MAGNET (RE)TRAINING

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Abstract

In 2008, the LHC magnets circuits have been commissioned. In some cases, the magnets experienced quenches, showing some detraining with respect to the previous performance level reached during individual test. In this paper we summarize the training quenches that took place during hardware commissioning for all LHC superconducting magnets. This allows giving estimates for the next hardware commissioning campaign, and for the needed training to reach a given energy. Data show that 6.5 TeV is within reach with a limited amount of training, whereas today it is difficult to estimate the training needed to reach 7 TeV. The case of the dipoles, which dominate by far the training time due to their number and to the longer recovery time, is analysed using a MonteCarlo method that relies on the test data. The retraining shown by the Firm3 dipoles is partially explained by this method.

INTRODUCTION

Superconducting magnets rarely reach the superconductor critical current as estimated from measurements on short samples (what is usually denoted by “short sample limit”) during the first test. In general, the magnet has a first quench at a current level which can be between 70% and 90% of the short sample limit. After this quench, the magnet trains, i.e. reaches successively higher and higher currents. A “good” magnet, which is not limited by conductor instabilities or degradation, reaches at least 95% of the short sample current. It is common understanding that the training process has a mechanical origin and is due to a successive settling of the coil in more stable positions due to the shock created by the quench. Magnets can exhibit a rather wide spectrum of training patterns, from very little training to a very long one. Notwithstanding the experience acquired during 30 years of manufacturing and operating superconducting magnets, the relation between training, design and manufacturing procedures is far to be understood.

After test, magnets are warmed up and installed. During commissioning, the magnets usually quench at a current value that is larger than the first virgin quench, but lower than the last one (see Fig. 1). This detraining can be relevant for machine operation, since it requires time during the hardware commissioning.

For the LHC, all magnets have been tested and trained during the production to an “ultimate” value, 5%-10% larger than nominal. In 2008 the machine has been commissioned; some families of magnets have shown some detraining, and other no detraining at all. In this paper we summarize these data, comparing them to the test data.

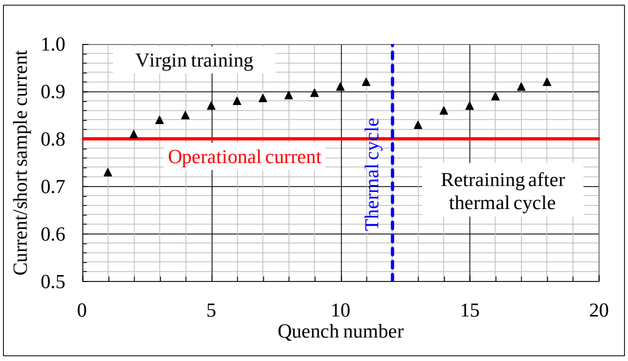

Figure 1: Typical training and detraining of a superconducting magnet.

TRAINING DURING HARDWARE COMMISSIONING

In the following, we will present the data relative to the hardware commissioning of the LHC superconducting magnets. Five tables are given for a beam energy ranging from 5 to 7 TeV, with 0.5 TeV steps. For each energy, we give:

- the magnet family;
- the current to reach that energy according to the design values;
- the number of individual magnets;
- the number of quenches per magnet to reach that energy;
- the fraction of magnets that reached that energy;
- an estimate of the total number of quenches needed to train all the magnets of that family.

5 TeV

Starting with 5 TeV, we see that for instance all magnets in all sectors reached that value without any quench. One triplet out of eight was not powered due to lack of time. From the experience of the 2008 hardware commissioning, the whole machine should reach 5 TeV without quenches.

Table 1: Training for reaching 5 TeV.

Magnet	Current (kA) at **5 TeV**	#	Quench / magnet	% trained to **5 TeV**	Estim. # of quenches
MB	8.46	1232	0.00	100%	**0**
MQ	8.46	392	0.00	100%	**0**
MQM 1.9 K	3.85	66	0.00	100%	**0**
MQM 4.5 K	3.08	20	0.00	100%	**0**
MQY 4.5 K	2.58	24	0.00	100%	**0**
MQXA	5.11	16	0.00	88%	**0**
MQXB	8.54	16	0.00	88%	**0**
MBX	4.11	4	0.00	100%	**0**
MBRC IP1-5	3.14	4	0.00	100%	**0**
MBRC IP2-8	4.32	4	0.00	100%	**0**
MBRS	3.94	4	0.00	100%	**0**
MBRB	3.94	4	0.00	100%	**0**

5.5 TeV

The situation for 5.5 TeV is given in Table 2. For the dipoles, 6 octants out of 8 (i.e., 924 dipoles) reached 5.5 TeV, with one quench. This corresponds to having around 0.001 quenches per magnet. The other magnet family that quenched are 1 MBRS separation dipoles (0.25 quench per magnet), and 2 MQM at 4.5 K (0.1 quenches per magnet). Since these are rare events, all these estimates are affected by a large statistical error.

Table 2: Training for reaching 5.5 TeV.

Magnet	Current (kA) at **5.5 TeV**	#	Quenches / magnet	% trained to **5.5 TeV**	Estim. # of quenches
MB	9.31	1232	0.0011	75%	**1**
MQ	9.31	392	0.00	100%	**0**
MQM 1.9 K	4.24	66	0.00	100%	**0**
MQM 4.5 K	3.39	20	0.10	100%	**2**
MQY 4.5 K	2.84	24	0.00	100%	**0**
MQXA	5.62	16	0.00	88%	**0**
MQXB	9.39	16	0.00	88%	**0**
MBX	4.52	4	0.00	100%	**0**
MBRC IP1-5	3.46	4	0.00	100%	**0**
MBRC IP2-8	4.75	4	0.00	100%	**0**
MBRS	4.34	4	0.25	100%	**1**
MBRB	4.34	4	0.00	100%	**0**

6 TeV

The situation to reach 6 TeV is shown in Table 3. For the dipoles, two out of eight octants reached this energy, with 3 quenches, namely sector 4-5 and 5-6. This gives 0.01 quenches per magnet, corresponding to an expected value of about 12 quenches for bringing the whole machine at 6 TeV. Three out of four separation dipoles MBRS reached 6 TeV with 3 quenches (1 quenches per magnet). All the MQM at 4.5 K reached 6 TeV, with 2 quenches (0.10 quenches per magnet). All the other magnets reached this energy without quenches.

Table 3: Training for reaching 6 TeV.

Magnet	Current (kA) at **6 TeV**	#	Quenches / magnet	% trained to **6 TeV**	Estim. # of quenches
MB	10.16	1232	0.010	25%	**12**
MQ	10.16	392	0.00	25%	**0**
MQM 1.9 K	4.62	66	0.00	100%	**0**
MQM 4.5 K	3.69	20	0.10	100%	**2**
MQY 4.5 K	3.09	24	0.00	100%	**0**
MQXA	6.13	16	0.00	88%	**0**
MQXB	10.24	16	0.00	88%	**0**
MBX	4.93	4	0.00	100%	**0**
MBRC IP1-5	3.77	4	0.00	100%	**0**
MBRC IP2-8	5.19	4	0.00	75%	**0**
MBRS	4.73	4	1.00	75%	**4**
MBRB	4.73	4	0.00	100%	**0**

6.5 TeV

The situation to reach 6.5 TeV is shown in Table 4. The sector 5-6 has been the only one trained to this energy, reaching it in 17 quenches. This would correspond to 0.11 quenches per magnet, i.e. a total number of 136 quenches. Indeed, we observe that nearly all quenching magnets are from Firm3. Since sector 5-6 contains larger fraction of magnets from Firm3 than usual (56%), we normalize this number to the actual proportion of Firm3 magnets present in the whole machine (33%). This brings our corrected estimate to 0.07 quenches per magnet instead of 0.11, and to a total number of 84 quenches for reaching 6.5 TeV. In this estimate, we assume that dipoles from the other firms have a negligible number of quenches. The 20 MQM operating at 4.5 K reached 6.5 TeV with 7 quenches, thus giving 0.35 quenches per magnet. Three quenches were needed to training all MQY to 6.5 TeV. 25% of quadrupoles have reached 6.5 TeV with 1 quench.

Table 4: Training for reaching 6.5 TeV.

Magnet	Current (kA) at **6.5 TeV**	#	Quenches / magnet	% trained to **6.5 TeV**	Estim. # of quenches
MB	11.00	1232	0.068	13%	**84**
MQ	11.00	392	0.010	25%	**4**
MQM 1.9 K	5.01	66	0.02	100%	**1**
MQM 4.5 K	4.00	20	0.35	100%	**7**
MQY 4.5 K	3.35	24	0.13	100%	**3**
MQXA	6.64	16	0.00	88%	**0**
MQXB	11.10	16	0.00	88%	**0**
MBX	5.34	4	0.00	100%	**0**
MBRC IP1-5	4.09	4	0.00	100%	**0**
MBRC IP2-8	5.62	4	0.33	75%	**1**
MBRS	5.13	4	1.67	75%	**7**
MBRB	5.13	4	0.00	100%	**0**

7 TeV

We have no experience of any sector of main magnets (neither dipoles nor quadrupoles) trained up to 7 TeV: for this reason we will not give any estimate. Recent work [1] based on a semi-logarithmic extrapolation gives 900±300 as a tentative estimate. For the other magnets, 32 quenches were needed to bring the 20 MQM quadrupoles to nominal (1.6 quenches per magnet), plus 12 MQY (0.5 quenches per magnet), and four MQM at 1.9 K (0.06 quenches per magnet). The inner triplet MQXA and MQXB reached nominal without quenches. 75% of the separation dipoles reached nominal; the MBRS (D3) and MBRC (D2) needed about 2 quenches per magnet to reach nominal.

Table 5: Training for reaching 7 TeV.

Magnet	Current (kA) at **7 TeV**	#	Quenches / magnet	% trained to **7 TeV**	Estim. # of quenches
MB	11.85	1232	???	0%	**???**
MQ	11.85	392	???	0%	**???**
MQM 1.9 K	5.39	66	0.06	100%	**4**
MQM 4.5 K	4.31	20	1.60	100%	**32**
MQY 4.5 K	3.61	24	0.50	100%	**12**
MQXA	7.15	16	0.00	88%	**0**
MQXB	11.95	16	0.00	88%	**0**
MBX	5.75	4	0.00	100%	**0**
MBRC IP1-5	4.40	4	0.00	100%	**0**
MBRC IP2-8	6.05	4	2.33	75%	**9**
MBRS	5.52	4	2.00	75%	**8**
MBRB	5.52	4	0.00	100%	**0**

Which magnets suffered from re-training ?

In the case of dipoles, the 27 training quenches occurred in 27 different magnets. For the MQM, the 32 quenches occurred in 12 different magnets, with some magnets having up to four quenches. For the MQY, the 12 quenches occurred in 5 magnets, with one magnet having 6 quenches. For the separation dipoles, 14 quenches occurred in 5 different magnets.

Impact on commissioning

The training time during commissioning is largely dominated by the main dipoles, all the other magnets being in the shadow. This for three different reasons:

- Their number in the machine is much larger than all other magnets
- The circuit include 154 dipoles, and therefore no parallelization is possible (individually powered magnets can be trained in parallel). On the other hand, one can train different sectors in parallel and therefore the relevant time is the time needed for training one sector and not the whole 1232 dipoles.
- The recovery time for the cryogenic conditions after a dipole quench is much larger than for the other magnets.

During the 2008 hardware commissioning, a maximum of two training quenches per day has been reached [2]. One could envisage to having up to three quenches per day. Therefore, the 10 quenches needed to train one sector at 6.5 TeV, according to the 5-6 experience, could be done in less than one week. If the other sectors show a similar behaviour, the time needed to train the machine to 6.5 TeV will be of about one week per sector.

HARDWARE COMMISSIONING TRAINING VERSUS VIRGIN TRAINING

Here we compare the training during the tests carried out on single magnets during the production to the training in the tunnel during the hardware commissioning. The dipoles have been manufactured by three firms, showing some variability in the quench behaviour during test. In order to reach the nominal current of 11850 A, we had 0.6 quenches per magnet for Firm1, 1.2 for Firm2, and 1.0 for Firm3 [3]. The comparison with the results of hardware commissioning is given in Figs. 2-4. The largest current value of 11173 A, corresponding to 94% of the nominal, has been reached in sector 5-6. In the other sectors the hardware commissioning has been stopped at lower current levels. Firm1 magnets reached 94% of nominal in 5-6 without quenches, Firm2 had a few quenches, whereas the 84 dipoles of Firm3 needed 27 quenches. This corresponds to 0.32 quenches per magnet needed for retraining magnets to 94% of the nominal values. The training campaign was then stopped.

The main quadrupoles also had about 1 quench per magnet to reach nominal in virgin conditions, see Fig. 5. During hardware commissioning they show no need of retraining, reaching nominal with a few quenches.

The inner triplet insertion quadrupoles MQXA and MQXB reached nominal with 1.6 and 0.15 and quenches per magnets respectively (see Figs. 6 and 7). For the MQXA case, virgin data relative to cold masses 11 to 14 were affected by an instability related to the test station [4], and removing the tests affected by this problem one finds a lower value of about 1 quenches per magnet to reach nominal. Both magnet families reached nominal in 7 sectors out of 8 without quenches.

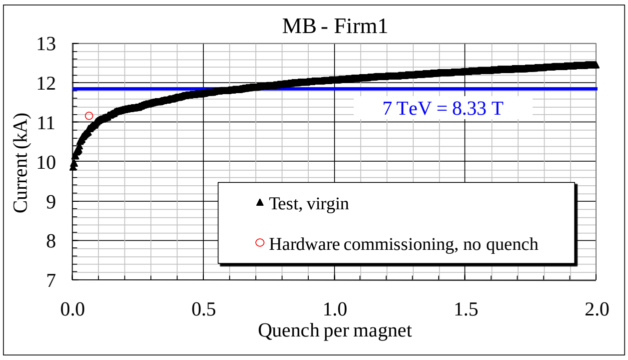

Figure 2: Virgin training versus training during hardware commissioning in main dipoles, Firm1.

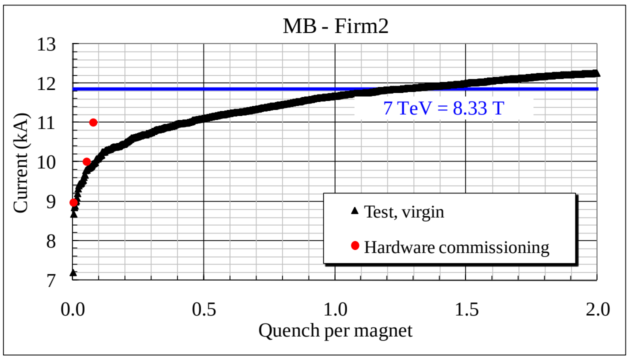

Figure 3: Virgin training versus training during hardware commissioning in main dipoles, Firm2.

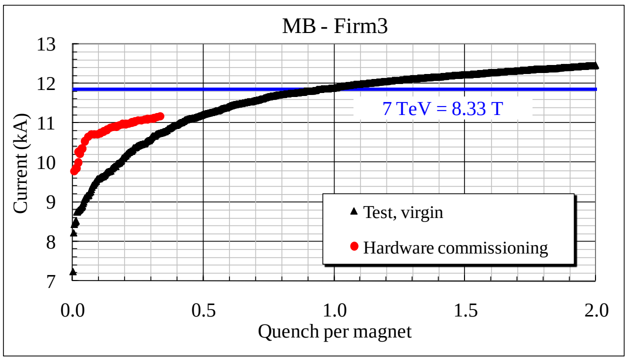

Figure 4: Virgin training versus training during hardware commissioning in main dipoles, Firm3.

The insertion quadrupoles MQM work at two different temperatures: 20 are at 4.5 K and 66 are at 1.9 K. During test, the MQM at 1.9 K reached nominal with 0.5 quenches per magnet (data based on a sample of 35 magnets, i.e. 50%, which have been tested in vertical cryostats), see Fig. 8. In the tunnel, the magnets reached nominal with a few quenches.

The MQM at 4.5 K reached nominal during the virgin test with about 1 quench per magnet at the “Block4” test facility in vertical cryostats (data based on a small sample of 5 magnets, i.e. 25%,). All these magnets have been tested in an horizontal cryostat at the “Sm18” test facility, showing a longer training to go to nominal, of about 3 quenches per magnet. In the tunnel, the needed retraining has been of about 1.5 quenches per magnet, i.e. between Block4 and Sm18 data, see Fig. 9. A more detailed analysis of the possible causes of this difference, and of the retraining in the tunnel, is given in [5].

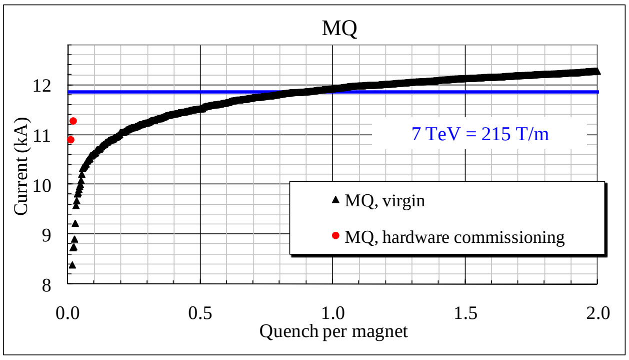

Figure 5: Virgin training versus training during hardware commissioning in main quadrupoles.

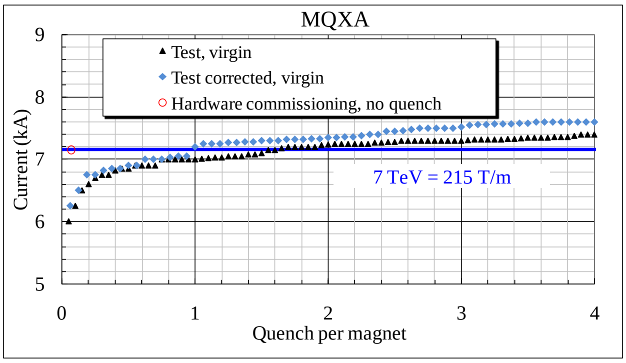

Figure 6: Virgin training in inner triplet quadrupoles MQXA. The set of corrected data excludes tests on cold masses 11 to 14 [2].

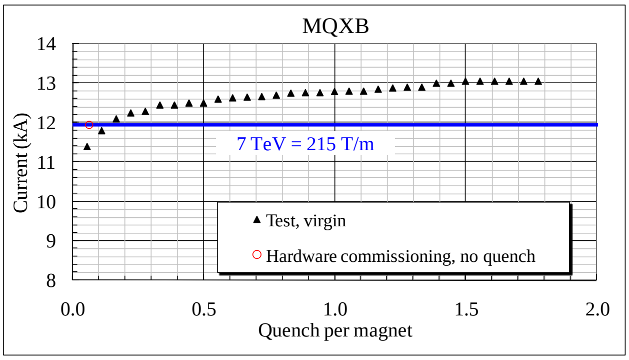

Figure 7: Virgin training versus training during hardware commissioning in inner triplet quadrupoles MQXB.

The 24 MQY reached nominal in a vertical cryostat with about 0.5 quenches per magnet. The magnets were then tested again in horizontal cryostats, reaching nominal with about 1.1 quench per magnet. In the tunnel, 12 quenches were needed to reach nominal, corresponding to the same rate. Indeed, half of these quenches occurred in the same magnet Q4.L8, and removing the data relative to this case, one obtains 0.25 quenches per magnet to reach nominal, see Fig. 10.

Summarizing, a wide phenomenology of training during tests and in the tunnel has been observed. In the following, we will analyse in detail the case of the dipoles, which are the more relevant for the time requirements of hardware commissioning.

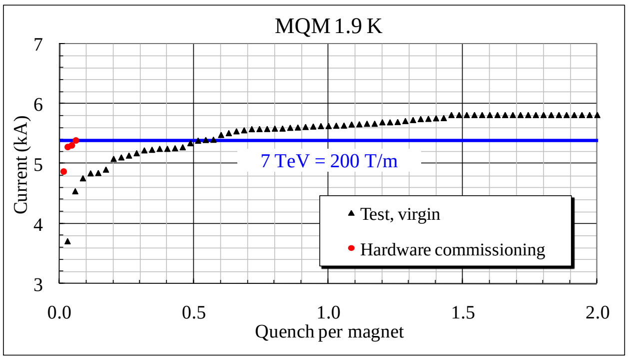

Figure 8: Virgin training versus training during hardware commissioning insertion quadrupoles MQM at 1.9 K.

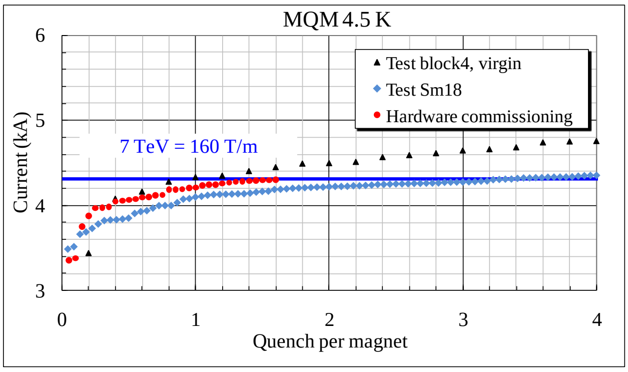

Figure 9: Training on test bench at block4 and Sm18 versus training during hardware commissioning insertion quadrupoles MQM at 4.5 K.

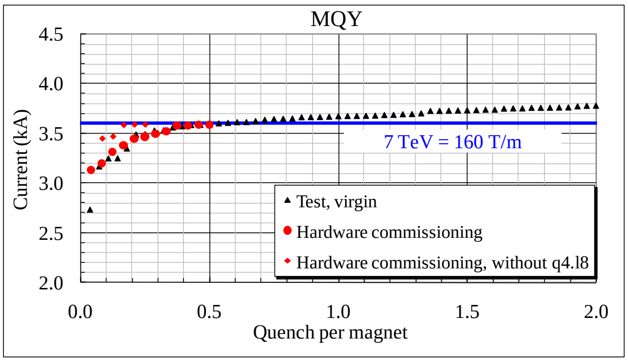

Figure 10: Virgin training versus training during hardware commissioning insertion quadrupoles MQY.

THE CASE OF THE MAIN DIPOLES

The retraining of dipoles from Firm3 during hardware commissioning has been a surprise for the community. Indeed, some traces of an anomalous behaviour of these magnets can be found in the test data carried out during the production phase.

All dipoles have been trained up to nominal at CERN after reception from the manufacturing, i.e. in virgin conditions. The global view of the virgin training is given in Fig. 11. Here, the whole set of the dipole quenches is put together, and ordered. This plot would be the result of an hypothetic hardware commissioning of a machine made by three sectors, each one containing magnets from the same Firm, in the hypothesis of having installed the magnets without testing. The plot is normalized to the number of magnets.

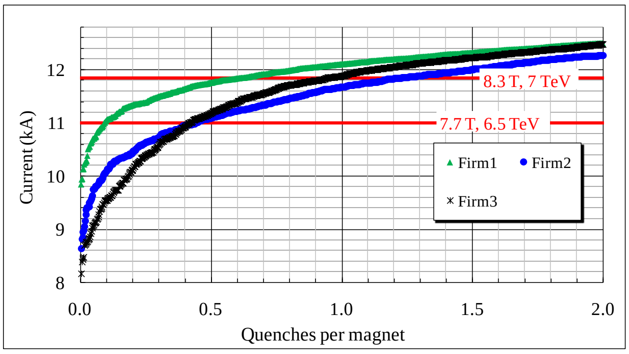

Figure 11: Virgin training of the main dipoles, normalized to the number of magnets.

As observed in the previous section, there is some difference in performance between firms. Firm1 magnets reach nominal with about 0.6 quenches per magnet, Firm3 with about 1 quench per magnet, and Firm2 with about 1.2 quenches per magnet. This hypothetic machine, i.e. the LHC without test of the magnet, would reach nominal with about 1 quench per magnet, i.e. around 1200 quenches. This would be the scenario in case of a total loss of memory, without a worsening of the magnets.

Firm3 magnets exhibit the longer training at low field. Around 6.5 TeV the virgin behaviour of Firm2 and Firm3 magnet are similar, both needing 0.4 quenches per magnet to reach that energy. Note that Firm1 magnets need only 0.1 quenches per magnet to reach 6.5 TeV. Firm3 magnets have the slowest training for low fields, but they are the fastest to reach the ultimate current at 12800 A.

In sector 5-6 we have a large number of magnets from Firm3: 84 out of 154. The plot relative to the virgin training of magnets which are in sector 5-6 is shown in Fig. 12. This plot contains the qualitative features of the hardware commissioning data, i.e. a training behaviour up to 6.6 TeV dominated by Firm3 and a few quenches from Firm2.

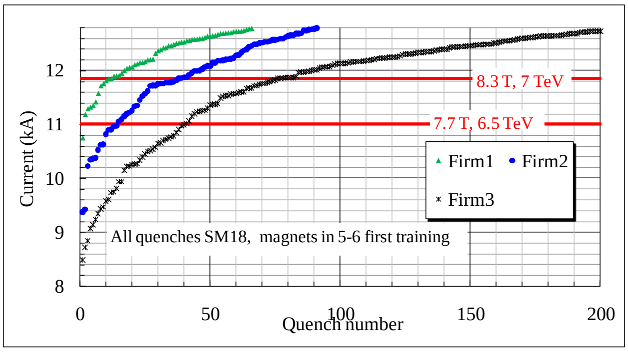

Figure 12: Virgin training of the main dipoles present in sector 5-6.

A sample of magnets has been tested in SM18 after a thermal cycle, i.e., it has been tested virgin, warmed up, cooled down, and tested again. This is exactly what happens during hardware commissioning to most of the magnets, excluding all considerations relative to storage time and ageing. This fraction of magnets (11%) has been chosen between magnets which had a long virgin training to reach ultimate current.

We now analyse the correlations between the first virgin training quench and the first quench after thermal cycle. In general, magnets which had a low first quench gain considerably after the thermal cycle, and magnet that have a high first quench do not gain so much (see Fig. 13). We model these correlations with a deterministic linear part plus a random Gaussian part. The plot is shown in Fig. 13 and 14 for Firm1 and Firm2. In both firms we never have cases of magnets getting worse after a thermal cycle, i.e., all dots are above the zero in the y axis.

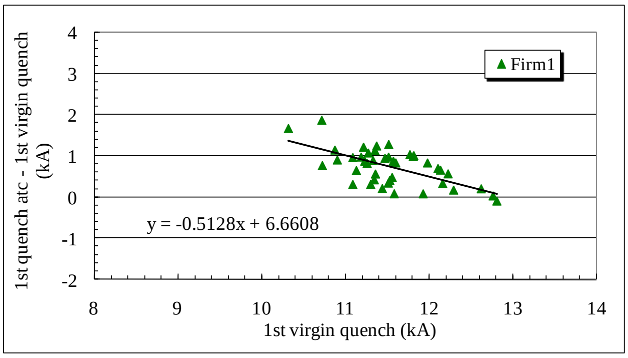

Figure 13: Gain between first quench after thermal cycle versus first virgin quench for 42 magnets tested from Firm1.

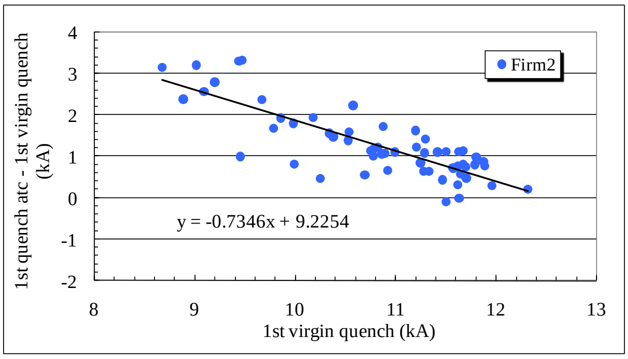

Figure 14: Gain between first quench after thermal cycle versus first virgin quench for 58 magnets tested from Firm2.

The case of Firm3 looks different, since a few cases have a lower current of the first quench after thermal cycle than in the virgin case (see Fig. 15). The sample is low and the cases are only 4 out of 36, but some anomaly can be detected. Using the above discussed correlations we project the virgin data of the sector 5-6 to the condition after a test and a thermal cycle. We need a MonteCarlo method since the random part of the correlation cannot be neglected. Results are shown in Fig. 16: one finds a good quantitative agreement up to 6.3 TeV, with a few Firm2 magnets, about 5 Firm3 magnets, and no Firm1 magnets. From 6.3 TeV the hardware commissioning data clearly show an excessive training: after 27 quenches we should have reached 11600 to 11850 A, instead of 11170 A. This means that the energy is about 4-6% lower than what estimated for that number of quenches.

According to this method, one would need about 50 quenches to reach 7 TeV in sector 5-6, and something less in the other sectors which have less Firm3 magnets. Unfortunately, all the key of the analysis are the correlation plots shown in Figs. 13-15 and the statistics is not so large.

What will happen after a second thermal cycle is also not known, i.e. if the magnets will needed a second re-training or not. The next years of LHC operation will tell us more on these issues.

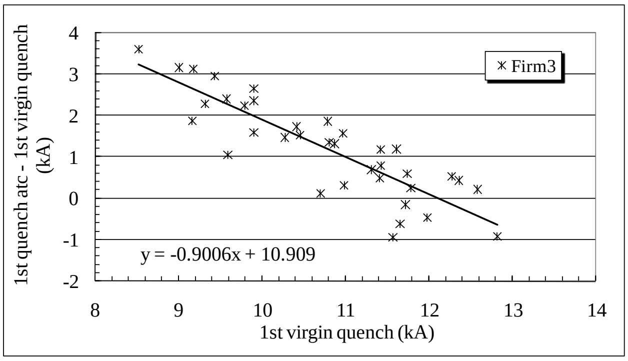

Figure 15: Gain between first quench after thermal cycle versus first virgin quench for 36 magnets tested from Firm3.

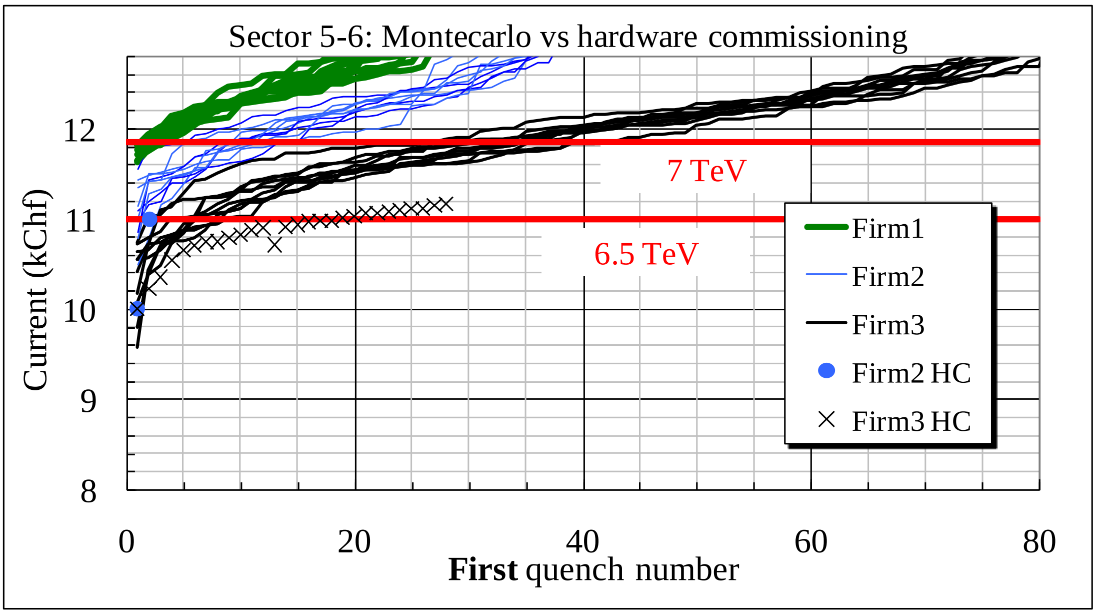

Figure 16: Estimated training in sector 5-6, first quench only, based on test data, versus hardware commissioning data.

CONCLUSIONS

During 2008 the LHC superconducting magnets have been commissioned. The whole machine reached 5 TeV without any training quench in the tunnel. With the important exception of the main dipoles and quadrupoles, plus a few isolated cases, all magnets have been commissioned to 7 TeV.

Some magnet families (MB from Firm3, MQM at 4.5 K, MQY, some separation dipoles) have shown the need of retraining, quenching in the tunnel before reaching nominal current. With the relevant exception of Firm3 main dipoles, all the other families showing retraining are working at 4.5 K. The other magnets reached nominal with a few or with no quenches at all.

The training time during commissioning is by far dominated by the main dipoles. One sector has been trained up to 6.6 TeV, with about 30 quenches, mostly from the magnets of the same manufacturer. If this sector is statistically significant, the LHC could reach 6.5 TeV with less than one week of training per sector.

The fact that the dipole re-training is dominated by dipoles manufactured by Firm3 can be justified in terms of the performance assessment on individual magnets done during the production. Indeed, the projection of the test data would foresee an energy of 6.8-7 TeV after 30 quenches, and not 6.6 TeV as obtained in the tunnel. Notwithstanding several hypotheses made to justify this behaviour, the origin of this loss of performance is unknown. Since the curve of energy versus number of quenches flattens considerably above 6.5 TeV, estimates to reach 7 TeV are at the moment very difficult to be given. What is also unknown is if the magnets will need a retraining after each warm-up or not.

ACKNOWLEDGEMENTS

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