REQUIREMENTS FOR CRAB CAVITY SYSTEM AVAILABILITY IN HL-LHC

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Abstract

Crab Cavities will be installed in the High Luminosity LHC in order to increase the effective peak luminosity through a partial compensation of the geometric factor. This will allow extending the levelling time resulting in an increased production of integrated luminosity. Based on the availability of the LHC during 2016 operation, the expected yearly-integrated luminosity of the future HL-LHC was estimated using a Monte Carlo model. Crab cavity faults were added to the observed failure distributions and their impact on integrated luminosity production as a function of fault time and fault frequency was studied. This allows identifying a breakeven point in luminosity production and defining minimum system availability requirements for the crab cavities to reach the design goal of 250 fb^{-1} of integrated luminosity per year.

CRAB CAVITIES AND INCREASED LUMINOSITY

In the High-Luminosity upgrade program of the Large Hadron Collider (HL-LHC), it is planned to use smaller beam sizes at the interaction points and higher bunch intensities in order to achieve higher instantaneous luminosities. The relevant parameters of the HL-LHC are recalled in Table 1 [1].

Table 1: HL-LHC Luminosity Parameters

Name	Nominal value	Unit
Levelled luminosity	5×10^{34}	cm^{-2}.s^{-1}
Beam energy	7	TeV
Beam emittance	2.5	µm
β*	20	cm
1 σ bunch length	1.2 (9)	ns (cm)
Half-crossing angle	295	µrad
Bunch intensity	2.2×10^{11}	protons
Beam intensity	6×10^{14}	protons
Luminosity lifetime	5	hours

The higher current in the beams requires a twice larger crossing angle in the interaction points to reduce the effects of long-range parasitic beam-beam interactions on beam lifetime. The larger crossing angle causes the reduction of instantaneous luminosity due to the geometric factor R_φ given by: $R_\varphi = \sqrt{1 + (\varphi \frac{\sigma_z}{\sigma_x})^2}^{-1}$,

where φ is the half-crossing angle and σ_x and σ_z the transverse and longitudinal beam sizes respectively. For the HL-LHC the reduction of instantaneous luminosity becomes significant, i.e. around 69%, as compared to 15% in the current LHC. To compensate for this reduction, crab cavities will be installed in the HL-LHC to tilt the beam in the crossing plane [2]. The nominal installation foresees a set of four crab cavities for each of the two beams and on each side of the two high luminosity interaction points, ATLAS and CMS. However, following the recent re-baselining of the HL-LHC project, only half of the crab cavities will be installed, allowing for a partial compensation of the crossing angle only.

Another method to recover some of the lost effective peak luminosity is to use flat optics in the HL-LHC, i.e. to use different beam sizes in the crossing and perpendicular planes to compensate the geometric luminosity reduction factor [3]. In the following, the use of such optics will also be evaluated in comparison with crab cavities.

MONTE CARLO MODEL

In order to cope with limitations imposed by the maximum number of collisions per bunch crossing in the experiments, the HL-LHC will be a levelled machine, meaning that the instantaneous luminosity will be kept at 5×10^{34} cm^{-2}s^{-1} by adjusting the beam size. In this scenario the yearly amount of produced collisions will depend more strongly on the reliability and availability of the accelerator rather than on the effective peak luminosity, $\mathcal{L}_{peak}$. In order to make accurate predictions on the luminosity production and to assess the benefits of different operational scenarios, a Monte Carlo model was developed to simulate luminosity production in the LHC [4]. In this study, the model was adapted to the HL-LHC parameters in order to study the influence of crab cavity failures on availability.

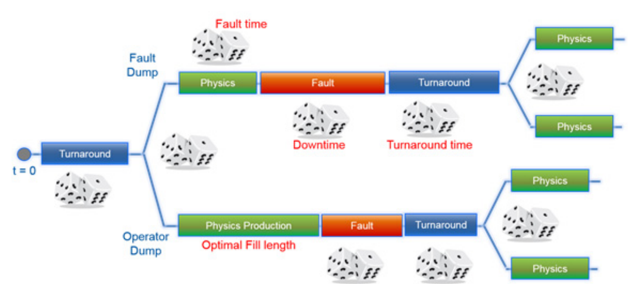

Figure 1: Schematic sequence of modes used in the Monte Carlo model to simulate LHC luminosity production.

In the simulation model the LHC changes from one accelerator mode to another based on random numbers: “turnaround” when the next fill is being prepared; “phys-

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ics production" when collisions are produced; "fault" when the machine is unavailable. The faults and time spent in each mode are drafted from distributions fitting the failure data gathered during the summer 2016 [5]. This period of operation was chosen for its good availability in order to make estimations for HL-LHC steady operation and focus on the impact of crab cavities. A schematic sequence of machine modes used in the model is shown in Fig. 1. The parameter values used in the model to simulate HL-LHC operation are detailed in Table 2.

Table 2: Average LHC Availability Parameters Used in the Simulations. The distributions are chosen to fit LHC data. The longer turnaround after a normal dump compared to after a fault comes from planned interventions.

Name	Normal value	Value after a fault	Distribution
Time in physics before fault	9h	-	exponential
Fault duration	2.2 h	5.6 h	lognormal
Turnaround time	5.2 h	4 h	lognormal

The time spent levelling the luminosity in the model is derived from the available effective peak luminosity:

$$\tau_{lvl} = \frac{N_0 - \sqrt{N_0^2 \frac{\mathcal{L}_{lvl}}{\mathcal{L}_{peak}}}}{2\sigma_{pp}\mathcal{L}_{lvl}},$$

where τ_{lvl} is the levelling time, N_0 the initial number of particles in each beam, $\mathcal{L}_{lvl}$ the levelled luminosity, $\mathcal{L}_{peak}$ the effective peak luminosity, and σ_{pp} the proton-proton cross-section.

Once the levelling is not possible anymore the luminosity decays exponentially. If no fault occurs, the beam is dumped after the optimal fill length, maximising luminosity production over the year, which was not done in 2016. The model detailed above was used to simulate luminosity production in four reference scenarios: round and flat optics, with and without crab cavities. In each case, one thousand 160-day long years of LHC operation were simulated and average metrics were computed. A detailed output of the model for the case with round optics and without crab cavities is shown in Fig. 2. One can see the relatively low variance of the yearly luminosity production due to the many fills per year (~200). The relevant outputs of the model in all four cases are summarized in Table 3, where physics efficiency is the proportion of the time spent producing collisions. One can see that the gain from using flat optics is two thirds of the one expected from the use of crab cavities. Using both simultaneously leads to a 50% increase in yearly luminosity production compared to using none. One can however not assume the use of crab cavities or flat optics without considering their associated faults in the model to affect the time spent in collisions. This effect originates from the fact that with a shorter optimal fill length one would need to dump the beam more often to refill the LHC, spending more time in the "turnaround" mode.

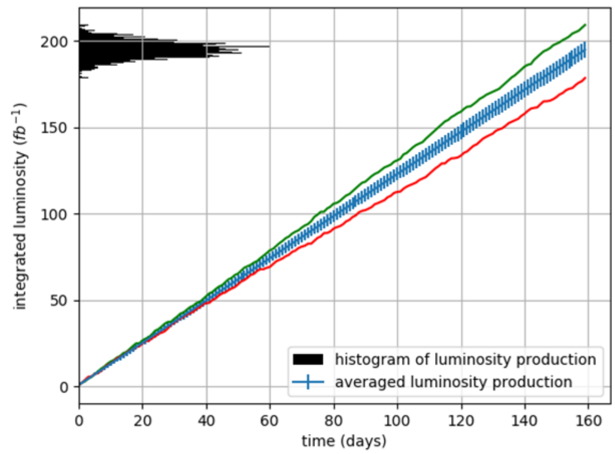

Figure 2: Simulation result without crab cavities and round optics. The years yielding the least and most luminosity are highlighted in red and green. A histogram of yearly luminosity production is shown on the y-axis.

IMPACT OF EXISTING LHC RF SYSTEM ON AVAILABILITY

Assessing the effect of crab cavity failures on availability without experimental data on crab cavity operation is challenging, in particular as such cavities have never been operated with a hadron beam. The influence of existing RF systems on availability was taken as a reference in order to explore a realistic availability parameter-space for crab cavity failures.

A first relevant system to be used as input is the KEKB crab cavity system. This set of two crab cavities is based on a different technology than the one foreseen for HL-LHC [6] and operates on an electron beam with top-up injection. It is nonetheless relevant as it is part of a large accelerator complex using a high-power beam. A 2014 report [7] suggests that cavities have failed on average every 18 hours of operation for the High-Energy Ring. This very high failure rate has to be weighed against the five times lower failure rate observed during later opera-

Table 3: Simulation Results Without Crab Cavity Failures

Optics scenario	Effective luminosity ($cm^{-2}.s^{-1}$)	Levelling time (hours)	Optimal fill length (hours)	Physics efficiency (%)	Yearly luminosity production (fb^{-1})
Round w/out CC	5.95×10^{34}	1.25	6.9	40	195±5.3
Round w/ CC	11.7×10^{34}	5.2	8.9	48	272±7.2
Flat w/out CC	8.3×10^{34}	3.4	7.75	43	245±6.5
Flat w/ CC	16.3×10^{34}	6.75	10	50	295±8.1

tion. One could expect a similarly good behaviour for the HL-LHC system after a first commissioning period.

Another relevant system is the LHC RF consisting of eight accelerating cavities. The analysis of the 2016 data for LHC operation shows [5] that they have failed on average every 90 hours of operation and have led to a downtime of 0.7 hours after each fault. This short downtime is to be expected for a system where the recovery of cryogenic conditions is fast, such as for cavities.

One should however envisage that a failure affecting crab cavities might have repercussions on other systems. The crab cavities will give a strong transverse kick to the beam and, due to the power available, have very short timescales for failures [8]. It is therefore possible that a failure in a crab cavity leads to consequent particle losses and to the quench of a superconducting magnet in the LHC ring. The recovery from such a magnet quench would take around 8 hours. Considering all of the above (typical availability parameters for RF systems in large accelerator complexes and LHC operation) the availability parameter space considered for this study was constrained to a Mean Time Between Failures (MTBF) from 10 to 90 hours and downtimes due to crab cavity failures between 0 and 10 hours. However, the size of this parameter space does not reflect the impact of the number of cavities on availability as the failure rates typically scale linearly with the number of systems and the HL-LHC will have 16, i.e. eight times more crab cavities than KEKB.

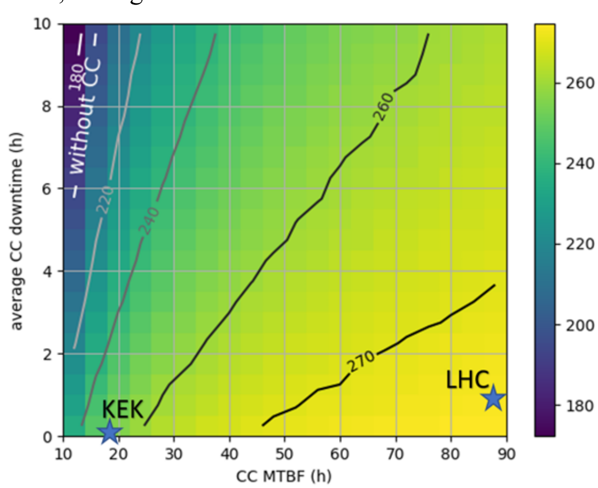

Figure 3: Yearly luminosity production as a function of average CC downtime and Mean Time Between Failures (MTBF) with round optics.

IMPACT OF CRAB CAVITY FAILURES ON HL-LHC AVAILABILITY

The results shown in Table 3 were updated to consider crab cavity failures. Such failures are modelled with two parameters, their MTBF and average downtime. Due to the relatively high failure rates considered in this study, these failures were implemented so that they could also affect fills dumped by the operators (as shown in the lower branch in Fig. 1). The model was run with crab cavity availability parameters using the range defined in the previous section and for round and flat optics. The effect of crab cavity failures on quantities averaged over a thousand simulated years for each set of parameters is illustrated in Figs. 3 and 4.

The luminosity outputs of the model without crab cavities is recalled with a thicker white iso-luminosity line labelled “without CC”. This defines the breakeven line for crab cavity availability, where the increased levelling time is absorbed by the extra dumps due to crab cavity faults and therefore no luminosity production is gained.

One can see that, even if the crab cavities perform like the KEKB ones, one would still gain 25% of integrated luminosity with round optics and 10% with flat optics. If crab cavity operation was as efficient as the LHC accelerating cavities, one would gain respectively 40% and 20%. In this case, crab cavity failures have only a negligible effect on the overall machine availability.

On the other hand, if the crab cavities lead to a quench requiring a recovery of 8 hours every time they experience a failure, one would only gain luminosity if they fail less than every 15 and 28 hours of physics production respectively. This is equivalent to 46 and 70 actual hours considering the physics efficiencies of 33% and 40 %.

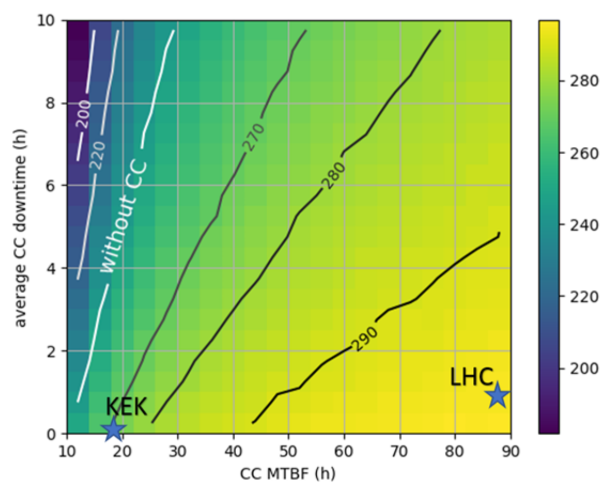

Figure 4: Yearly luminosity production with flat optics.

CONCLUSIONS

Crab cavities are an essential part of the Hi-Lumi upgrade of the LHC that can lead to a 35% gain in yearly luminosity production. This gain will occur even with low crab cavity availability, and even if possible quenches are induced every second or third day of operation. However, the luminosity gained from crab cavities is strongly dependent on the downtime induced by failures (e.g. ±4% luminosity per extra hour of average downtime if the failures are frequent) and, thus, on the criticality of such failures. It is therefore necessary to perform further studies to improve the understanding of crab cavity failures, their consequences and potential mitigations [9], as well as improving operational margins on cavity operation in order to lower the frequency of such failures to a minimum.

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