DIPOLE RETRAINING FOR 7 TEV

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Abstract

We outline the present understanding of the retraining of the main dipoles in the LHC sector 5-6 during 2008 hardware commissioning. Even though part of the observed retraining can be explained through the test of individual magnets taken during the production, there is an additional unexplained detraining. The energy of 6.5 TeV seems clearly at hand with a very limited retraining. We present the best estimates of the training needed to reach the range 6.5-7 TeV, using different methods. We then analyse correlations between performance and production procedures and components: the present stage of analysis does not show any trace of correlations, but the analysis is not yet completed. There is also no indication of a correlation with the storage time.

INTRODUCTION

During the 2008 hardware commissioning campaign, all the LHC dipole sectors were brought to a current equivalent to an energy of 5 TeV [1,2]. Six of them were brought to 5.5 TeV after a minimal training of one quench in 2 magnets (out of 924). Two sectors reached 6 TeV with 3 quenches. Sector 5-6 was intentionally pushed further to see the limiting factors (see Fig. 1). The sector rapidly reached 6.2 TeV (corresponding to 10.5 kA) in a few quenches. Then, a slow training took place, with 6.5 TeV reached after ~20 quenches, and 6.6 TeV after nearly 30 quenches. The training was then stopped. Quenches all happened in different magnets, with a possible exception of one case. The apparently odd feature is that nearly all quenches happened in the magnets assembled by Firm3, two only from Firm2 and none from Firm1. Even though this sector contained 55% magnets from Firm3, with respect to the 1/3 ratio present in the whole machine, this larger ratio is not enough to explain the overwhelming majority of Firm3 quenches.

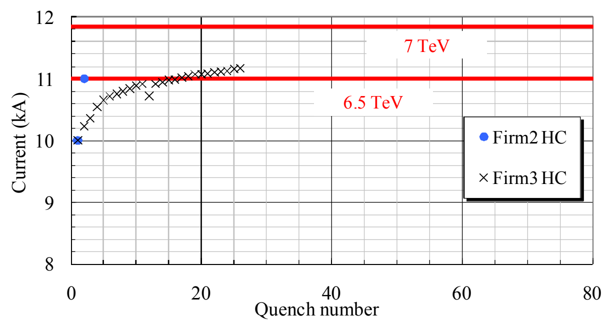

Figure 1: Training of sector 5-6 during 2008 hardware commissioning [1,2].

The critical missing information is how the other sectors would have trained in the 10-12 kA range. Other relevant issues related to the training retention are the following ones: (i) Is this a problem of Firm3 magnets? (ii) If yes, is this the problem of all Firm3 magnets or only of a batch? (iii) What is going to happen after warm-up and cool-down? Will it be necessary to train again in the range 10-12 kA? (iv) Are these quenches in the straight part of the magnet or in the head, as most of the quenches in the LHC dipoles?

The LHC incident of September 19th 2008 and the discovery of the weaknesses in the accelerator prevented from pushing the other sectors to higher current levels. According to the present plan the LHC will not be pushed to energies beyond 3.5 TeV before 2013.

FORECAST TO REACH 7 TEV

MonteCarlo method based on correlations between before and after thermal cycle

After the 5-6 results, the training data of individual dipoles have been critically reviewed. In Ref. [2,3], a MonteCarlo method has been proposed to estimate the needed training on the ground of the data of individual tests. During individual tests, all dipoles were trained up to a level of current ranging from 12 to 13 kA, i.e., well beyond nominal, and about 10% of them went through a thermal cycle and successive training to estimate the training retention. Since the correlation in the behaviour before and after a thermal cycle is not deterministic, one has an intrinsic variability and therefore one needs a MonteCarlo. The method correctly estimates the level of the first quench in the range of 10 kA, and shows that to reach 11 kA one has to expect an overwhelming majority of Firm3 quenches (see Fig. 2). On the other hand, the sector should have reached 11.2 kA with ~10 quenches of Firm3 magnets, and not ~25. Moreover, the slope of training found during hardware commissioning is much lower than what given by the MonteCarlo method.

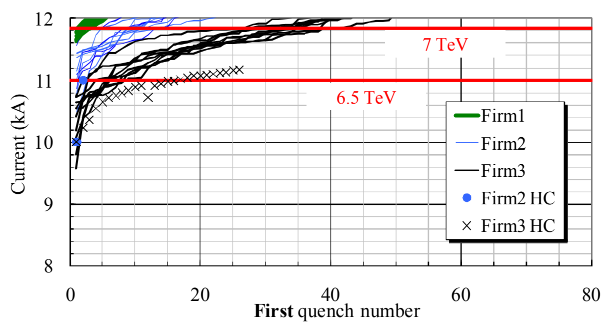

Figure 2: Training of sector 5-6 during 2008 hardware commissioning versus MonteCarlo forecast [2,3].

Rescaling the data of Fig. 2 to the 1/3 ratio between dipole assemblers present in the whole machine, one can give an estimate of about 400 quenches needed to reach 7

TeV, i.e. 50 quenches per octant (see Table 1). This estimate looks optimistic according to the 5-6 experience.

Table 1: Quenches needed to reach 7 TeV according to the MonteCarlo methode

	Sector 5-6		A generic sector	
	Percentage	N. quenches	Percentage	N. quenches
Firm1	19%	5	33%	9
Firm2	26%	15	33%	19
Firm3	56%	35	33%	21
All	100%	55	100%	49

Scaling

Previous estimates to reach 7 TeV were giving about 25 quenches per octant to reach nominal [4]. This estimate was based on the following facts: (i) the whole set of 1232 dipoles takes 1.0 quenches per magnet to reach nominal in virgin conditions, i.e. 154 quenches per sector; (ii) the subset of 136 dipoles tested after thermal cycle show a reduction of the number of quenches to reach nominal of about 80% between virgin conditions and after thermal cycle (1.75 to 0.35, see Figure 3). Reducing the 1 quench per magnet of 80%, one gets a global estimate for the machine of 0.2 quenches per magnet, i.e. 30 quenches per sector. Since the dipoles to be tested after thermal cycle were selected between the magnets showing poor performance in virgin conditions, a statistical bias was to be taken into account, leading to an estimate of 25 quenches per octant.

The same data can also be rescaled with a different, but equally sound, approach. Assuming no correlation in the behaviour before and after thermal cycle, one can apply the 0.35 quenches per octant (see Figure 3) needed to reach nominal after thermal cycle and measured on the sample as a property of the whole set of LHC dipoles. In this case the probability of quenching to reach 7 TeV is ~1/3, i.e. one needs 50 quenches per octant and the value of the MonteCarlo is recovered. This shows how these scalings can be non trivial, containing hidden hypotheses that can lead to pretty different results.

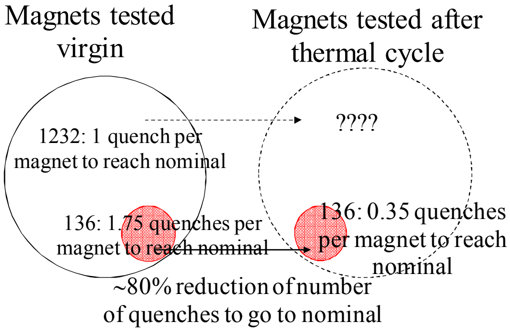

Figure 3: Diagram summarizing the dipole performance in individual tests [1,2].

Extrapolation of hardware commissioning data

In Ref. [1] it has been first observed that the training curve becomes linear in a semi-logarithmic plot; the extrapolation provides about 200 quenches to reach nominal for sector 5-6, and rescaling for the whole machine one should need 110 quenches per sector, neglecting the contribution of the other Firms. The extrapolation is somewhat unphysical, since the dipole performance cannot grow indefinitely (even in a log scale!) as it is limited by the conductor performance. Indeed, in the range 10-11 kA the scaling works pretty well. A more refined fit with an arctangent in semi-logarithmic scale keeps the physics and provides similar results [3].

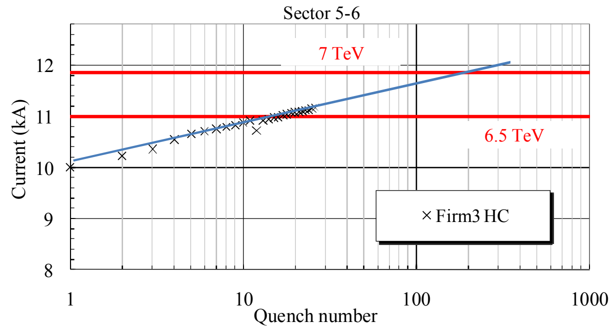

Figure 4: Logarithmic extrapolation proposed in [6].

A summary of the results given by the different methods is given in Table 2.

Table 2: Quenches needed to reach 7 TeV: summary of different methods

Method	Quenches per octant to reach 7 TeV	Comments
Scaling-1	30	Based on test data
Scaling-2	50	Based on test data
MonteCarlo	50	Based on test data
Extrapolation	110±25	Based on HC data

ANALYSIS

The Firm3 anomaly

Several investigations have been started to better understand the anomalous behaviour of Firm3. In fact, in Ref. [2,3] we reported on the trace of a lower performance of Firm3 magnets with respect to two different aspects:

- Firm3 dipoles show a slower training for virgin magnets in the range 7-10 kA (see Fig. 5).
- Firm3 dipoles after thermal cycle show a larger loss of training retention. In particular, a few dipoles showed a net loss of performance between the first virgin test and the test after thermal cycle, contrary to the other Firms (see Fig. 6).

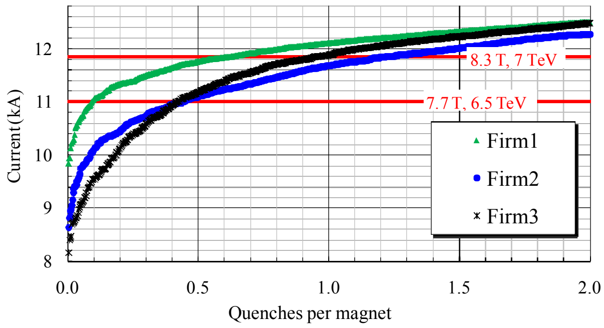

Figure 5: Cumulated data of virgin training, split per magnet assembler.

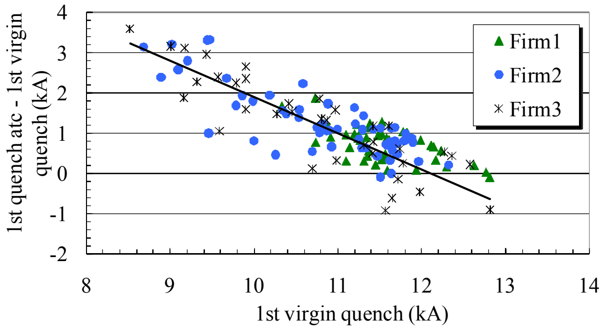

Figure 6: Gain in current between first quench in virgin conditions and first quench after thermal cycle.

An additional feature has been found more recently through the analysis of the quench location [5]. The first virgin quench takes place in the heads for 97-100% of the cases, in all Firms. On the other hand, for the second quench the location is in the heads for about 90% in Firm1 and Firm2, but 98% in Firm3 (see Table 3). This indicates a different behaviour, but one can argue if this means that the Firm3 straight part is better than Firm1-2 or that the Firm3 heads are worse than Firm1-2.

Table 3: Fraction of quenches in the coil ends in virgin conditions.

	1st virgin quench			1st quench after thermal cycle		
	Average	Stdev	% in heads	Average	Stdev	% in heads
Firm1	8.32	0.40	97%	8.70	0.27	89%
Firm2	7.87	0.53	100%	8.53	0.38	88%
Firm3	7.35	0.79	96%	8.57	0.46	**98%**

Storage time

One of the first hypotheses done to explain the performance loss was the storage time before installation. In Fig. 7 we plot the storage time for the dipole as a cold mass (i.e. between arrival at CERN and cryostating) for the whole set of 5-6 Firm3 dipoles and for the subset which quenched [5]. The two distributions look similar. The same analysis is carried out in Fig. 8 for the storage time of the cryostated magnets, i.e. the time between test and installation. In this case the time can reach two years. Also in this case there is no trace of larger quench probability in 5-6 for magnets with a larger storage time.

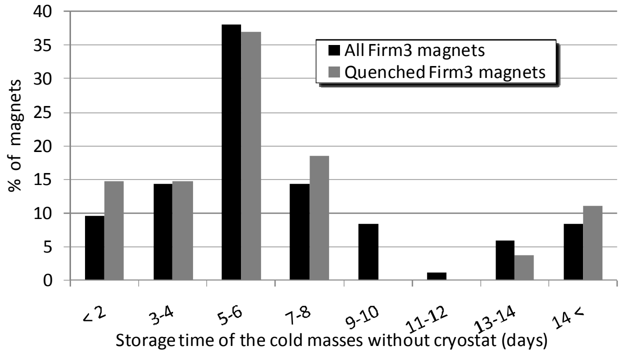

Figure 7: Storage time between arrival at CERN and cryostating for Firm3 magnets in 5-6, all magnets versus quenched magnets.

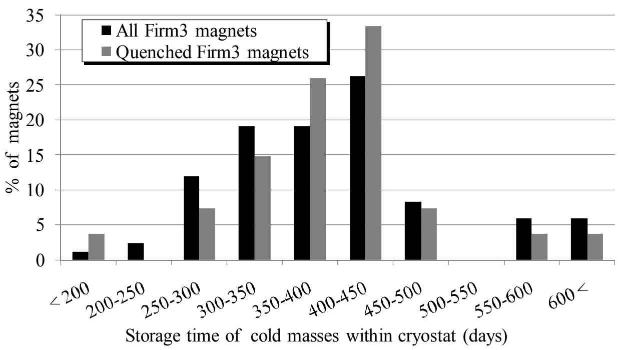

Figure 8: Storage time between arrival at test and installation for Firm3 magnets in 5-6, all magnets versus quenched magnets.

Coil properties

The analysis of the measurements carried out during the production [6] shows that Firm3 coil outer layer modulus were in between Firm1 and Firm2 (see Fig. 9). The inner layer data show a similar feature. This excludes the hypothesis that the performance loss is due to a stress release during storage due to a softer coil.

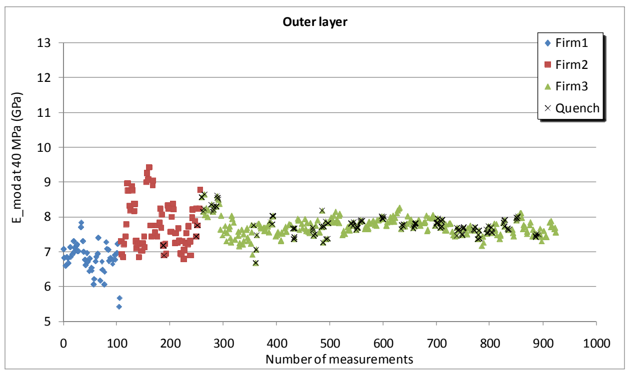

Figure 9: Elastic modulus of the outer layer of dipole coils of magnets in sector 5-6, and magnets which quenched (crosses) during sector training.

Collars

The dipole stainless steel collars were produced by two manufacturers (CP1 and CP2). Most of CP1 collars went to Firm3, whereas CP2 collars were mainly used by Firm1-2 (see Table 4). A priori, an anomaly in Firm3 could also be attributed in the CP1 collar producer. Firm1 had 20 magnets done with CP1 collars, and Firm3 had 9 magnets done with CP2 collars. Whereas for Firm1 the performance of the two batches is similar (see Fig. 7), Fim3 magnets assembled with CP2 collars show a better performance with respect to magnets assembled with CP1 collars (see Fig. 8). Indeed the sample is very small and it is hard to draw conclusions.

Table 4: Collars producers used in magnet assemblers.

	CP1		CP2	
	Number	%	Number	%
Firm1	21	5.2%	386	94.8%
Firm2	1	0.2%	443	99.8%
Firm3	401	97.8%	9	2.2%

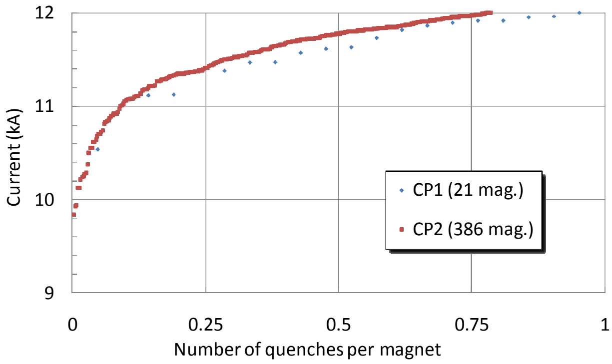

Figure 7: Performance in virgin condition of Firm1 magnets, split according to collar manufacturer

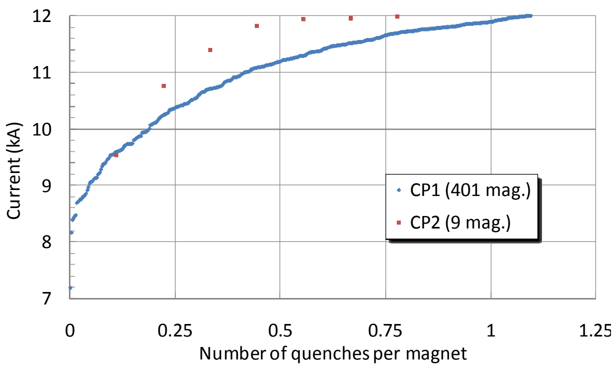

Figure 8: Performance in virgin condition of Firm3 magnets, split according to collar manufacturer

TESTS ON 3-4 MAGNETS DONE AFTER THE INCIDENT

After the 3-4 incident, several tens of dipoles have been brought to surface and replaced with spare magnets. All the spare magnets were from Firm2, and had not been previously tested. Therefore, 26 Firm2 spare dipoles have been tested in virgin conditions: they reached nominal with 25 quenches, i.e. ~1 quench per magnet. This behaviour is in agreement with the Firm2 data gathered during production in virgin conditions (see Fig. 5), i.e. they showed no performance degradation.

Among the dipoles removed from sector 3-4, 16 were not damaged and they were tested, and reinstalled: 4 from Firm1, 10 from Firm2 and 2 only from Firm3. The magnets needed between 0.25 and 0.6 quench per magnet to reach nominal (see Table 5). This is in agreement with what expected from the MonteCarlo method, within the thin statistics. The two Firm3 magnets took one quench to reach nominal, i.e. no significant degradation of the performance has been observed (see Table 5).

Table 5: Quench performance of magnets from 3-4 tested in 2009.

	3-4 magnets			MonteCarlo
	Number	Quenches to 7 TeV	Quenches/ magnet to 7 TeV	Quenches/ magnet to 7 TeV
Firm1	4	1	0.25	0.20
Firm2	10	7	0.70	0.39
Firm3	2	1	0.50	0.39

CONCLUSIONS

The energy of 6.5 TeV should be reached with a few quenches in the whole machine. In order to reach 7 TeV one can guess a number between 50 and 100 quenches per octant. This is only an educated guess, since no sectors have been reached this level of energy. We also discussed previous estimates giving about 25 quenches per octant, showing their justification.

This longer training is due to magnets assembled by Firm3. Even though traces of an anomalous behaviour were present in the individual test data, today we cannot manage to reproduce the behaviour during hardware commissioning on the ground of these data.

Coil modulus and storage time do not appear to play any role. What is attributed to the dipole assembler could as well be attributed to the collar manufacturer: Firm3 dipoles were all assembled with CP1 collar manufacturer, and vice-versa.

The recent tests on individual magnets removed from 3-4 sector show no degradation of performance w.r.t. expectations.

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