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HL-LHC PERFORMANCE WITH A 200 MHZ RF SYSTEM

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Abstract

The HL-LHC performance could considerably benefit from having a 200 MHz RF system. This would allow to inject longer bunches with larger bunch intensity from the SPS and to perform bunch length leveling if required. Performance estimates of various configurations are presented in this paper.

MERITS OF A 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 [1]. The possible RF operational modes at collision energy are shown in Table 1 [2]. 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 [3].

Table 1: Possible configurations of the 200 and 400 MHz RF systems in the LHC [2], 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 normal conducting cavities have been already proposed [4] 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 [5] for the LHC.

A reduction of electron cloud is expected for longer bunches. Figure 1 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

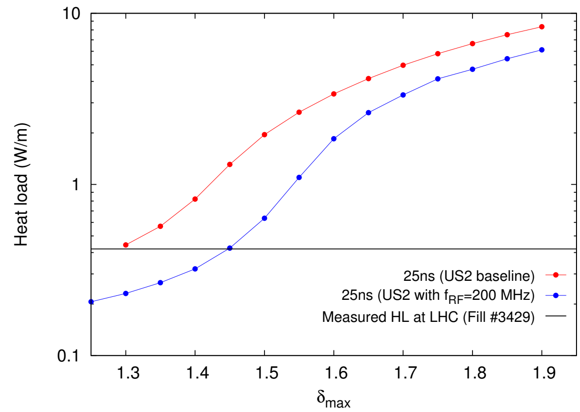

Figure 1: Heat load due to electron cloud in the arc dipoles at 7 TeV for the HL-LHC (US2) for the baseline scenario (red curve) and an alternative scenario using a 200 MHz system as main RF (blue curve).

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 [6]. 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 [7]. 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% [8].

Another beneficial effect from the longer bunches is the reduction of the beam induced heating due to impedance. 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 effective impedance by [9]

$$\Im Z_y^{eff}{}_{max} = \frac{4\pi(E_t/e)\tau_b Q_s}{N_b e \beta_y^{av}} \quad (1)$$

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 $Q_s = 9\times10^{-4}$ for the 200 MHz scenario the relative reduction of the TMCI threshold is 1.36.

More accurate TMCI simulations are done using [10] and [11] assuming Gaussian bunch densities. The degra-

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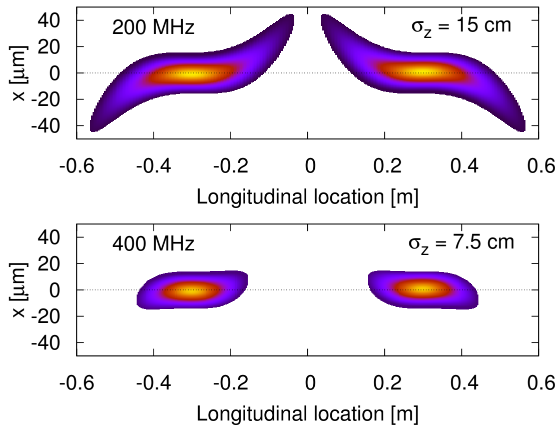

Figure 2: Illustration of the crab cavity RF curvature effect on the collision process for the nominal RF system (400 MHz) and the alternative of 200 MHz. The beams contours correspond to 2 σ envelope for a β^*= 15 cm.

dation of about a factor 1.5 is confirmed and the threshold is decreased to 2.6 $\times$ 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 [12]. 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. 2 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 [13] or strong-strong [14] 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 [15]. 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$\times$$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.

US2 PERFORMANCE

In the following 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. In presence of crab cavities $\xi_{x,y}$ is approximated by an ideal head-on interaction. 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 US2 scenario [16] 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 [17]. 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 2 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. 3. 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.

SUMMARY & OUTLOOK

Using 200 MHz as the main RF system in the LHC has been identified as a very promising alternative for achieving the US2 performance goals. 200 MHz provides the best yearly integrated luminosity with 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 [15]. 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.

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Table 2: 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

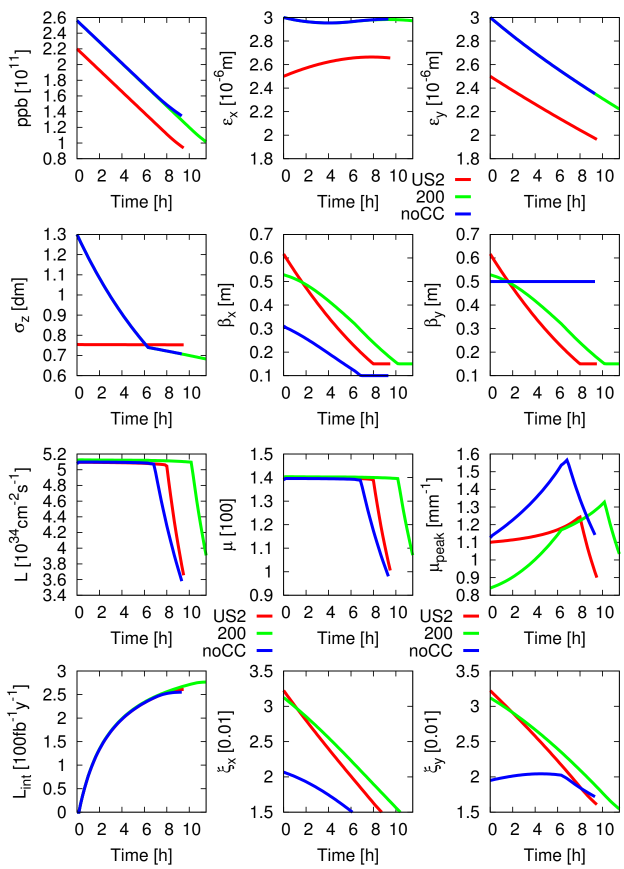

Figure 3: Fill evolution of the US2 baseline, 200 MHz alternative with 400 MHz crab cavities and a back-up option without crab cavities.

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