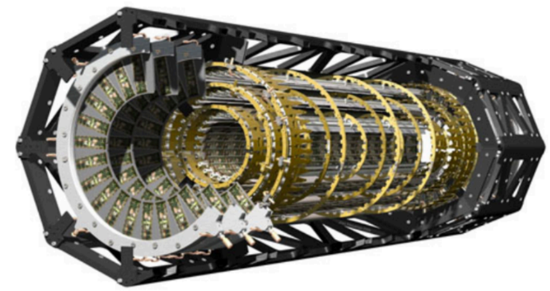
Operational Experience and Performance with the ATLAS Pixel Detector at the Large Hadron Collider



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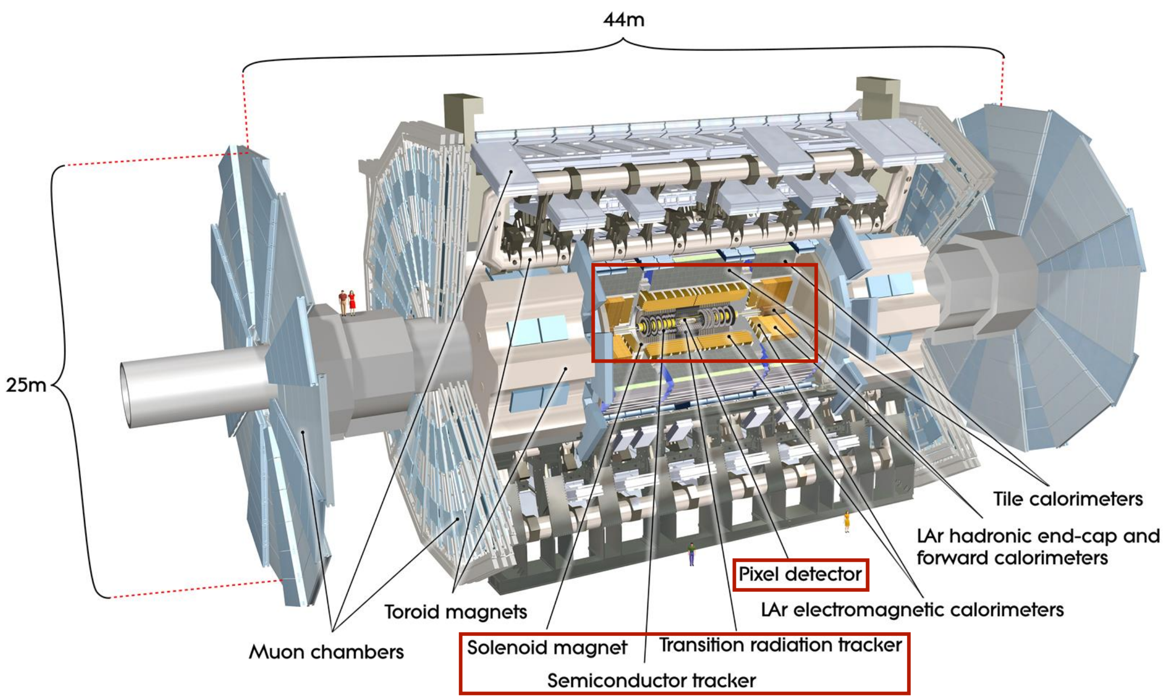
Vertex 2019, Lopud

14 October 2019

U.S. DEPARTMENT OF ENERGY Office of Science

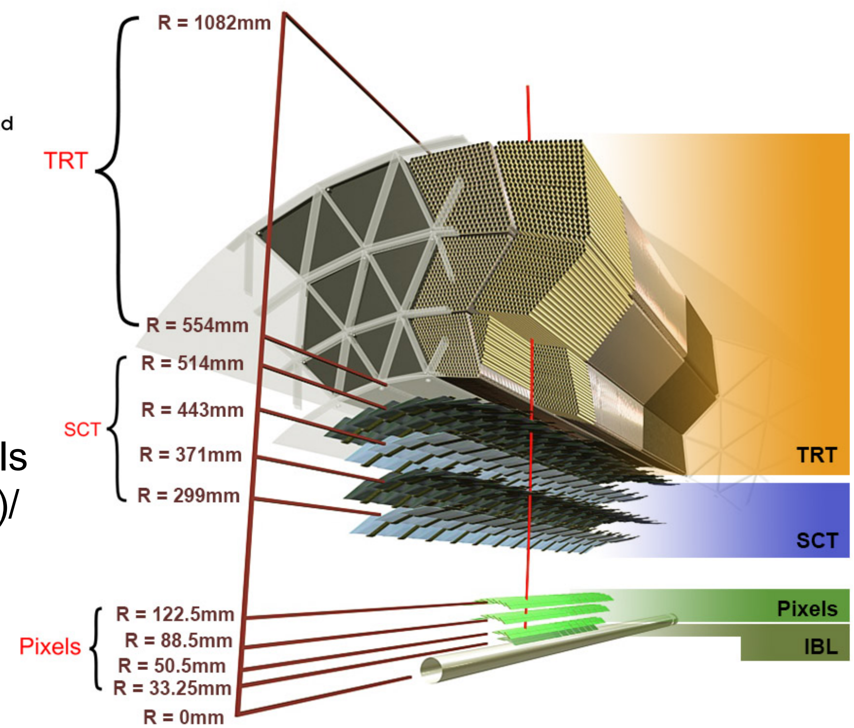
SLAC NATIONAL ACCELERATOR LABORATORY

The ATLAS Inner Detector



The ATLAS Inner Tracker:

1. Pixel Detector
2. Silicon Strip Detector (SCT)
3. Transition Radiation Tracker (TRT)



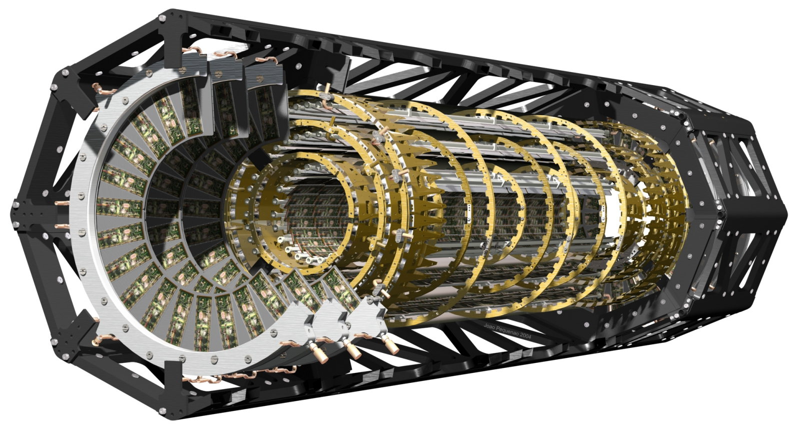
TRT:
- 35000 channels
- 130 μm resolution
- 4 mm element size

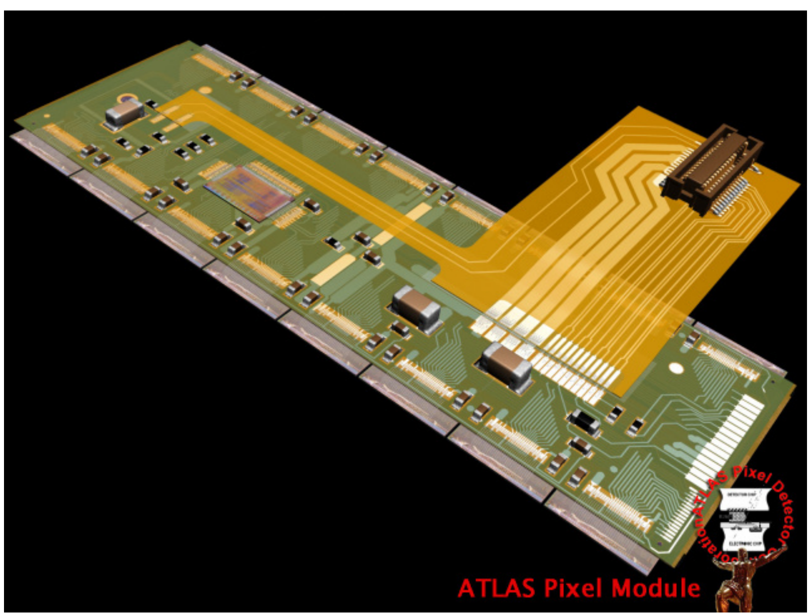
SCT:
- 6.3 million channels
- 17 μm x 570 μm resolution
- 130 μm x 12 cm element size

PIX/IBL:
- 92 million channels
- 10 x 115 μm (PIX)/ 8 x 40 μm (IBL) resolution
- 50 μm x 400 μm / 250 μm (IBL) element size

The Pixel Detector

- Three barrel layers and 2 x 3 endcap disks.
- Barrel radii 5.05 cm, 8.85 cm, 12.25 cm.
- Angular coverage $|\eta| < 2.5$
- 1744 modules.
- 1.7 m^2 of silicon.
- C_3F_8 evaporative cooling.
- 43 institutes participate.





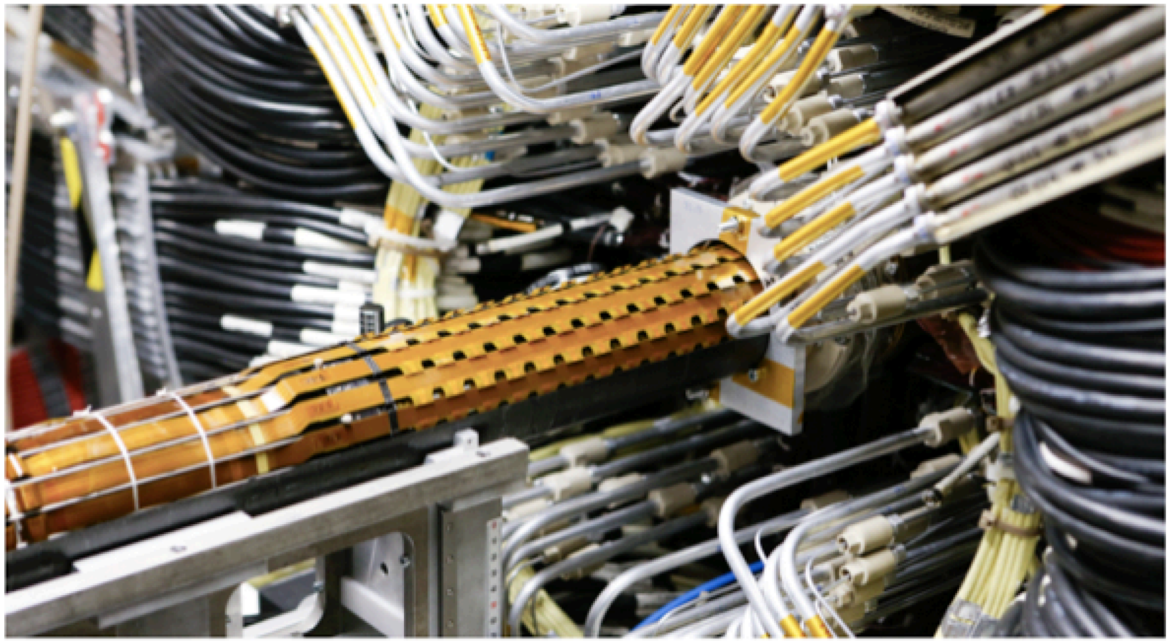
Each pixel module consists of

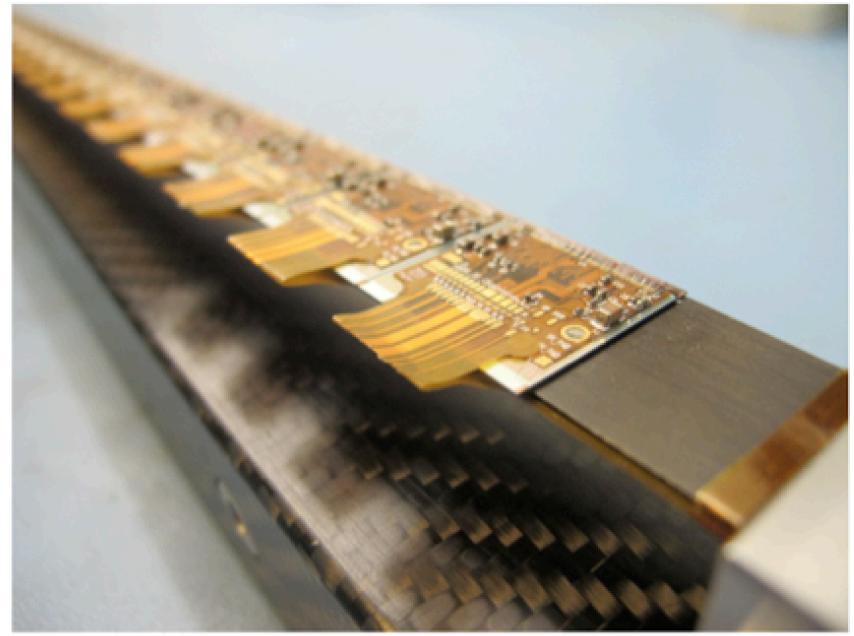
- 1 planar n-on-n sensor 60.8 mm x 16.4 mm active area, 250 μm thick.
- 16 FEI3 frontend chips plus one controller (MCC) in 0.25 μm CMOS technology.
- 1 flex that provides the electrical connections.

Additional properties:

- The frontends are bump-bonded to the sensors with solder and indium bumps.
- 46080 pixels per module.
- 8-bit Time-over-threshold information per hit.
- Radiation hard to $1 \times 10^{15}\ n_{eq}/cm^2$.

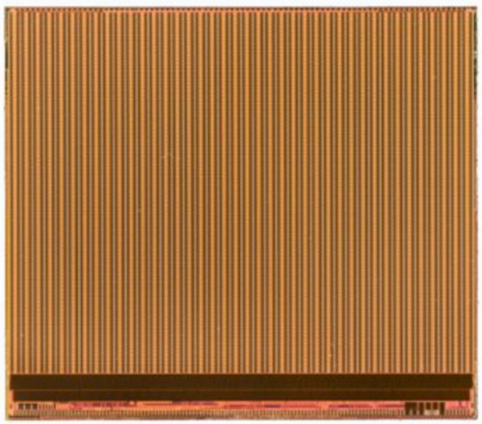
IBL (Insertable B-Layer)





- New innermost layer of the Pixel Detector, added in the 2013-2014 LHC shutdown.
- 14 staves in a turbine-like geometry at a radius of 3.2 cm.
- 448 FEI4 frontends.
- CO_2 evaporative cooling.
- Rad hard up to 5 x 10^{15} n_{eq}/cm^2.

IBL (Insertable B-Layer)

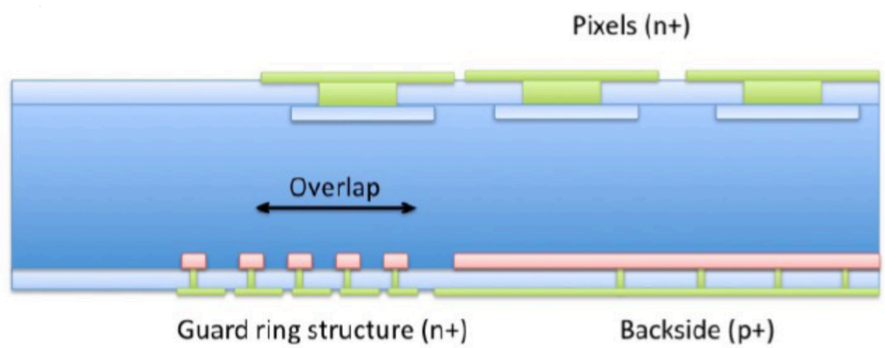


Sensors	Planar (n on n)	3D (2 columns)
Thickness	200 µm	230 µm
Area (frontends)	2	1
Usage in IBL	Central part	Outer parts

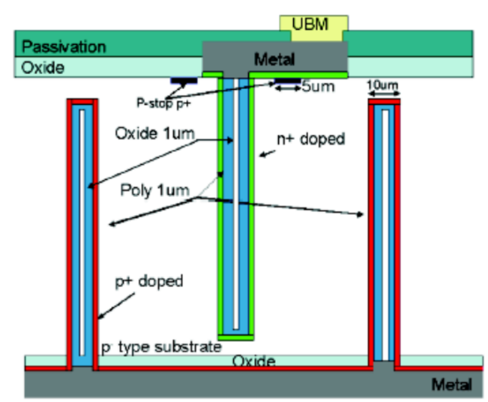
Frontend Chip (FEI4):

- 26880 pixels.
- 336 rows (phi) and 80 columns (z).
- 2 cm x 1.8 cm in size.
- 130 nm CMOS.
- Solder-bump-bonding to sensors.
- 4-bit time-over-threshold information.

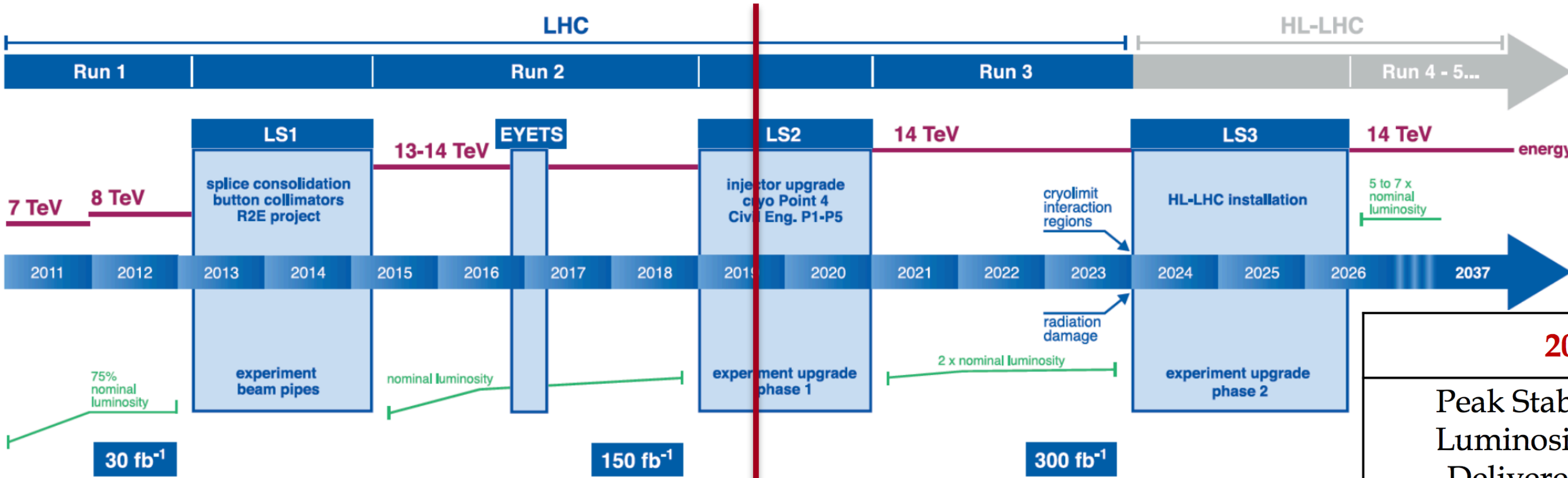
Planar

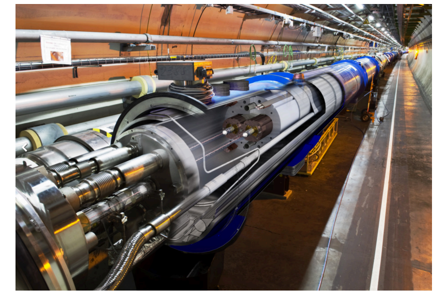


3D

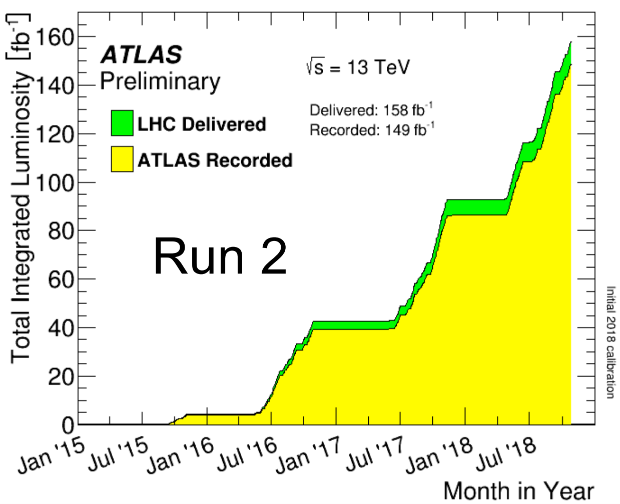


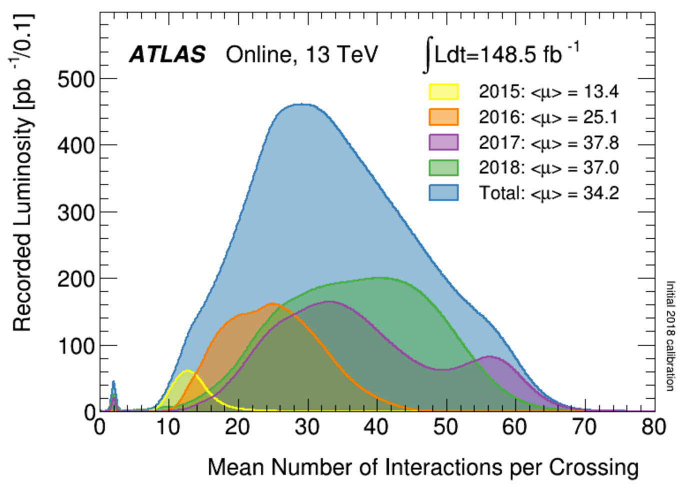
LHC Overview





Oct 2019, middle of LS 2





Three more years of data taking after LS2!

2018 LHC RECORDS	
Peak Stable Luminosity Delivered	2.14×10^{34} cm^{-2}s^{-1}
Maximum Average Events per Bunch Crossing	90.5
Maximum Stable Luminosity Delivered in one day	935.5 pb^{-1}
Maximum Stable Luminosity Delivered for 7 days	5.374 fb^{-1}
Fastest Turnaround to Stable Beams	1 hr, 46 min
Maximum Colliding Bunches	2544
Maximum Charge per Bunch Colliding	1.83×10^{11}
Average Specific Luminosity	6.94×10^{30} cm^{-2}s^{-1}(10^{11} p)$^{-2}$

Pixel Operations Overview

- Detector in great shape after 10 years of operation!
- Even though 2018 had the highest luminosity the deadtime was routinely below 0.2 % for both Pixel and IBL.
- DQ efficiency over the entire Run 2 at 99.5 %. In 2018 it was even 99.8 %.
- The non-operational fraction of modules is 4.5 % in total. Some of those can be recovered.

DQ Efficiency

ATLAS pp Run-2: July 2015 – October 2018										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.5	99.9	99.7	99.6	99.7	99.8	99.6	100	100	99.8	98.8
Good for physics: 95.6% (139 fb^{-1})										

Disabled Modules

Layer	Failures/Total	Percentage
Disks	15/288	5.2
B-Layer	18/286	6.3
Layer 1	29/494	5.9
Layer 2	33/676	4.9
Total (Pixel)	95/1744	5.5
IBL	3/448	0.7
Total	**98/2192**	**4.5**

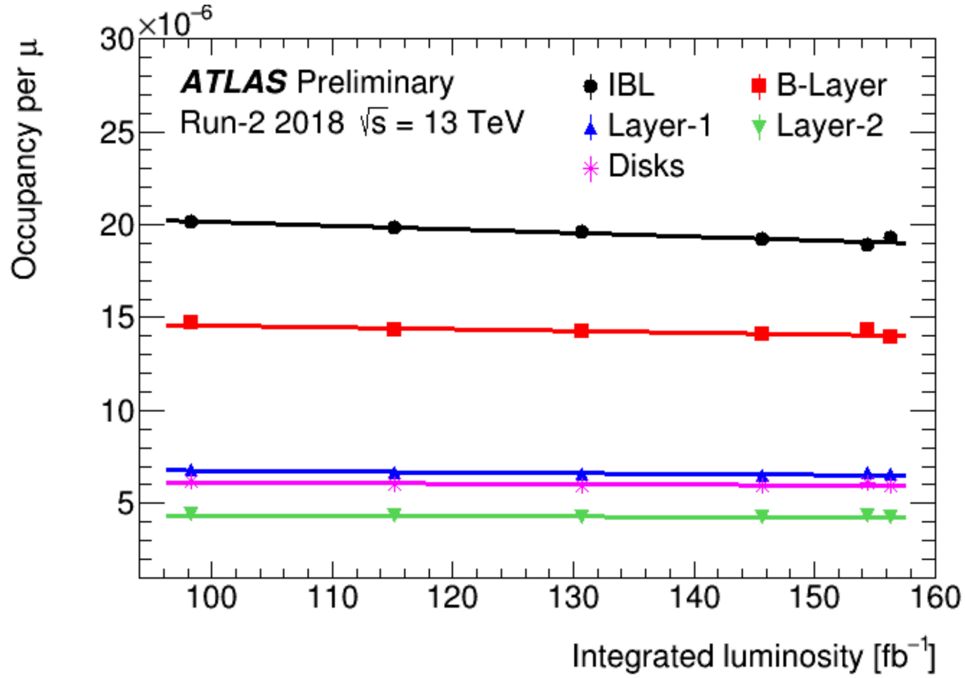
Threshold evolution

Thresholds in electrons

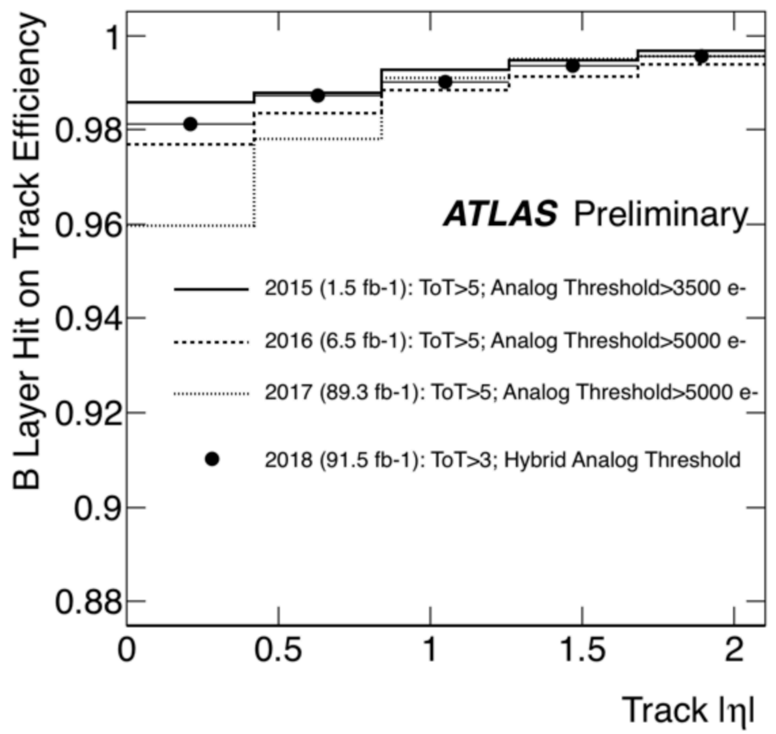
Layer	2015	2016	2017	2018
IBL	2500	2500	2500	2000
B-Layer	3500	5000	5000	4300*
Layer1/2	3500	3500	3500	3500
Disks	3500	3500	4500	3500

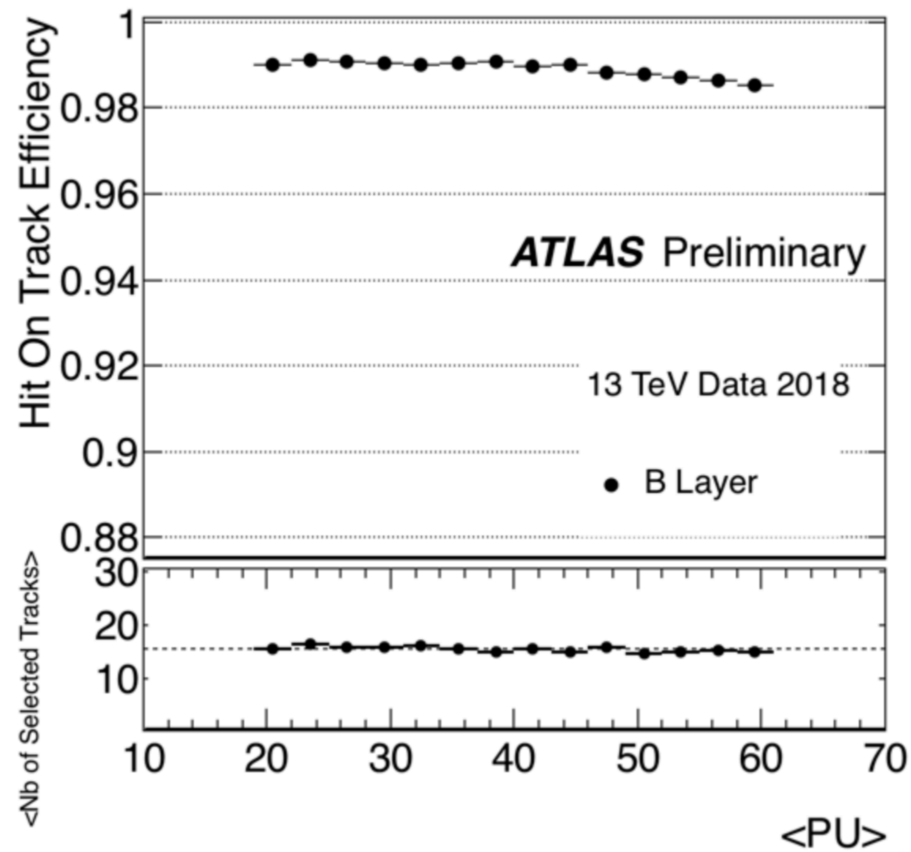
*Inner part of the B-layer only. Only digital threshold lowered for the outer part.

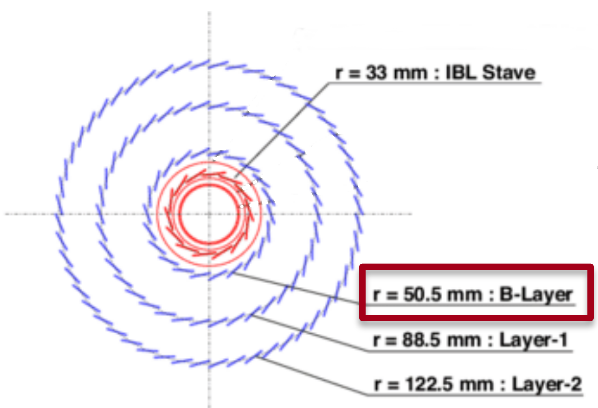
- Occupancy decreases over time due to radiation damage. The threshold can be decreased to counteract efficiency losses.
- On the other hand increased machine performance (high pile-up and trigger rate) requires an increase of the thresholds to keep bandwidth usage in range.
- **Reoptimize thresholds every year to keep the efficiency high while keeping the bandwidth manageable.**



Hit-on-track Efficiency in the B-layer

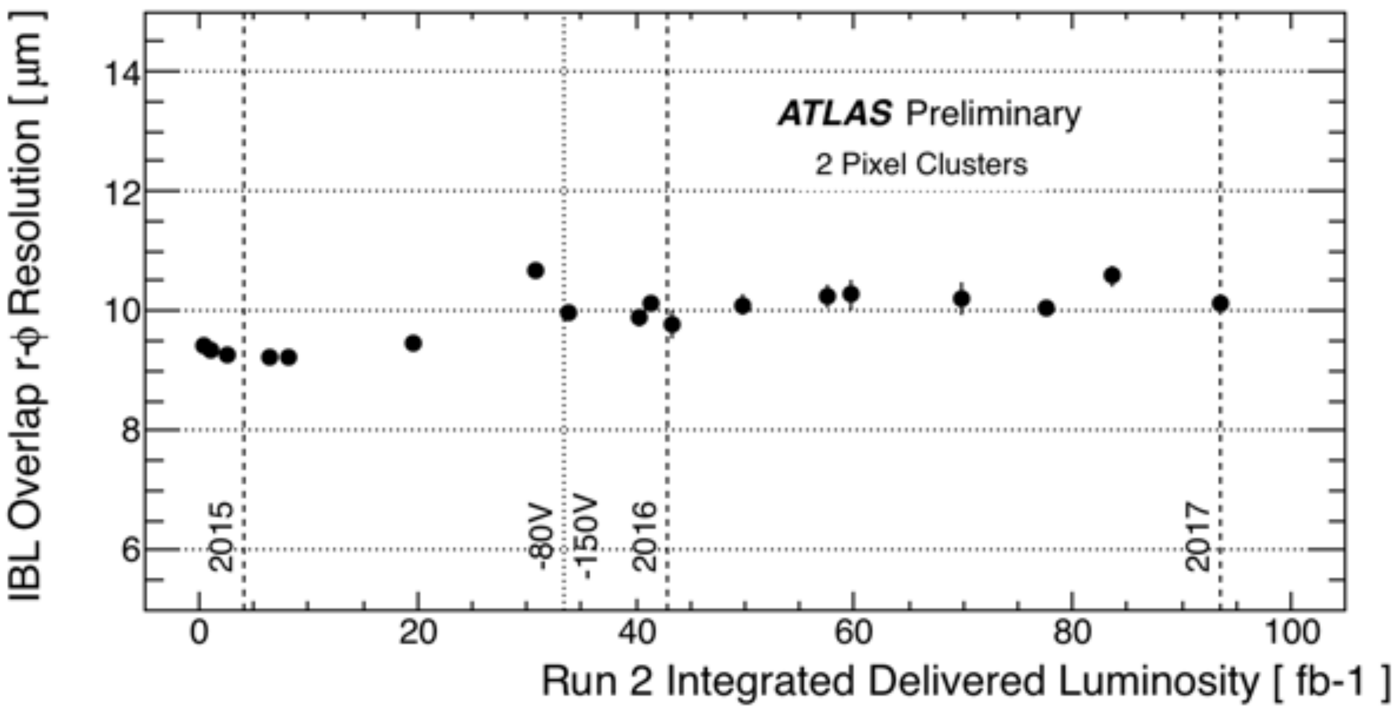


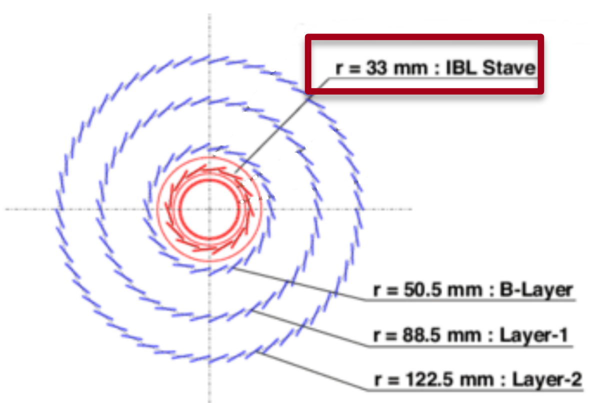




- The B-layer has the highest threshold because of bandwidth considerations.
- More radiation damage than other (old) Pixel layers.
- Almost full efficiency recovery after lowering thresholds!
- Good stability of efficiency at high pile-up.

IBL Spatial Resolution



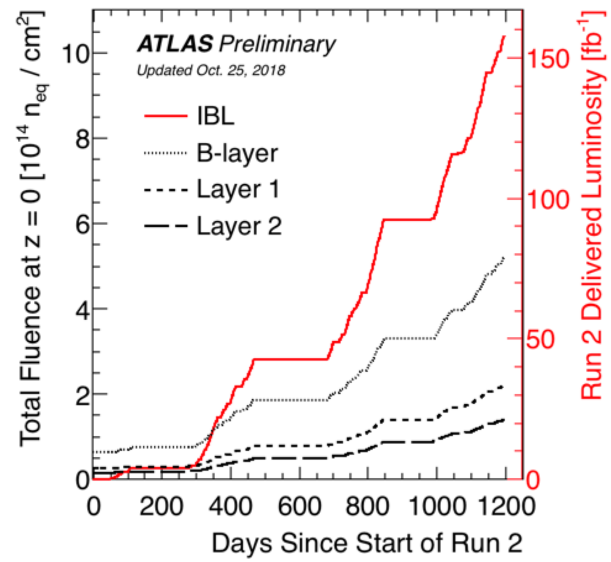


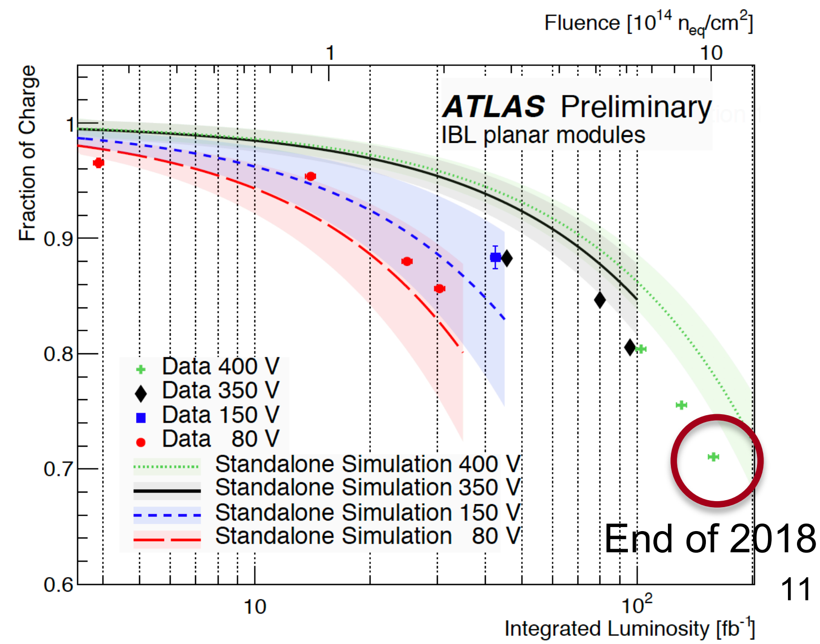
- The spatial resolution is very stable.
- Slight worsening after initial radiation dose.

Radiation Damage

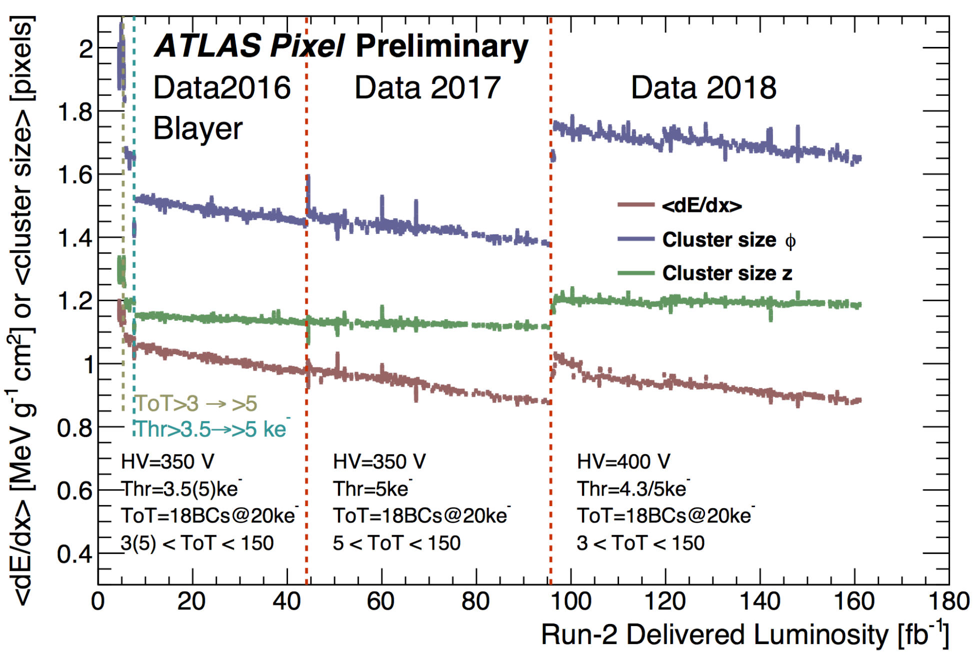
Layer	End of Run 2 [n_{eq} cm^{-2}]	Limit [n_{eq} cm^{-2}]
IBL	9×10^{14}	5×10^{15}
B-Layer	4.5×10^{14}	1×10^{15}

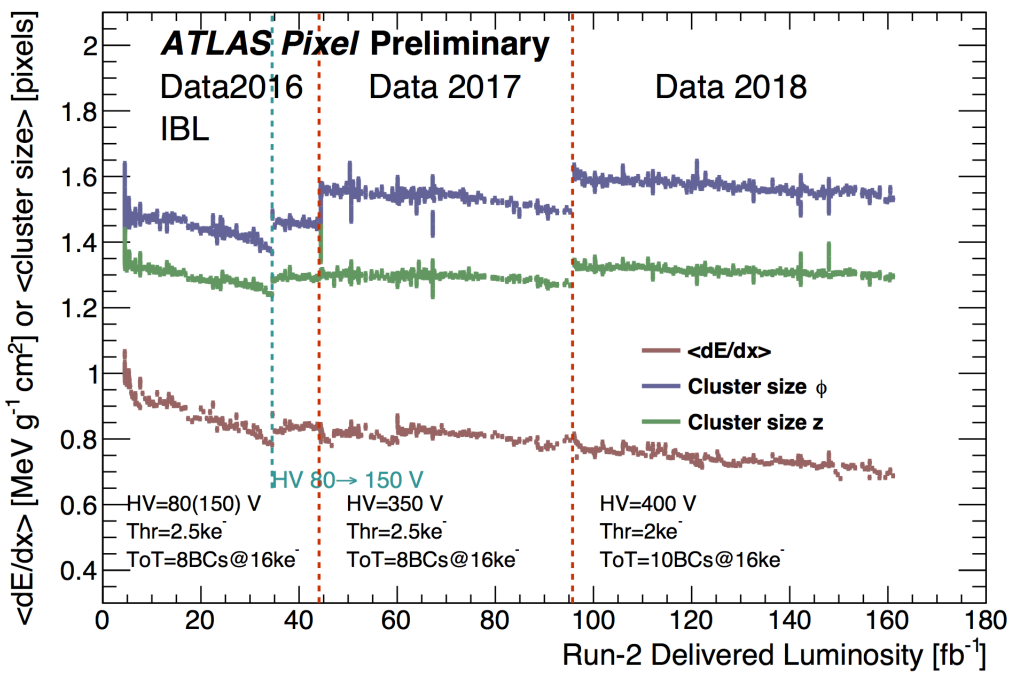
- Radiation damage effects are getting to be significant for the performance of the detector.
- We are now somewhere around 40 - 50 % of the total fluence depending on the luminosity in run 3.
- Models are used to understand and predict radiation damage effects.
- The ATLAS Monte Carlo now includes radiation damage effects.
- The operational parameters (HV, thresholds, temperature) can be adjusted to counteract the effects.





dE/dx



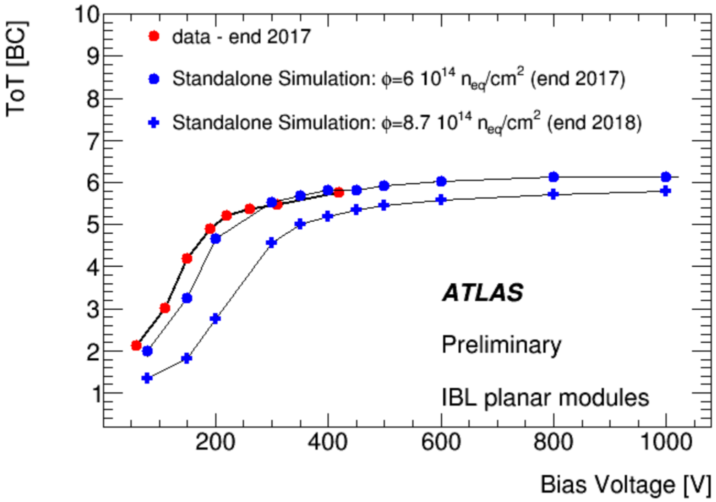


- Due to the decreasing charge collection efficiency the measured dE/dx decreases.
- Also the HV can have an influence if the detector is not fully depleted.
- Threshold changes show up as steps in dE/dx as well since hits below threshold do not get recorded.

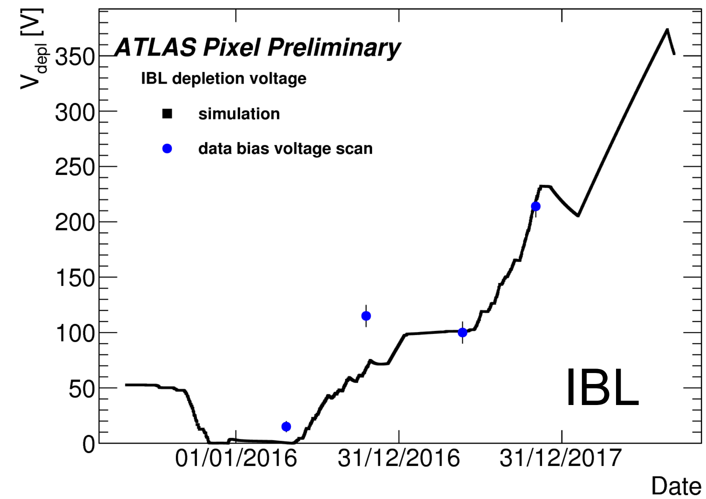
Depletion Voltage Evolution

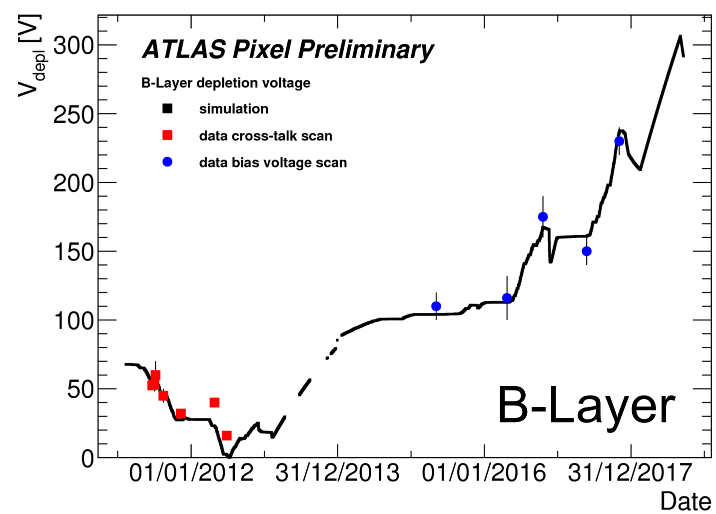
RUN-2 HV

HV	2015	2016	2017	2018
IBL	80V ⇨	150V ⇨	350V ⇨	400V
B-layer	250V	350V	350V	400V
Layer-1	150V	200V	200V	250V
Layer-2	150V	150V	150V	250V
Endcap	150V	150V	150V	250V



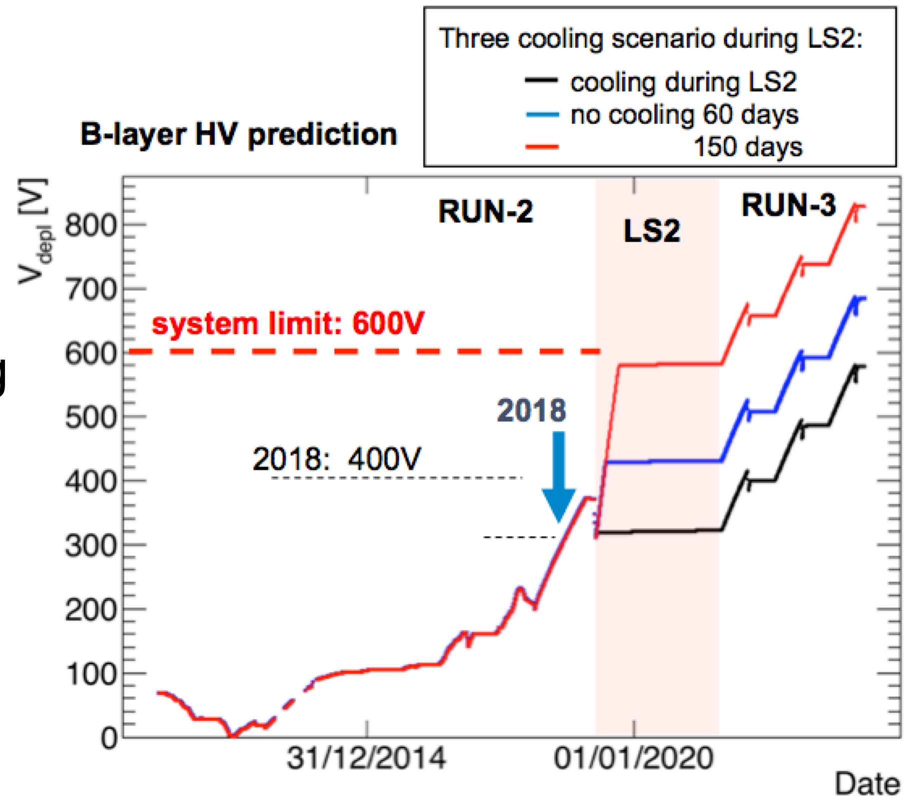
- The High Voltage settings are increased at each start of the year according to the predictions of the simulation in order to keep the sensors fully depleted for the entire year without having to readjust the voltage.
- The depletion voltage is monitored by plotting time-over-threshold against high voltage in special high voltage scans during collisions.
- The operational limit for IBL is 1000 V, for B-layer 600 V.





Reverse Annealing

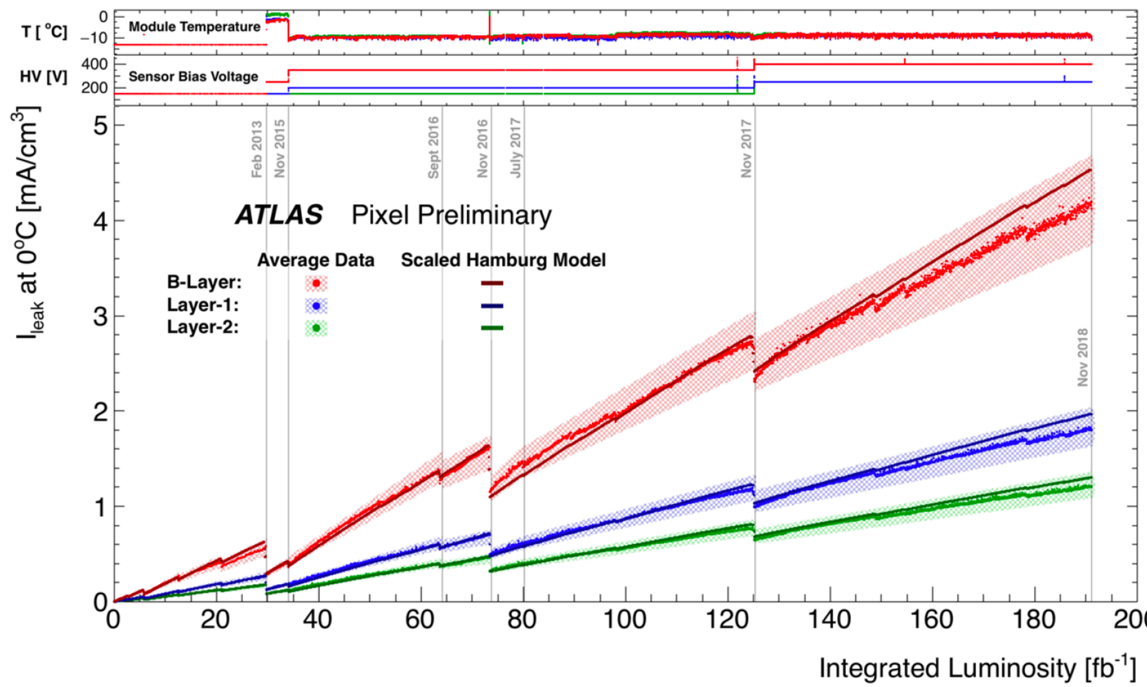
- Keeping the detector cold during the long shutdown is critical to prevent reverse annealing from driving the depletion voltage through the roof, in particular in B-layer and IBL.
- Unfortunately we cannot avoid warming up the detector because of several other projects requiring access to the inside of the inner detector, as well as maintenance on the cooling system.
- The target is to stay warm for less than 60 days during the shutdown.
- Up to now the detector was warm for 17 days.
- Expecting about 2 more weeks which would result in a total of 31 days.

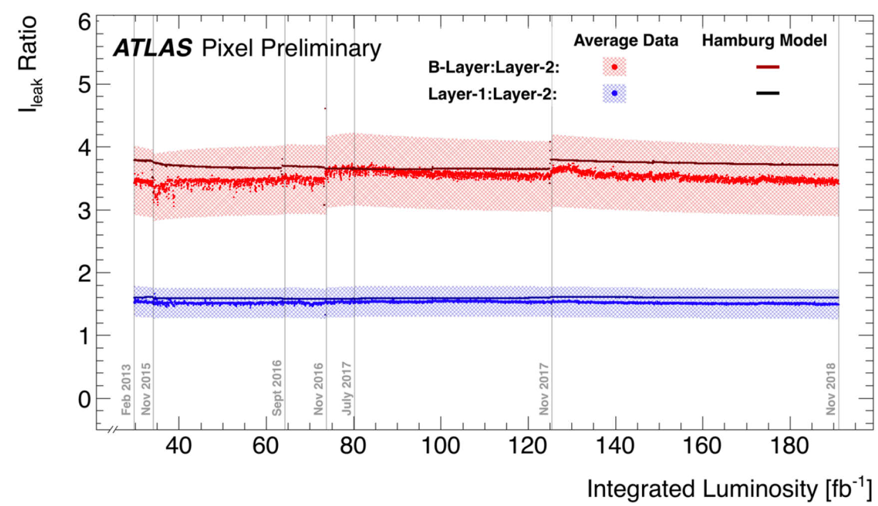


Keep Pixel cold whenever possible!

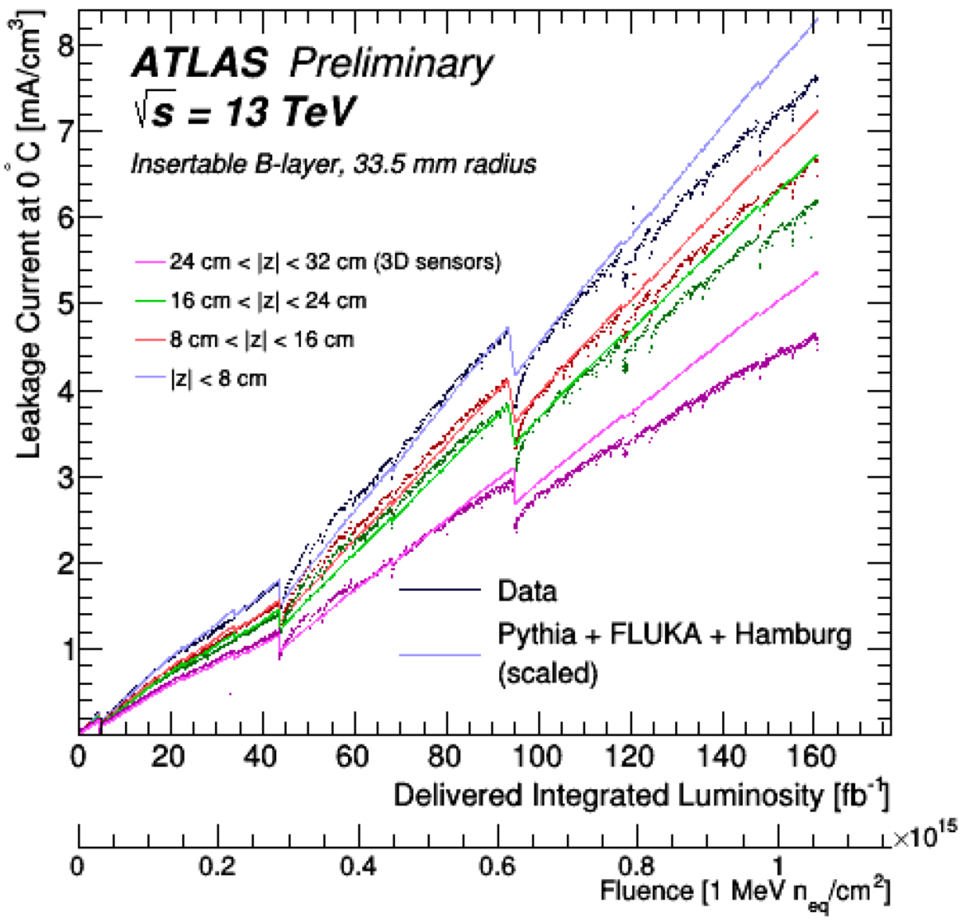
Leakage Current Pixel

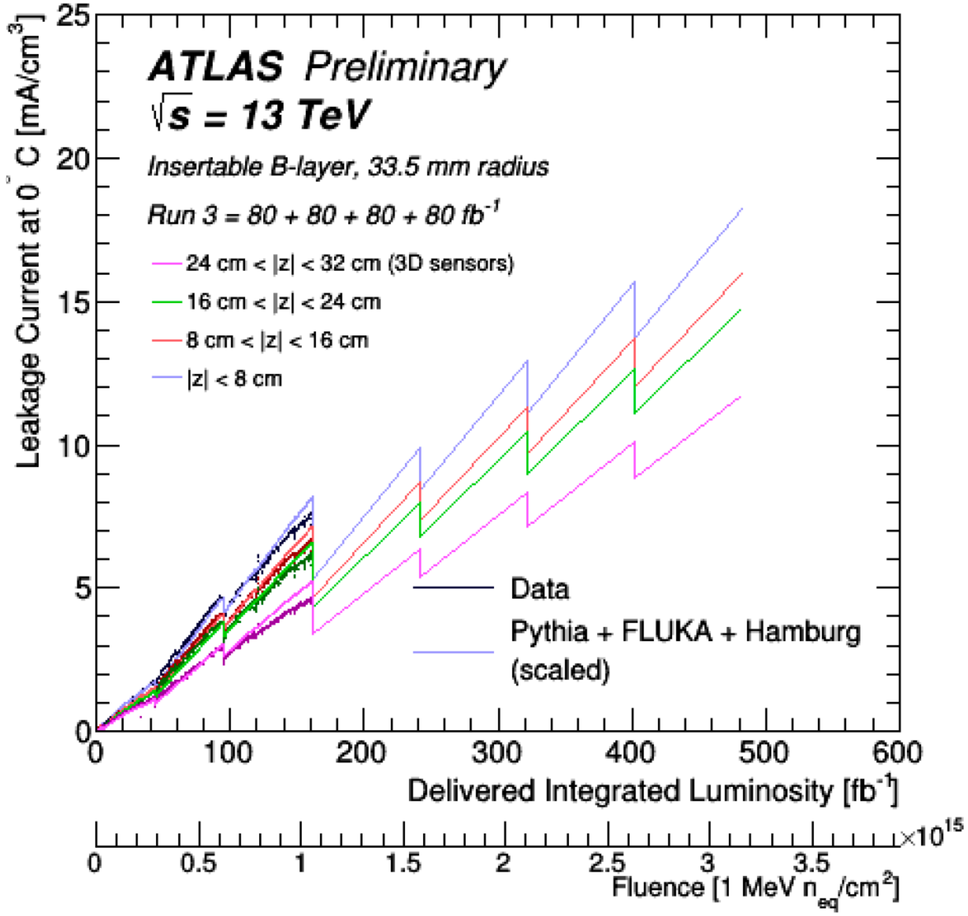
- The evolution of the leakage current can be described with the Hamburg model.
- Global scaling factors are, however required.
- Towards the end of run 2 the leakage current is overestimated.
- The ratio of the leakage currents between layers remains more or less constant.
- Predictions until the end of Run 3 indicate a final B-layer leakage current per module of 0.7 mA at -12^{o}C. The power supply can deliver 2 mA per module.





Leakage Current IBL

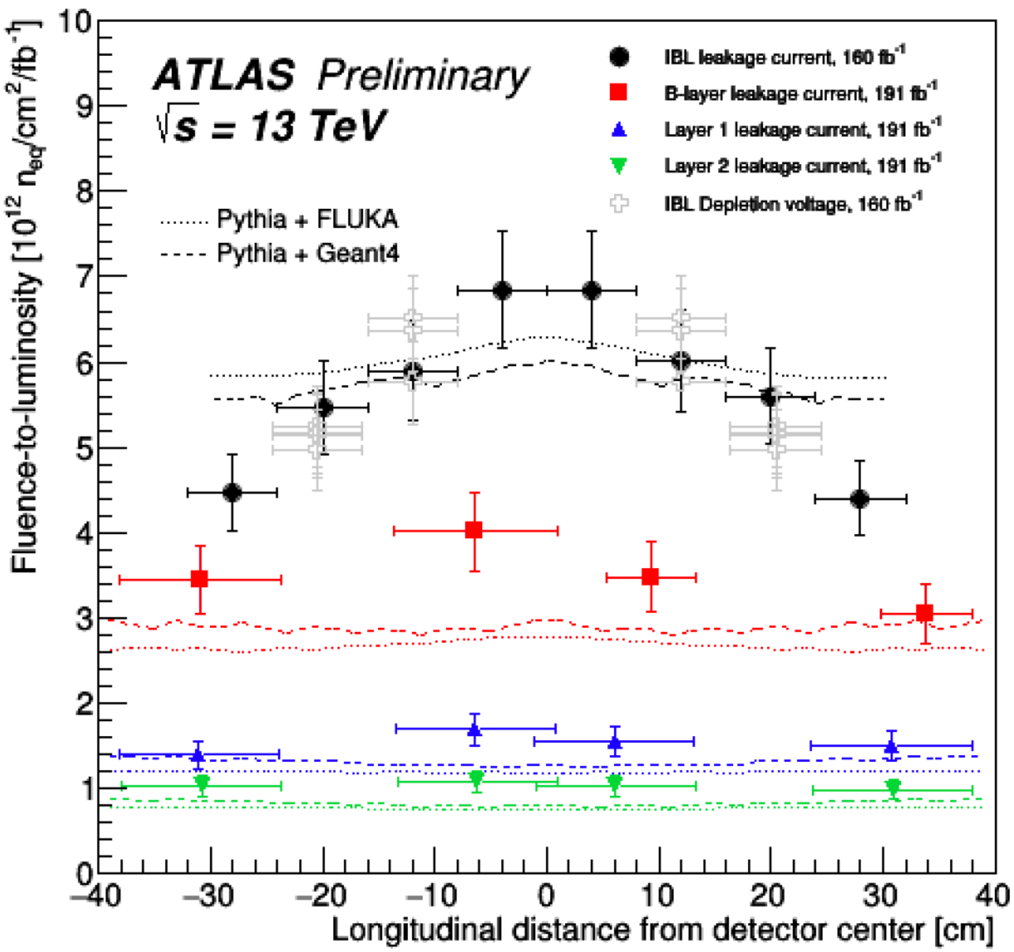




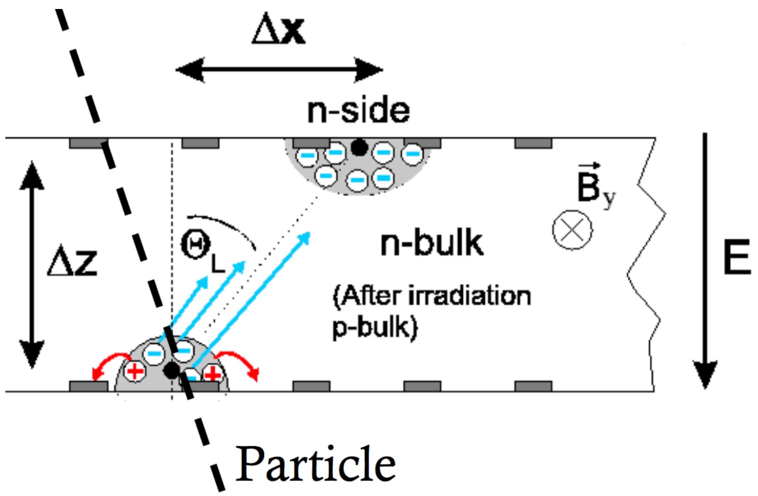
- Comparison of the IBL leakage current with the Hamburg model shows similar features as for Pixel.
- A scaling factor per z range is needed to match the Hamburg model.
- Towards the end of run 2 the leakage current is overestimated by the model.
- At the end of run 3 (worst case, assuming 4 years of 80 fb^{-1}) the leakage current at $0^{o}C$ reaches up to 2.9 mA per sensor. The HV power supply can deliver almost twice that that so there is good margin.

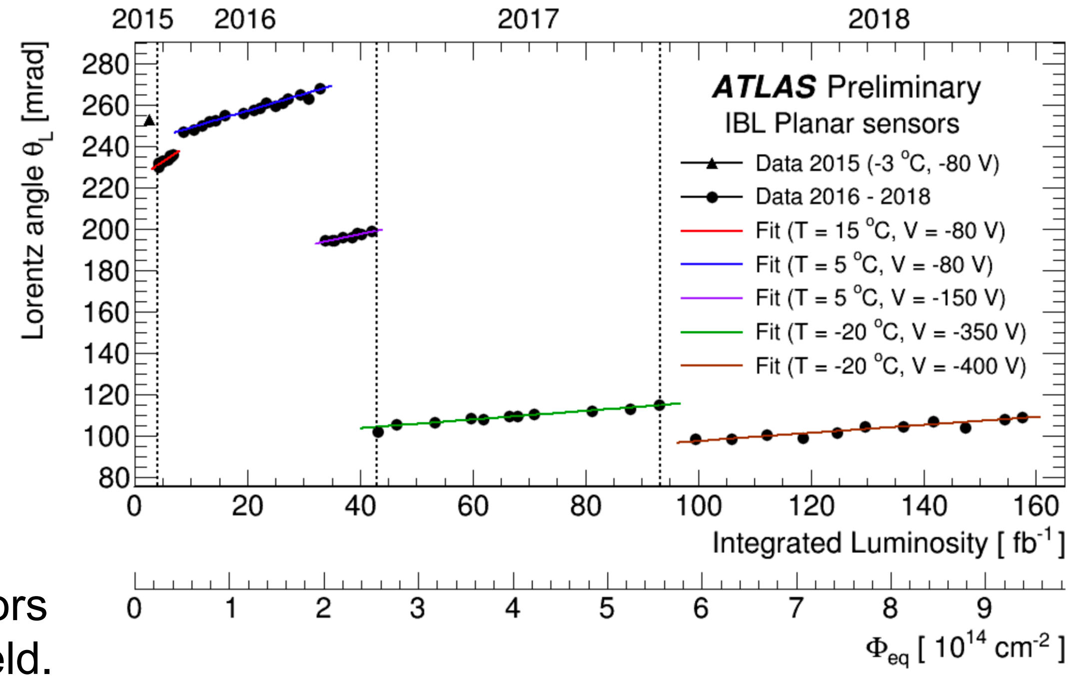
Fluence vs. z

- Comparison of simulated fluence with the fluence obtained from the leakage currents using the Hamburg model.
- Simulated fluence for Pixel slightly below leakage current fluence.
- IBL simulated fluence quite flat along z. The leakage current fluence has a strong z dependence.
- The z dependence is also observed in the depletion voltage.

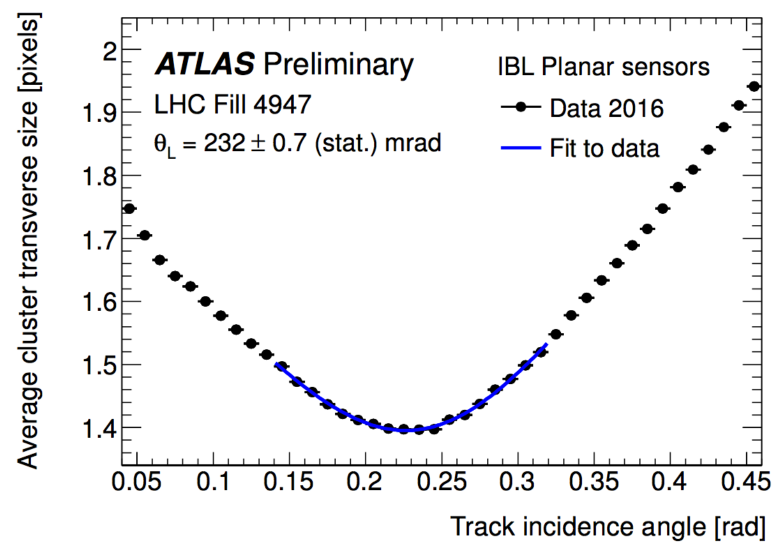


IBL Lorentz Angle



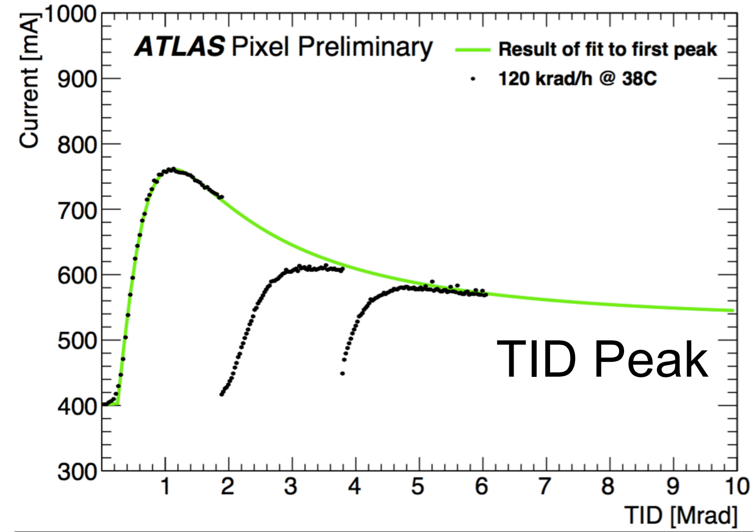


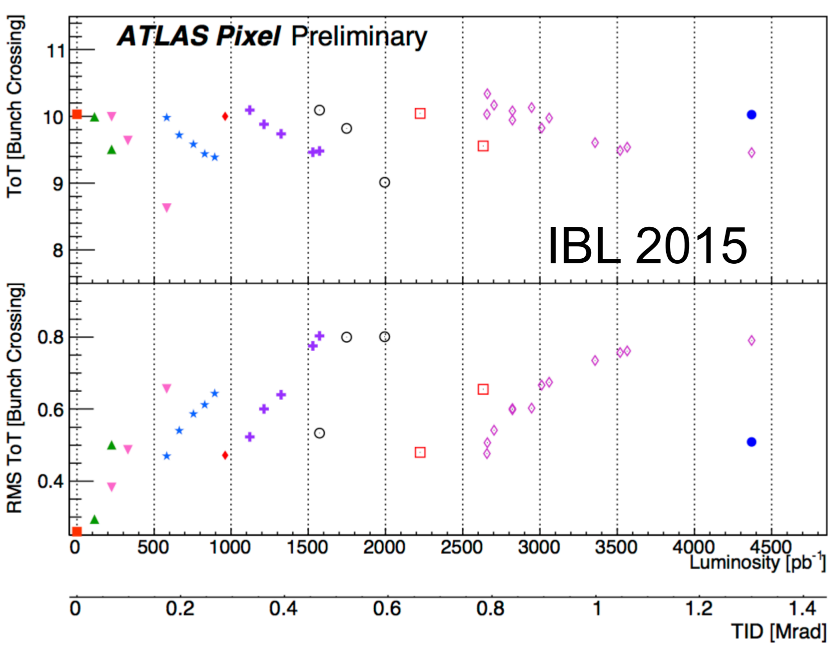
- Charges drift transversally in planar sensors because of the perpendicular magnetic field.
- The angle between electric field and the drift direction is called the Lorentz angle.
- This effect introduces a bias on the cluster position reconstruction.
- The electric field changes with radiation damage.
- This results in a drift of the Lorentz angle with integrated luminosity (lower plot).

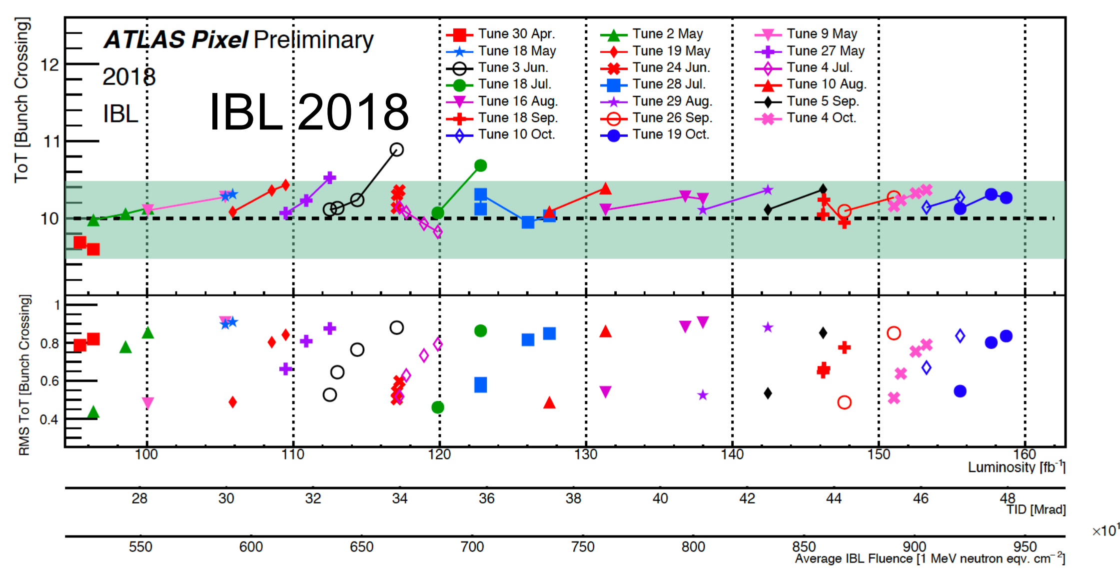


Calibration Drift

- The leakage currents inside the transistors of the FEI4 readout chip (130 nm IBM process) show a strong dependence on TID with a peak at 1 Mrad.
- The leakage currents have a direct impact on the tuning of feedback currents and thresholds.
- In 2015 we were on the rising edge of the TID peak. Now we are on the falling edge.

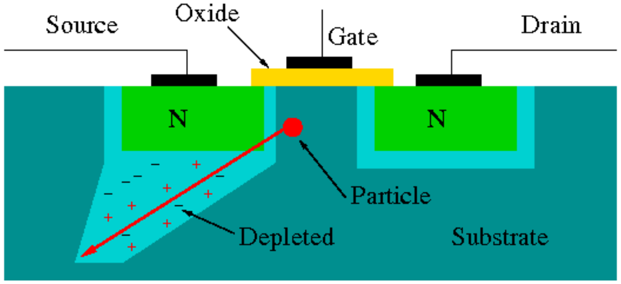


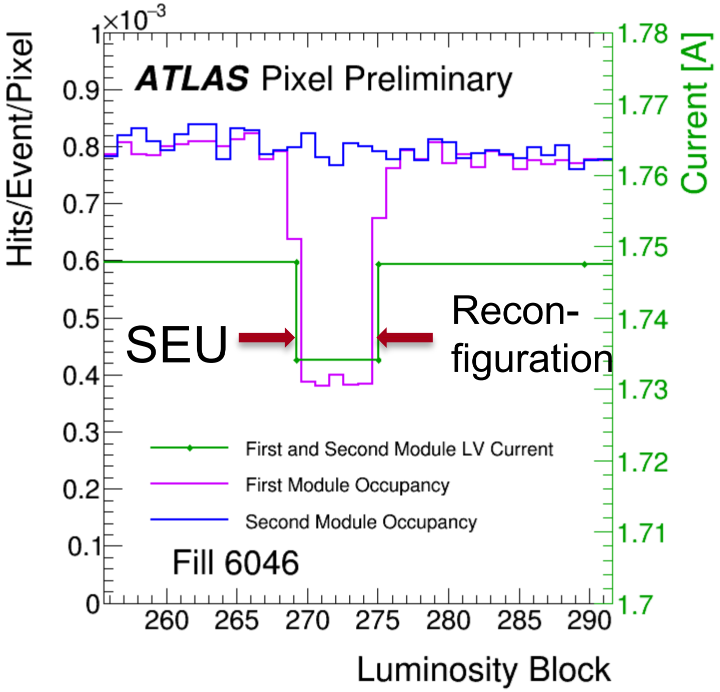




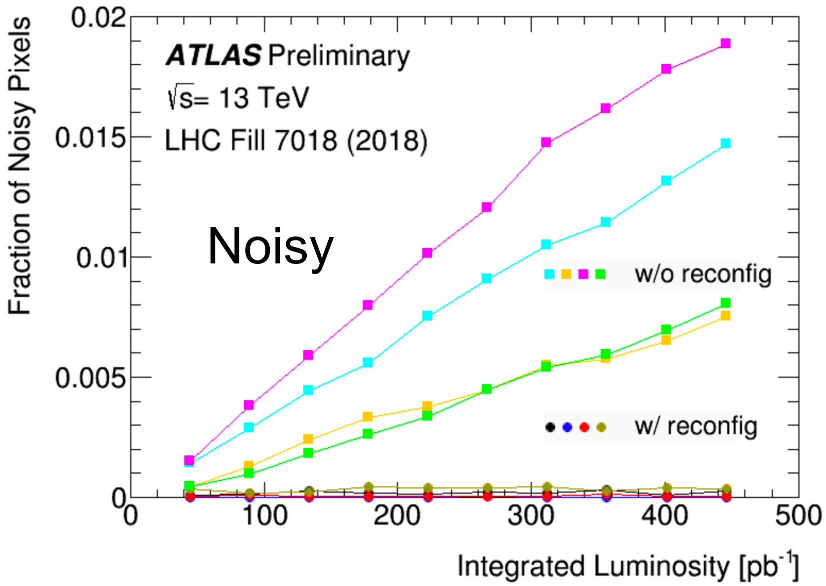
Single Event Upsets

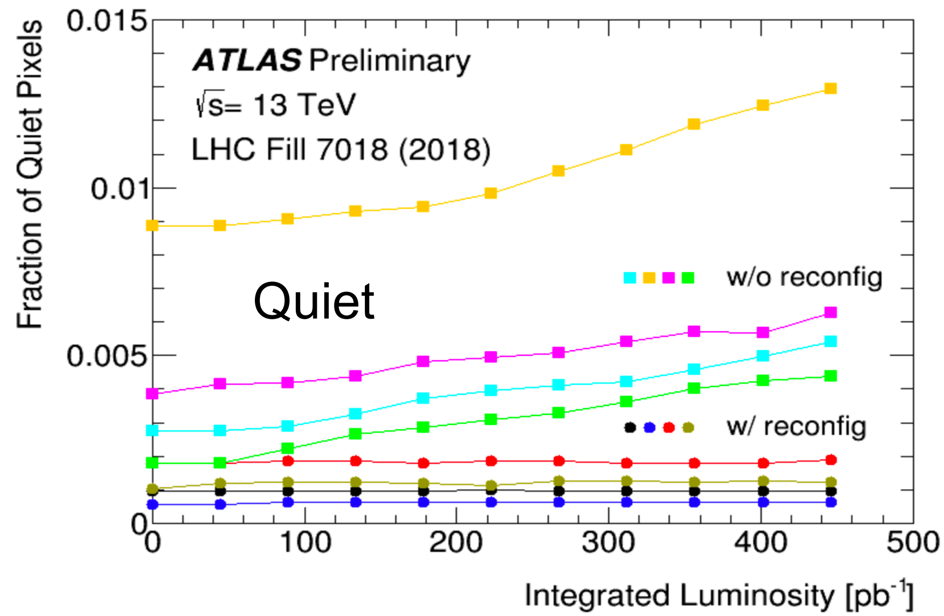
- Particles crossing the frontend chip can cause register settings to be corrupted.
- The consequence of a global register being upset is often a drop in occupancy or a change in current consumption.
- The global registers in the FEI4 are implemented as triple DICE latches.
- The main upset mechanism are glitches on the load line (SET).
- As a countermeasure the global registers in IBL are reloaded during a 2 ms gap that is provided by ATLAS every 5 s without incurring any deadtime.



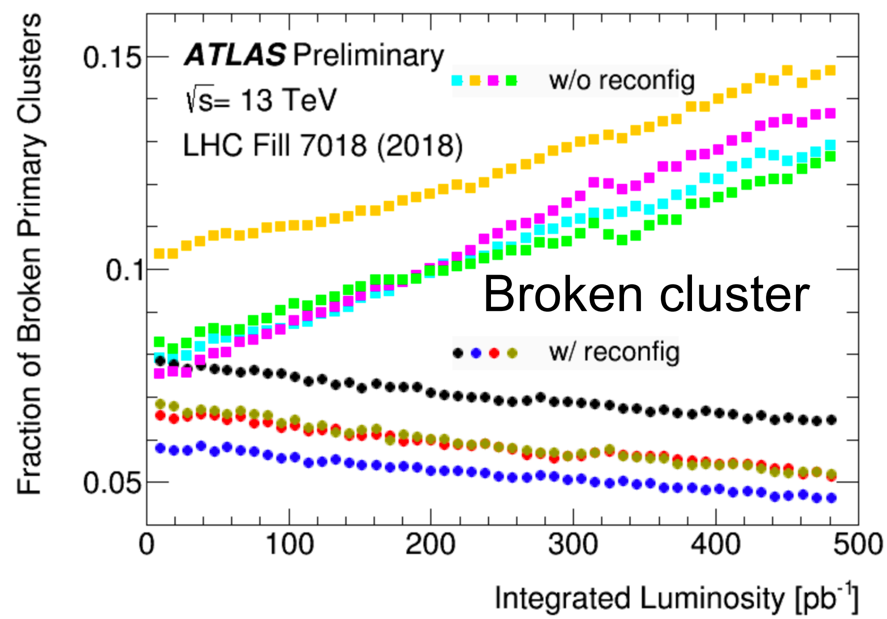


SEUs in Single Pixels



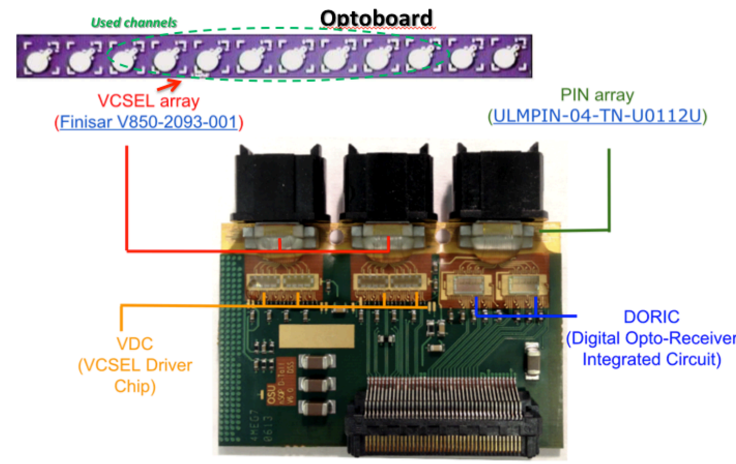


- SEUs can cause single pixels to become noisy if the threshold DAC setting is affected.
- SEUs can also cause pixels to become quiet if the enable bit is hit.
- It is not possible to reconfigure the entire frontend every 5 seconds.
- Instead a scheme was implemented to partially reconfigure every 5 seconds which results in full reconfiguration every 11 minutes.
- Tested in Run 2, full deployment in Run 3.

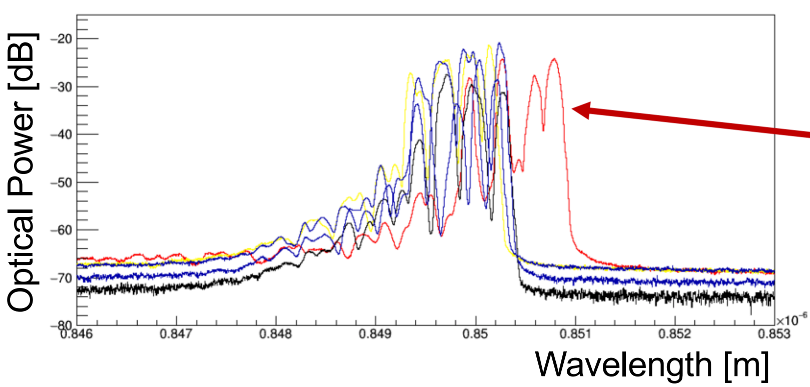


Optoboard Replacement

- The main hardware issue that Pixel is experiencing is a high failure rate of the VCSELs used for data transmission on the detector.
- The failures started about 2 years after installation of the optoboards.
- The cause of the failures is not known, possibly humidity or thermal cycling of VCSELs during operation due to non-DC-balanced transmission.
- About 30 boards were replaced before the run of 2018.
- 20 additional VCSELs have died since then.



In 2020 all suspicous optoboards will be replaced!

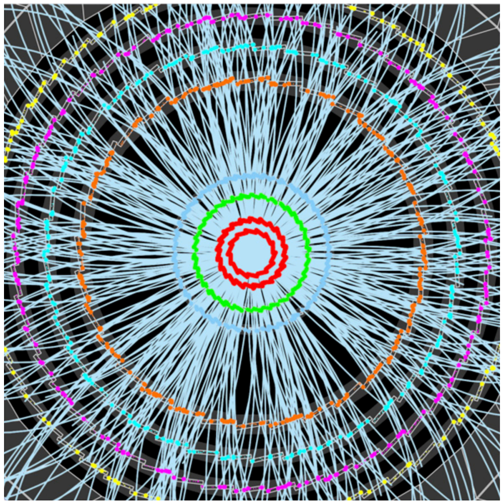


Shifted spectrum predictor for death long before failure.

VCSEL light from data fiber

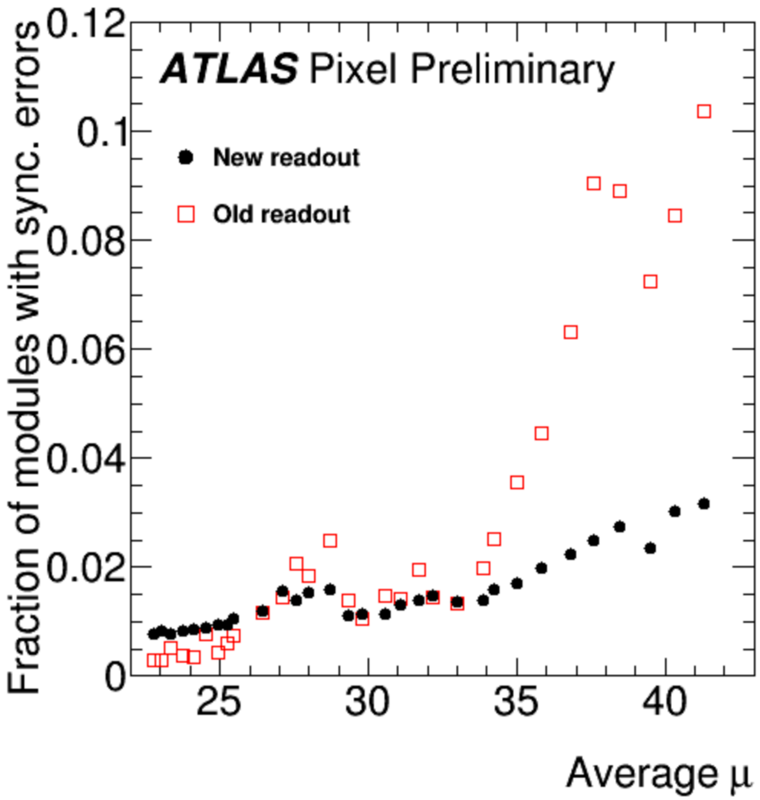
Summary and Conclusion

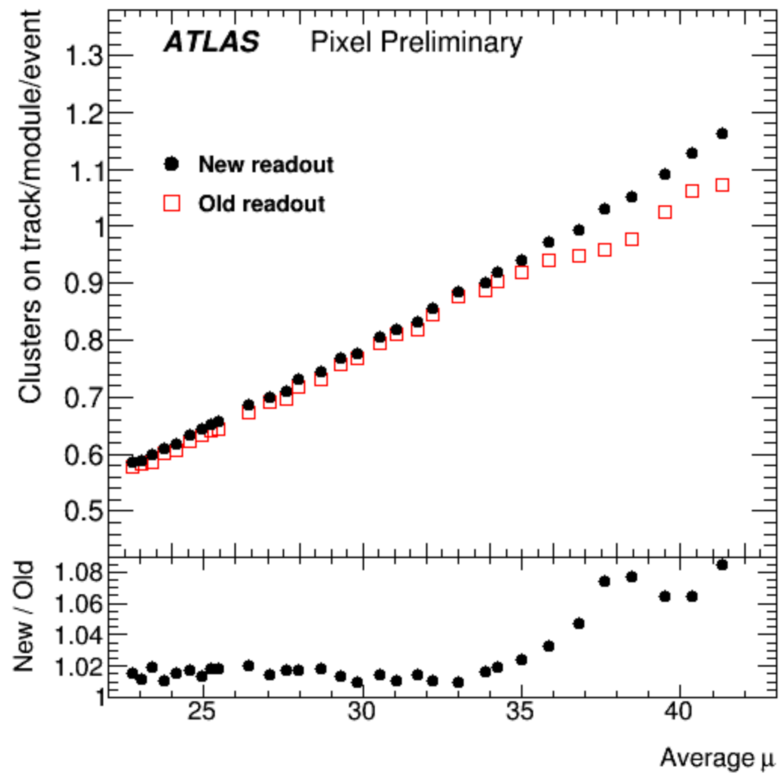
- LHC Run 2 is over.
- The ATLAS Pixel detector has delivered excellent performance.
- Radiation damage is becoming noticeable.
- The operational parameters have to be retuned to guarantee optimal data quality and efficiency.
- LHC is in shutdown for two years. For Pixel the biggest project is the replacement of the optical data transmitters on the detector.
- Three more years of running in Run 3.



Backup

Desynchronization

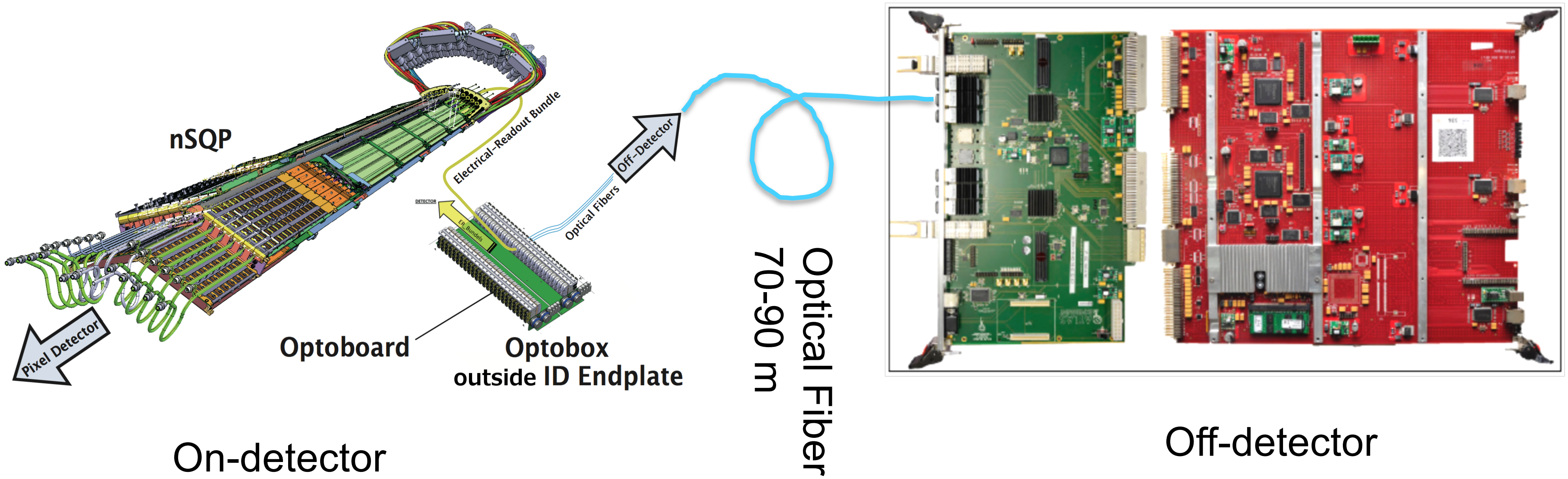




- Luminosity and pile-up are much larger than originally specified.
- High occupancy can lead to buffer overflows resulting in event fragments being associated with the wrong event (“desynchronization”).
- A periodic reset of the frontend ASICs and of the firmware in the backend every 5 seconds was introduced to resynchronize all data sources.

Substantially improved data taking efficiency!

Readout System



- On-detector (as of 2014):
  - Readout per module (no multiplexing) at 80 Mbps (Layer 2, disk 1/3) and 160 Mbps (others).
  - Configuration and commands to the modules at 40 Mbps.
  - 6.6 m (IBL 5 m) of twisted pair electrical readout cable.
  - Conversion into optical signals on ID endplate.
- 70-90 m of optical rad-hard multimode fiber.
- Off-detector (now unified using IBL readout hardware everywhere):
  - 116 Back-of-crate cards (BOC) and readout drivers (ROD) in VME crates.
  - 2 (4) s-link fibers for Pixel (IBL) data output at 160 MB/s per s-link.
  - Spartan 6 and Virtex 5 FPGAs.
  - PowerPC on Virtex 5 (ROD) heavily used for configuration and monitoring.