay to quench detection depends on the detection threshold (3 V).

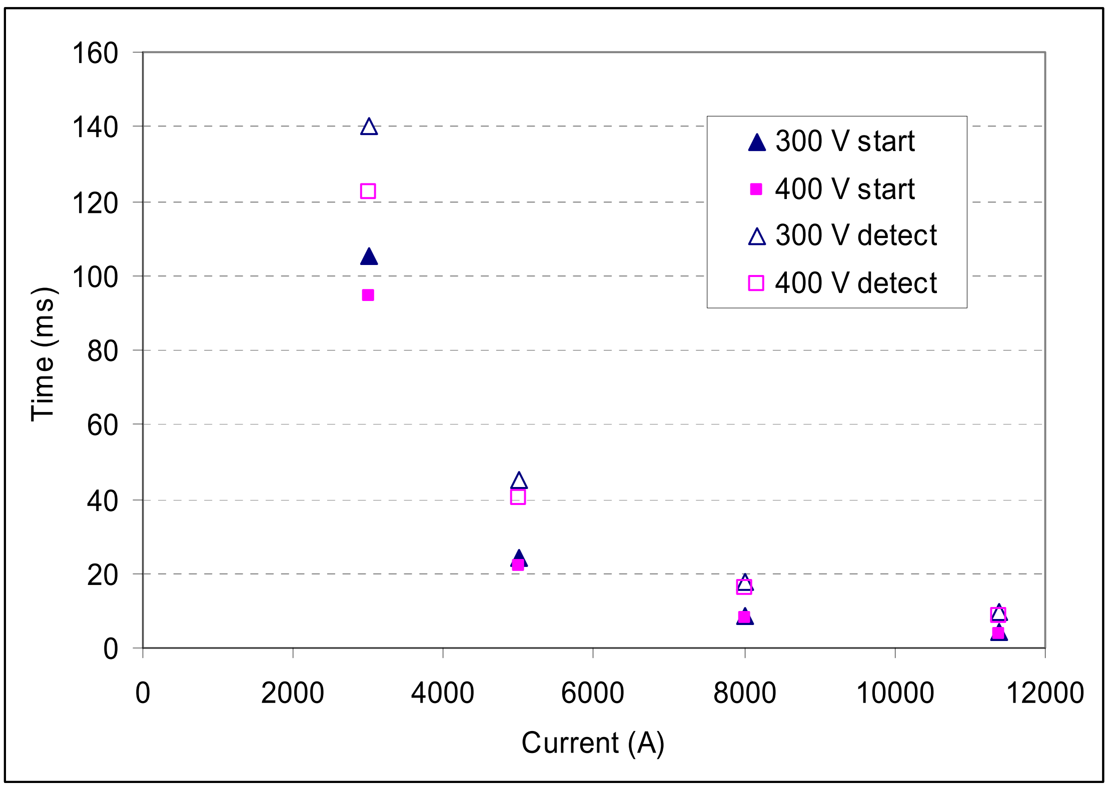


Fig.5.1. Protection heater delay at different current and different HFU capacitor voltage. Full markers show the delay to quench start; open markers show the delay to quench detection (affected by the high threshold)

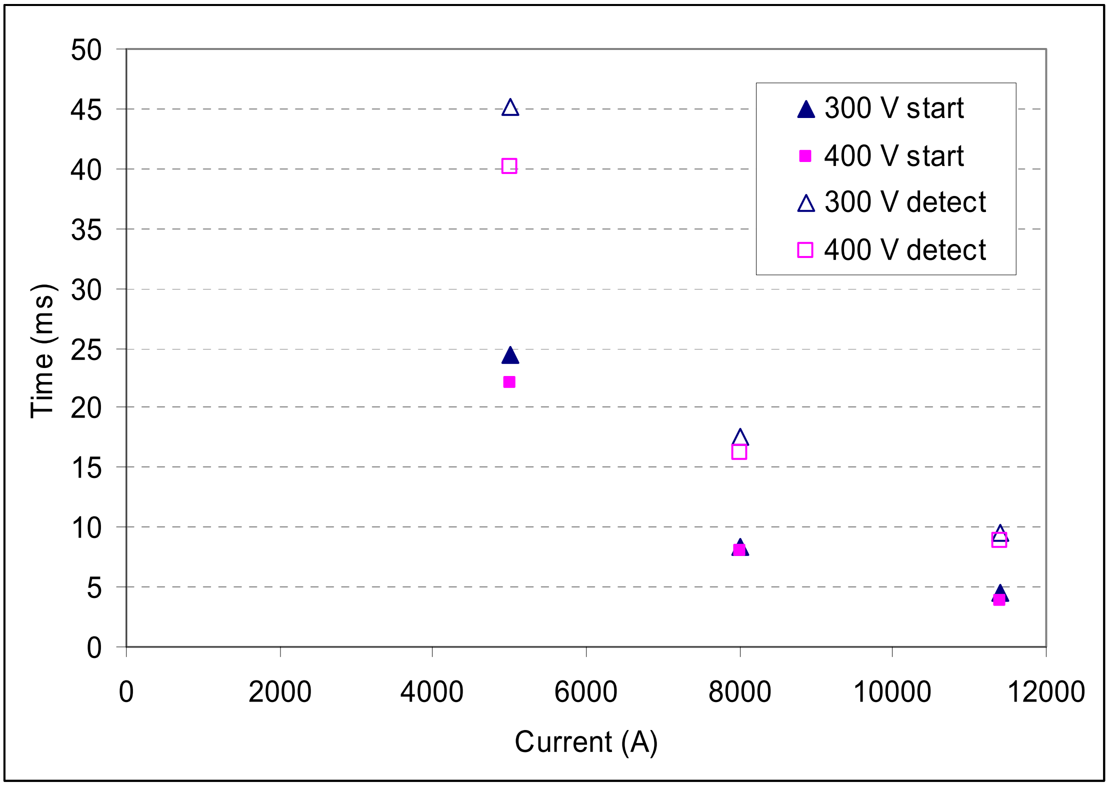


Fig.5.2. Detail of previous picture showing delays at high current.

6. Spot Heater study

Spot heater was mounted on the internal layer of each coil. Initial test of the Heater Firing Units, when we tried to fire all spot heaters together with the protection strip heater, and later the spot heater studies confirmed that spot heater induced quenches were observed only in two out of four coils: 23 and 21.

Spot heater study was done at 4.5K temperature. HFU1 and HFU2 connected to the strip heaters were set in a protection mode with 200V capacitor voltage and 0ms delay. HFU3 was connected to all spot heaters in parallel. Spot heaters were manually fired at 10000A and 8000A magnet current (spot heater capacitor voltage was 40V and 50V respectively). Detection delay time (= |quench onset time|) was measured as 19.6ms at 10000A and 46.5ms at 8000A. MIITs were 5.3 at 10000A, and 6.0 at 8000A. In both cases first quenching segment was observed in coil 23.

7. Strain gauge results

Coils 20,21,22,23 were used in TQS02a, having for the first time Titanium islands instead of Bronze. Similar to previous coils each coil had 3 strain gauges,: two gauges were attached to the inner layer island at the magnet center measuring azimuthal and axial strain and a single axial gauge was placed near the lead end. The gauges where thermally compensated by gauges mounted on stress-free titanium element. Fully compensated strain gauges were used on the shell and the axial tie rods. Measured strain "ε" in two principal directions "z, θ" (and no shear) were converted into stress "σ" using the relationships below with the Modulus, and Poisson ratio for titanium (islands) and aluminum (shell):

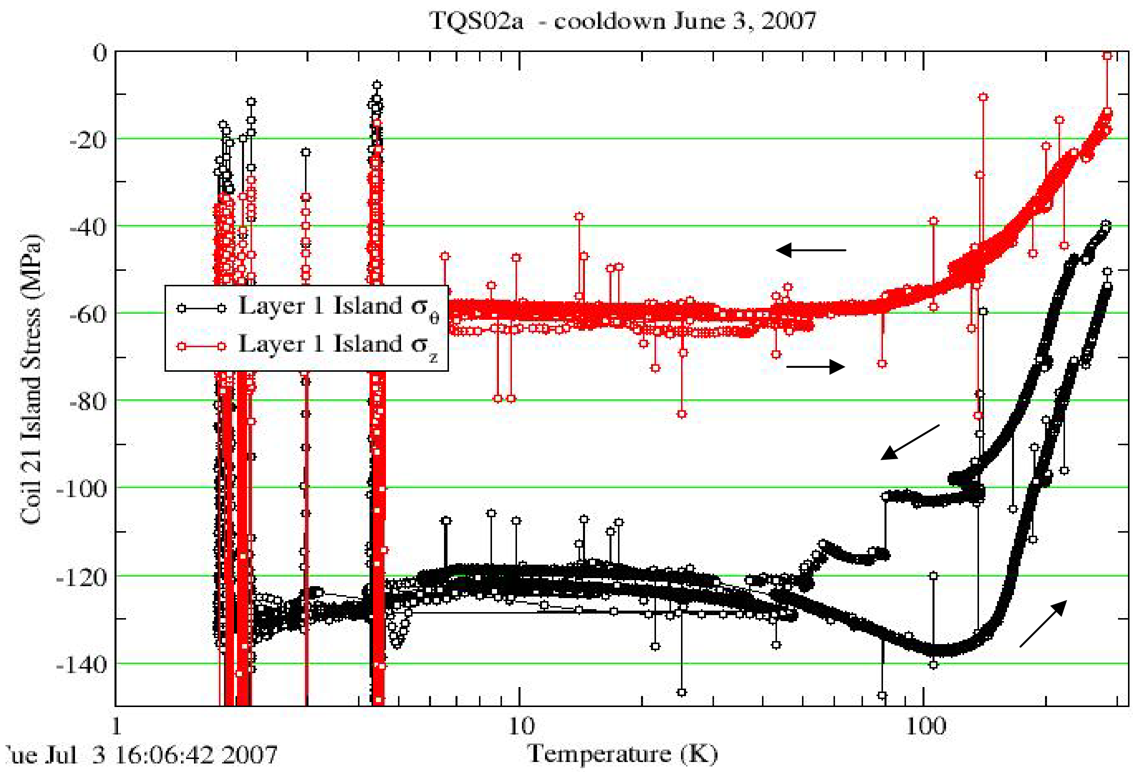
$$\sigma_\theta = \frac{E}{(1-\nu^2)}(\varepsilon_\theta + \nu\varepsilon_z) \quad \sigma_z = \frac{E}{(1-\nu^2)}(\varepsilon_z + \nu\varepsilon_\theta).$$

A comparison of stress in the structure and coils between TQS01,b,c and TQS02a is shown in the table below.

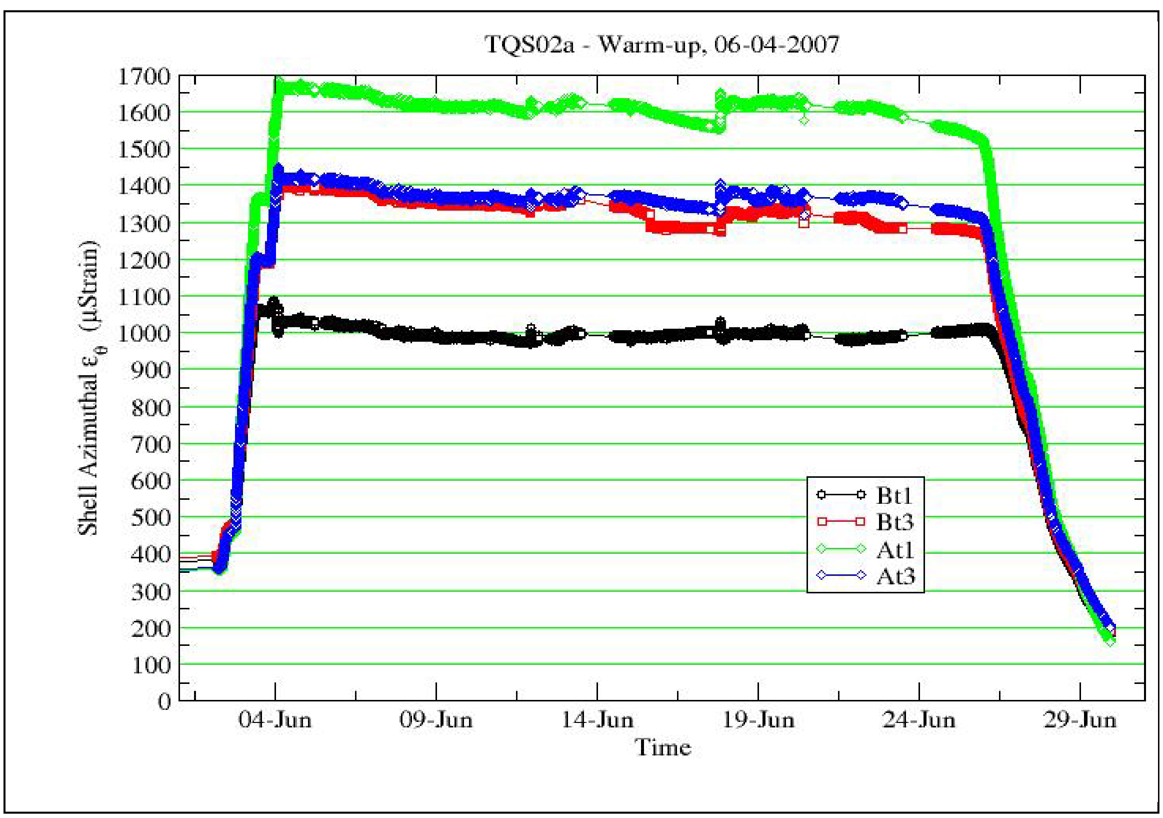
	TQS01	**TQS01b**	**TQS01c**	**TQS02a**
Maximum current (A)	10602 (4.4K) 11019 (3.2K)	9932 (4.4K)	9570 (4.4K) 10521(1.9K) 9989 (4.4K)	12269 (4.4K) 12463 (1.9K) 11935 (4.4K)
Iss (%)	87% (4.4K)	82% (4.4K)	80-82% (4.4K) 80% (1.9K)	
Shell cold (MPa) - t	+152	+158	+142	+158
Shell cold (MPa) - z	+143	+140	+137	+140
Rods cold (MPa) - z	+113	+116	+148	+118
Island cold (MPa) -t	-198	-202	-162	-142
Island cold (MPa) -z	+34	+34	+39	-87

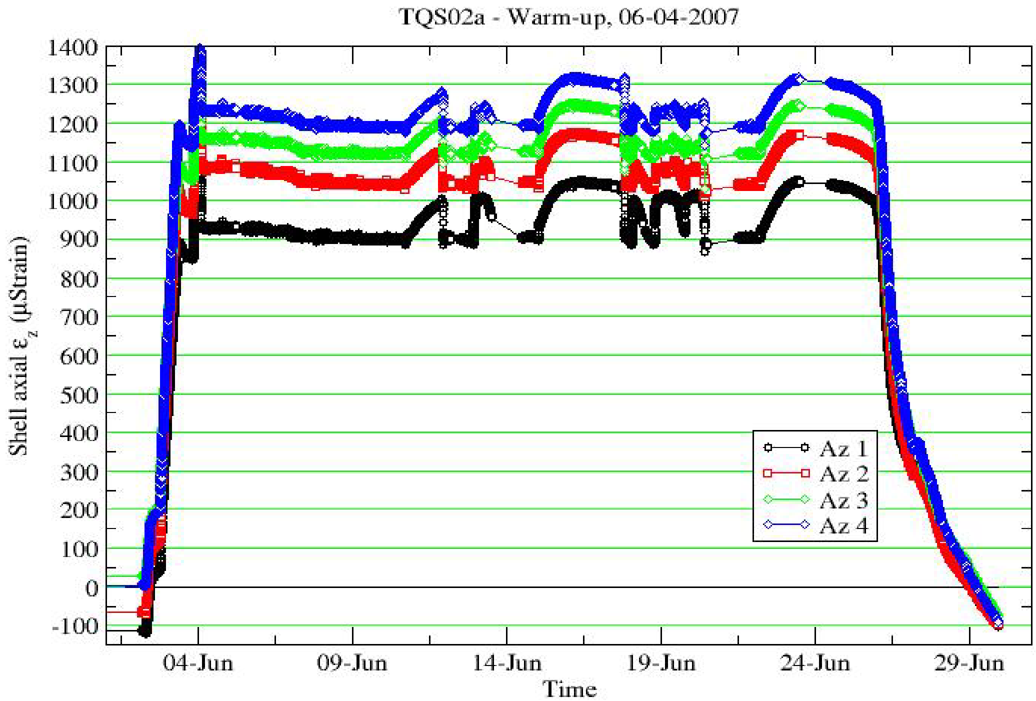
Many more plot files can be found at:
http://supercon.lbl.gov/caspi/download/TQS02a/

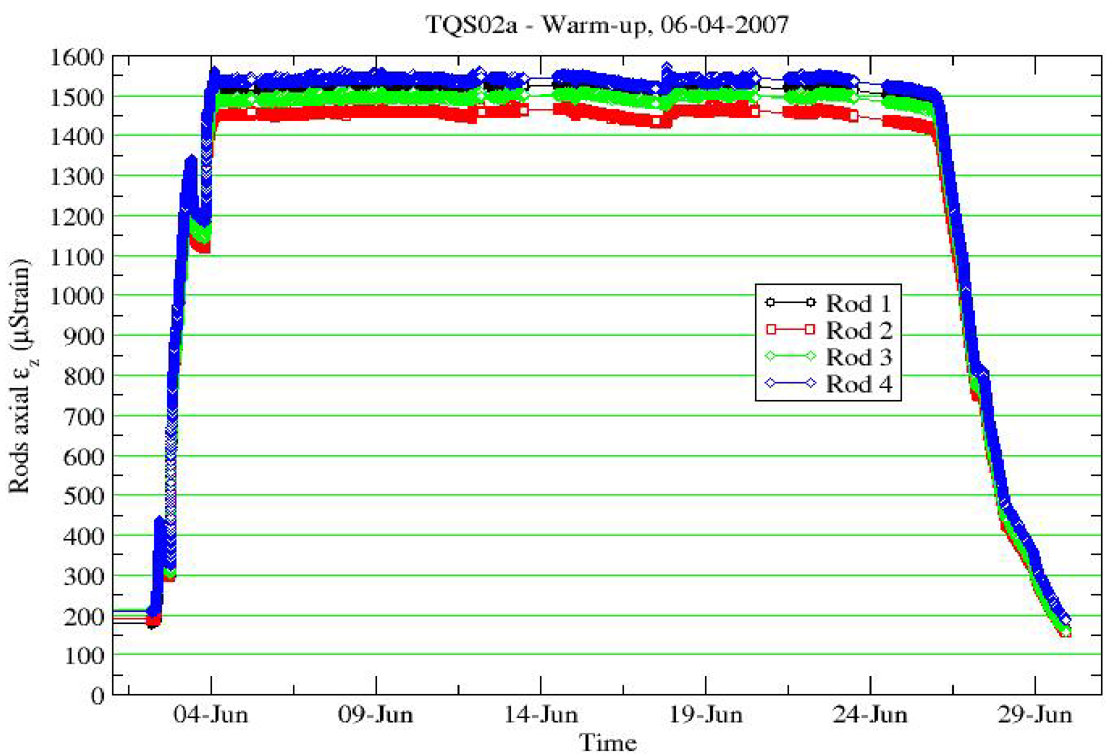
The measured strain or stress during the entire test is shown in the following figures:

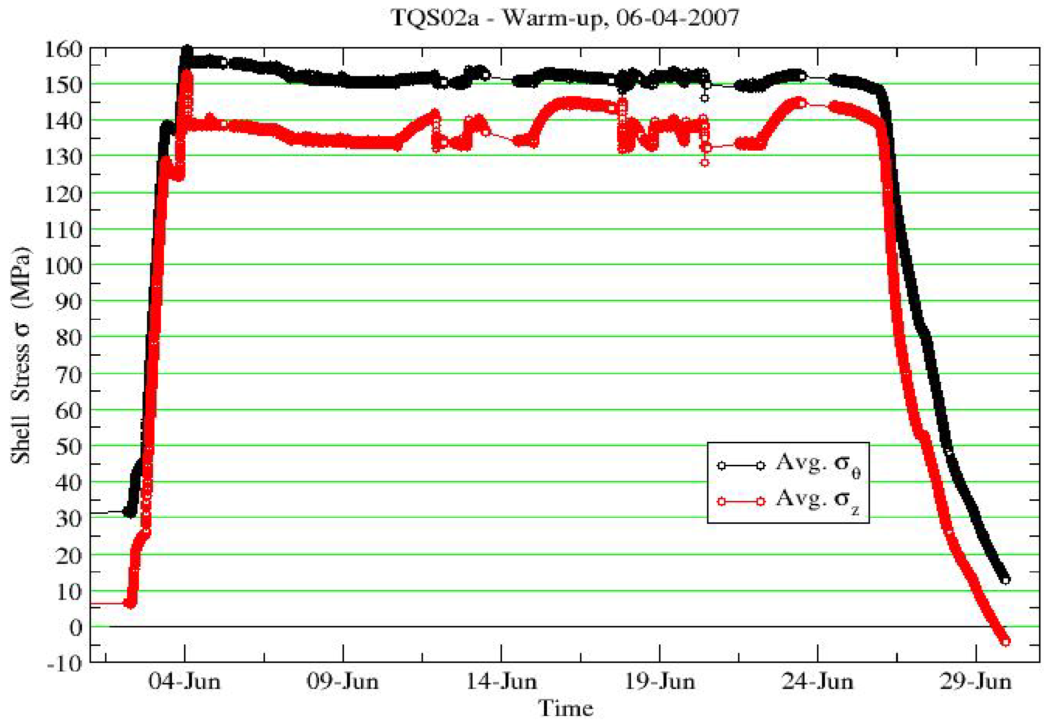


A typical measured stress of coil 21 during cool-down and warm-up is shown above. Coils 20,22, and 23 have shown similar behavior.

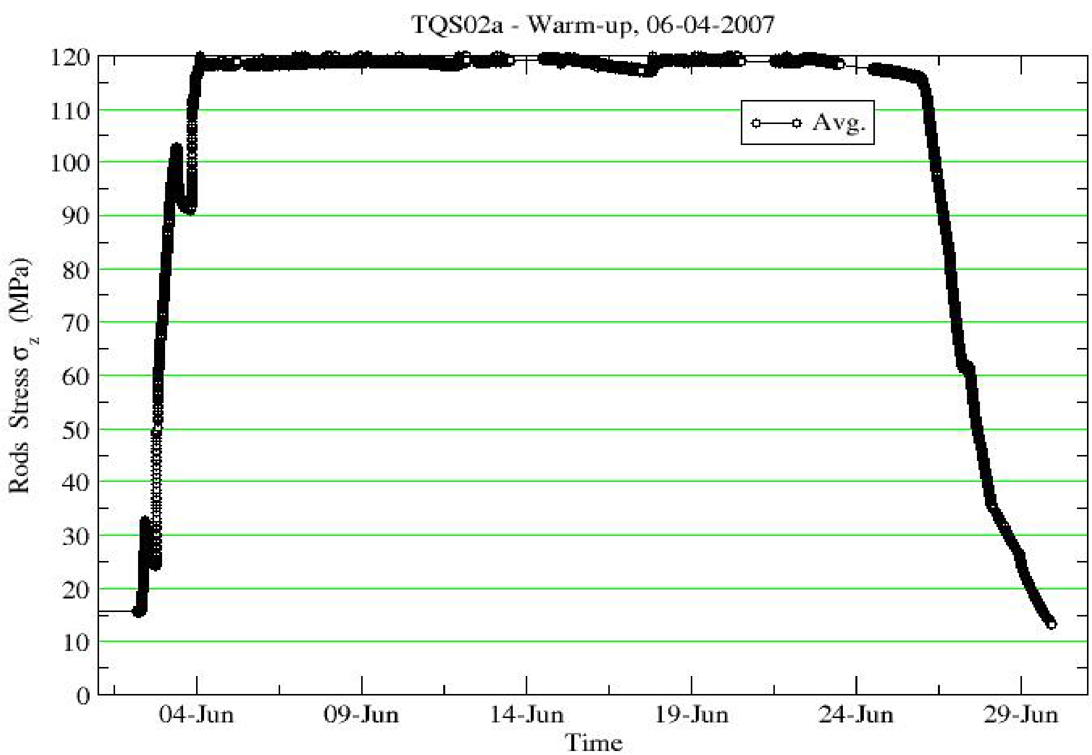



TQS02a - Warm-up, 06-04-2007
Shell axial ε_z (µStrain)
Time
Az 1
Az 2
Az 3
Az 4
04-Jun
09-Jun
14-Jun
19-Jun
24-Jun
29-Jun

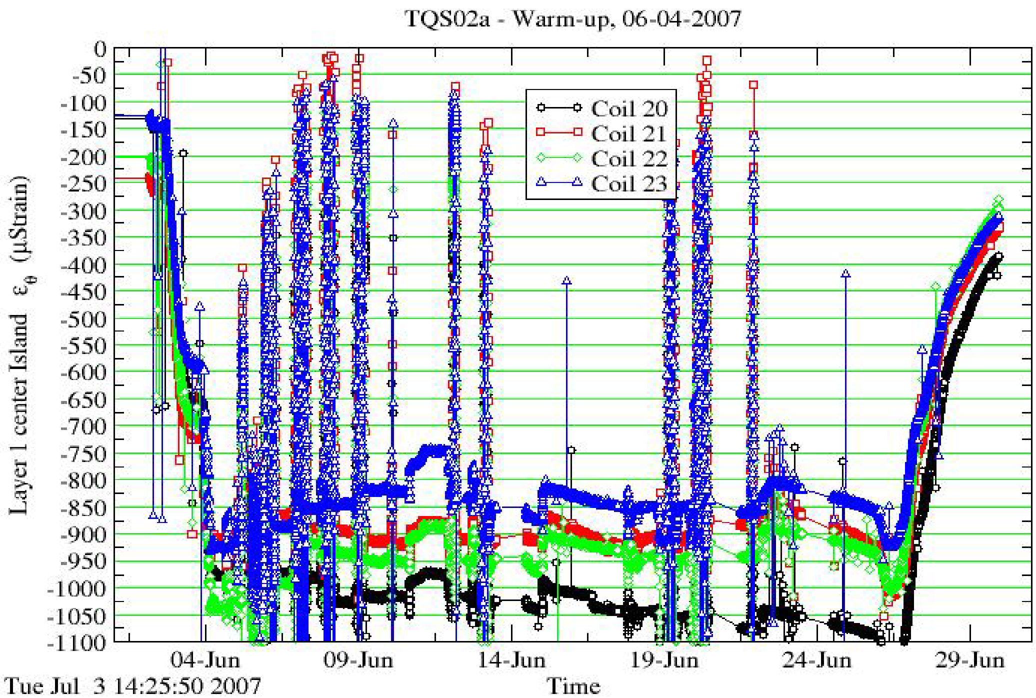

TQS02a - Warm-up, 06-04-2007
Rods axial ε_z (µStrain)
Time
Rod 1
Rod 2
Rod 3
Rod 4
04-Jun
09-Jun
14-Jun
19-Jun
24-Jun
29-Jun

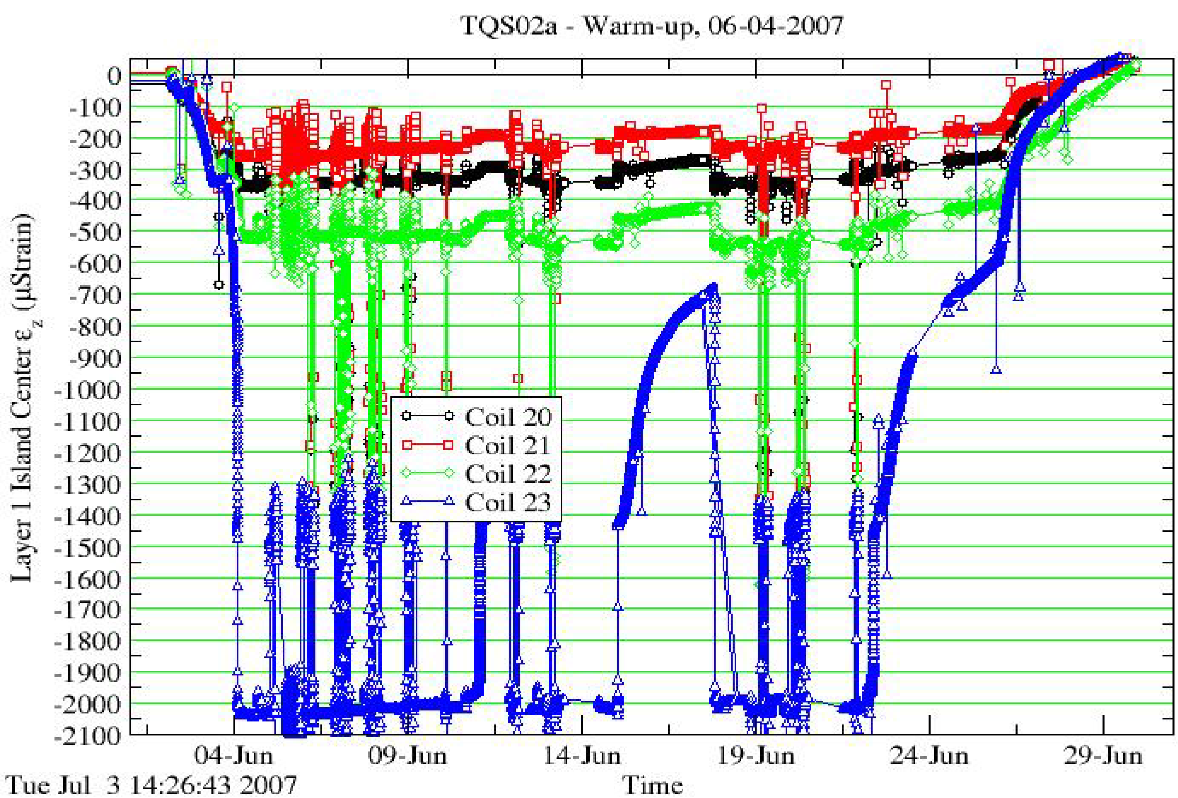


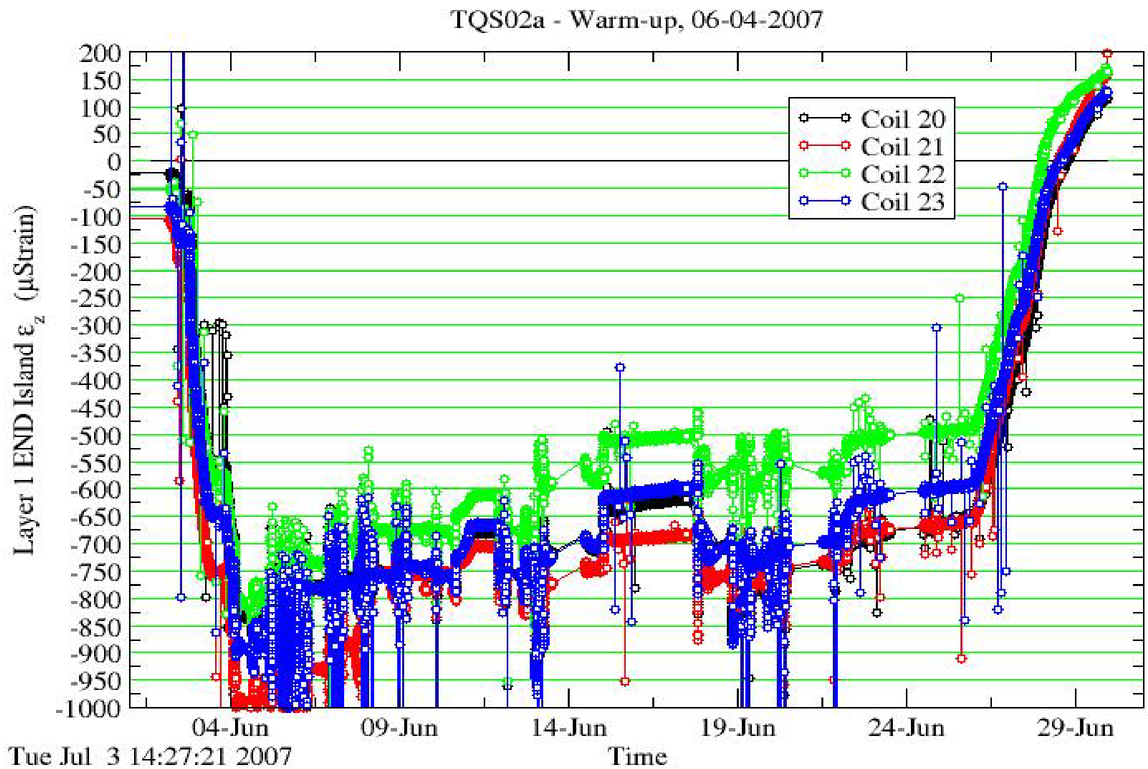
TQS02a - Warm-up, 06-04-2007
Shell Stress σ (MPa)
Time
Avg. σ_θ
Avg. σ_z
04-Jun
09-Jun
14-Jun
19-Jun
24-Jun
29-Jun

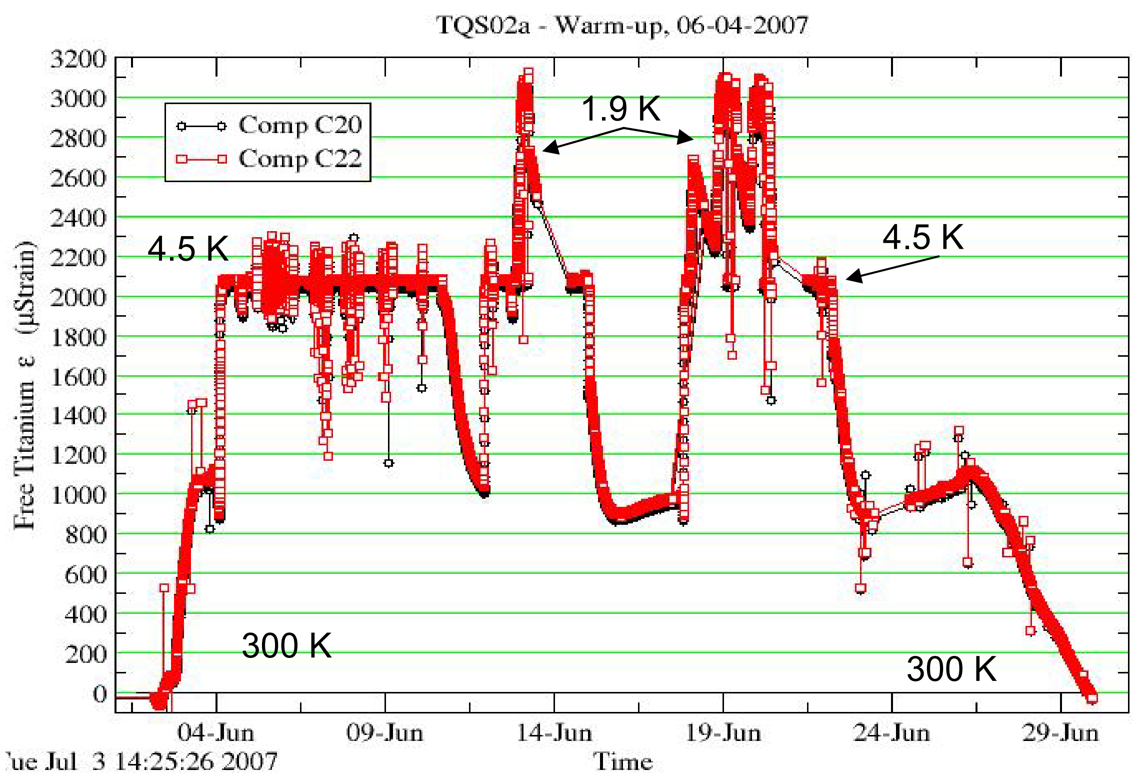


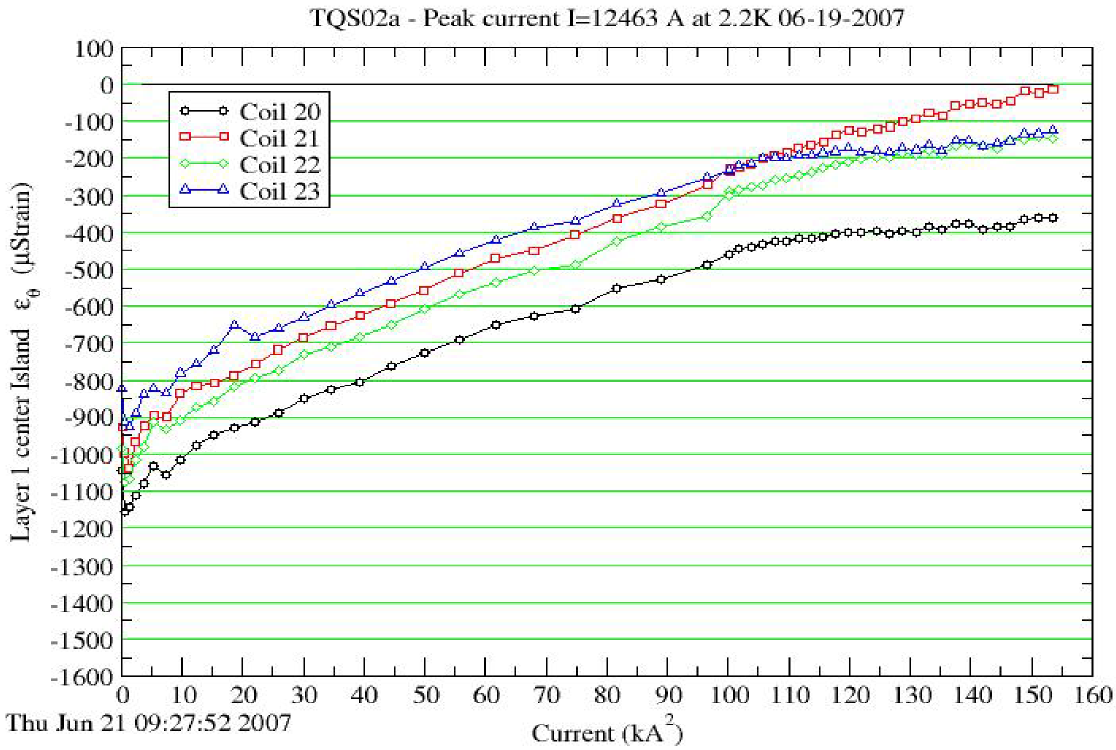
TQS02a - Warm-up, 06-04-2007
Rods Stress σ_z (MPa)
Time
Avg.
04-Jun
09-Jun
14-Jun
19-Jun
24-Jun
29-Jun


TQS02a - Warm-up, 06-04-2007
Layer 1 center Island ε_θ (μStrain)
Coil 20
Coil 21
Coil 22
Coil 23
04-Jun
09-Jun
14-Jun
19-Jun
24-Jun
29-Jun
Time
Tue Jul 3 14:25:50 2007

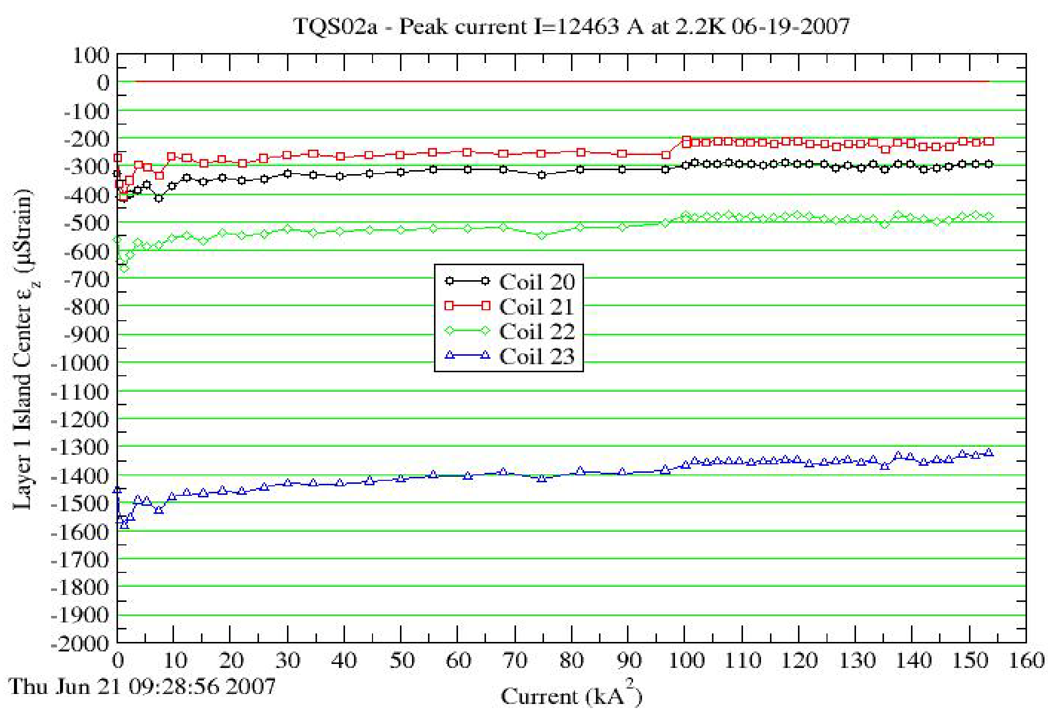

TQS02a - Warm-up, 06-04-2007
Layer 1 Island Center ε_z (μStrain)
Coil 20
Coil 21
Coil 22
Coil 23
04-Jun
09-Jun
14-Jun
19-Jun
24-Jun
29-Jun
Time
Tue Jul 3 14:26:43 2007

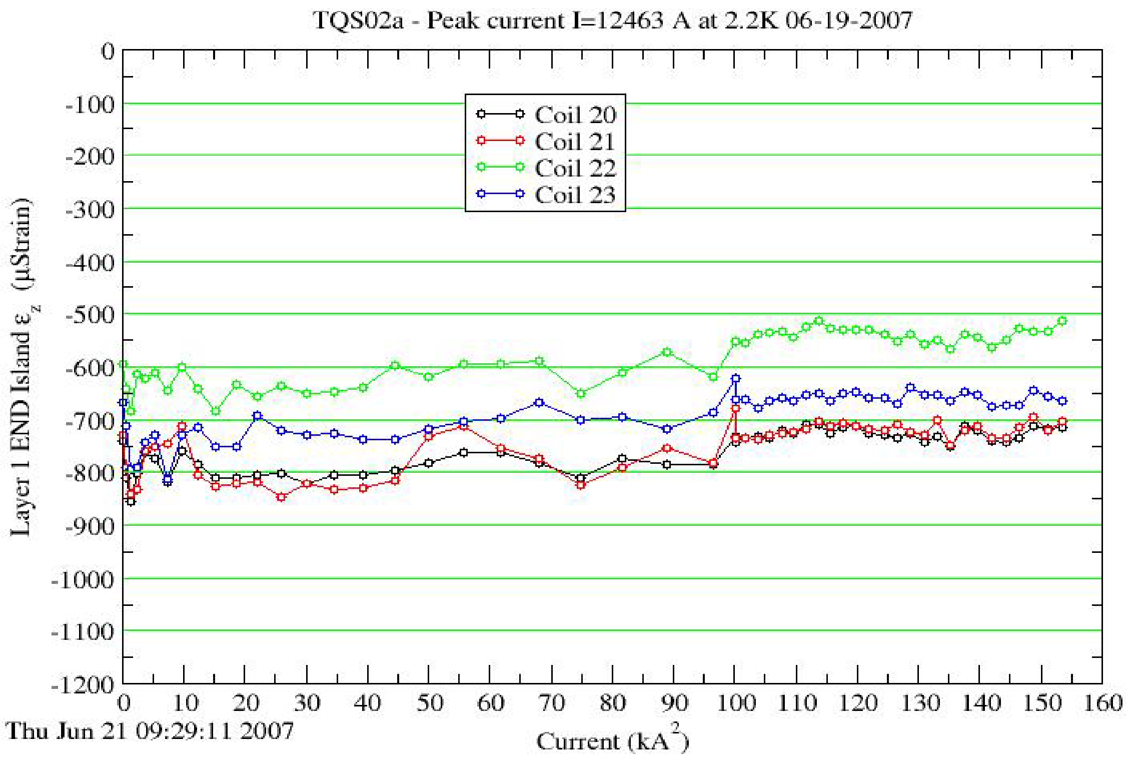

TQS02a - Warm-up, 06-04-2007
Coil 20
Coil 21
Coil 22
Coil 23
Layer 1 END Island ε_z (μStrain)
Time
04-Jun
09-Jun
14-Jun
19-Jun
24-Jun
29-Jun
Tue Jul 3 14:27:21 2007


TQS02a - Warm-up, 06-04-2007
Comp C20
Comp C22
1.9 K
4.5 K
4.5 K
300 K
300 K
Free Titanium ε (μStrain)
Time
04-Jun
09-Jun
14-Jun
19-Jun
24-Jun
29-Jun
ue Jul 3 14:25:26 2007

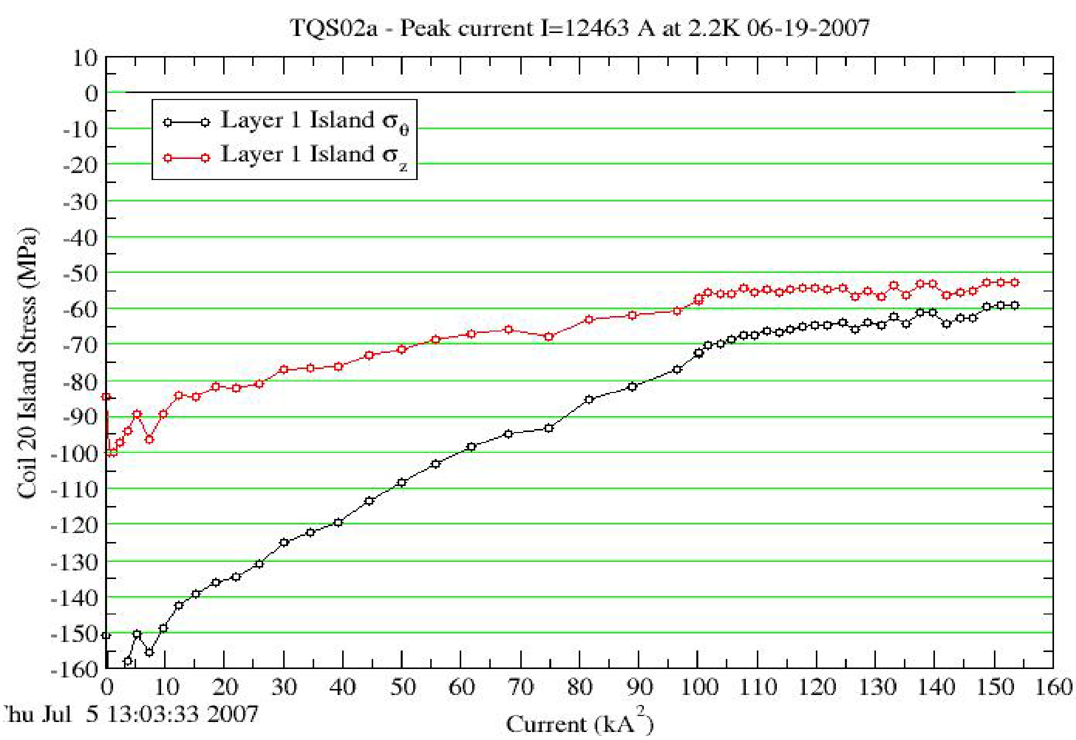


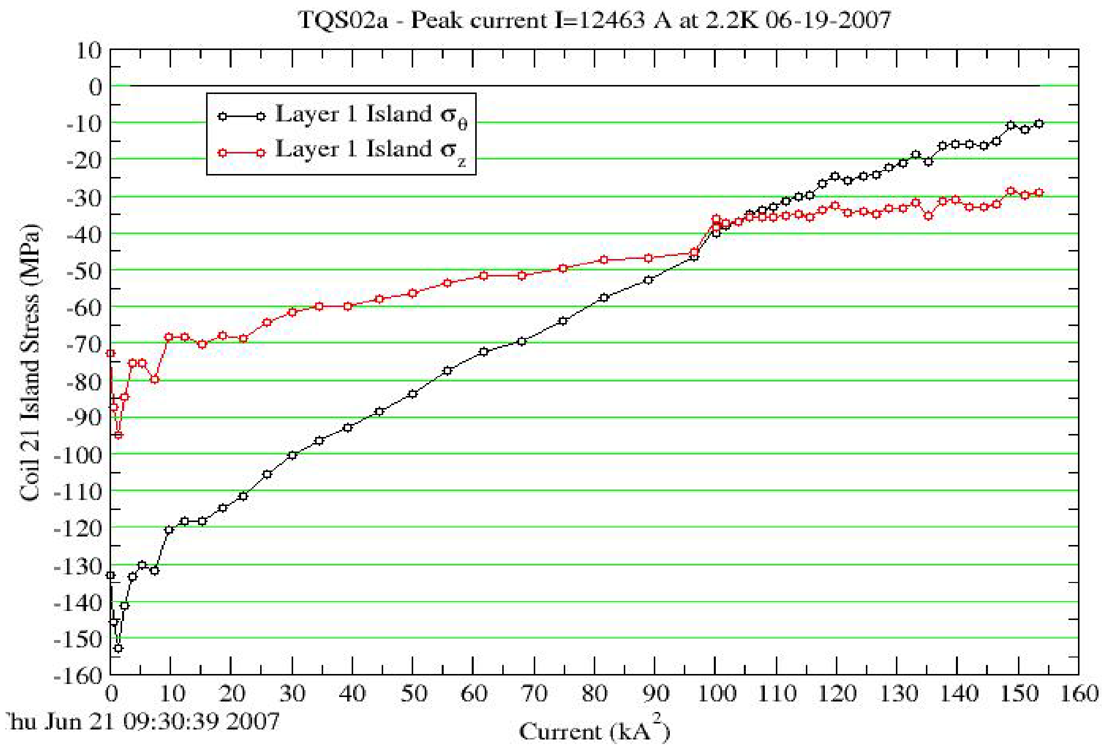
Axial strain in the island center (see below). The strain in coil 23 developed an "odd" offset below 10K and its absolute value can not be trusted.

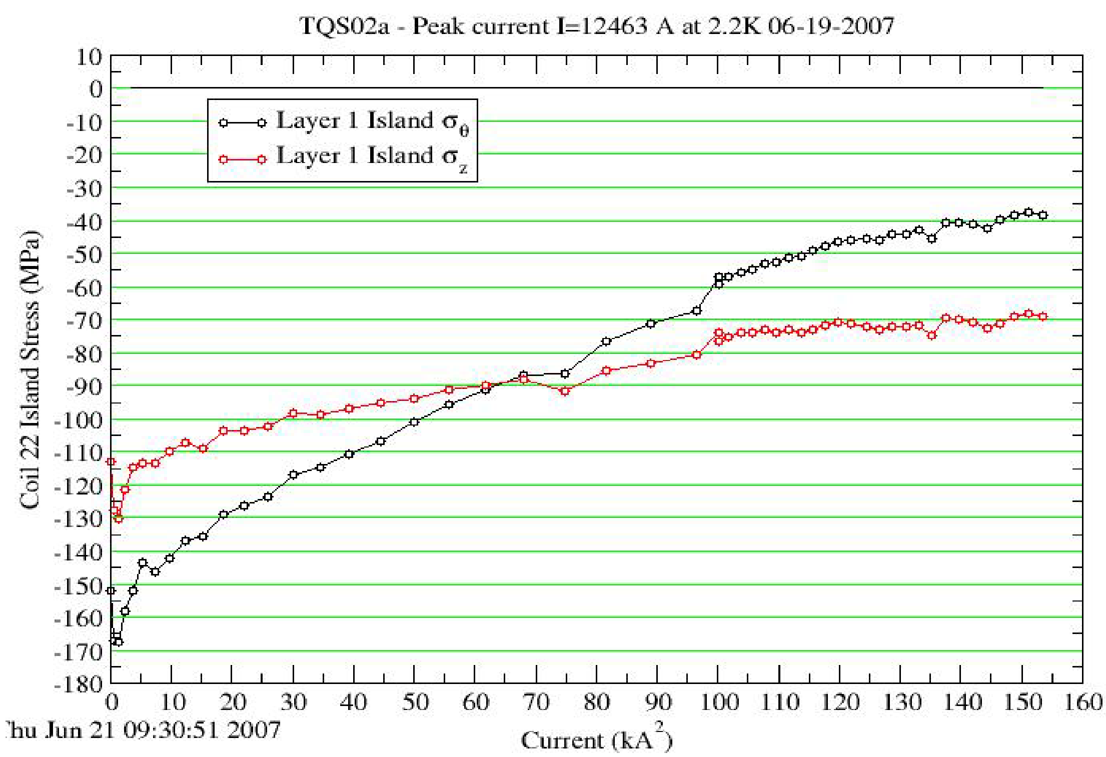


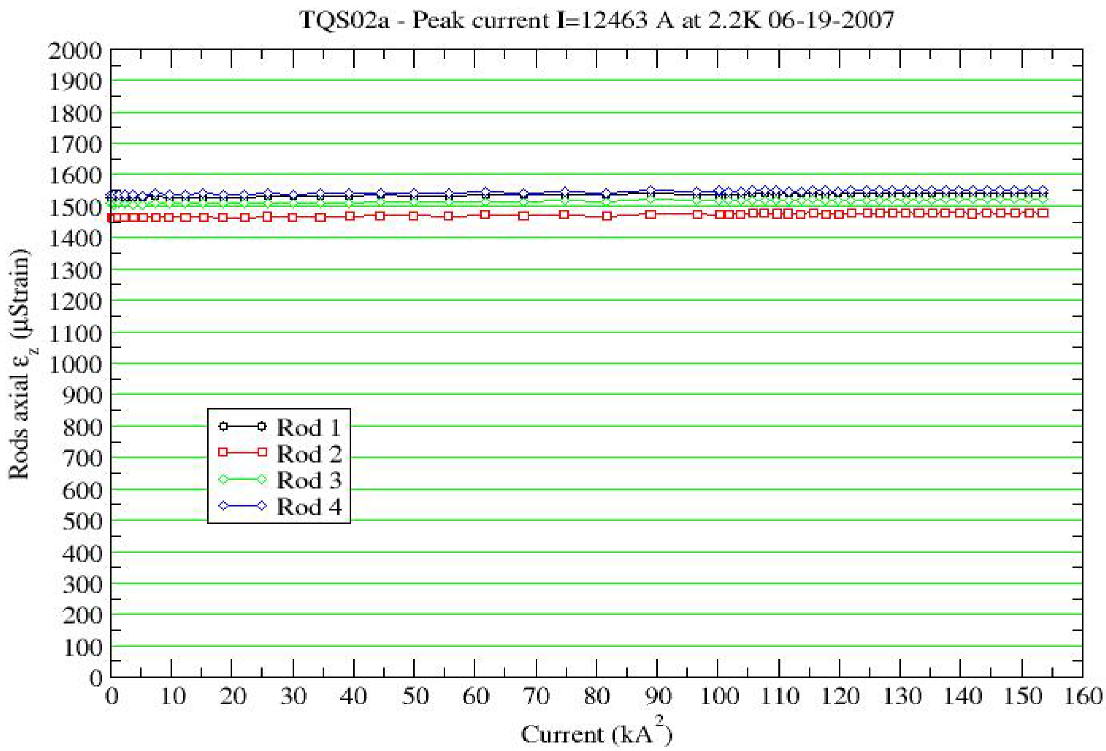


Axial strain near the magnet "ends" (above)




TQS02a - Peak current I=12463 A at 2.2K 06-19-2007
Layer 1 Island σθ
Layer 1 Island σz
Coil 21 Island Stress (MPa)
Current (kA²)
'hu Jun 21 09:30:39 2007


TQS02a - Peak current I=12463 A at 2.2K 06-19-2007
Layer 1 Island σθ
Layer 1 Island σz
Coil 22 Island Stress (MPa)
Current (kA²)
'hu Jun 21 09:30:51 2007


TQS02a - Peak current I=12463 A at 2.2K 06-19-2007
Rods axial ε_z (μStrain)
Current (kA^2)
Rod 1
Rod 2
Rod 3
Rod 4
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160

8. Quench Antenna Data

A quench antenna was used during training at 4.5 and 1.9K. The "KEK/HGQ" quench antenna consists of three stationary coil segments, each 0.35 m long and separated by 0.105 m long couplings. Each coil is made with four windings that are sensitive to normal and skew sextupole and octupole magnetic flux changes, at a radius of 23 mm. The probe was positioned in the bore of the magnet so that the second antenna coil, C2, was centered on the magnet coil center. Data analysis showed that windings in C2 recorded flux change signals almost for all quenches, while C1 windings recorded signals for most quenches at 1.9K. Only few signals were recorded in C3. Figure 9.1 shows for every training quench the difference between the time of the first signal in the quench antenna coils (in all windings of C1, C2 and C3) and the time of the quench start according to voltage taps data. This difference is within few msec with very few exceptions. Therefore almost all training quenches started in the magnet body (mostly close to the lead end from quench # 27). Quench antenna was not installed for the quenches 31 and 32 (in preparation to the magnetic measurements).

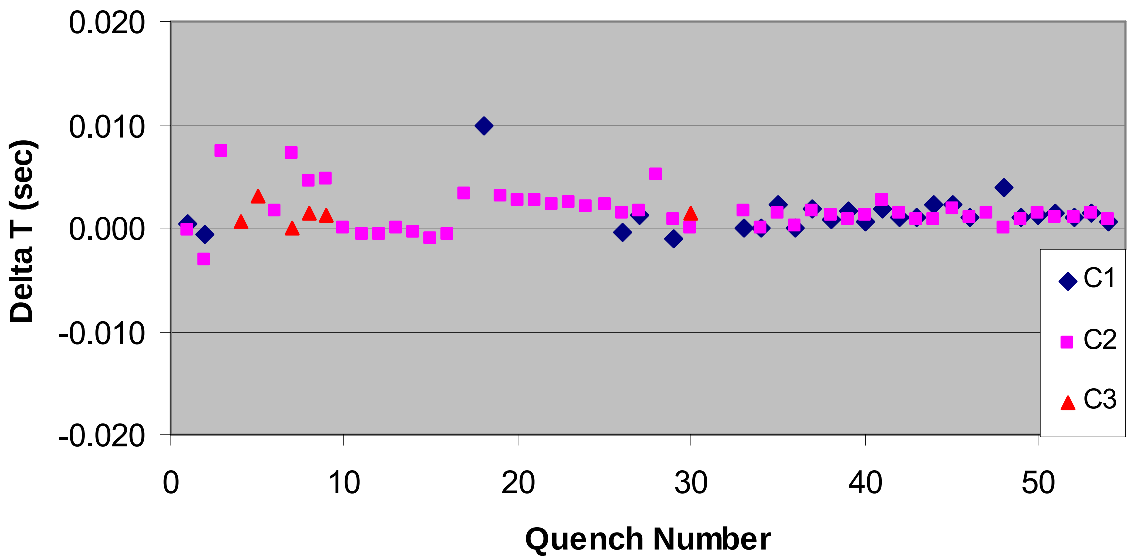


Figure 9.1 Difference between start of signal in quench antenna coils, and in voltage taps during training.

9. RRR measurement

Estimates of RRR in TQS02a coil segments have been made using data captured during the final warm up of the magnet. We started warming the magnet up at about 6:00pm on June 21st reaching 19K temperature at 11:00am on June 22nd and the room temperature (302K) at about 10:00am on June 29th, as shown in Fig.10.1.

Voltages across "fixed" (used for quench protection) and "configurable" (used for quench onset location) voltage tap segments were monitored by the Pentek data loggers, while a current of alternating polarity, +/- 10A, was put through the magnet. We used the RRR-configuration of the amplifier gain for the voltage tap segments (i.e. configuration with increased gains for the "fixed" and "configurable" voltage tap segments). Due to underestimated coil resistance in the configuration file enlarged amplifier gains were set in the RRR-configuration. As a consequence some of the configurable VT signal voltages reached the 5V saturation level by noon of June 26 when magnet was at 180K. To keep the gains unchanged for RRR-measurement we reduced the Kepco trim current from +/- 10A to +/- 2.5A.

Data for all segments are shown in Fig.10.2 and Table 10-I. RRR of inner and outer coil layers are shown in Fig.10.3.

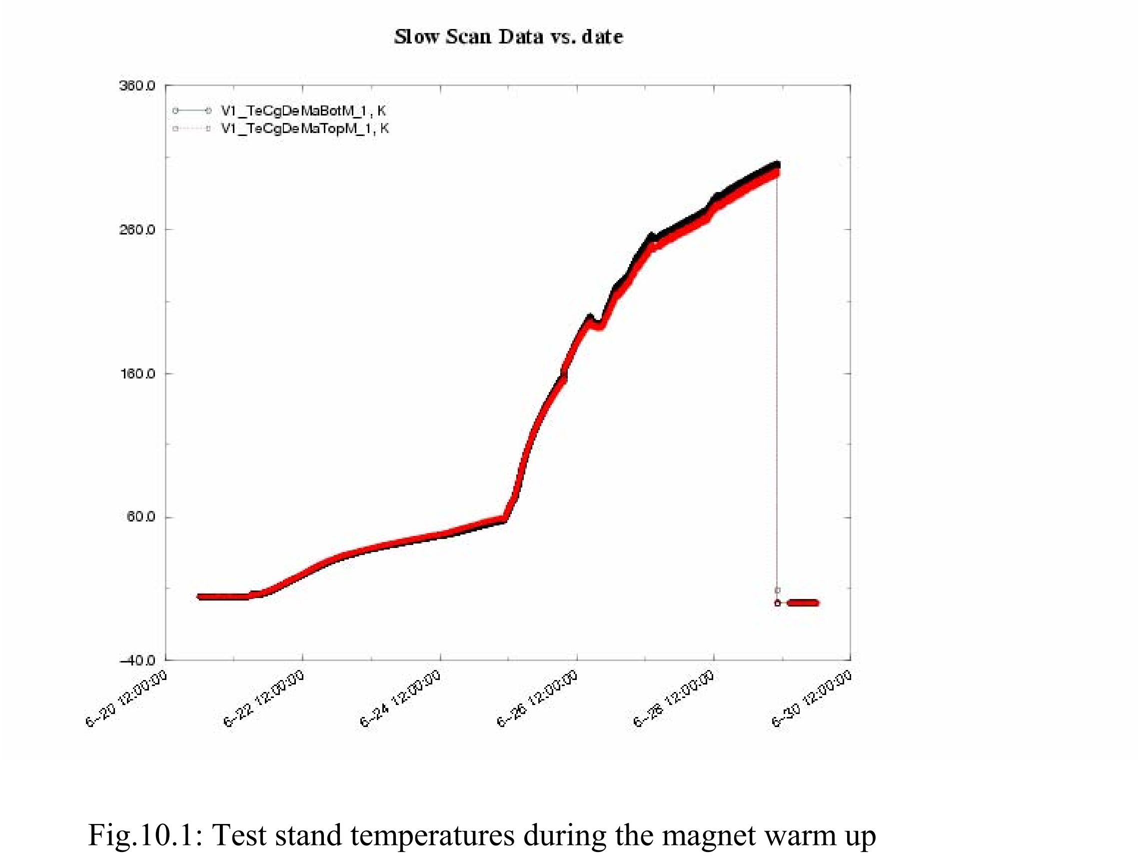


Fig.10.1: Test stand temperatures during the magnet warm up

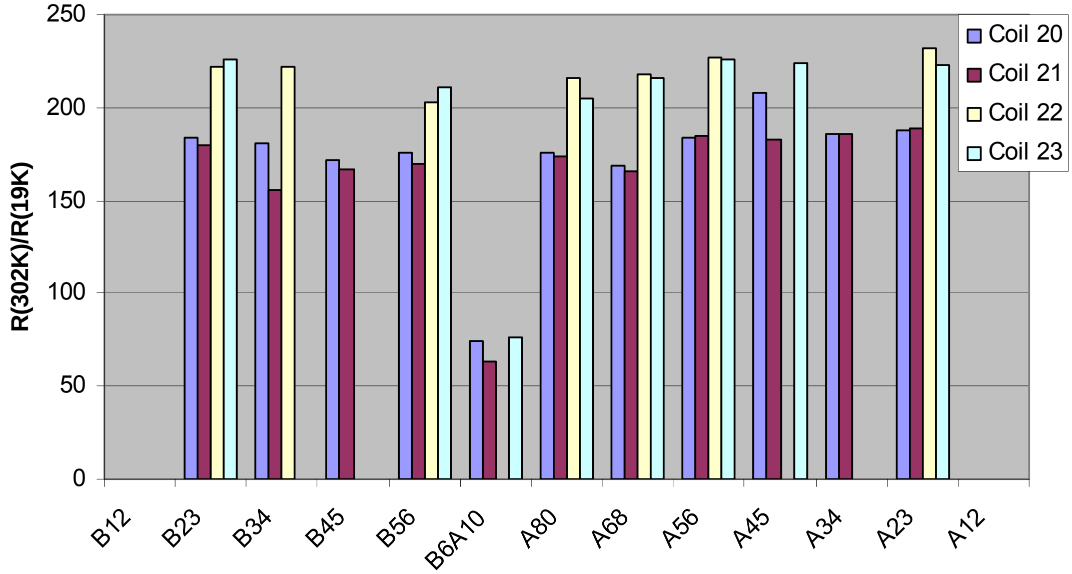


Fig.10.2: RRR data for different voltage tap segments and coils

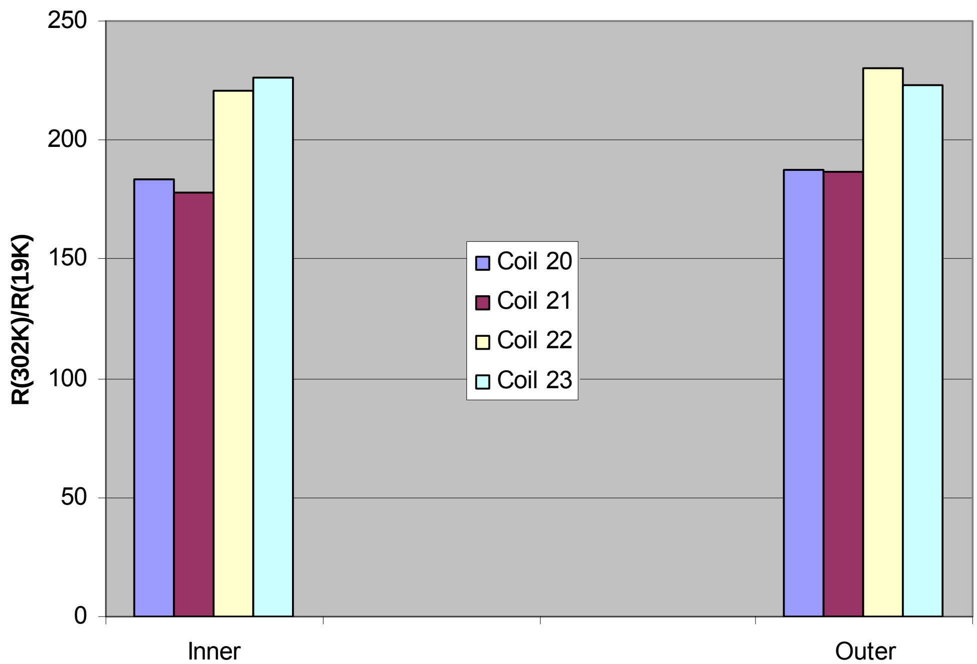


Fig.C: 10.3 of inner and outer coil layers

	Coil 20			Coil 21			Coil 22			Coil 23		
	R(19K)	R(300K)	RRR	R(19K)	R(300K)	RRR	R(19K)	R(300K)	RRR	R(19K)	R(300K)	RRR
B12.SnTi		0.387			0.384			0.8456			0.38262	
B23.Omt	0.413	75.81	183.56	0.423	75.87	179.36	0.34	75.301	221.47	0.335	75.8413	226.39
B34.OLS	0.0115	2.08	180.87	0.0134	2.089	155.90	0.00925	2.0534	221.99		1.12396	
B45.ORE	0.002715	0.465	171.27	0.002815	0.4694	166.75	N/A	N/A	N/A		1.01212	
B56.ORS	0.0109	1.912	175.41	0.0113	1.9217	170.06	0.0093	1.8906	203.29	0.00915	1.92755	210.66
B6A10.Ramp	0.0157	1.17	74.52	0.0183	1.1494	62.81		0.2009		0.015	1.14665	76.44
A80.IRS+RE	0.0097	1.703	175.57	0.0098	1.6998	173.45	0.0075	1.6204	216.05	0.0083	1.7011	204.95
A68.ILS+LE	0.0145	2.453	169.17	0.01475	2.4436	165.67	0.011	2.4013	218.30	0.0115	2.4801	215.66
A56.T2-5	0.1095	20.122	183.76	0.109	20.086	184.28	0.0884	20.0902	227.26	0.0888	20.0864	226.19
A45.T6	0.0253	5.246	207.35	0.0287	5.2498	182.92	N/A	N/A	N/A	0.0241	5.40218	224.17
A34.T7Rs	0.0114	2.121	186.05	0.0114	2.123	186.23		0.1053		N/A	N/A	N/A
A23.Imt	0.364	68.422	187.97	0.362	68.443	189.07	0.295	68.3712	231.77	0.316	70.331	222.57
A12.SnTi		0.371			1.667			0.3688			0.036351	

Table 10-I: RRR data for all segments

10. Quench origin location

Time-of-flight quench-origins were calculated for several quenches during the initial training of TQS02, using the following three times: quench-onset, 1st exit and 2nd-exit (when available). The time-of-flight distance assumed the known V-tap locations and equal quench-propagation speeds for both quench-fronts. If the time of the 2nd quench-front's exit was not visible (e.g., when the V-tap DAQ was blinded by the dump-transient voltage) the following quench-speeds were assumed: 20m/s (inner layer), and 10m/s (outer layer). The following quench-origins were analyzed: Q1,2,3,4,7,8,10,11,15,17,25, 26,27, as indicated in the table below, plotted on a Theta/Z-scaled version of the two pole-turns (Fig. 10.1).

TQS02		1st 4.5K Training		Yplot					Xplot
Q##	Coil	Q-O.Ref.Seg		Y(QO)	Z.near.tap	Lref.seg	ToF	L.ToF	Z.ToF
(#)	(ID)	(ID)		(mm)	(mm)	(mm)	(ratio)	(mm.rel)	(mm)
Q1	**21**	**A10B6 (Ramp)**		-6.00	-230.0	352	0.23	80	-310.0
Q2	**21**	**B4B5 (ORE)**		-6.00	326.6	135	0.50	67	393.9
Q3	**20**	**B4B5 (ORE)**		6.00	326.6	135	0.47	64	390.1
Q4	**20**	**A8A10 (IRS+RE)**		-9.08	0.0	499	0.37	182	316.2
Q5	**21**	**B3B4(ORS)+B2B3 (Omt)**		-26.51	0.0	900	#VALUE!	#VALUE!	#VALUE!
Q6	**21**	**B3B4(ORS)+B2B3 (Omt)**		-26.51	-230.0	352	#VALUE!	#VALUE!	#VALUE!
Q7	**22**	**A8A9 (IRE)**		9.08	314.6	184	1.10	202	348.0
Q8	**20**	**A6A8 (ILS+LE)**		9.08	314.6	713	0.06	42	273.0
Q9	**20**	**A6A8 (ILS+LE)**		9.08	314.6	713	#VALUE!	#VALUE!	#VALUE!
Q10	**20**	**A6A8(ILS+LE)**		9.08	314.6	713	0.20	144	170.6
Q11	**20**	**A6A8(ILS+LE)**		9.08	314.6	713	0.24	174	140.2
Q12	**20**	**A6A8(ILS+LE)**		9.08	314.6	713	#VALUE!	#VALUE!	#VALUE!
Q13	**20**	**A6A8(ILS+LE)**		9.08	314.6	713	#VALUE!	#VALUE!	#VALUE!
Q14	**20**	**A6A8(ILS+LE)**		9.08	314.6	713	#VALUE!	#VALUE!	#VALUE!
Q15	**20**	**A6A8(ILS+LE)**		9.08	314.6	713	0.39	279	35.6
Q16	**20**	**A6A8(ILS+LE)**		-6.00	-230.0	713	#VALUE!	#VALUE!	#VALUE!
Q17	**21**	**B2B3 (Omt)**		-6.00	314.6	900	0.19	734	1048.3
Q18	**21**	**TiTi-splice (20i21o)**		-6.00	-230.0	352	#VALUE!	#VALUE!	#VALUE!
Q19	**21**	**B3B4(ORS)+B2B3 (Omt)**		-6.00	-230.0	352	#VALUE!	#VALUE!	#VALUE!
Q20	**21**	**B3B4(ORS)+B2B3 (Omt)**		-6.00	-230.0	352	#VALUE!	#VALUE!	#VALUE!
Q21	**21**	**B3B4(ORS)+B2B3 (Omt)**		-6.00	-230.0	352	#VALUE!	#VALUE!	#VALUE!
Q22	**21**	**B3B4(ORS)+B2B3 (Omt)**							
Q23	**21**	**B3B4(ORS)+B2B3 (Omt)**							
Q24	**21**	**B3B4(ORS)+B2B3 (Omt)**							
Q25	**21**	**B3B4(ORS)+B2B3 (Omt)**		-26.51	326.58	557	0.44	247	79.8
Q26	**21**	**B3B4(ORS)+B2B3 (Omt)**		26.5	-230.0	557	0.04	23	-207.4
Q27	**0**	**0**		-26.5	326.6	556.6	0.47	259	67.6

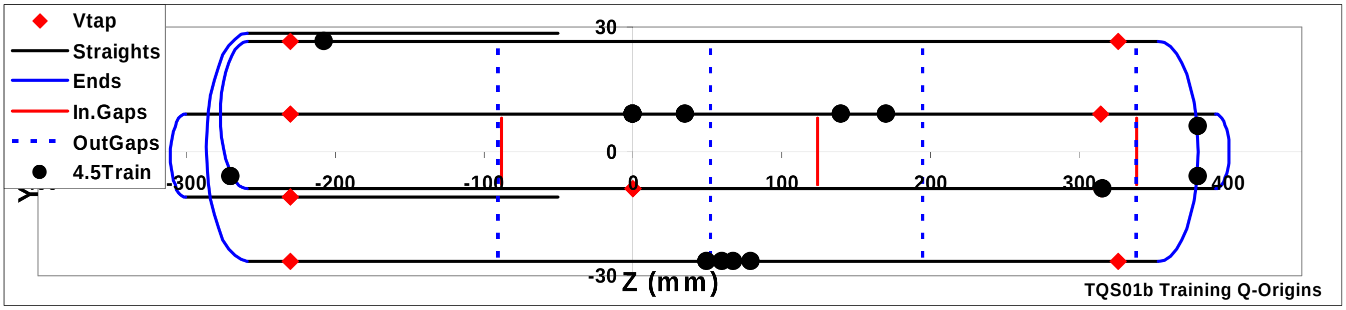


Fig. 10.1: Quench-origin plot for some of TQS02's early training quenches. Refer to the table to identify the coil. The first three training quenches originated in the outer layer ends, close to its transit across the inner pole-island. Middle training quenches occurred in the inner pole turn straight-sections. 4.5K plateau quenches always had multiple starts in the outer layer. The first onset occurred near the middle of the lead-in side (bottom of plot) a second pole-turn onset originated shortly later just inside the V-tap demarcating the start of the interlayer "Ramp" segment (top left in plot).

11. Magnetic Measurements

The field quality magnetic measurements were made with the VMTF vertical drive system and LHC/EMS rotating harmonic coil readout cart. Several data sets were captured: warm z-scan before cool down, z-scans at 4.5 K and 1.9K. A full cold measurement program is described below. A 0.1 m long tangential probe, with 2 dipole, 2 quadrupole and 1 tangential windings, was utilized. This probe was specially built for these measurements with a radius of 2.17 cm, optimized to the warm finger ID. The positive direction of the z-axis for the scans is pointing from the magnetic center to the lead end, from which the probe was inserted. Each measurement (e.g., at one z-position) contains data from at least 25 full rotations of the probe, and z-scans steps were equal to the length of the probe.

The cold magnetic measurement program at 4.5 and 1.9 K is consisted of the following measurements:

a. Z-scans at 4.5 K: 6.5, 8.0 and 10.5 kA
b. Z-scans at 1.9 K: 12.3 Tm/m (LHC injection, estimated to be 0.583 kA), 100 Tm/m (estimated to be 5.15kA). A measurement at high current (~I_{qmax}– 0.6kA) was not performed at 1.9 K.
c. Eddy current loops: 20 40 and 80 A/s up to 10 kA with the probe positioned in the center of the magnet
d. Dynamic effects measurement, which included a current accelerator profile, similar to the one used in LHC MQXB quads (15 min. duration of the injection plateau and the probe positioned in the center of the magnet).

All magnetic measurement results are presented at 17 mm reference radius, the official radius adopted for LHC. A detailed magnetic measurements summary is posted at the following URL:

HTTP://tdserver1.fnal.gov/velev/magnets/web/magnets/TQS02/TQS02a_mag_meas.html

Table 11.1 summarizes the quadrupole strength (T*m/m) and transfer function (TF) versus the excitation current, measured when the probe was positioned at the center of the magnet body (z=0 m). The 16% degradation of the TF at high currents is expected due to the iron saturation.

Fig. 11.1 shows the TF versus z coordinate profiles at 0.58, 5.15 and 10.5 kA. The integral magnetic lengths are calculated to be 0.712, 0.723 and 0.735 m at these currents.

Requested Current (A)	-10	10	583	4000	5155	10000
Measured Current (A)	-10.81	10.80	583.84	3997.74	5152.42E	9995.80
Field (T*m/m)	0.2336	0.2336	12.48	83.92	104.58	184.92
TF (T/kA)	21.71	21.62	21.38	20.99	20.29	18.50

Table 11.1 Strength and TF at different currents in the body of the magnet

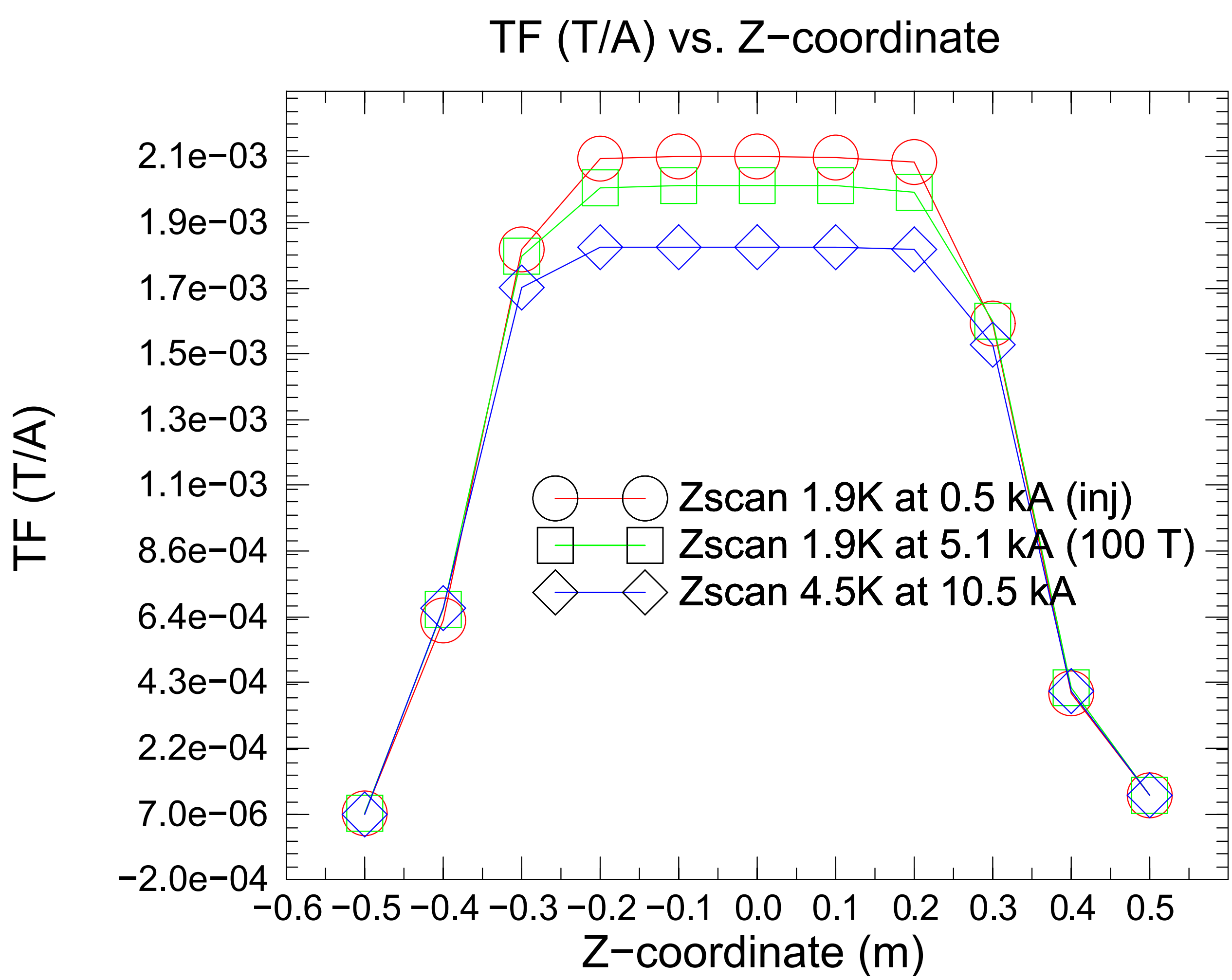


Figure 11.1. The magnet TF versus z coordinate at 0.583, 5.15 and 10.0 kA.

Table 11.2 summarizes the harmonics at injection (0.583 kA) and maximum measured current (10.5 kA), averaged over the magnet (left) and for the center body position (right). In general, the field harmonics are in the order of several units. The b_5 and b_6 at injection are observed to be relatively large, ~ 10 units, similar to TQS01c.

Table 11.2. TQS02 body and average harmonics at different currents

Multipole(units)	Average Injection	Average 10.5 kA	Body only Injection	Body only 10.5kA
b_3	1.71E+00	8.50E-01	1.90E+00	6.16E-01
b_4	-1.77E-03	4.51E-01	5.14E-02	5.66E-01
b_5	7.75E+00	-3.69E-01	7.54E+00	-7.40E-01
b_6	-1.29E+01	1.72E+00	-1.29E+01	1.85E+00
b_7	-2.88E-03	9.83E-03	1.11E-02	2.37E-02
b_8	-6.73E-04	-2.15E-02	2.31E-03	-1.92E-02
b_9	-7.62E-02	2.29E-02	-9.43E-02	1.12E-02
b_10	1.03E-01	-1.25E-02	1.17E-01	-6.81E-03
a_3	3.49E-01	2.46E-01	5.37E-01	4.04E-01
a_4	-2.15E+00	1.13E+00	-1.99E+00	1.44E+00
a_5	4.40E+00	-2.30E-01	3.94E+00	-7.49E-01
a_6	4.49E-01	1.07E-01	3.62E-01	9.59E-02
a_7	-3.79E-02	-2.50E-02	-4.78E-02	-4.20E-02
a_8	6.43E-03	-1.37E-02	3.12E-02	2.29E-03
a_9	-3.09E-02	9.25E-03	-4.34E-02	6.34E-04
a_10	2.55E-03	5.24E-03	2.96E-03	3.56E-03

Figure 11.2 shows the dodecapole versus time. The current profile used in this measurement was derived from the profile of production inner triplet LHC quadrupole (LQXB) measurements. The duration of the injection porch was set to 15 min at 12.8 T, accordingly to the LHC specifications. One can observe that *the b6 decay and snapback*, which are commonly observed in NbTi magnets, *are not present* (see the time interval from ~700 to ~1600 s).

Current loops at 20, 40 and 80 A/s for TQS02 quadrupole have been executed. The b_6 difference between the ramp rate loops is small, indicating small or negligible eddy current effect on the hysteresis loop, similar to what was observed in TQS01c measurements. The b_6 hysteresis loops are shown in Figure 11.3.

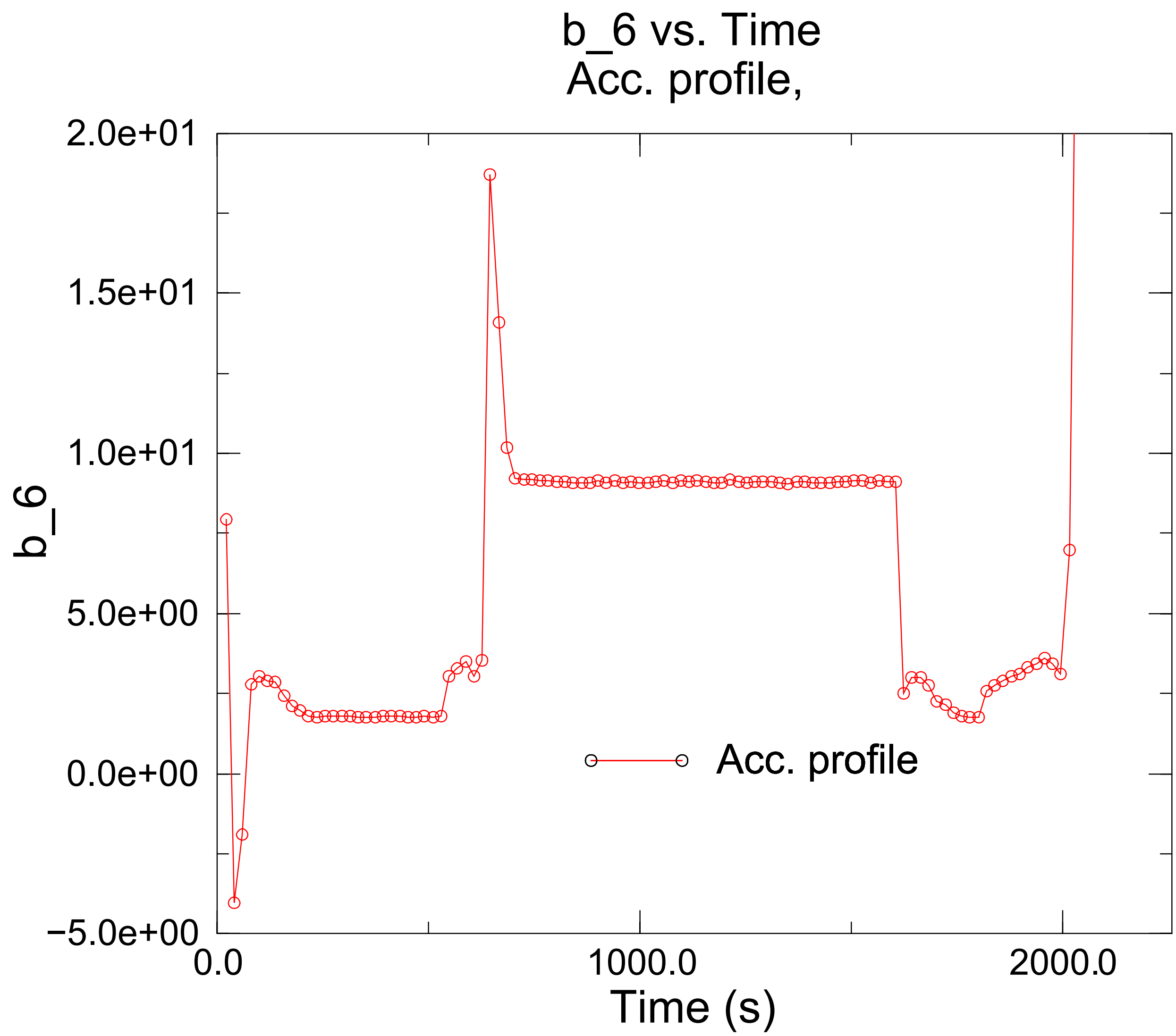


Figure 11.2. Dodecapole (b_6, in units) versus time (s): current profile simulates an accelerator operation.

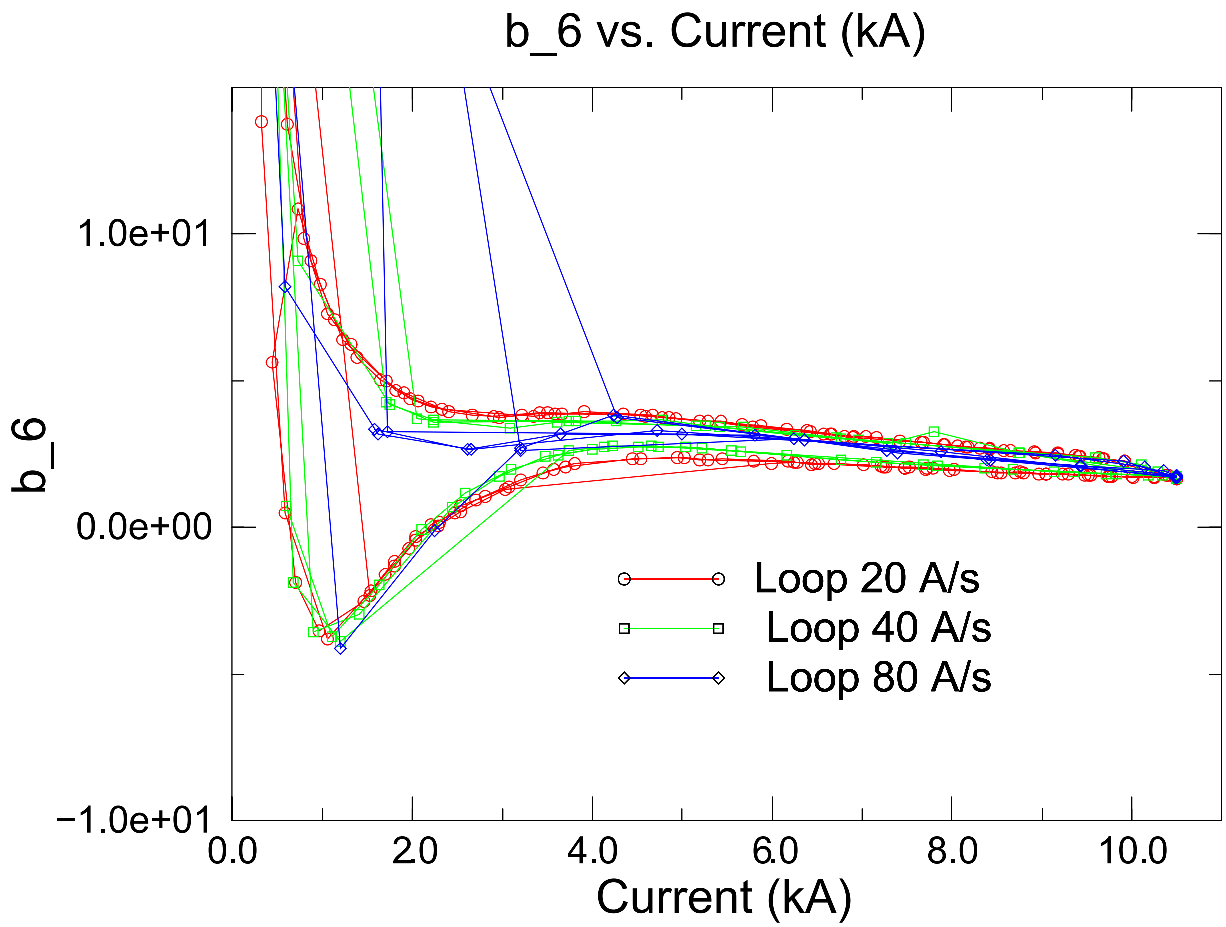


Figure 11.3. Dodecapole (b_6) versus excitation current at different ramp rate 20 (red), 40 (green) and 80 (blue) A/s.

References

1) 1. C. Donnelly, G. Ambrosio, G. Chlachidze, S. Rahimzadeh-Kalaleh
"TQS02a Voltage Spike Analysis",
FNAL TD-07-015, LARP note July 2007