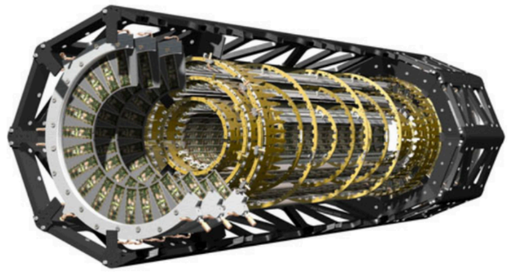
Operational Experience and Performance with the ATLAS Pixel Detector at the Large Hadron Collider



Martin Kocian *for the ATLAS Collaboration*

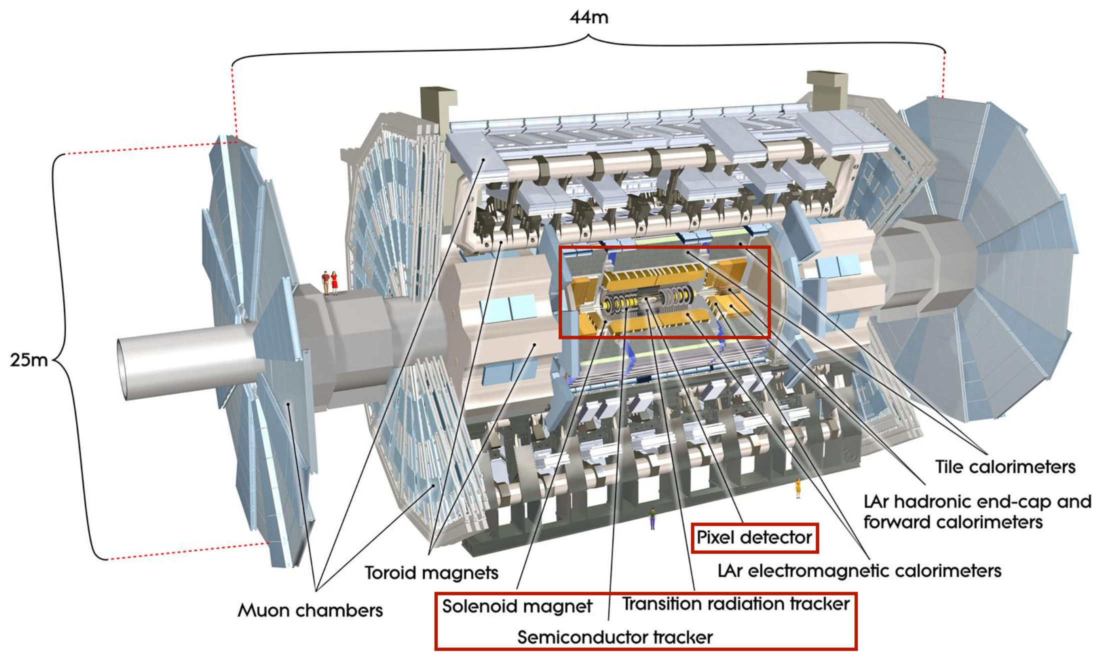
PIXEL 2018, Taipei

10 December 2018

U.S. DEPARTMENT OF ENERGY Office of Science

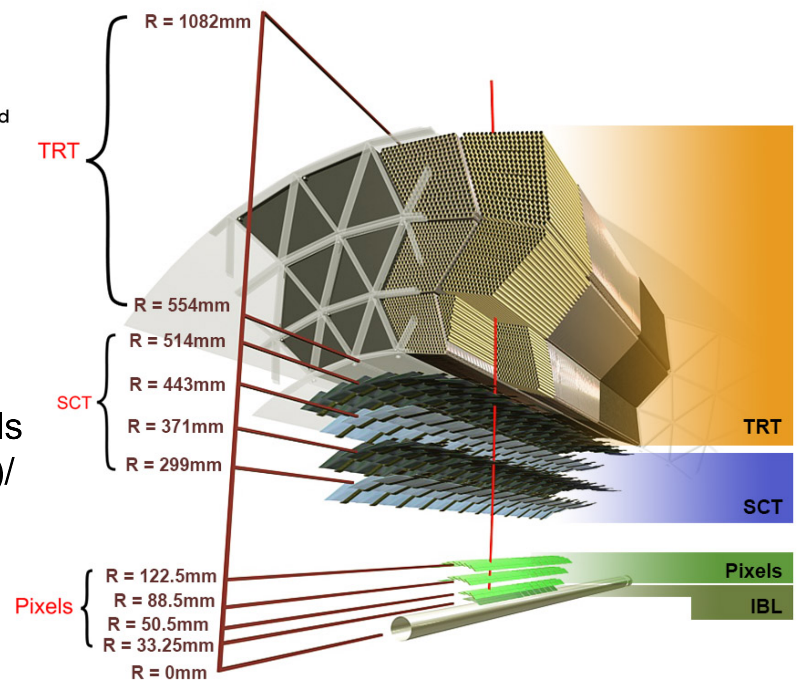
SLAC NATIONAL ACCELERATOR LABORATORY

The ATLAS Inner Detector



The ATLAS Inner Tracker:

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



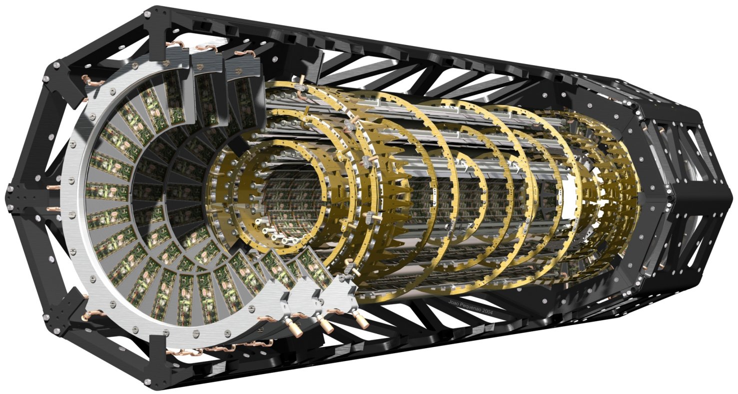
TRT:
- 35000 channels
- 130 μm resolution
- 4 mm element size

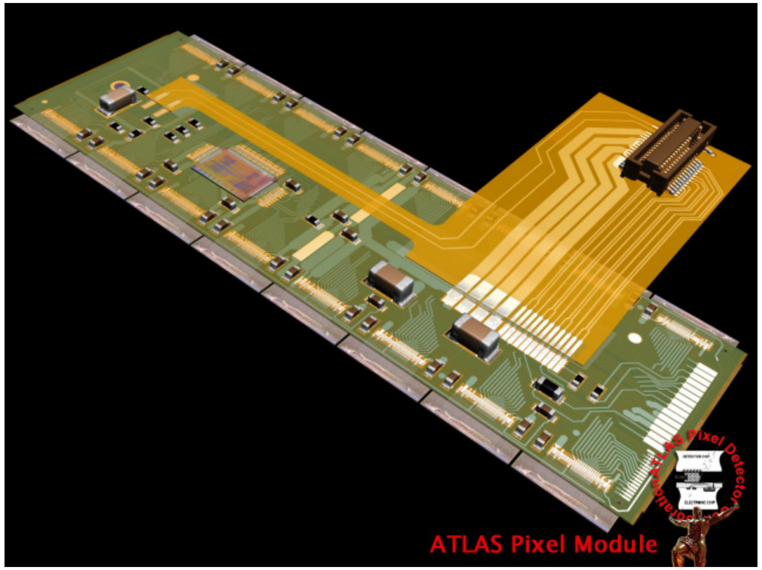
SCT:
- 6.3 million channels
- 17 μm x 570 μm resolution
- 130 μm x 12 cm element size

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.
- 41 institutes participate.





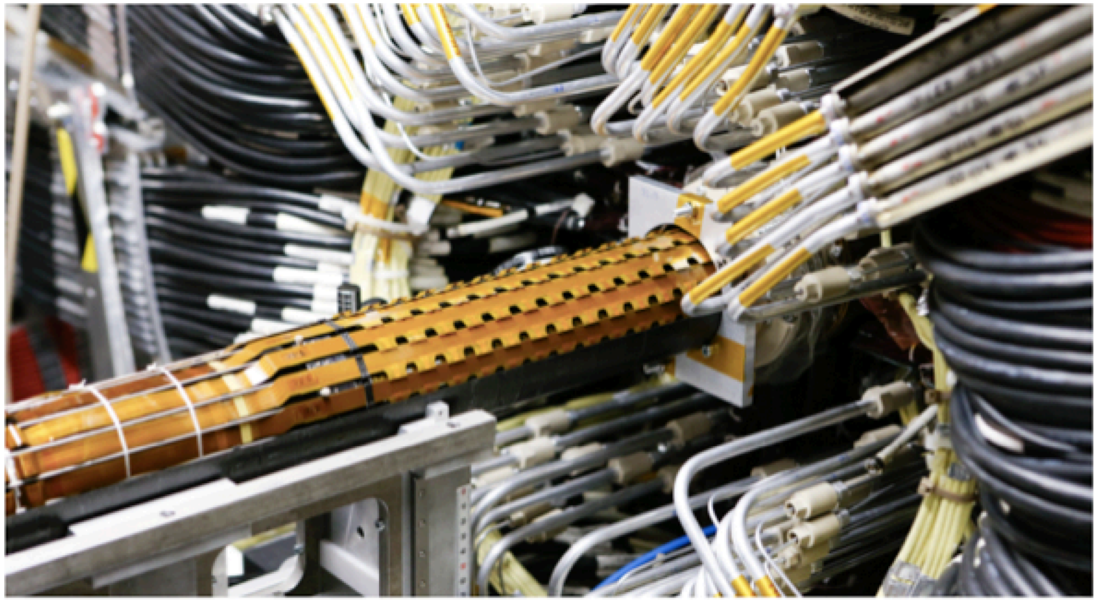
Each pixel module consists of

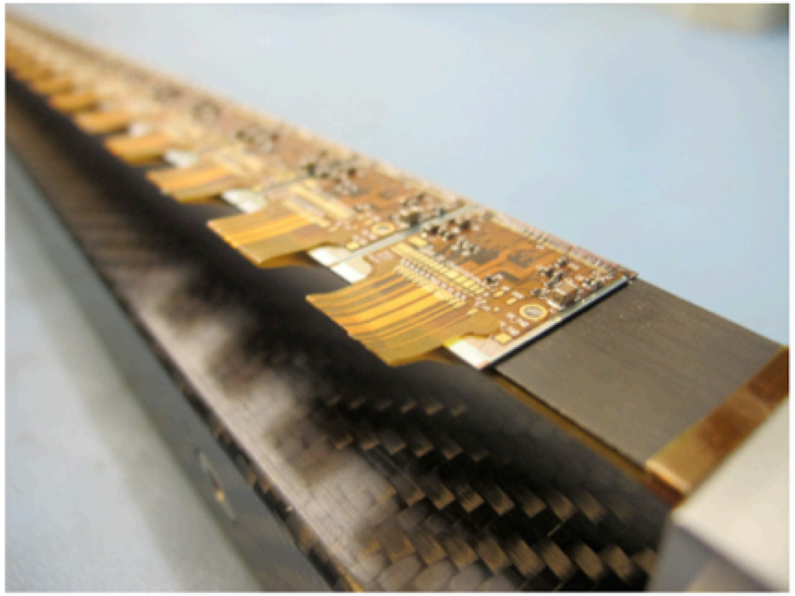
- 1 planar n-on-n sensor 60.8 mm x 16.4 mm active area, 250 μm thick.
- 16 FEI3 frontend chips plus one controller (MCC) in 0.25 μm CMOS technology.
- 1 flex that provides the electrical connections.

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 $1 \times 10^{15}\ n_{eq}/cm^2$.

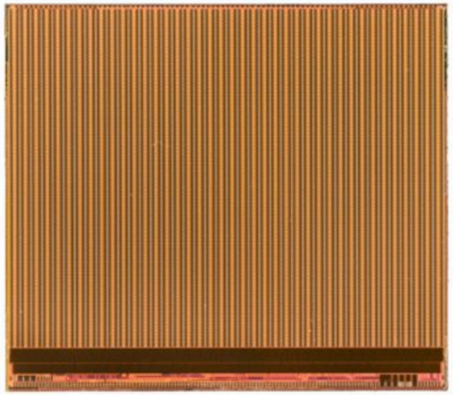
IBL (Insertable B-Layer)





- 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.

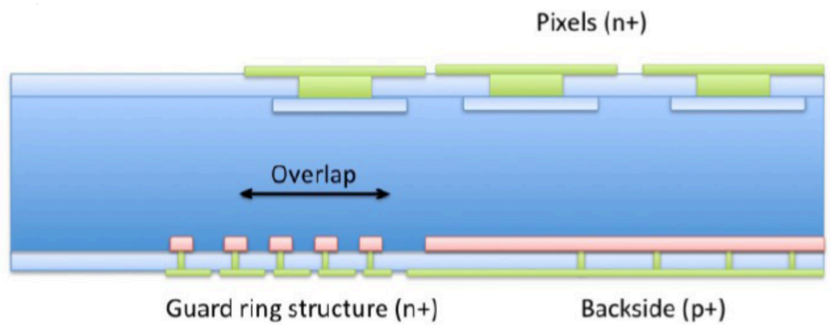
IBL (Insertable B-Layer)



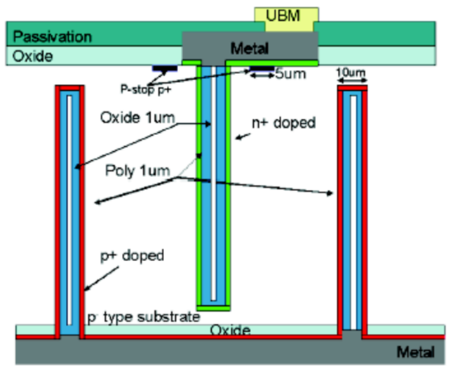
Frontend Chip (FEI4):
- 26880 pixels.
- 336 rows (phi) and 80 columns (z).
- 2 cm x 1.8 cm in size.
- 130 nm CMOS.
- Solder-bump-bonding to sensors.
- 4-bit time-over-threshold information.

Sensors:
- Planar:
  - n-on-n.
  - 200 μm thickness.
  - Slim edge technology.
  - 2 frontends per sensor.
  - Used in the central part of IBL.
- 3D:
  - 230 μm thickness.
  - 2 columns per pixel.
  - 1 frontend per sensor.
  - Used in the outer parts of IBL.

Planar

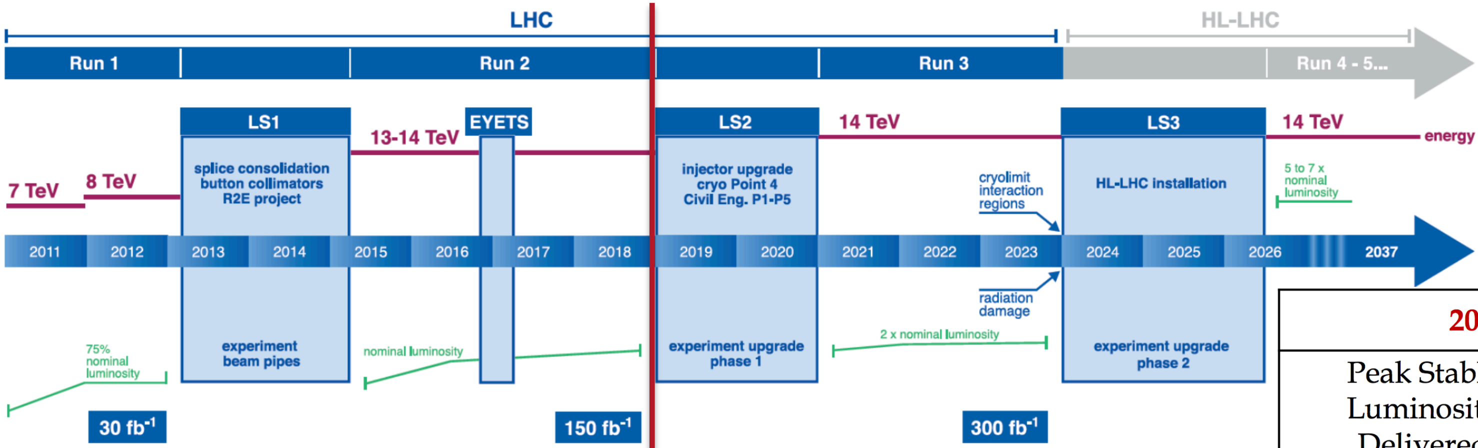


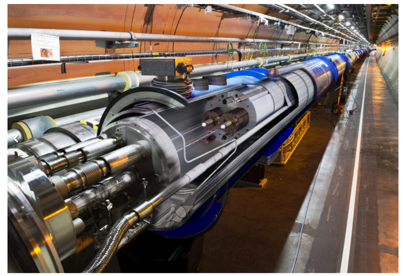
3D



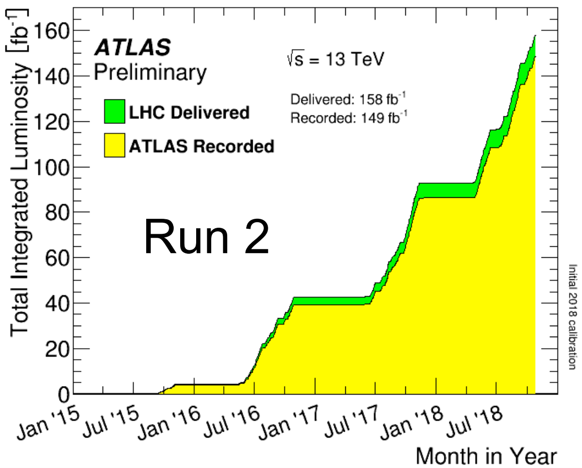
LHC Overview

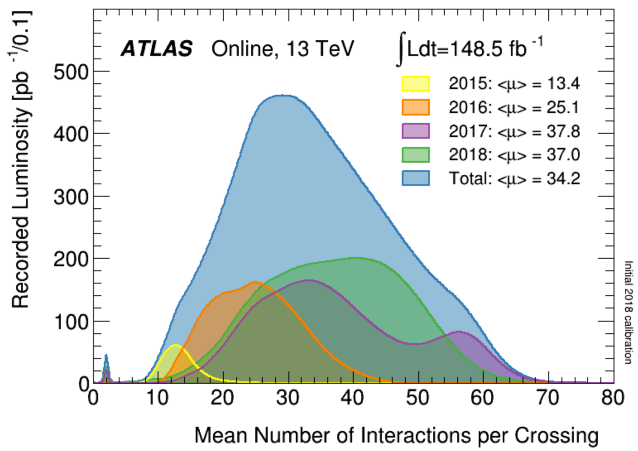
SLAC





Dec 2018, end of Run 2





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)$^{-2}$

Three more years of data taking after LS2!

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 at 99.8 % for this year.
- The non-operational fraction of modules is 4.3 % in total. Some of those can be recovered.

DQ Efficiency

ATLAS pp data: April 25-October 24 2018

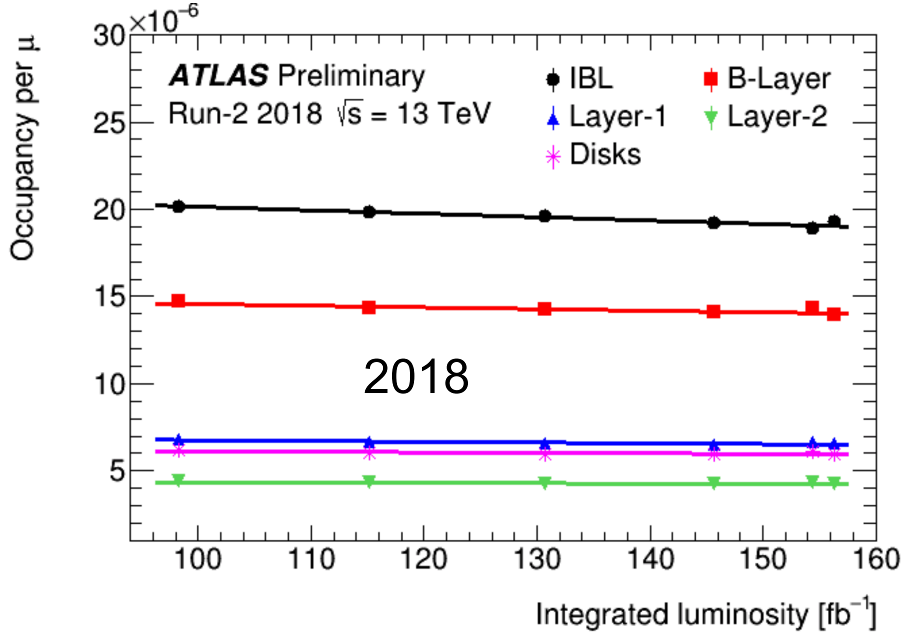
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.8	100	99.7	100	99.8	99.7	100	100	100	99.6
Good for physics: 97.5% (60.1 fb^{-1})										

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions at $\sqrt{s}$=13 TeV between April 25 – October 24 2018, corresponding to a delivered integrated luminosity of 63.8 fb^{-1} and a recorded integrated luminosity of 61.7 fb^{-1}. Dedicated luminosity calibration activities during LHC fills used 0.7% of recorded data and are included in the inefficiency. The luminosity includes 193 pb^{-1} of good data taken at an average pileup of μ=2.

Disabled Modules

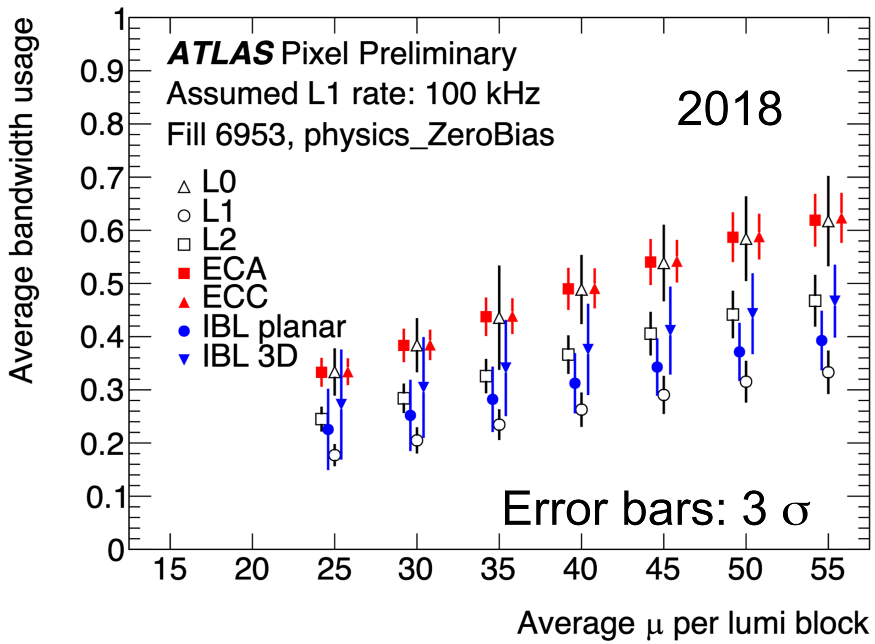
Layer	Failures/Total	Percentage
Disks	15/288	5.2
B-Layer	17/286	5.9
Layer 1	28/494	5.7
Layer 2	31/676	4.6
Total (Pixel)	91/1744	5.2
IBL	3/448	0.7
Total	**94/2192**	**4.3**

Bandwidth



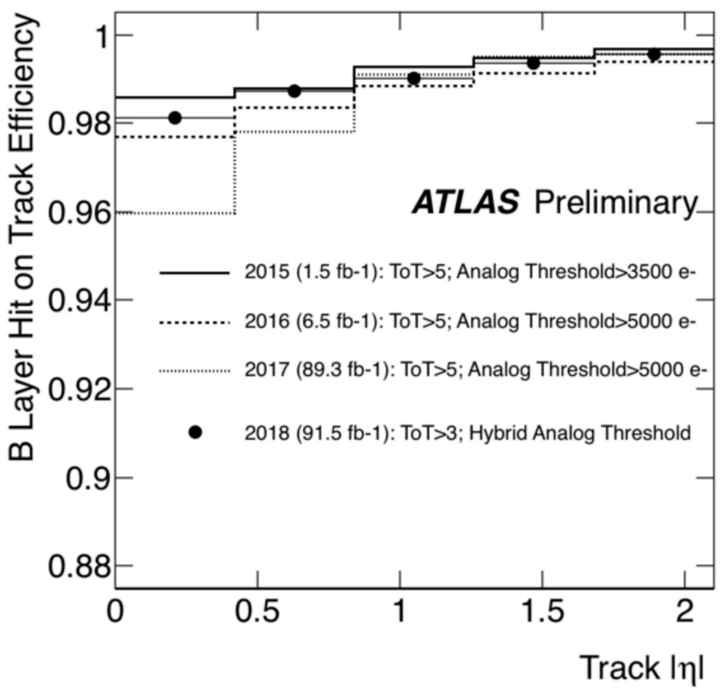
Threshold	2017	2018
IBL	2500e, ToT>0	**2000e**, ToT>0
B-layer	5000e, ToT>5	**4300e(*), ToT>3**
Layer-1	3500e, ToT>5	3500e, ToT>5
Layer-2	3500e, ToT>5	3500e, ToT>5
Endcap	4500e, ToT>5	**3500e**, ToT>5

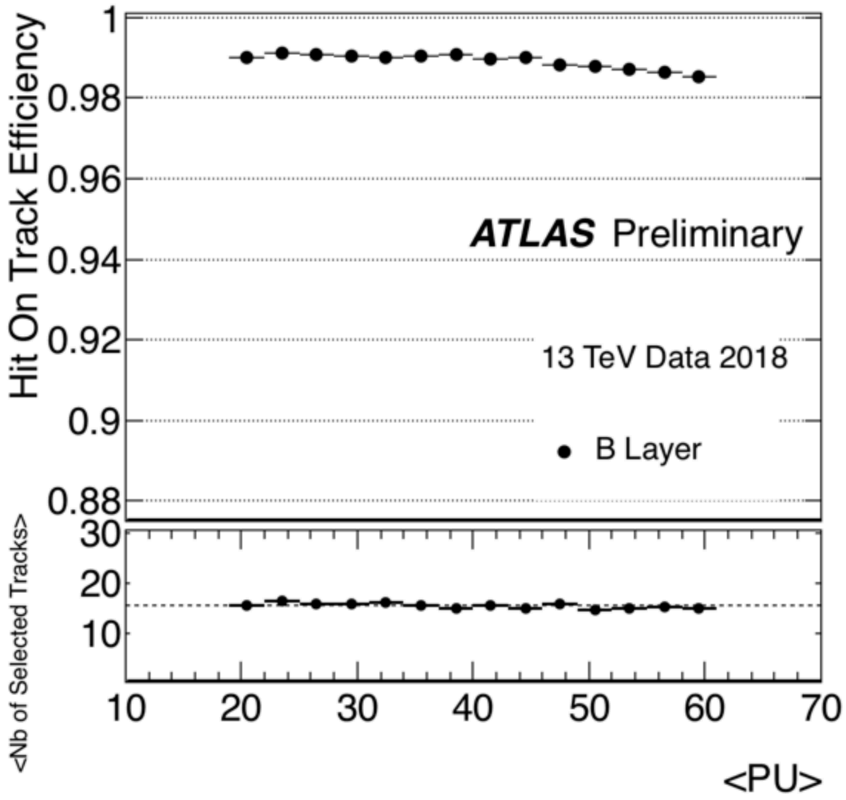
(*) M1A/M0/M1C : 4300e, otherwise : 5000e

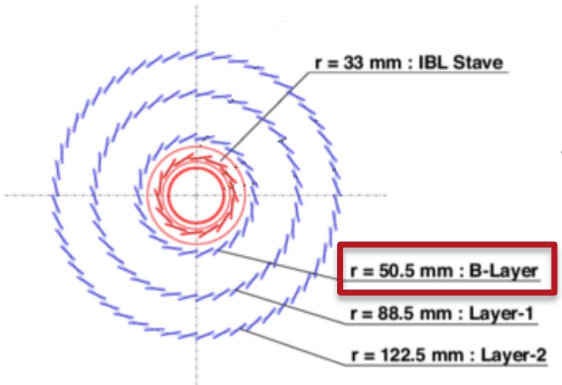


- Occupancy decreases due to radiation damage.
- The thresholds were lowered at the beginning of 2018 to optimize efficiency.
- Bandwidth usage is required to stay below 80 % at 100 kHz trigger rate and a pile-up of 60.
- Typical values at the start of run in 2018 were a pile-up of 55 and a trigger rate of 83 kHz.

Hit-on-track Efficiency in the B-layer

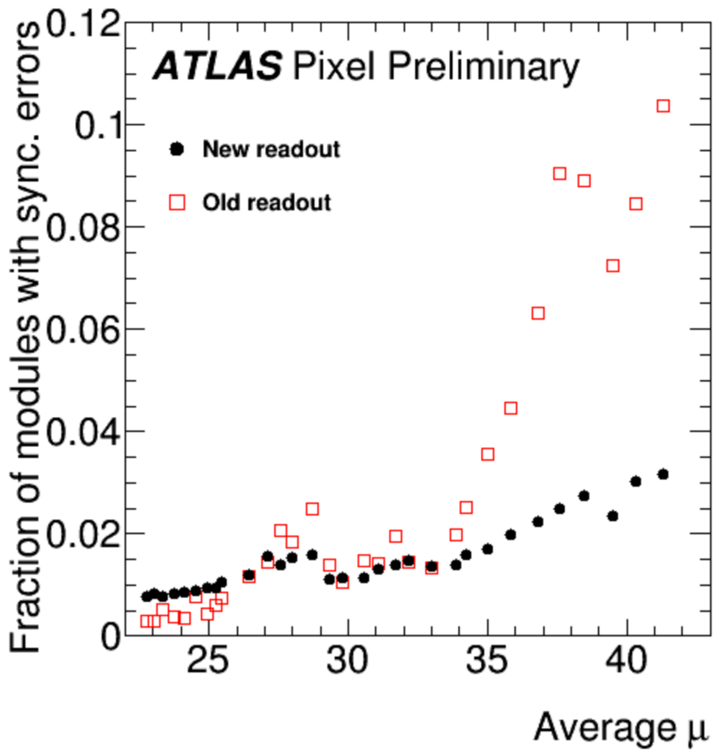


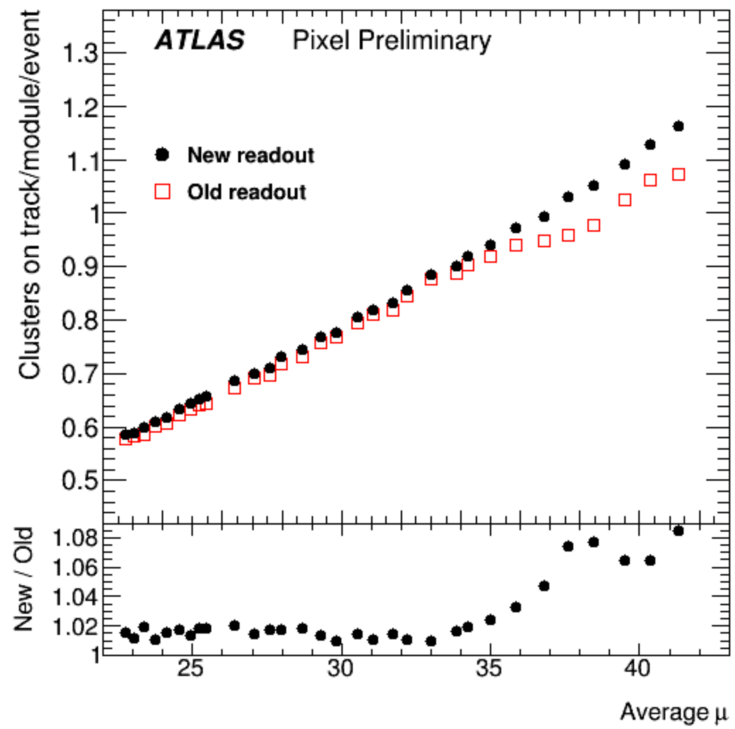




- The B-layer has the highest threshold because of bandwidth considerations.
- More radiation damage than other (old) Pixel layers.
- Almost full efficiency recovery after lowering thresholds!
- Good stability of efficiency at high pile-up.

Desynchronization



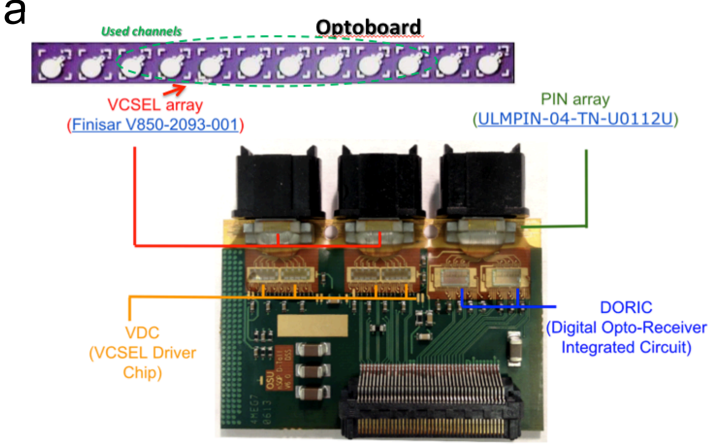


- Luminosity and pile-up are much larger than originally specified.
- High occupancy can lead to buffer overflows resulting in event fragments being associated with the wrong event (“desynchronization”).
- A periodic reset of the frontend ASICs and of the firmware in the backend every 5 seconds was introduced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

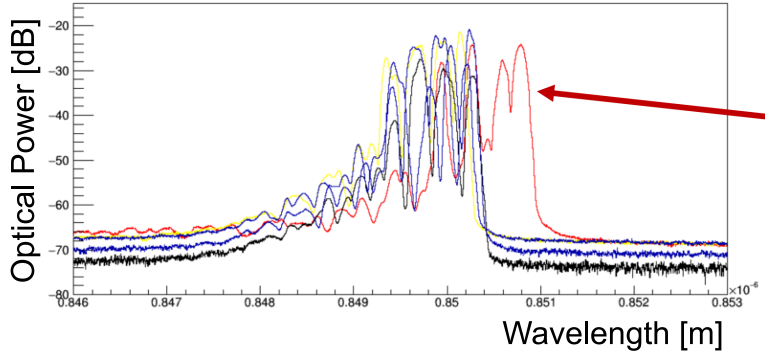
Substantially improved data taking efficiency!

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.
- 19 new VCSELs died in 2018.



In the long shutdown all optoboards will be replaced!

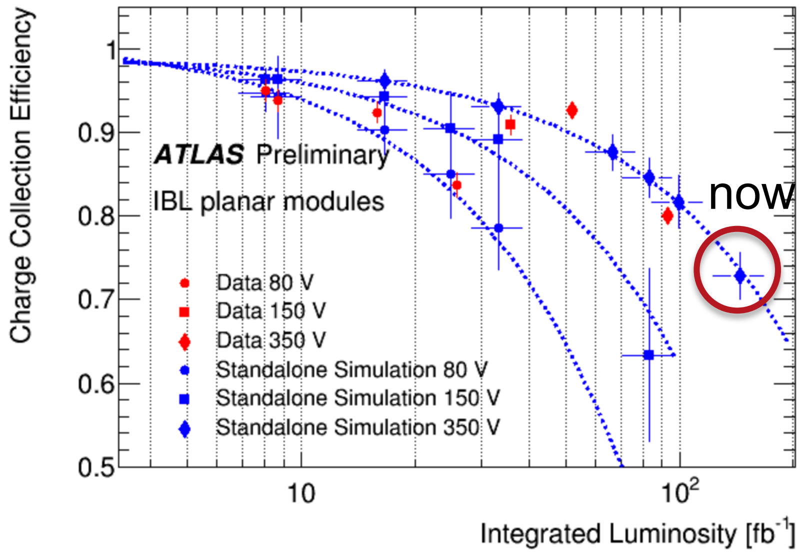


Shifted spectrum predictor for death long before failure.

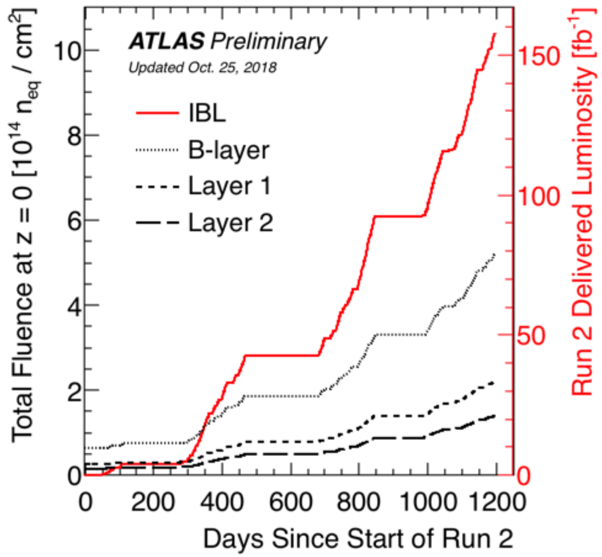
VCSEL light from data fiber

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}

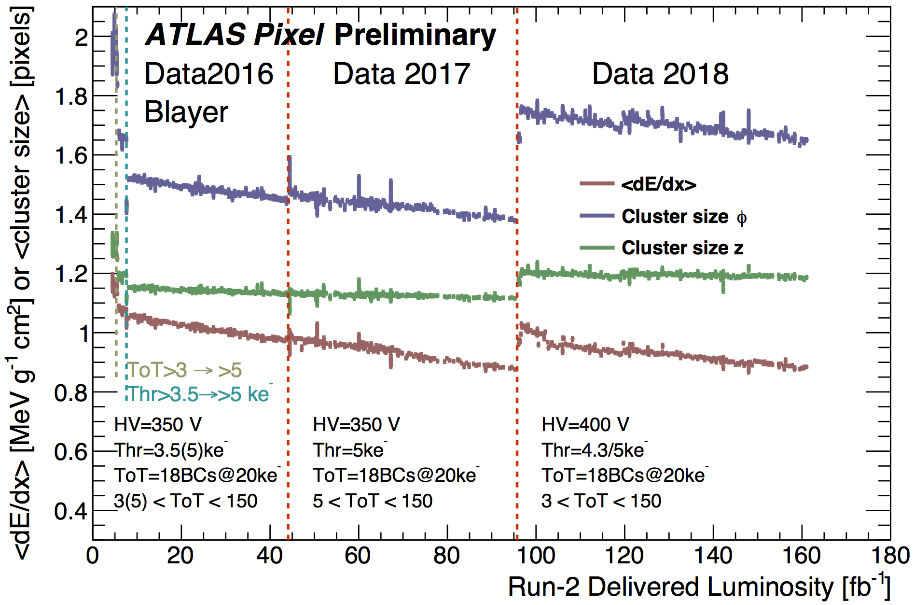


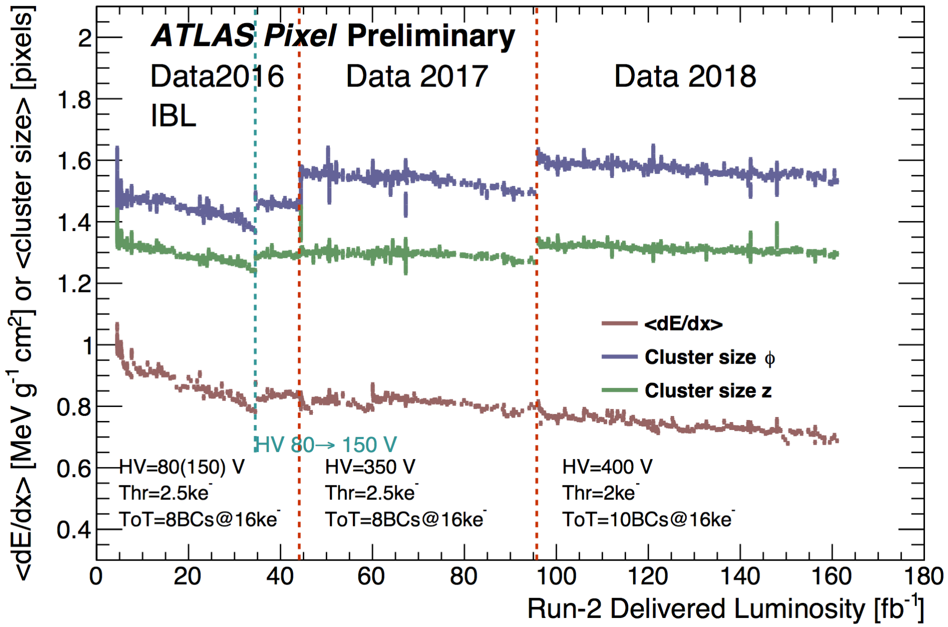
- Radiation damage effects are getting to be significant for the performance of the detector
- We are now somewhere around 40 - 50 % of the total fluence depending on the luminosity in run 3.
- Models are used to understand and predict radiation damage effects.
- The ATLAS Monte Carlo now includes radiation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



➔ Talk by Marco Bomben on Tuesday

dE/dx



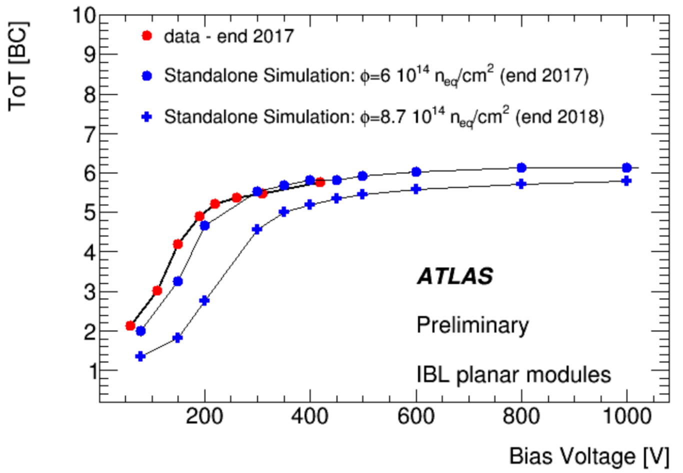


- Due to the decreasing charge collection efficiency the measured dE/dx decreases.
- Also the HV can have an influence if the detector is not fully depleted.
- Threshold changes show up as steps in dE/dx as well since hits below threshold do not get recorded.

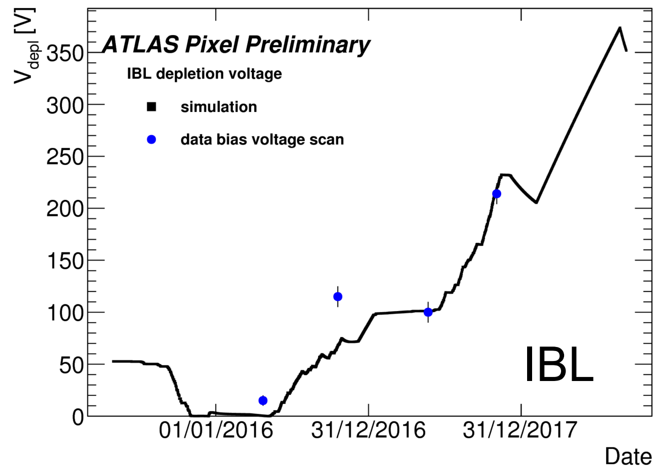
Depletion Voltage Evolution

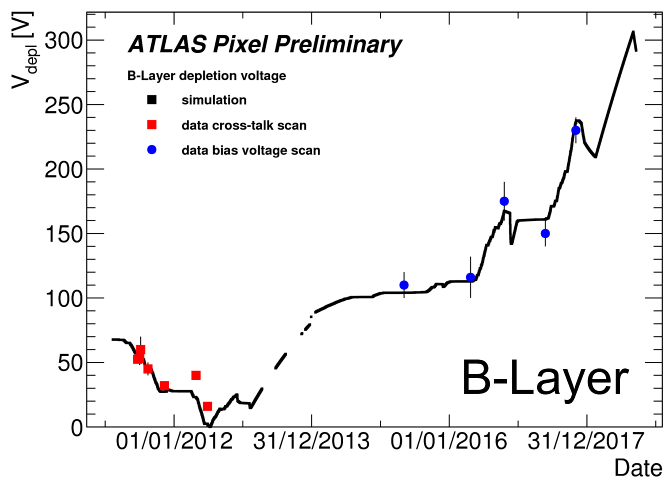
RUN-2 HV

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



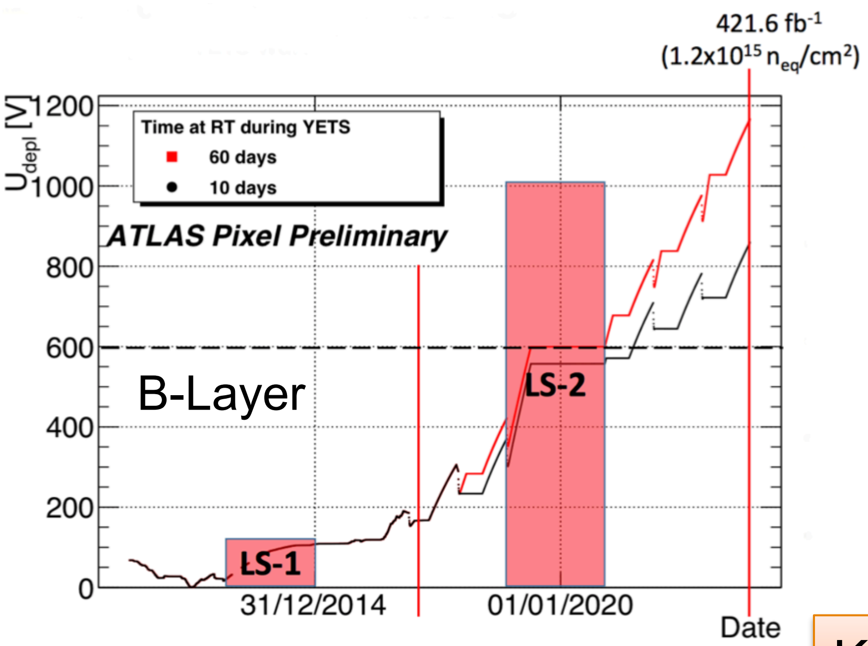
- The High Voltage settings are increased at each start of the year according to the predictions of the simulation in order to keep the sensors fully depleted for the entire year without having to readjust the voltage.
- The depletion voltage is monitored by plotting time-over-threshold against high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

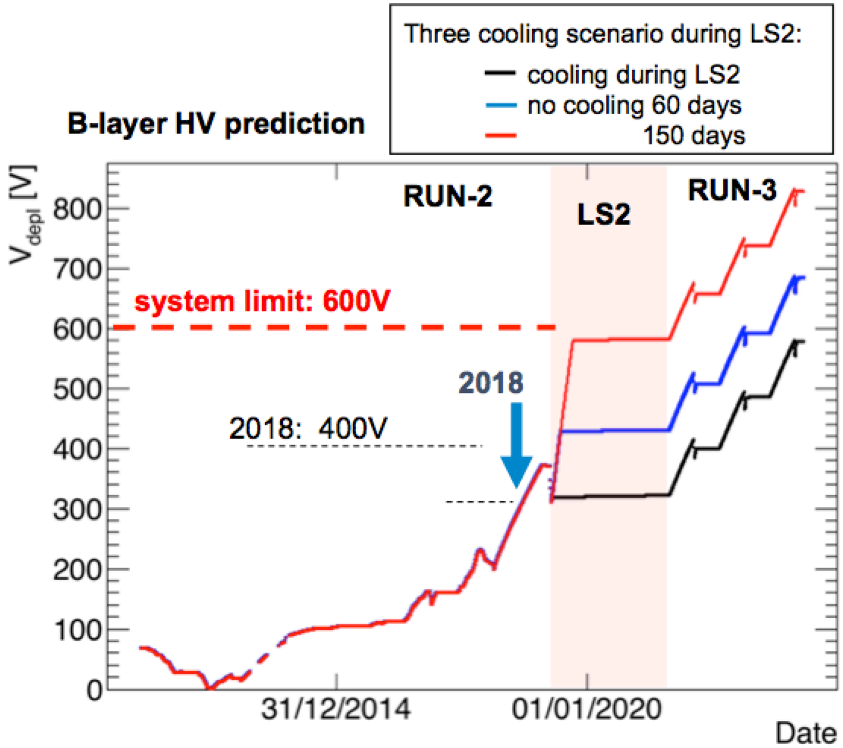




Reverse Annealing

- 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.



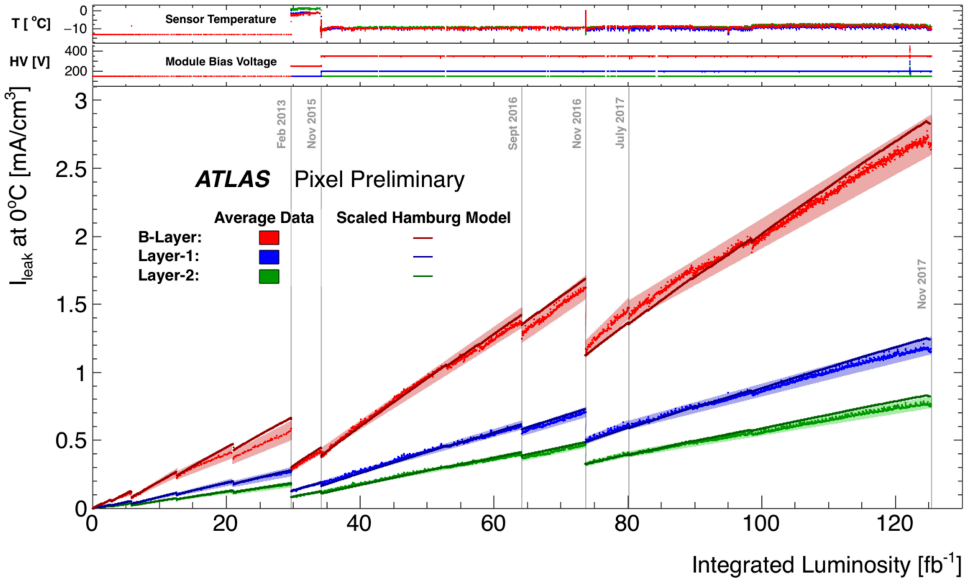


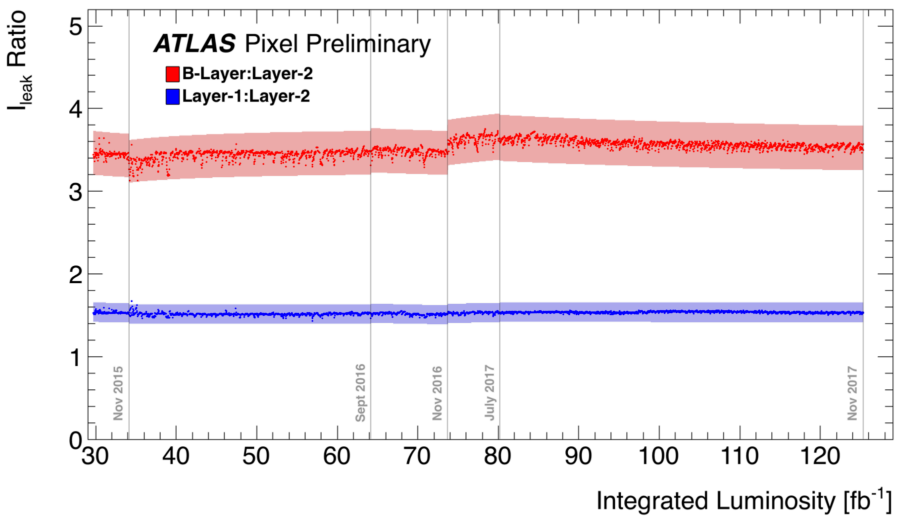
- Unfortunately we cannot avoid warming up the detector because of several other projects requiring access to the inside of the inner detector.

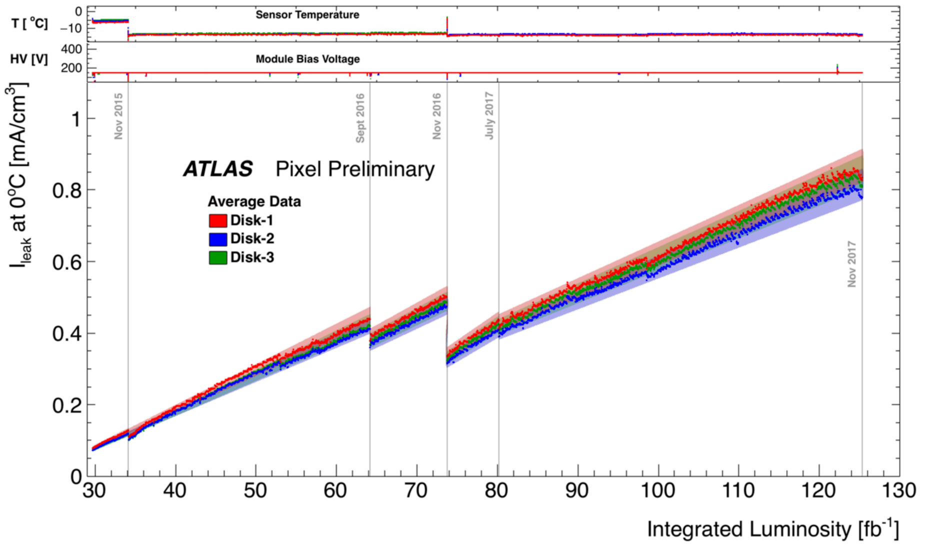
Keep Pixel cold whenever possible!

Leakage Current

- The evolution of the leakage current can be described with the Hamburg model.
- A global scaling factor is, however required.
- The ratio between layers is more or less constant.

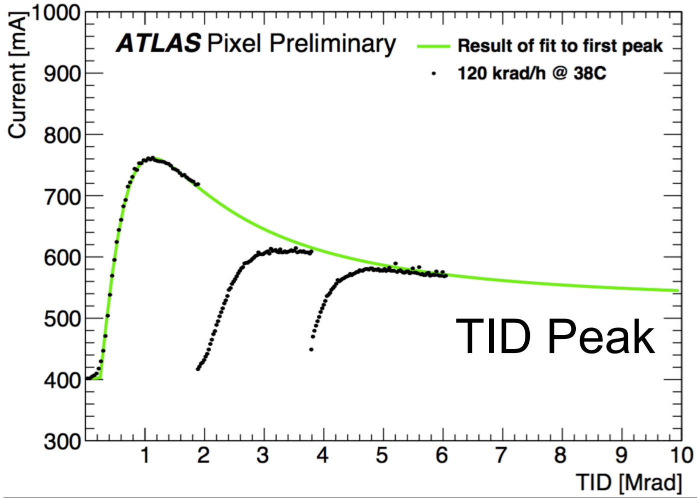


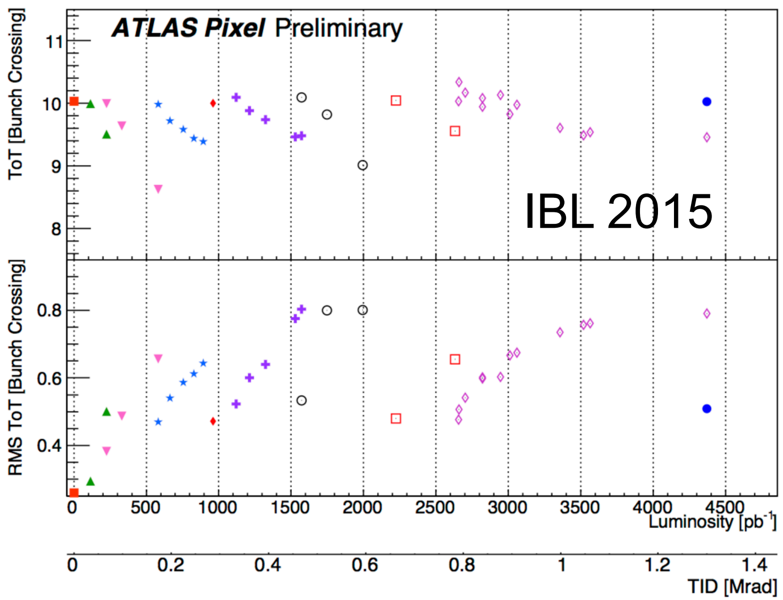




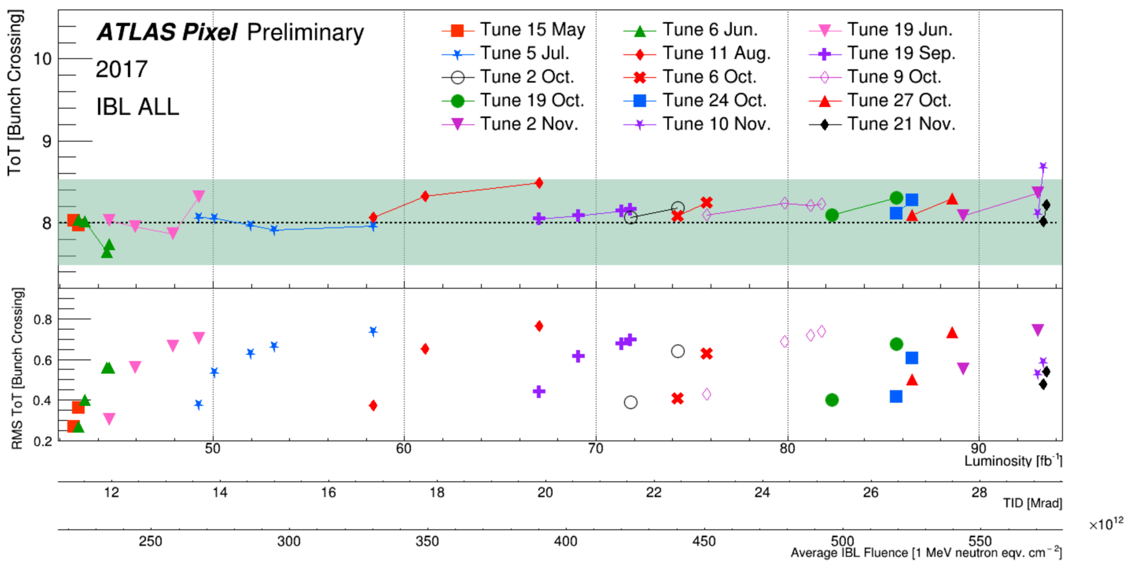
Calibration Drift

- 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.



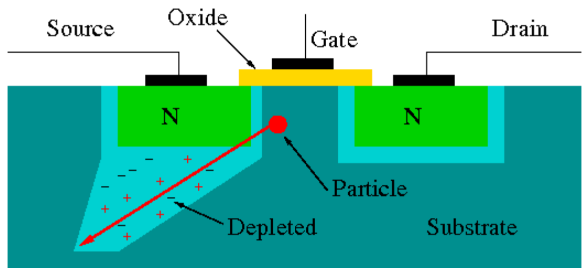


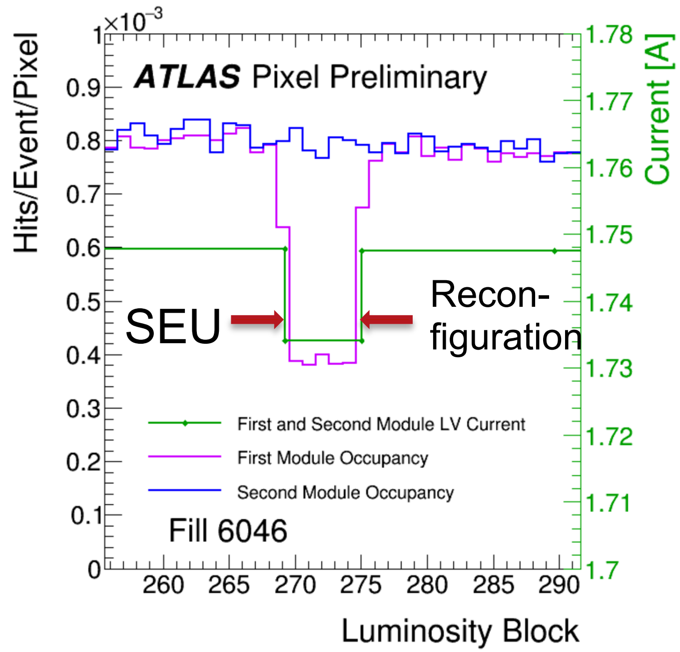
In 2017 the tuning point was 10 instead of 8.



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.
- 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.
- Local pixel registers can also get corrupted by SEUs.

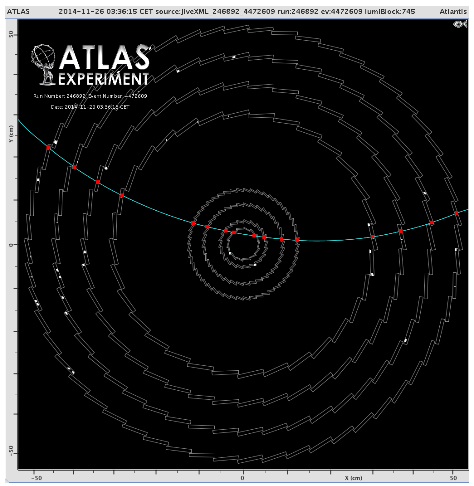




➔ Talk by Yosuke Takubo on Wednesday.

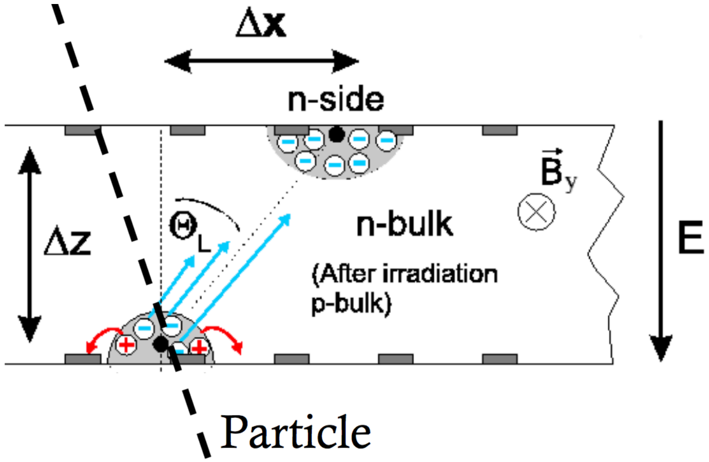
Summary and Conclusion

- LHC Run 2 is now 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.
- Now the LHC will shut down for two years. The main hardware project for the Pixel detector is the replacement of the optoboards.
- Three more years of running in Run 3.

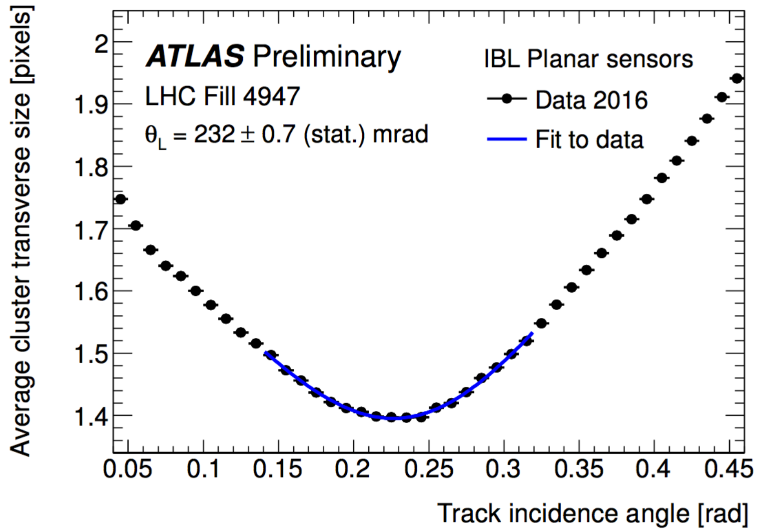


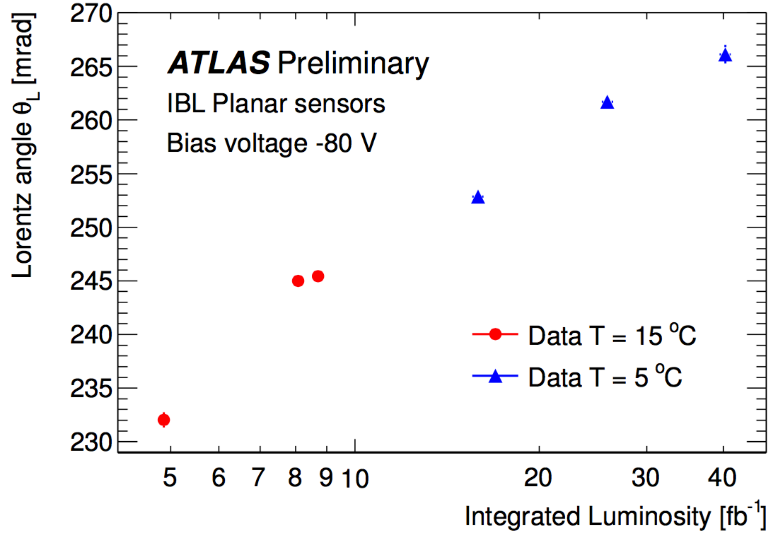
Backup

IBL Lorentz Angle

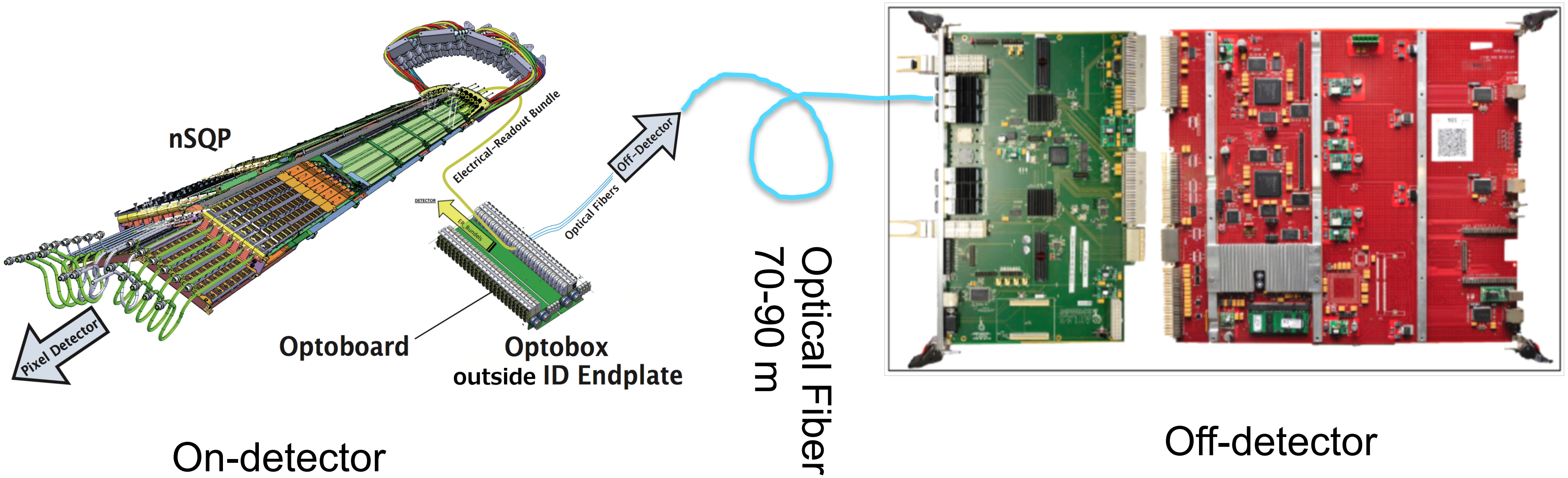


- Charges drift transversally in planar sensors because of the perpendicular magnetic field.
- The angle between electric field and the drift direction is called the Lorentz angle.
- This effect introduces a bias on the cluster position reconstruction.
- The electric field changes with radiation damage.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





Readout System



On-detector

Off-detector

- 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.