PROCEEDINGS OF SCIENCE

The CMS Tracker Performance in Run 3

Tiziano Bevilacqua[a,b,*] **on behalf of the CMS collaboration**

[a] *University of Zürich,*
Rämistrasse 71, Zürich, Switzerland
[b] *Paul Scherrer Institute,*
Forschungsstrasse 111, Villigen, Switzerland
E-mail: tiziano.bevilacqua@cern.ch

The tracking system of the CMS experiment consists of two tracking devices, the Silicon Pixel and Silicon Strip detectors. The tracker was specifically designed to very accurately determine the trajectory of charged particles or tracks. In this poster, the preliminary performance of the tracker detectors during the Run 3 operation will be summarized, with particular emphasis on the expected changes in detector performance with increasing irradiation. In addition, results of the complex tracker alignment procedure will be highlighted.

The Eleventh Annual Conference on Large Hadron Collider Physics (LHCP2023)
22-26 May 2023
Belgrade, Serbia

*Speaker

https://pos.sissa.it/

PoS(LHCP2023)292

1. Introduction

The CMS experiment collected data corresponding to an integrated luminosity of 146.4 fb^{-1} at 13 TeV during Run 2, the data taking period that lasted from 2016 to 2018. This was followed by a period of maintenance, consolidation, and upgrades that lasted until 2022. In July 2022, the LHC successfully resumed its high-energy proton-proton collisions, achieving a center of mass energy of 13.6 TeV. This marked the beginning of Run 3. During the first year of data taking it was of particular importance to maintain the required performance levels for data collection, and to cope with and anticipate detector ageing effects, caused by the high instantaneous luminosity (IL) conditions in which CMS is operating.

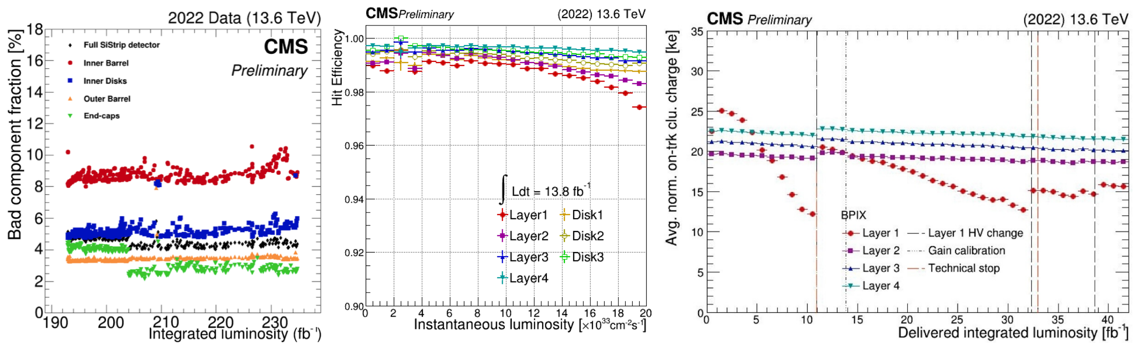
2. The CMS Tracker System

The CMS Tracker System is the innermost part of the CMS detector. It provides measurements of the tracks of charged particles thanks to its granularity and fast response and is composed of two sub-detectors:

- **Pixel Detector:** arranged in 4 barrel layers (BPIX) and 3 disks on each end (FPIX), it is the closest sub-detector to the interaction point ($2.9 < r < 16$ cm). It provides three-dimensional position measurements of the hits from the interaction of charged particles with its sensors, with a hit position resolution of approximately 10 μm for the transverse coordinate and from 20 μm to 40 μm for the longitudinal coordinate [1].
- **Strip Detector:** it surrounds the pixel detector. The 10 barrel layers (up to $r = 110$ cm) and three small plus nine large disks on each end are arranged in four subsystems: The Tracker Inner Barrel (TIB) and Disks (TID), the Tracker Outer Barrel (TOB) and the Tracker EndCaps (TEC) [1].

3. Phase-1 Pixel Detector refurbishment

During the extended end of the year (EOY) technical stop of the LHC in 2016/2017 the original CMS pixel detector was replaced with an upgraded pixel system (Phase-1) designed to improve the performance toward higher rate capability and increased radiation tolerance. The Phase-1 pixel detector also features an additional disk in each endcap, and an additional layer in the barrel region, reducing the distance from the collision point to the first layer from 4.4 to 2.9 cm. Within the BPIX detector, Layer 1 (L1) is the pixel layer most susceptible to radiation damage. During Run 3 the radiation exposure in L1 is expected to surpass the permissible operational limits [2]. Therefore the Phase-1 Pixel Detector was extracted from CMS and a new L1 was manufactured and installed in 2021. The new modules feature improved Read Out Chips (ROCs) and



(a) (b) (c)

Figure 1: a) Fraction of bad components in the Strip Tracker as function of integrated luminosity. The initial offset of 193 fb^{-1} corresponds to the integrated luminosity of Run 1 and Run 2. b) HE as function of IL for the Pixel Tracker. c) Averaged Normalised On-track Cluster Charge as a function of integrated luminosity for the BPIX Layers.

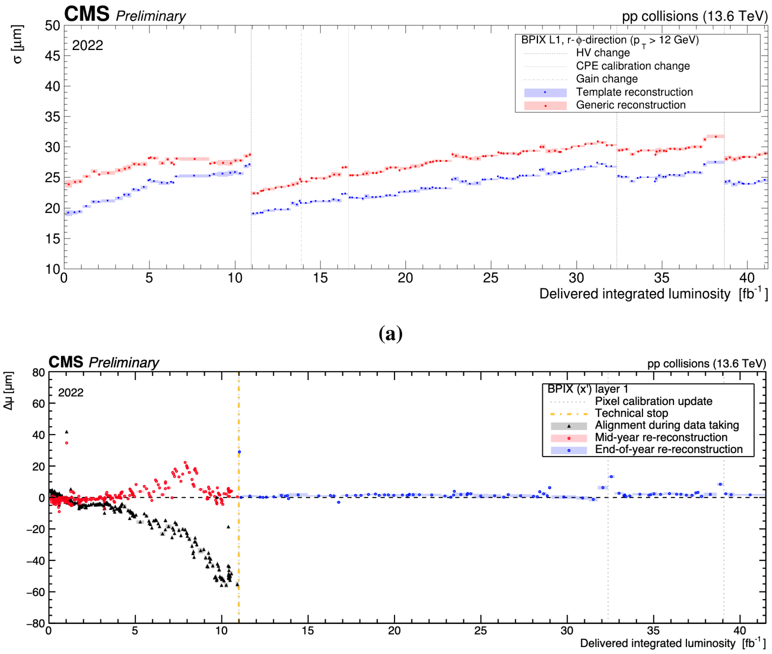
Token Bit Manager (TBM) ASICs [3], designed to rectify issues discovered during Run 2 [2]. The improved ROCs have better shielding of the calibration pulse injection circuit leading to reduced pixel cross-talk and noise. Moreover, they have an improved time-stamp buffer logic, reducing the occurrence of timing errors and loss of data synchronization. In addition, L1 is now equipped with new High Voltage (HV) cables with better insulation that, together with upgraded power supplies, allow for the HV to be ramped up to over 800 V, compared to 450 V in Run 2 [3]. This feature in combination with a lower noise level is crucial to operate the detector with very high efficiency [4] despite the radiation damage foreseen throughout Run 3. The entire readout chain of the innermost layer is now designed to cope with a particle hit rate of up to 600 MHz/ cm^2. The extraction of the pixel detector also allowed to repair system-level issues and individual modules in other pixel layers/disks. For FPIX it was also possible to harmonize the low and high voltage supply lines, and for both BPIX and FPIX, the DC-DC converter boards were replaced with new ones featuring an improved and more radiation hard ASIC (FEAST2.3) [3].

4. Run 3 Pixel and Strip Tracker performance

Throughout 2022 the CMS Tracker maintained consistent performance also at highest instantaneous luminosity and pile-up conditions. Both the Pixel and Strip detectors maintained a high number of working channels, with more than 98(95)% of working channels in the Pixels (Strips); as well as a high hit detection efficiency (HE) (measured for working channels), more than 98(99)% for the Pixel (Strip) Tracker [5], [6]. In Fig. 1a the evolution of the global fraction of module components flagged as bad in each sub-component of the Strip Tracker for offline reconstruction is presented as a function of integrated luminosity. The drop in the bad component fraction around 205 fb^{-1} is due to the recovery of a cooling loop in the TEC. Since the TEC accounts for more than 40% of all modules the drop is well visible in the bad component fraction for the entire strip tracker. Increases in the bad component fraction in specific runs could be promptly mitigated by recovering issues in either data acquisition or powering [5]. In Fig. 1b the HE is presented as a function of instantaneous luminosity for the Pixel Detector. With increasing instantaneous luminosity it decreases due to the increasing particle flux. This is especially true for L1 and L2 in the BPIX, since they are located closer to the interaction point. The performance of the newly installed L1 is significantly improved with respect to what was observed in Run 2. The HE was decreasing at high instantaneous luminosity much faster, going from 96% to 92% in the interval ranging from 16 to 20×10^{33} cm^{-2} s^{-1} [6], [8].

5. Radiation effects

The Pixel detector operates in an extremely harsh radiation environment due to its location close to the collision point. Effects of the radiation damage are visible in the degradation of HE and average cluster charge over the course of the year. This is particularly evident for the innermost layer that at the end of the 2022 data taking period has already collected a dose of about 13 Mrad or 3×10^{14} neq. To avoid loss in performance it is necessary to mitigate the effects of radiation damage during data-taking. This is achieved by increasing the reverse bias voltage of the detector (the L1 high voltage (HV) was increased from 150 V to 400 V throughout 2022), and performing calibrations over the course of the year. Annealing during periods without beam, like Technical Stops (TS) or EOY shutdowns, also play a beneficial role in the recovery of performance. The impact on the cluster charge and residual distributions is shown in Fig. 1c and Fig. 2a. The cluster charge and residual distributions, especially in the innermost layer of BPIX, exhibit distinct and rapid changes caused by the impact of radiation. This phenomenon was anticipated and is likely attributed to the initial charge carrier inversion, which is expected to stabilize and align with the behavior of the other layers and disks over time [6]. In Fig. 2a the trend of the width of the residuals distribution in the transverse plane is presented for BPIX L1. The hit positions are calculated with two different algorithms: a generic one (red dots in Fig. 2a) which is based on the track position and angle and is used in the High Level Trigger and in the early tracking iterations offline; and a template based one (blue dots in Fig. 2a) which relies on detailed cluster shape simulations predicted by PixelAv [10] [9] and is used in the final fit of each track in the offline reconstruction. Here as well as in Fig. 1c the degrading effects of radiation damage on the performance can be observed. The positive effect of increasing the high voltage of the Pixel Detector and updating the calibrations of gain and Cluster Position Estimator (CPE) can be seen in correspondence of the vertical dashed lines.



(a)

(b)

Figure 2: a) Trends of the width of the residuals distribution in the transverse plane for L1 of the BPIX as a function of integrated luminosity. b) In the barrel region, the Distributions of Median Residuals can be obtained separately for the modules with E field pointing radially inwards or outwards. The difference of their mean values $\Delta\mu$ in the local-x (x') direction, constitutes an index of goodness in recovering Lorentz angle effects. $\Delta\mu$ is shown for the BPIX modules in L1 as a function of the delivered integrated luminosity.

6. Tracker alignment

The precise determination of the geometry of the tracking system is crucial for accurately measuring the momentum of charged particles and reconstructing primary and secondary vertices. The process used to establish the geometry parameters of the tracking system is known as tracker alignment. This procedure takes care of calculating the aligning parameters for the position, rotation and curvature of each module of the Tracker (O(10^5) parameters), such that the residuals on the track coming from the alignment is less than the one coming from the uncertainty on the hit position ($\sigma_{\text{align}} \leq \sigma_{\text{hit}}$). The alignment is performed as a global track fit of all parameters *via* the least-square minimization of the sum of squares of normalised track-hit residuals. The alignment is performed both online, with a limited statistics, and offline with increased granularity. For this procedure the alignment constants are derived from an automated alignment process that operates as part of the Prompt Calibration Loop (PCL). At the start of Run 3 before the first TS, the pixel detector is aligned on a semi-granular basis, at the level of half barrels in the BPIX and half cylinders in the FPIX. For the first time in Run 3 starting from the TS, a more granular calibration was in place also online, integrated in the PCL (HG-PCL). Here the pixel detector is aligned with a much finer granularity, moving from 36 to $\sim 5k$ parameters, while the strip is kept fixed. The impact of these new developments can be seen in Fig. 2b, where the distribution of median residuals in the BPIX L1 is presented as a function of integrated luminosity. The black points correspond to the results provided by the automated alignment in the Low Granularity PCL configuration. The red points indicate the geometry for the mid-year re-reconstruction obtained with both an offline alignment derived using collision and cosmic tracks recorded at 3.8 T, and the output of the automated alignment procedure in the HG-PCL configuration for the last $\sim 2\,\text{fb}^{-1}$ of data taking before TS. The blue points correspond to the alignment constants provided by the automated alignment in the HG-PCL configuration for the EOY re-reconstruction, with the pixel detector aligned with higher granularity [7].

References

[1] The CMS Collaboration, *Description and performance of track and primary-vertex reconstruction with the CMS tracker* *Journal of Instrumentation* (2014) 1748-0221/9/10/P10009

[2] CMS Tracker Group, *The CMS Phase-1 Pixel Detector Upgrade* *JINST* (2014) 16/02/P2027

[3] L. Noehte, *CMS Phase-1 pixel detector refurbishment during LS2 and readiness towards the LHC Run 3* *Journal of Instrumentation* (2022) 10.1088/1748-0221/17/09/C09017

[4] T. Rohe et al., *Fluence dependence of charge collection of irradiated pixel sensors* *Nuclear Instruments and Methods in Physics Research* (2005) 10.1016/552/1-2/232–238

[5] The CMS Collaboration, *CMS Silicon Strip Tracker Performance Results in 2022* (2023)

[6] The CMS Collaboration, *CMS Technical Design Report for the Pixel Detector Upgrade* (2022)

[7] The CMS Collaboration, *Tracker alignment performance in 2022 (addendum)* (2022)

[8] A. Dominguez et al., *Pixel Detector Performance in Run 3* CERN-LHCC-2012-016, CMS-TDR-11

[9] M. Swartz et al., *A new technique for the reconstruction, validation, and simulation of hits in the CMS Pixel Detector* *PoS* Vertex 2007, CMS-NOTE-2007-033

[10] M. Swartz, *CMS pixel simulations* *Nucl. Instrum. Methods Phys. Res., A* (2003), 511/88-91