The 4^{th} International Conference on Technology and Instrumentation in Particle Physics
May, $22^{nd} - 26^{th}$ 2017, Beijing, China

Operational Experience with the ATLAS Pixel Detector

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May 22^{nd} 2017

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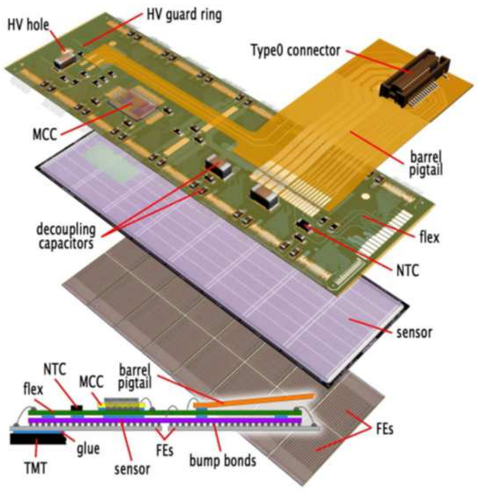
Outline

- Introduction
  - Run 1 detector
  - Run 2 detector
- Operation and performance during Run 2
  - LHC operation in Run 2
  - Detector performance in Run 2
- Readout upgrades and radiation effects
- Conclusions and Future

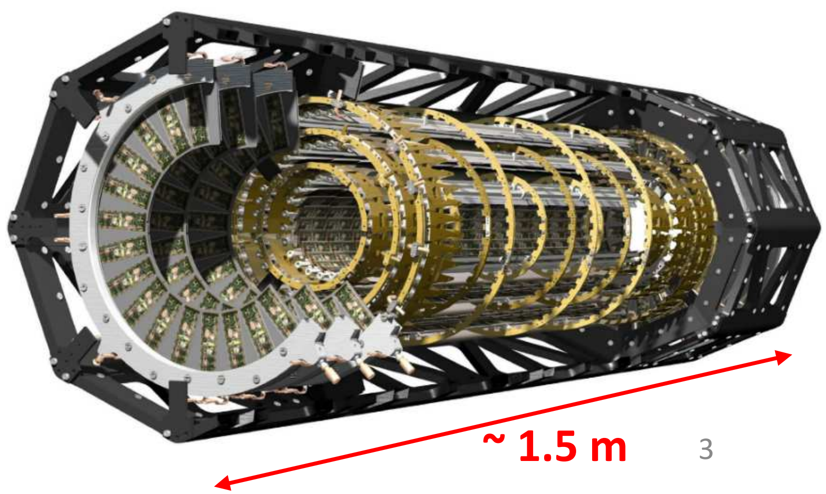
The ATLAS Pixel Detector During Run 1



- **Sensor:**
- n-on-n implants.
- 1.64 cm x 6.08 cm x 250 µm.
- 328 columns (50 µm pitch).
- 144 rows (400 µm pitch).

- **Front-end chips:**
- DSM 0.25 µm CMOS.
- 16 front-end per sensor.
- Analog block: Amplification and discrimination.
- Digital: Readout, ToT computation.

- 3 cylindrical layers closed by two end-caps having three disks each.
- Layers at 50.5, 88.5 and 122.5 mm.
- Disks at ± 495, ± 580 and ± 650 mm.
- Layer names, from beam axis: B-Layer, Layer 1 and Layer 2.
- 80 millions channels, 1.7 m^2 of silicon.
- 1744 modules with 46080 readout channels each.



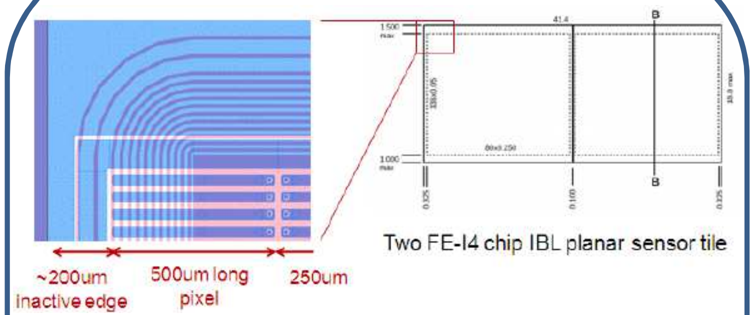
Pixel Upgrade at LHC First Long Shutdown (LS1 2013-2014)

- Increase of pile-up in Run 2: Need for more redundancy to reduce fake tracks for best tracking and b-tagging.
- Concern about module failures: Need to compensate failures and B-Layer degradation because of radiation damage and higher luminosity.
- Improve performance: Benefit from new technologies and go closer to the beam, allowing better resolution on impact parameters.

Insert a new innermost pixel layer (IBL)

- Observed mortality of VCSEL in the backend (humidity) rose concern about the inaccessible VCSEL of the internal services: Displace the optoboards outside the tracker endplates, to make them accessible.
- Anticipating the increase of the bandwidth of Layer 1: Doubling the number of data fibers of Layer 1.
- 88 dead modules and 60 dead frontends at the end of Run 1 (5.3 %): Repare disconnections where possible.

Build and install new Service Panels (nSQP)

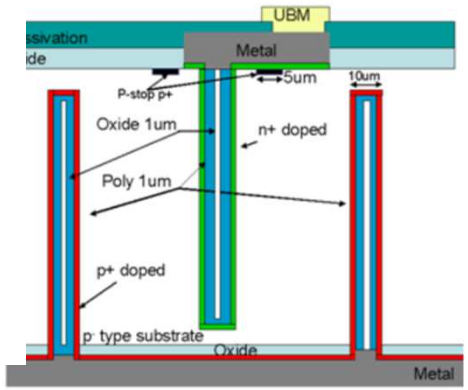


Slim Edge Planar Sensor

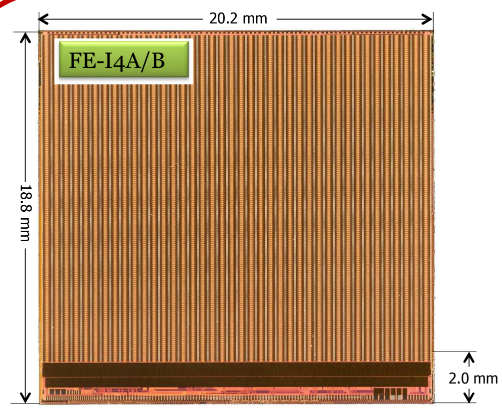
- n-in-n, p-spray
- 41.3 × 18.54 mm^2, 2 FE-I4 chips
- 200 µm thick
- 50 µm × 250 µm pixels

3D Sensors

- p bulk
- 20.5 × 18.8 mm^2, 1 FE-I4 chip
- 230 µm thick
- 50 µm × 250 µm pixels

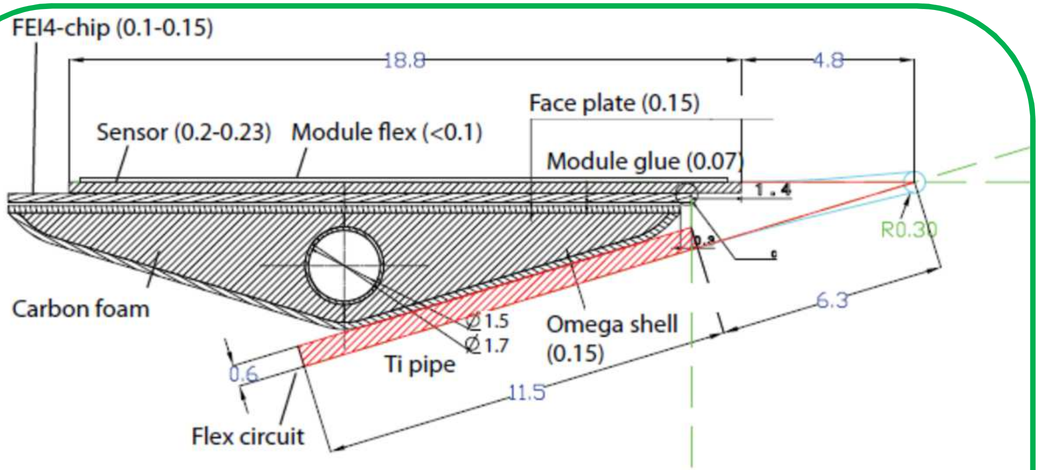


The IBL in a Nutshell



FE-I4 chip

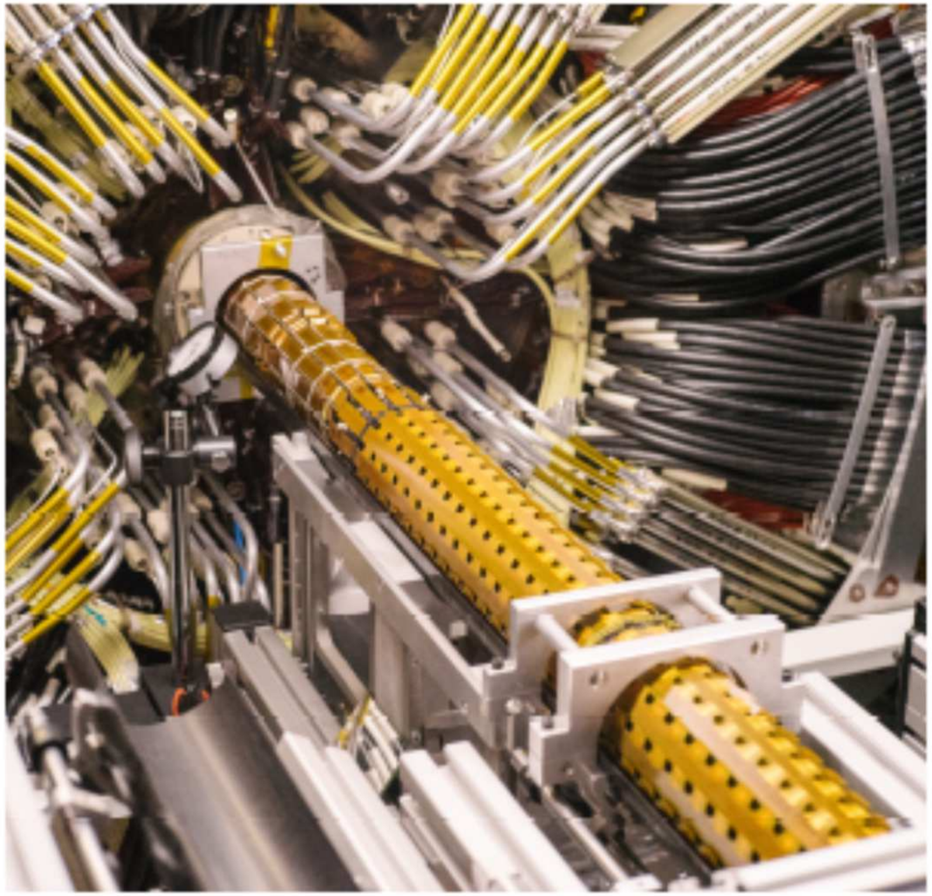
- 130 nm CMOS Process
- 26880 channel
- 150 µm thick
- Bump-bonded to sensor
- 4 bits dynamic range
- 256 cycles latency
- 160 Mbits/s bandwidth

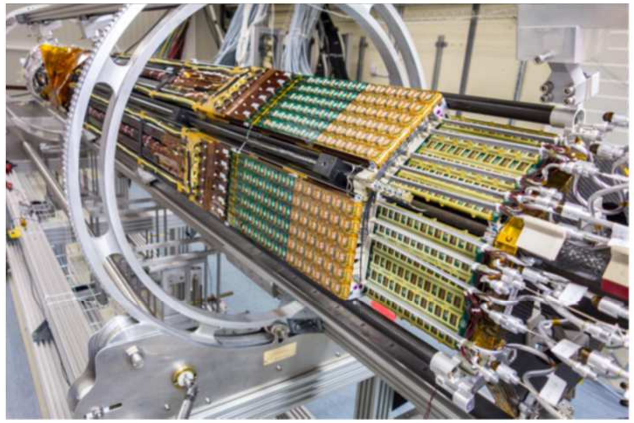


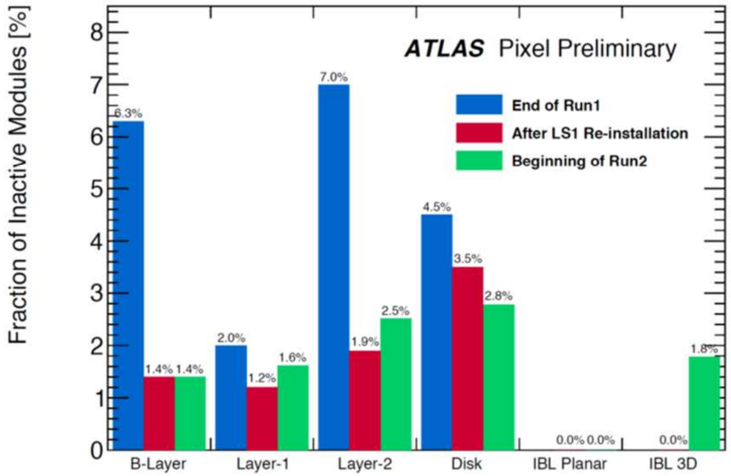
Stave cross section

- Carbon foam surrounded by carbon laminate
- Titanium cooling pipe (CO_2 evaporative cooling)
- Polyimide-Al-Cu flex for services

IBL Insertion and nSQP Integration

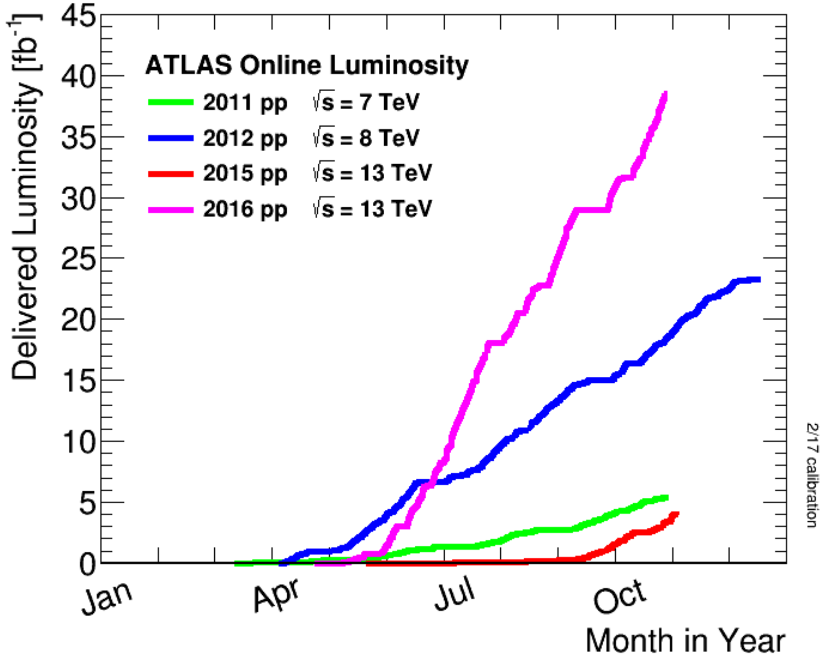






LHC and ATLAS Operation in Run 2

- LHC delivered more than 40 fb^{-1} during 2015 and 2016, at a total energy of 13 TeV.



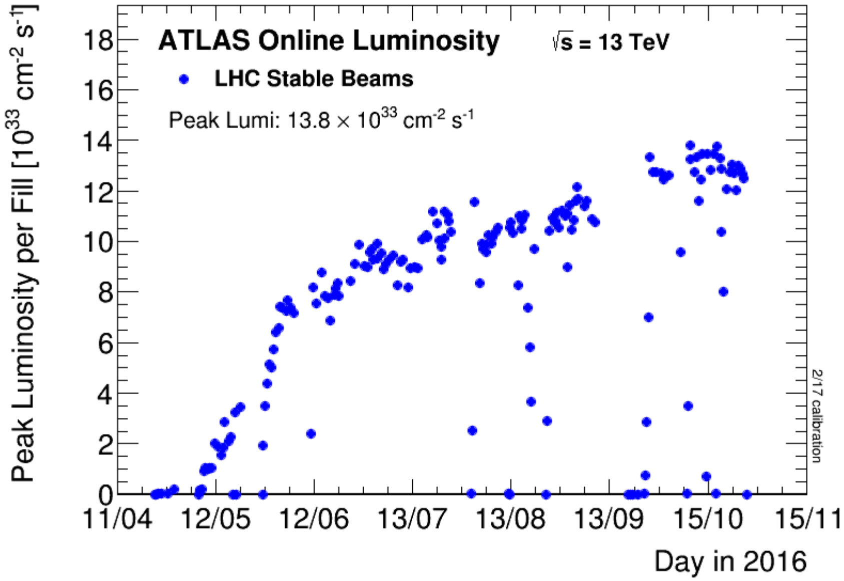
- The 4-layer Pixel Detector operated with a high "good-for-physics" fraction of 98.9 % in 2016.

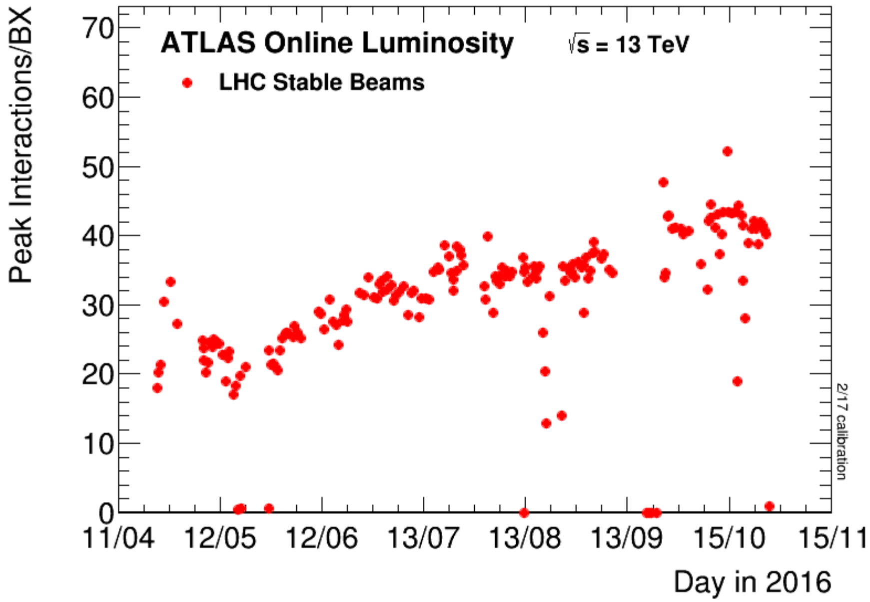
ATLAS pp 25ns run: April-October 2016											
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets		Trigger
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid	L1
98.9	99.9	99.7	99.3	98.9	99.8	99.8	99.9	99.9	99.1	97.2	98.3
Good for physics: 93-95% (33.3-33.9 fb^{-1})											

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 April-October 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.7 fb^{-1}. Analyses that don't require the toroid magnet can use that data.

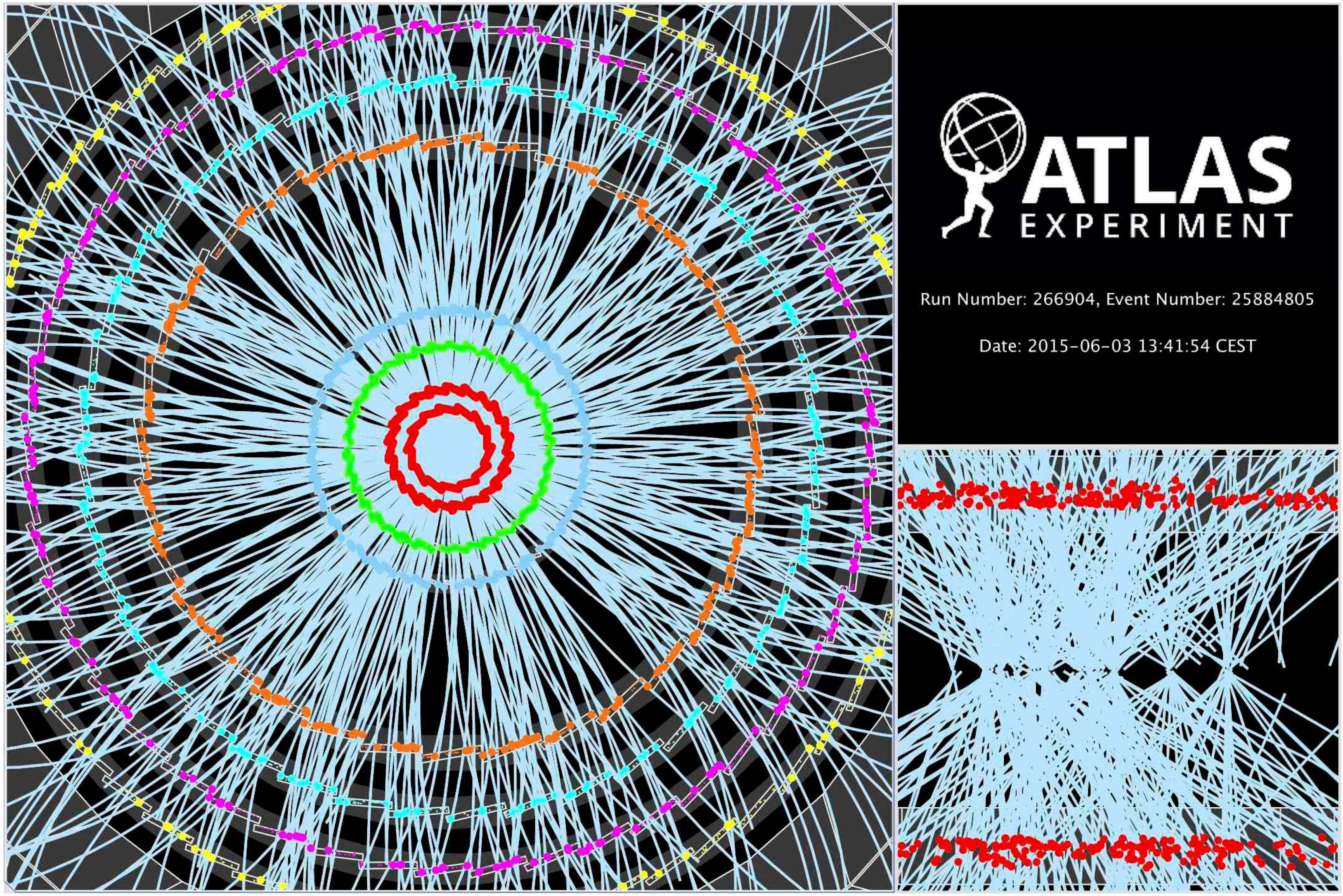
Luminosity and Pile-up in Run 2

- During 2016, LHC routinely exceeded its forseen nominal performance ($10^{34} cm^{-2} s^{-1}$and an average pile-up of 23).
- First level trigger (LVL1) and data acquisition maximum rate went to 85 kHz and 1 kHz respectively. Target for LVL1 is 100 kHz in 2017.



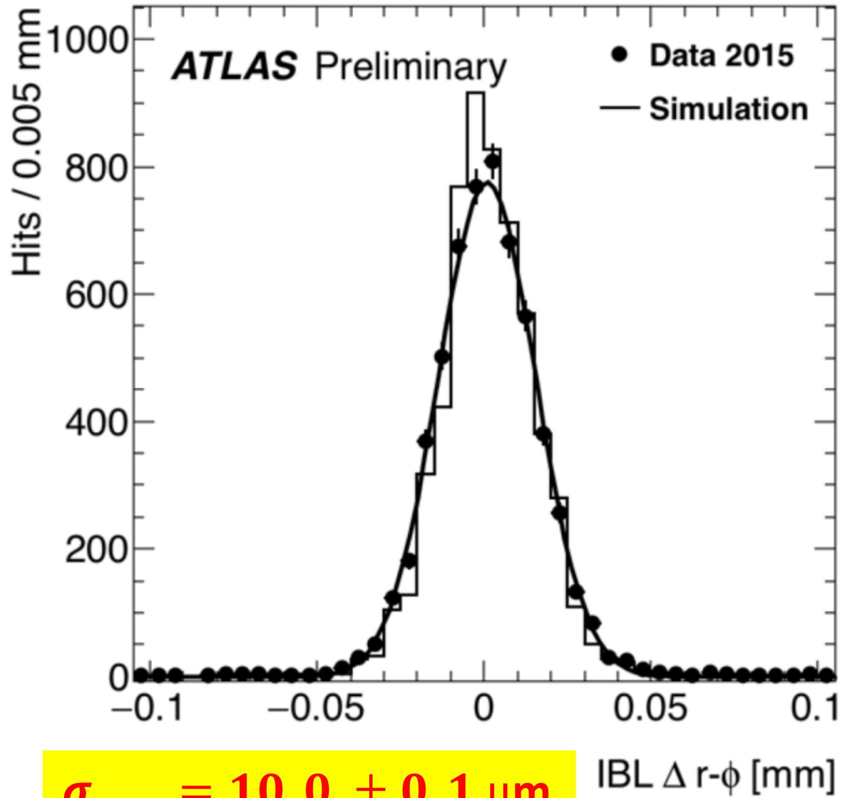


Reconstruction of an ATLAS Event With 17 Individual Collisions

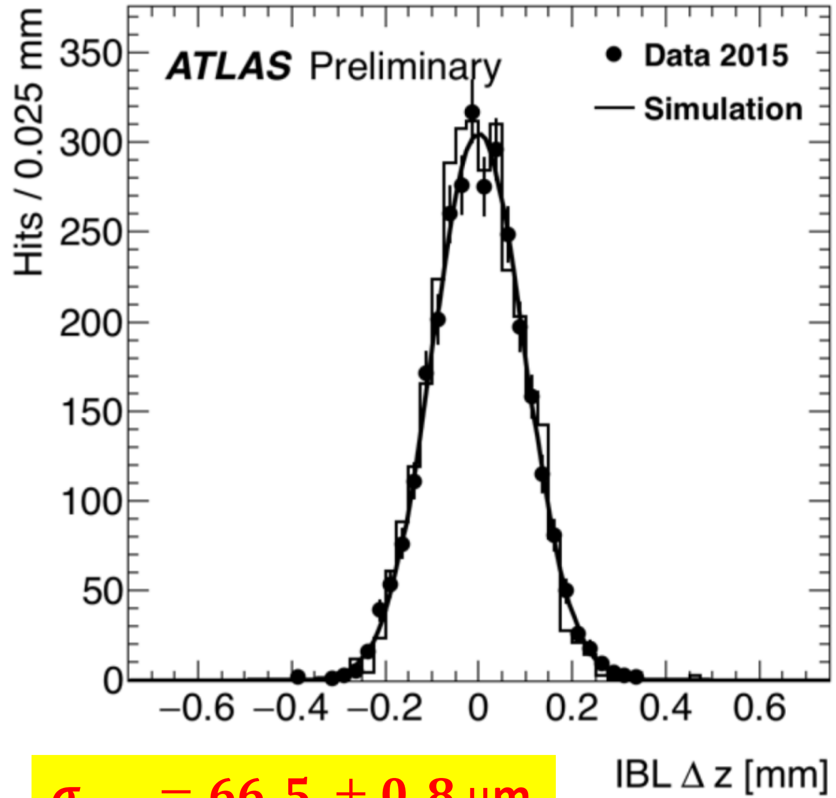


The IBL Resolution

- IBL resolution measured by using the measurement difference between two IBL sensors in their phi-overlap region.
- In agreement with test beam measurements.



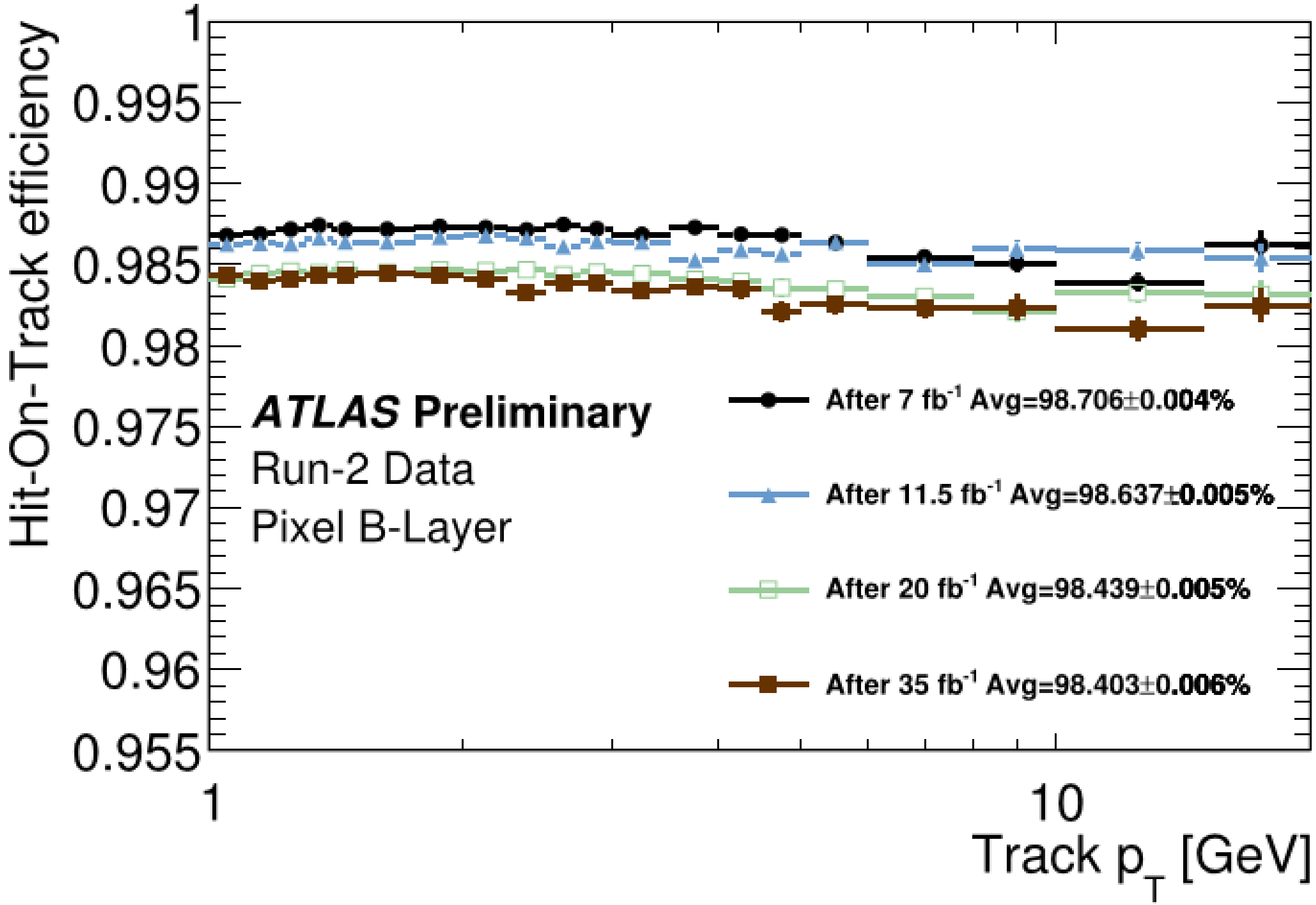
$\sigma_{r-\varphi} = 10.0 \pm 0.1$ μm



$\sigma_{r-z} = 66.5 \pm 0.8$ μm

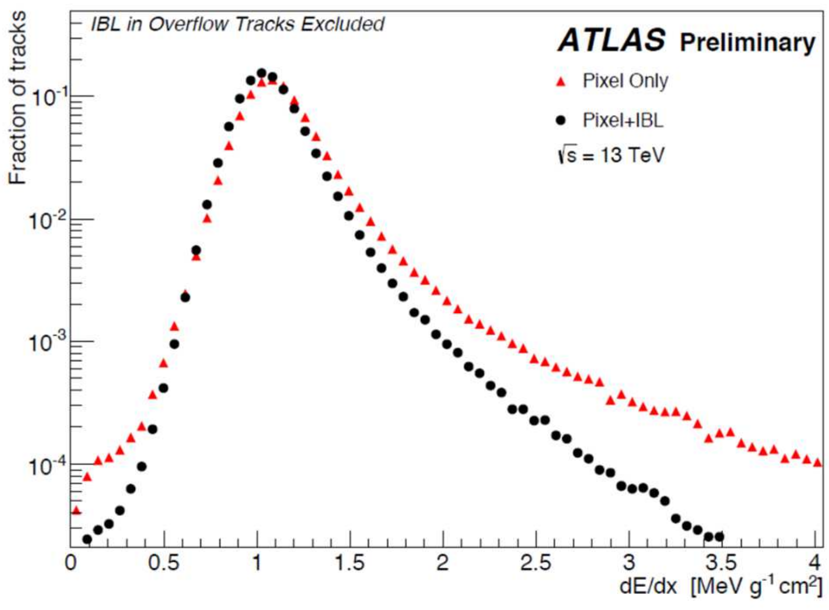
Efficiency of the B-Layer

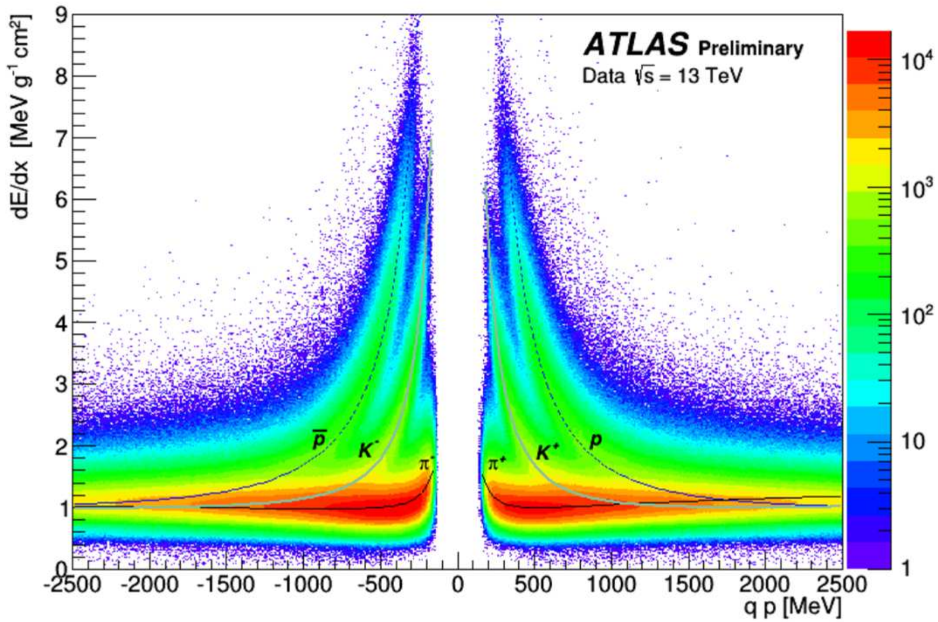
- B-Layer efficiency for muons measured by the ratio $\frac{N_{hits}}{N_{expected\ hits}}$ and its slight degradation with absorbed fluence:



dE/dx Measurement in Run 2

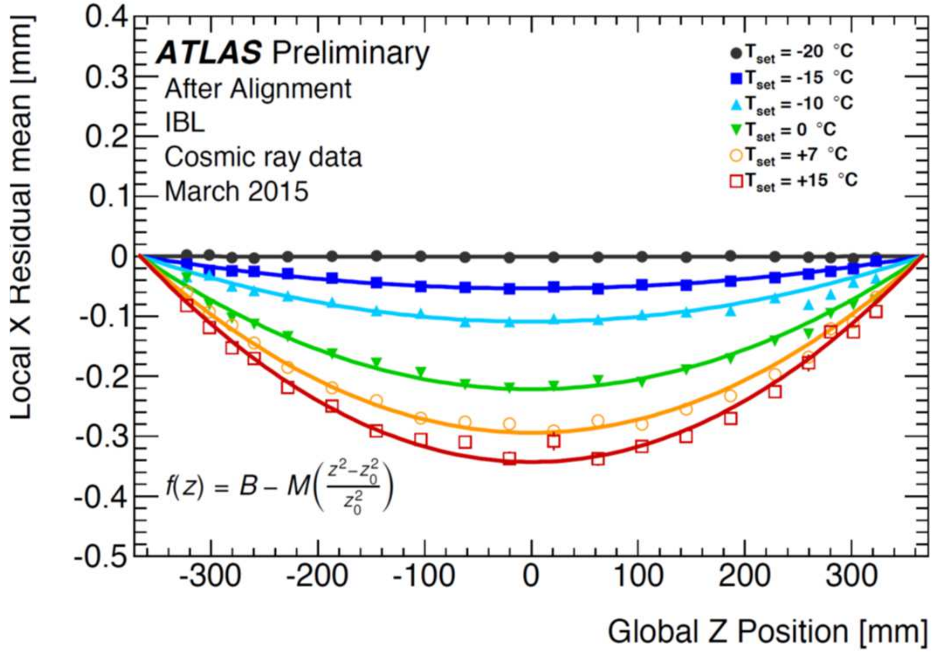
- Resolution on dE/dx improved with IBL:

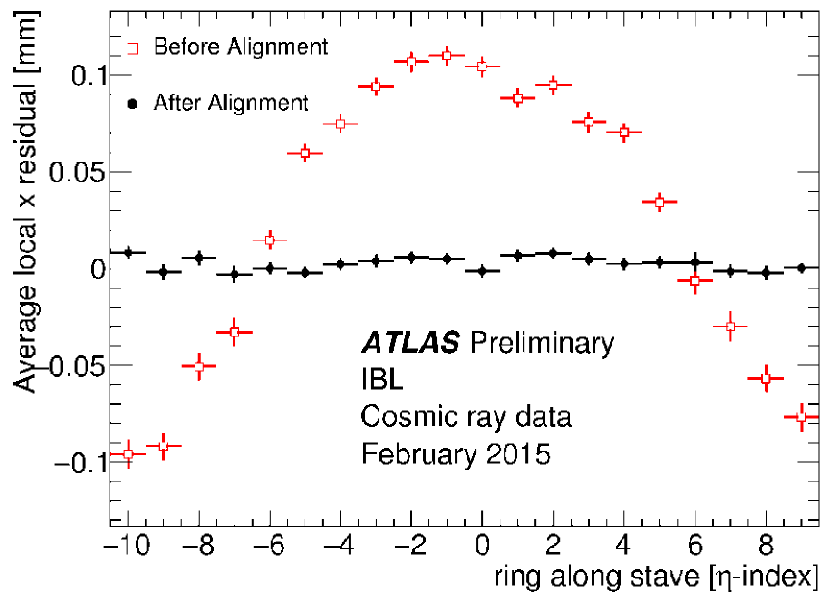




IBL Distorsions

- IBL stave distortion issue discovered during commissioning with cosmic rays in February 2015.
- It was found to be temperature dependent (10 µm/K).
- It was traced back to a CTE mismatch between the service flex and the stave structure, which bends the stave at operation temperature.
- Alignment performed for each run, to mitigate the effects on tracking, thanks to the achieved temperature stability (0.2 K rms).





Upgrades to Face Increasing Pile-up

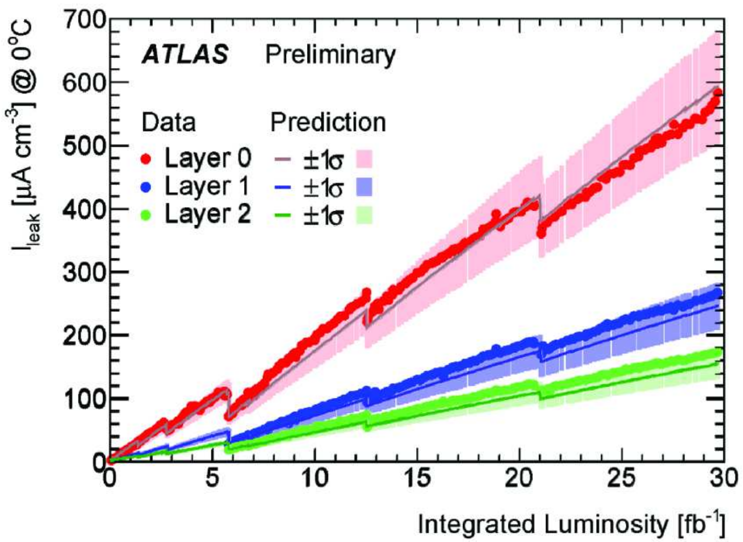
Module Link Occupancy at 100kHz L1					
	μ	B-Layer 160Mbps	Layer-1 160Mbps	Layer-2 80Mbps	Disks 80Mbps
Maximum in 2016	40	60%	81%* → 41%	119%* → 59%	75%
Maximum in Run 2	60	81%	103%* → 52%	159%* → 79%	96%
Maximum in Run 3	80	101%	125%* → 63%	188%* → 94%	115%

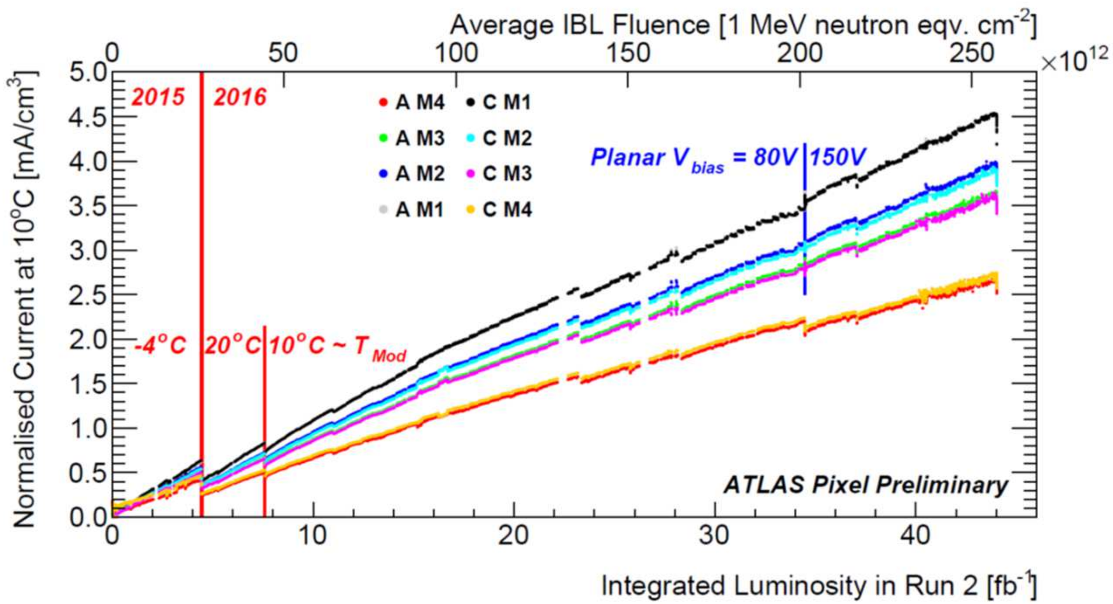
* Before upgrade

- Layer 2: IBL-like backend electronics installed and bandwidth doubled during 2015/2016 LHC stop.
- Layer 1: IBL-like backend electronics installed and bandwidth doubled during 2016/2017 LHC stop.
- B-Layer and Disks: IBL-like backend electronics to be installed in 2017/2018 LHC stop. For 2017, threshold increase for Disks is anticipated.

Radiation Effect on the Pixel Leakage Current

- Leakage current increases with absorbed fluence.
- Annealing periods are clearly visible.

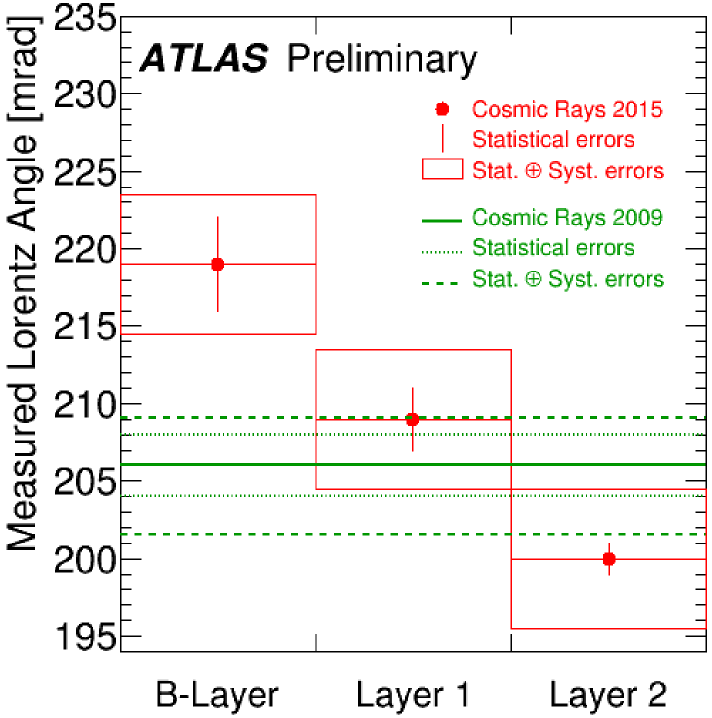




M1 groups: Most central in pseudorapidity
M4 groups: At the end of acceptance

Illustration of Radiation Damage Effects in Data

- Example: The Lorentz angle variation between commissioning with cosmic rays before Run 1 and before Run2.
- The low electric field region inside the bulk grows with absorbed fluence, leading to an increase of the Lorentz angle.
- Fluence decreases with radius: The Lorentz angle of the B-Layer is higher in Run 2 than in Run 1, while the Lorentz angle of the two other layers is still compatible with it.
- A simulation model is under construction and will provide soon a better data/MC agreement.



Conclusions and Future

- The 4-layer ATLAS Pixel Detector operates successfully during the LHC Run 2.
- IBL was subject to a few issues, all solved, without noticeable impact on the data quality nor on the ATLAS integrated luminosity.
- Readout upgrades to help in facing over-performance of LHC.

- A strategy is being discussed for the end of Run 2 (2017-2018) and Run 3 (2021-2023), to face luminosities of 2 and 3 $10^{34} cm^{-2} s^{-1}$ respectively. Luminosity leveling is also considered with LHC and other experiments.
- Radiation effects are being watched and modelised, to be able to exploit the ultimate potential of the detector.

- The whole ATLAS tracker will be replaced by the new ITK tracker in 2024-2025, for data acquisition at the High Luminosity LHC, starting in 2026.