US1: WHAT DO WE GAIN IN BEAM PERFORMANCE*

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Abstract

The Upgrade Scenario 1 (US1) of the Review of the LIU and LHC Upgrade (RLIU) plans aims at a yearly integrated luminosity of ca. 170 fb^{-1} assuming a total of 160 scheduled operation days for luminosity production and a total of 2000 fb^{-1} over a period of 10 years of operation starting with an integrated luminosity of 300 fb^{-1} after RunII of the LHC. This paper evaluates the required beam parameters for reaching the US1 goals and the required hardware modifications in the LHC and the injector complex. The presented study assumes already all hardware upgrades analysed within the Performance Improving Consolidation (PIC) [1][2][3].

ASSUMPTIONS FOR THE PERFORMANCE EVALUATION

In the following we assume approximately one year long shutdowns every 3 to 4 years with a total of 160 days of scheduled proton-proton physics production every operating year. In order to evaluate the feasibility of a given beam parameter set for reaching the US1 performance goal of 170 fb^{-1} per year we use the concept of a Performance Efficiency which we define as the time fraction needed in a perfect operation cycle (operation with minimum Turnaround time between fills and optimum fill length) for reaching the US1 performance goal. The LHC operational experience showed a Performance Efficiency of 50% during the last year of the RunI operation. In the following we assume a value of 50% as feasible for the HL-LHC operation.

For the Injector Complex we assume the operation of LINAC4, full mitigation of any electron cloud limitations (e.g. vacuum beam pipe coating in the SPS or reduced Secondary Emission Yield (SEY) via beam scrubbing or a wide band feedback system), 2 options for the upgrade of the SPS RF system (low level upgrade and power upgrade) and the operation with either the standard 25ns bunch preparation scheme with 72 bunches per PS cycle, yielding a total of 2760 bunches in each ring of the LHC using 8 SPS injections with 4 PS batches, 3 SPS injections with 2 PS batches and one SPS injection with 1/6 PS batch and resulting in 2736 colliding bunches in IR1 and IR5 for operation with 25ns, or the Batch Compression Beam Merging Scheme (BCMS) for operation with 25ns bunch spacing [4] yielding a total of 2604 high brightness bunches with 48 bunches per PS extraction and up to 6 PS transfers per SPS fill into the LHC and 2592 colliding bunches in the IP1 and IP5.

Figure 1 shows the ideal LHC Turnaround time, amounting to a total of 180 minutes or approximately 3 hours and Table 1 lists the break-down of the minimum LHC Turnaround time.

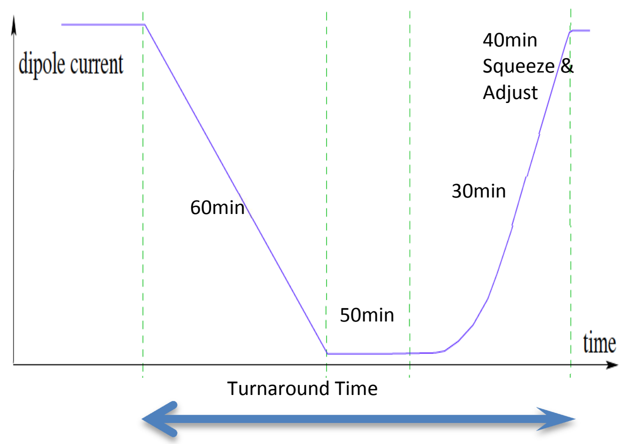

Figure 1: The ideal LHC Turnaround time, amounting to a total of 180 minutes or approximately 3 hours.

Table 1: Break-down of the Turnaround time in the HL-LHC era (Courtesy of M. Lamont) [5].

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

Table 2: Number of bunches and colliding bunch pairs for the standard and the BCMS 25ns filling schemes that are used for this study.

Scheme	Total bunches	IR1/5 Collisions	IR8 Collisions	IR2 Collisions
Standard 25ns	2748	2736	2452	2524
BCMS 25ns	2604	2592	2288	2396

Table 3: Beam parameters at SPS extraction and at the LHC in collision for 6 cases (PIC, SPS LLRF upgrade, LLRF and SPS power upgrade for the standard and the BCMS 25ns schemes) assuming 20% emittance blow-up and 5% intensity losses between SPS extraction and beam collisions at top energy in the LHC.

	SPS Extraction		LHC collision			
	Bunch population [10^{11}]	ε_n (H/V) [μm]	Bunch population [10^{11}]	$\varepsilon_{n\ coll.}$ (H/V) [μm]	Blow-up [%] / Intensity loss wrt SPS [%]	IBS growth times trans / long [h]
BCMS† PIC	1.58	1.25/1.25	1.5	1.5/1.5	20 / 5	8/16
Standard‡ PIC	1.58	1.25/1.25	1.5	1.5/1.5	20 / 5	8/16
BCMS & LLRF	1.45	0.91/0.91	1.38	1.09/1.09	20 / 5	4/12
Standard & LLRF	1.45	1.37/1.37	1.38	1.64/1.64	20 / 5	11/19
BCMS & LLRF & Power	2.0	1.37/1.37	1.9	1.64/1.64	20 / 5	8/14
Standard & LLRF & Power	2.0	1.88/1.88	1.9	2.26/2.26	20 / 5	15/20

† 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.

Table 4: Beam parameters at SPS extraction and at the LHC in collision for 6 cases (PIC, SPS LLRF upgrade, LLRF and SPS power upgrade for the standard and the BCMS 25ns schemes) assuming emittance blow-up such that the IBS growth rates are longer than the optimum LHC run length.

	SPS Extraction		LHC collision			
	Bunch population [10^{11}]	ε_n (H/V) [μm]	Bunch population [10^{11}]	$\varepsilon_{n\ coll.}$ (H/V) [μm]	Blow-up [%] / Intensity loss wrt SPS [%]	IBS growth times trans / long [h]
BCMS‡ PIC	1.58	1.25/1.25	1.5	1.5/1.5	20 / 5	8/16
Standard‡ PIC	1.58	1.25/1.25	1.5	1.5/1.5	20 / 5	8/16
BCMS & LLRF	1.45	0.91/0.91	1.38	1.8/1.8	98 / 5	13/22
Standard & LLRF	1.45	1.37/1.37	1.38	1.8/1.8	31 / 5	13/22
BCMS & LLRF & Power	2.0	1.37/1.37	1.9	2.65/2.65	93 / 5	22/25
Standard & LLRF & Power	2.0	1.88/1.88	1.9	2.65/2.65	41 / 5	22/25

Table 2 summarizes the number of bunches and colliding bunch pairs for the standard and the BCMS 25ns filling schemes that are used for this study [3].

Assuming a theoretical peak luminosity of 7 10^{34} cm^{-2} s^{-1} and a levelled maximum luminosity for operation of 5 10^{34} $cm^{-2}s^{-1}$ for US1, the luminosity lifetime becomes approximately 10 hours due to luminosity burn-off, the luminosity levelling time approximately 2 hours and the ideal run length for a maximum integrated luminosity becomes approximately 8 hours (2 hours levelling and 6 hours operation with luminosity decay) for the ideal Turnaround time (3 hours) and a perfect operation cycle. The maximum theoretically obtainable integrated yearly luminosity becomes in this case 340fb^{-1} for 160 physics operation days and the US1 performance goal requires Performance Efficiency of 50%. In other words, reaching the US1 performance goals with 50% Performance Efficiency requires a theoretical peak luminosity of approximately 7 10^{34} cm^{-2} s^{-1}.

BEAM PARAMETERS IN THE INJECTORS AND THE LHC

Table 3 summarizes the expected beam parameters at extraction from the SPS and at the LHC in collision as a result of the LIU upgrade in the Injectors with the connection of LINAC4 to the PSB and H- injection and the electron cloud consolidation in the SPS. Table 3 summarizes the parameters for six options: baseline PIC of the injector complex, PIC in Injector complex plus SPS with Low Level RF (LLRF) upgrade and PIC in injector complex plus SPS with LLRF and RF power upgrade and for both for the standard 25ns and the BCMS schemes bunch preparation schemes in the PS. The SPS LLRF system upgrade allows a modulation of the RF power along the revolution period and thus an increase in the bunch population of the 25ns LHC beam in the SPS. The SPS RF power upgrade allows a further increase of the bunch population [1][2]. The energy upgrade of the PSB extraction might also be required for providing larger margins for space charge effects in the PS at injection (implying a full upgrade of the LHC injector complex for the case with SPS LLRF and RF power upgrade). We therefore assume in the following a full LIU upgrade implementation for the US1 study.

The possible filling schemes in the LHC are presented in Table 2 where the total number of bunches and the corresponding number of colliding pairs in IR1 and IR5 are listed for the BCMS and the Standard production schemes assuming up to 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.

Experience with the LHC RunI has shown that beam intensity losses of a few percents must be expected during the LHC cycle from SPS to LHC transfer to collisions at top energy in the LHC. Losses are mostly occurring:

- At injection (e.g. satellite bunches preceding or following the main SPS bunch train bunches);
- During the injection plateau in the LHC 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 in the LHC when the collimators are moved closer to the beam to their final settings;
- When the two beams are brought in collision at top energy in the LHC.

In the following analysis we assume an intensity loss of 5% during the full cycle from SPS extraction to collisions in the LHC.

In addition, an average transverse emittance blow-up of 20% has been considered from SPS extraction to beam collisions at top energy in the LHC. The 20% emittance blow-up is consistent with the LHC operational experience from RunI. All estimates in the following assume that any additional emittance growth due to Intra Beam Scattering (IBS) is small compared to the already accounted for 20% emittance blow-up and imply that the IBS emittance growth rates must be long compared to the average fill length (Ł larger than 10 hours).

The resulting beam parameters for collisions in the LHC are listed in Table 3 together with the assumed total emittance blow-up and intensity loss from SPS extraction to collisions in the LHC at top energy and the resulting IBS emittance growth rates in the LHC at collision energy. One clearly observes that the expected IBS emittance growth rates are too small for all cases, except for the reference PIC cases. Table 4 lists therefore modified beam parameters where we assume a controlled emittance blow-up between the SPS extraction and the LHC injection such that the IBS emittance growth rates are clearly larger than 10 hours during the full LHC cycle. A comparison between Table 3 and Table 4 illustrates that the LHC cannot really benefit from the higher brightness beams that can be generated in the injector complex with full LIU upgrade and with the BCMS scheme. Rather, the LHC performance for US1 will be maximised for the standard 25ns scheme, which offers a slightly larger number of bunches for collisions in IR1 and IR5.

POTENITAL ISSUES FOR HL-LHC WITH US1

Electron cloud

Electron cloud is one of the main potential limitations expected for the operation with 25ns beams. Electron cloud effects include emittance blow-up and heat-load on the beam screen. The experiments conducted in the LHC in 2012 [6] 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, which is 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 for beam intensities above nominal LHC beam parameters;
- 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 LHC arc 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 Arc34 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 RunII start-up in 2015.

The possibility to inject and accelerate beams with the characteristics indicated in Tables 2 and 4 relies on the effectiveness of the scrubbing in reducing the SEY in the dipoles down to 1.3 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 as part of the LHC PIC [7].

The new HL-LHC triplets and the D1 separation dipoles in the Interaction Regions 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.

Impedance

Collimators are the largest source of impedance in the LHC at high frequencies, this might limit their minimum opening and correspondingly the minimum β* reach of the LHC. In the following we assume that eventual impedance limitations can and will be addressed in the LHC by an upgrade of the collimation system to low impedance collimator jaws.

The single beam stability limits are shown in Fig. 2 for different upgrade scenarios for the present collimation system (blue line) and for Mo secondary collimators (purple line) [8].

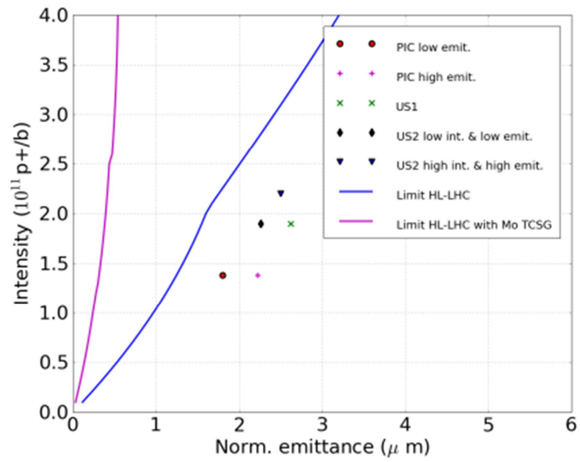

Figure 2: Single-beam stability limits for the present collimation system (blue line) and for the upgraded collimation system with Mo collimators (purple line). PIC low-emit=BCMS beam parameters, PIC high emit.=Standard beam parameters The collimator settings used for the calculation are the assumed HL-LHC baseline with a 2 sigma retraction in IR7 [9].".

The effects of chromaticity (assumed to be 15 units), Landau Octupoles (positive polarity of 550 A) and an ideal bunch-by-bunch transverse damper (50 turns damping time) are included in the estimates in Figure 2 [10].

The beam parameters for the upgrade scenarios in Table 4 are close to the stability limit based on extrapolations from 2012 observations for the present collimation system while "metallic" secondary collimators using a metallic Molybdenum coating offer a comfortable margin and should be implemented already as part of the Performance Improvement Consolidation [7].

Unknown sources of emittance blow-up

The required large emittance blow-up between SPS extraction and LHC collision beams for IBS considerations provides comfortable margins for the emittance budget. We therefore do not assume that unknown sources of emittance blow-up are potential issues for the US1.

Aperture limitations

The US1 assumes full implementation of Performance Improving Consolidation in the LHC and therefore assume the replacement of the existing LHC triplet and normal conducting D1 magnets with new, large aperture superconducting magnets in IR1 and IR5.

Pile-up Density

A luminosity of 5 10^{34}cm^{-2}s^{-1} corresponds to approximately 140 events per bunch crossing. Assuming the longitudinal bunch parameters from Table 5 and head on beam-beam collisions this corresponds to a pile-up density of approximately 1 event per mm of luminous region. For the operation with crossing angle and constant luminosity of 5 $10^{34} cm^{-2} s^{-1}$ the pileup density can increase approximately to up to 1.5 events per mm luminous region depending on the detailed beam parameters and the resulting geometric luminosity reduction factor. In case the longitudinal pile-up density limits the detector performance (e.g. 1 event per mm luminous region) the maximum achievable performance of the US1 configurations needs to be readjusted accordingly (e.g. up to 50% reduction of the maximum acceptable luminosity and operation with luminosity levelling).

Long Range Beam-Beam interactions

The full HL-LHC upgrade assumes a 12 σ separation for the parasitic long-range beam-beam interactions of the two counter rotating beams in the common vacuum beam pipes of Interaction Regions of the LHC. The associated loss in performance via the geometric luminosity reduction factor will be compensated for in the HL-LHC via the use of Crab Cavities. The increase in the beam separation with respect to the Run1 configurations has been introduced for reducing the larger accumulated long-range beam-beam interactions with 25ns bunch spacing and the increase in the number of long-range beam-beam interactions with the longer Nb_3Sn triplet magnets. For the US1 scenario we assume operation without Crab Cavities and the performance loss due to the geometric luminosity reduction factor can not be compensated. In order to minimize the performance loss for US1, we assume for US1 a reduced long-range beam-beam separation of 10 σ. The reduction in the long-range beam-beam separation with respect to the nominal HL-LHC upgrade is hoped to be feasible with the use of long-range beam-beam compensation measures (e.g. the use of electric wires or an electron beam with opposite field as generated by the passing proton beams). However, the use of wire compensators poses difficulties for the integration of the wires into the global LHC collimation hierarchy and the use of electron beams is still far from technically feasible. Long-range beam-beam interactions might therefore impose in the end a larger than 10 σ beam separation and might thus limit the performance reach for the US1 operation. Increasing the parasitic long-range beam-beam separation from 10σ to 12σ implies a performance loss between 7% and 15% from the geometric luminosity reduction factor alone, depending on the optics configuration (ca. 7% performance loss for operation with flat and ca. 15% performance loss for operation with round beams). Further performance reduction will come from the aperture loss and the required larger β* values, resulting in a potential net performance reduction between 10% and 25%.

Both aspects, the operationally acceptable minimum beam separation with operation of 25ns bunch spacing at 7 TeV beam energy and for flat optics and the technical feasibility of compensation devices, need to be addressed with high priority during the RunII operation of the LHC.

LHC OPTICS

Given the large aperture of the HL-LHC triplet and D1 magnets, the minimum β* achievable in IP1 and IP5 is limited by the aperture of the remaining matching section devices. In particular, the TAN, Q5, D2 and Q4 elements will become the aperture bottlenecks after the installation of the new HL-LHC triplet and D1 magnets (see Table 4).

Without the use of Crab Cavities the performance reach can be further improved by the use of flat beams at the Interaction Points and a larger beam size in the plane of the beam-crossing angle. The US1 performance reach has therefore been evaluated for two optics configurations: round beam and flat beam options. The minimum β^* reach depends for each option on the actual beam emittance values and the minimum acceptable collimation settings. In the following we assume that β^{**} values of 0.2m are within reach for US1 with round beam operation and β^{**} values of 0.4m/0.2m for US1 with flat beam operation. Table 4 shows the required aperture in terms of n_1 [15] for various optics configurations [11]. The best performance for flat beam operation is expected for a β^{**} aspect ratio of 0.4m/0.1m [12]. However, this aspect ratio seems to be just outside the aperture reach of the LHC with new triplet and D1 magnets but otherwise unchanged Matching Section elements and might imply increased quadrupole strength for Q5 in IR6 and additional sextupole strength.

Table 4: Minimum aperture values calculated using the methods in Ref. [15] in the LHC Matching Sections with new Triplet and D1 magnets but otherwise unchanged Matching Sections [11].

SQUEEZE OPTICS (6.5 TeV)			minimum over IR1/5 §					
β* /[m]	x-angle [μrad]	TAS	MQX	D1	TAN	D2	Q4	Q5
0.1/0.4	±165	16	13.0	13.8	**9.2**	12.5	12.4	12.2
0.2/0.4	±165	22.6	18.5	19.6	13	17.8	17.5	17.4
0.3/0.3	±190	24.6	18.8	19.9	15.2	19.3	18.3	19.6

PERFORMANCE AT 6.5 TEV

The performance reach of US1 has been evaluated for 8 different configurations:

- Round beam configuration with standard 25ns filling scheme and upgrade of the SPS LLRF system.
- Flat beam configuration with standard 25ns filling scheme and upgrade of the SPS LLRF system.

§ The aperture is calculated using the "proposal 1" aperture margins in [11]

- Round beam configuration with BCMS 25ns filling scheme and upgrade of the SPS LLRF system.
- Flat beam configuration with BCMS 25ns filling scheme and upgrade of the SPS LLRF system.
- Round beam configuration with standard 25ns filling scheme and upgrade of the SPS LLRF system and the SPS RF power.
- Flat beam configuration with standard 25ns filling scheme and upgrade of the SPS LLRF system and the SPS RF power.
- Round beam configuration with BCMS 25ns filling scheme and upgrade of the SPS LLRF system and the SPS RF power.
- Flat beam configuration with BCMS 25ns filling scheme and upgrade of the SPS LLRF system and the SPS RF power.

A beam-beam separation of 10 σ has been assumed for all cases at the parasitic beam-beam encounters. This choice is more optimistic as indicated by the preliminary results of weak-strong simulations [13][14] and might require at least a partial compensation of the long-range beam-beam interactions at the parasitic beam-beam encounters. Table 5 summarizes the assumed longitudinal beam parameters in collision and Table 6 performance targets for US1.

Table 5: Longitudinal parameters in collision.

Total RF Voltage [MV]	16
ε_L[eV.s] at start of fill	2.5
Bunch length (4 σ)[ns]/ (r.m.s.) [cm]	1.0/7.5

Table 7 summarizes the resulting performance reach for the different configurations and a peak (levelled) luminosity of 5 10^{34}cm^{-2}s^{-1}.

Table 7: Parameters and estimated peak performance for two options (flat and round beams) options with a long-range beam-beam separation of 10 σ and a levelled luminosity of 5 10^{34}cm^{-2}s^{-1}for two bunch production schemes (Batch Compression Merging Scheme and Standard) and different SPS upgrade scenarios (LLRF only and LLRF plus RF power upgrade).

Case	β^* [m/m]	$\varepsilon^*_{n\ coll}$ [μm]	# Coll. Bunches IP1,5	Xing angle [μrad]	Bunch Intensity [10^{11}]	Theoretical L_{peak} [cm^{-2}s^{-1}]	Integrated Yearly Luminosity [fb^{-1}] / required Performance Efficiency [%]	Optimum Run Length [levelling + decay + Turnaround]
Round Beam BCMS SPS LLRF	20/20	1.80	2592	360	1.38	4.0 10^{34}	219 / 78	0 + 5 + 3
Round Beam Standard SPS LLRF	20/20	1.80	2736	360	1.38	4.4 10^{34}	237 / 72	0 + 5 + 3
Flat Beam BCMS SPS LLRF	40/20	1.80	2592	255	1.38	4.4 10^{34}	237 / 72	0 + 5 + 3
Flat Beam Standard SPS LLRF	40/20	1.80	2736	255	1.38	4.65 10^{34}	258 / 66	0 + 5 + 3
Round Beam BCMS LLRF & Power	20/20	2.65	2592	364	1.9	5.2 10^{34}	317 / 54	0.2 + 5 + 3
Round Beam Standard LLRF & Power	20/20	2.65	2736	400	1.9	5.5 10^{34}	339 / 50	0.6 + 5 + 3
Flat Beam BCMS LLRF & Power	40/20	2.65	2592	326	1.9	5.7 10^{34}	343 / 50	0.8 + 5 + 3
Flat Beam Standard LLRF & Power	40/20	2.65	2736	360	1.9	6.0 10^{34}	363 / 47	1.2 + 5 + 3

Table 8: Parameters and estimated peak performance for different options (flat and round beams) with a long-range beam-beam separation of 10 σ and a levelled luminosity of 2.5 10^{34}cm^{-2}s^{-1}for various bunch production schemes (Batch Compression Merging Scheme and Standard) and full SPS upgrade scenario (LLRF plus RF power upgrade).

Case	β^* [m/m]	$\varepsilon^*_{n\ coll}$ [μm]	# Coll. Bunches IP1,5	Xing angle [μrad]	Bunch Intensity [10^{11}]	Theoretical L_{peak} [cm^{-2}s^{-1}]	Integrated Yearly Luminosity [fb^{-1}] / required Performance Efficiency [%]	Optimum Run Length [levelling + decay + Turnaround]
Round Beam BCMS LLRF & Power	20/20	1.85	2592	364	14	5.17 10^{34}	266 / 64	8.3 + 3 + 3
Round Beam Standard LLRF & Power	20/20	2.25	2736	400	14	5.46 10^{34}	271 / 63	9.3 + 3 + 3
Flat Beam BCMS LLRF & Power	40/20	1.85	2592	326	14	5.67 10^{34}	270 / 63	9.2 + 3 + 3
Flat Beam Standard LLRF & Power	40/20	2.25	2736	360	14	6.0 10^{34}	275 / 62	10.2 + 3 + 3

Table 6: Integrated luminosity targets for the PIC scenario

Int. luminosity end 2021/end 2035 [ab^{-1}]	0.31/2
Number of years of operation after 2021	10
Target luminosity/year [fb^{-1}]	170

A peak luminosity of 5 10^{34}cm^{-2}s^{-1} implies a pile-up density of up to 1.5 events per mm of luminous region. In case the pile-up density is limited by the detector performance one needs to introduce a lower levelled peak luminosity for the US1 evaluation. Table 7 re-evaluates the US1 performance for a levelled peak luminosity of 2.5 10^{34}cm^{-2}s^{-1} (e.g. a maximum pile-up density of ca. 1 event per mm luminous region). Tables 7 and 8 illustrate that the US1 performance goal of 170fb^{-1} per year with a Performance Efficiency of 50% is within reach for scenarios with a full LIU upgrade (LINAC4, e-cloud mitigation in the injector complex and SPS LLRF and RF power upgrade) if the pile-up density in the experiments is not limited (e.g. up-to 1.5 events per mm luminous region are acceptable). In case the pile-up density in the experiments is limited to less than 1 event per mm luminous region, one needs to limit the levelled luminosity to 2.5 10^{34}cm^{-2}s^{-1} and the required Performance Efficiency for achieving an annual integrated luminosity of 170 fb^{-1} increases to 62%, which might still be within reach but will certainly be challenging from the operation point of view.

SUMMARY AND CONCLUSIONS

The luminosity target of 170 fb^{-1}/year can be attained with a Performance Efficiency of 50%, the standard 25ns filling scheme and a flat beam optics with a β^* ratio of 40cm/20cm at the IP and with a full upgrade of the LHC injector complex (an increase of the PS injection energy might be required for obtaining sufficient margins for the space charge effects in the PS) if the HL-LHC experiments are not limited by the pile-up density (number of events per length of luminous region) but only by the total number of events per bunch crossing (we assumed here 140 events per crossing which corresponds to a peak luminosity of 5 10^{34}cm^{-2}s^{-1}).

In case the pile-up density is limited to a maximum of 1 event per mm luminous region, one needs to reduce the peak acceptable luminosity to 2.5 10^{34}cm^{-2}s^{-1} in each experiment. In this scenario one requires a Performance Efficiency of a little more than 60% for the production of 170fb^{-1} per year using the standard 25ns filling scheme and a flat beam optics with a β^* ratio of 40cm/20cm at the IP and with a full upgrade of the LHC injector complex. Or, expressed differently, assuming a 50% Performance Efficiency for a levelled luminosity of 2.5 10^{34}cm^{-2}s^{-1} in each experiment, one expects an annual integrated luminosity of 140fb^{-1}, which falls slightly short of the US1 goal considered for the RLIUP workshop but still represents a remarkable performance level for the HL-LHC with PIC only (new triplet and D1 magnets and potentially low impedance collimators) and full LIU upgrade.

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