

Retraining of the 1232 Main Dipole Magnets in the LHC

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Abstract— The Large Hadron Collider (LHC) contains eight main dipole circuits, each of them with 154 dipole magnets powered in series. These 15-m-long magnets are wound from Nb-Ti superconducting Rutherford cables, and have active quench detection triggering heaters to quickly force the transition of the coil to the normal conducting state in case of a quench, and hence reduce the hot spot temperature. During the reception tests in 2002-2007 all these magnets have been trained up to at least 12 kA, corresponding to a beam energy of 7.1 TeV. After installation in the accelerator, the circuits have been operated at reduced currents of up to 6.8 kA from 2010-2013, corresponding to a beam energy of 4 TeV. After the first Long Shutdown of 2013-2014, the LHC runs at 6.5 TeV, requiring a dipole magnet current of 11.0 kA. A significant number of training quenches was needed to bring the 1232 magnets up to this current. In this paper, the circuit behavior in case of a quench is presented, as well as the quench training as compared to the initial training during the reception tests of the individual magnets.

Index Terms—accelerator magnet, quench protection, superconducting coil

I. INTRODUCTION

THE Large Hadron Collider (LHC) accommodates 1232 main superconducting twin-aperture dipole magnets, which are powered in eight independent circuits, each stretching over one sector of 3 km length [1]. The 154 dipole magnets in each sector are housed in 27 cryogenic cells, and operate in a static bath of pressurized helium II, cooled by heat exchange with flowing saturated helium II. The cold part of each circuit contains as well four 13 kA gas cooled current leads incorporating stacks of Bi-2223 tape [2], and a large number of busbar cables, linking the dipoles together. Each circuit (see Fig. 1) is powered by a 13 kA power converter.

The coils of these magnets consist of an inner and outer layer, wound from two types of Nb-Ti superconducting keystoneed Rutherford cable; see Table I. The inner and outer cables have been produced by different firms [3], according to the same functional specification. The 1232 magnets (plus spares) have been assembled by three different manufacturers [4], in the following denoted as Firm-1, Firm-2 and Firm-3, with only a few minor differences in tooling and procedures.

The magnets have a nominal central field of 8.33 T at a current of 11.85 kA, corresponding to a beam energy of 7 TeV; see Table II. The inductance of a single circuit is 15.4 H and its total stored energy equals 1.1 GJ at nominal current. The protection of the dipoles and the circuit is ensured by individual quench detection systems [5], cold by-pass diodes, quench heaters, and two independent energy-extraction systems [6], and is described in more detail in Section II.

All dipole magnets have been individually tested at CERN in the years 2002-2007 especially regarding field uniformity and quench behavior [7]. A brief summary of the results of these reception tests is presented in Section III. Note that the data in this paper are based on the 1232 dipole magnets that are presently installed in the LHC, not taking into account the 44 spare magnets. About 10% of the magnets were re-trained after one or more thermal cycles. After the reception tests the magnets were stored up to several years before being installed in the LHC.

After installation in the LHC tunnel, all main dipole circuits were tested without beam during the so called ‘hardware commissioning phase’ [8],[9], in order to verify the proper functioning of all hardware and software associated with the circuits and ensure a safe and efficient machine start-up.

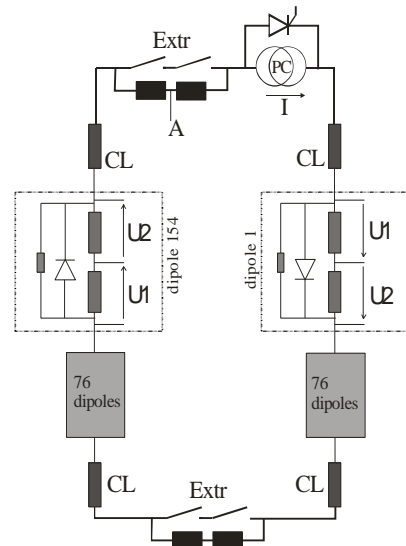


Fig. 1. Schematic view of a dipole circuit of one sector of the LHC. Note that only the first and last dipoles of the circuit are shown in more detail. The system is grounded at point A by a circuit of resistances and a fuse. Each dipole is bypassed by a cold diode and shunted by a 100 Ω damping resistance. PC=Power Converter; CL=Current Lead; Extr=Energy Extraction system.

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TABLE I
MAIN SPECIFICATIONS OF THE CABLES USED FOR THE LHC DIPOLE
MAGNETS [1]

	Inner coil	Outer coil
Cable width	15.1 mm	15.1 mm
Mid-thickness	1.90 mm	1.48 mm
Number of strands	28	36
Cable insulation	2 layers of 50.8- μ m-thick polyimide with 50% overlap, and 1 layer of 68.6- μ m-thick polyimide with 2 mm spacing	

TABLE II
MAIN SPECIFICATIONS OF THE LHC DIPOLE MAGNETS [1]

Nominal central field	8.33 T
Nominal current	11850 A
Operating temperature	1.9 K
Magnetic length	14.312 m
Inductance at nominal field	98.7 mH
Stored energy at nominal field	6.93 MJ
Number of turns per pole, inner layer	15
Number of turns per pole, outer layer	25
Inner coil diameter	56 mm
Distance between aperture axes	194 mm
Bending radius	2804 m

During this first commissioning phase, only one of the eight circuits (denoted as S56) was trained up to 11.2 kA (see Section IV), whereas the other seven circuits were only tested up to 9.3 kA. The incident in September 2008 [10] resulted in serious damage of one sector and revealed a systematic problem in the busbar connections of the main dipole and quadrupole circuits. To avoid similar problems, the magnets were operated in 2010-2012 at a reduced current of up to 6.8 kA, corresponding to a beam energy of 4 TeV. During the first Long Shutdown of 2013-2014, all busbar interconnects were consolidated and reinforced with additional copper shunts [11]. In the coming years the LHC is planned to be operated at a beam energy of 6.5 TeV, requiring a dipole magnet current of 10980 A. In the beginning of 2015, all eight circuits have therefore been retrained to this current plus a small margin of 100 A, i.e. 11080 A, requiring 175 training quenches. The results of these training quenches are presented in Section V and compared to the training during the reception tests and the training in S56 in 2008.

II. PROTECTION IN CASE OF A QUENCH

The protection of the dipole magnets relies on fast and reliable detection of resistive voltages based on a floating bridge detector, which continuously compares the voltages U_1 and U_2 of the two apertures [5]. As soon as the differential voltage U_1-U_2 reaches the threshold voltage (200 mV for the reception tests and 100 mV in the LHC), the quench detection is triggered (after a short evaluation time of about 10 ms), initiating within 5 ms a discharge of the quench-heater power supplies of the quenching magnet. At the same time the

Powering Interlock Controller switches off the power converter, after which a bypass thyristor across the converter terminal ensures the circuit continuity. About 20-50 ms later the heat developed in the quench heaters causes the transition to the normal state of a large part of the coil of the quenching magnet. The resistive voltage build-up in the coils opens the bypass diodes and causes a fast decay of the current in the quenched magnet.

In the LHC the circuits are composed of 154 magnets in series, and the circuit current cannot be discharged at the same rate as the current in the quenching magnet. The circuit protection is therefore ensured by additional cold bypass diodes, and two energy extraction systems [6]; see Fig. 1. As soon as the voltage over the quenching magnet reaches the turn-on voltage of the bypass diode of about 6 V (at 1.9 K), the diode starts to conduct, and the current in the quenching magnet commutes into the diode within a few 100 ms. The switches of the two energy extraction systems are triggered about 350 and 600 ms after quench detection, respectively, and, due to the two additional dump resistances of 75 m Ω each, the circuit current decays with a time constant of about 100 s. During this decay the current bypasses the quenched magnet, warming up the cold diode, whose forward voltage quickly drops from 6 V to 1 V when heating up.

During the decay of the circuit current, heat flow from the quenching magnet usually causes secondary quenches of neighbouring magnets located in the same cryogenic cell, as soon as the temperature of a part of the coil raises above the current sharing temperature. Most adjacent quenches occur after about 40-100 s at currents of about 4-8 kA. During the quench event, the pressure rise due to the increase in helium temperature is limited to about 18 bar by means of a relief valve.

III. TRAINING DURING RECEPTION TESTS

When a superconducting magnet is powered for the first time it may not reach the short sample limit of the conductor, but quenches before. During successive quenches the current that is reached usually increases, a process which is called *training*, and generally believed to be due to the setting of the conductor or coil in a more stable position. During the reception tests in 2002-2007 all magnets were individually cooled down to 1.9 K and ramped up with 10 A/s until a quench would occur, or until 12850 A was reached. Due to time constraints, the training of about half of the magnets was stopped between 12000 A and 12850 A [12]. In total 1115 quenches were needed to train to the nominal current of 11850 A; see Table III. In order to compare the training during reception with the training in the LHC (see Section V), also the number of quenches needed to reach 11080 A was calculated, which equals 413. Sorting all quench data of the individual magnets by increasing quench current, makes it possible to build a training curve as if the magnets of each firm were put in series. The result is shown in Fig. 2, in which the number of quenches in Firm-1, Firm-2 and Firm-3 is normalized to the number of magnets, i.e. 400, 420, and 412 respectively. The majority of the magnets required none or a single quench to reach 11080 A, and only 1% for Firm-1, 5%

for Firm-2, and 8% for Firm-3 needed 2 or 3 quenches. Similarly, on average 95% of the magnets needed 0, 1 or 2 quenches to reach 11850 A, and only 3% for Firm-1, and 6% for Firm-2 and Firm-3 needed 3 to 6 quenches. The data show a significant difference among the three firms. Firm-1 magnets trained 2 and 1.6 times faster up to 11850 A than Firm-2 and Firm-3 respectively. Similarly, Firm-1 magnets trained 3.9 times faster up to 11080 A than the other two firms.

TABLE III
QUENCH BEHAVIOR OF THE 1232 DIPOLE MAGNETS DURING THE INDIVIDUAL RECEPTION TESTS

	Firm-1	Firm-2	Firm-3	All
Number of magnets	400	420	412	1232
Nr quenches to reach 11850 A	244	485	386	1115
Nr quenches to reach 11080 A	47	183	183	413

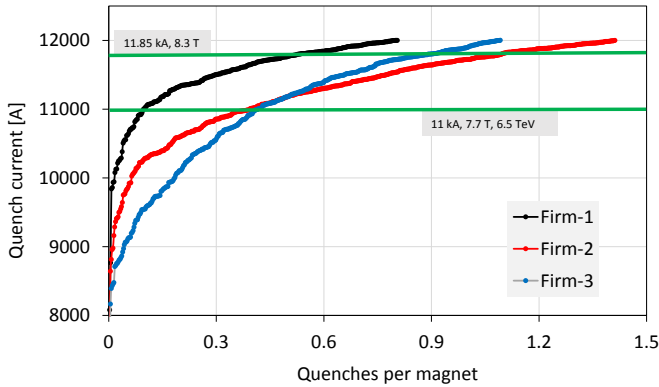


Fig. 2. Training curve to 12 kA for the 1232 dipole magnets presently installed in the LHC.

666 out of the 1232 magnets have also been tested up to 12850 A, see Table IV, showing that this current was reached for the three firms in about 4 quenches per magnet on average.

TABLE IV
QUENCH BEHAVIOR OF THE 666 DIPOLE MAGNETS DURING THE INDIVIDUAL RECEPTION TESTS THAT WERE TRAINED TO 12850 A

	Firm-1	Firm-2	Firm-3	All
Number of magnets	166	243	257	666
Nr quenches to reach 12850 A	591	1032	961	2584
Nr quenches / Nr of magnets	3.56	4.25	3.74	3.88

Almost 10% of all magnets have been re-trained after a thermal cycle, usually within a few weeks of the first cool-down, and without removing the magnets from the test station. These magnets were in most cases those that trained slower during the first cool-down (but always reached at least 12 kA) and are therefore not a representative subset of all the magnets. The overview in Table V clearly shows that the number of training quenches needed to reach 11850 A was about $240/37=6.5$ times less during the 2nd cool-down than during the 1st cool-down. A reduction of a factor of $68/8=8.5$

was observed when comparing the quenches required to reach 11080 A. The magnets therefore showed a good memory, at least over a period of several weeks, irrespective of the magnet manufacturer.

TABLE V
QUENCH BEHAVIOR OF THE 116 DIPOLE MAGNETS THAT HAVE BEEN RE-TESTED AFTER A THERMAL CYCLE

	Firm-1	Firm-2	Firm-3	All
Number of magnets	33	55	28	116
Nr quenches to reach 11850 A during the 1 st cool-down	54	119	67	240
Nr quenches to reach 11850 A during the 2 nd cool-down	6	21	10	37
Nr quenches to reach 11080 A during the 1 st cool-down	4	34	30	68
Nr quenches to reach 11080 A during the 2 nd cool-down	1	3	4	8

Magnets showing a low first training quench current gained on average a lot after the thermal cycle, as shown in Fig. 3; see also [13]. Magnets with a first training quench below 11.3 kA during the 1st cool-down always had a 1st training quench after the thermal cycle that was larger. Only 9 out of 116 magnets showed detraining, i.e. the thermal cycle resulted in a deterioration of the quench performance.

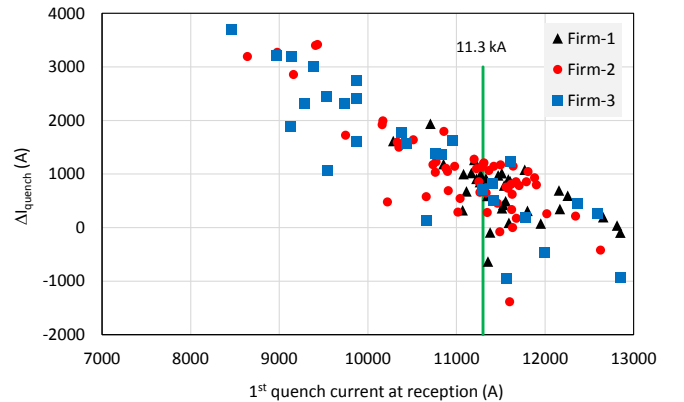


Fig. 3. Difference between 1st training quench after thermal cycle and the 1st training quench at reception (ΔI_{quench}) plotted versus the 1st training quench at reception.

Assuming that the magnets would have a similar behavior in the LHC, one could calculate the number of quenches to train all magnets to 11080 A in the LHC. This results in $(400/33)*1=12$ for Firm-1, $(420/55)*3=23$ for Firm-2, and $(412/28)*4$ for Firm-3 (denoted by Estimate A in Table VI). However, this approach is pessimistic since the data of Table V are biased by the fact that, on average, these magnets trained slower than the entire population. Estimate B takes this bias into account, by scaling Estimate A to the quench probability presented in Tables III and V. So Estimates A are scaled by a factor $(47/400)/(4/33)$ for Firm-1, a factor $(183/420)/(34/55)$ for Firm-2 and $(183/412)/(30/28)$ for Firm-3, giving for Estimate B values of 12, 16 and 24, respectively.

TABLE VI
ESTIMATED NUMBER OF QUENCHES NEEDED TO TRAIN THE 1232
MAGNETS IN THE LHC TO 11080 A

	Firm-1	Firm-2	Firm-3	All
Number of magnets	400	420	412	1232
Estimate A	12	23	59	94
Estimate B	12	16	24	52

IV. TRAINING OF ONE SECTOR OF THE LHC IN 2008

In 2008 one octant of the machine (called S56), containing 154 magnets (28 magnets from Firm-1, 42 from Firm-2, and 84 from Firm-3) was trained up to 11173 A; see Table VII. A total of 24 quenches were needed to reach 11080 A, and another 4 to reach 11173 A [14,15], at which current the training was interrupted. Successive quenches always occurred at a higher current except for one quench showing a detraining of 190 A. Almost all quenches occurred in Firm-3 magnets. During the initial reception tests (see Section II) the same magnets required 60 quenches. It follows that Firm-2 magnets show good memory, whereas Firm-3 magnets show partial memory. Only one of the 154 magnets in S56 was tested after a thermal cycle during the reception tests. It is, however, obvious that the Firm-3 magnets train much more than estimated by comparing the quenches in Table VII (22 quenches in 84 magnets) to the Estimate B in Table VI (24 quenches in 412 magnets). Apparently the good memory that Firm-3 magnets showed during the reception tests slowly vanished in time. In [13] it was concluded that there is no indication that the duration of the long-term storage, between reception and installation in the LHC, could have affected the performance.

TABLE VII
QUENCH BEHAVIOR OF THE 154 DIPOLE MAGNETS IN ONE SECTOR S56
OF THE LHC (2008)

	Firm-1	Firm-2	Firm-3	All
Number of magnets	28	42	84	154
Nr quenches to reach 11080 A				
– Reception 1 st cool-down	1	15	44	60
Nr quenches to reach 11080 A				
– LHC 2008	0	2	22	24

V. TRAINING OF 8 SECTORS OF THE LHC IN 2015

In the beginning of 2013 the LHC was warmed-up to room temperature, and in the following one and a half years all busbar interconnects were consolidated. In the end of 2014 the LHC was cooled-down again to 1.9 K and in the beginning of 2015 all 1232 dipole magnets in the 8 sectors of the LHC were trained up to 11080 A. In total 175 quenches occurred; 5 in Firm-1 magnets, 27 in Firm-2 magnets and 143 in Firm-3 magnets. Successive quenches in the same circuit were always at a higher current, except for a few cases showing detraining between 0-120 A. After the 1st cool-down of the reception tests, the 1232 magnets required 413 quenches to reach

11080 A. Plotting the quench results per firm (in a similar way as Fig. 2), shows that Firm-1 and Firm-2 magnets have a good memory since training in the LHC is 9 respectively 7 times faster than during reception. Firm-3 magnets, however, show only partial memory with a training which is only 30% faster than during reception. During reception 75 quenches occurred in Firm-3 magnets below 10 kA; in the LHC only 7. On the other hand, the slope of the training curve between 10 and 11.1 kA is smaller in the LHC. Note that none of the Firm-1 and Firm-2 magnets quenched twice. Among the 143 quenches in Firm-3 magnets, 120 magnets quenched once, 10 magnets quenched twice, and 1 magnet quenched 3 times. For those magnets that quenched 2 or 3 times, the 2nd quench current was always higher than the 1st one and the 3rd quench current was higher than the 2nd. Comparing the number of quenches in the LHC with Estimate B (see Table VI) shows that, within about a factor 2, the training of the Firm-1 and Firm-2 magnets is in agreement to the estimate, whereas Firm-3 magnets train significantly more.

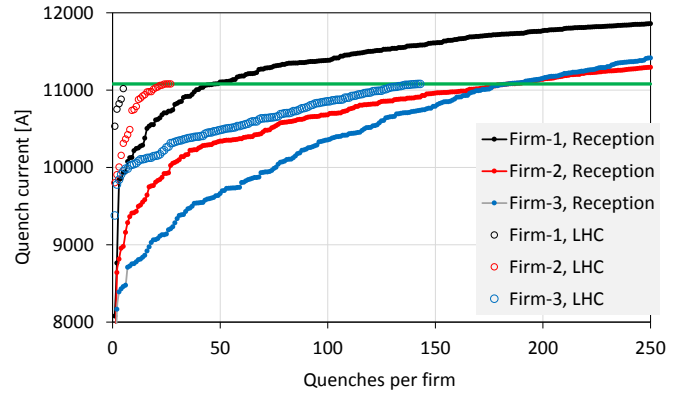


Fig. 2. Training curve to 11080 A for the 1232 dipole magnets in the LHC (round circles), as compared to the training during reception (solid dots). The green line corresponds to 11080 A.

Of special interest is to compare the training of S56 in 2008 (see Section IV) with the training in 2015; see Table VIII. Note as well that 13 of the 16 quenches in Firm-3 magnets in 2015 occurred in magnets that did not quench in 2008.

TABLE VIII
COMPARISON OF THE TRAINING OF S56

	Firm-1	Firm-2	Firm-3	All
Number of magnets	28	42	84	154
Nr quenches to reach 11080 A				
– LHC 2015	0	0	16	16
Nr quenches to reach 11080 A				
– LHC 2008	0	2	22	24
Nr quenches to reach 11080 A				
– Reception 1 st cool-down	1	15	44	60

Of course, the statistics are low, but one can conclude at least that despite the combined effect of time, thermal cycle, and powering (up to 6.8 kA) the magnets of Firm-1 and Firm-2 retained their memory. Extrapolating this result implies that

these magnets will probably need as well only a short training after future thermal cycles. The training behavior of the magnets from Firm-3 is less predictable. Many magnets with good training performance during reception show detraining in the LHC. The fact that the magnets from Firm-3 retain their quench memory only partially implies that a similar amount of training is likely needed after future thermal cycles.

Another interesting result is found by looking in detail to the Firm-3 magnets that quenched in the LHC and compare them to their behavior during reception; see Fig. 5. The horizontal axis shows the magnet ID in chronological order of production. It is clear that the behavior is not uniform over the production and that especially the magnets in the production batch 140-240 quenched more often in the LHC, and in many cases at currents several kA below their 1st quench during reception. There is no clear correlation between the Firm-3 magnets that quenched during reception below 11080 A and those that quenched in 2015 below 11080 A. Further data analysis shows that during reception, the Set 1 of 266 magnets did not quench below 11080 A, while the remaining Set 2 of 146 magnets quenched once or more below 11080. In 2015, 79 out of Set 1 (30%) and 52 out of Set 2 (so 36%) quenched once or more.

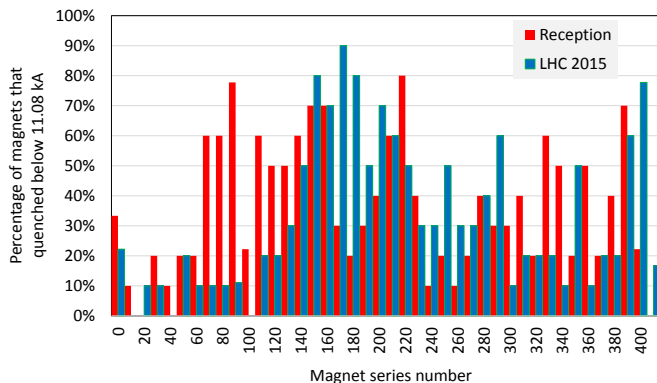


Fig. 5. Percentage of Firm-3 magnets that quenched below 11080 A during reception (red bars) and in the LHC (blue bars).

After the re-training of all the magnets in the LHC the 8 circuits underwent one more cycle to 11080 A and a few cycles to 10980 A, as part of the hardware commissioning. During these tests, another 8 training quenches occurred at constant current, 3 of them in Firm-2 magnets and 5 in Firm-3 magnets. After the commissioning the LHC has been operated with daily current cycles to the nominal current of 10980 A. In the first 4 months, 4 more training quenches occurred at nominal current, all of them in Firm-2 magnets, possibly related to slow relaxation processes, setting the cable or coil in a more stable position.

VI. CONCLUSION

This paper presents a brief overview of the training behavior of the 15-m long Nb-Ti dipole magnets of the LHC, which have been assembled by three different firms, with only few minor differences in tooling and procedures. The quench data of the reception tests in 2002-2007, and two training

campaigns in the LHC (in 2008 and 2015) are summarized for training up to 11080 A. This resulted in a unique data set containing more than 1200 magnets stretching over a period of more than ten years including several thermal cycles and hundreds of powering cycles. The data show that the magnets of Firm-1 and Firm-2 train 7-9 times faster in the LHC in 2015 as compared to the reception tests. These magnets almost completely retain their quench memory over the past 10 years. This would of course be very beneficial for future training campaigns. The magnets from Firm-3 train only about 1.3 times faster in the LHC as compared to the reception, but also in a very unpredictable way. Many magnets with good training performance during reception show detraining in the LHC, in many cases up to several kA. It seems very likely that a significant number of the Firm-3 magnets will train again after future long shutdowns of the LHC. In the meantime, investigations are ongoing to better understand the origin and possibly propose ideas for faster training.

In the first 5 months of LHC operation, 4 training quenches occurred at a constant current of 10980 A, which is from an operational point of view acceptable.

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