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

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on behalf of the ATLAS Collaboration

TREDI2020 – 15th Trento Workshop on Advanced Silicon Radiation Detectors
17-19 February – TU Wien – Austria
The ATLAS detector @ LHC

The ATLAS Inner Tracker

- **Pixel Detector**
- Silicon Strip Detector (SCT)
- Transition Radiation Tracker (TRT)
# The Pixel (+IBL) Detector

## Pixel

<table>
<thead>
<tr>
<th>Sensor Technology</th>
<th>$n^+\text{-in-}n$ (only planar) 1 mm inactive edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Thickness</td>
<td>250 μm</td>
</tr>
<tr>
<td>Front End Technology</td>
<td>FE-I3 250 nm CMOS</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>50 x 400 μm$^2$ (short side along R-φ)</td>
</tr>
<tr>
<td>Radiation Hardness</td>
<td>50 Mrd (500 kGy) ~ $1 \times 10^{15}$ n$_{eq}$·cm$^{-2}$</td>
</tr>
</tbody>
</table>

## IBL

<table>
<thead>
<tr>
<th>$n^+\text{-in-}n/n^+\text{-in-}p$ (planar/3D) ~200 μm inactive edge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IBL</strong></td>
</tr>
<tr>
<td>Sensor Thickness</td>
</tr>
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## Insertable B-Layer (IBL) removed in 2014 (Run 2)

- **3 + 1 barrel pixels layers**
- **3 + 3 pixels endcaps**

- **2024 modules, 92 M channels, 1.92 m$^2$ of silicon**
Facing the unexpected @ LHC

Run 1 vs Run 2 conditions for a typical fill:

- Bunch crossing spacing or BX (ns)
  - BX time: 50 → 25
- Pile-up or \( \mu \) (# interactions per BX):
  - Average: \( \sim 20 \rightarrow \sim 35 \)
  - Peak: \( \sim 40 \rightarrow \sim 60 \)
- Instantaneous luminosity (cm\(^2 \) s\(^{-1}\)):
  - Peak: \( \sim 7 \times 10^{33} \rightarrow \sim 2 \times 10^{34} \)
- Integrated luminosity (pb\(^{-1}\)):
  - Average: \( \sim 150 \rightarrow \sim 500 \)
- Level 1 trigger rate (kHz):
  - L1A Rate: \( \sim 70 \rightarrow \sim 100 \)
Pixel/IBL at the start of Run 2

- Impact parameter resolution improvements after IBL insertion (2015)
- IBL spatial resolution $\sim 10 \, \mu m$ for the transverse $R$-$\phi$ plane (2015)
- B-Layer Hit-on-track efficiency $> 98\%$ (2016)
Detector operation in Run 2

**OCCUPANCY vs PILE-UP**
- Occupancy (hit/pixel/event) scales with pile-up
  - several challenges due to **big event size** joint to an **high trigger rate**!
  - high link bandwidth usage $\sim 70\%$

**DESYNCRONIZATION**
- Desynchronization (event id. mismatch between Pixel modules and ATLAS) **within 1\%** despite the increased luminosity along the years.

**DEADTIME**
- Busy time in ATLAS further reduced in 2018 following previous year trends
  - **Pixel and IBL dead time routinely $\sim 0.2\%$**
**Fluence and Integrated Dose**

<table>
<thead>
<tr>
<th></th>
<th><strong>Pixel</strong></th>
<th></th>
<th><strong>IBL</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Integrated Luminosity (fb(^{-1}))</td>
<td>Fluence B-Layer (n(_{eq})·cm(^{-2}))</td>
<td>Dose B-Layer (Mrd)</td>
<td>Integrated Luminosity (fb(^{-1}))</td>
</tr>
<tr>
<td>Run 1</td>
<td>~30</td>
<td>&lt;10(^{14})</td>
<td>~5</td>
<td></td>
</tr>
<tr>
<td>Run 1 + Run 2</td>
<td>~190</td>
<td>~5(\times10^{14})</td>
<td>~28*</td>
<td>~160</td>
</tr>
<tr>
<td>End of Run 3 (2024?)</td>
<td>~450**</td>
<td>&gt;10(^{15})</td>
<td>&gt;~50 Mrd</td>
<td>~420**</td>
</tr>
</tbody>
</table>

* Assuming the same Energy (13 TeV) in Run 1, Run 2, Run 3.
** Assuming an integrated lumi of 260 fb\(^{-1}\) delivered in Run 3.

Calculated using Pythia/Fluka to end of Run 3:

- IBL within specifications (5\(\times10^{15}\) n\(_{eq}\)·cm\(^{-2}\)/ 250 Mrd)
- B-Layer above specifications (1\(\times10^{15}\) n\(_{eq}\)·cm\(^{-2}\)/ 50 Mrd)

⇒ **Full ATLAS tracker will be replaced at HL-LHC!**

⇒ See [Q. Buat](#) and [J. Lange](#) talks later.
Thresholds

Evolution of FE-I4 parameters in IBL due to known TID effect on transistor leakage currents (130 nm IBM):

➔ regular retuning needed!

Time over Threshold (ToT)
• **dE/dx and cluster size decrease** due to the decreased charge collected (slow slope).

• **HV increased** to assure the detector was fully depleted.

• **Threshold changes** show up (as steps) in dE/dx since hits below threshold do not get recorded

→ thresholds increased in B-Layer (2016) and Disk (2017) due to limitations on the read-out bandwidth between modules and off-detector electronics.
• IBL hit spatial resolution quite stable:
  • used only clusters with two pixels in the overlap region
  • small degradation observed by the end of 2017 (~ 95 pb⁻¹).

• Charge collection constantly measured via bias voltage scans performed for different integrated luminosity
  • MPV of the fitted Landau distribution of TOT clearly affected
  • decrease of plateau values associated to shape changes.
• **Hit occupancy per \( \mu \)** decreases with integrated luminosity (2017).

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

Increase HV to fully deplete the sensors and decrease the thresholds to recover from the loss of charge collection efficiency.

### RUN-2 HV

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<th>2018</th>
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<tr>
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<td>80V</td>
<td>150V</td>
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<td>150V</td>
<td>200V</td>
<td>200V</td>
<td>250V</td>
</tr>
<tr>
<td>Layer-2</td>
<td>150V</td>
<td>150V</td>
<td>150V</td>
<td>250V</td>
</tr>
<tr>
<td>Endcap</td>
<td>150V</td>
<td>150V</td>
<td>150V</td>
<td>250V</td>
</tr>
</tbody>
</table>

• However, **bandwidth limitations from module to off-detector electronics** appear if thresholds too low!

**ATLAS Run2 benchmark**

L1Trigger = 100 kHz

\[ <\mu> = 60 \]
• Different thresholds within the same detector layer (B-Layer) were explored:

5000e (high $|\eta|$ modules) vs 4300e (low $|\eta|$ modules)

• Recovering hit on track efficiency in the central area (more affected by radiation damaged) without increasing too much the occupancy elsewhere.

Recovered the 2015 efficiency!

Hybrid analog threshold configuration in B-Layer

Hit on track efficiency vs $\mu$ at $\sim$99%
Depletion voltage

Higher bias voltage needed for full depletion and efficient charge collection:

- Hamburg model predictions vs data from bias voltage scan (or cross talk scan before type inversion)

- Full depletion is well predicted by the Hamburg Model at lower fluences and over predicted at higher fluences.
Leakage currents

- Measured leakage currents quite well described (annealing, temperature dependence) by the Hamburg Model but:
  - scaling factor per layer and z bin is required
  - towards the end of Run 2, the leakage currents seem overestimated.

- **Pixel**: Leakage current per module expected at the end of Run 3 within the power supply limitation (< 2 mA per sensor).

- **IBL**: Leakage current per module expected at the end of Run 3 within the power supply limitation (< 5 mA per sensor).
Fluence-to-luminosity conversion factors extracted from the leakage current, Lorentz angle and Depletion Voltage measurements:

- **less fluence at at high |z| on IBL data** respect to Pythia + FLUKA/Geant4 predictions

- **more flat distributions for outer Pixel layers.**
• Keeping the detector cold during LS2 to prevent reverse annealing
  ➔ keep the depletion voltage under control (B-layer, IBL).

• Warm up periods unavoidable due to the ID maintenance during LS2

• Target to stay **warm for < 60 days** during the LS2.

• Detector warm for **17 days up to now**.

• Expecting about 2 more weeks ➔ total of 31 days.

• Exploring colder operating set points in these days (-25°C/-30°C).

<table>
<thead>
<tr>
<th>Temp set point during LS2</th>
<th>PIXEL</th>
<th>IBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Unpowered</td>
<td>-5 °C</td>
<td>-5°C</td>
</tr>
<tr>
<td>Detector Powered (Cosmics)</td>
<td>-20 °C</td>
<td>-20°C</td>
</tr>
</tbody>
</table>
Radiation damage studies

- New Pixel digitization model was developed and is now under validation before entering the official ATLAS simulation.

*Recent paper available here: JINST 14 (2019) 06 P06012*

- Charge carriers will drift toward the collecting electrode due to **electric field**, which is deformed by **radiation damage (double peak)**.

- Their path will be deflected by magnetic field (Lorentz angle) and diffusion.

- Electron and hole lifetime inversely proportional to fluence:
  - charge trapping,
  - reduction of the collected charge.

- Available for both **Planar** and **3D** sensors.
**Charge Collection Efficiency (CCE)** for IBL modules with $|\eta|<0.2$ at the end of Run 2 is $\sim 70\%$

- MPV at the end of Run 2 $\sim 10$ ke, with a front-end threshold of 2 ke.

**Lorentz Angle** extracted from a fit to the cluster size vs track incident angle:

- big variations when bias voltage or temperature change
- further changes due to changing electric field shape inside the sensor

→ probing the electric field profile.
SEE: big charge deposit in FE electronics can flip the state of a global or local memory cell.

- IBL FEs started being affected by SEE in 2017 → periodical reconfiguration of FE global registers.
- However, increase of:
  - noisy pixels (pixels firing in the empty bunches)
  - quiet pixel (pixels not firing in colliding bunches)
  due to SEE in single pixel latches that modify:
    - local threshold DAC (TDAC)
    - return to baseline DAC (FDAC)
    - enable bit.
- Solved by a periodical reconfiguration of the FE global register + single pixel latches
  → clear gain from reconfiguration in test run in 2018.
- The fully FE reconfiguration every few minutes will be the default approach in Run 3!
Conclusion and future plans

- Several operational challenges/adjustments since beginning of Run 2:
  - lowered thresholds for IBL, B-Layer and Disk
  - increased bias voltage for all the layers.
  - time for consolidation, automatization and optimizations!

- Pixel/IBL dead time reached minimal values (~0.2%), with an excellent data quality (99.5%) despite the high pile-up/luminosity.

- Reliable and efficient operation of planar sensors (small inactive edge) at full depletion voltage (400 V).

- Novel 3D technology used successfully for the first time in HEP, operating at lower HV (40 V).

- Fundamental to understand and forecast the effects of radiation:
  - validate the new digitization model available for the MC
  - mitigate the radiation damage (Vth, HV, Cooling)
    - keep the detector cold (-5°C)
    - decrease the operating temperature (< -20°C)
  - enhance the FE reconfiguration operation to limit the impact of SEE.
Back-up
- 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
• **High failure rate of VCSELs** since start of Run 2 (on-detector data transmission).

• Cause of the failures not fully understood:
  - humidity
  - thermal cycling of VCSELs due to non-DC-balanced transmission.

• About **30 boards** were already **replaced** before the start of 2018 run
  - **20 new VCSELs** died in 2018/2019
    → 20 modules not operational.

• Failed (or suspected to fail) optoboards will be **replaced next summer**
  - better sealing planned to decrease humidity.

**Possible to predict the failure**

Shifted spectra of the single VCSEL respect to the rest of the channels in the array.
• 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!
Expectations for 2017 were:
Limitations to be expected in module to read-out system bandwidth

→ Pixel high lumi task force recommended an occupancy reduction in Disk.

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
**Pixel operational parameters in 2018**

<table>
<thead>
<tr>
<th>Threshold</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBL</td>
<td>2500e, ToT&gt;0</td>
<td>2000e, ToT&gt;0</td>
</tr>
<tr>
<td>B-layer</td>
<td>5000e, ToT&gt;5</td>
<td>4300e(*), ToT&gt;3</td>
</tr>
<tr>
<td>Layer-1</td>
<td>3500e, ToT&gt;5</td>
<td>3500e, ToT&gt;5</td>
</tr>
<tr>
<td>Layer-2</td>
<td>3500e, ToT&gt;5</td>
<td>3500e, ToT&gt;5</td>
</tr>
<tr>
<td>Endcap</td>
<td>4500e, ToT&gt;5</td>
<td>3500e, ToT&gt;5</td>
</tr>
</tbody>
</table>

*central Eta: 4300e  high Eta: 5000e*

Keep adjusting threshold and HV but…

**limitations on the read-out bandwidth** if thresholds decreased too much!

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**Run 2 Bias Voltage Evolution**

<table>
<thead>
<tr>
<th>HV</th>
<th>2015</th>
<th>2016</th>
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**ATLAS Run2 benchmark**

$L1Trigger = 100$ kHz  
$\langle \mu \rangle = 60$

Module to read-out system bandwidth usage needs to stay within 80%
Validation with data 

Bias Voltage Scan

Using standalone simulation (see slides from Trento Workshop) to predict MPV of the fitted landau distribution of the ToT as a function of bias voltage for fixed fluence.

<table>
<thead>
<tr>
<th>Bias Voltage [V]</th>
<th>ToT [BC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>400</td>
<td>2</td>
</tr>
<tr>
<td>600</td>
<td>3</td>
</tr>
<tr>
<td>800</td>
<td>4</td>
</tr>
<tr>
<td>1000</td>
<td>5</td>
</tr>
</tbody>
</table>

Standalone Simulation:

- ATLAS Preliminary IBL planar modules
  - Both data and simulation charge to ToT are tuned at the same value
  - Good agreements in both shape and plateau position
  - Correct Bias Voltage Working point to avoid under depletion

End 2017

End 2018

Charge Collection Efficiency as a function of Luminosity for IBL with data from Run 2

- Using Trapping constant for electrons and holes:
  - $\beta_e = 4.5\pm1.0 \times 10^{-16}$ cm$^2$/ns
  - $\beta_h = 6.5\pm1.5 \times 10^{-16}$ cm$^2$/ns

- Simulation points error bars
  - 1x: 15% on fluence-to-luminosity conversion
  - 2y: radiation damage parameter variations

- Data points error bars
  - 1x: 2% on luminosity
  - 2y: ToT-charge calibration drift

Good agreement with data, but very large uncertainties. Essential to understand what operational condition to use in the future.

Model Predictions and Data Comparison

Measure and predict the charge as a function of fluence / bias voltage. Nice agreement thus far, but large uncertainties - need to bring these down to make precise predictions!
dE/dx in simulation

ATLAS Simulation Preliminary

$p_T^{track} > 1 \text{ GeV}$

Cluster dE/dx [MeV cm$^2$/g]

IBL
B-layer
Layer 1
Layer 2

No Radiation Damage
Beginning Run 2
~15 fb$^{-1}$
Near End of 2016
Near End of 2016
End of 2017
End of 2018

Fluence [1 MeV cm$^{-1}$ n$_{eq}$ cm$^{-2}$]

Bias Voltage [V]
HV settings have been adjusted to ensure a well depleted sensor:

- ** HV increase in all the layers in 2018! **

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<tr>
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<td>150V</td>
<td>250V</td>
</tr>
</tbody>
</table>

- Radiation damage will be particularly severe in Run 3.

- 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).
FE-I4 SEU studies

- ATLAS Preliminary
  
  $\sqrt{s} = 13$ TeV
  
  LHC Fill 7018 (2018)

- ATLAS Pixel Preliminary
  
  LHC Fill 6356
  
  LI_S02_C_M4_C8
  
  LI_S05_C_M4_C8
  
  LI_S06_C_M4_C8
  
  LI_S07_C_M4_C8

- ATLAS Pixel Preliminary
  
  RunMode=OFF, Register = 1

2018, $\sqrt{s} = 13$ TeV

LHC Fill 7333

Rate of bit flips per fb

Shift Register = 0

0 $\rightarrow$ 1

24 GeV protons PS

Integrated luminosity [pb$^{-1}$]

Cumulative fraction of GCM bit flips

Fraction of Broken Primary Clusters

Integrated Luminosity [pb$^{-1}$]

Fraction of Pixels with outputEnable bit-flips

Integrated Luminosity [pb$^{-1}$]