Summary on HQ / HQM tests

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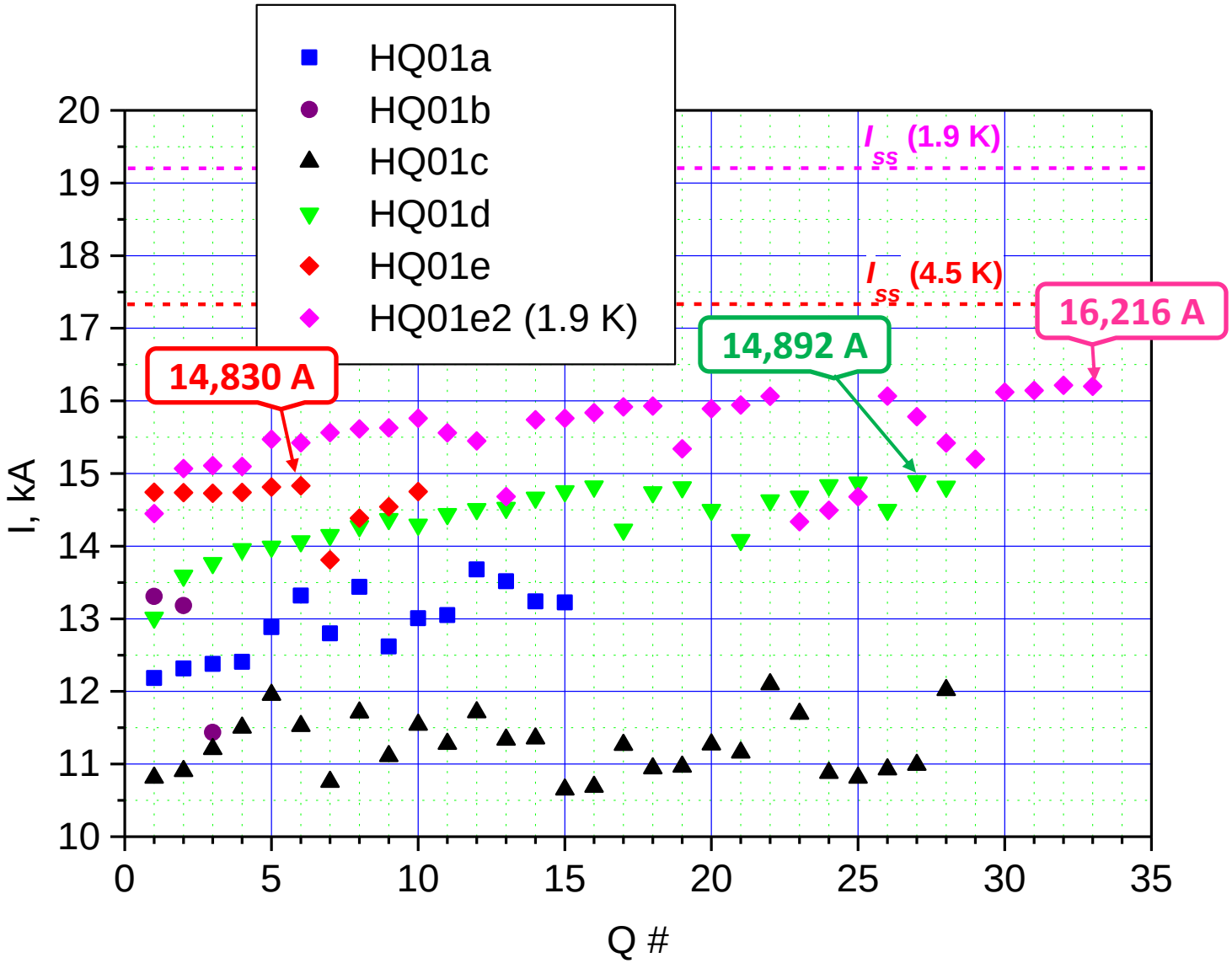
Outline

- HQ01 magnet test results (timeline, quench current and quench locations)
- HQ01M mirror tests (timeline, quench current and quench locations)
- Ramp rate dependence (HQ magnet vs mirror tests)
- Field quality and flux jump related issues
- Summary on current results and remaining problems

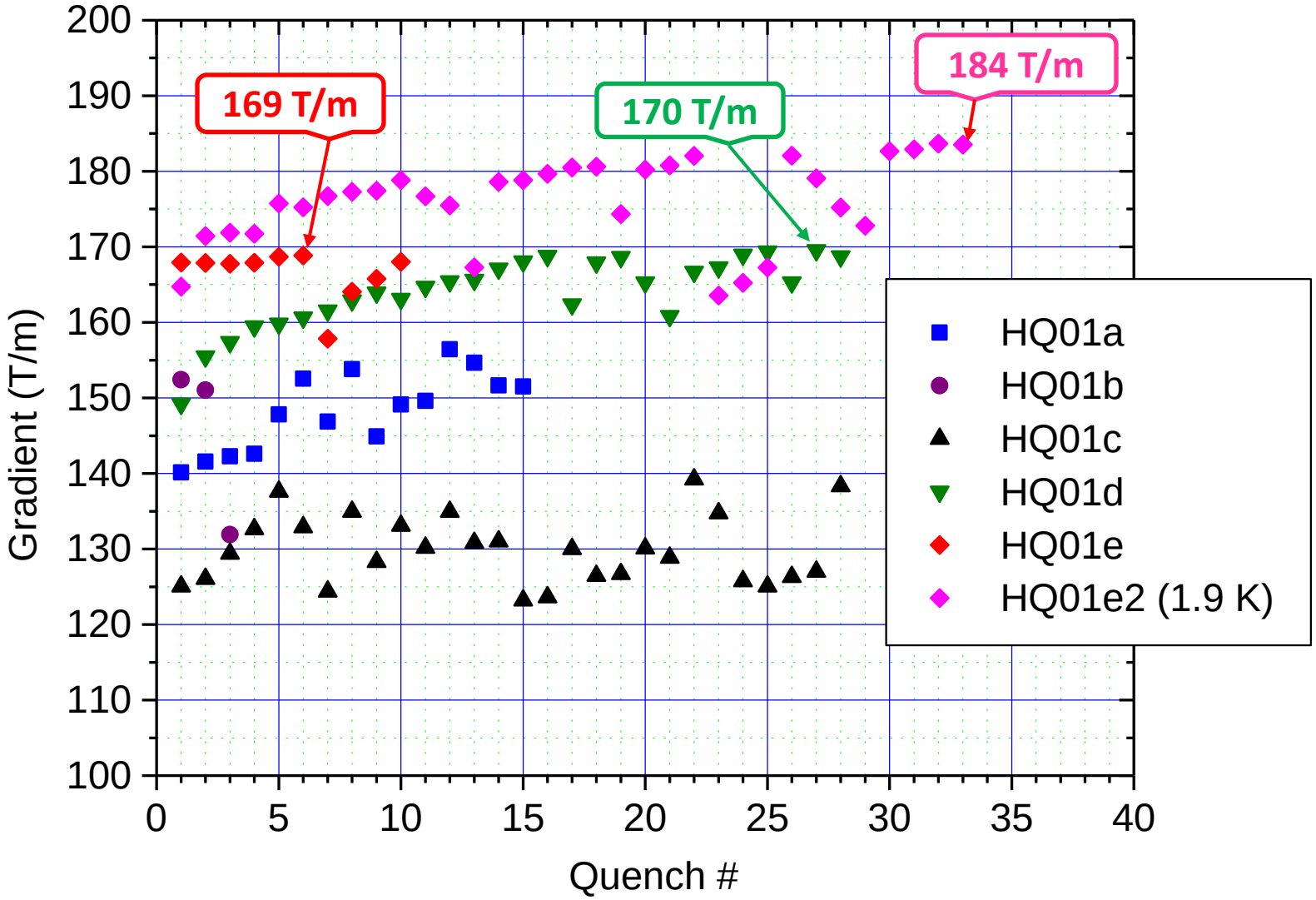
HQ Magnet Tests

- **HQ01a**: Used Coils 1,2,3 and 4. Showed moderate training and reached max gradient of 156 T/m at 4.5 K. Performance was limited by mid-plane quenches in Coil 3. Coil 2 trace insulation damage was discovered upon warm-up.
  - → *Coils 2 and 3 were replaced with 5 and 6*
  - → *Coil-structure shims were revised*
- **HQ01b**: First quench at 150 T/m. Insulation failure on the 3rd quench in Coil 6.
  - → *Insulation and electrical QC procedures were reviewed / improved.*
  - → *Coils 4 and 6 were replaced with 7 and 8*
- **HQ01c**: Lower quench levels; magnet is limited at ~135 T/m by mid-plane multi-turn quenches in Coil 1. Spontaneous quenches observed while holding current steady for 1-3 min. Insulation is OK now.
  - → Coil 1 replaced with Coil 9
  - → Coil design optimized to prevent stand damage during reaction
- **HQ01d**: Reached 170 T/m (86% of SSL) performance upon training, limited by pole-turn quenches
  - → Reloaded to increase pre-stress
- **HQ01e**: Reached 169 T/m, no further training
- **HQ01e2**: No change in performance at 4.5 K; reached 184 T/m at 1.9 K

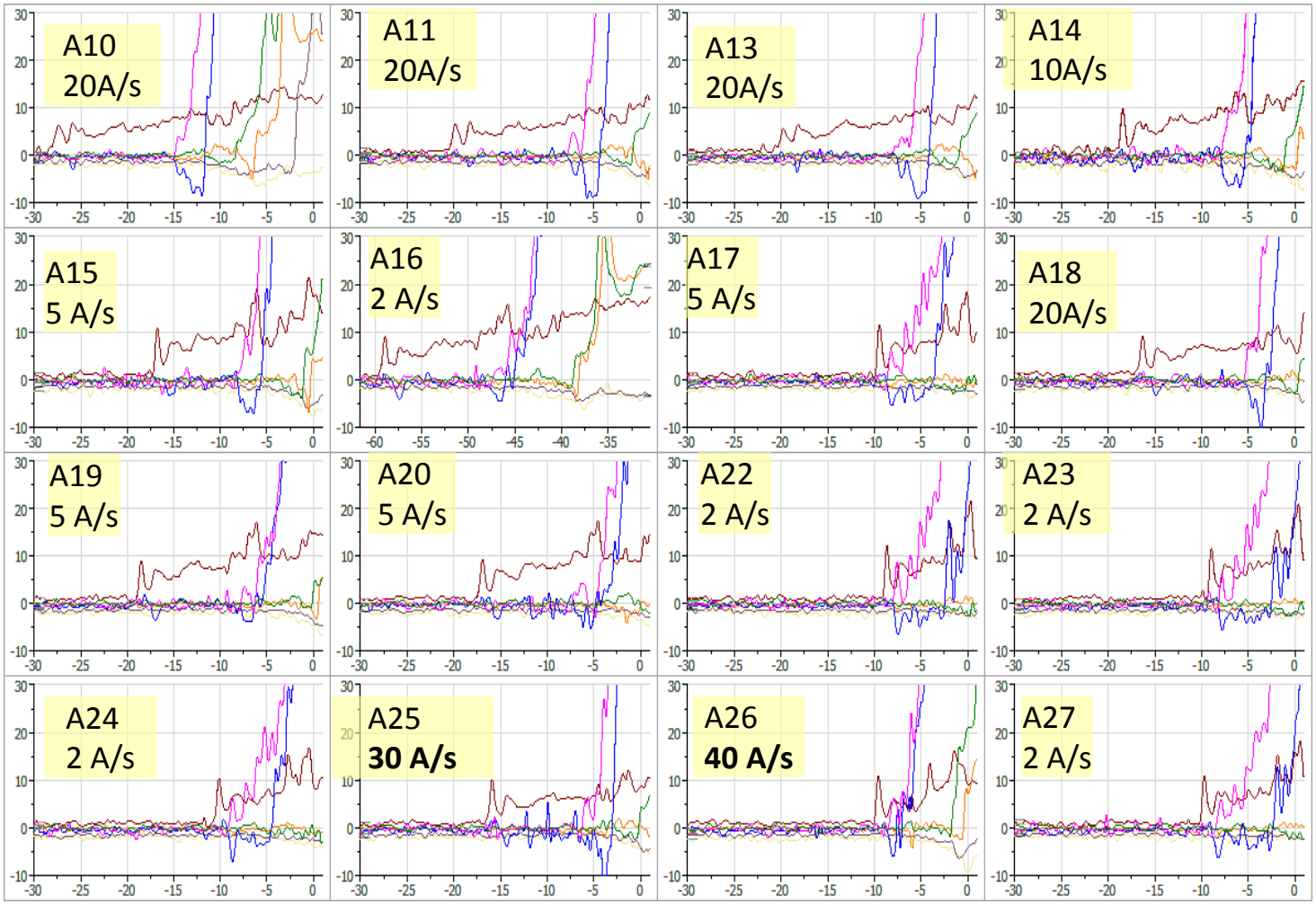
Magnet training summary (current)



Magnet training plot (gradient)



Quench locations HQ01a



3A23 midplane turn is responsible for all the quenches

HQ01c quench locations

20 A/s quenches:

PQ08: 1A24 : -24.2 ms -> 1B23,1B53,8B24,8A23: -6.9 ms
PQ09: 1A24 : -24.2 ms -> 1B23,1B53: -7.5 ms
A23: 1A24 : -23.1 ms -> 8B24, 8A23,1B23,1B53: -6.5 ms
A24: 1B23,8A23,8B24,8A53,1B53 : -5.3 ms -> 1A24,1A810 : -4.3 ms
A25: 1A24 : -19.4 ms -> 1B23,1B53, 8A23,8A53,8B24: -4.0 ms
A26: 1A24, 8A23,8A53,8B24: -5.3 ms -> 1B53, 1B23: -4.3 ms

10 A/s quenches:

A38: 1A24: -24.5 ms -> 1B53: -4.3 ms
A40: 1A24: -32.0 ms -> 8A23: -4.9 ms

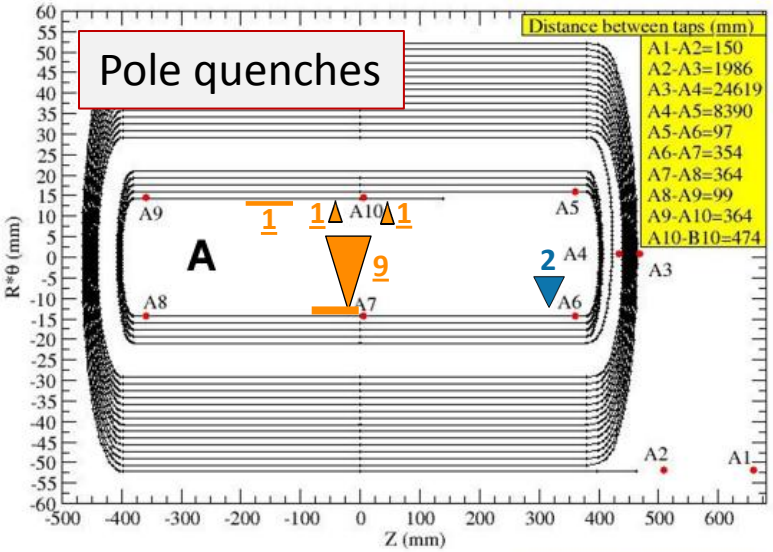
Holding quenches:

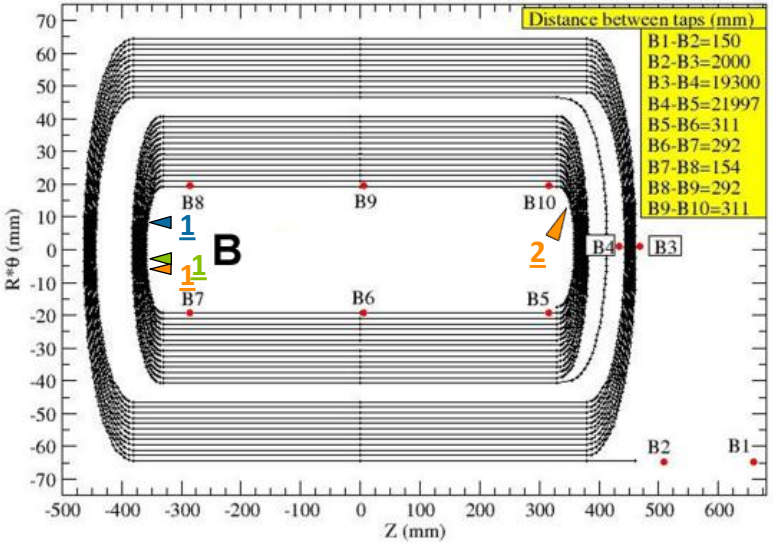
A36: 1A24: -17.5 ms -> 1B23: -14.0 ms
A37: 1A24: -18.7 ms -> 8A24,8A53, 8A23,1B23: -5.7 ms
A39: 1A24: -31.2 ms -> 8A23: -8.3 ms
A41: 1A24: -21.3 ms -> 1B23, 8B24,8A53: -12.6 ms
A42: 1A24: -28.0 ms -> 8B24: -10.5 ms
A43: 1A24: -34.2 ms -> 1B23,8B24,8A53,8B54: -23.8 ms
A47: 1A24: -24.5 ms -> 1B23,8B24,8A53,8B24: -23.9 ms
A48: 1A24: -45.5 ms -> 8B24: -34.4 ms
A50: 1A24: -79.0 ms -> 1B53: -55.2 ms

1A24 multi-turn is responsible for all the quenches

HQ01d quench locations

A#	COIL	SECTION	SEGMENT	LOCATION	GRADIENT (T/M)
5	5	RE	B78;B76	80 MM FROM B8	149
7	8	RE	B87;B76	70 MM FROM B7	155
8	7	?	A23	MIDPLANE	157
9	8	RE	A78	30 MM FROM A7	159
10	8	STRAIGHT	A910	50 MM FROM A10	160
11	5	?	A54	MT 1ST OUT TURN	161
12	8	STRAIGHT	A910	N/D	162
13	8	RAMP	A10B10	51 MM FROM A10	163
14	8	STRAIGHT	A78	21 MM FROM A7	164
15	9	RE	A78	58 MM FROM B8	163
16	8	STRAIGHT	A78	23 MM FROM A7	165
17	8	STRAIGHT	A78	25 MM FROM A7	165
18	9	STRAIGHT	A67	38 MM FROM A6	166
19	8	STRAIGHT	A78	19 MM FROM A7	167
20	8	STRAIGHT	A910	20 MM FROM A10	168
21	8	STRAIGHT	VT A7	A7	169
22	7	?	A23	MIDPLANE	162
23	7	?	A23	MIDPLANE	168
24	8	STRAIGHT	VT A7	A7	169
25	7	?	A23	MIDPLANE	165
27	7	?	A23	MIDPLANE	167
28	8	?	B23	MIDPLANE	167
29	8	STRAIGHT	A910	24 MM FROM A10	169
34	8	RAMP (LE)	A10B10	38 MM FROM B10	165
36	8	STRAIGHT	VT A7	A7	170
38	9	STRAIGHT	A65	34 MM FROM A6	169





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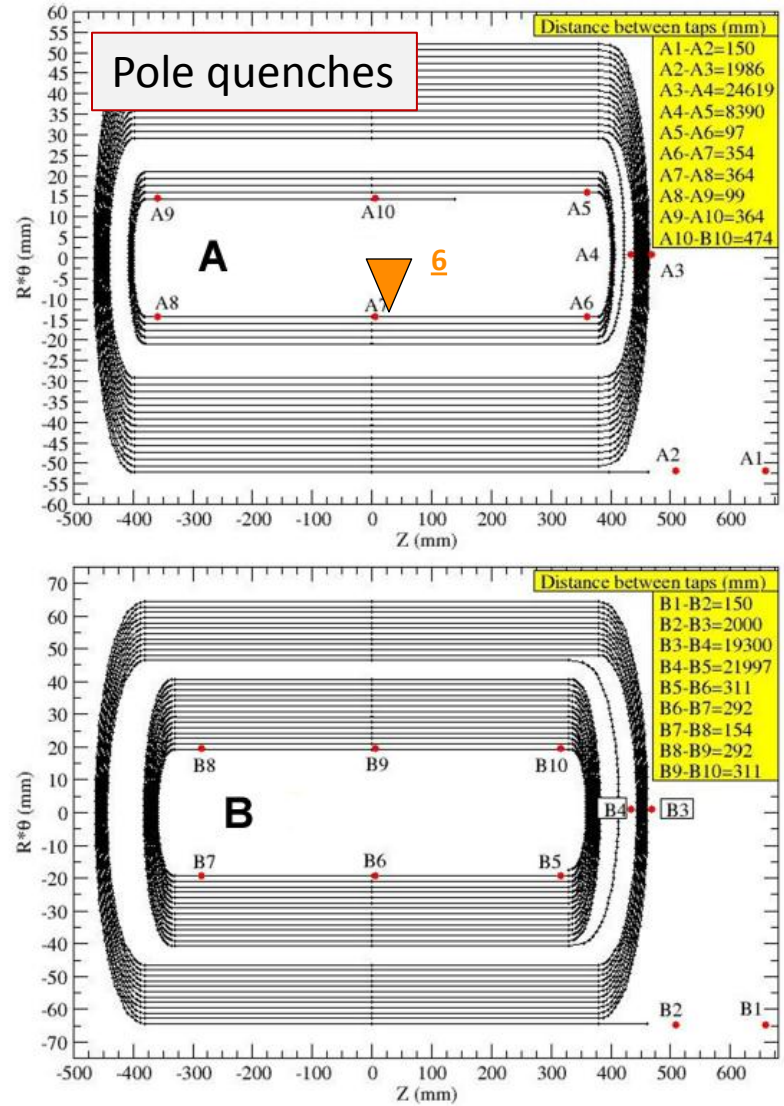
HQ01e quench locations

A#	COIL	SECTION	SEGMENT	LOCATION	GRADIENT (T/M)
1	**8**	STRAIGHT	A76; A87	A7	168
2	**8**	STRAIGHT	A76; A87	A7	168
4	**7**	LE	A23	MIDPLANE	168
5	**8**	STRAIGHT	A76; A87	A7	168
6	**8**	STRAIGHT	A76; A87	3CM FROM A7 TO LE	169
7	**8**	STRAIGHT	A76; A87	5CM FROM A7 TO LE	169
RR06	**7**	LE	B52	MIDPLANE	158
8	**7**	LE	A23; B52	MIDPLANE	164
10	**7**	LE	A23	MIDPLANE	166
11	**8**	STRAIGHT	A76; A87	A7	168



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HQ01e2 quench locations

Quench			1.9 K	Start position		
No.	Gradient	Current	dI/dt	Coil	Pole	Precursor
(-)	[Tesla/m]	[A]	[A/s]	(-)	(-)	Volt. Taps
1		14447	20	7	Inner	A03-A02
2		15070	20	7	Inner	A03-A02
3		15110	20	7	Inner	A03-A02
4		15098	20	7	Inner	A03-A02
5		15472	5	8	Inner	A03-A02
6		15424	5	8	Ramp	A10-b10
7		15563	5	9	Inner	a08-a07
8		15615	5	8	Inner	A07-A08
9		15628	5	9	Inner	A07-A06
10		15761	5	5	Inner	A06-A08
11		15560	5			
12		15449	5	7	Inner	A03-A02
13		14682	5	7	Inner	A03-A03
14		15740	5	7	Inner	A03-A03
15		15761	5	9	Inner	A07-A06
16		15838	5	8	Ramp	A10-B10
17		15918	5	9	Inner	A07-A06
18		15928	5	9	Inner	A07-A06
19		15341	5	5	Inner	A02-A03
20		15891	5	9	Inner	A07-A06
21		15943	5	9	Inner	A07-A06
22		16063	5	8	Inner	A07-A08
23		14337	20	7	Inner	A03-A02
24		14493	20	7	Inner	A03-A02
26		14680	13	7	Inner	A03-A02
28		16066	13	5	Inner	A02-A03
29		15783	13	7	Inner	A04-A03
30		15421	13	7	Inner	A02-A03
31		15197	13	7	Inner	A02-A03
37		16120	5	7	Inner	A02-A03
38		16144	5	9	Inner	A08-07
39		16216	5	8	Outer	B05-B04
40		16202	5			

Quenches at 4.3 K			4.3 K			
Quench				Start position		
No.	Gradient	Current	dI/dt	Coil	Pole	Precursor
(-)	[Tesla/m]	[A]	[A/s]	(-)	(-)	Volt. Taps
18		13953	20	7	Inner	7 A04 -A03
19		13941	20	7	Inner	7 A04 -A03
20		14620	20	8	Inner	A03-A06
21		14618	20	8	Inner	A06-A07
22		13831	20	7	Inner	A04-A03
23		14681	5	8	Inner	A06-A07
24		14681	5	8	Inner	A06-A07
25		14670	5	8	Outer	B05-04
26		14666	5	8	Inner	A06-A07
27		14669	5	8	Inner	A06-A07
28		13909	20	7	Inner	A04-A03

HQ coil mirror tests

- **HQM01**: Coil 12 - coil with cored cable, ~80% of SSL. Anomalous "maximum" in quench performance around 100 A/s ramp-rate, reaching ~14.2 kA. "Holding quenches" between 14.0 and 14.2 kA
  - → *Introduced 2.2 mm axial gap*
  - → *Increased space per turn for ~5%*
  - → *Core material was removed from the splice regions*

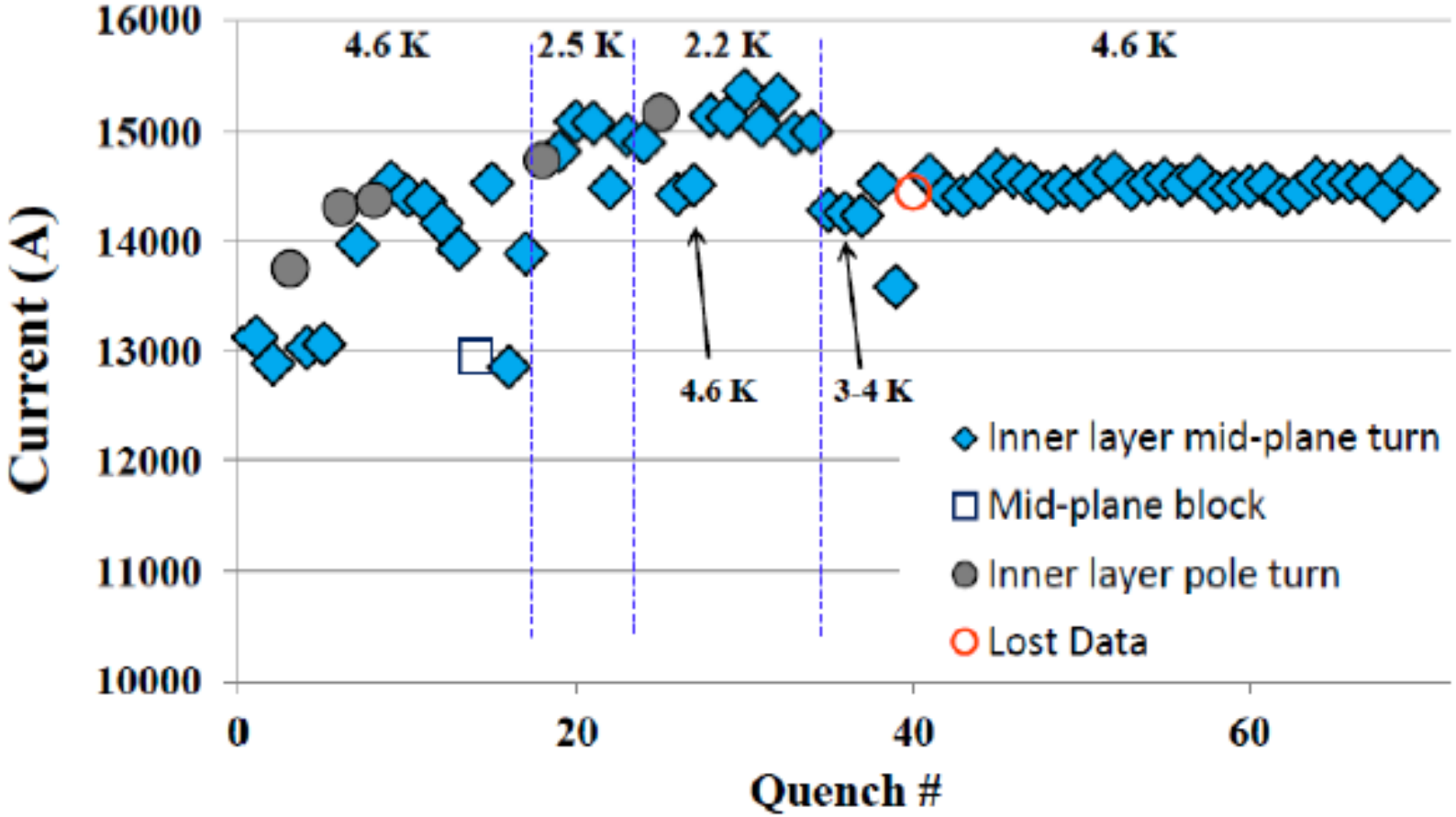
- **HQM02**: Coil 13. Reached 91% of SSL at 4.6 K and 89% at 2.2 K

- **HQM03** – never happened, as Coil 14 was found to be electrically faulty

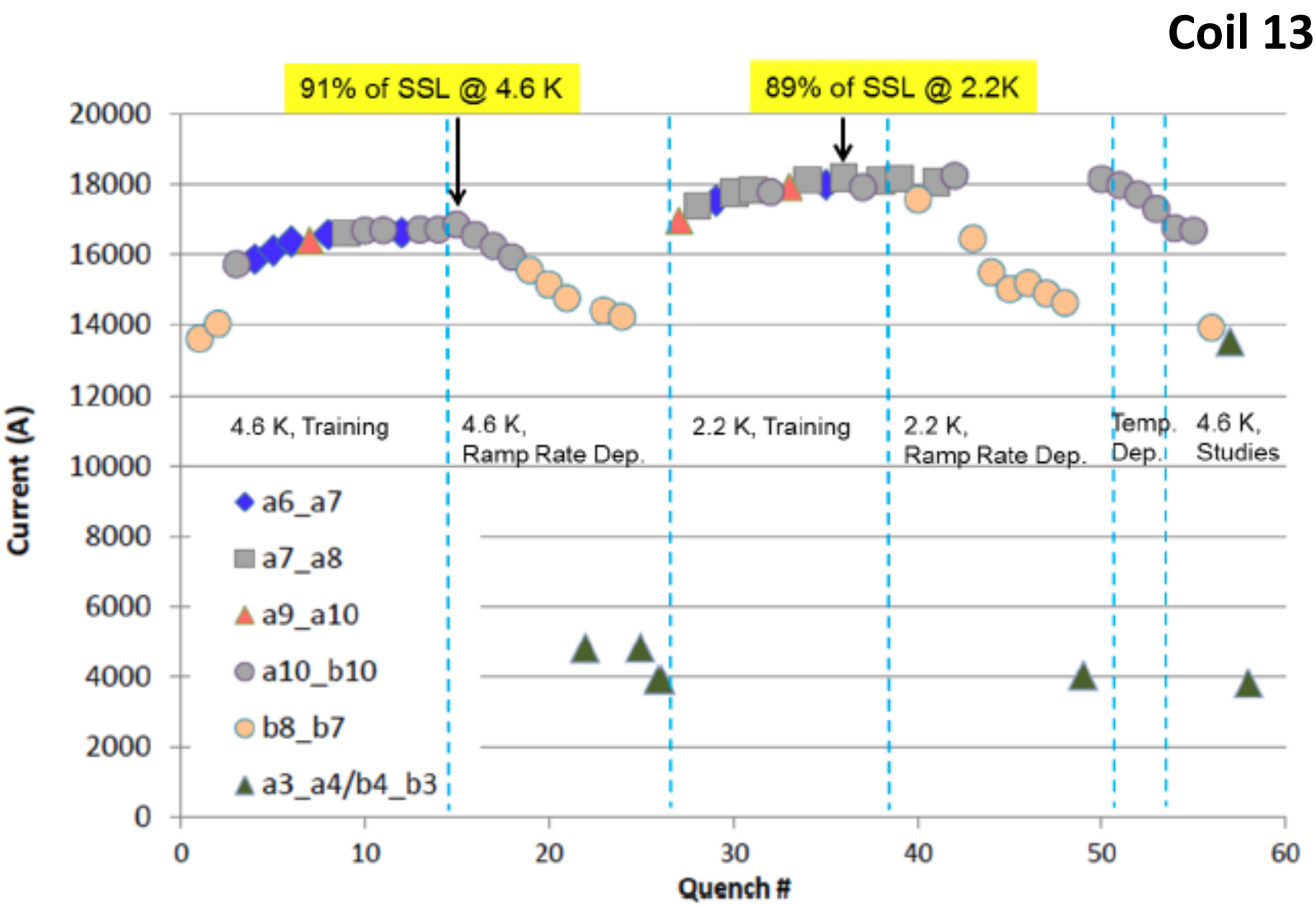
- **HQM04:** Coil 15. In progress, reached 96% of SSL.

Quench locations HQM01

Coil 12



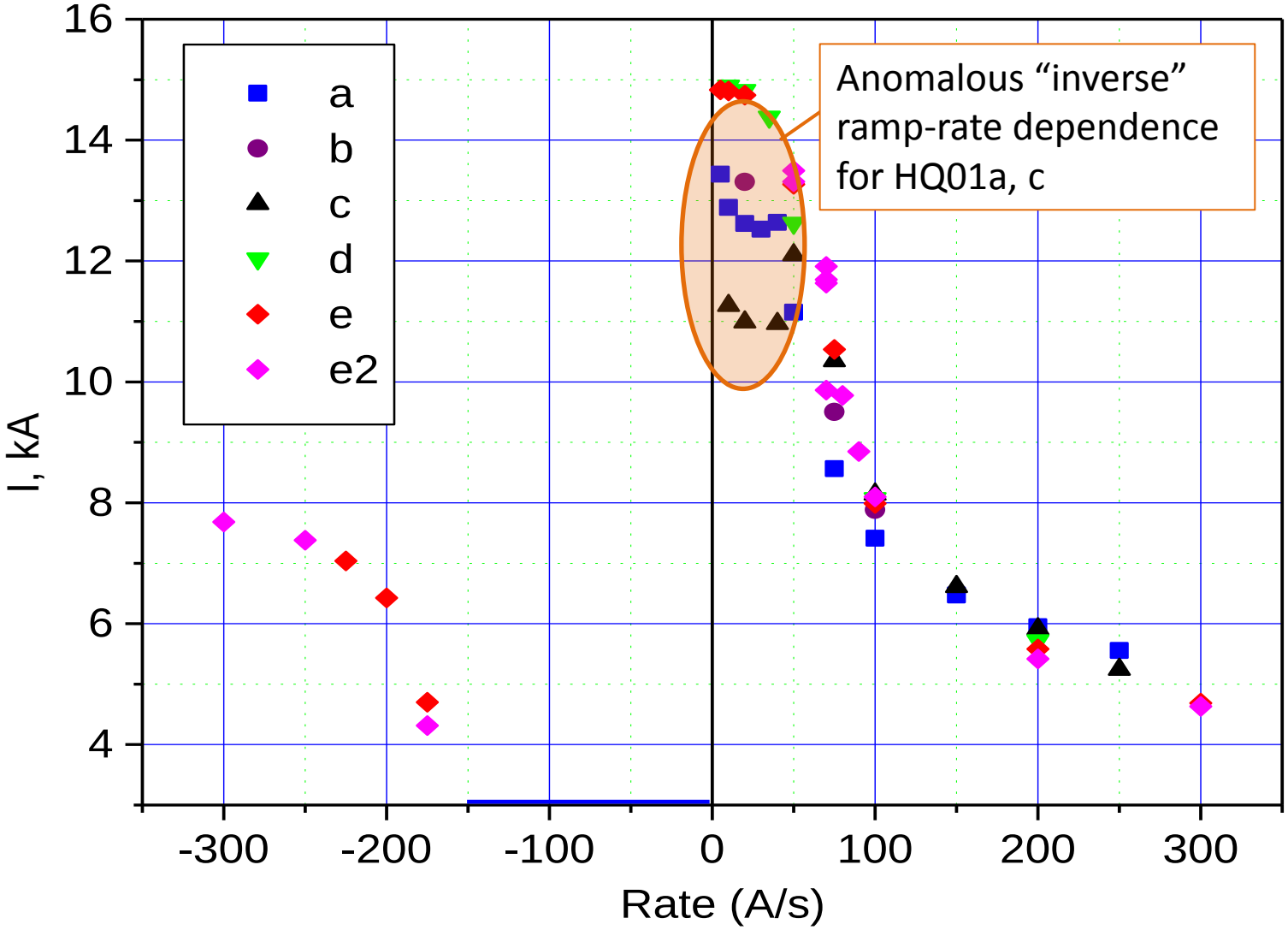
Quench locations HQM02



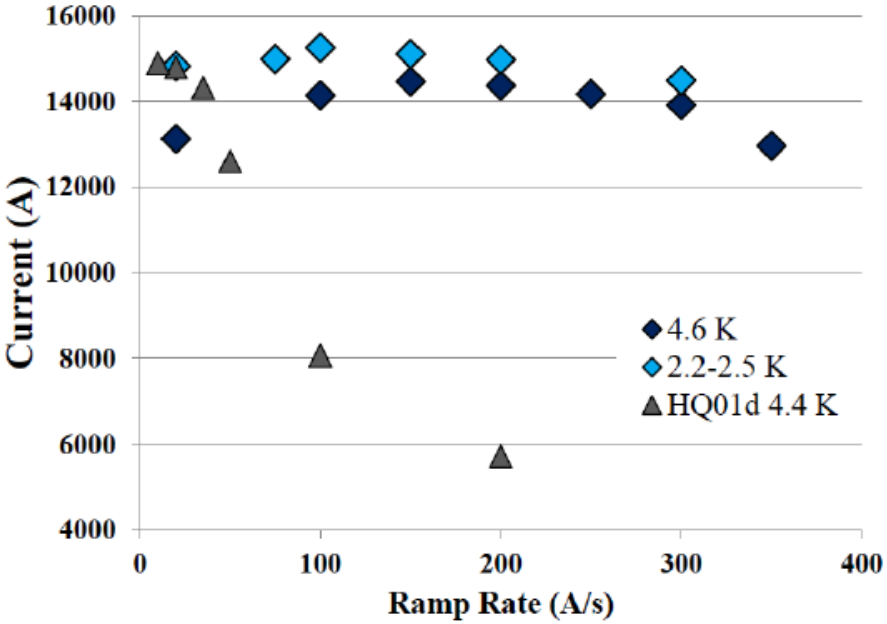
HQ test table – full summary

Test name		Date	Coils #	Max I_q(A)	Max I_q % ss	Max grad (T/m)	# of training quenches (to the plateau)	Quench locations	
								MT	Pole
HQ01a		05/10	1,2,**3**,4	13680	79	**156**	15 (6)	15	0
HQ01b		06/10	1,4,5,6	13308	77	**152**	3 (-)	2	1
HQ01c		10/10	1,5,7,**8**	12099	70	**139**	28 (-)	28	0
HQ01d		04/11	5,7,**8**,9	14892	86	**170**	28 (15)	5	23
HQ01e		07/11	5,7,**8**,9	14830	86	**169**	10 (1)	4	6
HQ01e2	**4.3 K**	04/12	5,**7**,8,9	14681	85	**167**	11 (1) *4.5 K*	6	5
	1.9 K			16262	85	**184**	33 (33) *1.9 K*	17 (+2?)	14
HQM01	**4.6 K**	05/11	12	13068	85	----		14	3
	2.2 K			14822	81			10	1
HQM02	**4.5 K**	09/11	13	16858	91	----	14 (10)	0	14
	2.2 K			18182	89		12 (8)	0	12
HQM04		04/12	14		96	In	progress…		

Ramp-rate dependence (HQ magnet)

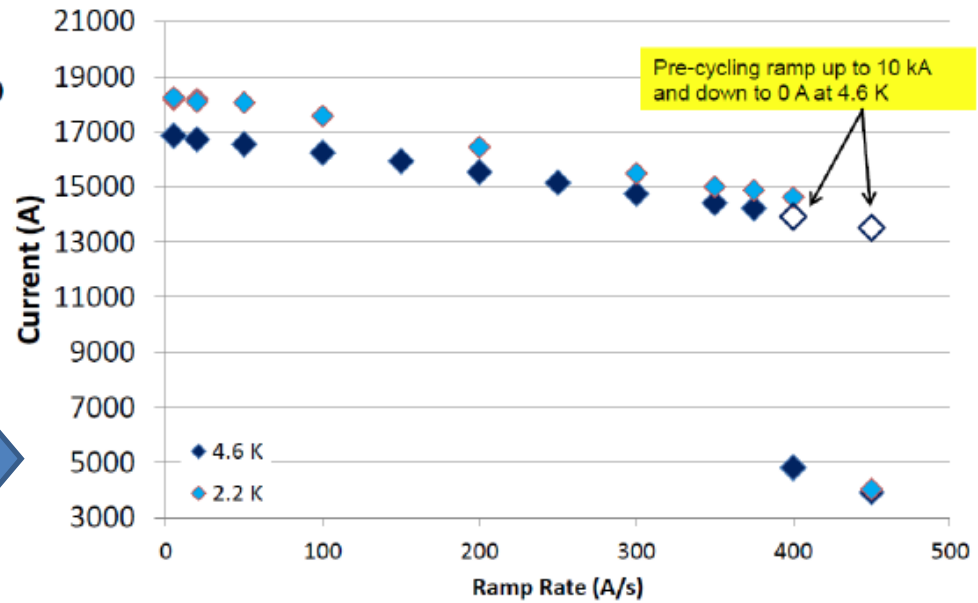


Ramp-rate dependence (mirror tests)

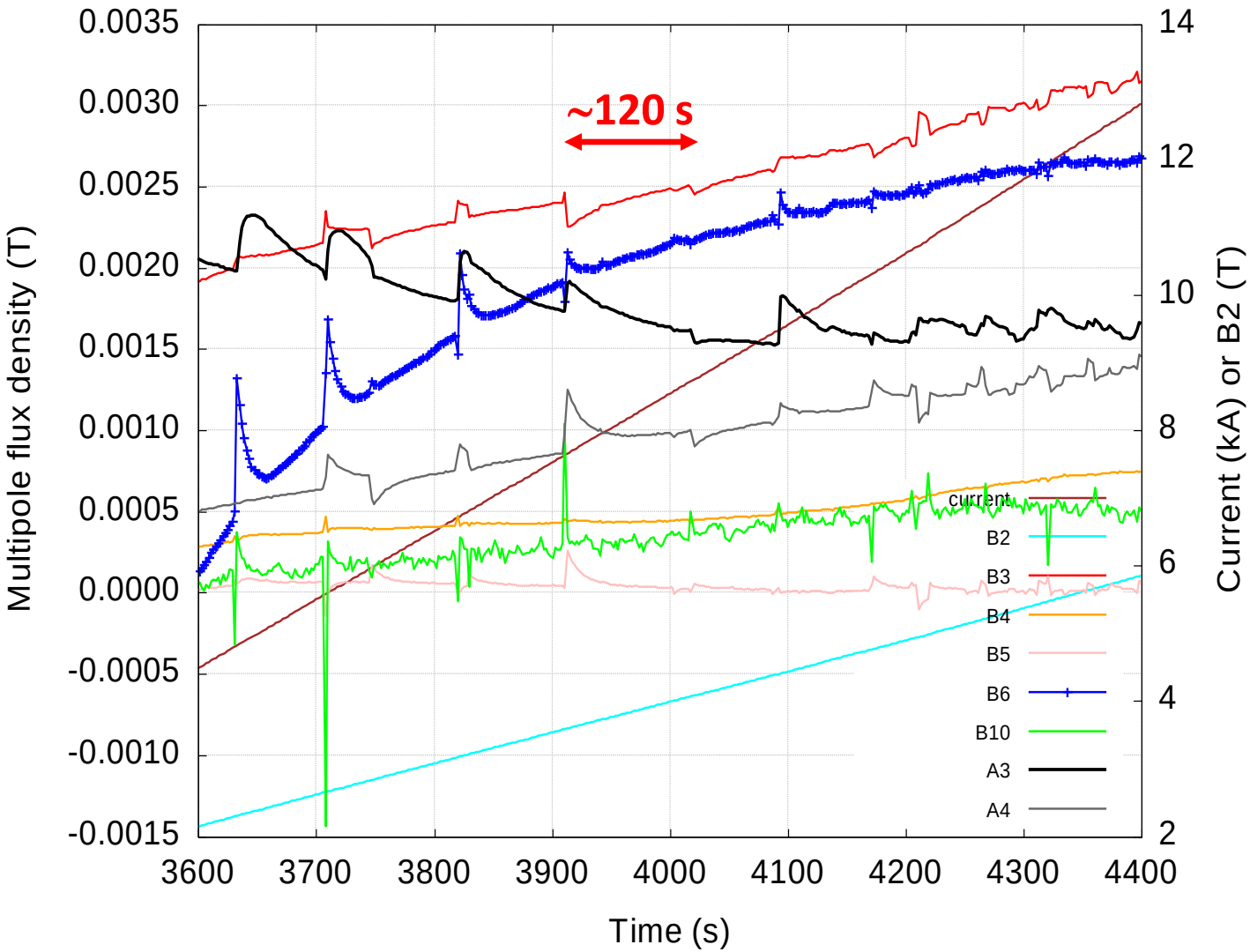


HQM01 – Coil 12

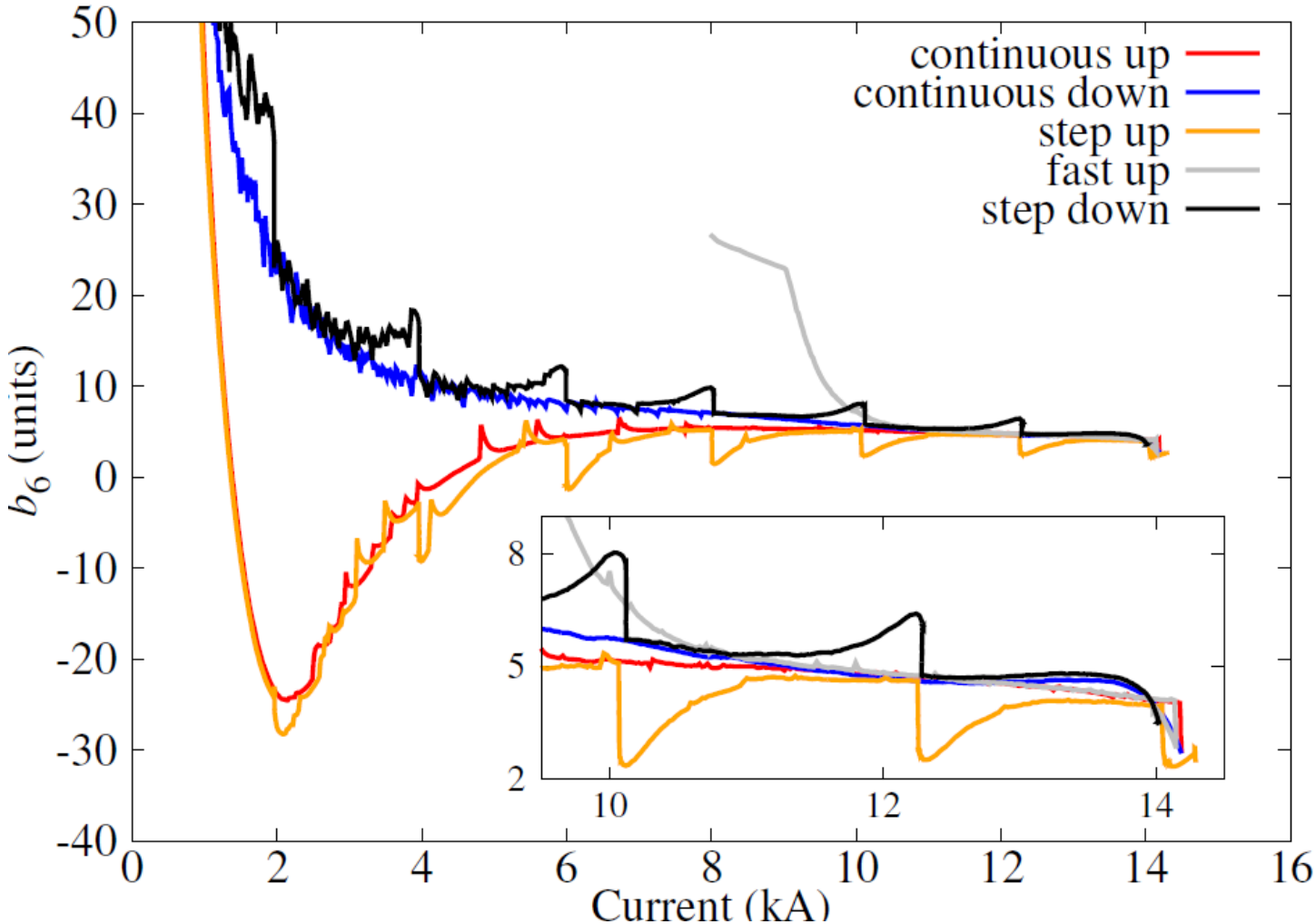
HQM02 – Coil 13



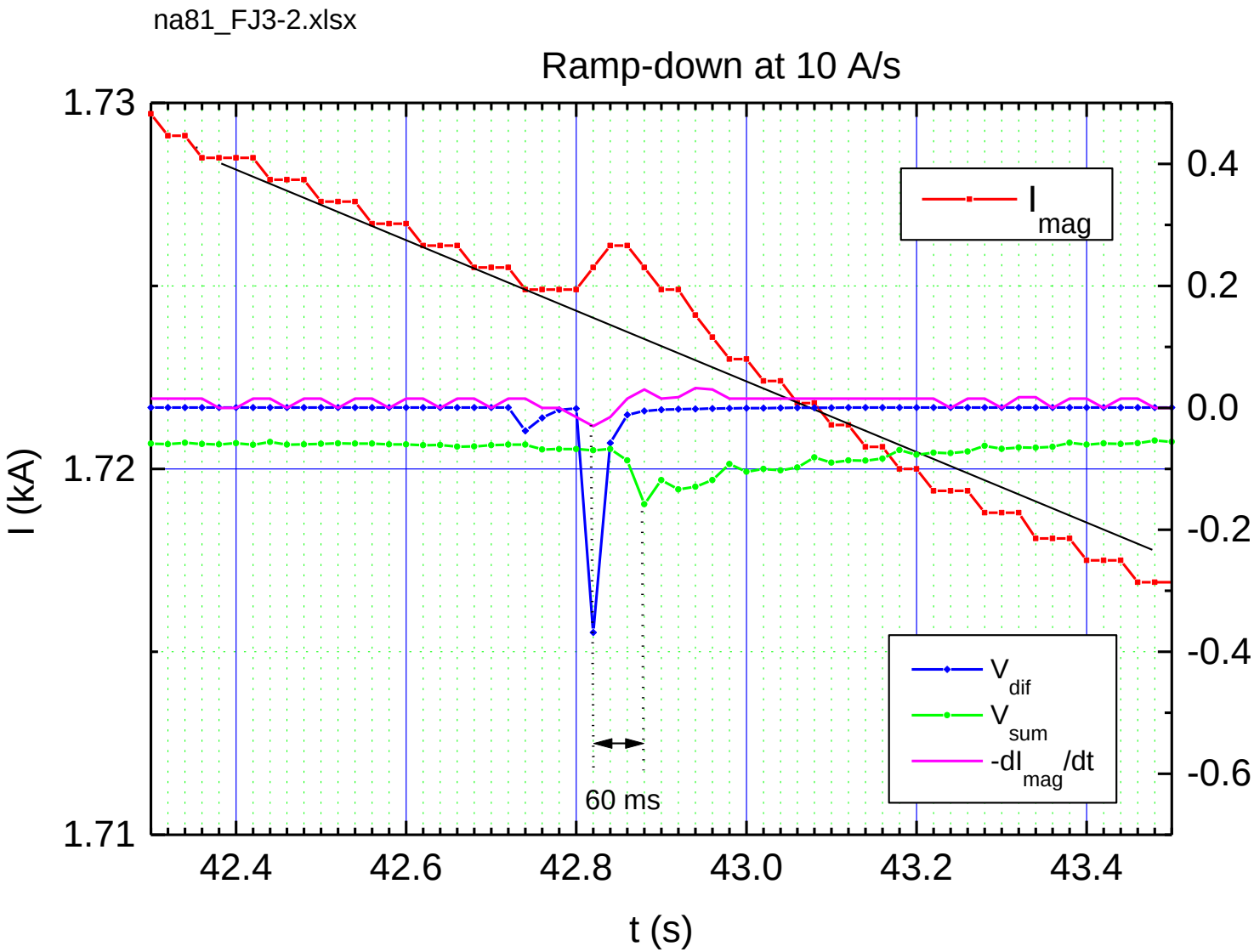
Field spikes during the ramping



Spikes and relaxation during the stair-step measurement



Flux jump and power supply response



Results to date

- We have successfully addressed an electrical insulation issues seen in the first HQ01a,b tests
- We have adjusted tension in the cable by increasing axial gaps and amount of space per turn, to eliminate strand damage in the outer turn during reaction / impregnation
- We have shown performance of 83-84% of short sample at max gradient of above 170 T/m at 4.5 K and 184 T/m at 1.9 K in HQ magnets and up to 96% in the mirror
- We have shown that the HQ magnet can be operated at 1.9 K and the presently used cable does not show an instability
- Repeatability of magnetic cycle at 1.9 K; acceptable harmonics for accelerator use

Remaining questions

- Origin of relatively long training in HQ magnets; pole turn quenches at 10-15% below SSL. Origin of occasional “de-training” manifested with the mid-plane quenches.
- “Inversion” of the ramp-rate dependences seen in HQ01c,d and HQM01. Holding quenches.
- AC losses and their distribution within the magnet. Role of current plateaus in training performance
- Origin of very long relaxation time of the field harmonics in response to the current change and/or flux jumps.
- Flux jumps: statistics, localization and temperature dependence of amplitude. Connection between flux jumps and magnet inductance variation; role of power supply regulation in achieving required stability.
- Persistent-current effects at the injection level

Open for discussion…