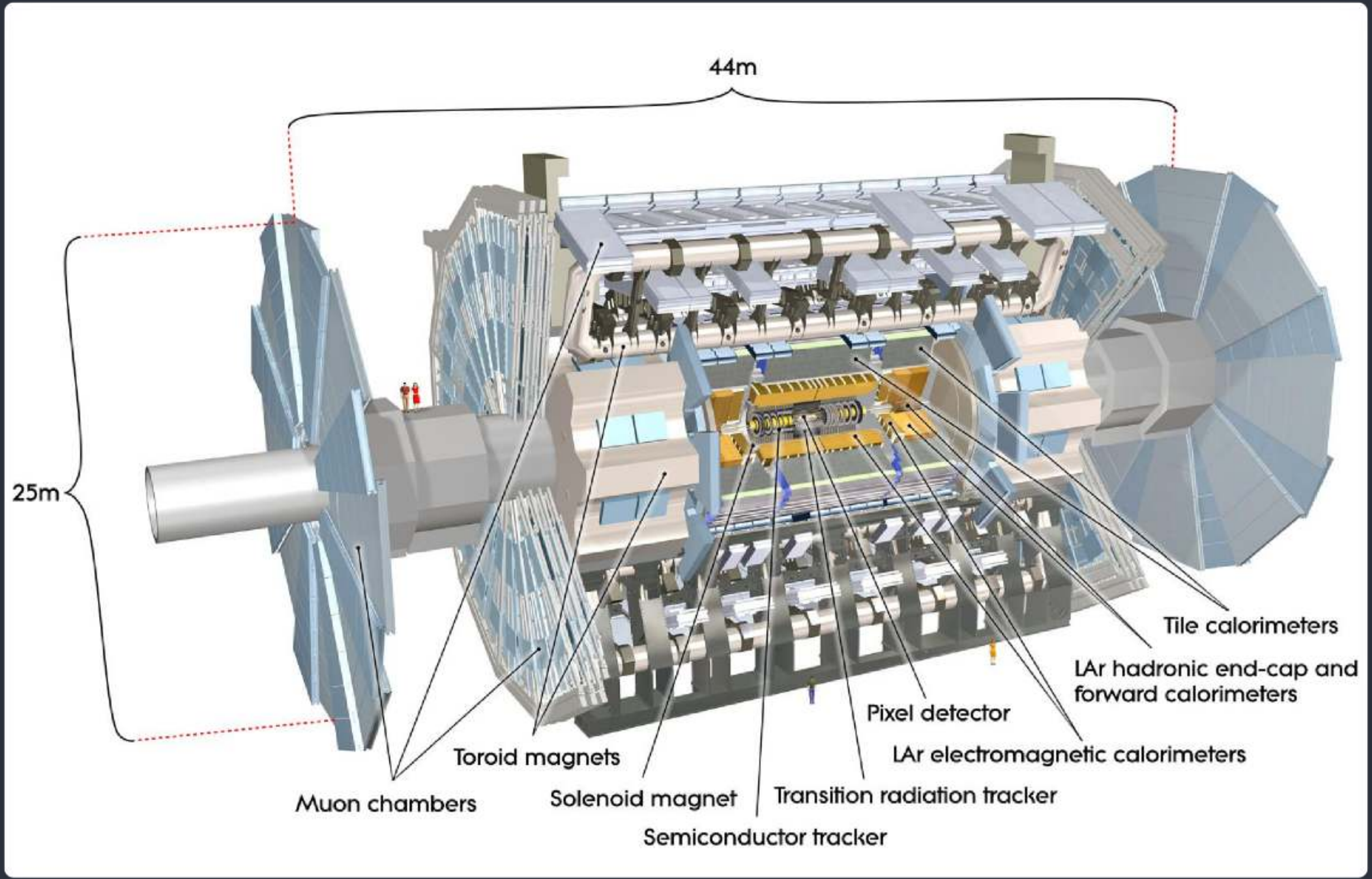
Experience with the ATLAS Inner Detector

Masahiro Morinaga on behalf of ATLAS Collaboration

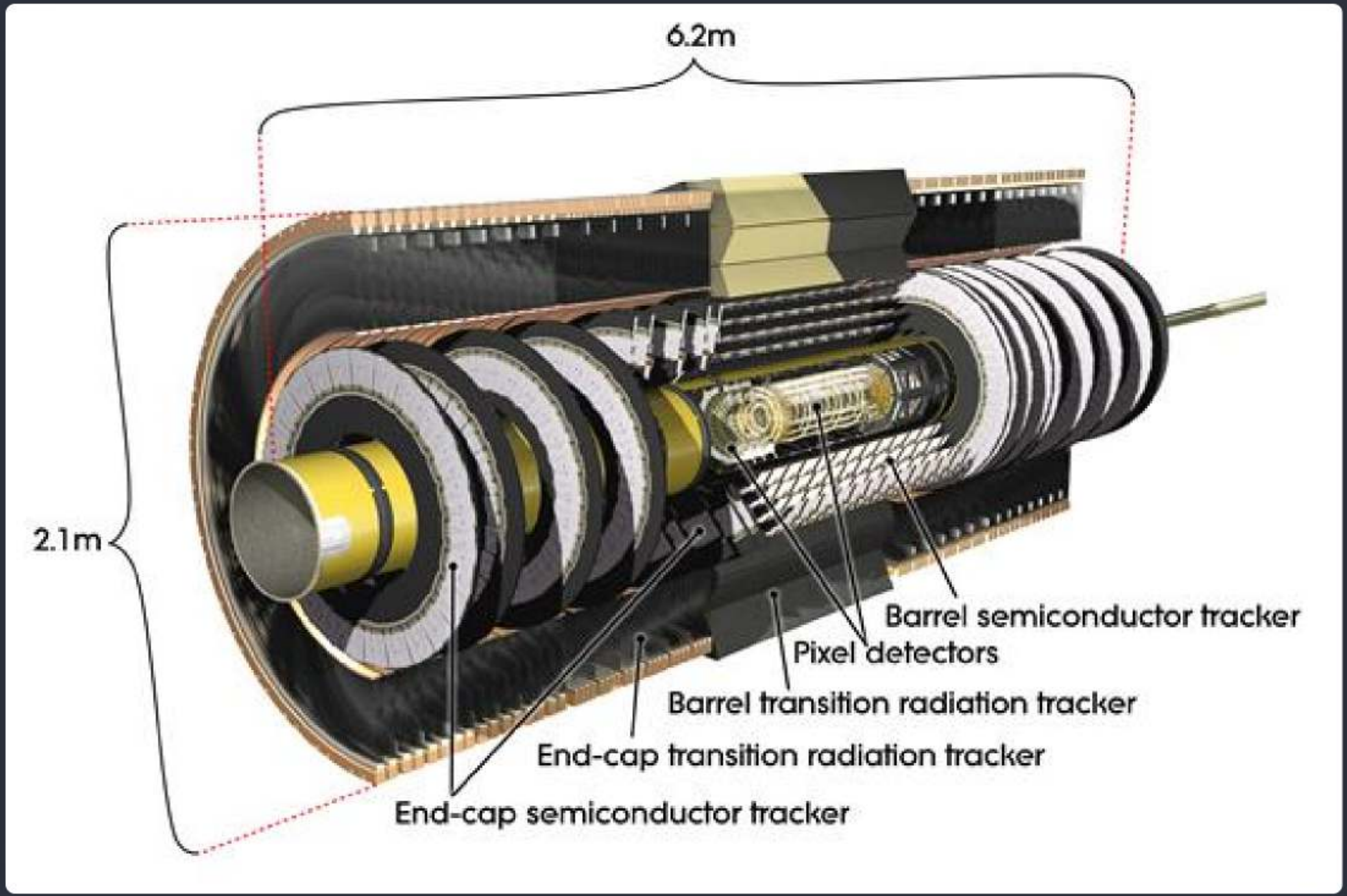
The University of Tokyo
(ICEPP, Beyond AI)

ATLAS Detector



- Multi-purpose detector at LHC collison Point1.
- Optimized for collision with Proton-proton.
- Higgs, BSM, SM measurement...

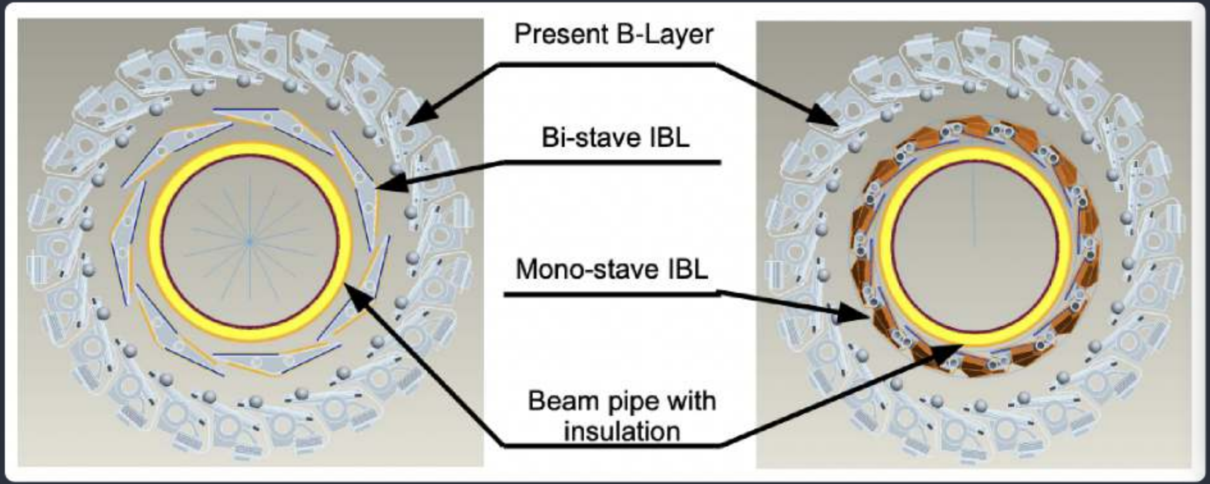
ATLAS Inner Detector

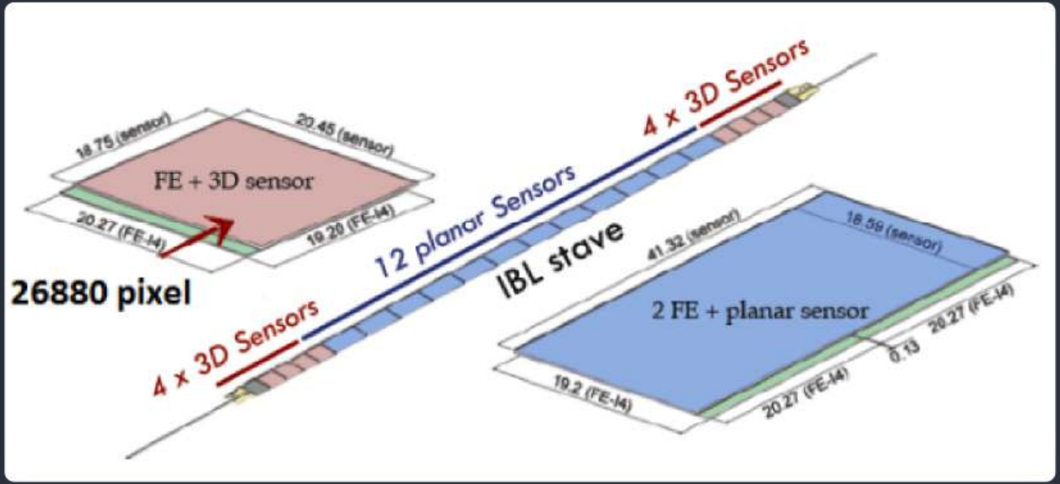


consists of three different detectors:

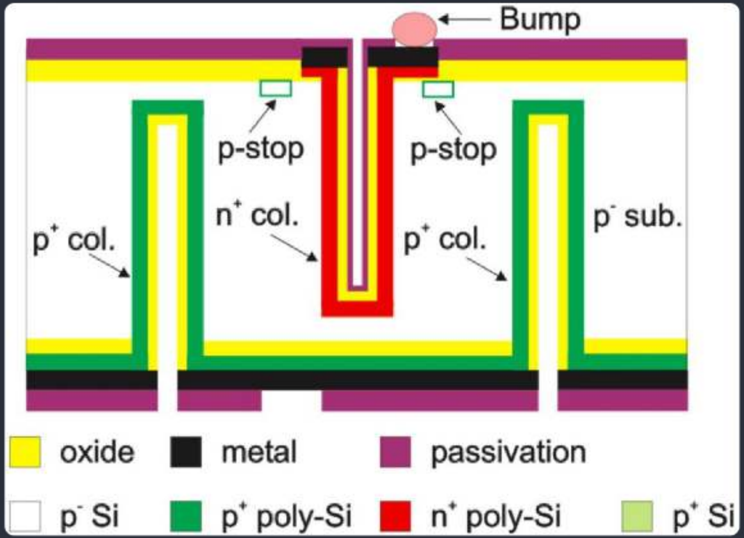
- **Insertable B-Layer(IBL)/ Pixel**:
  - Inner four layers
  - 92 million channels
  - 8μm /75μm resolution (IBL)
  - 10μm /115μm resolution (Pix)
- **SemiConductor Tracker(SCT)**:
  - 6.3 million channels
  - 17μm /570μm resolution
- **Transition Radiation Tracker (TRT)**:
  - 35,000 channels
  - 130μm resoltion
- ***This talk focuses on IBL/Pixel and SCT in Run1/Run2 operation and beyond***

Insertable B-Layer(IBL)

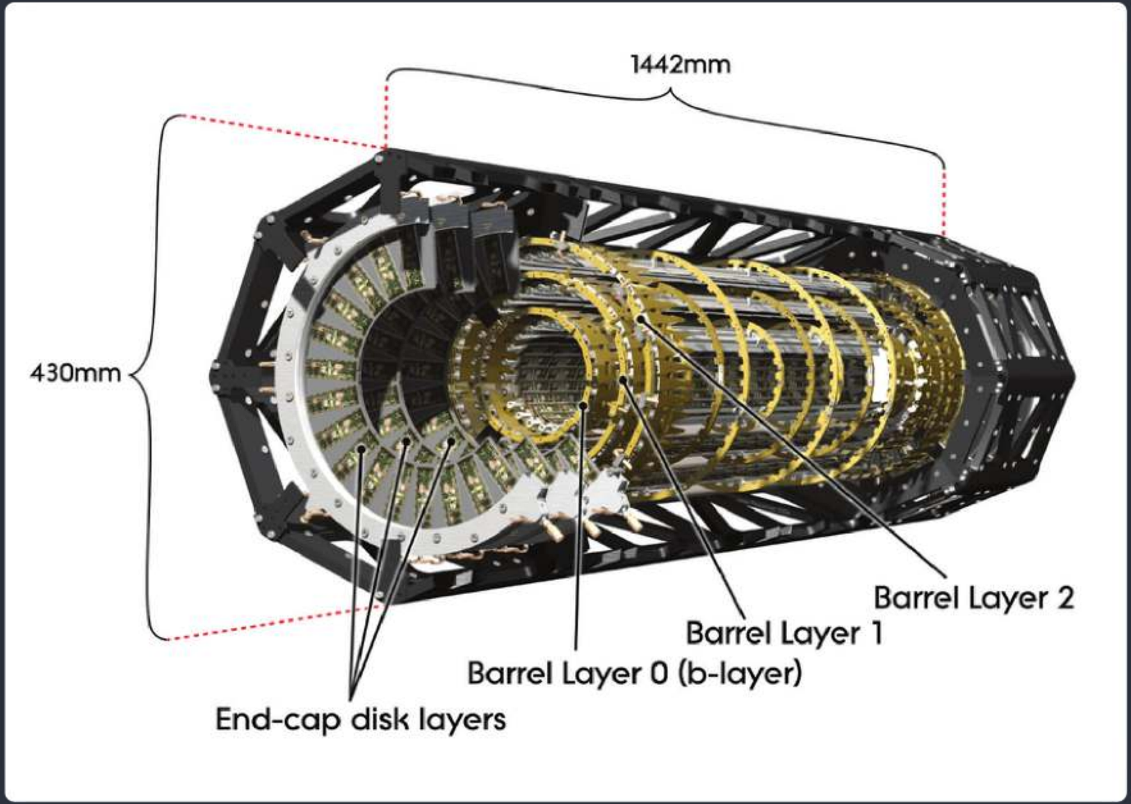


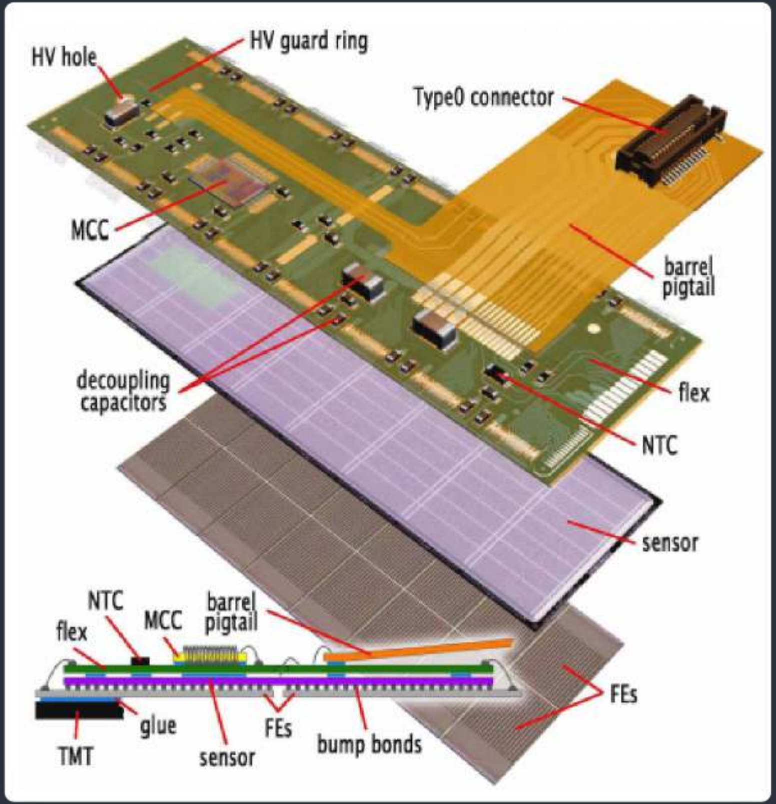


- Innermost pixel barrel layer installed in 2014(Radius: 3.3cm)
- Sensor techology: n-in-n planar(75%) and 3D(25%)
- *IBL is the first detector to use a 3D sensor in HEP Experiments.*
- Pixel size $50 \times 250\mu\mathrm{m}^2$
- FE-14 Front-end ASIC
  - 130 nm CMOS technology
  - Provides charge information with 4-bits ToT
- CO2 evaporative cooling
- Radiation tolerance: up to $5 \times 10^{15}\mathrm{n_{eq}}/\mathrm{cm}^2$



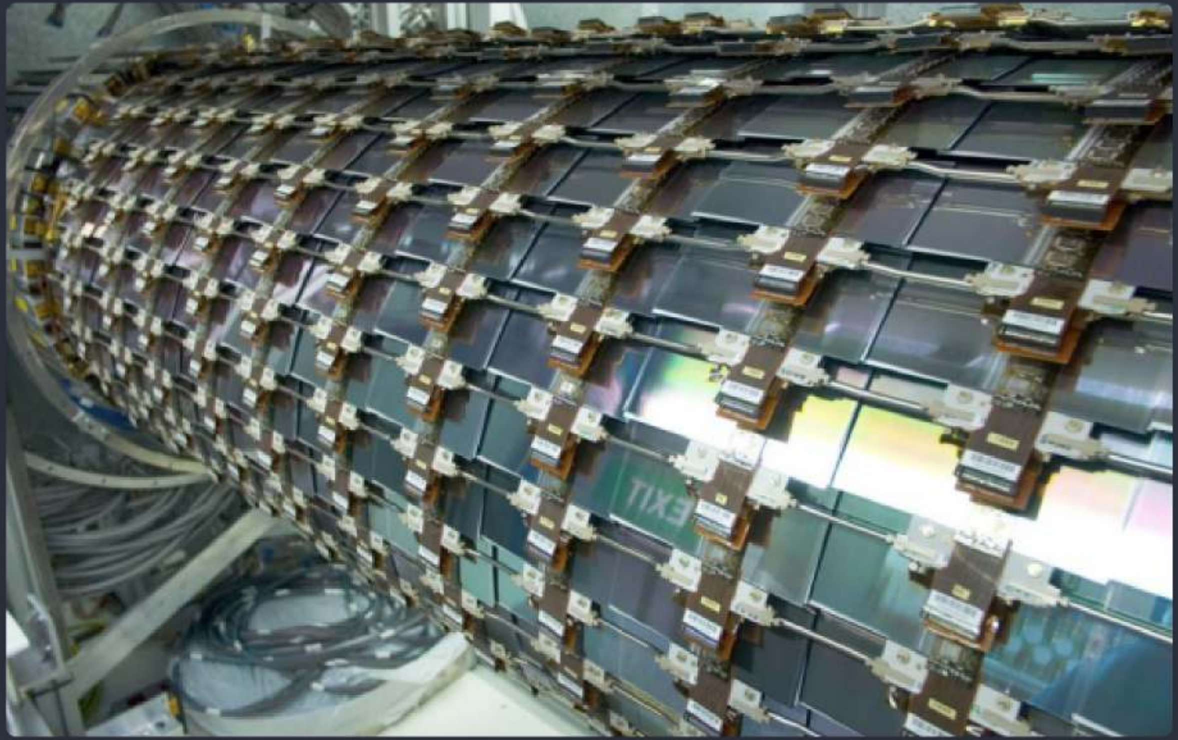
Pixel

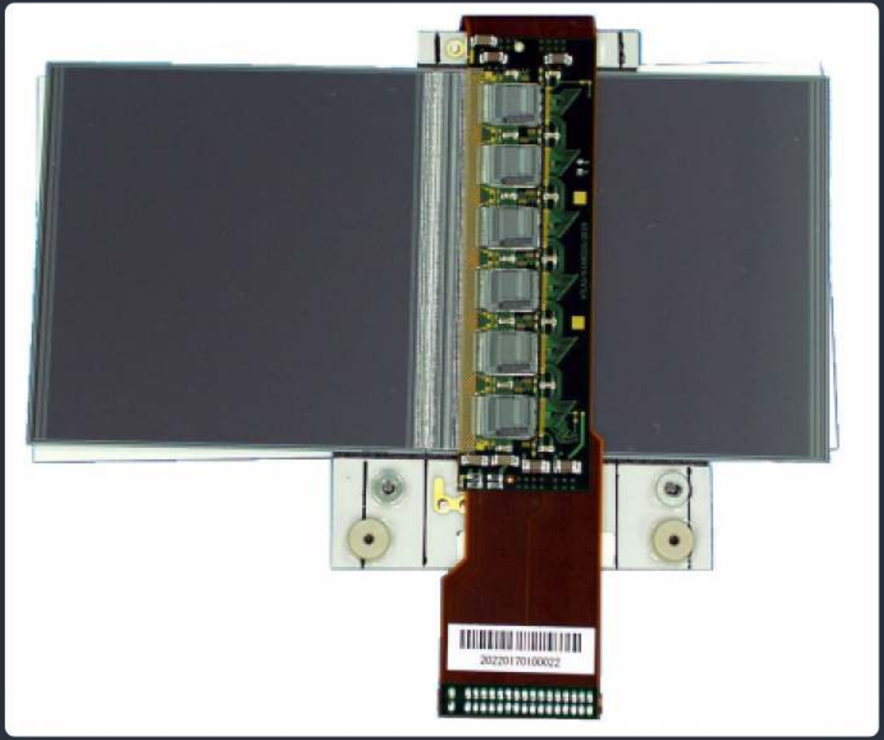




- Pixel detector existing since Run1 with 3 barrel layers and 3 x 2 endcap disks(B-Layer, Layer1, Layer2 in barrel)
- n-in-n planar sensor technology, pixel size : $50 \times 400 \mu\mathrm{m}^2$
- FE-I3 Front-end ASIC:
  - 250 nm CMOS techonology, Provides charge information with 8-bits ToT
- One Pixel module with 16 FE-I3 and 1 MCC(controller chip)
- C3F8 evaporative cooling
- Radiation tolerance: up to $1 \times 10^{15} \mathrm{n_{eq}}/\mathrm{cm}^2$

SemiConductor Tracker(SCT)

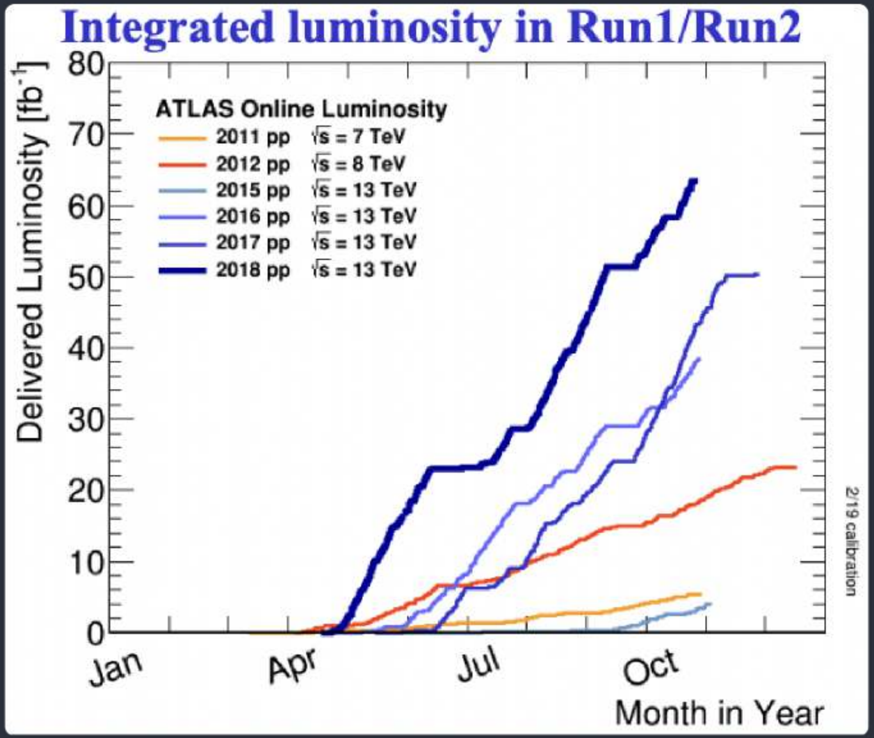


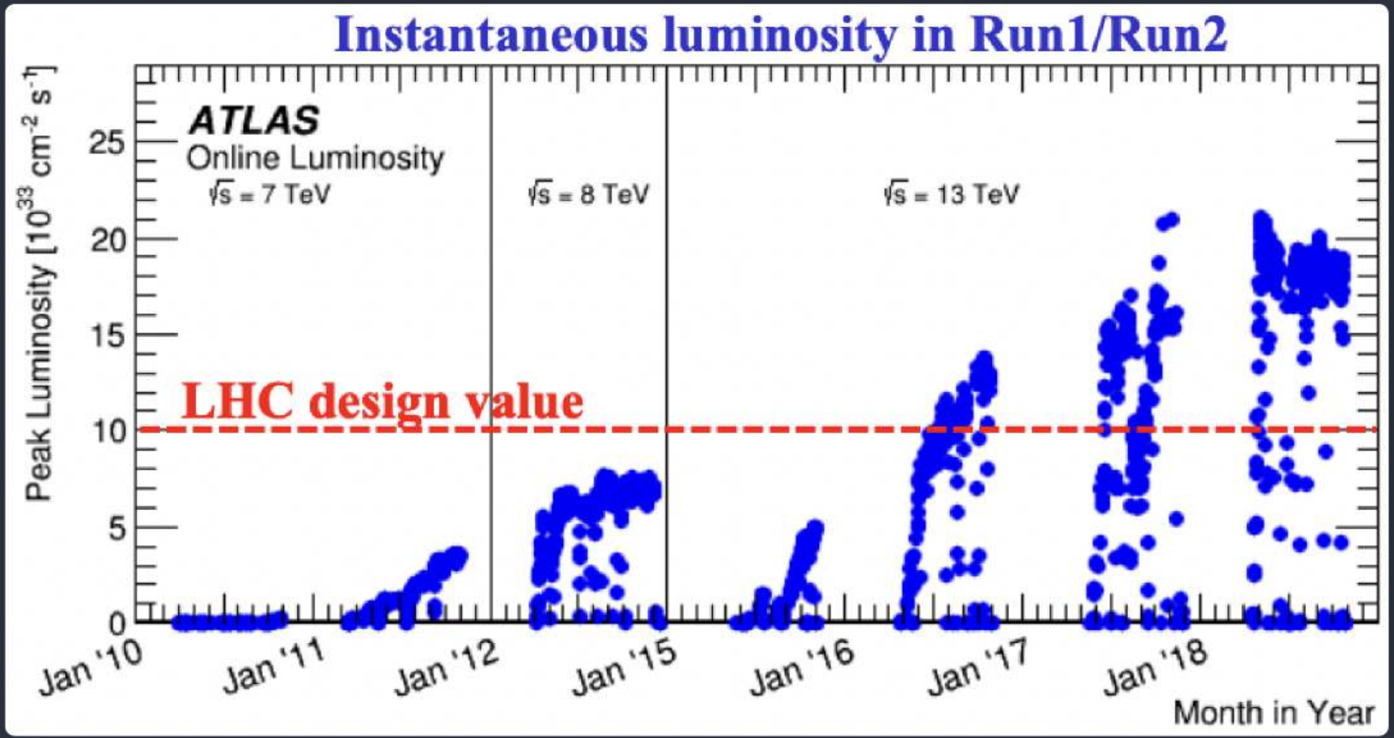


- Silicon strip detector with 4 barrel layers and 9 x 2 endcap disks
  - The detector is operated since Run1
- 80μm strip pitch with 12.8 cm length
- One module consists of front/rear sensor layers with 40 mrad stereo angle.
  - 768 x 2 strip/module
- 6 ABCD Front-end chips per one side $\rightarrow$ 12 per module.
- Provides binary hit pattern with 3bits

Overview of Run1/Run2 operation

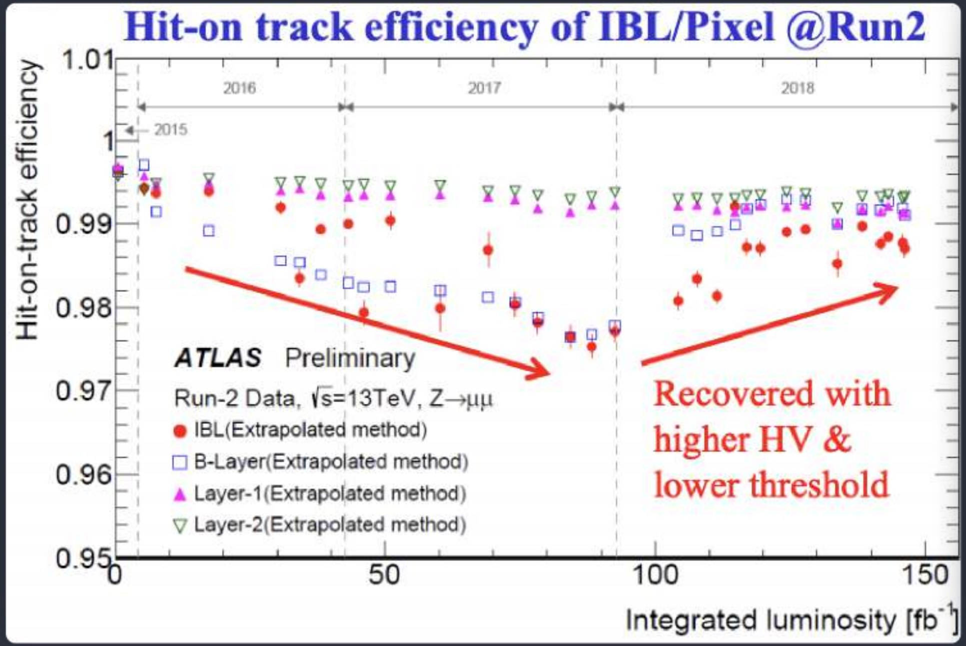
ATLAS Run1/Tun2 data-taking

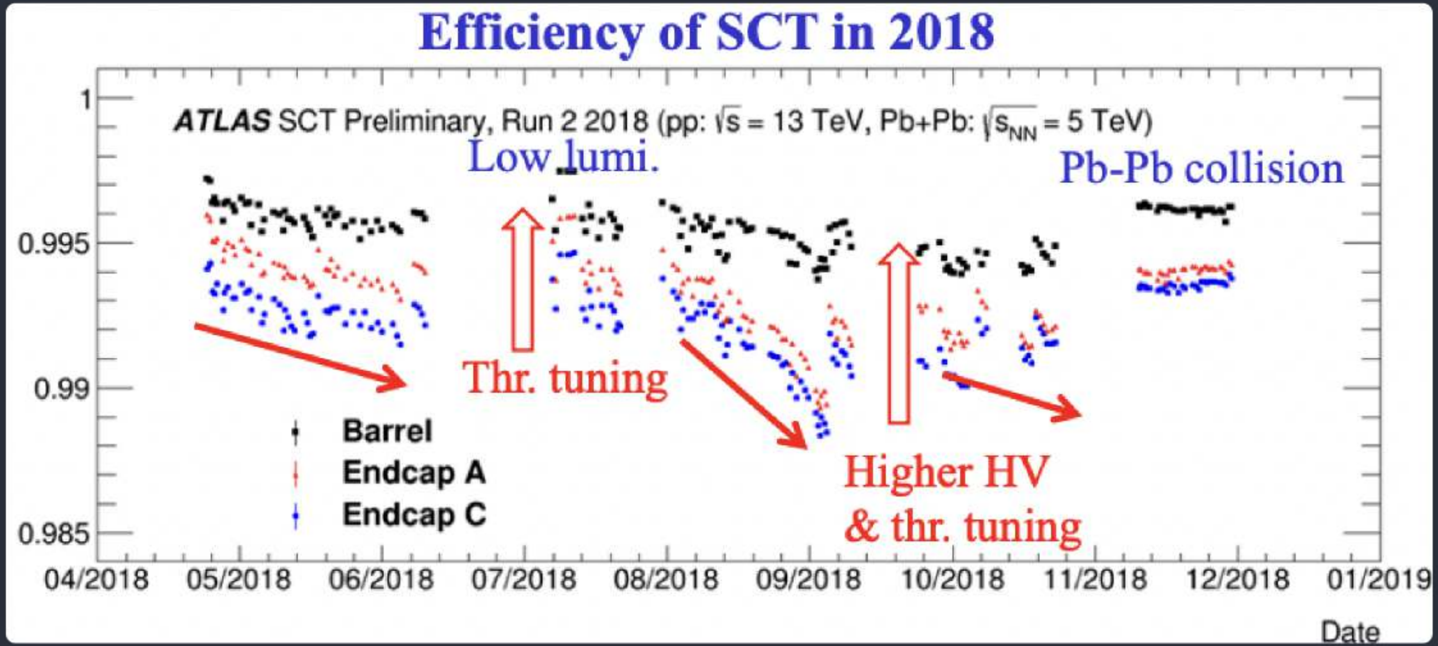




- ATLAS collected 5.1/21.3 fb^{-1} with 7/8TeV in Run1 (2010-2012) and 149 fb^{-1} with 13TeV in Run2 (2015-2018)
- **The instantaneous luminosity reached 2 times larger that LHC design value in Run2(LHC design value: $1.0 \times 10^{34}\mathrm{cm}^{-1}\mathrm{s}^{-1}$)!!**
- ***Inner detector was operated successfully with high data-taking efficiency even in high luminosity condition***

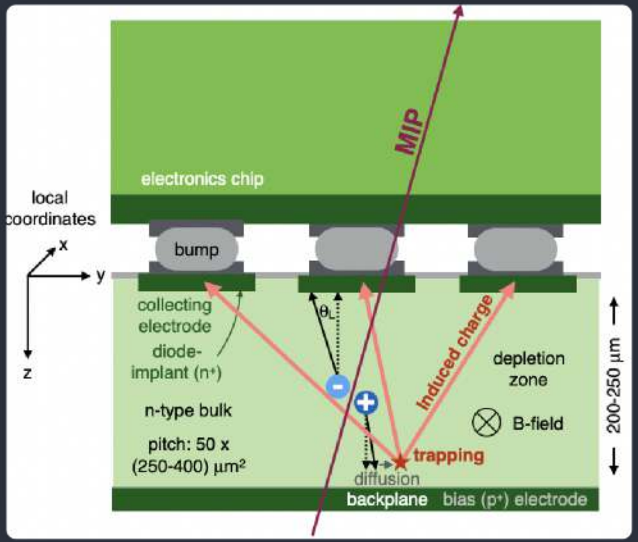
Hit-on-Track Efficiency

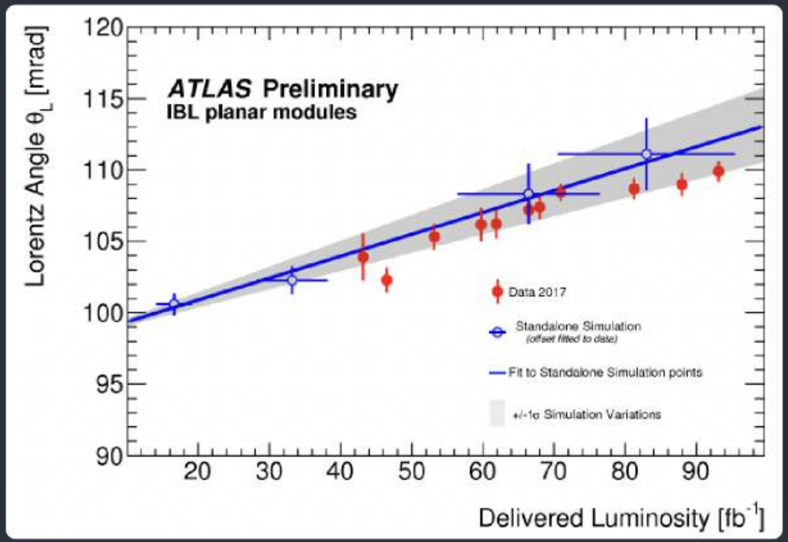


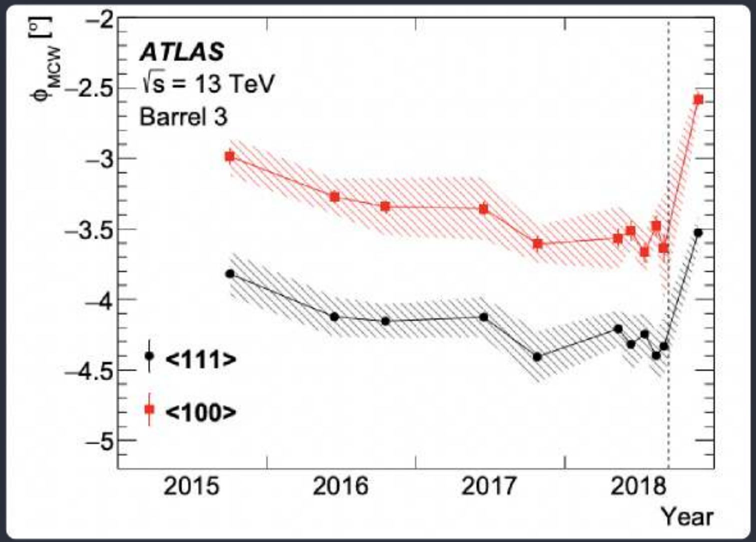


- Hit-on-track of efficiency dropped in IBL and B-Lauer before ~90 fb^{-1}.
  - IBL: the radiation damage after then.
  - B-Layer: radiation damage: Recovered with higher High-Voltage and lower threshold!!
- Increasing noise caused efficiency loss in SCT.
  - Detuning of threshold due to TID(Total Ionization Dose).
  - Under depletion of the sensors also contributes.

Lorentz Angle Measurement

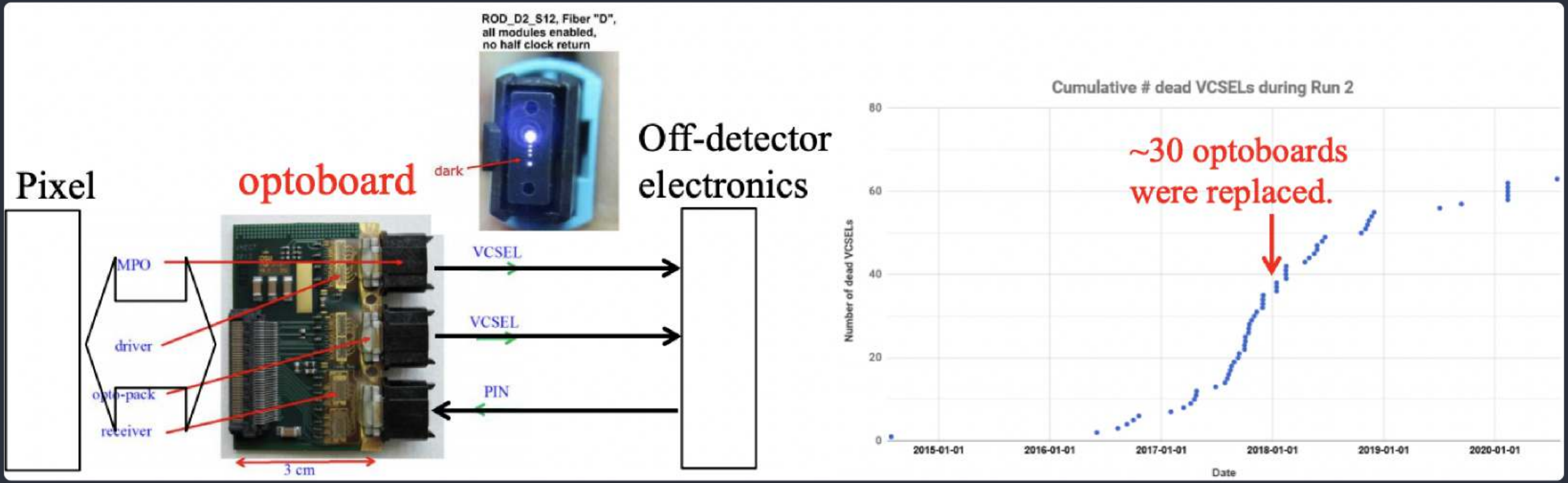






- Lorentz angle is an important quantity and it is sensitive to deformations in the electric field wihtin a sensor.
- IBL : clear dependency with regard to integrated luminosity, and temperature, HV and radiation damge.
- SCT : ϕ_{MCW}, MCW: the incidentangle with minimum cluster width (MCW) represents the Lorentz angle.
  - In 2018, HV was increased, so ϕ_{MCW} recovered.

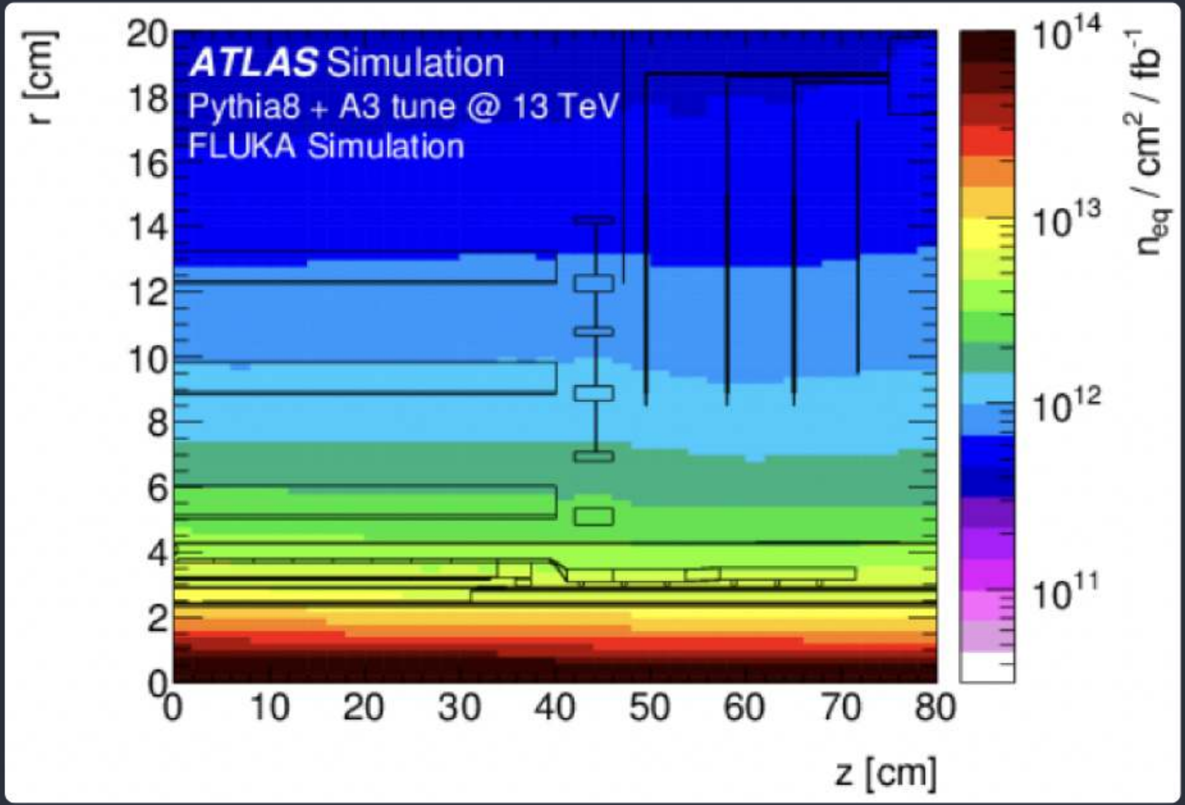
Failure of Optoboards in Pixel

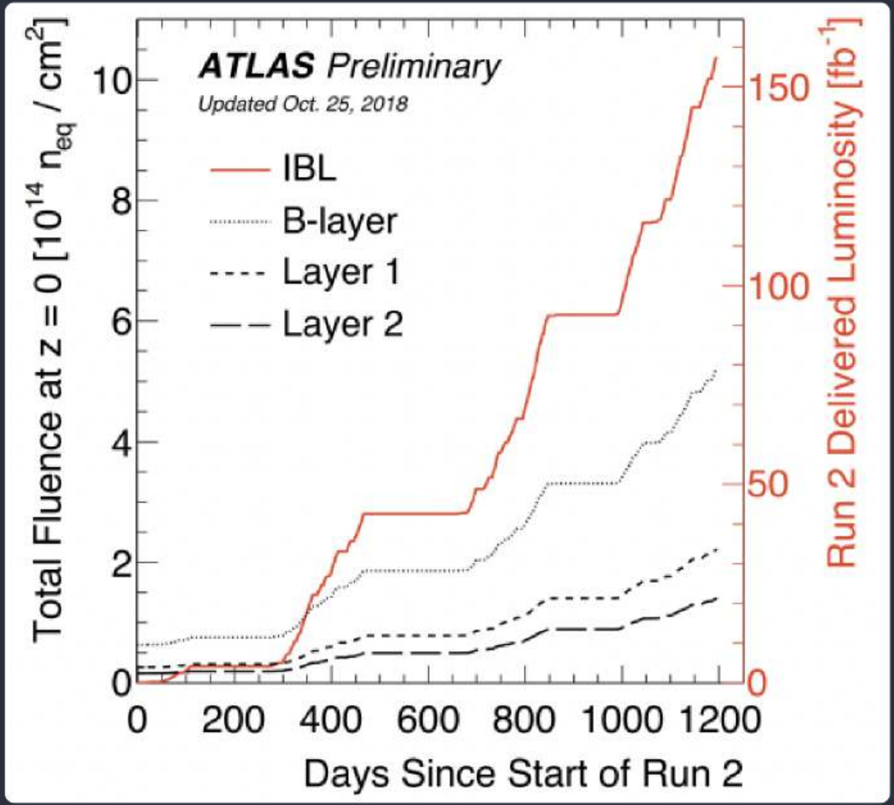


- Pixel had issue of a high failure rate of the VCSELs on optoboard, which is used for data transmission on the detector.
    - The cause of the failure is not known, possibly humidity.
    - ~30 boards were replaced before 2018 run, but ~30 additional VCSELs have died since then...
- **In this year, all suspicious optoboards have been replaced!!**
    - Added a protection for humidity.

Detector Performance and Radiation Damage

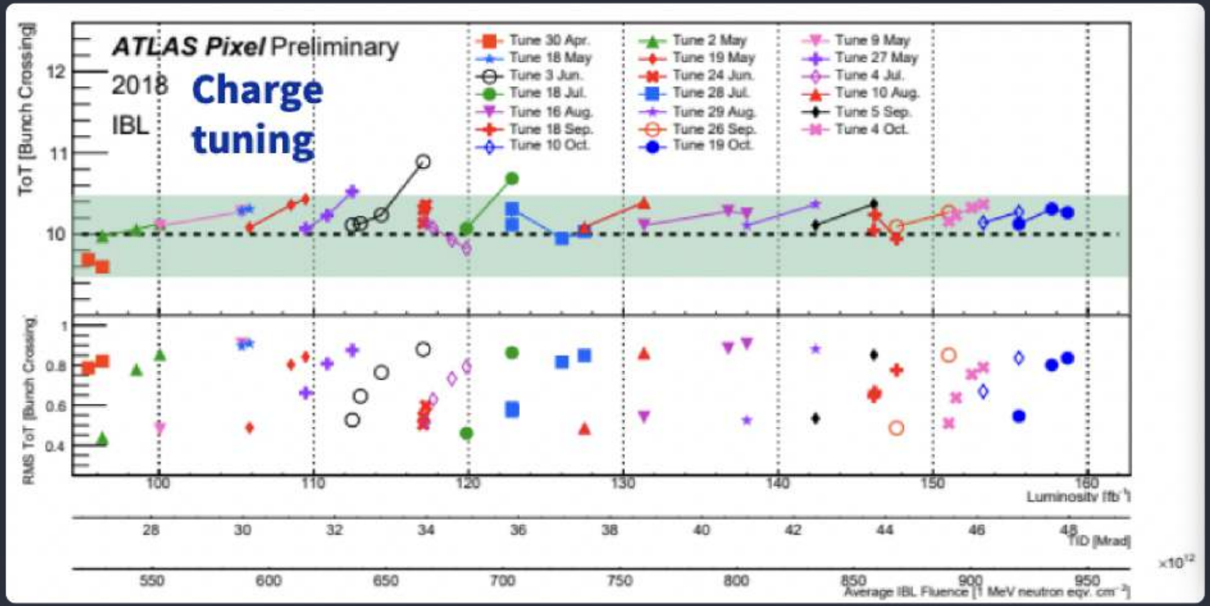
Fluence Estimation

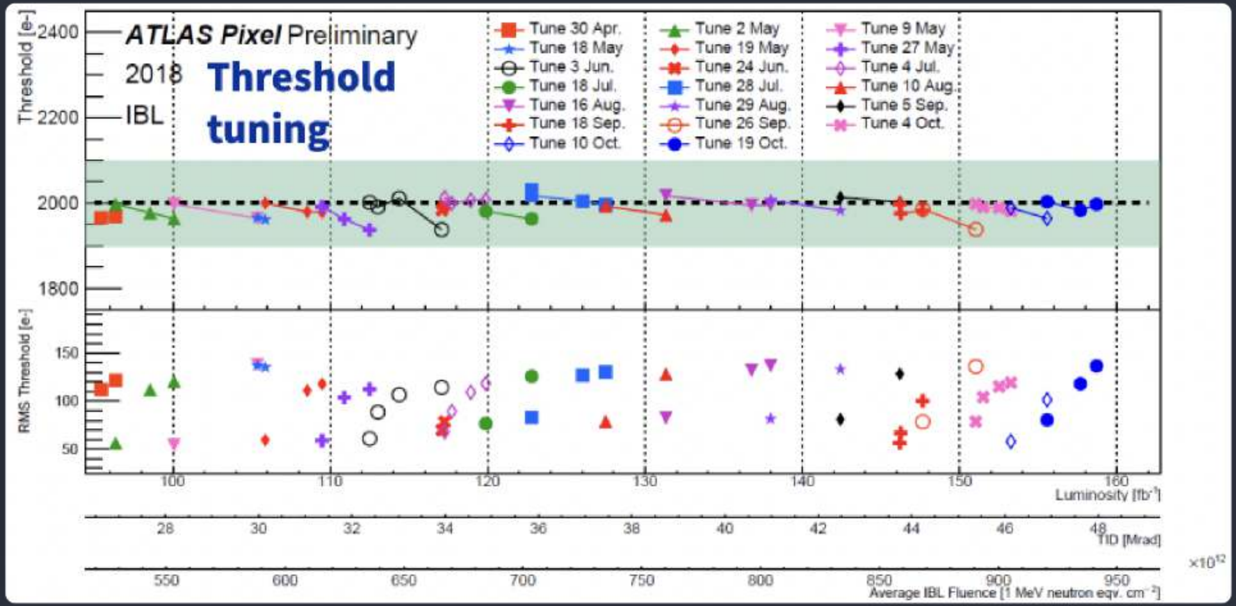




- 1 MeV $\mathrm{n_{eq}\,cm^{-2}}$ per fb^{-1} with estimated using Pythia8 + FLUKA.
- Fluence/fb^{-1} for IBL z= $0 : 6.2 \times 10^{12}\mathrm{n_{eq}/cm^2/fb^{-1}}$ (mostly pions)
- Luminosity measured using dedicated sub-detectors

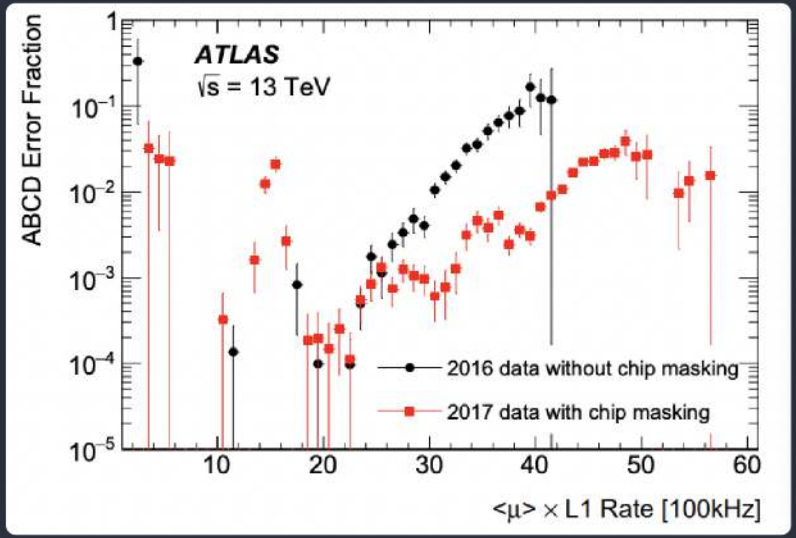
IBL Re-tuning

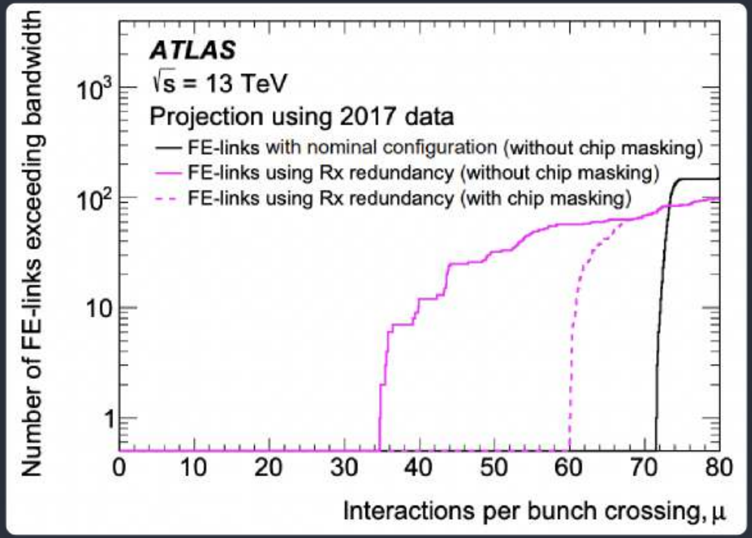


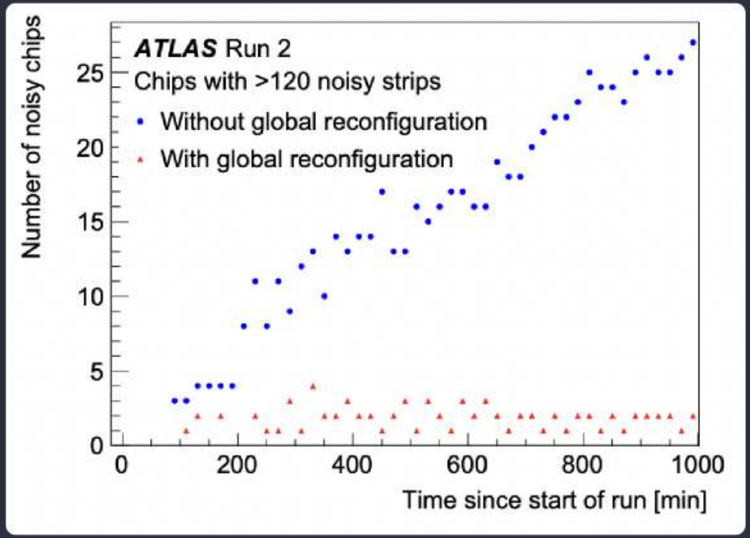


- Change of transistor leakage current due to Total Ionising Dose(TID) known in IBM 130 nm CMOS techology
  - Retuning of IBL charge responce(ToT) and theshold after irradiation
- By retuning every ~5 fb^{-1} the ToT mostly stays within 0.5 bunch crossings and the threshold within 100 electrons(green bands)
- More information can be found at TID effect on electronics.

SCT Re-tuning

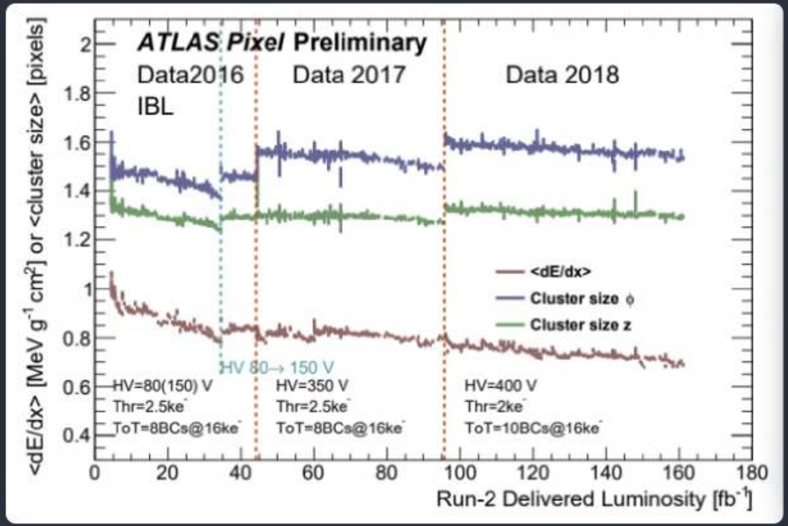


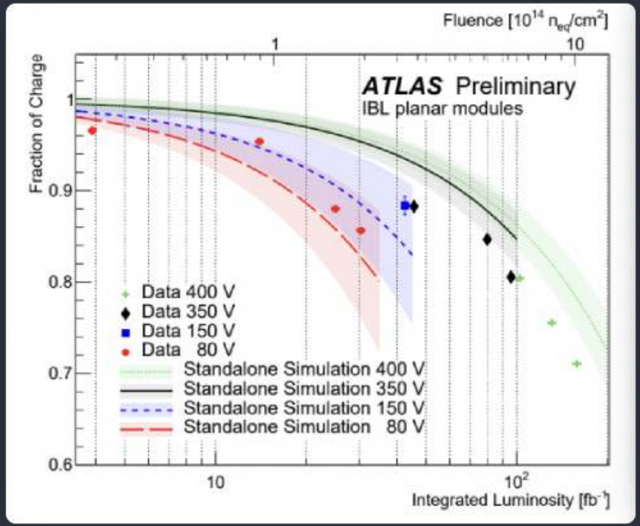


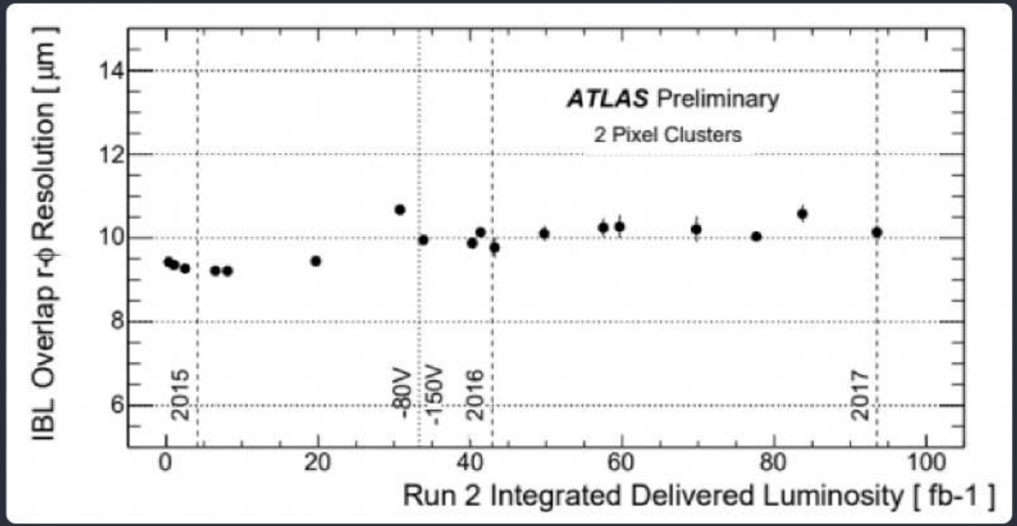


- **Chip masking** : Per FE-chip masking instead of module-by-module, the chip masking was done by dynamically during collision data-taking.
  - It helps to recover error fraction and FE-links bandwidth.
- **RX Redundancy** : Recovery of FE-link lost using an skip link from back-plane module.
  - This helps to recover data loss of 6 chips(on one module) to just one chip.
- **Global reconfig** : Recovery from Single-event upsets(SEUs) within the internal threshold register of an ABCD chip.
  - This process was activated every ~90 minnutes and took ~1.2 sconds.

IBL: Evolution of <dE/dx> and Cluster Size, Charge Collection Efficiency

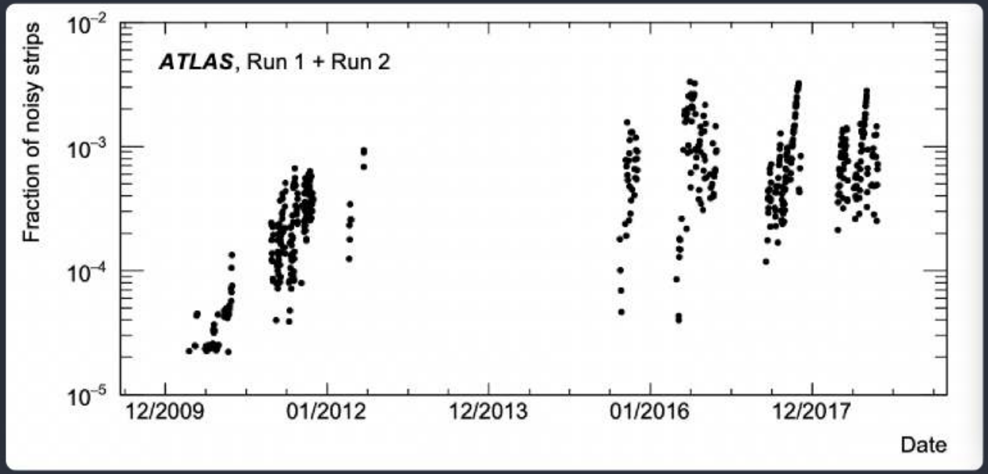


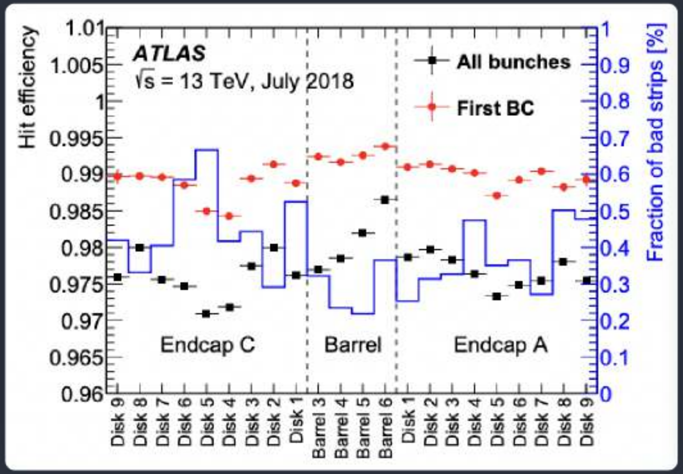


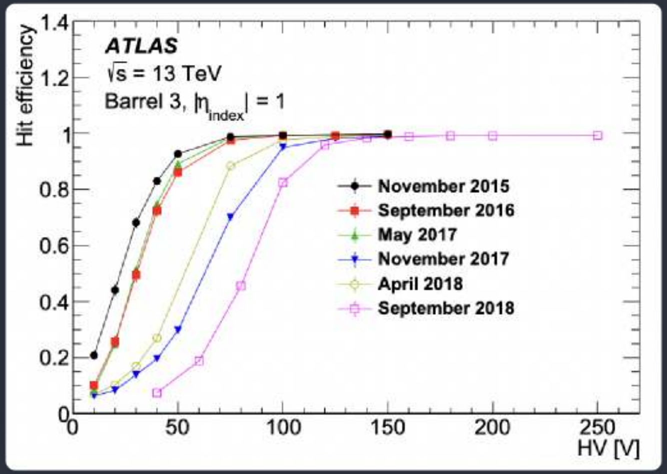


- **<dE/dx> and Cluster size:**
  - Increased radiation damage $\rightarrow$ less collected charge(shallow downwards slope in <dE/dx>) and hence smaller cluster size in (ϕ, z)
  - Increase in HV $\rightarrow$ full depletion and reducing threshold to mitigate effect of less charge, increasing thresholds due to limitation in bandwidth.
  - End of Run2 $\rightarrow$ set lower thresholds and increase HV $\rightarrow$ mitigate effects of radiation damage!!
- **Charge Collection Efficiency(CCE)**:
  - Increasing int. lumi. $\rightarrow$ radiation damge to sensor bulk $\rightarrow$ reduction of collected charge.
  - @160 fb^{-1} only 70% of initial charge $\rightarrow$ very small impact on tracking as can be seen in the evolution of two-cluster resolution.
  - End of Run2: @70% CCE for IBL modules MPV is about 10ke- with a 2ke- threshold(tuning)

SCT: Evolution of Noisy Strips and Hit Efficiency

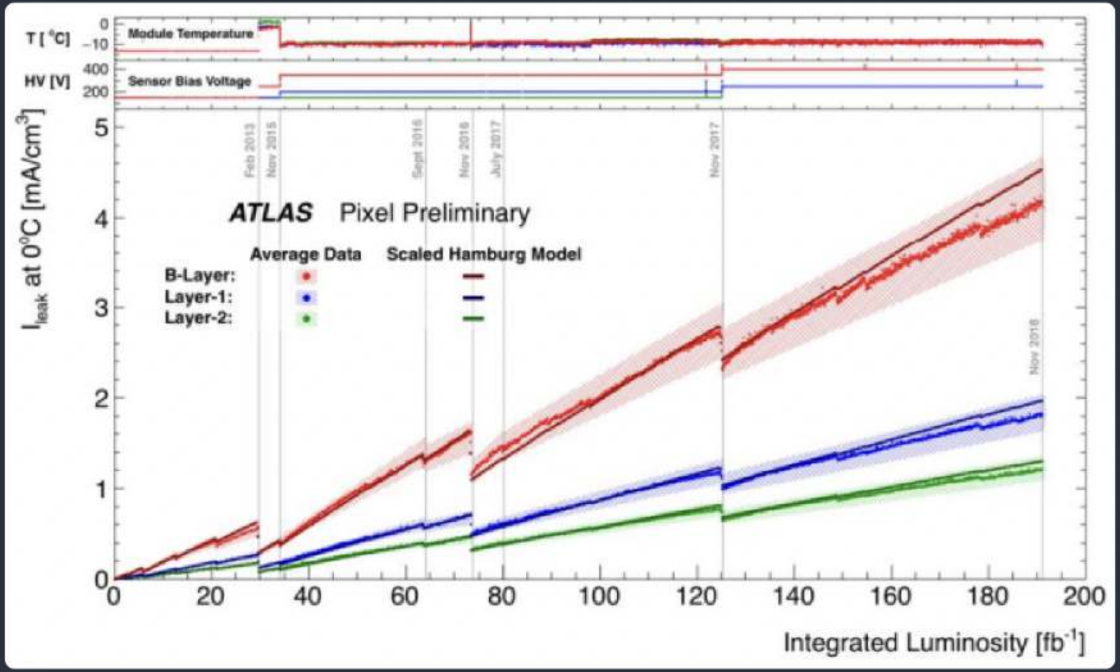


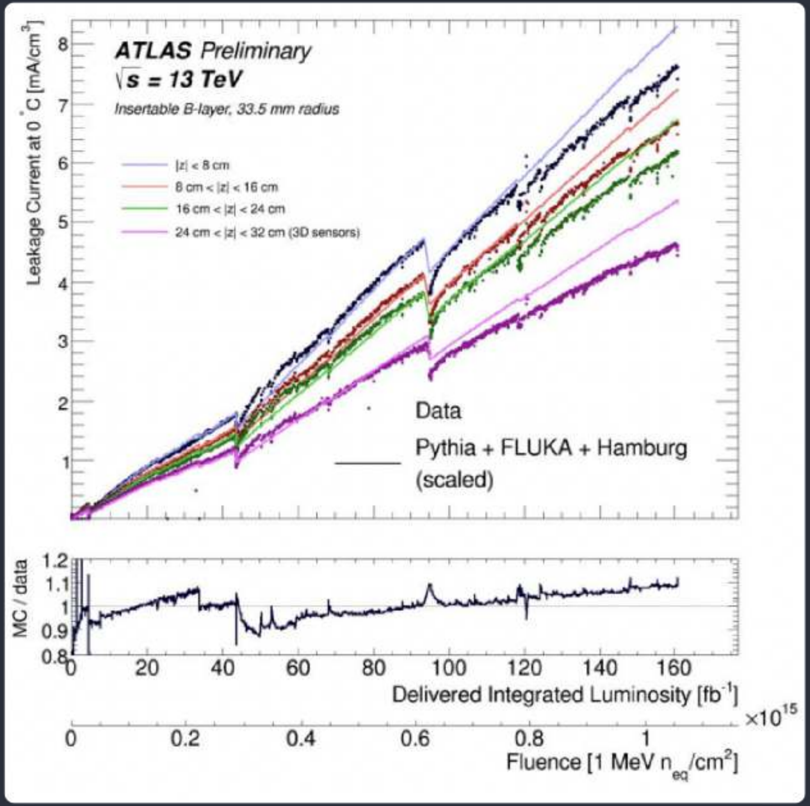




- **Noisy Strips** : Increased a fraction of noisy strips at high fluence.
    - Monitor noisy strips and calibrate a threshold strip-by-strip.
- **Hit Efficiency** : hit efficiency on track
    - Monitor a hit efficiency at begining of run and all bunchs → decreasing an efficiency over one collision run.
    - Monitor a hit efficiency as a function of high-voltage over date → significantly decreasing efficiency over time.

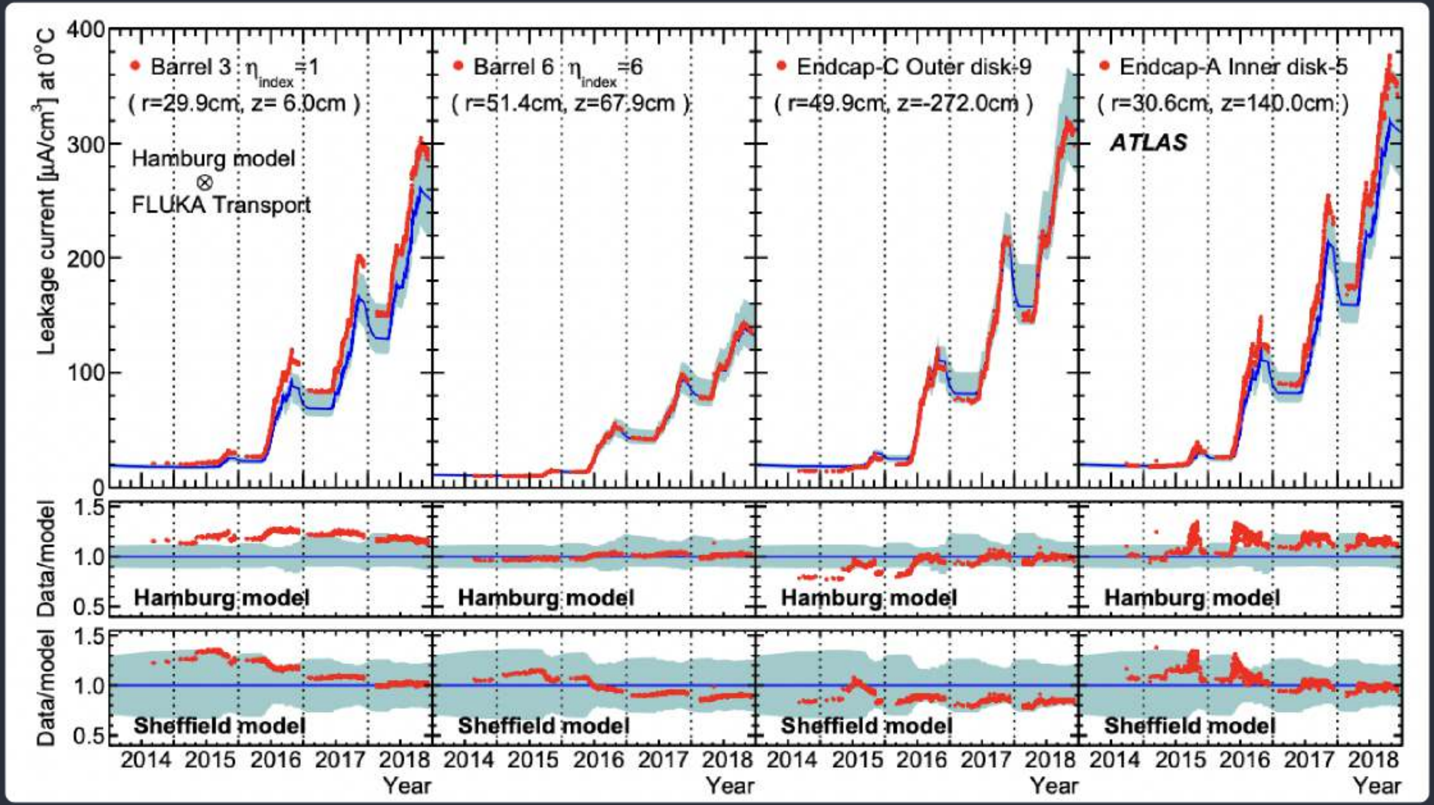
IBL/Pix: Modelling Radiation Damage: Leakage Currents





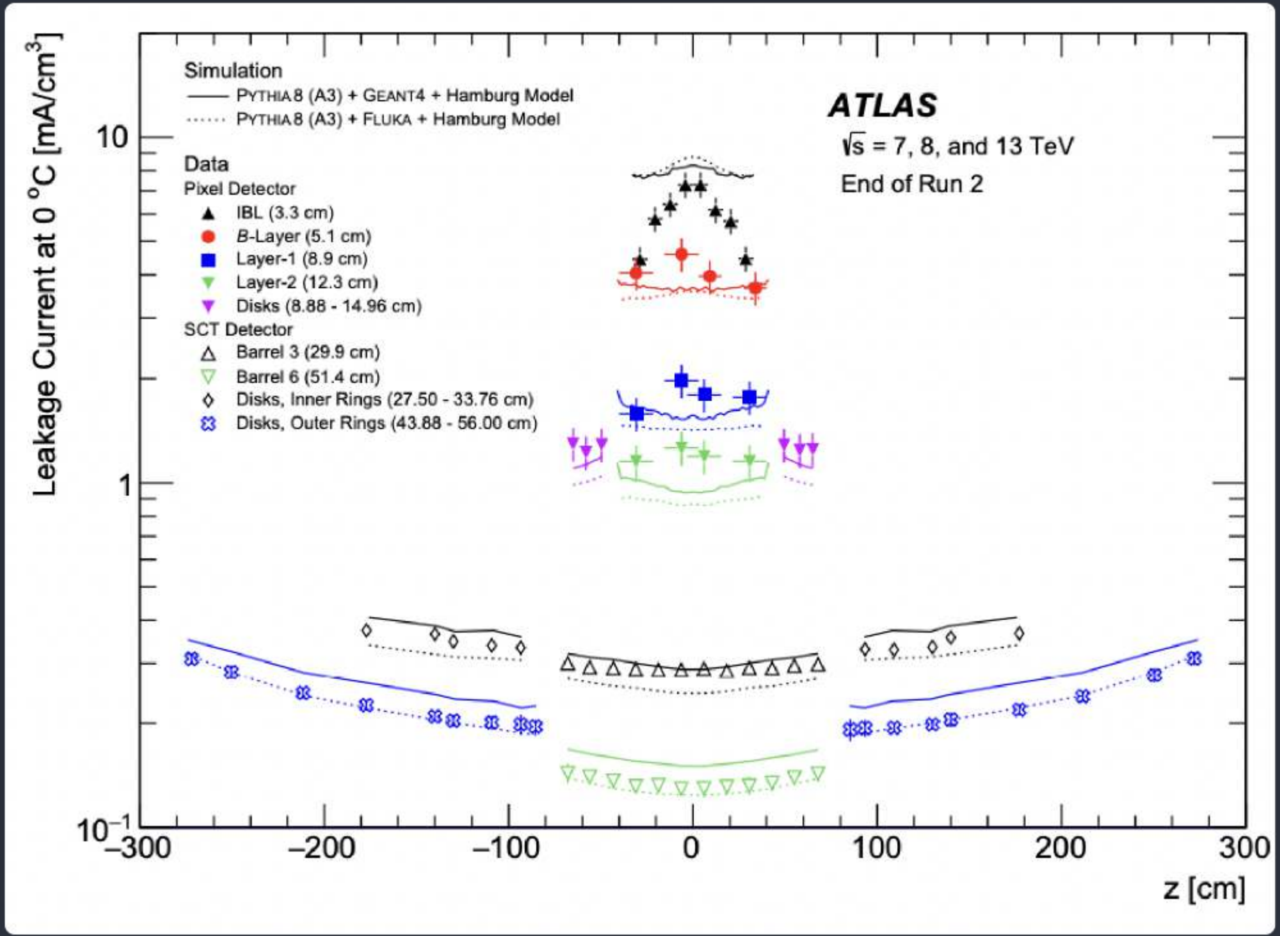
- Leakage current easily accessible quantity to monitor radiation damage.
- Modelled by Hamburg Model(input: temperature, annealing, scaling) with reweighting.
- Slight over prediction at high fluences.

SCT: Modelling Radiation Damage: Leakage Currents



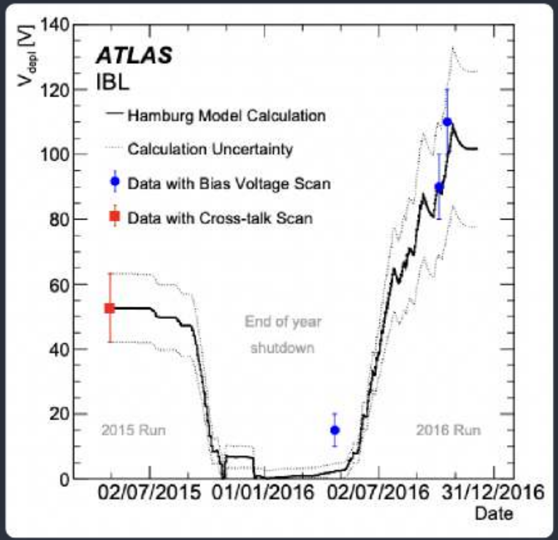
- Same estimation as the IBL/Pix for the SCT.
  - Two Barrel and Endcap region with the innermost and outermost SCT layers.
  - Barrel: can see clear radius dependency.
- Tends to have under prediction at high fluences, but it's within error bands...

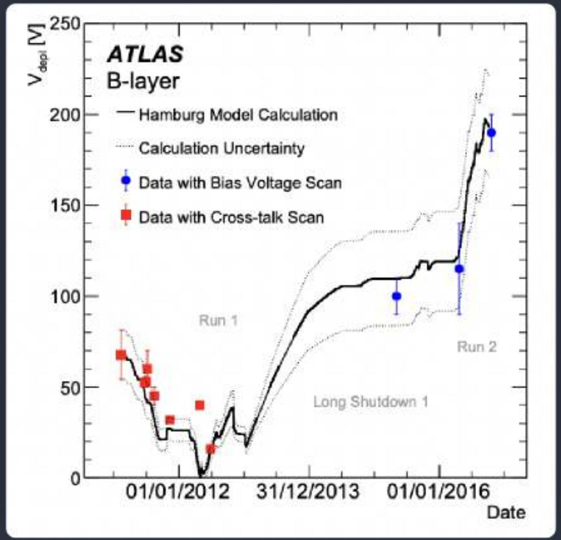
Leakage Current Comparison

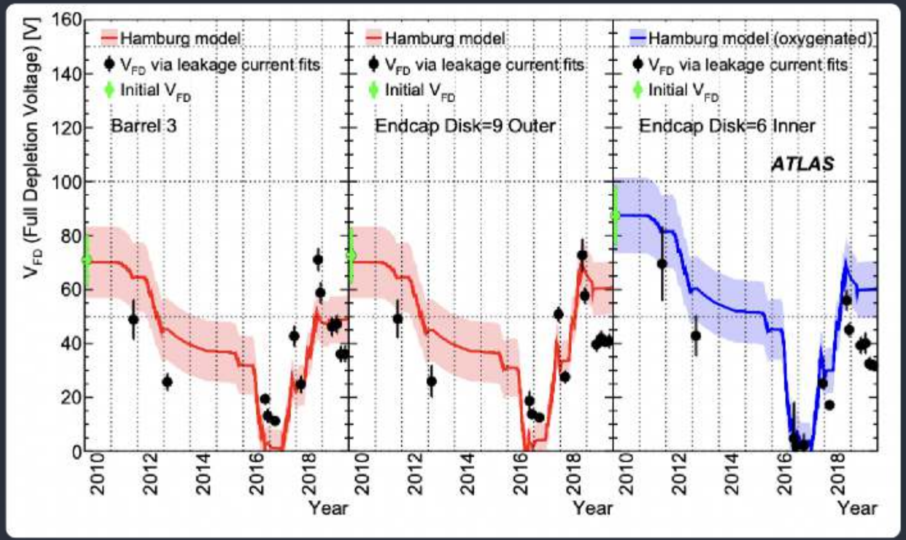


- The leakage current at the end of Run2.
- The fluence rate prediction agrees well with the IBL data at $|z| = 0$ and with all the SCT data.
- $|z|$-dependence observed in the IBL data
- the overall fluence is significantly higher than predicted for the outer pixel layers.
- The fluence on the inner layers is mostly determined by the primary charged-pion flux, which is relatively constant as a function of η.
- In contrast, a significant fraction of the fluence in the outer layers of the SCT is due to neutrons that are produced by interactions with material in the dense regions of the ATLAS calorimeters.

SCT: Full Depletion Voltage







- Pix/IBL : Depletion voltage measured via *cross-talk scans*(before type inversion) and *bias-voltage scans*(after type inversion)
  - B-Layer in good agreement with prediction at low fluences.
  - For IBL, the Hamburg model overpredicts the depletion voltage at high fluence, not the other way round.
- SCT : Depletion voltage measured via *I-V curves*.
  - I-V cureve : measure HV current and fitting a break point.

Summary and Conclusions

- IBL/Pixel and SCT were operated successfully in stable condition during Run1/Ru2.
- The effect of radiation damage on silicon sensor appeared both in IBL/Pix and SCT.
  - Higer leakage current, higher depletion voltage, lower charge collection efficiency.
  - Modeling of radiation damage on IBL/Pixel is summarized in
    - Modelling radiation damage to pixel sensors in the ATLAS detector.
  - Performance and radiation damage on SCT is summarized in
    - Operation and performance of the ATLAS semiconductor tracker in LHC Run 2
- A significant number of Pixel VCSELs has failed during Run2, therefore all suspicious opotoards were replaced in early this year.

Backup