Commissioning and first results from the CMS phase-1 upgrade pixel detector

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on behalf of the pixel upgrade team

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http://www.physik.uzh.ch/dam/jcr/ac88d87-52d7-4e6f-b8e8-f6daff43a39/CMStune.jpg
CMS:
A general-purpose detector designed to observe any new physics phenomena at the LHC, that is compact: 15 m high, 21 m long, 14000 tonnes; is designed to detect muons very accurately; and has the most powerful solenoid magnet (3.8T) ever made.

LHC:
6.5 TeV per proton beam
2808 bunches per beam
25ns bunch spacing (40MHz)
Luminosity design: $2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

SILICON TRACKERS
- Tiled 1100x150 μm
- 16m$^2$ - 66560 channels
- Microstripes (80x130 μm) - 300m$^2$ - 9.63M channels

SUPERCONDUCTING SOLENOID
- Nibium titanium coil carry $B = 14.0\text{T}$

MUON CHAMBERS
- Endcaps: 240 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
- Horizontal Drift Tube Tubes: 16800 channels

PRESHOWER
- Silicon strips - 16m$^2$ - 157,000 channels

FORWARD CALORIMETER
- Steel + Quartz fiber - 2,000 channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000, Penetrating PoWO4 crystals

HADRON CALORIMETER (HCAL)
- Steel + Plastic scintillator - 9,000 channels

Compact Muon Solenoid
## New CMS Phase I Pixel detector

### Phase 0
- Disks per forward pixel detector: 2
- Layers per barrel pixel detector: 3
- Readout: 40 MHz analog

### Phase I
- 160 Mbit digital
- 2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}

For luminosities (lumi) up to:
- 1.53 \times 10^{33} \text{cm}^{-2}\text{s}^{-1} (peak lumi)

### Backend
- VME (Versa Module Europa)-based

### Cooling
- Single-phase 
- \(C_6F_{14}\) cooling

### Channels
- ~66 million channels

### Two-phase \(CO_2\): reduced material budget

124 million pixel channels: 87.7% more pixels compared to the previous system
Pixel Phase I detector timeline 2017

Installation: 28/2
Checkout: 08/3
Calibrations: 25/3
18/4 First global run

Cosmics
Physics

First stable beam: LHC fill 5698

B=3.8T

https://cds.cern.ch/record/1820058/files/LHC_Plan.png

https://cds.cern.ch/record/1820058/files/LHC_Plan.png
CMS phase I pixel detector expected performance


CMS TDR http://cds.cern.ch/record/1481838
CMS phase I pixel detector efficiency

Phase 0:
1.53 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}
(peak lumi)

Phase I
2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}
(design lumi)

CMS phase I pixel detector performance

See talk by Viktor Veszpremi on tracking performance and alignment
CMS Phase I pixel detector hit resolution

See also talk by Viktor Veszpremi on tracking performance and alignment

https://twiki.cern.ch/twiki/pub/CMS/PixelOfflinePlotsAugust2017
The CMS Phase-I upgrade pixel detector

Beam pipe radius: 22.5mm (LS1)

http://d29qn7q9z0j1p6.cloudfront.net/content/roypta/373/2032/20140046/F2.large.jpg
Phase I modules

- 285 μm thick n⁺-in-n silicon sensors (same)
- 100x150 μm² pixel size (same)
- **One sensor geometry** for entire pixel detector
- **2 × 8 readout chips** (ROCs) per module
- **Faster digital ROCs**: 40 MHz analog → 160 Mbit/s digital
- Module **readout bandwidth increased** by a factor of 2 (4 for layers 1 and 2): 40 MHz → 320 Mbit/s

See also [https://agenda.infn.it/getFile.py/access?contribId=130&sessionId=10&resId=0&materialId=slides&confId=10190](https://agenda.infn.it/getFile.py/access?contribId=130&sessionId=10&resId=0&materialId=slides&confId=10190)
Phase I readout chips

**Readout chip (ROC) PROC600**
- CMOS ASIC
- handles hit rate of 600 MHz/cm²
- 2x2 clusters in the double columns: transmits cluster information
- Dose expected for Layer 1: 120 MRad
- thresholds ~3000 e-

**Readout chip (ROC) psi46dig v2.1r**
- 250nm complementary-symmetry metal–oxide–semiconductor (CMOS) application-specific integrated circuit (ASIC)
- 80x52 pixels
- pulse-height readout
- 160 Megabit per second (Mbps) at (multiplexed) 160 MHz
- double column drain architecture
- 8bit analog-to-digital converter (ADC)
- thresholds ~1800 e- (was: 3500-e)
- data streams from 2 ROC banks merged inside the TBM

Token bit manager (TBM):
320 Mbps parallel readout at 400MHz
Supply tube

New: Two-phase CO$_2$: reduced material budget
Before: Single-phase C$_6$F$_{14}$ cooling

10V supplied

BPix supply tube (x4)

FPix 3 disks

~5.6m

BPix 4 layers

FPix service cylinder (x4)

DC-DC converters (radiation hard CERN FEAST2 chip)
Communication and control unit (CCU)
Data Acquisition (DAQ)

Figure: Complete overview of the μTCA DAQ system of Phase1 pixel detector. Courtesy of Weinan Si.

New: micro-TCA(Telecommunications Computing Architecture)-based DAQ
Before: VME(Versa Module Europa)-based
16 Pixel front-end controller (Pixel FECs):
Distribute clock, trigger and fast signals to pixel modules, program digital to analog converter (DAC) registers of ROC and TBM

3 Tracker FECs:
program auxiliary components in pixel supply electronics like opto-hybrids and DC-DC converters via inter-integrated circuit (I\textsuperscript{2}C) interface and peripheral interface adapter (PIA) port of a CCU

108 Front-end drivers (FEDs):
Decode incoming data stream from detector front-end, each assemble all 24 channels’ (12 fibers) data into event fragments, then push to central DAQ

Advanced Mezzanine Card (AMC), based on CTA card (variant of FC7) which holds a Xilinx Kintex 7 Field Programmable Gate Array (FPGA). Capable to drive/receive links of up to 10Gb/s

See also https://indico.cern.ch/event/239180/contributions/1659595/attachments/563055775699/FC7.pdf
Checkout

1. optimize and test basic optical connection
   ➔ see light from the fiber
2. adjust supply: signal delays, light yield...
   ➔ see idle pattern of module
3. adjust external 400MHz TBM phase
   ➔ see TBM headers/trailers
4. adjust internal 160MHz TBM phase/ROC ports
   ➔ see ROC headers
5. inject and readout test hits
   ➔ see hits

Assumed: 1 ROC internal charge unit is 50e⁻
Single Event Upsets (SEUs)

- **Stuck TBMs**
  Solution: powercycle

- **Loss of portcards**
  Solution: Reprogram portcard

- **Conventional ROC SEUs**
  Solution: Reprogram ROCs

And also:

- **To reduce pixel dead time:**
  - Automatization of powercycling and reprogramming.

- **To improve cluster properties:**
  - Private synchronized ROC reset:
    1. Pause triggers
    2. Pause for $m_1$ orbits (read out buffers)
    3. Send pixel only resync command
    4. Pause for $m_2$ orbits
    5. Re-enable triggers

[Image](https://twiki.cern.ch/twiki/pub/CMSPublic/PixelOfflinePlots2017/SPixelQuality-run297099.png)
Layer 1 and 2 timing

1/2 clock shift between barrel layer 1 and 2 but delay chip shared in single φ sector
PROC600 faster than psi46dig

→ Speed up L2, slow down L1, with working point of 98% efficiency, e.g.:
Layer 2 100 → 250V gained 1-2 ns

See also talk by Viktor Veszpremi on tracking performance and alignment
Leakage current in phase 0 barrel pixel detector

Average current per ROC normalized to active sensor volume [µA/cm³]

\[ V = 0.81 \text{ cm} \times 0.81 \text{ cm} \times 285 \text{ µm} \]

\[ E_g = 1.21 \text{ eV}, \quad T_{\text{ref}} = 273.15 \text{ K} \]

Actual sensor temperature:

\[ T = T_{\text{coolant}} + 10^\circ \text{C} \]

- Detector temperature -10°C
- Sensors 0°C
- Fluctuations due to temperature fluctuations (not taken into account)
- Currents averaged over all channels in a layer.

\[
I(T_{\text{ref}}) = I(T) \left( \frac{T_{\text{ref}}}{T} \right)^2 \exp \left( - \frac{E_g}{2k_B} \left[ \frac{1}{T_{\text{ref}}} - \frac{1}{T} \right] \right)
\]
Leakage current in phase 0 forward pixel detector

- Detector temperature -10°C ➔ sensors 0°C
- Fluctuations due to temperature fluctuations (not taken into account)
- Currents averaged over all channels in a disk.

**TS** technical stop
**YETS** year end technical stop
**MD** machine development
Leakage current phase I barrel pixel detector run 2

Average current per ROC normalized to active sensor volume [µA/cm$^3$]

$V = 0.81 \text{ cm} \times 0.81 \text{ cm} \times 285 \mu\text{m}$

$E_g = 1.21 \text{ eV, } T_{\text{ref}} = 273.15 \text{ K}$

Actual sensor temperature:

$T = T_{\text{coolant}} + 10^\circ\text{C}$

https://twiki.cern.ch/twiki/bin/view/CMS/PixelApprovedPlots
Conclusion

- Phase 1 pixel upgrade successfully installed during winter 2016-2017 EYETS: this was a significant milestone in the CMS phase I upgrade project;
- 2017 pixel commissioning was challenging but performance benefits are starting to be realized;
- The CMS phase I pixel system is now successfully taking data;
- DAQ is performing smoothly;
- Initial studies show that performance of more complex functions like *vertexing* is already better than with the phase 0 pixel detector.

*We successfully commissioned the CMS Phase I pixel detector to achieve performance of the same level as the phase 0 pixel detector under higher instantaneous luminosity and will continue commissioning to improve performance.*
Backup
Analog current for phase 0 barrel detector

Analog current per readout chip averaged over all channels in each layer group.

**Note:** layer 3 was calibrated less often.

**TS** technical stop

**YETS** year end technical stop

**MD** machine development
Digital current for phase 0 barrel detector

Digital current per readout chip averaged over all channels in each layer group.

**LS** long shutdown
**TS** technical stop
**YETS** year end technical stop
**MD** machine development
Leakage current in phase 0 pixel barrel layer 1: transverse plane

Nonhomogeneous increase due to displacement of barrel detector center with respect to beam spot

Run 2, after recentering the barrel detector with respect to beam spot, excluding new modules installed in LS1 (→ radiation dose differences)
Phase 0 vs phase I resolutions from simulation

CMS Simulation preliminary 13 TeV

Vertex x/y resolution (µm) vs Number of tracks for t\bar{t} events (⟨PU⟩=35)

CMS Simulation preliminary 13 TeV

Vertex z resolution (µm) vs Number of tracks for t\bar{t} events (⟨PU⟩=35)

https://twiki.cern.ch/twiki/pub/CMS/Public/TrackingPOGPerformance2017MC
Pixel phase 0 and I detector resolution

CMS Preliminary 2015 $\sqrt{s} = 13$ TeV

Track $p_T > 12$ GeV
- Prompt reconstruction
- Final reconstruction

CMS Preliminary 2017 $\sqrt{s} = 13$ TeV

Barrel Pixel Layer 3
- Triplet Residuals
  - Student-t function fit
  - $\mu = 0.44^{+2.94}_{-1.94}$ μm
  - $\sigma = 37.79^{+5.21}_{-5.59}$ μm
  - RMS = 80.46 μm

Track $p_T > 12$ GeV

https://twiki.cern.ch/twiki/pub/CMSPublic/PixelOfflinePlots2016/
https://twiki.cern.ch/twiki/pub/CMSPublic/PixelOfflinePlots2017/
Residuals CMS Phase I pixel detector

$\sqrt{s} = 13$ TeV

CMS

Preliminary 2017

Template reconstruction

Track $p_T > 4$ GeV

Forward Pixel Disk 2
- Triplet Residuals
- Student-t function fit

$\mu_r = 0.07 \pm 0.04 \mu$m

$\sigma_r = 16.8 \pm 0.03 \mu$m

RMS = 31.78 $\mu$m

$\sqrt{s} = 13$ TeV

CMS

Preliminary 2017

Template reconstruction

Track $p_T > 12$ GeV

Barrel Pixel Layer 3
- Triplet Residuals
- Student-t function fit

$\mu_r = -0.14 \pm 0.03 \mu$m

$\sigma_r = 22.23 \pm 0.04 \mu$m

RMS = 38.39 $\mu$m

https://twiki.cern.ch/twiki/pub/CMSPublic/PixelOfflinePlots2017/
Residuals in data and simulation

https://twiki.cern.ch/twiki/pub/CMS/PixelOfflinePlotsAugust2017
CMS phase I and phase 0 on track cluster charge