Operational experience with the ATLAS Pixel Detector

Hongtao Yang\textsuperscript{1}

on behalf of the ATLAS collaboration

\textsuperscript{1}Lawrence Berkeley National Lab

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Introduction

- Detector operation is fundamental to the success of an experiment
- Pixel Detector is at the center of ATLAS
  - Crucial for physics: reconstructs tracks and vertices
  - Faces great challenges: pileup, radiation
- This talk will focus on ATLAS Run 2 proton-proton data-taking at \( \sqrt{s} = 13 \) TeV in 2017
ATLAS Pixel subsystem

- Innermost part of the ATLAS detector surrounding beam pipe
- 4 barrel layers and 3 endcap disks on each side, providing coverage for $|\eta| < 2.5$
  - IBL was added for Run 2
- Providing excellent spatial resolution for tracking and vertex reconstruction
- Radiation hardness matching LHC requirements
• Originally 3 barrel layers in Run 1
• In total 80M electronic channels
• Frond-end: FE-I3 based on 250 nm CMOS technology
  • 2880 (18×160) channels
  • Pixel size 50 × 400 μm²
• Sensor: n-on-n planar, 250 μm thick
• Module: 16 FE-I3 chips bump bounded to one sensor and connected to one MCC
Insertable B-Layer (IBL)

- **New innermost layer** added during 2013-2014 LHC shutdown between beam pipe and b-layer
- 12M electronic channels in total
- FE-I4 chip: 130 nm CMOS
  - 26880 (80 × 336) channels
  - Pixels size 50 × 250 μm²
- Two sensor technologies tested
  - Central: planar n-in-n, 200 μm thick
  - Edge: 3D n-in-p, 230 μm thick

(a) Side A

- Z = 0
- 3D
- Planar
- 3D

Side C

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Improvement from IBL

- Impact parameter resolution is paramount for vertexing and b-tagging performance
- IBL significantly improves the resolution of impact parameters, in particular at low pT
- Also it ensures performance robustness when B-layer starts to deteriorate from radiation damage
LHC is running beyond designed parameters

### Proton-proton collisions

<table>
<thead>
<tr>
<th></th>
<th>Design</th>
<th>2017 records</th>
<th>2017 ATLAS leveling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [TeV]</td>
<td>7</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Nominal luminosity [10^{34} cm^{-2} s^{-1}]</td>
<td>1</td>
<td>2.06</td>
<td>1.53</td>
</tr>
<tr>
<td>Bunches per beam</td>
<td>2808</td>
<td>2544</td>
<td>1866</td>
</tr>
<tr>
<td>Max. avg. events per bunch crossing</td>
<td>23</td>
<td>78.6</td>
<td>58</td>
</tr>
</tbody>
</table>

**ATLAS Online, 13 TeV**
\[
\int \text{Ldt} = 86.5 \text{ fb}^{-1}
\]

- **2015**: \(\langle \mu \rangle = 13.4\)
- **2016**: \(\langle \mu \rangle = 25.1\)
- **2017**: \(\langle \mu \rangle = 38.1\)
- **Total**: \(\langle \mu \rangle = 32.0\)

**ATLAS Preliminary Data 2016, \(\sqrt{s} = 13\) TeV**

- IBL
- B-Layer
- Layer-1
- Layer-2
- Disks

**Recorded Luminosity [pb^{-1}]**

- 2015: \(<\mu> = 25.1\)
- 2016: \(<\mu> = 38.1\)
- 2017: \(<\mu> = 32.0\)

**Mean Number of Interactions per Crossing**

- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80

**Online, 13 TeV**

**ATLAS**

**Ldt = 86.5 fb^{-1}**
Backend readout upgrade

- New backend readout introduced with IBL in Run 2 to cope with bandwidth issue
  - B-layer and Disks were upgraded this year (without bandwidth improvement)

<table>
<thead>
<tr>
<th>µ</th>
<th>B-layer 160 Mbps</th>
<th>Layer-1 160 Mbps</th>
<th>Layer-2 80 Mbps</th>
<th>Disks 80 Mbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>50%</td>
<td>33%</td>
<td>49%</td>
<td>62%</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td>92%</td>
<td>139%</td>
<td>86%</td>
</tr>
<tr>
<td>80</td>
<td>101%</td>
<td>125%</td>
<td>188%</td>
<td>115%</td>
</tr>
</tbody>
</table>

“↓” indicate the impact of backend readout upgrade
Threshold adjustments

• As LHC is outperforming, need to reduce data volume from B-layer and Disks by increasing thresholds
  - Time-over-threshold: increase from 3 to 5 bunch crossings for b-layer
  - Threshold: b-layer up to 5000e (2016) and disks up to 4500e (2017) from 3500e

• Small impacts from the adjustment
• Combined with readout upgrade, pileup is now under control!
Maximizing performance

- During data-taking many issues can occur, in particular under high intensity condition
  - Mis-matched event fragments (sync. error) on module or ROD
  - Single event upset where module configuration bits flipped
  - Detector becomes busy / timeout
- Auto recovery actions essential for high efficiency data-taking!
Automatic recovery actions

- A periodic central ATLAS Event Counter Reset Signal (ECR) is sent every \textbf{5s}, surrounded by \textbf{2ms} window without triggers. Most corrective actions built around ECR:

1. FE-sync (firmware): resetting at ECR internal trigger FIFO and clearing all memory of events in FE-I3 chip

2. Reconfiguration of IBL FE-I4 global registers at ECR (firmware/software)

3. Flushing backend FIFO at ECR

4. QuickStatus (SW): monitoring readout status, and taking corrective actions when busy / timeout error occurs
Synchronization errors in 2017

- Synchronization error rate decreased in all layers until Sept. mainly due to automatic recovery actions.
- After Oct., luminosity increased again, resulting in increased synchronization errors (mainly from sync. errors on the ROD, see backup for details).
Summary of 2017 data taking

### ATLAS pp 25ns run: June 5-November 10 2017

<table>
<thead>
<tr>
<th>Inner Tracker</th>
<th>Calorimeters</th>
<th>Muon Spectrometer</th>
<th>Magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>SCT, TRT</td>
<td>LAr, Tile</td>
<td>MDT, RPC, CSC, TGC</td>
</tr>
<tr>
<td>100</td>
<td>99.9, 99.3</td>
<td>99.5, 99.4</td>
<td>99.9, 97.8, 99.9, 100</td>
</tr>
</tbody>
</table>

**Good for physics: 93.6\% (43.8 fb^{-1})**

Luminosity weighted relative detector uptime and good data quality efficiencies (in \%) during stable beam in pp collisions with 25ns bunch spacing at $\sqrt{s}=13$ TeV between June 5 – November 10 2017, corresponding to a delivered integrated luminosity of 50.4 fb\(^{-1}\) and a recorded integrated luminosity of 46.8 fb\(^{-1}\). The toroid magnet was off for some runs, leading to a loss of 0.5 fb\(^{-1}\). Analyses that don’t require the toroid magnet can use these data.

- Pixel has \(~100\% data quality efficiency
- Dead-time in 2017 was reduced tremendously thanks to the firmware and software recovery actions
- **Successful year of data-taking for pixel** under challenges imposed by the outperforming machine
Radiation damage

- Most important effect in the sensor bulk, caused by non-ionizing interactions
  - Increasing depletion voltage caused by change in effective doping concentration
  - Decreasing signal collecting efficiency and dE/dx caused by charge trapping
  - Change in cluster size and Lorentz angle caused by deformed electrical field
  - Increasing leakage current
  - Annealing makes situation more complicated

- More details in Lorenzo Rossini’s talk on Wednesday
• Starting to see impact on original pixel layers, in particular B-layer
• Need to adjust operation parameters in order to maintain performance
Radiation impact on IBL

• Fluence rate at IBL per fb⁻¹: 5.9-6.6×10^{12} [1 MeV n_{eq}/cm²]
  • Rest of Pixel barrel only experiences 50% of the IBL fluence rate
• Total ionizing dose per fb⁻¹: 0.3-0.35 Mrad
• Can compare leakage current between 3D and planar for detecting sensor depletion
• Detector closely monitored, and bi-weekly tuned to control radiation effect on the FE chip
Conclusion

- 2017 was a very challenging year for ATLAS Pixel Detector operation
- Readout upgrade and threshold adjustments managed to cope with high pileup
- Firmware and software corrective features significantly reduce inefficiency and dead time
- Radiation damage will be next challenge. Closely monitoring the detector status and mitigate the effects
- ATLAS Pixel Detector is ready for continued successful operation in 2018 and onward
Backup
Large Hadron Collider at CERN
Schema of 3D sensors
Pixel detector readout system

- Read-out System (ROS)
- Central Trigger Processor (CTP)
- Local Trigger Processor (LTP)
- TTC Interface Module (TIM)
- Back of Crate (BOC)
- Readout Driver (ROD)
- Single Board Computer

Hybrid Module

Opto Board

In Crates

Raw Data

Optical Fibre

ATLAS Central

On Detector
Synchronization errors on ROD (up) and module (down)

ATLAS Pixel Preliminary
$\sqrt{s} = 13$ TeV, ROD
2016 data
2017 data

ATLAS Pixel Preliminary
$\sqrt{s} = 13$ TeV, MOD
2016 data
2017 data

Date [dd/mm]

Average fraction of module with sync. errors

Average instantaneous luminosity [10^{34} cm^{-2} s^{-1}]

BLAYER
LAYER1
LAYER2
ENDCAP-A
ENDCAP-C
Luminosity

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