HL-LHC ALTERNATIVES

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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 three alternatives that could potentially improve the LHC performance: (i) the alternative filling scheme 8b+4e, (ii) the use of a 200 MHz RF system in the LHC and (iii) the use of proton cooling methods to reduce the beam emittance (at top energy and at injection).

The alternatives are assessed in terms of feasibility, pros and cons, risks versus benefits and the impact on beam availability.

ALTERNATIVES AND MERITS

This section introduces three alternatives to the HL-LHC baseline considered in this report together with their merits and weak points. Electron cloud effects in the HL-LHC era could seriously hamper the luminosity upgrade. Therefore special attention is put in the evaluation of electron cloud effects for the different alternatives.

Filling scheme 8b+4e

By performing a double splitting instead of triple splitting in the PS it is possible to generate fewer and more intense bunches. Basically a PSB bunch is split into 8 bunches rather than 12. The usual 12 bunch structure is preserved keeping 4 empty bucktes in between the micro-batches of 8 bunches. For details on the generation of this scheme see [1]. Following the upgrade of the injector chain, the 8b+4e scheme would allow 1840 bunches to be injected into the LHC with 2.4e11 ppb if the LHC is filled without further changes to the bunch pattern.

The outstanding merit of this alternative is the huge reduction of electron cloud effects plus the fact that this filling scheme can be implemented from 2015 without any cost (8b+4e bunch population in 2015 might be 1.6×10^{11} ppb). Figure 1 shows simulations of the heat load due to electron cloud per aperture in the LHC dipoles using the parameters as expected in 2015 for the baseline and for the 8b+4e scheme. A measurement of heat load during 2012 is shown in the figure as a pessimistic reference for tolerable levels of heat load. A large reduction factor in heat load thanks to the 8b+4e scheme is observed, allowing, in principle, operation with secondary emission yields as large as $\delta_{max} \approx 1.6$. Considering HL-LHC parameters the 8b+4e scheme also generates considerably lower heat load than the nominal 25 ns scheme, yet it requires $\delta_{max} \lesssim 1.4$, as illustrated in Fig. 2.

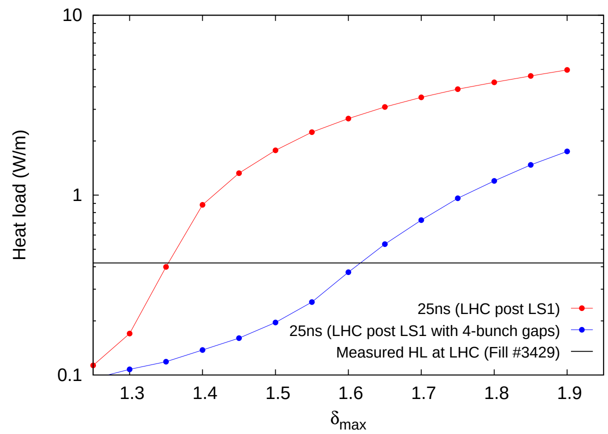

Figure 1: Heat load versus maximum secondary emission yield due to electron cloud per aperture in the LHC dipoles using the parameters as expected in 2015 for the baseline and for the 8b+4e scheme. The inferred heat load from measurements in 2012 is also shown.

During discussions in the RLIUP workshop on how to maximize the number of bunches in the LHC, a proposal was made to inject 7 instead of 6 PSB bunches into the PS. In the nominal filling scheme this would imply losing few (three or four) bunches at the end of the batch while extracting to the SPS, with the consequent transfer of trains made of 80 or 81 bunches. However, this option turned out to fit particularly well into the 8b+4e scheme, as 7 injections can be made from the PSB to the PS and no bunches would need to be removed at extraction thanks to the four empty buckets [2]. The SPS would be filled with the following bunch train structure:

$$4 \times (7 \times (8b + 4e) + 4e) + 572e \qquad (1)$$

This optimized scheme produces more luminosity thanks to the larger number of bunches but also yields slightly larger heat load due to electron cloud, see Fig. 2. A filling pattern in the LHC has been prepared using this scheme [3] yielding 1960 colliding bunches in the main interaction points (120 more than for the initial 8b+4e). This optimized scheme is used in the rest of the paper.

The feasibility and performance of the 8b+4e scheme should be experimentally assessed via beam tests starting in the LHC injector chain already in 2014.

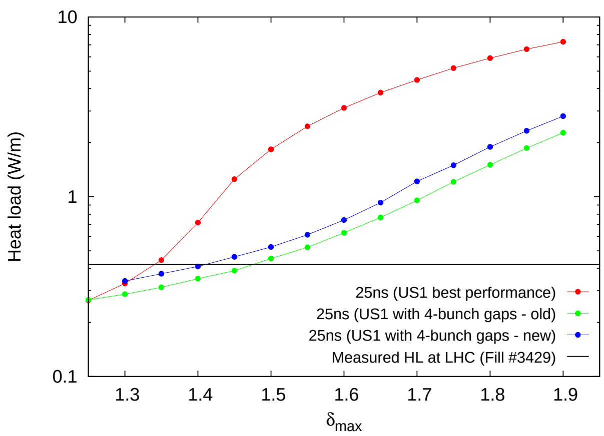

Figure 2: Heat load versus maximum secondary emission yield due to electron cloud per aperture in the LHC dipoles using the US1 parameters for the baseline and for the two 8b+4e filling schemes. The inferred heat load from measurements in 2012 is also shown.

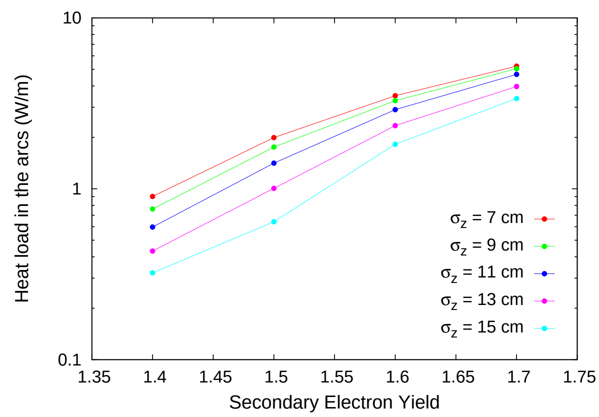

Figure 3: Heat load due to electron cloud in the arc dipoles at 7 TeV for the HL-LHC (US2) for different values of the bunch length with $N_b = 2.5 \cdot 10^{11}$ ppb. We can see how the heat load reduces monotonically with an increasing bunch length. In addition, the SEY multipacting threshold displaces towards higher values for longer bunch lengths.

Table 1: Possible configurations of the 200 and 400 MHz RF systems in the LHC [4], showing emittance, voltages and bunch length. The last row combines the possibility of using the 400 MHz system for bunch shortening or lengthening.

ϵ_s [eVs]	200 MHz [MV]	400 MHz [MV]	σ_z [cm]
3	0	16	8.77
3	3	0	15.7
2	6	0	12.6
2	6	3	10.8-15.5

200 MHz main RF in the LHC

Using a 200 MHz system as main RF throughout the LHC cycle allows to inject more intense and longer bunches into the LHC and to optionally level luminosity with bunch length. The possible RF operational modes at collision energy are shown in Table 1 [4]. A minimum voltage of 3 MV is required for the 200 MHz RF system. However this minimum voltage gives no operational margins to modify the bunch length. 6 MV is the preferred 200 MHz voltage. Bunch length luminosity leveling, in combination with β^* leveling, is considered to maximize the integrated luminosity with the possibility of full capture in the 400 MHz system during physics. Single steps of bunch length luminosity leveling were experimentally demonstrated in the LHC [5].

200 MHz normal conducting cavities have been already proposed [6] and manufactured for the LHC in order to optimize the beam capture at injection. However these cavities have not been installed and would not be sufficient to ramp the beam energy. Only recently a first compact design of 200 MHz superconducting cavities has been proposed [7] for the LHC.

A reduction of electron cloud is expected for longer bunches. This is shown in Fig. 3 by plotting simulated heat load in the dipoles for various bunch lengths versus secondary emission yield. A monotonic behavior is observed in the range of interest. Figure 4 compares the heat load for the HL-LHC baseline and the 200 MHz alternative. A significantly lower heat load due to electron cloud in the dipoles is observed in the 200 MHz case for $\delta_{max} < 1.6$.

The heat load due to electron cloud in the quadrupoles needs to be addressed for longer bunches. Nevertheless simulations show that head load in the arc quadrupoles is strongly reduced when increasing the bunch charge between 1.5×10^{11} ppb and 2.2×10^{11} ppb for secondary emission yields between 1.2 and 1.6 [8]. Measurements in the LHC with 25 ns bunch spacing during bunch lengthening by 40% in the energy ramp do not reveal any visible increase in the heat load [9]. Yet, there was one observation with 50 ns bunch spacing of a slight heat load increase in the triplets when increasing bunch length by 17% [10].

Another beneficial effect from the longer bunches is the reduction of the beam induced heating due to impedance. Figure 5 shows the beam induced heating versus the rms bunch length [11]. Reductions of a factor ≈ 5 for the upgraded injection kicker (MKI) and ≈ 2 for the 17.3 mm beam screen are expected when increasing the bunch length from 7.5 cm to 13 cm.

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

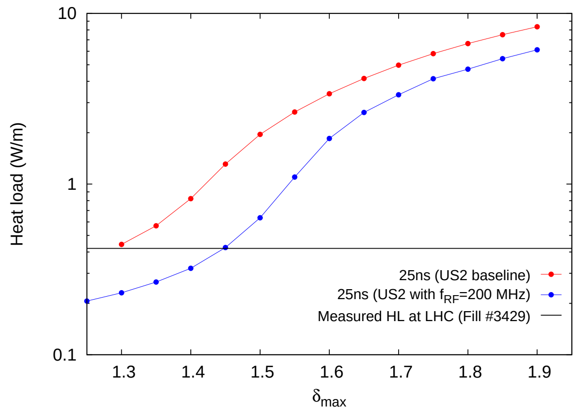

Figure 4: Heat load due to electron cloud in the arc dipoles at 7 TeV for the HL-LHC (US2) for the baseline scenario (red curve) and an alternative scenario using a 200 MHz system as main RF (blue curve).

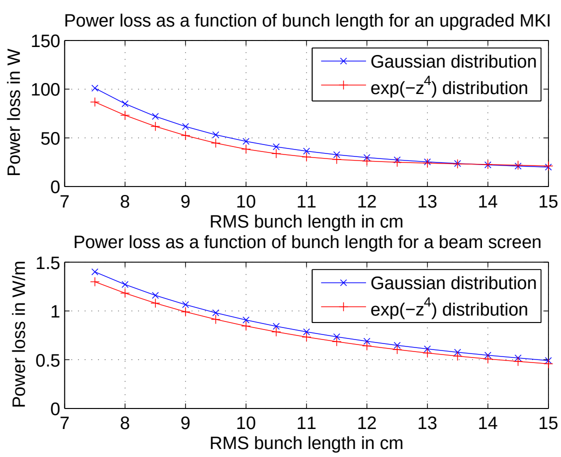

Figure 5: Heating due to impedance versus rms bunch length for the injection kicker (MKI) and the beam screen [11].

effective impedance by [12]

$$\Im Z_y^{eff}{}_{max} = \frac{4\pi(E_t/e)\tau_b Q_s}{N_b e \beta_y^{av}} \quad (2)$$

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 6 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 [13] is used in the eigenvalue solver code presented in [14] assuming Gaussian bunch densities. The degradation of

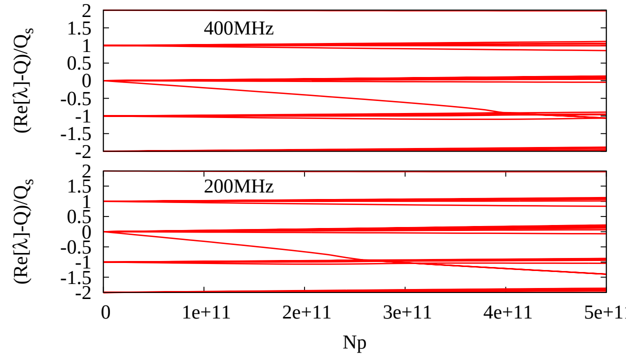

Figure 6: TMCI threshold at zero chromaticity for 200 MHz (bottom) and 400 MHz (top) main RF systems.

about a factor 1.5 is confirmed and the threshold is decreased to 2.6×10^{11} ppb which is barely 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 relaxed intensity thresholds, for instance, in SOLEIL [15]. Alternative materials for the 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. 7 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 [16] or strong-strong [17] simulations. Nevertheless these simulations should be revisited using the new configuration. Furthermore a reduction of the crab cavity frequency to 320 MHz has been considered after the RLIUP workshop [18]. This causes a negligible increase in integrated luminosity but a significant reduction of peak pile-up density, reaching 0.8 mm^{-1}.

The merits of the 200 MHz main RF system follow: (i) a significantly lower electron cloud, (ii) larger bunch charge (possibly 2.56×10^{11} ppb), (iii) factors between 2 and 5 lower heat-load coming from impedances and (iv) the possibility of leveling luminosity by reducing bunch length during the fill.

Cooling protons

Recently various cooling techniques have been proposed for protons in the LHC [19, 20, 21]. Most of these techniques require challenging hardware at top energy. However performing cooling at injection energy prior to the energy ramp would require a more affordable hardware and synergies could be established with the LHeC ERL test fa-

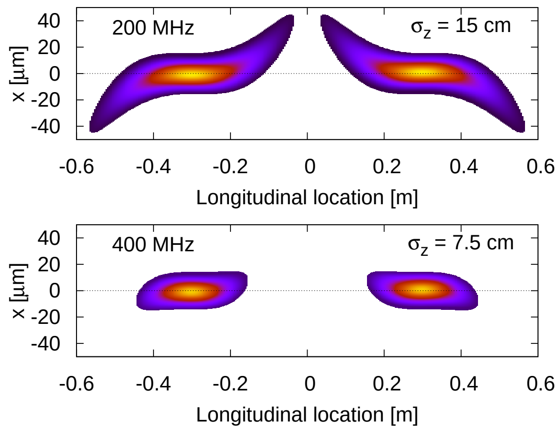

Figure 7: Illustration of the crab cavity RF curvature effect on the collision process for the nominal RF system (400 MHz) and the alternative of 200 MHz. The beams contours correspond to 2 σ envelope for a β^*= 15 cm.

cility. Nevertheless even assuming 1 hour of cooling at injection to halve the transverse emittances does not render any improvement in the integrated luminosity. This is due to the increased turn-around time and the presence of IBS during the fill, which blows up the cooled emittance. Possible future developments on cooling techniques should be followed up since an affordable cooling at collision energy will certainly improve the HL-LHC performance.

PERFORMANCE EVALUATION

In the following sections the various alternatives are compared in terms of 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 [16] 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 yearly integrated performance is computed assuming 160 days dedicated to proton physics (including the turn-around time of 3 hours) with a 50% efficiency. Efficiency is defined as:

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

where N_{fills} is the number of fills, $T_{physics}+T_{turn-around}$ 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.

US1 PERFORMANCE

The US1 scenario [22] sets a yearly integrated luminosity goal of 170 fb^{-1}. The baseline approach to reach this goal assumes the installation of the new large aperture triplet in the LHC but without crab cavities and without any modification of the matching section. A separation of 10 σ is assumed at the long-range encounters, which should be compared to the nominal 9.5 σ. Although β^* leveling would strongly mitigate the long-range interactions, it is not guaranteed that such separation can be achieved without degradation of the dynamic aperture during the whole fill due to the larger bunch population. Therefore the possibility of using long-range compensation wires is under study to allow for the 10 σ separation.

Table 2 compares the performance of the US1 baseline scenario to various alternatives. The first alternative simply considers a flatter beam at the IP by increasing the β^* function in the crossing plane. This reduces the integrated luminosity only by 7% while reducing the peak pile-up density from 1.5 mm^{-1} to 1.1 mm^{-1} (27% reduction).

The next two alternatives can be regarded as the backup scenarios in case electron cloud makes 25 ns not operational. These are 8b+4e and 50 ns [23]. The 8b+4e gives 11% lower integrated luminosity than the baseline US1 with 20% lower peak-pile up density. The small performance degradation makes this option extremelly interesting. The 50 ns alternative features lower performance with almost twice longer fills, which makes it considerably less interesting.

It should be noted that head-on and long-range beam-beam effects should be reviewed for all scenarios to find appropriate compromises and that the 8b+4e alternative enhances the head-on beam-beam by about 15-20%.

The last alternative considered for US1 is using a 200 MHz main RF system in LHC. This proves to be the best performing option providing between 232 fb^{-1} and 240 fb^{-1} per year with peak pile-up densities between 1.1 mm^{-1} and 1.4 mm^{-1}, depending on the β^* in the crossing plane. This largely exceeds the goal of 170 fb^{-1} per year.

Figure 8 shows the evolution of the relevant machine and beam parameters during the fill for the baseline and the main alternatives 8b+4e and 200 MHz.

Table 2: Performance comparison of the US1 baseline to various alternatives. 200 MHz features the performance with significantly lower electron cloud than the baseline.

	N	ϵ	$\beta^*_{x,y}$	L_{year}[fb^{-1}]		Opt. fill	Pile-up	
	[10^{11}]	[μm]	[cm]	Opt.	6h	length [h]	total	[mm^{-1}]
US1	1.9	2.62	20,40	181	181	6.1	140	1.5
flatter	1.9	2.62	20,80	169	168	6.6	128	1.1
8b+4e	2.4	2.2	20,80	160	156	7.5	143	1.2
50ns	3.5	3.0	20,80	142	118	12	143	1.1
200MHz	2.56	3.0	20,80	232	224	8.1	138	1.1
200MHz	2.56	3.0	20,40	**240**	228	8.5	138	1.4

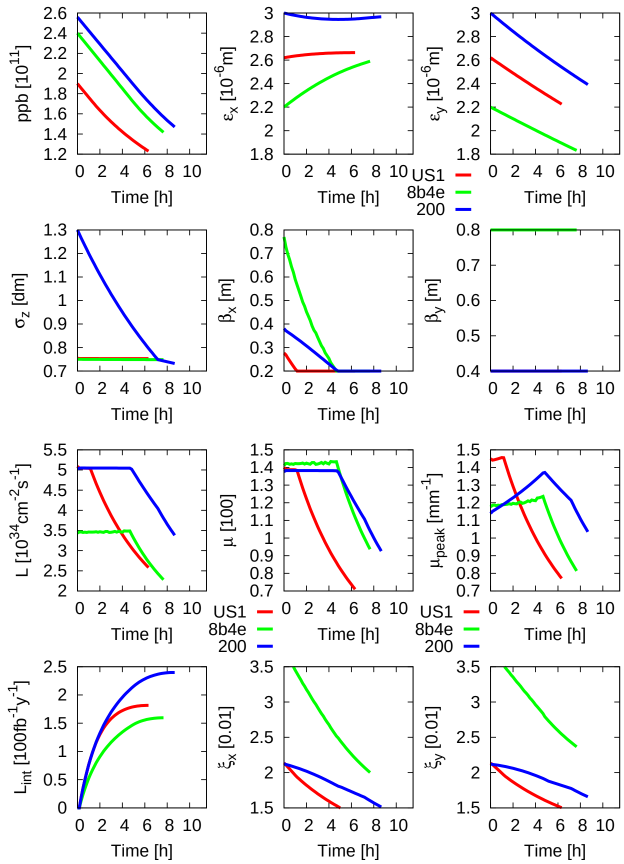

Figure 8: Comparison of the US1 baseline (red) to the 8b+4e (green) and 200 MHz (blue) alternatives. β_x is the beta function in the separation plane.

US2 PERFORMANCE

The US2 scenario [24] sets a yearly integrated luminosity goal of 250 fb^{-1}. The baseline approach to achieve this goal corresponds to the complete HL-LHC upgrade with crab cavities and a modified matching section allowing to achieve lower β^* than in US1. A more comfortable beam separation at the long range encounters of 12 σ is assumed for US2 throughout this report. For flat beams alternatives in US2 12 σ might again need the use long range wire compensators [25]. The main alternative to this scenario is the addition of the 200 MHz main RF system which increases the yearly integrated luminosity by 6% using 11 hours fills. Table 3 shows the performance of the US2 baseline, the 200 MHz alternative with 400 MHz crab cavities and a back-up solution in case crab cavities would not be operational in hadron machines. The detailed evolution of the various machine and beam parameters during the fill is shown in Fig. 9. Bunch length leveling is assumed in the 200 MHz alternatives for a maximum luminosity performance. This, in turn, produces a large peak pile-up density. Means to decrease the peak pile-up density are addressed in the next section.

PEAK PILE-UP DENSITY LEVELING

In general it is possible to level at constant peak pile-up density rather than at constant luminosity. This implies a reduction of the integrated luminosity. The first scheme including peak pile-up density leveling at 0.65 mm^{-1} is named “crab kissing” and it is described in [26, 27].

We consider two other ways to achieve an efficient peak pile density leveling. The first one is particularly interesting since it does not require any new hardware contrary to the crab-kissing which assumes crab-cavities also in the parallel separation planes. This consists in the usual β^* leveling with σ_z=10 cm but targeting peak pile-up density rather than luminosity.

The second one includes the use of 800 MHz RF cavities to flatten the longitudinal bunch distribution, see Fig. 10, and β^* leveling. Table 4 shows the performance for the US2 baseline and these two peak pile-up leveling techniques. Peak pile-up density can be effectively reduced to 1 mm^{-1} without any new hardware integrating 250 fb^{-1} per year. The 800 MHz RF system further reduces the peak pile-up density to 0.9 mm^{-1} slightly increasing the integrated luminosity to 252 fb^{-1}.

Peak pile-up density is also possible in the 200 MHz alternative scenario. The most convenient is to assume flat optics at the IP with a bunch length not shorter than 10 cm and using β^* leveling. Table 5 shows the performance of this option in 2 steps. A peak pile-up density of 1 mm^{-1} is

Table 3: Performance of US2 baseline and 200 MHz alternatives with 400 MHz crab cavities. 200 MHz with crab cavities gives the best performance with lower electron cloud and it is robust against non-working crab cavities.

	N	ϵ	$\beta^*_{x,y}$	L_{year}[fb^{-1}]		Opt. fill	Pile-up	
	[10^{11}]	[μm]	[cm]	Opt.	6h	length [h]	total	[mm^{-1}]
US2	2.2	2.5	15,15	261	232	9.3	140	1.3
200MHz	2.56	3.0	15,15	**276**	234	11	140	1.3
200MHz (no CC)	2.56	3.0	10,50	255	233	10	139	1.6

Table 4: Performance of the peak pile-up leveling techniques in the baseline scenario.

	N	ϵ	$\beta^*_{x,y}$	L_{year}[fb^{-1}]		Opt. fill	Pile-up	
	[10^{11}]	[μm]	[cm]	Opt.	6h	length [h]	total	[mm^{-1}]
US2	2.2	2.5	15,15	261	232	9.3	140	1.2
β^*-level	2.2	2.5	15,15	250	232	9.5	142	1.0
800MHz	2.2	2.5	15,15	252	232	9.1	141	0.9

Table 5: Performance of the peak pile-up leveling techniques in the 200 MHz scenario.

	N	ϵ	$\beta^*_{x,y}$	L_{year}[fb^{-1}]		Opt. fill	Pile-up	
	[10^{11}]	[μm]	[cm]	Opt.	6h	length [h]	total	[mm^{-1}]
200MHz	2.56	3.0	15,15	276	234	11	140	1.3
σ_z=10cm	2.56	3.0	7.5,30	272	233	11	140	1.1
β^*-level	2.56	3.0	7.5,30	272	233	10	141	1.0

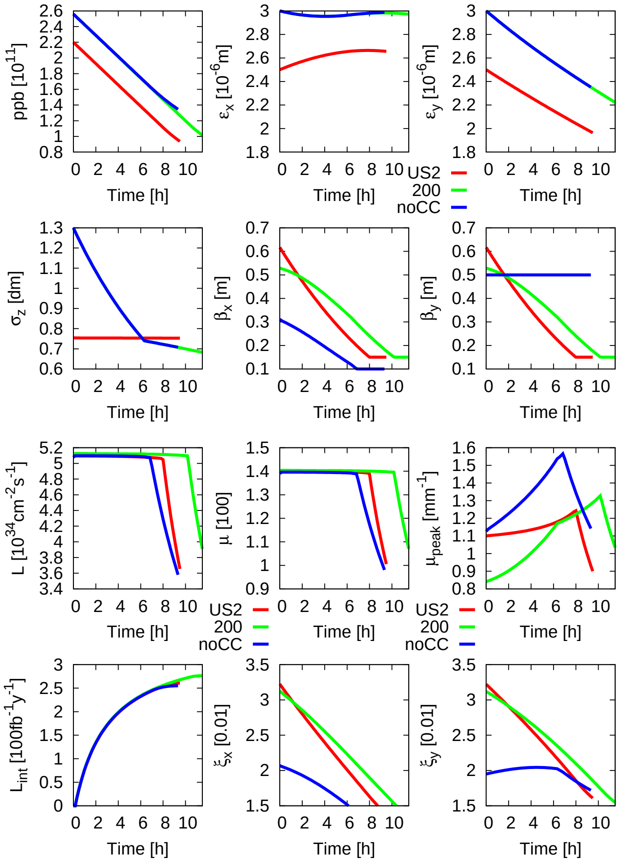

Figure 9: Fill evolution of the US2 baseline, 200 MHz alternative with 400 MHz crab cavities and a back-up option without crab cavities.

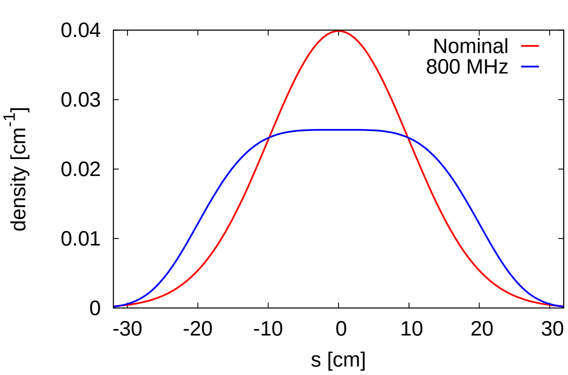

Figure 10: Longitudinal bunch distribution for a nominal bunch with σ_z= 10 cm and a flatter bunch using 8 MV 800 MHz system to provide 12.5 cm rms bunch length.

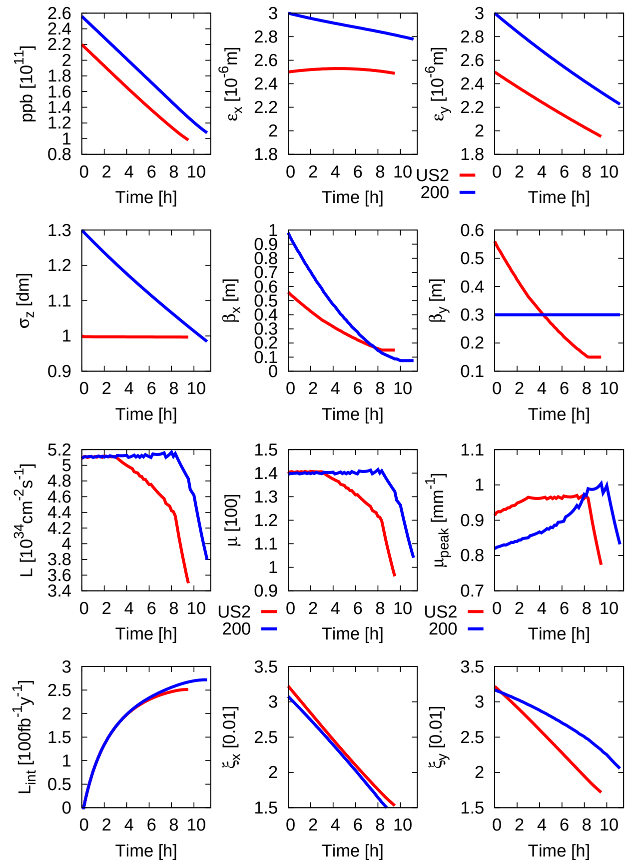

Figure 11: Fill evolution for the US2 baseline and the 200 MHz alternative with 400 MHz crab cavities using β^* for leveling peak pile-up density.

achievable with an integrated luminosity above 270 fb^{-1}.

Figure 11 compares the baseline and the 200 MHz alternative fills using leveling techniques to stay at maximum 1 mm^{-1} pile-up density.

Another effective means to reduce the peak pile-up density is to reduce the crab cavity frequency to 320 MHz or even 200 MHz [18]. Crab cavity voltage needs to increase proportionally to the reduction in crab cavity frequency. With 320 MHz crab cavity peak pile-up density is lowered to 0.8 mm^{-1}.

SUMMARY & OUTLOOK

Using 200 MHz as the main RF system in the LHC has been identified as a very promising alternative for achieving both the US1 and US2 performance goals. 200 MHz provides the best yearly integrated luminosity with a significantly reduced electron cloud and impedance heating. No obstacle is found to keep crab cavity frequency at 400 MHz. Actually, a reduction in the crab cavity frequency only improves the peak pile-up density [18]. The 200 MHz alternative is also very robust against non-working crab cavities. Nevertheless 200 MHz superconducting cavities require a completely new RF design never tested in circular accelerators. Further R&D efforts are required to evaluate the feasibility of this proposal.

If electron cloud makes it impossible to operate with 25 ns beams the filling scheme 8b+4e shows significant advantages over the 50ns. The 8b+4e alternative has no extra cost and can already be used in 2015.

Peak pile-up density leveling with β^* in US2 to $\lesssim$1 mm^{-1} is possible without any extra hardware and little performance degradation, for the baseline and for the 200 MHz alternative. A more uniform bunch distribution obtained with a double RF system (400+800 MHz or 200+400 MHz) can further reduce the pile-up density to $\approx$0.9 mm^{-1}. To reach lower pile-up densities the crab cavity frequency might be reduced (0.8 mm^{-1}) [18] at the cost of larger crab cavity voltage. The lowest pile-up density of 0.65 mm^{-1} is accessible via the crab-kissing scheme [26, 27], but being rather costly in terms of new hardware.

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