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Report

LHC Full Energy Exploitation Study: Operation at 7 TeV

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Abstract

This is the first report of a three volume study on the full energy exploitation of the LHC. The report summarizes the necessary preparations and consolidation work and the potential performance reach for operating the LHC at its nominal beam energy of 7TeV.

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1 Introduction and Executive Summary

1.1 Introduction and Context

The LHC operation started in 2010 at a reduced beam energy of 3.5 TeV in order to minimize the risk of damage in case of failures of the magnet interconnections. The beam energy was increased first to 4TeV in 2013 and finally to 6.5 TeV in 2015 after a thorough consolidation and repair work of all LHC magnet connections during the Long Shutdown 1 (LS1) in 2013 and 2014. The operation energy in 2015 was set short of the nominal beam energy of 7TeV in order to limit the number of required training quenches and speed up the restart of the machine after LS1. The study on the full energy exploitation of the LHC evaluates the required steps and potential implications and performance limitations for pushing the LHC beam energy beyond the 6.5 TeV operation energy of the LHC in 2016. The study is organized into three parts: a first part looks at increasing the beam energy to the nominal LHC design energy of 7 TeV; a second part looks at an increase of the beam energy towards the ‘ultimate’ LHC beam energy of 7.7TeV (9T magnetic field in the main dipole magnets) for which all hardware of the LHC has been initially designed; and a third part looks at the options and implications for pushing the LHC operation energy beyond the ultimate operation energy by considering significant hardware modifications for the LHC. However, the last part is clearly distinct from the study for the HE-LHC which looks at a full replacement of the existing machine with new dipole magnets of at least 16T maximum operating field.

The content of this report addresses the first part of the study and aims at providing information on the required time, the potential performance reach and possible hardware implications (e.g. failure rates and Mean Time between Failure of equipment) for pushing the LHC beam energy towards the nominal value of 7 TeV. The material of this report aims at guiding future discussions and the decision-making process on how and when to best push the LHC operation beam energy beyond the initial value of RunII in 2016.

1.2 Executive Summary

The main points of this first report are to estimate the time required for training the magnet system for operation at 7TeV, to identify potential bottle necks in the technical infrastructure and to recommend technical upgrades prior to the operation at 7TeV and to estimate the potential performance reach of the machine at 7TeV beam energy. The main outcomes of the study and the ensuing discussions at the 2017 LHC performance workshop at Chamonix include:

- Organization of a training campaign for two sectors, S34 and S45, towards 7 TeV operation before the EYETS 2016/2017;
- Observation of multiple magnet quenches in the trained sectors at higher magnetic fields;
- Observation of a second short to ground in a magnet diode box following a training quench in S34;
- Validation and documentation of the diode box short removal tool (capacitive discharge);
- Validation of the statistical behavior of the magnet training in the tunnel and estimate of the required time for training the magnet system for operation at 7TeV;
- Compilation of a consistent set of beam parameters and machine settings (e.g. β^* , collimation) for operation at 7TeV beam energy based on the operational experience of the LHC during Run I and the first year of Run II operation;
- Estimate of the machine availability and efficiency of the LHC for operation at 7TeV;

- Observation that electron cloud effects, impedance and UFOs do not impose special limitations for increasing the beam energy to 7TeV;
- Observation that the cryogenics, vacuum, beam instrumentation, magnet power converter and RF systems do not impose limitations for increasing the beam energy to 7TeV (except for the triplet cryogenic system that imposes limitations on the maximum acceptable peak luminosity);
- Estimate for the potential machine performance reach when pushing the beam energy to 7TeV either before or after LS2;

In agreement with the LHC experiments, the discussions ensuing the preparation of this first report led to the decision to keep the beam energy at 6.5TeV during the full LHC RunII period and to plan for operation at 7TeV only after LS2, after the repair of some magnet non-conformities and the consolidation of the diode box insulation during LS2. An important outstanding decision is to determine if one still conducts magnet training to nominal energy in part of the machine before LS2 and before all sectors are warmed up for the consolidation of the diode boxes. In the framework 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.

1.3 Recommendations and Lessons learned from the powering exercise prior to EYETS 16/17

In particular, we recommend the following powering tests before the start of LS2:

- Powering of the standalone quadrupole magnets of the long straight sections. 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 7TeV after LS2.
- Powering of the separation / recombination and dogleg dipole magnets of the insertions. Some of these magnets, for example the D3 magnets, did not yet reach nominal currents after LS1. In general, we would recommend that all stand-alone magnet circuits that have not reached nominal current are trained once to nominal values before LS2.
- Training of one of the main dipole circuits to nominal current. Even with the training exercises in S34 and S45 before the EYETS 2016/2017 we have no main dipole circuit in the machine that actually reached nominal current. We recommend to train at least one sector to nominal current before LS2 in order to eliminate potential other problems than those related to the diode boxes. A good candidate for such a training would be S12 which is expected to have a rather fast training to nominal current.

2 Operational Parameters and Assumptions

Beam parameters and settings are assumed to be identical to those of the end-of-year operation in 2016, albeit without the limitations on the total number of bunches per batch as was imposed in 2016 by the limitations of the SPS dump and LHC injection system. The report assumes ‘just’ an energy increase with respect to the 2016 operation. The impact of additional modifications during LS2 will be discussed in a separate chapter.

Table 2-1 contains the beam and machine parameters in collision during the proton run in 2016 with the collimator settings (in R.M.S. beam sigma for a normalized emittance $\epsilon^*=3.5 \mu\text{m}$) listed in Table 2-2. In 2016 the bunch population had been limited to

Table 2-1: 6.5 TeV and 7 TeV LHC parameters in collision for 25 ns operation in 2017 based on 2016 machine parameters.

Parameter	LHC (standard)	LHC (BCMS)	LHC (standard)	LHC (BCMS)
Beam energy in collision [TeV]	6.5	6.5	7	7
Particles per bunch, N [10^{11}]	1.25	1.25	1.25	1.25
Number of bunches per beam	2760	2556	2760	2556
Number of collisions in IP1 and IP5*	2748	2544	2748	2544
N_{tot} [10^{14}]	3.45	3.20	3.45	3.20
Beam current [A]	0.62	0.58	0.62	0.58
Crossing angle in IP1 and IP5 [μrad]	370	300	370	300
Minimum normalized long-range beam-beam separation [σ]	10.4	9.9	10.7	10.3
Minimum β^* [m]	0.4	0.4	0.4	0.4
ε_v [μm]	3.5	2.5	3.5	2.5
RF Voltage [MV]	12	12	12	12
ε_L [eVs]	2.2	2.2	2.3	2.3
R.M.S. energy spread [0.0001]	1.1	1.1	1.1	1.1
R.M.S. bunch length [cm]	8.3	8.3	8.3	8.3
IBS horizontal in collision [h]	82	39	85	40
IBS longitudinal in collision [h]	43	28	45	29
Piwinski parameter	1.08	1.04	1.13	1.06
Total reduction factor R_0 at min. β^*	0.68	0.69	0.66	0.69
Beam-beam tune shift/IP	0.0030	0.0042	0.0029	0.0042
Peak luminosity L_{peak} [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	1.30	1.72	1.37	1.82
Levelled luminosity for $\mu = 60$ [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	2.3	2.1	2.3	2.1
Triplet heat load limit in luminosity [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	1.75	1.75	1.62	1.62
Levelling time [h] (assuming no emittance growth) ‡	-	-	-	3.6
Number of collisions in IP2/IP8	2494/ 2572**	2215/ 2332**	2494/ 2572**	2215/ 2332**
Maximum # bunches per injection	288	144	288	144

*Assuming one less batch from the PS for machine protection (pilot injection, transfer line steering with 12 nominal bunches) and non-colliding bunches for experiments (background studies, etc.).

‡ The total number of events/crossing is calculated with an inelastic cross-section of 81 mb (ATLAS and CMS Collaborations, 30 September 2013).

**The lower number of collisions in IR2/8 compared to the general-purpose detectors is a result of the agreed filling scheme, aiming as much as possible at an equal sharing of collisions between the experiments.

Table 2-3 summarizes the LHC parameters in collision at 6.5 and 7 TeV for a potential optimized machine configuration based on:

- a reduction of the normalized beam-beam long-range separation to 9 sigmas based on the 2016 LHC experience, see Ref. [1].

- an optimization of the collimator settings as shown in Table 2-4 assuming the same setting in sigma for both energies (i.e. a reduction of the settings in mm wen increasing the energy).

Table 2-2: Collimator settings in 2016. Settings in R.M.S. beam size (for $\epsilon^*=3.5 \mu\text{m}$) at 6.5 TeV.

Collimator	Setting [σ]
TCP IR7	5.5
TCSG IR7	7.5
TCLA IR7	11.0
TCP IR3	15.0
TCSG IR3	18.0
TCLA IR3	20.0
TCSG IR6	8.3
TCDQ IR6	8.3
TCT IR1/5	9.0
Protected Aperture 1/5	9.9
TCT IR2	37.0
TCT IR8	15.0

approximately 1.15×10^{11} p/bunch and the maximum number of bunches transferred per injection from the SPS to the LHC has been limited to 96 bunches because of:

- Vacuum spikes in the LHC injection kicker MKI (in particular in Point 8) during the injection process
- A vacuum leak in the SPS High energy beam dump absorber (TIDVG).

Interventions took place in the SPS and LHC during the 2016/2017 Extended Year End Technical Stop (EYETS) to address these limitations. It is expected that the bunch population can be increased up to the maximum achievable in the injectors before the LIU upgrade in LS2 (1.3×10^{11} p/bunch at SPS extraction) and that the number of bunches per SPS to LHC transfer can be increased to 288 and 144 bunches for the Standard and BCMS beams, respectively. The latter number being limited by the insufficient attenuation provided by the SPS-to-LHC transfer line collimators (TCDI), Ref. [2]. These assumptions have been made to estimate the total number of bunches that can be achieved in collision in the LHC. Further optimizations of the filling schemes have been achieved during the 2017 run reducing the spacing between injected bunch trains in the LHC from 900 ns to 800 ns and by reducing the spacing among PS batches in the SPS from 225 to 200 ns. Further optimization of the filling scheme can be performed acting on the sharing of the numbers of colliding pairs in IP1/5 with respect to those in IP2 and IP8 which will result in different luminosity sharing between the corresponding experiments. From the experience in 2016, losses during the cycle are in the range of $\sim 1\%$ and for that reason a bunch population of 1.25×10^{11} p/bunch has been conservatively considered in collision. The maximum average pile-up μ acceptable by the experiments (assumed here to be 60, Ref. [3], before the HL-LHC upgrade and the maximum luminosity compatible with the available triplet cold mass cooling capacity represent additional limitations to be taken into account for the estimate of the integrated luminosity. The value of the luminosity corresponding to a pile-up of $\mu = 60$ is listed in the parameter tables that follow, while the expected limit in the instantaneous luminosity resulting from the energy deposition in the triplet cold mass and the limitations of the triplet cooling power is expected to be $1.75 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at 6.5 TeV and $1.62 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at 7 TeV. For the configurations where the expected peak luminosity exceeds the most stringent among the above two limitations (the first depending on the number of bunches) levelling will be considered.

Table 2-3: 7 TeV LHC nominal parameters for 25 ns operation with optimized parameters.

Parameter	LHC (standard)	LHC (BCMS)	LHC (standard)	LHC (BCMS)
Beam energy in collision [TeV]	6.5	6.5	7	7
Particles per bunch, N [10^{11}]	1.25	1.25	1.25	1.25
Number of bunches per beam	2760	2556	2760	2556
Number of collisions in IP1 and IP5*	2748	2544	2748	2544
N_{tot} [10^{14}]	3.45	3.20	3.45	3.20
Beam current [A]	0.62	0.58	0.62	0.58
Crossing angle in IP1 and IP5 [μrad]	355	315	355	310
Minimum normalized long-range beam-beam separation [σ]	9.0	9.0	9.0	9.0
Minimum β^* [m]	0.33	0.30	0.30	0.28
ε_v [μm]	3.5	2.5	3.5	2.5
RF Voltage [MV]	12	12	12	12
ε_L [eVs]	2.2	2.2	2.3	2.3
R.M.S. energy spread [0.0001]	1.1	1.1	1.1	1.1
R.M.S. bunch length [cm]	8.3	8.3	8.3	8.3
IBS horizontal in collision [h]	82	39	85	40
IBS longitudinal in collision [h]	43	28	45	29
Piwinski parameter	1.14	1.25	1.26	1.35
Total reduction factor R_0 at min. β^*	0.66	0.62	0.62	0.60
Beam-beam tune shift/IP	0.0029	0.0038	0.0027	0.0037
Peak luminosity L_{peak} [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	1.53	2.04	1.73	2.30
Levelled luminosity for $\mu = 60$ [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	2.3	2.1	2.3	2.1
Triplet heat load limit in luminosity [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	1.75	1.75	1.62	1.62
Levelling time [h] (assuming no emittance growth) [‡]	-	3.6	3.3	7.7
Number of collisions in IP2/IP8	2494/ 2572**	2215/ 2332**	2494/ 2572**	2215/ 2332**
Maximum # of bunches / injection	288	144	288	144

*Assuming one less batch from the PS for machine protection (pilot injection, transfer line steering with 12 nominal bunches) and non-colliding bunches for experiments (background studies, etc.).

[‡] The total number of events/crossing is calculated with an inelastic cross-section of 81 mb (ATLAS and CMS Collaborations, 30 September 2013).

**The lower number of collisions in IR2/8 compared to the general-purpose detectors is a result of the agreed filling scheme, aiming as much as possible at an equal sharing of collisions between the experiments.

Table 2-4: Optimized collimator settings at 7 TeV.
Settings in R.M.S. beam size (for $\epsilon^* = 3.5 \mu\text{m}$) at 7 TeV.

Collimator	Setting [σ]
TCP IR7	5.0
TCSG IR7	6.5
TCLA IR7	10.0
TCP IR3	15.0
TCSG IR3	18.0
TCLA IR3	20.0
TCSG IR6	7.3
TCDQ IR6	7.3
TCT IR1/5	7.5
Protected Aperture 1/5	8.5
TCT IR2	37.0
TCT IR8	15.0

Table 2-1 summarizes also the possible LHC parameters in collision at 7 TeV assuming the 2016 operational machine configurations and an increase of the number of bunches to the maximum possible for the Standard and BCMS beams. Levelling will be required for the BCMS beam. It is assumed that the collimator settings in mm will remain the same for both energies in order to maintain the impedance constant. This conservative approach increases the operational margins (larger long range beam-beam normalized separation, larger normalized aperture of the collimators in R.M.S. beam sigmas). Alternatively, a reduction of the β^* is conceivable while maintaining the operational margins in normalized aperture constant.

3 Magnet training

3.1 General features of the LHC dipoles

The main LHC dipoles were produced by three manufacturers referred as 1000, 2000 and 3000 series respectively. The 1232 main dipoles installed in the LHC are powered in eight circuits (called sectors) of 154 magnets in series. The repartition of the three series in each sector is far from being equal (see Table 3-1), and was firstly established on geometry and field quality criteria, and then on installing magnets requiring longer training in the middle of a cell and not close to quadrupoles, where beam losses are larger, Ref. [4].

Table 3-1: Magnets installed in the eight LHC sectors, and total number of quenches to reach 11080 A in 2015 (in brackets the number of second plus third quenches)

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

In this report, we will use two reference values for the LHC energy:

- 6.5 TeV, that requires a training to 11080 A, for an operational current of 10980 A (a 100 A margin is taken). This corresponds to an operational bore field of 7.73 T, and a 20% margin on the loadline.
- 7.0 TeV, that requires a training to 12000 A, for an operational current of 11850 A (a 150 A margin is taken). This corresponds to an operational bore field of 8.33 T, and a 14% margin on the loadline.

3.2 Summary of the training campaigns in 2008 and 2015

In 2008, all circuits have been brought to 9130 A, Sector 45 to 10300 A and Sector 56 to 11173 A, i.e. 93 A more than what we have defined as operation at 6.5 TeV, Ref. [5]. Sector 56 data showed three important features:

- A non-negligible fraction of magnets (19%) needed to quench before reaching 11173 A.
- A relevant difference between the three series has been observed: 93% of the quenches occurred in 3000 series magnets, 7% in the 2000 series magnets, and none in 1000 series.
- One magnet only quenched twice, i.e. 97% of the quenches occurred in different magnets (we had 97% of “first quenches”).

Soon after the commissioning, the 2008 incident required warm up and replacement of 30 dipoles in sector 34. In 2010, the eight circuits were commissioned to 6 kA without quenches; after this commissioning, the LHC operated at 3.5 TeV. In 2012 the circuits were commissioned to 7 kA without quenches and the machine operated at 4 TeV in 2012. The LHC has been totally warmed up during the Long Shutdown 1 (LS1) in 2013-2014 to carry out the consolidation of the magnet interconnection splices.

In 2015, all sectors have been brought to 11080 A, corresponding to an operational beam energy of 6.5 TeV. After this commissioning, the LHC operated at 6.5 TeV in 2015 and 2016. This campaign confirmed the three features already seen in 2008 (see Table 3-1):

- 11080 A were reached with 172 quenches, confirming that a non-negligible fraction (~14%) of the LHC magnets need a quench to reach this current;
- 82% of the quenches occurred in 3000 series magnets, 16% in 2000 series magnets and 2% in 1000 series magnets;
- 94% of the quenches occurred in different magnets (“first quenches”).

Moreover, the comparison of the training of sector 56 in 2008 and in 2015 shows that in general quenches in 2008 and in 2015 occurs in different magnets (only 3 out of 26 occur in the same magnets). This suggests that there is not a subset of slow trainers, but that training should be modeled as a statistical event with a probability distribution associated to the whole set of magnets.

The second important element coming from the comparison of 2008 and 2015 training campaigns is that data are compatible with a model where at each warm up and cool down the quench distribution is identical, i.e. there is neither improvement nor degradation in the magnet behavior. The statistics is low, fluctuations are large: for a sample of 50 magnets (the typical number of magnets in a sector of the same manufacturer) with a quench probability of 20%, statistical fluctuations (with a two sigma statistical error) give a result of 10 ± 5 quenches, i.e. a variability of a factor three that can be seen at each warm up. Therefore, degradation or improvement phenomena in quench performance are likely to be masked by fluctuations.

The 2015 campaign allowed to have for the first time a view on the performance of the whole set of the LHC dipoles after a thermal cycle. Note that during the production, only 10% of the

magnets, with a highly non-uniform sampling, was tested after thermal cycle. The 2015 data show that a significant difference of quench performance is seen along the 3000 series production. In particular, the magnets installed in sector 45 have a larger fraction of first quenches (63%) with respect to the whole 3000 series (34%). Moreover, both 2000 and 3000 series first quenches are compatible with a Gaussian tail, see Fig. 3-1. A posteriori, the quench distributions of the individual tests were also found compatible with Gaussian tails (see Ref. [6] for more details). On the other hand, data of 1000 series are still too few to support any analysis.

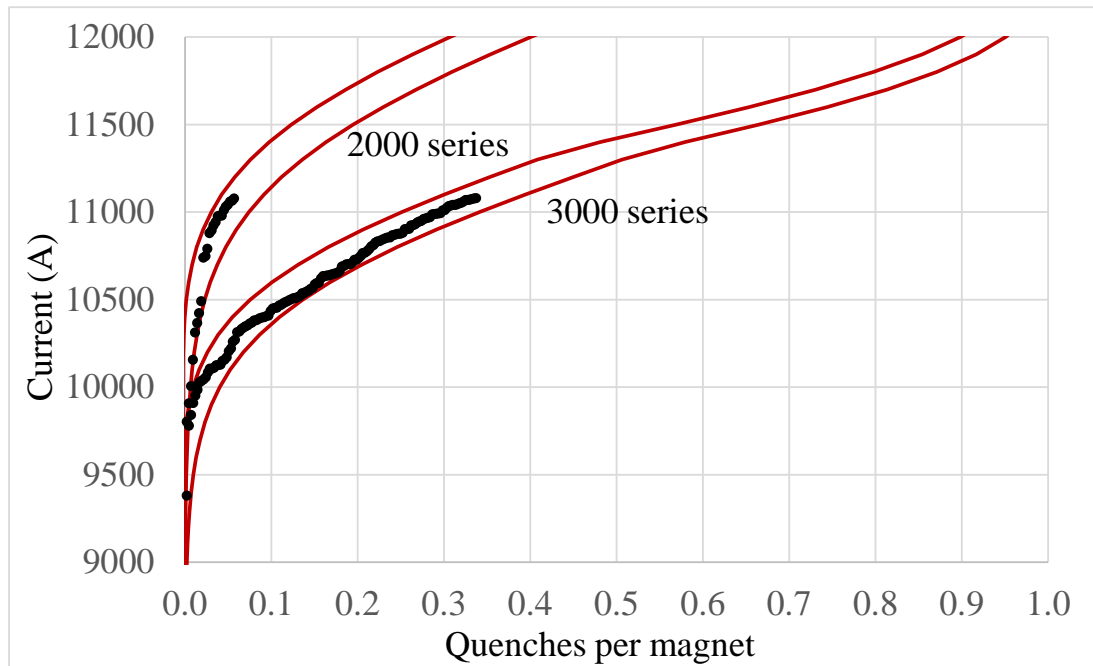


Fig. 3-1: Training in 2015 (first quench) in 2000 and 3000 series, and Gaussian fit with two sigma error.

The Gaussian tail fit of Fig. 3-1 allows to extrapolate towards 7 TeV. The extrapolation has two main sources of uncertainty: the second quenches of the 3000 series are not known, and could become relevant in the range between 6.5 TeV and 7 TeV. For this reason, it had been decided to power sector 45 towards 7 TeV ahead of the Extended Year End Technical Stop (EYETS) of 2016 / 2017. Secondly, the statistics for the 1000 series is missing, and the fit for the 2000 series is relying on only little data. For this reason, it has been decided to power also sector 34 towards 7 TeV ahead of EYETS 2016 / 2017, to have wider statistical samples.

3.3 Training campaigns in 2016 and 2017

During the training campaign of 2016, Sector 34 reached 11415 A with 8 quenches, and Sector 45 reached 11536 A with 24 quenches (see Table 3.2). The main results can be summarized as follows.

- We observed a negligible number of quenches in the 1000 series (1 out of 92 magnets), confirming that the training is still a negligible phenomenon in 1000 series and leaving the uncertainty on the estimate of number of quenches needed to reach 7 TeV for the whole 1000 series installed in the LHC (between 20 and 70);

- We observed 7% of 2000 magnets quenching, in agreement with the Gaussian fit;
- We observed 13 first quenches in 3000 series, and 10 second quenches. The number of first quenches is lower than expected (at the limit of the two sigma statistical error). The number of second quenches allows to build a Gaussian for the second quench. If this is associated to the batch 3150-3230 and 3370-3416, one can expect a 55% probability to quench at 12 kA, i.e. 70 quenches.

Table 3-2: Magnets installed in the 34 and 45 sectors, and number of quenches above 11080 A in 2016 (in brackets the number of second plus third quenches)

2016: quenches from 11080 A to 11415/11536 A					
sector	1000	2000	3000	total	current (A)
34	1	1	6 (2)	8 (2)	11415
45	0	7	17 (8)	24 (8)	11536
total	1	8	23 (10)	32 (10)	

In 2016, sector 12 had to be warmed-up to replace a magnet during the YETS 2016-2017. This is expected to be the fastest sector to be trained, since it contains only 9 3000 series magnets, and about 100 magnets of the best part of the 2000 production. In 2013, it took 7 quenches to reach 11080 A, corresponding to a 5% probability, and a statistical error of 4.5% (i.e. 6 quenches). In 2017, the sector reached 11080 A with 2 quenches after the magnet replacement and thermal cycle, compatible with a stationary situation in which the same training is needed after each thermal cycle (estimates done for the Chamonix 2017 workshop predicted between 0 and 10 training quenches). Nevertheless, data cannot exclude that a gradual improvement of the training after each thermal cycle takes place. The two magnets quenching in 2017 were not quenching in 2013, confirming that training is a statistical event associated to a set of magnets.

3.4 Outlook for 7 TeV

One can give an indication on the expected behavior for a training of the machine to 7 TeV through the extrapolation of the Gaussian fit of the 2015 and 2016 commissioning data. Considering an homogeneous production, we can consider a 85% probability for a quench for 3000 series magnets, i.e. ~330 quenches, plus 33% for the 2000 series, i.e. ~140 quenches, a 5% to 18% probability for the 1000 series (20 to 70 quenches). On the top of these ~530 quenches, one has to add the 70 second quenches, getting to 600 quenches. A more realistic estimate can consider splitting the production of 2000 and 3000 in two batches each, one with faster training and one with slower, and this would bring the estimate down to 500 total quenches.

The statistical error associated to this estimate is ± 35 quenches (due to fluctuations related to the limited sample of 1232 dipoles). On the top of this intrinsic variability (that will be present at each warm up and cool down), we have the error associated to the limited knowledge of the parameters of the fit, the error associated to the 1000 series and the error associated to the limited data available for the second quench.

Considering a maximum of 2 quenches per day, a training of the order of one month will be needed for each sector. The sectors containing the worst part of the production should be trained first to reduce to global training time. In particular sector 45 would need around 110 training quenches, i.e., two months. On the other hand, sector 12 could be trained to 7 TeV in only a couple of weeks. The training campaign at the end of 2016 also generated an electric short to ground in one of the magnet diode boxes in Sector 34. This is the second occurrence of this fault type since the training campaign

after LS1 and more faults of this type can be expected for future training campaigns (see Section 13 for more details). It is difficult to estimate the probability of future faults of this type and CERN is conducting a study on potential mitigation measures during LS2. More details are discussed later in this report but it is worthwhile to note at this stage that a short in the magnet diode box occurred so far for the high current training twice over approximately 400 training quenches.

4 Powering aspects

From the power converter side, there is no limitation to operate the machine at 7 TeV, excluding the effect of radiation to electronics which are considered in a specific chapter below.

Going from 6.5 TeV to 7 TeV will increase the current of the power converters by 7.7%. All LHC power converters were designed and tested individually during their acceptance tests at their maximum current corresponding to the ultimate beam energy of 7.56 TeV, (corresponding to 9T magnetic field in the main dipole magnets). For the main dipole converter, the current is 10980 A for 6.5 TeV, 11820 A for 7 TeV and 12840 A for 7.56 TeV, while the maximum current of the power converter is 13000 A.

The current at 7 TeV will be 9% below the maximum current of the power converters keeping some margin.

The power converter's losses, which are evacuated in the air and special water circuits, will also increase. However, the cooling systems were designed for the ultimate beam energy. During the first hardware commissioning campaign in 2008, all power converters were tested together in their final location and environment in short-circuit (including DC cables but without the superconducting magnets) at ultimate current during 8 hours and 24 hours at nominal current (corresponding to 7 TeV). These tests successfully qualified the warm powering part of the magnet circuits at nominal current.

The power converter availability shouldn't be impacted by this current increase. Many power converters were consolidated during LS1 to improve their reliability. From operational statistics, when the current increase from 4 TeV (2012) to 6.5 TeV (2016), this did not produce any effect on the failure rate. Furthermore, most of the failures comes from the power converters of the corrector magnets which are not operated at their full current.

Some power converters are already working at their maximum current, like ATLAS solenoid at 20kA or CMS solenoid at 20kA, without any reliability issue. The ATLAS power converter is from the same family as the ones for the main quadrupoles in the machine. This type of power converter is made of sub-converters rated 3.25 kA connected in parallel to obtain the maximum current. An additional sub-converter is added to improve reliability thanks to this redundancy. A failure of a sub-converter doesn't stop operation, which allows to obtain excellent availability of this power converter family. The redundancy principle is implemented in almost all high-current power converters.

The magnet quench campaign will generate more stress on the power converters as they have to stop brutally at full current and transfer the current to the thyristor crowbar circuit. Up to now, this process always performed very well without any issue.

The sensitivity of the power converters to electrical perturbations could be slightly higher as the internal reserve energy will have a reduce capacity to compensate for disturbances.

5 Operation and Beam Dynamic Aspects

5.1 Hardware Non-conformities

Three types of hardware non-conformities might prevent operating the LHC at the nominal beam energy of 7 TeV, namely high resistance of the internal splices of main dipoles and quadrupoles; the performance of quench heaters; and the magnet quench performance.

The magnets featuring the largest values of the resistance of their internal splices have been removed during LS1. The only case that was planned for exchange during LS1, but which in the end could not be implemented is the Q7.R3 (<https://twiki.cern.ch/twiki/bin/view/MP3/SummaryIssues>, n.d.). It is worthwhile stressing that the distribution of the resistance values of the internal splices of the main magnets installed in the LHC ring is not considered a showstopper for pushing the machine energy to its nominal value. Possibly, replacing a few more magnets could be envisaged during LS2, but this should be meant as a means to increase the safety margin for operating the machine at 7 TeV rather than a pre-requisite for reaching 7 TeV beam energy.

Currently there are a few magnets that are protected only by a reduced number of quench heaters (<https://twiki.cern.ch/twiki/bin/view/MP3/SummaryIssues>, n.d.), such as RD1.R8, operated with 1 heater instead of 2, and RQ4.L8 and RQ4.R2, both operated with 7 out of 8 heaters. However, the current configuration is not considered to prevent operation at higher energy. It is also worthwhile highlighting that the real issue with quench heater failures is shorting the coil to ground, which never occurred so far.

The situation concerning the quench performance of the LHC magnets is more involved. It is worth reminding that all main magnets were tested individually up to ultimate currents during the acceptance tests, and the remaining magnets, namely correctors, independently powered dipoles (IPD) and quadrupoles (IPQ), were always tested up to nominal current. In this respect, all magnets were conforming to the specifications (apart from some MQTLI quadrupoles, see later) for operation at 7 TeV.

During the various powering campaigns carried out in the LHC tunnel, the powering levels used for the tests had been adjusted to the energy of each run, thus enabling some reduction of the time required for the commissioning of the powering system.

However, at the end of Run I in February 2013, an extensive powering campaign was carried out, see Refs. [7, 8], which provides some insight on the performance reach of the LHC magnets in the tunnel. The results obtained can be summarized as follows:

- Triplets, IPDs (apart from D3.L4), MQYs and MQMs at 1.9 K did not show any particular issue in reaching the 7 TeV-equivalent powering.
- After 7 quenches D3.L4 reached only 5784 A instead of the required 5860 A. The powering tests have been stopped at that current to avoid stressing the magnet mechanically. It is believed that no fundamental limitations would prevent this magnet from reaching the nominal performance. However, it is worth underlining that in case of an unforeseen issue preventing the magnet from reaching a higher operating current, this magnet would limit the energy of the LHC to 6.9 TeV. The magnet operation at nominal current should therefore be tested before LS2.
- After three quenches Q5.R2 reached 4202 A instead of 4310 A. Also, in this case, the powering tests have been stopped to avoid stressing the magnet mechanically. It is believed that no fundamental limitations would prevent this magnet from reaching the nominal performance. It is important to stress that an analysis of the currents used during operations and MDs in 2016, hence including also ATS optics, shows that the maximum current is never exceeding 3000 A,

which ensures that a large safety margin is available even if the magnet would not reach its nominal performance.

- Concerning the MQMs at 4.5 K, it is worth noting that the Q5.R1 and Q6.L8 magnets required many more training quenches to reach 4100 A as compared to the other magnets of the same family. Nevertheless, also these two magnets are not expected to limit the overall machine performance.

It is worth recalling in this context the case of the so-called weak MQTLIs. These magnets were not performing according to specification since the beginning of LHC construction, and the decision was taken to install them in specific locations of the LHC ring where the optics was well defined, to ensure an accurate estimate of the performance needed to achieve 7 TeV. To this aim, it was decided to equip part of the special SSS magnets in the IRs 3, 6, and 7 with these magnets. Therefore, unless a significant degradation from the performance at acceptance occurs, these magnets will not prevent the LHC to operate at its nominal energy. To-date, there are no indications of any performance degradation.

Finally, it is worth mentioning that the strength level of the IR2 and IR8 triplet quadrupoles at injection does not allow ramping them at constant normalized strength, and hence at constant optics, up to 7 TeV. Therefore, operation beyond 6.5 TeV will require an optics change for IR2 and IR8 during the ramp. MQX1 and MQX3 impose this limit, while it would be possible to ramp the Q2 at constant strength up to 6.6 TeV. Such a change will imply reducing the triplet strength at constant beta* value.

Other non-conformities imply some orbit correctors of type MCBY, namely RCBYV5.L4B2, RCBYHS4.L5B1, RCBYH4.R8B1, RCBYHS5.R8B1, possibly due to inter-turn short circuits (<https://twiki.cern.ch/twiki/bin/view/MP3/SummaryIssues>, n.d.). During the various hardware commissioning campaigns, the maximum current limitations have been reduced (together with the ramp rate) so that currently the LHC is operated with the following current limits (absolute values):

- RCBYV5.L4B2, 50 A
- RCBYHS4.L5B1, 50 A
- RCBYH4.R8B1, 50 A
- RCBYHS5.R8B1, 40 A

These values should be compared to the following typical (and rounded values) operational currents used during 2016 p-p operation:

- RCBYV5.L4B2, -5 A
- RCBYHS4.L5B1, -24 A
- RCBYH4.R8B1, 4 A
- RCBYHS5.R8B1, -22 A

The situation seems very safe for the case of energy increase to 7 TeV. Nevertheless, powering tests will be carried out during the 2016-17 EYETS, to increase the current limit by about 10% with respect to the situation during 2016 operation.

5.2 Implications of the non-conformities on operation/performance

Even if the analysis presented earlier is mainly based on the optics used in 2016 (operation or MD), and hence with β^* values that are slightly larger than what could be a possible in the next years and at 7 TeV, the outcome is also representative for possible future situations. In fact, all optics are always matched with respect to the 7 TeV limits of the quadrupoles (apart from the triplets in IR2 and 8) and the Q5 and Q6 magnets, among which there are some potential difficult cases (see above). The general tendency is of a strength reduction when β^* is reduced. Hence, any future reduction of β^* value should not invalidate the current analysis at least down to the values considered in Table 2-1 and Table 2-3. The same conclusion applies to the ATS optics where the strength of the Q5.L6 quadrupole during the telescopic squeeze is not expected to be limiting for the parameters considered in Table 2-1 and Table 2-3, Ref. [9].

5.3 Implications on stability and beam-beam effects

Bunches of $1.3 \cdot 10^{11}$ p/b within transverse emittances of $2 \mu\text{m}$ can be delivered by the injectors and the stability limits are estimated for the conservative case where no blow-up occurs during the ramp. The octupole current required to stabilize the beam is plotted in Figure 5-1 for different values of the chromaticity assuming the collimator settings in Table 2-2 and Table 2-4 for the energies of 6.5 and 7 TeV. For the simulations, it is assumed that the coupling (C-) can be controlled down to $\sim \Delta Q / 10$, with ΔQ being the tune separation, and that the transverse damper can provide a damping time of less than 100 turns. With these assumptions, the simulations show that a Landau octupole current of less than 300 A is sufficient to guarantee the single bunch stability against impedance-induced instabilities.

This is the case for both octupole polarities and independent of the beam distribution and in the pessimistic assumption that there is no enhancement of the effective corrector strength due to an increase of the beta functions in the arcs (possible with the ATS optics).

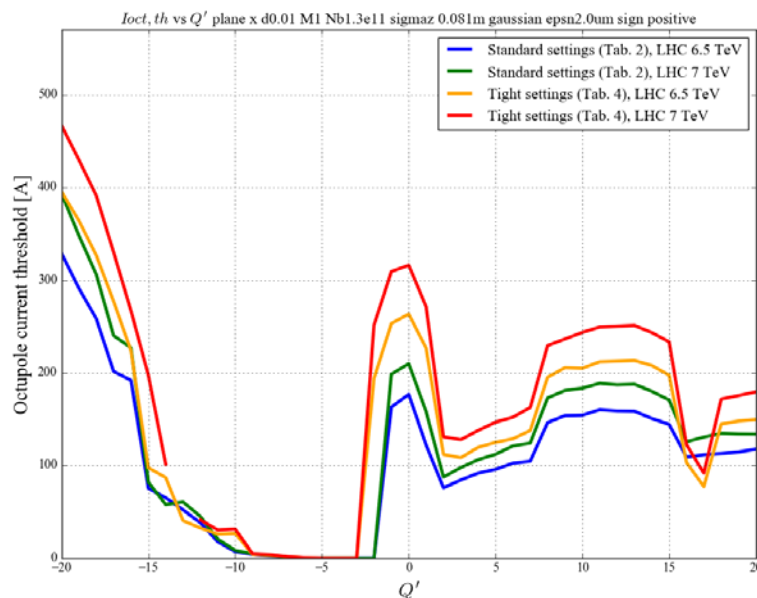


Fig. 5-1: Single-bunch threshold in the Landau octupoles' current vs. chromaticity, assuming a damping time from the transverse damper of 100 turns for bunches of 1.3×10^{11} p and with a transverse normalized emittance of $2 \mu\text{m}$. Blue: 6.5 TeV - collimator settings as in Table 2-2. Green: 7 TeV collimator settings as in Table 2-2. Orange: 6.5 TeV - collimator settings as in Table 2-4, Red: 7 TeV - collimator settings as in Table 2-4.

The impact of electron cloud effects on beam stability at 7 TeV should change only marginally with respect to 6.5 TeV and most likely, it should reduce as a combination of the three main effects:

- Enhancement of the beam rigidity (proportional to the relativistic gamma) reducing the growth rate as $1/\gamma$;
- Reduction of the beam size increasing the growth rate as $\sqrt{\gamma}$ [10];
- Enhancement of the average rate of synchrotron radiation photons (proportional to the relativistic gamma) mostly affecting the total number of electrons but not the electron cloud central density, which affects beam stability.

No impact on beam stability is expected from beam-beam effects if the normalized long-range beam-beam separation is maintained above 9 sigmas as indicated in Table 2-1 and Table 2-3 taking into account that the head-on beam-beam tune shift/spread does not depend on the beam energy. With the current (positive) polarity of the Landau octupoles, the interplay with long-range interaction is constructive for the stability diagram and as long as the stability at flat-top is ensured the same applies throughout the betatron squeeze.

5.4 Implications on cycle duration

The variation of the cycle duration is expected to be marginal. The ramp and the ramp down phases will be slightly longer by approximately 120 and 300 s, respectively, with the present hardware configuration. Means for reducing the triplet magnet ramp-down time are presently being considered but they will benefit equally the duration of both the 6.5 and 7 TeV cycles.

The squeeze is not expected to take longer as the current of the matching section elements, which are determining the length of the squeeze at present, decreases during the squeeze.

It is expected that there will be no need to change the pre-cycle functions because of the different operation energy.

6 Cryogenic and Vacuum

6.1 Operational Considerations

Fig. 6-1 shows the beam induced heat load on the beam screens of the LHC arcs for a physics fill performed with 25 ns bunch spacing at the end of 2016. The main contributions to the heat deposition are given by the impedance of the beam screen, the synchrotron radiation and the electron cloud.

The expected contribution from the first two mechanisms is shown by the dashed line and is summarized for the beam parameters at the start of collision in the first two rows of Table 6-1 when extrapolated to the beam parameters assumed in Table 2-1 and Table 2-3. This accounts for about 21% of the cooling capacity available on the beam screens, which amounts to 160 W per half-cell, corresponding to 1.5 W/m/beam.

Assuming the same beam parameters for operation at 6.5 TeV and 7 TeV, and that 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 in any case very small as shown in Table 6-1.

A more significant increase (about 35%) 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 about 13% of the total available cooling capacity.

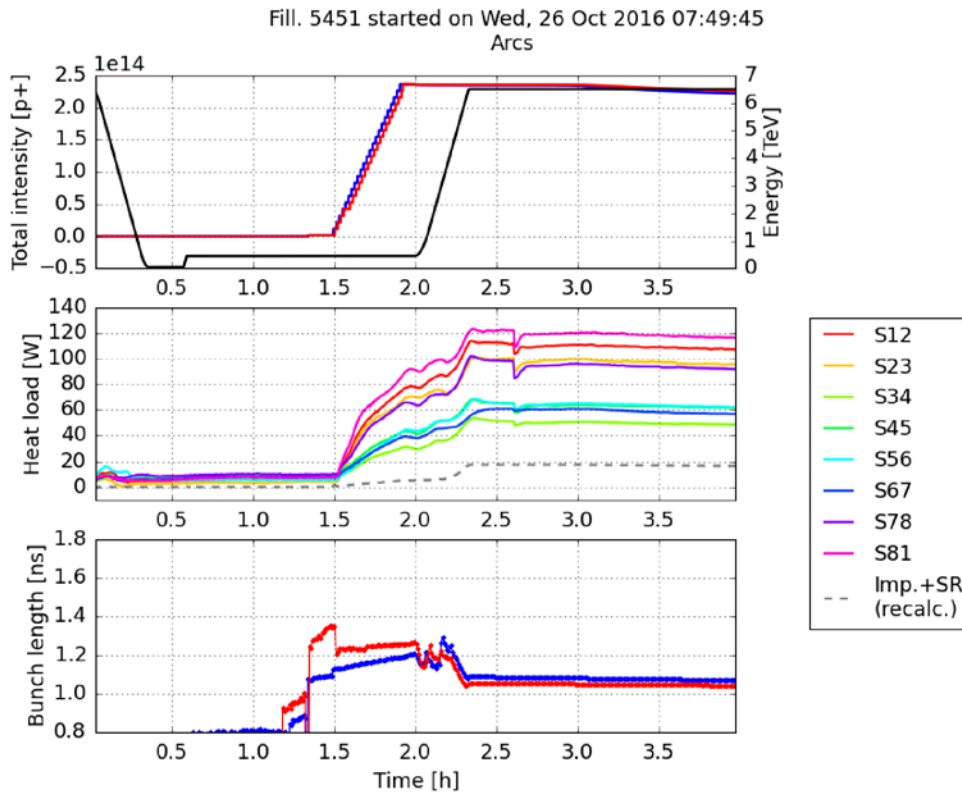


Fig. 6-1: Heat load measured in the LHC arcs during a physics fill with beams consisting of 2040 bunches distributed in trains of 72 bunches in 2016. The heat load values are in Watts per half-cell. The dashed line shows the heat load expected from impedance and synchrotron radiation

Table 6-1: Heat load expected on the arc beam screens at collision energy from the different heating mechanisms. Comparison between 6.5 TeV and 7.0 TeV assuming the beam parameters in Table 2-1 and Table 2-3.

Energy [TeV]	6.5		7.0	
	Standard	BCMS	Standard	BCMS
Scheme				
Impedance heating [W/half-cell]	13.1	12.2	13.2	12.3
Synchrotron radiation [W/half-cell]	15.1	14.0	20.4	19.0
Electron cloud [W/half-cell]	218	180.1	240	198

The heat load on the beam screens during physics production in 2015 and 2016 was 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 (in 2016 more stringent intensity limitations came from the injectors). The origin of the significantly different heat load values measured in the different sectors is at the moment still not understood and it is still under investigation. For that reason, the average heat load per arc half-cell in the worst sector has been considered for the following estimates, assuming the same surface conditioning levels as achieved at the end of 2016.

From Table 6-1, we can see that all cases exceed the maximum available cryogenic power of 160 W per half-cell and conclude that further conditioning is needed to fill the machine in all considered configurations with the maximum number of bunches, with the most critical situation being for the standard beam. After an initial decrease of the SEY inferred from the heat load measurement in the first half of 2016, no significant evolution has been observed in the second half of 2016. Scrubbing and operation with longer trains (4×72 bunches) is necessary in order to provide an estimate of the amount of time required to operate the machine with the maximum number of bunches indicated in Table 2-1 and Table 2-3.

As is shown in Fig. 6-1, most of the heat load develops already at 450 GeV while the increase observed over the ramp is limited to 20-30 W per half-cell. Provided that the beam parameters at collision energy stay the same as during 2016 operation, the main change on the e-cloud formation due to the increased beam energy is related to the increased production of photoelectrons due to the synchrotron radiation impinging on the beam screen. The number of photons emitted by the beam scales linearly with the beam energy, therefore the effect of beam energy increase to 7 TeV is expected to be quite limited, lower than 25 W/half-cell, as reported in Table 6-1.

6.2 Vacuum system

The impact of the intensity and energy increase to LHC design values on the vacuum system is studied for 3 scenarios:

a) Intensity ramp-up to nominal by increasing the number of bunches

In 2016, the beam current stored in the LHC ring was ~ 0.45 A with nominal bunch populations ($1.15 \cdot 10^{11}$ protons/bunch). The beam current can be increased towards nominal by increasing the total number of bunches stored in the ring. Doing so, the photon and electron fluxes increase linearly with the beam current. We assume here that the associated molecular gas desorption due to photon and electron irradiations increases also linear with the beam current¹.

The arc gas density therefore scales like:

$$P_{I_nominal} = (P_{SR,2016} + P_{Ec,2016}) \left(\frac{I_{nominal}}{I_{2016}} \right) = P_{2016} \left(\frac{I_{nominal}}{I_{2016}} \right) \quad (1)$$

where PSR and PEC refer to the synchrotron radiation and the electron cloud induced power depositions respectively. With $I_{2016} \sim 0.45$ A, and a nominal intensity of 0.58 A, the pressure in the arc will increase by approximately by a factor ~1.3.

As shown in Fig. 6-2, the average pressure along the arc was ~ $3 \cdot 10^{-9}$ mbar in 2016, with 6.5 TeV beam energy. Thus, the expected pressure, measured at room temperature, PRT, with nominal beam intensity and 6.5 TeV is ~ $4 \cdot 10^{-9}$ mbar.

¹ Indeed the electron cloud part might increase more than linearly due to the change in filling pattern (in particular for the standard beam) with the increase of the train length.

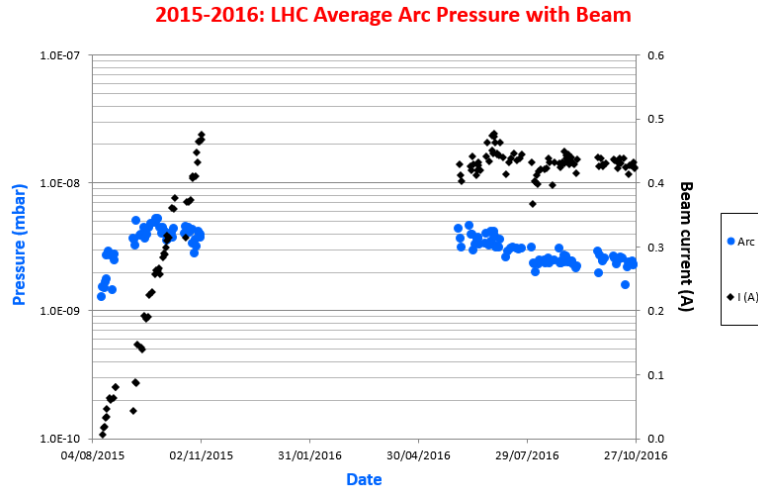


Fig. 6-2: LHC average arc pressure and beam current during 2015 and 2016.

In order to estimate the impact of the intensity ramp up on the beam lifetime, the gas density into the arc shall be derived from the expected pressure at room temperature. According to equation (2), following unit conversion, ideal gas law and thermal transpiration corrections, the corresponding gas density at 15 K is equal to $4.3 \cdot 10^{14} \text{ H}_2/\text{m}^3$.

$$n = \frac{100 P_{RT} \sqrt{\frac{T_{BS}}{300}}}{k T_{BS}} \quad (2)$$

The 100h design beam life time corresponds to a gas density of $1.2 \cdot 10^{15} \text{ H}_2/\text{m}^3$. Thus, scaling from the 2016 operation data, the expected beam lifetime at nominal beam current will be $\sim 300 \text{ h}$, *i.e.* well above the luminosity beam life time.

- The intensity ramp up to nominal beam intensities will stimulate further gas desorption but the beam life time will remain larger than the design value.
- The impact of the beam intensity increase towards nominal for other equipment located in the long straight sections follows a similar behavior as that of the LHC arcs (*i.e.* gas density increase by a factor of approximately 1.3).
- The intensity ramp up to nominal will increase the pressure of equipment located in the long straight sections by $\sim 30 \%$.

The intensity ramp-up will increase also the heat load stimulated by the resistive wall impedance. For some specific components, which have been shown to be sensitive to these effects in the past (e.g. TDI, MKI, collimators), there might be an associated increase of the thermal desorption induced by the temperature increase. At constant bunch intensity and length, the dissipated power onto the component shall increase linearly. At room temperature, the specific heat being constant, the temperature of the component will increase linearly with the beam intensity. However, the thermal gas desorption varies exponentially with the temperature, therefore, the pressure due to thermal desorption scales like:

$$\begin{aligned}
P, thermal_{I_{nominal}} &= P, thermal_{2016} e^{\frac{T_{nominal}}{T_{2016}}} \\
&= P, thermal_{2016} e^{\frac{I_{nominal}}{I_{2016}}}
\end{aligned} \tag{3}$$

So, when increasing the beam intensity towards nominal by increasing the number of bunches, the pressure due to thermal outgassing might increase by approximately a factor 4 in case the actual pressure around the component is dominated by the resistive wall effect.

- Pressure in equipment which are dominated by thermal outgassing due to resistive wall effects will be multiplied by ~ 4 following the intensity ramp up to nominal.

b) *Energy increase to nominal*

When increasing the proton beam energy, the synchrotron radiation photon spectrum will also increase towards higher energy, stimulating further the gas desorption. It has been show in the laboratory (EPA), Ref. [11], and recently confirmed with LHC data, that the photo-desorption yield can be empirically linearly fitted to the critical energy. Since the gas load scales like the critical energy and varies with the third power of the beam energy, Ref. [11], at nominal energy, the expected pressure increase due to synchrotron radiation will be approximately a factor 1.2 higher than during 2016 operation.

$$P_{SR,7 TeV} = P_{SR,2016} \left(\frac{E_{nominal}}{E_{2016}} \right)^3 \tag{4}$$

The impact of the beam energy increase on the electron cloud is driven by the production of photoelectrons. Since the photon flux varies linearly with the beam energy, at nominal energy, the photoelectron flux will be multiply by $\sim x1.1$. This photoelectron flux will add on to the electron cloud flux. However, in the actual multipacting regime (i.e. a SEYmax above mutlipacting threshold), the electron cloud is dominated by the production of secondary electrons. In this case, the impact of the increase of the photoelectron flux onto the gas density is expected to be negligible.

$$P_{EC,7 TeV} \approx P_{EC,2016} \tag{5}$$

To evaluate the impact of the beam energy increase to 7 TeV, it is therefore important to disentangle the molecular desorption stimulated by synchrotron radiation and electron cloud. But, the decoupling of both contributions cannot be fully achieved in the LHC arc due to the large background pressure owing to thermal outgassing around the vacuum gauges ($\sim 10^{-9}$ mbar) and the low pressure in presence of beam (see Fig. 1). Therefore, as shown in equation (6), a conservative approach has been chosen here to evaluate the impact of the beam energy increase.

$$P_{7 TeV} = P_{SR,7 TeV} + P_{EC,7 TeV} \leq P_{2016} \left(\frac{E_{nominal}}{E_{2016}} \right)^3 \tag{6}$$

Thus, the expected pressure measured at room temperature in the arc will be $\sim x1.2$ higher as compared to 2016 pressure values. It is estimated that the arc pressure will reach $\sim 4 \cdot 10^{-9}$ mbar with nominal beam energy and ~ 0.45 A.

- Similarly, to the beam intensity ramp up to nominal values, the impact of the beam energy increase to 7 TeV on the beam lifetime is negligible.

The pressure increase for equipment located in the long straight sections is expected to be negligible due to the lower synchrotron radiation photon flux and critical energy generated by D1 and D2 than the arc. In 2016, the measured pressure increase due to synchrotron radiation around devices located more than 100 m downstream from the LHC arc, is $\sim 10^{-10}$ mbar.

- LHC operation at nominal beam energy will have a negligible impact on pressure levels for equipment located in the long straight sections.

c) *Beam intensity and beam energy increase to nominal*

The impact of the beam intensity and beam energy increase to nominal can be derived from the combination of equations (1) and (6). The expected pressure in the LHC arc is thus:

$$P_{nominal} = P_{2016} \left[\left(\frac{I_{nominal}}{I_{2016}} \right) + \left(\frac{E_{nominal}}{E_{2016}} \right)^3 \right] \quad (7)$$

The expected pressure measured at room temperature in the LHC will therefore increase approximately by a factor 1.6, reaching a maximum pressure of $\sim 5 \cdot 10^{-9}$ mbar. The corresponding beam lifetime at this pressure is ~ 200 h and therefore still larger than the LHC design value.

- Operating the LHC with nominal beam intensity and beam energy under otherwise identical conditions as during the 2016 operation will stimulate further gas desorption but the beam life time will still remain larger than the LHC design value.

6.3 Cryogenic

Two main limitations were identified during Run 2 on the cryogenic system and need to be considered for operation at 7 TeV. First concerns the heat load on the beam screen circuit, where heating effect from electron cloud exceeds nominal values by factor of 1.5-2 depending on sector and beam parameters. The second limitation is expected on the ITs cold mass cooling loop, where bayonet heat exchanger was modified to increase mechanical behavior of the system.

Beam screen circuit and electron cloud

During LS1 selected beam screen valve poppets were upgraded to guarantee possibility for heat load compensation of ~ 2 W/m per aperture (refer to report from Evian 2014). This modification allows for full use of global cooling capacity delivered by 4.5 K refrigerators. Experience shows that equally distributed cryogenic capacity in all BS cooling loops over a sector allows for heat compensation of 1.6 W/m per aperture (equivalent of 160 W/arc half cell). Approaching cryogenic performance limits, it should be considered that each cryogenic plant has own specificity coming from design margins and heat load coming from different sectors is not equal. For this reason, any calculation gives uncertainties to the results and only dedicated capacity test can confirm individual limits of the cryogenic plants. Such test was performed on the plant supplying beam screen circuit in sector 2-3 with limit of 195 W/half-cell (9.3 kW at 4.5-20 K circuit) and on the plant supplying sector 7-8 with limit of 195 W/half-cell (10.3 kW at 4.5-20 K circuit). Both limit values are applicable for steady state conditions. All remaining cryogenic plants will have to be tested to learn the real capacity limits. However, operation experience shows that their capacity should not be lower than of two tested cryogenic plants.

It is worth to mention that installed capacity of tested cryogenic plants for 4.5-20 K circuit is 7.6 kW (LHC DR p.328). Compensation of any higher heat load is possible from capacity savings coming from lower than expected heat load on the cold mass circuit.

Currently the limit of 160 W/half-cell is considered as maximum guaranteed operation limit of the cryogenic plants at 6.5 TeV. It is considered that further optimization of the process will allow for keeping the same guaranteed value for 7 TeV operation.

Total heat load in the ITs and cryogenic performance limitation

Design values for the heat load compensation in the IT at P1 and P5 are 193 W for nominal condition, where 182 W comes from secondaries, and 476 W for ultimate case, where 440 comes from secondaries (LHC DR p. 317). The main contributors to vary the beam induced heat load are beam energy and instantaneous luminosity. As expected, the maximum value of the heat load appears just on the beginning of collisions period with peak luminosity values. The equivalent heat load with reduced operation parameters can be recalculated according to applicable scaling law (see LHC DR p.316).

Analysis performed on Run 2 data shows that ITs at P1 and 5 were loaded from beam induced heating up to nearly 200 W with energy of 6.5 TeV and L_{peak} between 1.2-1.4 Hz/cm². The applied scaling law shows that nominal beam induced heat load is lower from theoretical 182 W to at least 152 W.

During TS2 dedicated capacity test was performed checking the cooling performance of the system. The simulated beam induced heat load of 250 W was compensated by cryogenic cooling power. The value of 250 W corresponds to L_{peak} of $1.75 \cdot 10^{34}$ Hz/cm² at 6.5 TeV or to $1.63 \cdot 10^{34}$ Hz/cm² at 7 TeV². Theoretical calculation shows that new bayonet heat exchanger should compensate for 320 W what would give $2.1 \cdot 10^{34}$ Hz/cm² at 7 TeV (to be confirmed by dedicated performance test).

- The value of 250 W is considered today as maximum guaranteed operation limit.

7 Collimation and BLMs

7.1 Collimation

The performance of the LHC collimation system up to 6.5 TeV, with small β^* down to 40 cm, has been very satisfactory, Ref. [12]. In principle, possible concerns for beam operations at higher energies include:

- cleaning performance³ versus quench limits of superconducting magnets around IR7, with higher stored beam energies and reduced quench margins with higher currents in the coils;
- instabilities from collimator impedance, possibly arising with beams of smaller geometrical emittance or tighter collimator gaps;
- collimation of physics debris around the high-luminosity points, in presence of higher peak luminosity of more energetic colliding beams;
- robustness constraints for specified failures at top energy, with higher energy beams.

In addition, “soft” limitations to operations might arise from system setup time, β^* reach from collimation hierarchy and protection considerations. Ref. [13], hardware and software availability.

Also thanks to collimation system upgrades that took place in LS1, Ref. [14], addressing operational efficiency in changes of IR configurations, physics debris collimation and software reliability, we consider now that only the first two items in the list – quench performance and beam stability matter – are possible concerns.

² Remark: The estimation of luminosity limit is given only as indication; the cryogenic group considers heat load expressed in Watts as valid communication unit.

³ Collimation cleaning depends on energy and settings but for the changes considered here, differences can be considered as minor at this stage. Performance reach will be assessed in detail for a final proposed configuration if necessary.

For the operation at 7 TeV addressed within the scope of this document, three setting scenarios are considered for collimation: (1) a scenario where collimators are kept at the same settings in millimeters, which ensures the possibility to keep the same β^* of 40 cm as in 2016; (2) a scenario where the same settings in units of RMS beam size are used, corresponding to gaps scaled with the square root of (7.0/6.5) \rightarrow 1.04 times smaller than in 2016; (3) a scenario with the tighter collimator settings of Table 2-4 proposed in Ref. [15] as a scenario for 2017 operation, therefore not yet demonstrated by operational experience but assumed to be feasible. The latter is considered with both beam size options. A further push of β^* that could be allowed thanks to the reduction of geometric emittance with the higher beam energy are possible but are not discussed here in detail (see Table 2-3 for possible estimates, to be reviewed based on the 2017 operational experience).

These collimator setting scenarios are used in Section 2, where it is concluded that all configurations are expected to be compatible with the beam parameters considered for 7 TeV. It is noted that these setting scenarios are considered both for proton and heavy-ion operation.

At this stage, the scaling of quench limits at higher beam energy and with larger current in the magnets remains a concern for going to 7 TeV. The latest quench tests were performed in 2015, both with protons and lead ion beams, Ref. [16, 17]. Two quench tests were successful in that quenches were achieved for the case of steady, or nearly steady, beam loss scenarios. The quench that occurred with the lowest value of peak energy deposition was achieved with lead ion beam at magnet currents corresponding to a beam energy of 6.37 Z TeV. In this case, a quench was observed with peak losses in superconducting coils not exceeding ~ 15 mW/cm³, Ref. [16]. Proton quench tests at 6.5 TeV did not succeed in quenching magnets around IR7, with peak beam losses at 6.5 TeV up to about 600 kW, Ref. [18].

Based on these results, and remaining at 6.5 TeV, no issues would be expected for protons until Run III. The case of heavy ion beams is more critical: present estimates, see Ref. [19], indicate a limit of about 5 MJ stored beam energy with Pb ion beams at 7 TeV⁴. About 11 MJ were achieved at 6.5 TeV in 2016 during the Pb-p run, but at this stage we cannot guarantee safe operation with the anticipated 20 MJ of stored energy for Pb-Pb operation at 7 TeV. More reliable estimates could be achieved if additional quench tests were to be performed at 6.5 TeV in 2017 (although only protons will be available that year), trying to produce even higher beam losses to what has so far been achieved. One should also consider performing quench tests with both beam to see possible asymmetries between the two sides of IR7.

Apart from collimation losses, another potential source of quenches in heavy-ion operation are the beams of single-electron ions created by the bound-free pair production process at the interaction points. These are due to electromagnetic interactions between nearby nuclei, carry much more power than the luminosity debris and are focused on a specific location in the dispersion suppressor. They also increase significantly with energy. A strategy for displacing these losses to harmless locations using orbit bumps was already demonstrated in 2015 and can be applied around the ATLAS and CMS experiments, Ref. [16]. The installation of the TCLD collimators around the ALICE experiment during LS2, combined with orbit bumps, will allow the luminosity to be pushed to the maximum acceptable to ALICE without quenches. These losses might have required the luminosity at IP2 to be levelled below the optimum value of 10^{27} cm⁻²s⁻¹ if there were any Pb-Pb operation at 7 Z TeV before LS2. However, following the discussion at Chamonix 2017, this option has essentially been ruled out.

In 2016, the hardware and software availability of the collimation system was excellent, Ref. [20], with only 3 collimator-caused dumps in stable beam throughout the year. Since the effect

⁴ This estimate assumes a minimum beam lifetime at top energy of 0.2 h, which is smaller than what was observed in 2016 during the Pb-p run but is considered as a safer design value for future operation with pushed ion beam parameters.

from a $\sim 7\%$ increase in beam energy when moving to 7 TeV operations is expected to be negligible, we have at this stage no reason to expect a degradation of the system availability. On the other hand, the system is ageing so that we must continue the performance monitoring in 2017 to provide firmer estimates of expected availability in future years.

7.2 BLM Thresholds

Every BLM has individual beam abort thresholds for different integration times and discrete beam energy levels. The energy range between the injection energy of 450 GeV and the flat top energy of 7 TeV is divided into 28 discrete energy levels for which different thresholds can be defined for each BLM family. In general, the threshold value of a certain BLM for a fixed integration time decreases as the beam energy increases. The values of the thresholds and their dependence on beam energy are based on specific physical models. The thresholds active during 7 TeV operation are 2 energy levels above the ones applied during 6.5 TeV operation in 2015 and 2016. No modification of threshold tables is required as the underlying models have already been extended to 7 TeV. The only exception are BLM thresholds with a correction at top energy (e.g. due to luminosity or collimation-induced losses), which need to be adjusted to the new energy level. In addition, some empirical adjustments might be necessary during operation, similar to the ones carried out in 2015 and 2016.

Considering the lower threshold values, it is important to verify that the electronic noise of the BLM system, especially noise spikes, will not accidentally trigger unnecessary beam aborts. Fig. 7-1 shows the noise-to-threshold ratio for the shortest integration time ($40\ \mu\text{s}$) for all BLMs around the LHC rings. The noise values represent the maximum signals recorded in absence of beam between August and September 2016. The thresholds are the ones corresponding to 7 TeV operation. The ratio is smaller than 1% for most of the BLMs, with the exception of BLMs in S12, where thresholds had been decreased by a factor of 10 in August 2016 as a temporary measure to reduce the risk of quenches in view of the suspected inter-turn short in MB.A31L2. These thresholds will be reverted to higher values after the EYETS 2016/2017. The analysis confirms that if external noise sources remain at the same level it is unlikely that the BLM noise will trigger unnecessary beam dumps at 7 TeV.

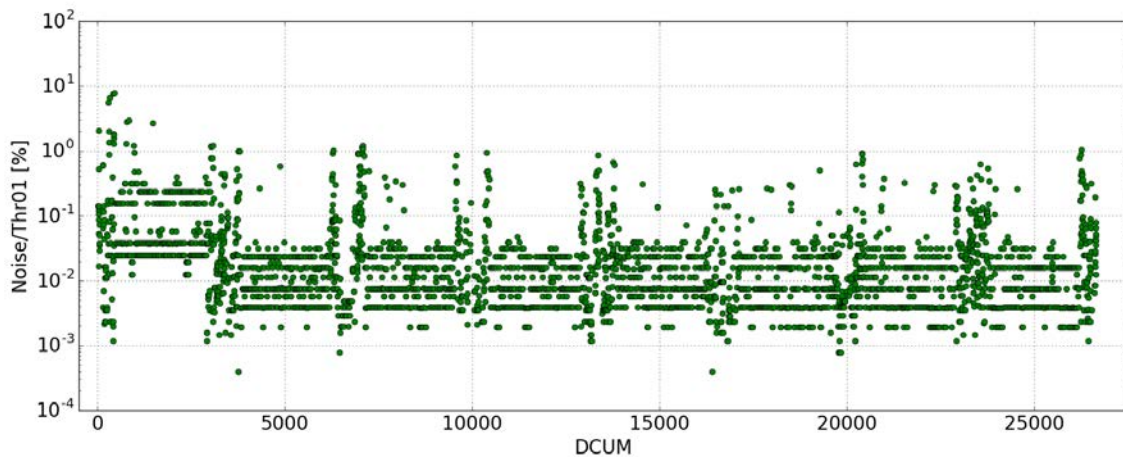


Fig. 7-1: Ratio of the maximum noise values measured in absence of beam (Aug-Sept 2016) and 7 TeV BLM thresholds (in the shortest integration time for $40\ \mu\text{s}$).

8 Beam Instrumentation Aspects

An increase in the machine energy from 6.5 TeV to 7 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 sections 7.2 and 10.1, with the resulting effect on machine availability treated in section 12.3. The influence of a reduction in the setup beam flag (SBF) intensity on its determination by the DCCT system is also treated in section 10.1. The wirescanner intensity limit at top energy will be slightly reduced from $\sim 1.6 \times 10^{12}$ to $\sim 1.55 \times 10^{12}$ protons, i.e. limited to some 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 $\sim 30\%$ in going from 6.5 TeV to 7 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 2.9nm to 2.5nm depositing ~ 21 mW of mainly X-ray power ($\sim 30\%$ more than at 6.5 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 (see section 12.1) will lead to a slightly 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 at top energy.

9 RF system and Damper

9.1 RF System

The RF systems were of course conceived and designed to run for an exploitation at 7 TeV, so no major upgrades are to be expected. However, the experience collected with runs 1 and 2 allows better estimates of stability and performance limitations.

9.2 Stability Limits

Running at the same bunch population as today, $1.15 \cdot 10^{11}$, the increase in energy by 7.7% would allow us to run with the exact same voltage and bunch length as today (12 MV, 1.1ns resulting in 2.2 eVs longitudinal emittance) with identical stability margins. An assumed bunch population increase of 10% ($1.15 \cdot 10^{11}$ to $1.3 \cdot 10^{11}$) could be coped with a slight increase of bunch length by 2% (1.10 ns to 1.12 ns or 82.5 mm to 84 mm rms).

Running at full nominal voltage (16 MV) would allow to reduce the bunch length to 1.07 ns (80 mm rms) with the same stability margin – this would of course have a negative effect on RF system availability and ageing. Due to a smaller damping time at 7 TeV bunches will shrink much faster, so more stability margin at the beginning of the physics could be useful.

Controlled longitudinal emittance blow-up used in the acceleration ramp is today working at the brink of producing diverging bunch lengths (with $1.15 \cdot 10^{11}$ ppb and 1.10 ns target bunch length).

To maintain the stability limits as described above is estimated sufficient to assure bunch length convergence.

9.3 Transverse damper system ADT

The electronic gain in the damper system must be increased proportional to the beam energy (by 7.7%) to maintain the same damping time as today. If stability margins are kept, a damping time of 100 turns for the lower coupled bunch modes should be sufficient, which can be achieved by correctly distributing the gain in the amplification chain to avoid saturation. The maximum available kick strength will be the amplitude of oscillation, from which the damper can recover the beam in case another element in the machine suddenly moves the beam. The maximum kick strength at 7 TeV is 130 nrad (2 μ rad at 450 GeV) and limits recovery to a maximum excursion; this limit is estimated to be 1 mm.

10 Machine Protection

10.1 Quench Limits and Margins as a function of beam energy

The increased energy is not expected to have a major impact on machine protection for the LHC. The machine interlock systems and their reliability are energy independent, however a few points should be kept in mind as they might have an impact on machine operation and availability (see as well Chapter 12 for the overall assessment):

- The value of the setup beam flag (SBF) will decrease from 1.12E10p (at 6.5TeV) to 1.03E10p (at 7TeV). 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 quench protection system is not expected to be impacted by the energy increase. While the quench margins of the main magnets will reduce with increased energy, the QPS threshold will remain identical as for 6.5TeV. Powering of corrector circuits is not linearly dependent on energy and the impact of 7 TeV operation is considered negligible.
- The number of asynchronous beam dumps is expected to increase due to the higher risk of erratic's in the beam dump elements. All generators will be upgraded and large-scale changes and subsequent validation program are planned during LS2 (See Chapter 11 for more details). So far, no asynchronous beam dump was observed at higher beam intensity, hence a first occurrence might require some time to assert the integrity of the dump protection elements, magnets in the LSS of point 6, TCTs.
- Quench limits and margins as function of energy and UFO scaling: For the 2016 run the BLM thresholds for the short running sums (RS01-RS05) in the arcs and dispersion suppressors were set to 1.5 times the assumed magnet quench level in order to limit the number of unnecessary dumps due to UFOs (the BLM system still assures a protection against magnet damage, which is typically several orders of magnitude higher than the magnet quench levels). This strategy has proven to be very effective in optimizing machine availability (4 dumps, 3 of which in sector 1-2 where BLM threshold were decreased mid of August 2016 as one of the mitigation measure for the suspected inter-turn short of MB.A31L2). This strategy also implies tolerating a certain number of quenches during operation.

Both in 2015 and 2016, 3 UFO-induced quenches were observed, although with different BLM threshold settings and a different machine conditioning status. These numbers are therefore not conclusive for an absolute extrapolation of the number of UFO-quenches to 7 TeV. In the coming years, it is foreseen to retain the present threshold strategy, if there is no necessity to reduce the risk of UFO-induced quenches (like it was the case for S12 in 2016). The following reasoning can be applied

to estimate a relative increase of the number of quenches. Operation at 7 TeV has the following implications:

- The quench level for transient (UFO-like) loss durations decreases by 20-30% (as predicted by QP3 and as implemented in the present BLM thresholds, Ref. [21, 22])
- The energy density in superconducting coils per inelastic nuclear proton-UFO collision increases by about 12% (as predicted by FLUKA calculations, Ref. [23]).

Based on these assumptions, one can conclude that the minimum number of inelastic proton-UFO collisions required to induce a quench is about 30-40% less at 7 TeV than at 6.5 TeV. As illustrated in Fig. 10-1, this implies that the number of events which can potentially induce a quench increases roughly by a factor 2 to 4. For comparison, both in 2015 and 2016 three beam induced quenches were observed, whereas BLM thresholds for UFO like losses were set a factor of 3 higher in 2016 wrt to 2015 operation.

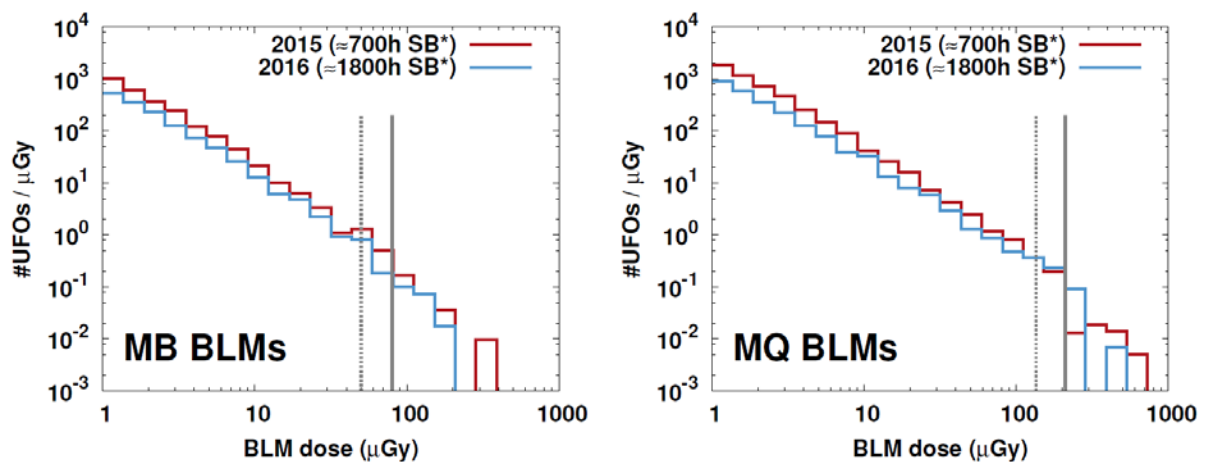


Fig. 10-1: Number of UFOs integrated over 2015 (red) and 2016 (blue) as a function of the BLM dose (left: MB BLMs, right: MQ BLMs). All events left of the solid vertical line are too small to induce a quench at 6.5 TeV (based on 2015 and 2016 experience), while all events left of the dashed line are too small to induce at quench at 7 TeV (assuming that the minimum number of inelastic proton-UFO collisions to induce a quench is 35% less at 7 TeV). The dashed line is affected with some uncertainty.

10.2 R2E: Radiation to Electronics

Kickers:

For the LHC machine dump system, running at 7 TeV will involve a voltage increase of both the deflection generators (MKD) and dilution generators (MKB). For the MKBV the 1.6 kV operation is low enough to rule out the risk of destructive Single Event Burnout (SEB) effects due to high-energy hadrons (HEH). However, the MKD GTO (gate turn-off thyristor) voltage will be increased from 2.7 to 2.9 kV, and the MKBH from 2.5 to 2.7 kV, for 7 TeV operation⁵. As shown in the plot below, Ref. [24], the impact on the ABB and Dynex GTO cross section is significant, with an increase from 2e-10 cm² to 8e-9 cm² and 7e-8 cm² to 5e-7 cm² respectively.

⁵ In the case of the MKB, the selection of the voltages is still under discussion and the possibility of lowering the voltage in order to reduce the probability of erratic is also being considered.

Especially in the case of the Dynex GTO, used in the MKBH generators, such a large cross section could potentially lead to destructive failures despite the very low radiation levels measured in the UA areas during the 2016 operation, with an estimated upper limit of $8e4$ HEH/cm², Ref. [25]. However, it is to be recalled that during LS1, the 300 Dynex GTOs in the MKD generators were replaced with the less sensitive ABB ones, therefore the more sensitive GTOs are now only present in the less critical MKB system. A failure in the MKB will lead to a synchronous dump. In addition, the shielding in the cable ducts connecting the UA with the LHC tunnel (RA) was reinforced during LS1.

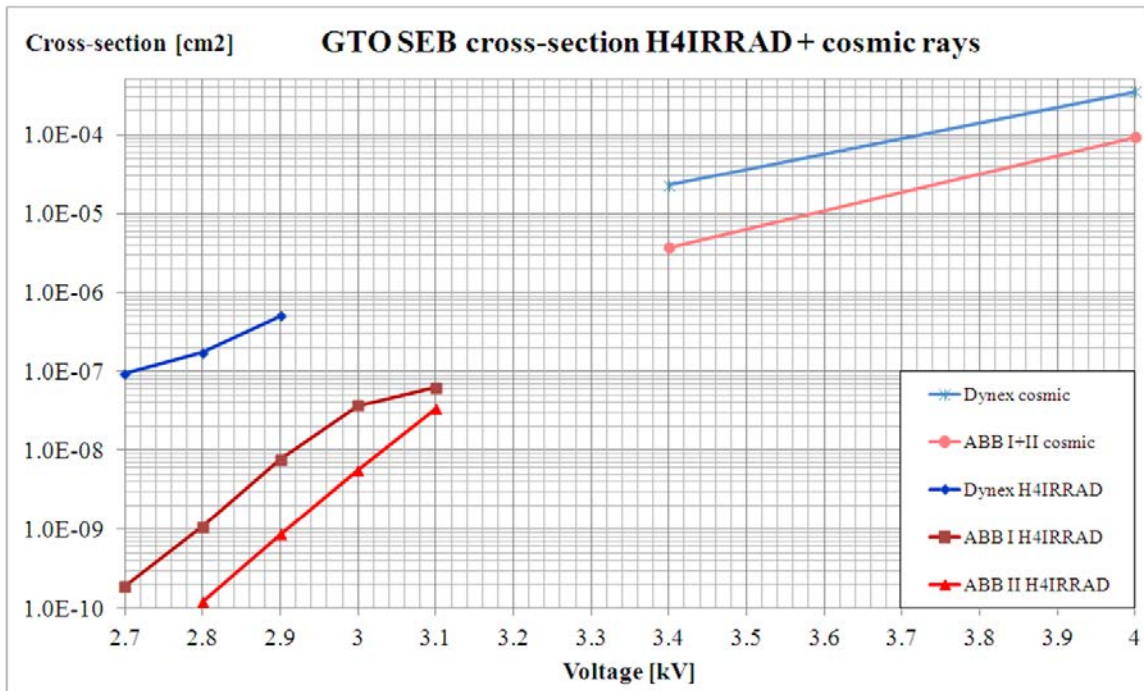


Fig. 10-2: GTO SEB cross section as a function of voltage for the Dynex (MKBH and MKBV) and ABB (MKD) generators as measured at the H4IRRAD facility and using cosmic radiation at ground level.

Radiation levels in the RRs:

As expected through dedicated simulation studies and observed during the 2016 run (see Fig. 10-3), the TCL settings in P1 and P5 strongly affect the radiation environment in the RR (13, 17, 53 and 57) alcoves, hosting a large quantity of critical equipment, notably the 120A, 600A and 4-6-8 kA power converters. Therefore, the TCL collimator settings in the 7 TeV runs will be crucial in determining the expected radiation levels, and thus could lead to slight increases in observed failures rates. However, the design limits for the equipment to be installed in the RRs is already compliant with the worst-case annual (50 fb^{-1}) radiation level. For the 2017/18 YETS, this should then be taken into account for the deployment of the FGClite radiation tolerant power converter controls.

It is important to note that – in view of HL-LHC operation only – that in case this would become a limiting requirement for appropriate electronic component choices or system designs (as to be analyzed during the early equipment qualification process), some additional shielding could be installed possibly leading to a reduction of a factor of 2-3.

The possible adoption of the ATS optics expected to induce a loss increase in the DS in P1 and P5 and respective R2E impact would have to be monitored and subject to further investigation.

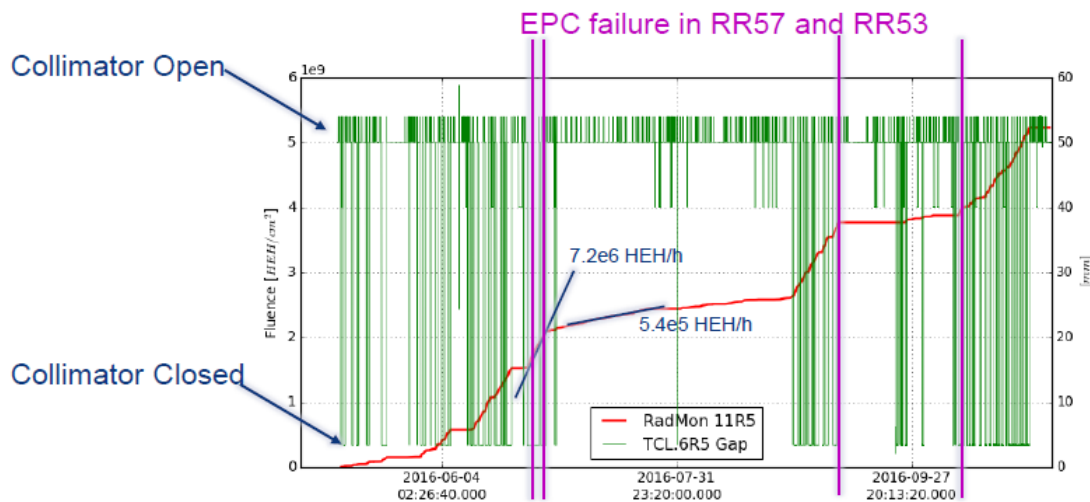


Fig. 10-3: Radiation level in the point 5 RR (tunnel side) as measured by the RadMON monitor correlated with the TCL6 settings.

ARC:

The radiation levels in the LHC ARC depend directly on the vacuum level, which in turn can be related to the e-cloud and scrubbing performance, which will need to be conditioned for the 7 TeV run. Therefore, the impact of the 7 TeV operation on the radiation levels in the LHC ARC will be carefully monitored through the normalized values of the relevant BLMs and RadMONs. Given the experience from 2015 and 2016 operation, this is however not expected to be a limiting factor nor to significantly contribute to equipment lifetime doses.

Particle losses in collimation areas (P3/P7):

The radiation levels in the RR and DS/ARC areas of P3 and P7 hosting a large number of electronic equipment are dominated by the losses in the primary collimation system. The latter could potentially significantly increase due to possible lifetime degradation related to the 7 TeV operation, thus increasing the radiation levels and associated R2E failures. Therefore, the relevant radiation levels will also be carefully monitored from a very early stage of the operation.

11 Machine Dump System

The LHC beam dump systems comprise several subsystems potentially 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 supposed to be designed for the LHC nominal energy of 7.0 TeV and the ultimate intensity of $1.7 \cdot 10^{11}$ p/bunch in 25 ns with $3.75 \mu\text{m}$ transverse emittance, Ref. [26].

However, the combination of difficulties in reaching the performance specification, performance problems revealed in the last years of 6.5 TeV operation and also significant changes in the operational LHC beam parameters mean that the performance reach at 7 TeV needs to be explicitly re-evaluated for each subsystem.

11.1 Extraction and dilution kickers MKD and MKB

The extraction kickers MKD are permanently charged with a voltage directly proportional to the beam energy. Run 1 experience at 6.5 TeV already revealed a weakness in the design of the MKD switches, with local electric field levels a factor of almost 2 above the accepted engineering level for air insulation, Ref. [27]. This led to some erratic triggering of MKD switches in tests and in operation, Ref. [28], which would lead to the serious case of a pre-triggered asynchronous dump, Ref. [29]. As a result, the switch has been redesigned with additional insulation and increased physical clearances at critical locations, to reduce the maximum field to the target of 1.5 MV/m. All generators will be upgraded to the new standard, but the large-scale changes and subsequent validation program needed mean that this consolidation can only take place during LS2. In the meantime, a mitigation program has been put into place to minimize environmental contamination, including periodic switch inspection and cleaning, reduction of the openings in the enclosures and some local increases of critical radii on mechanical parts. These measures have succeeded in keeping the system operating reliably in 2016, at 6.5 TeV, but have imposed a costly periodic maintenance.

Operating of the system at 7 TeV imposes a conditioning and testing at a higher voltage, which would logically be that corresponding to around 7.5 TeV. At present, with the known weaknesses in the switch and enclosure design, no sustained 7.5 TeV testing has been made, for fear of significant damage to the operational installation (GTO switches, charging capacitors, ...), and also because of the need to requalify the MKB system after separate problems needed to be solved in the 2016/17 EYETS (see below). The earliest opportunity for such a 7.5 TeV test period (reliability run) would be the start of the 2017/18 YETS, which if successful would allow attempting 7 TeV operation in 2018. However, it would be preferable to finish the generator consolidation in LS2 and to qualify the system for 7 TeV operation then, to avoid operating at the maximum voltage with a known weakness in the system.

It should be noted that the voltage issues of the MKD could be cured by increasing the main capacity, but at the cost of increasing the rise time. A 40% increase in capacity would lead to 18% reduction of the main voltage, which would open the possibility to operate up to 7.5 TeV at a voltage corresponding today to 6.3 TeV, without need to replace the stacks. The rise time would increase by several hundred ns to about 3 ms (with new trigger transformer and present stacks). The changes would also reduce the overshoot in the kicker waveform which would result in slightly larger aperture margins, Ref. [30]. Additional direct consequences of reducing the voltage would be a reduction in SEB probability (see R2E section above), to lower than today at 6.5 TeV.

For post-LS2 operation, 7 TeV should not pose any issues for the MKD system, and we should be at least as reliable as the present system at 6.5 TeV. But for now, we cannot quantify the reduced availability of the system until a dedicated 7.5 TeV reliability run is made.

The dilution kickers MKBH and MKBV are also permanently charged with a voltage directly proportional to the beam energy. Operation in 2016 revealed two weaknesses in the MKBH system (which has a much higher charging voltage than MKBV), with problems of HV hold-off and also EMC coupling between generators, Ref. [31]. An intense diagnosis and mitigation program was needed from the second Technical Stop through the EYETS, to attempt to understand and solve the issues (preventing a dedicated 7.5 TeV reliability run as had been initially planned). The main aim of the EYETS reliability run in 2016 therefore was modified to validate 6.5 TeV operation.

The EMC coupling issues appear to have been solved, Ref. [31], with the solution involving extra shielding and common-mode rejection on the retrigger lines having already been deployed during the EYETS in 2016/2017. However, the underlying HV breakdown weaknesses are still present and potentially exacerbated by the use of the Dynex GTO switches in the MKBs – these are known to be more susceptible to SEB (see R2E section above), and the effects could be linked to radiation. The mitigation of careful inspection and cleaning of the generators has also been instigated, and a consolidation program has been defined for LS2, which could include a new retriggering circuit as long-term mitigation of any MKB coupling.

For the MKBH generators, therefore, the present situation is that operation at 6.5 TeV is already problematic, requiring sustained and careful mitigation, until the consolidation in LS2 is completed. Post LS2, operation at 7 TeV should be at least as reliable as the 6.5 TeV operation seen to date

11.2 Extraction septa MSD

The MSD septa are comprised of three types MSDA, MSDB and MSDC that differ in the septum thickness and the saturation behavior. 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, Ref. [32], 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.

11.3 Protection devices TCDS and TCDQ

The protection devices TCDS and TCDQ were both designed for the so-called LHC “ultimate” beam, although the TCDS performance was expected to be at the limit for this set of parameters, Ref. [33]. Importantly, the transverse emittance of the beam is not very important for the damage limits of the devices themselves, since the beams are always swept. It should be noted that the worst-case load case for the devices was taken as the single kicker pre-trigger asynchronous dump.

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. Instead, limits have been extrapolated from existing analyses and from scaling of the appropriate quantity, where either protection efficiency per se (dilution) or diluter robustness are concerned. This approach has, for instance, also been used to derive limits for high-brightness beam types, Ref. [34].

Overall, operation with 7 TeV as compared to 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, provided that the total beam energy and transverse energy densities for the failure cases are comparable to those of the design parameters (also at 7 TeV). Assuming a very conservative scaling with the square root of the transverse emittance, the 7 TeV intensity limit per bunch at 2 μm would be around 1.3×10^{13} protons per bunch for 2808 bunches, which lies clearly above the foreseen intensities for the LHC and HL-LHC operation.

11.4 Beam dump block TDE and entrance window VDWB

The TDE beam dump block and VDWB entrance window were also both designed for the so-called LHC “ultimate” beam, Ref. [35]. The transverse emittance of the beam is only 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. The increase in beam energy from 6.5 to 7 TeV does not affect the system safety in this respect.

The recent (2016) issues with leaks on the beam dump block entrance and exit flanges are still under investigation, and are possibly linked to vibrations at the moment of the beam dump, or to the pressure variations following the heating of the dump core and N₂ protective atmosphere. The 8% extra energy (for identical beam current) is not expected to pose any significant new risks, although clearly it may exacerbate any existing weaknesses and slightly reduce the availability of the system.

11.5 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 TeV, for the BTVS, BTVD and BTCDD screens, the ionization BLMs, the BCT current transformers, or the BPMD pick-up.

11.6 Conclusion

The beam dump system does not pose any hard limit preventing operation at 7 TeV, or limiting the beam intensity. The beam intercepting devices were all designed for the original ultimate beam parameters at 7 TeV, and the 7 TeV use-cases are basically the same as 6.5 TeV. However, the known HV hold-off weaknesses in the MKD and MKBH generators in conjunction with the planned consolidation program in LS2 mean that a careful validation of the system for 7 TeV operation can only take place in the 2017/18 YETS, if 7 TeV operation is to be attempted in 2018. A more comfortable scenario would be to plan 7 TeV operation after LS2. The option of reducing the MKD operating voltage by increasing the main capacitor values should be investigated.

12 Considerations concerning overall machine efficiency and integrated luminosity

12.1 General Operational Considerations on Parameter Evolution during a Physics Fill

The evolution of the beam parameters in collision was evaluated using a self-consistent model including Intra-Beam Scattering, synchrotron radiation and burn-off for an inelastic cross section of 81 mbarn, see Ref. [1]. The evolution of the transverse emittances and bunch length versus time for a total physics time of 20 hours and for the initial beam parameters considered in Table 2-1 are plotted in Fig. 12-1, with the blue and red curves corresponding to the BCMS beam, whereas the yellow and purple ones correspond to the standard LHC beam. Levelling is performed when either the luminosity limit imposed by the experiments on the maximum average pile-up (here assumed to be 60 events per crossing, Ref. [3]) or by the maximum acceptable heat load on the triplet cold masses is exceeded.

The effect of higher brightness (for BCMS) and faster radiation damping (at 7 TeV) is observed when comparing the evolution of the transverse emittances and bunch lengths. It is interesting to point out, that for these initial bunch parameters only for the case of BCMS at 6.5 TeV, the damping is less strong (especially in the horizontal plane). In particular, we assume here that longitudinal blow-up is applied as soon as the bunch length shrinks down to 1 ns.

The evolution of the bunch population and of the peak luminosity for CMS during the fill are shown in Fig. 12-2. ATLAS will reach higher luminosity because the vertical emittance is damping faster and the geometric reduction factor from the crossing angle is becoming smaller. It is worth noting, the quasi-parabolic evolution of the luminosity for the standard beam, between the longitudinal emittance blow-up steps, due to the clear dominance of radiation damping, that shrinks fast all beam sizes.

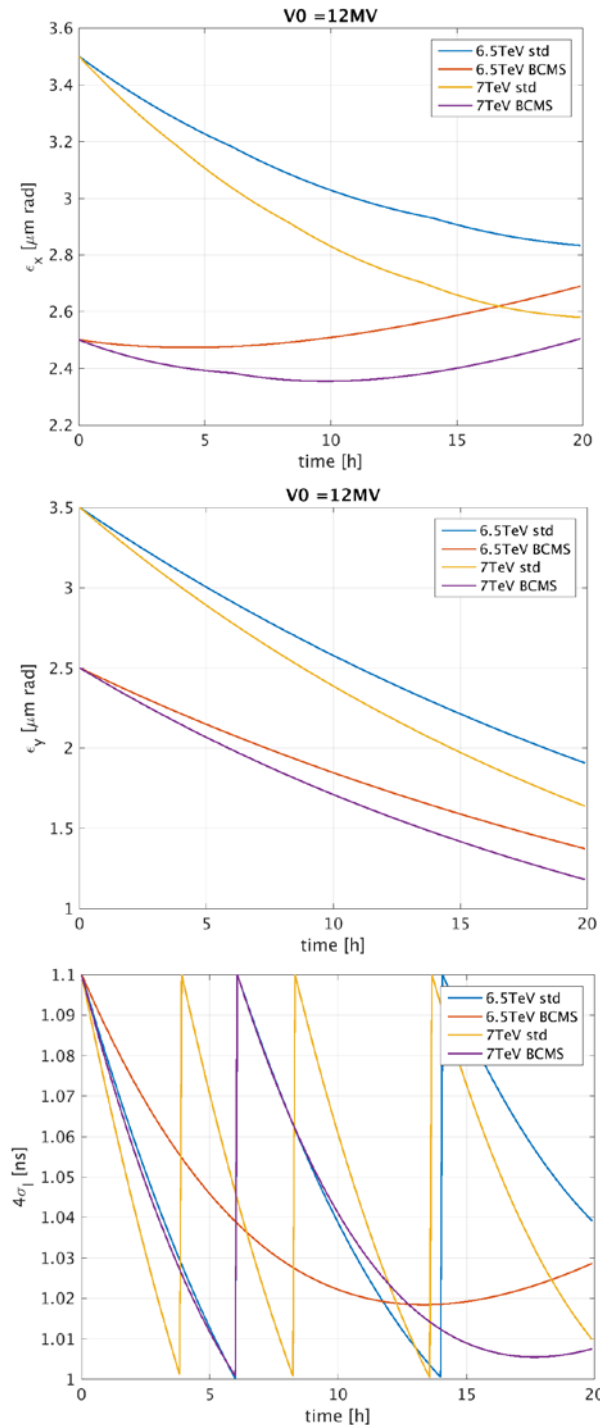


Fig. 12-1: Evolution with time of horizontal (top), vertical (middle) emittances and bunch length (bottom) for the BCMS (red and purple) and Standard (blue and yellow) LHC beams for the 2017 machine parameters and the two energies of 6.5 and 7 TeV.

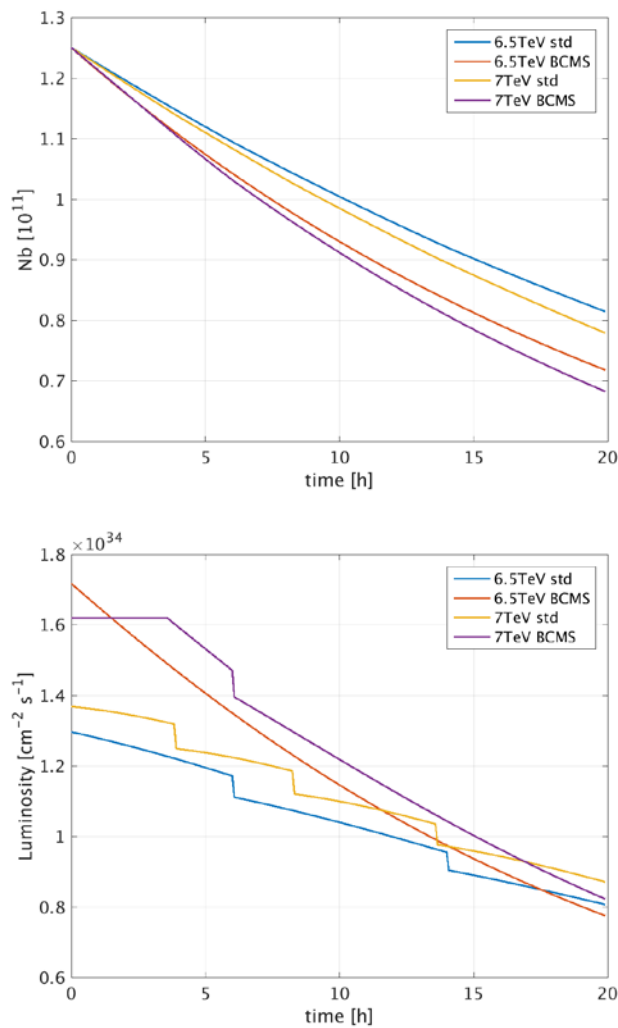


Fig. 12-2: Evolution with time of bunch intensity (top) and luminosity (bottom) for the BCMS (red and purple) and Standard (blue and yellow) LHC beams for the 2017 machine parameters and the two energies of 6.5 and 7 TeV.

The evolution of the integrated luminosity per day, considering a turn-around time of 4 h, based on the experience of the 2016 run is shown in Fig. 12-3 for a machine availability of 100%. The optimal physics fill length changes from almost 18-20 hours to approximately 10-12 h, from the standard to the BCMS beams, whereas the variation of the optimal fill length due to an energy change from 6.5 TeV to 7 TeV is much less pronounced and almost negligible for the nominal beam parameters. In all cases, though, the maxima are quite flat, indicating that even when fixing a physics fill length of the order of ~15 h for all scenarios, the deviation from the maximum integrated luminosity will be rather small. In the same plot, the value of the maximum attainable luminosity per day is displayed, assuming 100% machine availability.

The corresponding plots comparing the performance at 6.5 TeV and 7 TeV with the optimized machine parameters in Table 2-3 are shown in Fig. 12-4, Fig. 12-5 and Fig. 12-6. In that case, the BCMS beam has to be levelled for a longer time and finally the evolution of the luminosity is comparable for all cases, leading to comparable integrated luminosities per day. The performance for the studied cases is summarized in Table 12-1.

Table 12-1: Integrated luminosity parameters assuming an ideal 100% machine availability. Comparison between 6.5 TeV and 7.0 TeV assuming the beam parameters in Table 2-1 and Table 2-3 and 100% efficiency.

Energy [TeV]	6.5		7.0	
Scheme	Standard	BCMS	Standard	BCMS
Integrated luminosity [$\text{fb}^{-1}/\text{day}$] for Table 2-1 parameters	0.75	0.85	0.80	0.90
Integrated luminosity [$\text{fb}^{-1}/\text{day}$] for Table 2-3 parameters	0.83	0.94	0.92	0.99

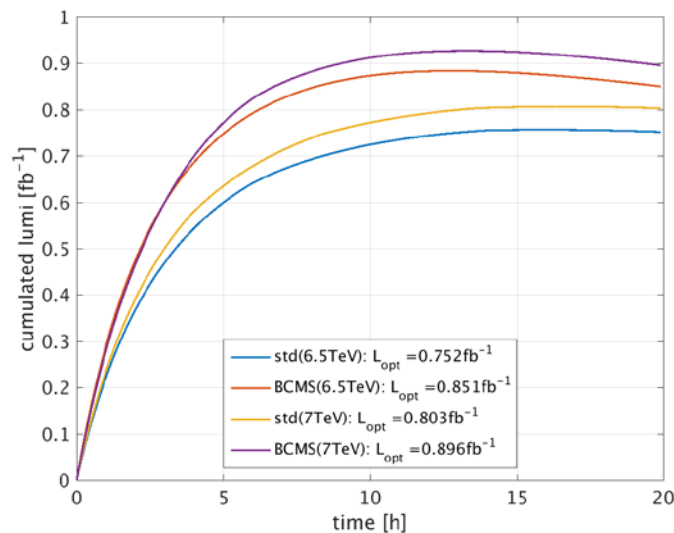


Fig. 12-3: Evolution of integrated luminosity with time for one day of physics, considering a turn-around time of 4 h for the BCMS (red and purple) and Standard (blue and yellow) LHC beams for the 2017 machine parameters and the two energies of 6.5 TeV and 7 TeV.

The saturation effects of the magnets are not negligible but are well understood and, based on this information and on the present experience, no significant impact on recommissioning is expected from an energy increase. The re-commissioning and optics measurement and correction steps are expected to be very similar to those required after any end of year stop.

Quantifying the impact of operation at 7 TeV on LHC physics efficiency implies estimating the additional number of premature dumps due to the energy increase and the related impact on system downtime. Experience from LHC Run 1 and Run 2 suggest that the following factors will potentially have an impact on operation at higher energies:

- Expected quench rate and number of beam aborts
- Time available for physics production
- Overall machine efficiency and integrated luminosity

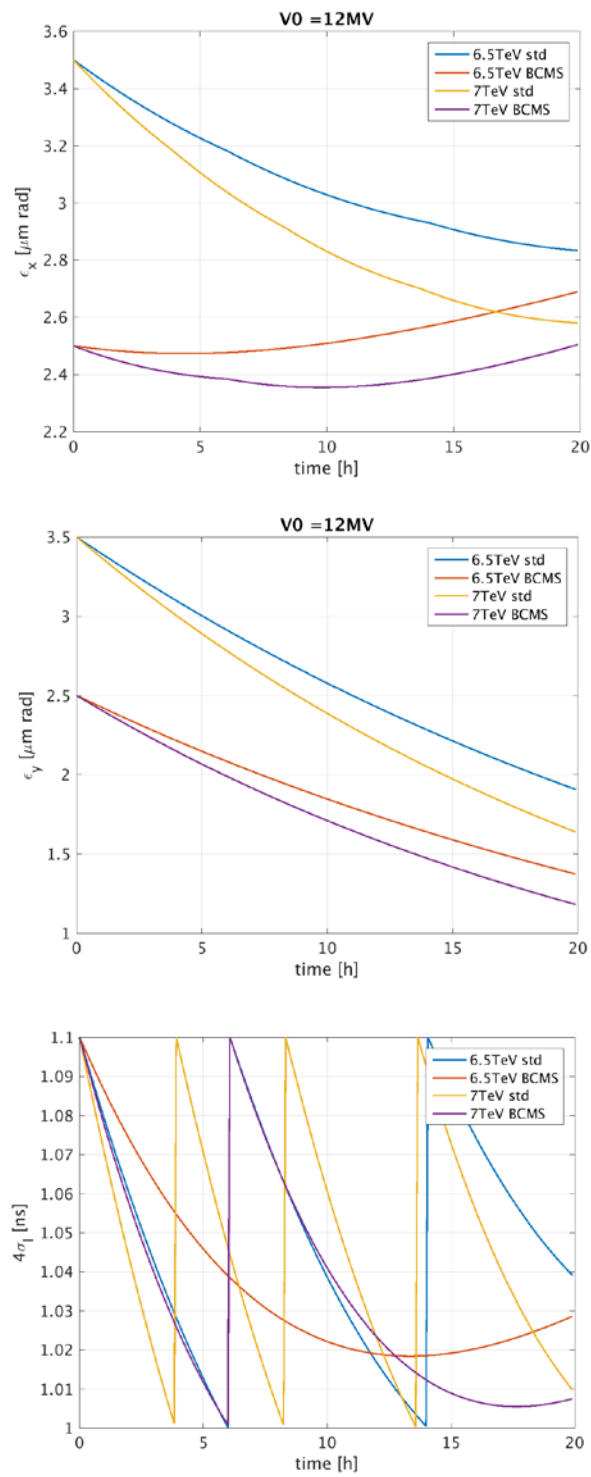


Fig. 12-4: Evolution with time of horizontal (top), vertical (middle) emittances and bunch length (bottom) for the BCMS (red and purple) and Standard (blue and yellow) LHC beams for optimized machine parameters at 6.5 and 7 TeV.

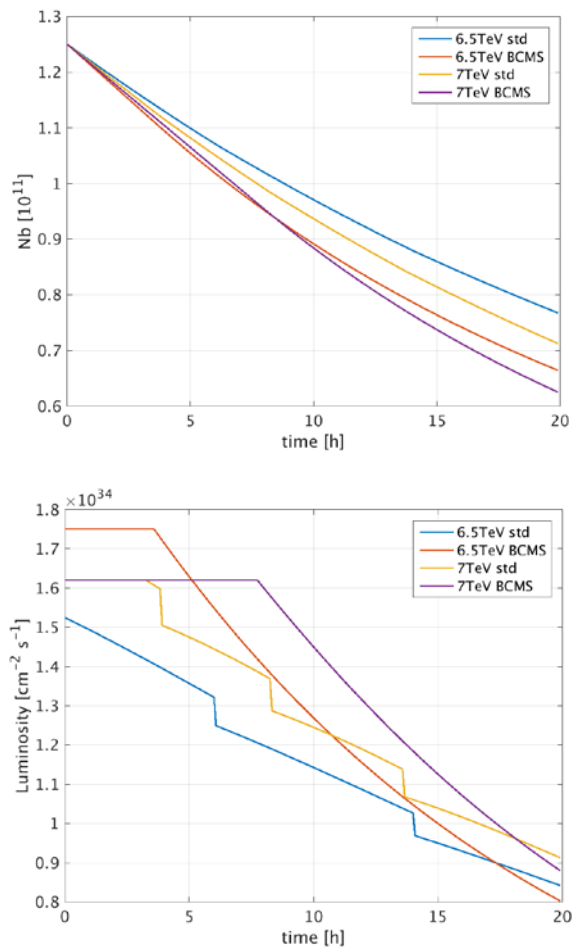


Fig. 12-5: Evolution with time of bunch intensity (top) and luminosity (bottom) for the BCMS (red and purple) and Standard (blue and yellow) LHC beams for the optimized machine parameters at 6.5 and 7 TeV.

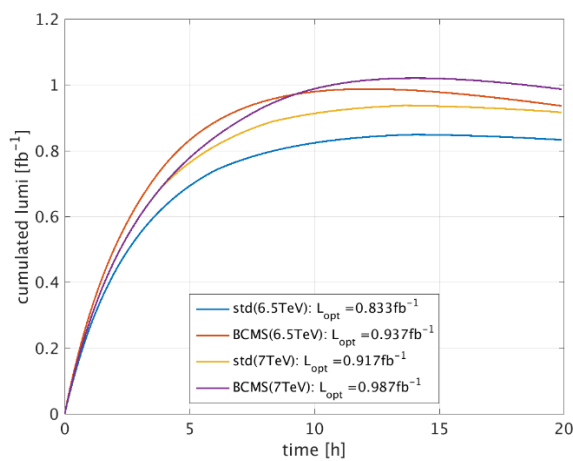


Fig. 12-6: Evolution of integrated luminosity with time for one day of physics, considering a turn-around time of 4 h for the BCMS (red and purple) and Standard (blue and yellow) LHC beams for the optimized settings at 6.5 TeV and 7 TeV.

12.2 Machine Efficiency degradation due to the cryogenic system

The achievable peak luminosity will be influenced by the limits imposed by the triplet cooling. The guaranteed value for operation at 7 TeV is $1.63 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ but operation in 2017 achieved already values as high as $1.75 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Beyond this value, losses of cryogenic conditions might be experienced, with a direct impact on machine availability. The limits imposed by steady state effects of e-cloud at 7 TeV [see Chapter 6] and the cryogenic cooling capabilities have been quantified. Excessive heat loads represent potentially a global limitation for operation with higher beam current, therefore not only related to the energy. It is assumed that operation will be carried out in the allowed parameter space imposed by cryogenic constraints. Nevertheless, depending on the selected beam parameters, it might be necessary to modify the optimized cryogenic configuration of 2016, featuring four cold compressor units out of eight, and make use of all cold compressor units. This statistically implies doubling the expected failure rate. In 2016 only two failures of cold compressors occurred (0.5 failures/year/cold compressor).

Studies are ongoing to further improve the developed cryogenic feed-forward system that allows compensating for dynamic heat loads, specifically during injection and dump phases. This aspect represents one of the main contributors to the excellent performance of the cryogenic system in 2016.

The higher energy stored in the beams and in the magnets at 7 TeV implies longer quench recoveries. Experience from the 2016 training campaign shows between 20 and 50 % longer quench recovery times (8 – 15 h) with respect to 6.5 TeV operation. As an estimate, one could consider 10 h for an average quench recovery at 7 TeV.

12.3 Machine Efficiency degradation due to UFOs and BLM thresholds

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 estimate 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 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). 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 LS2 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 2016 for BLMs installed on or close to TCTs, the Roman Pots or individually powered quadrupole magnets.

12.4 Flat-top quenches in operation

The number of flat-top quenches in operation at 7 TeV will depend on the margins achieved during the magnet training campaign. It is assumed that the magnets will be trained to 7 TeV with a margin of 150 A, namely to 12 kA. This implies 50 A more margin with respect to what achieved for operation at 6.5 TeV. Under these assumptions, flat-top quenches in operation are not expected to be a limiting factor for LHC availability.

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. A procedure to recover from such events has been put in place and validated. This requires around 5 working days to be finalized before recovering operating conditions (including the ELQA campaign and subsequent powering tests). Given the higher concentration of quenches during the training campaign compared to nominal operation, the probability of having such an event during the physics production period is considered negligible. This factor is therefore not accounted when evaluating the impact on machine availability.

12.5 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 separately in the section 'Radiation to electronics'). 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. Based on these elements, no major impact on the power converter failure rate is expected going to 7 TeV, thanks to available margins. From LHC operation in 2016 (213 days), 71 trips were observed, with 1.6 h average recovery time. In 2016, a total of 15 failures due to power converters occurred in stable beams, leading to a premature dump. A similar impact is expected also for operation at 7 TeV.

12.6 Machine Efficiency degradation due to Beam dumping system

In 2016, two erratic triggers of a dilution kicker (MKB) were observed in operation, leading to a synchronous beam dump and requiring the replacement of a MKB generator (10 h). In addition, one preventive generator replacement was carried out. This operation entails performing a system re-validation (5 h) to verify the correct functionality of the system. The performance for operation at 7 TeV will depend on the effectiveness of the mitigation strategies that will be applied during the 2016-2017 EYETS (mainly cleaning of the generators, installation of better dust protection...) and in LS2.

Similarly, also MKD kickers can exhibit erratic triggers. In this case, nevertheless an asynchronous beam dump is performed, potentially leading to the quench of several magnets when operating with high beam intensities and subsequent longer recovery times. In addition, some hours might be required afterwards to confirm the correctness of the abort sequence, the sanity of the dump protection elements, TCTs, etc... It is assumed that 2 days will be necessary to recover from such event. The mitigations deployed during the LS1 have proven to be very effective in order to limit the number of erratic triggers of MKDs (cleaning procedures and improved isolation of the generators). It is therefore expected to observe, as from design specifications, one asynchronous dump per beam per year.

12.7 Machine Efficiency degradation due to Radiation to electronics

The expected increase of High Energy Hadron (HEH) fluence going from 6.5 to 7 TeV is not significant, therefore no sizeable impact on the number of SEU-dumps is expected. If the energy increase to 7 TeV will take place after the YETS 2017-2018, the FGCLite (radiation tolerant power converter controls) will have been deployed as well in the RRs, thus further reducing the impact of radiation effects. Overall, based on 2016 experience, it is expected to have in the order of 0.2 dumps/fb⁻¹.

12.8 Cycle duration

Operation at 7 TeV will require longer times for performing magnet ramps. The time difference between the duration of the ramp-up phase at 6.5 TeV and at 7 TeV is about 120 s. The time difference between the duration of the ramp-down phase at 6.5 TeV and at 7 TeV is approximately 5 min. 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 7 h. The occurrence of more failures requiring pre-cycles could potentially lead to a longer average turnaround (see paragraph 12.9).

12.9 Conclusions on Machine Efficiency for Operation at 7 TeV: impact on physics efficiency

Based on the experience with the 2016 LHC run and the factors discussed in paragraphs 12.2 to 12.8, two scenarios were considered ('conservative' and 'relaxed'), to assess the potential impact of operation at 7 TeV on the machine efficiency. Starting from 2016-like fault distributions for all systems, the underlying assumptions for these two scenarios are reported in Table 12-2 for systems concerned by the energy increase. 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 limited to a factor 1.5. These numbers were considered as all failure modes in Table 12-2 require at least one pre-cycle to recover operating conditions.

Based on the presented assumptions, one concludes:

- a loss of availability of 5 - 15 % is estimated due to operation at 7 TeV with respect to operation at 6.5 TeV in 2016. This corresponds to a loss of physics efficiency of 4 - 10 %.

Following the discussions at Chamonix 2017 it was decided to move to 7TeV operation not before LS2.

Table 12-2: Assumptions for failure rates and recovery times for the availability assessment for 7 TeV LHC operation.

System/ Failure Mode	Conservative		Relaxed	
	Occurrence (1/year)	Downtime (Days)	Occurrence (1/year)	Downtime (Days)
MKD erratic	4	8	2	4
MKB erratic	6	4	4	3
Flat-top quench	10	4	5	2
UFO-induced quench	10	4	3	1
Cold-compressor failure	4	4	2	2

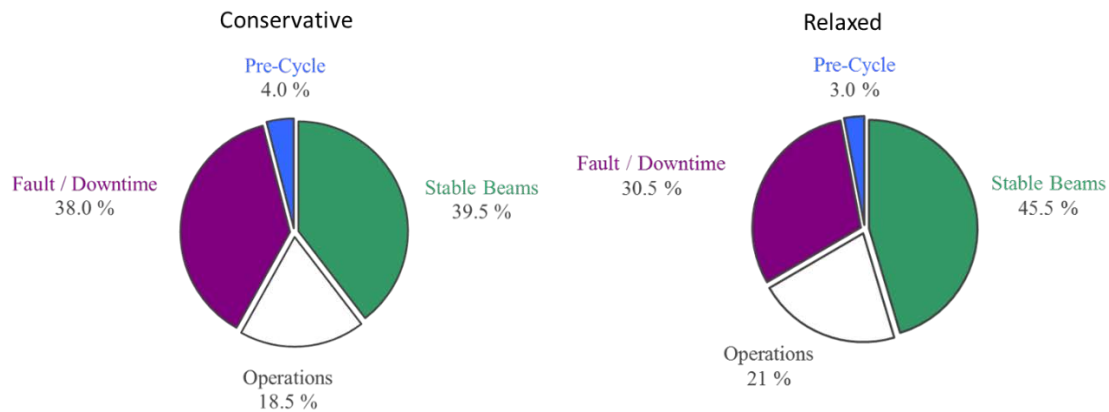


Fig. 12-7: Expected LHC availability for 7 TeV operation for the ‘conservative’ and ‘relaxed’ assumptions discussed in paragraph 12.9.

13 Modifications foreseen during LS2 and that might impact on the above analysis

One of the risks associated with extensive training of the LHC arc magnets, as would be necessary to achieve energies in excess of 6.5 TeV per beam, is to induce electrical faults in the main circuits, dipole (and quadrupole). This happened twice over the 252 quench events since 2014, 2 [single] shorts to ground occurred in cryo-dipoles, one in March 2015, the other in December 2016, both during commissioning/training campaigns, and both located in the diode box. Based on previous experience and finding during series construction and test of the arc magnets, it is known that the diode box is a delicate location, where metallic debris blown by helium during quenches can touch live bus-bars and connections and yield an electrical fault. It is expected that with the increase of the current in the magnets during the training campaign and the occurrence of multiple quenches at high current, the risk of electrical shorts will increase.

In the follow-up of the LHC Performance Workshop held at Chamonix in January 2017 (<https://indico.cern.ch/event/580313/>), the CMAC issued recommendations aiming at a detailed risk analysis, devising methods to mitigate electrical faults, and specifically studying the possibility to remove debris in all magnets, to clean and better insulate the diode boxes and establish the necessary time and resources required to do it, possibly during LS2.

A Working Group was setup in the TE department to answer these recommendations and issue a report for May 2017. It will address the following items:

- Perform a detailed risk analysis of the potentials problems caused by magnet training,
- Identify methods (if any) for debris removal, including but not limited to flushing,
- Propose mitigation methods in case of electrical faults (if any), including but not limited to the Earth Fault Burner (EFB),
- Proposal conceptual design and technical options to reinforce the dipole diode insulation,
- Establish time and resources to implement this plan during LS2,
- Integrate this activity in the LS2 scope and assess the impact on budget and schedule.

This is still work in progress and a final recommendation of the working group will be issued at a later stage in a separate report.

14 Summary and Conclusions

No critical circuit non-conformities have been identified, which would limit the operation at 7 TeV in the present optics configuration. Albeit some hardware components might imply extended training times (e.g. circuit RD3.L4 had shown a rather slow magnet training in the past and has therefore only been trained for operation up to 6.9TeV) and reduced machine efficiency for operation at 7 TeV (e.g. the LHC beam dump kicker system might feature higher fault rates due to voltage breakdowns when being pushed to 7 TeV operation). However, all these hardware limitations can be addressed and mitigated during LS2 such that there should be no hardware limitation for operation at 7TeV after LS2.

The strength level of the IR2 and IR8 triplet quadrupoles at injection is determined by machine protection considerations at injection (phase advance between MKI and TDI) and does not allow ramping them at constant normalized strength, and hence at constant optics, up to 7 TeV. Therefore, operation beyond 6.5 TeV will require an optics change for IR2 and IR8 during the ramp. MQX1 and MQX3 impose this limit, while it would be possible to ramp the Q2 at constant strength up to 6.6 TeV. Operating IR2 and IR8 at 7TeV will imply reducing the triplet strength at constant beta* value after the injection process has been finalized.

The results of the 2016 training campaign of sectors S34 and S45 towards 7 TeV confirmed the initial estimates in the number of expected magnet training quenches and the statistical behavior of the magnets for each training campaign after a thermal cycle. Given the purely statistical behavior of the magnets during the training campaign after each thermal cycle, one can expect in the order of 530 first quenches plus approximately 70 second quenches, yielding a total of approximately 600 quenches in the entire machine before reaching 7TeV. A more optimistic estimate can be derived by splitting the production of the 2000 and 3000 magnet series productions into two batches each, one with faster and one with slower training, which would bring the estimate down to approximately 500 quenches in total.

The training campaign in 2016 also revealed that an extensive training campaign of all sectors towards 7 TeV must be prepared to face multiple magnet quenches at higher magnetic fields. This has an impact on the recovery time for obtaining the cryogenic conditions for continuing the circuit powering after a training quench. Concerning the recovery time for the cryogenic system it appears prudent to assume not more than 2 training quenches per 24 hours per sector.

Based on the statistical analysis of the magnet training and the experience with the training quenches and recovery of cryogenic conditions after a given quench one can estimate approximately 25 days of training for bringing the machine to 7TeV before LS2 (as the machine underwent already a significant number of training quenches) and approximately 35 days of training after warm-up/cooldown in LS2 once the existing training memory has been lost. These estimates apply to each sector and provide the total training time only if the sectors with the slowest training start their training at the beginning of the training campaign and if all sectors are trained in parallel towards the end of the training campaign.

The training campaign in 2016 also revealed that an extensive training campaign of all sectors towards 7 TeV must be prepared to face additional short-to-ground earth faults in the magnet diode box and raises in particular the worry about two coinciding earth faults in one sector which could have devastating consequences on the hardware installed in the LHC tunnel. The discussions at the 2017 Chamonix performance workshop highlighted these risks and lead to the decision to launch the preparatory work for intervening on the diode boxes during LS2 (cleaning of the boxes and implementing additional insulation at the level of the half-moon connection).

Together with the existing technical limitations of the LHC beam dump kicker system that are foreseen to be solved during LS2 and the only marginal interest of the experiments to move to a higher collision energy in the LHC before LS2 led to the decision at the 2017 Chamonix performance workshop to push towards operation with 7TeV beam energy only for after LS2 and to assure that the required consolidation work (diode insulation and dump kicker system) will be addressed during LS2.

However, the decision to plan the move for 7 TeV operation for after LS2 still leaves open the question of the best time for performing a first global training campaign of all the magnets to 7 TeV. Leaving such a test until after LS2 bears the risk of missing potential show stoppers and hardware faults that only reveal themselves once the magnets are powered close to 7 TeV. Performing this 'test' before LS2 bears the risk of equipment damage due to performing the campaign before implementing the consolidation work on the dipole diode boxes and that the training campaign will need to be performed twice as most (if not all) sectors in the LHC will be warmed up during LS2 and will therefore lose their training memory. A dedicated study has therefore been launched to look at options for performing the magnet training as early as possible in the LHC after the vital hardware modifications have been implemented in LS2 so that the magnet could remain cold until Run III or could still be repaired without too much impact on the start of the Run III period.

15 Annex 1

A.1 Introduction

The main LHC dipole magnets may under certain conditions develop after a quench in the tunnel earth faults in the area of the so called ‘half-moon’ connections that connect the parallel cold bypass diodes to magnets. This connection is located in the lowest point of the cold-mass and rapid helium flows may cause metallic debris – residual from the assembly technological process – to move into the diode container. These helium flows may occur not only during the flushing of the cryogenic installation, but also during quenches at high currents. In certain circumstances these metallic debris may cause – in combination with the non-ideal mechanical assembly and insulation of the diode boxes - the development of an earth fault. Such cases have been observed twice in the LHC machine: once in 2015 during the magnet training after LS1 and once during the magnet training in during the EYETS 2016 / 2017. In both cases, the fault occurred in Sector 34 and could be eliminated with the Earth Fault Burner.

With only 2 observed earth faults during the training it is not easy extrapolate with a high value of accuracy, but taking into account the total number of 204 training quench events it seems that the probability of earth faults in the region of diode containers may be in the order of 1 earth fault per 200 to 400 quench events. It may also be that the probability is higher at higher quench currents as more magnets may quench and more violent helium movements occur in the cold mass. In any case, the observation of these two earth faults underlines the need to be ready and prepared for addressing such earth faults during future magnet training campaigns.

The elimination must follow strict procedure as it is not fully risk-free. This chapter describes the details of such earth fault elimination and takes as an example the actions performed in December 2016. A detailed report on the Earth Fault Burner and the procedure for its application can be found in EDMS 1741891.

A.2 Application of the Earth Fault Burner

Application of the Earth Fault Burner must be preceded by the following diagnostic steps:

- Verification of the circuit fuse.
- Disconnection of the DC warm cables and identification if the fault occurs in the warm or cold part of the circuit.
- Precise localization of the earth fault in the cold part of the circuit.
- Confirmation via X-rays of the nature of the fault and its location in the ‘half-moon’ connection.
- Pre-qualification of the magnet for the application of the Earth Fault Burner.

If the above measures support that the earth short is located in the ‘half-moon’ connection and that the nature of the short is metallic debris, the Earth Fault Burning method can be applied for removing the fault. The cryogenic cell in which the magnet is located needs to be stabilized at 3.3 K and the pressure needs to be increased to about 1.6 bar. These conditions ensure no superfluid helium in the burning area – this would limit gaseous helium bubbles generation which help with the displacement of the accumulated debris. The discharge for the Earth Fault Burner is initiated remotely from the CCC with the help of a dedicated application that automatically records and stores the measurement curves from 6 measurement channels.

A.3 Tests after the application of the Earth Fault Burner

After the application of the EFB the circuits need to be checked. It can be seen immediately after the discharge if the fault remained or not: if the RB line remained charged to a certain voltage and the capacitor bank was not completely discharged it means that the discharge was at least partially successful. This is then fully verified with the standard ELQA TP4-B HV test procedure that defines

the minimum voltage withstand level of cold RB circuits to be at 2100 V with the expected leakage current of less than 50 μ A. ELQA MIC is also performed to check the integrity of the instrumentation of the affected magnet. Another X-ray image should be acquired in addition to these qualification tests to verify the state of the debris in the half-moon area after the Earth Fault Burner application. Fig. 14-1 shows the X-ray image of the ‘half-moon’ connector of the magnet affected by the short during the EYETS 2016/2017.



Fig. A-1: X-ray image of the ‘half-moon’ connector of the affected magnet during EYETS 2016/2017: before and after burning of the fault.

A.4 Potential Damage of Other Components

Potential damage to other components during the Earth Short Burning includes:

- Overtoltage in the chain:

The RB line is composed of multiple distributed parasitic capacitances and multiple inductances connected in one circuit. In case the earth fault disappears immediately after the EFB is triggered (or it is not present at all at the moment of EFB triggering) a voltage overshoot is expected. The maximum should appear at the end of the line (in the conducting direction of bypass diodes). According to simulations it can reach 50% of the EFB voltage. This effect can be strongly reduced by installing short-circuits at each dipole magnet of the affected powering line.

- Damage to bypass diodes:

After a discharge of the EFB capacitor bank into the RB circuit a propagation of a voltage wave is expected along the magnet chain. This means that differential voltage across bypass diodes may occur (especially in case the EFB is placed at the cathode side of these diodes). This risk is mitigated by installing short-circuits across each diode in the affected line. This is done at the level of I-taps at the D20 connector on the IFS box of each magnet.

- Damage to the helium enclosure:

Earth fault burning carries a slight risk of damaging the helium enclosure in the area near the earth fault. This risk is extremely small as the energy available in the capacitor bank (2.8 kJ) is not sufficient to burn a hole in the 2 mm Inox enclosure. This possibility defines the maximum stored energy that can be relatively safely used and will be taken into account during the development of the upgraded version of the Earth Fault Burner.

- Damage to the instrumentation wires:

The instrumentation wires may get damaged in case they are not conform to the specification. There is a number of such cases in the LHC machine. This risk is mitigated by performing a detailed qualification check of affected I-taps. In case the I-taps of the selected magnet cannot be used, another magnet nearby (towards the anode side) can be used to inject the current from the EFB.

A.5 Earth Fault Burner hardware

So far a modified HDS power supply was used for the EFB. Originally it was designed to operate with 100 A. It means that operation at 600 A may lead to damages in the internal structure of the apparatus. Work is now being carried out to develop a more robust version that could carry currents of up to 2 kA or more without getting damaged. This way one can be confident that single earth faults that may occur in the future can be quickly solved. The Following parameters are available in the EFB version 2016:

$$\begin{aligned}V_{\max} &= 900 \text{ V} \\C &= 7 \text{ mF} \\E &= 2.8 \text{ kJ} \\I_{\max} &= 400 \text{ A} \\R_{\text{series}} &= 2 \Omega\end{aligned}$$

A.6 Unresolvable Earth Fault Burning Scenarios

While the location of the fault can be established with high precision and 2 D projection of the debris that provokes the fault can be acquired thanks to the X-ray apparatus, the exact composition of the metallic particles that create the fault cannot be known without opening of the interconnection. The two occasions of earth faults observed so far in sector 3-4 could be cured with the appropriate application of the EFB, but there may be situations in which the EFB will not be effective. There is therefore no guarantee that all earth faults can be eliminated in the future and performing future magnet training campaigns bare a non-negligible inherent risk of damaging a given magnet in the machine. It should be noted that also different types of shorts or non-conformities may arise during quench training (inter-turn shorts, shorts at the level of quench heaters...) which might entail the need for replacement of magnets as they cannot be cured with the described equipment.

Such damage can happen either by pinching the pieces between the busbar and the helium enclosure or by permanently welding the piece in position by the discharge. This might occur if the piece is so thick that the resistance is not dissipating enough heat with the maximum EFB current and not enough helium bubbles are produced to dislocate the piece. As only 2 cases were treated with the EFB in the LHC machine, and both were successful, many more cases would be required to estimate the probability for the occurrence of unrepairable faults in real operation conditions. However, laboratory tests have demonstrated that as long as the piece remains unfixed mainly incorrect application of the EFB can lead to unresolvable faults.

- The probability for unsuccessful earth fault burnings is therefore estimated to be low. However, exact numbers are not easy to calculate without more statistical data.

Experiments show that too weak pulses may cause the piece to stick and get fixed. Therefore, it is recommended to use as high as possible current, energy and voltage. This approach maximizes the probability of successful fault elimination.

A.7 Potential Risk for future Magnet Training Campaigns and Mitigation options

The occurrence of two simultaneous shorts in one circuit bares the risk that the stored electro-magnetic energy inside the circuit can no longer be properly extracted from the circuit after the magnet quench(es). Such a scenario could result in severe hardware damage that would require the exchange

of a number magnets. Following discussions at the Chamonix 2016 workshop and recommendations from the C-MAC CERN therefore launched a study for mitigating the electrical fault problem at the root by a hardware intervention during LS2.

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