Evaluation of charge collection efficiency of strip-type silicon sensors

Shigeki Hirose (U. Tsukuba)

S. Kita (U. Tsukuba), M. Bomben (CNRS/IN2P3),

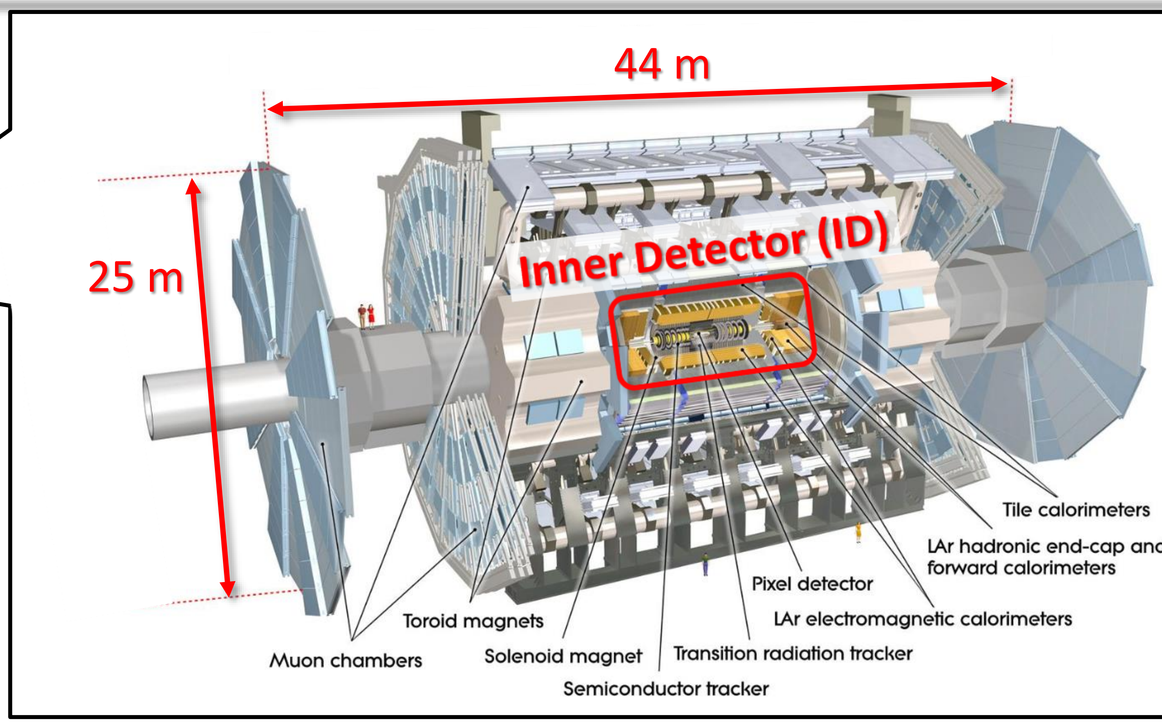
H. Otono (Kyushu U.), S. Shirabe (Kyushu U.), M. Togawa (KEK)

23 May 2024

2024 Joint Workshop of FKPPN and TYL/FJPPN

ATLAS Experiment at LHC

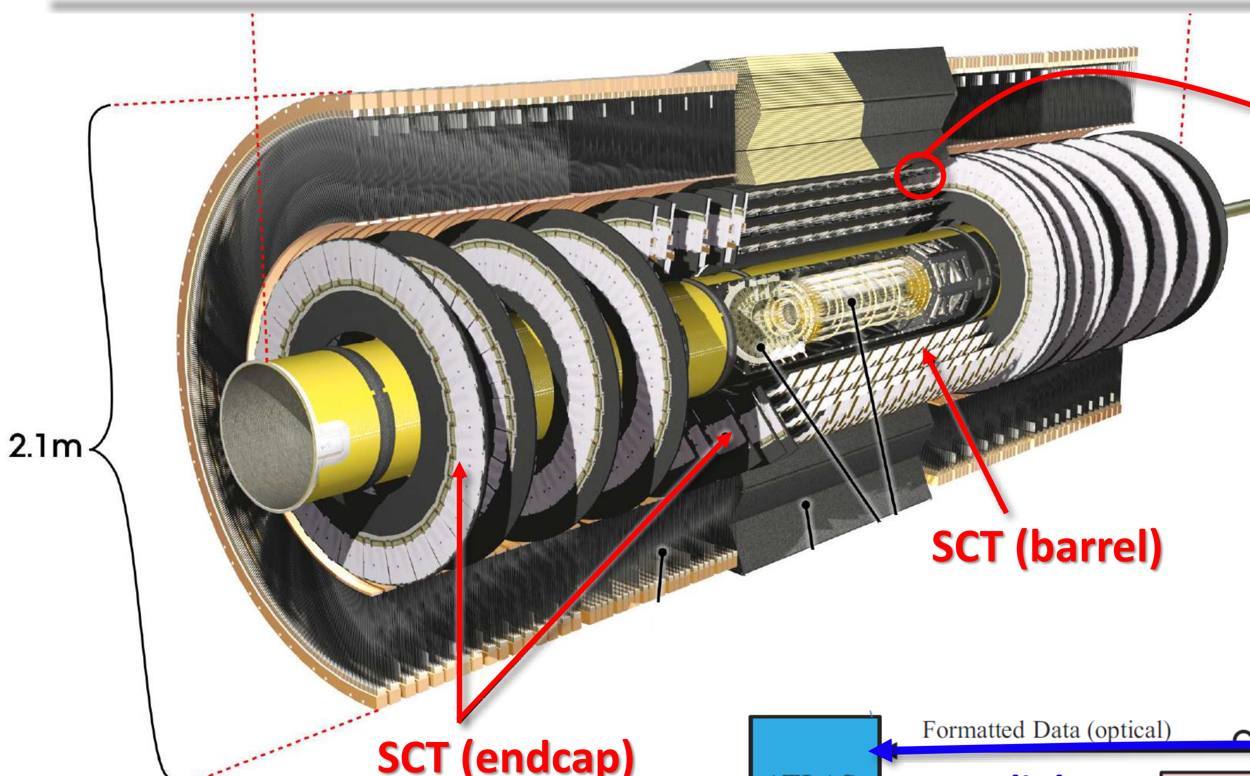
- Circumference = 27 km
- pp collision at $\sqrt{s}$ = 13.6 TeV
- Bunch per 25 ns

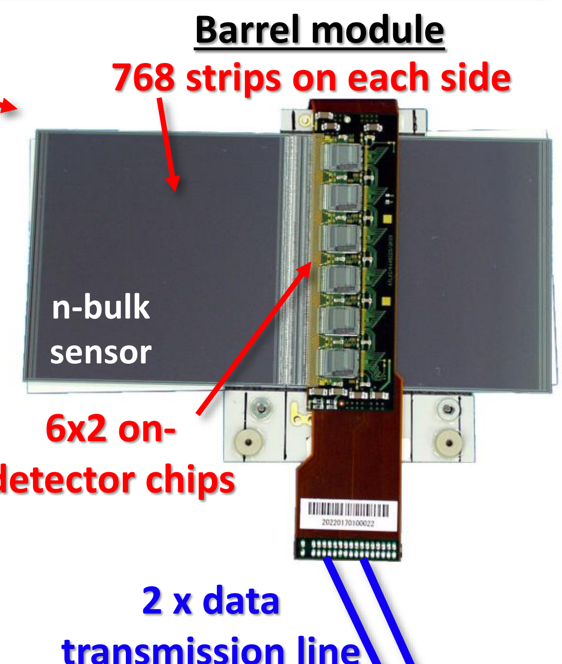


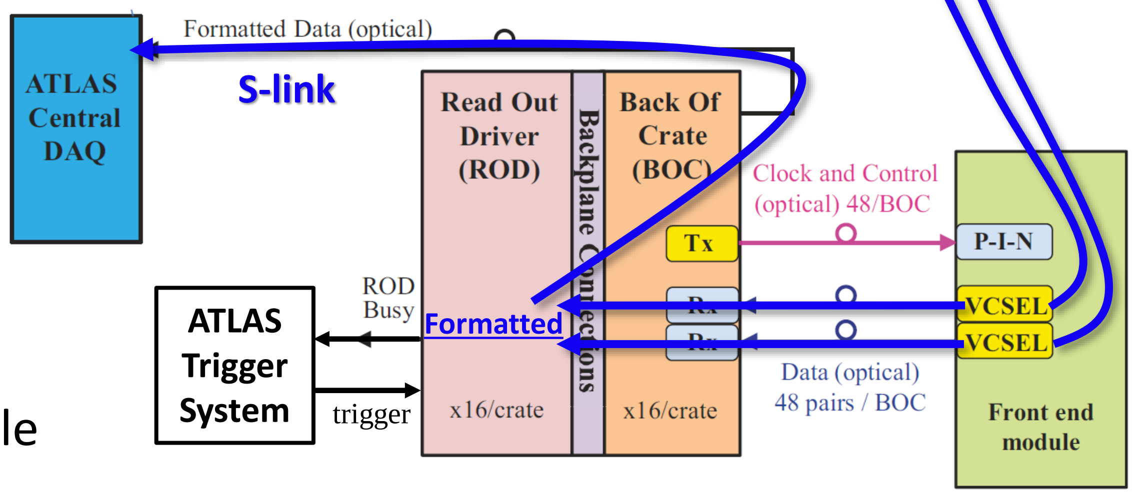
- ATLAS detector
  - Targets high-p_{T} objects from decays of massive particles
  - Messy environment of pp collisions due to QCD

    → Track finding performance of ID is essential for all physics analyses
- Semiconductor Tracker (SCT): one component of ID

■ SemiConductor Tracker (SCT)







- 4 layers (barrel) and 9×2 disks (endcaps)
- > 6M channels
  - Only binary readout; stable system is important

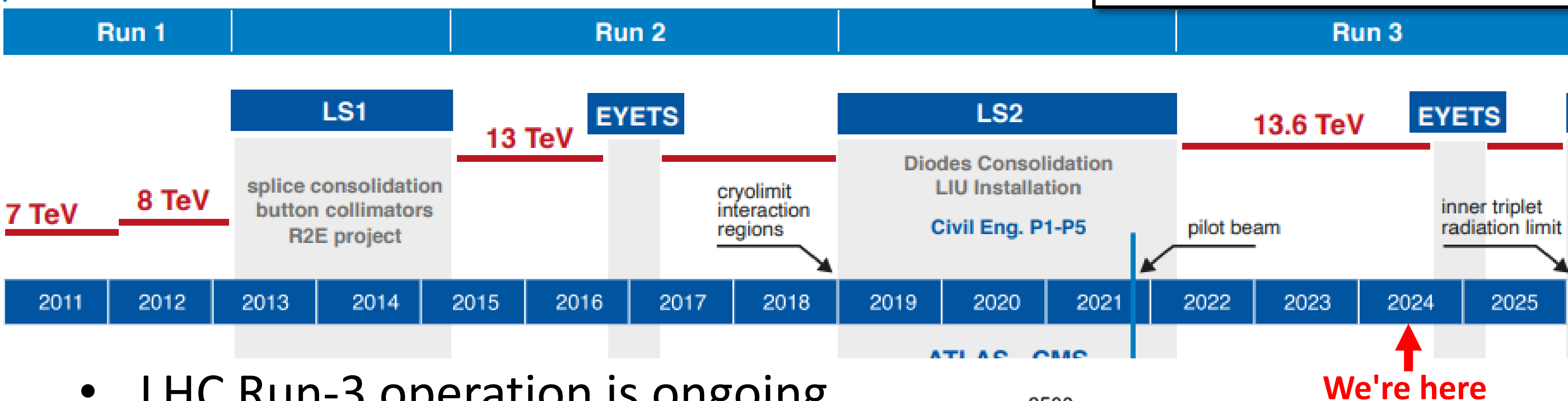
■ Operation of SCT

- SCT has been operated throughout data-taking

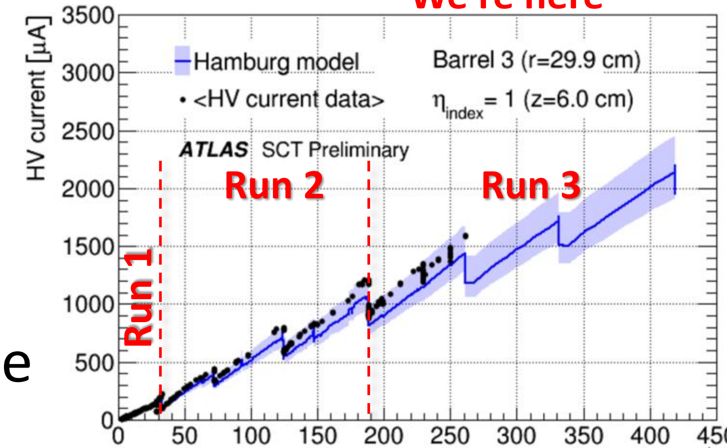
Run 1
L_{peak} = 8 × 10^{33} /cm^2/s (max)
$\int L$ = 26.4 fb^{-1} (7 or 8 TeV)

Run 2
L_{peak} = 21 × 10^{33} /cm^2/s (max)
$\int L$ = 147 fb^{-1} (13 TeV)

Run 3
L_{peak} = 21 × 10^{33} /cm^2/s (max)
$\int L$ = 82 fb^{-1} (13.6 TeV)
(As of 20 May)

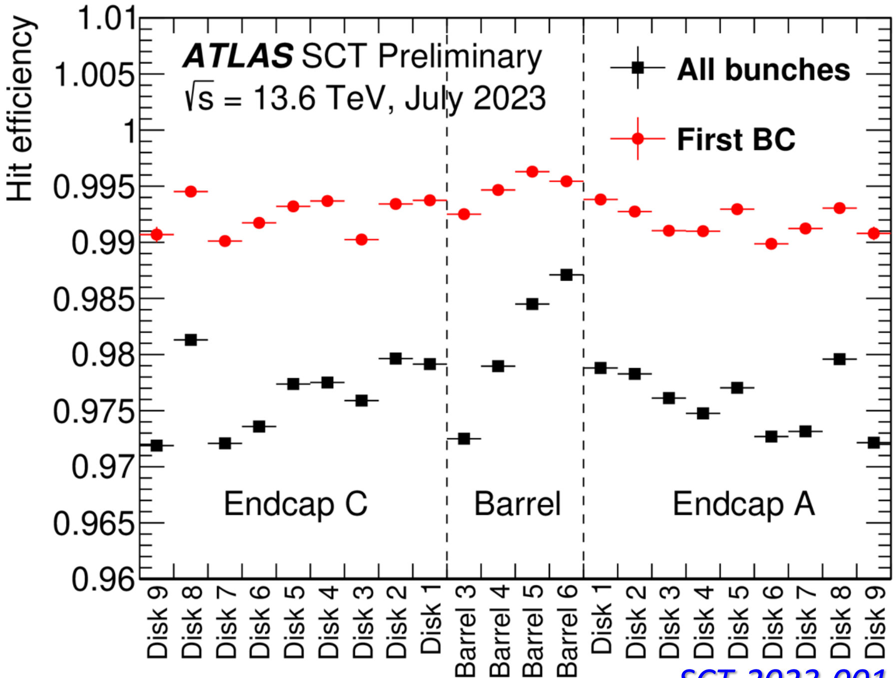


- LHC Run-3 operation is ongoing
  - Accumulation of radiation damage is significant; leakage current on the inner most layer reaches ~2 mA/module (design: up to 5 mA/module)
- Understanding of the radiation damage is key for safe operation until 2025

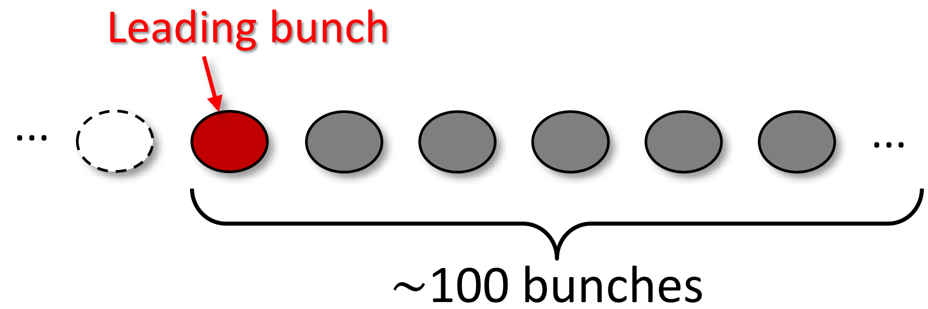


SCT-2023-002

■ Performance in Run 3



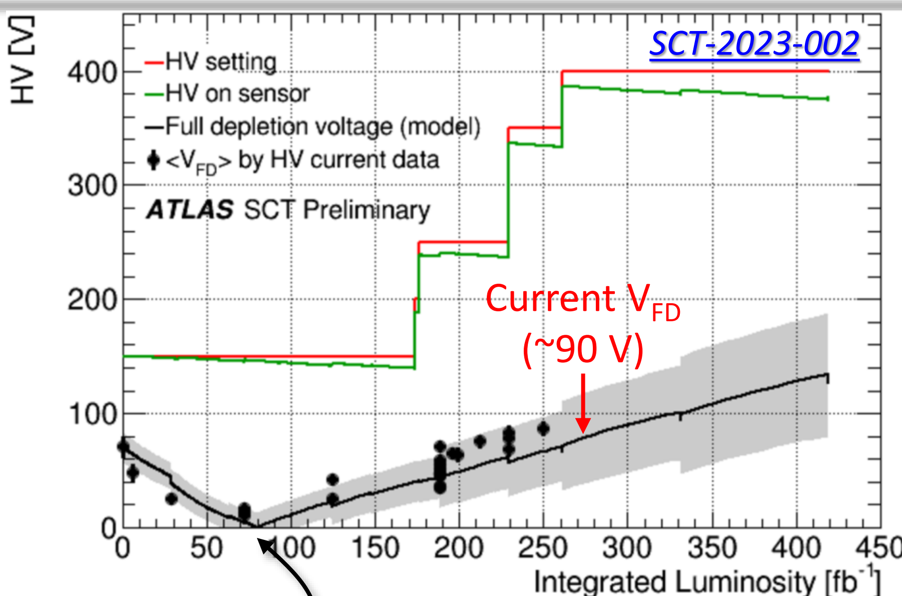
SCT-2023-001

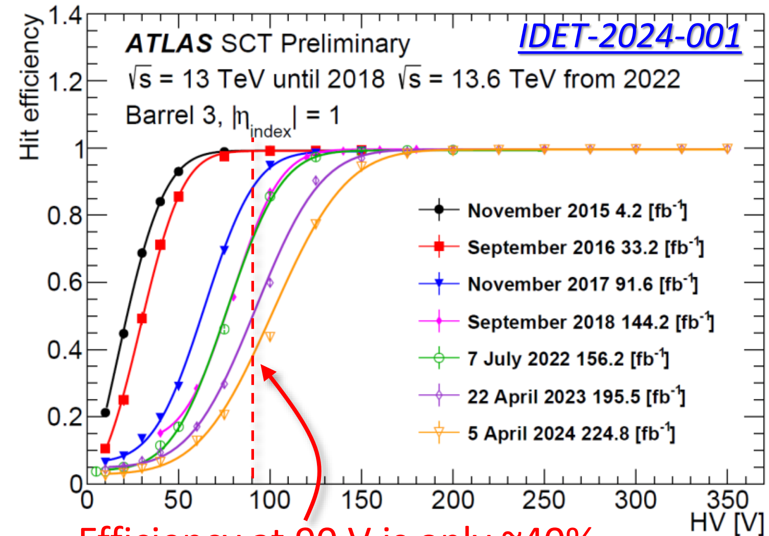


"No hit in the previous bunch" is required
→ Overall efficiency loss around 1%
(negligible impact for tracking)

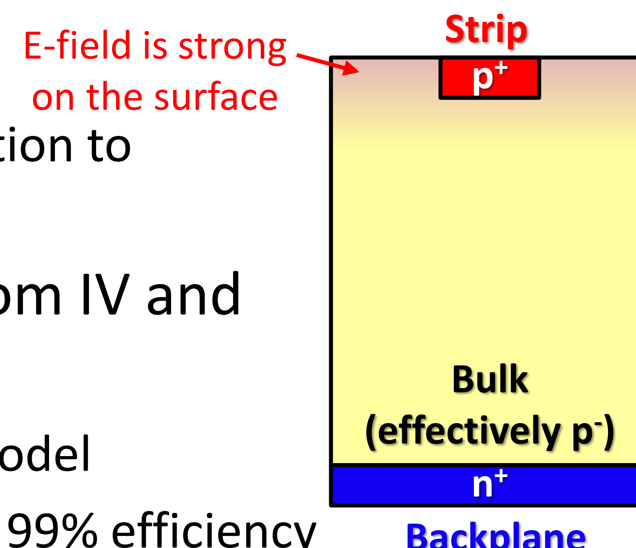
- Stable system has been already established in Run 2
  - 98% of the elements are active
  - Slight increase of problems in the backend electronics (no impact on data quality so far)
  - Intrinsic efficiency of > 99% is still maintained in Run 3; however we significantly increased the operation HV

■ Full depletion voltage



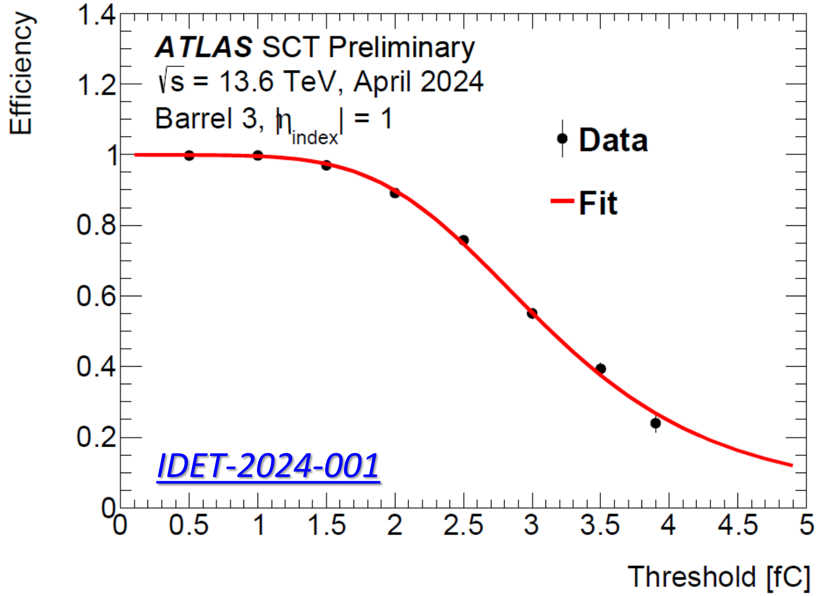


- Type inversion observed around 2017
  - pn junction on the rear side; need full depletion to efficiently collect charge
- Full depletion voltage (V_{FD}) estimated from IV and efficiency vs HV
  - V_{FD} from IV well agrees with the Hamburg model
  - However, need much higher HV required for 99% efficiency



Good to understand the current charge collection efficiency (CCE)

Charge collection efficiency



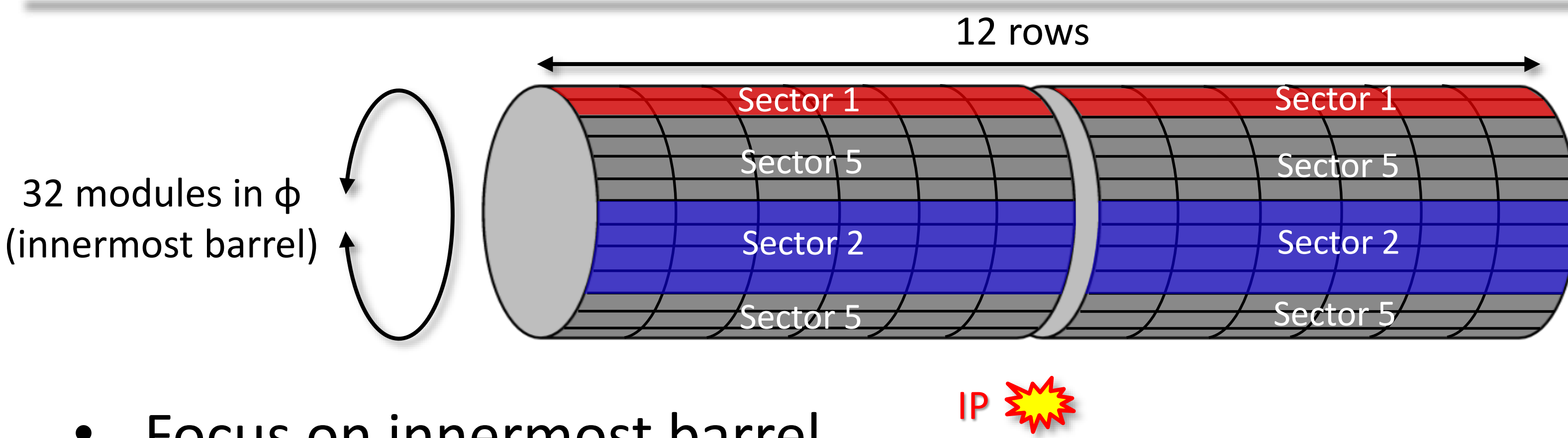
$$\epsilon(q) = p_1[1 - \mathrm{erf}(Tf(T))]$$

$$\begin{cases} f(T) = 1 + 0.6\tanh(-p_2 T) \\ T = \dfrac{(q - p_3)}{\sqrt{2}p_4} \end{cases}$$

p_i (i = 1, 2, 3, 4) are parameters determined by fit

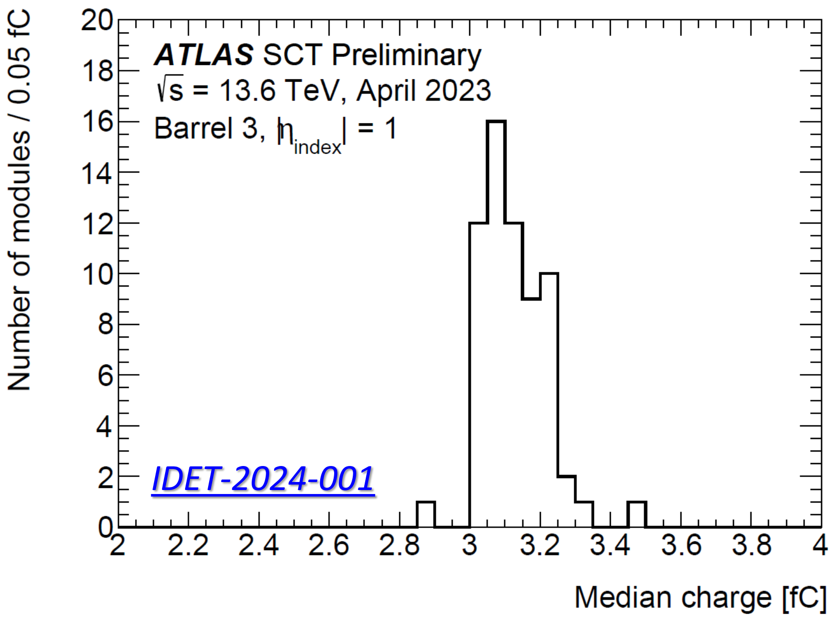
- SCT uses binary readout, so we cannot directly measure CCE
- However, median charge can be extracted by threshold scan
  - Perform a 'skewed' error function to account for the Landau distribution of charge
  - Median charge = threshold for 50% efficiency

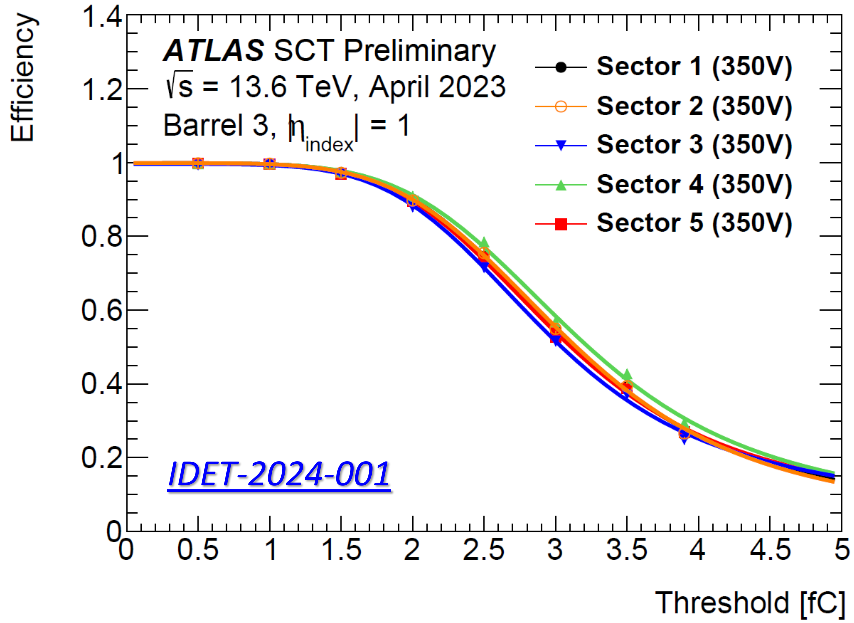
Strategy of the measurement



- Focus on innermost barrel
  - Most significant radiation damage: expected to be 6.4×10^{13} n_{eq}/cm^2
  - Select modules on the inner two rows closest to the IP; charged particles pass through in perpendicular to the sensor
    → There are $32 \times 2 = 64$ modules usable
- Impossible to perform (threshold × HV) scan
  - Too time consuming → Too large impact on physics data quality
- Divide the modules into 'octants' and set different HV
  - **ϕ dependence of radiation damage is small**
  - Four octants have different HV (Sectors 1-4)
  - Rest of octants have the operational HV: 350 V

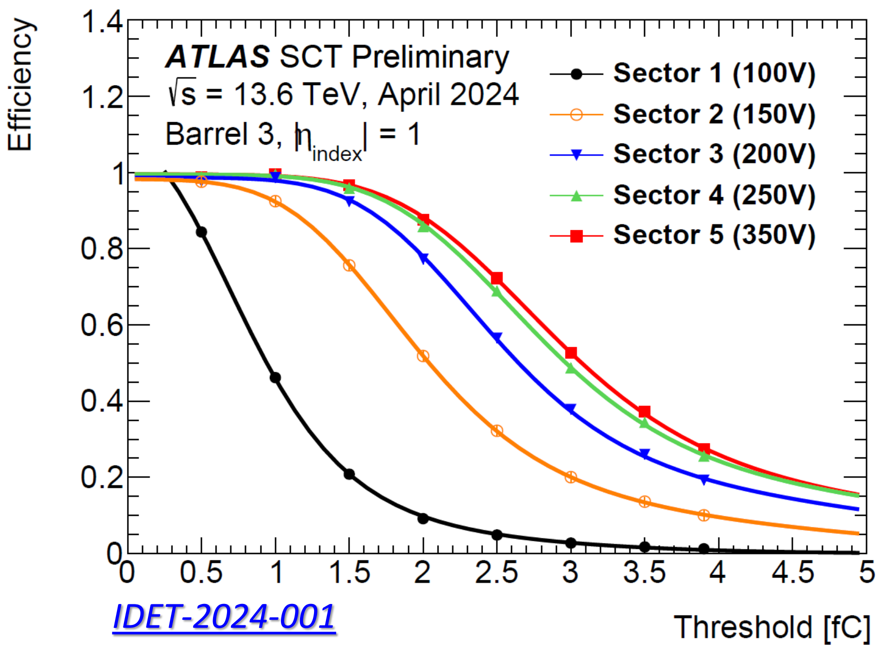
■ Validation of the strategy

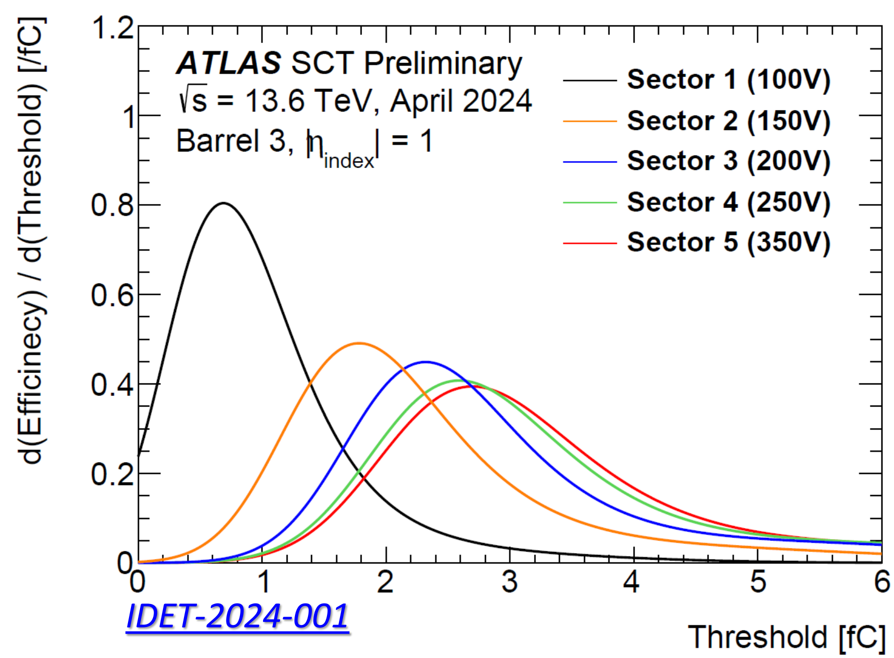




- Validation performed using the previous threshold scan data
  - All modules set at 350 V; consistent results are expected for all sectors
- Module-by-module measurement
  - Variation is ~3% s.d.; sufficiently small
  - Two outliers → Their impact is marginal once averaged by 8 modules
- Results from all the five sectors are very consistent!

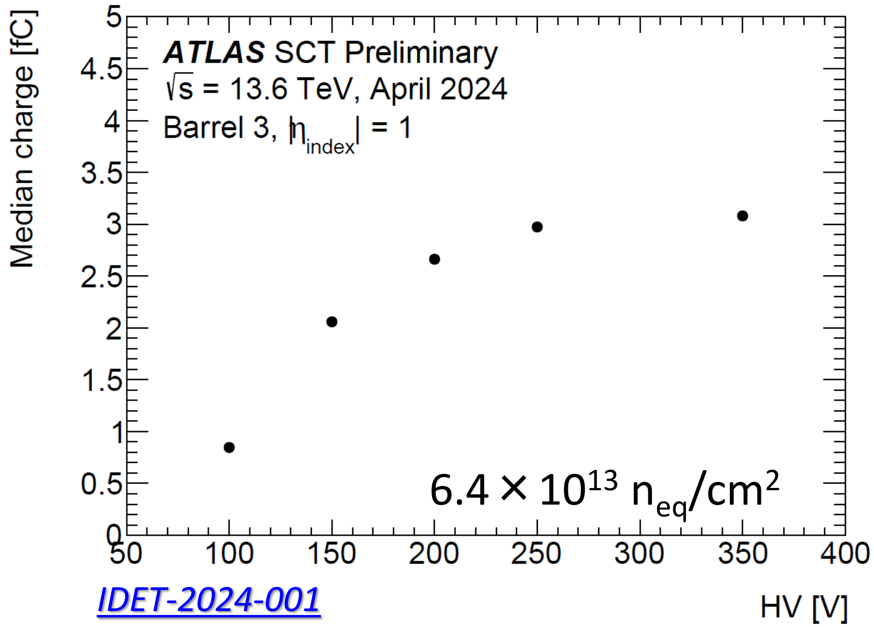
■ Threshold scan with different HV



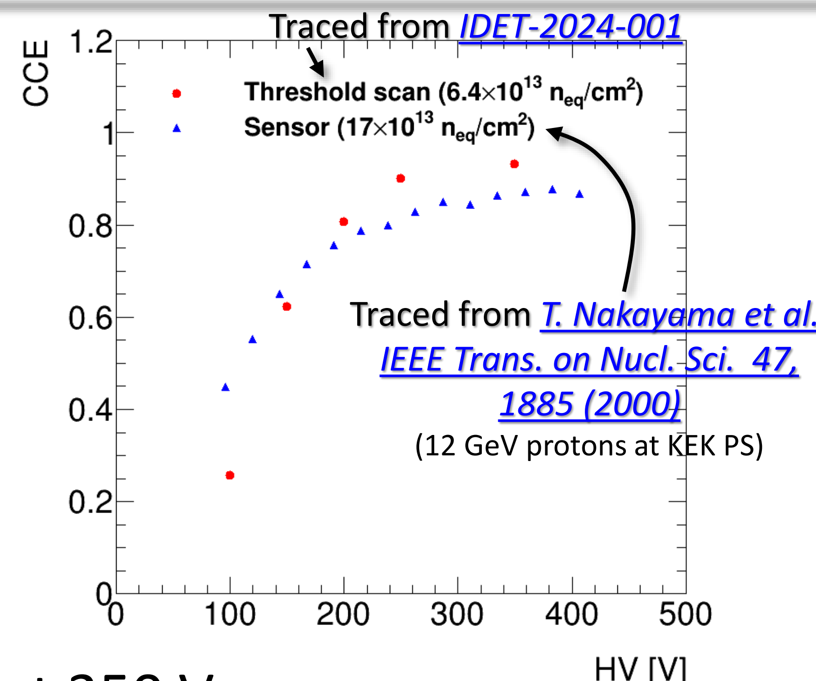


- Performed HV scan with different HV setting in April 2024
  - Set five HV points: 100 V, 150 V, 200 V, 250 V, 350 V (operation HV)
- Measurement successful
  - Derivatives of the fitted functions provide good estimate of the charge distribution
    → First time that we measured charge distribution of significantly irradiated sensors in the actual SCT detector!

■ CCE vs HV

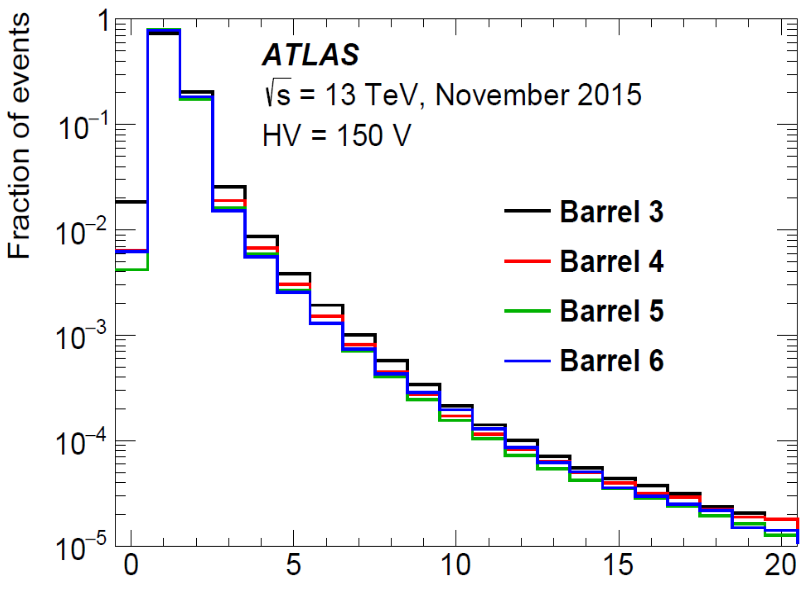


IDET-2024-001

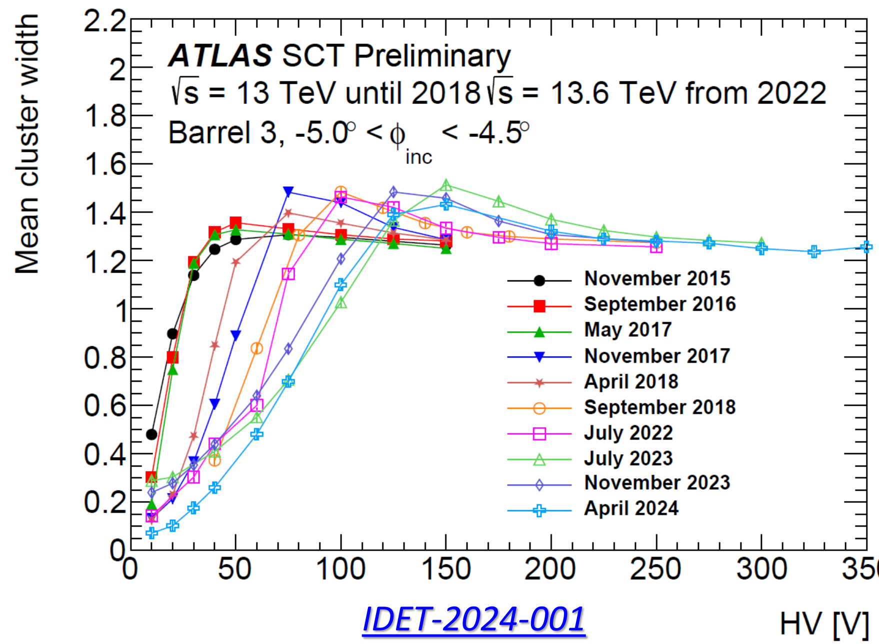


- The plateau of the CCE is ∼3 fC at 350 V
  - SCT sensor is 285-μm thick; 3.3 fC is expected without irradiation → CCE ∼90%
- Comparison with results from irradiated sensors
  - The CCE at plateau looks reasonable, but our result is significantly lower at low HV → Need further investigation
  - N.B. charge leakage to the neibouring strips may affect the CCE estimates

■ Further studies: cluster size



ATLAS, JINST 17 (2022) P01013

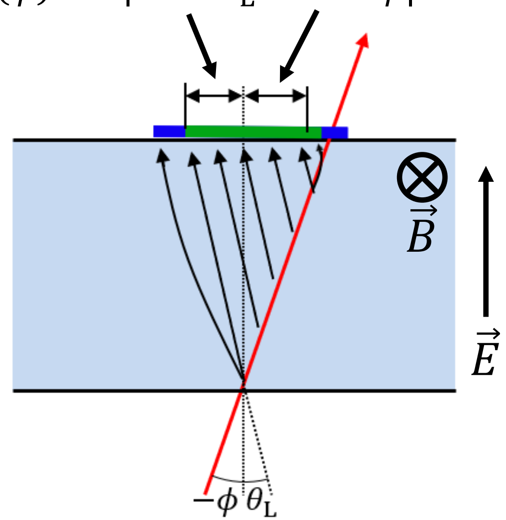


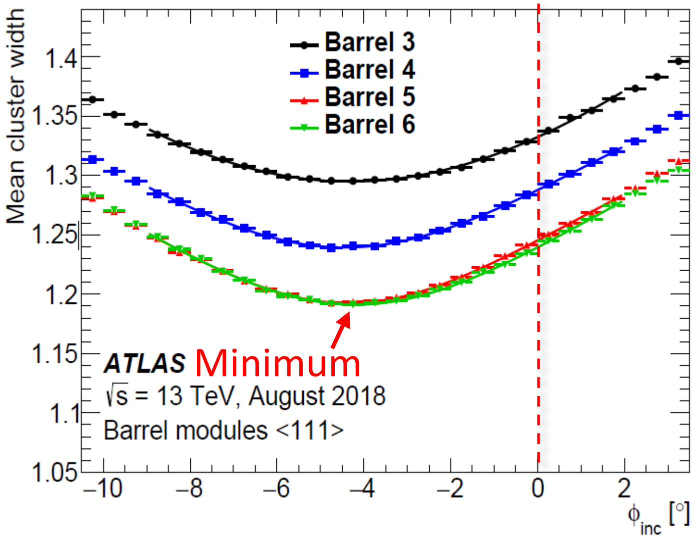
IDET-2024-001

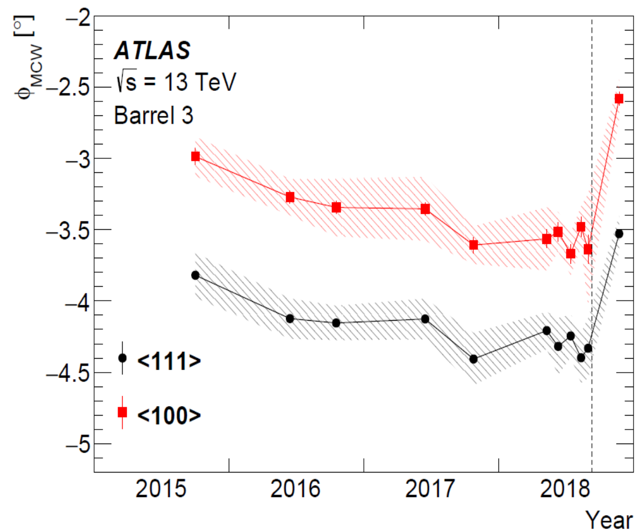
- Cluster size is also a parameter reflecting the collected charge
  - Cluster = consecutive strips with a hit induced by a charged particle
  - Cluster size is typically 1, but can be ≥ 2 with ~30% of the time
- HV dependence
  - A 'bump' appeared after type inversion
  - Maybe due to E-field shape near the surface, but exact reason not yet understood

■ Lorentz angle

$$f(\phi) = a|L\tan\theta_{\mathrm{L}} - L\tan\phi| \times G$$







ATLAS, JINST 17 (2022) P01013

- Charge motion is affected by the solenoid field
  - Charge is collected at the slightly deviated position
    → Incident angle (ϕ_{inc}) corresponding to the minimum cluster size is significantly shifted from 0°
- Lorentz angle is affected by internal E-field
  - Reflects distortion in the E-field due to radiation damage
  - It is also affected by change of the operation HV

Summary

- SCT is operated since the beginning of LHC operation
  - Established stable DAQ system which can handle 2x higher luminosity than its original design
  - SCT is now under Run 3 operation while significantly irradiated

    → Stable operation required until the end of 2025 with understanding the irradiated detector
- Various studies are possible
  - Successfully measured CCE of the SCT for the first time using the radiation-damaged real SCT detector
  - Other key performance such as efficiency, cluster size, ...

Japan (H. Otono, S. Hirose et al.,)
- Silicon detector operation
- Silicon sensor R&D

France Team (M. Bomben et al.,)
- Silicon sensor simulation

Obtain knowledge from the 'real' detector
- Improve radiation models
- Extract useful information at the LHC environment towards HL-LHC