Training the dipoles

- Training during HWC

- Estimate to reach 6, 6.5, and 7 TeV

- Quench propagation

Arjan Verweij, TE-MPE

Acknowledgment to everybody involved in the HWC

Quench

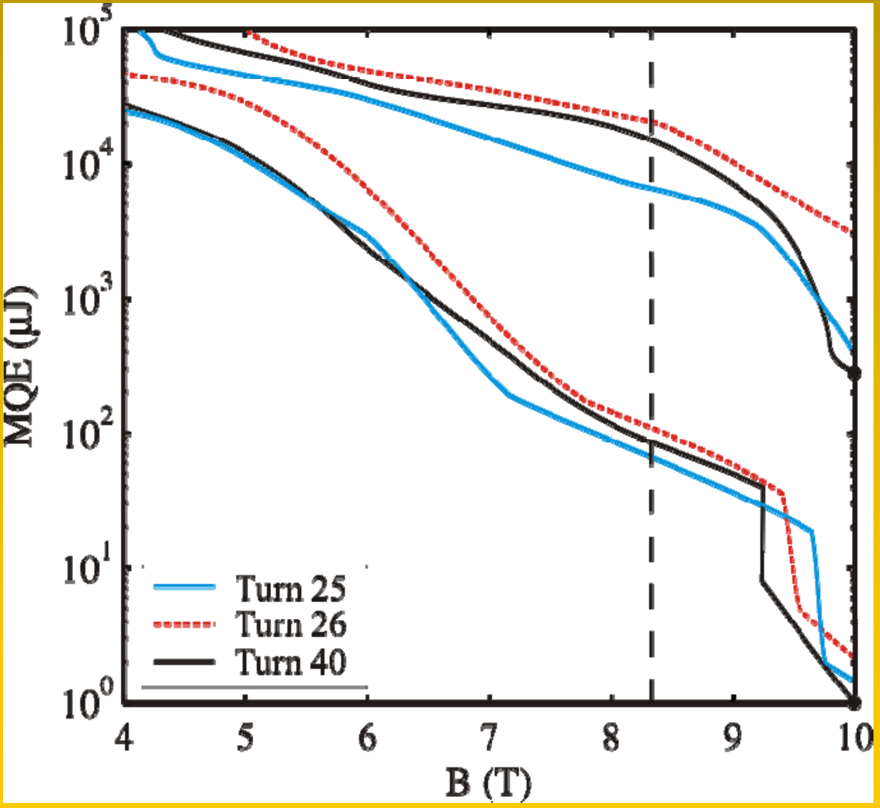
Dipole Quench: Transition from the superconducting to the normal state (usually due to local temperature rise), resulting in a detectable resistive voltage, exceeding the threshold voltage for a duration larger than the discrimination time.

Quench classification:

- Heater induced/provoked quench
- Natural (training) quench
- Secondary quench (due to increase of the bath temperature, ramp rate, etc)
- (Beam induced quench)

Circuit quench: Heater induced/Natural quench + secondary quenches.

A local energy deposition of about 100 μJ is enough to trigger a quench (i.e. a falling raindrop of 2 mm diameter).

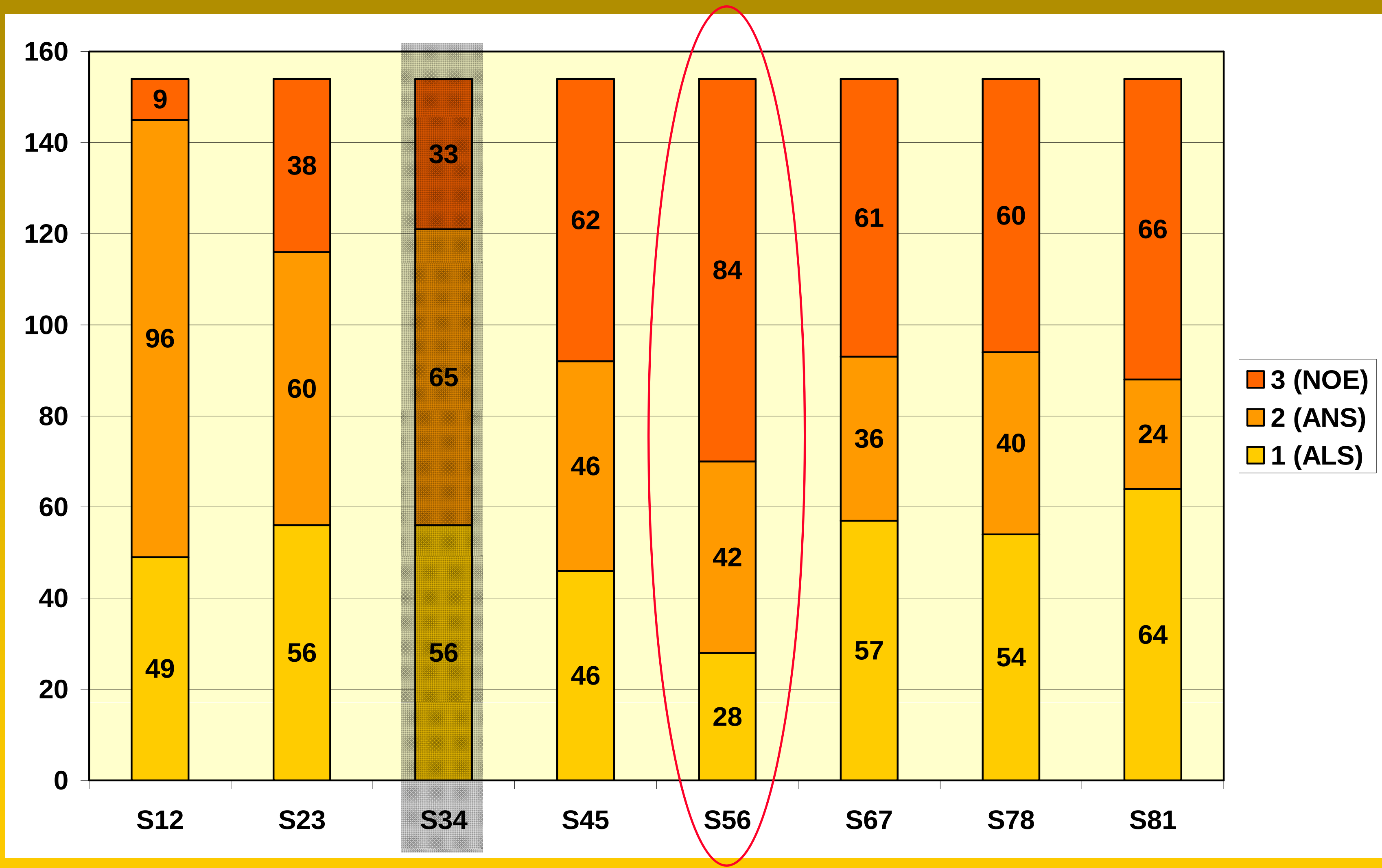


Calculations based on experiments, G. Willering, PhD thesis 2009

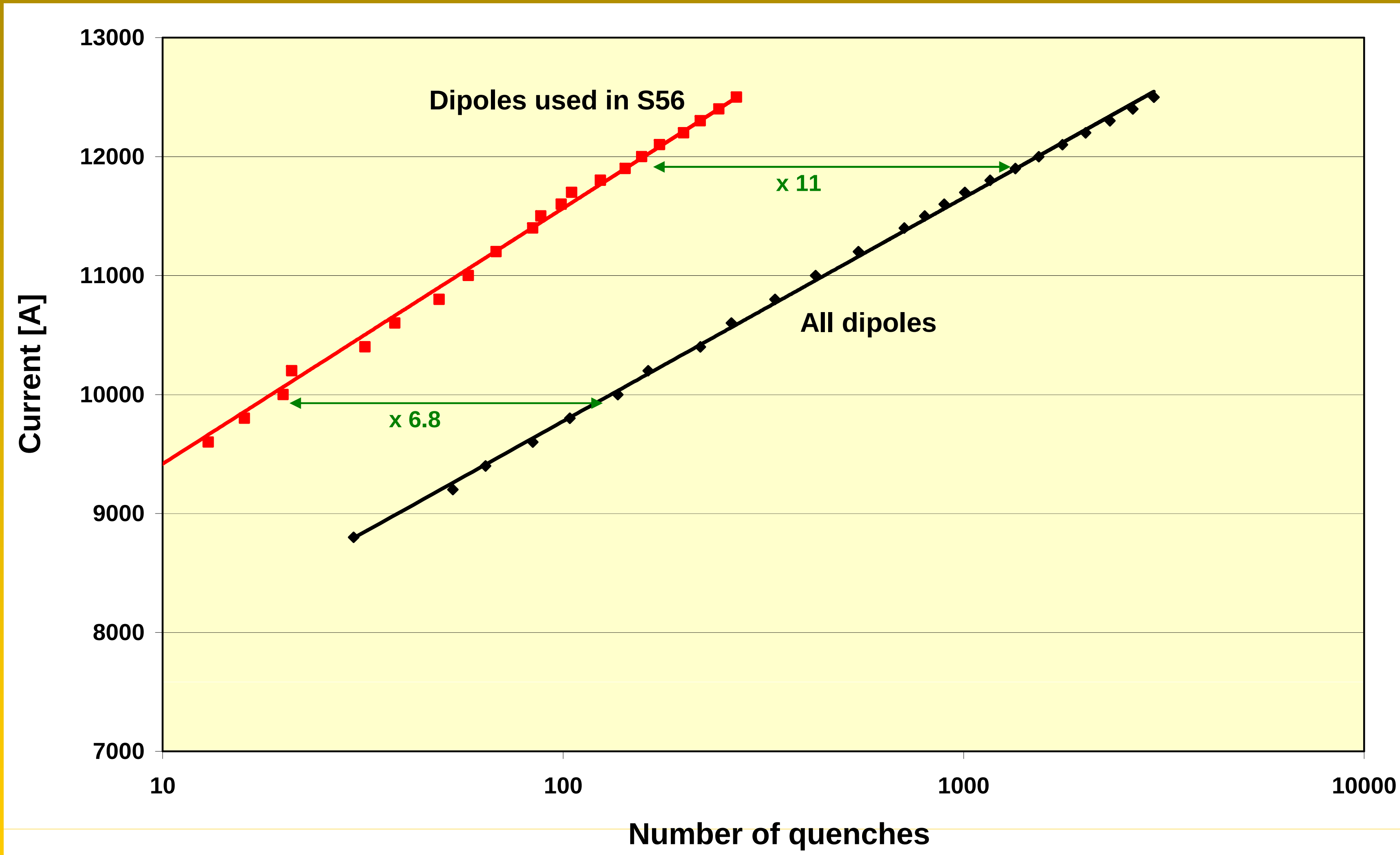
RB circuit quenches during HWC

Sector	1st training quench [A]	I_max [A]	# training quenches	Starting in:		
				# ALS	# ANS	# NOE
1-2	-	9310	0	0	0	0
2-3	-	9310	0	0	0	0
3-4	-	8715 (bus)	0	0	0	0
4-5	9789	10274	3	0	0	3
5-6	10004	11173	27	0	1	26
6-7	-	9310	0	0	0	0
7-8	8965	9310	1	0	1	0
8-1	-	9310	0	0	0	0

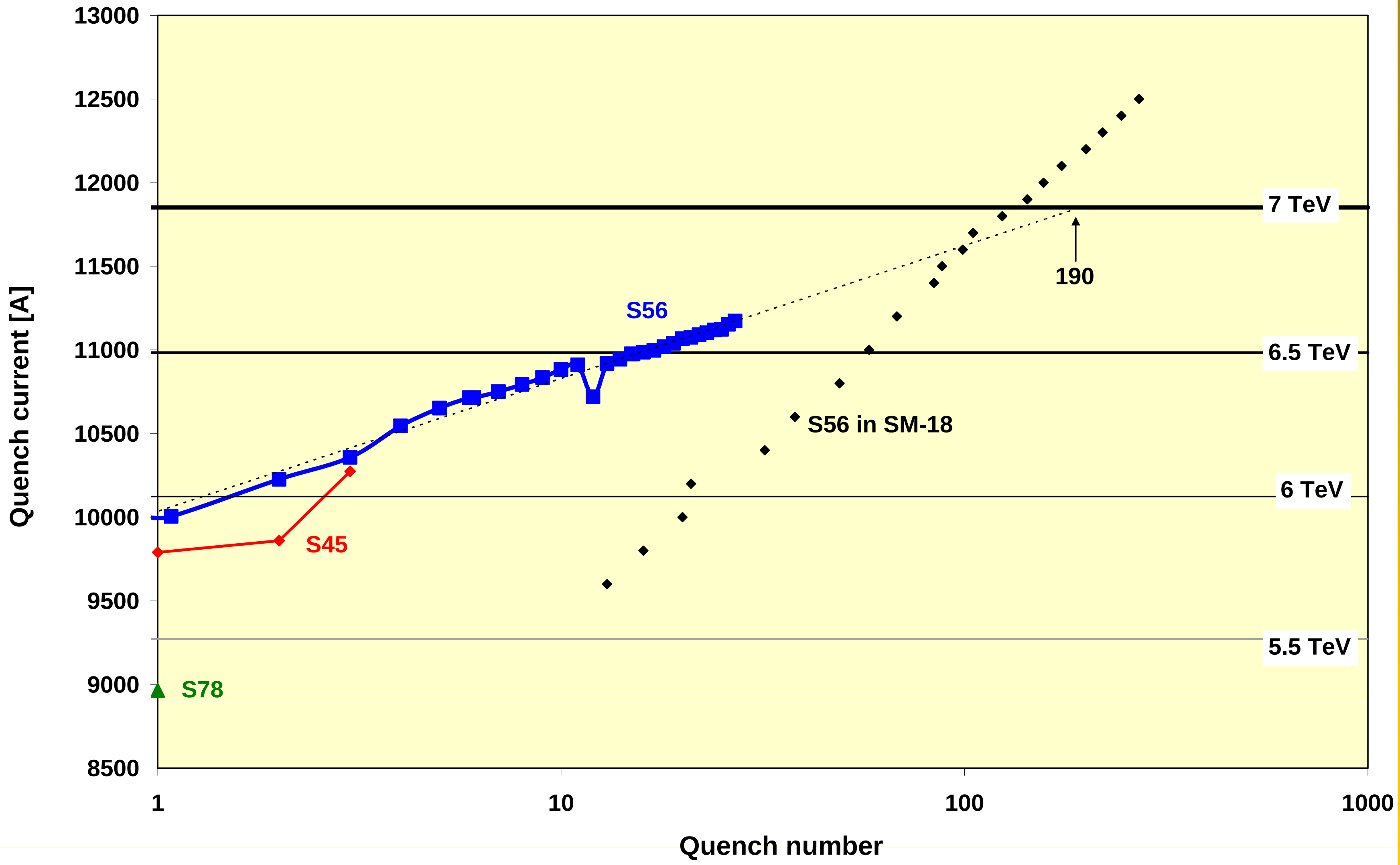
Magnet distribution per sector



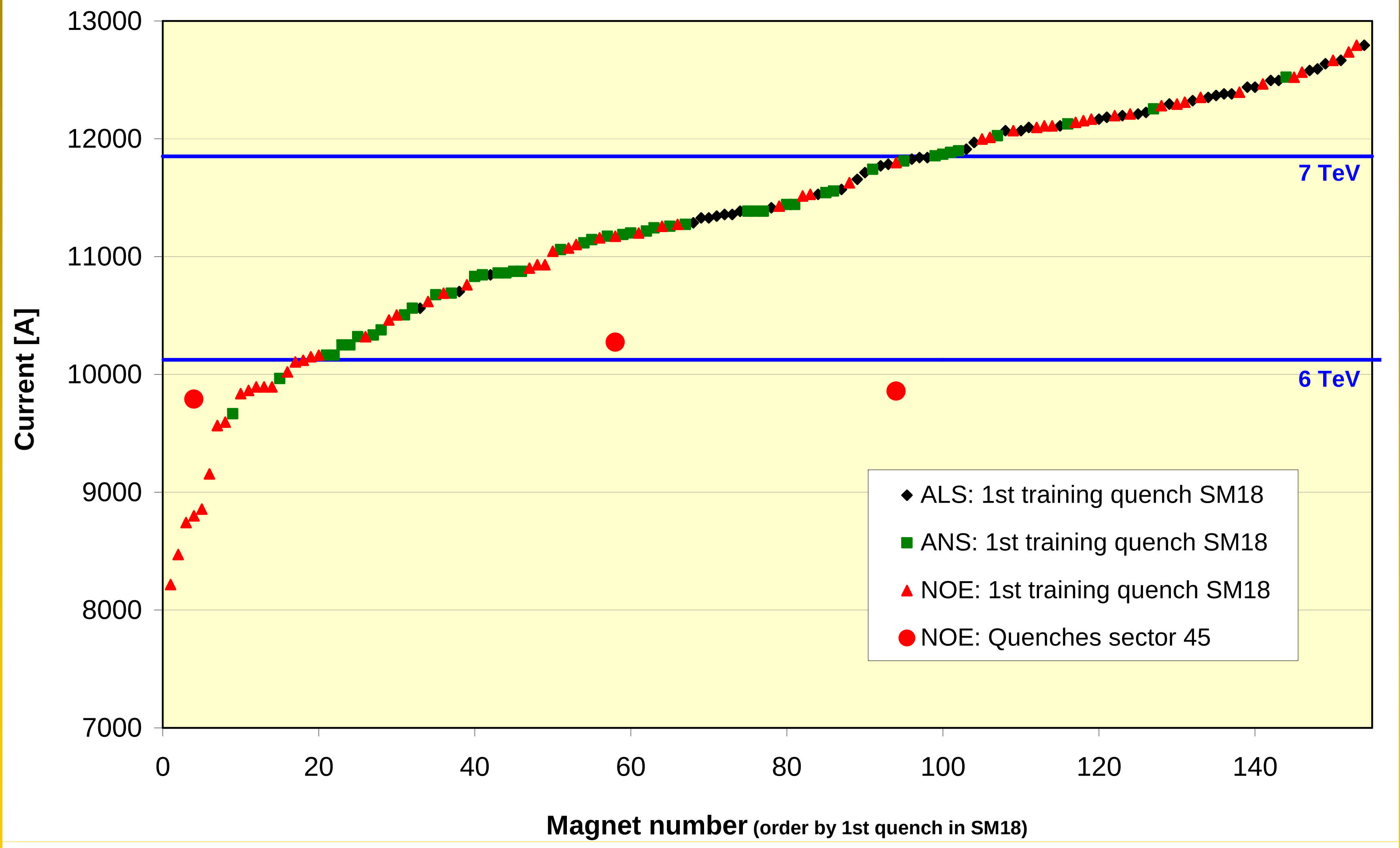
Nr. of quenches in SM-18 to reach given current



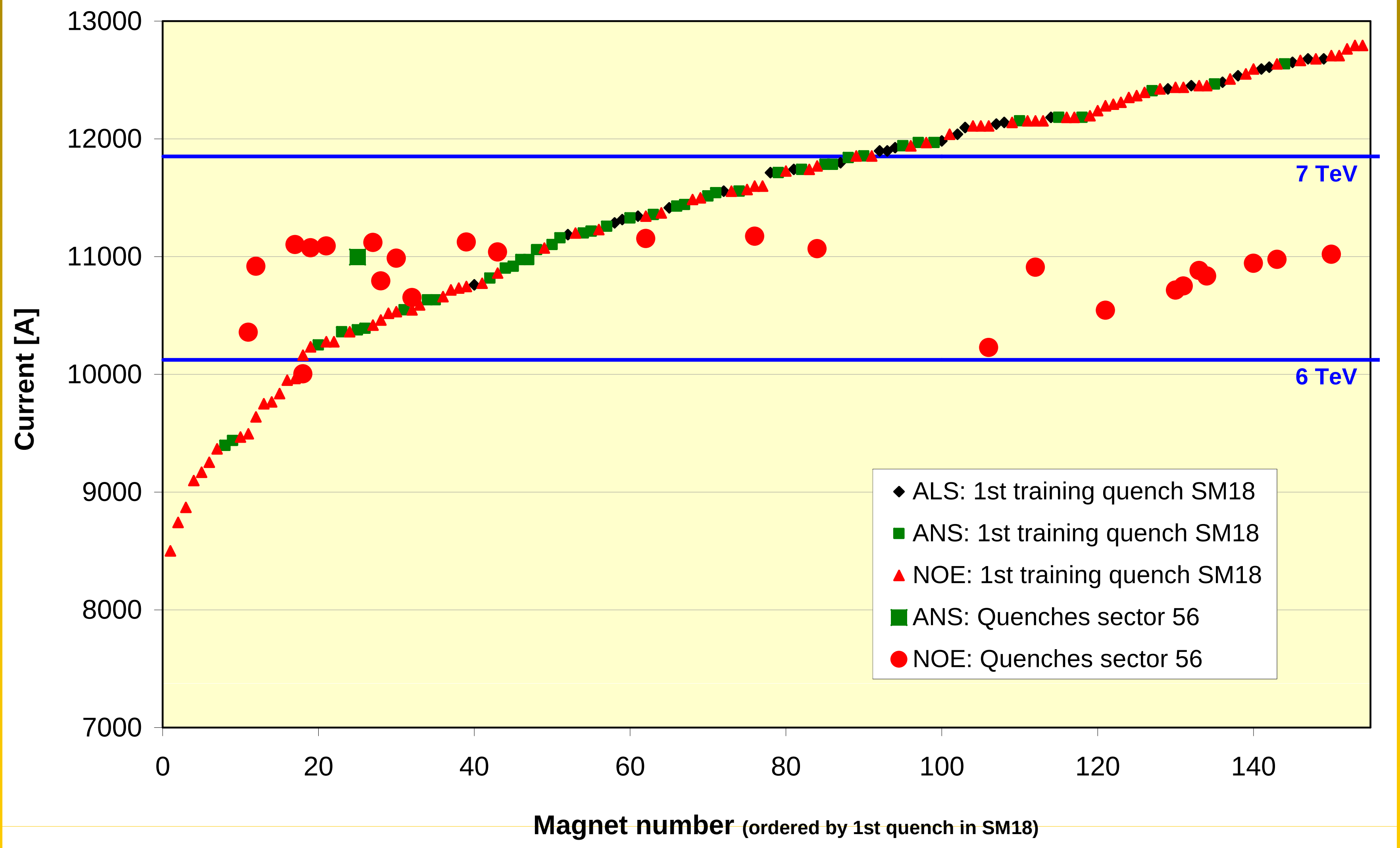
Training during HWC



RB circuit S45: comparison with SM-18

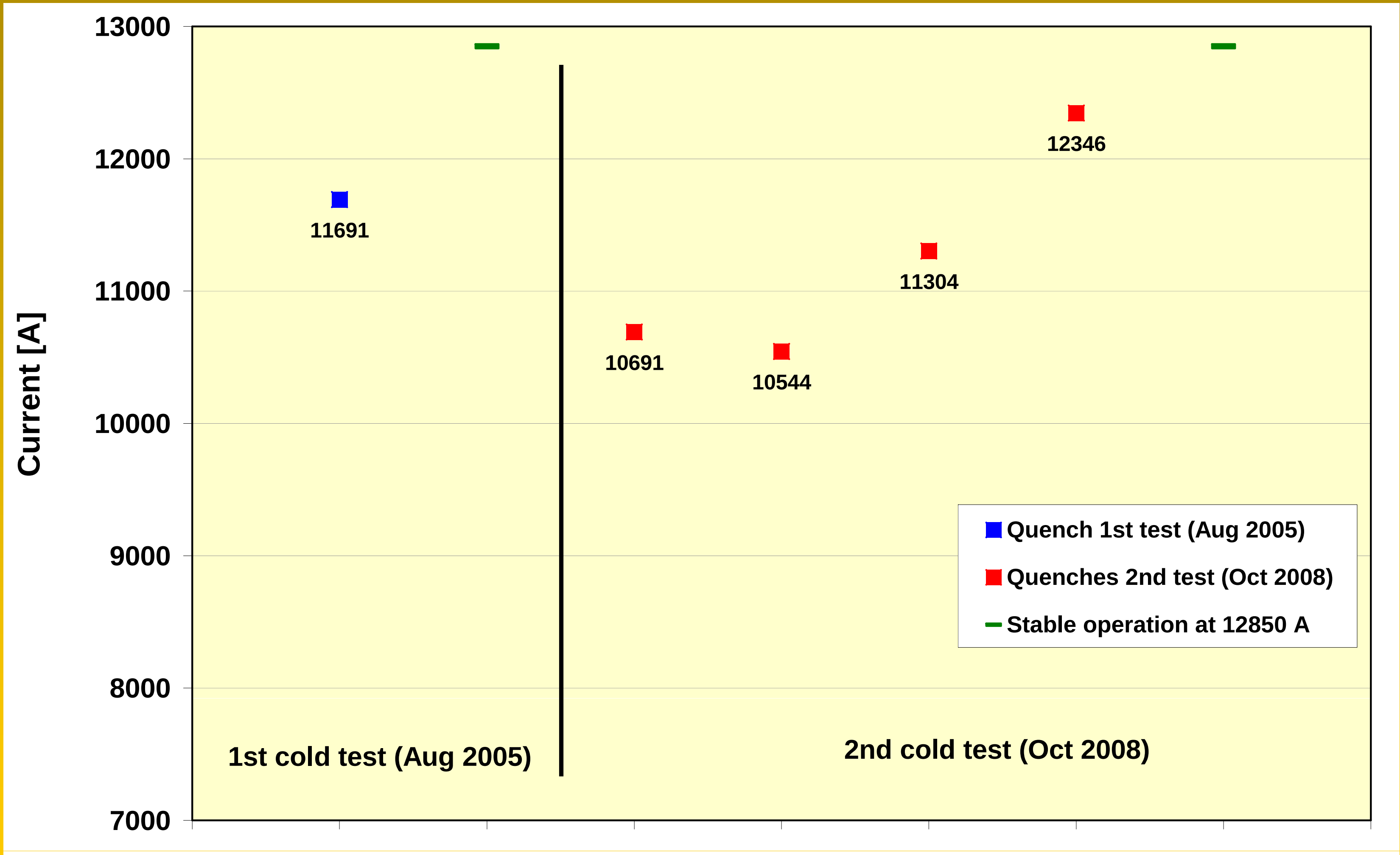


RB circuit S56: comparison with SM-18



Retesting of NOE magnet 3383 in SM-18

Note: 3383 suffered a transport accident, during which diode, IFS box and N-line were damaged



Data from N. Catalan Lasheras

Estimated dipole training to reach 6 and 6.5 TeV

Sector	Number of magnets			Number of quenches	
	ALS	ANS	NOE	@ 6 TeV (±2)	@ 6.5 TeV (±30%)
1-2	49	96	9	0	4
2-3	56	60	38	1	8
3-4	56	65	33	1	8
4-5	46	46	62	2	12
5-6	28	42	84	1	15
6-7	57	36	61	2	12
7-8	54	40	60	2	12
8-1	64	24	66	2	13
Total	**154**	**154**	**154**	**11**	**84**

Est. 1: Based on 115 MB's that have been submitted to a thermal cycle in SM-18 (2008 before HWC, P. Xydi and A. Siemko)

Est. 2: Extrapolation from sector 5-6 data + est. 1 for ALS & ANS

Est. 3: 2 quenches per NOE magnet + est. 1 for ALS & ANS

Est. 4: 3 quenches per NOE magnet + est. 1 for ALS & ANS

Estimated dipole training to reach 7 TeV

Sector	Number of magnets			Number of quenches			
	ALS	ANS	NOE	Est. 1	Est. 2	Est. 3	Est. 4
1-2	49	96	9	22	41	40	49
2-3	56	60	38	23	97	92	130
3-4	56	65	33	21	87	83	116
4-5	46	46	62	22	145	136	198
5-6	28	42	84	21	190	178	262
6-7	57	36	61	20	142	133	194
7-8	54	40	60	14	140	132	192
8-1	64	24	66	19	151	142	208
Total	**154**	**154**	**154**	**162**	**993**	**936**	**1349**

The number of "circuit quenches" might be a bit smaller as compared to the number of "dipole quenches" due to "parallel training" of 2 or more dipoles during the same circuit quench.

Est. 1: Based on 115 MB's that have been submitted to a thermal cycle in SM-18 (2008 before HWC, P. Xydi and A. Siemko)

Est. 2: Extrapolation from sector 5-6 data + est. 1 for ALS & ANS

Est. 3: 2 quenches per NOE magnet + est. 1 for ALS & ANS

Est. 4: 3 quenches per NOE magnet + est. 1 for ALS & ANS

RB quench propagation

Cryogenic recovery time: see talk Serge Claudet

Almost instantaneous (within 1 sec)

Observed 11 times on 8 different magnets. Caused by:

- an almost equal quench current
- an unbalance > 100 mV (triggering the QPS) due to very different inter-strand coupling currents between the 2 apertures,
- traveling voltage waves due to the opening of the dump switches,
- other noise.

See also the talk of Karl Hubert Mess.

Through thermal propagation (typical delay 30-300 s)

Observed for all quenches > 6 kA.

Statistics for quenches > 9 kA:
propagation to 1 dipole: 3
propagation to 2 dipoles: 9
propagation to 3 dipoles: 15
propagation to 4 dipoles: 6
propagation to 5 dipoles: 1

Example thermal quench propagation (I_q=10274 A)

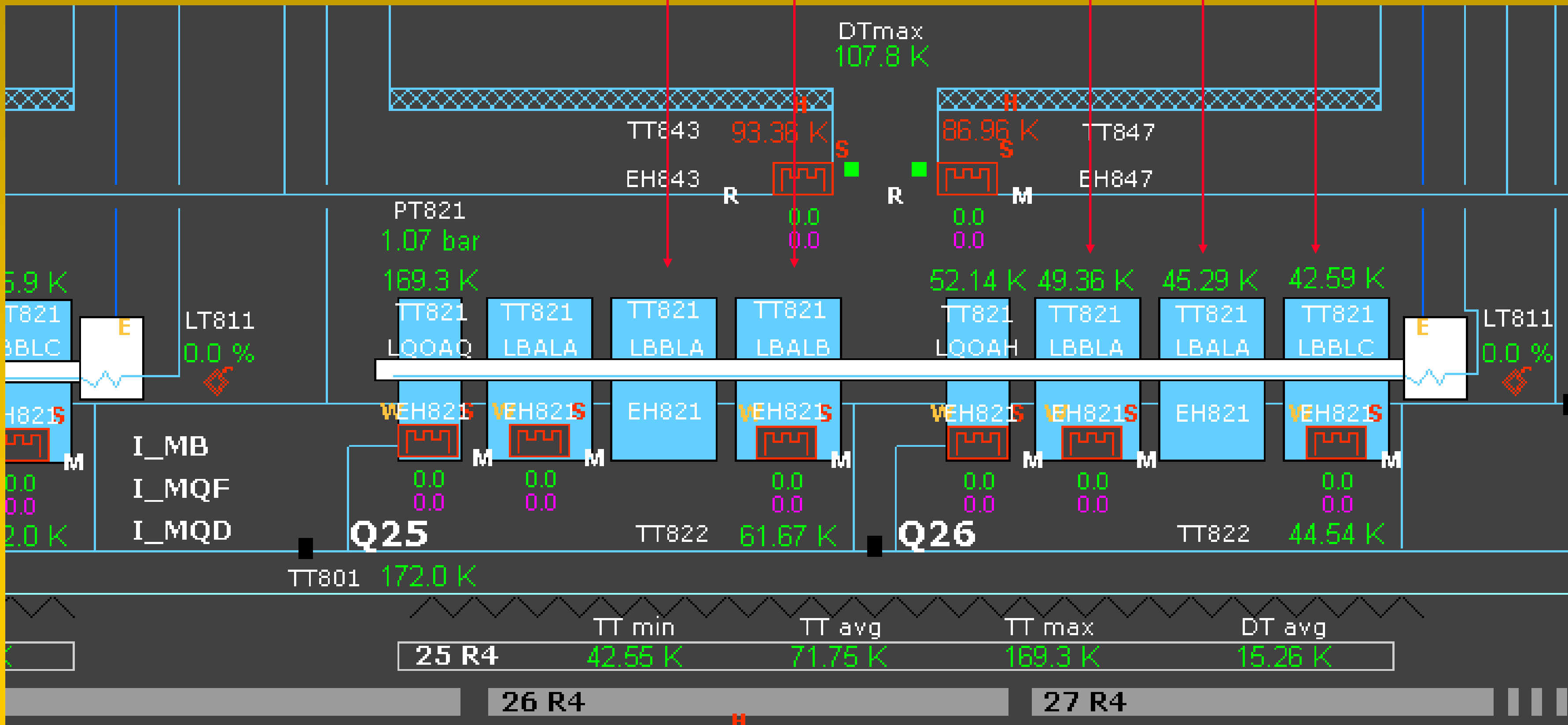
LBBLA.27R4: 0 s, 10274 A

LBALB.26R4: 109.1 s, 3330 A

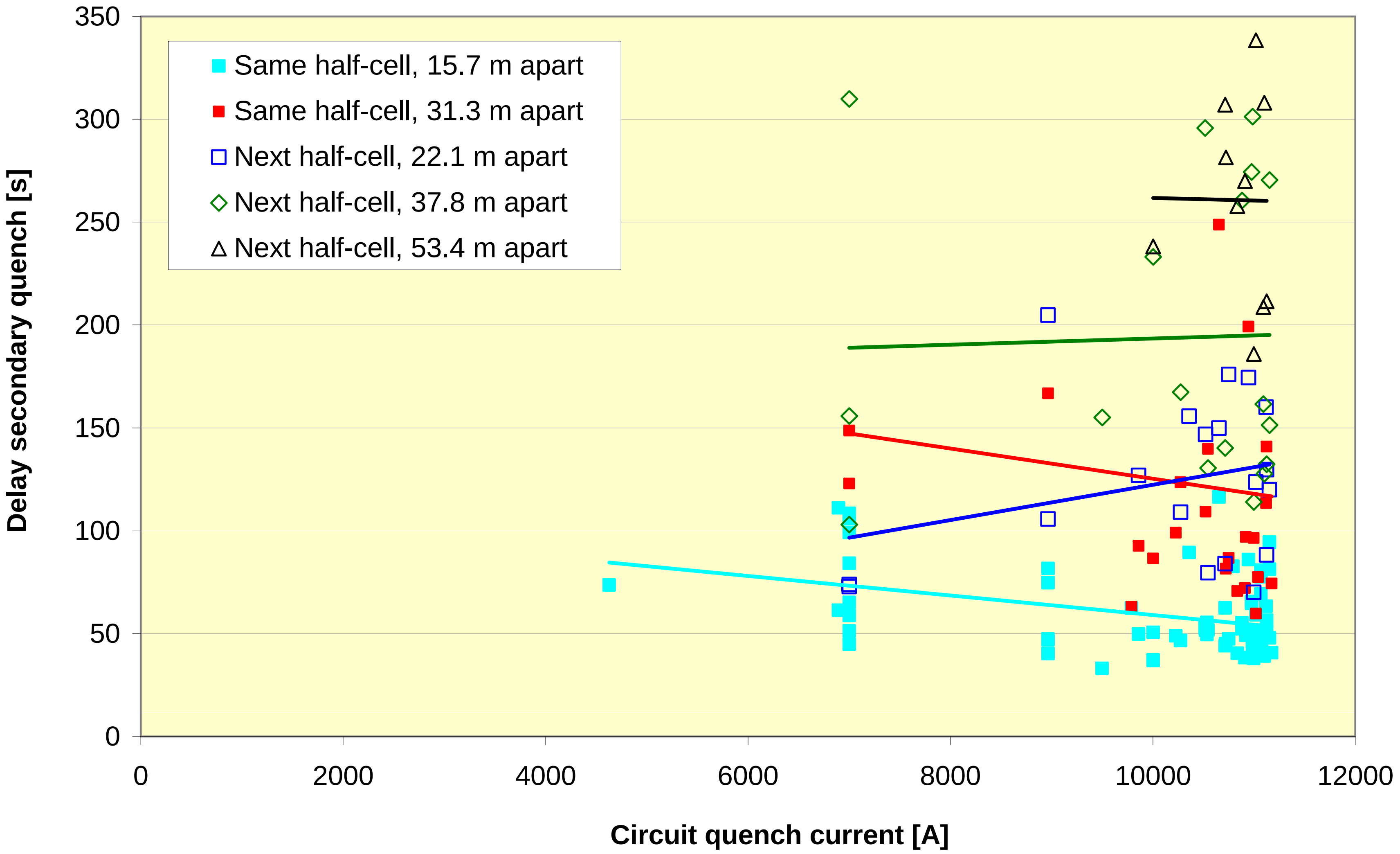
LBALA.27R4: 46.6 s, 6464 A

LBBLA.26R4: 167.4 s, 1748 A

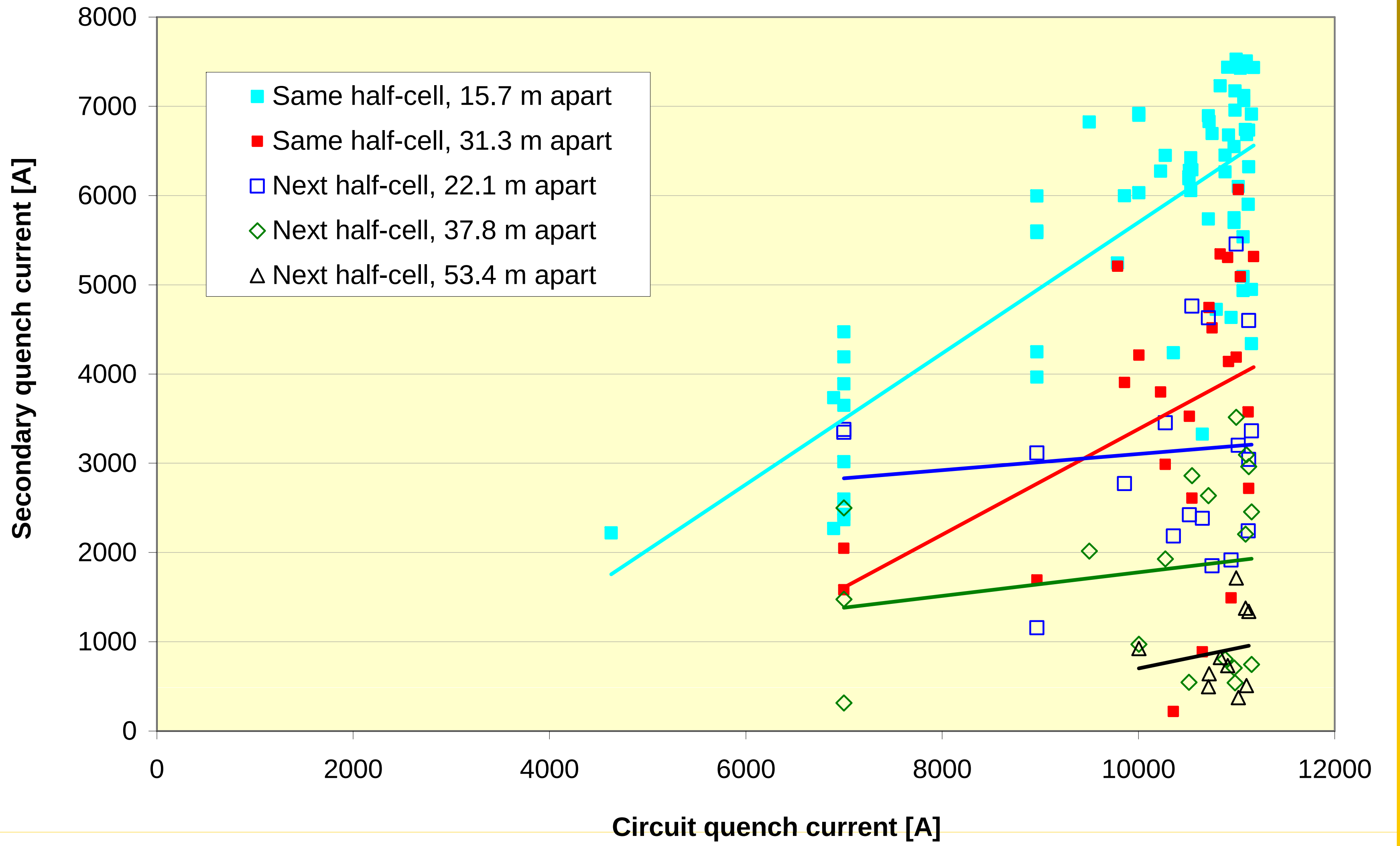
LBBLC.27R4:
123.5 s, 2844 A
(355.7 s, 238 A)



Thermal quench propagation



Thermal quench propagation



Reproducibility of thermal quench propagation

Quench starting in B30R7 at 3 different currents

	Quench at 6.9 kA	Quench at 7.0 kA	Quench at 9.0 kA
B30R7	0	0	0
C30R7	61.3 s	58.8 s	40.2 s
A30R7	111.1 s	108.4 s	47.0 s

Quench starting in C15R5 at 2 different currents

	Quench at 10.7 kA	Quench at 10.9 kA
C15R5	0	0
B15R5	45.1 s	38.3 s
A15R5	81.5 s	72.1 s
C14R5	281 s	270 s

High-field-heater firing

SM-18 at warm	1150
SM-18 at cold, 1500 A	1150
SM-18 at cold, training	4100
HWC at cold, 0 A	1700
HWC at cold, I > 0 A	240

Due to secondary quenching, each quench causes the firing of the heaters of about 4 magnets.

Conclusion: Dipole training

- 6 sectors reached 9310 A (5.5 TeV) without a quench. 1 sector showed 1 quench<9310 A, and in 1 sector a busbar joint opened/melted before reaching 9310 A.

- Training of S56 showed a completely unexpected behaviour of the NOE magnets, triggering quenches well below the respective 1st training quenches in SM-18.

- All training quenches in S56 happened (for the moment) on different magnets, except in one case when a NOE magnet showed a detraining step (10910 A $\Rightarrow$ 10720 A).

- Retest in SM-18 of one NOE magnet (that was not installed in the tunnel and previously tested in Aug 2005) showed a similar time-relaxation effect.

- The expected number of RB circuit quenches needed to reach 6, 6.5, and 7 TeV is about 10, 80, and 900 respectively. Note that 900 is a rough estimate since it is based on a large extrapolation of the S56 training curve and the re-test of only one NOE magnet. Assuming training in all 8 sectors in parallel, with 3 quenches per day would then require about 60 days to reach 7 TeV, and about the same number of heater firings as the entire SM-18 test campaign.

Conclusion: Quench propagation

- **Thermal quench propagation time is strongly affected by current level, cell geometry, cooling conditions, etc.**

- **Large variations in quench propagation time are observed for different positions in the sector. Reproducibility seems however good.**

- **High field (>7 T) dipole quenches usually cause 2-4 adjacent magnets to quench while ramping down the circuit. Due to long propagation times (typically 30-100 s to the nearest neighbour) the total dissipated energy in a half cell is about twice the stored energy of a single MB.**

- **Several cases have been observed where the MB-MB propagation time was less than 1 s, due to unbalanced coupling currents, traveling waves, noise and similar quench current level.**