The CMS Pixel Detector for Run 3

Grace Haza on behalf of the CMS collaboration

CERN Detector Seminar

03 May 2024
CMS for Run 3

The detector that will be with us for > 400 fb^{-1}

⇒ Critical time ahead for data-taking before another Long Shutdown!
Tracking detectors of CMS

Silicon Pixel Tracker
-> Barrel Pixels and Forward Pixels

Silicon Strip Tracker
-> Tracker Inner Barrel, Tracker Inner Disk, Tracker Outer Barrel, Tracker Endcap
Pixel detector

**Barrel pixels (BPix)**
- 4 layers
- 1184 total modules

**Forward pixels (FPix)**
- 3 disks * 2 rings on each end
- 672 total modules

- Pixel Phase 1 installed winter 2016/2017
- 4 hit coverage up to $|\eta| < 3$
Module design

Signal and power cables

Token bit manager (TBM) chip
- Receives clock, level 1 trigger accept, configuration data
- Orchestrates readout
- 2 TBM/module in Layer 1

Silicon sensor
- (150x100) µm²
- 280 µm n-in-n

Read out chips
PSI46dig
- Digital readout
- Double column drain
- > 90% efficiency up to 200MHz/cm² hit rate

PROC600
- Specialized for Layer 1
- Dynamic cluster drain
- > 90% efficiency up to 600MHz/cm² hit rate

Base strip
Transition from LS2 to Run 3

- Pixels extracted at the end of Run 2 and kept cold and dry in boxes in clean room at Point 5
- Refurbishment in Spring 2021
- Reinstallation in Summer 2021
- BPix stored in two halves and FPix stored in four quarters
New DCDC converters

• Issue with DCDCs used in Run 2
  ➡ Fault in FEAST chip design that led to unsafe charge buildup, breaking DCDC
  ➡ Leakage current drained through preamplifier when ROC is not powered correctly
  ➡ Problem only started after DCDC was irradiated
• DCDCs with new version of FEAST v2.3 chip eliminate this problem
• All DCDC converters of BPix and FPix replaced with this upgrade
BPix improvements

• Completely new Layer 1 has significant improvements
  ➡ Readout chip decreased dynamic inefficiency and reduced crosstalk
  ➡ New TBM with additional delay option
  ➡ New high density interconnect for more robust HV operation

• Some (8 out of 10 damaged) Layer 2 modules replaced

• previous version of TBM:
  compromise between Layers 1 and 2 for timing setting
  • extra relative delay possible with new TBM
FPix improvements

- Cooling connections
  - Old version of inlet had nut directly welded to cooling pipes
  - Little torque necessary to break connection
  - New cooling connections made robust with rotating nut and custom fitting

- Filter boards
  - Boards have 4 independent HV lines instead of 2
  - Increase in HV granularity to match LV granularity
Moved underground...
...and installed in center of CMS
Active detector fraction

BPix : 96.2 %
FPix : 97.9 %
QPLL of BPix Sector 7
Layers 3 & 4 fails to lock to LHC clock
Cluster charge distributions

On-track cluster charge consistent across detector
Cluster charge measurement

Cluster charge measured as function of bias voltage to determine when settings should be adjusted

Current settings

- Layer 1: 450V
- Layer 2: 350V
- Layer 3 & 4: 250V
- Ring 1: 350V
- Ring 2: 300V
Layer 1 radiation damage

Layer 1 evolving rapidly

- HV bias scans performed regularly to monitor performance
- Layer 1 began Run 3 with HV bias of 150V, now at 450V
Resolution

Great position resolution

- Performance consistent with expected evolution
- Comparable to performance seen in 2022 and Run 2

2022:
- $\sigma = 9.80 \pm 0.12 \, \mu m$
- $\sigma = 10.77 \pm 0.18 \, \mu m$

2022:
- $\sigma = 22.49 \pm 0.29 \, \mu m$
- $\sigma = 18.39 \pm 0.33 \, \mu m$
Tracking performance: Point of closest approach

Before and after issue in BPix Sector 7 Layers 3 and 4

- Good data and MC agreement
- Z coordinate is wrt pixel detector barycenter
- Simulation set to approx. match position of beam in data wrt pixel barycenter
- MC distributions narrower and a single Gaussian
- Spread of Z coordinate in data distributions affected by lumi leveling
Summary

• Detector refurbished with several improvements for Run 3
• Smooth installation and commissioning
• Detector in good health with continuous monitoring and calibrations
• Overall successful performance in data collection with proton-proton collisions with inst. lumi up to $2.1 \times 10^{34}$ cm$^{-2}$s$^{-1}$ and heavy ion collisions
• Looking forward to the rest of Run 3!
Backup
Hardware connections

UXC power racks
- HV
- LV analog/digital
- Control

Service cylinders/supply tubes
- Filter board
- Filter board
- Filter board
- DCDCs
- CCU

Detector

Module:
- TBM + ROCs

 UXCD backend racks
- DOH
- pxFEC
- tkFEC
- FED
- POH
- RCK
- RDA
- TPLL decode
- QPLL filter
- Delay25 phase adjustment among clock and signals
- Gate Keeper LVDS to LCDS and vice versa Close the channel when not used
- LCDS drivers

Portcard
- Optical
- Electrical

Data (digital readout at 400 Mb/s)
Radiation environment for BPix Layer 1

2021-2023: CMS/ATLAS collected an integrated luminosity of about 73 fb⁻¹

• Particle fluence/flux = 8.4 * 10^{14} - particles/cm² (1MeV neutron equivalent/cm²)

• Dose = 280 kGray (28 Mrad)

At the end of LHC Run 3, estimating integrated luminosity of 230 fb⁻¹

• Particle fluence/flux = 2.3 * 10^{15} - particles/cm² (1MeV neutron equivalent/cm²)

• Dose = 93 Mrad
QPLL issue

- Quartz controlled PLL circuit does not lock to LHC clock
- Layers 3 and 4 of one sector of barrel pixels affected
- Modules are not currently read out
  - Fixing the issue would require extracting and reinstalling pixel detector
DCDC issue in Run 2

- Flaw in FEAST chip design
- When DCDC disabled, charge build up on circuit due to irradiation, causing DCDC to break

Impact:

- converters not used to power cycle modules
- powercycling needed for stuck TBMs
- reduced power supply voltage to 9V
- high current trips in power groups with higher number of modules
- disabled a few DCDC converters to prevent trips
- no broken DCDC converters in 2018
DCDC damaged modules

DCDC damaged modules not correctly powered

• Sensor leakage current cannot be drained efficiently if the ROC is not powered
• Bias voltage (HV) ON and module power (LV) OFF leads to bad grounding
• Leakage current is drained through the pre-amplifier, damaging the pre-amplifier and the module
• Damage seems to accumulate with radiation and distance from beamline
• 6 (accessible) Layer 1 modules replaced during 2017-18 YETS out of total 8 damaged modules in Layer 1
• Accessible DCDC-damaged modules in Layer 2 were replaced during LS2
Alignment

- Alignment performed with cosmic rays, 900GeV collisions, 13.6TeV collisions
- Distributions are medians of track-hit residuals
- Hit prediction obtained from all other track hits
- Median of distribution taken for each module
- Width of this distribution constitutes a measure of the local precision of the alignment results
- Deviations from zero indicate possible biases

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Tracking performance: $Z\rightarrow\mu\mu$

Before and after issue in BPix Sector 7 Layers 3 and 4

→ Good data and MC agreement
Tracking performance: $Z \rightarrow \mu\mu$

- MC simulation for $Z \rightarrow \mu\mu$ is Pythia 8 Drell-Yan to $\mu\mu$ with Tune CP5 for the underlying event
- MC distributions are normalized to reproduce the number of reconstructed vertices in data
- Tracks with requirements:
  - Global Particle Flow muons
  - $|\eta| < 2.4, \ p_T > 5 \text{ GeV}$
  - $\chi^2/\text{nDOF} < 10$, impact parameter in the transverse plane with respect to the beamspot $|d_{xy}, \text{BS}| < 0.02 \text{ cm}$, and in the longitudinal plane with respect to the beamspot $|d_{Z, \text{BS}}| < 20 \text{ cm}$
  - at least one valid hit in the pixel detector, at least 8 valid hits in the strip detector, has hits in at least 2 muon stations
  - relative isolation within a cone of radius $\Delta R = 0.4$ less than 0.3
  - two highest $p_T$ tracks must have $75 \text{ GeV} < m_{\mu\mu} < 105 \text{ GeV}$
Tracking performance: Point of closest approach

- ZeroBias events
- selected using only the information on the beam-beam coincidence
- highPurity tracks with $p_T > 1$ GeV
- MC simulation for the ZeroBias events is a Pythia 8 generic QCD with Tune CP5 for the underlying event
- MC distributions normalized to reproduce the number of reconstructed vertices in data
Hit efficiency

- Hit efficiency affected by gain calibration, HV setting, and annealing during technical stops

- High hit efficiencies for all layers and disks
Hit efficiency and hit residuals measurement

**Hit efficiency** is the probability to find any cluster within 1mm around an expected hit independent of the cluster quality
- Measured using muon tracks with pT > 2 GeV
- Bad components of the pixel detector are excluded from the measurement

**Hit residuals measurement:**
- Triplet method
  - pT > 12 (4) GeV tracks with hits in 3 layers (disks) are selected and refitted using hits in two of three layers (disks) for the BPIX (FPIX).
  - Trajectory is extrapolated to remaining layer (disk) and residuals with the actual hit are calculated for the BPIX (FPIX).
  - Residual distribution fitted with the Student-t function to obtain the mean offset (μ) and resolution (σ)
    - Residual offset (mean) and resolution are obtained from the fit
  - Triplets considered:
    - Layer 3: propagate from hits on Layer 2 and 4
    - Disk 2: propagate from hits on Disks 1 and 3

- Reconstruction:
  - Generic:
    - Simple algorithm based on track position and angle
    - Used in our High Level Triggers (HLT) and early track iterations offline
  - Template:
    - Algorithm based on detailed cluster shape simulations
    - Used in the final fit of each track in the offline reconstruction
Automasked channels

- Problem greatly mitigated by adjusting phases of the 400MHz data transmission (relative phase of readout chip and TBM)
  - Calibrations do not always predict a good setting for high rate data transfer
- Automasking of Layer 1 modules now very low, usually 1% of channels
Automasked channels

- Channels masked during data-taking due to readout errors
  - **Layer 1**: operational problem first mitigated by increasing number of allowed readout errors before channel masking
  - **Layer 2-4**: unrecoverable SEUs accumulate over a fill
- Recovery action at certain pile up
- Data quality remained good for CMS
Automasked channels

- **Fill 8736**: Channel auto-masked if there are 30 Out-of-Sync (OOS) errors seen in one minute in the channel
- **Fill 8817**: OOS setting was changed from 30 OOS/minute to 63 OOS/minute
- **Fill 8821**: The Token Bit Manager phase settings of several modules in BPix Layer 1 were changed
Automasked channels: fill details

Fill 8736 (8 May 2023):
  • Number of bunches: 1805
  • Peak instantaneous luminosity: $1.56 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
  • Peak PU: 61.401

Fill 8817 (24 May 2023):
  • Number of bunches: 2345
  • Peak instantaneous luminosity: $2.05 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
  • Peak PU: 62.299

Fill 8821 (25 May 2023):
  • Number of bunches: 2345
  • Peak instantaneous luminosity: $2.12 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
  • Peak PU: 64.316

• All fills have the same trigger rate