EXPECTED QUENCH LEVELS OF THE MACHINE WITHOUT BEAM: STARTING AT 7 TEV ?

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Abstract

The quench training performance of about 900 LHC main dipoles and 200 main quadrupoles cold tested to date will be presented and commented. From these results an estimate of the number of quenches that could be required to operate the whole machine at nominal energy without considering beam loss effects will be presented. The energy level at which the machine could be operated without being disturbed by training quenches at the early phase of the commissioning will also be addressed. The missing and required information necessary to improve these predictions will be pointed out.

INTRODUCTION

Like most large superconducting magnets, LHC main dipoles (MBs) and quadrupoles (MQs) exhibit premature training quenches, i.e. a progressive increase of the current level reached after repeated quenching. The settling mechanism occurs mostly during the current ramping-up phase. During quenches, thermal gradients and thermo-mechanical shocks arise and can destabilise mechanically the magnet coil leading to a detraining of the magnet quench performance. Training and detraining quenches are mostly originated from conductor motions or micro-fractures of insulating materials under the action of Lorentz forces. All these mechanical events occur stochastically and were specially investigated for LHC main dipoles [1]. They give rise to transient energy released within the coil winding as it is energised that can exceed locally the enthalpy margin of the conductor and provoke a quench.

Another effect that characterises the quench performance of a superconducting magnet is the so-called memory effect. It determines the ability of a superconducting magnet to "keep in mind" partially or completely after a thermal cycle, its previous quench current level. Like the training, the memory effect is an out-of-equilibrium process and may be affected by long time storage. It can also "overtrain" after repeated thermal cycling and the effect of training retention after a thermal cycle will drive mostly the quench performance of the superconducting magnets in the LHC tunnel during their first powering cycles.

In this article, the training quench performance of LHC main dipoles and quadrupoles measured to date on test benches will be presented. From a statistical analysis of these results and additional hypothesises, the average number of training quenches that can be required to reach the nominal energy of the LHC (7 TeV) will be given by octant together with a measure of the expected dispersion. An estimation of the training quench probability will also be proposed for MBs as a function of the magnet current.

CASE OF LHC MAIN DIPOLES

Training Quench Performance of MBs

The histogram of the cold tested MBs as a function of the number of training quenches required to reach the nominal field of the LHC is given in Fig.1. Before the Thermal Cycle (TC), about 38.1 % of MBs reached without training quench the nominal field during their first powering. After a TC performed on ~12.7 % of MBs, mostly for reason of weak quench performance, this proportion reached ~75.5 % (Fig.2). In other words, after TC ~24.5 % of MBs required at least one training quench to reach the nominal field equal to 8.33 T. All MBs that did not reach the nominal field were rejected and repaired in industry before to be re- tested at cold.

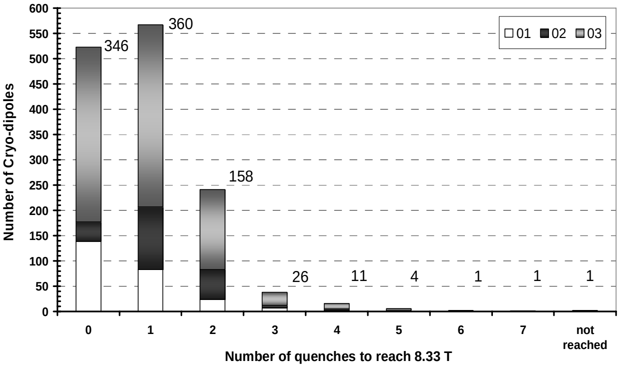

Figure 1: Histogram of the 907 MBs cold tested to date and produced by the three European manufacturers as a function of the number of training quenches after the 1st cool-down.

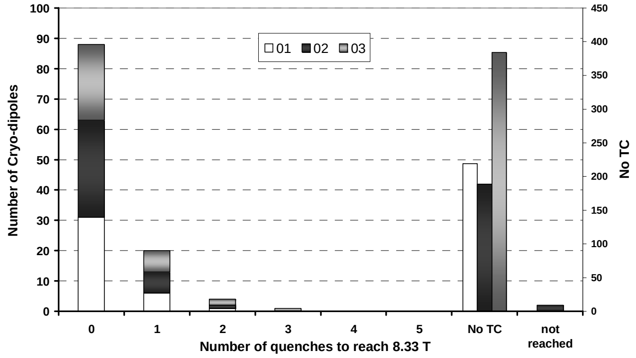

Figure 2: Histogram of the 115 MBs submitted to a Thermal Cycle (TC) as a function of the training quench performance after the 2nd cool-down.

From the simplest extrapolation of the results of Fig.2, assuming no detraining effect and that MBs submitted to a TC will not quench in the tunnel, the number of quenches that may occur during the first powering cycles is (1232-115)×(0.17+2×0.03+3×0.01) ≈ 300 i.e. about 40 by octant. This number corresponds to a worst case scenario with a low probability of occurrence as it is based on a biased statistics coming from the sample of the weakest MBs for which a TC was performed. This estimate will be corrected in the next paragraph.

Estimate of the Number of Quenches by octant for MBs to reach the nominal field of the LHC

The result oriented cold test program for MBs and MQs was reviewed and streamlined in 2003 [2]. As a result, the quench performance was first based on a two quench criteria [3] and a thermal cycle performed for cryomagnets that did not reach 9 T after 8 quenches. In 2005, the rule was slightly modified to improve the assessment of the quench performance. It is now based on a three quench criteria [4] with the same rule for the extended test with a TC. The obvious consequence of these test programs is to introduce a statistical bias for the sample {MBs with TC} that must be corrected for a reliable training quench prediction for the machine.

One of the possible ways is to consider the statistics of the number of quench needed to reach the nominal field during cold tests. In Table 1, the two main parameters summarizing these statistics, i.e. the average and the standard deviation, are given for the data coming from the two samples {MBs with TC} and {MBs with no TC}.

Table 1: Statistics for MBs related to the number of quenches to reach the nominal field of 8.33 T

Sample	{MBs with TC}	{MBs without TC}
Average Number before TC	1.82	1
Standard Deviation	1.35	1
Average Number after TC	0.33	0.181*
Standard Deviation	0.78	0.58**
Population	115	785

* assuming the same reduction of 82 % after TC as for {MBs with TC}
** assuming the same reduction of 42 % after TC as for {MBs with TC}

The average number of quenches to reach 8.33 T is found to be reduced by 82 % after a TC for the sample {MBs with TC}. Assuming the same reduction for MBs not submitted to a TC, in average a fraction of about 0.181 MBs can quench once below the nominal field during their 1st powering cycles in the tunnel without beam. From this average value, the number of quenches that can be expected to occur below the nominal field is simply equal to (1232-115)×0.181/8 ≈ 25 training quenches by octant. To estimate the possible dispersion around this average value, the same approach can be used for the standard deviation after the TC and the standard error is found to be about (1232-115)×0.58/(8×$\sqrt{785}$) ≈ 3 training quenches by octant. The "blind statistics" gives 2 times this number, a more conservative estimate.

The implicit assumptions made for the above estimates are now underlined before to be commented:

i) No "nasty" MBs will be accepted;
ii) No drift in quench performance for future MBs;
iii) No quench is expected for MBs submitted to a TC on test benches;
iv) No long time relaxation effect of the quench performance of the trained magnets;
v) No detraining quenches.

The hypothesis i) do not require further development as the acceptance of the remaining MBs should be based on the same criteria. In addition a reserve of 30 MBs was ordered. For ii), as the firm producing the MBs with quench performance above the average had already delivered all its production, a slight drift may occur and has to be looked at. Concerning iii), all the MBs for which at least two TC were performed, reached 8.33 T without quench after the third cool-down. For iv), the two targeted MBs for the study of the long term stability did not reveal a significant drift of the quench performance but of course the statistics is too poor [5]. The last hypothesis v) is the most questionable. It can be relaxed and an estimate of the number of quench due to a detraining effect can be given. The probability to have a detraining effect around the nominal field after a TC was found to be ~4 % from the sample {MBs with TC}. If it is assumed that when a MB quenchs, in average its two neighbours will also quench because of the quench-back induced by the warm GHe, then the number of additional quenches due to the detraining effect is of the order of 0.04×3×25 < 5 by octant, i.e. a value comparable with the estimated standard error. The detraining effect will be a more serious problem when the magnets will be pushed to current value much higher than the nominal one.

Quench probability versus current for MBs

From the cumulative statistics of MBs (Fig.3), it can be seen that the probability level of 0.181 reported in Table 1 and used to estimate the number of quenches to reach nominal field after a thermal cycle corresponds to the curve of the 2nd quench level for the sample {MBs with no TC}. This result can be interpreted considering that in average the gain in the quench performance obtained with a third and subsequent training quench(es), is lost during the TC due to the incomplete memory effect.

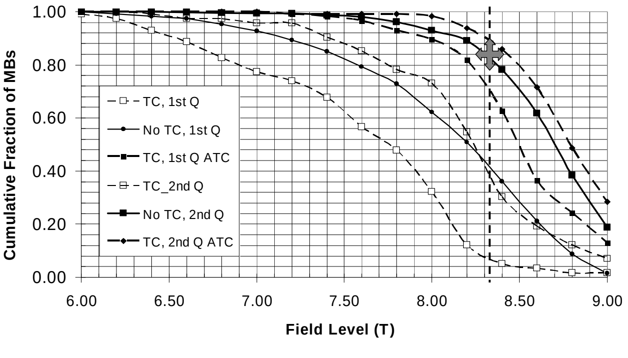

Figure 3: Cumulative statistics of MBs related to the field level reached without quench.

As a consequence, the data of the 2nd quench level for the sample {MBs with no TC} were considered as the most representative to estimate the probability to have a MB quench as a function of the B field. They were plotted in Fig.4 using a semi-logarithmic scale. An exponential increase of the probability can be observed as a function of the magnetic field with a characteristic value equal to 0.381 T. The probability to have a quench is very close to 1 for the ultimate field of the machine equal to 9 T. If the magnetic field is reduced by 1 T from the nominal field, the probability to have a training quench of a MB fall-down from 0.18 to 0.01.

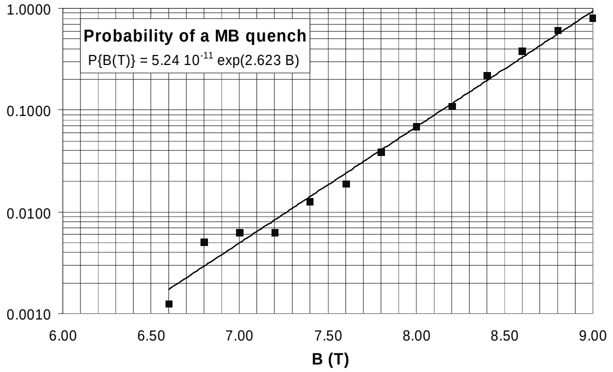

Figure 4: Estimate probability of a MB quench deduced from the cumulative statistics of the 2nd quench level for the sample {MBs with no TC} and considered as the most representative.

CASE OF LHC MAIN QUADRUPOLES

Training Quench Performance of MQs

The histogram of the cold tested MQs as a function of the number of training quenches required to reach the nominal field gradient of 223 T/m is given in Fig.1. Before the thermal cycle, about 56.1 % of MQs reached the nominal field during their 1st powering without training quench. After a TC performed on only 9 MQs for reason of weak quench performance, this proportion is equal to 3/9. In other words, 6/9 MQs required at least one training quench to reach the nominal field gradient. The memory effect of MQs seems to be weaker with respect to MBs but the statistics is poor.

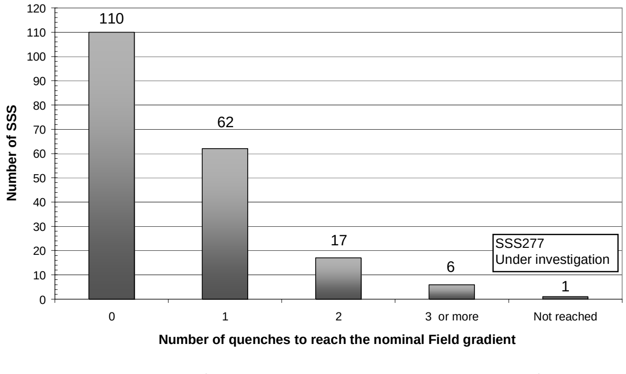

Figure 5: Histogram of the 196 MQs cold tested to date as a function of the training quench performance after the 1st cool-down.

Estimate of the Number of Quenches for MQs by octant to reach the nominal field

The same approach as for MBs can be applied. From the results given in Table 2, the number of quenches that can be expected to occur below the nominal field gradient is simply equal to 360 × 0.17/8 ≈ 8 training quenches by octant. An estimate of the standard error obtained from the quadratic sum of the three relative error contributions gives about 3 training quenches by octant.

Table 2: Statistics for MQs related to the number of quenches to reach the nominal field gradient of 223 T/m

Sample	**{MQs with TC}**	**{MQs without TC}**
Average Number before TC	2.33	0.58
Standard Deviation	1	0.70
Average Number after TC	0.67	0.17*
Standard Deviation	0.50	0.35**
Population	9	196

* assuming the same reduction of 71 % after TC as for {MQs with TC}
** assuming the same reduction of 50 % after TC as for {MQs with TC}

HOW TO IMPROVE THE ESTIMATES ?

The statistics concerning the quench performance of MQs after a thermal cycle is not sufficient to allow a precise estimate of the average number of quenches that can occur below the nominal field gradient in the tunnel without beam. The values could be reassessed when all MQs will be cold tested.

The assumption iv) made for the estimates and concerning the long time relaxation of the training quench performance during the storage is questionable also for MQs. It is based on results obtained for only two MB cases and no study were performed for MQ.

More generally, to reduce the uncertainty of the predictions, the same statistical approach could be re-iterated by considering each octant individually with its specific content in MQs and MBs.

CONCLUSION

Some of the main superconducting magnets exhibited training quench(es) below the LHC nominal current during their first powering on test benches. After a thermal cycle, a great improvement of the quench performance was observed. The average numbers of quenches below nominal current were found to be reduced by 82 % and 71 % for MBs and MQs respectively.

As a first estimate and from extrapolations of present data, **25-30 ±6 and 8 ±6 training quenches by octant for MBs and MQs respectively** are expected during the hardware commissioning phase before reaching the LHC requirements for a 7 TeV beam energy. The uncertainties are given for both magnet types at ± 2σ whereas the systematic error for MBs is related to possible detraining effect. At the level of probability of few %, training quenches will start typically at current value in MBs of about 11 kA (6.5 TeV) and probably at a close level for MQs. To improve the estimations for MQs, the memory effect needs to be study and more statistics is required. When all main magnets will be cold tested, these numbers can be reassessed, octant by octant.

It must be emphasized that only training quenches are considered in this article but many other quench types can occur during the hardware commissioning phase, such as the ones due to bad electrical connections or cryogenic problems. Such possibilities stress the importance of the diagnostic that should be successful after each quench.

Expected quench Levels of the Machine without Beam: Starting at 7 TeV ?

It depends on the time available for training quenches but this objective should be maintained as much as possible. As a baseline strategy, any “spare” time should be dedicated to the training of magnets, all octants in parallel. This is a part of the hardware commissioning and then a dedicated analysis will be required after each training quench to give the green light for the next powering. The same approach as for cold tests on benches should be maintained and the acquired experience used. Postmortem Tools should be available as well as trained experts for the analysis. Finally, training quenches could come from magnets other than MBs and MQs but also, other more serious problems could arise before starting the training of a certain number of magnets in the LHC machine…

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