THE HIGH LUMINOSITY CHALLENGE: POTENTIAL AND LIMITATIONS OF HIGH INTESITY HIGH BRIGHTNESS BEAMS IN THE LHC AND ITS INJECTORS*

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Abstract

High-intensity and high-brightness beams are key ingredients to maximize the LHC integrated luminosity and to exploit its full potential. This contribution describes the optimization of beam and machine parameters to maximize the integrated luminosity as seen by the LHC experiments, by taking into account the expected intensity and brightness reach of LHC itself and its injector chain as well as the capabilities of the detectors for next run and foreseen upgrade scenarios.

INTRODUCTION

The LHC proton-proton programme aims at steadily increasing the luminosity production rate in the next two decades, in order to reach the target of 3000 fb^{-1} with the High-Luminosity LHC project (HL-LHC) [1, 2]. High intensity, high brightness beams are key ingredients to reach these goals. Several interventions associated to long shutdowns (LS), will address and overcome several limitations. Notably the LHC injector upgrade project (LIU) [3, 4], scheduled for implementation during LS2, aims at providing the most intense and bright beams that LHC can store, accelerate, and collide with high efficiency and reliability. In the following we discuss the intensity and brightness limitations in LHC and injectors, together with their potential in terms of expected integrated luminosity for ATLAS and CMS experiments.

LHC LIMITATIONS

The LHC has being designed to store and collide 2808 25 ns spaced bunches populated by 1.1 10^{11} protons in two counter-rotating beams. Magnet apertures have been specified to allow a normalized emittance of 3.75 µrad to be used operationally [5]. Together with β^*=55 cm, the beam parameters allow reaching the so-called nominal luminosity of 1 10^{34} cm^{-2}s^{-1}. During Run I the LHC operated at 50 ns and with up to 1.7 10^{11} protons per bunch (ppb) in 1380 bunches, which represented the best parameters to maximize the integrated luminosity in the presence of strong e-cloud effects observed and anticipated for 25 ns beams [6]. However, 50 ns beams saturate quickly the reconstruction capabilities of the detectors due to the large pile up of events per crossing. Therefore, Run II will be devoted to establish 25 ns bunch spacing beams to aim at doubling the integrated luminosity for about the same pile up, thanks to the higher-than-nominal bunch intensities that may be obtained from the injectors' chain after mitigation measures addressed during LS1, and an aggressive plan of scrubbing with special beams [7].

On a longer time scales, it is expected to be possible to bring in collision $2.2\cdot10^{11}$ ppb for a total of about 1 A of circulating beam current, provided that: a) e-cloud issues are solved by increasing the cooling capacity of the standalone quadrupoles (possibly including also coating of the upgraded ones), and by efficient scrubbing of the arcs; b) coupled-bunch instabilities are stabilized by the transverse damper; c) single-bunch instabilities can be stabilized by means of Landau octupoles or by the head-on beam-beam tune spread in a collide-and-squeeze operation mode (see Ref. [8] and references therein). It is expected that 5% of the total intensity is lost during the whole cycle, but keeping and average lifetime below 22 h and in any case never lower than 0.2 h.

Large bunch intensities associated with small emittance result also in large emittance blow-up due to intra-beam scattering (IBS), which has to be added to that generated by unknown noise sources (about 10 % from injection to stable beam and more in the vertical plane). Figure 1 shows the expected horizontal emittance blow-up as predicted by an IBS model through an injection, ramp and squeeze cycle [9], to which a 10 % should be added to account for observed and unknown sources of emittance growth. High brightness beams, in particular those that can be obtained with small emittance, may surpass the damage limit of the injection protection devices in case of failure scenarios, because of the energy density. A programme to replace these devices with more robust material is foreseen for after LS2 [10]. Nonetheless, it is worth noting that small emittances, even if not completely exploitable due to, e.g., IBS effects, provide a natural safety margin against growth effects. For large emittance, the very good alignment of the LHC magnets resulted in ample margins to fit comfortably nominal emittance beams with the typical injection oscillations.

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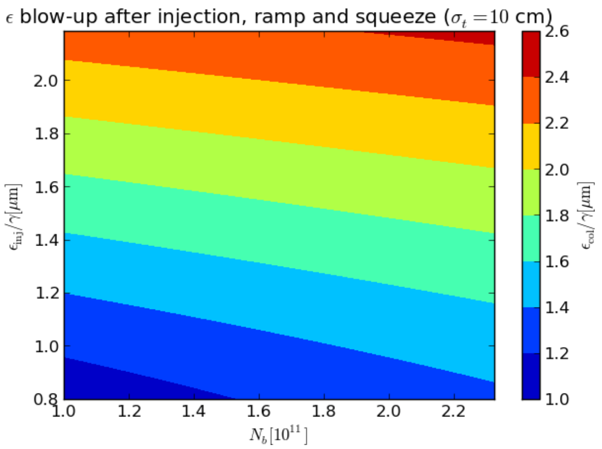

Figure 1: IBS emittance growth through injection, ramp and squeeze as a function of the injected emittance and bunch population for longer-than-nominal bunches. The emittance growth can be fairly fitted in almost all the parameter space by $\Delta\varepsilon \approx 0.2\ \mu m \cdot N_b/\varepsilon_{inj}$, where N_b is the bunch population in units of 10^{11} and ε_{inj} is the emittance in units of μm.

INJECTORS' LIMITATIONS

LHC injectors existed long before the LHC ring and served former experiments, while now provide beams also to fixed target experiments at different extraction energies. The injector chains for proton LHC beams [11] starts with Linac2 that provides 50 MeV bunches to the four rings the PSB, which accelerates them to 1.4 GeV for the injection of 4+2 bunches in two PS injections. During the PS cycles, the injected bunches are further split multiple times to obtain a train of 72 bunches with a 25 ns structure that is injected from 2 or 4 times in the SPS at 26 GeV. The SPS accelerates the bunch trains that are injected 12 times to fill the LHC. The injector chain proved already to be able to provide beams that exceed the nominal LHC beams [12]. Further progress are expected during the Run II thanks to an alternative beam production scheme called BCMS that allows to inject less bright beams in the PSB for the same final intensity in the SPS thanks to 4+4 bunches injected in the PS and a reduced number of longitudinal bunch splitting [13]. The cost is however producing fewer bunches per train, resulting in less bunches available in the LHC. Some of the known injector limitations will be further mitigated by the LIU project that with the new Linac 4 [14], the PS injection energy increase to 2 GeV [15] and the upgrade of the SPS RF system [16] will lower the brightness limitations of the Booster and PS and increase the maximum intensity in the SPS (see Ref. [17] and reference therein). It is possible to summarize the beam parameter for different scenarios configurations by a brightness limitation coming from either the Booster or the PS and a total intensity limitation given by the accelerating system of the SPS [18]. Figure 2 shows a synthesis of the above-mentioned limitations as a function of injected emittance and bunch population for scenarios post-LS1 and post-LS2 on top of the integrated luminosity expectations of the LHC that will be discussed in the next section.

LUMINOSITY POTENTIAL REACH

The LHC hosts four detectors: ATLAS and CMS for high luminosity collision, LHCb for precise measurements at lower luminosity and Alice devoted to the Heavy Ion program. The experiments require the maximum usable integrated luminosity not exceeding the event pile-up or peak luminosity limits [19]. The present limits need to be increased after LS3 (with about 300 fb^{-1} accumulated) in order to keep increasing the statistical significance of the acquired data, that will otherwise saturate at constant luminosity. The HL-LHC upgrade foresees both an upgrade of the experiments [20] and of the LHC ring to fulfil the goal of reaching 3000 fb^{-1} in the following decade of LHC operations thanks not only to the increased intensity but also to the reduction of β* and the installation of crab cavities (see Ref. [21] and reference there in). Table 1 shows the present and upgraded pile-up and luminosity limits.

Table 1: Assumed detector limits for the LHC after LS1 and after LS3 in terms of maximum average event pile-up or maximum luminosity

Exp.	**LHC**	**HL-LHC**
ATLAS	50 events/crossing	140 events/crossing
CMS	50 events/crossing	140 events/crossing
LHCb	4 to 6 10^{32} $cm^{-2}s^{-1}$	4.5 events/crossing
Alice	5 10^{29} to 2 10^{30} $cm^{-2}s^{-1}$	2 10^{31} $cm^{-2}s^{-1}$

The LHC annual operation planning consists in about 160 days of scheduled physics time and the rest is needed for shutdown, maintenance, intensity ramp-up and machine development. The registered performance efficiency is around 50 % due to faults of several origins [22]. The minimum turnaround time is estimated to be about 3 hours [23]. The maximum number of bunches depends on the production scheme. The standard one is favoured with 2748 bunches over the 2608 of the BCMS, due to the larger number of PS injections needed to fill the SPS and correspondingly more gaps in the LHC filling scheme [24].

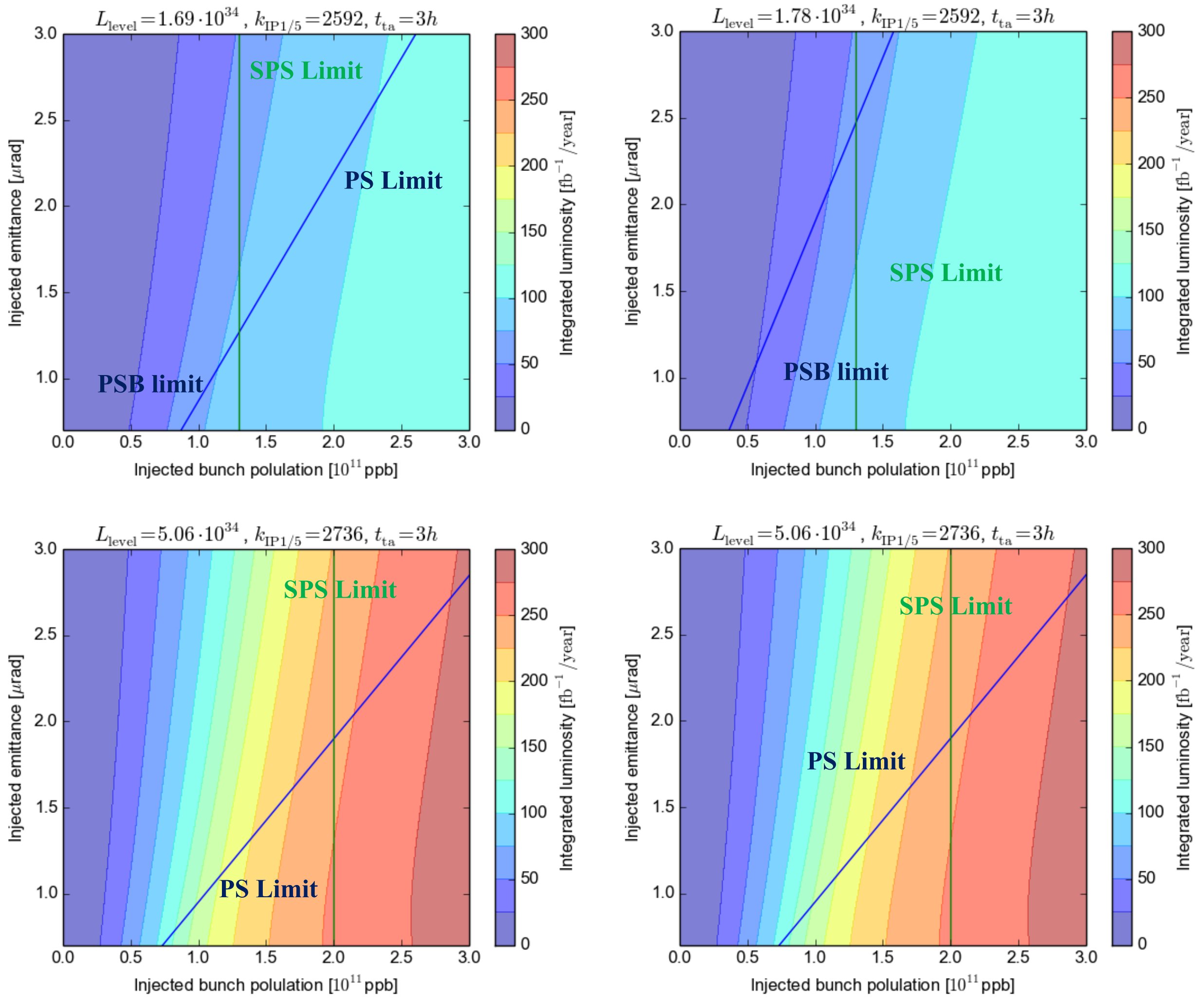

Figure 2: Yearly luminosity expectation as a function of the injected emittance and bunch population from the injectors for different post-LS1 (top, β*=60 cm) and post-LS3 (bottom, β*=15 cm, crab cavities) scenarios with the BCMS (left) and standard (right) beam production scheme for the same pile up limit. The luminosity model only includes burn-off and injection to stable beam expected losses and emittance blow-up (IBS plus noise sources). 80 days of continuous successful fills are assumed resulting from 160 days of scheduled physics and 50% of performance efficiency. The green lines represent the bunch population limitation of the SPS and the blue lines the brightness limit in the PSB and PS.

For a given scenario it is possible to compare the brightness curves obtainable by the experiments and the expected yearly-integrated luminosity in order to identify the optimal working point. Figure 2 shows the expected yearly luminosities using a simple luminosity evolution model that includes only the burn-off [25] as a function of the injected emittance and intensity assuming the 10 % of emittance blow-up plus IBS and 5 % losses. This simplified model is realistic in the parameter range of interest, although is optimistic for low emittance beams for which the IBS growths during collision contribute to decrease the luminosity lifetime, which is partially restored by radiation damping at 7 TeV. Table 2 shows the expected daily luminosities with a more refined differential model that includes burn-off, IBS and synchrotron radiations. From the plots one can conclude that for any scenario the optimal point is when the brightness is larger with the maximum intensity. The BCMS scenario, although offering higher brightness, pays a large price due to the smaller number of bunches, which still makes it attractive for after LS2, but it is definitely less performing for the HL-LHC case for which the luminosity lifetime is the only lever arm to reduce the number of fills per year. It has to be noted that for the HL-LHC it is essential to be able to obtain long fills as shown in Table 2. Due to the key role of bunch intensity on the integrated luminosity, an alternative scenario, in which a 200 MHz main RF system is installed in the LHC ([26], and references therein) in the LHC, is under study and can potentially allow an increase in the injected intensity from the SPS, although studies needs to confirm it. The system,

Table 2: Daily luminosity expectation for different LHC scenarios Post LS1 and Post LS2 by using differential luminosity model that includes burn-off, IBS and radiation damping

Scenario	Bunch Spacing (ns)	Bunch Population (10^{11})	Production scheme	ε_{coll} (μm)	Pile-up Max/Lev.	Daily Luminosity (fb^{-1})	Fill duration (h)	Levelled time (h)
LHC 6.5 TeV β*=60 cm	25	1.2	Standard	2.8	30/50	0.58	10.1	no level
			BCMS	1.7	50/50	0.78	7.5	no level
	50	1.6	Standard	2.0	76/50	0.53	8.1	5.6
			BCMS	1.6	95/50	0.52	7.8	4.4
HL-LHC 7 TeV β*=15 cm	25	1.9	Standard	2.3	419/140	2.99	7.2	5.7
			BCMS	1.9	510/140	2.93	7.8	6.7
	25	2.2	Standard	2.5	517/140	3.17	8.6	7.3
	50	3.5	Standard	3.0	517/140	1.7	15	14.1

together with the existing 400 MHz RF system, could allow increasing the bunch length to reduce electron cloud effects, reduce IBS growth rates, and provide flat longitudinal bunch charge density. Yet another bunch production scheme called 8b+4e [27], which replaces few bunches with empty buckets in 72 bunch trains, can substantially decrease the electron cloud thank to the increase gaps at the cost of 30% less bunches and therefore being half-way in between 25 ns and 50 ns integrated luminosity expectations.

CONCLUSION

The LHC and HL-LHC rely on high brightness high intensity beams to fulfill the target performance, thanks to the upgrade plans involving not only the LHC ring, but also the whole injectors' chain, together with the progress in understanding and overcoming the potential performance limitations. At constant brightness, larger intensity offers the best performance reach when coupled with long fills, thanks to the larger luminosity lifetime that compensates the physics efficiency loss due to the turnaround time. Conversely, if unexpected beam dumps are very frequent, brightness through low emittance is competitive if it also contributes to increase the reliability. If lower emittance is associated with smaller number of bunches, the brightness gains is outweighed by the resulting smaller leveled luminosity leading to overall smaller integrated luminosity in HL-LHC scenarios. Gains from very low emittance are also mitigated by early blow-up due to IBS.

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