HL-LHC: INTEGRATED LUMINOSITY AND AVAILABILITY *

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Abstract

The objective of LHC operation is to optimise the output for particle physics by maximising the integrated luminosity. An important constraint comes from the event pile–up for one bunch crossing that should not exceed 140 per bunch crossing. With bunches every 25 ns the luminosity for data taking of the experiments should therefore not exceed $5*10^{34}$ $s^{-1}cm^{-2}$. For the optimisation of the integrated luminosity it is planned to design HL-LHC for much higher luminosity than acceptable for the experiments and to limit the initial luminosity by operating with larger beam size at the collision points. During the fill, the beam size will be slowly reduced to keep the luminosity constant (as already done in LHCb). The gain from luminosity levelling depends on the average length of the fills. Today, with the LHC operating at 4 TeV, most fills are terminated due to equipment failures, resulting in an average fill length of about 5 h. In this paper we discuss the expected integrated luminosity for HL-LHC as a function of fill length and time between fills, depending on the expected Mean Time Between Failures of the LHC systems with HL-LHC parameters. We derive an availability target for HL-LHC and discuss steps to achieve this.

INTRODUCTION

After three successful years of LHC operation the interest to push the integrated luminosity towards its nominal parameters and further is the driving factor for future studies. A systematic study of machine availability has become a necessity for the optimization of the integrated luminosity. Its application to future LHC upgrades can be exploited for predictions on possible future scenarios and operational targets.

For HL-LHC the target for the integrated luminosity per year is 250 fb^{-1}, assuming 150 days of operation [1]. This paper discusses the integrated luminosity as a function of machine availability, based on the observation of fault and turnaround times during the 2012 LHC proton (p-p) operation (201 days) [2]. A Monte-Carlo simulation model for calculating the integrated luminosity was validated with these observations. The extension of the model to HL-LHC is discussed and the results are presented together with possible future operational scenarios.

INPUT DATA ANALYSIS

Definitions

The parameters of the Monte-Carlo model for the integrated luminosity are derived according to the following definitions:

- Stable beams time [h]: the time period in which the beams are in collision for luminosity production.
- Turnaround time [h]: the time period from a beam dump of a fill to the beginning of the next stable beams, excluding the fault time.
- Fault time [h]): the sum of all fault times, for faults occurring between a dump and the next stable beams.
- Peak luminosity $[10^{30}$ $s^{-1}cm^{-2}]$): initial value of the instantaneous luminosity.
- Luminosity lifetime [h]: time constant of the exponential decay of the luminosity.
- Machine failure rate [%]): percentage of fills in stable beams followed by a fault (before next stable beams).

Distributions

The distributions of stable beams time, fault time, peak luminosity and luminosity lifetime were derived from 2012 operation, excluding periods for machine developments and technical stops, and fitted with appropriate probability density functions (pdf). Fig.1 shows the distribution of fault time and the adopted exponential pdf. The parameters of all the distributions are given in Table 1 (μ is the average value of the distribution, σ the standard deviation).

The total turnaround time in 2012 was deduced by subtracting the total stable beams time and fault time from the 201 days of 2012 p-p operation, leading to 1612 h.
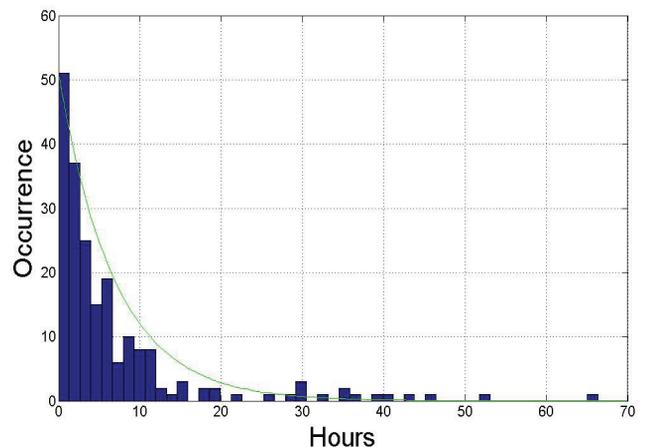
Figure 1: Fault time distribution of the 2012 LHC p-p operation.

Table 1: 2012 Distributions of Stable Beams Time, Fault Time, Peak Luminosity and Luminosity Lifetime

	pdf type	μ	σ
Stable Beams Time	exp	6.08	-
Fault Time	exp	6.92	-
Peak Luminosity	gauss	6285.80	569.06
Luminosity Lifetime	gauss	10.05	3.19

MONTECARLO MODEL FOR INTEGRATED LUMINOSITY

The distributions of stable beams time and fault time allow reproducing a realistic timeline of LHC yearly operation: the designed algorithm produces a sequence of random fault time, average turnaround time and random stable beams time iteratively until the total operational time (201 days) is reached. The observation of 2012 operation shows that the machine failure rate is about 70%; this is modelled with an additional random number.

The integrated luminosity depends on peak luminosity and luminosity lifetime distributions. The integrated luminosity is calculated by integrating the luminosity exponential decay function for each stable beams time and summing all the obtained values. The described procedure is repeated for an arbitrary number of times in order to derive the output distributions for integrated luminosity, total fault time, total turnaround time, total stable beams time and number of fills, which all show a Gaussian profile. The presented numbers refer to 1000 simulated years of operation.

Validation with 2012 Operation

The results and relative errors obtained by applying the model to 2012 operation are presented in Table 2.

Table 2: Model Results for 2012 Operation (201 days): Parameters of Output Gaussian Distributions and Relative Errors

	μ	σ	2012 Observation	Error [%]
Integrated Luminosity	23.00	0.79	23.27	1.14
Total Stable Beams Time	1786.42	75.87	1794	0.42
Total Fault Time	1416.63	83.79	1418	0.09
Total Turn Around Time	1611.02	49.03	1612	0.06
Fills in Stable Beams	294.82	8.97	295	0.06

The model allows estimating the yearly Integrated Luminosity with ~1% error. Its accuracy is limited by the accuracy of the input statistics.

Model Extension to HL-LHC

The extension of the model to HL-LHC is straightforward for the determination of the operational timeline (fault time, turnaround time, stable beams time). For the calculation of the integrated luminosity, a modification is necessary to model the luminosity levelling. The peak Luminosity is constant ($5*10^{34}$ $s^{-1}cm^{-2}$) whereas the luminosity lifetime is still randomly determined. Observations in 2012 showed that higher peak luminosity leads to lower luminosity lifetime, therefore the distribution of luminosity lifetime was derived based on the last part of 2012 operation with higher peak luminosities (the average luminosity lifetime goes from 10.05 to 9.32 h). The luminosity-levelling time (~6.5 h) is determined by calculating the necessary time to go from 10^{35} to $5*10^{34}$ $s^{-1}cm^{-2}$ (in an exponential decay), each time according to a different random luminosity lifetime. If the luminosity-levelling time is longer than the stable beams time, the integrated luminosity is given by the product of peak luminosity times stable beams time; if the luminosity levelling time is shorter than the stable beams time, then an exponential decay is considered, and the integrated luminosity will be the sum of the two contributions (luminosity levelling + exponential decay).

HL-LHC OPERATION: SIMULATIONS

2012-like Operation

As a first step, the figures from 2012 operation for fault time and stable beams time have been assumed for HL-LHC (Table 1). The average turnaround time from 2012 operation is also kept: this choice is based on the assumption that the increased time for ramp-up and ramp-down will be compensated by the increased experience in running the LHC and the possible combination of some beam modes, as is currently under discussion for future operation.

Fig.2 shows the output distribution of integrated luminosity; the parameters of the other output distributions are presented in Table 3.
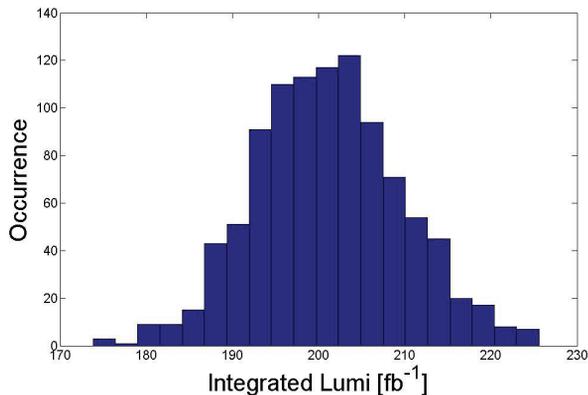
Figure 2: Distribution of integrated luminosity for HL-LHC, based on figures from 2012 operation.

Table 3: Model Results for HL-LHC Operation (150 days), Based on the Figures from 2012 Operation

	μ	σ
Integrated Luminosity	201	8.57
Total Stable Beams Time	1336	66.58
Total Fault Time	1053	70.51
Total Turn Around Time	1200	42.69
Fills in stable beams	220	7.81

According to the presented assumptions, the total integrated luminosity is ~201 fb^{-1}. In this respect, a possible gain could be obtained by optimizing the fill length. A fill reaches its optimum duration when the instantaneous luminosity becomes equal to the average luminosity production for the operational period. This concept of optimization was approximated in the simulations in a second stage, by intentionally terminating fills which would exceed 13 h. At this time the average instantaneous luminosity has become ~2.5 *10^{34} s^{-1}cm^{-2}.

A sensitivity analysis to the average fault time was performed and the outcome, both for optimized (optimized stable beams times) and non-optimized (stable beams times from 2012) operation, and different machine failure rates, is presented in Fig. 3.
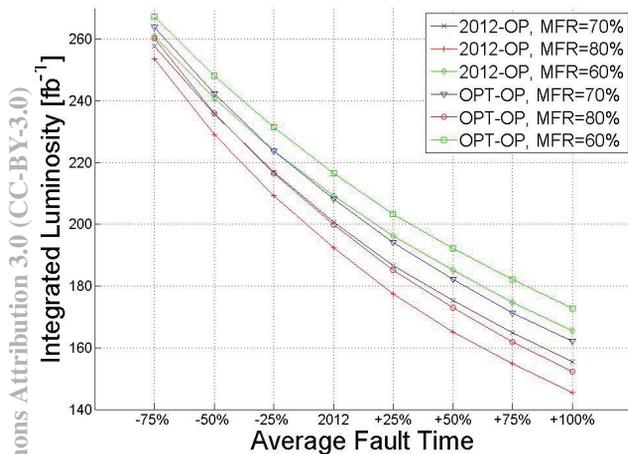
Figure 3: Integrated luminosity versus fault time. Different curves are presented for 2012-like (2012-OP) and Optimized (Opt-OP) operation, for different Machine Failure Rates (MFR).

HL-LHC Operation and Fault Times

The results of the sensitivity analysis show that a significant reduction of the average fault time (about 50%) and machine failure rate (10%) would be necessary in order to match the expectations (250 fb^{-1}).

To assess the impact of future operational scenarios, the following classification of faults is proposed:

- I: Short faults (0-1 h): faults which can be solved without access in the tunnel (e.g. by remote reset).
- II: Faults requiring one access (1-4 h)
- III: Faults requiring multiple accesses (4-12 h).
- IV: Long faults (>12 h) requiring major interventions (e.g. long cryogenics stops, others).

The increased operational energy (6.5-7 TeV) is likely to have an impact on fault times. Systems such as power converters and cryogenics will operate much closer to their limits. Ageing of the equipment might also require additional interventions and repairs (impact on category II). The probability for beam induced quenches and Unidentified Falling Objects (UFOs) will increase. In case of a quench a cool-down will be necessary, thus increasing the number of faults in category III. Exploiting the redundancy of cryoplants which allowed for high availability in 2012 will not be possible at 7 TeV (impact on category III). At the same time the increased experience with LHC systems and future mitigations might reduce the number of faults in III, hence reducing the average fault time. Faults in IV are expected to have a similar impact on availability with respect to 2012, being difficult to predict and mitigate.

At higher energy more conservative settings will likely be adopted, increasing the machine failure rate, but decreasing the average fault time, which will be dominated by single event upsets (SEUs) and fast failures leading to short fault time (I). Preliminary estimates indicate that an increase of 10% of the failure rate leads to a decrease of the average fault time of ~10%. Fig. 3 shows that in these conditions ~210 fb^{-1} could be reached.

CONCLUSIONS

A model for quantifying the impact of machine availability on the yearly integrated luminosity was developed and validated, based on 2012-LHC operation. Its extension to HL-LHC was discussed. An integrated luminosity of ~200 fb^{-1} is a realistic target if the same figures of 2012 operation can be maintained.

Making accurate predictions for future operational scenarios is not possible at the moment. A sensitivity analysis to the average fault time and failure rate was therefore carried out. Preliminary predictions show that ~210 fb^{-1} could be reached with conservative machine settings in case of optimized operation. A further improvement for the integrated luminosity could be achieved through the use of crab cavities [3], which would allow for higher peak luminosity and, hence, longer luminosity levelling tme. The impact of this will be studied with a second version of the model.

REFERENCES

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