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PICS: WHAT DO WE GAIN IN BEAM PERFORMANCE[*]

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Abstract

The beam parameters in the LHC resulting from the Performance Improvement Consolidation (PIC) activities presented in [1][2] will be briefly recalled and motivated assuming that LINAC4 will be operational as PS-Booster Injector. The corresponding limitations in the LHC are outlined. Based on the above performance an estimate of the LHC yearly integrated luminosity will be provided. The evaluation of the need and extent of the performance and reliability improvement for some of the PIC items might imply additional information: the necessary machine studies and the specific operational experience required during Run 2 will be summarized.

BEAM PARAMETERS IN THE INJECTORS AND LHC

The beam parameters expected at extraction from the SPS and at the LHC in collision as a result of the Performance Improvement Consolidation in the Injectors are summarized in Table 1. It is assumed that LINAC4 is connected to the PS-Booster with an H^- injection and that the SPS RF low level system is upgraded to modulate the RF power along the revolution period in order to allow an increase of the bunch population of the 25 ns LHC beam in the SPS. A further increase of the bunch population would require an upgrade of the RF power which is not considered as part of the PIC scenario [3][1].

Table 1: Beam parameters at SPS extraction and at the LHC in collision

	SPS Extraction		**LHC collision (min. value – IBS)**	**LHC collision**		
	Bunch population [10^{11}]	**ε_n (H/V) [μm]**	**ε_n (H/V) [μm]**	**Bunch population [10^{11}]**	**$\varepsilon_{n\ coll.}$ (H/V) [μm]**	**Blow-up [%]**
BCMS[*]	1.45	1.45/1.45	1.74/1.45	1.38	1.85/1.85	27
Standard[†]	1.45	1.85/1.85	2.09/1.85	1.38	2.25/2.25	21

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[*] BCMS=Batch Compression Merging and Splitting scheme providing 48 bunches with 25 ns spacing per PS extraction.

[†] Standard production scheme providing 72 bunches with 25 ns spacing per PS extraction.

Experience during Run I has shown that beam intensity losses of few percents can be expected during the cycle. Losses are mostly occurring:

- At injection (e.g. satellite bunches preceding or following the main SPS bunch train bunches).
- During the injection plateau and at the start of the ramp (e.g. uncaptured particles or particles leaving the bucket because of large angle intra-beam scattering).
- During the ramp when the collimators are moved closer to the beam to their final settings.
- When the two beams are brought in collision.

An intensity loss of 5% distributed along the cycle is assumed during the LHC cycle from SPS extraction to collisions in the LHC. The losses at high energy are supposed to respect the minimum allowed lifetime of 0.2 h assumed for collimation and cleaning requirements.

A transverse emittance blow-up of 10 to 15 % on the average of the horizontal/vertical emittance has been considered in addition to that expected from Intra-Beam Scattering (IBS). The transverse emittances after injection, ramp and squeeze including IBS blow-up have been estimated and are listed in Table 1 assuming no coupling between the horizontal and vertical planes. This assumption is consistent with the observations made at the LHC at injection and during the cycle in 2012 after correction of the machine coupling. The IBS emittance blow-up has been estimated assuming that the r.m.s. bunch length is kept constant at 10 cm by means of a controlled longitudinal emittance blow-up during injection and ramp when the RF voltage is increasing linearly from 6 MV at injection to 16 MV at flat-top. The duration of the various phases of the LHC cycle used for the simulations is shown in Table 2.

The beam parameters in collision are listed in Table 1 together with the total emittance blow-up from SPS extraction.

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Table 2: Break-down of the turn-around time in the HL-LHC era (Courtesy of M. Lamont) [4].

Phase	Duration [min]
Ramp down/pre-cycle	60
Pre-injection checks and preparation	15
Checks with set-up beam	15
Nominal injection sequence	20
Ramp preparation	5
Ramp	25
Squeeze/Adjust	40
Total	180

The possible filling schemes in the LHC are presented in Table 3 where the total number of bunches and the corresponding number of colliding pairs is listed for the BCMS and Standard production schemes assuming 6 (respectively 4) PS injections per SPS cycle. 12 non-colliding bunches have been included on request of the experiments for providing beam-gas interaction data necessary for background evaluation.

Table 3: Filling schemes for 25 ns spacing beams (Courtesy of B. Gorini).

Filling scheme	Total	IP1-5	IP2	IP8
BCMS	2604	2592	2288	2396
Standard	2748	2736	2452	2524

Potential issues: electron cloud

Electron cloud is one of the main potential limitations expected for the operation with 25 ns beams. Electron cloud effects include emittance blow-up and heat-load on the beam screen. The experiments conducted in 2012 [5] have demonstrated that:

- Emittance blow-up occurs mainly when multipacting occurs in the main dipoles.
- A reduction of the Secondary Electron Yield (SEY) down to ~1.45 sufficient to reduce significantly the electron cloud build-up in the dipoles at injection can be achieved after a few days of scrubbing.
- The above value of the SEY is not sufficiently low to avoid multipacting in the main quadrupoles at injection and in the dipoles during the ramp.
- A SEY as low as 1.3 can be attained in the beam screen of the triplets indicating that low values of the secondary electron yield are within reach in cryogenic surfaces and in the presence of magnetic fields close to 2 T (magnetic field at the beam screen surface in correspondence of the triplet quadrupoles' poles at 4 TeV).
- No appreciable decrease of the SEY below 1.45 has been observed after scrubbing for several hours in the dipoles at 4 TeV in the presence of electron clouds.
- The maximum acceptable heat load in the Stand Alone Modules (SAM) was limiting the rate at which the beam could be injected while the maximum acceptable heat load in the Arc 34 beam screen was limiting the maximum number of bunches that could be accelerated taking into account the margin for the transients in the beam screen circuits temperature at the start of the ramp. Both these limitations will be relaxed for the 2015 start-up.

The possibility to inject and accelerate beams with the characteristics indicated in Tables 1 and 3 relies on the effectiveness of the scrubbing in reducing the SEY in the dipoles down to 1.4 or lower to avoid multipacting. According to the present experience it will not be possible to reach sufficiently low SEY to suppress multipacting in the main quadrupoles, for that reason an upgrade of the cryogenics is necessary [2].

The new HL-LHC triplets and the D1 separation dipoles in the Interaction Regions (IR) 1 and 5 will have beam screens coated with low SEY materials and, if necessary, they will be equipped with clearing electrodes to suppress multipacting. Similar countermeasures might have to be applied for the triplets and D1 in IR 2 and 8.

Potential issues: impedance

Collimators are the largest source of impedance in the LHC at high frequencies, this might limit their minimum opening and correspondingly the collimation efficiency and the minimum β* reach of the LHC. Interplay between impedance, transverse feedback and beam-beam effects are one of the possible origin of the instabilities observed in 2012 although this is not fully understood yet [6].

The single beam stability limit for the beam parameters corresponding to the various upgrade scenarios are shown in Fig. 1 for the present collimation system (blue line) and for Molybdenum secondary collimators (purple line) approximating the Molybdenum coated Molybdenum-graphite collimators. The collimator settings used for the calculation are presented in [7].

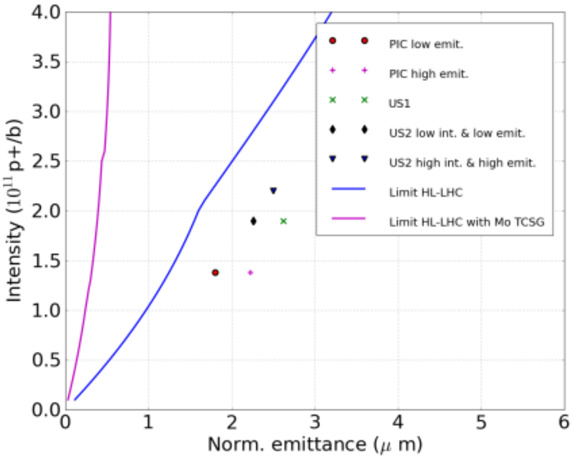

Figure 1: Single-beam stability limits for the present collimation system (blue line) and for the upgraded collimation system with Molybdenum collimators (purple line). PIC low-emit=BCMS beam parameters, PIC high emit.=Standard beam parameters.

The effects of chromaticity (assumed to be 15 units), Landau Octupoles (positive polarity - 550 A) and an ideal bunch-by-bunch transverse damper (50 turns damping time) are included [8].

The beam parameters for all the upgrade scenarios are quite close to the stability limit based on extrapolations from 2012 observations for the present collimation system while "metallic" collimators based on Molybdenum coated Molybdenum-graphite composites offer a comfortable margin and should be implemented already as part of PIC [2].

Potential issues: unknown sources of emittance blow-up

The values of the transverse emittance considered in collision (Table 1) are based on the assumption that the unknown sources of transverse emittance increase (in addition to IBS) can be kept under control so to have a relative emittance increase of less than 15% with respect to the injected beam transverse emittance.

The above goal has not been reached during Run I and emittance blow-up larger than 30% (see Fig. 2) has been observed in particular for one of the two beams (Beam 2) and for one plane (Horizontal). The proposed goal, although challenging, appears to be attainable taking into account the experience in the injectors and taking into account that this is mostly affecting one plane and one beam. The absolute value of the emittance increase seems to be constant irrespective of the initial emittance, pointing to an additive source of blow-up.

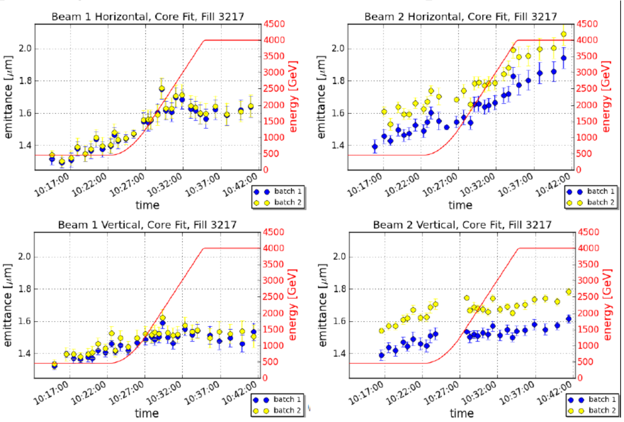

Figure 2: Transverse emittance evolution during a machine development session for Beam 1 (left) and Beam 2 (right) for the horizontal (top) and vertical (bottom) planes, respectively [9].

OPTICS

Given the large aperture of the HL-LHC triplets the minimum β* achievable in IP1 and IP5 is limited by the aperture in the matching section where TAN, Q5, Q4, D2 become aperture bottlenecks.

Two optics [10][11] have been considered for the estimate of the performance of the PIC scenario and adapted to the HL-LHC triplets and nominal LHC layout [12]. These optics configurations have different values of the beta functions at the IP in the crossing (β^*_{xing}) and in the separation plane (β^*_{sep}) so to have the possibility of reducing the crossing angle and reduce the pile-up density:

- β^*_{xing} = 40 cm/ β^*_{sep} = 20 cm.
- β^*_{xing} = 50 cm/ β^*_{sep} = 25 cm.

the latter providing more margin in aperture for a slightly reduced performance [13].

Flat beam optics likely require larger normalized beam-beam separations as compared to round beam optics (i.e. with $\beta^*_{xing} = \beta^*_{sep}$). Larger β* ratios (>2) might imply even larger normalized beam-beam separations although they could provide better performance (see Fig. 3) where the expected peak luminosity is plotted as a function of β^*_{xing} and β^*_{sep} . The lines corresponding to constant β^*_{xing} / β^*_{sep} ratios are indicated in yellow.

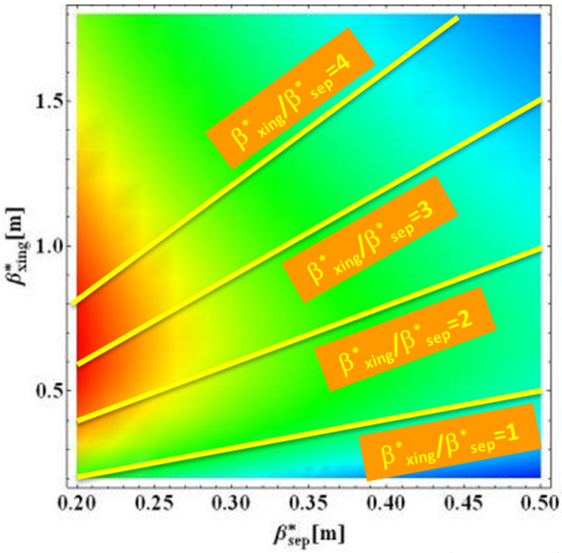

Figure 3: Peak luminosity as a function of β^*_{xing} and β^*_{sep}. The minimum value of the peak luminosity (1.2×10^{34} cm^{-2}s^{-1}) lies the blue area while the maximum value (2.6×10^{34} cm^{-2}s^{-1}) lies in the red area. A constant normalized beam-beam separation of 14 σ has been considered.

PERFORMANCE AT 6.5 TEV

Peak performance

The peak performance at 6.5 TeV has been estimated for the parameters listed in Tables 1, 3 and 4 and it is summarized in Table 5.

A normalized beam-beam separation of 14 σ has been assumed at the first parasitic encounter for the considered β* ratio of 2. This choice is supported by the preliminary results of weak-strong simulations for the beam parameters considered [14][15] but it will have to be validated by further studies and verifications.

Table 4: Longitudinal parameters in collision

Total RF Voltage [MV]	16
ε_L[eV.s] at start of fill	3.6
Bunch length (4 σ)[ns]/ (r.m.s.) [cm]	1.33/10

Table 5: Parameters and estimated peak performance for the two considered optics

	$\varepsilon^*_{n\ coll}$ [μm]	# Coll. Bunches IP1,5	Xing angle [μrad]	BB separation [σ]	L_{peak} [10^{34} $cm^{-2}s^{-1}$]
BCMS – 40/20	1.85	2592	364	14	2.9
Standard - 40/20	2.25	2736	400	14	2.5
BCMS – 50/25	1.85	2592	326	14	2.7
Standard – 50/25	2.25	2736	360	14	2.3

Integrated performance over one fill

The estimate of the integrated luminosity requires determining the luminosity evolution during a fill. The beam intensity evolution has been evaluated taking into account:

- Burn-off due to luminosity considering a total cross-section of 100-110 mb. The most pessimistic value of 110 mb has been retained for the estimations for the centre-of-mass energy of 13-14 TeV [16][17][18].
- An additional (unknown) source of intensity loss with a lifetime of 200 hours has been considered based on 2012 experience.

The emittance evolution has been determined including the following sources:

- Intra-Beam Scattering (IBS). No coupling has been assumed based on Run I experience;
- Radiation damping.
- An additional (unknown) source of vertical emittance blow-up with a lifetime of 40 hours has been added based on observations during Run I.

A finite difference method in steps of 5 minutes has been considered to properly account for the intensity evolution and of the evolution of the IBS lifetime as a function of the bunch population.

This method applied to 2012 fills with bunch populations comparable to those considered for the PIC scenarios represents fairly well the evolution of the bunch population, relative transverse beam sizes and ATLAS and CMS luminosities as indicated in Fig. 4, 5 and 6 for fill 2728 where no sign of beam instabilities have been observed at high energy.

The initial value of the transverse emittance (assumed to be equal for both beams and both planes) is estimated from the luminosities and average bunch populations measured at the beginning of the physics fill. The initial longitudinal emittance is estimated from the measured bunch length and RF voltage.

The relative beam size evolution is determined by normalizing the beam size measured by the synchrotron radiation beam profile monitor (BSRT) to the beam size measured at the beginning of the fill with the same monitor. Some visible beam size increase is observed for beam 2 only during the fill and immediately following a luminosity optimization scan when the separation of the two beams is varied in IP1 and IP5 to maximize the luminosity in these interaction points.

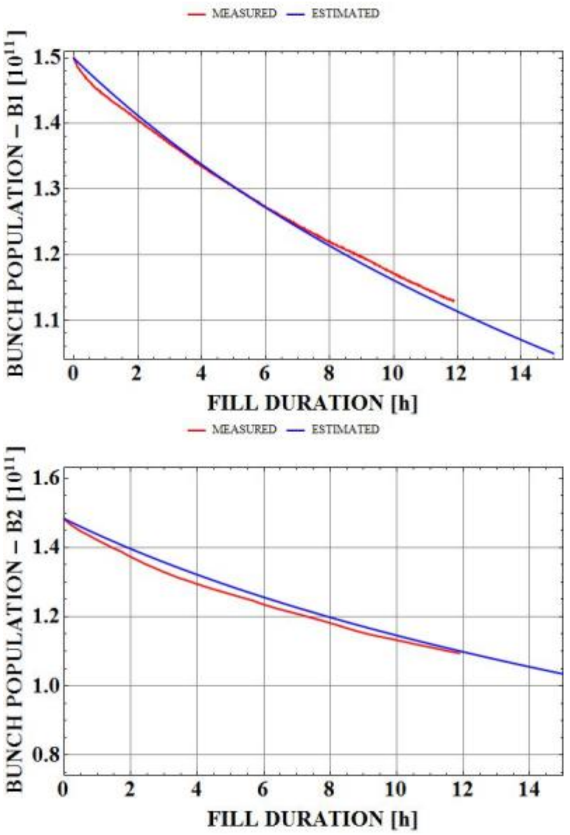

Figure 4. Average bunch population evolution measured (red) during fill 2728 for beam 1 (top) and beam 2 (bottom) compared with the evolution estimated with the model above described (blue).

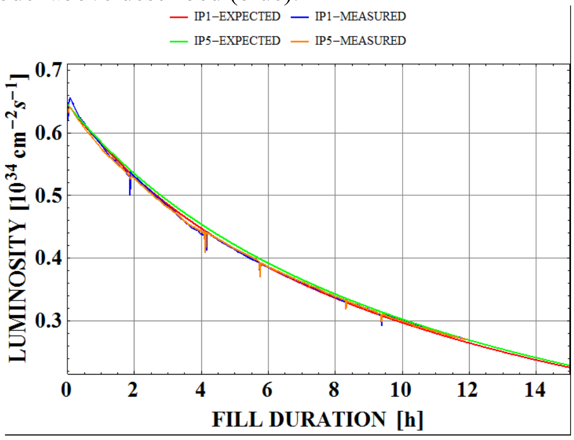

Figure 5. Luminosity evolution as measured in IP1 (blue) and IP5 (red) compared to those expected in IP1 (red) and IP5 (green).

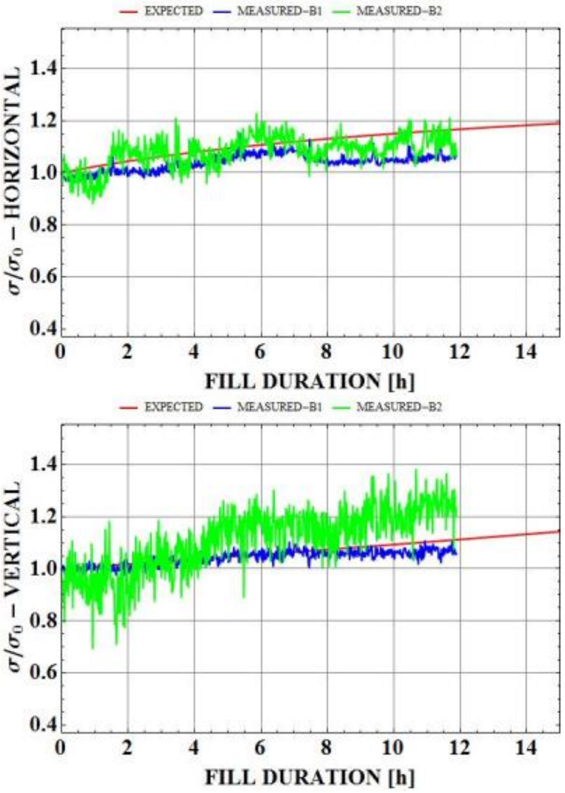

Figure 6. Relative beam size evolution measured by the BSRT in the horizontal (top) and vertical (bottom) planes for beam 1 (blue) and beam 2 (green) during fill 2728. The evolution estimated with the model above described is plotted in red.

Yearly integrated performance

The integrated luminosity targets for the PIC scenario are listed in Table 6.

Table 6: Integrated luminosity targets for the PIC scenario

Int. luminosity end 2021/end 2035 [ab^{-1}]	0.31[19]/1
Number of years of operation after 2021	10
Target luminosity/year [fb^{-1}]	70

Parameters defining the machine performance efficiency are required in order to determine the yearly integrated luminosity starting from the performance during a typical fill.

The *performance efficiency* (η) required to achieve the target yearly integrated luminosity L_{target} is the percentage of scheduled physics time spent for successful fills (including minimum turn-around) defined as:

$$\eta = \frac{L_{target}}{L_{fill}} \frac{T_{around-min} + T_{fill}}{T_{spt}} \times 100$$

where:

- L_{fill} = luminosity integrated during one fill of duration T_{fill}.
- $T_{around-min}$ = minimum turn-around time.
- T_{spt}=time spent in physics for luminosity production.

L_{target}/L_{fill} gives the number of successful fills per year. The performance efficiency (η_{6h}) for T_{fill}=6 h (average value in 2012) and for the optimum fill length based on the luminosity evolution and on the considered turn-around time (η_{opt}) will be evaluated.

We also define the *physics efficiency* (ϕ) as:

$$\phi = \frac{L_{target}}{L_{fill}} \frac{T_{fill}}{T_{spt}} \times 100$$

corresponding to the percentage of the scheduled physics operation time that the machine actually spends in physics. This parameter is particularly important for ALICE and LHCb which are constantly running in levelling mode.

The physics efficiency for T_{fill}=6 h (ϕ_{6h}) and for the optimum fill length (ϕ_{opt}) will be estimated.

Table 7 lists the values of the performance and physics efficiencies for the 2012 LHC run and a series of other parameters contributing to define the integrated performance.

Table 7: efficiency parameters for the LHC 2012 run

Scheduled Physics Time for p-p luminosity production (T_{spt}) [days]	190.5[‡]
Minimum Turn-Around Time ($T_{around-min}$) [h]	2.2
Average Fill length T_{fill}[h]	6.1
Integrated Luminosity (L_{int}) [fb^{-1}]	23.3
Physics efficiency ϕ [%]	36
Fills that made it to physics (N_{fill})	295
Performance efficiency η = N_{fill}*($T_{around-min}$+T_{fill})/T_{spt}*100 [%]	53.5

The parameters used to estimate the HL-LHC integrated performance are listed in Table 8.

Table 8: parameters assumed for HL-LHC performance estimate.

Scheduled Physics Time for p-p luminosity production/year (T_{phys}) [days]	160
Minimum Turn-Around Time [h]	3
Average Fill length [h]	6 or optimum
Performance Efficiency – goal [%]	50
Pile-up limit [events/crossing]	140
Pile-up Density limit – baseline (stretched) [events/mm/crossing]	1.3 (0.7)

The parameters defining the yearly HL-LHC performance for the 40/20 and 50/25 optics and for the beam parameters and corresponding peak performance listed in Table 1, 3 and 5 are listed in Table 9. It has been assumed that the ATLAS and CMS detectors will be upgraded and will be capable of handling a pile-up as

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[‡] The 2012 operation had an extended proton physics period (one additional month) as the ion operation was scheduled only for the beginning of 2013.

high as 140 events/crossing. A "visible" cross-section of 85 mb has been considered for determining the pile-up event rate [18].

The optimum fill lengths are determined to maximize the ATLAS and CMS luminosities. In all cases considered the physics efficiency will be larger than 25%. In this case an integrated luminosity of more than 5.5 fb^{-1}/year could be delivered to LHCb provided the detector is upgraded to accept pile-up levels of at least 4.5 events/crossing.

Table 9: Integrated performance estimate for the 40/20 and 50/25 optics for the BCMS and Standard beams

	Lev. Time [h]	**Opt. Fill length [h]**	**η_{6h}/η_{opt} [%]**	**ϕ_{6h}/ϕ_{opt} [%]**	**Int. Lumi for η=50% for 6h /opt. fill length [fb^{-1}/y]**	**Max. Mean Pile-up density/Pile-up [ev./mm]/[ev./xing]**
BCMS – 40/20	-	6.5	37/37	25/26	93/94	0.97/84
Standard - 40/20	-	7.3	40/40	27/28	87/88	0.79/69
BCMS – 50/25	-	6.8	39/39	26/27	89/89	0.77/78
Standard - 50/25	-	7.6	43/42	28/30	82/83	0.63/64

From Table 9 we can conclude that:

- All the proposed configurations allow to achieve the target integrated luminosity per year with performance and physics efficiencies compatible with 2012 values.
- Fill lengths are comparable (although slightly longer) to 2012 average, this underlines the importance of a consolidation to increase reliability.
- 50/25 optics provides a reduced pile-up density for a small reduction of the integrated luminosity and it relaxes constraints on aperture/optics.
- The standard PS production scheme provides slightly lower performance but it is more tolerant to additive sources of blow-up.

The maximum acceptable pile-up limit of 140 is not reached for any of the proposed configurations. A limitation of the acceptable pile-up to 45 which is comparable to the values acceptable today by the experiments would on the other hand limit the performance in terms of integrated luminosity per year (see Table 10) that would then become marginal unless a significant improvement in the performance efficiency and (in particular) fill length are reached as compared to 2012 targets. In this case the BCMS and standard filling schemes provide the same performance with a slight advantage for the standard scheme due to the larger number of bunches and therefore larger levelling luminosity for the same pile-up limit. Furthermore the IBS growth times are longer due to the larger transverse emittance of the beam produced with the standard scheme which also makes it less sensitive to additive sources of blow-up.

Table 10: Integrated performance estimate for the 40/20 and 50/25 optics for the BCMS and Standard beams for a pile-up limit of 45.

	Lev. Time [h]	**Opt. Fill length [h]**	**η_{6h}/η_{opt} [%]**	**ϕ_{6h}/ϕ_{opt} [%]**	**Int. Lumi for η=50% for 6h /opt. fill length [fb^{-1}/y]**	**Max. Mean Pile-up density/Pile-up [ev./mm]/[ev./xing]**
BCMS – 40/20	6.8	10.2	49/45	33/34	71/79	0.53/45
Standard - 40/20	5.3	9.6	47/44	31/33	75/80	0.53/45
BCMS – 50/25	6.2	9.8	49/45	33/35	71/77	0.45/45
Standard - 50/25	4.5	9.2	47/45	32/34	74/78	0.46/45

The assumed distribution in the fill length (all fills have the same length T_{fill}) is likely optimistic (i.e. over-estimating the performance by 10-20%) [20], but an improvement in reliability could be expected as a result of the consolidation and in particular from:

- The installation of superconducting links in point 1, 5 and 7 allowing to move power converters to the surface away from radiation fields that could induce Single Event Upsets (SEU) or other form of Radiation to Electronics (R2E).
- Upgrade of the cryogenics in point 4 and additional cryogenic plants for IR1 and 5 providing more margin for operation.

KEY QUESTIONS AND STUDIES REQUIRED DURING RUN 2

The attainment of the peak performance indicated in Table 5 relies on the capability of operating the machine with 25 ns beams with negligible emittance blow-up due to electron cloud. For that it will be necessary to demonstrate the feasibility of reducing the Secondary Electron Yield in the beam screen of the LHC dipoles down to 1.3-1.4 by scrubbing with dedicated beams in 2015.

The LHC machine performance in 2012 has been limited by instabilities occurring at high energy during the squeeze and the collision process. The origin of these instabilities is not completely understood and will require additional simulations and experimental studies to quantify more precisely the stability limits for single and two-beams and possible mitigation measures.

Both optics configurations considered feature a smaller β^* in the separation plane (by a factor 2) as compared to that in the crossing plane. The study of the beam-beam effects with flat beams and large tune spread is required to validate this approach. As a possible back-up scenario an optics with β^*=30 cm in the both planes and a normalized beam-beam separation of 12 σ could be considered at the expense of a smaller integrated luminosity (~ -12 %).

Significant emittance blow-up has been during the LHC cycle has been observed in 2012. The tight emittance budget implies the understanding and the minimization of any source of blow-up in addition to IBS and in particular the minimization of the sources of additive emittance blow-up that could strongly affect the performance with small emittance beams like those produced with the BCMS scheme in the PS.

Preliminary tests have been done in 2012 to demonstrate the feasibility of β* levelling, these will have to be further pursued during Run II to validate this levelling scheme as a possible solution for luminosity levelling also for small emittance beams and low β* values implying an excellent control of the orbit at the Interaction Point.

The extrapolations to higher energy of the collimation efficiency, quench limits and beam lifetime must be validated in order to assess the need for the installation of Dispersion Suppressor collimators with 11T dipoles in IR7 [21].

SUMMARY AND CONCLUSIONS

The luminosity target of 70 fb^{-1}/year can be attained comfortably with 40/20 optics with the beams delivered by the injectors as a result of their Performance Improvement Consolidation. This is true provided that the maximum event pile-up acceptable by the general purpose detectors ATLAS and CMS is increased well above the present values.

The beams obtained by the BCMS production scheme in the PS allow reaching a slightly higher performance as compared to those obtained with the standard scheme although the latter are less sensitive to additive sources of emittance blow-up because of their larger transverse emittance.

The 50/25 optics provides more margin in aperture and offers a reduction of the pile-up density below 0.7 events/mm for a small reduction of the integrated luminosity but still within the target.

The key questions and studies required to validate the assumptions made for the performance evaluation have been sketched.

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