The operational experience and performance of the ATLAS SCT during Run-2 and LS2, and the first impression from Run3 operations

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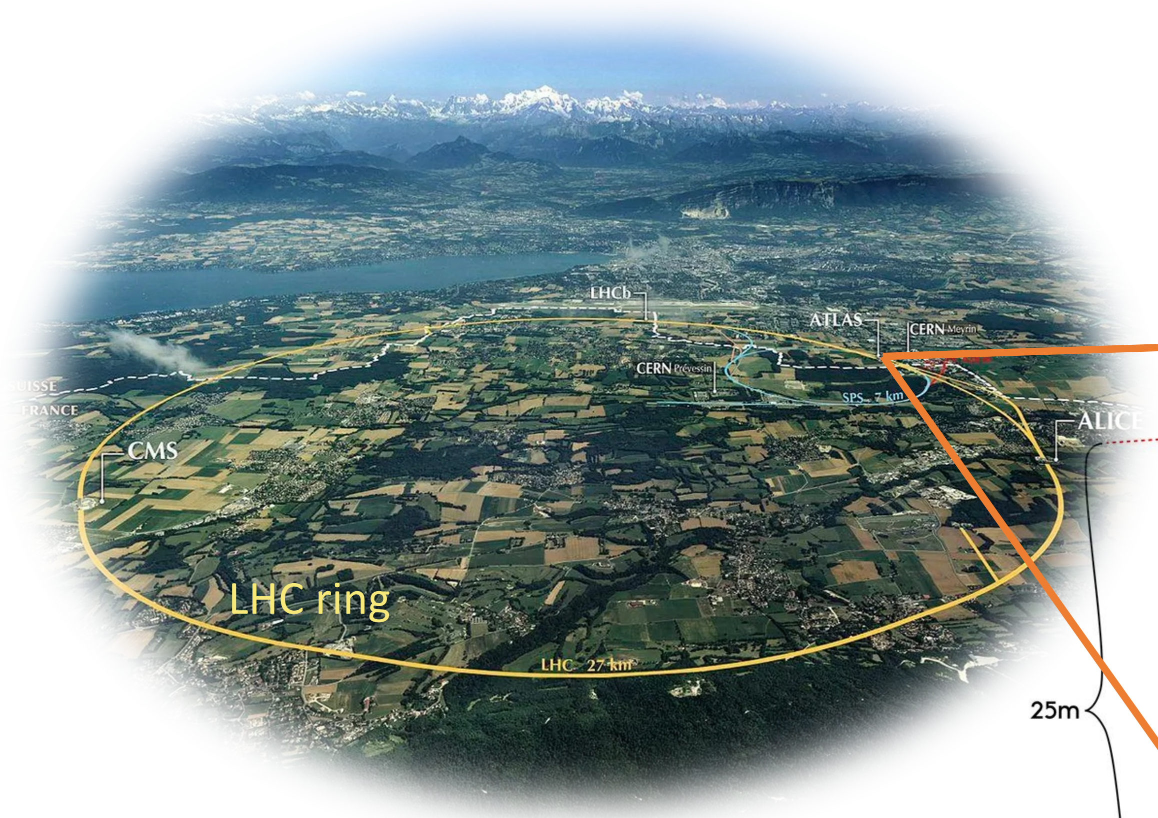
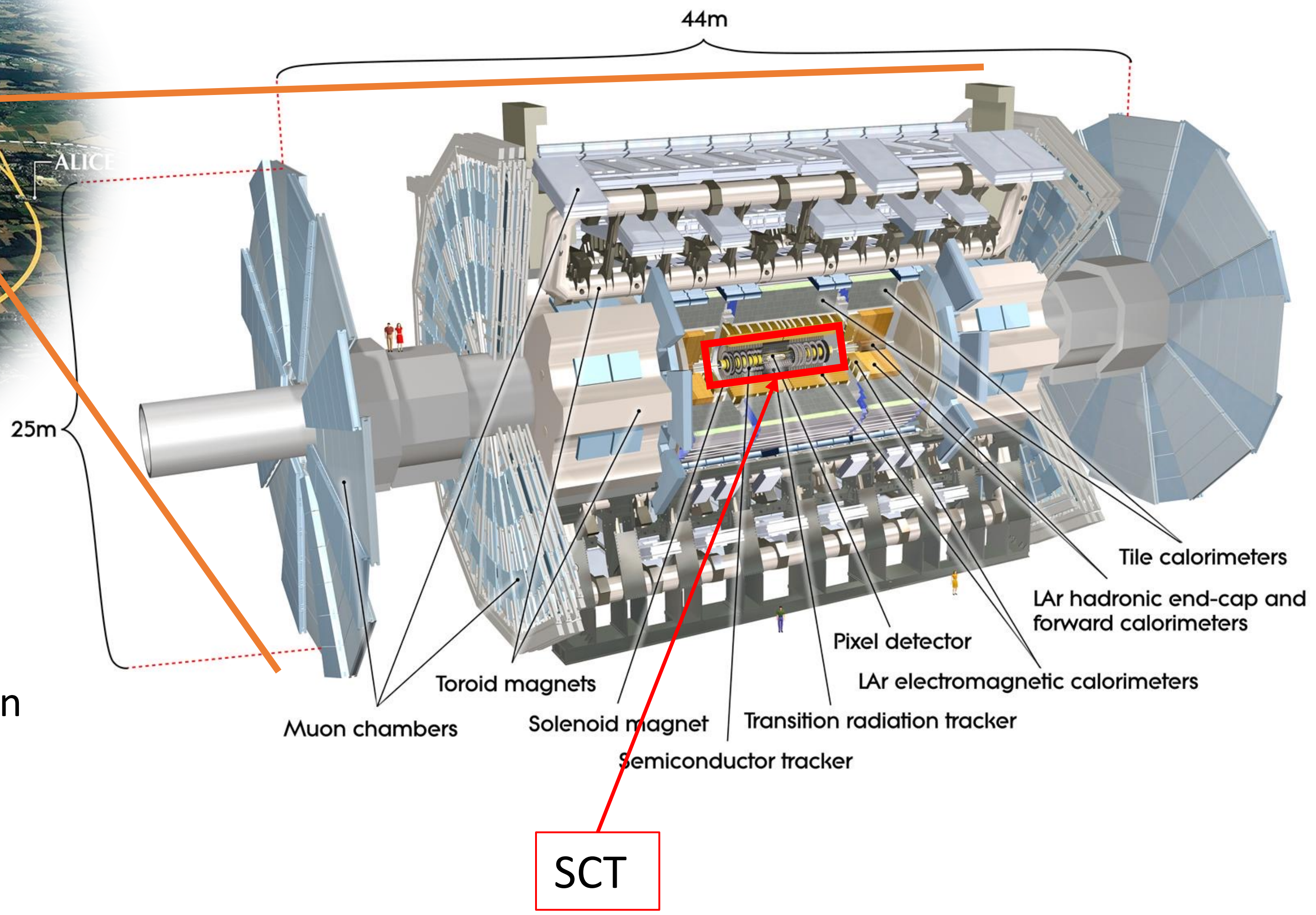
TIPP2023 – Cape Town

ATLAS at the LHC

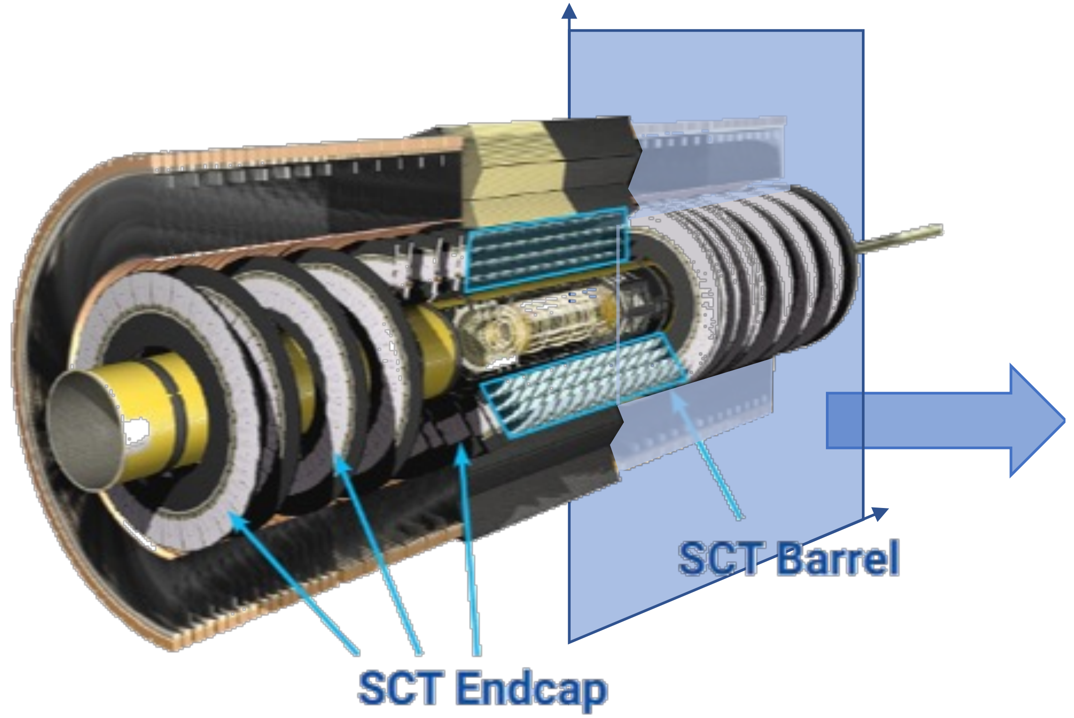


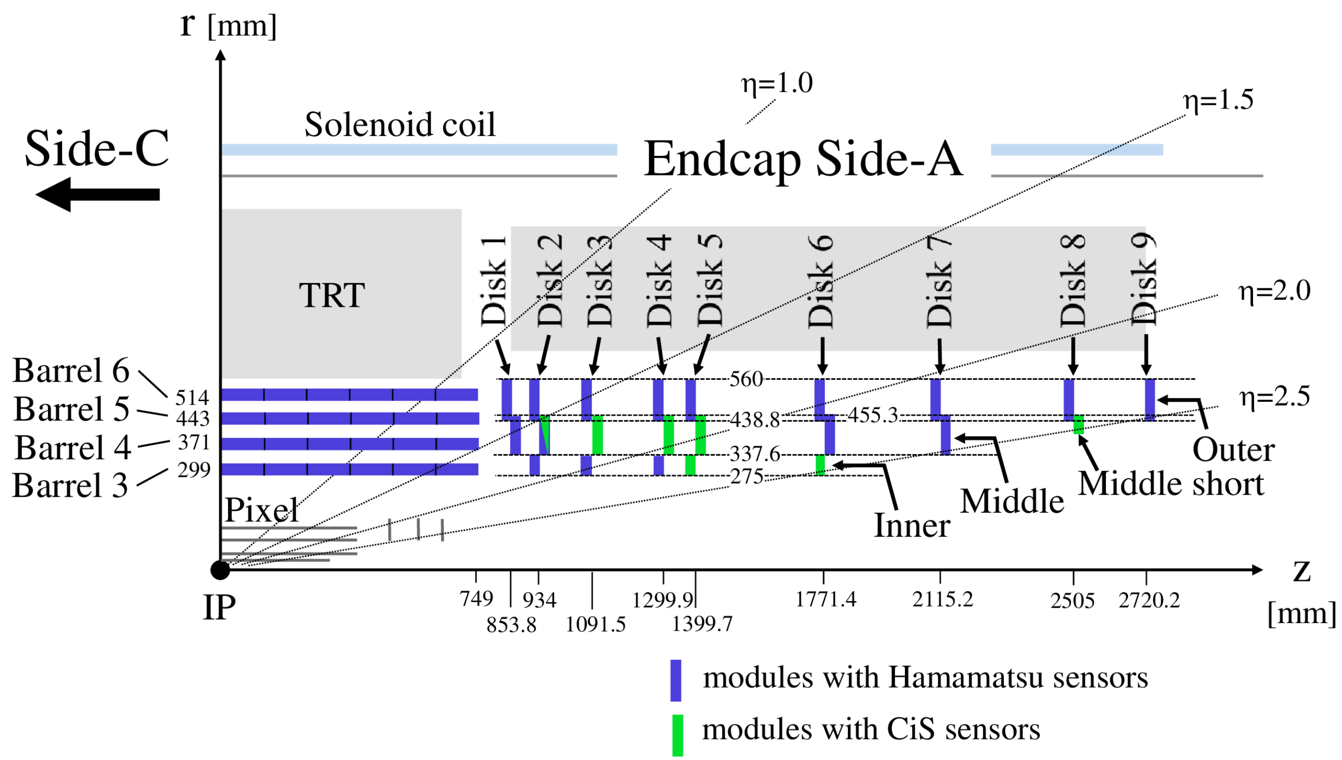


The ATLAS detector:

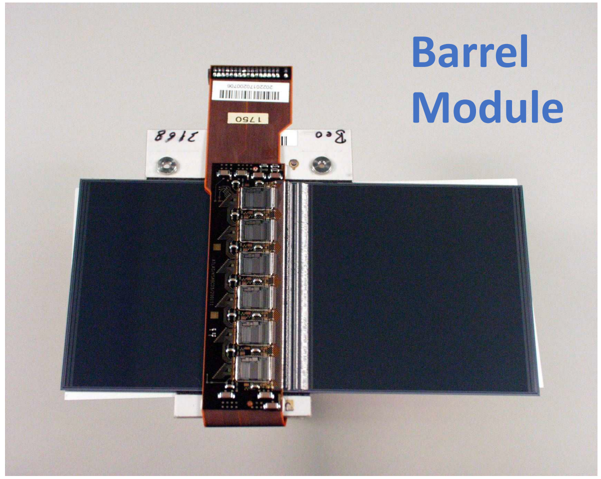
- Multipurpose detector
- Detect the particles coming from proton-proton interactions
- Reconstruct the tracks and the energies of the particles
- Cylindrical shape with a layered structures

The SCT detector

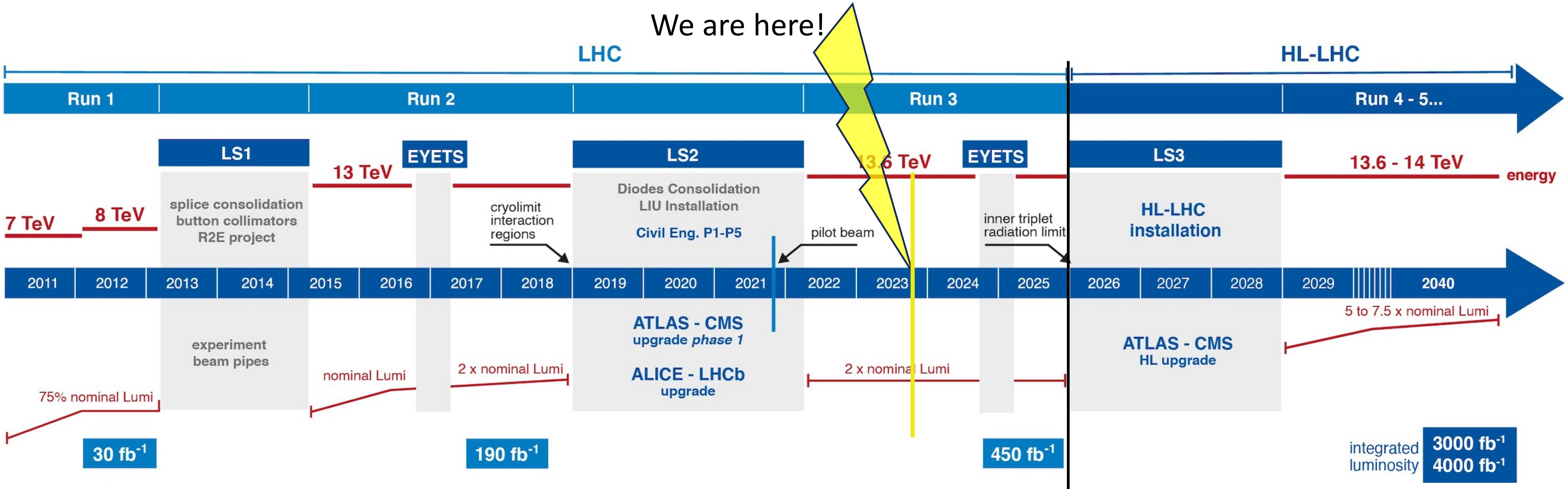




- SCT (**S**emi**C**onductor **T**racker): **4088 modules** organized in 4 barrel & 9 endcap disks (per side)
- Typically, module consists of 4 strip-sensors, two per side
  - The sides are glued back-to-back at 40mrad stereo angle
- Silicon sensors are **p-on-n type**, 285um thick, manufactured by *Hamamatsu* and *CiS*
- We have 786x2 strips per module with strip pitch of 80µm and strip length of 12.8cm➔ $\sim 6 \cdot 10^6$ strips.



Where do we stand today?



We are at the ~half of the LHC run3

Main goal:

- Take good quality data with the SCT detector until end of 2025 (when SCT -and the whole tracker- will be replaced by the ITk)

We will show the **detector condition today** and **evolution of performance since LHC Run2** (Run2 performance)

Where we stand today?

Now

Disabled component	Start of Run 2 (2015)	End of Run 2 (2018)	Start of Run 3 (2022)	December (2022)	August 2023
Modules	38	42	46	47	50
Chips	59	83	85	81	82
Strips	11452	14895	24071	15310	15565
Fraction of active strips	98.8%	98.6%	98.3%	98.4%	98.4%

No. of redundancies used	Start of Run 2 (2015)	End of Run 2 (2018)	Start of Run 3 (2022)	December (2022)	August 2023
RX links	136	153	155	156	155
TX links	20	55	58	59	50

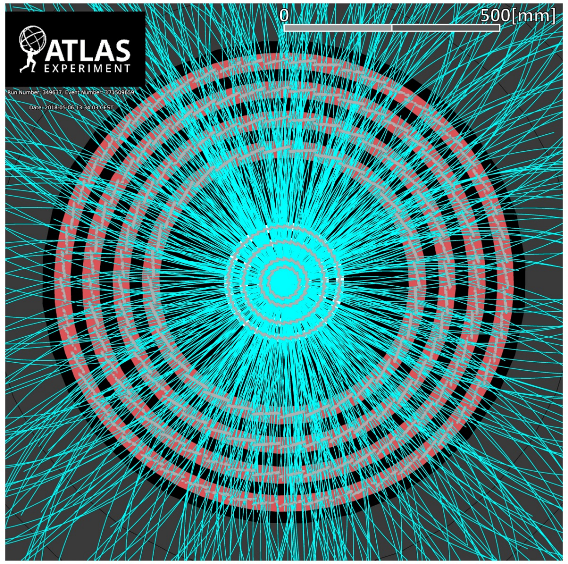
SCT is in good shape with **98.4% of strips still active** after **13 years of operation!**

SCT designed for 700 fb^{-1} of 14TeV $p - p$ collisions

- $\sim 260\text{fb}^{-1}$ luminosity collected so far
  - ➔ Safe margin for further operation in Run3…
  - ➔ **challenging running conditions** (instantaneous Luminosity much larger than assumed at design level)

…but Radiation affects SCT parameters:

➔ Understand these effects for continuing safe and efficient SCT operation



Dense environment at the LHC

Detector operation

SCT operation target:

- High hit efficiency (> 99%)
- Noise occupancy < 5×10^{-4}

Calibration performed every few weeks between LHC beam fills

- Optical & digital calibration
- Trim range scan
- Response curve scan

The performance and radiation effects are monitored through periodic scans

- HV scan
- IV scan
- Threshold scans
- Noise measurements
- Timing scan
- …

We will see the **latest results today**

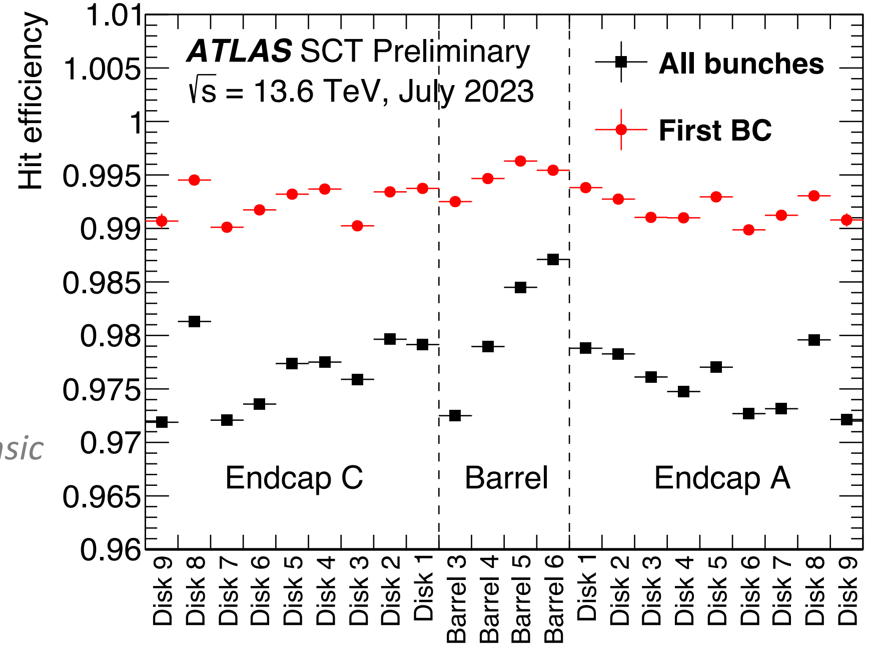
- We will see **ageing of the sensor due to radiation damage…**
- … but also **confirm good performance**, well within the limits for safe operation

Hit Efficiency

Hit efficiency per track defined as:

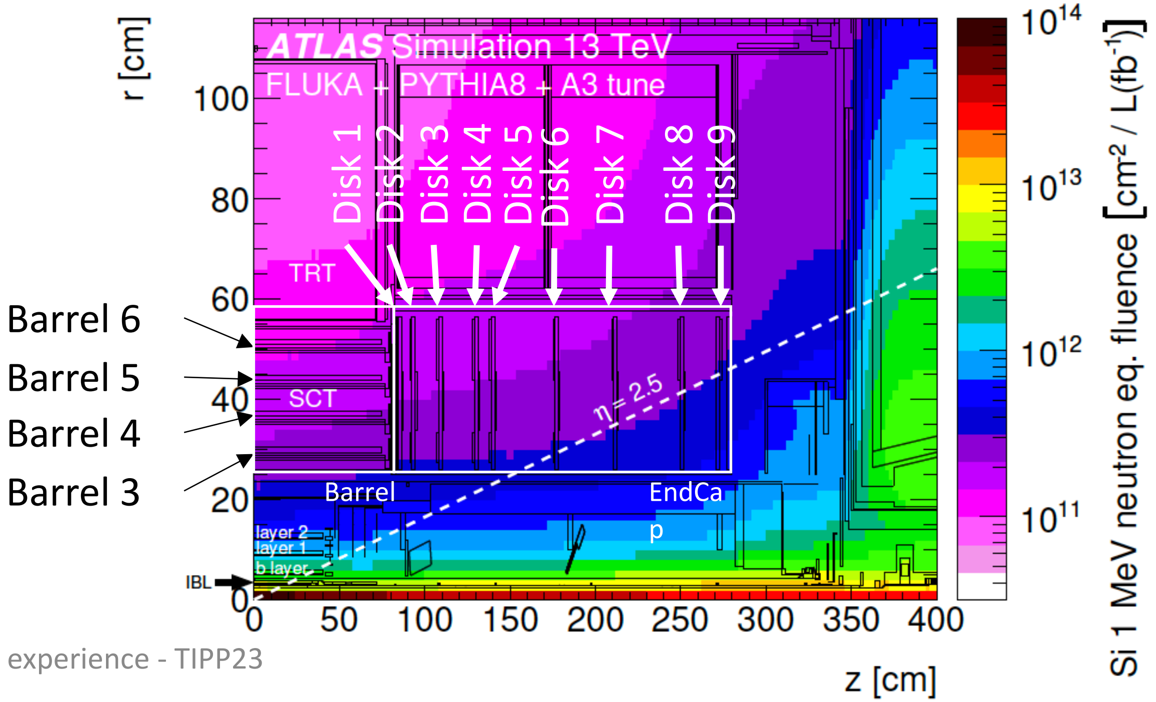
$$\epsilon_{\text{hit}} = \frac{N_{\text{cluster}}}{N_{\text{cluster}} + N_{\text{hole}}}$$

SCT uses *01X* readout mode (avoid hits from prev. bunch crossing)
➔ *'All bunches hit Eff.'< intrinsic efficiency*



- So far Run3 (2022/2023) $\epsilon_{hit}^{1^{st}bc} \sim$ 99 %
  - Within targeted performance

- Radiation damage results in increasing strip depletion voltage
  - hit efficiencies can drop below 0.99
  - Intrinsic hit efficiency is monitored, and the High Voltage (HV) increased when necessary.



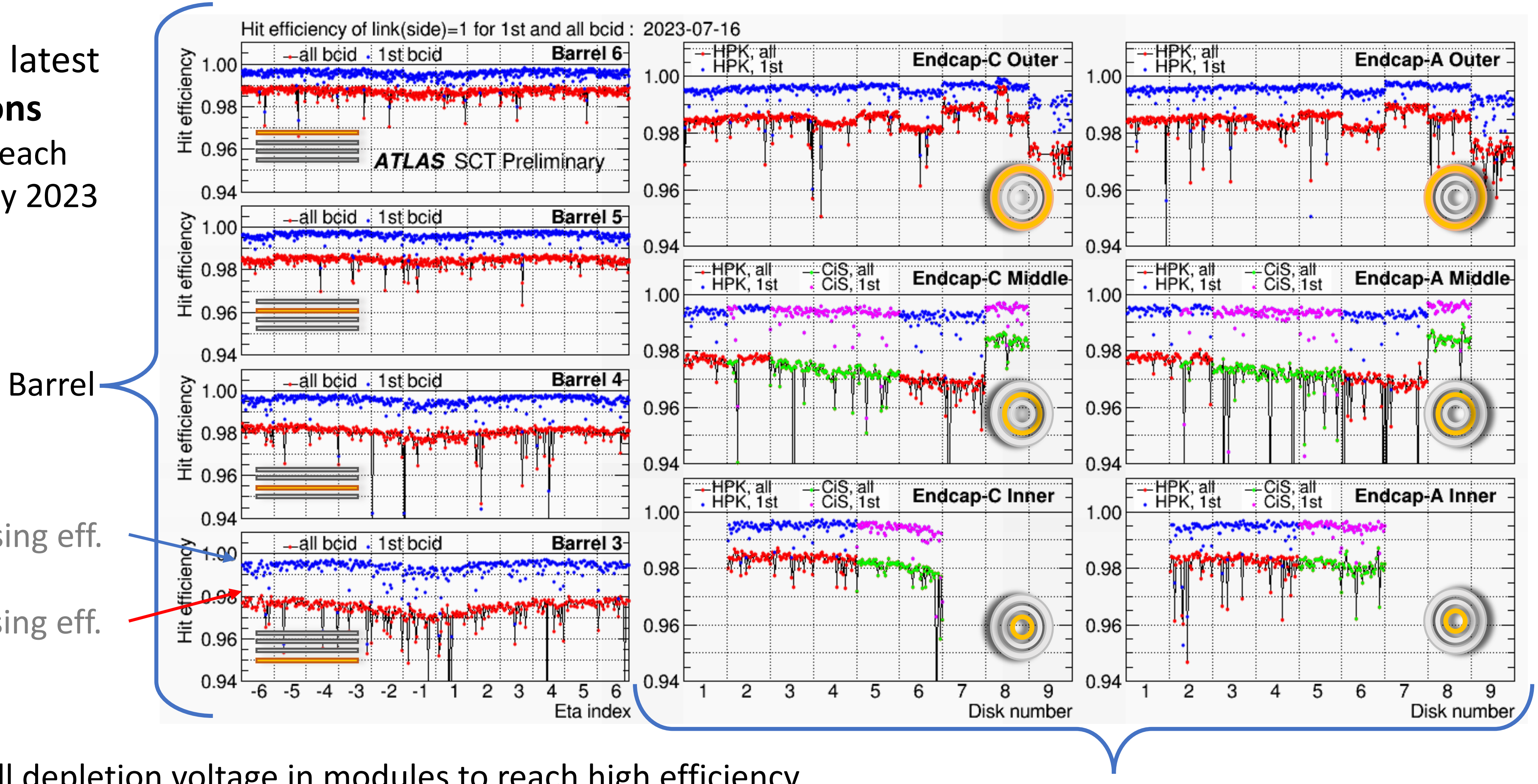
Some numbers (from FLUKA+PYTHIA8) about radiation…
1MeV n-eq. fluence $[\text{cm}^{-2}]$ for total Luminosity $(\sim 260\text{fb}^{-1})$

- Barrel3 ➔ $6.3 \cdot 10^{13}$
- Barrel6 ➔ $3.6 \cdot 10^{13}$

Hit efficiency – a global view

'Snapshot' of the latest **detector conditions**

- Hit efficiency in each module as of July 2023



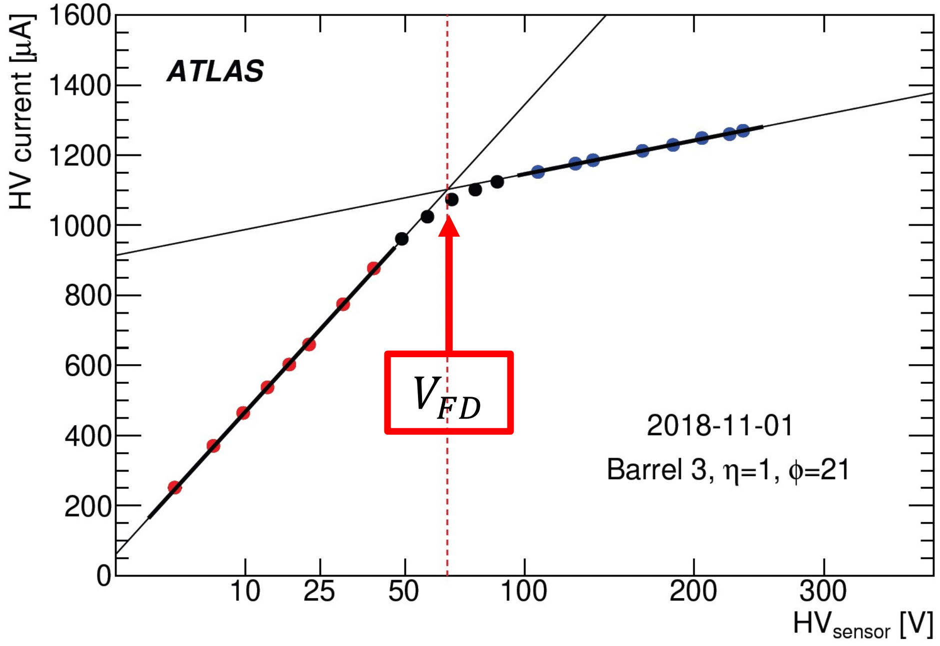
Need to reach full depletion voltage in modules to reach high efficiency
Monitored through IV scans and HV scans…

V_{FD} & Leakage current (IV scans)

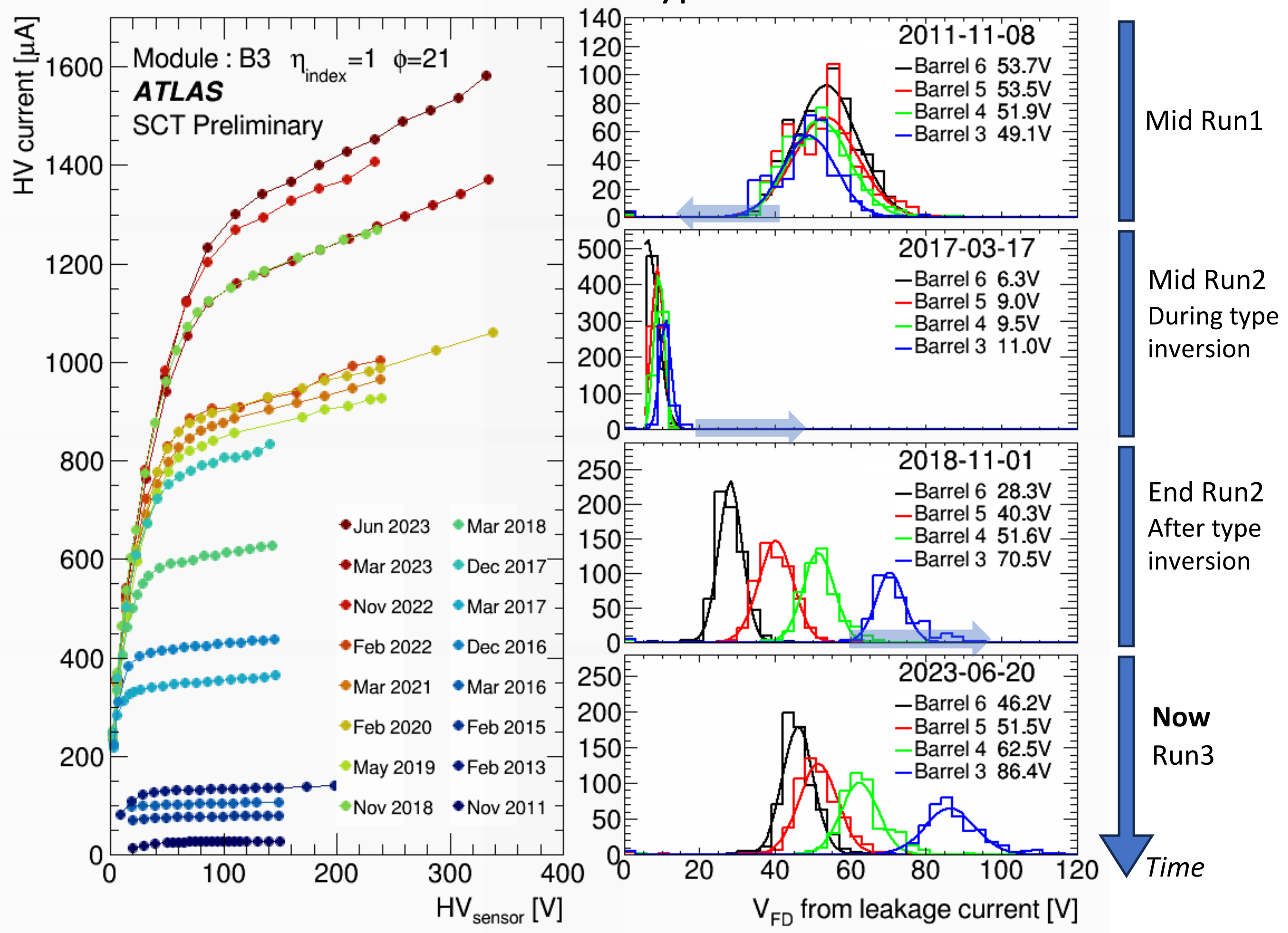
V_{FD} can be measured from kink *in leakageCurrent-vs-HV* lines

- Leakage current proportional to depletion volume
  - If full depletion ➔ leak. current ~ constant

- Fitting $HV\ current\ - vs - \sqrt{V_{sensor}}$ with two lines
  ➔ Intersetion point == V_{FD}



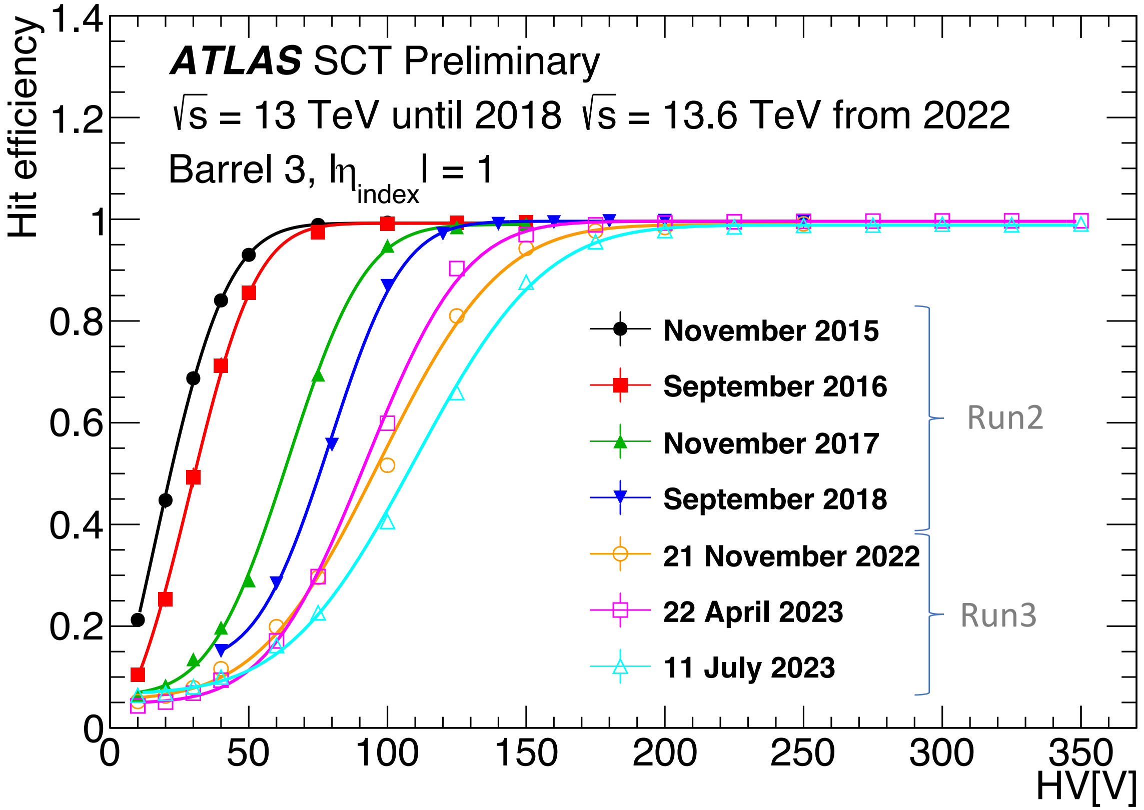
IV scans in run2 ➔ deduce type inversion

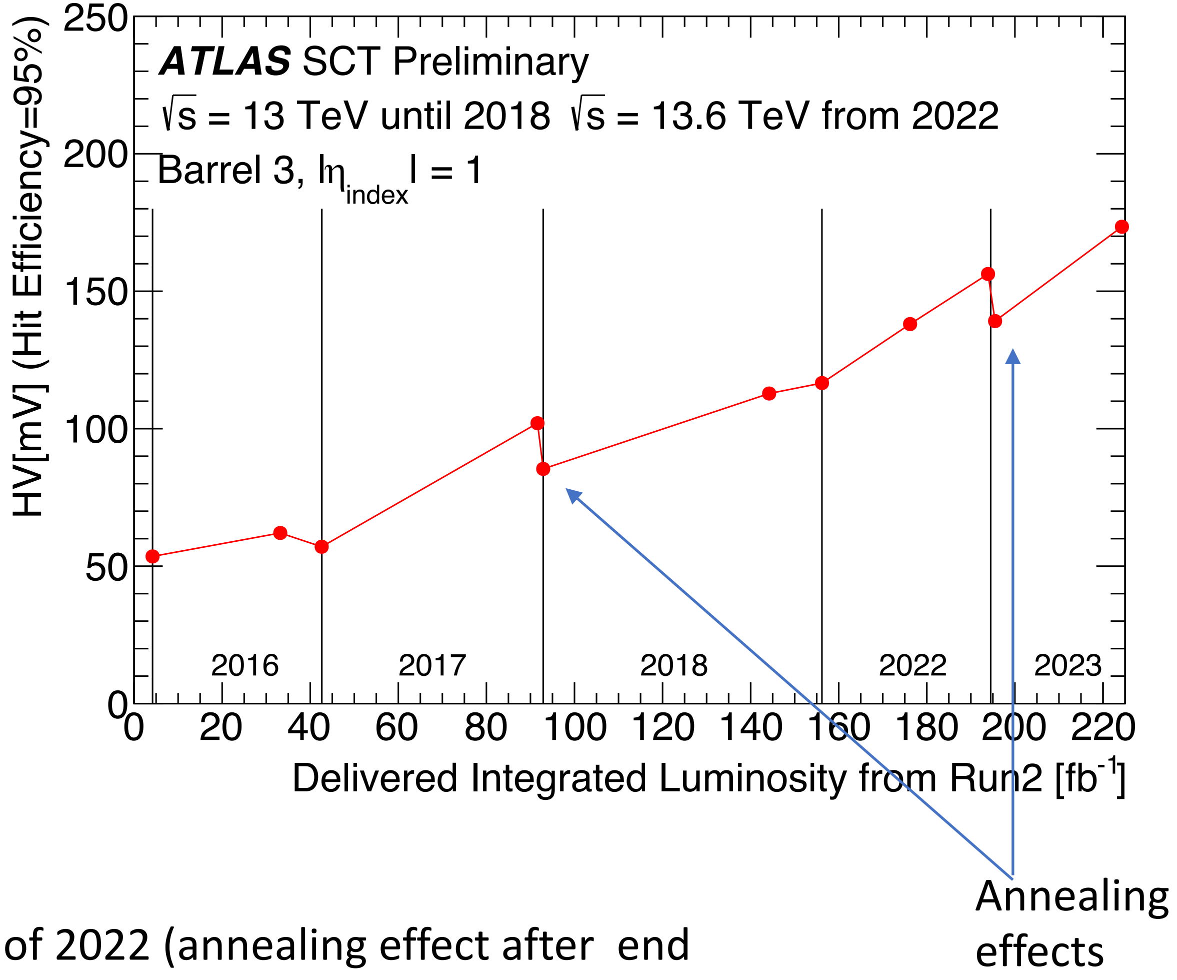


HV scan

After type inversion the HV needed to have full depletion can be considerably higher than V_{FD} from IV scan.

- Hit efficiency is monitored through HV scans





- HV Scan run from beginning of Run1 to July 2023
- HV(hit efficiency $=$ 95%) decreased by 20V wrt end of 2022 (annealing effect after end of the year shutdown)

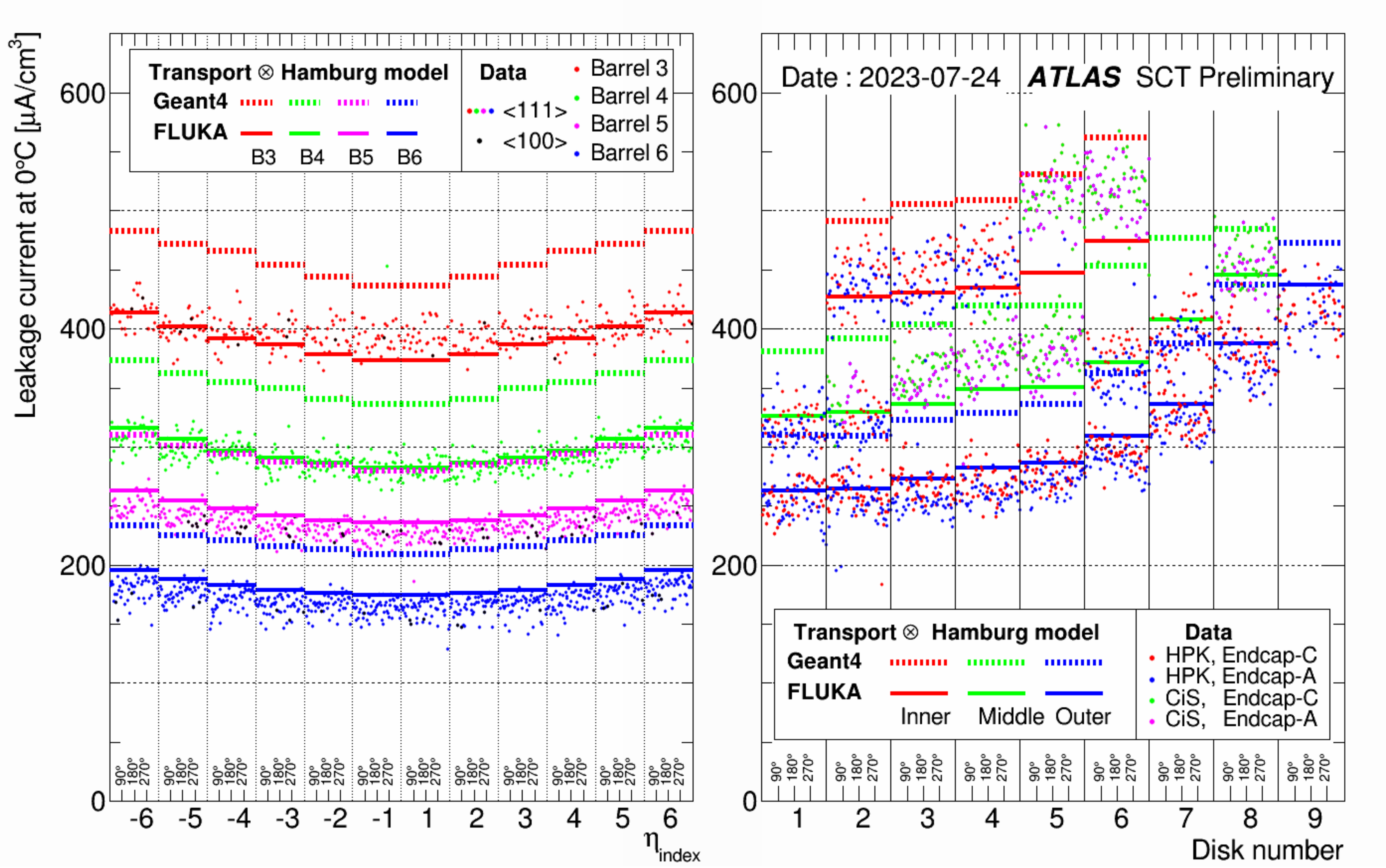
Leakage current

'**Snapshot**' of latest **detector conditions**

- **leakage current** for all module in SCT as of July 2023
- Values are 'normalized' to $T = 0°C$

Leakage current increases with radiation damage

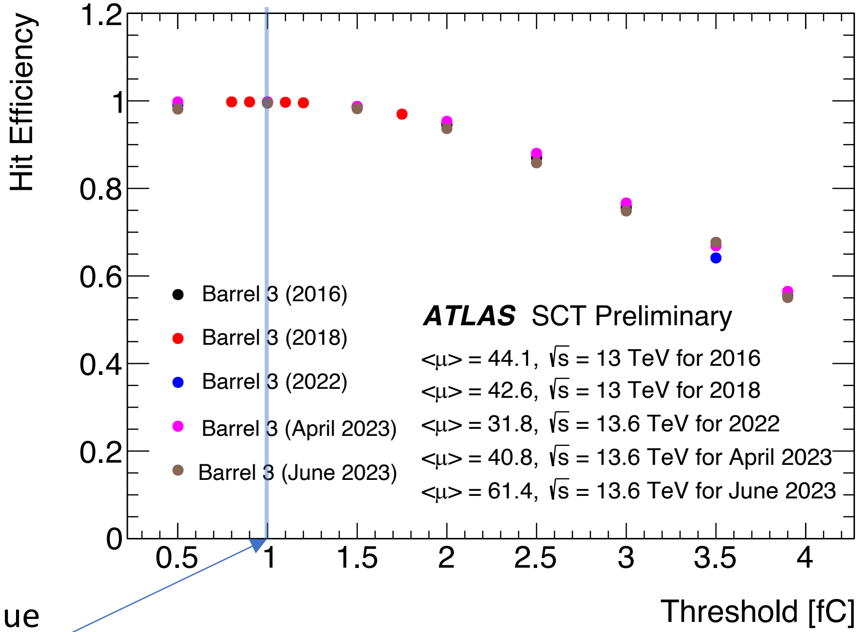
- Clearly higher for layers closer to the interaction point

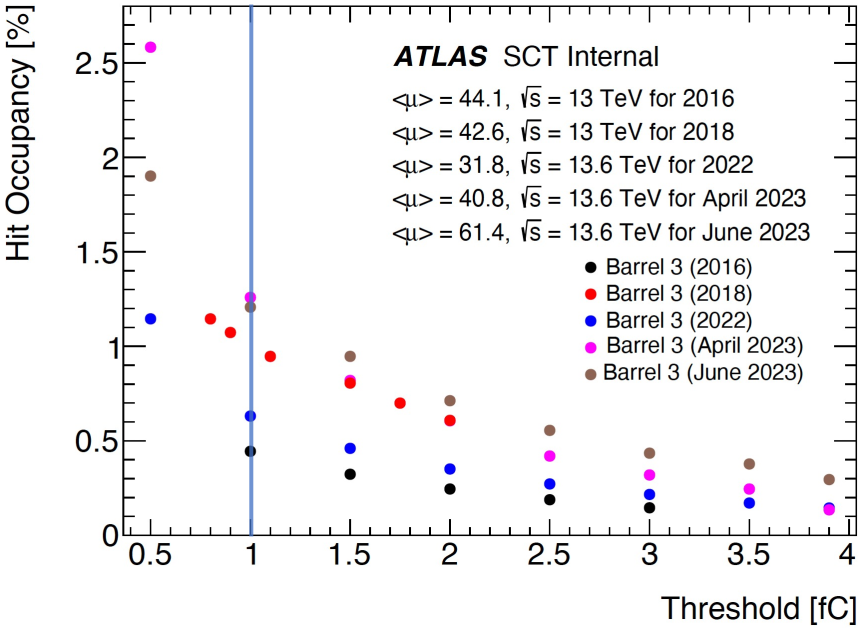


Noise - Threshold Scan

- To keep high efficiency need to set threshold as low as possible
  - Possible only if noise is low
- Optimal threshold parameter can change because of radiation
  - Threshold scans in 2023 shows that 1 – 1.5 fC is still a good range
  - Keep using the 1fC threshold value

$$Occupancy = \frac{N\ module\ above\ threshold\ per\ event}{Total\ N\ modules}$$





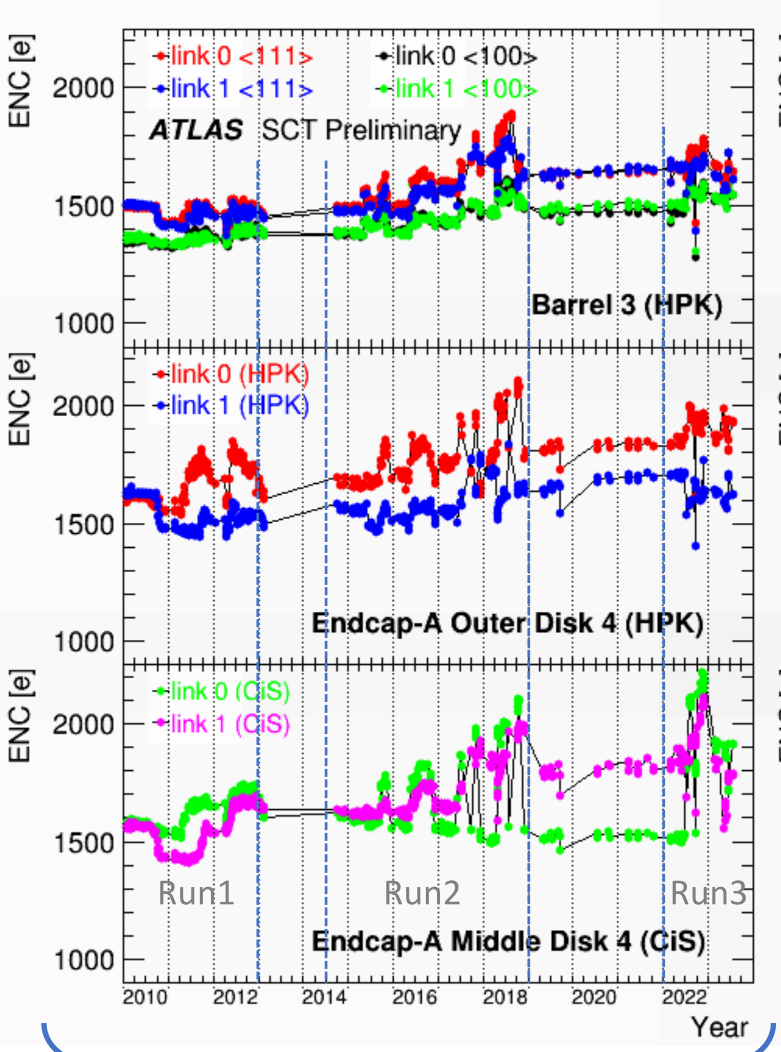
Threshold value currently used

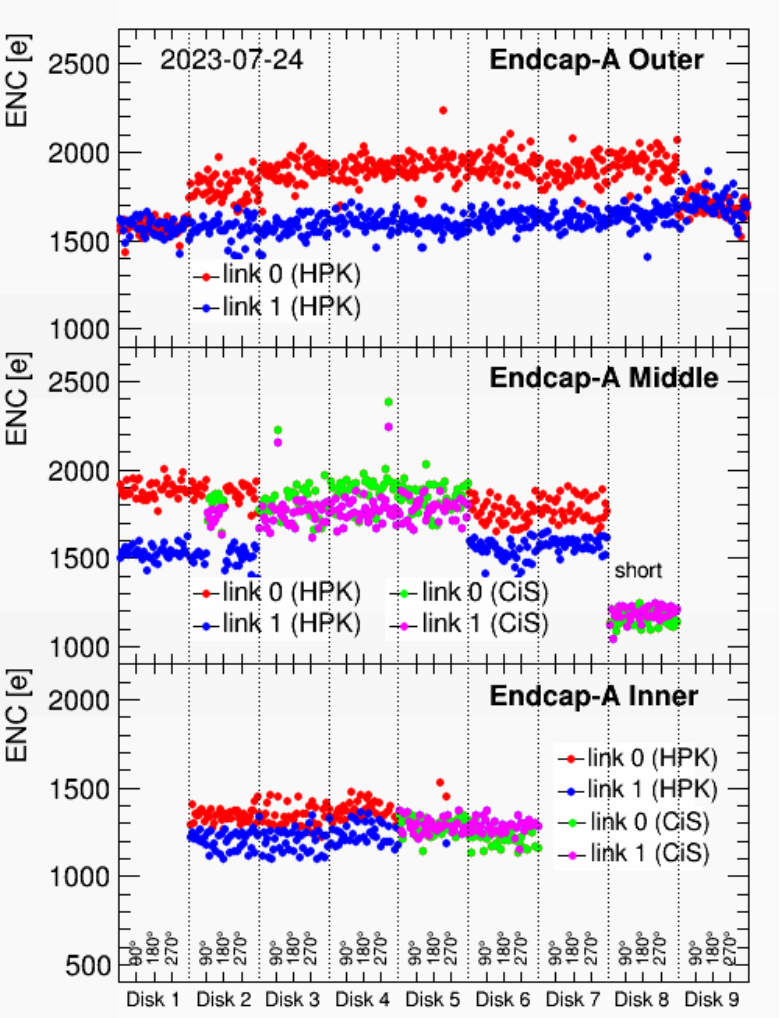
Noise measurement

- Noise constantly monitored
- Noise at most 2300e (0.37 fC) so still much lower than the 1 fC hit threshold

- Two ways of determining noise
  - From response curve test
  - From noise occupancy test

  ➔ Good correlation between the two measurements (see backup)





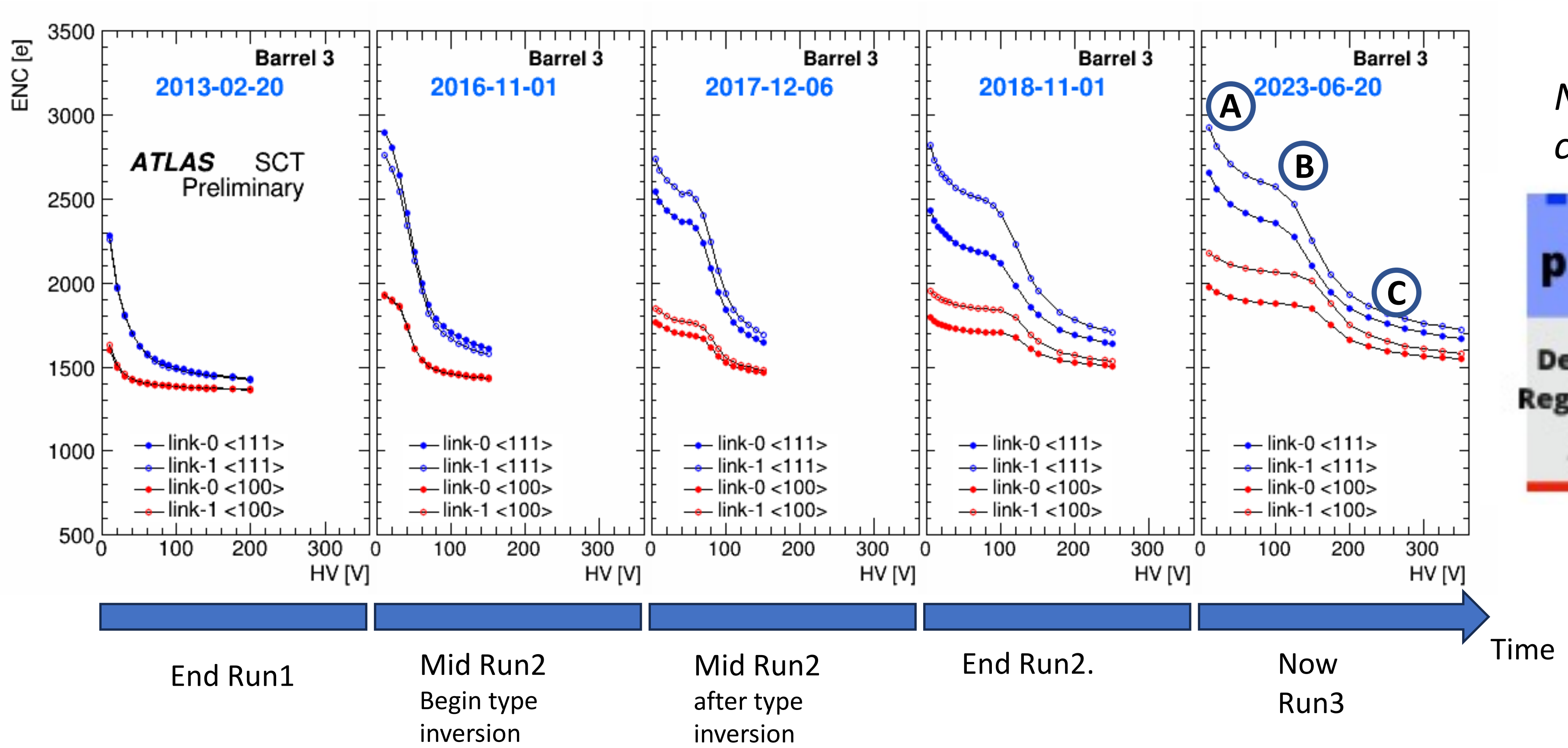
Time evolution for Noise from start of Run1 (2012) to July 2023

Noise situation as of July 2023

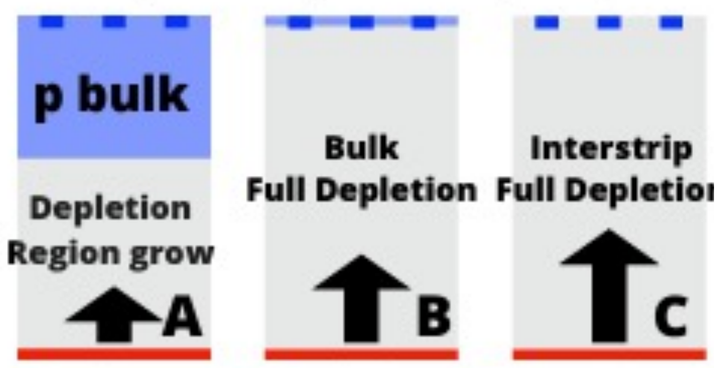
Noise & HV

Noise was measured periodically in a series of response curve scans or noise occupancy scans performed while varying HV

- **A knee-like structure** appeared after **type inversion** and its evolution results from changes in full depletion voltage

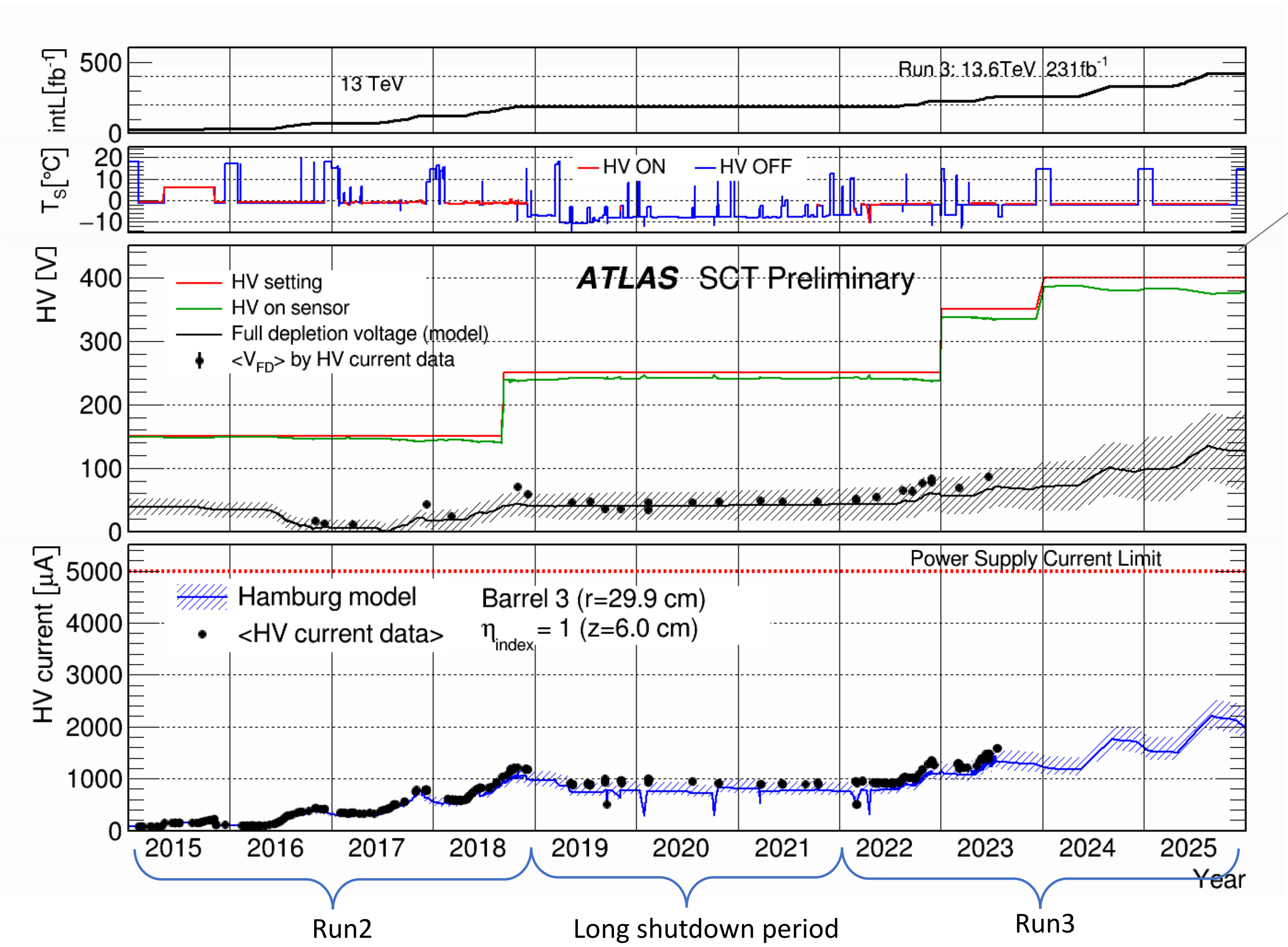


Noise related to interstrip capacitance



HV & leak. Current Predictions (Barrel3)

- Evolution of detector condition since Run2…
- … and predicted evolution until end of Run3



HV limit on sensor is 500V

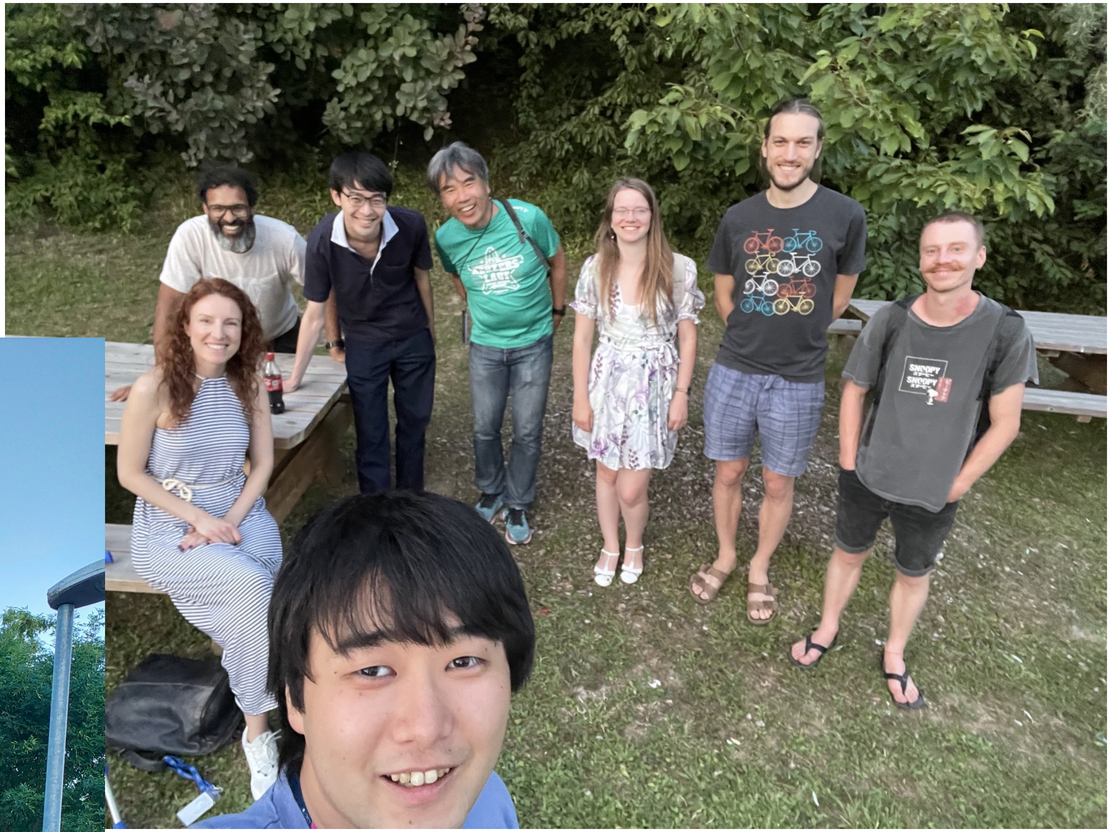
- Measured V_{FD} agrees well with model prediction and continues to increase since type inversion in 2016 (but should not exceed 180V)
- Leakage current is expected to be well below power supply limit still at the end of Run 3

Enough margin for Run3 operation in both HV and HV current.

Conclusion

- SCT had a good start of Run 3!
- Detector in good condition with 98.4% of active strips
- Regularly performed routine calibrations as well as special tests (IV scan, HV scan, threshold scan)
  - Ensuring highly efficient data taking and monitoring radiation damage effects
- We now observe more pronounced radiation damage effects
  - But safe margin for efficient operation until the end of Run3 (in 2025)…
  - … when SCT will reach end of duty!

Thanks for the *attention!*



The (enlarged) SCT team

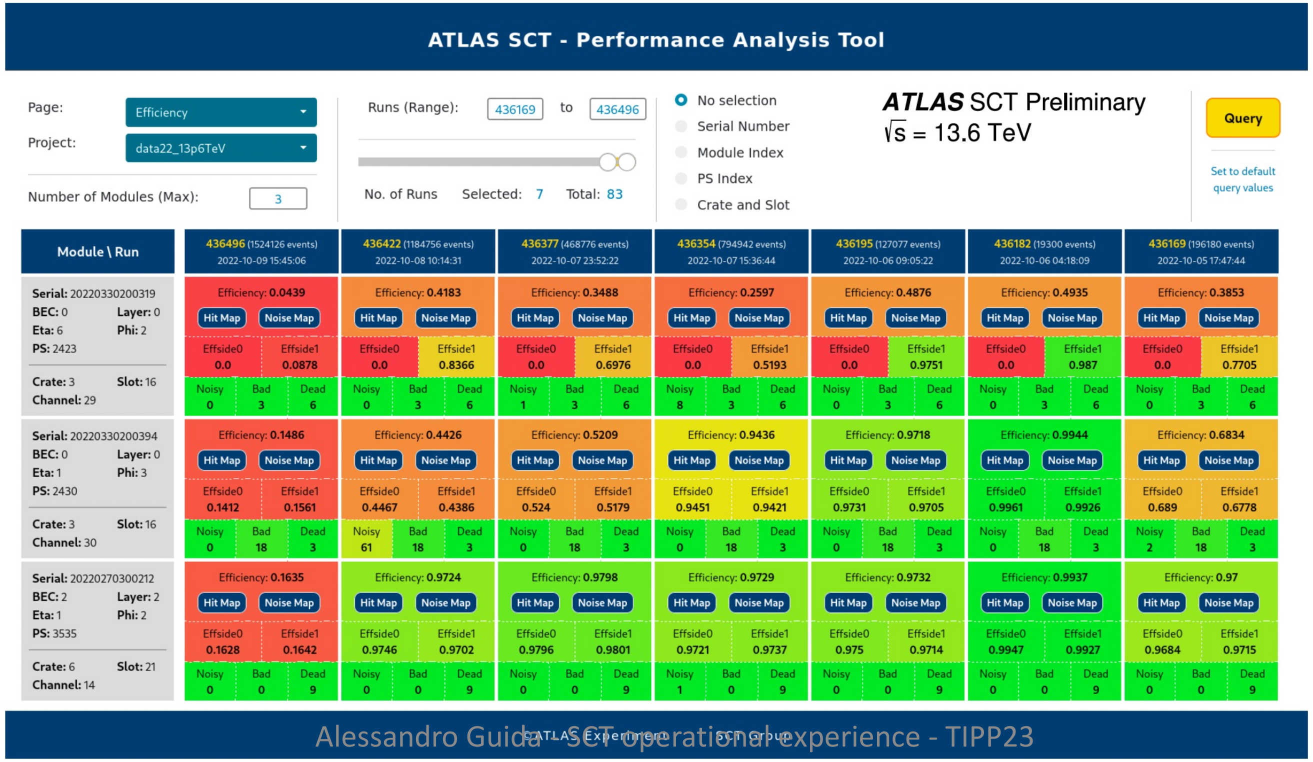
Backup

Performance Analysis Tool (PAT)

- PAT is a web-based tool developed by the SCT community to quickly spot inefficient modules and display the related performance information, like hit maps, module configuration, etc

- The tool consists of two components: Database using MySQL format which synchronises information from conditions DB, detector control system DB, module configuration DB, and output XML les from Calibration Loop

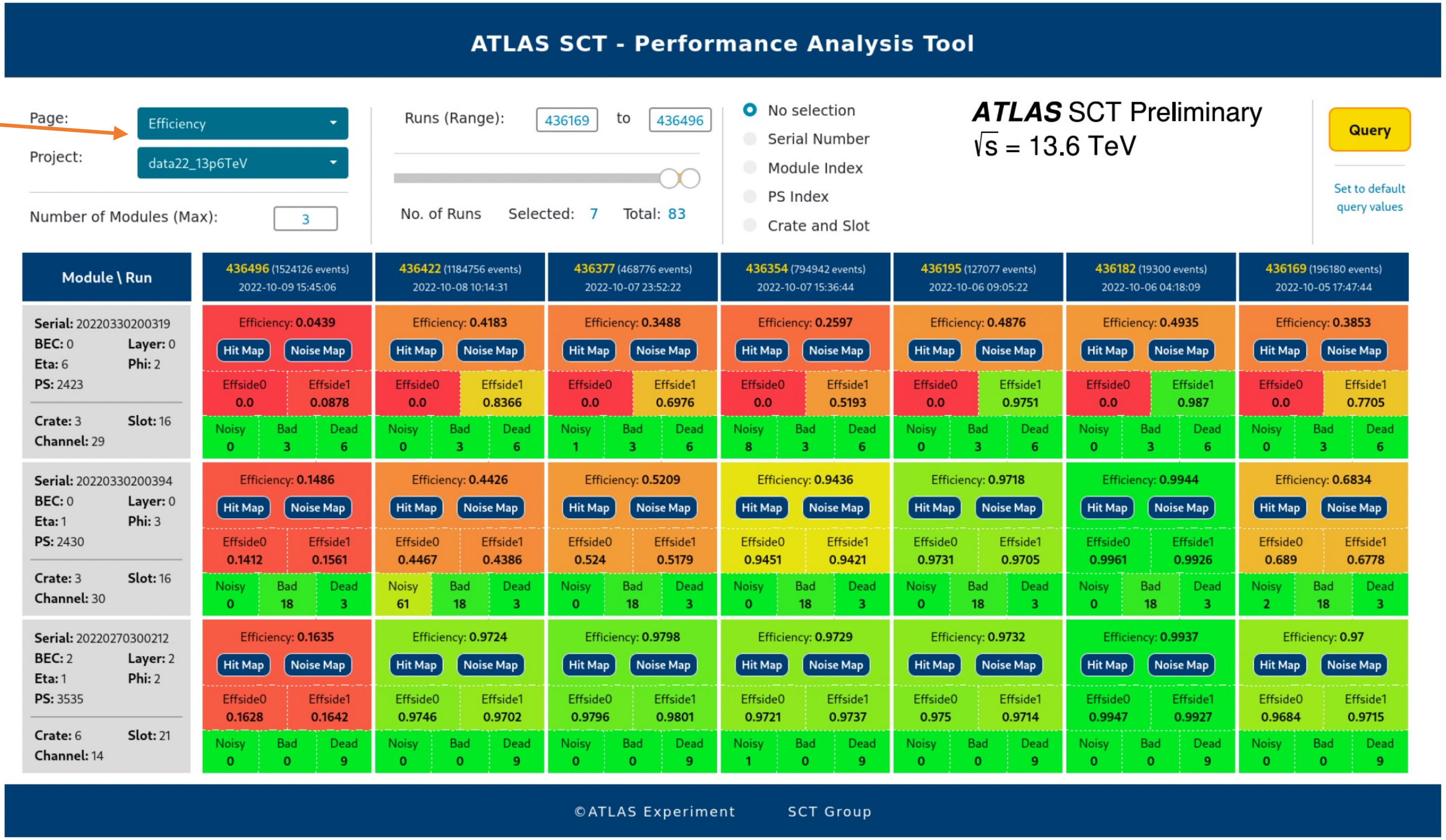
- Web display which takes data from the databases and displays it in an interactive webpage



Performance Analysis Tool (PAT)

Other performance pages

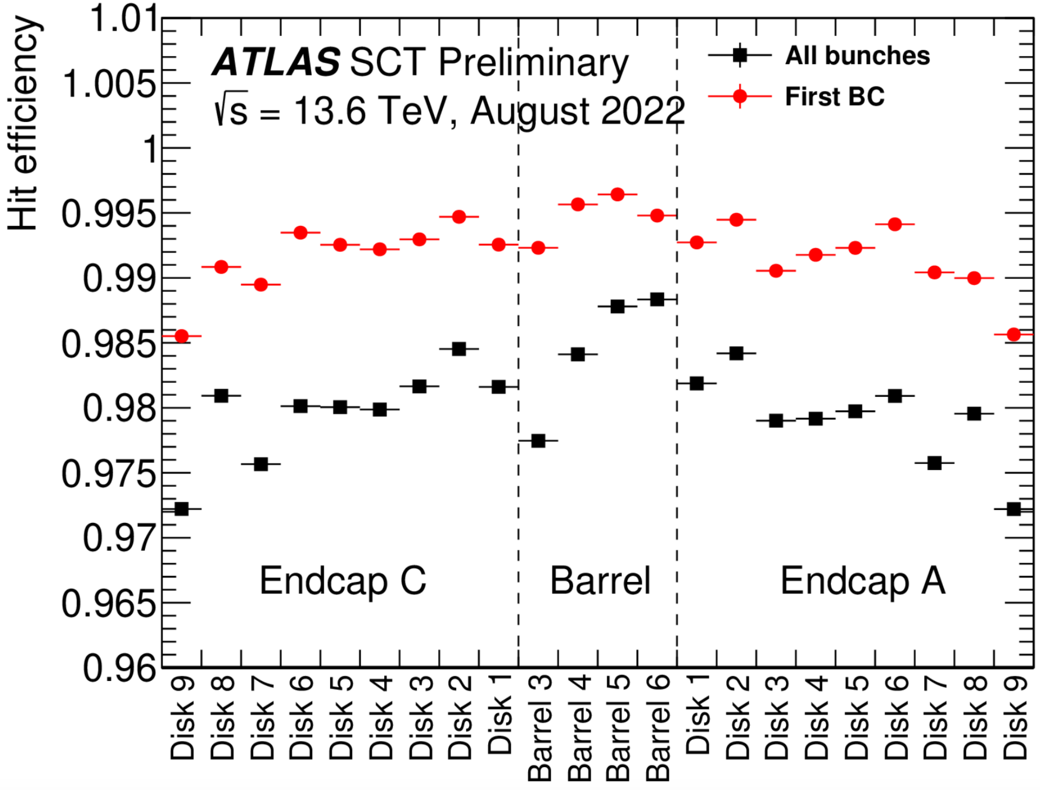
Module listed in order of increasing efficiency



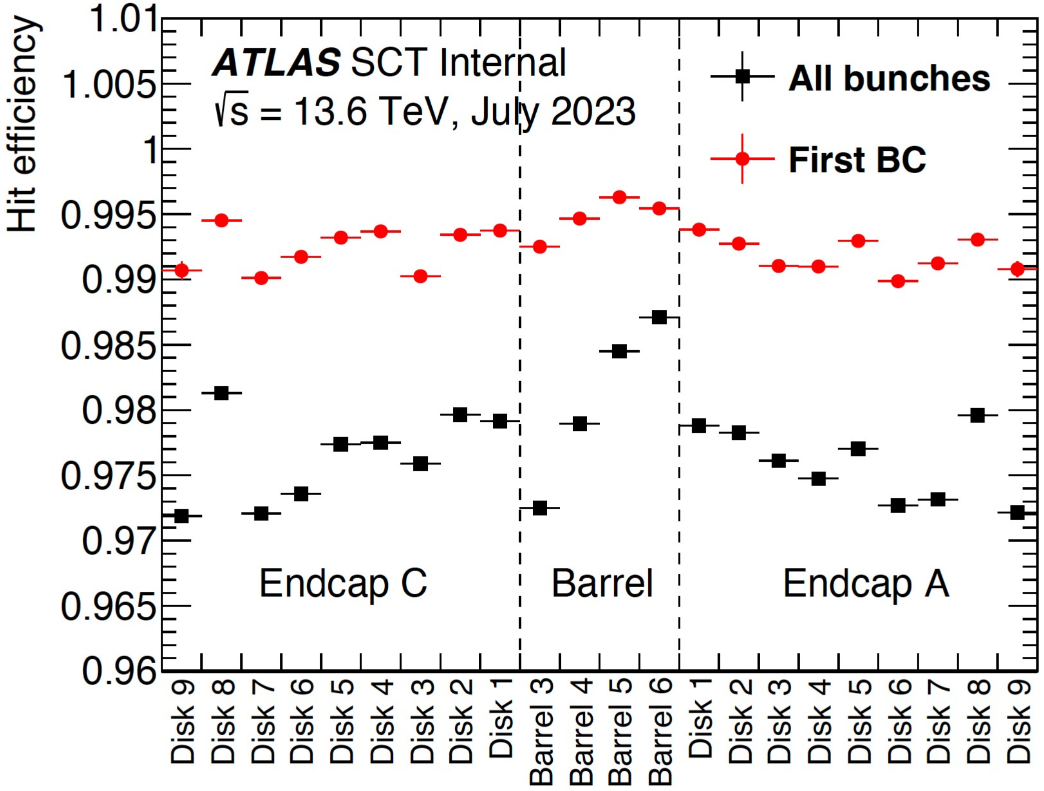
Module \ Run	436496 (1524126 events) 2022-10-09 15:45:06	436422 (1184756 events) 2022-10-08 10:14:31	436377 (468776 events) 2022-10-07 23:52:22	436354 (794942 events) 2022-10-07 15:36:44	436195 (127077 events) 2022-10-06 09:05:22	436182 (19300 events) 2022-10-06 04:18:09	436169 (196180 events) 2022-10-05 17:47:44
Serial: 20220330200319 **BEC:** 0 **Layer:** 0 **Eta:** 6 **Phi:** 2 **PS:** 2423 **Crate:** 3 **Slot:** 16 **Channel:** 29	Efficiency: 0.0439 Hit Map Noise Map Effside0 0.0 Effside1 0.0878 Noisy 0 Bad 3 Dead 6	Efficiency: 0.4183 Hit Map Noise Map Effside0 0.0 Effside1 0.8366 Noisy 0 Bad 3 Dead 6	Efficiency: 0.3488 Hit Map Noise Map Effside0 0.0 Effside1 0.6976 Noisy 1 Bad 3 Dead 6	Efficiency: 0.2597 Hit Map Noise Map Effside0 0.0 Effside1 0.5193 Noisy 8 Bad 3 Dead 6	Efficiency: 0.4876 Hit Map Noise Map Effside0 0.0 Effside1 0.9751 Noisy 0 Bad 3 Dead 6	Efficiency: 0.4935 Hit Map Noise Map Effside0 0.0 Effside1 0.987 Noisy 0 Bad 3 Dead 6	Efficiency: 0.3853 Hit Map Noise Map Effside0 0.0 Effside1 0.7705 Noisy 0 Bad 3 Dead 6
Serial: 20220330200394 **BEC:** 0 **Layer:** 0 **Eta:** 1 **Phi:** 3 **PS:** 2430 **Crate:** 3 **Slot:** 16 **Channel:** 30	Efficiency: 0.1486 Hit Map Noise Map Effside0 0.1412 Effside1 0.1561 Noisy 0 Bad 18 Dead 3	Efficiency: 0.4426 Hit Map Noise Map Effside0 0.4467 Effside1 0.4386 Noisy 61 Bad 18 Dead 3	Efficiency: 0.5209 Hit Map Noise Map Effside0 0.524 Effside1 0.5179 Noisy 0 Bad 18 Dead 3	Efficiency: 0.9436 Hit Map Noise Map Effside0 0.9451 Effside1 0.9421 Noisy 0 Bad 18 Dead 3	Efficiency: 0.9718 Hit Map Noise Map Effside0 0.9731 Effside1 0.9705 Noisy 0 Bad 18 Dead 3	Efficiency: 0.9944 Hit Map Noise Map Effside0 0.9961 Effside1 0.9926 Noisy 0 Bad 18 Dead 3	Efficiency: 0.6834 Hit Map Noise Map Effside0 0.689 Effside1 0.6778 Noisy 2 Bad 18 Dead 3
Serial: 20220270300212 **BEC:** 2 **Layer:** 2 **Eta:** 1 **Phi:** 2 **PS:** 3535 **Crate:** 6 **Slot:** 21 **Channel:** 14	Efficiency: 0.1635 Hit Map Noise Map Effside0 0.1628 Effside1 0.1642 Noisy 0 Bad 0 Dead 9	Efficiency: 0.9724 Hit Map Noise Map Effside0 0.9746 Effside1 0.9702 Noisy 0 Bad 0 Dead 9	Efficiency: 0.9798 Hit Map Noise Map Effside0 0.9796 Effside1 0.9801 Noisy 0 Bad 0 Dead 9	Efficiency: 0.9729 Hit Map Noise Map Effside0 0.9721 Effside1 0.9737 Noisy 1 Bad 0 Dead 9	Efficiency: 0.9732 Hit Map Noise Map Effside0 0.975 Effside1 0.9714 Noisy 0 Bad 0 Dead 9	Efficiency: 0.9937 Hit Map Noise Map Effside0 0.9947 Effside1 0.9927 Noisy 0 Bad 0 Dead 9	Efficiency: 0.97 Hit Map Noise Map Effside0 0.9684 Effside1 0.9715 Noisy 0 Bad 0 Dead 9

Run listed in inverted chronological order

Hit Efficiency 2022-vs-2023

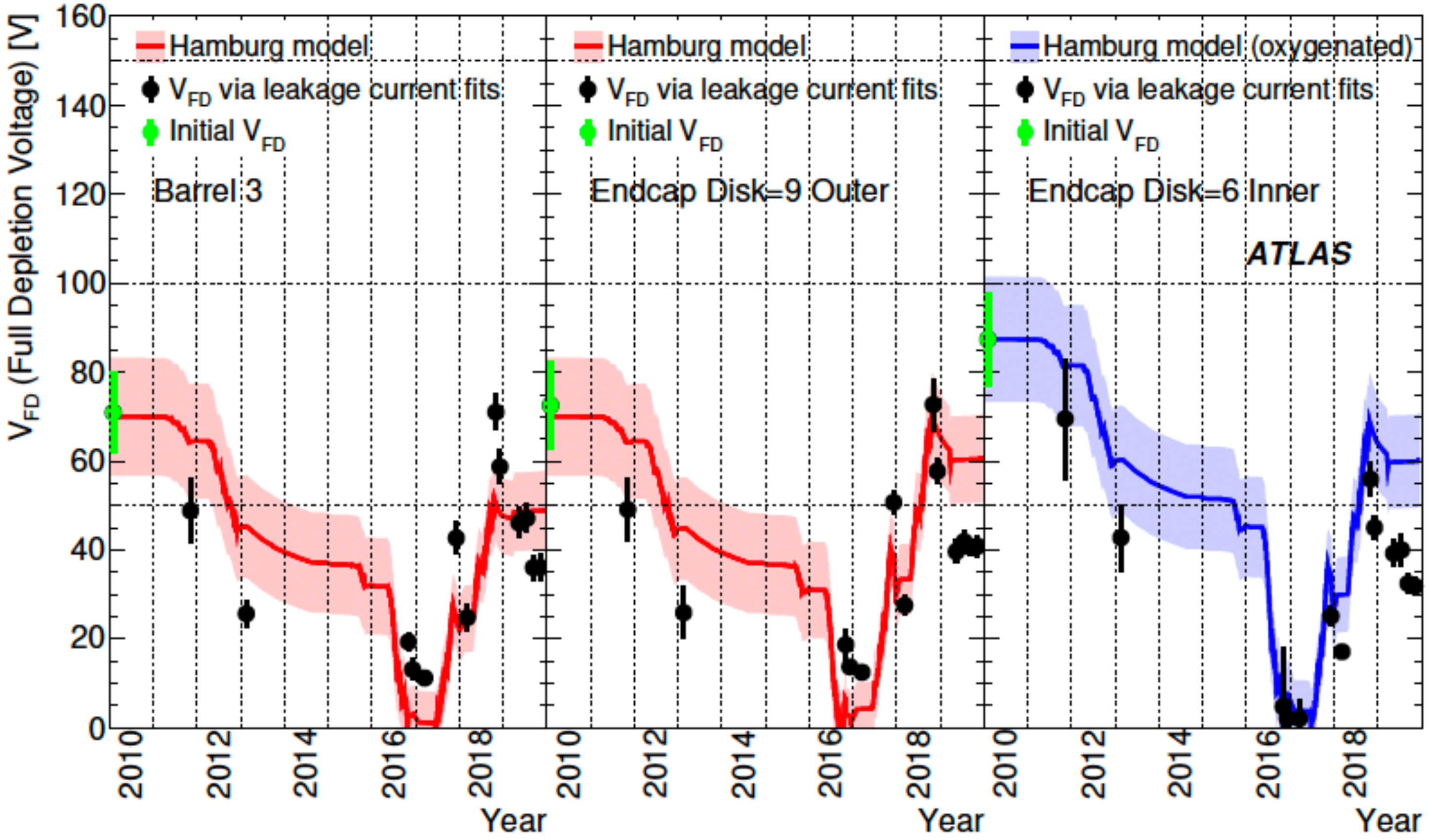


Last year hit efficiency



This year hit efficiency

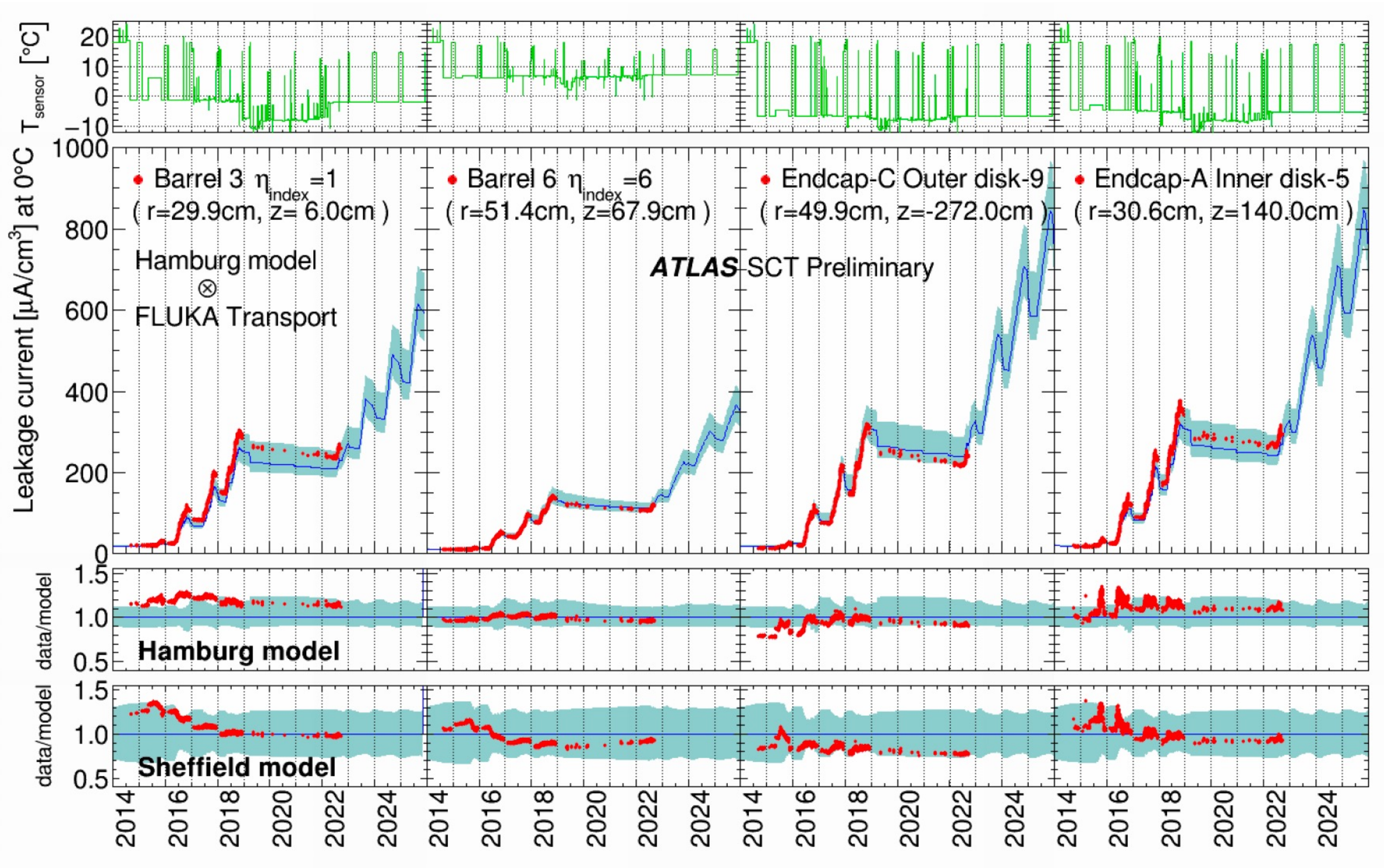
V_{FD} and type inversion



Depletion Voltage as measured in IV scans from Run1 till end of Run2

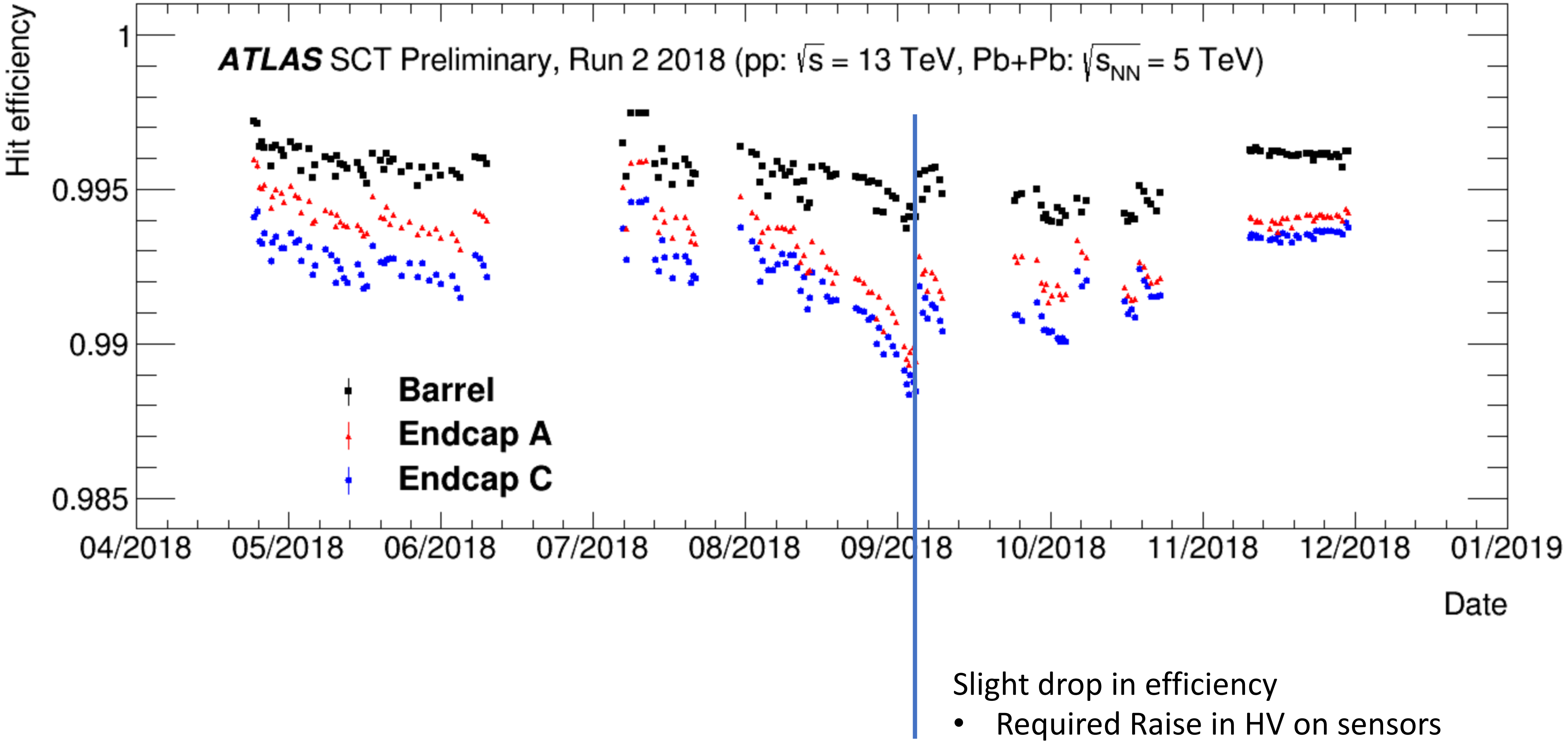
- Type inversion visible between 2016-2017

Leakage current



Evolution of the leakage current between Run2 and beginning of Run3

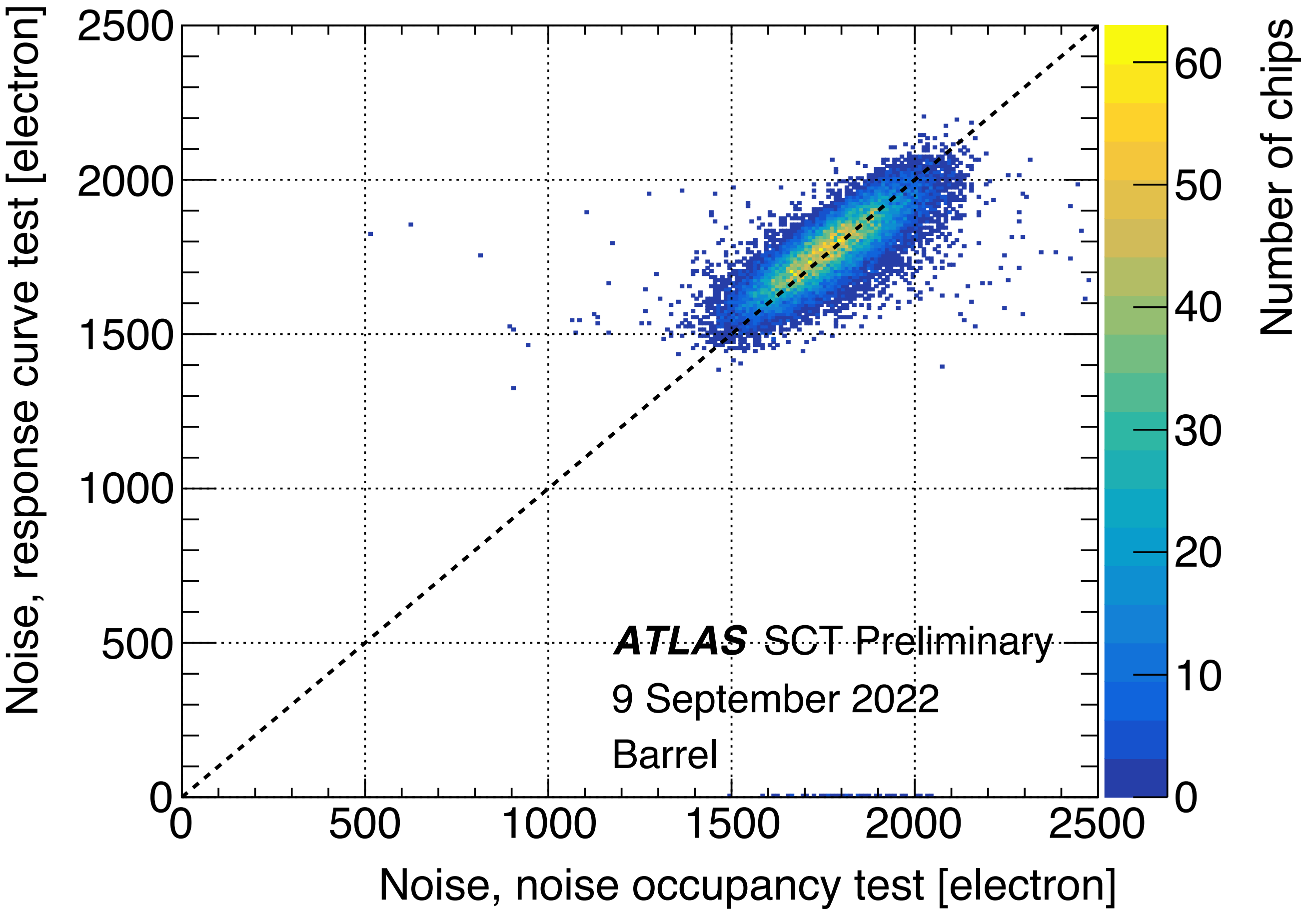
Hit Efficiency during Run 2



Slight drop in efficiency

- Required Raise in HV on sensors

Noise measurements

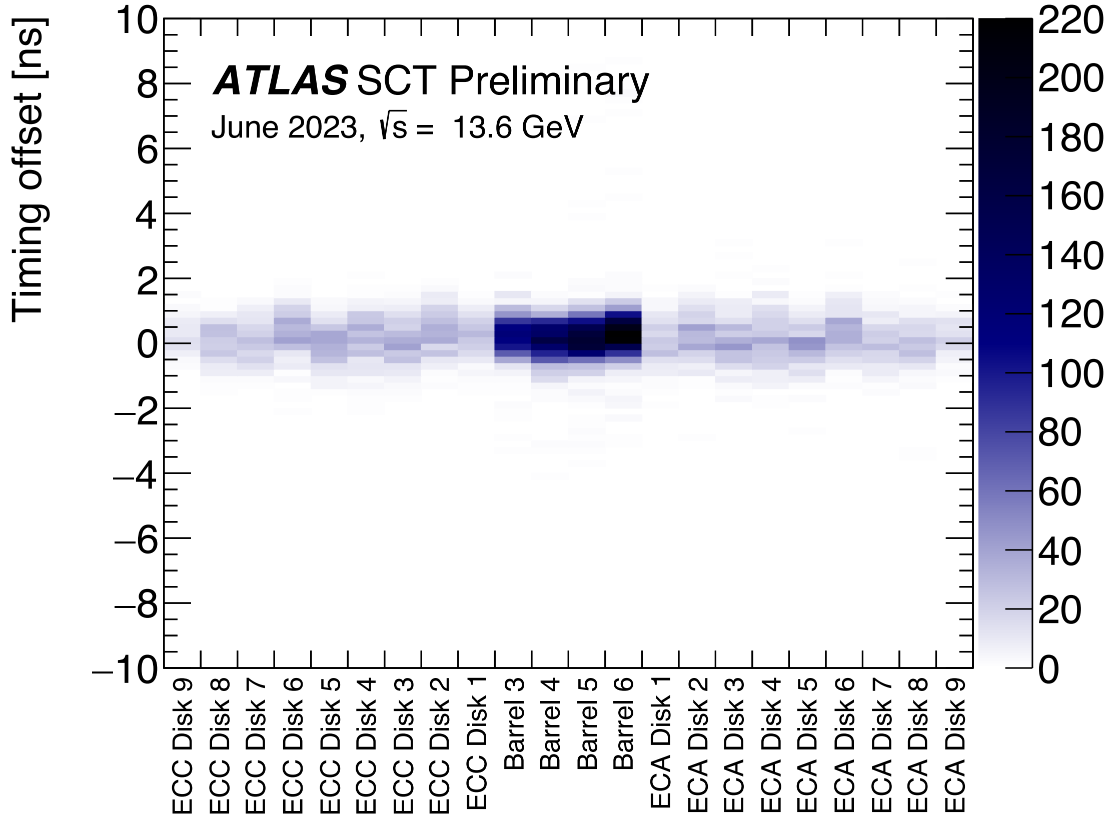


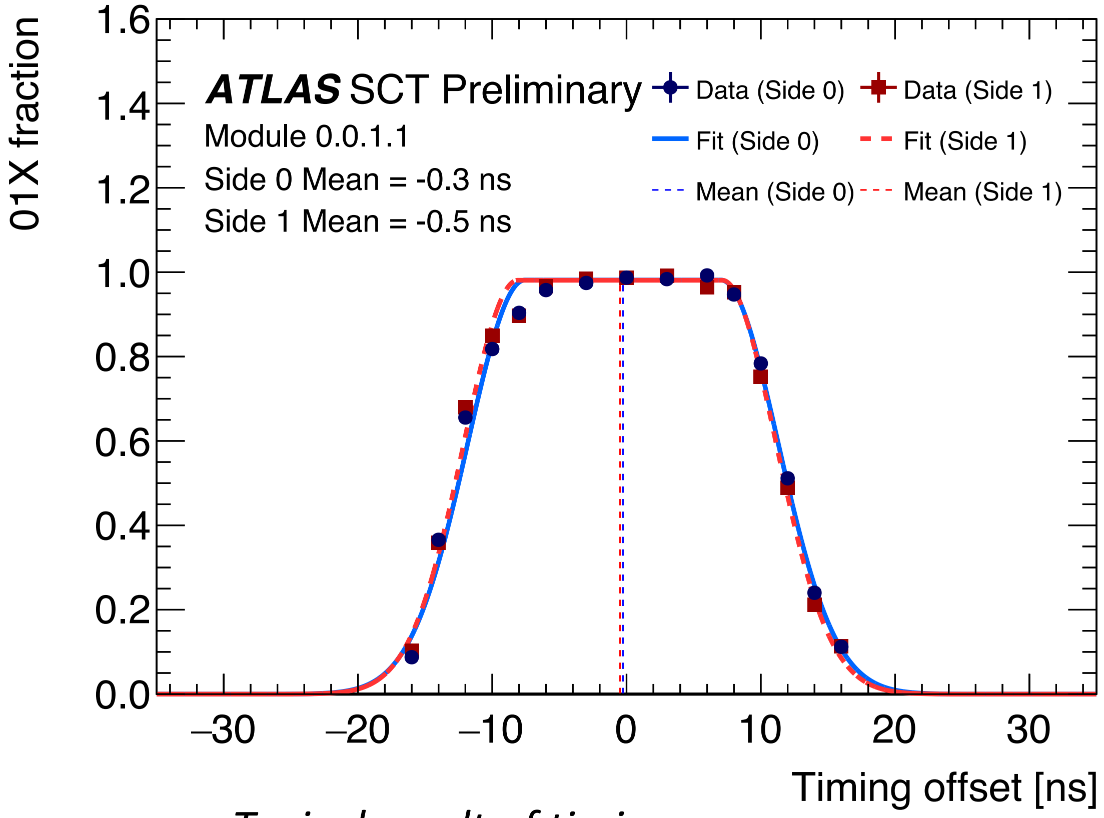
Two ways of measuring the noise

- Noise occupancy scan
- Noise from response curve scan

The two show clear correlation

Timing of the SCT

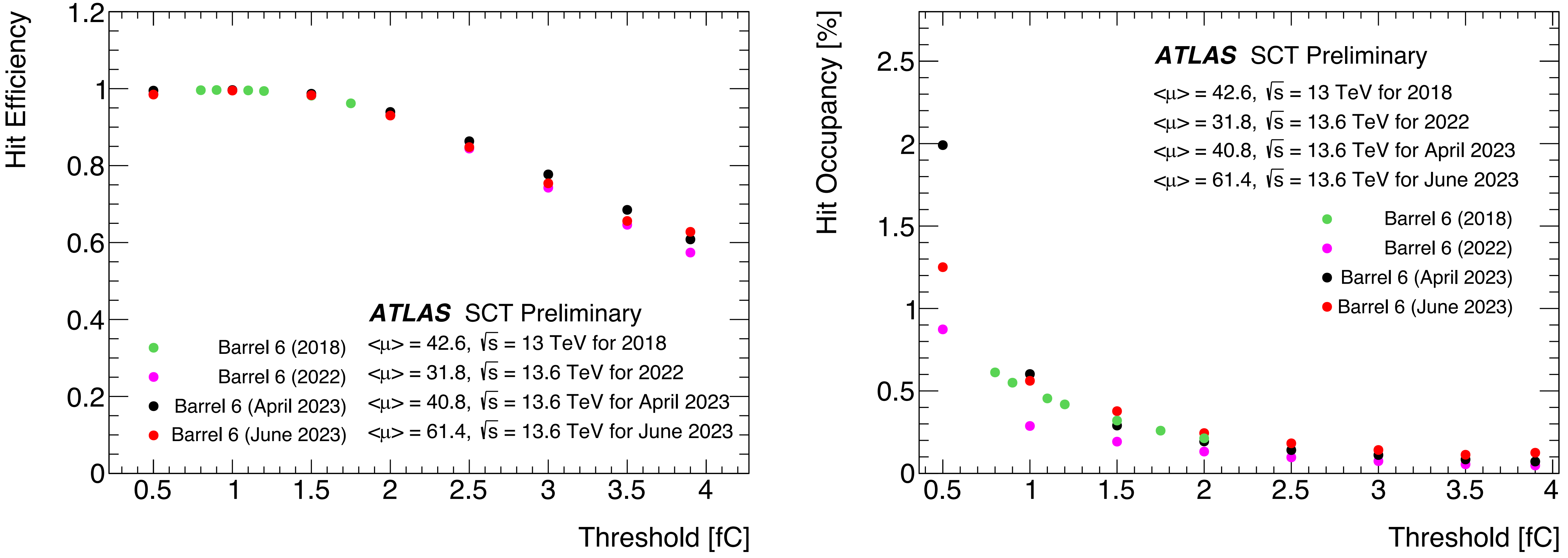




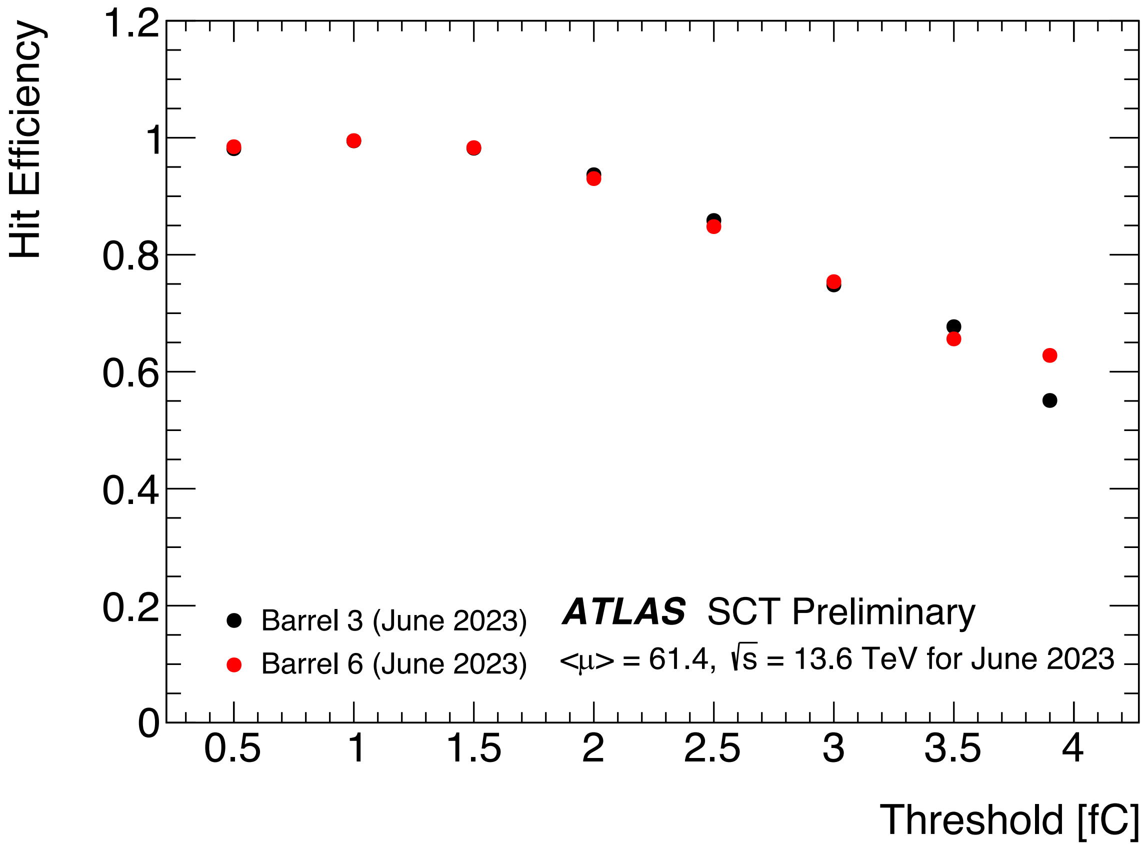
Typical result of timing scan

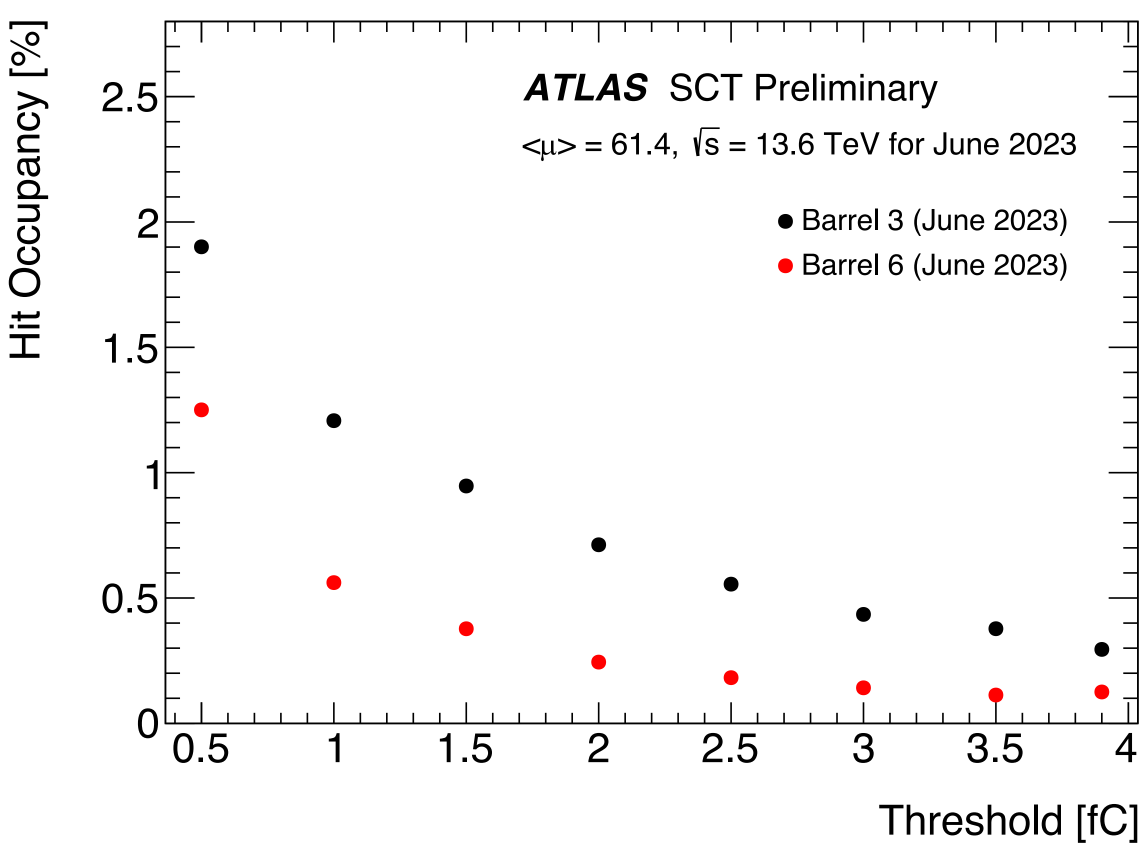
Timing offset are applied to compensate length of optical fibres (for trigger signal) , delay of trigger electronics and time-of-flight

Threshold scan

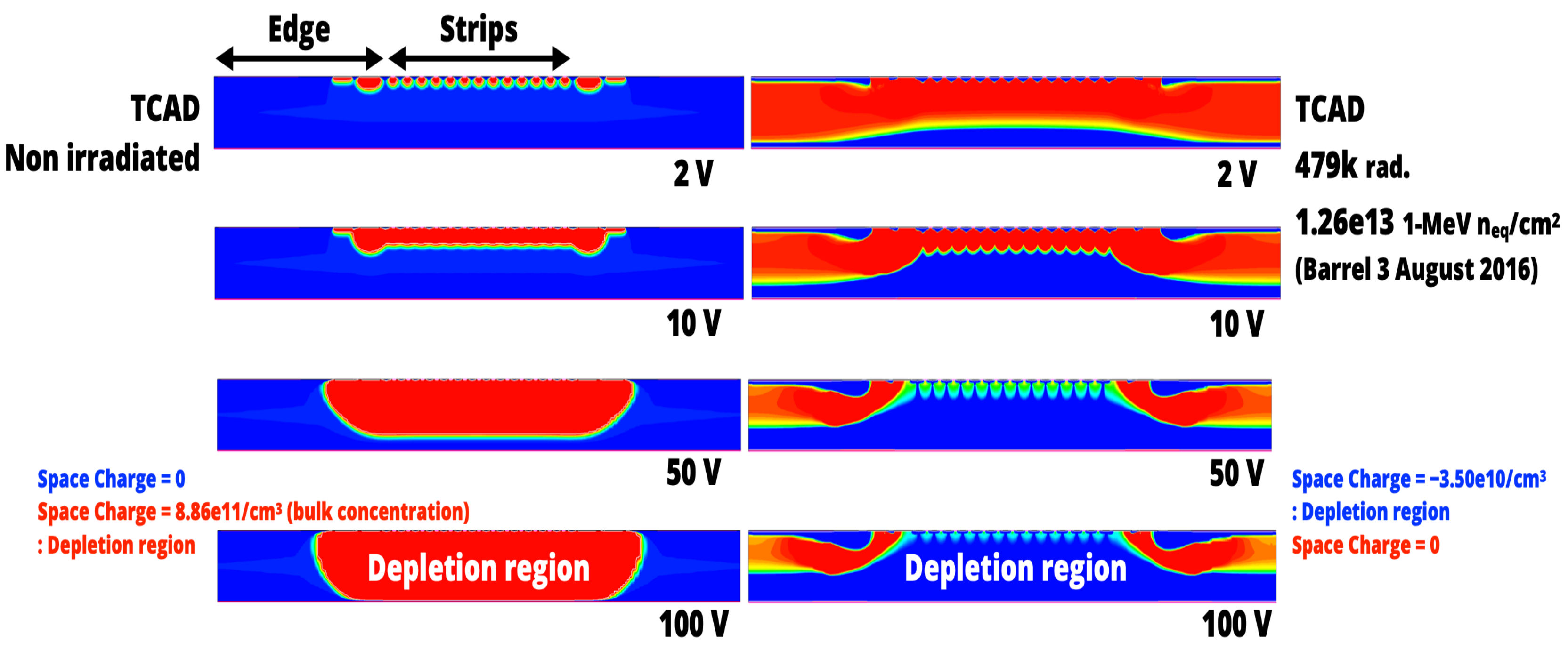


Threshold scan





Type inversion



TCAD simulation of irradiated and non irradiated sensor