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Luminosity reduction caused by phase modulations at the HL-LHC crab cavities

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ABSTRACT

The design of the High-Luminosity Large Hadron Collider (HL-LHC) requires two pairs of crab cavities to be installed either side of Interaction Points (IPs) 1 (ATLAS) and 5 (CMS) to compensate for the geometric reduction in luminosity due to the beam crossing angle at the IP. The HL-LHC beam current is a factor of two larger than the LHC design value. The existing RF system has insufficient power to use the existing low level RF (LLRF) scheme for HL-LHC and therefore a new scheme is proposed which results in an irregular bunch pattern in the ring; here in referred to as a phase modulation. In this paper we study the effect of this phase modulation on the crab cavity scheme and the resulting impact on peak luminosity. We have developed an analytical model to calculate the luminosity and its dependence on the related beam and RF parameters. We compare this model to tracking simulations in PYTRACK and show a good agreement between the model and simulations. In the case of a coherent phase error between the counter-rotating bunch trains, having the maximum expected time shift of 100 ps (0.25 radians at the RF frequency), the reduction of analytical peak luminosity is found to be 1.89% when the crabbing voltage is 6.8 MV. For incoherent phase errors, the luminosity reduction for a 100 ps phase error is 5.67%; however the expected incoherent phase error is significantly less than 100 ps. These reductions are not foreseen as an issue when the crabbing scheme is used for luminosity levelling during physics experiments.

1. Introduction

The HL-LHC project due to receive first beams in 2026, aims to increase the luminosity of the LHC from its current design value of 1×10^{34} cm^{-2} s^{-1} by a factor of five for the nominal scenario [1]. Key features of the luminosity upgrade are the reduced transverse beam size and the increased crossing angle introduced to mitigate long-range beam–beam effects [2]. The design crossing angle at ATLAS and CMS (IPs 1 and 5 respectively) is 285 μrad and operation prior to 2018 has typically been close to this value [3]. The HL-LHC has an increased crossing angle of around 500 μrad [1]. Version 1.3 of the HL-LHC baseline optical parameters for collisions with β^* near 0.15 m [1] are summarized in Table 1; where β^* is defined as the value of the β-function at the IP.

The overlap density of the colliding bunches is reduced with the presence of a crossing angle as shown in Fig. 1. The resulting luminosity loss is expressed by the Piwinski reduction factor (R);

$$R(\theta) = \frac{1}{\sqrt{1 + \left(\frac{\sigma_z}{\sigma_x^*}\frac{\theta}{2}\right)^2}}, \tag{1}$$

where σ_x^* is the transverse beam size at the IP, σ_z is the r.m.s bunch length and θ is the full crossing angle.

Crab cavities are RF deflectors, phased so that the nominal bunch centroid receives no kick, while the head and tail receive transverse kicks in opposite directions, to rotate the bunch envelope. In order to recover the geometric overlap at the IPs in the HL-LHC, superconducting crab cavities [4–6] will be installed both up- and down-stream of IPs 1 and 5, partially compensating the geometric luminosity reduction at the IPs (Fig. 1). A full compensation is not required as this would result in the peak luminosity being too high and excessive pile up for the experiment. A partial compensation allows for a constant peak luminosity during physics runs by using a luminosity levelling scheme [7–9]. The crab cavities are being first tested in CERN's Super Proton Synchrotron (SPS) prior to installation in the LHC.

The HL-LHC project plans to use a local crabbing scheme [10] to create local crabbing bumps around the IPs. In this scheme, the crab cavities after the IP are situated at a betatron phase advance, $\mu = \pi$, downstream of the first set of crab cavities, and the Twiss parameters, α and β are the same, thus cancelling the effect of the upstream crab cavities; the downstream crab cavities will be referred to here as anti-crab cavities.

The planned scheme requires two cavities to achieve the required crabbing voltage V_1 before the IP and another two for the required anti-crabbing voltage V_2 after the IP (for two beams and two IPs sixteen

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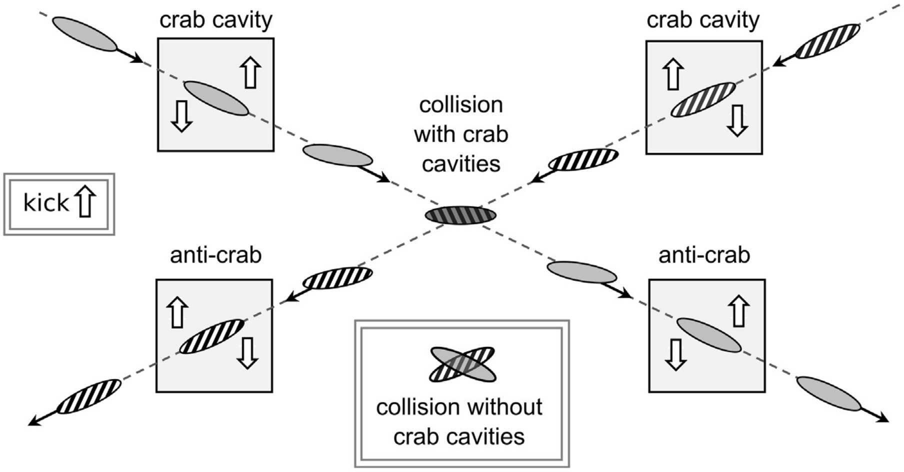

Fig. 1. Simplified diagram of the collisions at the IP with and without crab cavities. There is a π phase advance between crab and anti-crab cavities.

Table 1
List of parameters for the baseline optics (HL-LHCV1.3).

Machine circumference	26 659 m
Proton energy at collision	7 TeV
Beam intensity N	2.2×10^{11} ppb
Number of bunch n_b	2748
r.m.s bunch length (σ_z)	9.0 cm
Bunch spacing	25 ns
Longitudinal emittance	3.03 eVs
Harmonic number	35 640
Transition gamma	55.76
Transverse normalized emittance $\epsilon_{n(x,y)}$ (r.m.s)	2.5 μm
Revolution frequency	11.2455 kHz
Synchrotron frequency	23.8 Hz
RF frequency of main cavity	400.79 MHz
Total RF voltage of main cavity	16 MV
Full crossing angle	480 μrad
Crab cavity voltage	3.4 MV/cavity
Crab cavity RF frequency	400.79 MHz

cavities in total are required). The total crabbing voltage required for full compensation at the IP [11] is given as

$$V_1 = \frac{cE_s \tan\theta/2}{e\omega\sqrt{\beta^*\beta_{c.c}}\sin\mu}, \tag{2}$$

where c is the speed of light, E_s is the energy of the synchronous particle, e is the charge of the proton, ω is the angular frequency of the crab cavity RF, μ is the betatron phase advance between the upstream crab cavity and the IP, β^* and $\beta_{c.c}$ are the β functions at the IP and crab cavity locations respectively. The crab cavities are to be installed at locations where $\beta_{c.c}$ is large to reduce the required cavity voltages as determined by Eq. (2). The phase advance from the crab cavity to the IP and the IP to the anti-crab cavity are set as $\mu = \pi/2$. The required total anti-crab voltage after the IP is given by

$$V_2 = -R_{22}V_1, \tag{3}$$

where, assuming a deflection in the x-direction, R_{22} is the (2,2) element of the 6×6 transfer matrix describing the transformation of particle trajectory from one crab cavity to the corresponding anti-crab cavity. Neglecting the transverse coupling and dispersion, the transfer matrix can be considered as a 2×2 matrix, where R_{22} describes how an angular deflection at the first cavity transforms into an angular deflection at the second cavity. Because of the π phase advance and similar values of beta functions at crab and anti-crab cavities, R_{22} is close to -1 for the HL-LHC.

There are various gaps in the LHC bunch train arising from the rise times of the injection and extraction kickers for the proton synchrotron (PS), the SPS and the beam dump kicker of the LHC (abort gap). A representative bunch structure of the LHC bunch train is shown in Fig. 2. Consequently there is strong transient beam loading in the accelerating RF cavities (as opposed to the crab cavities) as there is full beam loading during a PS batch of 72 bunches (shown in blue) and zero beam loading during the gaps (shown in white).

To keep the accelerating cavity amplitude and phase constant over a full train of bunches making a whole turn of the LHC in the presence of transient beam loading, the klystron forward power takes an amplitude and phase modulation as dictated by the Low Level RF controls (LLRF) that responds to the gaps. Charged bunches passing through a cavity change its amplitude and phase. Acceleration cavities are detuned in the presence of high beam currents acting in quadrature to the RF current in order to reduce the power demanded from the amplifiers (klystrons at the LHC for the accelerating cavities). Because the cavities are detuned, the power demanded then peaks during each gap in the bunch train. The LHC's detuning scheme was optimized at the outset so that the demand for klystron power during gaps does not exceed 300 kW. This is achieved by detuning the cavity for half the peak beam current, hence the name "half detuning" [12,13]. The half-detuning scheme requires 200 kW average klystron power for the nominal LHC beam current (2808 bunches, 1.15×10^{11} particles per bunch). After optimization of the coupling between klystron and the cavity, the power requirement scales linearly with the beam current. The beam current for HL-LHC is almost double the nominal LHC current (2748 bunches, 2.2×10^{11} particles per bunch [1]), hence using the half detuning scheme, the required klystron average power will be near 400 kW and the peak power will be near to 600 kW. This level exceeds the klystron saturation power of 300 kW installed prior to 2008. All the accelerating RF systems installed at this time were designed for a maximum of 300 kW continuous wave (CW) operation. Increasing the RF power available for acceleration would require a significant modification of the RF power chain, including high voltage power supplies, klystrons, circulators, loads and input couplers [14]. To overcome the issue without major upgrades of the RF system, a new detuning scheme was proposed, tested in the LHC during 2016, and has been operationally available since 2017 [13,15]. This scheme modulates the klystron phase but not its amplitude. The cavity amplitude is kept constant during the turn. As a consequence, bunch timing can no longer be perfectly maintained. The phase of bunches with respect to the RF clock progressively slip during the bunch train but then are finally recovered during the abort gap. With this scheme the klystron power is constant for the whole turn. The required klystron power is minimized by full detuning of the acceleration cavity for the average beam current. The full detuning scheme was first proposed by D. Boussard in 1991 [16]. Power coupling from the waveguide into the cavity must still be adjusted for the peak klystron power. The level of coupling is specified by the external quality factor Q_e.