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Design of the TEPX luminometer for the CMS experiment at the HL-LHC

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The design and expected performance for precision luminosity measurement of the Tracker Endcap Pixel (TEPX) detector for the CMS experiment at the upcoming High-Luminosity LHC (HL-LHC) is described. The TEPX detector is composed of 4 double-sided double disks at each end of CMS covering the range of $|z|$ from 175 to 265 cm, each disk made of 5 rings composed of silicon sensors, with a total of 800 million pixels distributed across the 8 disks. Disk 4 Ring 1 (TEPXD4R1) will be dedicated to luminosity and beam-induced background measurements, utilising the same method as that of the rest of TEPX, namely pixel cluster counting. For the HL-LHC, the goal is to achieve a final uncertainty of 1% for offline luminosity measurements. The expected performance of the TEPX and TEPXD4R1 luminometers in terms of statistical precision for van der Meer scan calibration and for physics conditions, as well as the linearity performance of each disk are presented.

Keywords: Tracker endcap pixel; high-luminosity; van der Meer.

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1. Introduction

In high-energy collider physics, precise measurements of Standard Model processes and searches for new physics require an accurate knowledge of the luminosity. Luminosity measurements rely on the precise determination of event rates for a given luminometer. The statistical uncertainty arises from the event counting process during calibration and physics runs. These uncertainties are then propagated to the measured luminosity. The upcoming High Luminosity phase of the LHC (HL-LHC), will come with various upgrades (Phase-2) for the Compact Muon Solenoid (CMS) detector, in order to keep up with the challenging radiation environment. One of these upgrades will be geared at the tracker, specifically, the Tracker Endcap Pixel (TEPX) detector. The detector at each side of the experiment is composed of four double-sided double disks of pixel modules, each disk made of five concentric rings. The detector will perform tracking and luminosity measurements, while one of its rings, disk 4 ring 1 (TEPXD4R1) will be designated for luminosity and beam-induced background measurements only. The Pixel Cluster Counting (PCC) method will be used to provide precise luminosity determination, taking advantage of the high density of pixels and the relatively low hit occupancy. The PCC method was one of the main methods of offline luminosity measurement for CMS in Run 2 (2015-2018) [1–4].

2. Luminosity

The LHC collides particles (protons and heavy ions) grouped into bunches, with trains of consecutive bunches with 25 ns spacing being made. The bunches are circulated both clockwise and anticlockwise and are forced to cross at specific intersection points, where several p-p collisions occur during a crossing (pileup). A collision between bunches is known as an event, and several particle interactions are produced during these events. The quantity that measures the ability of a particle collider to produce interactions is called luminosity. The event rate R per time unit of a particular process p with a cross-section σ_p is given by:

$$R = \mathcal{L}_{\text{ins}}\sigma_p. \tag{1}$$

Here, the instantaneous luminosity, $\mathcal{L}_{\text{inst}}$, is the proportionality factor with units of cm^{-2}s^{-1}, and the cross section is proportional to the likelihood that a particular interaction takes place. Since the rate of a rare event increases as the rate of interactions grows, the luminosity is a key parameter for the performance of a particle collider.

Considering N_b being the number of colliding bunches and assuming all the bunches have head-on collisions, the luminosity of all the colliding bunches is given by [2]:

$$\mathcal{L}_{\text{ins}} = N_b N_1 N_2 f \int_{\infty}^{-\infty} dx \int_{\infty}^{-\infty} dy \rho_1(x,y)\rho_2(x,y), \tag{2}$$

where $N_{1,2}$ are the particles per colliding bunch, f is the revolution frequency and $\rho_{1,2}$ are the particle density distributions in the transverse plane of the two beams, assuming all bunches of a given beam are identical. Assuming that the particle density distributions are uncorrelated in the transverse coordinates, *i.e.* $\rho(x,y) = \rho(x)\cdot\rho(y)$, they can be factorized in terms of x and y, thus, Eq. (2) can be written as

$$\mathcal{L}_{\text{ins}} = N_b N_1 N_2 f \int_{\infty}^{-\infty} \rho_1(x)\rho_2(x)dx \int_{\infty}^{-\infty} dy\rho_1(y)\rho_2(y). \quad (3)$$

In practice, the particle density distributions in the transverse plane are not known, and a calibration of the detectors has to be done during a van der Meer beam separation scan, in order to obtain these integrals.

3. Calibration using the van der Meer method

The calibration of the luminometers is done by performing van der Meer (vdM) scans, where the goal is to determine the calibration constant σ_{vis} (visible cross section), defined as the peak event rate measured during the vdM scan, divided by the luminosity per bunch crossing (bx), $\mathcal{L}_{bx}$.

In practice, the beam distributions are not known, thus the integrals in (3) cannot be calculated analytically. The vdM scan enables the determination of these integrals by separating the two beams in the transverse direction and moving them across each other, while measuring the resulting rates (Fig. 1(Left) illustrates this process). The integrals can then be expressed as

$$\int \rho_1(x)\rho_2(x)dx = \frac{1}{\sqrt{2\pi}\Sigma_x}, \quad (4)$$

where

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int R_x(\Delta x)d\Delta x}{R_x(0)}.$$

Here, a new parameter Σ_x, the beam overlap width along the x axis, is introduced, while $R_x(\Delta x)$ is the measured rate when the beams are separated by a distance Δx. Doing the same for the y axis, Σ_y can be obtained, thus Eq. (3) can be rewritten:

$$\mathcal{L}_{\text{ins}} = \frac{N_1 N_2 N_b f}{2\pi\Sigma_x\Sigma_y}, \quad \text{and we define} \quad \mathcal{L}_{bx} = \frac{N_1 N_2 f}{2\pi\Sigma_x\Sigma_y}. \quad (5)$$

Here $\mathcal{L}_{\text{ins}}$ only holds for identical bunches, otherwise, the instantaneous luminosity is derived by summing up the bunch-by-bunch luminosity ($\mathcal{L}_{bx}$). Once measurements have been taken, the rate is plotted as a function of beam separation and a Gaussian-like function is fitted to the data, as shown in Fig. 1(Right). Using this function, the integral in Eq. (4) can be calculated and the overlap width determined. Using Eqs. (1) and (5) the calibration constant σ_{vis} can be expressed as:

$$\sigma_{vis} = \frac{R_{peak}}{\mathcal{L}_{bx}} = \frac{2\pi\Sigma_x\Sigma_y}{N_1 N_2 f} R_{peak}, \quad (6)$$

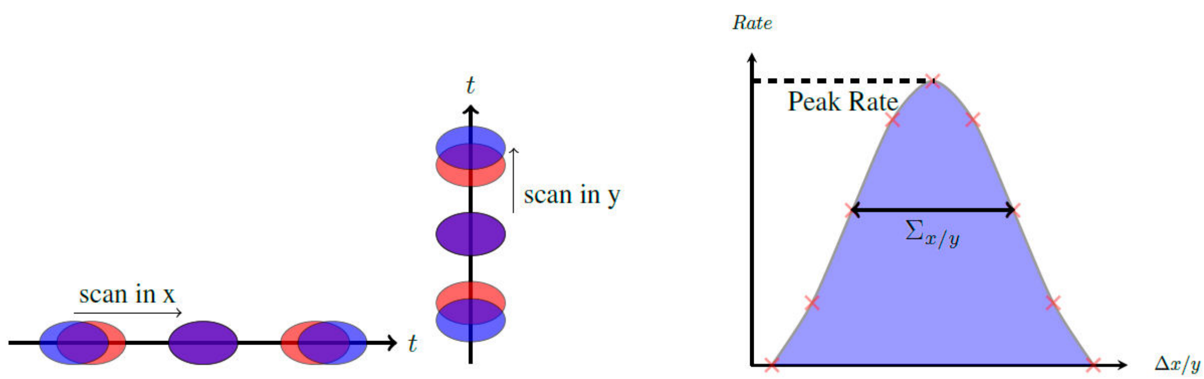


FIGURE 1. *Left*: A diagram showing the relative beam position at different points in time of the scan (on the x and y axis), the beams (red and blue) are moved across each other. *Right*: An example of a Gaussian function (blue) being fitted to the rate measurements (red crosses) as function of the beam separation during a vdM scan.

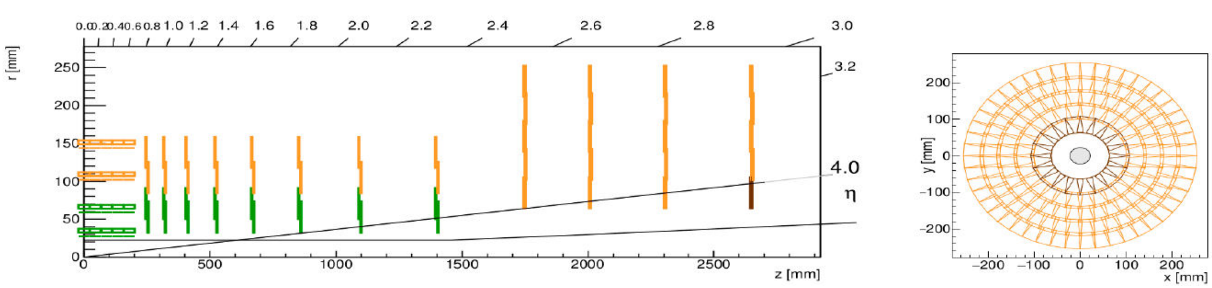


FIGURE 2. *Left*: Drawing of the CMS Phase-2 inner tracker. The last four orange lines between 1700 mm and 2700 mm correspond to the TEPX detector. *Right*: Front view of one of the disks of the TEPX detector. Two types of modules will be used in the inner tracker, modules with 2 and 4 pixel chips. The modules will be arranged in 2×1 and 2×2, and are depicted with green and orange, respectively. TEPXD4R1, the innermost ring of the last disk, is marked by black [6].

where R_{peak} is the measured rate at the head-on position of the scan [2]. σ_{vis} is measured for each bunch crossing (bx) and then averaged. The original procedure can be found in Ref. [5].

4. Detector design

For Phase-2 of CMS the entire existing silicon pixel and strip trackers will be replaced. Figure 2 shows the $r - z$ layout of the three sections of the Phase-2 inner tracker: the tracker barrel pixel (TBPX), composed of four cylindrical layers of modules, the tracker forward (TFPX) and the tracker end-cap (TEPX) pixel detectors, made of eight and four disks of pixel modules, respectively, at each side of the experiment.

The TEPX detector has a range of 175 cm to 265 cm on the $|z|$ direction and a radius between 63 mm and 255 mm. To guarantee hermetic coverage, each ring has a different number of pixel modules. TEPX is composed of 800 million pixels, distributed over an area of about 2 m^2, and will operate at trigger frequency of 750 kHz for physics and an additional 75 kHz for luminosity.

TEPXD4R1, lies beyond a pseudorapidity of $|\eta| = 4$ and consists of 20 modules, with an inner radius of 63 mm and an outer radius of 108 mm. This luminometer may run at a trigger frequency of 825 kHz (in physics data taking) to several MHz (in calibration runs).

5. Statistical performance for PCC

The number of counts per event is taken from simulated measurements for the CMS Phase-2 detector with pileup of 200. The statistical precision of the TEPX luminometers is shown in Table I.

The statistical precision for event rates during a vdM scan is calculated using the same data sample used for physics runs, but to account for the lower pileup (≈ 0.5), the mean number of clusters per event is divided by 400, since that data correspond to a pileup of 200. During the vdM scan, the TEPXD4R1 luminometer will run at a total readout frequency of 2000 kHz (or more), while the TEPX luminometer will run at 1000 kHz. Table II shows the results.

Using the estimated cluster rates from simulation, a vdM scan toy simulation study was created to calculate the statistical uncertainty for σ_{vis} by performing a fit to the rates v.s. beam separation. Table III shows the result.

TABLE I. Statistical precision in % for pileup 200. The first column shows the estimated precision for 1 bx and the second for all 2748 filled bx, for 1 s integration period [7].

	1 bx, 1s	2748 bx, 1s
TEPXD4R1 Clusters	0.1	0.002
TEPX Clusters	0.095	0.002

TABLE II. Statistical precision in % for pileup 0.5. The first column shows the estimated precision for 1 bx for an integration period of 1s while the second for a 30 s integration period [7].

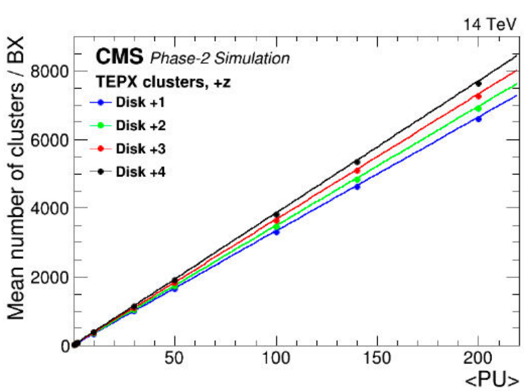
	1 bx, 1s	1 bx, 30s
TEPXD4R1 Clusters	1.3	0.24
TEPX Clusters	0.52	0.096

TABLE III. Results from the vdM toy simulation study based on the estimated cluster rates. The table shows the relative uncertainties for σ_{vis} ($\delta\sigma_{\text{vis}}/\sigma_{\text{vis}}$) for 1 bx and for all 150 bx that are expected to be filled in the special vdM calibration period [7].

	$\delta\sigma_{\text{vis}}/\sigma_{\text{vis}}(\%)$, 1bx	$\delta\sigma_{\text{vis}}/\sigma_{\text{vis}}(\%)$, 150 bx
TEPXD4R1 Clusters	0.066	0.0054
TEPX Clusters	0.027	0.0022

5.1. Linearity performance

The linearity of the detector is an important parameter. The determination of the calibration constants is done by perform



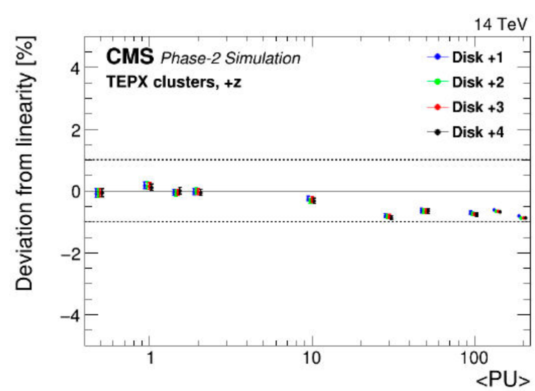


FIGURE 3. *Left*: Simulated mean number of pixel cluster per bx for each disk of TEPX, as a function of pileup. A linear function is fitted to the pileup values between 0 and 2, and then the line is extrapolated to higher pileup values. *Right*: Deviation from linearity for pixel cluster counting with TEPX. The nonlinearity is calculated as the relative difference between the points and the fitted function on the left [7].

ing vdM at low pileup, $\mu = 0.5$, and it is then extrapolated to physics fills with a pileup of ≈ 200. This extrapolation is a possible source of uncertainty when the detector response is not linear. An ideal detector will demonstrate a linear relation between the measured event rate and the instantaneous luminosity (or pileup). The plots in Fig. 3 show the linearity performance of each disk of the TEPX luminometer, as a function of pileup.

6. Conclusion

In this work, the statistical precision of the TEPX luminometer is studied using simulated data. For physics runs (pileup of 200), the TEPX and TEPXD4R1 luminometers achieved a statistical precision per bunch per 1 s below 0.1% for pixel cluster counting. In vdM conditions (pileup of 0.5), the TEPX and the TEPXD4R1 statistical precisions are 0.1% and 0.24% per bunch per 30 s. This translates to a precision well below 0.1% per bunch for the calibration constant (σ_{vis}). Both luminometers also achieve linearity deviations below 1% up to a pileup of 200. These results show an excellent expected performance for TEPX luminometers, assuring it will provide precise luminosity measurements for the HL-LHC phase.

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