Operation, Calibration and Performance of the CMS Silicon Tracker

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On behalf of the CMS collaboration

ICHEP 2010 – 22-28 July – Paris
The CMS Tracker
The CMS Tracker

The largest silicon tracking detector ever built!

- must provide low occupancy for LHC high luminosity
- high-precision tracking for heavy flavour identification
- coverage up to $|\eta| < 2.5$

**Strips**
- 9.3M channels
- ~ 200 m$^2$ sensor area
- 10 barrel layers
- 9 (+3) endcap disks

**Pixels**
- 66M channels
- ~ 1.1 m$^2$ sensor area
- 3 barrel layers
- 2 endcap disks
- innermost layer at r = 4.3 cm
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Operational fractions
strips: 98.1%
pixels: 98.3%
Strip DAQ & Commissioning

Strip DAQ in a nutshell

- readout chips can operate in peak and deconvolution mode
  - **peak mode** (used in 2009): 1 sample readout; robust to time misalignment; low noise
  - **deconvolution** (default): 1 readout of 3 weighted samples; indispensable for 25ns bunch spacing in LHC; needs pulse shape tuning; higher noise
- analog readout over optical links for each L1 trigger
- off-detector digitization and zero suppression
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**Strip commissioning**

- tune lasers for optical readout links
- optimize readout chip (pulse shape, analog baseline)
- noise and pedestal measurement strip-by-strip
- synchronization on module-level
  - scanning signal peak with collisions allows to correct synchronization down to < 1ns
Pixel DAQ in a nutshell

- zero suppression in readout chip; adjustable threshold per pixel
- analog readout over optical links for each L1 trigger
- off-detector digitization
Pixel DAQ & Commissioning

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Pixel commissioning

- calibrate readout chain: timing, output gain, laser settings for optical readout links
- response calibration pixel-by-pixel
- zero suppression threshold optimization
- fine delay timing scan with collisions
  \( \rightarrow \) maximize efficiency and cluster size

Hit finding efficiency

optimal working point
Preparing for collisions: Cosmic Run At Four Tesla

- CMS registered hundreds of millions of cosmic rays in two periods in 2008 and 2009
- these cosmics were used by the tracker for a multitude of calibrations
  - adjust detector timing
  - operate strips in deconvolution mode for extended period
  - measure hit efficiencies
  - align the tracker as good as possible with cosmics
  - measure Lorentz angle
  - test the tracking algorithms

- this allowed the tracker to be ready for collisions with a remarkably well-prepared detector!
High - Energy Collisions at 7 TeV
LHC @ CERN
30.03.2010
Charge Collection

Signal-to-noise ratio in strips

- from on-track clusters
- agrees well with expectation
  - thick sensors (outer barrel) collect more signal than thin sensors (inner barrel and disks)
  - more noise with increasing strip length
  - deconvolution readout (default) has higher noise

<table>
<thead>
<tr>
<th></th>
<th>TIB</th>
<th>TID</th>
<th>TOB</th>
<th>TEC thin</th>
<th>TEC thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>900GeV, peak</td>
<td>27.4</td>
<td>26.7</td>
<td>34.1</td>
<td>28.8</td>
<td>35.7</td>
</tr>
<tr>
<td>7TeV, deconvolution</td>
<td>19.4</td>
<td>18.5</td>
<td>22.5</td>
<td>19.2</td>
<td>23.7</td>
</tr>
</tbody>
</table>

Pixel charge

- measured from hits on good tracks
- scaled by track path length and sensor thickness
- good overall data-MC agreement in both barrel and endcaps validates the readout chain calibration

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Hit Efficiency

**Strip hit reconstruction efficiency**
- module-by-module efficiency determination
- allowed to spot and fix several issues
  - remaining inefficiencies being followed up
- very high efficiency 99.9%
  when excluding known problems

**Pixel hit reconstruction efficiency**
- look at hits on tracks seeded from the pixels
- very high efficiency > 99%
  - layer 1 efficiency underestimated by ~1.5%
    due to secondaries originating outside layer 1
  - not an inefficiency and well modeled
Hit Resolution

Strip & pixel hit resolution

- use hits in overlapping modules in barrel
- from residual of double difference of hit and track position
  - ~insensitive to misalignment
  - minimizes multiple scattering
  - as good as no effect from track extrapolation

- strips: measured in cosmics
  - agreement with simulation
  - $\sigma \sim 17 \mu m$ in inner layers

- pixels: from collisions
  - good agreement with simulation
  - $\sigma_x = 12.7 \pm 2.3 \mu m$ (MC: $14.1 \pm 0.5 \mu m$)
  - $\sigma_y = 28.2 \pm 1.9 \mu m$ (MC: $24.1 \pm 0.5 \mu m$)

<table>
<thead>
<tr>
<th>Sensor [\mu m]</th>
<th>Pitch [\mu m]</th>
<th>Resolution [\mu m]</th>
<th>Track angle [0° – 10°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIB 1-2</td>
<td>80</td>
<td>Measurement</td>
<td>17.2 ± 1.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MC Prediction</td>
<td>16.6 ± 0.5</td>
</tr>
<tr>
<td>TIB 3-4</td>
<td>120</td>
<td>Measurement</td>
<td>27.7 ± 3.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MC Prediction</td>
<td>26.8 ± 0.7</td>
</tr>
<tr>
<td>TOB 1-4</td>
<td>183</td>
<td>Measurement</td>
<td>39.6 ± 5.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MC Prediction</td>
<td>39.4 ± 1.3</td>
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<tr>
<td>TOB 5-6</td>
<td>122</td>
<td>Measurement</td>
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Lorentz Angle \( \theta_l \) for pixels and strips

- Lorentz force on drifting charges
  - maximal in barrel: B perpendicular to E
  - important effect on cluster position estimates
  - direct impact on alignment
- \( \tan(\theta_l) \) measured with cosmics from minimum of cluster width versus incident track angle
  - BPIX: \( 0.409 \pm 0.001 \) (stat) ; MC: \( 0.407 \pm 0.001 \)
  - FPIX: \( 0.081 \pm 0.005 \) (stat) ; MC: \( 0.080 \pm 0.004 \)
  - TIB: \( 0.07 \pm 0.02 \) (stat)
  - TOB: \( 0.09 \pm 0.01 \) (stat)
- \( \theta_l \) correction for strips in deconvolution mode
  - fraction of the charge does not reach strips in time for readout
  - reconstructed hit position is biased
  - correction validated with alignment and used in reconstruction
- verification with collisions
  - same result in BPIX with cluster width method
  - cross check with new “grazing angle” method: \( \tan(\theta_l) = 0.399 \pm 0.001 \) (stat)
Track-based alignment algorithms

- **global method “Millipede II”**
  - real module positions from residual minimization
  - matrix size reduction without loss of correlations or precision \(\rightarrow O(10^5)\) global parameters
  - only a few iterations necessary
- **local method “Hit and Impact Point (HIP)”**
  - local solution for each module, so no correlations
  - large number of iterations for large misalignment
- final results from running both in sequence
- first alignment campaign with cosmics
  - tracks mostly vertical, best results in barrel
  - results already close to ideal geometry
- alignment update with collisions
  - using high-quality tracks from minimum bias collisions
  - further improvement, most pronounced in forward region

Alignment outlook

- inclusion of beam halo, isolated muons, laser alignment data
- use mass constraints from resonances

See poster by Jula Draeger

*The Alignment of the CMS Silicon Tracker*
Particle identification using the strips

- all strip readout channels were calibrated to uniform energy response using particles

energy loss estimation \( \frac{dE}{dx} \) allows particle identification with the strip tracker

mass estimation from good tracks with \( \frac{dE}{dx} > 5\text{MeV/cm} \)

\[ \frac{dE}{dx} = K \frac{p^2}{m^2} + C \]
with \( K = 2.579 \pm 0.001 \)
with \( C = 2.557 \pm 0.001 \)

lack of deuterons in simulation!
Prompt Calibration

- several measurements have become calibration tasks, run on data straight from CMS
  - channel status, gain or response calibration, Lorentz angle, hit efficiency
- prompt reconstruction is delayed to be able to use these prompt calibration constants

Monitoring

- efficient recording of excellent data with the tracker possible due to fast-feedback and long-term monitoring of detector, DAQ and data quality
- essential tool: Data Quality Monitoring (DQM)
  - monitors the detector and reconstruction performance online for prompt feedback
  - used offline to look into details and for data certification
  - summary histograms, automated quality tests
  - integrates in central CMS DQM
- some new features still being developed
  - spy channel: read out raw, unprocessed data of a subset of events during normal data taking
  - goldmine of possibilities for monitoring and debugging
Conclusions

• the CMS tracker is the largest silicon tracking detector ever
  ➔ > 98% operational detector fraction

• commissioning, calibration and alignment
  ➔ profited fully from cosmic ray campaigns in 2008-2009
  ➔ this lead to remarkably well understood detectors,
    even before the first LHC collisions

• collisions at 900GeV, 2.36TeV and 7TeV
  ➔ collision data used to further improve calibrations and alignment routinely
  ➔ efficient tracker operations and excellent performance confirmed
• foundations and building blocks of the CMS tracker were summarized

• but the **excellence of the CMS tracker** becomes really apparent in the tracking, vertexing, b-tagging and in CMS physics analyses

• highly recommended:

  ➔ **Boris Mangano**: *Performance of Track and Vertex Reconstruction and B-Tagging Studies with CMS in pp Collisions at $\sqrt{s} = 7$ TeV*
  
  * in this session at 12h12

  ➔ **Jula Draeger**: *The Alignment of the CMS Silicon Tracker*
  
  * in the poster session

  ➔ and the many other CMS contributions!
References

- CMS Collaboration, *Commissioning of the CMS Experiment and the Cosmic Run At Four Tesla*, JINST 5:T03001, 2010
Strip Sensors & Modules

**Sensors**
- p+ implants in n-type silicon bulk
- n+ backplane for ohmic contact
- 320um and 500um sensors
- strip pitch 83um – 205um
- AC coupled readout
- bias voltage: 300V

**Modules**
- analog readout with APV25 chip: 128 channels x 192 cell pipeline
  (4.8us latency for L1 trigger)
- radiation tolerant 25um CMOS
- readout in peak and deconvolution modes
- data transfer via optical link
Pixel Sensors & Modules

**Sensors**
- n-on-n silicon, thickness
  - 285μm (BPIX), 270μm (FPIX)
- 150 x 100μm pixels
- 4160 pixels bump-bonded to PSI46 readout chips (ROC)
- bias: 150V (BPIX), 300V (FPIX)

**Modules**
- 16 or 8 ROCs / module (barrel)
- 21 or 24 ROCs / module (endcaps)
- ROCs readout in series
- datatransfer via optical link
## Operational Fractions

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<th>Component</th>
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<td>TIB/TID</td>
<td>96.3%</td>
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<td>TEC-</td>
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<tr>
<td>TEC+</td>
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<tr>
<td>TEC+</td>
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</tr>
<tr>
<td>Total pixels</td>
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<tr>
<td>Total strips</td>
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</tbody>
</table>
Strip Signal-to-Noise

S/N for all strip partitions - 7 TeV data - deconvolution

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Pixel cluster size

- good overall description by simulation
- discrepancy for small cluster sizes < 4
  → being further improved
Lorentz Angle

**Additonal plots for Lorentz Angle measurements**

- minimal cluster size method for the strips
  - one L4 TOB module shown

- grazing angle method in BPIX
  - use tracks with shallow impact angle
  - for each pixel in cluster determine drift distance from track
  - correlate with depth
  - averaging over many tracks
  - Lorentz angle is slope of linear fit
Strips Gain Calibration

CMS Preliminary 2010: Data with $\sqrt{s} = 7$ TeV

Parameter: Number of Clusters

Graphs show:
- Tickmark Calibration
- Particle Calibration
Beam Background

Beam background in pixels

- large tail observed in number of clusters in pixel detector (also to a lesser extent in strips)
- such events have large number of pixels/cluster in the barrel
  - from longitudinally grazing tracks
- beam-gas trigger veto, or cuts on cluster shape track quality and vertexing efficiently remove these background events
  - at 11kHz with nominal bunches, overlap with physics rate of ~ 0.1%
- but the large event size leads to buffer overflows in the pixel FEDs at high trigger rates
  - firmware modifications to deal with these events graciously

Cleaning: beam-gas veto, cluster shape, track quality, vertexing,...