JINST

Published by IOP Publishing for Sissa Medialab

Received: *December 14, 2017*
Revised: *February 26, 2018*
Accepted: *March 4, 2018*
Published: *March 15, 2018*

XII International Symposium on Radiation from Relativistic Electrons
in Periodic Structures — RREPS-17
18–22 September, 2017
DESY, Hamburg, Germany

Beam-dynamic effects at the CMS BRIL van der Meer scans

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Abstract: The CMS Beam Radiation Instrumentation and Luminosity Project (BRIL) is responsible for the simulation and measurement of luminosity, beam conditions and radiation fields in the CMS experiment. The project is engaged in operating and developing new detectors (luminometers), adequate for the experimental conditions associated with high values of instantaneous luminosity delivered by the CERN LHC. BRIL operates several detectors based on different physical principles and technologies. Precise and accurate measurements of the delivered luminosity is of paramount importance for the CMS physics program. The absolute calibration of luminosity is achieved by the van der Meer method, which is carried out under specially tailored conditions. This paper presents models used to simulate of beam-dynamic effects arising due to the electromagnetic interaction of colliding bunches. These effects include beam-beam deflection and dynamic-β effect. Both effects are important to luminosity measurements and influence calibration constants at the level of 1–2%. The simulations are carried out based on 2016 CMS van der Meer scan data for proton-proton collisions at a center-of-mass energy of 13 TeV.

Keywords: Beam dynamics; Simulation methods and programs

https://doi.org/10.1088/1748-0221/13/03/C03028

Contents

1 Introduction

BRIL (Beam Radiation Instrumentation and Luminosity) is a project of CMS experiment [1] at CERN. The project is focused on simulation and measurement of luminosity as well as beam conditions and radiation fields in CMS. BRIL is engaged in developing new detectors, compatible with the high luminosity experimental environments at the LHC. Today BRIL operates several detectors based on different physical principles and technologies. For example, the Hadron Forward Calorimeter (HF) [2] registers the Cherenkov radiation in quartz fibers that is induced when a charged particle passes through them. The Pixel Luminosity Telescope (PLT) [3] is based on silicon sensors and it counts three-plane coincident events online. The Fast Beam Conditions Monitor (BCM1F) [4] consists of crystal silicon and diamond sensors. This detector is sensitive to both collisions products and beam background thanks to fast readout.

The detectors (luminometers) are calibrated using the van der Meer Scan method. The goal of the van der Meer scan is to obtain the calibration constant for each luminometer. The method is described in section 2.

The main goal of this manuscript is to present effects that arise from the electromagnetic interaction of highly charged colliding bunches (beam-dynamic effects), as well as their influence on the detector calibration. These effects are described in section 3.

2 Van der Meer scan method for luminosity calibration

The van der Meer (vdM) scan is dedicated running condition for the detector calibration [5, 6]. During the vdM scan beams are scanned against each other in steps. Simultaneously the detector rate measurements are carried out. As result, one obtains the measured rates as a function of the beam separation. An illustration of that dependence is shown in figure 1. Measured rates are normalized by the product of the beam currents.

The vdM scan is required to evaluate the calibration constants (visible cross-section) σ_{vis} for each detector. The visible cross-section is the characteristic of detector. Typically, σ_{vis} refers to the

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pair of colliding bunches characterized by its unique identification number (BCID). One needs two vdM scans — the scan in the horizontal plane (X-plane) and the scan in the vertical plane (Y-plane) — to evaluate the visible cross-section. The visible cross-section is defined by the expression

$$\sigma_{\text{vis}} = \pi \Sigma_x \Sigma_y \left(R_{\text{max},x} + R_{\text{max},y} \right), \tag{2.1}$$

where the subscripts x and y refer to horizontal and vertical planes correspondingly, Σ is the beam overlap area width, and R_{max} is the normalized peak rate obtained from vdM scan data as shown in figure 1.

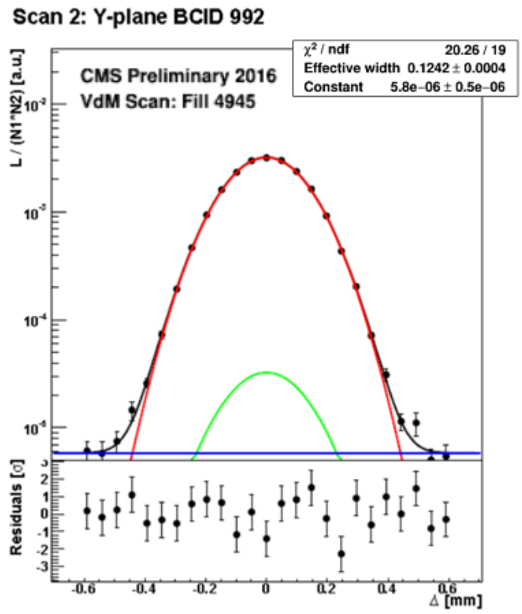

Figure 1. Typical results of a vdM scan (uncorrected luminosity). Data from PLT during the vdM scan on 18.05.2016 (LHC fill 4945) using proton-proton collisions at a center-of-mass energy of 13 TeV, BCID 992 [7]. The figure presents measured rates as a function of the LHC nominal beam separation Δ. Black points are experimental results, colored lines are the components of a Double Gaussian fit plus a constant background term, the black line is the resulting fit $F(\Delta) = a_1 f_1(\Delta) + a_2 f_1(\Delta) + \text{const}$. The width of the beam overlap area (effective width, $\Sigma = (a_1\sigma_1 + a_2\sigma_2)/(a_1 + a_1)$ where σ_1 and σ_2 are parameters of Gaussian components $f_1(\Delta)$ and $f_2(\Delta)$ of the fit $F(\Delta)$) is $\Sigma_y = 124\,\mu\text{m}$.

Online calibration of detectors during data taking is provided by using visible cross-sections obtained at vdM scans:

$$L' = R/\sigma_{\text{vis}} \tag{2.2}$$

where R are measured rates and σ_{vis} is the calibration constant for the detector. The calibrated luminosity L' does not depend on the detector and it characterizes the collision process itself.

3 Beam-dynamic effects

During the collision at the interaction point (IP) the bunch moves in the electromagnetic field of the opposite bunch. When the calibration constant is evaluated, the electromagnetic interaction of opposite bunches is one of the systematic error sources. There are two effects produced by this interaction — beam-beam deflection and dynamic-β — that should be taken into account. The influence of the considered effects on the average visible cross-sections (at experimental conditions of 2016 with proton-proton collisions at a center-of-mass energy of 13 TeV) is presented in table 1. LHC fill 4954 included 8 vdM scans: 4 X-plane scans and 4 Y-plane scans. A scan pair shown in table 1 consists of one X-plane and one Y-plane scans. The visible cross-sections were evaluated by using the formula (2.1) for each BCID. The average visible cross-sections shown in table 1 have been determined from the mean of all 32 cross-sections of separate BCIDs of fill 4954. The parameters used in the formula (2.1) were evaluated from experimental data by using a fit to a double Gaussian plus a constant background term (for details see in [6]). In the paper considerations are limited by data from PLT using vdM scan 17.05.2016 (LHC fill 4954) with proton-proton collisions at a center-of-mass energy of 13 TeV.

Table 1. Visible cross-sections, averaged over BCIDs ($\langle\sigma_{\text{vis}}\rangle$ [μb]). Column captions are: noCorr — calculations without corrections, bb — beam-beam correction applied, bb+dβ both beam-beam and dynamic-β corrections applied.

	$\langle\sigma_{\text{vis}}\rangle$ [μb]		
	noCorr	bb	bb + dβ
Scan pair 1	329.9 ± 2.8	334.7 ± 2.4	333.6 ± 2.3
Scan pair 2	329.6 ± 2.2	334.3 ± 1.9	333.6 ± 2.2
Scan pair 3	328.4 ± 2.8	333.7 ± 3.4	331.8 ± 2.3
Scan pair 4	330.2 ± 2.6	335.2 ± 2.5	334.1 ± 2.1

In the table 2 corrections and uncertainties are presented that arise due to beam-dynamics effects. Numbers in the column “bb corr” in table 2 represent the correction caused by beam-beam deflection. The correction was estimated as the relative difference between data in “noCorr” and “bb” columns of table 1. Uncertainties are defined from cross-sections for separate BCIDs (below $\sigma_{\text{vis,z}}$ where “z” is “noCorr” or “bb” or “bb + dβ” are visible cross-sections calculated without corrections or at beam-beam correction or at both beam-beam and dynamic-β corrections correspondingly). For example, values in “bb unc” column were obtained by the next way. At the first step the values $\sigma_{\text{vis,bb}}/\sigma_{\text{vis,noCorr}} - 1$ were calculated for separate BCIDs. At the second step the standard deviation of the obtained array has been calculated and this value is the uncertainty

Table 2. Corrections and uncertainties applied to uncorrected visible cross-sections. Column captions are: bb corr — correction caused by beam-beam deflection, bb unc and dβ unc — uncertainties appearing due to beam-beam deflection and dynamic-β correspondingly, over unc — overall uncertainty induced by beam dynamics effects.

	bb corr [%]	bb unc [%]	dβ unc [%]	over unc [%]
Scan pair 1	+1.4	0.5	0.4	0.6
Scan pair 2	+1.4	0.5	0.5	0.7
Scan pair 3	+1.6	0.6	1.0	1.2
Scan pair 4	+1.5	0.4	0.3	0.5

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caused by beam-beam deflection. The same method was used to obtain the uncertainty caused by dynamic-β (in "dβ unc" column) where the uncertainty is the standard deviation calculated for the array of values $\sigma_{\mathrm{vis,bb+d}\beta}/\sigma_{\mathrm{vis,bb}} - 1$. The overall uncertainty (in "over unc" column) is the square root of the sum of squared values of values in "bb unc" and "dβ unc" columns.

Corrections have been calculated as described in subsections 3.1, 3.2 where all expressions are written for the X-plane. Similar expressions for the Y-plane could be easily derived.

It should be noted, the calculations of dynamic-β effect and beam-beam deflection for LHC beam were carried out before at ATLAS experiment (at a center-of-mass energy 7 TeV [8] and 8 TeV [9]).

3.1 Beam-beam deflection

Beam-beam deflection is the deflection of one colliding bunch (the probe bunch) in the electromagnetic field of the opposite bunch. The effect means the actual beam separation at IP is larger than the nominal one Δ. As shown in figure 2(a) the correction to the nominal beam separation could be up to few μm for 13 TeV proton-proton (pp) collisions. The theoretical model of calculations is described below.

The theory of the effect is described in [10–12]. The probe bunch deflection is defined by the expression [12]:

$$\Delta u_x = \langle \theta_x \rangle \beta_x \frac{1}{2 \tan \pi Q_x} \tag{3.1}$$

where β_x and Q_x are correspondingly the β-parameter and accelerator tune at IP in the horizontal plane, $\langle \theta_x \rangle$ is the particle's deflection angle averaged over all particles in the probe bunch (in other words this is the deflection of the "bunch center of gravity"). The angle $\langle \theta_x \rangle$ is defined as described in [11]. The current implementation in the vdM scan analysis assumes the bunch has a Gaussian charge density and, therefore, the electric field of the opposite bunch could be described by Bassetti-Erskine formulas [10]. The following expressions could be obtained for the average deflection angle:

$$\langle \theta_x \rangle = \frac{N r_1}{\gamma} \frac{\sqrt{2\pi}}{\sqrt{\left|\sigma_x^2 - \sigma_y^2\right|}} \mathrm{Im}\left(F(\Delta_x, \Delta_y)\right), \langle \theta_y \rangle = \frac{N r_1}{\gamma} \frac{\sqrt{2\pi}}{\sqrt{\left|\sigma_x^2 - \sigma_y^2\right|}} \mathrm{Re}\left(F(\Delta_x, \Delta_y)\right). \tag{3.2}$$

In these expressions pp collisions are assumed, r_1 is the classical proton radius, N is the number of protons in the opposite bunch acting on the probe bunch, σ_x and σ_y are the transverse beam sizes in the corresponding plane, γ is the relativistic factor. The functions $F(x, y)$ are:

$$F(x, y) = W\left(\frac{x + iy}{\sqrt{2\left|\sigma_x^2 - \sigma_x^2\right|}}\right) - \exp\left[-\left(\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right)\right] \cdot W\left(\frac{x\frac{\sigma_y}{\sigma_x} + iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2\left|\sigma_x^2 - \sigma_x^2\right|}}\right), \tag{3.3}$$

where $W(z)$ is the complex error function.

The beam-beam correction (shown in figure 2(a)) is the sum of the deflections of two colliding bunches: $\delta x = \Delta u_{x1} + \Delta u_{x2}$ where the deflections are defined by formulae (3.1–3.3). A fit is applied to evaluate the beam overlap area width and the normalized peak rate in a manner similar to illustrated by figure 1 where corrected beam separation is used instead of nominal beam separation. Finally, the visible cross-section is calculated following the formula (2.1). Data presented in the column "bb" of table 1 are calculated as described in the beginning of section 3.

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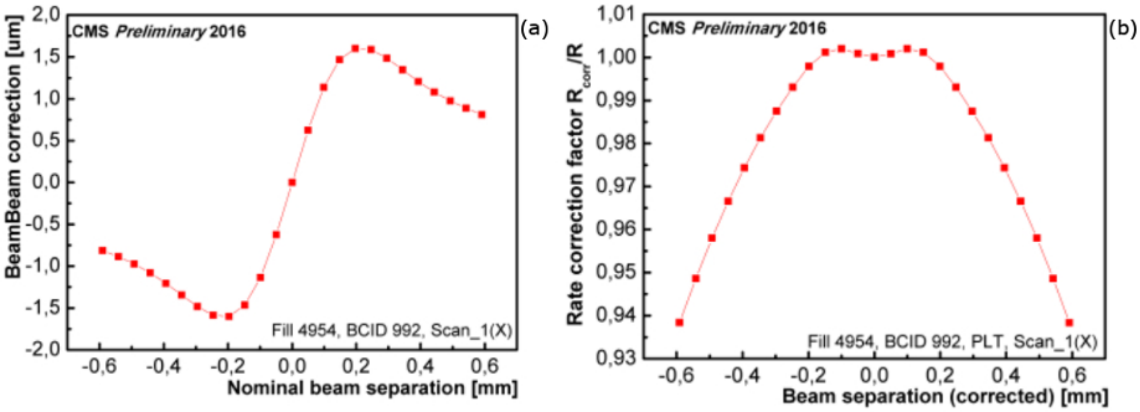

Figure 2. Corrections determined from the vdM scan analysis. Data from the X-plane vdM scan 27.05.2016 (LHC fill 4954, BCID 992) using proton-proton collisions at a center-of-mass energy of 13 TeV. (a) The beam-beam correction to the nominal beam separation Δ_x. (b) The dynamic-β correction to the measured rates R as a function of the corrected (i.e. after the beam-beam correction) beam separation.

3.2 Dynamic-β effect

Two beams act on each other as (de)focusing quadrupoles affecting the nominal β-parameter. In other words, the electric field of the opposite bunch distorts the charge distribution of the probe bunch and, therefore, it influences the transverse beam size as well as the measured luminosity. The general theory of the dynamic-β effect could be found in [13, 14].

In the current implementation, it is assumed that the undistorted bunch has a Gaussian charge distribution. The β-parameter with the beam-beam interaction β^* at IP and in the horizontal plane can be given as

$$\frac{\beta^*_{x0}}{\beta^*_x} = \sqrt{1 - (2\pi\xi_x)^2 + 2\,(2\pi\xi_x)\cot(2\pi Q_x)}, \tag{3.4}$$

where β^*_{x0} is the "unperturbed" (nominal) β, Q_x is the unperturbed horizontal tune and $\xi_x$is the beam-beam parameter:

$$\xi_x = \frac{\beta^*_{x0} N r_1}{2\pi\gamma\sigma_x\,(\sigma_x + \sigma_y)}. \tag{3.5}$$

The dynamic-β correction is the correction applied to the measured rates R. It defines rates R_{corr} for Gaussian bunches at the same beam separation. The correction eliminates the dynamic-β effect and turns measured rates back to reference settings (marked by "ref" in expressions below) at each scan point. In the current implementation the reference settings are settings at $\Delta_x = \Delta_y = 0$. The correction (for the X-plane) is defined by the expression:

$$\frac{R_{\text{corr}}(\Delta_x)}{R(\Delta_x)} = \sqrt{\frac{\beta^*_x(\Delta_x)}{\beta^*_{x,\text{ref}}}}\sqrt{\frac{\beta^*_y(\Delta_y)}{\beta^*_{y,\text{ref}}}}\exp\left[-\frac{1}{2}\left(\frac{\Delta_x}{\Sigma_x}\right)^2\left(1 - \frac{\beta^*_{x,\text{ref}}}{\beta^*_x(\Delta_x)}\right)\right]. \tag{3.6}$$

The measured rates could be decreased up to 10% as shown in figure 2(b). The ratio R_{corr}/R shown in figure 2(b) was calculated by the model based on formulae (3.4–3.6). The corrected rates R_{corr} are used instead of measured rates R when a fit is applied (together with corrected beam separation obtained as described in section 3.1). The visible cross-sections (2.1) and data in the column "bb+db" of table 1 are calculated as described in the beginning of section 3.

4 Conclusion

As shown in [6] the overall uncertainty of the luminosity measurement is estimated to be 2.5% in 2016 vdM scans. Beam-dynamic effects contribute with a relatively large portion in the overall uncertainty at 0.6%.

The beam-beam correction has been applied in [6] using the method described in this manuscript per scan and bunch crossing accordingly. As pointed out in [6] the beam-beam deflection not only contributed to the experimental uncertainty but it also caused a +1.5% correction to the visible cross-section. The new simulations presented here are in agreement with previous results. Data presented in the column "bb corr" in table 2 are close to the value +1.5%.

The de-focusing dynamic-β effect has not been simulated before for CMS. In this paper the first study of this effect during CMS van der Meer scans is presented. In [6] dynamic-β has been taken into account as the uncertainty of measurements at the level of 0.5%. The simulations of the dynamic-β effect performed following the presented model confirm this estimation, as shown in table 2. Nevertheless, it should be noted the corrections and uncertainties for scan pair 3 differ from corresponding results for other scan pairs. The detailed discussion on this question is beyond of the subject of this paper.

Acknowledgments

BRIL collaborators are very grateful to Tatiana Pieloni and Witold Kozanecki for the code that was used in the part of simulations. The research is funded from Tomsk Polytechnic University Competitiveness Enhancement Program grant, Project Number IPhT-72/2017.

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