TRAINING THE DIPOLES

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Abstract

During the hardware commissioning in 2008 more than 30 training quenches were performed in the main dipole circuits in sectors 4-5, 5-6, and 7-8. An overview of these quenches will be given, and the quench levels will be compared to the training observed in SM-18. Quench propagation to adjacent dipoles will be discussed, and an estimate will be given of the total number of training quenches required to reach 6, 6.5, and 7 TeV in all eight sectors.

INTRODUCTION

During the hardware commissioning in 2008 more than 30 training quenches were performed in the main dipole circuits in sectors 4-5, 5-6, and 7-8. Each sector contains 154 dipoles (MB) assembled by three different companies, Alstom (ALS), Ansaldo (ANS), and Noell (NOE), see Table 1. Note that the numbers for sector 3-4 denote the original distribution which will alter due to the repair work after the incident.

Table 1: Distribution of the dipole magnets per sector for each of the three cold mass assemblers

Sector	ALS	ANS	NOE
1-2	49	96	9
2-3	56	60	38
3-4	(56)	(65)	(33)
4-5	46	46	62
5-6	28	42	84
6-7	57	36	61
7-8	54	40	60
8-1	64	24	66
All	410	409	413

All the magnets have been powered to about 12.85 kA in SM-18 prior to installation in the machine. A total of about 4000 training quenches were performed in SM-18, see Figure 1. Note that the current that could be reached, according to the specification of the superconducting cable, is at least 13.8 kA (or 9.70 T central field). Figure 1 shows that all three types need about the same accumulated number of quenches to reach 12.5 kA. However the training of the ALS magnets is relatively fast for currents I smaller than 11 kA, whereas the training of the NOE magnets is relatively slow for I<10 kA, and relatively fast for 10 kA<I<11.5 kA.

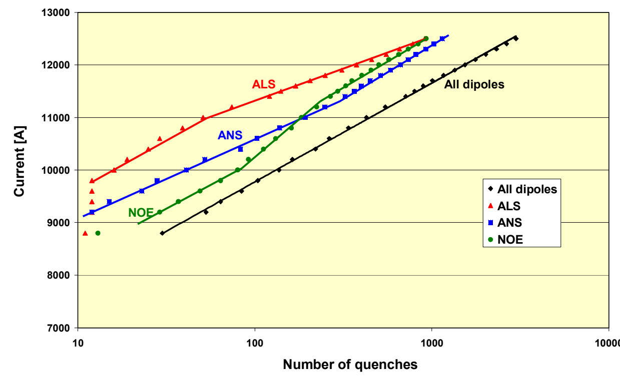

Figure 1: Current reached vs number of training quenches for all dipoles tested in SM-18. Breakdown per CMA shows the relative training 'speed'.

In the next section an overview of the quenches in the machine is given, and a comparison is made to the training observed in SM-18. Then an estimate will be given of the total number of training quenches required to reach 6, 6.5, and 7 TeV in all eight sectors. Finally quench propagation to adjacent dipoles will be discussed.

TRAINING DURING HWC

During HWC seven sectors have been powered up to 9310 A (5.5 TeV) with only one single quench in sector 7-8 at 8965 A, see Table 2. While powering sector 3-4 to 9310 A on 19/9/2008, the incident occurred about 600 A before the end of the ramp.

Table 2: 1st training quench, maximum current reached, and number of training quenches for the eight sectors.

Sector	1st training quench [A]	Maximum current reached [A]	Number of training quenches
1-2	-	9310	0
2-3	-	9310	0
3-4	-	8715 *	0
4-5	9789	10274	3
5-6	10004	11173	27
6-7	-	9310	0
7-8	8965	9310	1
8-1	-	9310	0

* Incident of 19/9/2008

Two sectors have reached higher currents after 3 and 27 training quenches respectively, see Table 2. Maximum currents of 10274 A and 11173 A were reached before training was stopped.

A break-down per CMA of the number of quenches in the sectors 4-5, 5-6, and 7-8 is shown in Table 3, clearly showing that the vast majority of quenches occurred in the NOE magnets.

Table 3: Distribution of the training quenches for each of the three cold mass assemblers

Sector	ALS	ANS	NOE
4-5	0	0	3
5-6	0	1	26
7-8	0	1	0

The training curve of sector 5-6 is depicted in Figure 2, along with the training on the same magnets as experienced in SM-18. Also the 4 quenches in sectors 4-5 and 7-8 are shown for completeness. The figure shows that the training in the machine is much slower than in SM-18: about 3 times more quenches were needed in the machine to reach 11.17 kA than in SM-18.

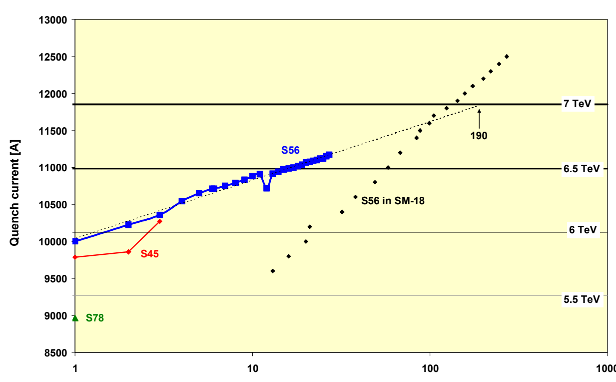

Figure 2: Training in sectors 4-5, 5-6, and 7-8. For comparison the training in SM-18 of the same 154 magnets of sector 5-6 is shown as well.

This unexpected slow training behaviour is illustrated differently in Figures 3 and 4, showing the first training quench in SM-18 for all the 154 dipoles of sectors 4-5 and 5-6 respectively, along with the quenches in the machine. The figures demonstrate very clearly that:

- The NOE magnets with a 1st training in SM-18 smaller than 11 kA show training in the machine above their 1st quench in SM-18.
- Many NOE magnets with a 1st training in SM-18 larger than 11 kA show a significantly lower 1st training in the machine, in some cases up to 2 kA lower. This degraded quench behaviour might be due to some sort of mechanical relaxation but the exact origin is unknown. The observed behaviour is contradictory to the conclusion drawn in [1], namely that long term storage does not affect the quench behaviour of the cryodipoles. However, the latter conclusion was only based on the retest of one single ANS dipole (nr. 2054) after 1 year of storage, whereas at present this effect is only observed on the NOE magnets.

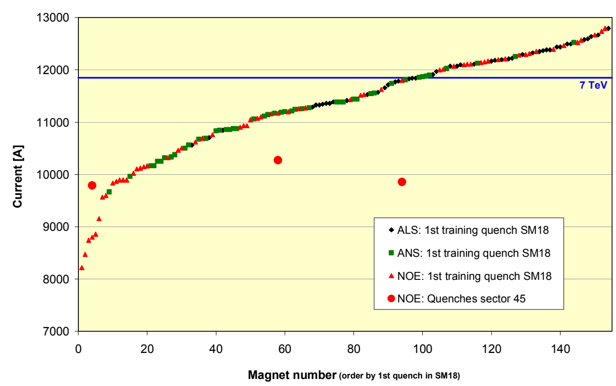

Figure 3: First training quench in SM-18 and the 3 training quenches in the machine for the 154 dipoles installed in sector 4-5.

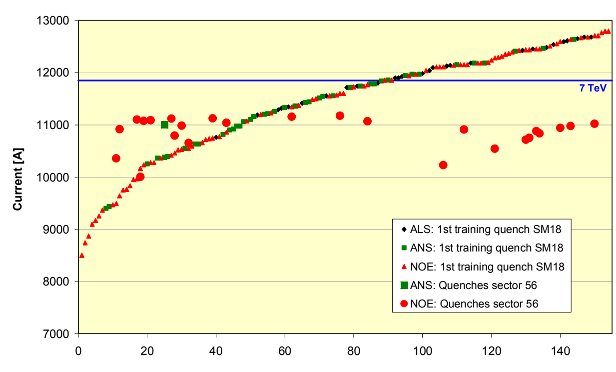

Figure 4: First training quench in SM-18 and the 27 training quenches in the machine for the 154 dipoles installed in sector 5-6.

No spare NOE magnets are available to examine this degraded quench behaviour on a test bench in SM-18, except dipole 3383. This magnet was not installed in the machine due to a transport accident during which the diode, the IFS box, and the N-line were damaged. It has been retested in Oct 2008, about 3 years after the 1st test in Aug 2005 (see Figure 5). During this 1st test it reached 12.85 kA with only a single training quench (at 11.7 kA).

However, during the 2nd test, 4 training quenches were needed before 12.85 kA could be reached. Furthermore, the first 3 of these 4 quenches were lower than the 1st training quench of the 1st cold test. Of course, it is not sure if this prolonged 2nd training is caused by the same effect as seen in the machine, or if it is due to the transport accident.

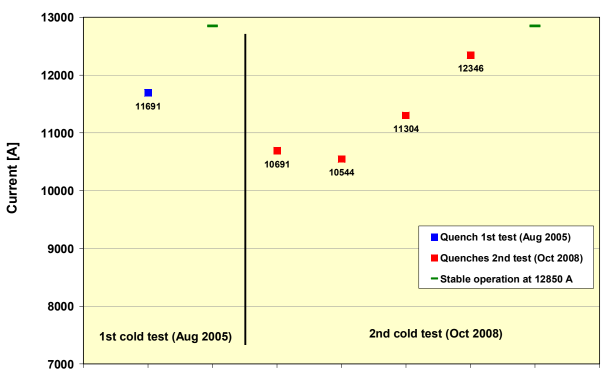

Figure 5: Training in SM-18 of dipole 3383 during the 1st and 2nd cold test.

TRAINING TO REACH 6-7 TEV

Based on the observed training in sector 5-6, and the magnet distribution as given in Table 1, it is possible to make rather good estimates of the required number of quenches needed to reach 6 TeV (7.14 T or 10.13 kA) and 6.5 TeV (7.73 T or 10.98 kA) in all sectors. The results, as given in Table 4, give a total of about 11 and 84 quenches.

Table 4: Required number of training quenches to reach 6 TeV and 6.5 TeV in all 8 sectors.

Sector	**6 TeV** (±2)	**6.5 TeV** (±30%)
1-2	0	4
2-3	1	8
3-4	1	8
4-5	2	12
5-6	1	15
6-7	2	12
7-8	2	12
8-1	2	13
All	**11**	**84**

An estimate of the number of training quenches needed to reach 7 TeV (8.33 T or 11.85 kA) is more difficult to make, simply because the highest current obtained so far in sector 5-6 is 11.17 kA, and the degraded quench behaviour of the NOE magnets is not understood. Before HWC started, an estimate has been based on the initial training in SM-18 as well as on the re-training after a thermal cycle [2]. This estimate gave an average of about 20 quenches per sector (see estimate 1 in Table 5). With the observed training of the NOE magnets in the machine, we now know that this is far too optimistic. Therefore 3 other estimates are made, which are based on the results of estimate 1 for the ALS and ANS magnets, and use a new estimate for the NOE magnets. Estimate 2 is based on an extrapolation of the training curve observed in sector 5-6. Estimates 3 and 4 are based on the retraining of dipole 3383 (see Figure 5) and assume 2 and 3 training quenches per NOE magnet respectively. The results in Table 5 indicate that one should expect about 1000 quenches altogether to reach 7 TeV. This number is however very approximate and a better estimate can only be made after at least one sector has trained to 7 TeV.

Table 5: Required number of training quenches, according to estimates 2, 3, and 4, to reach 7 TeV in all 8 sectors. For completeness, estimate 1, made before the start of the HWC [2], is given as well.

Sector	***Est. 1***	**Est. 2**	**Est. 3**	**Est. 4**
1-2	*22*	41	40	49
2-3	*23*	97	92	130
3-4	*21*	87	83	116
4-5	*22*	145	136	198
5-6	*21*	190	178	262
6-7	*20*	142	133	194
7-8	*14*	140	132	192
8-1	*19*	151	142	208
All	***162***	**993**	**936**	**1349**

QUENCH PROPAGATION

The 31 training quenches as well as the heater induced quenches at 7 kA have given a large amount of data concerning quench propagation from dipole to dipole.

On 11 occasions (on 8 different dipoles) a secondary quench occurred almost instantaneously (within 1 s after the circuit quench). These were triggered by:

- an almost equal quench current,
- an imbalance in the QPS signal, probably caused by very different inter-strand coupling currents in the two apertures,

- travelling voltage waves due to the opening of the switches,
- other noise.

Secondary quenching of adjacent dipoles due to thermal propagation was observed for all circuit quenches occurring above 6 kA. In most cases the quench propagation was limited to the same half-cell, although some quenches at higher currents would also propagate to the adjacent half-cell. Summarising all secondary quench data for circuit quenches above 9 kA, shows that in 3 cases the quench propagated to 1 dipole, in 9 cases to 2 dipoles, in 15 cases to 3 dipoles, in 6 cases to 4 dipoles and in 1 case to 5 dipoles. A graphical overview of all the delay times between circuit quench and secondary quench is shown in Figure 6. Due to the discharge time constant of the RB circuit of about 100 s, most secondary quenches occur at much smaller currents than the circuit quench current, as can also be seen in Figure 7.

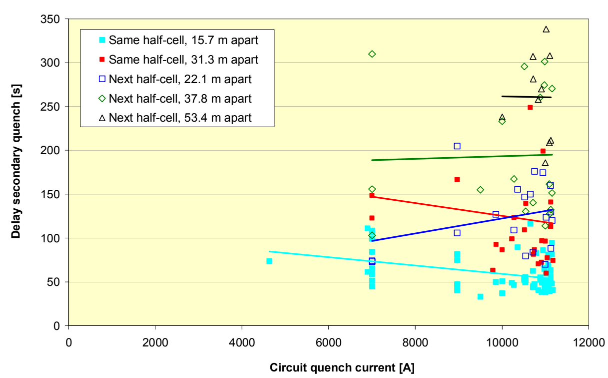

Figure 6: Delay time between circuit quench and secondary quenches, subdivided according to the distance between initial quenched magnet and secondary quenched magnet.

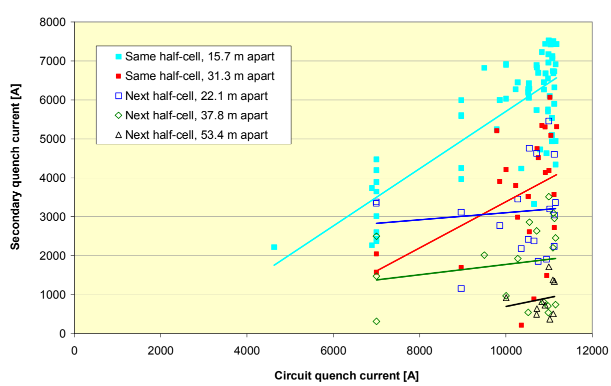

Figure 7: Secondary quench current vs circuit quench current, subdivided according to the distance between initial quenched magnet and secondary quenched magnet.

CONCLUSION

- During HWC of the RB circuits, six sectors reached 9310 A (5.5 TeV) without a quench. One sector showed one quench at 8.96 kA, and in one sector a busbar joint opened/melted before reaching 9310 A.
- All but one of the training quenches in sector 5-6 occurred in the NOE magnets. The current level of many of these quenches was well below the respective 1st training quenches in SM-18. This unexpected behaviour was reproduced during a retest in SM-18 of one NOE magnet (that was not installed in the machine), previously tested in Aug 2005. The origin of this degraded training behaviour is not understood.
- All training quenches in sector 5-6 happened (for the moment) on different magnets, except in one case when a NOE magnet showed a detraining step (from 10.91 kA to 10.72 kA).
- 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 training in sector 5-6 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 would cause about the same number of heater firings as the entire SM-18 test campaign.
- 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 dipole.
- Several cases have been observed where the dipole-to-dipole propagation time was less than 1 s, due to unbalanced coupling currents, traveling waves, noise and similar quench current level.

REFERENCES

[1] F. Seyvet et al., “Long term stability of the LHC superconducting cryodipoles after outdoor storage”, LHC Project Report 895 (2006), and proceedings MT-19 (2005).

[2] A. Siemko, P. Xydi, “Statistical expectation of retraining quenches in LHC main dipole magnets”, Presentation MaRiC 19/3/2008.