CERN-ACC-2019-0015

Oliver.bruning@cern.ch

Report

LHC Full Energy Exploitation Study: Operation at Ultimate Energy of 7.5 TeV

O. Brüning [editor], S. Antipov, D. Amorim, G. Arduini, A. Apollonio, A. Ball, V. Baglin, W. Bartmann, M. Battistin , N. Biancacci, L. Bottura, X. Buffat, M. Calvini, F. Cerutti, C. Bracco, K. Brodzinski, R. Bruce, J.-P. Burnet, E. Carlier, P. Chiggiato, S. Claudet, D. Delikaris, R. De Maria, R. Denz, E. Felcini, S. Gilardoni, M. Giovannozzi, B. Goddard, G. Iadarola, E. Jensen, R. Jones, R. Kersevan, M. Lamont, A. Lechner, R. Lindner, L.E. Medina Medrano, E. Métral, A. Mereghetti, D. Mirarchi, V. Montabonnet, M. Nonis, A. Oeftiger, S. Papadopoulou, Y. Papaphilippou, M. Pojer, L. Pontecorvo, A. Romano, S. Redaelli, W. Riegler, F. Rodriguez Mateos, S. Roesler, G. Rumolo, B. Salvant, F. Savary, V. Senaj, A. Siemko, G. Skripka, E. Todesco, R. Tomas, F.F. Van der Veken(1), A. Verweij, J. Wenninger, D. Wollmann, M. Zerlauth
CERN, Geneva, Switzerland, (1) CERN and University of Malta (Msida, Malta)

Keywords: LHC, HL-LHC, and ultimate Beam Energy

Abstract

This report discusses the feasibility and limitations for operating the LHC and HL-LHC at the ultimate beam energy of 7.5 TeV, corresponding to a main dipole magnetic field of 8.93 T and an operating current of 12748 A.

Presented at:

Geneva, Switzerland
January, 2019

Contents

1 Introduction ... 1

2 Executive summary of this report ... 2

3 Summary of findings of the first report for operation at nominal beam energy ... 3

4 Magnet Systems ... 4

4.1 Review of previous magnet training to ‘ultimate’ current ... 5

4.2 Benefits of training some magnets to nominal beam energy before LS2 ... 8

4.3 Estimate of the required time for training the LHC arc dipole magnet system for operation at ultimate beam energy ... 9

4.4 Estimate of the required time for training the LHC insertion magnets for operation at ultimate beam energy ... 12

4.5 Estimate of the required time for training the new HL-LHC magnets for operation at ultimate beam energy ... 13

4.6 Summary of the estimated total time for training the HL-LHC machine for operation at ultimate beam energy ... 14

4.7 Operating margins for the LHC superconducting magnets ... 14

4.8 Field Quality and magnet transfer functions ... 16

4.9 Risks associated with operating the LHC magnet system at 7.5 TeV ... 19

5 LHC Beam Dump System ... 20

5.1 Introduction ... 20

5.2 Extraction and Dilution Kickers MKD and MKB ... 21

5.3 Extraction Septa MSD ... 22

5.4 Protection Devices TCDS and TCDQ ... 23

5.5 Beam Dump Block TDE and Entrance Window VDWB ... 23

5.6 Dump System Instrumentation ... 23

5.7 Beam Energy Tracking System BETS ... 24

5.8 Conclusion on the LHC Beam Dump System ... 24

6 Beam Collimation ... 24

6.1 Layouts of the system after LS2 and after LS3 ... 25

6.2 Performance of the system after LS3 ... 25

6.2.1 Collimator setting assumptions at 7.5 TeV ... 25

6.2.2 Cleaning performance versus quench limits ... 26

6.2.3 Collimation of physics debris ... 29

6.2.4 Collimator robustness against design failures ... 29

6.2.5 Considerations for ion operations ... 30

7 Other Systems and Effects (not assumed to be critical for operation at ultimate beam energy) ... 31

7.1 RF and transverse damper system 31
7.2 Vacuum 31
7.3 Cryogenics 32
7.3.1 Non-upgraded part of the LHC running with HL-LHC beams 32
7.3.2 HL-LHC cryogenic equipment capacity (P1 and P5) 33
7.4 General Infrastructure 33
7.5 Beam Instrumentation 34
7.6 Magnet Powering 35
7.7 Orbit Correctability and Interaction Point Steering 35
7.8 Beam-Induced Heat loads 36
7.9 Beam stability 38
7.10 Aperture and optics considerations at 7.5 TeV 40
7.11 UFO effects 41
7.12 BLM thresholds 41
7.13 Machine Protection related aspects 42
7.14 Radiation protection aspects 43
8 Machine Efficiency and Availability 44
8.1 Machine Efficiency degradation due to the cryogenic system 44
8.2 Machine Efficiency degradation due to UFOs 44
8.3 Machine Efficiency degradation due to Magnet Quenches 44
8.4 Machine Efficiency degradation due to Power converters 45
8.5 Machine Efficiency degradation due to the Beam dumping system 45
8.6 Machine Efficiency degradation due to Radiation to electronics 45
8.7 Cycle duration 45
8.8 Conclusions on Machine Efficiency for Operation at 7.5 TeV: impact on physics efficiency 46
9 Potential Performance Reach 46
10 On the Implications for Experiments of LHC operation at 7.5TeV per beam 50
11 Summary and Conclusion 50
11.1 List of circuits that could potentially limit the energy reach of the LHC to below the ultimate beam energy of 7.5 TeV 51
12 References 54

1 Introduction

This report is the second of a planned series of three reports on the full energy exploitation of the LHC. The first report [1] addressed the question of the feasibility, required steps, and efficiency of operating the LHC at its nominal beam energy of 7 TeV and a main dipole magnetic field of 8.3 T (an increase of 0.5 TeV w.r.t. the operational beam energy in Run 2). This second report will address the question of feasibility, required steps, upgrades, and potential machine efficiency for operating the LHC machine at an 'ultimate' beam energy of 7.5 TeV, corresponding to a main dipole field of 8.93 T (the beam energy could even be 7.56 TeV, but 0.06 TeV is taken as operational margin in the analysis of this report). The third report discusses the feasibility of pushing the operational beam energy in the LHC beyond the ultimate beam energy by replacing part of the nominal NbTi magnets with 11 T Nb_3Sn magnets. While the LHC TDR features several definitions of 'ultimate' LHC goals and operation conditions, it lacks a consistent definition and coherent parameter set for operation at the 'ultimate' beam energy. Rather, the 'ultimate' beam energy is introduced as the ultimate powering scenario and performance reach for the main dipole circuits, but without specifying that this is indeed an eventual goal for the LHC machine operation. The LHC TDR leaves it open if this ultimate dipole field is solely a request for the dipole powering during the magnet acceptance tests or an actual performance goal for the LHC once one is willing to give up on engineering margins for the LHC equipment during operation.[1]

The first task of this report is therefore to prepare to express the goal of eventually operating the LHC machine at an 'ultimate' beam energy and to provide a uniform definition for the 'ultimate' LHC performance. The LHC TDR defines the ultimate beam energy as 7.56 TeV, corresponding to a main dipole magnet field of 9 T and an operating magnet current of 12850 A. In the following, we introduce a small operational margin to this definition and define the **'ultimate beam energy for operation' as 7.50 TeV, corresponding to a dipole magnet field of 8.93 T and an operating magnet current of 12748 A.**

The next aim of this report is to validate which equipment components are already capable and which ones would require additional upgrades for operating at 'ultimate' beam energy and to identify the compatibility with the HL-LHC beam parameters in such conditions. Two groups of equipment can be distinguished and the evaluation should be done for the nominal HL-LHC beam parameters and optics configuration wherever the beam energy density is relevant:

- Equipment that is planned to be upgraded for HL-LHC operation (either during the Long Shutdown 2 [LS2] and Long Shutdown 3 [LS3] or even during any of the Year End Technical Stops [YETS] before LS3). For this equipment one should estimate if the specifications can still be adapted to be compatible for operation at 'ultimate beam energy' with a summary of the implied extra costs and resources.
- Equipment that is not planned to be upgraded for HL-LHC operation. For this equipment one needs to identify if further upgrades are required for operation at 'ultimate' beam energy and to specify the needed budget and resources for the required upgrade and to identify when such an upgrade could potentially be foreseen.

The above mentioned discussions have led to the distribution of a memo by CERN's director for Accelerators and Technology [2] that expresses the operation at 'ultimate' beam energy as an explicit

---

[1] Discussions for the preparation of this report revealed that the lack of a coherent definition of the 'ultimate' LHC performance was actually intentional and that the LHC project encouraged each equipment group to define an 'ultimate' performance from different perspectives that reflect the particular challenges of the given equipment.

operational goal and, through the discussions at the 2018 LHC Performance workshop in Chamonix [3] to modifications for components that were foreseen to be upgraded during LS2 and LS3 [e.g. the capacitors of the LHC beam dump system].

The third aim of this report is to identify beam parameters and machine configurations that are compatible with operation at 'ultimate' beam energy and to estimate the potential performance reach of the LHC in this configuration. The starting point for this discussion are the baseline HL-LHC parameters.

For the purpose of this second report we assume that there are no limitations arising from magnet and circuit non-conformities for the operation at 7 TeV (as these have already been highlighted in the first report and need to be resolved before moving to an operation at 'ultimate' beam energy). Following the decision at Chamonix 2017 to not push the operational beam energy in the LHC to the nominal energy of 7 TeV before LS2 and the resulting memo by the CERN ATS director on the full energy exploitation, we assume that a push to operation at 'ultimate beam energy' will at the earlies be implemented at the end of the LHC Run 5 period, after the commissioning of the new HL-LHC equipment.

In particular, this second report aims at:

- Estimating the required time for training the full HL-LHC magnet system for operation at ultimate energy (corresponding to a dipole field of 9 T and a magnet current of 12850 A – the training therefore includes a margin of 100A with respect to the operational current);
- Investigating if limitations for operation at ultimate beam energy are imposed from the LHC hardware systems [e.g. cryogenics, vacuum system, beam instrumentation, RF system, collimation system and magnet power converter and circuit point of view];
- Describing the required upgrade work for components that might limit the machine performance at 'ultimate' beam energy [e.g. the circuits that could not yet been powered up to ultimate currents and the LHC beam dump system which foresees already upgrades during LS2 and LS3;
- Identifying potential limitations for the bunch intensities, brightness and number of bunches for operation at ultimate beam energy based on the operational experience of the LHC Run 2 period. For the optics and collimator settings we assume for the sake of simplicity and comparability that these remain identical to those foreseen for the nominal HL-LHC operation (e.g. β^* and collimation gaps are not re-optimizes utilizing the potential aperture gain due to the reduced emittance with operation at higher beam energies).
- Estimating the potential performance reach of the HL-LHC for operation at 'ultimate' beam energy.

2 Executive summary of this report

There are no intrinsic limitations in the LHC machine that would prevent operation at ultimate beam energy of 7.5TeV. However, the compatibility of the complete HL-LHC magnet system for operation at ultimate beam energy still needs to be demonstrated and a few magnet circuits will certainly require upgrades to their nominal configuration, e.g. Q5 in point 6 most certainly will require an upgrade of the cryogenic system from 4.5K to 1.9K operation. Furthermore, the time required for training the complete magnet system for operation at ultimate beam energy will require a substantial time investment, estimated between 6 and 12 month, that has to be deducted from the time otherwise available for luminosity production at nominal beam energy [loss of ca. 125fb^{-1}]. If not resolved and mitigated by other means, the larger than expected heat load due to electron cloud effects in the LHC Run2 operation will impose a beam intensity reduction at higher beam energy due to the increased heating from synchrotron radiation at higher beam energies, up to 7%.The reduction of the quench margins in the magnet system at higher beam energies will also imply more frequent beam aborts and, together with the longer cycle and recovery time for operation at higher beam energies, a loss between 5% and 30% in integrated luminosity when compared to the performance reach of the HL-LHC at nominal beam energy.

3 Summary of findings of the first report for operation at nominal beam energy

The first report addressed the open issues and estimated the performance reach of the LHC for operation at the nominal beam energy of 7 TeV [1]. The main aims of the first report were to estimate the time required for training the magnet system for operation at 7 TeV, to identify potential bottlenecks in the technical infrastructure, to recommend technical upgrades prior to the operation at 7 TeV and to estimate the potential performance reach of the machine at 7 TeV beam energy. The main outcomes of the study and the ensuing discussions at the 2017 LHC performance workshop at Chamonix [4] are:

- Organization of a training campaign for two sectors, S34 and S45, towards 7 TeV operation before the EYETS 2016/2017;
- Observation of fast secondary quenches for a given training quench in the trained sectors at higher magnetic fields, resulting in multiple magnet quenches and therefore longer cryogenic recovery times;
- Observation of a second short to ground in a magnet diode box following a training quench;
- Validation and documentation of the diode box short removal tool (capacitive discharge);
- Decision NOT to increase the beam energy to 7 TeV before LS2;
- Decision to carry out a consolidation of the diode insulation of all the LHC main dipole magnets during LS2; this consolidation should prevent shorts to ground in the diode box during training campaigns after LS2;
- Validation of the statistical behavior of the magnet training in the tunnel and estimation of the required time for training the magnet system for operation at 7 TeV;
- Compilation of a consistent set of beam parameters and machine settings (e.g. β^*, collimation gaps) for operation at 7 TeV beam energy based on the operational experience of the LHC during Run 1 and the first year of Run 2 operation;
- Estimation of the machine availability and efficiency of the LHC for operation at 7 TeV (between 39% and 45.5% in Stable Beams);
- Observation that impedance and UFOs do not seem to impose special limitations for increasing the beam energy to 7TeV;
- Observation that electron cloud effects might limit the acceptable beam intensities in the LHC if the secondary emission yield cannot be sufficiently conditioned during machine operation in Run 2 and Run3 [this would equally limit the performance of the HL-LHC at nominal beam energy],
- Observation that the cryogenics, vacuum, beam instrumentation, magnet power converter, collimation system and RF systems do not impose limitations for increasing the beam energy to 7 TeV (except for the current LHC triplet system that imposes limitations on the maximum acceptable peak luminosity and the above mentioned potential limitation in the arcs due to heat load from electron cloud);
- Estimation for the potential machine performance reach when pushing the beam energy to 7 TeV after LS2.

In agreement with the LHC experiments, the discussions ensuing the preparation of the first report led to the decision to keep the beam energy at 6.5 TeV during the full LHC Run 2 period and to plan for operation at 7 TeV only after LS2, after the repair of critical magnet non-conformities and the consolidation of the diode box insulation during LS2. These decisions have been documented in a separate memo by the CERN director of accelerators [2]. In the context of the study for the full energy exploitation of the LHC we think it is still an important milestone to validate that the machine has no major obstacles for reaching the nominal energy before the warm-up of all sectors in LS2. Without such an exercise one will run the risk of missing potential limitations that could have been removed during the LS2 interventions and thus, jeopardizing the operation at nominal beam energy after LS2. Following the discussions at the 2018 Chamonix workshop [3] it has been decided to conduct the following magnet training campaigns to 7TeV at the end of LHC Run2, before the interventions during LS2:

- Powering of the standalone quadrupole magnets of the long straight sections to a current corresponding to operation at 7TeV. The training exercise after LS1 ensued only the training of the main dipole magnets in the arcs. A training of the insertion quadrupole magnets should not take much time and would eliminate potential bad surprises with these circuits for operation at 7 TeV after LS2.
- Powering of the main quadrupole circuits of all the arcs to a current corresponding to operation at 7TeV: they were so far tested up to 7TeV only in two sectors.
- Powering of the separation / recombination and dogleg dipole magnets of the insertions to a current corresponding to operation at 7TeV. One of these magnets, D3.L4, did not yet reach nominal current, neither before nor after LS1. In general, we would recommend that all stand-alone magnet circuits shall be trained once to nominal values corresponding to operation at 7TeV before LS2 in order to confirm their performance reach.
- Training of at least one of the main dipole circuits to 12000 A, corresponding to 7 TeV operation. Even with the training exercises in S34 and S45 before the EYETS 2016/2017 we still have no main dipole circuit in the machine that actually reached nominal current. A good candidate for such a training would be S12 which is expected to have the fastest training to nominal current from the LHC sectors.

4 Magnet Systems

The LHC superconducting magnets were designed and constructed such as to allow the operation of the machine to its ultimate energy. As a consequence, the acceptance criteria applied for the tests in SM18 (and in the different laboratories constructing them) included the verification of the capability of all magnets to reach their “ultimate” current, values which are contained in the Design Report and stored in the Layout Database. Those currents are “hardware-related” values, which have no direct relation with the optics used in the machine: they thus match the current needed for 7.5 TeV for the dipoles (because of the fixed ring geometry) and main quadrupoles (due to the fixed cell optics), but might be different from the required currents in the standalone matching section quadrupoles for operation at 7.5 TeV beam energy (because of the variable insertion optics). Therefore, all magnets (excluding the main dipoles) were tested to their layout ultimate current, but **not all of them were tested to the current really needed when scaling the nominal LHC and HL-LHC optics to 7.5TeV**. Tables 1 and 2 list the currently known circuits that fall into this category. It is important to re-asses the ability of these circuits to reach the currents required for operation at ‘ultimate’ beam energy after the training campaign at the end of LHC Run 2.

Just before LS1, all circuits, excluding main dipoles and quadrupoles, were commissioned to the 7 TeV layout current in 2013. All of them, excluding the D3.L4 circuit, reached the commissioning current.

Recently (at the end of Run II in 2018), most of the circuits were again pushed to 7 TeV, including the main quadrupoles and one RB circuit. As a result, most of the concerns raised before LS1 could be removed. Moreover, a current margin (100 A for the main circuits and 50 A for individually powered dipoles and quadrupoles) was added to the commissioning current, to ensure a stable operation of the circuits at the 7 TeV equivalent current.

In this section we review the history and expected training to ultimate conditions. We then consider other operational aspects such as the margin left for operation at ultimate conditions and the field quality. We finally provide an estimate of the risk of faults due to higher electrical and mechanical operating stress.

4.1 Review of previous magnet training to 'ultimate' current

3.1.1.Main Dipole Magnets

Concerning the main dipole magnets, not all of them were tested up to the ultimate current, since different criteria were used along the production, which guaranteed that the nominal current was reached with a limited number of training quenches. In particular, as shown in Figure 1, the main dipoles that did reach the ultimate current are 41% of Firm1, 55% of Firm2 and 59% of Firm3; these 673 magnets (about half of all of the LHC dipole magnets) reached the ultimate current with a total of 1871 quenches (on average, 2.8 quenches/magnet).

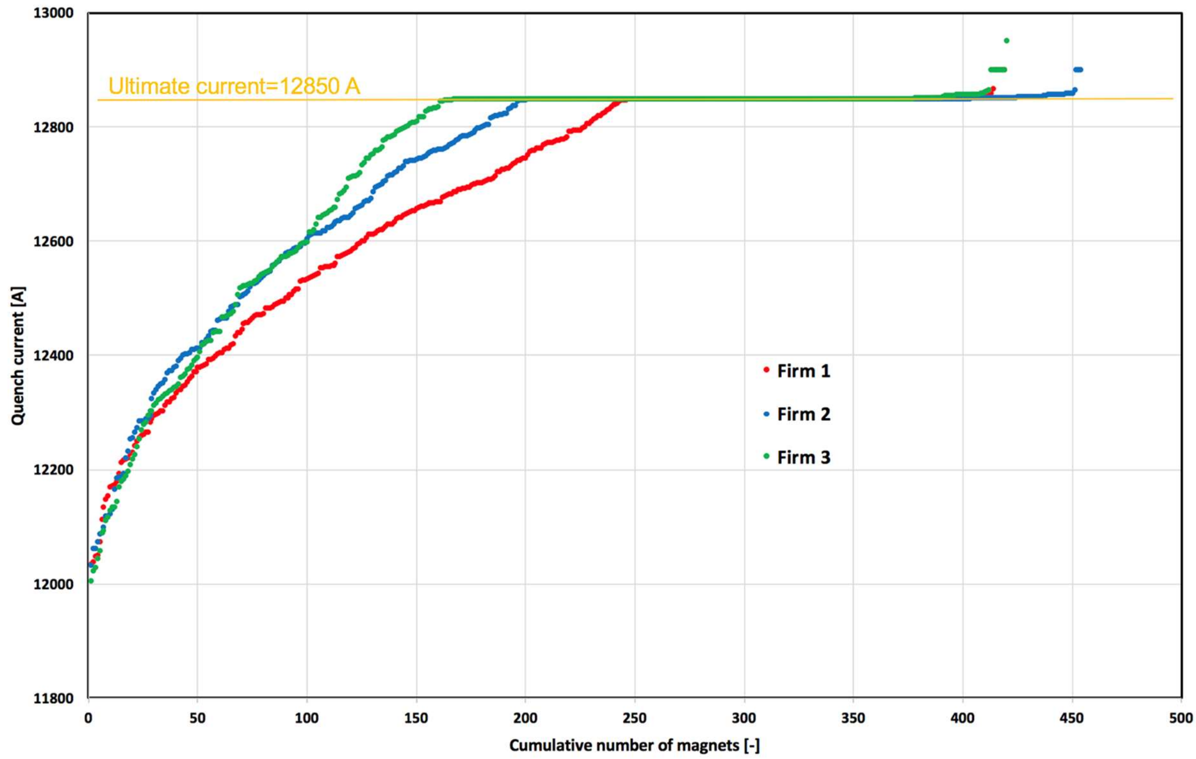


Figure 1. Maximum quench current experienced by the main dipole magnets in SM18.

In a few cases (some 30 magnets), the training in SM18 was pushed to a current larger than the ultimate value of 12850 A, namely to values between 12900 and 13250 A, corresponding to an operational beam energy of more than 7.8 TeV.

On the other side, during the various training campaigns performed in the LHC tunnel, the current was never pushed to values larger than 11536 A (corresponding to a beam energy of 6.82 TeV), a current to which one of the sectors of the LHC was trained during the powering campaign at the end of 2016, to investigate the training length for operation at 7 TeV.[2]

3.1.2.Main Quadrupole Magnets

For the main quadrupoles, they were all trained in SM18 to currents compatible with operation at 7.5 TeV: less than half of them were trained to the layout ultimate current of 12850 A, but all of them reached currents above the 7.5 TeV equivalent value requested by the HL-LHC optics (12 kA was the lowest value reached in a magnet, to be compared with the required 11.8 kA).

About 2000 training quenches were experienced on the main quadrupoles in SM18 on the nearly 400 magnets, but only 350 of them were needed to reach the 11.8 kA which are needed for 7.5 TeV.

During the powering campaign in 2018, before LS2, all main quadrupole circuits were trained towards the nominal current, but none of them managed to reach 11850 A, due to the small amount of time allocated for the tests and some technical issues. Among all, the quadrupoles of S78 reached a current value of 11652 A, experiencing only 5 training quenches.

3.1.3.Triplet Magnets

All magnets were qualified to their ultimate currents at the premises where they were manufactured [e.g. at KEK and FERMILAB]. During the different commissioning campaigns performed in the tunnel, they were qualified to 7 TeV currents with a reduced number of quenches. A Memo by the CERN director of the Accelerator and Technology Sector underlined that operation at 'ultimate' beam energy will at the earliest occur at the end of Run 4, after the commissioning of the new HL-LHC hardware [2]. The LHC triplet magnets in IR1 and IR5 will therefore have been replaced by the new HL-LHC Nb_3Sn triple magnets by the time operation at ultimate beam energy might be implemented. However, the insertions at IP2 and IP8 will still deploy the nominal LHC triplet magnets. The operational gradients of these magnets are set to a gradient that lies 10% to 15% below their technical nominal gradients in order to provide margins for the radiation dose coming from the experiments. Any configuration for operation at 'ultimate' beam energies needs to take these margins into account and needs to evaluate if eventual performance upgrades of the experiments in IR2 and IR8 require the introduction of further gradient margins [e.g. the luminosity upgrade of LHCb to a performance of 1-3 10^{34} $cm^{-2}s^{-1}$ which is currently under discussion].

Table 1: Individually powered magnets with layout ultimate currents lower than the values required for operation at 7.5 TeV plus a 50 A margin required for reliable operation.

Circuit	*I_Ult [A]*	*I_7.5 TeV[A]*	*Difference [A]*
RD1.R8	6100	6131	-31
RD1.R2	6100	6128	-28
RD4.L4	6650	6658	-8
RQ5.L6B2	3900	4215	-315
RQ5.L6B1	3900	4029	-129
RQ5.R6B1	3900	3979	-79
RQ6.L8B1	4650	4676	-26

---

[2] In another sector, S12, the dipole circuit was pushed towards nominal current in 2018 during a dedicated hardware powering campaign at the end of Run2. However, the main dipole circuit could not be trained to a current beyond the values corresponding to a beam energy of 6.77TeV due to lack of time.

RQ7.R8B1	5820	5843	-23
RQ8.L6B2	5820	5832	-12
RQ8.R6B1	5820	5831	-11
RQ7.L8B1	5820	5823	-3
RQ8.L4B2	5820	5822	-2
RQ5.R4B1	3900	3901	-1

3.1.4. Individually Powered Dipole [IPD] and Quadrupole Magnets [IPQ]

For the IPDs, the same considerations apply as done already for the main dipoles: they were all tested to the ultimate current on the test benches and no changes should come from new optics settings. Nevertheless, during the various machine commissioning campaigns, and in particular during the tests at the end of Run 1, RD3.L4 confirmed to be a slow trainer (already at the premises at BNL, where 17 quenches and one thermal cycle were needed on the test bench to reach the ultimate current value): because of that, during the powering tests to 7 TeV in 2013, the commissioning of the circuit was stopped, after several quenches, at an equivalent energy of 6.9 TeV. The monotonous increase in current and the already proven performance, suggest that the circuit could reach the ultimate current and it appears to be 'just' a question of time for the training. However, an uncertainty still exists and addressing the question if the magnet can actually be reliably operated at ultimate beam energy would require dedicated tests on the circuit for the validation.

Another case worth mentioning is RD2.R8, which showed in 2013 a cooling limitation at the level of the bus-bars, which was fixed, but might again show up at larger currents.

For what concerns the IPQs, they were also all tested to the layout ultimate current, during the acceptance tests, but, for some of them that are listed in Table 1, operation at 7.5 TeV will require additional hardware commissioning tests if the margin of 50 A needs to be maintained not only for the main circuits but also for the IPQs which are operated at approximately half the current with respect to the main circuits.

Table 1 shows the layout ultimate currents, compared to the current values which are required for operation at 7.5 TeV, with the difference between the two: only the critical cases are listed, where the required current for operation at 7.5 TeV is larger than the layout ultimate currents minus 50 A of operational margin [which means that the magnet was not tested to the 7.5 TeV current plus a margin of 50 A for a stable operation at that energy]. RD3.L4 is present in the table because of the problem of long training indicated above. The most critical cases is the Q5.L6 magnet around Point 6, for which an upgrade from 4.2 to 1.9 K was planned by the HL-LHC project but has recently [63rd TCC of December 2018] been dropped from the HL-LHC baseline as the upgrade is not required for the nominal HL-LHC operation and should therefore be treated as a machine consolidation once a decision for operation at ultimate beam energy has been taken. This reduction in operating temperature would have increased the capacity for operation at nominal and ultimate powering to 4500A and 4950A respectively, making them compatible with the requirements given in Table 1.

Most of these issues will be addressed in a dedicated training campaign at the end of LHC Run2, just before the start of LS2. It is vital to re-asses the above limitations after the training campaigns at the end of the 2018 operation period.

3.1.5.Corrector Circuit Magnets (600 A, 120 A and 60 A)

The case of the corrector circuits is different: all magnets have been qualified (during reception tests) up to the layout ultimate current, but optics modifications might require larger currents; at the same time, optics "adaptations" are easier for a corrector circuit. In this respect, the only ones which could have problems (according to the results of the past years) are the trim quadrupoles in the dispersion suppressor regions. Some of them are known to be slow training magnets, but several others showed sometimes degraded performance, during the past commissioning campaigns; their commissioning current has been reduced (halved in some cases) to avoid stressing the circuits with repeated quenches in the attempt to qualify them at current values which were not needed for operation. But the possible degradation of their performance has to be reviewed before implementing operation at 7.5 TeV. In Table 2, the list of circuits with stronger reduction in operational current is presented.

Table 2. Corrector circuits with strong operation current reduction w.r.t. the original layout values; the 7.5 TeV currents are lower, but further degradation of performance might appear in the future.

Circuit	*Commissioned*	*Requested for 7.5 TeV*
RQTL9.L7B2	400	382
RQTL11.R6B1	300	272
RQTL8.L7B1	200	127

That's why, the decision was taken to power those three circuits to larger current with respect to their limit during the powering tests at the end of 2018 before LS2, to check whether a degradation of performance is appreciable in time. The result is that all circuits are showing a constant behaviour in time, which points towards a reduced though stable operation in the future.

Other low current circuits which might present a possible limitation for the operation at 7.5 TeV are the orbit correctors in the matching sections close to the experiments: some of them had reduced performance in the past, possibly due to inter-turn shorts, and will have to be strictly monitored in the future. The last comment concerns the RQTD/F circuits, which had a significant retraining after LS1, but never required a reduction of the operating current.

It is worth noticing that some circuits are presently working to current values close to the ultimate. For example, the sextupole circuits, are routinely operated at 590 A, and are only limited by a hardware limitation on the quench detection system (the range of the DCCT), which prevents them from testing at larger currents. Increasing the powering and beam energy therefore either implies operation of the DCCTs at a slightly higher value than their current rating (e.g. 600A + 10%) – which has not yet been tested – or implies the replacement of the DCCTs with ones with a higher current rating. This is not expected to be a major concern or cost implication (ca. 100CHF to 200CHF per DCCT) for an eventual increase of the circuit powering. But the current configuration in the LHC imposes a limit for the maximum powering of these circuits in the present stage of the machine configuration.

4.2 Benefits of training some magnets to nominal beam energy before LS2

The tests executed at the beginning of LS1, aimed at reaching 7 TeV and were very important to identify weak elements in the superconducting circuits (either in the magnets or in the powering chains). 540 circuits were tested, including IPQs, IPDs, ITs, 600 A and some 120 A circuits; 773 successful tests were executed in 10 days (more than 1300 tests performed, including repetitions due to quenches or other kind of faults). Not all magnets could be powered to the layout nominal current. First among them, the dipoles, which had to undergo the splice consolidation during the shutdown. It will be therefore mandatory to train the RB circuit in at least one sector to 7 TeV before LS2, to confirm the length of the training campaign to that energy level and to check the loss of memory of Firm 1 and 2 at higher currents, but also to study the (EM induced) multiple quenches and investigate the possibility of mitigating them (through a QPS modification or filtering).

For the RQD/F circuits, they were tested only in two sectors (S23 and 78) up to 7 TeV to measure critical segments with non-linear resistance (2017-2018 YETS). It would be important to commission all of them to high current to study their training behaviour.

About the individually powered magnets, most of them were successfully tested up to 7 TeV equivalent current (with many quenches, above all on the MQM@4.5 K), with the exception (as said before) of the RD3.L4. It will therefore be fundamental to train the RD3.L4 to 7 TeV in order to validate that no real limitation exists. At the same time, it would be certainly fundamental to verify the training behaviour of some IPQs, in particular RQ5.R1 and RQ5.R5, which have shown a long training. Also, RQ5.L8 was changed in LS1 and the new magnet was never tested up to 7 TeV in the tunnel: testing this magnet to 7 TeV equivalent will proof that no limitation exists on the whole circuit and cooling system, as it happened on RD2.R8, which will be as well important to revalidate before LS2.

For what concerns the Q5 around Point 6, one of them (Q5.L6) was already powered to 4 kA during the 17/18 YETS. For the other (Q5.R6), it would be interesting to power it to a current larger than the layout current, to check whether the circuit can reach the ‘new’ nominal current and therefore investigate the (already foreseen) need to cool it down to 1.9 K in the HL-LHC era.

Powering some of the 600 A and 120 A circuits to their nominal 7 TeV current could be done in the shadow of the big circuits and would allow doing special tests on circuits with limitations (RQTLs and some 80-120 A circuit), to understand whether a degradation has occurred along the years.

In terms of the required investment (time and resources), the listed tests could be executed in a week, with the involvement of three operators on 24h shift (two from the operation team and one from cryogenics) and less than ten people from the equipment groups and analysis team, to fix on spot issues and analyse the test execution. One week subtracted either from physics operation or from the scheduled LS2 shutdown time represents of course a significant investment, but certainly an investment worth to be done if one wants to avoid discovering limitations two years later when there is no more time for interventions.

4.3 Estimate of the required time for training the LHC arc dipole magnet system for operation at ultimate beam energy

LHC dipoles were brought to 6.5 TeV operation in 2015, with a total of 175 quenches (see Table 3). Strong variations in the training behaviour were observed, both between the three manufacturers and within the production of a single manufacturer. Based on these data, the 1276 LHC dipoles can be split in five batches:

- Two fast training batches, namely the whole 1000 series production and the second half of the 2000 series; for which only about 1% of the magnets quenched to reach 6.5 TeV operation;
- Two slow training batches, namely the first half of the 2000 series production and part of the 3000 series; here about 10% of the magnets quenched to reach 6.5 TeV operation;
- One very slow batch, consisting of the 3126-3300 and the 3376-3416 magnets of the 3000 series; here about 50% of the magnets quenched to reach 6.5 TeV operation, and 5% required a second quench.

The quench distribution of each batch is fitted with a modified Gaussian distribution

$$P(x) = Ax^2 \exp - \frac{(x-\mu)^2}{2\sigma} . \qquad x < \mu$$

$$P(x)=0 \qquad x>\mu$$

where the constant A is used to normalize the distribution, and μ and σ are two free parameters. The fit result is shown in Figs. 2 and 3: in blue we show the distribution, and in red the integration of the distribution with a 2 sigma error associated to number of magnets present in the batch. The training curves of hardware commissioning are within this range. Based on these fits, one can extrapolate to the quenches needed to reach the 7 TeV operation, corresponding to 12000 A, finding about 500 quenches; obviously, extrapolation error grows with the target operation energy.

Table 3. Number of quenches needed to reach 6.5 TeV operation (training during the hardware commissioning campaign of 2015) for five batches with distinctly different training behaviour.

Batch	Number of magnets	First quenches to 6.5 TeV	Second quenches to 6.5 TeV
1000-1416	416	5	0
2001-2200	200	25	0
2201-2446	246	2	0
3001-3125; 3301-3375	200	21	0
3126-3300; 3376-3416	216	108	11
Total	1278	161	11

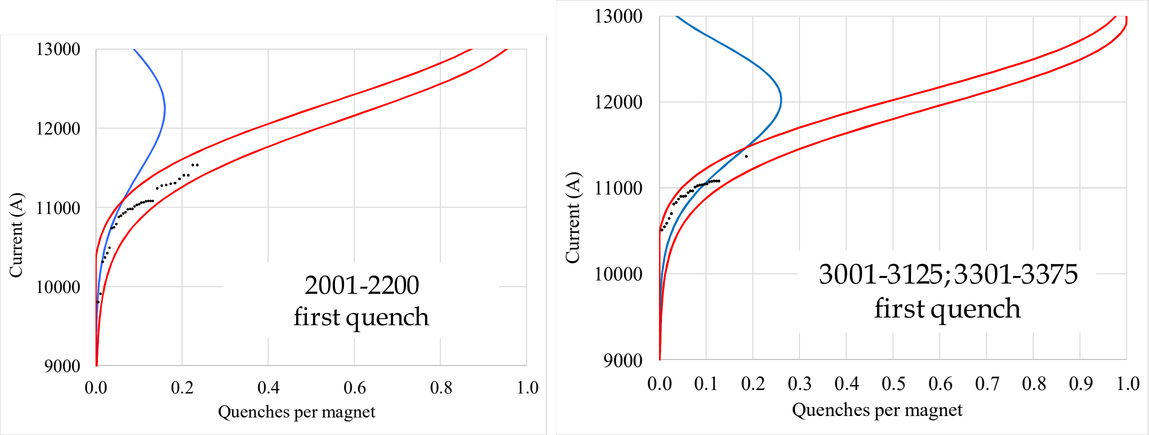


Figure 2. Modified Gaussian interpolation of 2000 slow trainers, first quench in the hardware commissioning (left); modified Gaussian interpolation of 3000 slow trainers, first quench in the hardware commissioning (right).

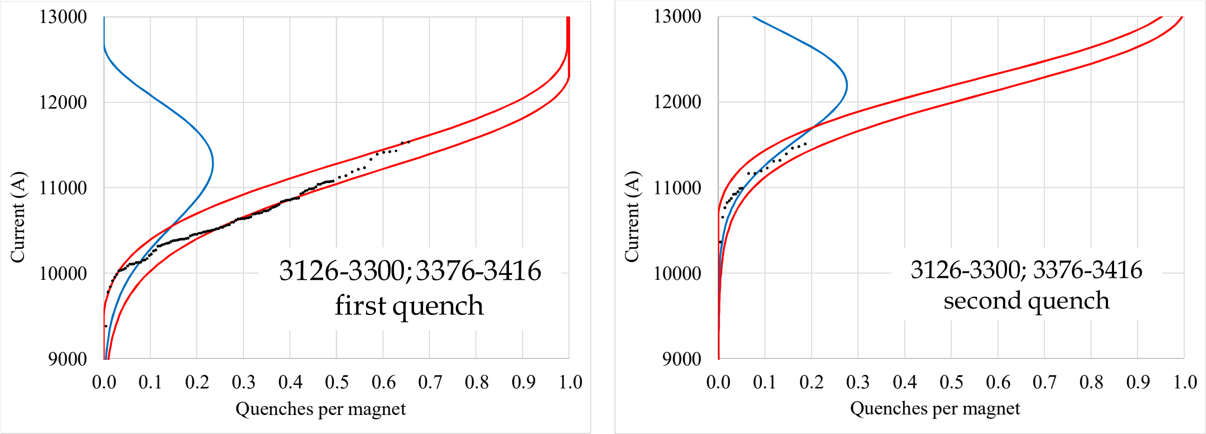


Figure 3. Modified Gaussian interpolation of 3000 very slow trainers, first quench in the hardware commissioning (left) and second quench in the hardware commissioning (right).

In the range between 7.0 and 7.5 TeV (12000 A to 12748 A) the extrapolation becomes particularly audacious. This is for two main reasons: (i) the modified Gaussian fit has large errors associated to the limited sample, since the only available data are the lower part of the tail, and (ii) above 7 TeV, only part of the magnets were trained, and therefore a non-negligible fraction of dipoles is in virgin conditions. Given this disclaimer, one can work out a lower bound to the number of quenches as shown in Table 4 by considering Figures 2 and 3 at the 12850A current needed for training the magnets for operation at 'ultimate' beam energy. 800 quenches is the estimate for the slow and very slow trainers, plus an unknown number of quenches in the faster trainers. In conclusion, 800 quenches is an optimistic lower bound, unless "new physics" is discovered, i.e. unforeseen phenomena accelerating the training in the 6.5-7.5 TeV range.

Another estimate can be obtained by using the data of individual tests; half of the magnets reached 7.5 TeV with around 3 quenches per magnet in virgin conditions. Assuming a total loss of memory (very pessimistic hypothesis) and that the second half of the magnets behaves identical as the first one (quite optimistic hypothesis) one ends up with 3600 quenches to reach 7.5 TeV.

Table 4. Extrapolation of the modified Gaussian fit to estimate the number of quenches needed to reach 7.5 TeV operation.

Batch	Number of magnets	% first quench to 7.5 TeV	Number of first quenches to 7.5 TeV	% second quench to 7.5 TeV	Number of second quenches to 7.5 TeV
1000-1416	416	-	-	-	-
2001-2200	200	~90%	~180	-	-
2201-2446	246	-	-	-	-
3001-3125; 3301-3375	200	~100%	~200	-	-
3126-3300; 3376-3416	216	~100%	~220	~95%	~200
Total	1278		~600		~200

With the present set of data (1232 magnets trained to 6.5 TeV, and 308 to 6.7-6.8 TeV, it is difficult to give something more precise than **1000 to 3600 quenches for reaching 7.5 TeV operation.** The error of the extrapolation will be reduced after LS2 once the machine will be trained to 7 TeV.

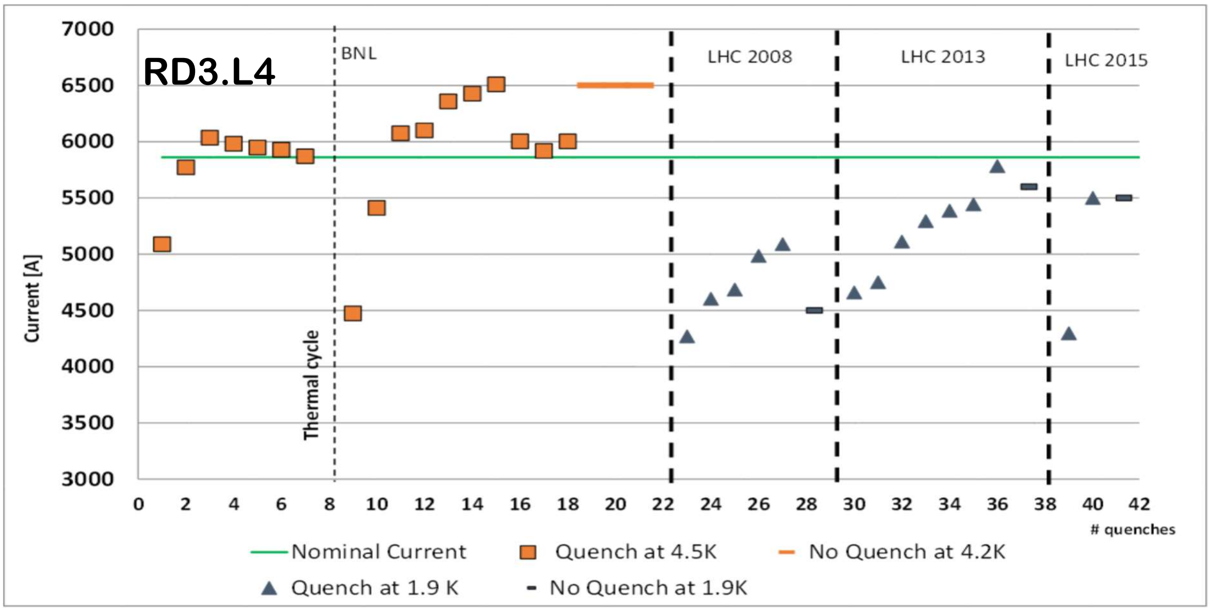
Concerning memory, the evidence today is that (i) once a sector is trained and kept at 1.9 K, there is neither need of further training nor degradation of performance, and (ii) when a sector has a thermal cycle to room temperature, a retraining is needed. In the second case, the statistics is too low to understand if the memory is fully lost or if it is only partially lost; available data are compatible with both scenarios.

To estimate the time required to train the LHC to 7.5 TeV, one should estimate the number of quenches in the different sectors, since this time will be determined by the slowest sector. In the optimistic hypothesis of 800 quenches, we can consider 200 quenches needed by the slowest sector, to account for the non-homogeneous distribution of performance. Assuming one quench every 12h can be done in a sector, waiting for the recovery of the cryogenic conditions, for the more optimistic case 100 days, i.e. a bit more than 3 months are needed.

In reality it must be considered that the sectors cannot be tested all in parallel because of the need for cryo operators to drive the recovery of the cryogenic conditions, but, above all, for the need of experts to analyse each quench. Keeping these two points in mind, we should probably consider 30% more days of the training of the LHC dipole magnets to 7.5 TeV. **In conclusion, the training campaign of the main dipole magnets after a full warm up of the LHC would take 3 to 4 months, and up to one year in the most pessimistic case.**

4.4 Estimate of the required time for training the LHC insertion magnets for operation at ultimate beam energy

Looking back at the data of the test facility and keeping in mind a possible (re)training of the individually powered quadrupoles and dipoles, we should foresee a number of quenches between 10 and 15 for the most critical magnets, from virgin state. If we consider the possibility of training to 7.5 TeV without thermal cycle after the training to 7 TeV, this number should be reduced by 5-7 quenches. Relevant are, in this sense, the two magnets shown in Figure 4: RD3.L4 and RQ5.R1. Both of them required a long training on the test bench and showed an important re-training in the tunnel during the different powering campaigns.



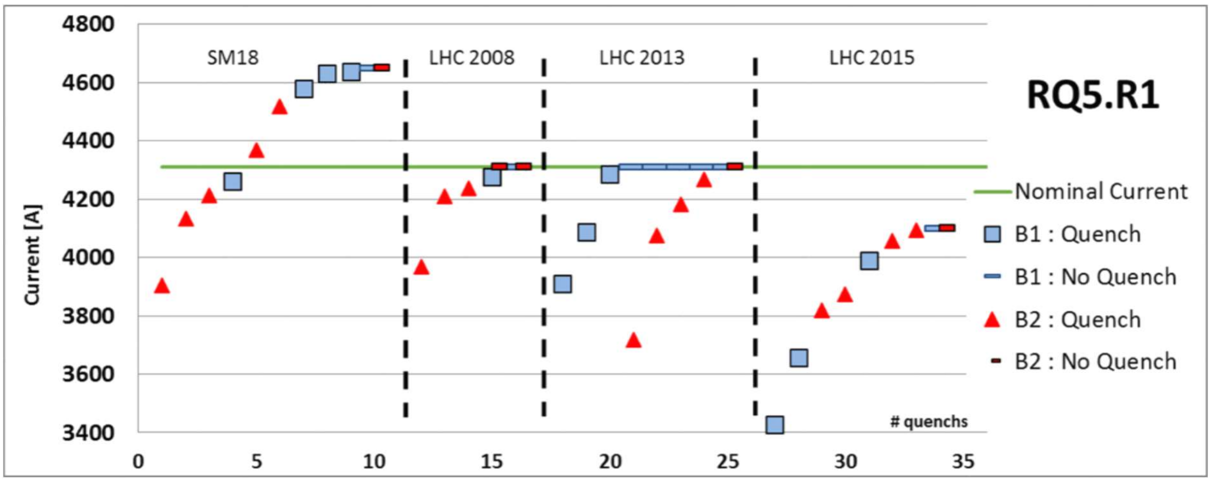


Figure 4. Quench curves of two individually powered magnets with particularly long training.

It is important to stress the fact that long re-trainings have been so far observed only on the individually powered magnets in the matching sections and not those in the dispersion suppression regions. This is important to be taken into account, since the critical magnets are therefore in separate cryogenic subsectors with respect to the main circuits, meaning that their training can be virtually done in parallel with the main dipoles. In general, it will not be longer than 2-3 days per magnet, considering the cryogenic recovery after a quench and the time for the analysis of the test by the experts. A parallelism in the test of the different circuits is also possible, only limited by the availability of the experts for the analysis of the tests and by the cryo operators that should recover the conditions after testing

4.5 Estimate of the required time for training the new HL-LHC magnets for operation at ultimate beam energy

The new HL-LHC magnets consist of the Nb_3Sn triplet, new superconducting separation and recombination dipole magnets, the new 11T dipole magnets for the collimator installation in the Dispersion Suppressor of IR7, and three types of correctors. The requirement for quench performance of the project is (i) be able to operate at 7.5 TeV energy, (ii) reach operation at 7 TeV with at most one quench after thermal cycle. No requirement is set on the number of quenches to reach 7.5 TeV operation, neither in virgin state nor after thermal cycle. At 7.5 TeV, the main Nb-Ti magnets work at 70% (recombination dipole D2) and at 82% of short sample (separation dipoles D1): therefore, the margin is larger than in the LHC dipole, that are operating at 91% of short sample. The correctors work at 50% of short sample, with larger margin than the main magnets, as it is in the LHC. In conclusion, the Nb-Ti magnets in the HL-LHC are expected to be transparent in terms of quenches needed to reach 7.5 TeV operation.

The training could become relevant for the Nb_3Sn magnets, namely 11 T and MQXF. We shall have four 11 T magnets, 16 MQXFA and 8 MQXFB. The 11 T at 7.5 TeV operate at 87% of the loadline and the MQXF at 84%. All magnets shall be trained during individual tests up to 7.5 TeV operation. In virgin conditions, the short models reached 7 TeV operation with order of 5 quenches, and no retraining is needed after thermal cycle. The 7.5 TeV operation is attained in virgin conditions with 20-30 quenches, and sometimes in an erratic way: today we have not yet enough experience to quantify the training needed for 7.5 TeV after a thermal cycle. In conclusion, we cannot exclude a significant training to reach 7.5 TeV operation. However, this should be anyway in the shadow of the main LHC dipole training, given the small number of the HL-LHC Nb_3Sn magnets.

4.6 Summary of the estimated total time for training the HL-LHC machine for operation at ultimate beam energy

For the above observations, the training of the whole machine to the ultimate energy will be dominated by the training of the main dipoles, and will take **4 to 12 month** in case of a complete warm up of the LHC. To the total number of days needed for the training of the main dipoles, we should probably add about two weeks to take into account the fact that while testing the dipoles, the other circuits of the arc cannot be tested and another week for all preliminary interlock tests.

4.7 Operating margins for the LHC superconducting magnets

Once trained to ultimate conditions of current and field, the magnets will be closer to their critical current, and the operating margin will be reduced. To give an estimate of the reduction of operating margin and its consequences, we take the main arc dipoles and quadrupoles as reference. Among the possible indicators of operating margin, two are most relevant: the temperature margin and the energy margin.

The temperature margin is defined as the difference between operating temperature and current sharing temperature, i.e. the temperature at which the superconductor reaches critical conditions. The temperature margin is intended as a measure of the temperature headroom available to a magnet operating in “quiet” conditions, at constant current and field, and no external perturbation. This is obviously a rather idealized situation, as the magnets are subjected to various sources of perturbations, including beam losses. To quantify the operating margin we hence also use the second indicator, the energy margin, defined as the energy required to initiate a quench in a magnet operating at given current, field and temperature. The energy margin provides a measure of the “tolerance” of the magnet to perturbations such as beam losses.

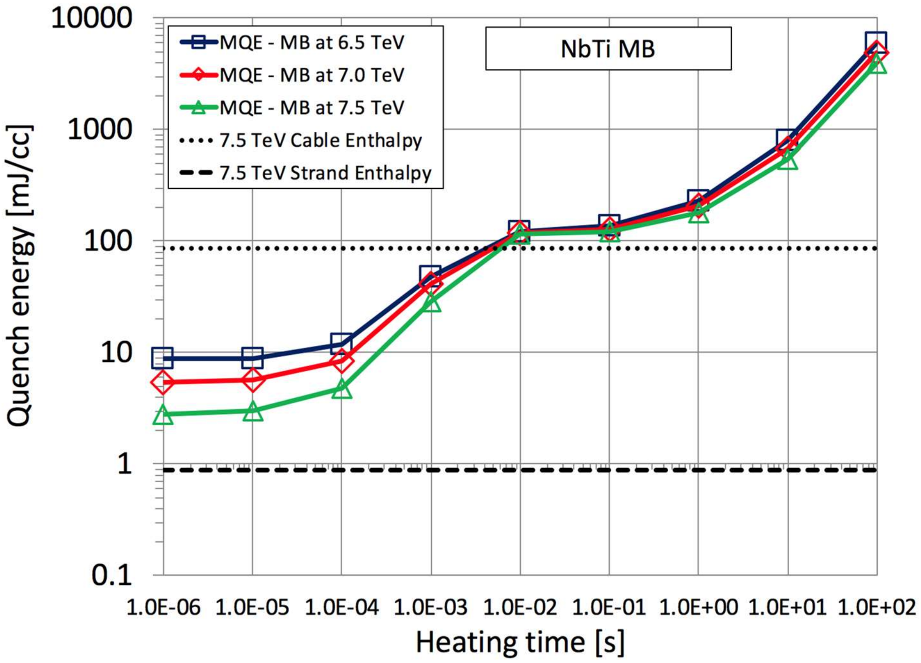


Figure 5: expected energy margin of the MB superconducting cables, for different beam energies, computed as a function of the characteristic time of perturbation events.

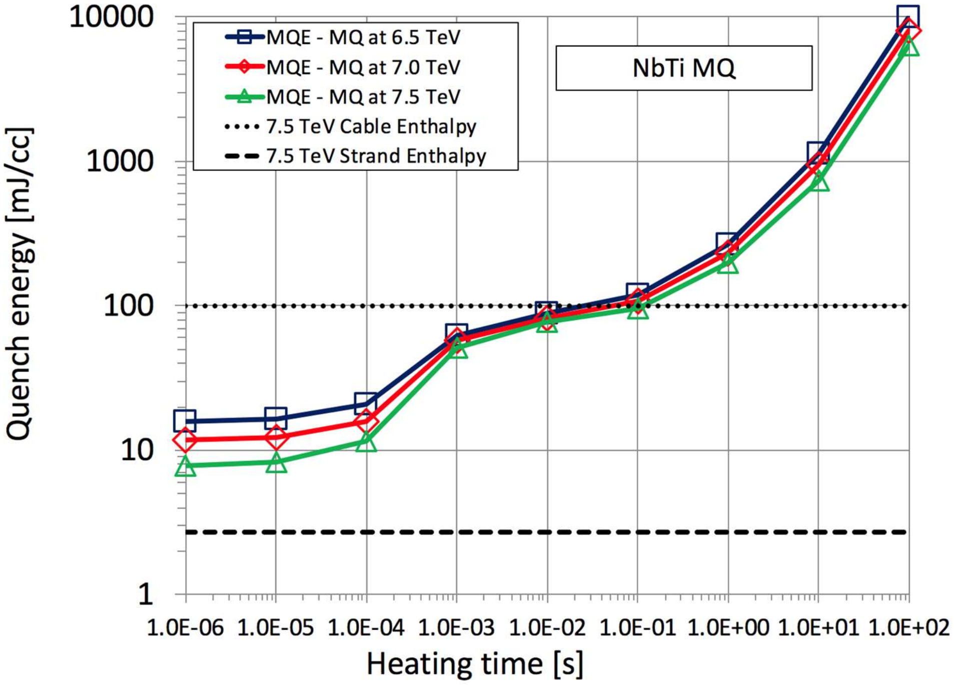


Figure 6: expected energy margin of the MQ superconducting cables, for different beam energies, computed as a function of the characteristic time of perturbation events.

The temperature margin of the inner layer cable of the main dipole is provided in [5], evaluated based on the peak field in the coil. In reality the margins should be evaluated as a function of the location where the coil may be subject to energy inputs. We give below an evaluation based on the use of peak field in the coil (as in [5]), and the field at the midplane, where beam losses may be highest. For the main quadrupoles we only consider the peak field location.

Table 5: Temperature margin of main dipoles and quadrupoles as a function of the beam energy.

Beam energy	[TeV]	6.5	7	7.5
MB temperature margin (peak field)	[K]	2.25	1.63	0.80
MB temperature margin (mid-plane)	[K]	2.40	1.82	1.07
MQ temperature margin (peak field)	[K]	2.61	2.07	1.47

As from Table 5, we observe that the temperature headroom available for operation decreases dramatically as the short sample limit of the magnets is approached. The loss in temperature margin in the MB from 7 TeV to 7.5 TeV is a factor two (referred to the peak field location). This is reflected by a somewhat less dramatic reduction if the mid-plane cable is considered, and in the case of the MQ, whose operating condition is more relaxed.

As anticipated, we also evaluate the energy margin of the MB and MQ as a function of beam energy. For this evaluation we need to consider a specific space and time spectrum of the perturbation. We have taken as a reference an energy deposition deposited over long lengths, as would be the case for a beam loss, and compute the energy margin as a function of the characteristic time scale of the perturbation. The details of the method used for this evaluation are reported in [6].

The results of this evaluation are shown in Figures 5 and 6, where we report the energy margin of the mid-plane cable in the MB and MQ magnets, evaluated as a function of the characteristic perturbation time for three beam energies in the range 6.5 to 7.5 TeV. We remark from there that the energy margin for fast perturbations (applicable to fast beam losses) drops dramatically at 7.5 TeV with respect to the values at 6.5 and 7 TeV. Focusing on the MB magnets, the energy margin at 7.5 TeV drops by more than half to below 50 % of its value at 7 TeV in the ultra-fast regime of 1 μs perturbation time. This reduction is somewhat less pronounced, to approximately 60 % to 75 % of the 7 TeV value, in the fast perturbation range 0.1 ms to 1 ms typical of UFO's. Finally, for very slow perturbations, 1 s up to steady state regime, the reduction is only by 10 %.

To understand these results, we plot in Figure 7 the values of energy margin for the MB cable at three selected time scales: ultra-fast (1 μs), fast (1 ms) and slow to steady (1 s) vs. the corresponding temperature margin from Table 5. As anticipated above, we see in Figure 7 that the correlation of energy margin to temperature margin (and thus, implicitly, to beam energy) is very different for fast and for slow transients. The reason is that in the fast regime the energy is absorbed locally, by the heat capacity of the cable and interstitial helium. Because heat capacity is very small at low temperature, and grows rapidly as the temperature increases, the effect of a reduction of temperature margin is very strong. On the other hand, for very slow to steady state energy inputs, the dominating mechanism is heat transfer to the helium bath. This is also a highly non-linear mechanism, very effective under a small temperature difference between the strand and helium, a few tens of mK, but rapidly saturating as the temperature difference increases. In this case a reduction of the temperature margin only has a marginal effect, as observed.

These considerations will provide background for the later discussion on quench limits from collimation (steady) losses, and UFO (fast) beam losses.

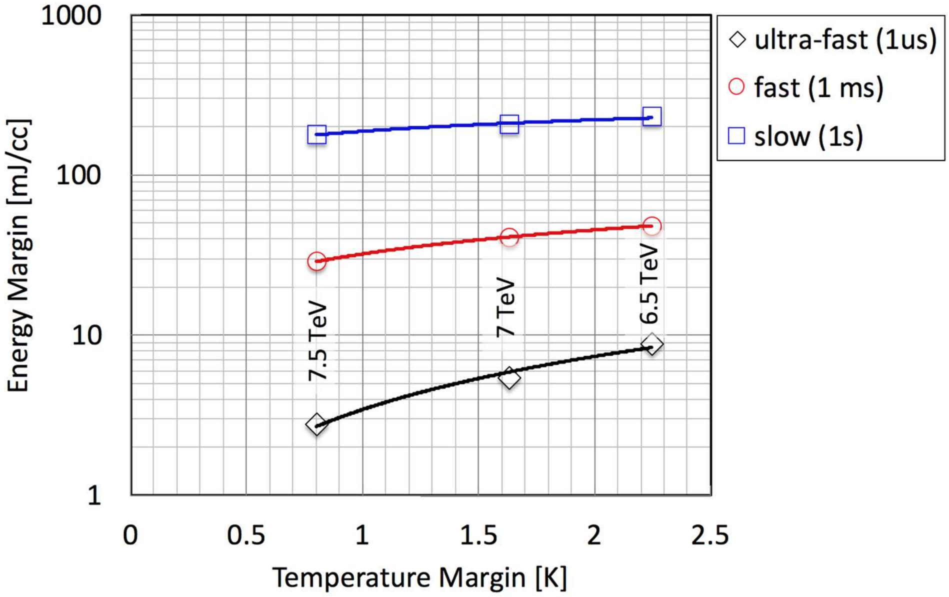


Figure 7: Expected energy margin in the MB superconducting cable for different beam energies, corresponding to different temperature margins. Three selected time scales are plotted, ultra-fast (1 μs), fast (1 ms) and slow (1 s).

4.8 Field Quality and magnet transfer functions

A number of studies have been carried out to assess the impact of Field Quality (FQ) on Dynamic Aperture (DA) for operation at 7.5 TeV for the case without beam-beam effects.

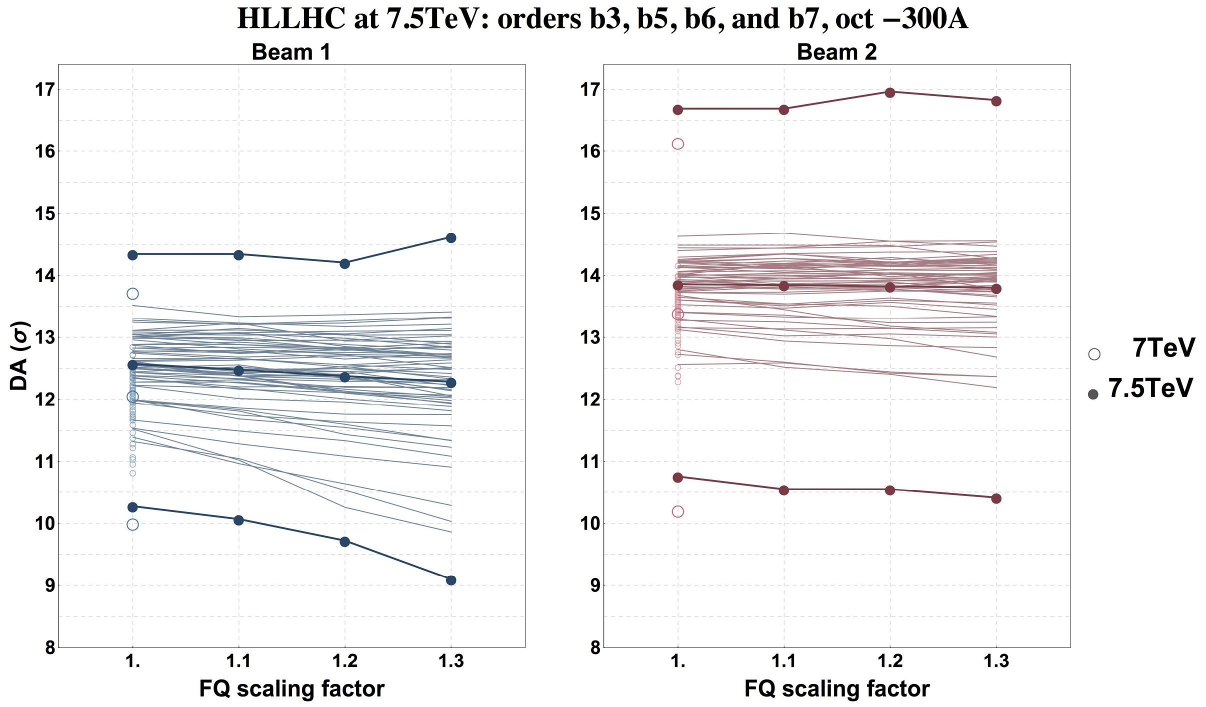
The machine layout selected is the HL-LHC V1.3 with nominal round optics [7]. The starting point for the FQ is the measured one for the LHC magnets, while for the HL-LHC magnets, i.e., the new insertion magnets in IR1 and IR5, the expected FQ tables from WP3 have been used [8], which should provide a somewhat conservative case. Given the lack of clear estimates for the behaviour of the FQ at ultimate energy for LHC and HL-LHC magnets, the following scenarios have been considered:

- The FQ remains constant between nominal and ultimate energy.
- The FQ changes between nominal and ultimate energy by an increase (in absolute value) of 10%, 20%, and 30%. Note that such an increase includes systematic, random, and uncertainty components. Each of these scenarios has two subcases, namely only b_3, b_5, b_6, and b_7 multipoles are increased (Case 1) or all multipoles are rescaled (Case 2).

In the numerical simulations performed, the various families of non-linear correctors or spool-piece circuits have been assumed to be fully conforming, i.e., all circuits have the nominal number of magnets with nominal performance. This implies that all existing circuits' non-conformities will be resolved before pushing the energy towards its ultimate value. Moreover, the assumption has been made that all correctors can reach the corresponding ultimate strength. In case a correction circuit would need more than ultimate strength, it is set to its ultimate strength in the numerical simulations.

The results of the simulations are shown in Figure 8 for both Beam 1 and Beam 2 and the scenarios for the FQ described above.

For each seed, the average over the 11 angles is displayed, while the curves with markers represent the minimum, the maximum or the average over seeds and angles respectively. The increase of DA for the case of constant FQ at 7.5 TeV can be understood in terms of reduction of physical emittance due to the higher beam energy. The simulations appear to show a higher sensitivity of Beam 1 to the value of the FQ scaling factor, while Beam 2 features a much smaller DA variation. A deterioration of FQ at 7.5



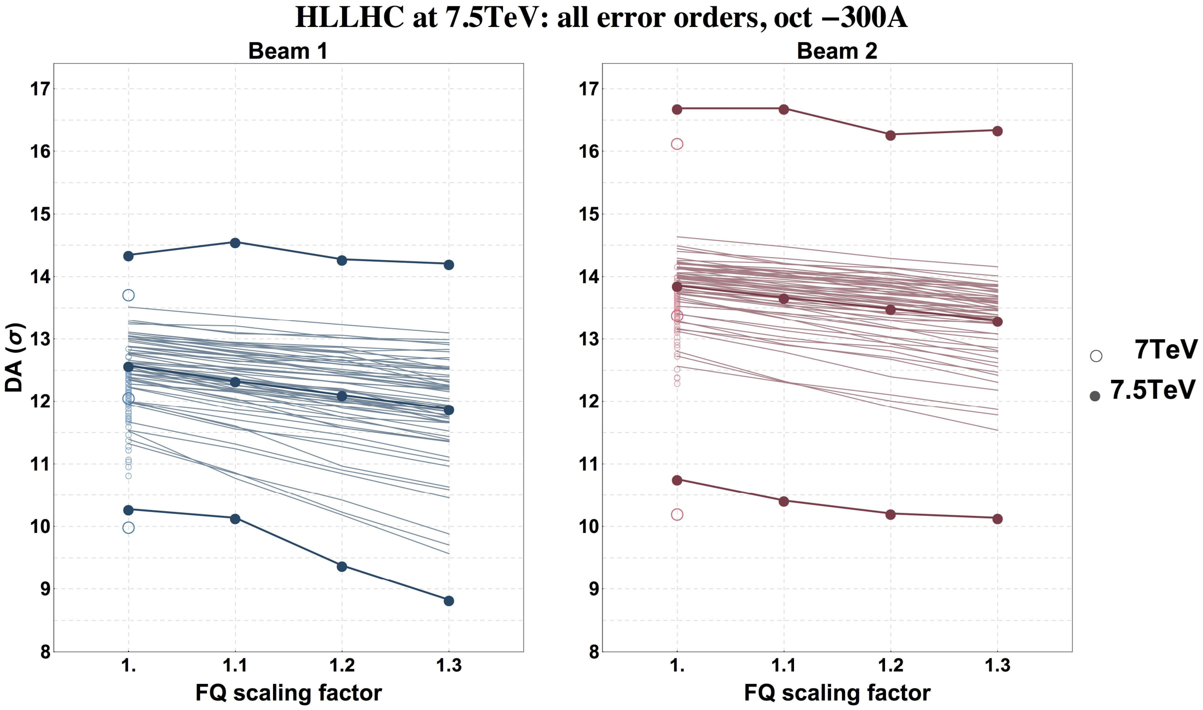
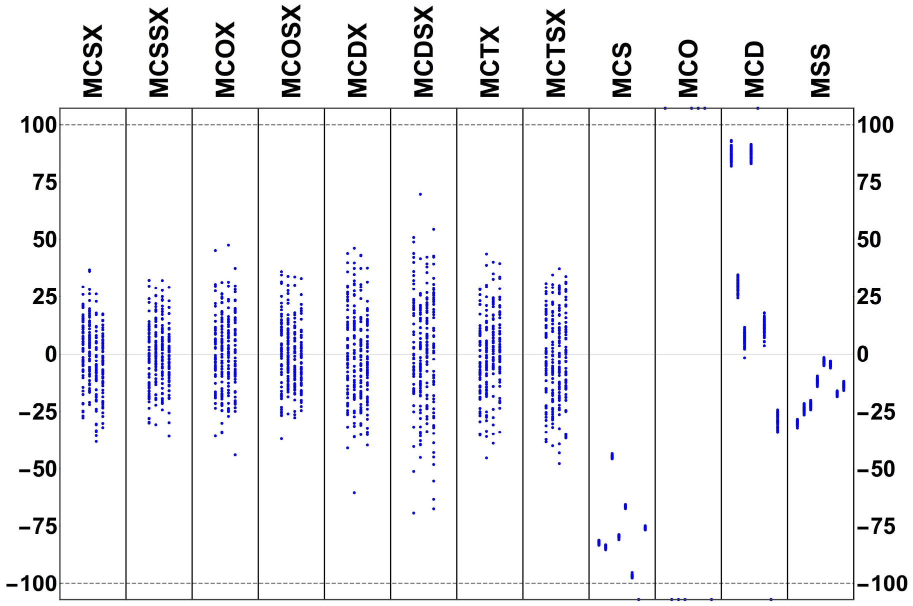


Figure 8: Simulated dynamic aperture for Beam 1 (left column) and Beam 2 (right column) for Case 1 (upper row) and Case 2 (lower row) as a function of the FQ increase factor for sixty realizations of the FQ errors. The full markers represent the DA at 7TeV, while the hollow one represent the DA at 7.5 TeV. One can clearly observe an increase in DA for the FQ scaling factor equal to 1.



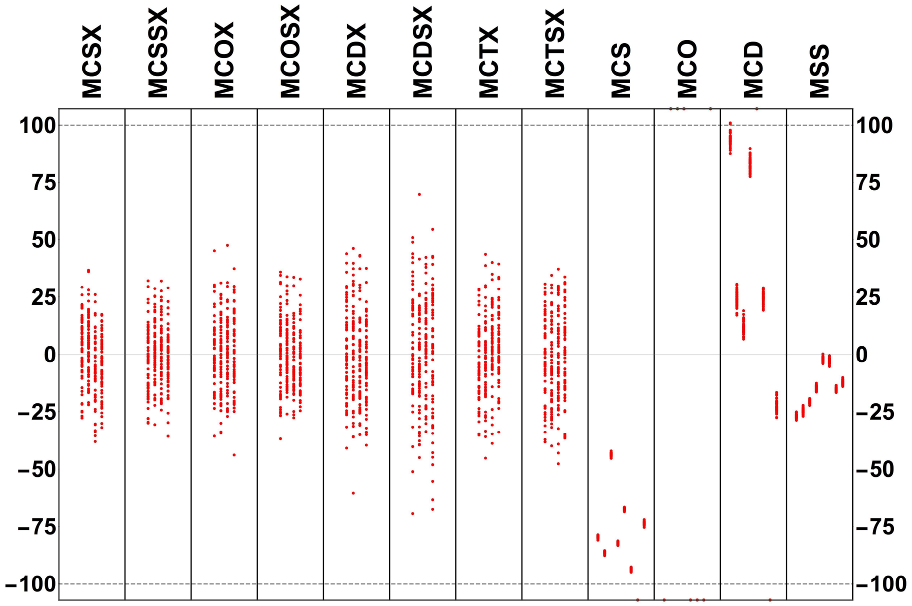


Figure 9: Summary of the needs in terms of correctors' strength for Beam 1 (upper) and Beam 2 (lower) for the FQ increase factor of 1.3. The extent of the vertical scale covers ultimate performance. The complete situation for the sixty seeds is shown here.

TeV by up to 10-20 % with respect to what is expected at 7 TeV could be tolerable, as it produces no significant DA reduction with respect to what is expected for operation at nominal beam energy. Therefore, provided that no significant deterioration of the field quality, i.e. larger than 10-20%, occurs between nominal and ultimate energy (as expected by the magnet experts), no significant deterioration in performance due to field quality is to be expected.

As far as the correctors strength is concerned, the situation is summarised in Fig. 9 for Beam 1 (upper) and Beam 2 (lower) for the worst FQ increase factor of 1.3. For all variants, Case 2 has been considered, only.

The only corrector circuits that are limited by their ultimate performance are the RCS circuit in sector 78, the RCO circuits in all sectors (but it is a well-known fact that they run out of strength at about a few TeV), and the RCD circuits for sector 56 and 78, for which the value of the systematic b_5 multipole is close to, or even beyond the target set by beam dynamics considerations [9].

In summary, in case of a modest worsening of the FQ at 7.5 TeV with respect to 7 TeV, at the level of 10% to 20%, no performance limitation is expected for the whole ring and the majority of correctors' circuits should provide the needed functionality.

4.9 Risks associated with operating the LHC magnet system at 7.5 TeV

Operation at 7.5 TeV implies an increase of the mechanical and electrical stress exerted on the magnets and powering circuits. Specifically, based on the scaling of electromagnetic forces and energy (square of the bore field, increase by 15% with respect to nominal operation at 7 TeV) and of the voltage during magnet quench fast power abort (proportional to the field, increase by approximately 7% with respect to nominal operation at 7 TeV) we anticipate the following increased risks (in perceived order of severity):

- Conductors and bus-bars movement in locations where the support is localised to single points, e.g. expansion loops in the interconnect area, or bus-bars along the cold mass. This could lead to shorts among conductors or to shorts-to-ground;
- Coils and bus-bars are subjected to increased voltage during a dump, which could cause electrical faults such as inter-turn shorts or shorts-to-ground;
- Increased hot-spot temperature in case of quench, e.g. by about 50 K in the case of the dipole magnets, which results in increased thermo-mechanical stress and could lead to electrical failures, e.g. in the insulation system.

In addition, the margin for operation at 7.5 TeV will be reduced by a factor of 3 to 4 as compared to operation at 7 TeV in the range of fast beam losses (1μs to 1 ms, see discussion in Section 3.7), which will most likely be associated with an increased rate of beam-induced quenches. Increasing the number of quenches and quench heater discharges will increase the cumulated risk of (in perceived order of severity):

- Short in a coil or coil to ground, or coil to quench heater;
- Other quench heater failures (e.g. in the wiring and connections);
- Failure of circuit components, e.g. switches;
- De-training of the quenched magnets;
- Mechanical failures (e.g. leaks) associated with the thermo-mechanical stress and the pressure increase during a quench.

None of the above risks will prevent the LHC from operation, and for all of them, the failing component can be replaced with a relatively long stop of accelerator operation (months in some cases). The failure rate associated with the above risks can be estimated using the analysis of the present failure rate, based on operation at 6.5 TeV [MT25], and assuming a scaling based on the increase of mechanical and electric stress of the type:

$$MTTF(7.5TeV) = MTTF(6.5TeV)/AF$$

where MTTF is the mean time to failure and AF is the acceleration factor. To give orders of magnitude we make the assumption that the MTTF will be dominated by electrical faults, and take a scaling for the acceleration factor AF based on a power function of the ratio of maximum voltage at the present operation energy vs. the ultimate value. As the maximum voltage will be proportional to the energy, AF can be estimated as follows:

$$AF = \left(\frac{7.5TeV}{6.5TeV}\right)^{\alpha}$$

where α is a power exponent that is customarily taken equal to 2 for electrical machines. The resulting acceleration factor is 1.33, and the MTTF (mean time to failure) is expected to decrease from the estimated value of 1764 yrs (operation at 6.5 TeV) to 1324 yrs (operation at 7.5 TeV), an increase of 25% in the expected number of failures.

5 LHC Beam Dump System

5.1 Introduction

The LHC beam dump systems (LBDS) comprise several subsystems affected by the choice of beam energy. These are:

- Extraction kickers MKD;
- Dilution kickers MKB;
- Extraction septa MSD;
- Septum protection TCDS;
- Mobile Q4 protection TCDQ;
- Beam dump entrance window VDSB;
- Beam dump block TDE;
- Beam instrumentation.

All subsystems were initially designed for the LHC nominal energy of 7.0 TeV and the ultimate intensity of 1.7 10^{11} p/bunch in 25 ns with 3.75 μm transverse emittance [5]. After the initial operational experience in Run 1 [10], and the upgrades planned in LS2 and LS3 for HL-LHC [1], the system should be compatible with 7.5 TeV operation with the nominal HL-LHC beam parameters of 2.2 10^{11} p/bunch in 25 ns with 3.75 μm transverse emittance, albeit with reduced margins (or lower intensity for the same margin) compared to 7 TeV, assuming additional upgrades with respect to the current HL-LHC baseline [11] that are already envisaged for operation at nominal beam energy.

In the following the limitations and expected performance reach at 7.5 TeV are discussed for each sub-system.

5.2 Extraction and Dilution Kickers MKD and MKB

The extraction kickers MKD are permanently charged with a voltage directly proportional to the beam energy. The kicker generators have been redesigned to improve the voltage hold-off, with the specified operational value corresponding to operation at 7.5 TeV [plus margins required for hardware commissioning and checkout], with deployment in LS2. The switch stack has a new geometry with additional insulation and increased physical clearances at critical locations, to reduce the maximum field to the target of 1.5 MV/m, and the main capacitance value is being increased by 18% from 1.40 μF to 1.64 μF. The associated rise-time increase has been largely cancelled by the better performance obtained with a new trigger transformer design, so that the LHC abort gap will at most increase from 3.0 to 3.1 μs. The changes also reduce the overshoot in the kicker waveform giving a slightly larger aperture margin at 450 GeV [12].

For 7.5 TeV operation, the system voltage with the new capacitors is illustrated in Figure 10. The operating voltage of 28.7 kV is to be compared with the 28.9 kV used today for the 7 TeV system reliability run and testing. The corresponding voltage needed for system testing (at 8.1 TeV) is 30.7 kV. Bearing in mind the other improvements, the high voltage performance of the MKD switches for 7.5 TeV operation (including sensitivity to SEB and probability of erratics) is expected to be very similar to (or better than) the excellent performance obtained in Run 2 at 6.5 TeV.

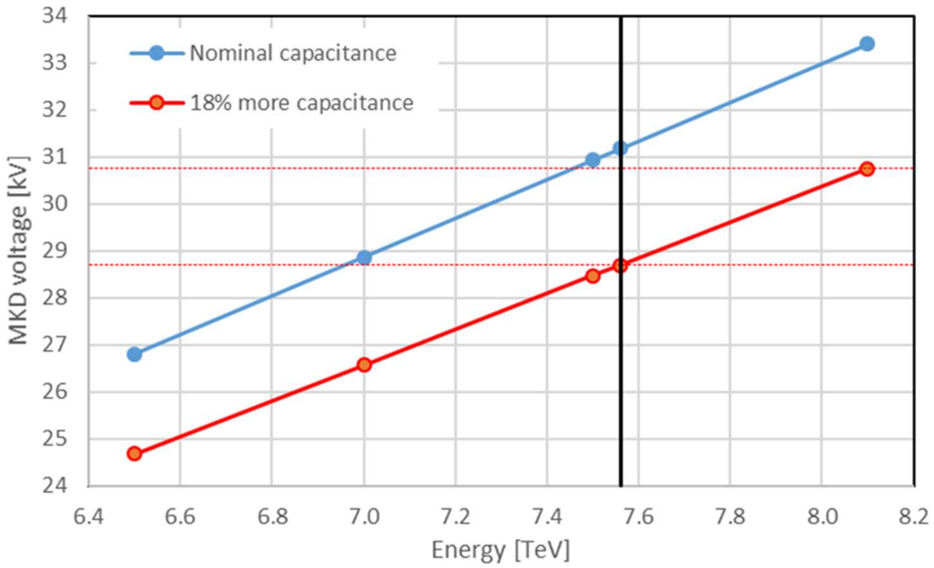


Figure 10. MKD voltage vs energy for original and upgraded (post LS2) system. The new operating voltage at 7.5 TeV is almost exactly the same as the voltage extensively used for testing and reliability runs at 7.0 TeV in the present system, for which the performance is already fully acceptable even without the additional HV improvements being deployed in LS2.

The dilution kickers MKBH and MKBV are also permanently charged with a voltage directly proportional to the beam energy. The MKBH generators (which have a much higher charging voltage than MKBV), have shown problems of HV hold-off and EMC coupling between generators [13]. The underlying HV breakdown weaknesses and susceptibility to radiation are being addressed by the deployment of new ABB GTO switches using the new MKD stack design, plus the deployment of a new retriggering circuit as long-term mitigation against any MKB coupling. Post LS2, as for the MKD, operation of the MKB system at 7.5 TeV should be at least as reliable as the 7.0 TeV testing seen to date. The observation in 2018 of a hitherto unexpected delayed coupled flashover in the MKBV system will require an additional improvement of the MKBH system to avoid or mitigate this failure mode, which for the present system could result in missing 3 out of 4 dilution kickers. Improvements to the high voltage insulation and the addition of 2 more MKBH kickers per beam will be proposed as modifications to the current HL-LHC baseline [11].

Testing of the main aspects of the performance reach and fault-rate for 7.5 TeV operation will be possible post-LS2, when most of the upgrades described in this section are complete, except for the additional MKBH kickers.

5.3 Extraction Septa MSD

The MSD septa are comprised of three types MSDA, MSDB and MSDC that differ in the septum thickness and the saturation behaviour. The septa were designed for 7 TeV operation and no issues are expected for 7 TeV running. A detailed analysis of the saturation performance of the different magnets and the overall transfer function has been made up to 7.5 TeV [14], and showed that, for the 7.5 TeV powering current, a very small downstream shift in the longitudinal kick center of the septum is produced, which has a negligible effect of shifting the extracted beam by about 0.3 mm at the beam dump. This does not need any correction. The extra saturation produces a negligible stray field change for the circulating beam. Finally, the power convertors and water-cooling have also been checked up to 7.5 TeV operation and should function without problem. These conclusions are valid for 7.56 TeV.

5.4 Protection Devices TCDS and TCDQ

The protection devices TCDS and TCDQ were both initially designed for the so-called LHC "ultimate" beam, with the TCDS performance at the limit for this set of parameters [15]. The transverse emittance of the beam is not very important for the damage limits of the devices themselves, since the beams are always swept.

A formal analysis of the performance reach of the devices for parameter sets which vary slightly from the design is a laborious task, requiring simulations of equipment failure cases, tracking particles for the devices loads, energy deposition simulations using FLUKA and time-coupled ANSYS simulations for thermo-mechanical response. The results are often subject to interpretation, as the engineering limits and accuracy of the knowledge of the material properties can influence greatly the conclusions.

Overall, operation with 7.5 TeV as compared to 7.0 TeV (or 6.5 TeV) will not cross any specific performance threshold that would present a significant additional risk of damage to the LHC or the systems themselves, as the transverse energy densities for the failure cases will be comparable to those with the 7.0 TeV design energy and parameters. Given that the system needs to work for the HL-LHC parameters with 2.3×10^{11} protons in 2.3 μm transverse emittance, and assuming a very conservative scaling with the square root of the transverse emittance ratio, the 7.5 TeV intensity limit per bunch at 2.2 μm would only be around 5% lower, at 2.15×10^{11} protons per bunch for 2808 bunches. Detailed studies of the exact sweeps with the 7.5 TeV beam parameters and optics will be needed to verify the exact values, but with the equipment redesigned for HL-LHC, there are unlikely to be limits for operation at 7.5 TeV from their robustness.

5.5 Beam Dump Block TDE and Entrance Window VDWB

The TDE beam dump block and VDWB entrance window were also both initially designed for the so-called LHC "ultimate" beam [16], and are also being upgraded for compatibility with the HL-LHC beam at 7.0 TeV. The transverse emittance of the beam is relevant for the stress level on the upstream window, but plays little role in the damage limits of the dump block and the downstream window. The systems were designed to withstand partial dilution failures, with a large redundancy allowing for at least two simultaneous missing kickers. An increase in beam energy from 7.0 to 7.5 TeV does not affect the system safety in this respect. For similar safety margins, the intensity limit at 7.5 TeV is likely to be around 2.1×10^{11} protons per bunch in the nominal emittance, again subject to full FLUKA and ANSYS simulations.

The recent (2016-17) issues with leaks on the beam dump block entrance and exit flanges will anyway need to be solved for the Run 3 and HL-LHC beams. These mitigation measures will be done with the operation at ultimate beam energy in mind and so operation at 7.5 TeV is not expected to pose any additional complication.

5.6 Dump System Instrumentation

A number of dedicated instruments are used to set up and (more importantly) monitor the quality of the beam dump actions. No performance degradation is expected from the energy increase to 7.5 TeV, for the BTVS, BTVD and BTCDD screens, the ionization BLMs, the BCT current transformers, or the BPMD pick-up.

5.7 Beam Energy Tracking System BETS

The BETS and energy distribution within the LBDS are encoded using 16 bits, and any energy above 7.8 is TeV is at present not possible. Since beam operation at 7.5TeV implies testing of the system at 8.1 TeV voltage (see section 4.2) a solution needs to be developed to increase the dynamic range of the BETS. One option would be an increase to 20 bits, which implies a rather significant development program with a completely new electronics and would have impact on other machine protection systems. New electronic interface cards (BEC, BEI) as well as the controller and interface crates would need to be developed for the various connected systems, which potentially include all of the main LHC dipoles, Q4, MSD, MKD, MKBH,MKBV, MSI and the TCDQ and TDI. This upgrade will require 18 months of work for 2-3 FTE, and is tentatively planned for LS3. It is presently not funded. Alternatively, one could envisage an increase of the energy step from 120MeV per bit to 125 MeV per bit, which comes at the small drawback of impacting tracking sensitivity (due to a larger error) at injection and at the start of ramp for LBDS, MKI and TCDQ. This seems however acceptable as the margins could be slightly relaxed for these low energy levels. This solution would allow to cover the full energy range up to 8.1 TeV even with the existing 16 bits system.

The compatibility of the BETS system with RB/MSD/Q4 DCCT also has to be checked for operation above 7.1 TeV, since it is probable that the functions become more non-linear. Finally, the distribution and reception of the energy through the Safe Machine Parameter (SMP) for the generation of the Safe Beam Flag (SBF) has also to be checked for all clients.

The commissioning overhead for the BETS and SMP would only be a few additional shifts, as most of the BETS can be tested transparently during HWC/beam commissioning and during the reliability runs.

5.8 Conclusion on the LHC Beam Dump System

When the HL-LHC upgrades are completed in LS3, the beam dump system will not pose any hard limit preventing operation at 7.5 TeV, nor will it severely limit the beam intensity. The beam intercepting devices all need to work for the HL-LHC beam parameters at 7.0 TeV, and the 7.5 TeV use-cases are basically the same. The known HV hold-off weaknesses in the MKD and MKBH generators are being addressed by the many improvements being made in LS2 to these sub-systems, including an increase of the main capacitance value to reduce the system voltage for a given current. The limited dynamic range of the BETS has been identified as one area where an upgrade is needed, to allow testing of the system with the required margin.

6 Beam Collimation

The following subjects are identified [17] as possible areas of concerns for the LHC collimation system at ultimate beam energy (in order of perceived risks):

- Collimation losses versus reduced quench limits of super-conducting magnets;
- Collimator robustness and machine protection functionality of the collimation system with higher energy densities;
- Cleaning of physics debris around high-luminosity collisions points, versus quench limits and versus limits of total radiation doses;
- Collimation impedance in case of operation with tighter settings as in the nominal HL-LHC configuration or different optics scenarios.

Other aspects of possible concerns, like for example operational efficiency, mechanical ware and effects from total radiation doses are not expected to be critical for the collimation system for changes in operating energy at the level of 10 %. The main aspects of the list above are discussed in Section 5.2 after a brief recap. of the collimation layout after LS3.

For HL-LHC, there are concerns about the operation and the collimation performance with highly populated transverse tails. This concern could be addressed by adding to the HL-LHC baseline hollow electron lenses [18][19] for active beam tail control. The operations at ultimate energy would benefit even more by this upgrade as the increase of stored energy amplifies the effects from over-populated tails.

6.1 Layouts of the system after LS2 and after LS3

In the present collimation upgrade baseline, major interventions are planned in LS2 and in LS3, as part of the HL-LHC upgrade and of the LHC Consolidation Projects. In LS2, the main activities planned are [20]:

- upgrade of the dispersion suppressor (DS) collimation around IP2 (without 11 T dipoles) and around IP7 (with 11 T dipoles);
- first stage of IR7 impedance reduction, with the addition of 4 low-impedance secondary collimators per beam with in-jaw beam position monitors;
- consolidation of 2 primary collimators of IR7 per beam with a new design with lower impedance and in-jaw beam position monitors;
- improvement of the passive absorbers that protect the IR7 warm magnets.

In LS3, the main planned activities are:

- re-design of the LHC high-luminosity insertions IR1 and IR5 to cope with the HL-LHC design luminosity;
- completion of the low-impedance upgrade of the secondary collimators in IR7;
- consolidation of the control system of the collimation system for a higher operational efficiency;
- completion of the consolidation of the primary collimators and of the remaining collimator devices that are not replaced as part of the HL-LHC upgrade.

Note that the last two items in the previous list are not yet approved and funded under the present Consolidation Project.

The upgrades listed above are presently designed to cope with sufficient margins with the nominal and ultimate performance of the HL-LHC at 7 TeV, with some caveats coming from the uncertainty of the scaling of quench limits of super-conducting magnets at higher beam energies than the 6.5 TeV value explored in the LHC Run II [11]. It is also noted that in the present planning, the ultimate beam energy is foreseen at the earliest at the end of Run 4, thus probably after the currently foreseen end of ion operations.

6.2 Performance of the system after LS3

6.2.1 Collimator setting assumptions at 7.5 TeV

The HL-LHC collimation has been designed to efficiently protect the machine from regular and accidental losses at a beam energy of 7 TeV [11]. Since the shadowing of the aperture is not affected by beam energy or emittance, and the effect of a different halo population at 7.5 TeV due to changes in the scattering physics is small, the 7 TeV design settings in mm will provide equivalent geometric protection of the aperture at 7.5 TeV, provided that the optics is the same. Nevertheless, since the quench limit is different, similar losses might be more critical – this is discussed in Section 3.7.

Table 6: Collimator settings (half-gap) at 7 TeV and at 7.5 TeV. Settings in R.M.S. beam size (for $\varepsilon^* = 2.5$ μm) for the minimum β* of 15 cm.

Collimator	Setting 7 TeV	Setting 7.5 TeV
TCP IR7 [σ]	6.7	6.9
TCSG IR7 [σ]	9.1	9.4
TCLA IR7 [σ]	12.7	13.1
TCLD IR7 [σ]	16.6	17.2
TCP IR3 [σ]	17.7	18.3
TCSG IR3 [σ]	21.3	22.0
TCLA IR3 [σ]	23.7	24.5
TCSG IR6 [σ]	10.1	10.5
TCDQ IR6 [σ]	10.1	10.5
TCT IR1/5 [σ]	10.1	10.5
TCT IR2 [σ]	43.8	45.3
TCT IR8 [σ]	17.7	18.3
Protected Aperture 1/5 [σ]	11.9	12.3

The simplest option for 7.5 TeV collimator settings is to assume that the HL-LHC collimator settings (in mm) are kept as for the operation at 7 TeV. Because of the higher beam energy, these settings are slightly larger in units of beam σ at 7.5TeV (scaled by a factor √(7.5/7)). These settings are listed in Table 6. If the gap openings in mm are kept as for the HL-LHC configuration, the collimator impedance will be the same as at 7 TeV – see Section 6.9.

Optionally, it could be considered to use, at 7.5 TeV, the 7 TeV settings in σ instead of in mm, i.e. the 7.5 TeV settings would be identical to the 7 TeV settings in σ as in Table 6. This would imply tighter gaps in mm. However, such studies of a potential optimization of the performance at 7.5 TeV through optimization of the collimator settings are outside the scope of this paper and we assume for the sake of transparent comparison of the performance reach for operation at 7 TeV and 7.5 TeV throughout this report the same collimator settings in mm and as stated in Table 6.

6.2.2 Cleaning performance versus quench limits

Figure 11 shows the expected variation of cleaning inefficiency at the most exposed cold magnets around IR7, which are in the dispersion suppressors [DS], as a function of the beam energy. The local cleaning inefficiency is defined as the number of particles lost per unit length in the cold aperture of the magnets, normalized to the total number of particles impacting on the betatron collimation system. Losses are shown for the two highest clusters of losses in the DS, for constant settings in mm. Here, we consider conservatively the layouts of Run II without the new HL-LHC TCLD collimators in the DS of IR7. These results are obtained from SixTrack simulations and do not include detailed energy deposition simulations in the magnet coils. It is concluded that the cleaning performance depends loosely on the beam energy in the range of interest, with a maximum degradation of up to 30 % from 6.5 TeV to 7.5 TeV. This increase of losses at constant collimator gaps in mm can be attributed to more forward scattering angles for higher energy protons. Although detailed simulations of energy deposition could not yet be performed at 7.5 TeV, one can expect that the energy deposited in the coils will increase proportional to the beam energy, adding up to another 8 % to what is estimated for the reference 7 TeV case, resulting in a total increase of ca. 23% in the deposited energy when comparing the cases of operating at nominal and ultimate beam energies. Even if total loss rates at ultimate beam energy will remain comparable to those observed in Run II and assumed for HL-LHC, the performance will depend primarily on this increase of the inefficiency, the increase in deposited energy and on the scaling of quench margins with higher magnet current.

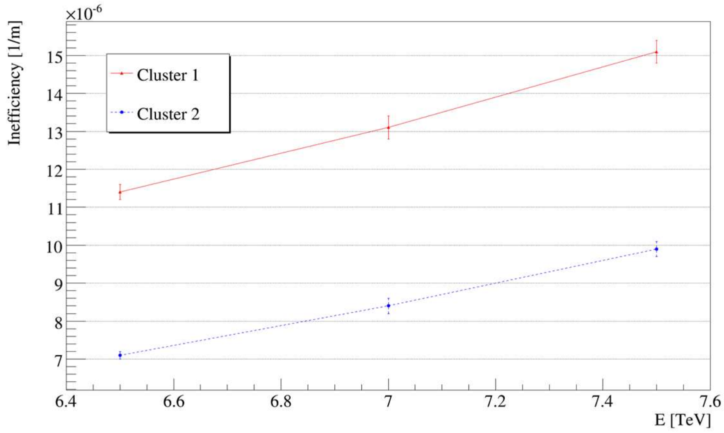
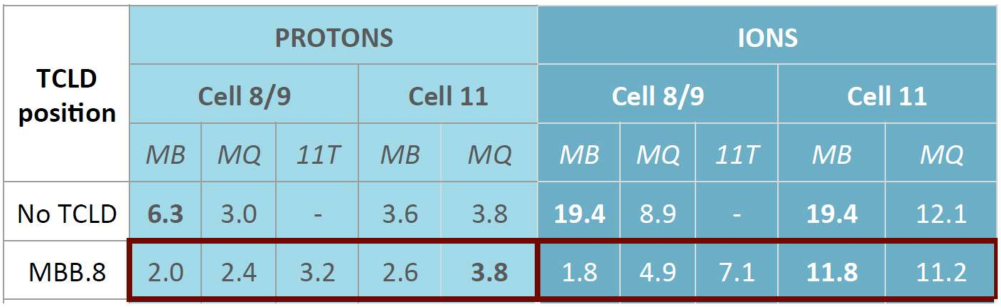


Figure 11: Cleaning inefficiency as a function of beam energy for the same mm settings of the collimators in IR7, for the two highest loss clusters in the DS around IR7. The increase of cleaning inefficiency at constant collimator gaps in mm can be attributed to more forward scattering angles for higher energy protons.

Table 7 shows the predicted [21] peak power deposition in cells 9 and 11 of the IR7 DS. Results refer to 12 minutes beam lifetime and HL-LHC beam intensity of 5.73 1014 protons, with and without the TCLD installed in the slot of MBB.8 (as per HL-LHC design [11]). Values for protons and ions at 7 Z TeV are given, for TCLD settings of 14~σ. A multiplication factor 3 should be applied to the numbers of Table 7 as shown in benchmarking collimation quench tests carried out in the past [22]. Table 7 shows the beneficial effect of the TCLD in reducing the peak power deposition in the main dipoles by a factor of 2. Ion quench tests carried out in 2015 ([23] and [24]) showed that the quench limit of the main dipoles for losses longer than a second is ~20-30 mW/cm^3 at 6.37ZTeV (already considering the factor 3). Note that for protons, collimation quench tests at 6.5TeV beam energy did so far not result in magnet quenches [25].

Table 7: Predicted [21] peak power deposition in cells 9 and 11 of the IR7 DS in mW/cm^3. Results refer to 12 minutes beam lifetime and HL-LHC beam intensity of 5.73 10^{14} protons, with and without the TCLD installed in the slot of MBB.8 (as per HL-LHC baseline [11]). Values for protons and ions at 7Z TeV are given, for the baseline TCLD settings of 14~σ. A multiplication factor 3 should be applied to these numbers, which have been computed for a perfect machine, in order to get realistic estimates.



TCLD position	**PROTONS**					**IONS**				
	Cell 8/9			**Cell 11**		**Cell 8/9**			**Cell 11**	
	MB	*MQ*	*11T*	*MB*	*MQ*	*MB*	*MQ*	*11T*	*MB*	*MQ*
No TCLD	**6.3**	3.0	-	3.6	3.8	**19.4**	8.9	-	**19.4**	12.1
MBB.8	2.0	2.4	3.2	2.6	**3.8**	1.8	4.9	7.1	**11.8**	11.2

For the relative scaling of quench limits to higher beam energies, we use the simulations presented in Figure 12 (from [26]) and look at the steady cases for losses of durations of 1 s and 10 s. Taking into account an estimated decrease of the quench limit by about 10% from 6.5 TeV to 7 TeV (see Fig. 12, yellow line of left graph and black line of right graph), one concludes that the HL-LHC operation at 7 TeV is fine with protons, but issues may still arise with ions: for example, from Table 7 one sees that the MB's might experience peak losses of more than 35 mW/cm^3 (including the factor 3 correction for machine imperfections) while the quench limit would be 10 % lower than the empirically found value of 20-30 mW/cm^3. Note that, in the framework of the HL-LHC project, the option of crystal collimation is under study to mitigate possible ion limitations.

Operation at the ultimate energy of 7.5 TeV is only foreseen at the earliest in Run 5 when no ion operation is foreseen, thus quenches with ions beams are not a concern for the scope of this document. We assumed that the quench limit will go down by another 10 % from 7 TeV to 7.5 TeV, such that the empirically found limit of 20-30 mW/cm^3 could decrease to 16-24 mW/cm^3. Instead, the estimated power deposition scaled up from Table 7 would only reach about 12 mW/cm^3 for the MBs, computed as 2.6 times 3, further increased by 30 % for cleaning inefficiency (Fig. 11) and by another 8 % from beam energy. Operational margins are clearly small, but in the worst case, one could dump the beams at an equivalently larger beam lifetime (e.g., 12 minutes x 30 % x 8 % = 17 minutes), or limit the beam intensity accordingly. Both options would result in a performance decrease that seems acceptable and would not introduce major showstoppers for operating at 7.5 TeV.

It is noted that it is important to pursue the program of quench tests with beams at 6.5 TeV (Run 2) and later 7 TeV, to decrease the uncertainties on the extrapolation of quench limits to 7.5 TeV and the characterisation of the cables of the 11 T dipole, to asses with measurements the actual quench limit. Finally, it is also important to carry out a complete simulation campaign to predict the margins to quench for the design cases of losses at the IR7 collimators, i.e. losses lasting between 1 s and 10 s with 12 minutes beam life time and steady state losses with 1 h beam life time. If margins to quench are loosely met, BLM thresholds at collimators can be adjusted operationally such that the loss rates are not as high as required by the design cases; in case margins are substantially missed, then the installation of the second TCLD unit during LS4 could be foreseen or one needs to limit the beam intensities for operation at 'ultimate' beam energy.

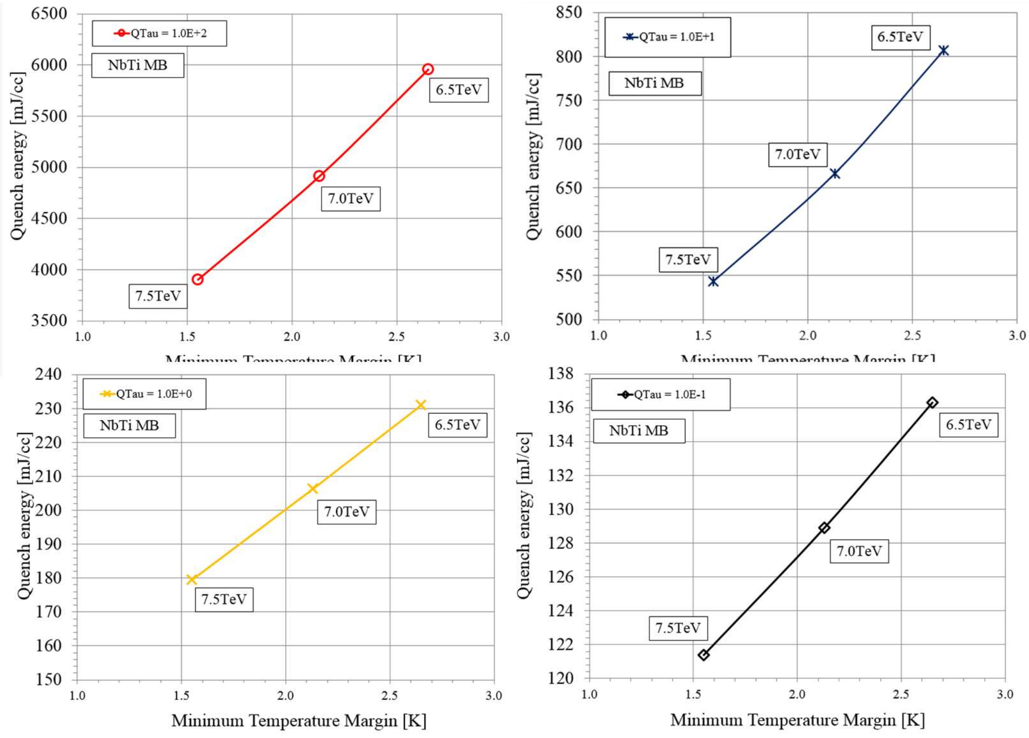


Figure 12: expected quench limit in the MB superconducting cable [26] for different beam energies and different durations of the loss (QTau is the duration of the loss in seconds).

6.2.3 Collimation of physics debris

In the HL-LHC baseline, three physics debris absorbers (TCL) and three fixed masks (TCLM) are installed on each side of the high-luminosity experiments in order to protect the matching section magnets and the dispersion suppressor. At 7.5 TeV, the energy carried by the debris will be 8% higher, at the same time as the quench limit will go down. This is not expected to be a bottleneck, however, energy deposition studies should be combined with updated quench limit estimates to draw final conclusions. Even if this would bring losses above the quench limits of the magnets in the matching sections and DSs around IP1 and IP5, an obvious alleviation is to operate at a 8 % lower, levelled luminosity.

6.2.4 Collimator robustness against design failures

The collimation system has been designed to withstand several failure scenarios without being damaged, in particular asynchronous beam dump, injection failure, and beam lifetime drops down to 12 minutes over 10 s, and down to 1 h continuously for an arbitrary duration.

Detailed simulations of these cases have not yet been carried out at 7.5 TeV. Nevertheless, the increase in beam energy by 8% is not expected to substantially limit performance. For the drops in beam lifetime, the BLM thresholds can be adjusted such that the beam is dumped at a slightly lower loss rate than at 7 TeV (i.e. approximately at 13 minutes instead of 12 minutes), such that the beam loss power is kept constant. Given that the beam lifetime is not expected to drop often to these values, the penalty is expected to be negligible.

For an asynchronous beam dump, the robustness of the dump protection collimators is discussed in Section 4. Concerning the ring collimation system, a simulation chain of tracking, energy deposition and thermo-mechanical studies have been performed of the most exposed tertiary collimators for the 7 TeV configuration [27]. With the foreseen HL-LHC upgrade of the material of the tertiary collimators to copper-diamond, their robustness is expected to increase by a factor 15-20, compared to the presently used Inermet collimators, and the increased damage potential from the higher beam energy is judged negligible compared to that factor. No detailed studies have yet been carried out concerning an asynchronous beam dump on secondary collimators. However, in terms of total lost energy, this case is less critical than injection failure scenarios, and it is not expected to be limiting at 7.5 TeV. Nevertheless, a full round of simulations should be carried out to verify these assumptions. The time required to carry out both tracking and energy deposition simulations is estimated at 6 months of an FTE.

The impact of injection failure on the collimation system has been studied for the standard HL-LHC scenario [28] and no change of the injection point is assumed due to the change of top energy.

6.2.5 Considerations for ion operations

Although it is not foreseen as a baseline at this stage to continue the heavy ion programme beyond Run 4 and even though a request for proton operation at higher beam energy does not imply automatically a request for higher beam energy with ion beams [one could always lower the beam energy again to the nominal values for ion beam collisions], we recall here some considerations about possible performance limitations related to heavy ion operations at 7.5 TeV equivalent.

Collimation in the LHC is known to be less efficient with heavy ion beams than with protons, since ion fragments escaping the primary collimator can be lost in the dispersion suppressor while bypassing the secondary collimators. The HL-LHC upgrade that will be performed in the IR7 dispersion suppressors, including one additional TCLD collimator per side, is expected to alleviate this bottleneck. However, the margins are not large and the uncertainties significant [29]. This could be a critical point for operation at 7.5 TeV and full simulations should be carried out to quantify the effect. In order to improve the energy deposition, it could be considered to install a second TCLD in cell 10 but clearly the cost of this solution would have to be balanced with the benefits for increasing the beam energy for operation with ion beams.

Another concern for heavy-ion operation are the collision products with an offset in magnetic rigidity, which have been created through bound-free pair production or electromagnetic dissociation. To protect the most exposed magnets, a solution will have been put in place for HL-LHC via the TCLD collimator installation in IR2 in combination with an orbit bump that displace the losses to the collimator. In IR1 and IR5, the orbit bump alone is enough, as the losses can be displaced to the empty connection cryostat. It is expected that the increase in beam energy can be absorbed in the design margin and that no further upgrade is needed to safely dispose of these losses, in these insertions. However, final studies should be performed with updated quench limit estimates at 7.5 TeV to verify this.

But as stated in the memo issued by the director of the Accelerator and Technology Sector [2], operation at ultimate beam energy is not foreseen to occur before the end of the first HL-LHC operation period in Run4 and ion operation in at the moment not in the baseline for operation beyond Run4.

7 Other Systems and Effects (not assumed to be critical for operation at ultimate beam energy)

7.1 RF and transverse damper system

The RF systems were conceived and designed to run for acceleration up to 7 TeV, but no significant upgrades will be necessary to accelerate up to 7.5 TeV. The conclusions of [1] – *mutatis mutandis* – remain valid; the limitations to be investigated are again the margins for the beam stability and the gain of the transverse damper system ADT.

Stability limits

Running at the same bunch population as today, the increase of the top energy is 15.4% w.r.t 6.5 TeV, but it still would allow to run at exactly the same RF voltages and bunch lengths as today. The stability margins would equally be identical. Due to the strong dependence of the stability limit on the bunch length, even a moderate increase in bunch population can be coped with by slightly increasing the bunch length. Also the controlled longitudinal emittance blow-up would follow the exact same principles. Maintaining the stability limits is estimated to be sufficient to assure stable bunch length. We estimate that the beams with 1.25^{11} ppb are stable at 7.5 TeV (with the same stability margin as today) with bunch lengths above 1.12 ns. For HL-LHC intensities of 2.2^{11} ppb, bunch lengths above 1.25 ns are required for stability.

Transverse damper system ADT

To reach the same damping times as today (100 turns), the electronic gain of the damper system must be increased proportionally to the beam energy, i.e. 15.4% w.r.t to the present 6.5 TeV. It is again important to distribute the gain to the different amplifiers to avoid saturation effects. It should be noted that the kick strength not only depends on energy but also on the beta function at the kicker locations, which must be considered when investigating ATS optics. The effectively reduced kick strength at 7.5 TeV effectively reduces the maximum excursion from which the ADT can damp within the desired 100 turns to about 1 mm.

7.2 Vacuum

From the vacuum side there should be no limitation to run the machine at 7.5 TeV. The main difference compared to the present operation at 6.5 TeV would be an increased critical energy of the synchrotron radiation (SR) generated in the dipoles, together with an increased photon flux.

The SR critical energy would go from the present 35.1 to 53.90 eV, and the linear photon flux density from 4.23 10^{16} to 5.62 10^{16} ph/s/m, at a beam current of 584 mA. The linear photon flux density would therefore be increased by 32.9%.

This increased SR flux would correspondingly generate more photoelectrons which could seed the e-cloud effect, but this is still believed to be manageable with current e-cloud mitigation measures (bunch pattern filling scheme and dedicated scrubbing runs).

The increased SR photon flux would also correspondingly generate a higher gas load, but this is not considered to be a problem, since there is a margin on the residual gas density with respect to the quench limit due to nuclear proton scattering on the residual gas molecules.

Figure 13 shows the photon flux spectra at 2.5, 3, 3.5, 4.0, 6.5, 7.0, and 7.5 TeV, for SR photons above 4 eV. The table indicates the linear SR photon density and the corresponding beam energy, at 584 mA beam current.

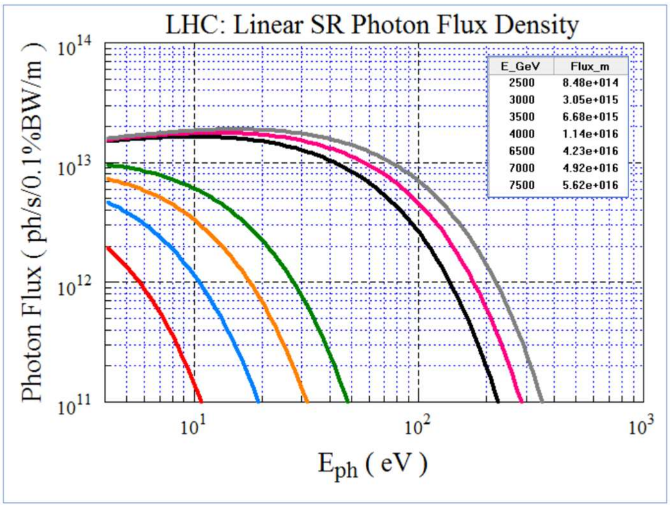


Figure 13: The linear Synchrotron Radiation Flux Density i.e. photons per 0.1% bandwidth for different proton beam energies. The table insert shows the linear SR photon density for the different proton beam energies for one meter long dipole.

7.3 Cryogenics

The below statement is made assuming that the ultimate run will be performed only after the LHC cryogenic infrastructure upgrade for the HL-LHC. The beam parameters considered for the analysis are presented in Table 8.

Regarding operation at 7.5 TeV the cryogenic refrigeration is reviewed at two levels: the local cooling capacity for individual devices and global capacity supplied by allocated cryogenic plant to an entire sector. Additionally, the analysis is split into two parts, for existing LHC cryogenic plants with associated equipment and new HL-LHC equipment.

The analysis was done using available operation data from selected LHC reference fill #6675.

Table 8: LHC upgraded beam parameters for 25 ns bunch spacing.

Parameter	Unit	Nominal	HL-LHC Baseline
Beam energy, E	[TeV]	7	7
Bunch population	[protons/bunch]	$1.15\ 10^{11}$	$2.2\ 10^{11}$
Number of bunches per beam, n_b	[-]	2808	2760
Luminosity, L	[$cm^{-2}s^{-2}$]	$1\ 10^{34}$	$5\ 10^{34}$
Bunch length	[ns]	1	1

7.3.1 Non-upgraded part of the LHC running with HL-LHC beams

Local cooling loops approach

Resistive heating:

The operation at 7.5 TeV will produce a substantial increase of the resistive heating affecting the 1.9 K and 4.5 K cooling loops in the arc and LSS sections respectively. This increase will require about 16% more refrigeration power in comparison with the 7 TeV runs (and about 35% more than at 6.5 TeV). All local cooling loops in the arc sections as well as installed power of 1.8 K pumping units can provide enough capacity for run at 7.5 TeV. Concerning the LSS equipment, a dedicated review of the local limitations must be performed including an update of the strategy on the cryogenic supply valves upgrade in order to allow the run at ultimate energy (only identified limiting valves could be upgraded, there is no need for a global replacement of all cryogenic valves in LSS).

Secondaries and ITs:

Heating from secondaries, compensated by means of the 1.9 K cooling in the IT, will increase by about 7 % in comparison with the 7 TeV runs (and about 15 % with respect to 6.5 TeV). The repaired bayonet heat exchangers of the current LHC triplet magnets are able to compensate only for 306 W (270 W of dynamic heat load), limiting the peak luminosity to less than 2 10^{34} $cm^{-2}s^{-1}$. However, the earliest implementation for operation at 7.5TeV is foreseen for LHC Run5 [3], after the HL-LHC upgrade and the replacement of the current triplet magnets. The new triplet magnets should not have the above mentioned limitation in the heat exchangers.

Beam gas scattering:

The beam gas scattering will increase linearly with the beam intensity. The related heat load generation will be deposited mainly on 1.9 K cooling loops. Considering HL-LHC beam intensity as presented in Table 8 and thermal measurements performed during Run2, the heat generation will increase in average per sector by about 50 W with respect to fill #6675, what can be fully compensated by the local cooling loops.

Global limitations

Considering the above mentioned increase of the heat load and the HL-LHC cryogenic and related upgrades at P1 and P5, the capacity required from the 1.8 K pumping unit will stay at a similar level as today. By consequence, the required 1.8 K pumping flow shall stay in range of 110 g/s per two sectors which is compatible with the present operating scenario of using one pumping unit for two LHC sectors. In this situation, the guaranteed capacity buffer for compensation of the beam screen heat load will be conserved as today at the level of 160 W/half-cell. It is strongly recommended to keep this operation scenario as long as possible for any applied beam parameters. This recommendation is explained by the savings in cryogenic capacity. The production run of the second 1.8 K pumping unit within the same cryogenic island costs overall cryogenic capacity and results in the reduction of margins for the beam screen heat load by about 30 W/half-cell.

7.3.2 HL-LHC cryogenic equipment capacity (P1 and P5)

The capacity of new cryogenic infrastructure at P1 and P5 is designed considering beam parameters given in Table 8 with 7.5 10^{34} cm^{-2} s^{-1} as ultimate luminosity. This approach concerns both, local refrigeration capacities of installed equipment in LSS and global cryoplant refrigeration power.

Considering the above design approach, the HiLumi cryogenic infrastructure should be able to cope with the heat load generated during an ultimate run at 7.5 TeV with standard HL-LHC beam parameters (L=5 10^{34} cm^{-2} s^{-1}).

7.4 General Infrastructure

The increase of energy of the LHC to 7.5 TeV has effect on the thermal load to be cooled by the water cooling and ventilation system. It is estimated that this effect is given by the new operational conditions of the power converters that will release around 14% more charge from DC cables and power converters. On the opposite, the new working conditions for cryogenic system will not require higher cooling power.

Therefore, the increase of energy has no impact on the ventilation system of the tunnel since present thermal load represents an increase of temperature by 3 °C in average between supply and extraction and the future value shall not modify these situation in a sensible way.

The cooling system for each sector is impacted by a higher request for cooling power. At present, the cooling stations locate in UW caverns are running at a lower exchanged power with respect to the design values but, on most cases, at a higher flow rate. This means that any additional cooling load on these circuits will not require a modification of the station only if the overall flow rate is kept constant and, therefore, the temperature difference on all equipment (presently between 1.7 and 4 °K according to the sector) can be increased close to the design value of 10 °K. Where this is not possible a modification of the station, mainly pumps and heat exchanger, shall be required. The only sectors where this problem is not supposed to appear are S2-3 and S5-6.

On the primary circuit of cooling towers, the flow rates are generally corresponding to the maximum allowed by the existing pumps. A small increase of the thermal load should not represent a limitation in the operation of the plants and, ideally, an increase of the temperature difference should be looked for.

7.5 Beam Instrumentation

An increase in the machine energy to 7.5 TeV is not expected to have an impact on the majority of beam instrumentation systems. The only major change is the reduction in BLM thresholds, the impact of which is covered in section 6.12. There is also the influence of a reduction in the setup beam flag (SBF) intensity on its determination by the DCCT system. Due to one of the 4 DCBCT acquisition channels exhibiting a factor 3 times higher noise level, this might lead to additional glitches of the SBF during cycles with probe beam. The wire scanner intensity limit at top energy will be further reduced to below 1.5×10^{12} protons, i.e. limited to less than 12 nominal bunches, due to the reduced quench limit of the downstream magnets.

No other issues are expected to arise. The BPM, BCT, tune and instability monitoring systems are all insensitive to beam energy and will continue to provide nominal performance. For the synchrotron light diagnostics, while the synchrotron radiation power emitted by the beam in the D3 magnet will increase by ~30% in going from 7 TeV to 7.5 TeV, the increase in photon flux in the 200-900 nm wavelength range of interest is negligible (the additional power coming from emission at lower wavelengths). This means that there will be little effect on the longitudinal density, abort gap and synchrotron light monitoring systems. For the undulator the peak emission wavelength shifts from 2.5nm (7TeV) to 2.2nm depositing ~30 mW of mainly X-ray power (~30% more than at 7 TeV) on the extraction mirror. While this power is not expected to result in a heating issue, the recommendation, as it is currently for running at 6.5TeV, would be to ramp down the undulator current during the energy ramp.

The reduction in the transverse beam size due to the increase in energy and the enhanced emittance decrease during a fill as a result of increased radiation damping will lead to a lower overall resolution for emittance measurements using the synchrotron light monitor, which is already operating close to the diffraction limit at 6.5 TeV.

This reduction in transverse beam size will also lead to a reduced noise power in the betatron sidebands of the Schottky system, making it even more difficult to measure chromaticity with this system at top energy.

Table 9: Main Dipole Circuit Current settings for different Beam energies

12.748kA	8.93T	7.5TeV	
12.840kA	9T	7.55TeV	Ultimate Energy
13.000kA	9.11T	7.64TeV	

7.6 Magnet Powering

From the power converter side, there is no limitation to operate the machine at 7.5 TeV. All LHC power converters were designed and tested individually during their acceptance tests at their ultimate current, 13kA for the main converters, corresponding to the LHC beam energy of 7.64 TeV (corresponding to 9.11T magnetic field in the main dipole magnets).

The losses in the air and water circuits will increase with an operation at ultimate beam energy. Table 9 shows the main dipole circuit current settings for different beam energies. However, the cooling systems was also designed for the ultimate LHC beam energy (12840A for the main dipole corresponding to a dipole magnetic field of 9T). During the first LHC hardware commissioning campaign in 2008, all LHC power converters were tested together in their final location and environment in short-circuit (without the superconducting magnets) at ultimate energy current during 8 hours and 24 hours for an equivalent energy of 7TeV without show stopper. Only an issue with the powering of RB.A78 was reported at ultimate energy at the level of the converter (transformer over-temperature) . This issue can/will be solved during Long Shutdown 2.

The power converter availability shouldn’t be impacted by this current increase. Many power converters were consolidated during LS1 to improve their reliability. From statistics, the current increase from 4 TeV (2012) to 6.5 TeV did not produce a sizeable effect on the failure rate. Furthermore, most of the failures come from corrector magnets not operated at full current.

The converters powering the main quadrupoles, the IPD/IPQ and the Triplets magnets are made of sub-converters used also in the ATLAS experiment at higher current since the beginning of the LHC operation, corresponding to 7.64 TeV LHC beam energy without any issues.

The magnet quench campaign will generate more stress on the power converters as it has to stop brutally at full current and transfer the current to the thyristor crow bar system. Up to now, this process always performed very well and no issue appeared.

The sensitivity of the power converters to electrical perturbations could be slightly higher as the margins decrease with slightly higher consumption.

7.7 Orbit Correctability and Interaction Point Steering

The entire LHC machine is re-aligned during each LS both radially and vertically. For the LSS and certain arc section known to exhibit faster or systematic ground movements (e.g. close to the middle of S78), the alignment is usually verified during each YETS, if required those sections are re-aligned around a smooth curve. The smooth curve itself evolves slowly with time.

The flat orbit rms, i.e. without any of the crossing angle or separation bumps, is typically between 0.3 and 0.35 mm. To achieve such a target, the typical rms orbit corrector strength is 10-12 μrad, with a few isolated deflections in the horizontal plane of up to 55 μrad. This is to be compared with the maximum deflection of the 60 A arc corrector of around 75 μrad at 7.5 TeV. From one year to the next the corrector strength evolves at the level of few mircrorads in the arcs. With such a good stability it is possible to inject the first beams of a year with the last settings of the previous year and immediately obtain a circulating beam. Based on the Run 1 and Run 2 orbit and alignment quality no problems are expected for flat orbit corrections at 7.5 TeV. In the arcs it is also possible to operate with some missing orbit correctors (circuit faults) provided they are isolated, i.e. not in consecutive cells.

In the LSS the corrector strength is usually moderate and poses no specific problems for operation at 7.5 TeV. The triplet area of IP8 is the only region where during Run 2 large strengths were required consistently on some MCBX magnets in the horizontal plane, the problem is exacerbated by the large crossing angle of -250 μrad at the IP. The largest MCBX currents approached the currently recommended limit of 400 A for combined horizontal and vertical corrector strength which is significantly below the design current of 550 A. This problem could however be solved by a radial realignment of the IR8 triplet magnets once the triplet support and remote alignment are consolidated after LS2.

Due to a steady upward movement of LSS5 with respect to the CMS detector of up to 0.2 mm per year, a vertical beam IP shift of -1.8 mm had to be implemented at IP5 in order to centre the beam spot inside the CMS pixel detector. Such a shift requires a significant fraction of the orbit corrector strength in LSS5 and is not sustainable in the longer term. With the 2018 optics (30/25 cm β^* ATS) and bump shape the maximum shift that could be applied at 7.5 TeV is around -2.5 mm. To ensure smooth operation and avoid performance issues due to such constraints it is therefore essential to maintain the beam line alignments with respect to the detectors within a range of ±1 mm. This might imply more frequent and extended alignment exercises of the LSS elements during the regular Year End Technical Stops and might imply slightly longer YETS and thus slightly shorter running periods for the physics program.

7.8 Beam-Induced Heat loads

Figures 14 and 15 show the simulated beam induced heat load on the beam screens of the LHC arcs for the nominal 25 ns bunch pattern at 7.5 TeV as a function of the bunch population for a Secondary Electron Yield (SEY) of 1.25 and 1.35, respectively. Details about the simulation model can be found in [30]. The contributions to the heat deposition given by the impedance of the beam screen, the synchrotron radiation and the electron cloud in the different magnets have been displayed separately in different colours. The chosen SEY values of 1.25 and 1.35 correspond to the estimated average values of SEY in the best (S34) and worst (S12) sectors, based on heat load measurements taken in August 2017 (averaged over the entire arc) [31].

The expected contributions from impedance and synchrotron radiation are summarized for the beam parameters in the first two rows of Table 10 for energies of 6.5, 7.0 and 7.5 TeV when extrapolated to the HL-LHC beam parameters assumed in Table 14. At 7.5 TeV, this alone accounts for 50% of the cooling capacity available on the beam screens, which was estimated to amount to 160 W per half-cell, corresponding to 1.5 W/m/beam.

Since the impedance contribution is affected by the change in beam energy only because the resistivity of the beam screen in the main magnets increases slightly due to the stronger magnetic field, the effect is almost negligible (below 1 W per half-cell), as shown in Table 10.

A more significant increase (about 80%) is observed in the contribution from the synchrotron radiation since the emitted power scales with the fourth power of the energy, but still this contribution would amount to only 28% of the cooling capacity of 160 W per half-cell.

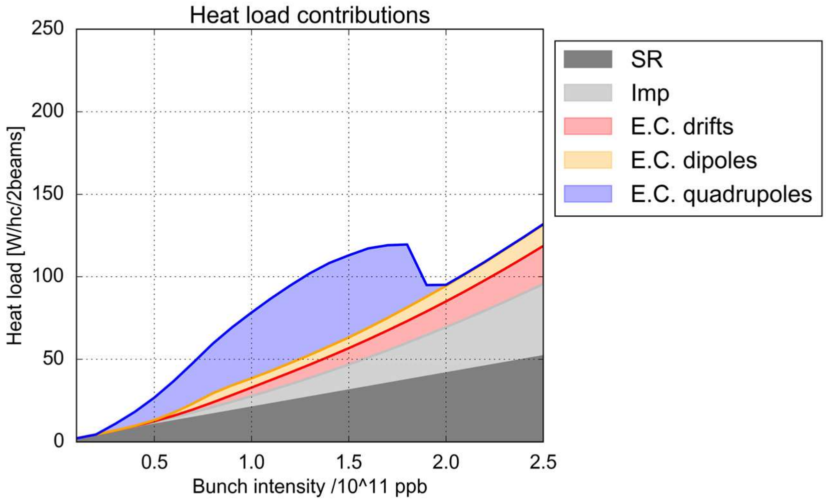


Figure 14: Simulated heat load in the LHC arcs for 25 ns bunch spacing and 7.5 TeV as a function of the bunch intensity for an SEY of 1.25. The heat load values are in W per half-cell for two beams. The different contributions are highlighted in different colours, as labelled.

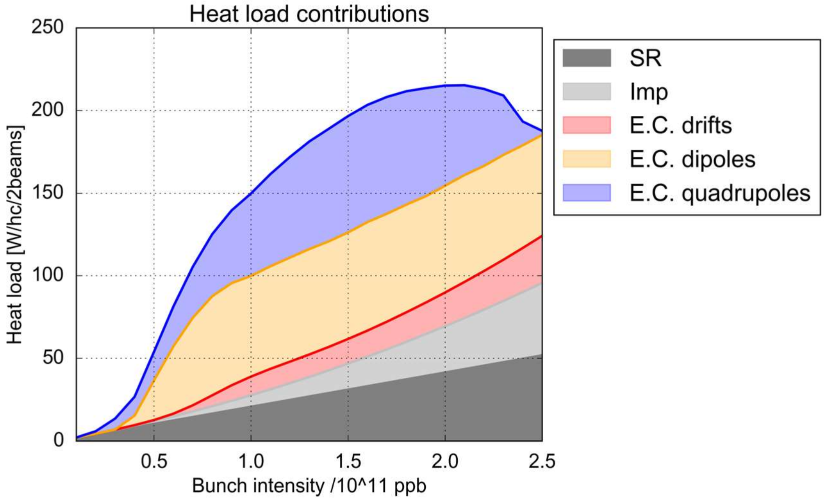


Figure 15: Simulated heat load in the LHC arcs for 25 ns bunch spacing and 7.5 TeV as a function of the bunch intensity for an SEY of 1.35. The heat load values are in W per half-cell for two beams. The different contributions are highlighted in different colours, as labelled.

The heat load on the beam screens during physics production in Run 2 (2015-2017) has been dominated by the electron cloud contribution. In 2015 this contribution was bringing the total heat load in some of the LHC sectors to the limit of the available cryogenic capacity, thus limiting the total number of bunches that could be brought into collisions. Later on, the intensity could be gradually increased thanks to beam induced scrubbing, reaching 2556 bunches in collision in 2017. During Run 2, large differences have been observed in the heat loads measured on the beam screens of the eight LHC arcs, which translate in the different SEY values considered in Figs. 14 and 15. The root cause of these differences in surface properties is still unknown and is presently under investigation [32][33].

From Table 10, we can see that this difference in SEY has a significant impact on the achievable performance. For the low-load sectors, the expected heat loads are comparable with the available cooling capacity of 160 W per half-cell for all the considered beam energies up to 7.5 TeV.

Instead, for the high-load sectors the expected heat loads significantly exceed the available cooling capacity already for the nominal beam energy of 7.0 TeV. In case the SEY cannot be further reduced for these sectors, the heat load induced by e-cloud will have to be mitigated using special filling schemes (e.g. 8b+4e or mixed schemes), with a loss of performance in the order of 15% [34]. Table 10 shows how this limitation exhibits a relatively weak dependence on the beam energy. In particular, for the high-load sectors the expected heat-load increase when increasing the energy from 7 TeV to 7.5 TeV is in the order of 7%.

Table 10: Heat load expected (in W/half-cell) on the arc beam screens at collision energy from the different heating mechanisms. Comparison between 6.5, 7.0 and 7.5 TeV assuming the HL-LHC beam parameters

HL-LHC (2.2e11)	6.5 TeV	7 TeV	7.5 TeV
Impedance	33	34	34
Synchr. Rad.	26	35	45
E-cloud SEY=1.25/1.35	22/128	26/131	30/134
Total	81/187	95/200	110/214

7.9 Beam stability

From impedance point of view the most critical point in the LHC cycle is at top energy before the beams are brought into collision. Here, the impedance of LHC is dominated by the resistive wall contribution of its collimation system (mostly by the primary and secondary collimators in IR7) and ~300 A in the Landau Octupoles are required to stabilize the HL-LHC beam in the most challenging, ultimate OP scenario [35][36][37], with the other sources of impedance, including the crab cavities, having a negligible impact.

Assuming the same collimator settings in mm as for the operation at 7 TeV (see Table 6 second column) the total impedance of the machine remains unchanged as we go from 7 TeV to 7.5 TeV. The impedance model is presented in Fig. 16 and it has been created using the IW2D code [38][39] based on the up-to-date HLLHCV1.3 optics [7] and includes the beam screen, collimators, crab cavities, and other contributors. Particular details of the HL-LHC impedance model can be found in [40].

From the ring impedance model one can estimate the impact of the higher energy on the Landau Octupole current required to stabilize the beam coupled-bunch modes with the DELPHI Vlasov solver [38][41]. The simulation parameters are listed in Table 11. The considered beam parameters correspond to those listed in Table 14 with the exception of the beam emittance that has been taken conservatively to correspond to the emittance at injection of the BCMS beam.

For this analysis, the chromaticity has been scanned from 0 to +20 units and several values of resistive damper damping times have been studied: 50, 100, and 200 turns. The results do not vary significantly for the operational range of chromaticities between 10 and 15 for all damper gains, in agreement with the current operational experience at LHC and macroparticle simulations. If we consider the baseline scenario for HL-LHC collimator upgrade (primary collimators in Molybdenum-Graphite (MoGr) and secondaries Molybdenum-Graphite with 5 μm Molybdenum (Mo) coating) the threshold increases by □10% in both planes (see Fig. 17). The required operational margin of a factor 2 with respect to the Landau Octupole maximum current is therefore maintained also for 7.5 TeV operation. Based on the collimator settings in Table 6, the impedance remains the same as in HL-LHC. Thus, the rms tune spread required to stabilize the beam is also the same. The only difference is in the required octupole current that increases slightly due to the increase in the beam energy.

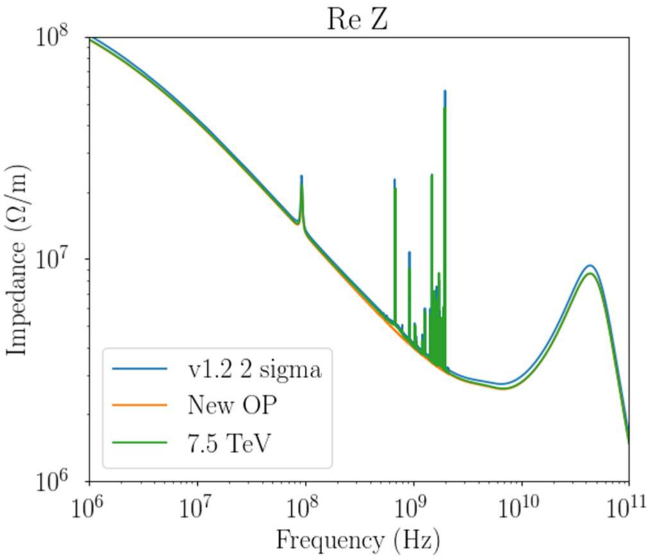


Figure 16: The total machine impedance for the Ultimate energy (green) is very close to the current operation scenario (yellow). The real part of impedance is plotted as a function of frequency for β^* = 41 cm. Present HL-LHC baseline coating of the collimators; 4 crab cavities of the DQW design per IP. The 'old' operational scenario with version 1.2 optics is also shown for reference (blue).

Table 11: Key parameters used to estimate the required Landau Octupole currents

Parameter	Value
Beam energy	7.5 TeV
OP scenario, β*	Ultimate, 41 cm
Beam intensity	2.3×10^{11} ppb
Number of bunches	2760
Norm. emittance	1.7 μm
Octupole polarity	Negative
Chromaticity Q'	10
Damper gain	0.01 turns^{-1}

The long-range beam-beam interactions will have an impact on the tune spread and consequently on the stabilization through Landau damping [42][43][44]. With the negative octupole polarity, preferred for its beneficial impact on the dynamic aperture [45][46], the destructive interplay with the effect of the long-range beam-beam interactions on the tune spread leads to a reduction of the stability margin during the squeeze. This effect remains acceptable in the HL-LHC baseline scenario, but in the ultimate scenario an improvement of the beam stability should be envisaged, for example by anticipating the increase of the arc β using the ATS optics in order to increase the effective strength of the octupoles already during the ramp as already proposed for the HL-LHC operation at nominal energy.

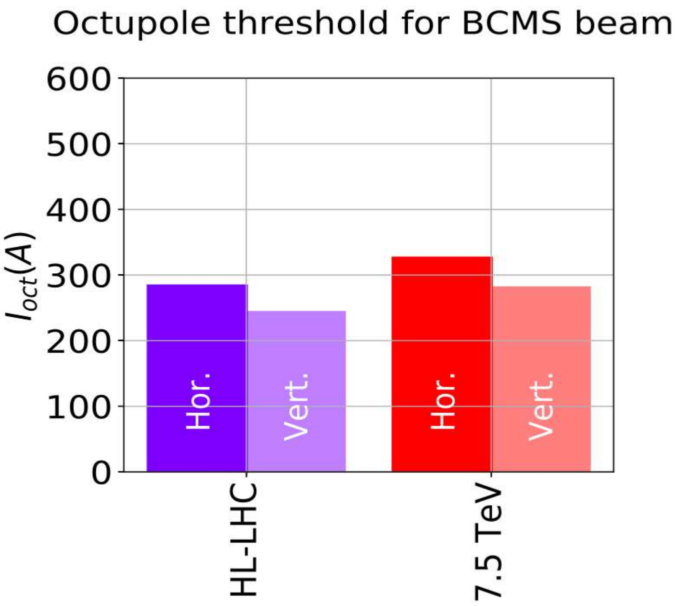


Figure 17: Landau Octupole current required to stabilize the beam in the horizontal and vertical planes for operation at 7 TeV (left) and 7.5 TeV (right). The worst-case scenario of the BCMS beam has been considered.

The effect of long-range beam-beam interactions during the squeeze would be reduced with the increased energy if the crossing angle remains constant, thus improving the stability margin. In case the normalized beam-beam long range separation is kept constant the conclusions obtained for the HL-LHC at the nominal energy remain valid at the ultimate energy.

Electron cloud (e-cloud) located in quadrupoles (these cover about 7% of the total machine circumference), is another potential driver of beam instabilities in the LHC [47]. Simulation studies have shown that, with the HL-LHC operational settings and beam parameters the integrated e-cloud central density stays well below the instability threshold, and thus e-cloud induced instabilities are not expected neither at injection nor at 7 TeV. The same is expected at higher energy due to the increased beam rigidity that further increases the electron cloud central density required to induce beam instabilities [48][49].

In summary no limitations are expected from beam stability due to impedance, beam-beam, and electron cloud effects when increasing the energy from 7 TeV to 7.5 TeV for the collimator configuration considered in Table 6 and the beam parameters indicated in Table 14.

7.10 Aperture and optics considerations at 7.5 TeV

Given the above mentioned limitation in the retraction of the TCDQ no significant reduction of the β* is possible and only a reduction of the crossing angle could be envisaged, therefore no aperture constraints are expected and indeed more margins should be available.

7.11 UFO effects

Estimating the impact of UFOs on operation is a particularly challenging task. The release mechanism of UFOs is at present not understood, there's therefore no possibility to reliably quantify the impact of the energy increase on the absolute UFO release rate. Nevertheless, based on experience, it is assumed that the latter will be dominated by the conditioning effects observed in operation (see Fig. 18), i.e. it will mainly depend if 7.5 TeV operation will be initiated in a year after a long shutdown (like in 2015) or throughout the run once some considerable conditioning already took place (like in 2016-2018). Here the assumption is made that the increase of energy per-se does not have a significant impact on the UFO dynamics but that implementing a beam energy increase before or right after LS3 will have a significant impact on the attainable machine efficiency.

A distinction has to be made for UFOs in the arcs and in the LSS. UFO rate estimates are based on the analysis of signals from BLMs. Significant statistics can only be gathered for the arcs, where the majority of BLMs are located. As a consequence, the following considerations only regard the arcs. For the LSS regions, the effect of localized UFOs can be mitigated with dedicated local corrections of BLM thresholds, as done on several occasions in 2015-2016 for BLMs installed on or close to TCTs, the Roman Pots or individually powered quadrupole magnets.

When increasing the beam energy from 6.5 to 7.5 TeV, the magnet quench levels will decrease between 60 and 75 % for typical UFO loss durations of 10^{-4}-10^{-3} seconds (see Section 3.7). This, combined with an increase of energy density in the coils per lost proton of about 30 % (as predicted by FLUKA simulations), leads to an increase in the number of UFOs which have the potential to induce a quench by a factor 5-13 (see Fig. 19).

7.12 BLM thresholds

Every BLM has individual beam abort thresholds for different integration times and discrete beam energy levels. In general, the threshold value of a certain BLM for a fixed integration time decreases as the beam energy increases. The decreasing trend depends on the underlying physical models and varies for different BLM families. The BLM system is already capable of handling thresholds up to a beam energy of 7.86 TeV, hence no system modification is needed for operation at 7.5 TeV. The threshold master tables however need to be extended to ultimate energy (presently they are only defined up to 7 TeV). This requires input from quench and damage level calculations and shower simulation studies. In addition, flattop correction (e.g. due to luminosity or collimation-induced losses) need to be adjusted to the new beam energy. Some empirical corrections might be necessary during operation, similar to the ones carried out in Run 2. This might also include UFO-related corrections in the straight sections as discussed in the previous section.

Considering the lower thresholds at ultimate energy, it is important to verify that the electronic noise of the BLM system, especially noise spikes, will not accidentally trigger unnecessary beam aborts. A previous analysis showed that the noise would remain below ~1% of the thresholds active at 7 TeV, which might increase to a few percent of the thresholds at 7.5 TeV. It is considered unlikely that such noise levels will trigger unnecessary beam dumps at 7.5 TeV, but checks need to be carried out with the eventual 7.5 threshold settings.

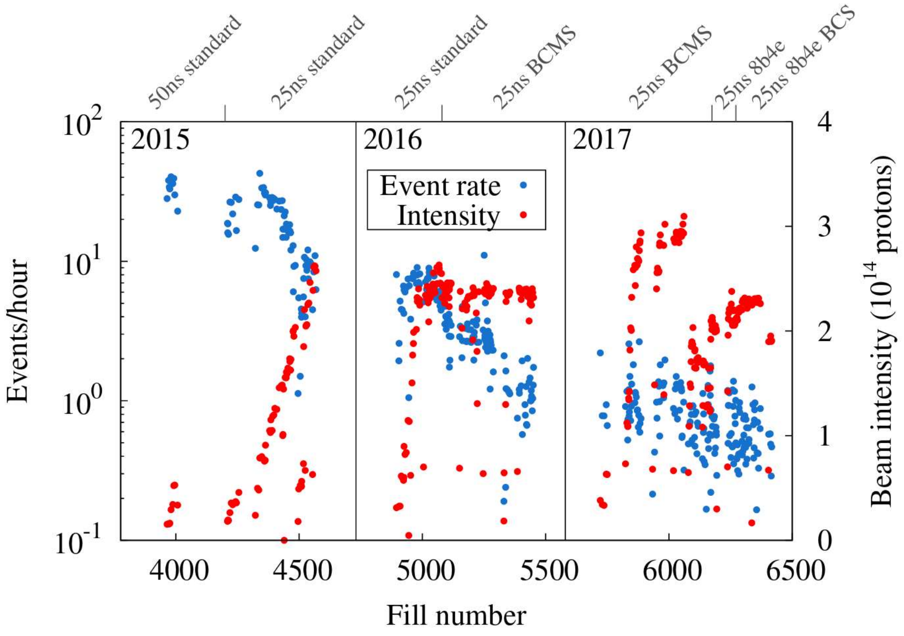


Figure 18: Evolution of the fill-by-fill arc UFO rate in stable beams from 2015 to 2017 (blue dots). The plot only considers fills lasting for more than 1 hour and with more than 100 bunches per beam. The red dots show the beam intensity at the beginning of each fill.

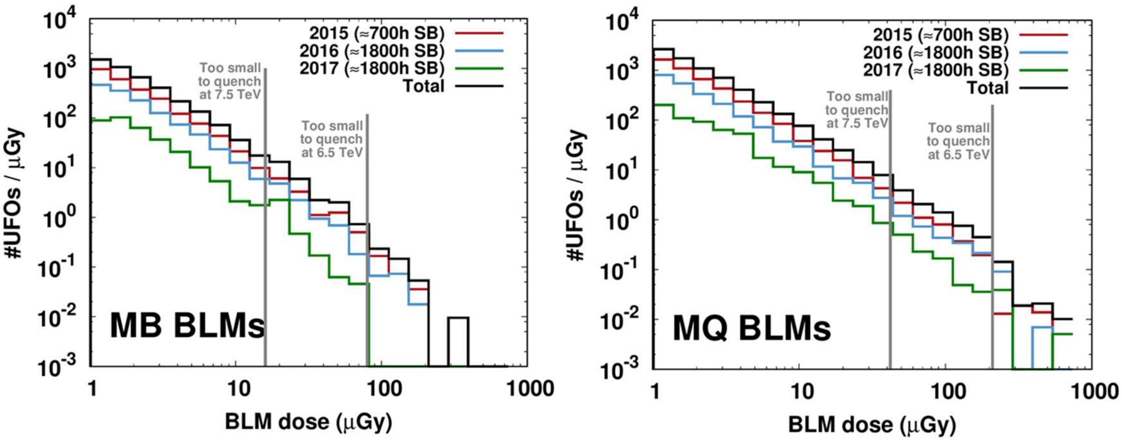


Figure 19: BLM ‘size’ distribution for dipole BLMs (left) and quadrupole BLMs (right).

7.13 Machine Protection related aspects

There is no fundamental limitation within the LHC machine protection system to operate at energies beyond the nominal value of 7 TeV. Several systems are however using the beam energy for the calculation of protection related parameters or sanity checks and will have to be modified and validated in order to assure reliable protection up to the ultimate beam energy of 7.5 TeV. While systems like the beam interlock system (BIS), powering interlock system (PIC) and quench detection system

(QDS) are independent to the beam energy, the following machine protection (or protection related) systems will require modifications or validation:

- LHC timing system: Validation of the reliable transmission of energy values up to 7.5 TeV;
- Safe Machine Parameter System (SMP): The logic equations calculating the setup beam flags as well as the flags for stable beams, movable devices allowed in, etc. have to be modified in order to be calculated correctly for (and up to) a flat top energy of 7.5 TeV;
- Beam Loss Monitoring system (BLM): It has to be verified that a beam energy window is available to accommodate energies up to 7.5 TeV, and BLM thresholds have to be defined and implemented accordingly for the ultimate beam energy (see as well chapter 7.2 for quench levels at higher energies);
- Beam Energy Tracking System (BETS) for extraction elements: Extraction elements such as the TCDQ, MKD and MKBs are using the energy value derived from 4 of the LHC main dipole circuits for tracking of the correct position or charging voltage during the extraction. The correct generation and transmission of and possible extensions of BETS tables has to be validated;
- LHC collimation system: The collimator functions and interlock limits (in particular the energy and beta* interlocks) need to be set-up and validated for energies up to 7.5 TeV if the absolute collimator positions in mm cannot be kept;

Operation at 7.5 TeV further reduces in many cases the operational margins for safe operation of the equipment, and while the contribution of downtime of the MPS systems themselves is not expected to increase, a detrimental impact on overall availability is to be expected when operating the machine at energies above 7 TeV (see Section 7 for more details).

As an additional measure, the most critical failure cases affected by the increased beam energy (erratic triggering of MKB/D, dilution kicker failure, asynchronous dump cases and powering failures in D1 magnets) should be re-verified in view of the increased beam energy and potential optics changes (see as well Section 4).

7.14 Radiation protection aspects

Assuming the same luminosity and losses for operation at ultimate beam energy, an energy increase from 7 to 7.5 TeV increases the prompt and residual radiation levels by less than 10%. This is well within margins of Radiation Protection quantity estimates for HL-LHC.

An indirect impact may arise from particle losses that scale stronger than linear with beam energy, including the probability of abnormal beam losses. Normal losses will mainly affect the activation levels around the machine. Related risks to personnel can be mitigated by strict implementation of optimisation measures during design and operation. Consequences of accidents (e.g., dose to personnel due to full loss of a stored beam) are comparable to that at HL-LHC and, consequently, are already limited by the same safety measures (e.g., shielding, access safety system, etc.).

8 Machine Efficiency and Availability

8.1 Machine Efficiency degradation due to the cryogenic system

Excessive heat loads (mainly driven by e-cloud [depending on the SEY]) potentially represent a global limitation for operation with higher beam current both at 7 and 7.5 TeV. It is assumed that operation will be carried out in the allowed parameter space imposed by cryogenic constraints (currently dominated by the limitation of heat-exchangers in the inner triplet and due to e-cloud in the arcs). Based on what is reported in Section 6.3, it is assumed that the cryogenic configuration will be the same as today's LHC, i.e. featuring 4 cold compressor units. The failure rate of cold compressor units based on 2016 and 2017 statistics is estimated to be ≤ 1 failure/year/cold compressor.

In 2017, a further optimization of the beam screen cryogenic feed-forward system that allows compensating for dynamic heat loads, specifically during injection and dump phases, was deployed. This update allows treating beam screen circuits individually, yielding an improved availability.

The higher energy stored in the beams and in the magnets at 7.5 TeV implies longer quench recoveries. Based on experience from the 2016 training campaign, between 25 and 65 % longer quench recovery times can be expected when going from 6.5 to 7.5 TeV operation. This estimate highly depends on the number of secondary quenches. Investing into a full understanding of the mechanisms triggering these secondary quenches and adopting appropriate mitigation measures via the QPS ('sunglasses' settings) should allow to reduce the number of secondary quenches at high current due to electro-magnetic coupling by up to 60%. As an estimate, 13 h are assumed for an average quench recovery at 7.5 TeV.

8.2 Machine Efficiency degradation due to UFOs

Estimating the impact of UFOs on operation is a particularly challenging task. Since the release mechanism of UFOs is at present not understood and there's no possibility to reliably quantify the impact of the energy increase on the absolute UFO release rate. Nevertheless, based on experience, it is assumed that the latter will be dominated by the conditioning effects observed in operation, i.e. it will mainly depend if 7.5 TeV operation will be initiated in a year after a long shutdown (like in 2015) or throughout the run once some considerable conditioning already took place (like in 2016 and 2017). Here the assumption is made that the increase of energy per-sector does not have a significant impact on the UFO dynamics but that implementing a beam energy increase before or right after LS3 will have a significant impact on the attainable machine efficiency.

When increasing the beam energy from 6.5 to 7.5 TeV, the magnet quench levels will decrease between 60 and 75%. This, combined with an increase of energy deposition in the coils per lost proton of about 30%, leads to an increase in the number of UFOs which have the potential to induce a quench by a factor 5-13. The UFO impact is discussed in detail in Section 6.11.

8.3 Machine Efficiency degradation due to Magnet Quenches

The number of flat-top quenches in operation at 7.5 TeV will depend on the margins achieved during the magnet training campaign. It is assumed that the magnets can be trained to 7.5 TeV with a margin of 150 A, namely to 12850 A. It is nevertheless difficult to state whether flat-top quenches will be a limitation for operation at 7.5 TeV. Better insights will only be possible after the training of one or more sectors to 7 TeV at the end of 2018.

When performing an availability assessment, also risks associated to the consequences of quench events should be taken into account. Shorts-to-ground can develop both in the warm part (DC warm cables, power converters, detection electronics) and cold part (busbar routing, instrumentation wires, coils, diode boxes) of a magnet circuit. The probability of developing a short-to-ground has been estimated based on the present experience with the machine. Currently, two shorts-to-ground over 252 quench events have been observed due to debris in the diode box. The probability of these events is considered negligible following the consolidations foreseen in LS2. Two more shorts-to-ground have been observed in the coils ('inter-turn short'), one in a machine dipole magnet (A31L2) and one in SM18. Given the higher field associated to operation at 7.5 TeV, these events are considered more likely to appear.

Another factor that should be considered is the potential degradation of quench heaters due to the possible higher number of discharges following quenches. A detailed analysis of quench heater faults can be found in [50]. A total of 10 faults has been observed over 7850 discharges for the main dipoles and 2 faults over 2500 discharges for IPDs and IPQs (none in the other circuits). The faults were however mainly observed following thermal cycles and hence not directly related to an increase of beam energy.

8.4 Machine Efficiency degradation due to Power converters

The magnet current increase from 4 TeV (2012) to 6.5 TeV (2015) did not produce a sizeable effect on the failure rate of the power converters (considerations regarding radiation-induced failures are treated in section 7.6). In fact, statistics show that most failures are observed on corrector magnets, which are not operated at full current, suggesting that the failure rate does not scale linearly with the energy. All power converters were already tested above ultimate parameters, including the related infrastructure. Based on these elements, no major impact on the power converter failure rate is expected when increasing the beam energy to 7.5 TeV, thanks to available margins.

8.5 Machine Efficiency degradation due to the Beam dumping system

Important modifications to MKB and MKD generators will be deployed in LS2, yielding a reduction of the operating voltage at 7.5 TeV to under the corresponding level at 6.9 TeV for the original LHC design. Given the strong dependence of the failure rate on the operating voltage of the generators, major improvements are expected in the reliability of the system. The targets for the LBDS remain the ones from the LHC design report, i.e. in average not more than one MKD erratic per beam per year (asynchronous dump) and one MKB erratic per beam per year (synchronous dump).

In case of an erratic MKB trigger several magnets will quench, implying long recovery times. It is assumed that 2-3 days will be necessary to recover from such an event, including quench recovery, event analysis, generator exchange and system revalidation with and without beam.

8.6 Machine Efficiency degradation due to Radiation to electronics

The expected increase of High Energy Hadron (HEH) fluence from 6.5 to 7.5 TeV is not significant, therefore no sizeable impact on the number of SEU-dumps is expected. As the energy increase will occur during the HL-LHC era, all R2E mitigations for HL-LHC will already be in place (including for example the deployment of the rad-tolerant power converter design in exposed areas), setting the target of R2E-induced dumps to 0.1 dumps/fb^{-1}.

8.7 Cycle duration

Operation at 7.5 TeV will require longer times for performing magnet ramps (up and down). The ramp-down in particular will be determined by the inner triplets in points 2 and 8 for HL-LHC, as 2-quadrant power converters will be deployed for the triplets installed in points 1 and 5. Globally, it is assumed that the cycle duration will not be strongly impacted by the energy increase. The turnaround time will be still dominated by the injection time and the possible occurrence of faults, with an expected average of about 5 h (not including faults). The occurrence of more faults requiring pre-cycles (e.g. quenches) could potentially lead to a longer average turnaround (see paragraph 7.8).

8.8 Conclusions on Machine Efficiency for Operation at 7.5 TeV: impact on physics efficiency

Based on the experience with the 2016-2017 LHC run and the factors discussed in paragraphs 7.1 to 7.7, two scenarios were considered (‘conservative’ and ‘relaxed’) to assess the potential impact of operation at 7.5 TeV on the machine efficiency. In the conservative scenario the starting point are the 2016 fault distributions for all systems, as 2016 was affected by isolated long stops (major fault of 18 kV transformer, flooding in LHC Point 3, several faults in the injector complex), which have not been observed in 2017. For the relaxed scenario, the 2017 fault distributions are instead taken as reference. In addition to these basic fault distributions, failures specifically associated to the 7.5 TeV exploitation of the LHC are considered. The corresponding assumptions for the two scenarios are reported in Table 12. In the ‘conservative’ scenario, it is also assumed to have an increase of a factor 2 of the number of pre-cycles due to faults. In the ‘relaxed’ scenario, the corresponding increase is instead limited to a factor 1.5. These numbers were considered, as all failure modes in Table 12 require at least one pre-cycle to recover operating conditions. It has to be noted that there are big uncertainties associated to the assumed occurrence rate of items listed in Table 12, mainly related to the number of quenches, both flat-top and UFO-induced. Thus, the numbers considered in the ‘conservative’ scenario have to be interpreted as a maximum tolerable number of stops that would be accepted in a year of operation without reconsidering the running strategy. If, for example, the number of quenches would significantly exceed 25 (flat-top and beam-induced), then one could consider a training to higher currents or a reduction of the operating energy to mitigate risks associated to quench events.

Based on the presented assumptions, we conclude: a loss of availability of 5 - 10 % is estimated for the relaxed scenario due to operation at 7.5 TeV with respect to the corresponding estimate at 7 TeV (see Fig 20 and [1]).

Table 12: Assumptions for failure rates and recovery times for the availability assessment for 7.5 TeV LHC operation.

	Conservative		Relaxed	
System/ Failure Mode	Occurrence (1/year)	Downtime (Days)	Occurrence (1/year)	Downtime (Days)
MKD erratic	4	12	2	6
MKB erratic	4	4	2	2
Flat-top quench	10	5	3	1.5
UFO-induced quench	15	7.5	3	1.5
Cold-compressor failure	2	2	2	2

Note that the presented estimates focus on systems potentially impacted by the energy increase. For a detailed availability assessment one should in addition consider the impact of new HL-LHC systems, such as crab cavities, SC links, new cryoplants, etc.

9 Potential Performance Reach

We assume that the main operational parameters for the LHC operation at 7.5 TeV (minimum β*, crossing angle, etc.) are the same as at 7 TeV. A possible optimization can be made by profiting of the smaller physical emittance of the beam that can allow a reduction of the aperture of the collimators in mm and a reduction of the crossing angle with a corresponding reduction of the minimum β*. The increase in performance is nevertheless expected to be limited due to the operation in levelling mode. Both nominal and ultimate scenarios with luminosity levelling at 5×10^{34} cm^{-2}s^{-1} and 7.5×10^{34} cm^{-2}s^{-1}, respectively, are considered. The main performance parameters are summarized in Table 15 in the assumption that the SEY in all sectors can be reduced to 1.25 similarly to what is assumed for HL-LHC. The same inelastic (81 mb) and total (111 mb) cross-sections as those at 7 TeV are used for the performance estimates at 7.5 TeV as the variation in the cross-section between these two energies is expected to be at the percent level similarly to what expected for the variation between 6.5 and 7 TeV [51]. The minimum turn-around time is expected to increase as a result of the longer time required for the energy ramp and for ramping down the magnets at the end of a physics fill. The estimated times are summarized in Table 14 both for the nominal and ultimate scenarios. The total numbers are rounded to the next 5 mins. It must be noted that the ramp-down time is determined by the IR2/IR8 triplet circuits. A reduction by up to 15 minutes could be potentially achieved by an upgrade of the corresponding power converters. It has nevertheless to be considered that experience shows that the turnaround duration is dominated by inefficiencies in the injection process and faults, so as reported in paragraph 7.7 the average turnaround considered for integrated luminosity estimates is 5 h.

The RMS luminous region longitudinal size is reduced as a result of the reduction of the crabbing angle provided by the crab cavities at higher energy. As a result of that, the peak (and effective) pile-up densities are expected to increase. Figure 20 shows the evolution of several parameters along the fill for the nominal and ultimate scenarios; the corresponding expectations for 7 TeV are included for comparison.

For a final quantification of the performance reach at ultimate beam energy the two scenarios (conservative and relaxed) described in paragraph 7.8 are considered. In the conservative scenario at 7.5 TeV it also is assumed that a reduction of 7 % in the total number of bunches would be required to cope with increased heat loads in case of SEY = 1.35 with respect to operation at 7 TeV (see paragraph 6.8). Table 13 summarizes the resulting availability and luminosity production in the different scenarios at 7 TeV and 7.5 TeV.

Based on Table 13, one can conclude that the expected impact on availability of operation at 7.5 TeV with respect to operation at 7 TeV is in the order of 5-15 %, with a corresponding impact on the integrated luminosity production (considering the possibility of a required intensity reduction) of 5-30 %.

Table 13: Expected availability and integrated luminosity at 7 TeV and 7.5 TeV.

	7 TeV		7.5 TeV	
	Conservative	Relaxed	Conservative	Relaxed
Availability [%]	67	74	50	71
Integrated Luminosity [fb^{-1}]	278	297	188	282

Table 14: Expected minimum turn-around time for the operation at 7 and 7.5 TeV [34].

	HL-LHC nom	**HL-LHC ultim.**	**HL-LHC nom**	**HL-LHC ultim.**
Beam Energy [TeV]	7.0	7.0	7.5	7.5
Phase				
Ramp-down [min]	40	40	43	43
Pre-injection set-up [min]	15	15	15	15
Set-up with beam [min]	15	15	15	15
Nominal injection [min]	30	30	30	30
Prepare ramp [min]	5	5	5	5
Ramp & Squeeze [min]	25	25	27	27
Flat-top [min]	5	5	5	5
Squeeze [min]	0	5	0	5
Adjust/collide [min]	10	10	10	10
TOTAL [min]	145	150	150	155

Table 15: 7 TeV and 7.5 TeV HL-LHC parameters in collision.

Parameter	**HL-LHC nom**	**HL-LHC ultim.**	**HL-LHC nom**	**HL-LHC ultim.**
Beam energy in collision [TeV]	7.0	7.0	7.5	7.5
Particles per bunch, N [10^{11}]	2.2	2.2	2.2	2.2
Number of bunches per beam	2760	2760	2760	2760
Number of collisions in IP1 and IP5*	2748	2748	2748	2748
N_{tot} [10^{14}]	6.1	6.1	6.1	6.1
Beam current [A]	1.10	1.10	1.10	1.10
Crossing angle in IP1 and IP5 [μrad]	500	500	500	500
Min. Norm. long-range beam–beam sep [σ]	10.5	10.5	10.9	10.9
Minimum β^* [m]	0.15	0.15	0.15	0.15
ε_{v} [μm]	2.5	2.5	2.5	2.5
RF Voltage [MV]	16	16	16	16
ε_{L} [eVs]	3.03	3.03	23.03	3.03
R.M.S. energy spread (q-Gaussian) [10^{-4}]	1.29	1.29	1.29	1.29
R.M.S. bunch length (q-Gaussian) [cm]	7.61	7.61	7.61	7.61
IBS growth times (H,V,L) [h]	19.6, ∞, 29.9	19.6, ∞, 29.9	20.7, ∞, 33.7	20.7, ∞, 33.7
Radiation damping time (H,V,L) [h]	51.9, 51.9, 25.9	51.9, 51.9, 25.9	42.2, 42.2, 2	42.2, 42.2, 21.
Max. Total CC voltage [MV]	6.8	6.8	6.8	6.8
Max. crabbing angle [μrad]	190	190	177	177
Max. Piwinski parameter	2.66	2.66	2.76	2.76
Total reduction factor R_0 at min. β^* w/o CC	0.342	0.342	0.332	0.332
Total reduction factor R_1 at min. β^* w. CC	0.716	0.716	0.670	0.670
Beam–beam tune shift/IP w. CC [10^{-2}]	0.86	0.86	0.79	0.79
Peak luminosity L_{peak} w. CC[10^{34} cm^{-2} s^{-1}]	17.0	17.0	17.0	17.0
Levelled luminosity [10^{34} cm^{-2} s^{-1}]	5	7.5	5	7.5
Events/xing μ (with levelling and CC)	131	197	131	197
Peak pile-up density [events/mm]	1.30	1.95	1.40	2.09
Levelling time [h]	7.4	3.6	7.6	3.7
Optimum fill length for min. turn-around [h]	8.5	5.3	8.8	5.4
Number of collisions in IP2/IP8	2494/2572	2494/2572	2494/2572	2494/2572
Maximum # bunches per injection	288	288	288	288

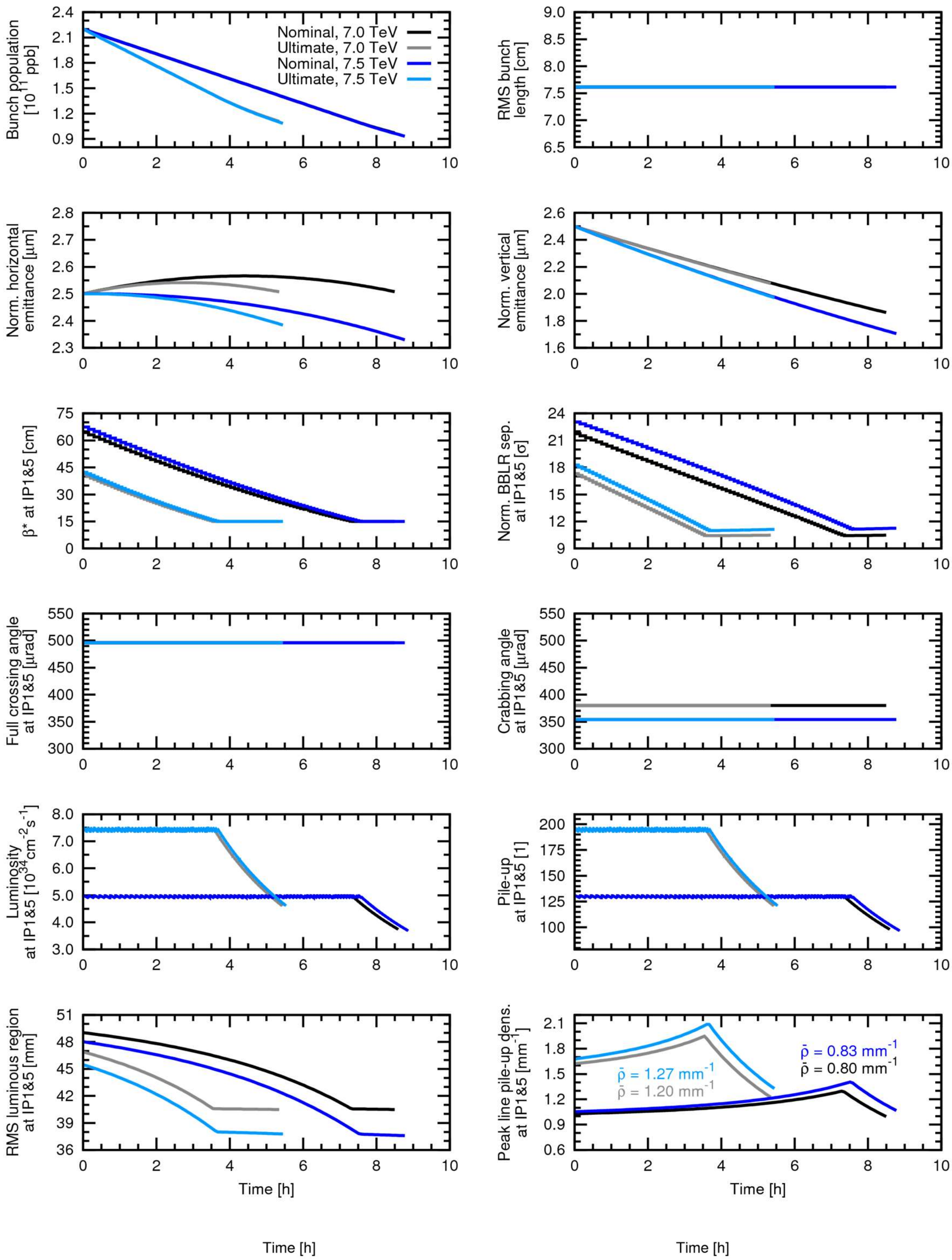


Figure 20: Fill evolution of the HL-LHC baseline for the nominal and ultimate scenarios at 7 TeV and 7.5 TeV.

10 On the Implications for Experiments of LHC operation at 7.5TeV per beam

The experiments observe the following points concerning the LHC operation with a beam energy of 7.5 TeV:

1. There are no significant technical showstoppers to running the experiments at 15 TeV.c.m. without significant modification, under the assumption that the beam backgrounds scale simply with beam energy, i.e. there is no deterioration in the performance of the collimation system, the dump kicker reliability, the aperture margins, etc, which could lead to anomalously large beam-related (not collision-related) backgrounds.
2. Changes would be needed to trigger parameters and an appropriately large simulated data set at the new c.m. energy would need to be generated, in the same way as will happen for the increase from 13 TeV to 14 TeV.
3. If a decision were made that LHC could or would run at 7.5 TeV energy per beam, after some date, then this may need to be taken into account in the optimisation of ATLAS and CMS forward physics detectors and their layout for post-LS3 operation, which is currently being discussed with a focus on low beta* operation. As usual, impedance studies will have to be repeated, based on expected LHC beam parameters.

From the experiment point of view, therefore, technical feasibility is no issue and it is more important first to establish the cost-benefit balance, from the physics output perspective, of moving to 7.5 TeV/beam at a certain point in the LHC lifecycle, compared with continuing the established performance at 7 TeV/beam.

The increase in parton luminosity resulting from increasing c.m. energy from 14 TeV to 15 TeV produces usefully large increases in some interesting standard model cross-sections [eg di-Higgs (~20%); ttH (~18%), ggH (12%); events containing B decays (~7.5%)], as well as a small improvement in high mass reach for the discovery of new particles. However, once the 14 TeV datasets become very large, the immediate gains in production rates from increasing the c.m. energy to 15 TeV have to be weighed against potential "lost" integrated luminosity at 14TeV resulting from the implementation time and any impact on peak luminosity or reliability. An additional factor is the technical overhead in combining results from data at different c.m. energies, in the same analysis cycle, if the higher energy dataset is comparatively small. Choosing an appropriate point in the analysis programme, shutdown/operation sequence and luminosity evolution is therefore important.

To get this timing right, it would be important to estimate:

- The time (additional to compulsory maintenance shutdowns) required for machine modifications, magnet training or other tune-up activities.
- The reliability, and luminosity, compared with 7 TeV, when running near the limit of sustainable beam energy.

One can then address the question of whether it is more beneficial for physics output (at a given future time) to move to 15 TeV c.m., or to continue to run at 14TeV.

11 Summary and Conclusion

For the purpose of this second report we assume that there are no limitations arising from magnet and circuit non-conformities for the operation at 7 TeV (as these have already been highlighted in the first report and need to be resolved before moving to an operation at 'ultimate' beam energy). Furthermore, we assume the same optics parameters for estimating the performance reach of the LHC for operation at ultimate energy as for the nominal HL-LHC [e.g. β^*, crossing angle and collimator settings]. The increase in beam energy wrt the nominal HL-LHC might provide room for a further optimization, but we consider this in the following as a second order iteration.

11.1 List of circuits that could potentially limit the energy reach of the LHC to below the ultimate beam energy of 7.5 TeV

All magnets (excluding the main dipoles) were tested to their layout ultimate current, but not all of them were tested to the current really needed when scaling the nominal LHC and HL-LHC optics to 7.5TeV. The triplet magnets in IR2 and IR8 fall into this category [see section 3.1.3] and Tables 1 and 2 list the additional currently known circuits that fall into this category. It is important to re-asses the ability of these circuits to reach the currents required for operation at 'ultimate' beam energy after the training campaign at the end of LHC Run 2. RD3.L4 is present in the tables because of the problem of long training indicated above in Section 3.1.4 and RD2.R8 showed in 2013 a cooling limitation at the level of the bus-bars.

The insertions at IP2 and IP8 will still deploy the nominal NbTi triplet magnets even after the startup of the HL-LHC operation in Run 4. The operational gradients of these magnets are set to a gradient that lies 10% to 15% below their technical nominal gradients in order to provide margins for the radiation dose coming from the experiments. Any configuration for operation at 'ultimate' beam energies needs to take these margins into account and needs to evaluate if eventual performance upgrades of the experiments in IR2 and IR8 require the introduction of further gradient margins [e.g. the luminosity upgrade of LHCb to a performance of 1-2 $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ which is currently under discussion].

Other low current circuits which might present a possible limitation for the operation at 7.5 TeV are the orbit correctors in the matching sections close to the experiments: some of them had reduced performance in the past, possibly due to inter-turn shorts, and will have to be strictly monitored in the future.

It is also worth summarising that some circuits are presently working at current values close to the ultimate. For example, the sextupole circuits, are routinely operated at 590 A, and are only limited by a hardware limitation on the quench detection system (the range of the DCCT), which prevents them from testing at larger currents.

It is vital to re-assess all these limitations and the performance reach of the new HL-LHC magnets after installation in the machine [e.g. the new 11T dipole magnets in the dispersion suppressor, the new triplet magnet and the new D1 and D2 separation and recombination dipoles and the new, refitted matching section quadrupole assemblies] prior to the planning of a machine operation at ultimate beam energy. Some of these issues will be addressed in a dedicated training campaign at the end of LHC Run 2, just before the start of LS2. But assessing the performance reach of the new HL-LHC components in the machine cannot be completed before the startup of the HL-LHC operation in Run 4 when the installation of all new HL-LHC hardware will have been completed.

In summary, the compatibility of the HL-LHC magnet circuits for operation at ultimate beam energy still needs to be demonstrated. However, only a handful of circuits could be identified that would require a powering current slightly above the 'ultimate' powering specification [of the order of 50A] when scaling the nominal LHC and HL-LHC optics settings to 7.5 TeV.

10.2 Potential limitations of the machine performance due to hardware limitations other than magnets

Apart from the above listed potential limitations of certain magnet circuits and leaving aside required outstanding simulation studies for operation at 7.5TeV [e.g. collimation simulations, BETS upgrade etc.], the operation at ultimate beam energy is not expected to be limited by other hardware components. The most critical hardware systems for operation at ultimate beam energy are the LHC Beam Dump System, the LHC Collimation system and the LHC cryogenic system.

The experience with the LHC beam dump system during the LHC Run 2 period identified several shortcomings in the system that need to be addressed / consolidated for operation with the HL-LHC beam parameters. When the HL-LHC upgrades are completed in LS3, the beam dump system will not pose any hard limit preventing operation at 7.5 TeV, nor will it severely limit the beam intensity. The beam intercepting devices all need to work for the HL-LHC beam parameters at 7.0 TeV, and the 7.5 TeV use-cases are basically the same. The known HV hold-off weaknesses in the MKD and MKBH generators are being addressed by the many improvements being made in LS2 to these sub-systems, including an increase of the main capacitance value to reduce the system voltage for a given current. The observed new failure mode of the dilution kicker system during Run2 needs to be addressed already for the nominal HL-LHC parameters and the limited dynamic range of the BETS has been identified as one area where an upgrade is needed, to allow testing of the system with the required margin. However, the identified effort for implementing these upgrades are relatively modest [at most 2 to 3 FTEs over 18 month] and could be implemented during LS3 [albeit not yet foreseen and budgeted in the HL-LHC baseline].

It is expected that the total energy deposited in the superconducting magnets for otherwise equivalent collimator settings increases approximately by 23% for operation at ultimate beam energy when compared to operation at nominal beam energy and with all other parameters being assumed to be identical [combination of higher cleaning inefficiency and higher beam energy]. The collimation system will undergo major upgrade stages in LS2 and LS3 that should be compatible with such an increase of the energy deposition for operation with protons. However, for ion operation this increase might impose non-negligible limitations to either the minimum acceptable beam lifetime or the acceptable beam intensities. But as the earliest potential operation at ultimate beam energy lies beyond the current planning for ion operation in the LHC [the ion operation is assumed to stop after Run 4] we do not consider this as a major limitation. In any case, any ion operation beyond Run 4 could in any case be conducted at lower beam energies than the proton beam operation. In any case, it is important to pursue the program of quench tests with beams at 6.5 TeV (Run 2) and later 7 TeV, to decrease the uncertainties on the extrapolation of quench limits to 7.5 TeV and the characterisation of the cables of the new 11 T dipole magnets, to assess with measurements the actual quench limit. Likewise, it is important to carry out a complete simulation campaign to predict the margins to quench for the design cases of losses at the IR7 collimators, i.e. losses lasting between 1 s and 10 s with 12 minutes beam life time and steady state losses with 1 h beam life time before implementing operation at ultimate beam energies.

The cryogenic load in the arcs of the LHC is dominated by the electron cloud effect and by synchrotron radiation. The LHC featured during Run2 a not yet fully understood difference in heat load between different sectors of the LHC. This difference is most likely attributed to contributions related to electron cloud activity and might indicate a limitation in the minimum attainable Second Emission Yield for electrons impacting on the beam screens. If this limitation cannot be mitigated with interventions during LS2 and LS3, the will limit the maximum acceptable beam current in the LHC. However, this would already impact the performance reach of the HL-LHC upgrade and increasing the beam energy from the nominal 7TeV to the ultimate value of 7.5TeV would impose an additional intensity reduction by ca. 7%.

In summary, no hardware limitations are expected for operation at ultimate beam energy apart from those that are already planned to be addressed with interventions during LS2 and LS3. In case the larger than anticipated heat load due to the electron cloud effect might impose an additional intensity reduction of up to 7% wrt the HL-LHC performance reach. The hardware compatibility of the new HL-LHC equipment is part of the HL-LHC upgrade plan. However, the

compatibility of the new HL-LHC equipment still needs to be demonstrated during hardware commissioning once the new hardware becomes available.

10.3 Potential limitations of the machine performance due to effects related to beam dynamics

The magnet field quality is assumed to show only a modest worsening at 7.5 TeV with respect to 7 TeV, at the level of 10% to 20%, and no performance limitation is expected for the whole ring and the majority of correctors' circuits should provide the needed functionality.

Depending on the exact cryogenic power available and on the minimum achievable SEY, a possible reduction of the number of bunches (by almost 10%) might be required in order to cope with the increased synchrotron radiation power at 7.5TeV beam energy. The levelled luminosity and integrated luminosity would then be reduced by the corresponding amount with respect to the 7 TeV operation.

Here the assumption is made that the increase of energy per-se does not have a significant impact on the UFO dynamics and the impedance related effects and on the related machine efficiency due to these effects, provided the beam energy increase is not implemented right after.

In summary, no beam dynamics limitations are expected for operation at ultimate beam energy apart from potential intensity limitations due to the increased synchrotron radiation power in case the secondary emission yield for the electron cloud effect cannot be conditioned to values below what has been observed in the LHC in the high heat load arcs during Run 2.

10.4 Expected magnet training time for operation at ultimate beam energy of 7.5 TeV

Approximately 500 training quenches are expected for training the main dipole magnet for operation at nominal beam energy after a thermal cycle, requiring between 1.5 and 2 month of magnet training. Approximately 800 to 1000 training quenches for training the main dipole magnets for operation at ultimate beam energy after a thermal cycle is expected in the most optimistic scenario, requiring approximately 4 month of magnet training, and more than 3600 training quenches are expected in a more pessimistic scenario, requiring up to one year of training.

Assuming an incremental magnet training, e.g. first training to 7TeV after LS3 and later to 7.5TeV without a thermal cycle [e.g. keeping the magnets cold during LS4 and LS5], one therefore expects an additional training time of at least 2 months and up to one year. For the performance reach estimation, we assume an additional incremental training time of 6 months, to be performed once. This estimate lies somewhere in the middle between the optimistic and pessimistic training time estimates. Assuming the operation at 'ultimate' beam energy will, at the earliest, be implemented after Run4, leaving 6 more years of operation after the transition to 'ultimate' beam energy, this translates to a loss of integrated luminosity of approximately 8% when looking at the last two LHC running periods [Run 5 and Run6]. Assuming further an annual integrated luminosity of 250fb^{-1} per year, this translates to an absolute loss of ca. 125fb^{-1}.

In summary, we assume an additional incremental training time of 6 month [that still has a significant error bar associated with it and could be as long as 12 month], to be performed once, resulting in an absolute loss of ca. 125fb^{-1} .

10.5 Performance estimate for operation at ultimate beam energy

As a starting point for the performance estimation we assume identical optics configurations and beam parameters for the comparison between operation at 7TeV and ultimate energy of 7.5TeV and assume the nominal HL-LHC parameters.

Based on experience from the 2016 training campaign, one expects between 25% and 65 % longer quench recovery times when comparing 6.5 and 7.5 TeV operation. As an estimate, 13 h are assumed for an average quench recovery at 7.5 TeV.

Focusing on the MB magnets, the energy margin at 7.5 TeV drops by more than half to below 50% of its value at 7 TeV in the ultra-fast regime of 1 ms perturbation time. This reduction is somewhat less pronounced, to approximately 60% to 75% of the 7 TeV value, in the fast perturbation range 0.1 ms to 1 ms typical of UFO's. Finally, for very slow perturbations, 1 s up to steady state regime, the reduction is only by 10 %.

Even if total loss rates at ultimate beam energy will remain comparable to those observed in Run II and assumed for HL-LHC, the performance will depend primarily on the increase of the inefficiency, the increase in deposited energy and on the scaling of quench margins with higher magnet current.

In Summary, combining the performance reductions due to the potential need of reduced beam intensity due to the cooling power limitation and electron cloud effects [up to 7% wrt nominal HL-LHC] and the reduction in efficiency due to the longer cycle and longer recovery times [ca. 5% to 15%], one obtains an overall loss of integrated luminosity for operation at 7.5 TeV of 5% - 30% with respect to HL-LHC operation at 7 TeV.

12 References

[1] O.Brüning *et al.*, 'LHC Full Energy Exploitation Study: Operation at 7 TeV', CERN-ACC-2017-0086, 2017.

[2] Memo on the Ultimate energy exploitation of the LHC by the CERN director of Accelerators and Technology, Frederick Bordry, 22nd September 2017; Reference: 1848761.

[3] Proceedings of the 2018 LHC Performance workshop in Chamonix; https://indico.cern.ch/event/676124/

[4] Proceedings of the 2017 LHC Performance workshop in Chamonix; http://chamonix-2017.web.cern.ch

[5] O.Brüning, *et al.* (eds.), LHC Design Report v.1 : The LHC Main Ring, CERN-2004-003-V-1, 2004, ISBN 92-9083-224-0

[6] M. Breschi, E. Felcini, P. P. Granieri, E. Bergonzoni, F. Breccia, A. Bevilacqua, P. Galassi, T. Winkler, and L. Bottura, "Modeling of beam loss induced quenches in the LHC main dipole magnets", Submitted for publication to Applied Superconductivity Conference. Seattle, 28/10/2018, to appear in IEEE Transactions on Applied Superconductivity.

[7] http://lhc-optics.web.cern.ch/lhc-optics/www/hllhc13/

[8] https://lhc-div-mms.web.cern.ch/lhc-div-mms/tests/MAG/docum/hilumi/Magnets/field_quality.xlsx

[9] O. Brüning, S. Fartoukh, "Field Quality Specification for the LHC Main Dipole Magnets", LHC-Project-Report-501, 2001.

[10] N. Magnin, ‘LHC Beam Dumping System: Status and Readiness for LHC Run2’, Proc. 5th Evian Workshop, CERN-ACC-2014-0319, 2014.

[11] High-Luminosity Large Hadron Collider (HL-LHC). Technical Design Report V.0.1, edited by Apollinari G., Bejar Alonso I., Brüning O., Fessia P., Lamont M., Rossi L., Tavian L., CERN Yellow Reports: Monographs, Vol.4/2017, CERN-2017-007-M (CERN, Geneva, 2017). https://doi.org/10.23731/CYRM-2017-004

[12] C. Wiesner, HL-LHC WP14 coordination meeting, https://indico.cern.ch/event/648065/

[13] E. Carlier, LHC Beam Dump System Performance in 2016, Proc. 7th Evian Workshop, 2017.

[14] A. Sanz Ull, The LHC MSD septa at 7.5 TeV, CERN EDMS 1736186 https://edms.cern.ch/document/1736186/1

[15] L. Massida, Structural Analysis of the TCDS Collimator New Design, CERN EDMS 716298 https://edms.cern.ch/document/716298/1

[16] HL-LHC WP14 coordination meetings, see e.g. https://indico.cern.ch/event/716080/

[17] A. Mereghetti, *Readiness of the LHC Collimation System for Operation at 7.5TeV*, Proceedings of the 2018 LHC Performance workshop in Chamonix; https://indico.cern.ch/event/676124/timetable/#20180201.detailed

[18] Review on the needs for a hollow e-lens for the HL-LHC: https://indico.cern.ch/event/567839/

[19] International Review on the e-lens technical readiness for the HL-LHC baseline: https://indico.cern.ch/event/648237/

[20] ECRs related to collimation changes during LS2: https://lhc-collimation-upgrade-spec.web.cern.ch/lhc-collimation-upgrade-spec/Documents.php#LS2

[21] C. Bahamonde, *et al.*, “Energy Deposition Studies in IR7 for HL-LHC”, 7th HL-LHC Collaboration Meeting, Madrid, 16th November 2017, https://indico.cern.ch/event/647714/contributions/2734508/attachments/1559446/2455114/Update_on_energy_deposition_for_IR7_for_HL-LHC.pdf

[22] E. Skordis, “Status of energy deposition studies for the 2015 proton and ion collimation Quench Tests”, presentation at the 209th LHC collimation working group 31/10/2016, https://indico.cern.ch/event/578326/contributions/2342873/attachments/1363779/2064928/2016_-_31_-10_CWG_-_E._Skordis.pdf

[23] M. Schaumann *et al.*, “LHC BFPP Quench Test with Ions (2015)”, CERN-ACC-NOTE-2016-0024, 2016, CERN, Geneva, Switzerland, http://cds.cern.ch/record/2127951/files/CERN-ACC-Note-2016-0024.pdf

[24] P.D. Hermes *et al.*, “LHC Heavy-Ion Collimation Quench Test at 6.37Z TeV”, CERN-ACC-NOTE-2016-0031, 2016.

[25] B. Salvachua *et al.*, “Collimation quench test with 6.5 TeV proton beams”, CERN-ACC-NOTE-2016-0015, 2016-0015 http://cds.cern.ch/record/2123852/files/CERN-ACC-NOTE-2016-0015.pdf

[26] E. Felcini, presentation at the 94th Collimation Upgrade Specification meeting, ColUSM, Link:https://indico.cern.ch/event/666560/contributions/2726444/attachments/1532932/2400045/2017_09_29_ColUSM.pdf

[27] E. Quaranta *et al.*, “Modeling of beam-induced damage of the LHC tertiary collimators”, Phys.Rev.Accel.Beams 20 (2017), doi: 10.1103/PhysRevAccelBeams.20.091002.

[28] F. Carra *et al.*, “New TCSPM Design – Outcome of HRMT-23: Robustness of the HL-LHC jaws”, 88th Collimation Upgrade Specification Meeting, 2nd May 2017, https://indico.cern.ch/event/634704/contributions/2568694/attachments/1452019/2239363/Workshop_LS2Materials_02_05_17_AccidentalScenarioLM.pdf

[29] C. Bahamonde https://indico.cern.ch/event/647714/contributions/2734508/

[30] P. Dijkstal *et al.*, “Simulation studies on the electron cloud build-up in the elements of the LHC arcs at 6.5 TeV”, CERN-ACC-NOTE-2017-0057.

[31] G. Iadarola *et al.*, “Summary of the overall heat load estimates”, 40th HL-LHC Technical Coordination Committee, 2nd November 2017, https://indico.cern.ch/event/676089/contributions/2767533/attachments/1551737/2438082/006_heat_load_overview_TCC.pptx

[32] G. Iadarola *et al.*, “Analysis of the beam induced heat loads on the LHC beam screens during Run 2”, CERN-ACC-NOTE-2017-0066.

[33] G. Iadarola *et al.*, “Heat loads in the LHC arcs: observations and comparison against models”, presentation at the LHC Machine Committee, CERN, 29 Aug. 2018, https://indico.cern.ch/event/753301/contributions/3120379/attachments/1706695/2750178/011_presentation_LMC_20180829.pptx

[34] G. Iadarola *et al.*, “Digesting the LIU high brightness beam: is this an issue for HL-LHC?”, presentation at LHC Performance Workshop 2018, Chamonix 31 Jan 2018, https://indico.cern.ch/event/676124/contributions/2775566/attachments/1592343/2520510/023_giadarol_chamonix.pptx

[35] E. Métral *et al.*, “Update of the HL-LHC Operational Scenarios for Proton Operation”, CERN-ACC-NOTE-2018-0002.

[36] S. Antipov, *et al.*, “Machine Impedance and HOM Power Update”, 7th HL-LHC Collaboration Meeting, Madrid, Spain, 13-16 Nov. 2017, https://indico.cern.ch/event/647714/contributions/2646112/attachments/1558633/2452414/Machine_impedance_and_HOM_power_update_7th_HL-LHC_Meeting.pptx

[37] E. Métral, *et al.*, “Beam Stability from Impedance (Including Effect of Coating) and Overall Summary for the Nominal Scenario Including All Effects”, 7th HL-LHC Collaboration Meeting, Madrid, Spain, 13-16 Nov. 2017, https://indico.cern.ch/event/647714/contributions/2646116/attachments/1558652/2453439/UpdateOfHLLHCScenarios_2017_Madrid_EM.pptx

[38] N. Mounet, "The LHC Transverse Coupled-Bunch Instability", PhD thesis, Ecole Polytechnique, Lausanne, Mar. 2012, CERN-THESIS-2012-055.

[39] N. Mounet, http://impedance.web.cern.ch/impedance/Codes/ImpedanceWake2D/user_manual_todate.txt

[40] B. Salvant, *et al.*, "HL-LHC Impedance Model", in preparation.

[41] N. Mounet, "DELPHI: an Analytic Vlasov Solver for Impedance-Driven Modes", HSC Meeting, CERN, 09/04/2014, https://espace.cern.ch/be-dep-workspace/abp/HSC/Meetings/DELPHI-expanded.pdf

[42] S.Fartoukh, "On the sign of the LHC octupoles", LMC Meeting, CERN, 11 Jul. 2012, https://cds.cern.ch/record/1972514/files/CERN-ACC-SLIDES-2014-0113.pptx

[43] X. Buffat, *et al.*, "Stability diagrams of colliding beams in the Large Hadron Collider", Phys. Rev. ST Accel. Beams 17, 111002 (2014).

[44] X. Buffat, *et al.*, "Beam stability and quality in the presence of beam-beam and transverse damper", 7th HL-LHC Collaboration Meeting, Madrid, Spain, 13-16 Nov. 2017, https://indico.cern.ch/event/647714/contributions/2646114/attachments/1558511/2452144/2017-11-15_BeamBeamInstability-expanded.pdf

[45] T. Pieloni, *et al.*, "Global compensation of long-range beam-beam effects with octupole magnets: dynamic aperture simulations for the HL-LHC case and possible usage in LHC and FCC", CERNACC-NOTE-2017-036.

[46] N. Karastathis, "Field quality to achieve the required lifetime goals (with beam-beam)", 7th HL-LHC Collaboration Meeting, Madrid, Spain, 13-16 Nov. 2017, https://indico.cern.ch/event/647714/contributions/2646093/attachments/1558612/2452655/nkarast_hllhcCollab_15112017.pptx

[47] A. Romano, *et al.*, "Beam Stability in the Presence of Electron Cloud", 7th HL-LHC Collaboration Meeting, Madrid, Spain, 13-16 Nov. 2017, https://indico.cern.ch/event/647714/contributions/2646113/attachments/1558570/2453796/HLLHC_Collaboration_meeting.pptx

[48] A. Romano, *et al.*, "Status Update on E-Cloud stability simulations for LHC", Joint E-Cloud-PyHEADTAIL Meeting, CERN, 12/05/2017, https://indico.cern.ch/event/638087/contributions/2585441/attachments/1458519/2252030/INSTAB_LHC_full.pdf

[49] A. Romano, *et al.*, "Stability with Electron Cloud", HL-LHC WP2 Meeting, CERN, 03/10/2017, https://indico.cern.ch/event/668032/contributions/2737059/attachments/1533844/2401981/HLLHC_Meeting.pdf

[50] Z. Charifoulline *et al.*, "Overview of the Performance of Quench Heaters for High-Current LHC Superconducting Magnets", IEEE Transactions on Applied Superconductivity (Volume: 27 , Issue: 4 , June 2017) http://ieeexplore.ieee.org/document/7792684/?reload=true

[51] B. Heinemann, “Inelastic Cross Section and Pile-Up values at HL-LHC”, Experiment Data Quality WG Meeting held on 8th December 2017, https://indico.cern.ch/event/647714/contributions/2646114/attachments/1558511/2452144/2017-11-15_BeamBeamInstability-expanded.pdf