Operational Experience and Performance with the ATLAS Pixel detector at the LHC

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on behalf of the ATLAS Collaboration

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The ATLAS detector @ LHC

- Pixel detector
- Toroid magnets
- Muon chambers
- Solenoid magnet
- Semiconductor tracker
- Transition radiation tracker
- LAr electromagnetic calorimeters
- LAr hadronic end-cap and forward calorimeters
- Tile calorimeters
- 44m
- 25m
**The Pixel (+IBL) Detector**

### 3 + 1 Barrel Layers and 3 Forward/Backward Disks

<table>
<thead>
<tr>
<th>Layers</th>
<th>&lt;Radius&gt; (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBL</td>
<td>3.30</td>
</tr>
<tr>
<td>B-Layer</td>
<td>5.05</td>
</tr>
<tr>
<td>Layer 1</td>
<td>8.85</td>
</tr>
<tr>
<td>Layer 2</td>
<td>12.25</td>
</tr>
</tbody>
</table>

**3 Layers Pixel Detector**
in ATLAS since **RUN 1 (2010)**

<table>
<thead>
<tr>
<th></th>
<th><strong>Pixel (Run 1 + Run 2)</strong></th>
<th><strong>IBL (Only Run 2)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Technology</td>
<td>n-in-n</td>
<td>n-in-n/n-in-p (planar/3D)</td>
</tr>
<tr>
<td></td>
<td>(only planar)</td>
<td></td>
</tr>
<tr>
<td>Sensor Thickness</td>
<td>250 μm</td>
<td>200/230 μm</td>
</tr>
<tr>
<td>Front End Technology</td>
<td>FE-I3 250 nm CMOS</td>
<td>FE-I4 130 nm CMOS</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>50 x 400 μm² (short side along R-φ)</td>
<td>50 x 250 μm² (short side along R-φ)</td>
</tr>
<tr>
<td>Radiation Hardness</td>
<td>50 Mrad $\sim 1 \times 10^{15}$ (1 MeV) $n_{eq} \cdot cm^{-2}$</td>
<td>250 Mrad $\sim 5 \times 10^{15}$ (1 MeV) $n_{eq} \cdot cm^{-2}$</td>
</tr>
</tbody>
</table>

**Insertable B-Layer (IBL)** added beginning **RUN 2 (2014)**

**1744 + 280 modules**

**80 + 12 million channels!!**
Big changes to Run 1/Run 2 running conditions:

- Bunch crossing spacing:
  - 50 ns \(\Rightarrow\) 25 ns

- Pile up (\(\mu\)) conditions:
  - 10 \(\Rightarrow\) 70 mean interactions/bunch crossing

- Instantaneous luminosity:
  - Up to \(\sim 2,2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}\)
  - Level 1 Trigger (speed at which we read out the FEs) up to 100 kHz.

### Integrated Luminosity

<table>
<thead>
<tr>
<th></th>
<th>Pixel (fb(^{-1}))</th>
<th>IBL (fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire Run 1</td>
<td>(~30)</td>
<td>0</td>
</tr>
<tr>
<td>Run 2 (up to now)</td>
<td>(~145)</td>
<td>(~115)</td>
</tr>
<tr>
<td>By the end of Run 2 (2018)</td>
<td>(~180)</td>
<td>(~150)</td>
</tr>
<tr>
<td>By the end of Run 3 (2023)</td>
<td>(~480)</td>
<td>(~450)</td>
</tr>
</tbody>
</table>

**Full ATLAS tracker will be replaced at HL-LHC!**
• Extremely challenging years after the insertion of IBL:
  - maintenance of two different detectors/read-out systems
    - Pixel read out systems gradually upgraded with more modern IBL read out hardware during winter shutdowns...
      ➔ fully unified in 2018!

• Several issues were encountered and solved or mitigated:
  - IBL distortion due to different coefficients of thermal expansion on the stave flex)
    ➔ dynamic alignment to follow temperatures variation along the fill.
  - IBL wire bonds oscillation on magnetic field
    ➔ protection from trigger resonance frequencies
- IBL Total Ionizing Dose (TID) effect causing relevant increase of FE currents

"Production and Integration of the ATLAS Insertable B-Layer"
JINST paper for more info about IBL

- Failures on both sides of the the Pixel on-detector ↔ off-detector communication (on-detector transmitters and off-detector receivers).
- Impact parameter resolution improvements after IBL insertion (2015 data)
- B-Layer Hit-on-track efficiency above 98% (2016 data)
- IBL spatial resolution ~ 10 µm for the transverse R-φ plane
Observations of radiation damage in 2017

- Observation of the radiation damage effect for Pixel:
  - **Pixel hit occupancy** (number of hits per pixel per event) per unit of $\mu$ decreases as a function of integrated luminosity ($\sim 125$ fb$^{-1}$ by end 2017).

\[ \text{Occupancy per $\mu, \times 10^{-6}$} \]

- Decrease the thresholds and increase the HV to compensate the lack of charge collection efficiency.

- Limitations on the read-out bandwidth if threshold decrease was too drastic!
Despite the increase of hit occupancy, Pixel is still within its specifications:

- Module to read-out system bandwidth usage < 80% if L1Trigger = 100 kHz
- $<\mu> = 60$

*ATLAS Run 2 benchmark*
Detector Performance in 2018

- Different analog thresholds within the same detector layer (B-Layer): 5000e vs 4300e
- Recovering hit on track efficiency in the central area without increasing the occupancy too much elsewhere.

⇒ recovered almost fully the 2015 efficiency!

Time evolution vs 2018 config

Good stability of the hit on track efficiency vs $\mu$ (~99%)
DEADTIME

• Dead time further reduced following previous year trends:
  • further optimization still possible…

2018 Pixel dead time routinely below 0.2%

DESYNCRONIZATION

• Desynchronization (mismatch in the event identifier between Pixel modules and ATLAS) under control (≤1% level) despite higher luminosity respect to 2017.

• New mechanism (under test) to avoid sending triggers to modules that are particularly “late” ➔ prevent de-synchronization instead of trying to cure it!
Modeling the radiation damage

New Pixel Digitization model developed for next MC releases:

- conversion between integrated luminosity and fluence computed using FLUKA 2011
  - IBL will reach \( \sim 10^{15} n_{\text{eq}}/\text{cm}^2 \) by end of 2018
  - compared with leakage current measurements.
- Most Probable Value of the fitted Landau distribution of the Time Over Threshold (TOT):
  - ratio between non-irradiated and irradiated sensor as a function of bias voltage
  - bias voltage scans

See Radiation Damage poster from M. Bindi
• IBL FEs affected by SEU with increasing radiation/luminosity already in 2017
  ➔ continuous reconfiguration of FE global registers every ~ 5 s
  ➔ no extra dead time introduced!

• However, increase of noisy pixels (up to +20% occupancy) or quiet pixels (up to 1% of pixels disabled) during the fill.
  ➔ See SEU poster from P. Liu

• Problem due to SEU in single pixel latches
  ➔ it can be solved by a full (including pixel single registers) and periodical (every few minutes) reconfiguration!

• Deploying new Sw/Fw implementation to fully reconfigure the FEs every few minutes (no extra dead time).
  … similar to ATLAS ITK future strategy:
  ➔ See SEU poster from P. Butti
Several challenges/upgrades since beginning of Run 2:
- now fully unified read out system,
- time for consolidation, automatization and other optimizations!

Some adjustments of the detector operational parameters needed at the begin of 2018:
- lowering thresholds for IBL, B-Layer and Disk and increasing bias voltage for all the layers.

Pixel/IBL dead time is now minimal (~0.2%) with an excellent data quality despite the high pile-up and luminosity in ATLAS.

Key component in the next years will be to understand the radiation damage of the detector:
  - new digitization model available for the MC promising results.
Back-up
Expectations for 2017 were:
• Pile-Up of ~60
• Peak luminosity up to $2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ → Challenging year for Pixel

- Max peak lumi.: $\sim 2.1 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
- Max PU: 78.1
- Exceeded 2016 integrated luminosity
Hit occupancy in disks was reduced by ~20% to maintain sustainable operation:

- increase analog threshold: 3500 e- → 4500 e-
- increase digital threshold: 5 (TOT) → 8 (TOT)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Analog Threshold [e-]</th>
<th>Digital ToT cut [BC]</th>
<th>Latency [BC]</th>
<th>Tuning</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-layer</td>
<td>5000</td>
<td>5</td>
<td>150</td>
<td>ToT = 18 @ 20,000 e-</td>
</tr>
<tr>
<td>Layer 1</td>
<td>3500</td>
<td>5</td>
<td>255</td>
<td>ToT = 30 @ 20,000 e-</td>
</tr>
<tr>
<td>Layer 2</td>
<td>3500</td>
<td>5</td>
<td>255</td>
<td>ToT = 30 @ 20,000 e-</td>
</tr>
<tr>
<td>Disks</td>
<td>4500</td>
<td>8</td>
<td>255</td>
<td>ToT = 30 @ 20,000 e-</td>
</tr>
<tr>
<td>IBL</td>
<td>2500</td>
<td>n/a</td>
<td>255</td>
<td>ToT = 8 @ 16,000 e-</td>
</tr>
</tbody>
</table>

Frist clear effects of the radiation damage:
- after accumulating ~45 fb\(^{-1}\), a decrease of charge collection efficiency (trapping) was observed:
  ➔ plan to increase HV in 2018 and possibly reduce the thresholds if bandwidth allows!
What has changed in 2018? LHC

- More colliding bunches in the ring…from ~2000 to 2544

- Pile-up always below 60 due to bunch intensity limitations
2018 vs 2017

Inst. Luminosity constantly higher than 2017 (similar/lower pile-up)!

60-70 fb\(^{-1}\) expected in 2018 ➔ 150 fb\(^{-1}\) Total RUN2 Lumi!

LHC Performance 2018

23.2 now

150 fb\(^{-1}\) Run 2

150 fb\(^{-1}\) Run 1 + Run2
The Run 1 Pixel read-out system went through a series of upgrades using the new IBL read-out:

- **Layer2** (2015/2016 Winter Shutdown)
- **Layer1** (2016/2017 Winter Shutdown)
- **B-Layer/Disks** (2017/2018 Winter Shutdown)

Overcome bandwidth limitations but also enhance debugging capability and Sw/Fw flexibility.

Finally in 2018, one unified read-out system that should bring Pixel many advantages on a longer term:

- the operation of different type of FEs will always be there but… transparent for most of the operations!
## Occupancy increase in 2018

<table>
<thead>
<tr>
<th>Detector Layer</th>
<th>Occupancy Increase 2018/2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBL</td>
<td>+5%</td>
</tr>
<tr>
<td>B-Layer</td>
<td>+26% (central Eta); +15% (high Eta)</td>
</tr>
<tr>
<td>Layer 1/2</td>
<td>~stable</td>
</tr>
<tr>
<td>Disk</td>
<td>+14%</td>
</tr>
</tbody>
</table>

### 2018 configuration tests

![Graph showing ATLAS Preliminary data on B Layer hit on track efficiency.](image)

ATLAS Preliminary
Assumed L1 rate: 100 kHz
Fill 6358

![Graph showing average bandwidth usage.](image)

05/07/2018
ICHTEP2018, July 4-11 2018, COEX – Seoul – South Korea
More Pixel performances

- Hits- on track efficiency clearly related to eta of the modules
- Reduction of the threshold particularly important to recover efficiency in the central area...the most important for the Physics.
- Effect visible also in IBL hit spatial resolution:
  - slightly degradation as a function of integrated luminosity (~95 fb⁻¹ by end of 2017)
  - only clusters with two pixels in the overlap region
  - effect correlated with reduction of charge collection efficiency.
Radiation damage studies

- New Pixel digitization model is ready to be included in release 22.
  
  https://twiki.cern.ch/twiki/bin/viewauth/Atlas/ PixelDigitizationRadDamage

- Paper expected by the end of the year.
  
  https://cds.cern.ch/record/2255825

Radiation damage introduces defects into the sensor bulk → increases the leakage current → increases the "depletion voltage" → decreases the collected charge → deforms the E-field (double-peak)
• HV settings have been adjusted to ensure a well depleted sensor:

⇒ HV increase in all the layers in 2018!

• Radiation damage will be particularly severe in RUN3.

• In order to avoid to run with the detector not fully depleted, Pixel should be kept cooled as long as possible during the LS2 (2 years long)

⇒ discussions on-going with the ATLAS Technical coordination and the Pixel Cooling experts.
• Simulated full depletion voltage of the IBL and B-Layer according to the Hamburg model.
• The prediction for 2018 assumes 70 fb\(^{-1}\) of integrated luminosity to be delivered to ATLAS.

Predictions for cluster dE/dx during different points of Run 2, taking into account charge loss from radiation damage.

The average dE/dx per pixel layer is estimated from reconstructed tracks with transverse momenta greater than 1 GeV.
SEU mitigation strategies

- Thread on the PPC Sw (ROD FPGA embedded system) that fills the BOC Tx FIFOs (1 per each module) with different content at each ECR.

- The content will depend on the ECR number configuring the corresponding FE-I4 Double Column (1 out of 40 DCs)

- Reconfigure only part of the latches (Threshold/Feedback current and Hit Enable) if not enough time during ECR (1 ms time window available)

- We should have the full detector reconfigured after 40 ECRs... → 200 seconds trying to anticipate the ITK reconfiguration concepts ;-)

- Sets of measurement with current probe is on-going in SR1 to establish the intensity and frequency of the current spikes induced by the reconfiguration commands
  - Standard trigger and Calibration commands are also under observation....