The operational experience and performance of the SCT detector during Run 2 and LS2, and the first impression from Run 3 operations

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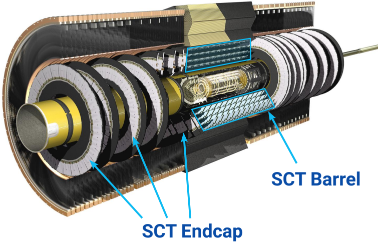
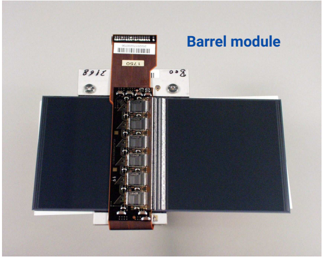
The 31st International Workshop on Vertex Detectors

24 October 2022

SCT detector

- SCT consists of 4088 modules organised in **4 barrel layers** (numbered 3–6) and **2×9 endcap disks**
- Each module consists of 4 sensors, two per side
  - The sides are glued back-to-back at 40 mrad stereo angle
- Silicon sensors are **p-on-n type**, 285 um thick, manufactured by Hamamatsu and CiS
- We have 786×2 strips per module with strip pitch of 80 um and strip length of 12.8 cm
- 12 ABCD readout chips are providing a binary readout with a 3-bit hit pattern
  - One bit per time slice: preceding, triggered, following bunch crossing





Operation during Long Shutdown 2 (2019–2021)

- During the period of **Long Shutdown 2**, SCT remained without LV and HV most of the time
  - **Cooling was maintained** to limit radiation damage effects
- Every few weeks SCT along with Pixel and TRT detectors were switched on for a week of operations
- During such weeks we had a chance to ramp up the HV and:
  - Run routine **calibrations and IV scan** during the day
  - Take cosmic data throughout the night
- Also took this opportunity to spend time on **hardware maintenance** with a major intervention of redesigning and replacing half of the power supply units

Where we stand today

Disabled component	Start of Run 1 (2010)	End of Run 1 (2012)	Start of Run 2 (2015)	End of Run 2 (2018)	Start of Run 3 (2022)	Now
Modules	28	30	38	42	46	**47**
Chips	36	55	59	83	85	**80**
Strips	10795	11363	11452	14895	24071	**24451**
Fraction of active strips	99.1%	99.0%	98.8%	98.6%	98.3%	**98.3%**

No. of redundancies used	Start of Run 1 (2010)	End of Run 1 (2012)	Start of Run 2 (2015)	End of Run 2 (2018)	Start of Run 3 (2022)	Now
RX links	108	132	136	153	155	**155**
TX links	126	up to 240	20	55	58	**58**

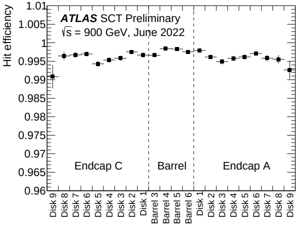
- SCT is still in good shape with **98.3% strips still active** after almost 13 years of operation despite challenging conditions
  - Run-2 and Run-3 instantaneous luminosity much larger than assumed in the design
- Large difference in the number of disabled strips between the end of Run 2 and beginning of Run 3 is related to now understood unnecessary masking of strips during calibrations
  - With new fixes applied we will be able to recover around 10000 masked strips

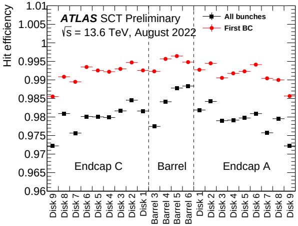
Hit efficiency

- SCT continues to take data with high efficiency
- We define per-track hit efficiency in terms of the number of clusters and holes associated with the track:

$$\epsilon = \frac{N_{\text{cluster}}}{N_{\text{cluster}} + N_{\text{hole}}}$$

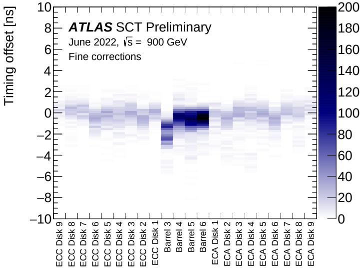
- Hit efficiency at the beginning of Run 3 with 900 GeV collisions was above 0.99 for all layers
- During pp collisions at 13.6 TeV the intrinsic hit efficiency (for the 1st BC) is mostly above 0.99
- Continuing radiation damage will result in increasing depletion voltage which in turn results in intrinsic hit efficiencies dropping below 0.99
  - Intrinsic hit efficiency will be monitored throughout Run 3 and the applied HV increased when necessary

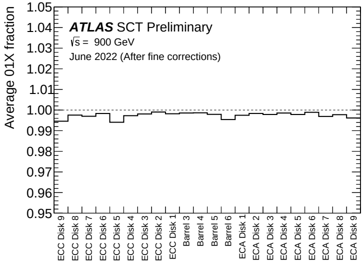




Timing adjustments

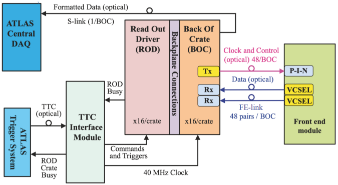
- SCT timing adjustment is performed by applying offsets as delays to the trigger signal
- Offsets were measured using *pp* collision data at a collision energy of 900 GeV and are twofold
- A **global correction** of −5 ns is applied due to trigger electronics upgrade
- **Fine corrections** are applied to account for:
  - Different length of fibers transmitting trigger signal
  - Delays in trigger electronics
  - Time of flight of particles from interaction point to module
- **No major changes** in fine corrections with respect to Run 2

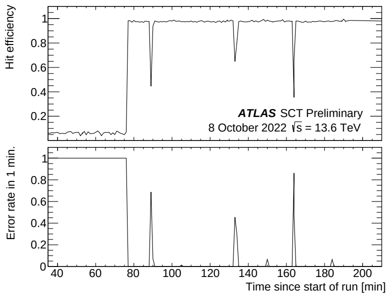




Currently investigated issues

- Although the start of Run 3 went smoothly, we have a few things to follow up on
- Towards the end of the intensity ramp up SCT started asserting BUSY more frequently than expected leading to multiple **ROD removals** per run
  - at the end of Run 2 we had on average 2 ROD removals per day
- The frequent ROD removals are currently under investigation and may be related to unexpected data coming and/or data being stuck in formatters
- Also observed a small number of modules (mostly from the same ROD) suddenly **losing efficiency** during the run which seems to be correlated with byte stream errors
- Although the impact on tracking is negligible (affected only 0.2% of modules), it is important to find the cause of this behaviour to ensure good stability of SCT DAQ system

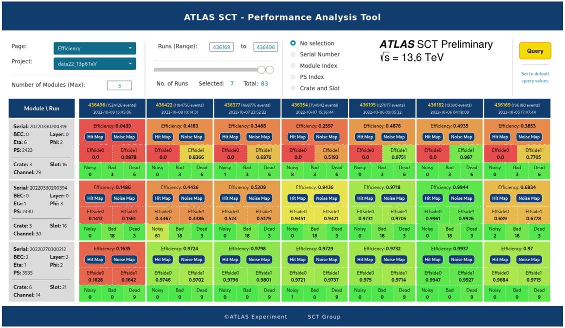




SCT Performance Analysis Tool (PAT)

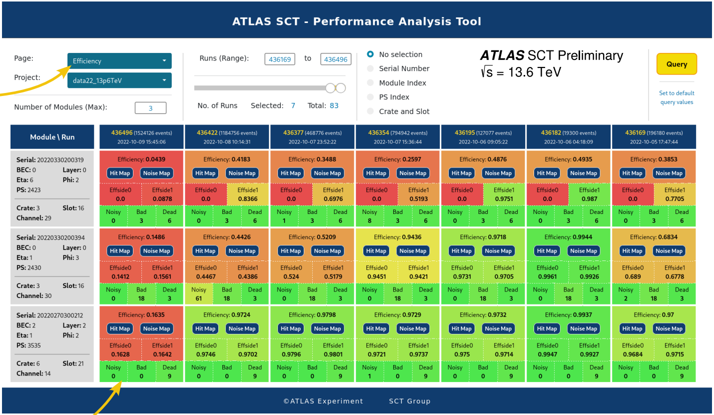
- **PAT** is a web-based tool developed by the SCT community to quickly spot inefficient modules and display the related performance information, like hit maps, module configuration, etc.

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



A closer look at PAT functionalities

Other performance pages



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

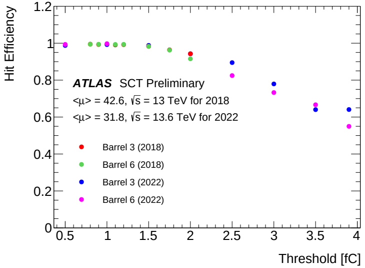
Modules listed in order of increasing efficiency (least efficient first)

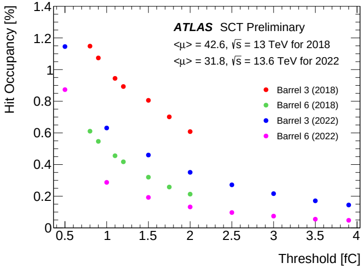
Scrollable

Runs listed in inverse chronological order (newest first)

Threshold scan

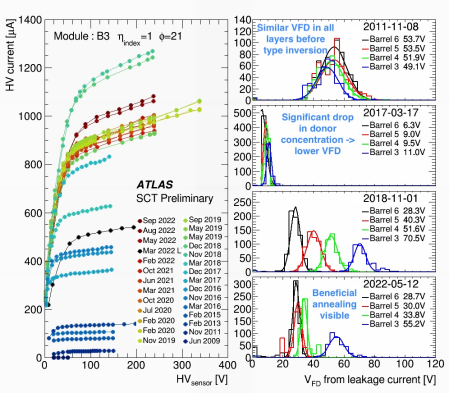
- **Threshold** is one of the important parameters that have to be optimised for operation
  - Need to provide as high efficiency as possible while maintaining minimal noise
- The threshold which was optimal before sensor irradiation is not necessarily optimal after detector operation for several years
  - Higher optimal value is expected
- With the radiation damage being more pronounced now in SCT we **performed a threshold scan** to check if a threshold update is necessary
- Recent results show that the range of 1–1.5 fC is **still providing high efficiency and good hit occupancy**
  - No need to change the currently used 1 fC

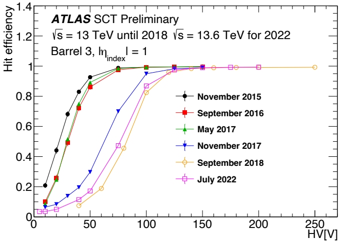




Full depletion voltage V_{FD}

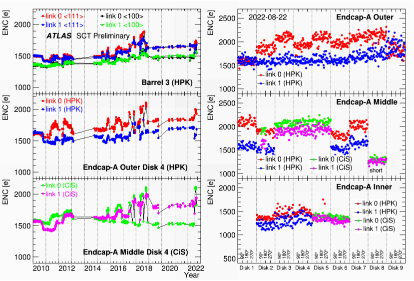
- V_{FD} needs to be monitored carefully to ensure good detector performance until the end of Run 3 operations
- V_{FD} cannot be measured directly
  - Estimated based on $I - V$ relation or dependence of quantities like hit efficiency on HV
- All results show a clear effect of **beneficial annealing** that happened during LS2 → decrease of V_{FD}

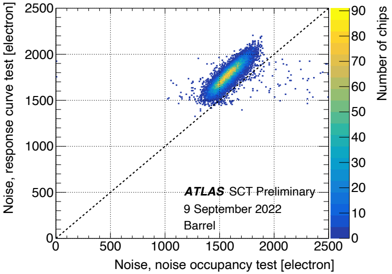




Noise measurements

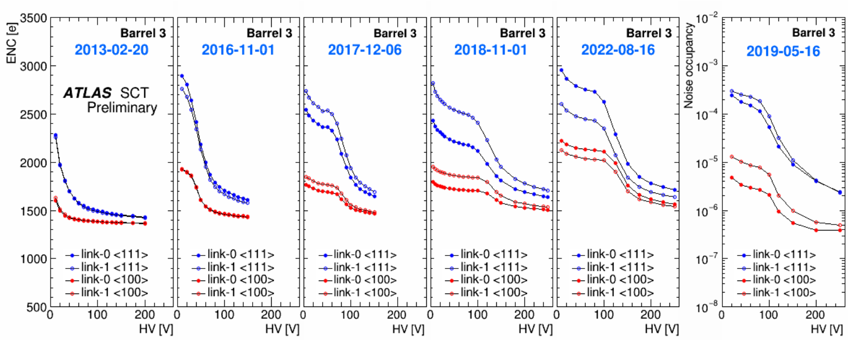
- Low input noise ⇒ Low thresholds ⇒ High tracking efficiency
- Link 0 typically characterised by higher noise
- Noise at most 2300e (0.37 fC) so still **much lower than the 1 fC threshold**
- Two methods of determining noise:
  - from response curve test
  - from noise occupancy test
- Observed a **good correlation** between the two measurements





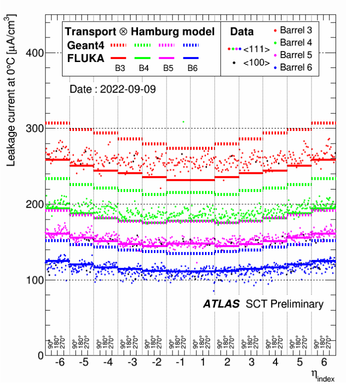
HV dependence of noise

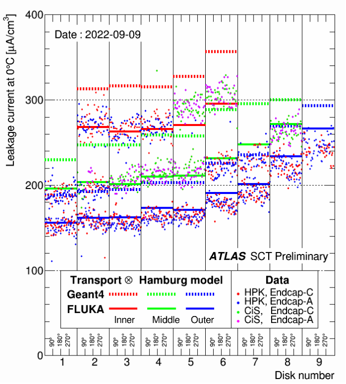
- Noise was measured periodically in a series of response curve scans or noise occupancy scans performed while varying HV
- **A knee-like structure** appeared after **type inversion** and its evolution results from changes in full depletion voltage



Leakage current measurement

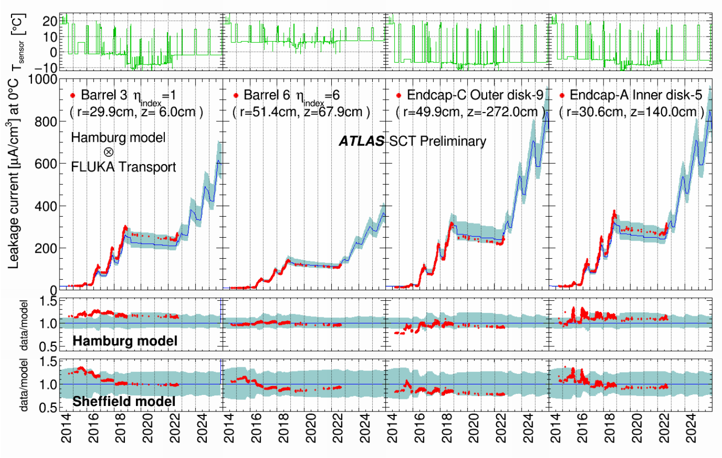
- As expected, higher leakage current observed in regions characterised by higher fluence (at higher η)
- In general **good agreement** observed between leakage current measured for both endcaps
- Modules belonging to the same group characterised by similar values of leakage current





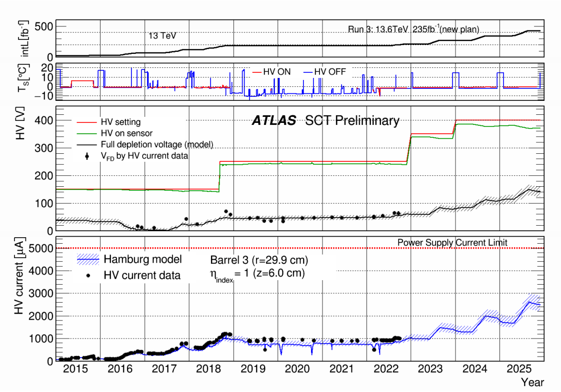
Evolution of leakage currents

- Measured leakage current values agree well with model predictions
  - Data are typically within 1σ systematic uncertainty



Barrel 3 predictions

- Measured V_{FD} agrees well with model prediction and continues to increase since type inversion in 2016 but **should not exceed 180 V**
- In order to ensure high efficiency we **plan to raise the HV twice** (to 350 and 400 V)
- Leakage current is expected to be well **below power supply limit** still at the end of Run 3



Summary and conclusions

- SCT had an **excellent start of Run 3**
- The detector is still in good shape with 98.3% strips still active
- 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
  - Looking at model predictions we are confident that **SCT will work stably and efficiently until the end of Run 3**

Backup slides

Effect of missing barrel layers (unlikely!)

- Studied effect of missing barrel layers on tracking as a result of radiation damage
  - Barrel 3 highly irradiated, barrel 6 kept at higher temperature due to TRT detector

- The drop in number of tracks **can be recovered** by loosening a requirement on number of silicon hits
  - However, at a price of introducing **more fake tracks**