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IMPACT OF MULTIPLE BEAM-BEAM ENCOUNTERS ON LHC ABSOLUTE-LUMINOSITY CALIBRATIONS BY THE VAN DER MEER METHOD

J. Wańczyk * † , EPFL and CERN, Geneva, Switzerland
X. Buffat , A. Dabrowski , D. Stickland , CERN, Geneva, Switzerland
T. Pieloni , EPFL, Laboratory of Particle Accelerator Physics, Lausanne, Switzerland
W. Kozanecki , IRFU-CEA, Université Paris-Saclay, France

Abstract

The LHC particle-physics program requires that the delivered luminosity be measured to an absolute accuracy in the 1% range. To this effect, the absolute luminosity scale at each interaction point (IP) is calibrated by scanning the beams across each other according to the van der Meer method. During such scans, the orbit and the shape of the colliding bunches are significantly distorted by their mutual electromagnetic interaction; the resulting biases, if left uncorrected, would absorb a major fraction of the systematic-uncertainty budget on the luminosity calibration. The present report summarizes recent studies of such biases in the single-IP configuration, and generalizes it to the more typical case where bunches collide not only at the scanning IP, but also experience additional head-on encounters at up to 3 locations around the ring. Simulations carried out with the COherent-Multibunch Beam-beam Interaction multiparticle code (COMBI) are used to characterize the dependence of beam–beam-induced luminosity-calibration biases on the phase advance between IPs, and to derive scaling laws that relate the multi-IP case to the simpler and better understood single-IP configuration.

ABSOLUTE LUMINOSITY CALIBRATION AND BEAM–BEAM INDUCED BIASES

van der Meer (vdM) calibration scans are commonly used to obtain the absolute luminosity scale at the LHC experiments [1]. These are designed to measure the detector-specific constant that relates the observed rate to the absolute instantaneous luminosity computed from measured beam parameters [2, 3]. Under the assumption of uncorrelated x and y planes, the transverse convolved beam widths Σ_x, Σ_y can be measured during a separation scan from the observed rate. The combined information from the vertical and horizontal scans, revolution frequency f_{rev}, bunch intensities N, and rate at the peak μ_{pk} allow to calculate the instantaneous luminosity as inferred from the measured beam parameters. Thus the luminometer-specific visible cross-section is obtained:

$$\mu^{vis} = \frac{\mathscr{L}_{inst}\sigma_{vis}}{f_{rev}} \rightarrow \sigma_{vis} = \frac{2\pi\Sigma_x\Sigma_y}{N_1 N_2}\mu_{pk}\,. \qquad (1)$$

The σ_{vis} measurement is affected by the beam parameters changing throughout the collision. The luminosity measurement during a vdM scan is biased by the electromagnetic interaction of the two beams, the so-called beam–beam (BB) interaction [4, 5]. Such effect has been extensively studied and modeled in several colliders [6–9]. Specifically for vdM analysis, a set of correction procedures have been developed to compensate for these effects during luminosity calibration scans [10–12]. The BB interaction affects the luminosity measurements in different ways. Introducing an orbit effect that will result in increased separation between the beams during the transverse scans. This can be computed analytically and can be corrected directly in the vdM analysis as described in [4, 8]. In addition, a change in the beta-beating is also present, the so-called dynamic beta effect [9, 12]. This has a direct effect on the beam widths at the IP and consequently to $\mathscr{L}_{inst}$. The beta-beating model has been extended in [10, 11] to account for amplitude-dependent BB effects and the resulting modification of the overlap integral due to the non-Gaussian beam shapes.As a consequence, with the aim of obtaining high-precision corrections, the overlap integral that defines the luminosity needs to be computed numerically. Currently, the strategy of all LHC experiments is to model the BB biases to the luminosity during vdM scans by numerical simulations and apply them to the measured quantities. The corrections can be used to single as well as to multiple BB interactions occurring during vdM scans, as commonly done at the LHC [2, 3]. A full description of this correction strategy applied to the luminosity analysis can be found in [11]. There are however some open questions that require further investigations. Simulation studies of the multi-IP configurations have shown some phase dependence that needs to be understood. In the case of two IPs (for example IP1 and IP2), where IP1 is colliding head-on and IP2 is performing a transverse scan (vdM type), the bias can be adequately estimated by assuming that the head-on colliding IP1 is acting as a quadrupole modifying the machine tunes and beta functions in a static manner [11], [12]. Thus, in the first approximation, the effect of a second IP colliding head-on can be modeled with a tune change and a change of β^*. However, the numerical simulations have shown that the phase advance between the two IPs is modulating slightly the σ_{vis} bias. Phase advance scans were performed with the COMBI [13] model, quantifying the modulation to around $< 0.1\%$ on σ_{vis} bias. The amplitude of that modulation depends on the machine tunes as well as the BB parameter. The example results are shown in Fig. 1. The aim of this study

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† jwanczyk@cern.ch

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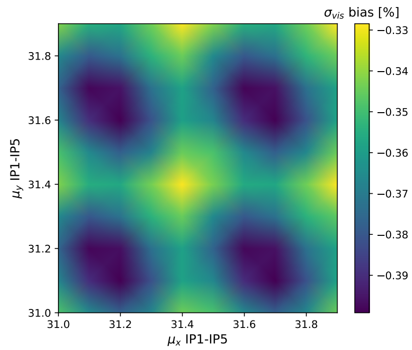

Figure 1: Visible cross-section bias as a function of phase advance for the 2 IPs configuration from multi-particle COMBI simulations (figure reproduced from [11]).

is to understand the nature of such periodicity. A simplified linear model based on transport matrices is used for the LHC lattice and the BB interactions as also used in [7, 14] for head-on collisions. The beam-beam kick has been extended to account for interactions with an offset similarly as in [13]. The resulting one-turn matrix has been generalized to evaluate the effect on $\mathscr{L}_{inst}$ and σ_{vis} for different phases between colliding IPs while keeping the global tune constant. Finally, the results of this model are compared to those of the multiparticle model.

VDM TRANSFER MATRIX MODEL

To obtain global properties for a Gaussian distribution of test particles going through the BB force of the counter-rotating beam the coherent BB kick has to be used in the beam-beam transport matrix as done in [7]. The mechanism at the origin of the periodic structures apparent in Fig. 1 can be understood qualitatively using analytical, one-turn matrix calculations. The description of the coherent BB interaction for a Gaussian particle distribution is obtained from the Poisson's equation, by integrating the single-particle kicks in the beam distribution:

$$\begin{aligned} k_s(u) &= -\frac{2Nr_p}{\gamma}\frac{e^{-u^2/4\sigma^2}}{2\sigma^2 u^4}\left(u^4 + 2u^2\sigma^2(e^{u^2/4\sigma^2}-1)\right) \\ k_{non-s}(u) &= -\frac{2Nr_p}{\gamma}\frac{e^{-u^2/4\sigma^2}}{2\sigma^2 u^4}\left(2u^2\sigma^2(e^{u^2/4\sigma^2}-1)\right) \end{aligned} \tag{2}$$

with $u \in \{x, y\}$, for the scanning and non-scanning direction during a separation scan. These formulas represent an average kick for the whole beam which is assumed to be a good approximation [14]. The resulting beta-beating depends on the total number of collisions and the associated tune shift. At the scanning IP, for example in the case of the 2-IPs configuration, it is given by:

$$\frac{\beta^*}{\beta_0^*} = \frac{\sin 2\pi Q - k_0\beta_0^* \sin 2\pi\mu_1 \sin 2\pi(Q-\mu_1)}{\sin 2\pi(Q+\Delta Q)}, \tag{3}$$

with phase advance μ_1 between the two IPs, and k_0 denoting the coherent kick caused by head-on collisions at the non-scanning IP. That formula contains an explicit dependence on the phase advance between the two IPs. The tune shift for the configuration with single collision ΔQ^w is obtained from the one-turn matrix:

$$\cos 2\pi(Q + \Delta Q^w) = \cos 2\pi Q - \frac{k_0\beta_0^*}{2}\sin 2\pi Q. \tag{4}$$

With an additional collision at a different location, the expression is recalculated. In the case of a scanning IP (s) in a transverse plane u, the symmetry in the two planes is removed, according to Eq. 2:

$$\begin{aligned} \cos 2\pi(Q + \Delta Q^{w+s}) &= \left(1 - \frac{k(u)k_0(\beta_0^*)^2}{4}\right)\cos 2\pi Q \\ -\frac{\beta_0^*}{2}(k(u)+k_0)\sin 2\pi Q &+ \frac{k(u)k_0(\beta_0^*)^2}{4}\cos 2\pi(Q-2\mu_1). \end{aligned} \tag{5}$$

In the latter, a slight modulation of the tune shift ΔQ^{w+s} is present with a half-period π that depends on the phase advance μ_1 between the IPs. It is shown in Fig. 2 with respect to a constant tune shift in case of a single collision.

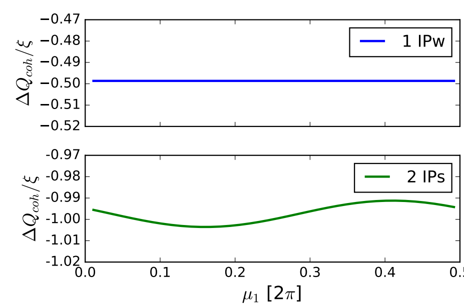

Figure 2: BB tune shift caused by single (1 IPw) and two head-on collisions (2 IPs) as a function of phase advance between the two collision points.

This tune shift is propagated to the beta-beating, according to Eq. 3. The additional phase-dependent term causes the ratio of the beam envelope changes to be non-constant when different numbers of collisions are compared. The combined effect of the two beams, expressed in a form that scales the convoluted beam width is shown in Fig. 3. The beating as observed at a given location, from a single collision at another location appears in phase with the 2 IPs configuration. In the ratio, however, the left-over phase dependence can still be observed. The dependence of a beam width σ changes over a separation scan is additionally presented in Fig. 4, compared to COMBI simulations for a Run-2 nominal lattice, showing a very good agreement.

The obtained beta-beating as well as the calculated orbit shift are subsequently used to estimate the full BB bias on the luminosity at each separation step using the Gaussian-beams approximation. It is shown in Fig. 5a, in terms of luminosity bias, denoting the difference in results when BB interaction is included with reference to no BB. Comparison to COMBI is shown, where the density profiles are described with macro-particles that receive an amplitude-dependent kick, and the

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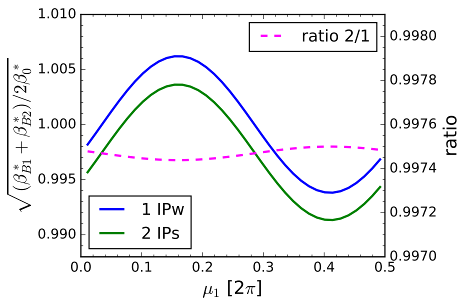

Figure 3: The combined beta-beating of two beams as a function of phase advance between two IPs, for a head-on collision, as measured at the scanning IP. Shown for a single collision at another IP (1 IPw) and including also the second collision (2 IPs).

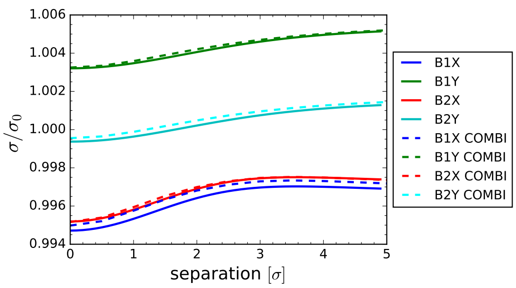

Figure 4: BB effect on beam widths directly from calculated beta-beating compared to COMBI simulated effect on the beam distribution RMS.

resulting overlap is more accurately evaluated. An additional check for the luminosity calculation was done in the single collision configuration, a comparison to both COMBI and MADX is shown in Fig. 5b. It is clear that the model works well at the head-on step, where the beam distribution cores are in full overlap. It diverges from COMBI calculation with separation, when the luminosity is a product of the tail particles. Based on Eq. 1 the bias on σ_{vis} is evaluated and is shown in Fig. 6. The absolute value of the estimated bias differs from the one defined by COMBI in Fig. 1 due to approximations used in the calculation, that are only valid in the Gaussian-bunch limit. This inconsistency is a direct result of significant differences presented in Fig. 5a, which are unavoidable in the analytical calculation, which was not aimed at reproducing the COMBI results completely. To improve the results the linearized model would have to be extended with a BB kick description more appropriate for particles in the tails of beam distribution, rather than the core, that play a bigger role in the luminosity bias at high beam separation. Nevertheless, the σ_{vis} periodicity with phase advance was successfully reproduced. The multi-IP tune shift dependence on the phase advances, and hence also the beta-beating, is scaled with the non-linear BB kick at each separation step. This effect does not vanish in the integrated bias over a full separation scan.

CONCLUSIONS

The impact of multiple beam-beam encounters on the LHC absolute-luminosity calibrations is accounted for in the luminosity analysis using a simple scaling law obtained by

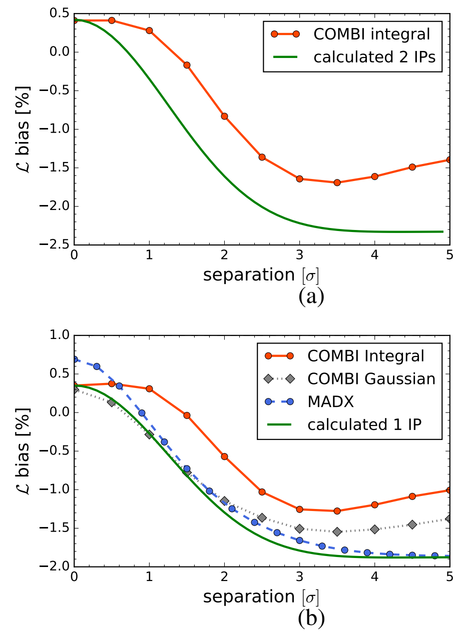

Figure 5: BB bias on the luminosity as a function of separation as calculated using the Gaussian distribution-based luminosity formula compared to COMBI and MADX simulations in the single IP (5b) and 2 IPs configurations (5a).

multi-particle simulations. However, despite of small amplitude 0.1%, the bias shows a deviation with periodic structure as a function of the phase advances μ between the IPs. With the aim to further understand the nature of such behavior, in this study, the vdM scan process with beam-beam interactions has been modeled by means of transfer matrices. The periodicity on the σ_{vis} bias due to the beam-beam induced beta-beating and orbit effects have been computed and compared to numerical models. The absolute σ_{vis} bias cannot be reproduced with the linear model proposed. While for head-on collision the model works as a good approximation for the luminosity bias, it deviates when separated collisions are considered. The periodic structure of the σ_{vis} bias has to be explored in the non-linear nature of the beam-beam force for large amplitude particles which are the ones contributing to the overlap integrals and for which the linearized model fails. It was also shown that there is no phase advance configuration that removes the beam-beam bias on the σ_{vis}.

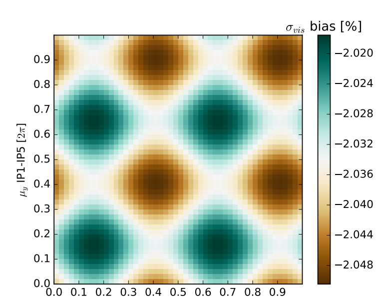

Figure 6: Visible cross-section bias as a function of phase advances between two collision points, for the typical vdM beam parameters, as obtained analytically.

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