Operational Experience and Performance with the ATLAS Pixel detector at the LHC

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on behalf of the ATLAS Collaboration

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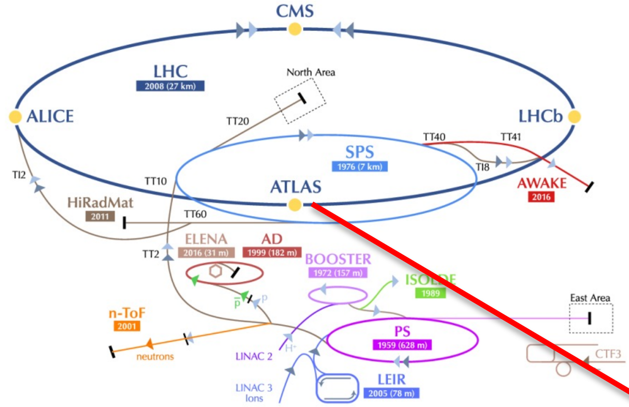
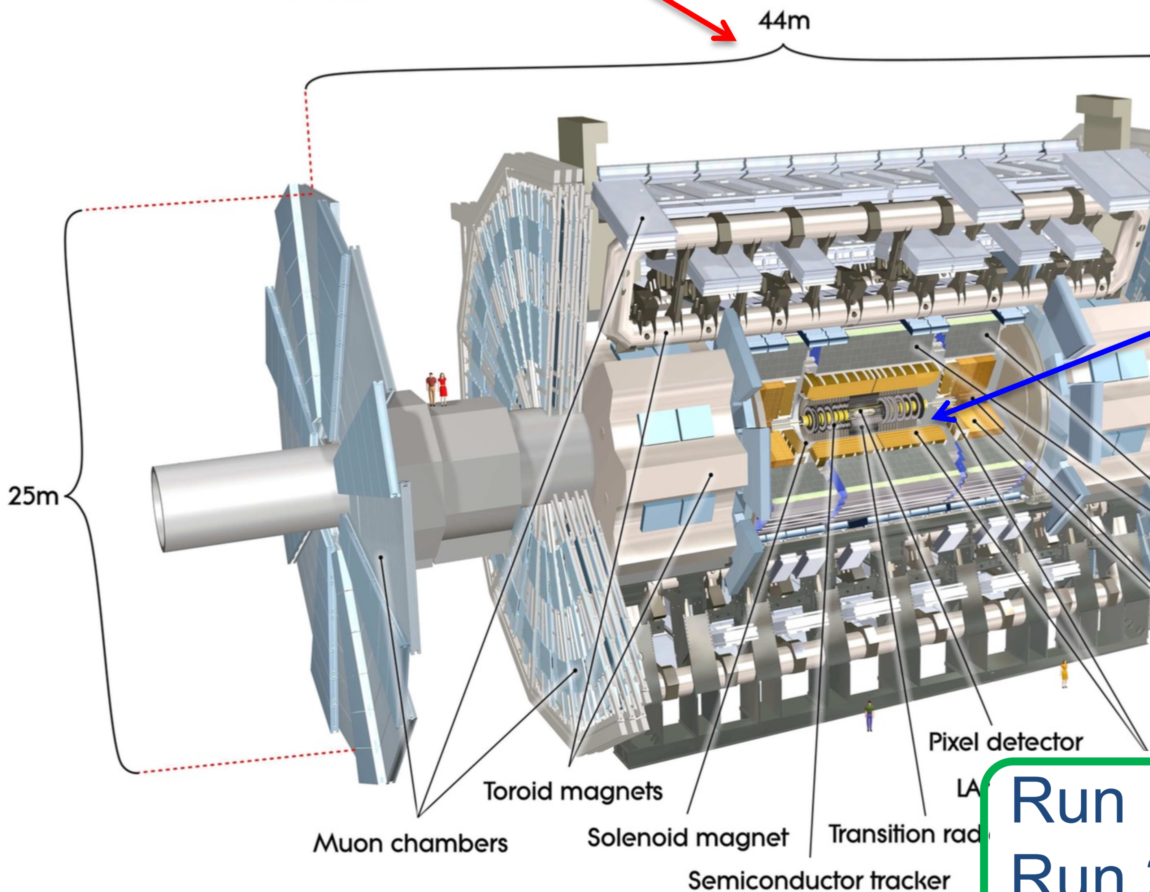
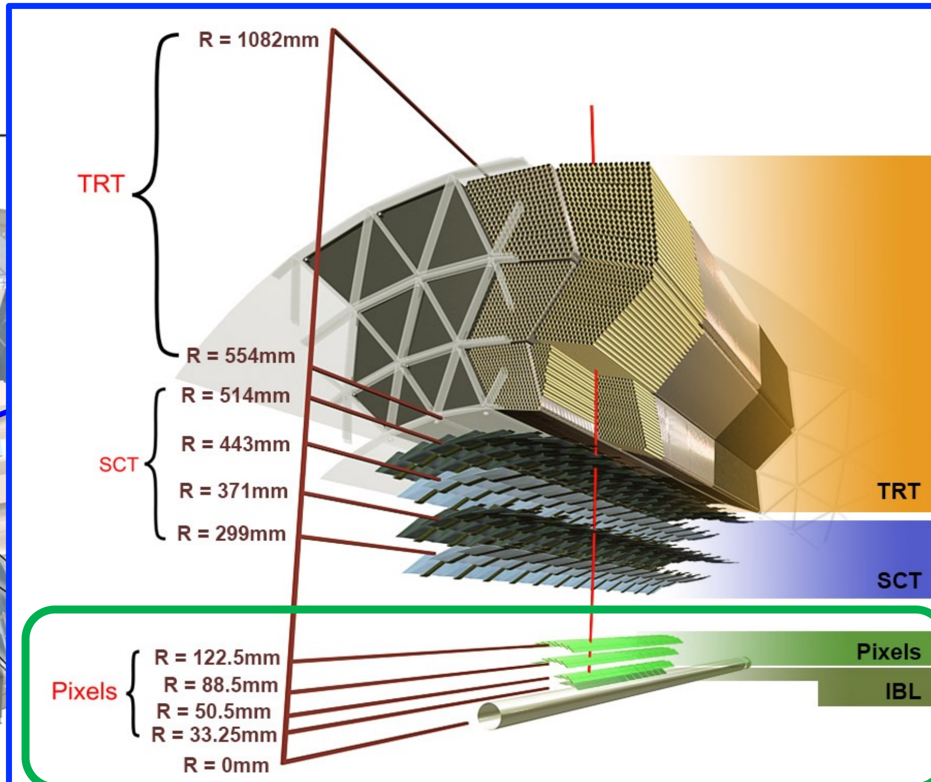
The ATLAS detector @ LHC





ATLAS **Inner Detector (ID)** tracker

- **Pixel Detector**
- Silicon Strip Detector (SCT)
- Transition Radiation Tracker (TRT)



Run 1 : 2010 - 2012 ➔ 3 pixel layers
Run 2 : 2015 - 2018 ➔ 4 pixel layers

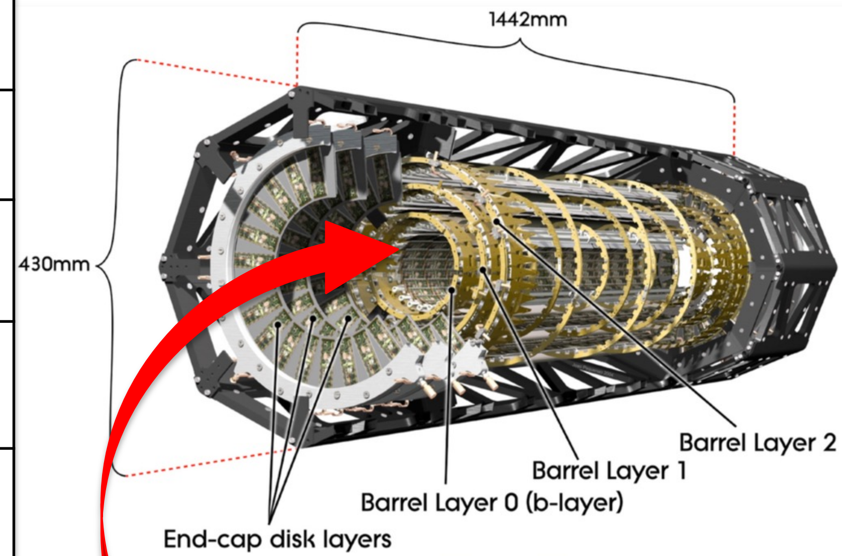
The ATLAS Pixel (+ IBL) detector

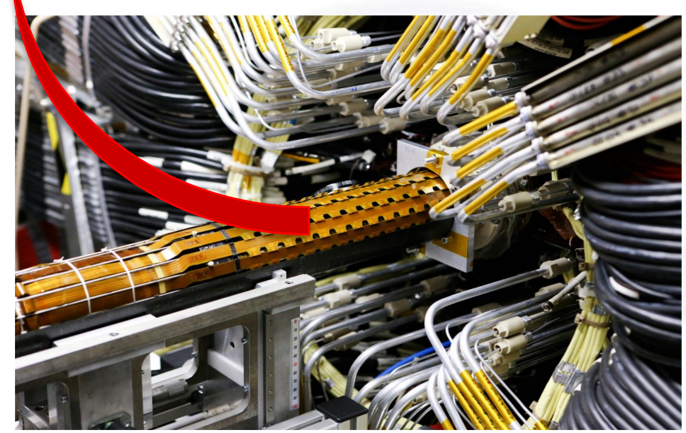
	Pixel (3 layers)		IBL (1 layer)
Sensor Technology	n^+-in-n (only planar)		n^+-in-n/$\mathbf{n^+}$**-in-*p*** (planar/**3D**)
Sensor Thickness	**250** μm		**200/230** μm
Front End Technology	FE-I3 **250** nm CMOS		FE-I4 **130** nm CMOS
Pixel Size	50 x **400** μm^2 (short side along R-φ)		50 x **250** μm^2 (short side along R-φ)
Radiation Hardness	**50 Mrad** (500 kGy) ~ 1 x 10^{15} $n_{eq}\cdot cm^{-2}$		**250 Mrad** ~ 5 x 10^{15} $n_{eq}\cdot cm^{-2}$
Barrel <Radius> or EndCaps $\text{Radius}_{\text{Min}}$	B-Layer	**5.05 cm**	**3.35 cm**
	Layer 1	8.85 cm	
	Layer 2	12.25 cm	
	EndCaps	8.88 cm	

2024 modules, **92** M channels,
1.92 m² of silicon

["Production and Integration of the ATLAS Insertable B-Layer"]

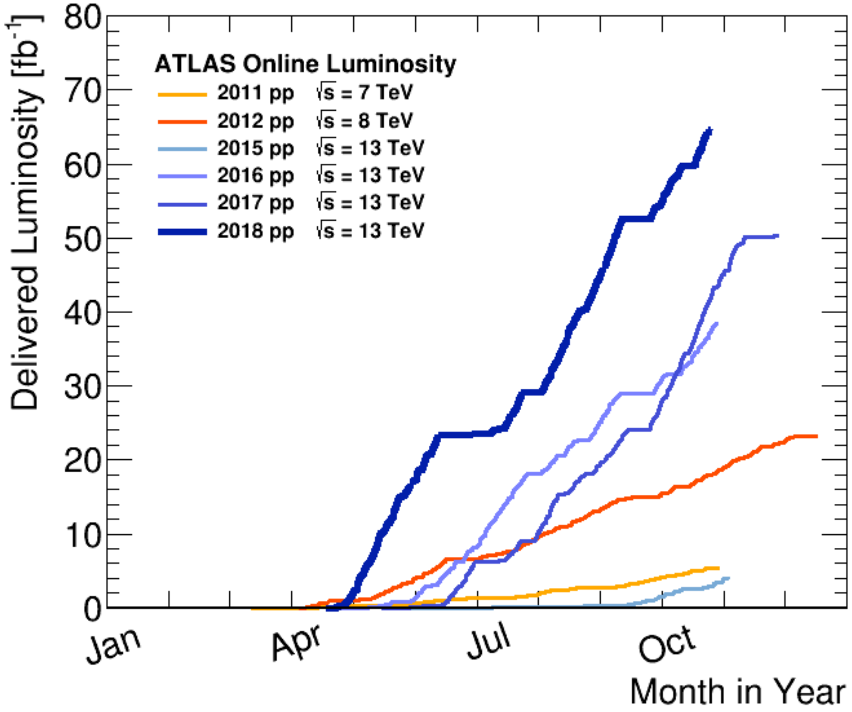
3 + 1 pixel **layers in barrel**
2 x 3 pixels **endcaps**

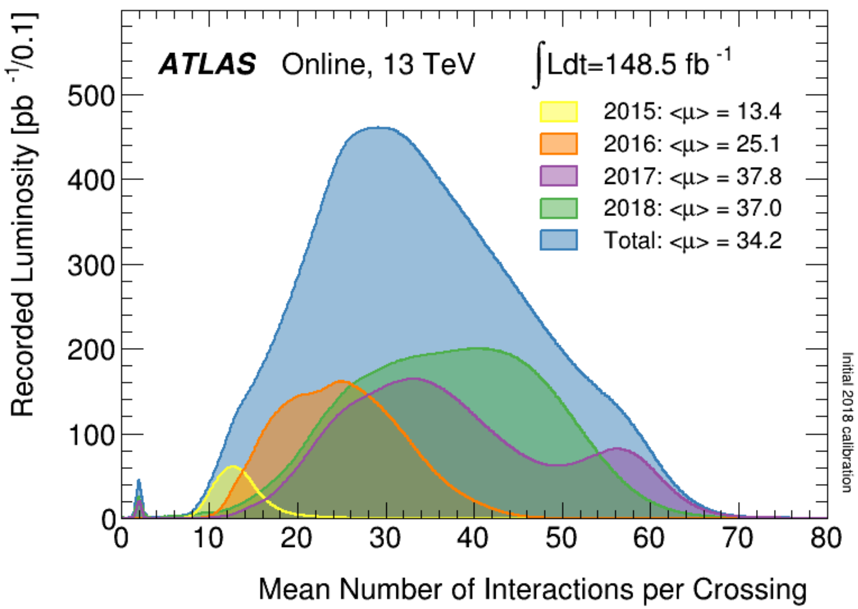




Insertable B-Layer (IBL)
added in 2014 (Run 2)

Facing the unexpected @ LHC





"End of Run 2" typical fill:

- Bunch crossing (BX) period: **25 ns**
- Pile-up or **μ** (#interactions/bunch crossing)
  - **Average ~ 35**
  - **Peak (fill start) ~ 55**

  ➔ **μ levelling at ~ 52 (~10 h)**
- Instantaneous luminosity ($cm^2\ s^{-1}$)
  - **Peak ~ 2 x 10^{34}**
- Integrated luminosity per fill (fb^{-1})
  - **Average ~ ~~0.5~~ ➔ ~ 1**
- Level 1 trigger rate (kHz):
  - **L1A Rate ~ ~~85~~ ➔ ~ 100**

Run 3 expectations

- Total Integrated luminosity

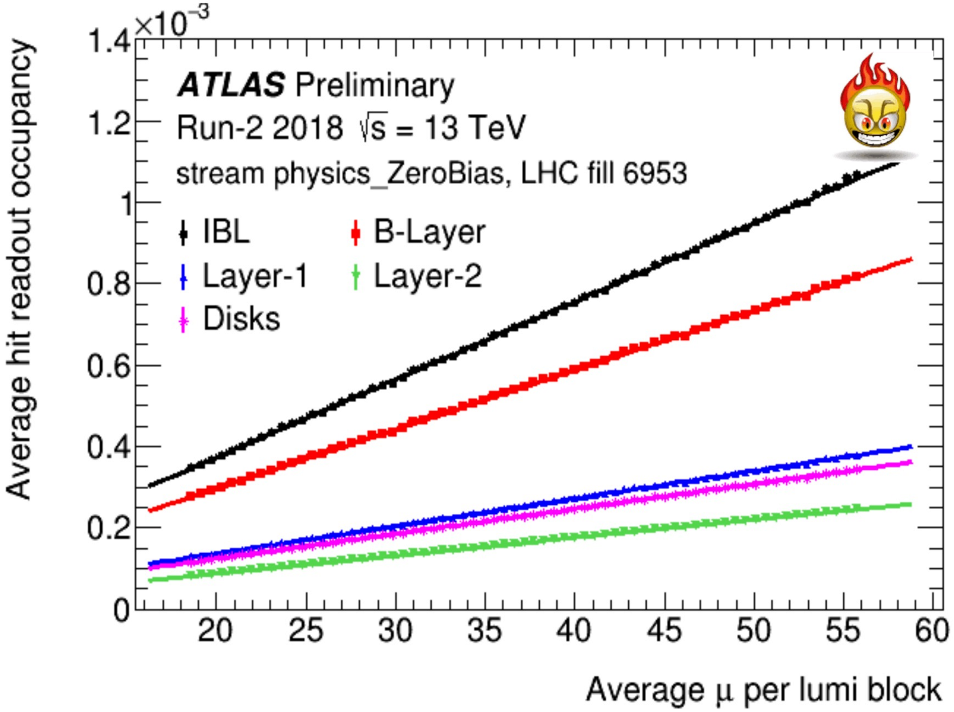
190 fb^{-1} (Run 1 + Run 2) ➔ **~ 290 fb^{-1}** (Run 3)

Up to **~480 fb^{-1}** before HL-LHC upgrade

Pixel operation in Run 2

OCCUPANCY vs PILE-UP

- Occupancy (hit/pixel/event) scales with **μ**
  ➔ **big event size** and **high trigger rate**
  ➔ **high bandwidth usage,** up to **70%!**



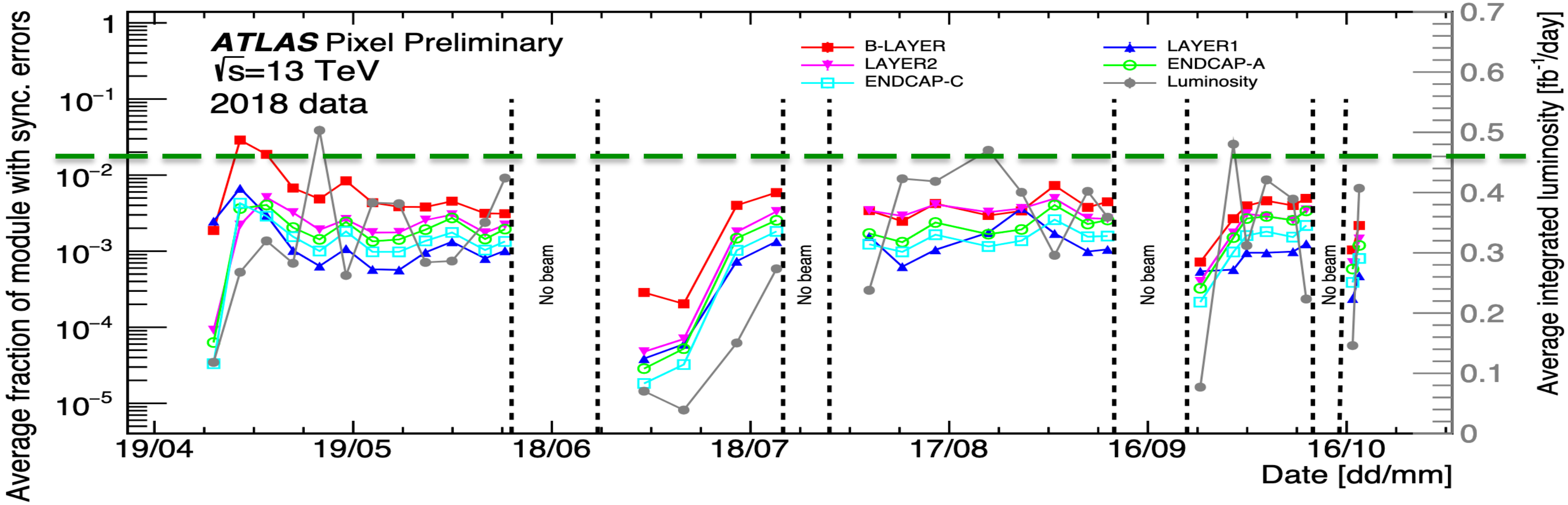
DEADTIME

- Loss of data acquisition time due to Pixel strongly decreased in Run 2 **<~ 0.2%** (2018)

DESYNCHRONIZATION

- Fraction of event identification mismatch **<~ 1%**

1%



The Pixel metamorphosis

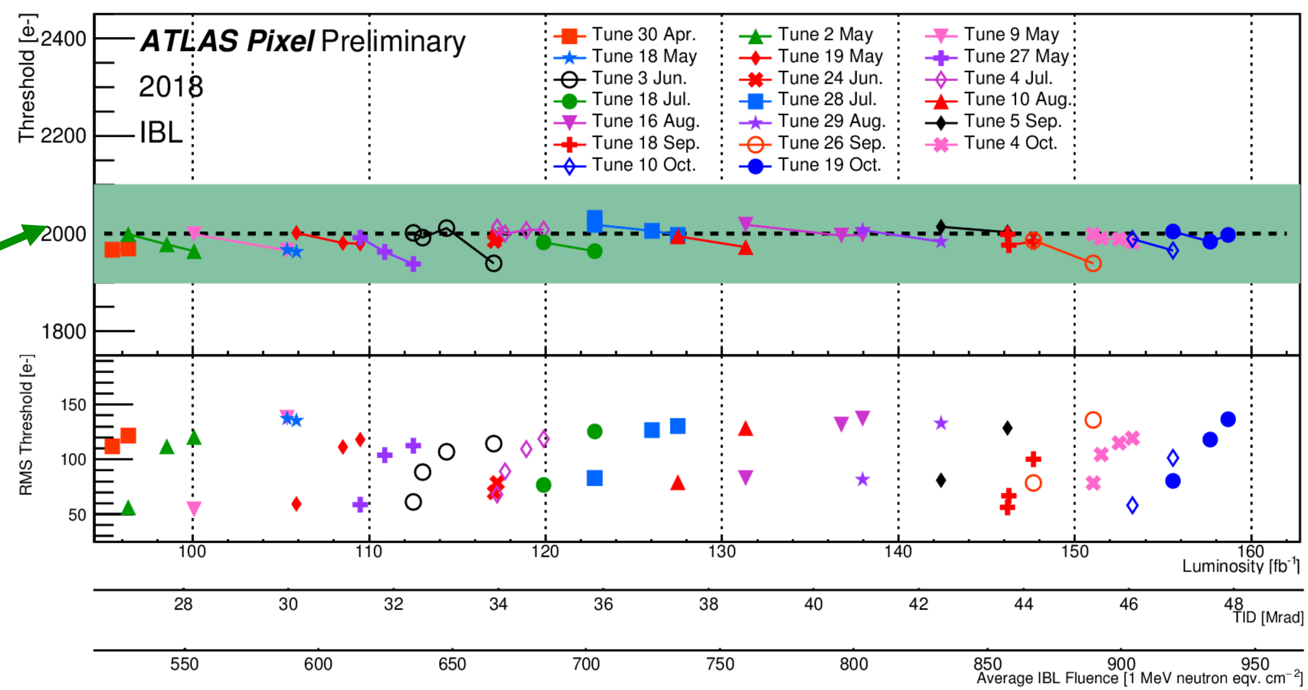
- Readout electronics/services upgrades and changes of configuration parameters to accommodate for **bandwidth limitations/radiation damage**.
  - *Read out speed*
  - ***Sensor bias voltage (HV)***
  - *Front-end latency*
  - *Analog/Digital thresholds*
  - *TOT target point for MIP*
  - *Threshold modulation vs eta*

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

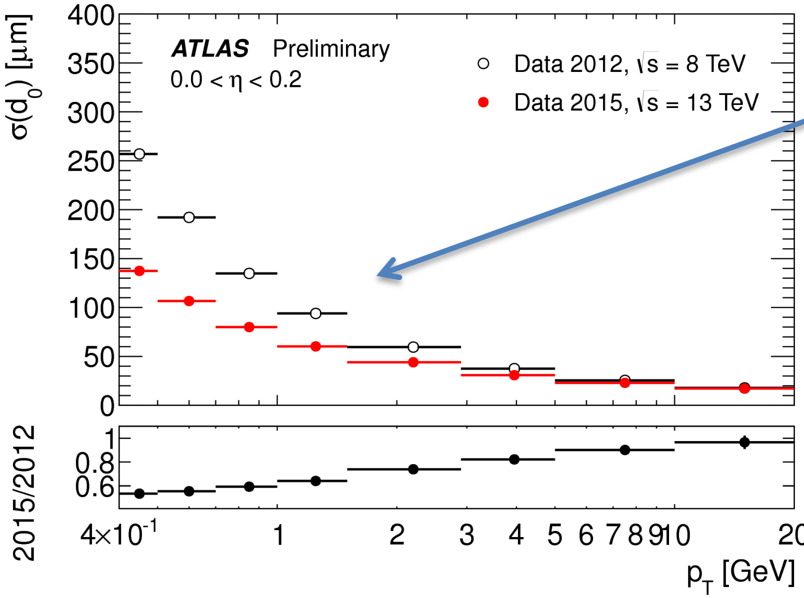
- **IBL**: Total Ionising Dose (TID) effect in front-end chips (FE-I4)

  ➔ drift of **Thresholds** and **Time-Over -Threshold (TOT)**

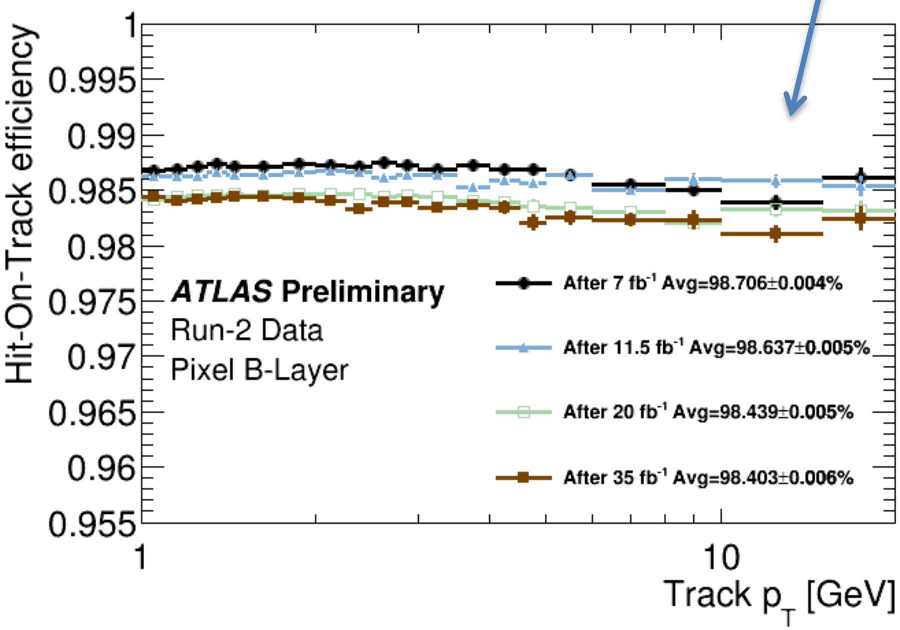
  ➔ regular (~weekly) re-tuning needed.

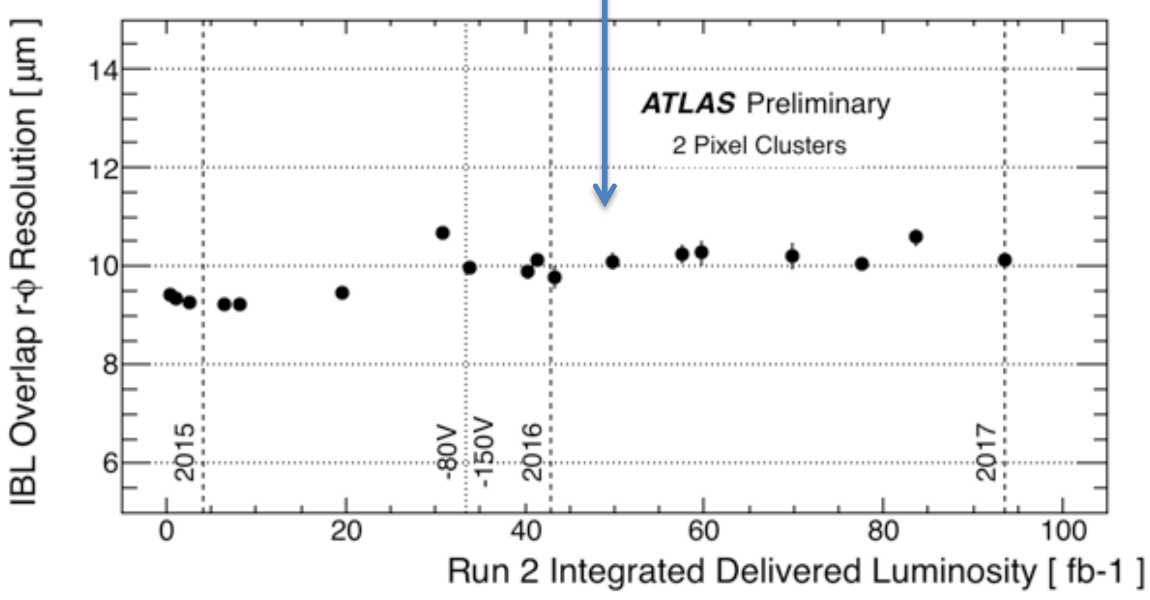


Pixel performance in Run 2



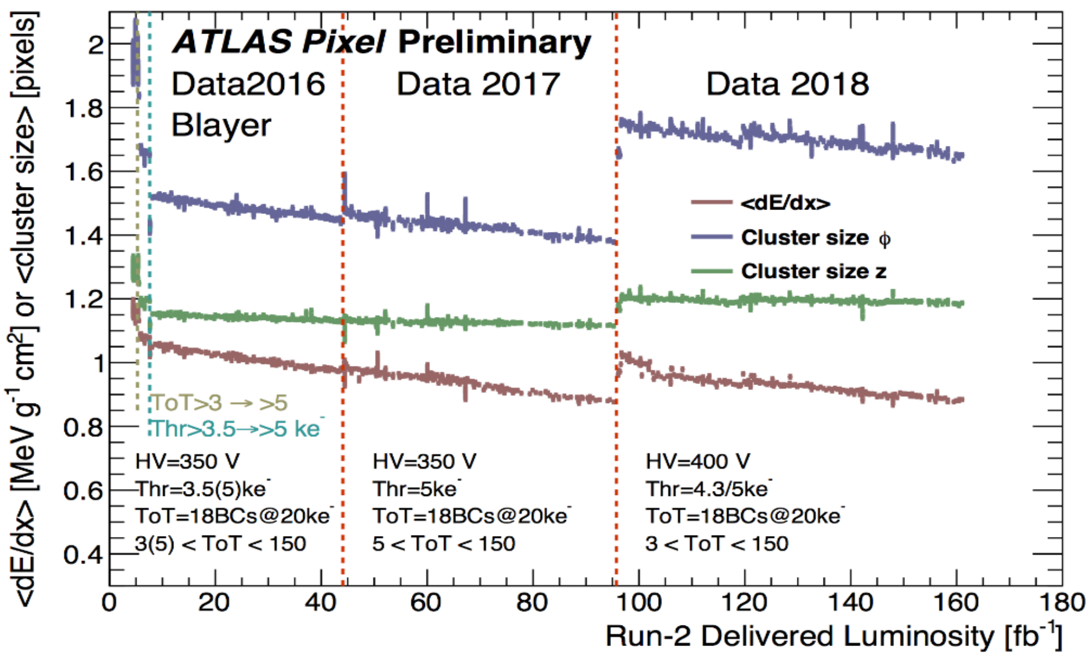
- **Impact parameter resolution** improvements after IBL insertion (2015)
- B-Layer **Hit-on-track efficiency > 98%** (2016)
- IBL **spatial resolution** (transverse R-φ plane) **~< 10 μm** over Run 2.

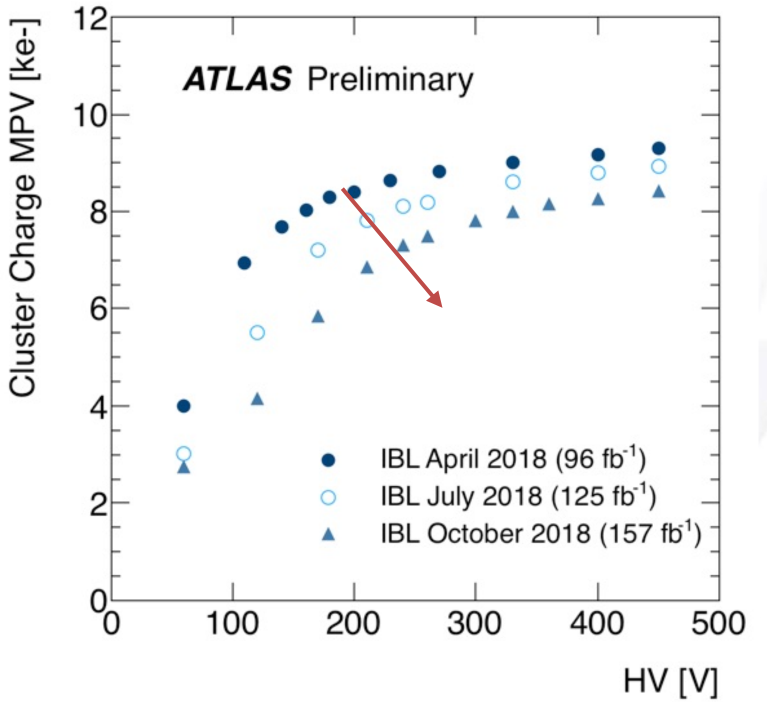




Impact of radiation on sensor

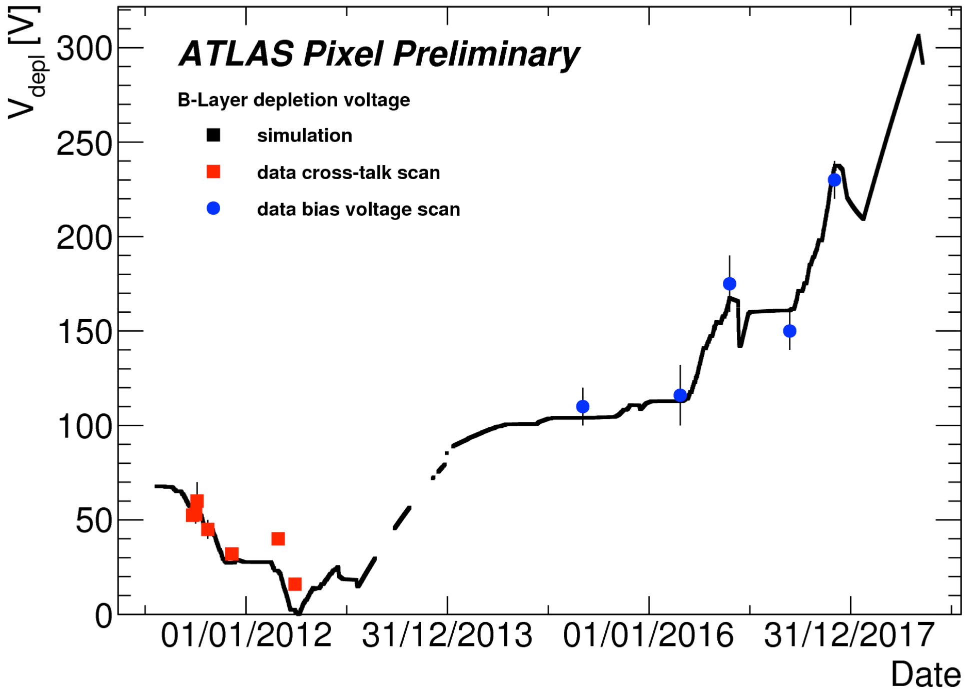
- **dE/dx and cluster size decrease** due to the decreased charge collection efficiency (slow slope).
- **HV (threshold) increase (decrease)** shows gain in dE/dx.
  - however, thresholds increased in 2016 due to bandwidth limitations (B-Layer).
- Charge collection constantly measured via **HV scans**
  - MPV of the fitted Landau cluster charge affected ➔ **decrease of plateau.**





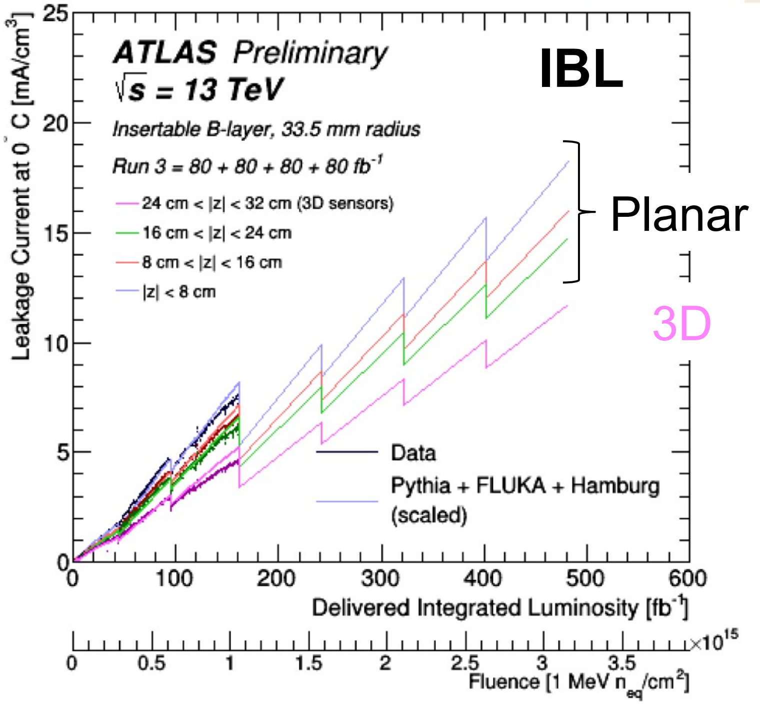
Depletion voltage/leakage current

- **Higher bias voltages** to guarantee a full depletion region.
- Hamburg model predictions matches well data from bias voltage scans (or cross talk) at low fluences.
- Data collected at the begin of each year to confirm predictions/set points for the year ahead.



- **Leakage currents** quite well described by Hamburg model (annealing, temperature)
  - slightly overestimated towards the end of Run 2.
- Extrapolation to end of Run 3 within the power supply limits.

→ [***Measurements of sensor radiation damage in the ATLAS inner detector using leakage currents***]()

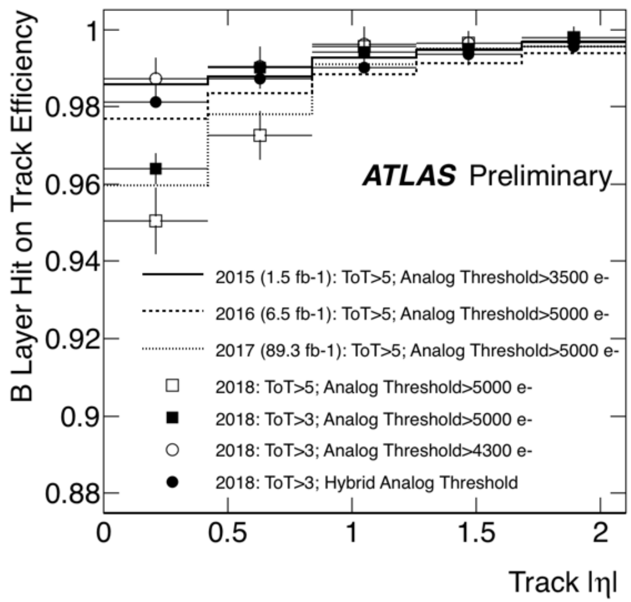


Fighting the radiation damage

Dual strategy

Minimize the impact (without forgetting the long-term picture)

- Detector parameter changes to recover/accommodate for rad. damage
  - HV, thresholds, tunings points.

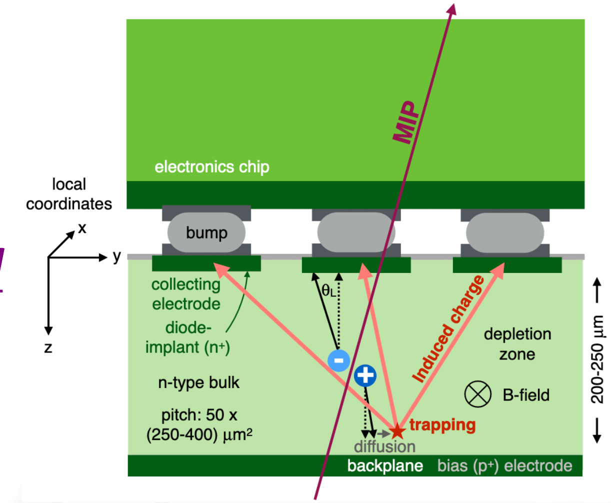


- Keep the detector cold to avoid **reverse annealing (higher depletion voltages)** and **high leakage currents**.

Characterize/model the radiation damage for Run 3

- Development of **new radiation damage (digitizer) MC.**

Modelling radiation damage to pixel sensors in the ATLAS detector

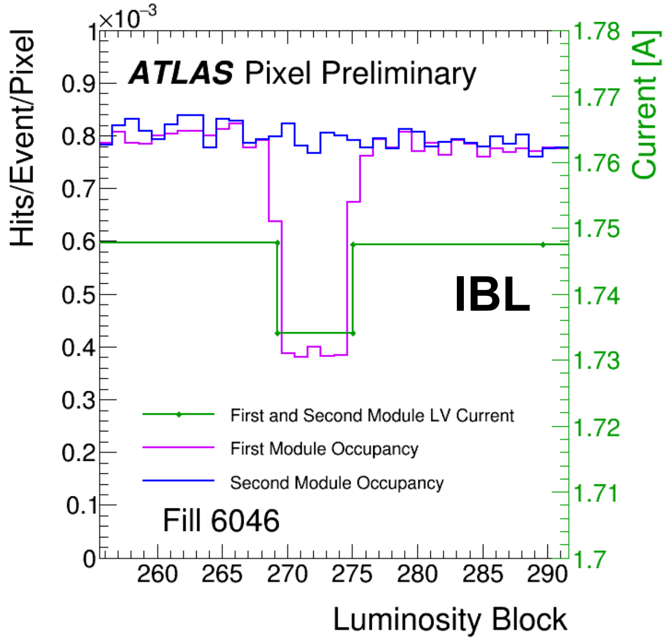


- Extensive validation of the new digitizer ➔ **official ATLAS Run 3 MC.**
- Exploit the radiation damage MC to train our clustering/tracking algorithms (**M**ixture **D**ensity **N**etwork).
- Extrapolate **depletion voltage/leakage current predictions** to the end of Run 3.

Impact of radiation on FE electronics

Single Event Effect (SEE): **big charge deposit** in FE electronics can flip the state of **global/local memory cells**.

- IBL FEs being affected by SEE (2017)
  ➔ **periodical reconfiguration of FE global registers** improved the operation stability/data quality.

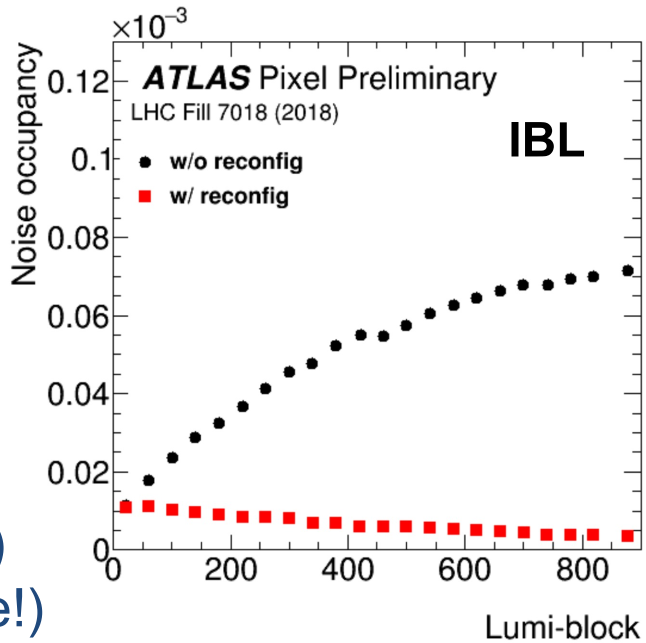


- As LHC delivered fills with higher integrated lumi (2018):
  - **noisy pixels** (pixels firing in the empty bunches)
  - **quiet pixel** (pixels not firing in colliding bunches)

  due to SEE in **single pixel latches!**

Measurements of Single Event Upset in ATLAS IBL

- Solved by adding the periodical reconfiguration of the **single pixel latches**
  ➔ clear gain observed during test run (2018).

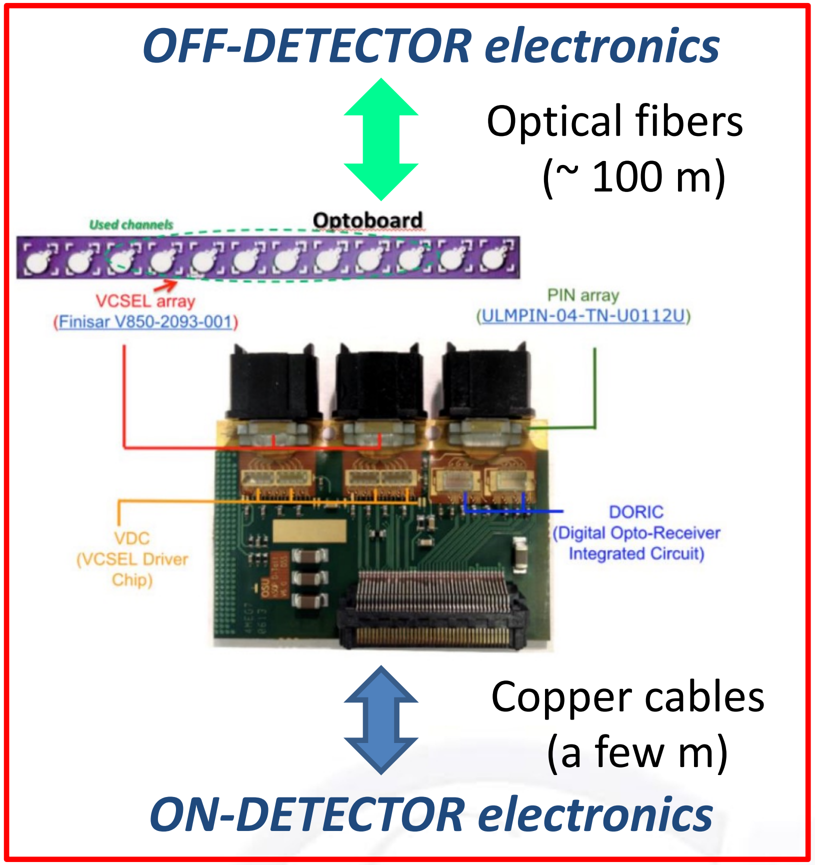


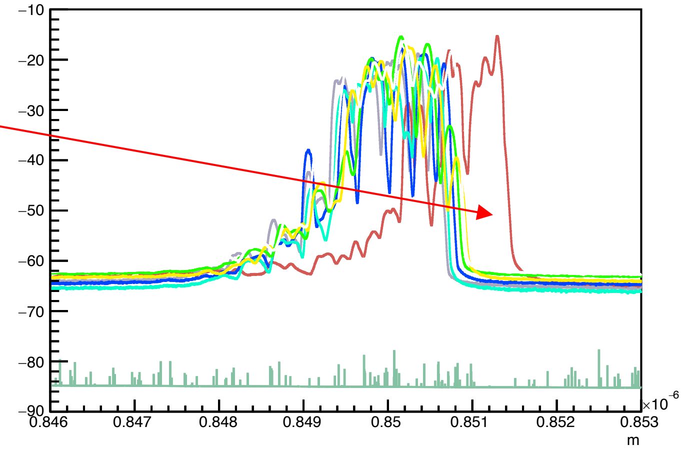
- Run 3 strategy: mitigate the **higher radiation per fill (luminosity levelling to higher luminosity/particle flux)**
  ➔Full FE reconfiguration every ~10 minutes (no dead time!)

Opto-Board replacement during LS2

- Relevant number of VCSEL (laser array) failures during Run 2 (**~3%**).
  - humidity being the main suspect.
- New **O**pto-**B**oard production (with new VCSELs) ➔ **>400** qualified.
- Selective replacement done (**178 OBs**) in February 2021.
  - replacement of OBs hosting dead VCSELs (**25 modules recovered**) or VCSEL alive with a shifted optical spectrum.
- Sealing of Optoboxes (hosting OBs) to keep the boards dry (humidity concern).

➔ no failures observed so far!





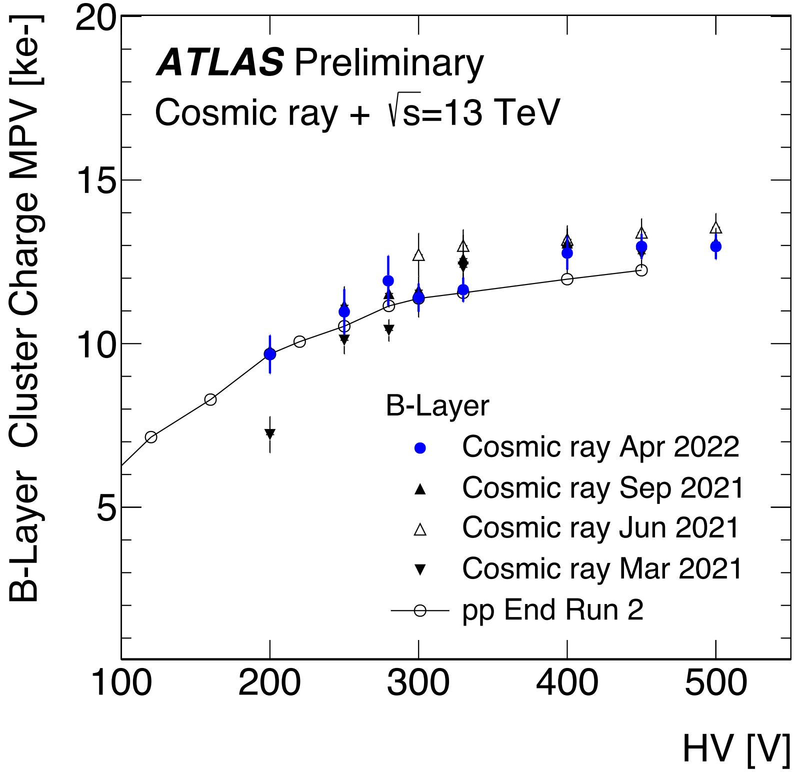
Detector status during LS2

- Detector kept **OFF (and cold)** most of the time.
  - Pixel (C_3F_8 evaporative) and IBL (CO_2 bi-phase) cooling very stable.
- Successful yearly maintenance of cooling systems
  - a few weeks at room temperature, **43 (23) days** in Pixel (IBL).
- A new thermosiphon system will serve as ID **Run 3 official cooling.**

Temp set point (LS2)	PIXEL	IBL
Detector OFF	-5 °C	-7.5°C
Detector ON (Cosmics)	-20 °C	-20°C

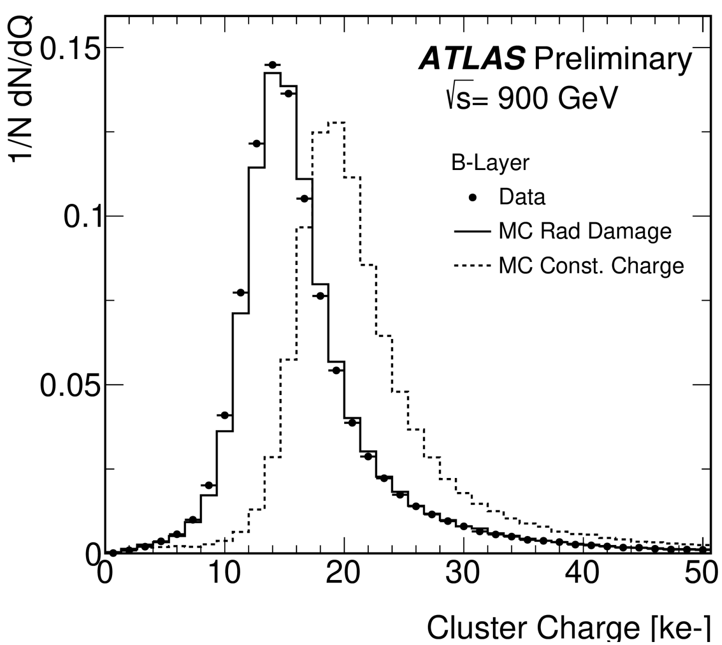
- Turn ON **two weeks every two months**
  - Calibrations and cosmic data taking
  - Monitoring noise and depletion voltage (annealing negligible)
  - Test of Run 3 configs

Vth	Run 2 (End Of)	Run 3 (Start of)
IBL	2000 e	1500 e
B-Layer	4300 e/ 5000 e	3500 e/ 4300 e
Layer 1	3500 e	3500 e
Layer 2	3500 e	3500 e
Disks	3500 e	3500 e

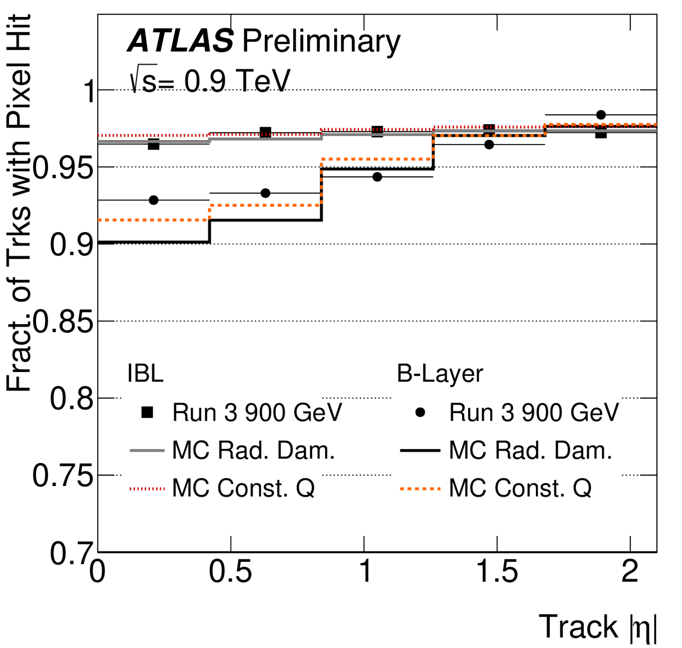


Exploiting first Run 3 collisions

- End of LS2 (cosmics) and begin of Run 3 (900 GeV collisions) used to test new configurations with **increased HV** and **lowered thresholds**.
- Effect of radiation damage on cluster charge data, **very well reproduced** by new **Radiation Damage MC!**
- Fraction of tracks with Pixel hits slightly affected in the central part of the detector (short silicon path traversed and higher radiation damage).



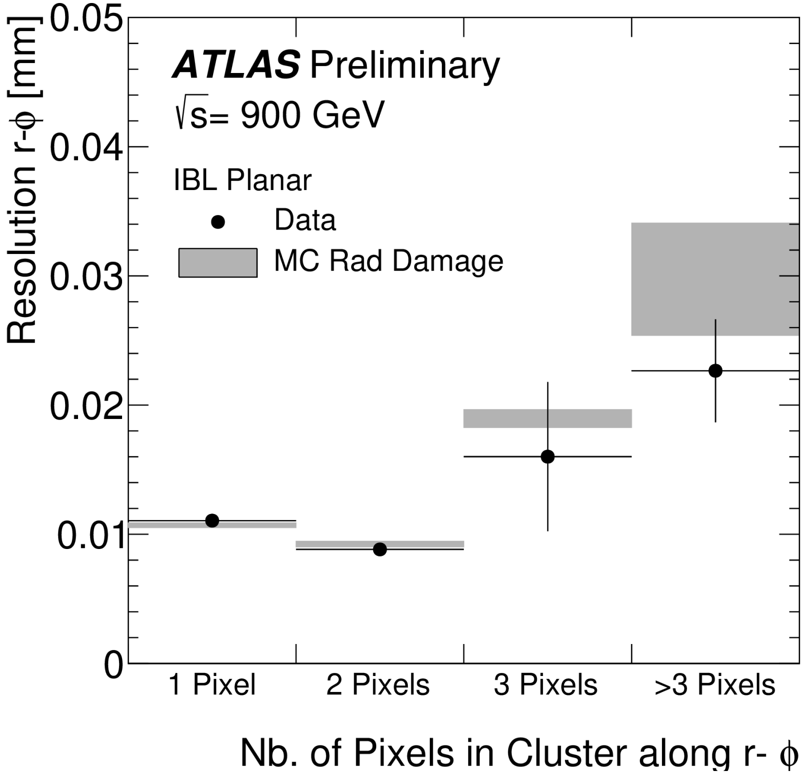
HV	Run 2 (End Of)	Run 3 (Start of)
IBL Planar IBL 3D	400 V 40 V	450 V 60 V
B-Layer	400 V	450 V
Layer 1	250 V	300 V
Layer 2	250 V	300 V
Disks	250 V	300 V

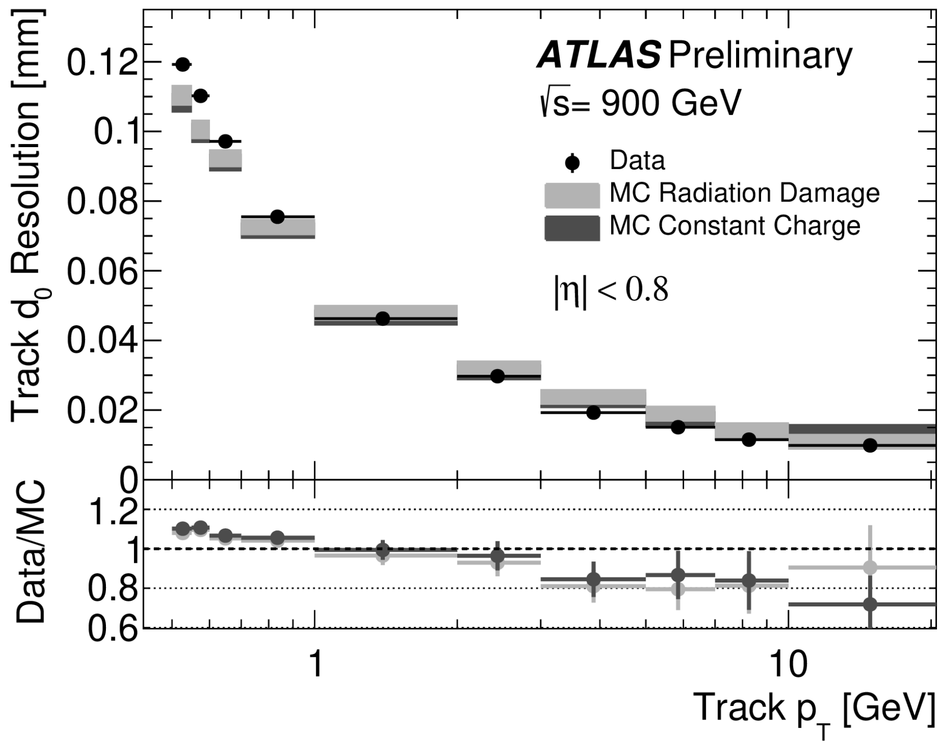


Performance of ATLAS Pixel Detector and Track Reconstruction at the start of Run~3 in LHC Collisions at s √=900 \GeV

Radiation Damage MC performance

- Spatial resolution (r-phi and z) computed using the overlap region:
  - **well reproduced** by new **Radiation Damage MC.**
  - **data improvements by using MDN** and **training it on Rad. Dam. MC samples.**
- Limited effect of radiation damage on the tracking performance for the Run 2 fluence: impact parameter $\mathbf{d_0}$ resolution **well reproduced** by both MC.





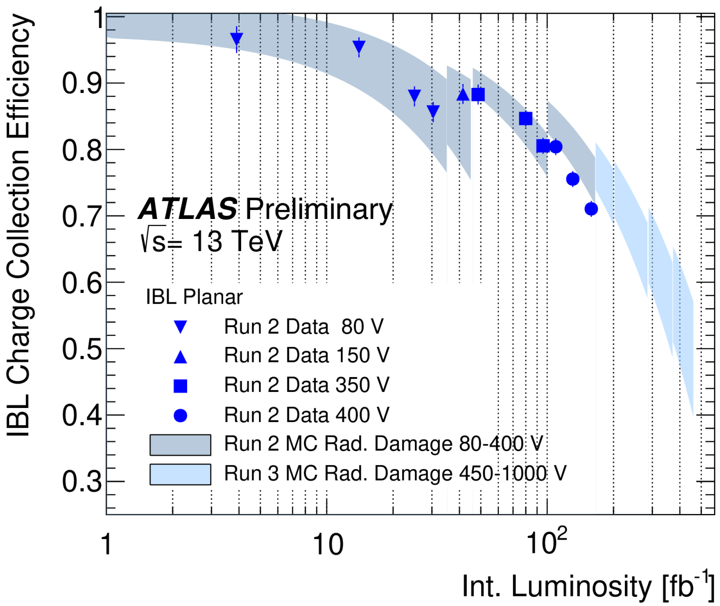
Conclusion and outlook

- Several operational challenges, upgrades and adjustments in Run 2:
  - strong effort to consolidate the detector system
  - **FE thresholds and bias voltages** changed almost yearly.
- Pixel **data taking efficiency** and **data quality** reached their peaks.

However, clear impact of radiation in inner Pixel layers!

- Understand and forecast the effects of radiation on sensors:
  - **new digitization model (fully ready/included in ATLAS Run 3 MC)**
  - so far, small implications for **tracking/vertexing**.
- Limit the impact on FE electronics.
- Use cold temperatures (possibly -25°C) to better operate the Pixel in Run 3.

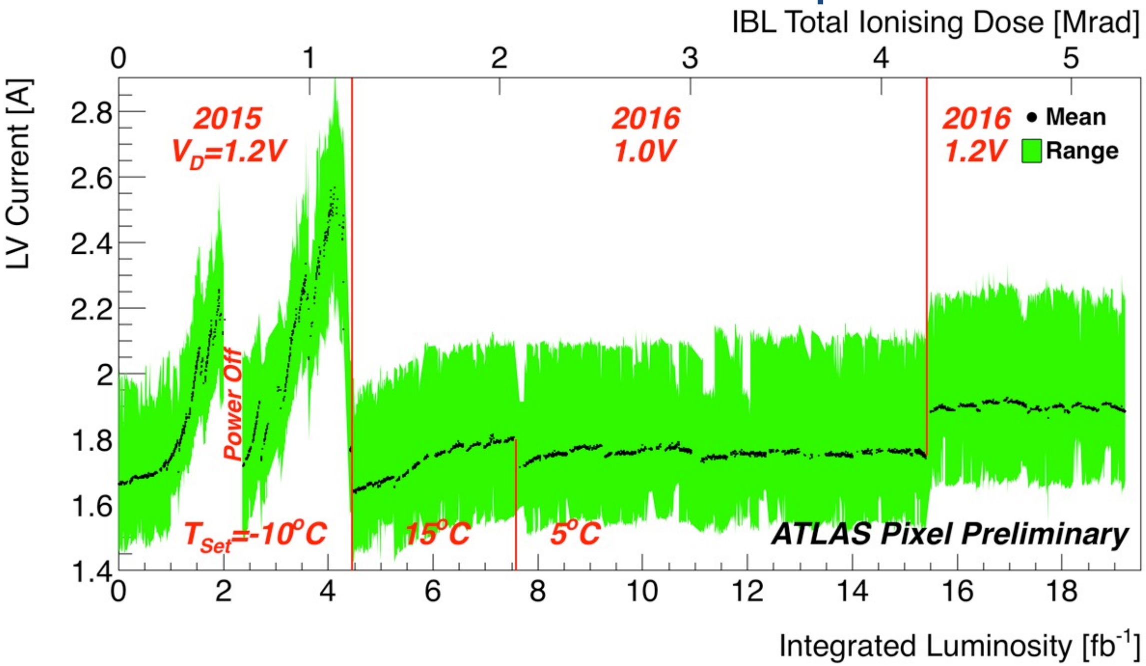
➔ Radiation damage is a key ingredient to plan the near future (Run 3)..
.. in view of the HL-LHC trackers.

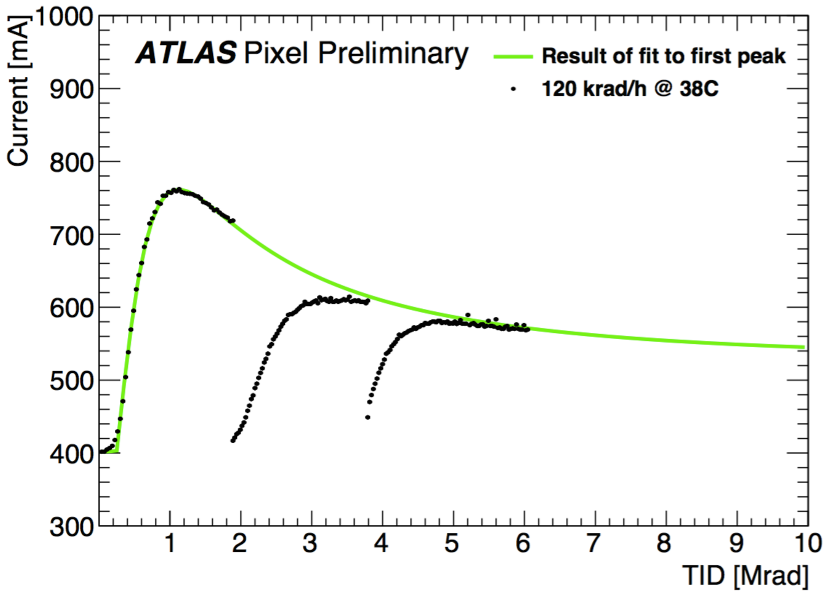


Back-up

Pixel/IBL at the begin of Run2

- IBL Total Ionizing Dose (TID) effect causing relevant increase of FE-I4 currents
  - Induced by the usage (~Millions) of 130 nm IBM transistor technology
    - Known to have a special leakage current evolution

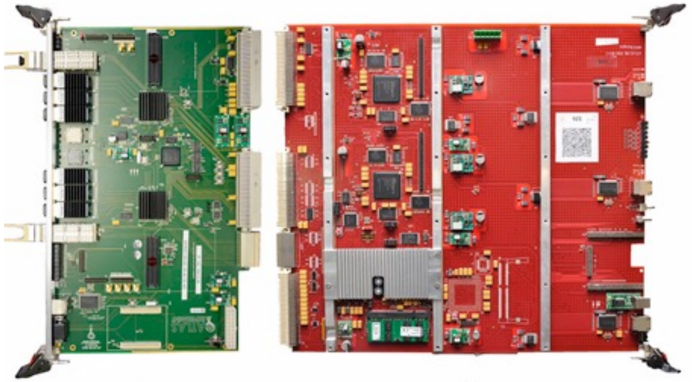




["Production and Integration of the ATLAS Insertable B-Layer"]() JINST paper for more info about IBL

Pixel Detector Read Out Upgrades

- The Run 1 Pixel read-out system went through a series of upgrades using the new IBL read-out:
  - Layer2 (2015/2016 Winter Shutdown)
  - Layer1 (2016/2017 Winter Shutdown)
  - B-Layer/Disks (2017/2018 Winter Shutdown)



a) b)

- Overcome bandwidth limitations but also enhance debugging capability and Sw/Fw flexibility.
- Finally in 2018, one unified read-out system that should bring Pixel many advantages on a longer term:
  - the operation of different type of FEs will always be there but…transparent for most of the operations!

Pixel operational parameters in 2018

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

*** central Eta: 4300e high Eta: 5000e**

Keep adjusting threshold and HV but…
limitations on the read-out bandwidth if thresholds decreased too much!

Run 2 Bias Voltage Evolution

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

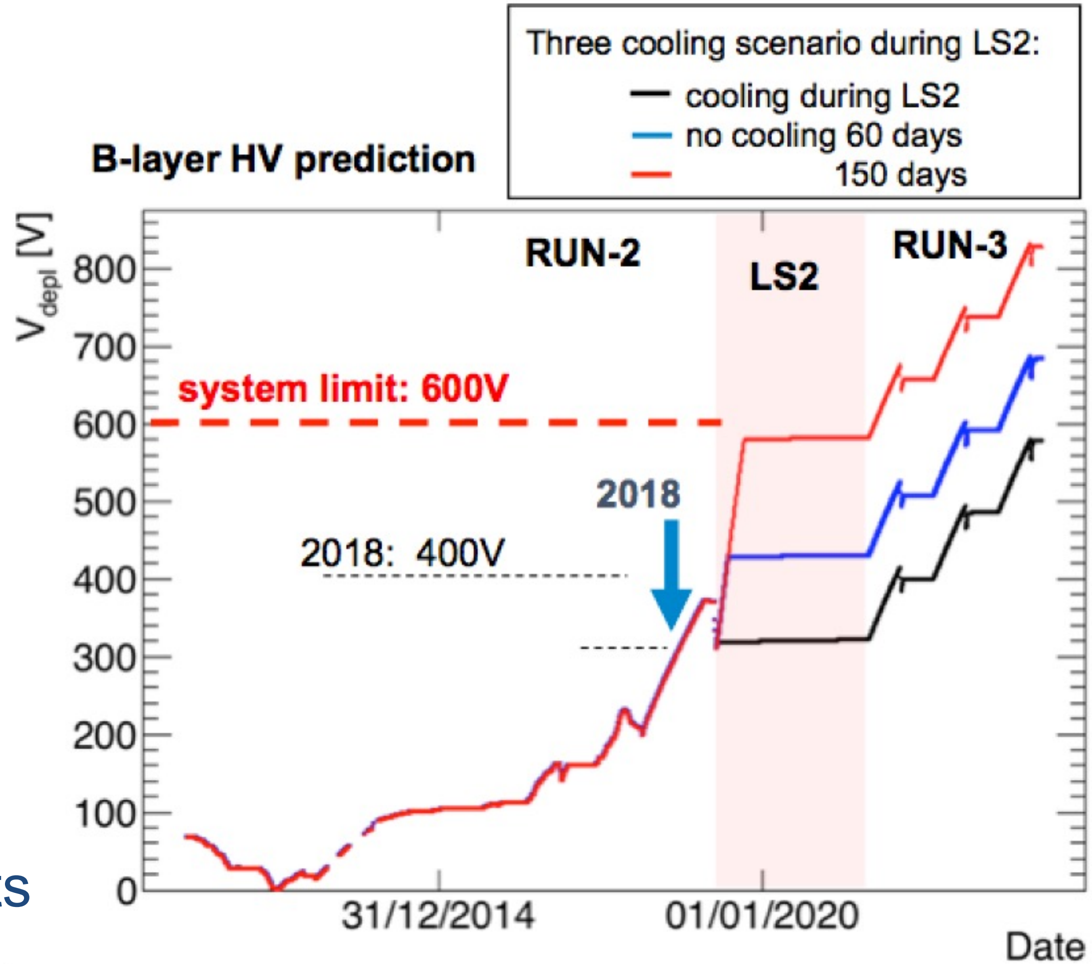
ATLAS Run2 benchmark

L1Trigger = 100 kHz
<μ> = 60

➔Module to read-out system bandwidth usage needs to stay within 80%

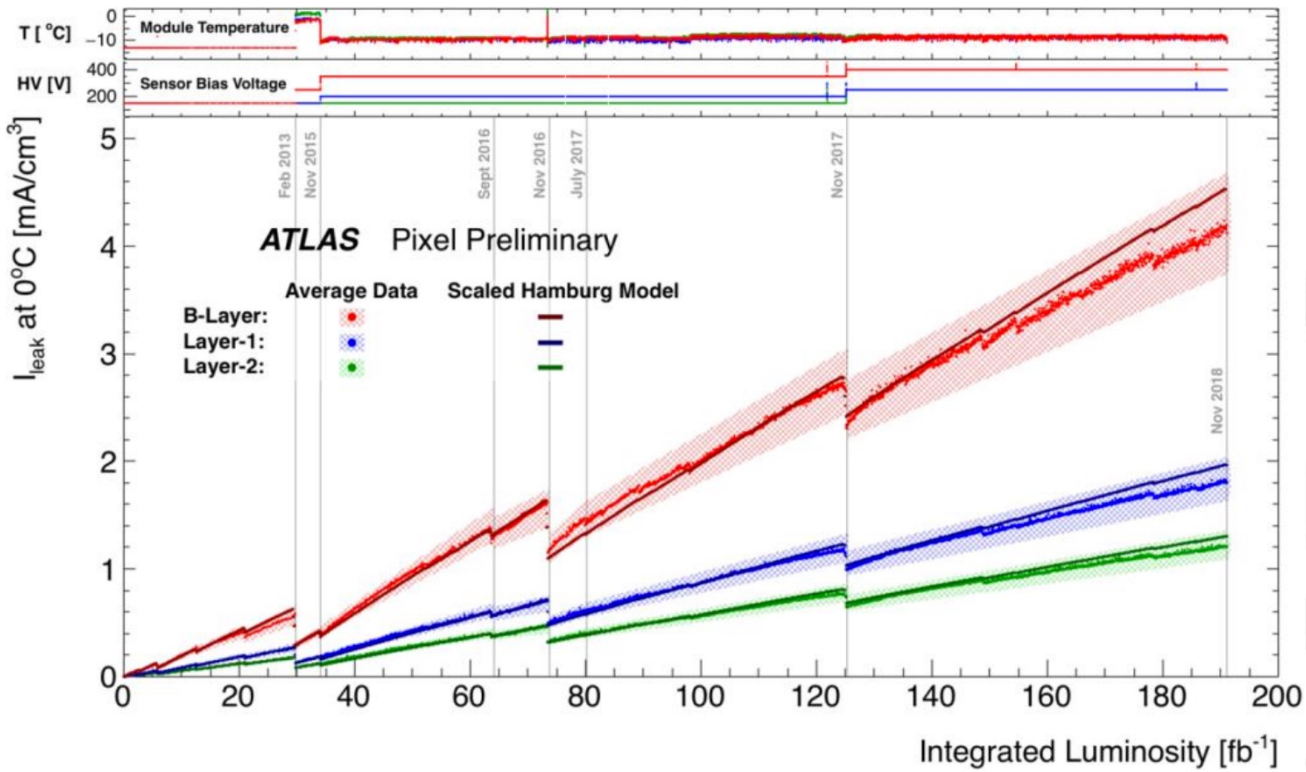
Fighting the reverse annealing

- **Keeping the detector cold during LS2** to prevent reverse annealing
  ➔ keep the depletion voltage under control (B-layer, IBL).
- Warm up periods unavoidable due to the ID maintenance during LS2
- Target to stay **warm for < 60 days** during the LS2.
- Detector warm for **43 (23) days** in Pixel (IBL)
- Exploring colder operating set points (-25°C/-30°C).for late Run 3.

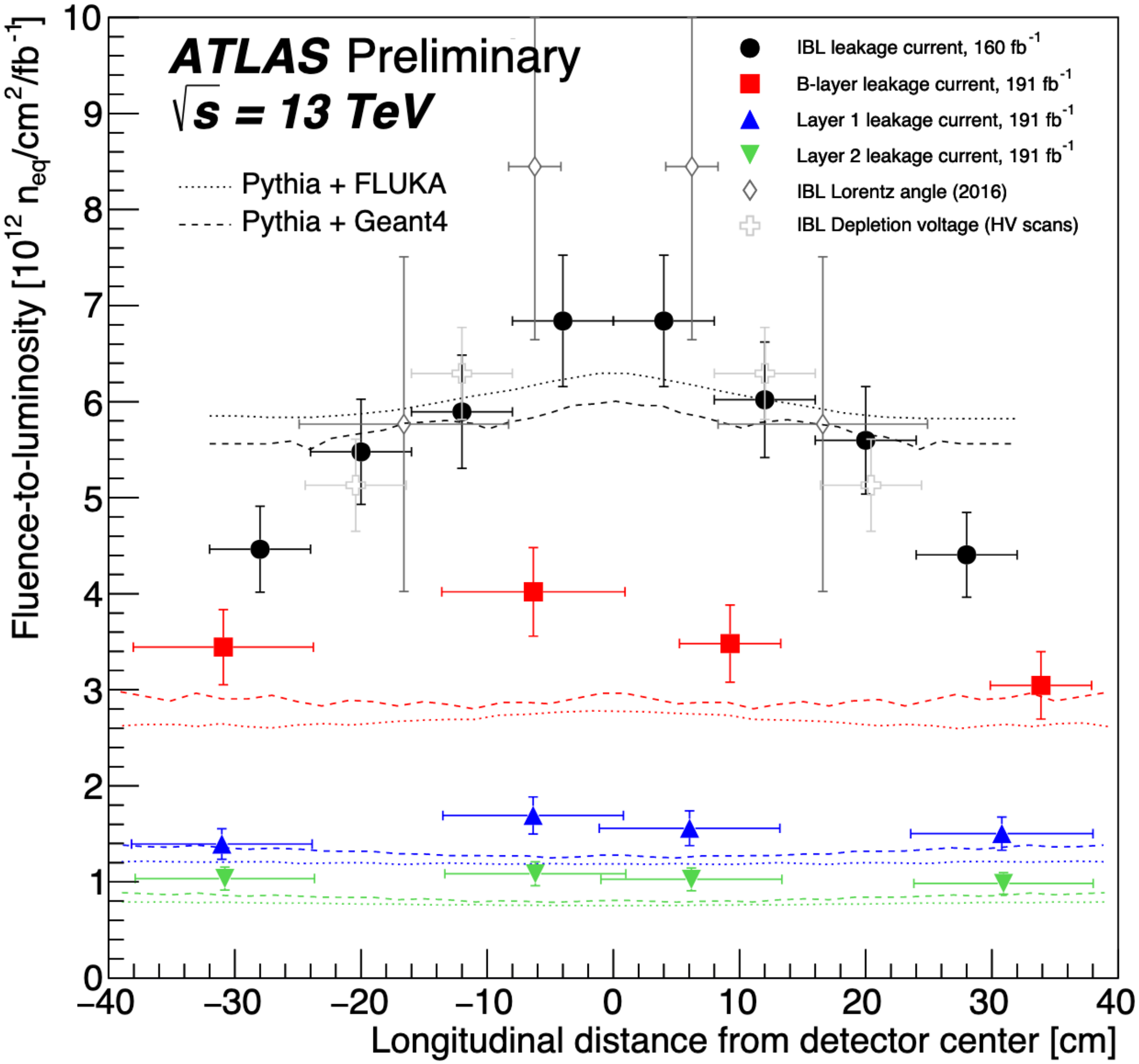


Pixel Leakage currents

- Measured leakage currents quite well described (annealing, temperature dependence) by the Hamburg Model but:
  - scaling factor per layer and z bin is required
  - towards the end of Run 2, the leakage currents seem overestimated.
- **Pixel:** Leakage current per module expected at the end of Run 3 within the power supply limitation (< 2 mA per sensor).



z-dependence comparisons



Fluence-to-luminosity conversion factors extracted from the leakage current, Lorentz angle and Depletion Voltage measurements:

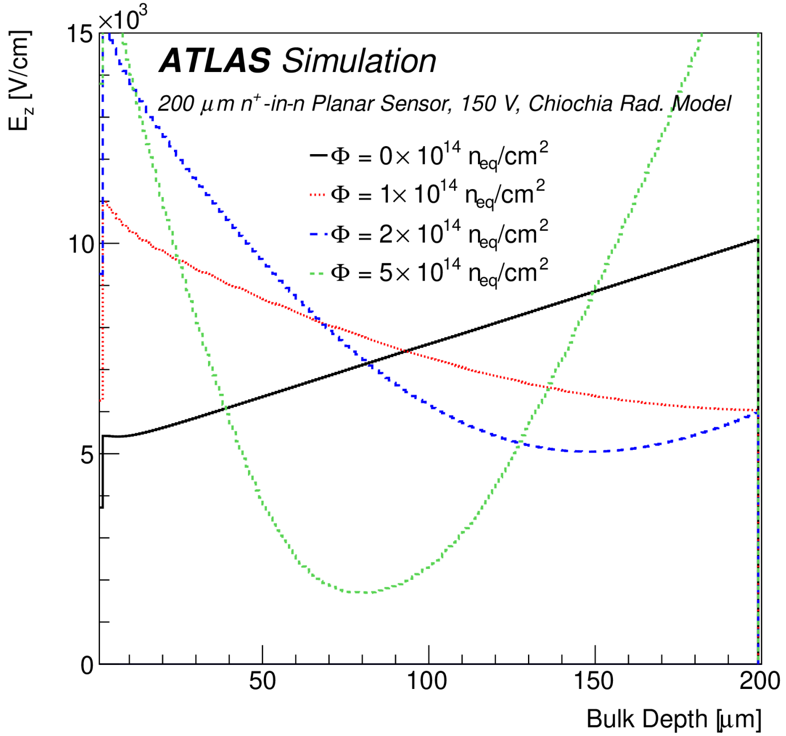
- **less fluence at at high |z| on IBL data** respect to Pythia + FLUKA/Geant4 predictions
- more flat distributions for outer Pixel layers.

Radiation damage studies

- New Pixel digitization model was developed and is now under validation before entering the official ATLAS simulation

  Recent paper available here: [JINST 14 (2019) 06 P06012]()

- Charge carriers will drift toward the collecting electrode due to **electric field**, which is deformed by **radiation damage (double peak)**.
- Their path will be deflected by magnetic field (Lorentz angle) and diffusion.
- Electron and hole lifetime inversely proportional to fluence:
  ➔ **charge trapping**,
  ➔ reduction of the collected charge.
- Available for both **Planar** and **3D** sensors.
  ➔ due to performance constraints (CPU), not used in IBL 3D and Pixel Disks



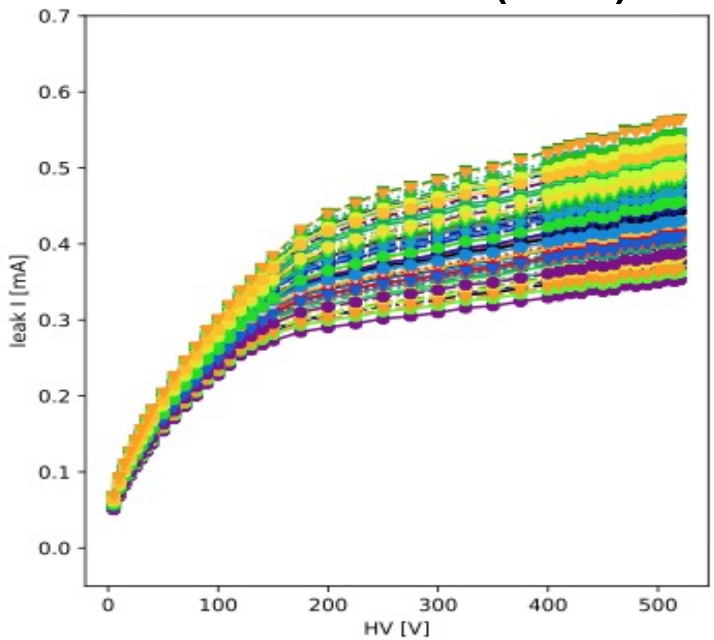
I-V scans

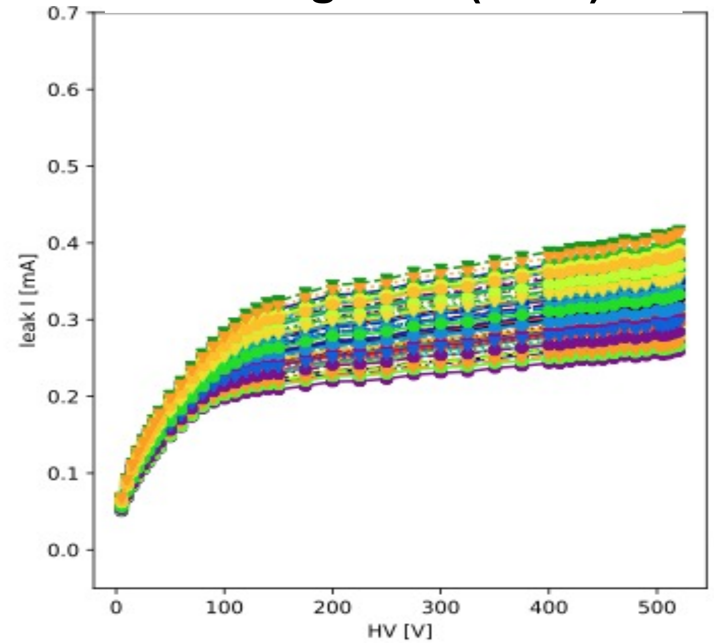
End of Run 2 (2018)

During LS2 (2020)

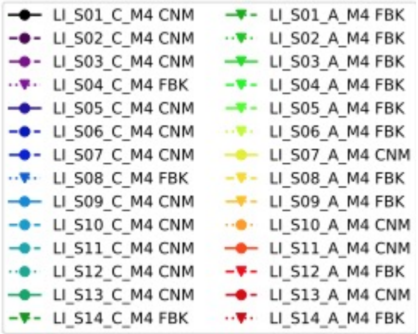
Planar

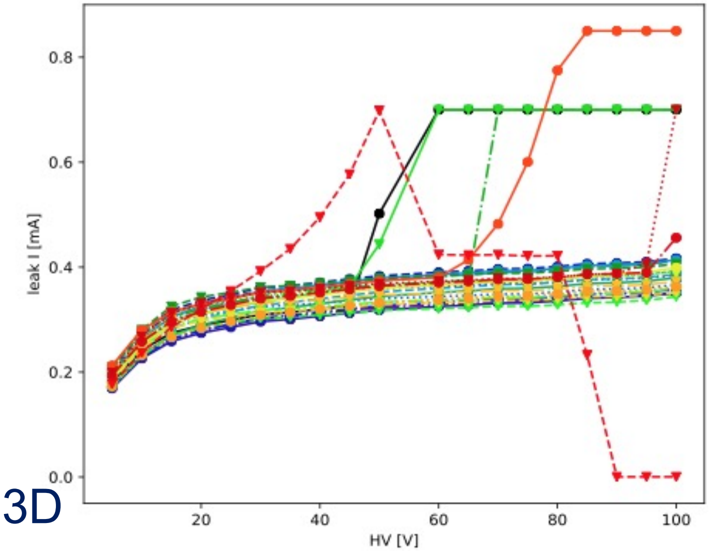
So far pretty standard behaviour for irradiated planar sensors.

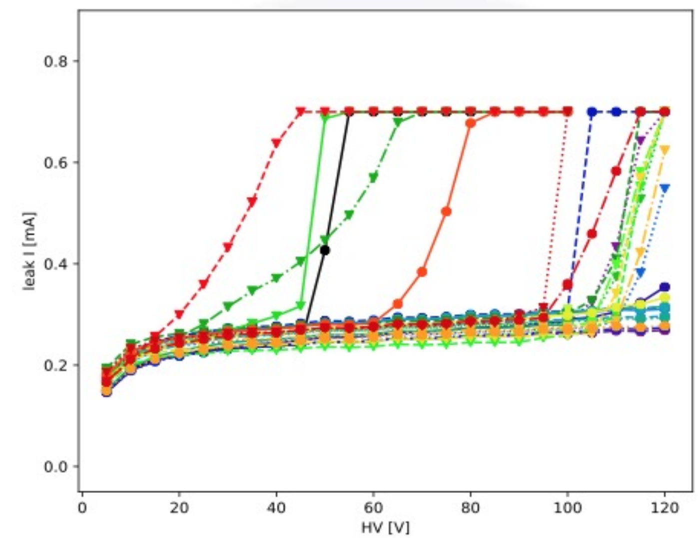




3D







Some criticalities in a few 3D sensors.

Leakage current vs Temperature

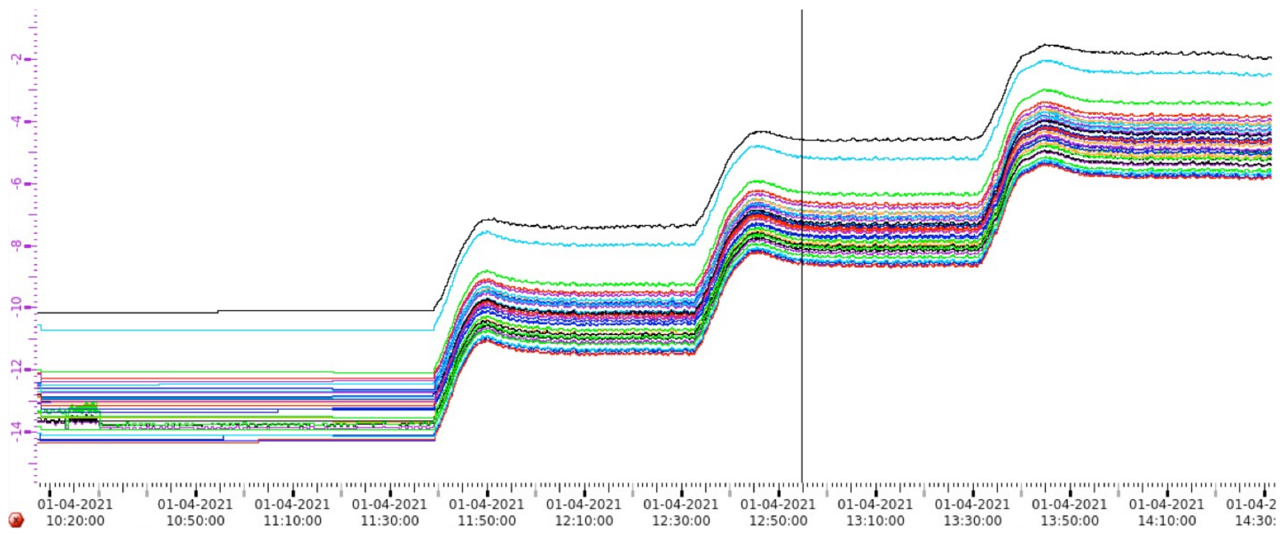
In order to retrieve the optimal E_{eff} for the temperature correction of the I_{Leak} , several temperature scans were taken.

$$I_{\text{leak}}(T_{\text{R}}) = I_{\text{leak}}(T) \left(\frac{T_{\text{R}}}{T}\right)^2 \exp\left[-\frac{E_{\text{eff}}}{2k_{\text{B}}}\left(\frac{1}{T_{\text{R}}} - \frac{1}{T}\right)\right]$$

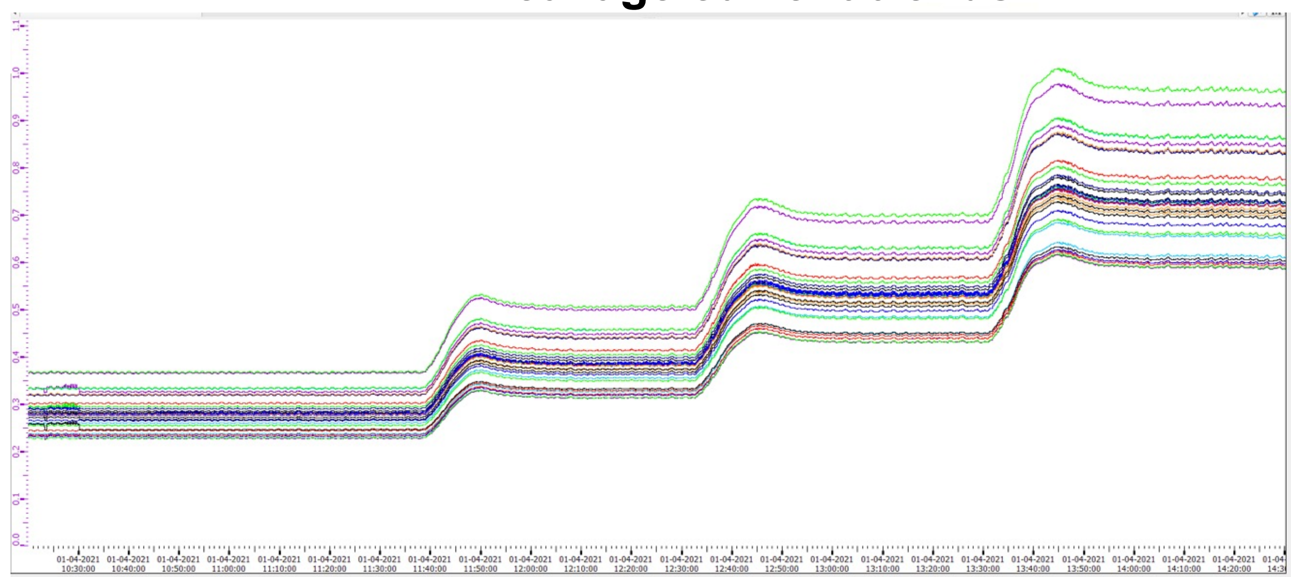
Last one on September 2021:

- - 20 °C setpoint temp.
  IBL: 0.30 +- 0.10 mA
- - 17°C setpoint temp.
  IBL: 0.41 +- 0.12 mA
- - 14°C setpoint temp.
  IBL: 0.56 +- 0.15 mA
- - 11°C setpoint temp
  IBL: 0.76 +- 0.21 mA

Temperature trends



Leakage current trends



HV evolution

- HV settings have been adjusted to ensure a well depleted sensor:

  ➔ **HV increase in all the layers in 2018!**

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

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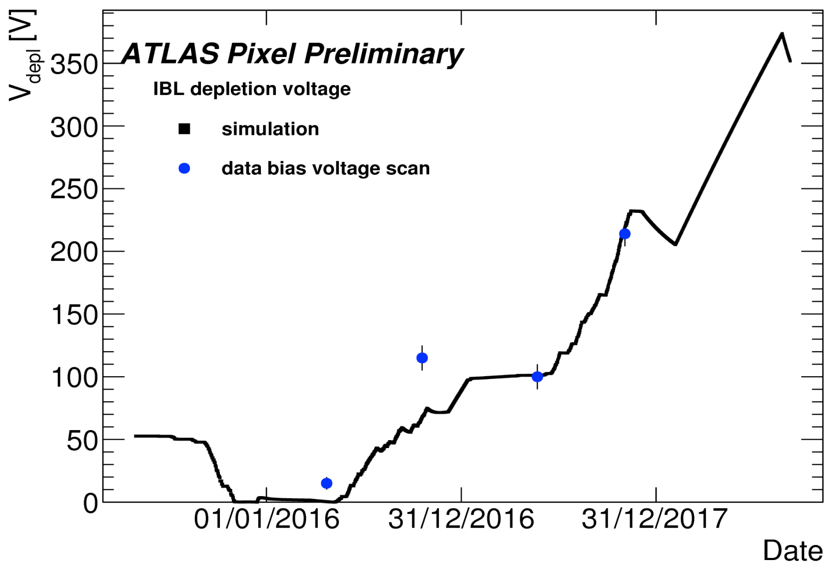
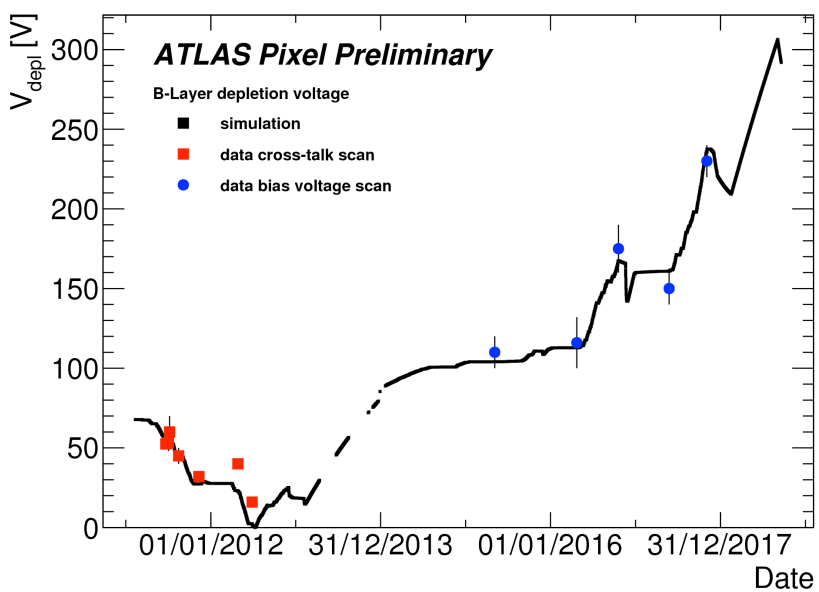
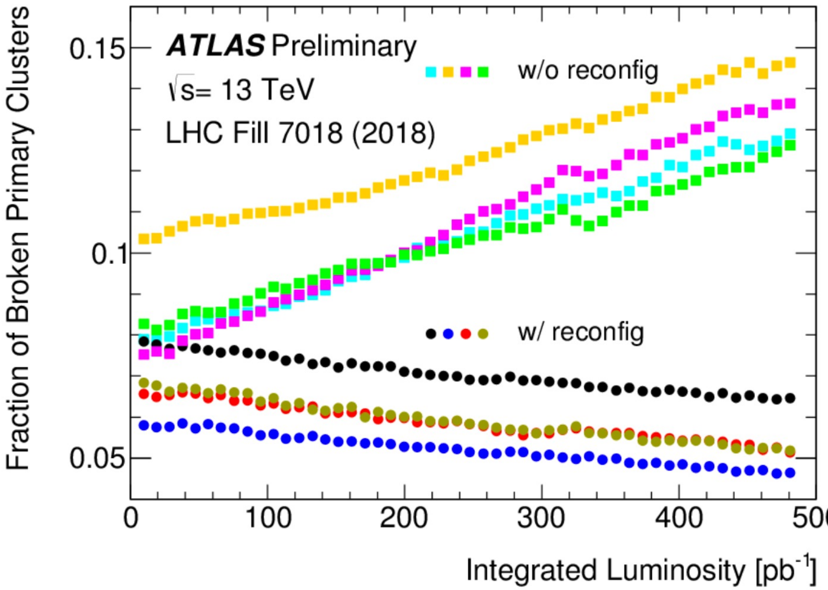
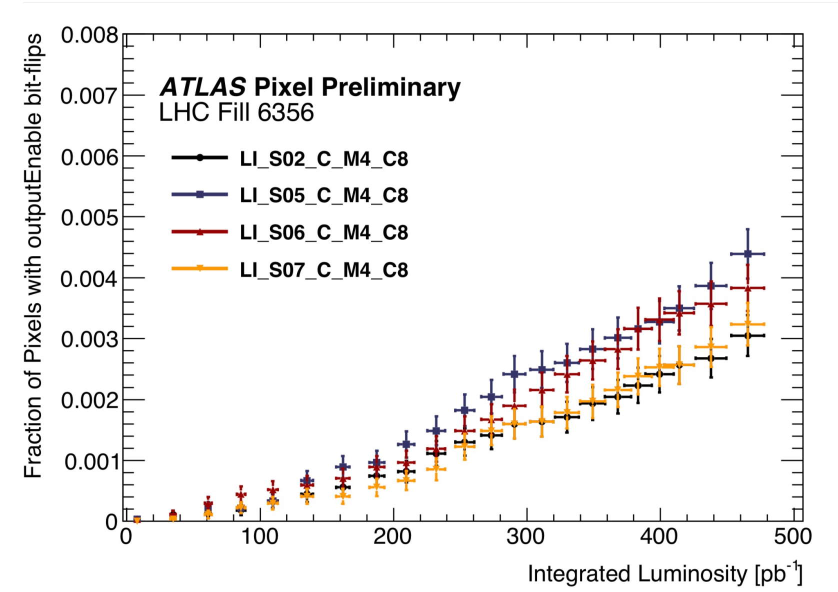
- In order to avoid to run with the detector not fully depleted, Pixel should be kept cooled as long as possible during the LS2 (2 years long).

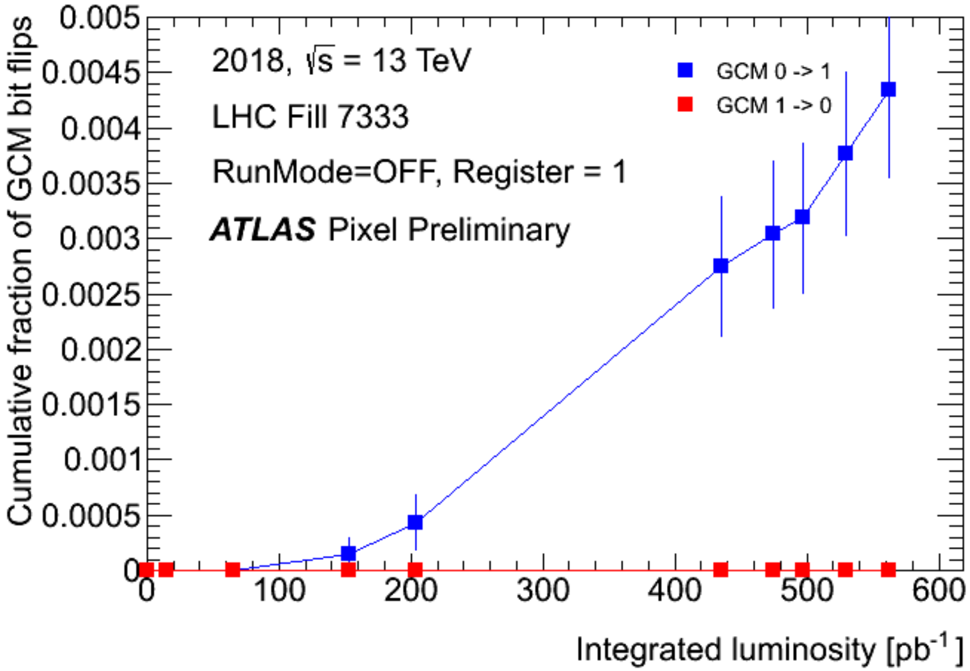


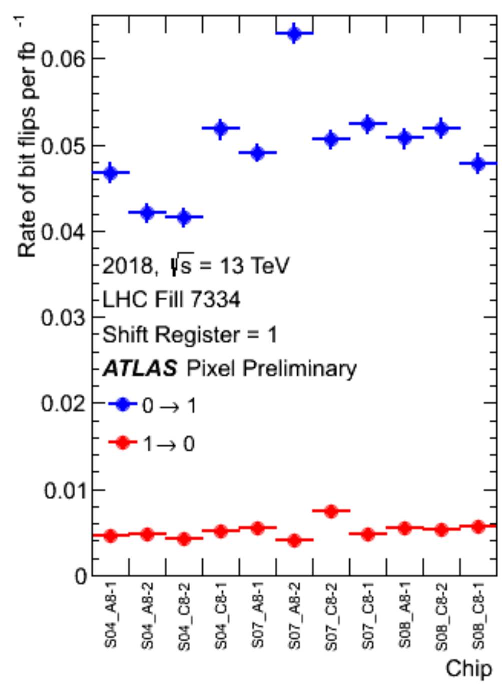


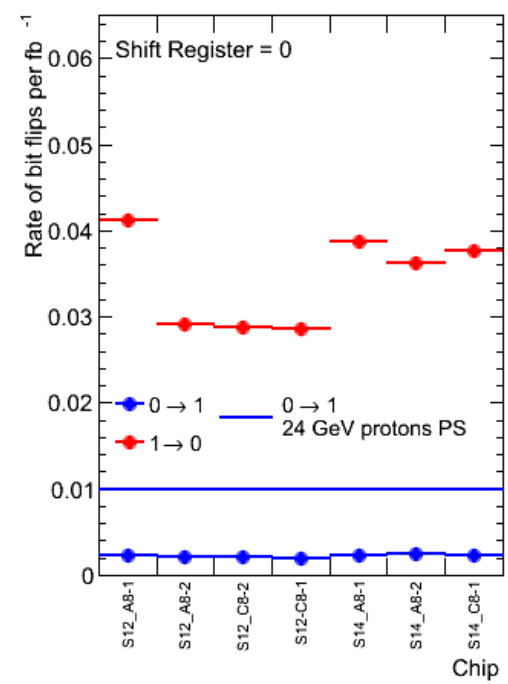
FE-I4 SEU studies



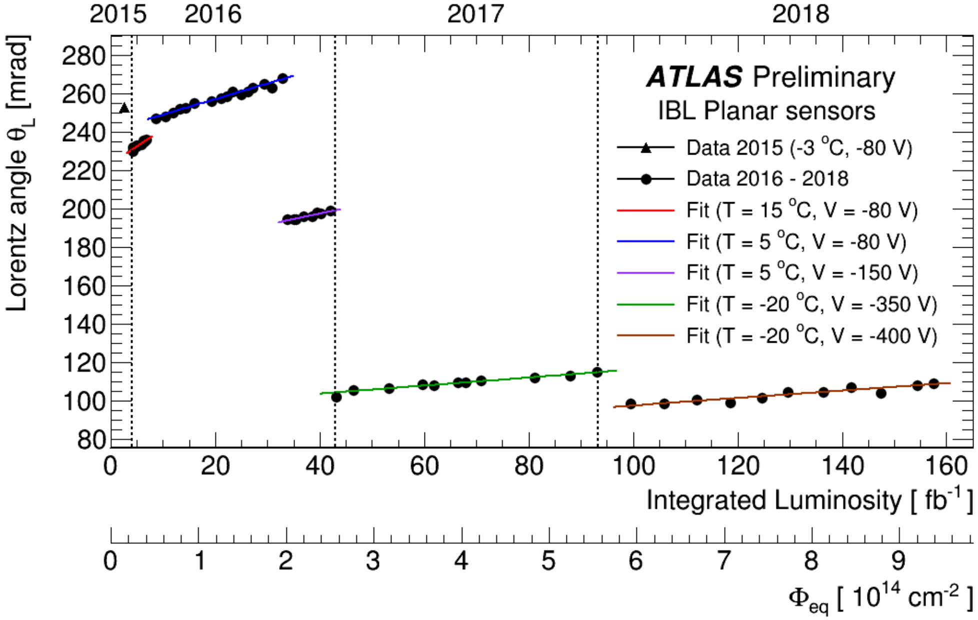


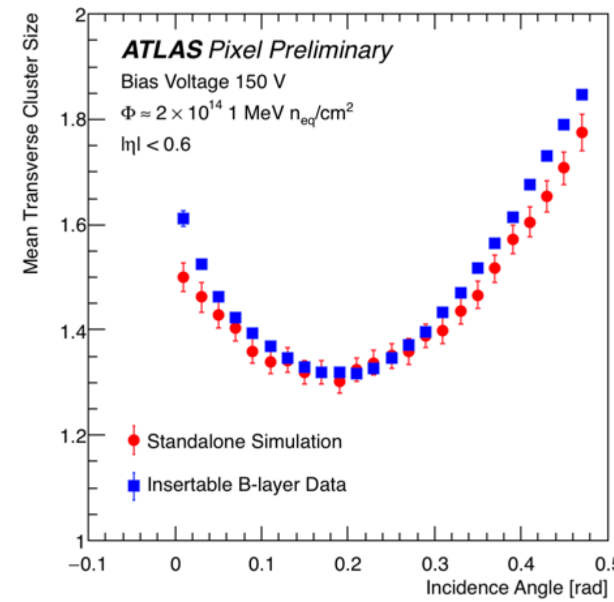


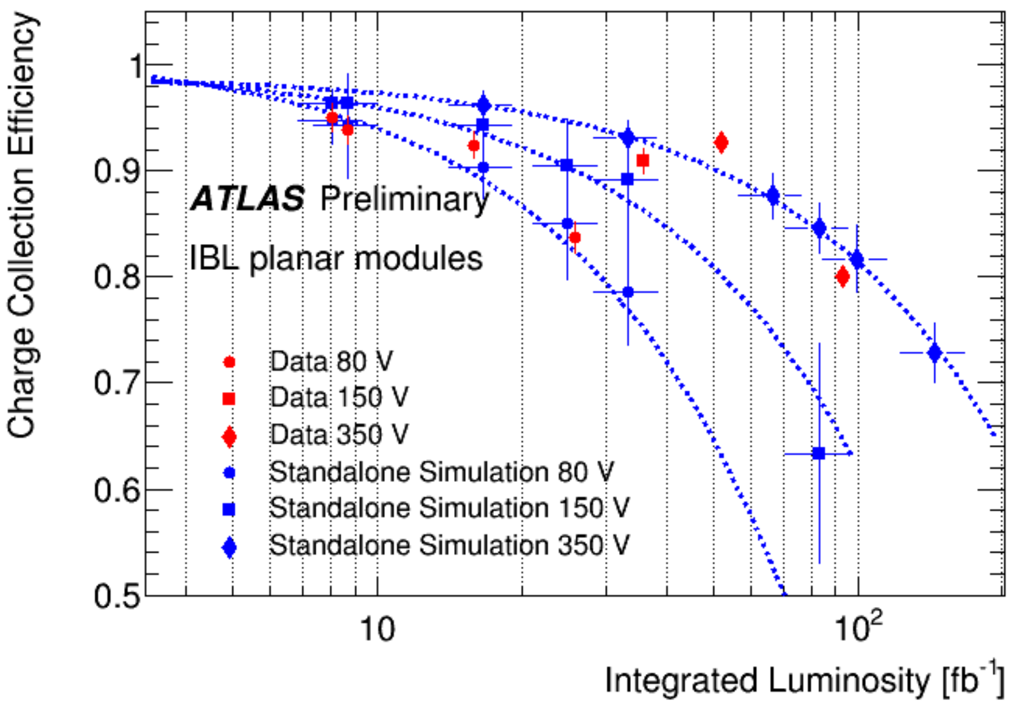


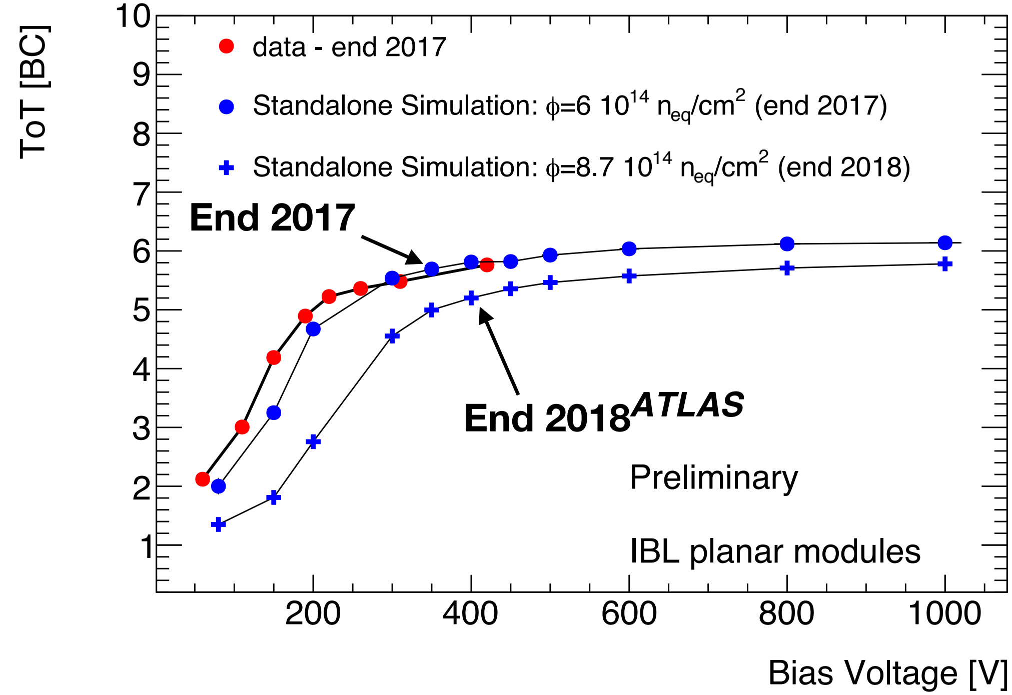


Modelling the radiation damage in the sensor









Results from 2022 Pub Note