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Training Behaviour of the Main Dipoles in the Large Hadron Collider

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***Abstract*—In 2015, the 1232 Nb-Ti dipole magnets in the Large Hadron Collider have been commissioned to 7.8 T operational field, with 172 quenches. More than 80% of these quenches occurred in the magnets of one of the three cold mass assemblers (3000 series), confirming what already observed in 2008. In this paper, the recent analysis carried out on the quench performance of the LHC dipole magnets is reported, including the individual reception tests and the 2008 and 2015 commissioning campaigns, to better understand the above-mentioned anomaly and give an outlook for future operation and possible increase of the operational field. The lower part of the quench probability spectrum is compatible with Gaussian distributions; therefore the training curve can be fit through error functions. An essential ingredient in this analysis is the estimate of the error to be associated to the training data due to sampling of rare events, allowing to test different hypothesis. Using this approach, an estimate of the number of quenches required to reach 8.3 T (corresponding to the 7 TeV nominal energy) is given, and we propose to have two LHC sectors trained towards this target before the next warm up of the LHC.**

***Index Terms*—Superconducting magnets, Niobium-tin, Type II superconductors, superconducting coils.**

I. Introduction

THE 1232 dipoles of the Large Hadron Collider [1,2] were designed to have a nominal field of 8.3 T, working at 86% of the maximum achievable field of 9.7 T (the so-called short sample field), and to reach 9 T in a ultimate configuration. In 2015, the LHC dipoles were powered to 7.7 T [3], i.e., at 80% of the short sample, and the LHC has since then operated in a very smooth and reliable way at the corresponding energy level of 6.5 TeV, exceeding eventually the nominal luminosity during 2016 operation.

A known bottleneck to push the LHC towards 7 TeV is the dipole retraining. In 2008, one eighth of the accelerator dipoles was powered to 6.6 TeV; unexpectedly, ~1/6 of these dipoles, all of the same manufacturer, quenched during the training campaign [4]. The LHC was expected to reach 7 TeV with small or negligible training, and with similar performance across the production [5,6,7]. A posteriori [8], traces of the slow training for this manufacturer could be found already in the production data. However, the analysis was not able to prove if the observed behavior in the installed dipoles during 2008 commissioning was already present at the acceptance test or if long-term phenomena have degraded the performance after the magnet construction; this question is still open today.

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In 2015, the commissioning campaign confirmed both the necessity of a non-negligible training to reach 6.5 TeV, and the differences in performance between the manufacturers. About 15% of the 1232 magnets quenched, corresponding to 172 quenches. Since one can have about two quenches per day per sector, hundreds of quenches have a non-negligible impact on the commissioning schedule. Moreover, the thermal and mechanical loads induce a risk of damage that is low in absolute numbers but, given the large number of magnets, is not negligible. For instance, during the 2015 campaign a short in a diode box appeared and was removed (burnt) with a well-calibrated pulse of current.

The aim of this paper is to present the indications on a possible path to push the LHC towards 7 TeV. This is important not only for increasing the LHC capability of discovering new particles, but also for the future projects to establish what is the field margin required in an accelerator made of thousands of main superconducting dipoles, as the Future Circular Collider [10] or a High Energy LHC [11].

After recalling the limited set of available data in Section II, we show in Section III that the comparison between the only sector trained to 6.5 TeV both in 2008 and in 2015 suggests that training should be described in terms of probability. A statistical model compatible with the observed behavior is proposed in Section III.B, and is used in Section IV to validate some hypothesis (with a given confidence level) on the homogeneity of the production, on the correlation of quench behavior between apertures, and on the behavior after a warm up. The statistical model implies that quenches are described by a distribution: their shape is analysed in Section V, proposing a modified Gaussian fit working both for the small set of 2015 data and for most of the production data. This fit is used in Section VII to have a glimpse on the possible behavior towards 7 TeV, and to propose a strategy to consolidate these estimates through a selective powering to 7 TeV of two sectors before the next LHC warm-up.

II. Available Data

The main LHC dipoles were produced by three industries referred as 1000, 2000 and 3000 series respectively [2]. The production of the 1232 dipoles plus 16 spares has been split in three series of 416 magnets, and a contract for 30 additional spares has been assigned to the 2000 series industry. The 1000 series has only 415 magnets, since one had a severe nonconformity and has not been rebuilt, but its components were reused; the 2000 series has 446 magnets, and the 3000 series has 416 magnets.

All magnets have been tested before installation in the tunnel [5]-[8] at 1.9 K at CERN. The test procedure aimed at validating quench performance, electrical conformity and field quality; it was based on the principle of training each magnet to the nominal current of 11850 A (8.3 T bore field) plus a margin (initially 8%, later lowered to 3%). If the magnet was not reaching the required performance, a warm-up and cool down (thermal cycle) was done and a second test was carried out. This happened for ~10% of the whole production, with 30 to 50 magnets tested per series. In case of insufficient performance, the magnet was rejected, disassembled and rebuilt. There were 20 rejected magnets, and 14 of them were tested after thermal cycle. Data of these magnets are not included in this analysis.

A total of 1232 magnets have been installed in the LHC machine, powered in eight circuits (called sectors, and named 12, 23, …, up to 81) of 154 magnets in series. The repartition of the three series in each sector is far from being equal (see Table I), and was firstly established on geometry and field quality criteria, and then on having longer training magnets in the mid of cell and not close to quadrupoles, where beam losses are more larger [12].

TABLE I
MAGNETS INSTALLED IN THE EIGHT LHC SECTORS, AND TOTAL NUMBER OF QUENCHES TO REACH 11080 A IN 2015 (IN BRACKETS THE NUMBER OF SECOND PLUS THIRD QUENCHES)

	installed per sector				Quenches to 11080 A in 2015				
sector	1000	2000	3000	total	sector	1000	2000	3000	total
12	50	95	9	154	12	2	1	4 (1)	7 (1)
23	56	58	40	154	23	0	2	15	17
34	44	81	29	154	34	1	7	8 (1)	16 (1)
45	48	44	62	154	45	0	3	46 (7)	49 (7)
56	28	42	84	154	56	0	0	17	17
67	57	36	61	154	67	0	1	19	20
78	53	40	61	154	78	2	10	6	18
81	64	24	66	154	81	0	3	25 (2)	28 (2)
LHC	400	420	412	1232	LHC	5	27	140 (11)	172 (11)

There have been three commissioning phases (2008, 2010 and 2015) interleaved by warm-ups of the LHC. In 2008, all circuits have been brought to 9130 A, sector 45 to 10300 A and sector 56 to 11173 A [4]. Soon after the commissioning, the 2008 incident [13] required warm up and replacement of 30 dipoles in sector 34. In 2010, the eight circuits were commissioned to 6 kA; after this commissioning, the LHC operated at 3.5 TeV. In 2012 the circuits were commissioned to 7 kA and the machine operated at 4 TeV in 2012. The LHC has been totally warmed up during 2013-2014 to carry out the consolidation of the busbar interconnects splices [14]. In 2015, all sectors have been brought to 11080 A [3], corresponding to proton beam energy of 6.5 TeV plus 100 A, with 172 quenches (see Table I). After this commissioning, the LHC operated at 6.5 TeV in 2015 and 2016.

III. A STATISTICAL MODEL

A. Hints from the sector 56 training

The 2008 campaign that brought one eight of the LHC (sector 56) to 11173 A showed a difference between the three series: 90% of the quenches occurred in 3000 series magnets. The 2015 campaign confirmed the anomaly of the 3000 series, accounting for 140 out of the 172 quenches to reach 11080 A.

The new element coming from the 2015 campaigns is that among the 17 magnets of the series 3000 quenching in sector 56 in 2015 (see Fig. 1), only 3 had also quenched in 2008. This means that we are not facing a deterministic phenomenon where always the same magnets quench (i.e. there is a subset of magnets with longer training), but rather a statistical phenomenon where the 84 magnets of 3000 series installed in sector 56 (see Table I) are an homogeneous set, with a 17/84~20% probability of quenching. Considering each commissioning campaign after a thermal cycle as an independent draw, the probability for a magnet to quench twice would be $(20\%)^2$~4%, so 3 out of 84. This hypothesis is the simplest compatible with the observed 3 magnets quenching both in 2008 and in 2015, and is also supported by data relative to individual test of dipoles tested between 2008 and 2015, showing lack of correlation in performance before and after a cool down [15]. In the next section, a framework to interpret the quench data according to this hypothesis is developed.

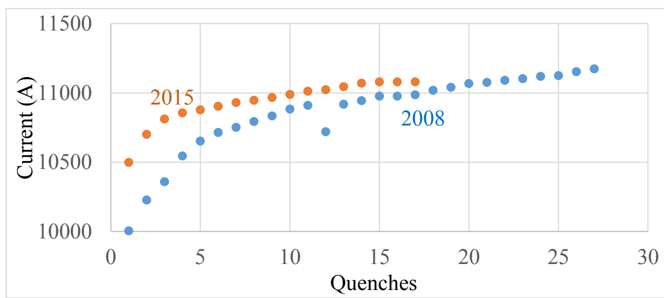

Fig. 1: Training for the 56 sector, only 3000 series, in 2008 and in 2015

B. Binomial distributions for quench

We assume that a set of magnets has associated a distribution of probability $P_1(I)$ for the first quench at current I, a distribution $P_2(I)$ for the second quench at current I, and so on, each satisfying the properties

$$\int_0^{I_{ss}} P_k(I)\,dI = 1 \qquad P_k(I) \ge 0 \tag{1}$$

where I_{ss} is the short sample current, i.e. the maximum current achievable in that magnet. The probability of having a first quench below current I is given by

$$p_1(I) = \int_0^{I} P_1(i)\,di \tag{2}$$

When a subset of N magnets is powered to a current I, on average $Np_1(I)$ will quench, with a sigma of $\sqrt{N(1-p_1)p_1}$, according to the binomial distribution. Therefore the training of N magnets (only first quench) will follow the curve $Np_1(I)$

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with a spread (one sigma) of $\sqrt{N(1-p_1)p_1}$.

To clarify this, a string of 50 magnets whose first quench belong to a Gaussian distribution, with average 11500 A and sigma 500 A is considered; we extract a number from the distribution for each magnet (see dots in Fig. 2, left). The training of this string will be given by reordering these values (see dots in Fig. 2, right). The training follows approximately the integral of the Gaussian distribution, with fluctuations due to the limited size (N=50 magnets) of the sample. If one draws several instances of the training of this string (what is called a MonteCarlo) one gets a cloud of lines, each one being a possible trainings of this string (see Fig. 3). The thickness of this cloud reduces for larger N, with the inverse of the square root of N. In our case of a small sample of a 50 magnets string this thickness is large: for instance, 11 kA can be reached with anything between 3 to 15 quenches, i.e. a factor 3 difference. In Fig. 3 we consider 20 realizations of the training, and a two sigma bound. Since two sigma gives a 95% confidence level, about one case out of the 20 should lay outside the average ± two sigma, as it is in the figure.

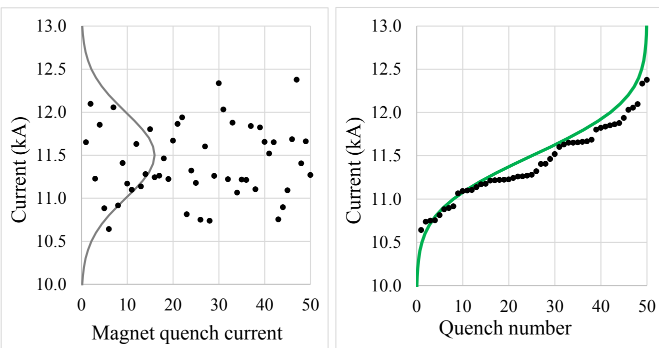

Fig. 2: Left: Example of a Gaussian distribution (grey curve), extraction of 50 quenches (dots): Right: reordering of quenches giving the training of a string of 50 magnets (dots) and integral of the Gaussian (green curve).

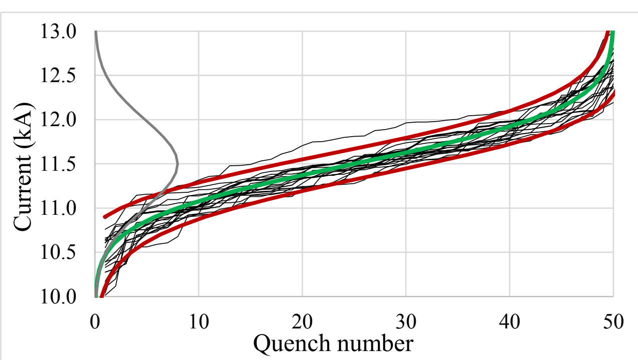

Fig. 3: Example of a Gaussian distribution (grey curve), integral giving training curve for a set of 50 magnets (green curve) with two sigma error (red curves), and 20 realizations of training drawn with a MonteCarlo method (black curves).

Note that we will always work with the integral of the distributions, and not with the distributions: this allows to avoid the binning choice and directly provides the training curve of a string of magnet, which is the observable during the magnet commissioning. The full training probability (first, second, and all other quenches) according to this approach is given by

$$t(I) = \int_0^I \sum_{k=1}^{\infty} P_k(i)di \qquad (3)$$

IV. Observed Behaviour at 6.5 TeV

The model outlined in Section III allows to draw some conclusions on the training behavior at 6.5 TeV. The distribution of quenches per sector and per manufacturer required to reach 11080 A during the 2015 campaign are given in Table I. Among the 172 quenches, an overwhelming 95% are first quenches: only 9 magnets quenched twice and one magnet thrice (so there is a total of 11 non-first quenches, all in 3000 series, as indicated in brackets in the table). The non-first quenches will be ignored since the data set is too scarce to draw any conclusion on the distribution $P_2(I)$ and $P_3(I)$.

A. *Differences between the three series*

The large difference of performance between the manufacturers is obviously significant: considering a two sigma error, the quench probabilities are

- 1000 series: 5/400=1.3%±1.1%
- 2000 series: 27/420=6.4%±2.4%
- 3000 series: 129/412=35%±5%

B. *Differences between sectors*

The same computation is done to see if there are significant differences between sectors. Results are shown in Fig. 4 for the 2000 and for the 3000 series, the set of data of the 1000 series being too small to make the analysis. There is a significantly worse performance in the magnets of the 2000 series installed in 78 and 81. Moreover, the 3000 series installed in sector 45 are significantly worse than the other sectors (with the possible exception of sector 12, where there are only 9 magnets of the 3000 series and statistics is too small to draw conclusions).

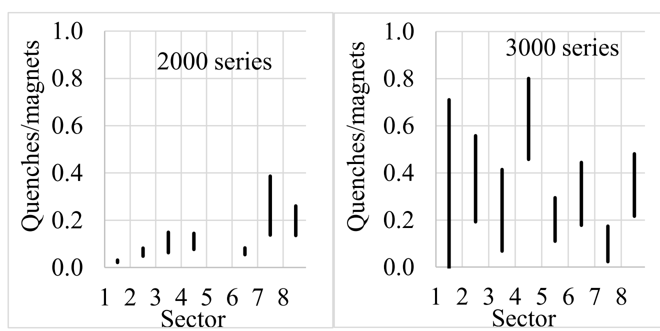

Fig. 4: Probability to quench before 11080 A during 2015 commissioning in the 2000 series (left) and in the 3000 series (right) split by sector.

C. *Differences along the production*

We now turn to differences in the magnet performance at 6.5 TeV along the production. We split each production in 8 batches of 52 magnets (9 for the 2000 series, whose production involved a total of 446 magnets). 1000 series is again ignored since the number of quenches to reach 11080 A is too low.

Data of 2000 series (see Fig. 5) indicate a worse performance in the first two batches: 18 out of 27 quenches belong to the first 104 magnets. This difference is at the limit

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of being statistically significant, with two sigma confidence level. Data of the 3000 series show a good performance for the first two batches, plus five batches with a 20-50% quench probability, and a fourth batch with a 50-80% probability. This fourth batch is responsible for the large number of quenches observed in sector 45 (see Table I). Summarizing, there are significant differences of performance along the magnet production for the 3000 series, and possibly also for the 2000 series, but with less statistical evidence.

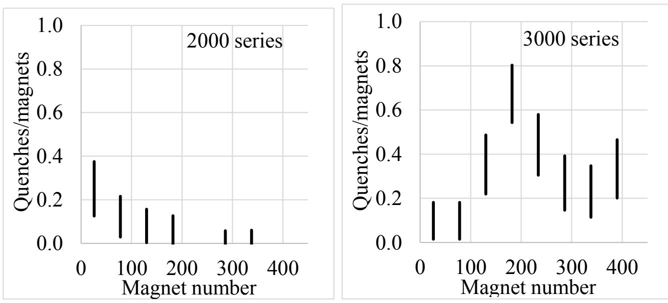

Fig. 5: Probability to quench before 11080 A during 2015 commissioning in the 2000 series (left) and in the 3000 series (right) split along the production in batches of 52 magnets.

D. *2008 vs 2015 training*

A crucial question for the training is the comparison of the performance before and after a warm up. We have experience of two sectors, with apparently contradictory results: sector 56 trained 30% faster in 2015 as compared to 2008 (see Fig. 1), and sector 45 trained three times slower (3 quenches in 2008, 10 in 2015). The crucial point is to add the statistical error due to the small sample (of the order of 50 magnets) – also in this case we use two sigma, i.e. a 95% confidence level.

- Sector 56 reached 11080 A with 23 quenches ± 8 in 2008, and with 17 quenches ± 7 in 2015;
- Sector 45 reached 10300 A with 3 quenches ± 3 in 2008, and with 10 quenches ± 6 in 2015.

So, when the statistical error is added, data are compatible with the assumption that the performance is the same after each thermal cycle, i.e. the full training has to be redone.

E. *Training and apertures*

The LHC magnets have two separate dipoles in a common mechanical structure made of stainless steel collars and iron yoke. A relevant question is if the quench in one aperture also trains the other one. If this is not the case, i.e., if there is no correlation, the 1232 two-in-one dipoles should be rather analysed as 2464 single aperture magnets.

Let us start from this hypothesis: since we had 140 first quenches in 824 apertures of the 3000 series (see Table I), i.e. a 17% probability of quenching one aperture, if the apertures were independent one would expect a $(17\%)^2$=2.9% probability of quench for two apertures, i.e. an average of 12 cases over 412 magnets. Moreover, since sector 45 probably belongs to a different distribution (see Fig. 4), we have to separate this case: this gives a total of 15 magnets quenching in both apertures, see Table II.

In the previous paragraph we observed that we had 9 magnets quenching twice: among them, 5 quenched in different apertures and 4 in the same aperture. Moreover one magnet quenched three times (twice in one aperture and once in the other one). So we obtain 6 magnets quenching in both apertures: this is smaller than the expected value of 15 in case of independent apertures. A MonteCarlo method gives an error of ±8 (two sigma) associated to the sampling, so the observed value is just below the two sigma limit. One can conclude that this scarcity of magnets quenching in both apertures gives some indication (at the limit of the 95% confidence level) that quenching one aperture partially trains also the other one. So the data is treated as belonging to 1232 magnets and not to 2464 apertures.

TABLE II
EXPECTED (IN THE HYPOTHESIS OF INDEPENDENT EVENTS) AND OBSERVED NUMBER OF QUENCHES ON BOTH APERTURES OF THE SAME DIPOLE

sector	quenches	apertures	quenches/ap	$(\text{quenches/ap})^2$	expected	observed
45	46	124	37%	14%	8.5	5
others	95	700	14%	1.8%	6.4	1

F. *Flattop quenches during operation*

During the 2015 operation, five magnets quenched at flattop current, i.e., about 100 A less than the 11080 A reached during the commissioning campaign. These "flattop quenches" occurred 30 minutes to 5 hours after reaching flattop, during the phase in which beams are colliding. The hypothesis of heating due to splices inside the magnet has been discarded since the five quenches occurred in five different magnets. An unexplained feature is that these flattop quenches all occurred in 2000 series magnets. In 2016 no flattop quenches were observed. More details are given in [15].

G. *Retraining after winter shutdown without warm-up*

During the 2015-2016 winter, the LHC had a three months technical stop where the magnets were kept below 40 K. After this pause, all magnets reached 11080 A with a total of three quenches only, two of 3000 series and one of 2000 series. So if the LHC is not warmed up, a negligible number of quenches are needed to reestablish operational conditions.

V. QUENCH DISTRIBUTIONS

A. *2015 training*

The shape of the distributions of the first quench in the 2015 training campaign is studied. Note that since training has been stopped to 11080 A, we access in most cases only to the left tail of the distribution. As stated before, we work with the integral of the distributions. We analyse the 2000 and 3000 series, finding the very interesting result that training data of the first quench are compatible with the integral of a tail of a Gaussian distribution (see Fig. 6), within the two sigma statistical error (sample of 400 magnets). A slightly better fit can be obtained by making a separate fit in the 3000 series for the part installed in sector 45. For the 1000 series we have not enough quenches to make a fit.

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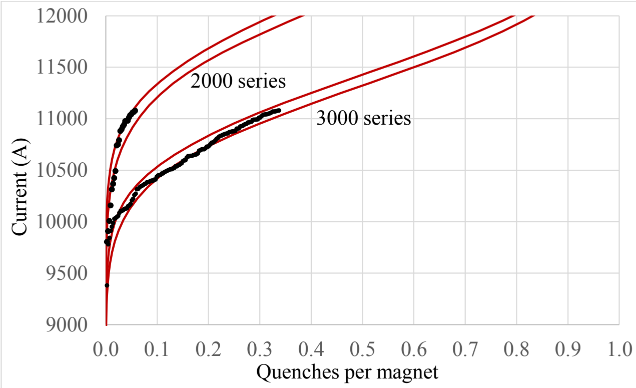

Fig. 6: Training in 2015 (first quench) in 2000 and 3000 series, and Gaussian fit with two sigma error.

B. Production data

To consolidate the previous analysis, the first and the second quenches that occurred during the individual test of the LHC dipoles are considered. A complete set of data is available and the Gaussian fit for currents in the critical range of 11-13 kA, not available in the 2015 campaign, can be checked.

Data shows an asymmetry in the distribution, corresponding to a skewness of -0.7 to -0.8; if we make a Gaussian fit on the lower part of the distribution (for probability lower than 0.5, see Fig. 7) the upper part is overestimated (ie the training is slower for higher currents). There is a physical barrier to the maximum performance given by the short sample limit, at 13.8 kA so it is not surprising that the distribution has a negative skewness.

Using a modified Gaussian, with 30% lower sigma in the higher part of the distribution (i.e. for current values larger than the average found with the Gaussian fit in the lower part) one recovers a very good fit over the whole range for the 1000 and 2000 series (see Fig. 8). The 3000 series is clearly not compatible with any Gaussian fit – this can be seen as an additional trace of the 3000 anomaly in the production data. The fit is good also for the second quench in all series, as shown in Fig. 9 – where data of the 3000 series are not show for sake of clarity (they are quite close to the 2000 series). The fit parameters are given in Table III, and compared to the fit relative to the training in 2015.

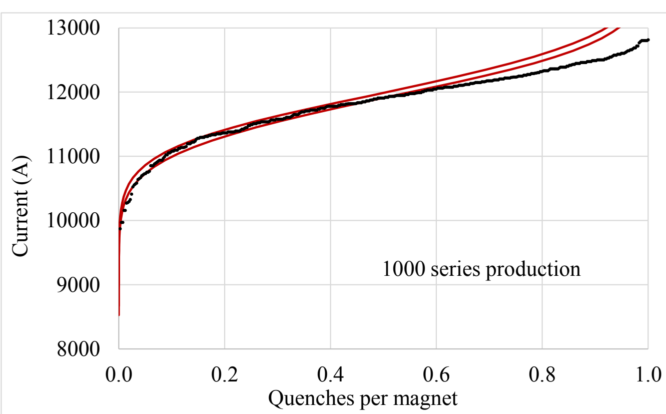

Fig. 7: Training (first quench) in 1000 series and Gaussian fit in the lower half.

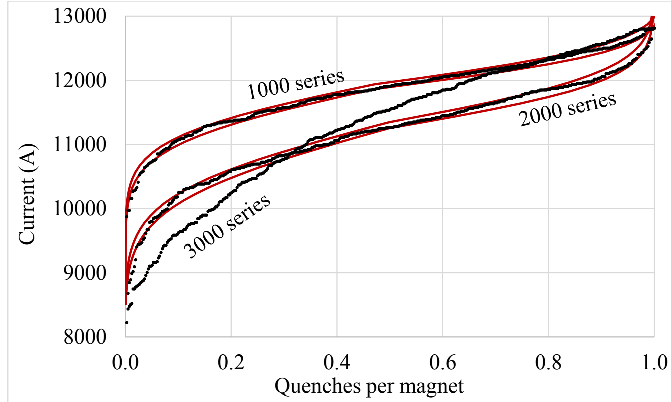

Fig. 8: Training (first quench) in 1000, 2000 series and Gaussian fit with 30% lower σ in the right part, plus 3000 series data.

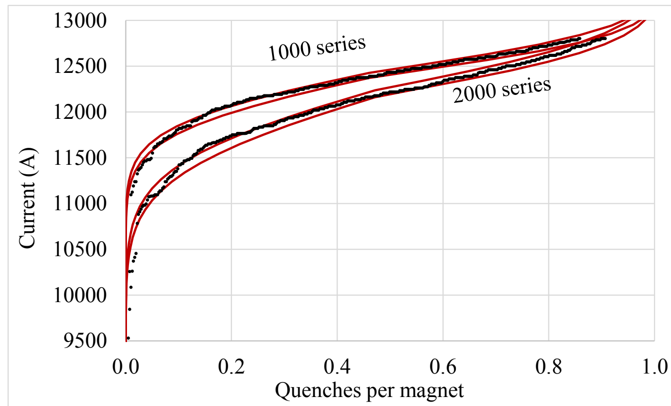

Fig. 9: Training (second quench) in 2000 series and Gaussian fit with 30% lower σ in the right part.

TABLE III
PARAMETERS OF THE MODIFIED GAUSSIAN FIT FOR THE FIRST AND SECOND QUENCHES IN THE LHC MAGNET PRODUCTION, AND FOR THE FIRST QUENCH IN THE 2015 CAMPAIGN

	First quench		Second quench		HC 2015	
	μ (kA)	σ (kA)	μ (kA)	σ (kA)	μ (kA)	σ (kA)
1000	12.000	0.700	12.500	0.500		
2000	11.350	0.900	12.300	0.700	12.300	0.800
3000			12.450	0.900	11.375	0.700

VI. DATA AFTER THERMAL CYCLE

The analysis of the data relative to quench performance After Thermal Cycle (ATC, i.e. test done on individual magnets that already went through a first training and a successive warm-up) is not trivial. In principle, the installed LHC should behave as the data ATC. The problem is that the sample is small, consisting of 30-50 magnets per series (see Table IV) and therefore the statistical errors are large. Moreover, the sample is biased since only the magnets not reaching the required performance were tested after thermal cycle. Finally, the sample has a second bias since it is far from being uniform along the production (most of the tests performed at the beginning of the production).

With these disclaimers, we give in Table IV the first quenches needed to reach 11080 A (6.5 TeV plus 100 A margin) and 12000 A (7 TeV plus 150 A margin) for the magnets tested ATC. The statistical error of 2 sigma is added, in the hypothesis of a uniform production.

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TABLE IV
FRACTION OF MAGNETS QUENCHING TO REACH 6.5 TEV AND 7 TEV OPERATION, TESTED AFTER THERMAL CYCLE, WITH BIAS DUE TO NONUNIFORM SAMPLING OF THE PRODUCTION

tested after thermal cycle		first quenches (excluding dismantled) to 6.5 TeV+100 A		7.0 TeV+150 A	
38	1000 series	0	0%	7	18%±12%
51	2000 series	1	2%±4%	18	35%±13%
33	3000 series	4	12%±11%	12	36%±17%

At 11080 A, the observed behavior of 1000 and 2000 series is compatible with the 2015 campaign: quench is negligible for 1000 series and occurs in a few percent of the 2000 series magnets. For the 3000 series, ATC data show a 12% quench probability (with a statistical error of 11%) - large, but not as large as the 35% (with a statistical error of 5%) observed in 2015. The sampling is very unfortunate, since, out of the 33 magnets tested ATC, 13 belong to the first two batches that showed fast training in 2015 (see Fig. 3). The fourth batch, with the slower training in 2015, had only one magnet tested ATC. Carrying out a separate analysis for the 3001-3104 batch (whose 13 magnets never quenched to reach 6.5 TeV) and 3105-3416, one obtains a 15%±14% probability, barely compatible what observed in 2015. So at 6.5 TeV, the 3000 series data ATC showed a considerable training, even though the very uneven sampling does not allow to conclude if these data are compatible with the 2015 commissioning. At 7 TeV, data show a leveling of the performance between the series.

VII. TOWARDS 7 TEV

One can give an indication on the behavior at 7 TeV through extrapolation of the Gaussian fit of the 2015 commissioning data, with a 30% reduction in the sigma in the upper half as suggested by the production data. This gives a 85% probability of quench for 3000 series magnets, i.e. ~330 quenches, plus 33% for the 2000 series, i.e. ~140 quenches. Using the hypothesis that the quench for the 1000 series corresponds to the second quench in the production (see Fig. 9) or to the behavior ATC (see Table IV), we can add a 18% probability to reach 12 kA, so another 70 quenches for a total of ~540 quenches (see Table V). Two additional estimates are given, where each series is split in homogeneous sets according to the sector (B) or to the production (C) as shown in Fig. 2 and 3. In general we find that 40-45% of the LHC magnets require a quench. In this estimate the second quench is not included.

The statistical error associated to the population size (1232 magnets) is ±40 quenches. So each time we have to make a warm-up of the LHC, differences in the number of quenches as large as 80 can be found, just for statistical reasons. On the top of this, there is the statistical error associated to the estimate of the Gaussian parameters, which is very large for the 2000 series, and for the 1000 series is based on heuristic arguments. To have a more reliable estimate, one or more sectors should be powered to 7 TeV. Since 161 first quenches have been already done to train all the LHC to 11080 A, it would be interesting to train before the next warm up, foreseen for 2018. Main unknowns are (i) validating the fit for the 2000 series, that relies on few data, (ii) validating the 18% hypothesis for the 1000 series, (iii) finding where the 3000 series start to have a second quench. The last point can be seen through training to 7 TeV sector 45, where 2/3 of the 3000 series magnets already had a first quench.

If only one sector is used to extrapolate to the whole LHC, one can show that the precision of the estimate is within a factor two. With a second sector one doubles the sample and the error is reduced by 30%, i.e. in the range +60% -35%.

TABLE V
GUESS OF FIRST QUENCHES NEEDED TO REACH 7 TEV PLUS 150 A IN EACH SECTOR, THREE DIFFERENT ESTIMATES.

sector	Estimate for 7 TeV (1st q. only) A	B	C	Done 2015	To do (before warming up) A	B	C
12	48	40	32	6	42	34	26
23	63	55	61	17	46	38	44
34	59	50	62	15	44	35	47
45	76	82	85	42	34	40	43
56	90	79	83	17	73	62	66
67	74	65	69	20	54	45	49
78	75	75	62	18	57	57	44
81	76	73	73	26	50	47	47
LHC	561	518	526	161	400	357	365

VIII. CONCLUSION

In this paper, the retraining phenomena in the LHC main dipoles are investigated on the ground of the 2008 and 2015 commissioning data, and of the individual test carried out during the production. Data is shown to be compatible with a statistical model where magnets at each warm up and cool down, quench with the same probability. The training curve is the integral of the probability distribution.

The statistical approach allows to state that data is compatible with the following hypothesis:

i. the same retraining is needed at each warm up;
ii. the differences between the three manufacturers are significant at 6.5 TeV;
iii. there are hints of significant differences in the performance at 6.5 TeV along the production of 3000 series, and possibly also for the 2000 series;
iv. there is a scarcity of double quenches indicating, at the limit of 95% confidence level, that training of one aperture reduces the training probability in the other one;
v. production data of magnets tested after the thermal cycle (Section VI) are compatible with what seen for 1000 and 2000 series, and at the two σ limit for the 3000 series.

A very interesting result is that 2015 data are compatible with Gaussian tails. Moreover, most of the production data are compatible with a modified Gaussian distribution, as discussed in section V.B. Using the modified Gaussian fit and the production data for guessing the missing information, we estimate that 40-45% of the LHC magnets should quench to reach 7 TeV, with large differences between manufacturers, plus an unknown number of second quenches. We plan to train two sectors towards 7 TeV before the next LHC warm up of the LHC. This would allow to consolidate this analysis and to better understand the overheads required for 7 TeV operation.

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