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AN ALTERNATIVE HIGH LUMINOSITY LHC WITH FLAT OPTICS AND LONG-RANGE BEAM-BEAM COMPENSATION *

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Abstract

In the baseline scenario of the High-Luminosity LHC (HL-LHC), the geometric loss of luminosity in the two high luminosity experiments due to collisions with a large crossing angle is recovered by tilting the bunches in the interaction region with the use of crab cavities. A possible backup scenario would rely on a reduced crossing angle together with flat optics (with different horizontal and vertical β^* values) for the preservation of luminosity performance. However, the reduction of crossing angle coupled with the flat optics significantly enhances the strength of long-range beam-beam interactions. This paper discusses the possibility to mitigate the long-range beam-beam effects by current bearing wire compensators (or e-lens). We develop a new HL-LHC parameter list and analyze it in terms of integrated luminosity performance as compared to the baseline. Further, we evaluate the operational scenarios using numerical simulations of single-particle dynamics with beam-beam effects.

INTRODUCTION

The HL-LHC is being designed to deliver an integrated luminosity of at least 250 fb^{-1}/year in each of the two high-luminosity LHC experiments, ATLAS and CMS [1, 2]. The ambitious performance target for ATLAS and CMS cannot be met without pushing to the extreme both the optics, namely β^* [3], and the beam parameters at the exit of the LHC injector chain [4]. It relies as well on a number of key innovative and challenging technologies, such as: (i) new larger aperture superconducting magnets in order to preserve the transverse acceptance of the two high-luminosity insertions at low β^*, and (ii) crab cavities, which are high-frequency RF transverse deflectors creating quasi head-on collisions at the interaction point (IP) despite of the crossing angle, hence preserving the luminosity gain with $1/\beta^*$. The instantaneous luminosity is however limited by several factors, in particular by the total number of interactions per bunch crossing (pile up) and its line density, which can rapidly degrade the quality of the data collected for the physics analysis. In this respect, the HL-LHC relies on a levelled luminosity not exceeding 5×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for a 25 ns bunch spacing (about 2750 bunches per beam), and corresponding to about 140 pile up (PU) events on average per bunch crossing with a peak line density of 1.25 event/mm. This is achieved through the use of challenging luminosity levelling techniques, presently via a gradual reduction of β^* in order to compensate for the proton burn off during the physics store. In order to sustain such a high luminosity over a typical period of 8-10 hours, the beam parameters, in particular the total beam current, shall correspond to a so-called virtual luminosity, which would be of the order of 2×10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ should all the other parameters, for instance β^*, be pushed to the limit at the beginning of the levelling process. The aim of this paper is to propose an alternative set of parameters and scenarios in terms of optics and hardware needed, which stays competitive with the present HL-LHC baseline both in terms of physics data quantity (integrated performance) and data quality (pile up density).

Table 1: Baseline Parameters of the HL-LHC Using Crab Cavities, Compared to Two Alternative Scenarios With Long-Range Beam-Beam Compensator.

Parameters	Baseline	Alt. 1	Alt. 2
Energy [TeV]	7		
Bunch spacing [ns]	25		
Number of collisions at IP1,5	2736		
Particles/bunch [10^{11}]	2.2		
Norm. emittance [μm]	2.5		
Bunch length [cm]	7.50	10.0	
β_x^*/β_y^* [cm] from start to end of levelling	68/68 → 15/15	47/47 →40/10	112/28 →40/10
Crossing angle [μrad]	590 ($12.5\,\sigma$)	280 ($9.7\,\sigma$)	
Levelled luminosity [$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	5.0		
Virtual luminosity [10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	19.6	10.5	
Levelling time [h]	8.3	5.2	
Pile up [events /crossing]	138		
Peak PU density [mm^{-1}]	1.25	1.31	
Luminous region (r.m.s.) [cm]	4.4	4.3	
Integrated luminosity [fb^{-1}] in 8 h → 10 h	1.44 →1.75	1.34 → 1.55	

PERFORMANCE REACH OF ALTERNATIVE SCENARIOS IN COMPARISON WITH THE BASELINE

The baseline parameters of the HL-LHC (25 ns version [5]) and two alternative scenarios are listed in Tab. 1. The list includes key values, such as the virtual luminosity (taking into account the hour-glass effect and the RF curvature

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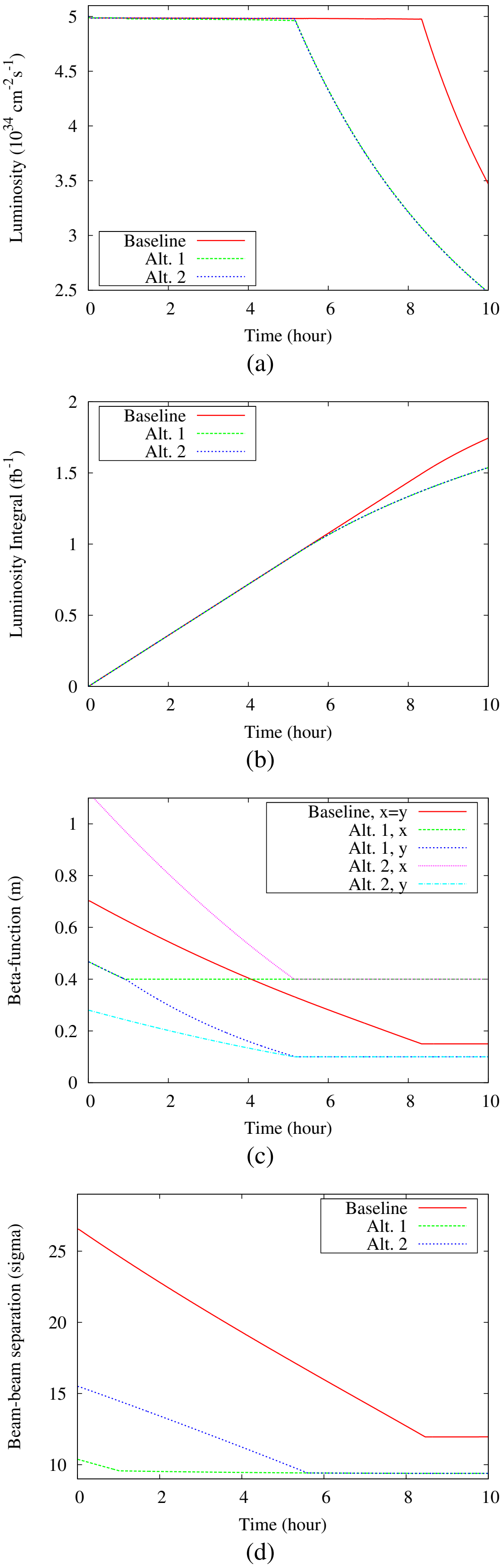

Figure 1: Instantaneous luminosity (a), integrated luminosity (b), β^* (c) and normalised beam-beam separation (d) vs. time during levelling for different HL-LHC scenarios.

of the crab cavity deflecting field), the r.m.s. size of the luminous region and the peak line pile up density reached at the lowest β^*(taking 85 mb for the inelastic hadron cross-section), the levelling time at 5×10^{34} cm^{-2}s^{-1}, and then the integrated performance over 8h or 10h of stable beam. The two proposed alternatives rely on the same beam parameters, and recover the geometric luminosity loss by using flat optics (crossing plane corresponding to the plane of highest β^*), and a substantially reduced crossing angle instead of crab cavities. The reduction of crossing angle is made possible through the use of long-range beam-beam compensators either in the form of current bearing wires [6], or electron-lenses [7]. The alternative Scenarios 1 and 2 are strictly equivalent in terms of the integrated luminosity performance, but differ in the levelling approach. In Scenario 1, the levelling starts from equal horizontal and vertical β-functions of 47 cm, and proceeds in the round mode until the β^* in the crossing plane reaches 40 cm, after which the β^* in the parallel separation plane is reduced to reach 10 cm at the end of the levelling. In Scenario 2, the levelling is performed at the constant ratio of two beta-functions (4/1), and starts at 112/28 cm. The key difference between the two scenarios is the normalized long-range beam-beam separation, which is almost constant in between 10.5-9.7 σ in Scenario 1, and varies between 16.2 and 9.7 σ in Scenario 2. While in both cases the luminous region and peak pile up density are preserved within a few percent, the alternative schemes provide a levelling time that is reduced by about three hours with respect to the baseline. However, the loss of integrated performance is only around 10%, assuming constant transverse and longitudinal emittances in all cases (which is a reasonable approach for comparing the different scenarios), and even for a challenging average fill length of 8-10 hours (to be compared with about 6 h in the LHC during the last year of Run I at 4 TeV/beam [8]). The evolution of key quantities during the store, such as luminosity and β^*, are shown in Fig.1.

MITIGATION OF LONG-RANGE BEAM-BEAM EFFECTS

Simulations of beam-beam effects in HL-LHC demonstrated that for the case of flat optics (with a β^* aspect ratio of 4/1) the beam-beam separation at the long-range parasitic encounters must be maintained from about 16.5 σ at the beginning of a store to above 12 σ at lower intensity towards the end of a store [9]. Assuming an alternated horizontal-vertical crossing angle at IP1 and IP5, the round optics is more robust with respect to long-range beam-beam effects due to the self-cancellation of the $2n+2$-pole like tune spread (or tune shift) induced by the parasitic collisions in IR1 and IR5, which allows operating at a separation between 12.5 and 9.5 σ [10]. Hence, as Fig. 1(d) suggests, the machine performance under both alternative scenarios would degrade due to long-range beam-beam effects over much of the levelling time.

Current bearing wires were initially proposed as a way to mitigate the long-range beam-beam effects [6] and successfully used in collider operations e.g. at DAΦNE [11]. This idea was applied to the alternative HL-LHC scenarios proposed, by placing beam-beam long-range compensator (BBLRC) devices on each side of both main IPs (4 per beam), and optimizing their distance to the beam and strength in order to compensate the most significant resonances. Weak-strong particle tracking simulations with Lifetrac code [12] were performed to predict the performance using the Frequency Map Analysis (FMA) and the evaluation of Dynamical Aperture (DA), together with multi particle simulations to assess the beam and luminosity lifetime. Despite of the net reduction of beam current after a couple of hours of luminosity production, the most critical situation is found to occur in the end of the levelling process where the β^* aspect ratio is maximal and/or the normalised crossing angle is minimal. Figs. 2 and 3 show the Frequency Map analysis of the alternative HL-LHC scenarios 1 or 2 in this situation (separation 9.7 σ, $N_p \sim 1.5\,10^{11}$/bunch, 40/10 cm flat optics for both alternative scenarios) without and with BBLRC, respectively. The application of BBLRC clearly mitigates some strong resonances. The supplementary simulations of DA also show a tremendous improvement — from 3.2 to 5.4 σ. The multiparticle tracking predicts no beam and luminosity lifetime degradation when BBLRC is switched on.

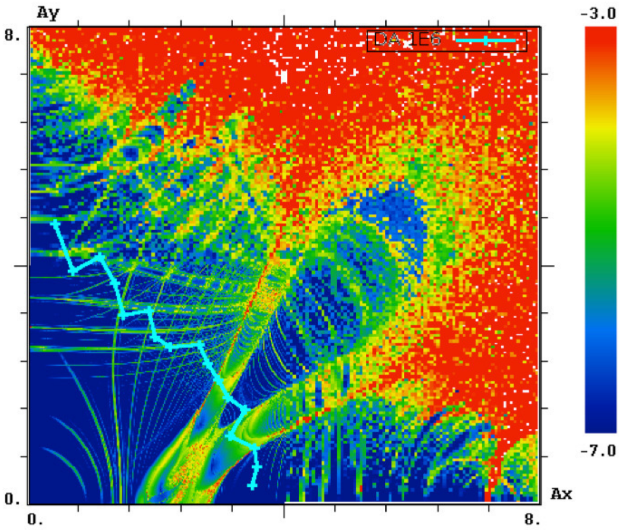

Figure 2: FMA plot at the end of levelling for the alternative scenario (1 or 2) without BBLRC. Axes are betatron amplitude in units of beam σ. Cyan line represents the DA (onset of particle loss) after 10^6 turns.

CONCLUSIONS AND OUTLOOK

Alternative HL-LHC scenarios based on (i) flat optics with reduced crossing angle, and (ii) mitigation of long-range beam-beam effects with current bearing wires or e-lens, offer an integrated performance which is very similar to that of the baseline scenario, with marginal degradation in terms of pile up line density. The long-range beam-beam compensation already demonstrated clear benefits in the case of a lepton machine at DAΦNE ϕ-factory, although the realization at the LHC is technically demanding. For the proposed HL-LHC alternative scenario, the most advantageous position of the wire is indeed at a distance of 9.4 σ from the circulating beam. Consequently, for collimation and machine protection related reasons, the electron lens offers a clear advantage over metal (material) wires. In this situation, the required electron lens parameters correspond to a current of 10 A of 10 keV e- over a length of 4 m, which would be similar to an integrated current of about 250A×m in a metal wire [7], and could be attained with present-day technology.

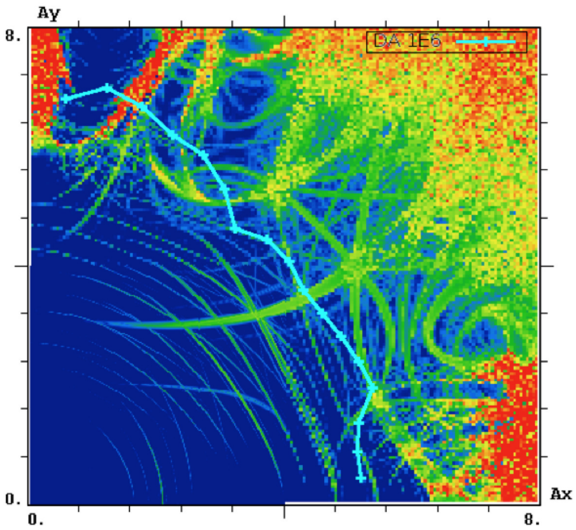

Figure 3: FMA plot at end of levelling for the alternative scenario (1 or 2) with BBLRC.

Finally, as a result of the large beam current targeted by the HL-LHC, it is worth noting the existence of optics solutions which, although very competitive in terms of performance, are potentially less demanding in terms of magnet aperture, both for the triplet and the matching section magnets, and by at least 15% (e.g. comparing the proposed 40/10 cm flat optics with 30/7.5 cm for which the aperture of the new HL-LHC magnets was initially calibrated [13], and then even further increased in the zone D2-Q4 for crab-cavity integration, see e.g. [14]). With very promising perspectives, this aspect would deserve to be investigated in much more details but would bring us well beyond the initial scope, which is mainly to present a possible and robust alternative to crab cavities for the HL-LHC.

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