# Integrated performance of the LHC at 25 ns without and with LINAC4

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# Abstract

The performance of the LHC above 6.5 TeV will depend on many factors. The available beams and their brightness defines together with achievable beta\* the potential peak luminosity. For some cases the peak luminosity and the associated event pile-up may degrade the quality of the data recorded by the experiments. Such cases will require luminosity leveling for which a number of options are available. The peak performance may also be limited by cooling capacities and other equipment related issues, including machine protection as well as UFOs. The 25 ns beams require in addition substantial periods of scrubbing. The performance of the LHC in terms of integrated luminosity will be evaluated for various scenarios involving 25 ns beams, taking into account potential limitations from the various sources.

# **25 NS BEAMS IN THE INJECTORS**

The expected performance of 25 ns beams in the injectors is discussed in detail by G. Rumolo in another contribution to this workshop [1]. A summary of the expected beam parameters at extraction from the SPS is given in Table 1. The bunch population is in all cases limited to  $1.3 \times 10^{11}$  ppb by the SPS RF system.

Between extraction from the SPS and start of collisions (stable beams) in the LHC, the following changes are considered:

• The intensity transmission is assumed to be 96% as achieved in 2012 with tight collimator settings,

Table 1: Achieved (in 2012) and expected beam parameters of 25 ns beams in the injectors for the standard and the BCMS production schemes. The scenario 'LS1' corresponds to the situation without Linac4, while the scenario 'L4' corresponds to the case with Linac4. N is the bunch population,  $\varepsilon^*$  is the normalized emittance.

Beam type	Scenario	N	$\varepsilon^*$	Limited by
		$(10^{11})$	(µm)	
Standard	Achieved	1.2	2.6	_
Standard	LS1	1.3	2.44	SPS
Standard	L4	1.3	1.65	SPS
BCMS	Achieved	1.15	1.4	_
BCMS	LS1	1.3	1.3	PS+SPS
BCMS	L4	1.3	1.3	PS+SPS

Table 2: Expected beam parameters of 25 ns beams at start of collisions after LS1 for the BCMS beam, the standard 25 ns beam and the standard beam with Linac4. For the BCMS beam there is no difference with or without Linac4. k is represents the number of colliding bunch pairs in AT-LAS/CMS,  $\theta$  is the half-crossing angle.

Beam type	Ν	$\varepsilon^{*}$	k	$\beta^*$	$\theta$
	$(10^{11})$	(µm)		(m)	$(\mu rad)$
BCMS	1.25	1.65	2590	40/50	150/140
Standard	1.25	2.9	2740	50	190
Standard+L4	1.25	2.0	2740	40/50	150/140

• An emittance blow-up of 15% is assumed in addition to the unavoidable blow-up from IBS. This is optimistic as compared to 2012 where the additional blow-up was typically 30%. It is also assumed that the blow-up from electron cloud, that is mainly observed at injection, is completely controlled.

The possible  $\beta^*$  values and the corresponding crossing angles were evaluated by R. Bruce [2]. Table 2 presents the beam parameters at start of stable beams, the number of colliding bunch pairs in IR1/IR5 (k),  $\beta^*$  and the half crossing angles  $\theta$ . Filling scheme variations may affect k at the level of around 5%.

# LHC PERFORMANCE LIMITATIONS

The maximum average pile-up is assumed to be limited to 45 events per bunch crossing. This value is also given as rough guideline for maximum acceptable pile-up in 2015. The pile-up is obtained from the luminosity assuming a visible cross-section of 85 mb at 6.5 TeV. For simplicity it is assumed in this document that it is also possible to level the luminosity at a pile-up of 45 events per bunch crossing, which is not (yet) guaranteed.

The cooling of the triplet magnets sets a limit to the maximum achievable luminosity of  $1.75 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ , with an uncertainty of 10 to 20%[3]. This limit will have to be explored in 2015 and beyond. A study will be launched to analyze all possible limitations in the triplet (starting with the limiting heat-exchanger) to evaluate possible actions during LS2.

The intensity and/or brightness of the beams may be limited by instabilities, even tough the 25 ns beam may be just stable up to  $1.3 \times 10^{11}$  ppb. In case of problems the beams may be stabilized at high energy by head-on beam-beam (squeeze in collision), but this makes operation more complex [4]. Other possible limitations to intensity are beam induced heating of equipment, electron cloud and UFOs. More experience must be collected on those item in 2015 and beyond.

# UFOs

Between 2010 and 2013, 58 beams were dumped in the LHC due to UFO events [5]. An extrapolation of the UFO loss spectrum to 6.5 TeV using the currently accepted quench levels predicts around 100 beam dumps per year from UFOs after LS1. From the current status of the quench test analysis [6] there may be an extra margin on quench level for millisecond timescales (factor 2) at 4 TeV. This result must still be confirmed and extrapolated to 6.5 TeV. If this factor also applies at 6.5 TeV, the number of dumps would be reduced by a factor 2-3. The UFO rate depends on the bunch spacing, and it is stronger with 25 ns, but a fast conditioning was observed over a few fills in 2012. Based on the experience from the startup in 2012, one has to expect serious deconditioning after LS1, it will probably take 2-3 months to recover a lower UFO rate.

#### Electron cloud

Scrubbing was demonstrated to be efficient at 450 GeV [7]. It lowers the electron cloud in dipoles, a reduction that is less evident in the quadrupoles (due to a significantly lower SEY thresholds). Despite high intensity two-beam operation in the triplets for around 2 years (high electron dose), the electron cloud still present in the triplets. The SEY in the triplet is estimated to be around 1.2-1.3, the value being deduced from observed heat-load and simulations. A significant increase of the heat load (by a factor 4) is observed in the arcs during the ramp due to electron cloud in the dipoles. No change in heat load is observed in the quadrupoles. The underlying mechanism is not yet understood.

The available cooling power in the arcs (around 250 W per half-cell) will possibly limit initial operation at 6.5 TeV with 25 ns beams. The limitations observed in the standalone magnets (SAMs) will be lifted during LS1. A projection of the current situation to 2015 yields a limitation to 50% of the total number of bunches at 25 ns ( $\approx$ 1400 bunches).

Ideas have been put forward to enhance scrubbing at 450 GeV with dedicated scrubbing beams. To enhance the electron cloud doublet beams with bunch spacings alternating 5 and 20 ns or 2.5 and 22.5 ns have been proposed. The implications and issues (for BI, RF, ADT) are under investigation [8].

## CONDITIONS

The performance predictions for 25 ns beams after LS1 are based on a high intensity proton run length of 160 days per year. It must be noted that periods of reduced luminosity (and intensity) are embedded in our runs. Such periods include initial intensity ramp up (up to a few weeks)



Figure 1: Relative contribution of the top-ten 2012 systems to the fault time. Courtesy A. Macpherson.

and fast intensity ramp up after technical stops (around two days). One should also not forget all the special runs like high-beta, LHCf, luminosity calibrations etc that are also embedded in the proton run and that cost a few percent of the running time.

Depending on the final performance and actual pile-up limitations,  $\beta^*$  leveling may be required for some time in each fill. To ease the setup and maximize efficiency it is important to train  $\beta^*$  leveling as soon as possible. A proposal to apply this technique for LHCb is under evaluation.

# Machine Availability

The past 2012 run can be split into three blocks in terms of machine availability. On a per-physics-fill basis the time can be split up into:

- 6.1 hours of stable beams,
- 4.8 hours of faults,
- 5.5 hours of turn-around ('the rest').

This results in a 36% stable beams fraction / physics efficiency. The turn-around block also accounts for test cycles (Q/Q measurements, feedback tests, loss maps, high beta setup etc), lost cycles, short tests that were inserted in a standard cycles as well as a certain number of pre-cycles. The minimum turn-around time was 2.2 hours.

A break-down of the failures is shown in Figure 1. The cryogenic system and the injectors account for roughly 1/3 of fault time in 2012. One should also note that the long term average SPS (injector) efficiency is  $85 \pm 5\%$ .

In comparison LEP1 reached physics efficiencies of over 50% in the period 1992-1994, see Figure 2. But the machine was much simpler and its fills were long. LEP2 had short(er) fills and an efficiency that is similar to LHC. A look at the weekly LHC stable beams efficiency in Figure 3 shows that with one exception in 2011, in the best weeks the LHC physics efficiency reached 45%.

The current accounting of faults and turn-around at the LHC is rather coarse. There is an ongoing effort between



Figure 2: LEP yearly physics efficiency. Up to 1995 LEP ran around 45 GeV, from 1996 on it ran above 80 GeV.



Figure 3: Weekly LHC physics efficiency in 2011 (blue) and 2012 (red).

the AWG (Availability WG) and operation to improve the modeling and information on the different phases. The aim is to build a tool that combines cycle information (beam modes, intensity, energy), Post-mortem information and fault information to provide a better model for faults and for the break-down of the 'turn-around time'.

After LS1 the cycle length will increase by  $\approx 20$  minutes. The baseline assumption for performance used here is that everything else remains the same except for the cycle length (same length of stable beams and of faults), and it is assumed that the turn-around time block includes two machine cycles for a total of 40 minutes. This leads to a stable beams efficiency of 35% which is used as a baseline for the performance evaluation. There are obviously many uncertainties, and such assumptions may be rather optimistic for a learning year like 2015.

## LUMINOSITY MODEL

To asses the performance a simple luminosity model is used for 6.5 TeV, based on 2012 observations during collisions. The ingredients are:

• Luminosity burn-off with a total cross-section of  $\sigma =$ 



Figure 4: Evolution of the lifetime of the beams in collision as a function of the time spent in stable beams. The data corresponds to the average over all high intensity fills recorded after the octupole polarity reversal in August 2012. Courtesy A. Gorzawski.

105 mb,

- Single beam lifetimes as observed in 2012 at 4 TeV,
- Emittance growth as observed during physics fills in 2012, corrected for the synchrotron radiation damping (time constant of  $\approx$  30 hours.

The model tracks the intensity, emittances and luminosity along a fill by updating the parameters at intervals of 30 seconds based on finite differences. The model is crosschecked with a simple analytic approach (simple closed formula) for exponential fill length distribution and constant averaged luminosity lifetime [9] and with a Monte-Carlo approach (courtesy A. Apollonio).

### Lifetime

Figure 4 displays the average intensity lifetime as a function of the time in stable beams for 2012 fills recorded after the octupole polarity reversal in August 2012. The lifetime including burn-off is in the range of 25 to 50 hours. It is assumed for this analysis that the single beam lifetime in the absence of collisions and burn-off is 60 hours.

## Emittance growth

A significant effective emittance growth was observed in collision (from the luminosity evolution) at 3.5 and 4 TeV. The effective growth (assuming equal growth in both planes) extracted from the luminosity of ATLAS and CMS is shown in Figure 5. The origin of the growth is not understood. IBS is not sufficient to explain the growth, an extra contribution with growth time around 40 h is required. It is also noteworthy that the growth in 2011 was significantly steeper than in 2012. A parametrization of the 2012 emittance evolution using a second order polynomial is used to model the luminosity at 6.5 TeV. The growth is corrected for radiation damping (damping time  $\approx$  30 hours).

When the luminosity model using the ingredients discussed just before are applied to 2012 conditions at 4 TeV,



Figure 5: Evolution of the average emittance extracted from the luminosity of ATLAS and CMS in collision. The 2011 data is obtained from an average of the period with  $\beta^*$  1 m (October-November 2011). The 2012 data is averaged over the period after the octupole polarity change in August 2012.Courtesy A. Gorzawski.

the luminosity evolution can be reproduced well [10]: in the first hour of stable beams, the luminosity lifetime is 6-8 hours, after 8 hours the luminosity lifetime has increased to 12-15 hours.

At 6.5 TeV the luminosity lifetime from burn-off alone at a luminosity of  $2 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$  is  $\approx 12$  hours.

#### Fill length distribution

The fill length distributions shown in Figure 6 are very similar in 2011 and 2012 and can be approximated by simple exponential distributions. Typically 30% of the fills are dumped by the operation crews, the rest is dumped by the MPS.

An exponential fill length distribution is used for the performance figures quoted in the next section. The influence of the fill length distribution can be estimated by comparing the average integrated luminosity per fill for different fill length distributions, see Figure 7: exponential (truncated at 20 hours), flat and delta function centred at the mean value. In all cases the mean fill length is set to 6.5 hours. The results depend on the lifetime assumptions, but for the model used here, the luminosity increases by 10% for a flat distribution and by 20% for a delta function (with respect to the exponential distribution). The fill length distribution for 2012 is in fact a combonation of an exponential distribution driven by faults (2/3 of the fills) and of mixture of a flat distribution and a smeared delta functions (from fills dumped by the operation crews, 1/3 of the fills). The change in integrated luminosity as compared to a pure exponential is around 5-10%. Am analysis of the optimum dump time shows that a 6.5 hours dump time is not too far from the optimum of 8-10 hours for the assumed length of turn-around and fault times.



Figure 6: Fill length distribution (length of stable beams) in 2011 (top) and 2012 (bottom).



Figure 7: Exponential and flat distributions with the same mean fill length of 6.5 hours.

# **PERFORMANCE ESTIMATES**

With Lianc4 the performance of BCMS and standard 25 ns beams is very similar. The higher leveled luminosity of the standard beam (due to the larger number of bunches) is compensated by a longer leveling time with BMCS beams. The integrated luminosity is in the range of 48-53  $\text{fb}^{-1}$ /year for a stable beams efficiency of 35% as shown in Figure 8. The potential peak luminosity  $\mathcal{L}_p$ , leveled luminosity  $\mathcal{L}_l$  and leveling times are indicated in Table 3. It must be noted that the leveled luminosities are at the triplet cooling limit, and that the peak luminosities of the BCMS beams and of the standard beam with Linac4 are well above the estimated limit. If the 2011 effective emittance growth is used in the model, the integrated luminosities increase by approximately 2%. The values increase by 5-10% for a mixed 2012-like fill length distribution (see previous section).

If no leveling is used there is a modest gain of a few  $fb^{-1}$ 

Table 3: Peak  $(\mathcal{L}_p)$  and leveled luminosity  $(\mathcal{L}_l)$  after LS1 for the various 25 ns beams in collision at the LHC.

Beam type	$\beta^*$	$L_l / 10^{34}$	$L_{p}/10^{34}$	Leveling
	(m)	$(\rm cm^{-2} \rm s^{-1})$	$(\rm cm^{-2} \rm s^{-1})$	time (h)
Standard+L4	0.4	1.65	2.1	1.6
BCMS	0.4	1.54	2.2	2.5
Standard+L4	0.5	1.65	1.9	0.7
BCMS	0.5	1.54	2.0	1.6
Standard	0.5	1.65	1.2	-



Figure 8: Integrated performance per year for the different beams as a function of the stable beams efficiency in case the luminosity is leveled according to Table 3.

due to the short leveling time and low(er) initial lifetime, see Figure 9. The BCMS and standard beams have again similar performance with Linac4, but the pile-up is higher with BCMS beams. The peak pile-up is around 66 events per bunch crossing for the BCMS beam with  $\beta^*$  of 0.4 m. The integrated luminosity increases to 50-55 fb<sup>-1</sup>/year for a stable beams efficiency of 35% without leveling.



Figure 9: Integrated performance per year for the different beams as a function of the stable beams efficiency in case the luminosity is NOT leveled.

## Monte-Carlo Model

A Monte-Carlo model had been developed by A. Apollonio for HL-LHC [11] to model luminosity (simplified), failures and turn-around and provide an as realistic as possible handling of the machine phases. If this model is applied to 25 ns operation post-LS1 assuming:

- 30% fills dumped by operation (the other following the exponential distribution),
- 6.2 hours of mean turn-around time,
- a fault time modeled by 4 LogNormal distributions,

then the results are consistent with the values quoted above, in the range of  $\approx 45 \text{fb}^{-1}$ . With this model it is also possible to evaluate the impact of UFO dumps: in the pessimistic scenario of  $\approx 100$  dumps/year, the yearly integrated luminosity is lowered by 15%.

#### SUMMARY

The expected integrated luminosity per year for 25 ns operation is in the range of 45-55 fb<sup>-1</sup> for an efficiency similar to 2012. Over 5 and 1/2 years of operation until LS3 around 250-300 fb<sup>-1</sup> would be collected. Without Linac4 it is recommended to use the BCMS beam, with Linac4 the standard 25 ns beam. There are currently many unknowns on the limitations, emittance, efficiency etc, but the situation should be clearer end 2015. It must be noted that the peak luminosity is always close to or above the expected triplet limitation. To reach luminosities of  $2.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$  as quoted in many reference plots and documents, the performance must be boosted further (lower  $\beta^*$ , smaller emittances etc) and the triplet limitation must be lifted.

With Linac4 the standard 25 ns beams and the BCMS beams have very similar performance. A small bonus for the standard 25 ns is a lower pile-up (by 10%). The emittances that are eventually achieved may make the difference between standard and BCMS schemes. It may be easier with the standard beam due to the larger emittance. To be sure to reach or exceed  $300 \text{ fb}^{-1}$  by LS3 one should aim to improve the average physics efficiency of the LHC from 35% to at least 40%. This requires a concerted long term effort on the availability of equipment.

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