HL-LHC ALTERNATIVES SCENARIOS

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Abstract

The HL-LHC parameters assume unexplored regimes for hadron colliders in various aspects of accelerator beam dynamics and technology. This paper reviews the possible alternatives that could potentially improve the HL-LHC baseline performance or lower the risks assumed by the project. The alternatives under consideration range between using flat beams at the IP, compensate the long-range beam-beam encounters with wires and adding new RF cavities with larger or lower frequencies with respect to the existing RF system.

ALTERNATIVES TO BASELINE

The HL-LHC project aims at achieving unprecedented peak luminosity and event pile-up per crossing by reducing the IP beta functions, increasing the bunch population and providing crab collisions with crab cavities. In the following three failure scenarios that could limit the HL-LHC performance are listed together with possible alternatives to the baseline HL-LHC configuration in order to still reach a reasonable performance.

Longitudinal multi-bunch instabilities appearing

These might be mitigated in a double RF operation either with 800 MHz RF system as a higher harmonic or for longer bunches with 200 MHz RF system as a main system [1] (the LHC 400 MHz system remains taking the function of a higher harmonic RF). In both cases the RF systems should be operated in bunch shortening mode as this has been experimentally demonstrated to be the robust approach in the SPS. This is in conflict with using the 800 MHz system for bunch flattening for peak pile-up density mitigation.

Electron cloud producing too large heat-load

This might be mitigated by using the 8b+4e filling scheme [2] or longer bunches with an 200 MHz main RF system. The 8b+4e scheme provides larger bunch charge with about 30% fewer bunches. The 200 MHz system might allow to provide bunches as long as 20 cm. Both options show a suppression of electron-cloud in the dipoles in simulations throughout the LHC cycle.

Crab cavities demonstrating not operational for hadrons

SPS tests, machine protection issues, crab cavity impedance, or emittance growth due to RF phase noise might eventually suggest that crab cavities cannot be operated in the HL-LHC. In this scenario it is mandatory to resort to flat optics at the IP. Magnetic or electromagnetic wires [3] might be placed near the separation dipoles in order to compensate for the long-range interactions allowing for a reduction of the crossing angle and therefore increasing the luminous region. A 200 MHz RF system might also help if it allows to increase the bunch intensity. This is expected for single bunch limitations, however multi-bunch instabilities might dominate the intensity reach. The latter limit is unknown and hence bunch intensity is assumed to be the same as for the baseline in the 200 MHz scenario.

ALTERNATIVES FOR PERFORMANCE

Another set of alternatives to the HL-LHC baseline configuration offer a better luminosity quality by reducing the pile-up density. It has been proposed that lowering the pile-up density might allow for a larger total pile-up and therefore larger luminosity. Three alternatives in this direction follow:

Peak pile-up density leveling with β^*

This alternative does not require any extra hardware and only slows down the baseline β^* leveling to ensure a peak pile-up density below certain value. Since in the baseline the largest peak pile-up is reached for a short time at the end of the β^* leveling process it is possible to reduce this largest peak pile-up with little or negligible impact in the integrated luminosity [4].

Longitudinal bunch profile flattening

A higher harmonic RF system might be used to lengthen and flatten the longitudinal bunch profile, however it has been remarked that this operational mode is not robust and demonstrated impractical in the SPS. Instead, RF phase modulation has already demonstrated to slightly flatten the longitudinal bunch profile [5] in the LHC. Further studies of this promising technique are required to assess its potential for the HL-LHC. Combining this last option with peak pile-up leveling with β^* offers the lowest possible peak pile-up without significant impact on performance and without any hardware modification to the current baseline.

Crab kissing

Crab kissing [6, 7, 8] can be realized in various ways. The initial proposal uses flat bunches, a magnetic or electromagnetic wire to reduce the crossing angle (to lower the crab cavity voltage) and crab cavities in the separation plane to maximize the luminous region. The compensating wire might not be needed if each crab cavity achieves 5 MV. The possibility of doing crab kissing in the crossing plane has also been explored.

MERITS AND PERFORMANCE

In the following sections the various alternatives are compared in terms of their merits, integrated luminosity, length of the optimum physics fill, peak pile-up density (μ_{peak}) and beam-beam tuneshift ($\xi_{x,y}$). These are calculated via simulations of the physics fill evolution. The estimate of the integrated luminosity requires determining the luminosity evolution during a fill. The beam intensity evolution has been evaluated taking into account the burn-off due to luminosity considering a total cross-section of 100 mb. The emittance evolution has been determined including Intra-Beam Scattering (IBS) with a coupling of 10% and Synchrotron Radiation (SR) damping. The bunch charge and emittances are updated every 10 minutes according to the current luminosity burn-off, IBS growth rates and SR damping. The bunch length is either kept constant assuming the use of longitudinal emittance blow-up techniques or purposely reduced by increasing RF voltage and/or letting SR damp the longitudinal emittance.

The overlap luminosity integral including the crab cavity RF curvature is derived from [9] by adding the hour-glass effect. The peak pile-up density is evaluated as the density of physics events exactly at the IP (s=0).

The effect of the RF curvature on the beam-beam tuneshift is only considered for the 200 MHz cases, where bunch length is assumed to be about 15 cm.

The yearly integrated performance is computed assuming 160 days dedicated to proton physics (including the turn-around time of 3 hours) with a 50% efficiency at and energy of 6.5 TeV. Efficiency is defined as:

$$N_{fills}\frac{T_{physics}+T_{turn-around}}{T_{run}}$$

where N_{fills} is the number of fills leading to physics, $T_{physics}+T_{turn-around}$ is the sum of the time in physics and the time needed to come back to physics and T_{run} is 160 days. All the fills are assumed to have the same length. This could correspond to the optimum fill length or to 6 hours. Both cases are presented in the following to assess the sensitivity to the fill length. Further details on beam parameters can be found at [10].

8b+4e filling scheme

The 8b+4e filling scheme has shown to strongly suppress electron cloud in the LHC dipoles for having fewer bunches but with larger bunch charge [4]. A brief description of the generation of this filling scheme in the injectors follows. Up to seven bunches are injected with two transfers from the PSB into h=7-buckets in the PS and accelerated to an intermediate flat-top at a kinetic energy of 2.5 GeV. Instead of the usual triple splitting RF manipulation involving RF systems at harmonics h=7, 14 and 21, a direct splitting from h=7 to h=21 in counter-phase results in pairs of bunches at h=21 with empty buckets in between. These bunch pairs are then accelerated in the PS to the flat-top energy on h=21 where each bunch is subsequently split in four as with the nominal production scheme for 25 ns bunch spacing. The PS circumference is thus filled with up to 7 batches of eight bunches spaced 25 ns with gaps of 120 ns between them. These gaps are short enough for the PS ejection kicker to trigger, so that in total 56 bunches with a pattern of 6×(8b+4e)+8b are transferred to the the SPS. It is worth noting that replacing the triple splitting by the direct double splitting in the PS should result in up to 50% higher intensity per bunch at first sight. However, due to longitudinal stability and beam loading considerations in the SPS, the intensity per bunch deliverable to the LHC injection is expected to be about 2.3×10^{11} ppb.

First experimental demonstrations of the 8b+4e filling scheme have already been conducted in the PS, see Fig. 1.

The 8b+4e filling scheme performance is compared to the HL-LHC baseline in Fig. 2. The lower number of bunches of the 8b+4e scheme implies a lower peak luminosity at the same number of pile-up events per crossing (μ). Thanks to the larger bunch population and lower emittances the yearly integrated luminosity is only reduced by about 24%.

200 MHz as main RF

Electron cloud is most critical at injection for emittance dilution (due to the lower beam rigidity) and during the ramp for the total heat deposition in the beam screens (due to the extra sources of heat load). The 200 MHz system offers the possibility of using extremely long bunches (up to 20 cm) at injection and during the ramp. Once at flattop the bunch length could be explored to find a balance between electron cloud effects and luminosity production.

Figures 3 and 4 show the heat load at injection in the dipoles and in the quadrupoles versus Secondary Emission Yield (SEY) and for different bunch lengths. From the 2012 experience it is expected that a SEY between 1.4 and 1.5 or even lower is at reach already in 2015. In this SEY window a 19 cm bunch length would almost totally suppress electron cloud effects in the dipoles. In the quadrupoles the heat load for the baseline parameters is considerably smaller and the dependence with bunch length is very weak. An interesting observation is that heat load increases for long bunches at very low values of SEY between 1.2 and 1.3.

Figures 5 and 6 show the heat load at 7 TeV in the dipoles and in the quadrupoles versus SEY and for different bunch

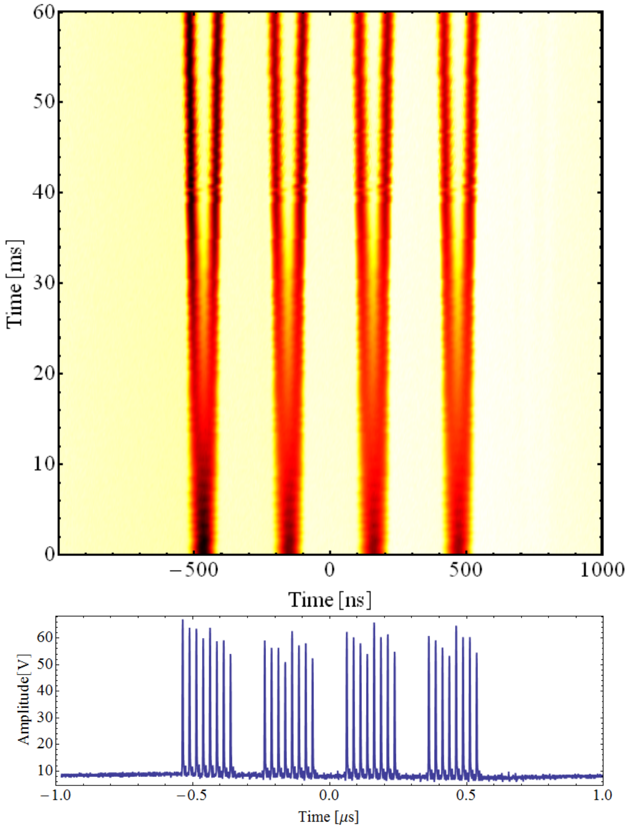

Figure 1: Proof-of-principle for the 8b+4e production scheme in the PS. Direct splitting of four bunches from h=7 to h=21 at E_{kin} = 2.5 GeV (upper plot), leaving an empty bucket between each pair of bunches. The subsequent splittings on the flat-top yield batches of 8 bunches spaced by 4 empty buckets at PS extraction (lower plot).

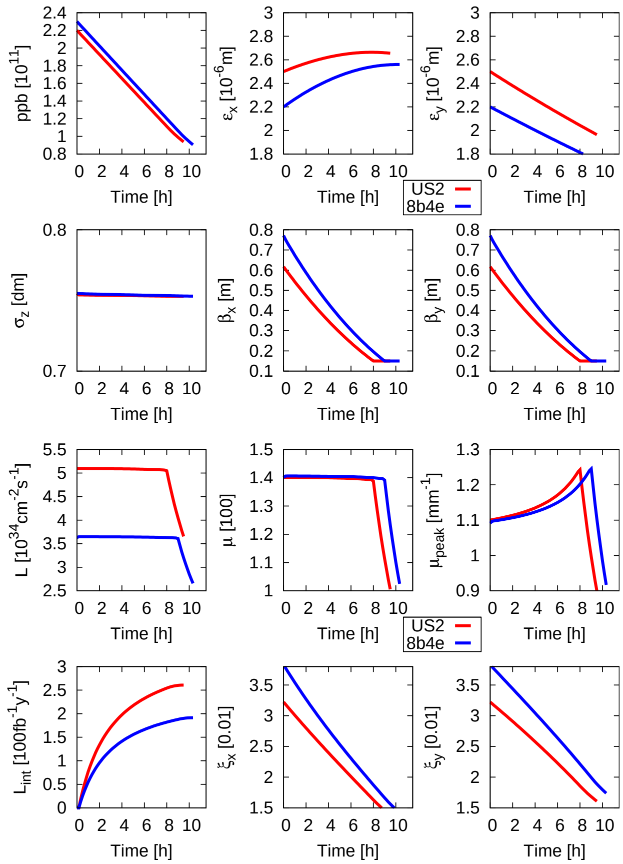

Figure 2: Performance comparison of the HL-LHC baseline (red) to the alternative 8b+4e filling scheme (blue). A reduction on the integrated luminosity of about 24% is observed in the 8b+4e scenario.

lengths. The electron cloud heat load at 7 TeV is almost identical to injection. The only significant difference is that at a SEY of 1.4 short bunches are more favorable in the quadrupoles. This might suggest that at top energy there might be an optimal bunch length below 20 cm that minimizes total electron cloud heat load.

The following operational scenario is therefore conceivable. Electron cloud effects render impractical the injection of the full beam with baseline parameters, while 19 cm long bunches generated with a 200 MHz main RF system strongly mitigate heat load and allow injection and ramp. At top energy an optimal bunch length is established considering luminosity performance and heat load. For practical reasons and to be conservative with performance, a bunch length of 15 cm at top energy is assumed in the simulations. Figure 7 compares the HL-LHC baseline fill evolution to the 200 MHz alternative.

The main limitation arising from the lower RF frequency is a reduction of the TMCI threshold. The LHC impedance is dominated by collimators and one can assume the TMCI threshold to be driven by the tune shift of the mode 0. In this case it is possible to analytically estimate the maximum

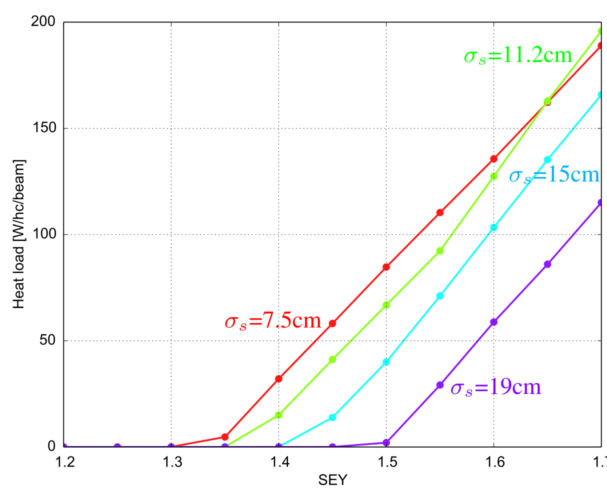

Figure 3: Heat load per half cell and per aperture at injection induced by electron cloud in dipoles versus SEY for 4 different bunch lengths.

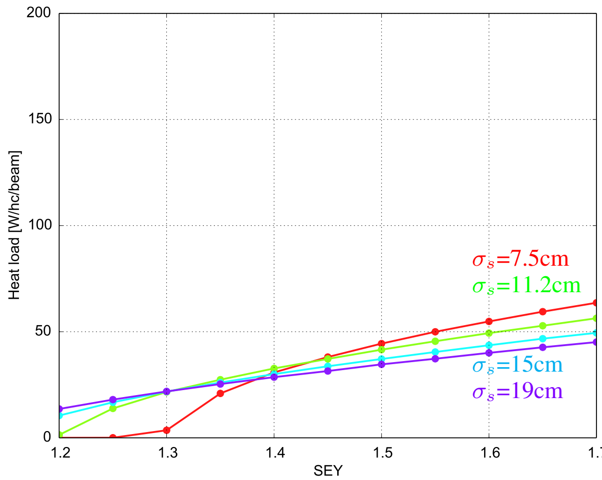

Figure 4: Heat load per half cell and per aperture at injection induced by electron cloud in quadrupoles versus SEY for 4 different bunch lengths.

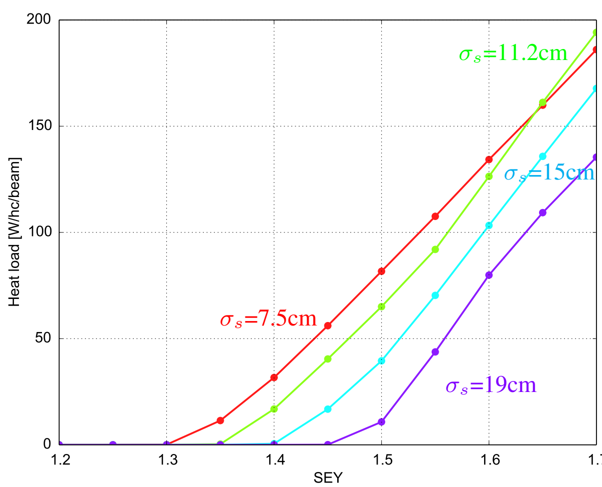

Figure 5: Heat load per half cell and per aperture at top energy induced by electron cloud in dipoles versus SEY for 4 different bunch lengths.

effective impedance by [11]

$$\Im Z_{y\ max}^{eff} = \frac{4\pi (E_t/e)\tau_b Q_s}{N_b e \beta_y^{av}} \tag{1}$$

where E_t is the beam energy, τ_b is the bunch length in seconds, Q_s is the synchrotron tune, N_b is the bunch population and β_y^{av} is the average β-function. The TMCI threshold is therefore proportional to the bunch length and the synchrotron tune. Using a bunch length of 12.6 cm and $Q_s = 9 \times 10^{-4}$ for the 200 MHz scenario the relative reduction of the TMCI threshold is 1.36.

Figure 8 shows a simulation of the TMCI threshold at zero chromaticity for 200 MHz and 400 MHz main RF systems. The HL-LHC impedance model as presented in [12] is used in the eigenvalue solver code presented in [13] assuming Gaussian bunch densities. The degradation by

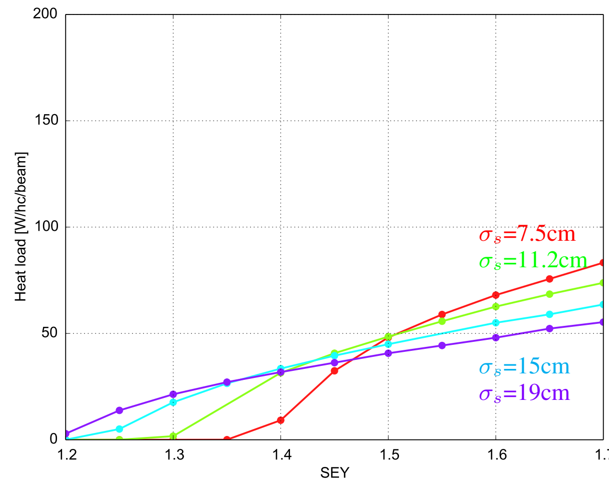

Figure 6: Heat load per half cell and per aperture at top energy induced by electron cloud in quadrupoles versus SEY for 4 different bunch lengths.

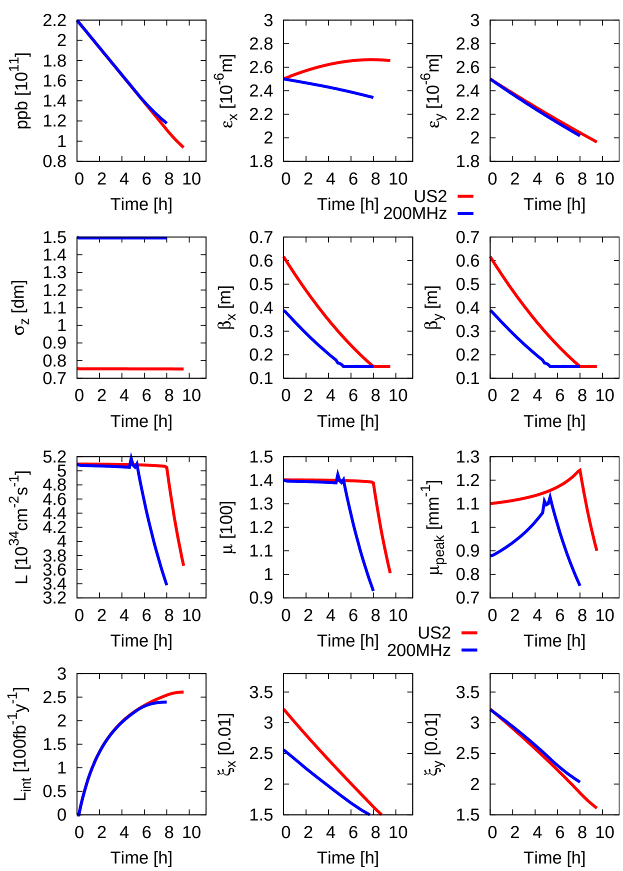

Figure 7: Performance comparison of the HL-LHC baseline (red) to the alternative of 200 MHz (blue) in order to suppress the electrons cloud effects. A bunch length of 15 cm is assumed during collision while at injection it could be as long as 20 cm. Performance is reduced only by about 7%.

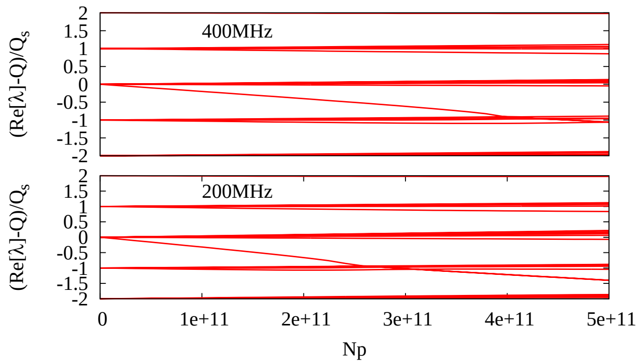

Figure 8: Comparison of the TMCI threshold at zero chromaticity between the design RF system (top) and the alternative at 200 MHz.

about a factor 1.5 is confirmed and the threshold is decreased to 2.6×10^{11} ppb which is above the foreseen operational bunch charge. It is possible that multi-bunch effects slightly decrease this threshold bringing the operational bunch charge below the target. This could be of some concern for beam stability but it has been shown that the use of transverse damper and chromaticity can increase intensity thresholds in various machines [14, 15, 16]. Note that for the LEP case, the same approach revealed almost no beneficial effect but it is thought to be caused by the large synchrotron tune [17].

Alternative materials for the HL-LHC collimators are also under consideration which could significantly reduce their contribution to the global impedance of the machine and hence increase the TMCI threshold.

Another concern of the 200 MHz system is its compatibility with 400 MHz crab cavities. An illustration of the beams encounter at the IP is depicted in Fig. 9 for the baseline and the 200 MHz alternative. The core of the beam (1 σ corresponding to the red area) is basically unaffected by the crab cavity RF curvature. A similar situation was studied when 800 MHz elliptical crab cavities and β^*= 25 cm were considered for the luminosity upgrade without finding any problem in Dynamic Aperture (DA) [9] or strong-strong [18] simulations.

Weak strong DA simulations have been performed for the new configuration of 200 MHz main RF and a crab cavity of 400 MHz. The strong bunch features a bunch length of σ_s=13 cm and is modeled with 19 slices transversely displaced according to Fig. 9. The particles in the weak bunch are tracked with 6 MV of 200 MHz and the local IR crab cavities. Again no degradation of DA is observed due to the RF curvature of the crab cavity, see Fig. 10. For reference, complete baseline DA studies can be found at [19].

Flat IP optics and beam-beam long-range compensation

In the scenario that crab cavities turn out to be not operational in the HL-LHC it is mandatory to use flat IP optics

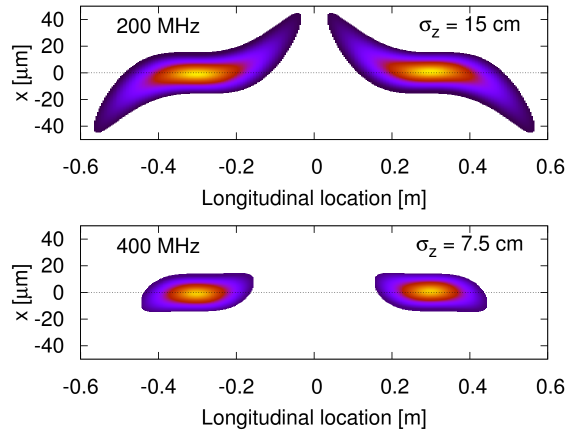

Figure 9: Illustration of the crab cavity RF curvature effect on the collision process for the nominal RF system (400 MHz) and the alternative of 200 MHz. The beams contours correspond to 2 σ envelope for a β^*= 15 cm.

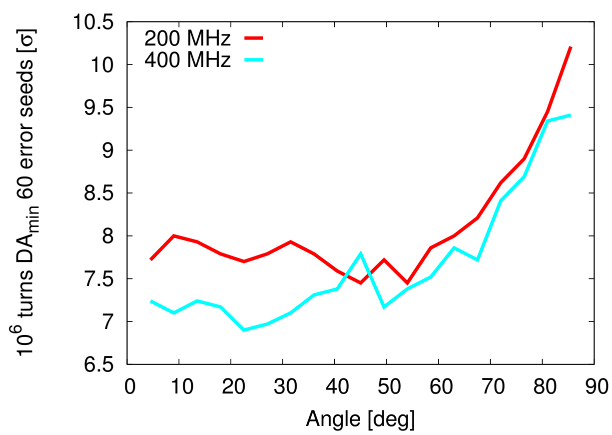

Figure 10: Dynamic aperture versus angle in the transverse plane including beam-beam interaction with the effect of the crab cavity RF curvature for the baseline HL-LHC scenario (cyan) and for the 200 MHz alternative (red). The initial momentum deviation follows the usual criteria of being at 2/3 of the RF bucket. The bunch charge is 1.1×10^{11} protons and β^* =15 cm corresponding to the last step of the β^* leveling.

to reduce the crossing angle and minimize the peak pile-up density. In [20] it is proposed to use $\beta^*_{x,sep}$=30,7.5 cm and a crossing angle of θ=320 μrad thanks to beam-beam long-range compensator devices. Figure 11, taken from [20], shows the feasibility of this proposal with dynamic aperture calculations. The usual criteria is that a dynamic aperture of at least 6σ is required for operation. In the case that beam-beam long-range compensators were not available the same study [20] suggests an operational configuration with the same IP beta functions and a slightly larger crossing angle θ=390 μrad, see Fig. 11. The feasibility of this crossing angle is also confirmed with more realistic

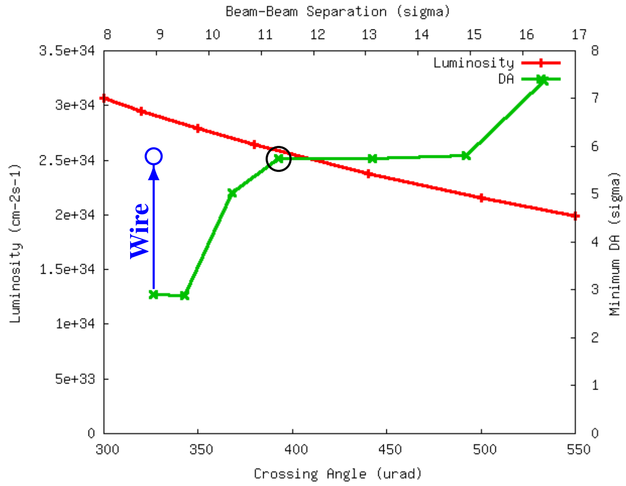

Figure 11: Dynamic aperture versus crossing angle for $\beta^*_{x,sep}$=30,7.5 cm, σ_z=10 cm, N=1.1×10^{11} ppb and including beam-beam interaction taken from [20]. Two operational conditions are highlighted with circles: using long-range compensator (blue) at θ =320 μrad and without long-range compensator (black) at θ =390 μrad.

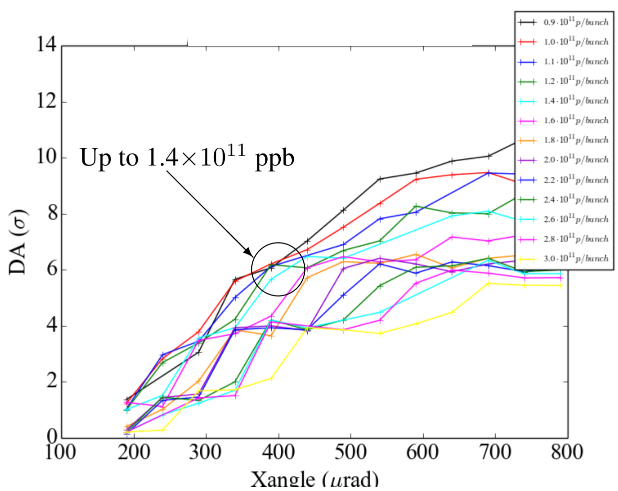

Figure 12: Dynamic aperture without long-range compensator versus crossing angle for $\beta^*_{x,sep}$=30,7.5 cm, σ_z=7.5 cm for various bunch intensities ranging between 0.9×10^{11} and 3×10^{11} ppb. The operational scenario highlighted with a circle at θ =390 μrad allows up to 1.4×10^{11} ppb.

simulations including the lattice errors [21, 22], see Fig. 12. Up to 1.4×10^{11} ppb are allowed with a crossing angle of θ =390 μrad for flat optics without long-range compensator. Intermediate optics and intensities during the β^* leveling process have also been verified to have a DA larger than or equal to 6σ.

Figure 13 compares the performance of the two scenarios considered above using flat optics, without crab cavities, with and without long-range compensator. The absence of crab cavities reduces the baseline performance by

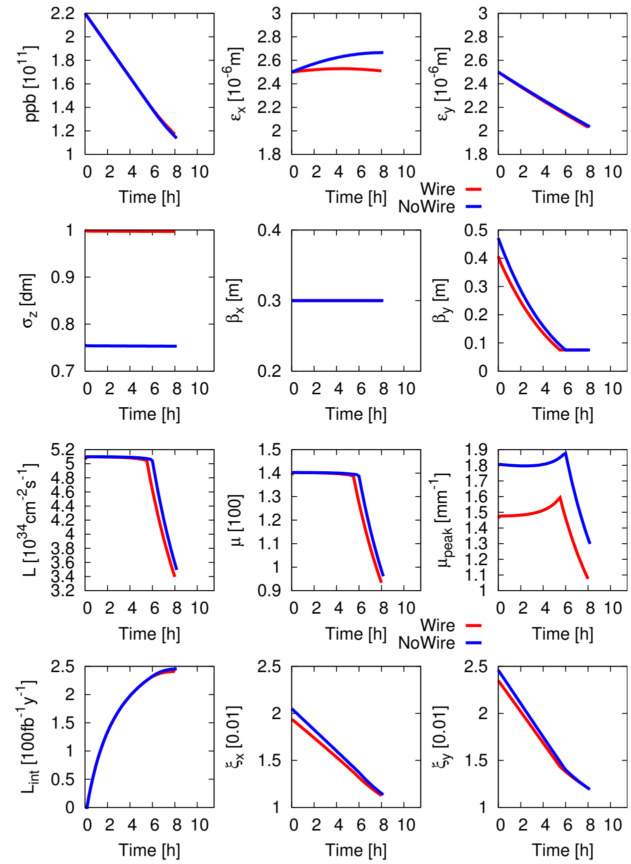

Figure 13: Performance for the scenarios without crab cavities as presented in Fig. 11 and 12 with and without beam-beam long-range compensator. Note that bunch lengths are different. Integrated luminosity is very similar while peak pile-up density is about 0.3 mm^{-1} larger in the absence of a long range compensator.

about 7% with a considerably larger peak pile-up density of 1.9 mm^{-1}. A wire can be used to reduce the crossing angle partially mitigating the large peak pile-up to 1.6 mm^{-1} but with similar performance.

Larger peak luminosity

In [8, 23] the option of allowing for larger pile-up but with lower peak pile-up density thanks to crab kissing is proposed. The main goal is to reach at least 3000 fb^{-1} in ten years. For this a lower β^* of 0.1 m was also assumed.

This scenario of allowing for larger pile-up can also be considered in the framework of the HL-LHC baseline leveling luminosity at 7.5×10^{34}cm^{-2}s^{-1} and keeping the minimum β^*=0.15 m. As shown in Fig. 14 the integrated luminosity per year reaches 310 fb^{-1} with a peak pile-up density of 1.7 mm^{-1}. This large peak pile-up density can be mitigated without assuming any extra hardware, just slowing the reduction of β^*. Figure 14 shows that a peak pile-up density of 1.4 mm^{-1} can be achieved with this technique keeping the 300 fb^{-1} per year. It is estimated that crab kissing with flat longitudinal distributions and β^*=0.15 m

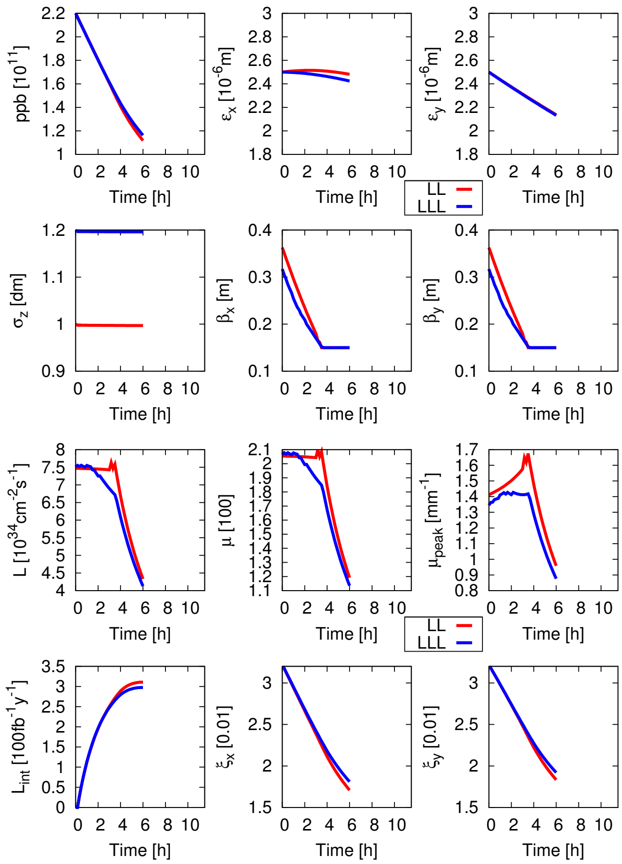

Figure 14: Performance for the baseline scenario with larger peak luminosity (LL) and another scenario where peak pile-up density is leveled with β^* (LLL).

	L_{int} [fb^{-1}]	Peak pile-up [mm^{-1}]
Larger Lumi.	310	1.7
Larger Lumi. leveled	300	1.4
Crab Kissing	300	1

Table 1: Scenarios with larger peak luminosity. Peak pile-up density is mitigated either with β^* leveling or with crab kissing.

should achieve similar performance with a significantly lower peak pile-up density of 1 mm^{-1}. Table 1 summarizes these 3 scenarios with larger peak luminosity.

SUMMARY AND OUTLOOK

We have shown that alternatives to the HL-LHC baseline exist to make the luminosity upgrade robust against foreseeable problems as e-cloud, non-operational crab cavities or too large peak pile-up density. Figure 15 summarizes the performance of all scenarios discussed in this work.

New promising alternatives have been proposed during this workshop, as the 80 bunch scheme [24]. New alternative scenarios are being discussed considering these new options and further optimized configurations [25].

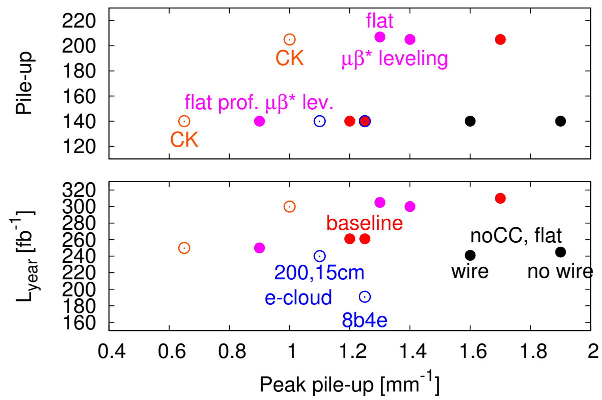

Figure 15: Summary chart showing pile-up (top) and integrated luminosity per year (bottom) versus peak pile-up density for the various scenarios considered in this work.

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