Operational Experience with the ATLAS Pixel Detector at the LHC

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On behalf of the ATLAS Collaboration
• The ATLAS Pixel Detector
• Operational Experience
• Tuning, calibration and performance
  • Threshold and noise
  • Charge measurement
  • Timing
  • Monitoring detector quality and radiation damage
• Examples of offline performance
• The ATLAS Pixel Detector

• Operational Experience

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• Examples of offline performance
The ATLAS Pixel Detector

- 3 hit-system for $|\eta| < 2.5$
  - 3 barrel layers
  - 2 x 3 endcap discs
- 1744 modules, 80M readout channels
- Innermost barrel layer at 5 cm
  - Radiation tolerance
    $500 \text{ kGy} / 10^{15} \text{ 1MeV n}_{\text{eq}} \text{ cm}^{-2}$
- Evaporative C3F8 cooling integrated in local support structures
  → Module temperatures < 0°C
  (Average temperature -13°C, warmest module at -5 °C)
The ATLAS Pixel Detector Module

- **Sensor:**
  - 250 μm thick n-on-n sensor
  - 47232 (328 x 144) pixels
  - Typical pixel size 50 x 400 μm²
    (50 x 600 μm² pixels in gaps between FE chips)
  - Bias voltage 150 – 600 V

- **Readout:**
  - 16 FE chips, 2880 pixels each
  - Zero suppression in the FE chip, MCC builds module event
  - Pulse height measured by means of Time over Threshold
  - Data transfer 40 – 160 MHz depending on layer
ATLAS Pixel Front-end Chip

- **Pixel cell:**
  - Amplifier with adjustable constant current feedback
  - Discriminator with 7-bit threshold adjust
  - Circuitry to measure Time over Threshold (ToT)
  - Possibility for analogue and digital test injection

- **End of Column**
  - Hit storage during Level-1 trigger latency
  - 64 memory buffers for each column pair of 2 x 160 pixels
  - Hit data: pixel ID + timestamp + ToT
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• Examples of offline performance
• Currently 77 disabled modules (4.4%)

• In 2008, after the installation, we had 25 non operable modules. So, in average, we have a failure increase of 0.6-0.7% per year. Outermost layer seems more fragile.

• Failures are highly correlated with cooling stops. We tried to reduce the thermal shock whenever possible.

• Not always possible to identify the exact reason for the malfunctioning. Most common failures are broken wire-bonds or dark optical links.

• Very stable operation: fully efficient D(A)Q
• Until “Stable Beams” are declared from the LHC, the sensor HV is off; This can be bypassed for calibration period.

• Warm start procedure:
  - Modules are configured at the start of each run
  - To avoid noise preamplifiers are off as long as HV is off
  - When stable beams are declared
    - HV is ramped up
    - Preamplifiers are enabled
• LHC is performing extremely well
  – Luminosity >7e33, almost at design value
  – Bunch spacing 50 ns ➔ a lot of pileup
• Effects of the high luminosity can be clearly seen in the number of module desynchronisations at the beginning of each fill

• We are trying to exploit all possibilities of the readout system to detect and correct these problems in real-time

Synchronisation errors vs. run time:
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• **Threshold scan:** inject varying test charges and measure response curve: error function fit yields threshold and noise

• **Threshold tuning:** inject fixed test charge (threshold target) and vary the in-pixel threshold DAC. 50%-point gives optimal value

• In 2008 started with setting of 4000 e, working out of the box

• Setting now is 3500 e, resulting in an increase in number of masked pixels, but still negligible (0.1%)

• A successful attempt at 3000 e has been made during cosmic data taking but resulted in masking of many high-capacitance pixels
  • More careful study will need to be done when beam schedule allows
  • At the moment not really necessary as number of split clusters is already greatly reduced at 3500 e
- Typical threshold dispersion after tuning: $\sigma \sim 40$ e
- Very few outliers in all pixel classes
  - To be checked whether this can be improved in the tuning algorithms
- Noise for normal pixels $\sim 170$ e, higher in ganged pixels ($\sim 300$ e) due to higher load capacitance
  - Reflected in threshold over noise, but still $>10$ for “worst” pixel class, $\sim 20$ for normal pixels
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• Time-over-threshold (ToT, length of discriminator signal) depends on
  - deposited charge
  - discriminator threshold
  - feedback current

• Information of the ToT (in units of 25 ns) is read out together with the hit information → measurement of the deposited charge
ToT Tuning and Calibration

- Time-over-threshold tuned pixel by pixel to 30 BC @ 20ke
- Calibration by means of test charge injections to reconstruct amount of deposited charge offline
- Used for analogue hit position and dE/dx measurements
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• Hits with lower charge suffer timewalk
• This leads to an “In-time threshold” higher than the discriminator threshold for a hit detection “in time”
• At 3500 e threshold:
  • Without compensation: 4800 e for normal pixels
  • Higher load capacitance has been compensated for in ganged and inter-ganged pixels
• Timewalk is compensated for by on-chip hit doubling (using ToT information)
  • In-time threshold 200 e above threshold
  • Data volume increases (Testbeam: 10%)
Timing: Homogeneity and Stability

• Several steps for adjustment of timing:
  • Trigger delays: from cosmic ray data
  • Cable lengths: values measured during installation
  • Final adjustment: timing scans with collisions

• After all adjustments: module-to-module dispersion: 0.007 BC (corresponds to 0.17 ns)
  • Measured from average detection time for large charges

• Stability can be measured from stability of optical link tuning
  • For most modules maximum delay band position changes $\leq$ 2 ns
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• Test of bump connectivity: combination of several calibration measurements
• Disconnected bumps:
  • Low noise
  • No cross-talk to neighbour
• Merged candidates
  • Digitally working, analogue dead pixels
• Example: particularly bad module: noise (top) and cross-talk hits (bottom)
  • Overall fraction of merged or disconnected bumps: 0.1%
• Several methods to measure leakage current
  – Power supplies (granularity 1 PS channel = 6 / 7 modules)
  – Current measurement boards in the fan-outs (granularity 1 module, in total 212 out of 1744 modules equipped)
  – Monleak-ADC in the FE-chip (granularity 1 pixel)

• Will present brief summary of the results here, for more details please refer to Stephen Gibson’s talk
• Power supply measurements:
  - Continuous archiving of the current (and temperature) values via DCS
  - Due to the power supply granularity, values are averaged at least over 6 or 7 modules (1 half-stave in the barrel)
  - Temperature correction of raw values using temperature as measured by on-module NTC

\[
I(T_{\text{ref}}) = I(T) \cdot \left( \frac{T_{\text{ref}}}{T} \right)^2 \cdot \exp \left( -\frac{1.21 \text{eV}}{2k_B} \left[ \frac{1}{T_{\text{ref}}} - \frac{1}{T} \right] \right)
\]

(all values corrected to 0 deg C)
• Measured values for the pixel barrel, averaged per layer
• Measurement agrees well with prediction, including annealing times
• Prediction scaled for quantitative agreement: Layer 0 +15%, other layers +25%

ATLAS Preliminary
Pixel barrel

\( \Delta I_{\text{leak}} \) [\( \mu \text{A cm}^{-2} \) @ 0°C]

Date
05/03/11 04/09/11 05/03/12 05/09/12

Data Prediction
- [layer 0] [±1σ]
- [layer 1] [±1σ]
- [layer 2] [±1σ]
• Monleak current
  - Calibration scan, performed during (most) technical stops
  - Measures the current of the preamplifier feedback branch of the single pixel → single-pixel leakage current
  - LSB of on-chip ADC: 0.125 nA
  - Not intended as precise measurement of the reverse-bias current but can reveal local differences of the current
  - Temperature correction as for the power supply measurement
• Qualitative agreement in Layer 0 and 1, for quantitative agreement prediction was scaled up by 15 – 25% (same scaling as for power supply meas.)

• NB: LSB of 0.125 nA/pixel corresponds to 25 nA/mm³
• Example of position dependent current: modules in the endcap discs (here: disc A1)

• Modules are oriented such that column # increases with increasing R Clear R-dependence of the leakage current
Error Sources

• A few words on the quantitative agreement:
  - The corrected leakage current is very sensitive to errors in the temperature measurement ($\Delta T = 0.5$ deg C $\Rightarrow \Delta I/I = 3 – 4\%$)
  - The leakage current is measured at the operating voltage of 150 V. This results in a current 10 – 15% higher than at full depletion (cf. I-V-Curves)

• Given these uncertainties / errors, 15% is an excellent agreement!

![Graph showing current vs voltage for ATLAS Preliminary data]

Pixel Iseg Power Supplies
15.2.2012, Standard T
15.2.2012, Low T
5.7.2009, Standard T

L0_B06_S2_C6
• Two methods to measure depletion voltage:
  - From the interpixel cross-talk (pre-type-inversion)
  - From tracks (post-type-inversion)

• Here: first method, more in Stephen Gibson’s talk
• Goal: measure voltage needed for full depletion \( V_{FD} \) during *calibration* time

• Idea: use cross-talk, i.e. inject charge into one pixel, read out neighbour

• Before type inversion:
  - When not fully depleted: (high-ohmic) short between pixels
  - When fully depleted: pixels are isolated from each other
  - Chose injected charge such that cross-talk hits are seen only for \( V_{bias} < V_{pinch-off} \approx V_{FD} \)

Example: single module close to depletion voltage

White: (already depleted) pixels with no crosstalk hits

Measurement shows structure of sensor production

Clear indication of damage vs. luminosity and annealing during warm-up periods
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• Pixels with hit rate higher than $10^{-5}$ in dedicated noise runs are masked online (0.1% @ 3500 e)

• A few additional noisy pixels ($1-2*10^{-5}$) are masked offline on run-by-run basis

• After offline masking noise rate $<10^{-9}$ corresponds to less than 0.1 noise hits per event in 80 million channels (without offline mask: ~1 hit/event in the full detector)
• Hit-to-track association efficiency for the different parts of the detector
• Disabled modules have been excluded, dead regions not
• (Full efficiency of the B-layer due to track selection)
• Efficiency ~99% for nearly all parts
  • Slightly lower efficiency in the outermost discs due to individual modules
• Charge sharing can be determined from ToT and is used to improve the spatial resolution

• Calibration measurement:
  - Residuals vs. charge sharing variable
    \[ \Omega = \frac{q_{\text{last}}}{q_{\text{first}} + q_{\text{last}}} \]
  - Slope is then used to correct “digital” hit position
• Residual distribution with newest alignment
• Width close to MC width for a perfectly aligned detector
Mass determination inverting Bethe-Bloch energy loss relation

~12% dE/dx resolution
• Measurement of Lorentz angle from cluster size vs. track angle

• Measured value close to expectation (225 mrad)
Conclusions

- The ATLAS Pixel Detector has been calibrated and tuned to a stable working point
  - 3500 e threshold
  - Time over Threshold of 30 BC for 20 ke charge
- Performance at this working point is good
  - Threshold Dispersion ~ 40 e, average noise ~ 170 e
  - < 3800 e average in-time threshold
  - Charge measurement resolution < 1000 e
  - Efficiency 98% - 99%
  - Online noise occupancy O(10^-8)
  - Offline performance as expected
  - Radiation damage effects agree well with predictions
- Preparing long shutdown 2013 / 2014
  - Installation of fourth pixel layer (IBL, presentation of M. Kocian) to complement current Layer 0
  - Exchange of services to recover part of the inactive modules is under study