STATUS OF THE LHC OPERATIONS AND PHYSICS PROGRAM

Stefano Redaelli for the LHC commissioning team, CERN, Geneva, Switzerland

Abstract

The Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) has just completed a successful first year of operation. In 2010, the primary goal to achieved a peak luminosity of 10^{32}cm^{-2}s^{-1} at a 7 TeV centre-of-mass energy was achieved and the machine achieved safely and reliably routine operation in the multi-MJ regime. The good results of 2010 have laid a solid foundation towards the achievement of the primary physics goal to deliver an integrated luminosity of 1 fb^{-1} in 2011. A fast and efficient LHC re-commissioning in 2011 lead already to a peak luminosity of 2.5×10^{32}cm^{-2}s^{-1} achieved in the fourth commissioning week. In this paper, the 2010 commissioning experience is reviewed and the present status and perspective are presented.

INTRODUCTION

The Large Hadron Collider (LHC) [1] saw in 2010 the first full year of operation at 3.5 TeV per beam, after the incident of September 2008 that required a major consolidation program in the tunnel and after a short engineering run at 1.18 TeV at the end of 2009 [2]. The choice of operating at half the design beam energy of 7 TeV per beam was taken to minimize the risk associated to superconducting splice burn-out. A design problem of the main circuit splices was indeed revealed by the massive monitoring campaign that followed the 2008 incident [3, 4]. A full consolidation program to overcome this energy limitation requires a long shutdown to fix all the super-conducting slices.

After a safe operation at 3.5 TeV in 2010, the LHC roadmap for the next few years has been discussed at the LHC Performance Workshop, Chamonix2011, held in January 2011 [5]. The two main outcomes of Chamonix2011 are that (1) the operating energy will be maintained at 3.5 TeV in 2011 and that (2) the machine run will be extended into 2012, with a first long shutdown in 2013 for the hardware consolidation that will remove the present energy limitations. The goal of this two-year long running period is to maximize the LHC physics outcome by either discovering or ruling out the existence of the Higgs boson. The choice of maintaining the same physics energy in 2011 was chosen as a risk-balance decision making that was eventually in favor of a fully safe operation.

After having introduced the basic road-map of the LHC operation, in this paper the 2010 operations is reviewed. Highlights of the LHC operations and the luminosity reach are outlined. The present status of LHC operations and the perspective for the 2011 run are then reviewed.

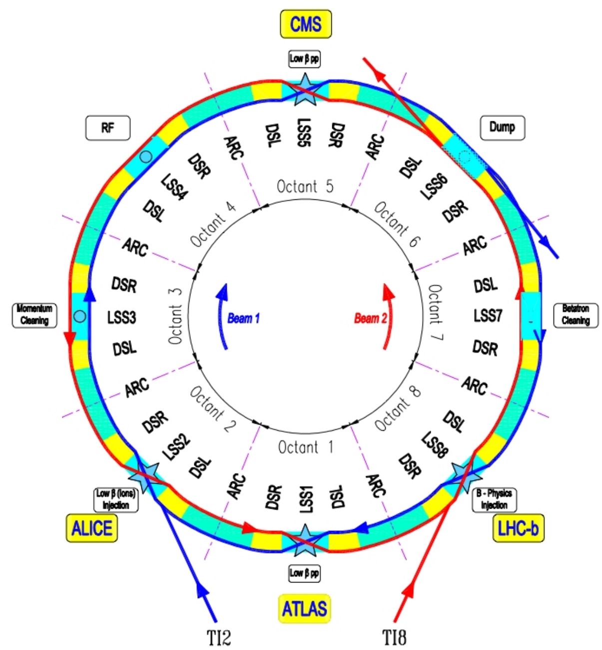

Figure 1: Illustrative layout of the 26.7 km-long LHC rings, featuring 8 arcs and 8 long straight sections (LSSs). Each LSS is surrounded by 2 dispersion suppressors (DSs) [1].

LHC LAYOUT AND PARAMETERS

A schematic view of the 26.7 km-long LHC ring is given in Fig. 1 [1]. The 70–140 m underground tunnel sits in the Geneva area between Switzerland and France. The LHC lattice has 8 arcs and 8 long straight sections (LSSs). Thanks to a two-in-one magnet design, the counter-rotating proton beams circulate in separated vacuum chambers and cross each other only in the experimental interaction regions (IRs): IR1 (that houses the experiments ATLAS [7] and LHCf [8]), IR2 (ALICE [9]), IR5 (CMS [10] and TOTEM [11]) and IR8 (LHCb [12]). The other straight sections are dedicated to the radio-frequency system (IR4), the beam dumping system (IR6) and the momentum (IR3) and betatron (IR7) collimation systems. The injections of the clockwise beam 1 and anti-clockwise beam 2 take place in IR2 and IR8, respectively.

The main LHC design parameters, the 2010 achievements and the forecast for 2011 are given in Tab. 1. The proton operation was stopped in favor of four weeks of

Table 1: LHC parameters for proton operation.

Parameter	Value		
	Design	2010	2011
Colliding beam energy [TeV]	7.0	3.5	3.5
Peak luminosity [10^{32}cm^{-2}s^{-1}]	100	2	5–10[1]
Maximum stored energy [MJ]	362	28	≈100
Single bunch intensity [10^{11}p]	11.5	12	12–14
Number of bunches	2808	368	1400 [2]
Bunch spacing [ns]	25	150	50-75 [2]
Norm. transv. emittance [μm]	3.5	2.5	2.5
β^* in IR1/IR5 [m]	0.55	3.5	1.5
β^* in IR2 [m]	10.0	3.5	3.0
β^* in IR8 [m]	10.0	3.5	10.0
Half Xing angle IR1/IR5 [μrad]	142.5	100	120
Half Xing angle IR2 [μrad][3]	80	100	80
Half Xing angle IR8 [μrad][3]	210	100	250

ion operation before increasing the total number of bunches above 368. Runs for physics were only done with 150 ns spacing. The figures on the total number of bunches that can be achieved in 2011, and hence the estimated peak luminosity, depend on the results of the scrubbing run foreseen the first half of April [13]. This was proposed to minimize the electron-cloud effects measured in 2010 [14, 15]. If they can be kept under good control, as suggested by first observations, the preferred running configuration will be the 50 ns spacing for a maximum number of bunches. In case of unexpected problems, the operation at 75 ns spacing or even at 150 ns as in 2010, remain fall-back options.

In any case, the 2011 parameter set relies on the excellent performance of the LHC injector chain in terms of beam emittances and single-bunch intensities. After detailed measurements of the super-conducting triplet aperture, it has also been decided to squeeze the beams further in IR1 and IR5, which provides a gain of a factor 2.3 in the peak luminosity, see Tab. 1. A number of additional important improvements of the machine cycle and of the turnaround time are also foreseen to maximize the integrated luminosity (see [16, 17] for details).

GOALS FOR 2010-11

The primary 2011 goal is to accumulate an integrated proton-proton luminosity of 1 fb^{-1} in ATLAS, CMS and LHCb at a center-of-mass energy of 7 TeV. The following items were identified as crucial milestones for the 2010 run in order to achieve the 2011 goal:

- achieve a peak luminosity of up to 10^{32}cm^{-2}s^{-1}, which would allow to accumulate 1 fb^{-1} in 2011;
- establish a reliable and safe operation in the multi-MJ stored energy regime, after a safe running period around 1–2MJ (i.e., around the state-of-the-art of other accelerators, like the Tevatron or the CERN ISR);
- get under control and gain solid operational experience on the basic machine phases, like injection, energy ramp and betatron squeeze.

In the next section, it will be shown that the goals above were successfully achieved in 2010. This statement is confirmed by the observation that initial 2011 performance: after only four weeks of commissioning, the record peak luminosity of 2010 has already been surpassed with 200 bunches instead than 368.

Even if the main focus of this paper will be dedicated to the proton operation with a centre-of-mass of 7 TeV, it is worth mentioning that the LHC 2011 schedule [13] foresees a reach program, including in particular:

- four weeks of ion physics at 7 TeV, like in 2010;
- proton physics at an intermediate energy of 1.38 TeV (ongoing at the time of this conference);
- special runs with beam unsqueezed to colliding β functions of 90 m in IR1 and IR5;
- luminosity calibration runs;
- special runs for Roman pots of TOTEM and ATLAS (ALFA experiment).

In addition, in 2011 there will also be dedicated time slots for machine development studies, mainly aimed at addressing various aspects of the presently foreseen LHC limitations and key aspects of the future LHC upgrades. The total time foreseen for special runs and for machine studies is 10 and 22 days, respectively, without taking into account the four weeks for ion operation [13].

HIGHLIGHTS OF 2010 OPERATIONS

The main milestones of the 2010 operations are listed in Tab. 2 [2]. The LHC experienced a rapid commissioning that lead to the achievement of the primary goal for 2010 of a peak luminosity of about 10^{32}cm^{-2}s^{-1}. The target value was exceeded by a factor 2. This is shown in Fig. 2 where the achieved peak luminosity at the beginning of the fill is given as a function of the fill number during the whole 2010 run. Preliminary figures by ATLAS and CMS are considered [7, 10].

In Fig. 3, the preliminary estimates of integrated luminosity in ATLAS and CMS are given. By the end of the

[1] A maximum peak luminosity of 2.5×10^{32}cm^{-2}s^{-1} was achieved on March 24$^{\rm th}$ with 200 bunches.

[2] Exact figures will be determined after the results of the scrubbing run foreseen for the first 10 days of April. The 150 ns spacing used in 2010 remains a fall-back option in case of unexpected problems after the with the electron cloud effects.

[3] External half crossing angle that does not take into account the additional angles from the spectrometer magnets, i.e. 135μrad in IR2 and 270μrad in IR8 at 3.5 TeV.

Table 2: Milestones of the 2010 LHC operations [2]

Date	Milestone
March	Initial commissioning, first 3.5 TeV collisions
April	Squeeze commissioning
May	Physics 13 on 13 with 2e10 ppb
June	Commissioning of nominal bunch intensity
July	Physics 25 on 25 with 9e10 ppb
August	3 weeks running at 1 – 2 MJ
Sept.	Bunch train commissioning
Oct.–Nov.	Phased increase in total beam intensity
Nov.–Dec.	Ion commissioning and physics

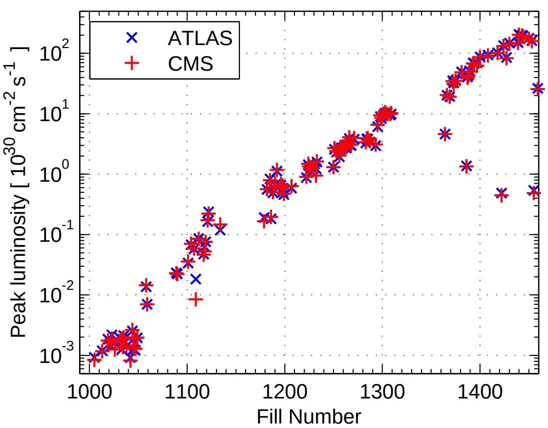

Figure 2: Preliminary peak luminosity in ATLAS and CMS as a function of the fill number during the 2010 run, from March until the end of October. Data are provided by M. Ferro-Luzzi on behalf of the ATLAS and CMS collaborations.

proton run, about 50 pb^{-1} were accumulated by both experiments. A list of 2010 records measured by ATLAS is given in Tab. 3. Figure 3 illustrates the interleaved commissioning and physics production modes of operation that characterized the 2010 run. In particular, three different running periods can be identified:

(1) Initial commissioning and luminosity run with single-bunch injections and reduced intensity;

(2) operation with up to 48 bunches of intensity above the nominal value of $1.15{\times}10^{11}$ p, with single-bunch injections;

(3) operation with bunch-train injections at 150 ns spacing, up to a total of 368 bunches, for luminosity performance ramp-up.

These periods were interleaved with dedicated commissioning phases, in particular for the preparation of the systems related to the LHC machine protection. These commissioning periods are indicated by the flat lines in the integrated luminosity graph of Fig. 3, as shown by the arrows. Clearly, both the machine and the detectors profited by this staged performance increase.

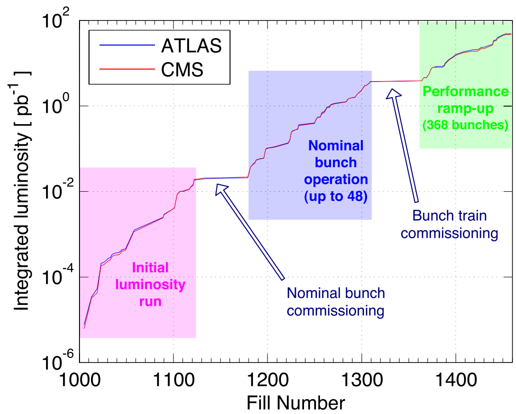

Figure 3: Preliminary integrated luminosity in ATLAS and CMS as a function of the fill number during the 2010 run [16], provided by M. Ferro-Luzzi on behalf of the ATLAS and CMS collaborations.

Table 3: Records of the 2010 LHC operations (ATLAS)

Parameter	Value
Peak stable luminosity [$10^{32}cm^{-2}s^{-1}$]	2.07
Maximum luminosity in one fill [pb^{-1}]	6.3
Maximum luminosity in one day [pb^{-1}]	5.98
Maximum luminosity in 7 days [pb^{-1}]	24.6
Maximum num. of colliding bunches	348
Maximum avg. events per bunch crossing	3.78
Longest time in Stable Beams for one fill [h]	30.3
Longest time in Stable Beams for one day [h]	22.8 (94.9%)
Longest time in Stable Beams for 7 days [h]	69.9 (41.6%)
Fastest turnaround to Stable Beams [h]	3.66

The commissioning progress was essentially driven by constraints from machine protection. In Fig. 4, the foreseen evolution of stored beam intensity versus time is compared to what was achieved. After an initial conservative ramp-up, the necessary confidence in the LHC operation was gained after a stable running period in the regime of a few MJ, which saw an excellent performance of the core systems for machine protection. See [18] for details. A good overview of all the accelerator systems can be found in [5] and [19].

The overall availability of the LHC in 2010 was 65 % [20], with peaks of 80 % per month achieved in November. The total fractional time time spent in physics was 25 %. These figures are very encouraging for the future and can be considered outstanding for the first year of operation of a machine of the complexity of the LHC.

It is worth mentioning three effects observed in 2010 that could potentially limit the LHC performance:

- The so-called "hump" is a noises of slowly-varying frequency observed on the stored beams, primarily on the vertical plane of beam 2. It caused emittance blow-up when sitting close to the tune lines and occasion-

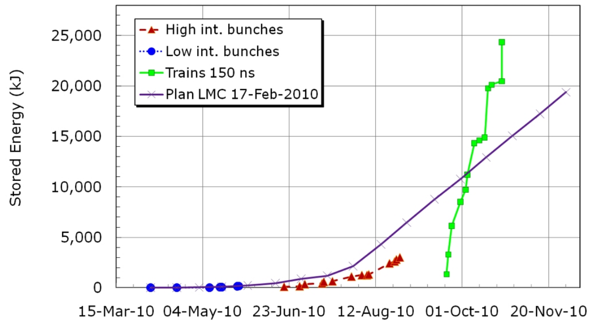

Figure 4: Predicted and achieved LHC beam stored energy in 2010. Courtesy of J. Wenninger [18].

ally large beam losses. The source of this noise was not found out, despite of the machine-wide investigations [21]. From the beginning of the 2011 operation, this effect did not affect the beam operation anymore. But the systematic monitoring will continue.

- Many sudden loss spikes with rise times of the order of 1 ms were recorded in the cold regions around the ring [22, 23]. These losses are referred to as Unidentified Falling Objects (UFOs) because they could possibly be explained by the interaction between the circulating beams and falling (dust) particles in the vacuum chamber. The losses from UFOs that occur in the cold regions far from the collimation sections are too fast to be cleaned away by the multi-turn cleaning mechanism. They often triggered preventive beam dumps when exceeding the thresholds of beam loss monitors. The UFO-induced losses pose problems for the superconducting magnets but obviously can affect severely the machine efficiency. So far [23], there is indication that the rate of UFOs depends on the total beam intensity but the intensity of associated beam losses dose not. So, it is believed that the problem can be cured by an appropriate choice of the loss thresholds in the time range of the UFO losses, without impact on machine safety. This assumptions will have to be confirmed in 2011 while operating at total intensities up to factors 3–4 larger than in 2010.

- As already mentioned, electron cloud phenomena were observed at the end of 2010 for increased number of bunches. After first observations in the common vacuum chambers already with trains at a 150 ns bunch spacing, the problem became apparent when trying to operate the LHC at 75 ns [14, 15]. Typical signatures of this effect are emittance blow-up along bunch trains, bad vacuum and beam instabilities. A dedicated scrubbing period is foreseen early on in the 2011 schedule. It is expected that operation at 50 ns spacing will be possible after scrubbing. Additional solenoids have been installed in various locations in the IRs at the end of 2010 as further mitigation mechanisms.

Table 4: Milestones of the 2011 LHC operations

Date	Milestones
19^{th} Feb.	First beam, circulating beams established
3^{rd} Mar.	First collisions at 3.5 TeV, beta*=1.5 m
5^{th} Mar.	Nominal bunches at 3.5 TeV
13^{th} Mar.	First stable beams, 3 bunches per beam, initial luminosity $\mathcal{L}_{\mathrm{in}}$=1.6×$10^{30}$cm^{-2}s^{-1}
18^{th} Mar.	32 bunches per beam, $\mathcal{L}$=3×10^{31}cm^{-2}s^{-1}
19^{th} Mar.	64 bunches per beam, $\mathcal{L}$=6×10^{31}cm^{-2}s^{-1}
20^{th} Mar.	136 bunches per beam, $\mathcal{L}$=1.45×10^{32}cm^{-2}s^{-1}
24^{th} Mar.	200 bunches per beam, $\mathcal{L}$=2.5×10^{32}cm^{-2}s^{-1}
25^{th} Mar.	Start of collision run at 1.38+1.38 TeV

STATUS OF 2011 OPERATION

The primary milestones of the 2011 LHC operations achieved by the time of this conference are listed in Tab. 4. Presently, the collision run at a centre-of-mass energy of 2.76 TeV is ongoing. It will last until March 27^{th} and then the first 4-day technical stop will take place. Next in the agenda are 10 days of scrubbing run with bunch spacing of 75 ns and 50ns.

Table 4 illustrates that the LHC beam re-commissioning after the short Christmas shutdown is proceeding rapidly. With respect to 2010, various improvements of the LHC machine cycle have been put in place [17]. In particular, the energy ramp and the betatron squeeze are now faster, an optimized injection strategy is applied, a better handling of dynamics orbit references was established. The initial 2011 experience validated the proposed changes. Details of these improvements cannot reported extensively on this short contribution but can be found in the proceedings of recent LHC operations and performance workshops [5, 19].

The maximum peak luminosity recorded by ATLAS and CMS at the time of this conference is 2.5×10^{32}cm^{-2}s^{-1} with 200 bunches in the machine, i.e 25% more than the best achieved in 2010 with 368 bunches. This improvement comes essentially from the smaller β functions, see Tab.1. The preliminary peak luminosity data recorded by ATLAS as a function of time are given in Fig. 5. It is seen that with a few high-luminosity fills, about the 60 % of the 2010 integrated luminosity has already been accumulated.

CONCLUSIONS

The first exciting year of LHC operation was very positive in various respects. It will be followed by two intense years of continuous operation and then by a long shutdown in 2013 for the consolidation work that will remove the present energy limitations of the super-conducting magnet system, allowing the design beam energy of 7 TeV. Already at half this energy, the physics outcome of the LHC is exciting and the community is looking forward to seeing the results of the next two years at higher luminosities.

In 2010, the LHC achieved and surpassed the pre-defined

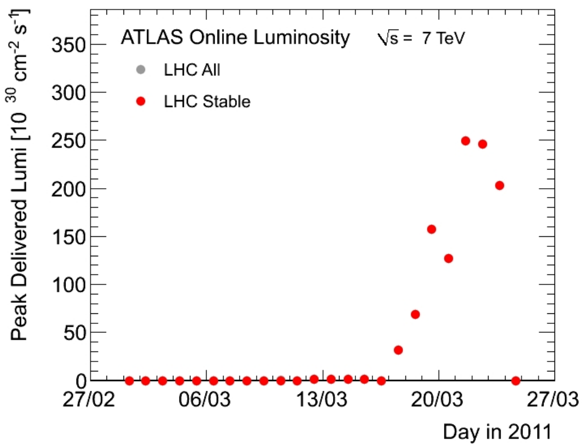

Figure 5: Preliminary peak luminosity as a function of time recorded by ATLAS. Courtesy of M. Ferro-Luzzi and the ATLAS collaboration.

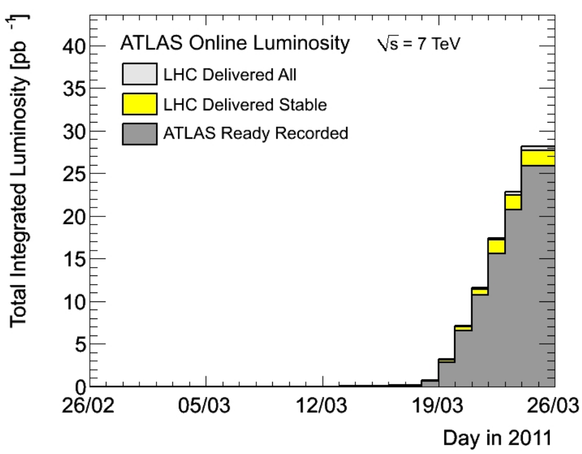

Figure 6: Preliminary integrated luminosity as a function of time recorded by ATLAS. Courtesy of M. Ferro-Luzzi and the ATLAS collaboration.

goals in term of proton peak luminosity. This laid a very solid foundation towards the primary physics goal of 1 fb^{-1} to be accumulated in 2011. Indeed, the remarkable maturity achieved by most accelerator systems, in particular for the ones relevant for machine protection, and several performance improvement factors within reach (larger number of bunches, smaller β functions, improved single-bunch intensities), suggests that peak luminosities between 5 and 10 ^{32}cm^{-2}s^{-1} could be achieved, corresponding to integrated luminosities between 1 fb^{-1} and 3 fb^{-1}.

This contributions has obviously been presented on behalf of the many teams involved in the LHC project. In particular, the author would like to acknowledged M. Lamont, M. Ferro-Luzzi, and J. Wenninger, who provided useful material, and the whole LHC operations team.

REFERENCES

[1] O. Brüning *et al.*, "LHC design report," CERN-2004-003-V1 (2004).

[2] M. Lamont, "Operational challenges (feed forward from Evian LHC operational workshop," proceedings of the LHC Performance Workshop, Chamonix2011, Chamonix (FR).

[3] CERN Press Release, Dec. 5, 2008, `http://public.web.cern.ch/press/pressreleases/Releases2008/PR17.08E.html`

[4] CERN Press Release, Aug. 6, 2009 `http://public.web.cern.ch/press/pressreleases/Releases2009/PR13.09E.html`

[5] Web proceedings of the LHC Performance Workshop, Chamonix2011, Jan. 2011, Chamonix (FR), `http://indico.cern.ch/conferenceDisplay.py?confId=103957`

[6] M. Ferro-Luzzi, "LHC 2010 operation – as viewed from the experiments," proceedings of the LHC Performance Workshop, Chamonix2011, Chamonix (FR).

[7] `http://atlas.web.cern.ch/Atlas/Collaboration/`

[8] `http://www.stelab.nagoya-u.ac.jp/LHCf/LHCf/index.html`

[9] `http://aliweb.cern.ch/`

[10] `http://cms.web.cern.ch/cms/index.html`

[11] `http://totem.web.cern.ch/Totem/`

[12] `http://lhcb.web.cern.ch/lhcb/`

[13] M. Meddahi "Operational schedule 2011 and potential performance," proceedings of the LHC Performance Workshop, Chamonix2011, Chamonix (FR).

[14] G. Arduini *et al.* "Beam observations with different bunch spacing and overall synthesis," proceedings of the LHC Performance Workshop, Chamonix2011, Chamonix (FR).

[15] M. Jimenez *et al.* "Vacuum and Cryogenics observations for different bunch spacing," proceedings of the LHC Performance Workshop, Chamonix2011, Chamonix (FR).

[16] S. Redaelli, "How to improve the turnaround," proceedings of the LHC Operations Workshop, Evian2010.

[17] S. Redaelli, "Optimisation of the nominal cycle," proceedings of the LHC Performance Workshop, Chamonix2011, Chamonix (FR).

[18] J. Wenninger "Experience with MPS during the 2010 run," proceedings of the LHC Performance Workshop, Chamonix2011, Chamonix (FR).

[19] Web proceedings of the LHC Operations workshop, Evian2010, Dec. 2010, Evian (FR), `http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=107310`

[20] W. Venturini Delsolaro, "Operational efficiency," proceedings of the LHC Operation Workshop, Evian2010, Evian (FR), Dec. 2010.

[21] G. Arduini *et al.*, "Hump: how did it impact the luminosity performance?", proceedings of the LHC Operation Workshop, Evian2010, Evian (FR), Dec. 2010.

[22] B.E. Holzer *et al.* "Losses away from collimators: statistics and extrapolation," proceedings of the LHC Operation Workshop, Evian2010, Evian (FR), Dec. 2010.

[23] M. Sapinski *et al.* "Is the BLM system ready to go to higher intensities?," proceedings of the LHC Performance Workshop, Chamonix2011, Chamonix (FR).