Performance study on radiation-damaged silicon sensors at LHC using TCAD simulation

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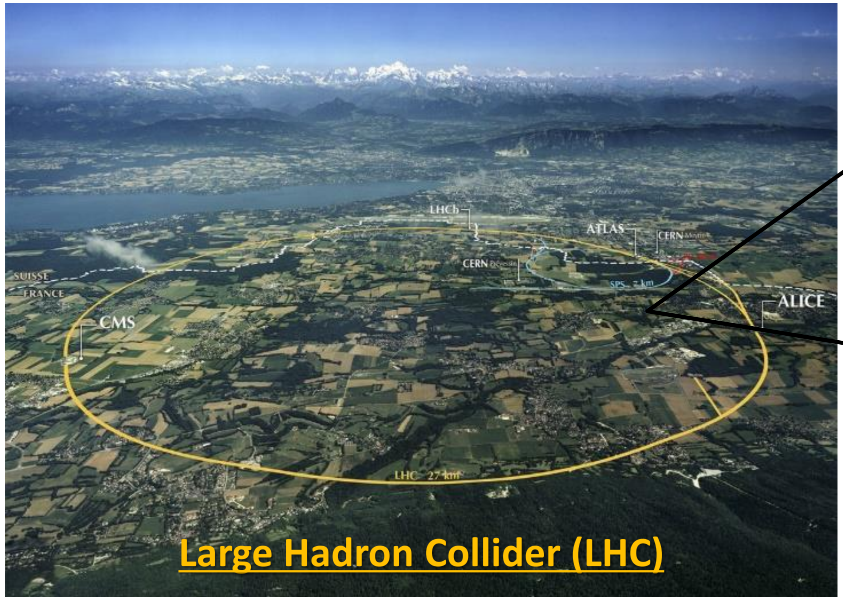
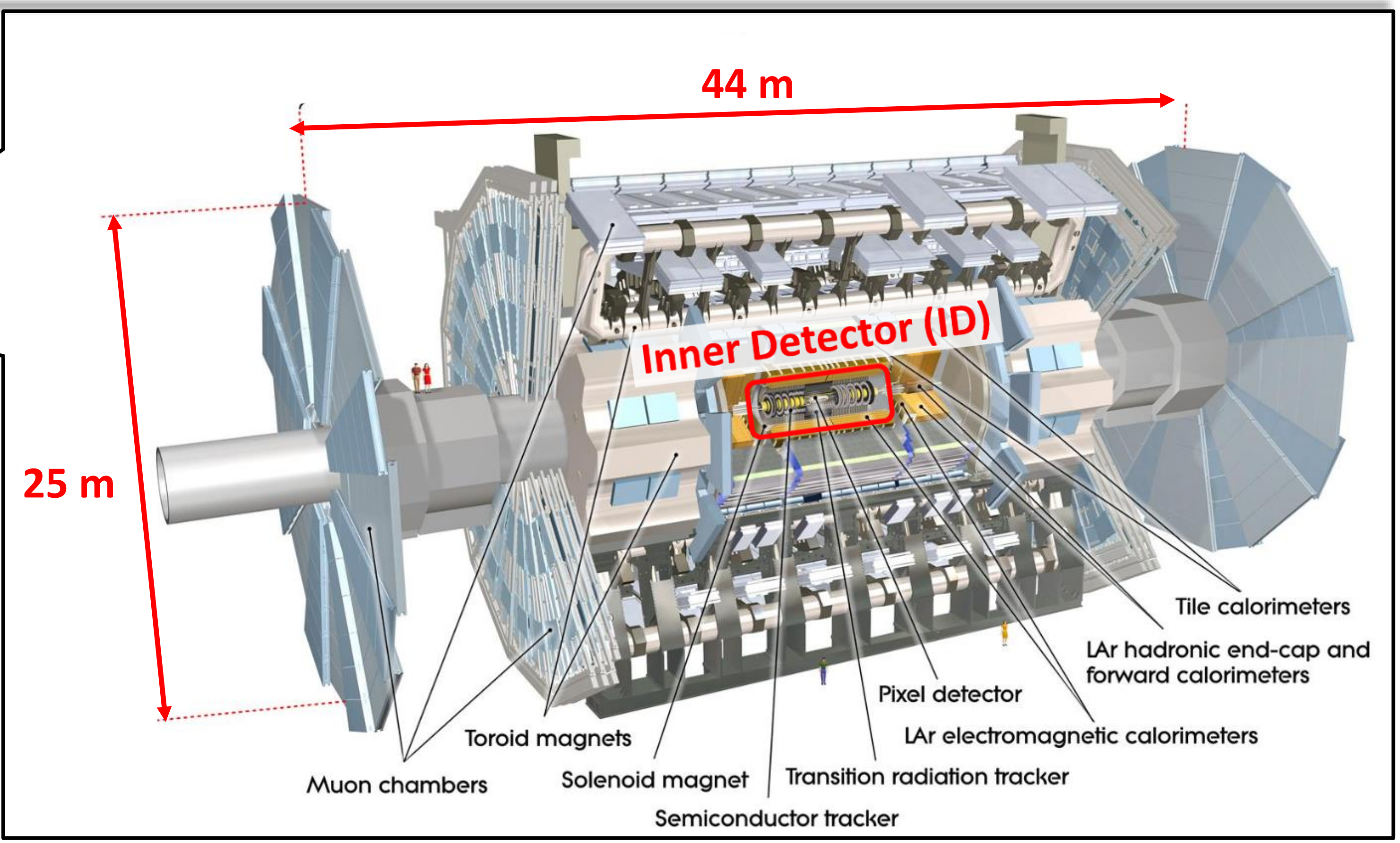
2025 Joint Workshop of FKPPN and TYL/FJPPN

■ ATLAS Experiment at LHC



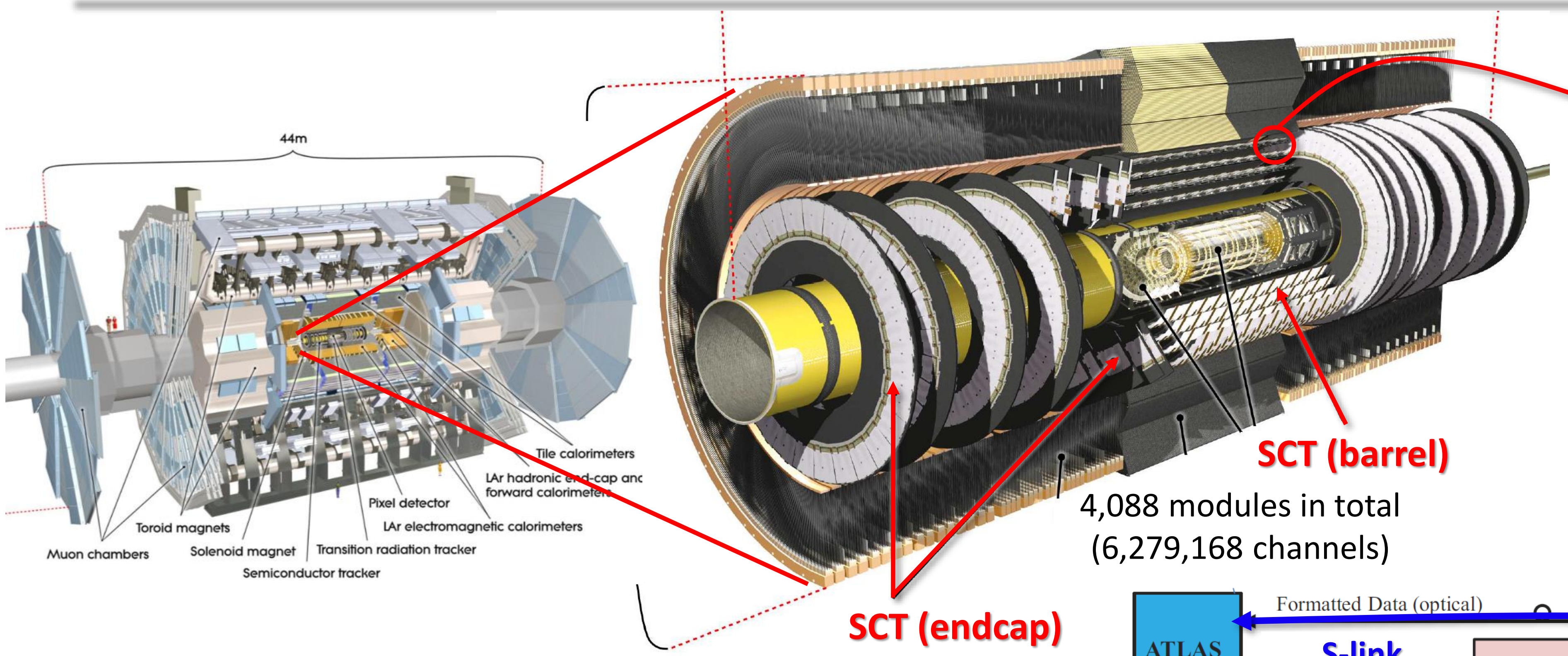


- Circumference = 27 km
- pp collision at $\sqrt{s}$ = 13.6 TeV
- Bunch per 25 ns

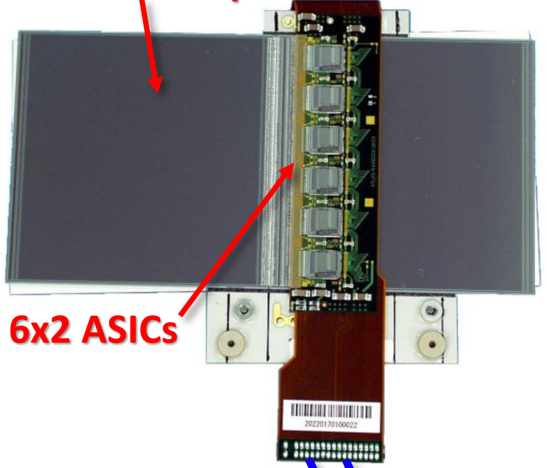
- ATLAS detector
  - Targets high-p_{T} objects from decays of massive particles
  - Harsh environment of pp collisions due to QCD interactions

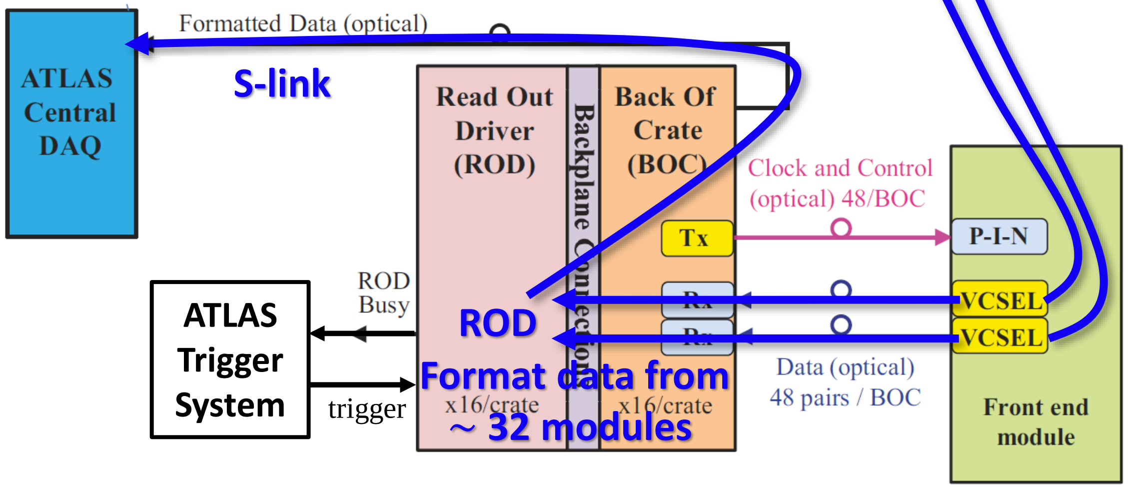
    → Track finding performance of ID is essential for all physics analyses
- Semiconductor Tracker (SCT): one of the three sub-detectors in the ID

SemiConductor Tracker (SCT)



4,088 modules in total
(6,279,168 channels)





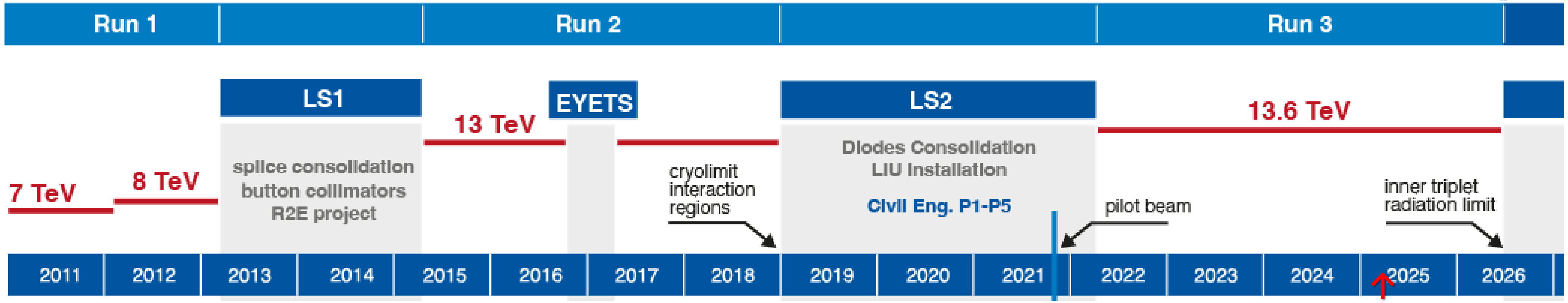
- 4 layers (barrel) + 9x2 disks (endcap)
- Covers the large volume
  - Essential in terms of p_T resolution
- Uses binary readout; only 0 (no hit) or 1 (with hit) can be read out

JINST 9 P08009 (2014)

■ SCT operation

- SCT has been operated throughout the ATLAS data-taking periods

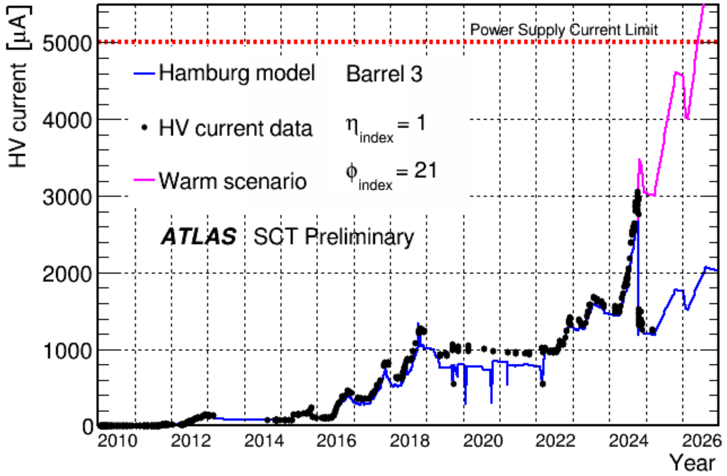
Run 1	Run 2	Run 3
L_{peak} = 8 × 10^{33} /cm²/s (max)	L_{peak} = 21 × 10^{33} /cm²/s (max)	L_{peak} = 21 × 10^{33} /cm²/s (max)
$\int L$ = 26.4 fb^{-1} (7 or 8 TeV)	$\int L$ = 147 fb^{-1} (13 TeV)	$\int L$ = 195 fb^{-1} (13.6 TeV)
		(As of 2025)



We're here

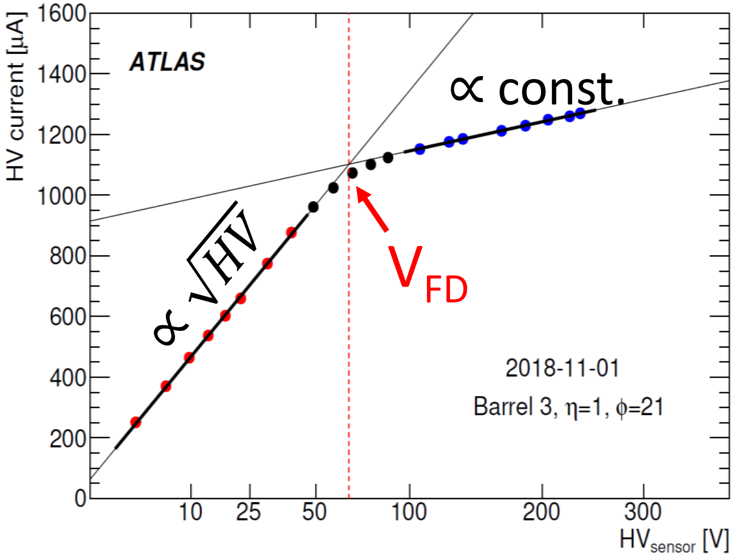
SCTD-2025-01

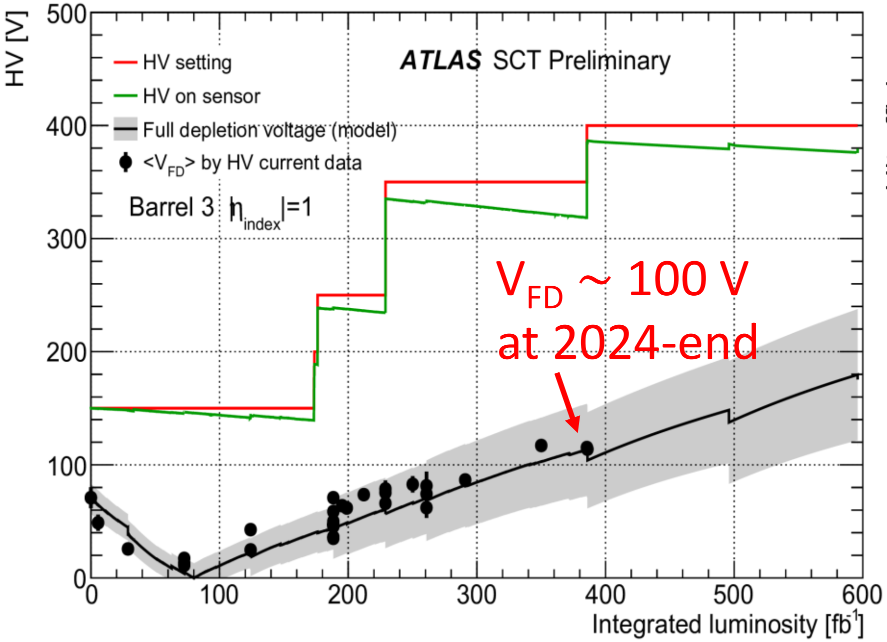
- LHC Run-3 operation is ongoing
  - Accumulation of radiation damage is significant; leakage current on the innermost layer reaches ~3 mA/module (design: up to 5 mA/module)
- SCT provides an interesting dataset as a large silicon detector irradiated at LHC for ~ 15 years!

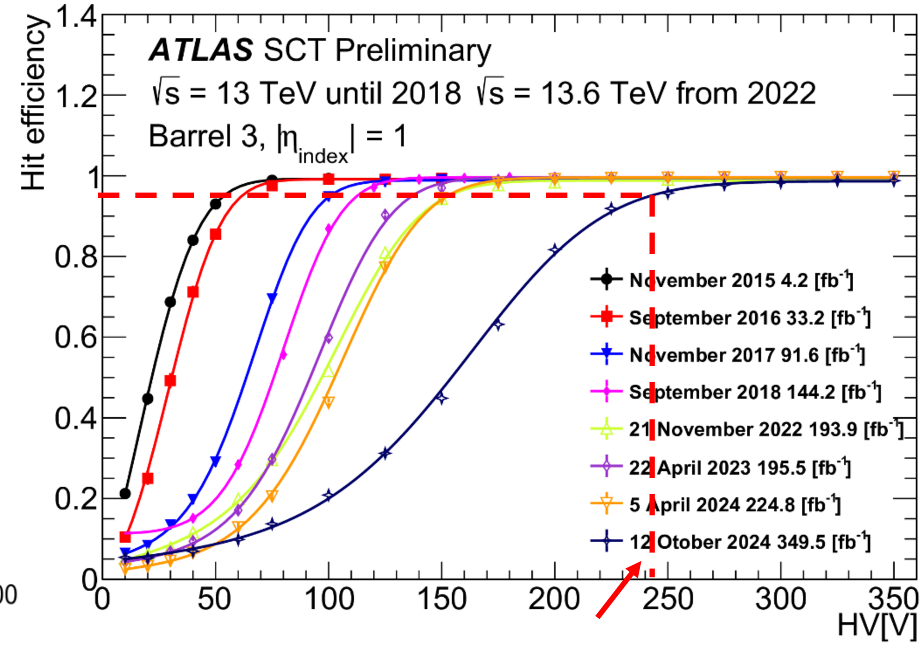


■ Overview of SCT performance today

SCT-2024-002





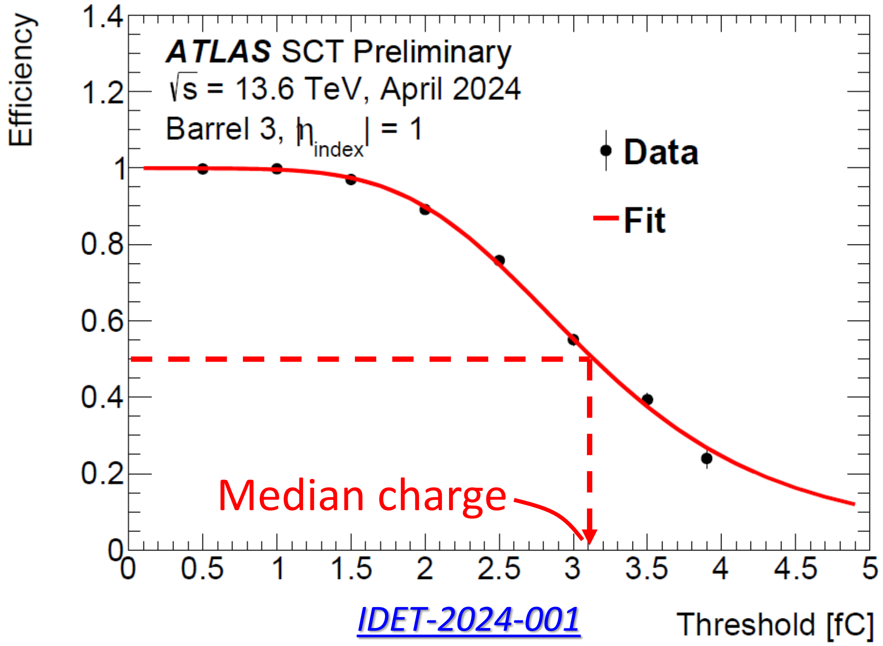


$V_{95\%}$ ~ 240 V at 2024-end

- SCT uses silicon sensors with n-type bulk
  - Type inversion to p-type is expected after irradiation of $\sim 2\times10^{13}$ n_{eq}/cm^2 due to increase of effective acceptor-like states → It was observed in around 2017
- After type inversion, higher bias voltage is required for full efficiency
  - Full bulk depletion ≠ Full efficiency anymore
    → Large difference between V_{FD} from IV (~ 100 V) and $V_{95\%}$ (~ 240 V)

Important to understand the difference in terms of the charge collection efficiency (CCE)

■ CCE measurement using a binary readout



IDET-2024-001

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

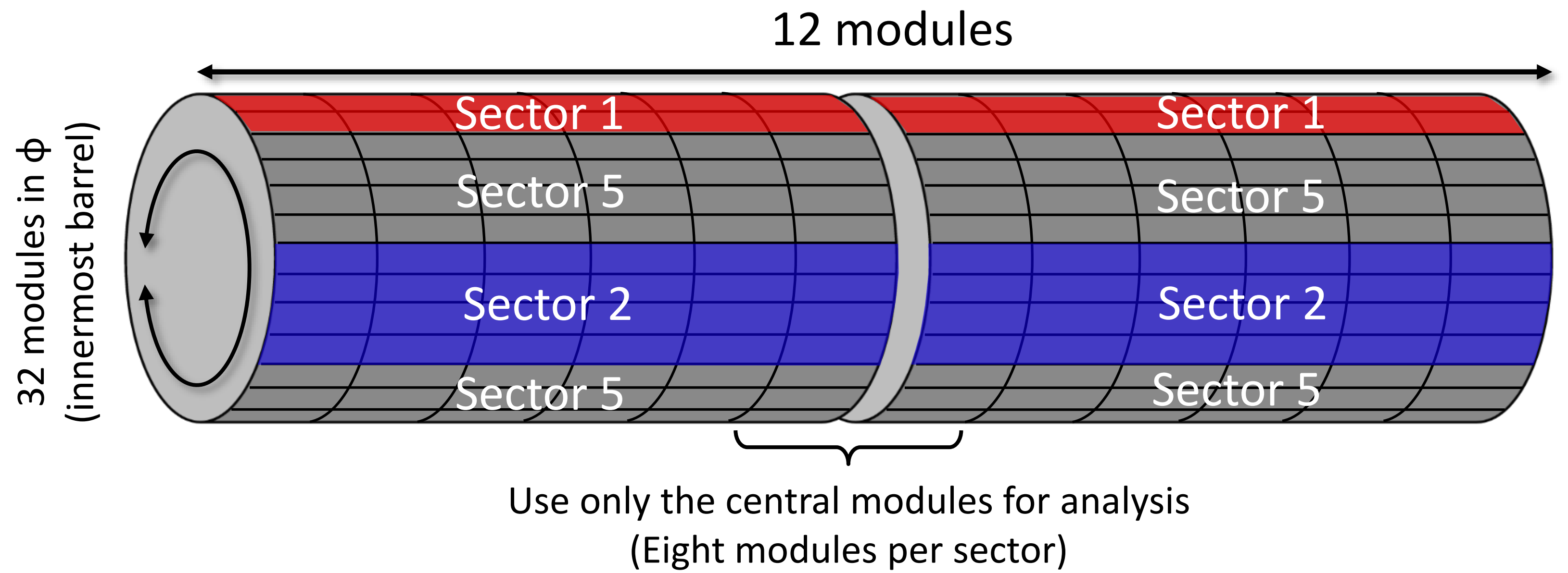
$$\begin{cases} f(T) = 1 + 0.6\tanh(-p_2 T) \\ T = \dfrac{(q - p_3)}{\sqrt{2}p_4} \end{cases}$$

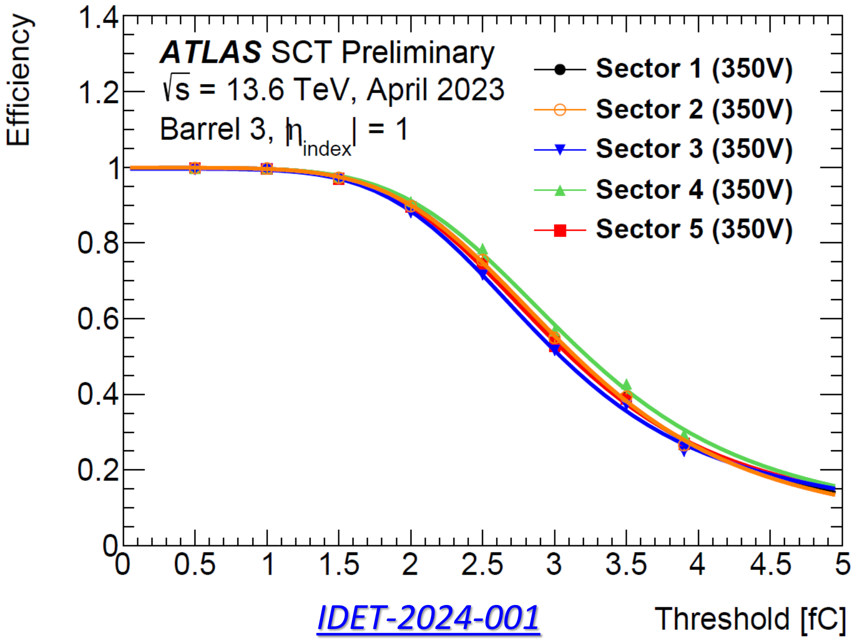
p_i (i = 1, 2, 3, 4) are parameters determined by fit

Y. Unno et al., IEEE Trans. on Nucl. Sci. 49, 1868 (2002)

- SCT uses binary readout, so we cannot directly measure CCE
  - No direct charge measurement such as Time-over-Threshold
- Median charge can be extracted from threshold scan data
  - Median charge = threshold for 50% efficiency
- Took ~ 30 mins. to complete one set of scans
  - Since a threshold scan needs to be done during pp data-taking, only a few scans per year possible to minimise impacts on physics data

Idea for CCE vs HV measurement

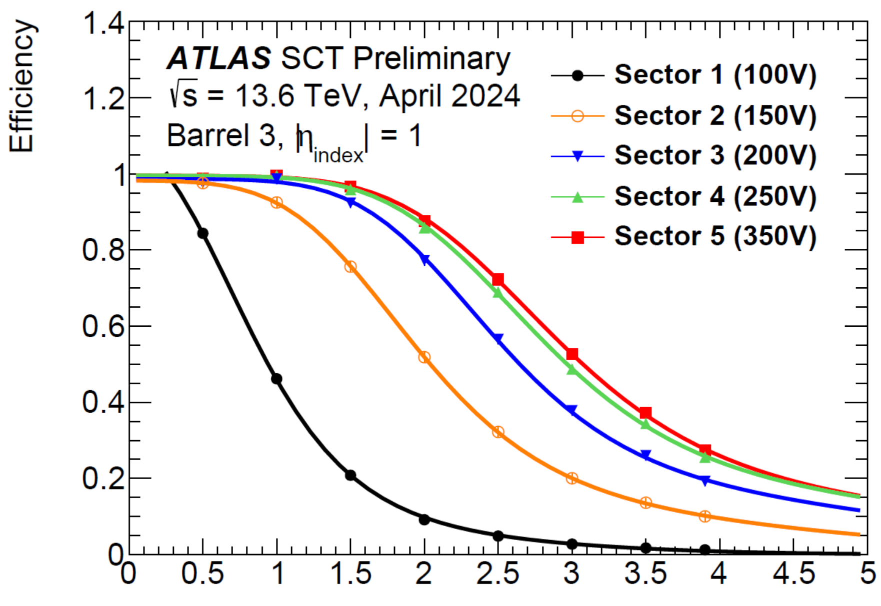




IDET-2024-001

- Radiation damage is uniform for ϕ direction
  - Divide the modules into 'octants' and set different bias voltages
    → CCE can be measured at different bias voltages in a single threshold scan!
  - Decided to keep Sector 5 (half of the modules) to be the nominal voltage so that this region can be used for the regular performance monitoring
- As a validation, compared the response curves with the operational voltage
  - the observed variation is < 10% → Good uniformity

CCE results



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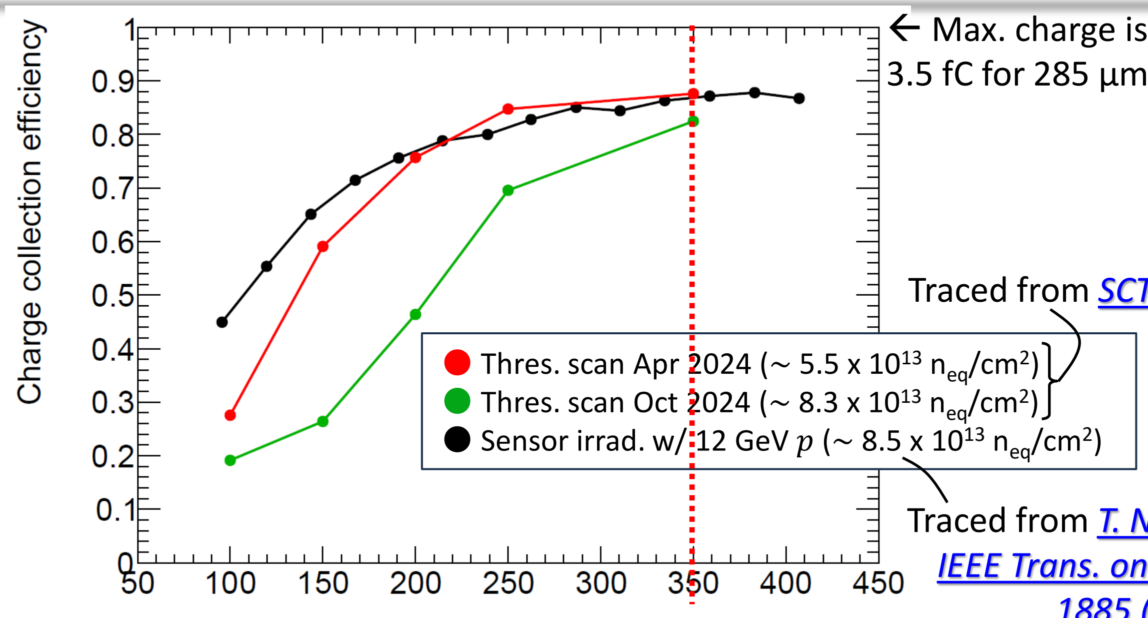


← Max. charge is assumed to be 3.5 fC for 285 μm thick sensor

Traced from SCT-2024-002

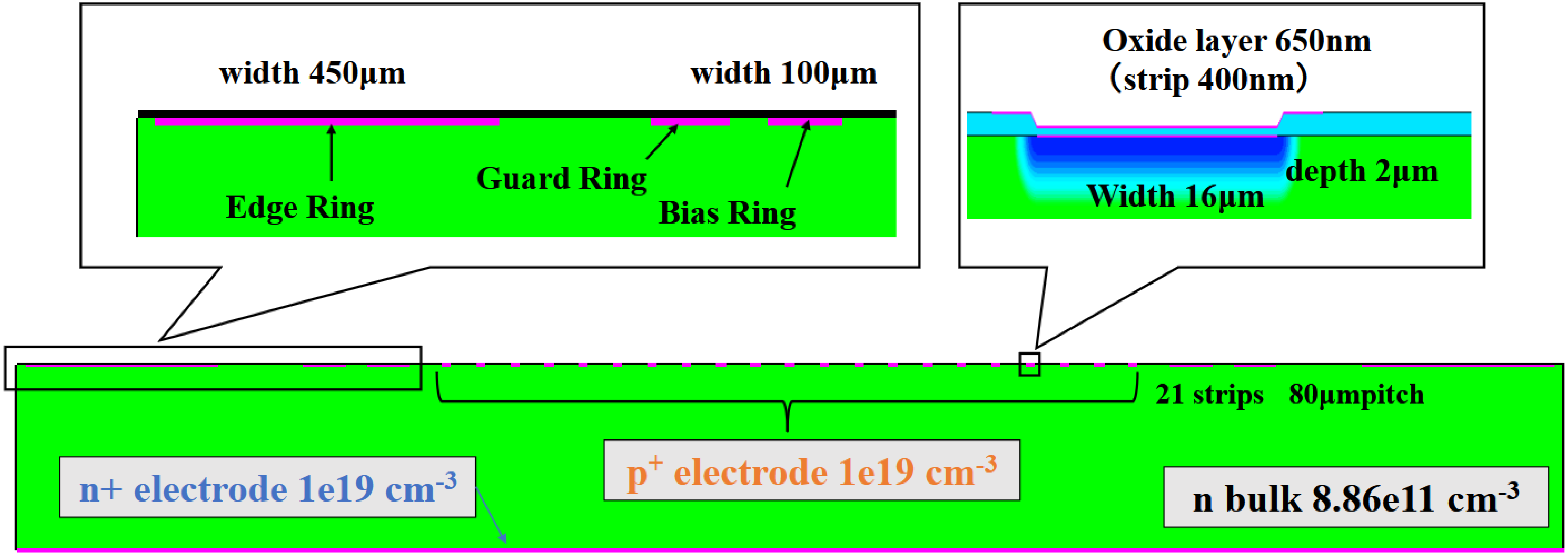
Traced from T. Nakayama et al., IEEE Trans. on Nucl. Sci. 47, 1885 (2000)

- Successfully measured the CCE vs bias voltage in April and October 2024
  - Set the bias to be 100 V, 150 V, 200 V, 250 V and 350 V
- Clear decrease between April and October is observed
  - CCE in October looks much lower than original expectation from sensor irradiation tests
    - N.B. need to consider annealing effects; new dataset after annealing during EYETS will be taken soon
- Important to understand the difference between sensor tests and real SCT
  - CCE is the most important quantity for efficiency

■ TCAD study for SCT

- To understand the CCE in the viewpoint of charge transport, TCAD is a useful tool
- Design of a 2D model for SCT sensors
  - Senser parameters are taken from SCT sensor paper: Nucl. Instrum. and Meth. A 578 (2007) 98

H. Suzuki, JPS Spring 2023



- Radiation damage needs to be parametrised (next page)

■ Radiation damage model for SCT sensors

H. Suzuki, JPS Spring 2023

- A simplified radiation model was considered based on R. Eber, PhD thesis, KIT (2013)
  - Start with the two damage states: one deep-acceptor state and one deep-donor state

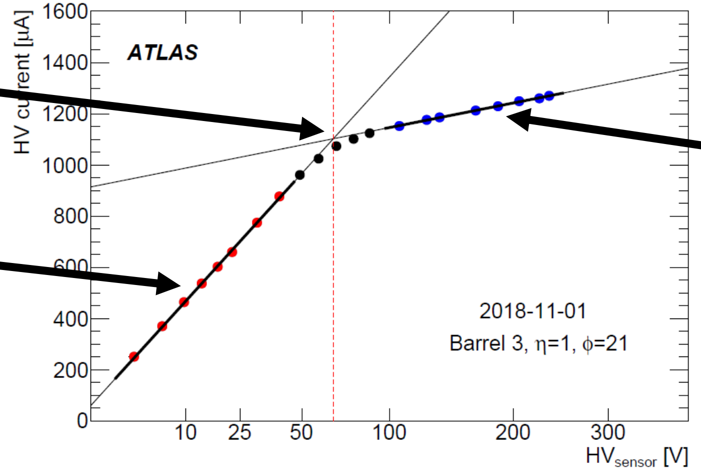
Defect type	Energy level [eV]	Carrier trapping xsec [cm^{-2}]	Defect concentration
Deep acceptor	$E_C - 0.525$	σ	$\phi \times \alpha$
Deep donor	$E_V + 0.48$	σ	$\phi \times \alpha \times r$

  - Three parameters to optimise
    - σ: carrier trapping cross-section (common for deep acceptor and deep donor)
    - α: damage introduction rate for deep acceptors
    - r: ratio of the introduction rate for the deep acceptors to the deep donors
  - First attempt was very phenomenological: use IV to determine these three parameters

Full depletion voltage is sensitive to $\alpha(1-r)$

I-$\sqrt{V}$ slope is sensitive to r

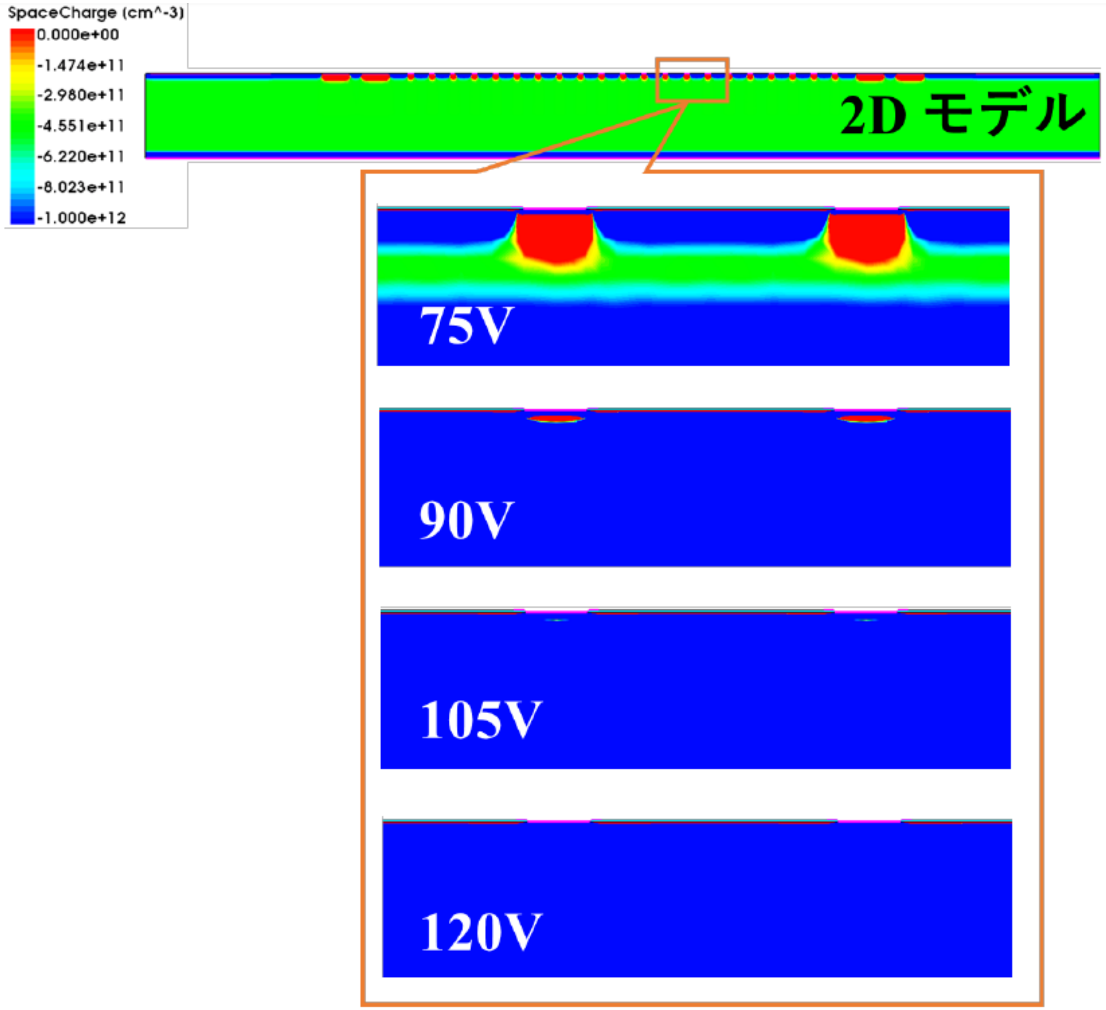
Not yet fully understood;
our observations in the next page



Absolute value of the leakage current after full depletion is controlled by all parameters

Difference of radiation damage from neutrons and charged hadrons are absorbed in these parameters

■ Results from the current SCT model



N.B. the assumption of radiation fluence is ~ 5.5 x 10^{13} n_{eq}/cm^2 = end of 2018 (V_{FD} ~ 50 V)

- Evolution of space charge concentration as a function of the bias voltage
  - Observed late strip isolation compared to bulk depletion
    → Consistent with observation from data that efficiency plateau is much higher than the bulk depletion voltage
- Our model is still immature...
  - Three parameters are fixed with three inputs
    → Uniquely determined; no prediction capability
- It's worth while to investigate:
  - Finding the best way to optimise the radiation parameters (with a new deep state?)
  - Full simulation including charge transport

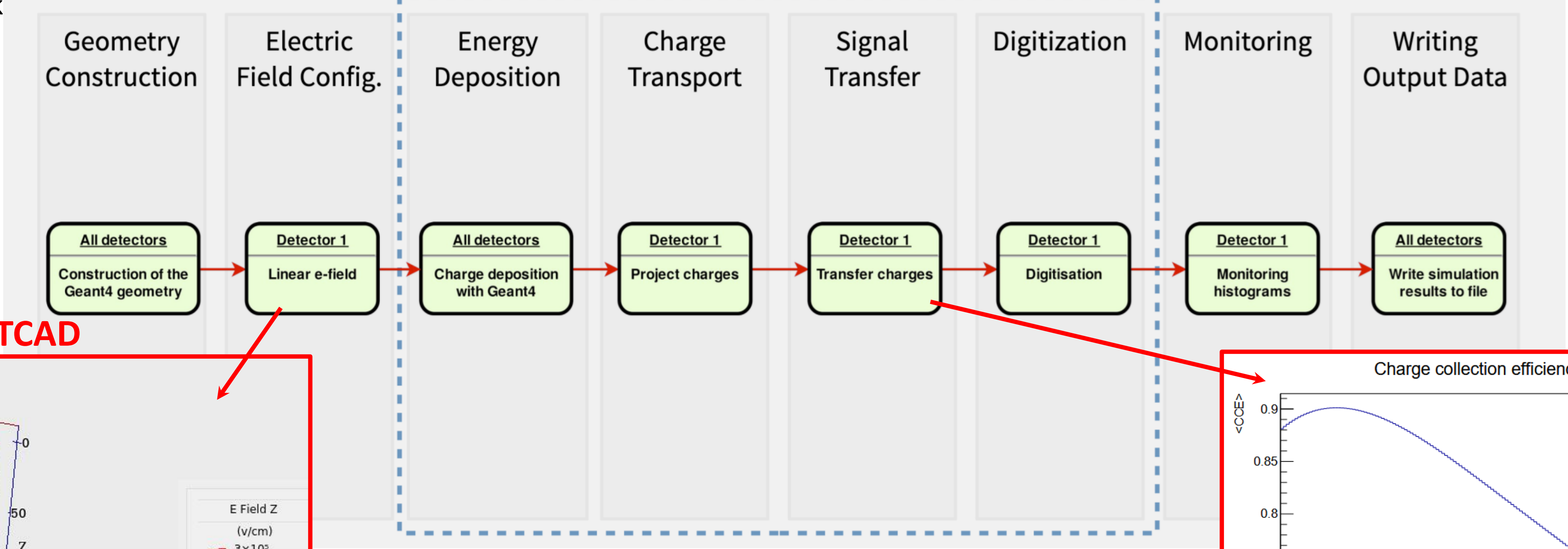
[M. Bomben, KEK ITDC Platform-B meeting 2025]

■ TCAD simulation study for Pixel

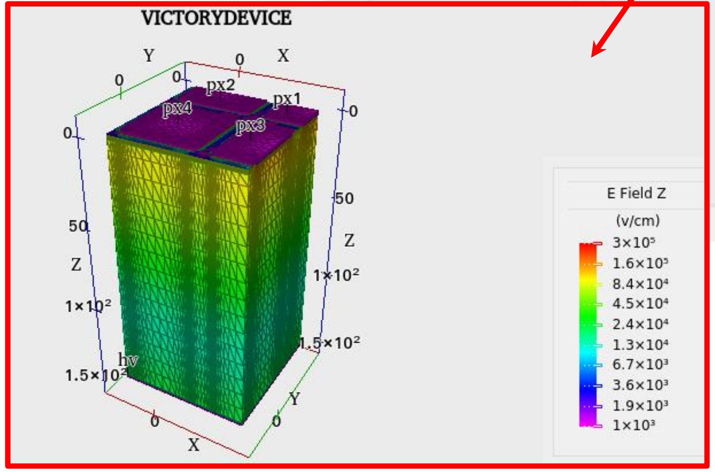
- France team has expertise on studies with TCAD (for E-field calculation) + Geant (for charge transport) [K. Nakkalil and M. Bomben, Sensors 2024, 24(12), 3976 (2024)]

Example of ATLAS ITk for HL-LHC (p-bulk sensors)

MC simulation (Geant-based Allpix Squared)

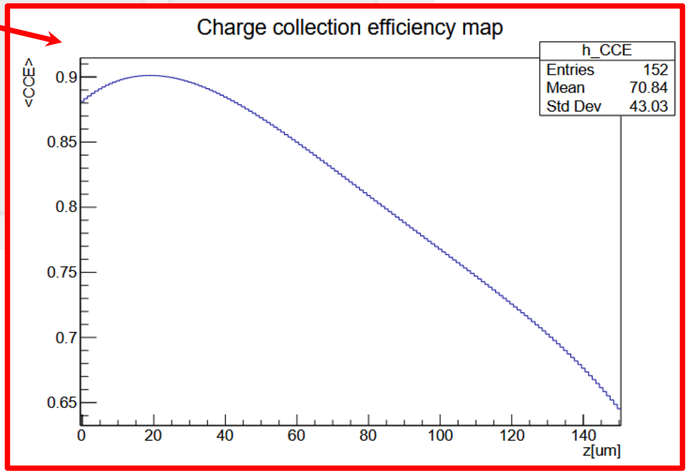


TCAD



Can be replaced by E-field obtained from TCAD

Detailed charge transport information in the sensor



[M. Bomben and K. Nakkalil, arXiv:2501.12253]

- A similar method can be applied to SCT?

Summary

- While ATLAS SCT is ending its operation, it provides a unique dataset for n-bulk silicon sensors irradiated at the LHC environment
  - Bias voltage required for 95% efficiency is significantly higher than the bulk depletion voltage
  - Successfully measured the CCE → Results indicated the CCE significantly lower than expectations from the sensor irradiation tests
- Plans for this research proposal
  - Improve our TCAD model for SCT to better understand observations from LHC data
    - Careful optimisation for the radiation parameters is important
  - Understand the charge collection properties from charge transport simulation

Japan Team (S. Hirose et al.,)

- SCT performance data from real SCT at the LHC environment

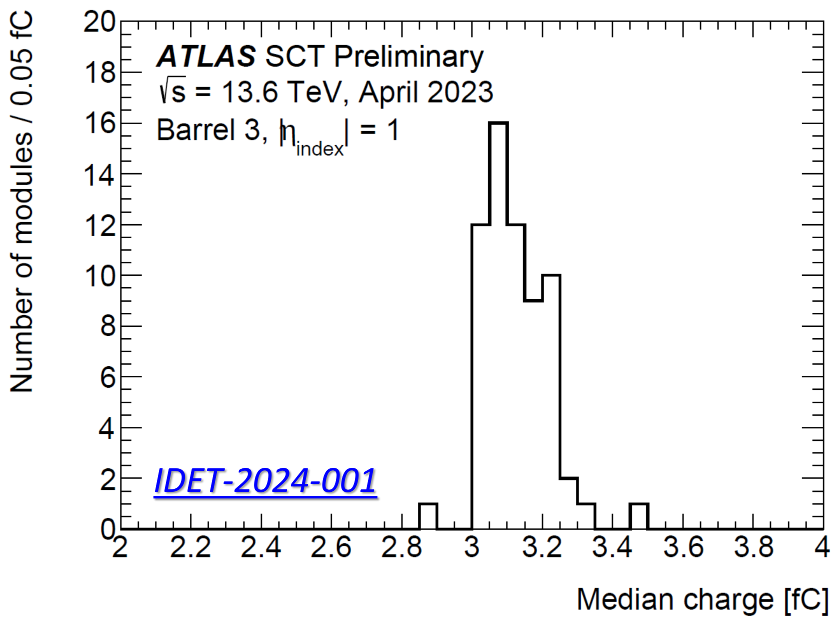
France Team (M. Bomben et al.,)

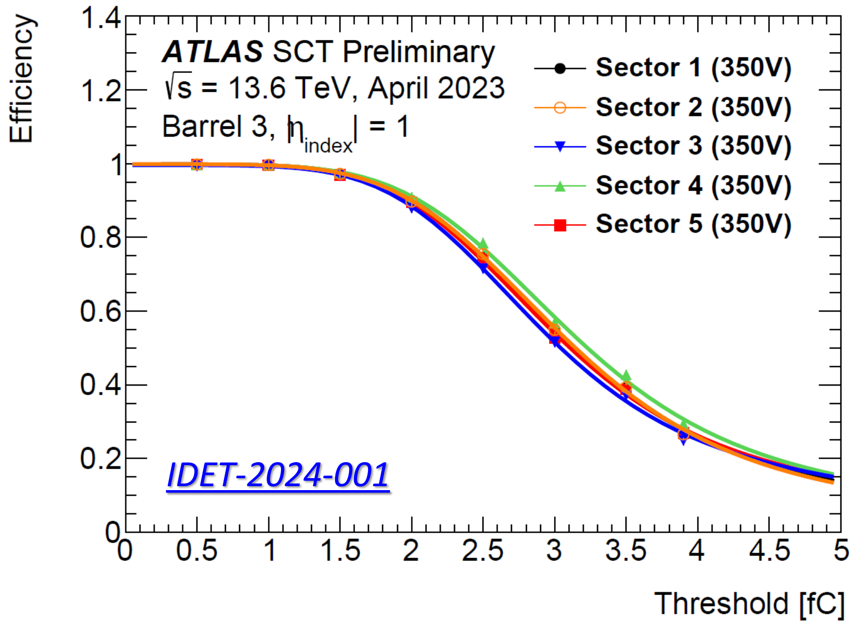
- Detailed sensor simulation with TCAD + Geant for ATLAS Pixel / ITk detectors

Obtain knowledge from the 'real' detector in combination with Pixel and SCT

- Understanding on irradiated silicon detectors at the LHC environment is important towards HL-LHC
- Improve radiation models for silicon detectors

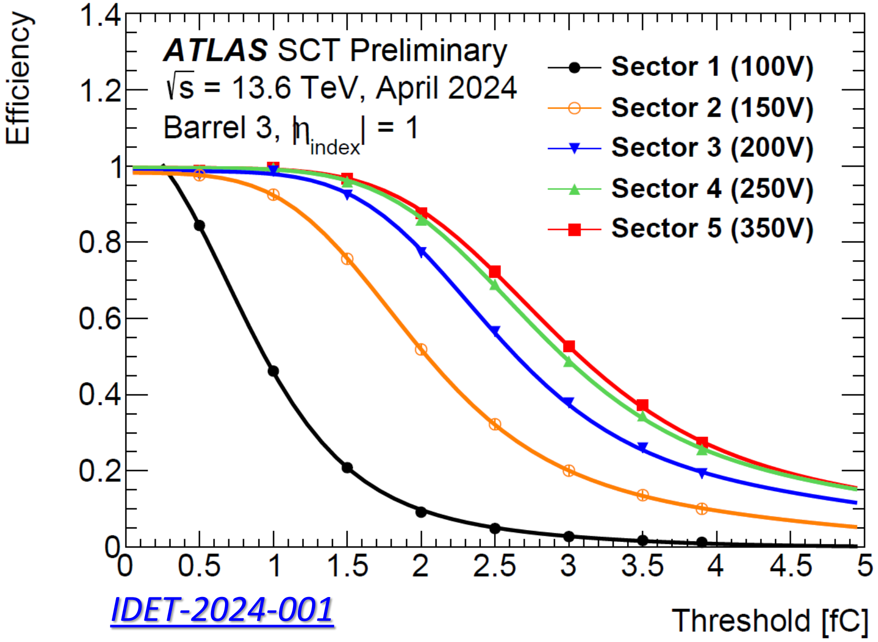
■ Validation of the strategy

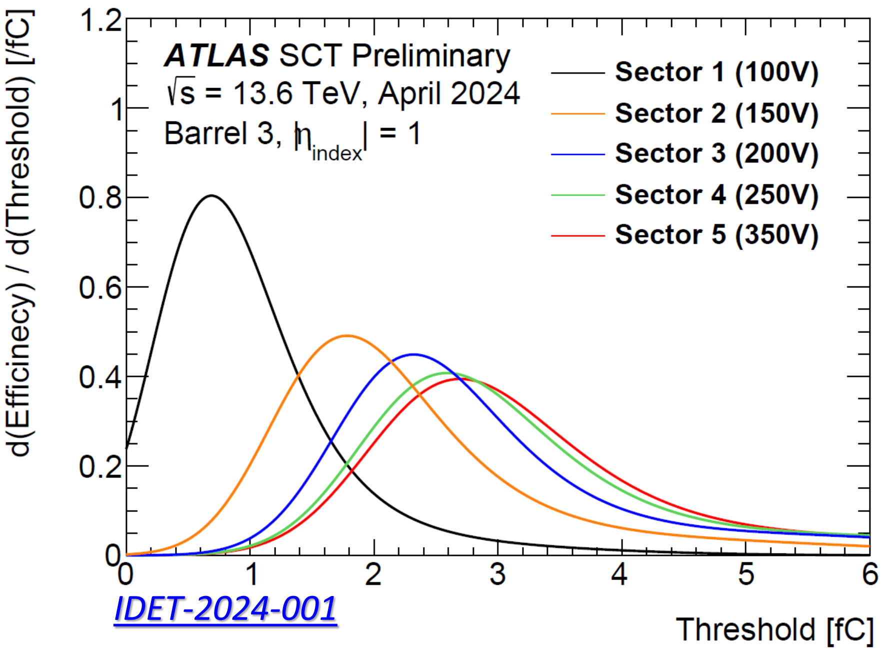




- Validation performed using the previous threshold scan data
  - All modules set at 350 V; consistent results are expected for all sectors
- Module-by-module measurement
  - Variation is ~3% s.d.; sufficiently small
  - Two outliers → Their impact is marginal once averaged by 8 modules
- Results from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

■ Threshold scan with different HV

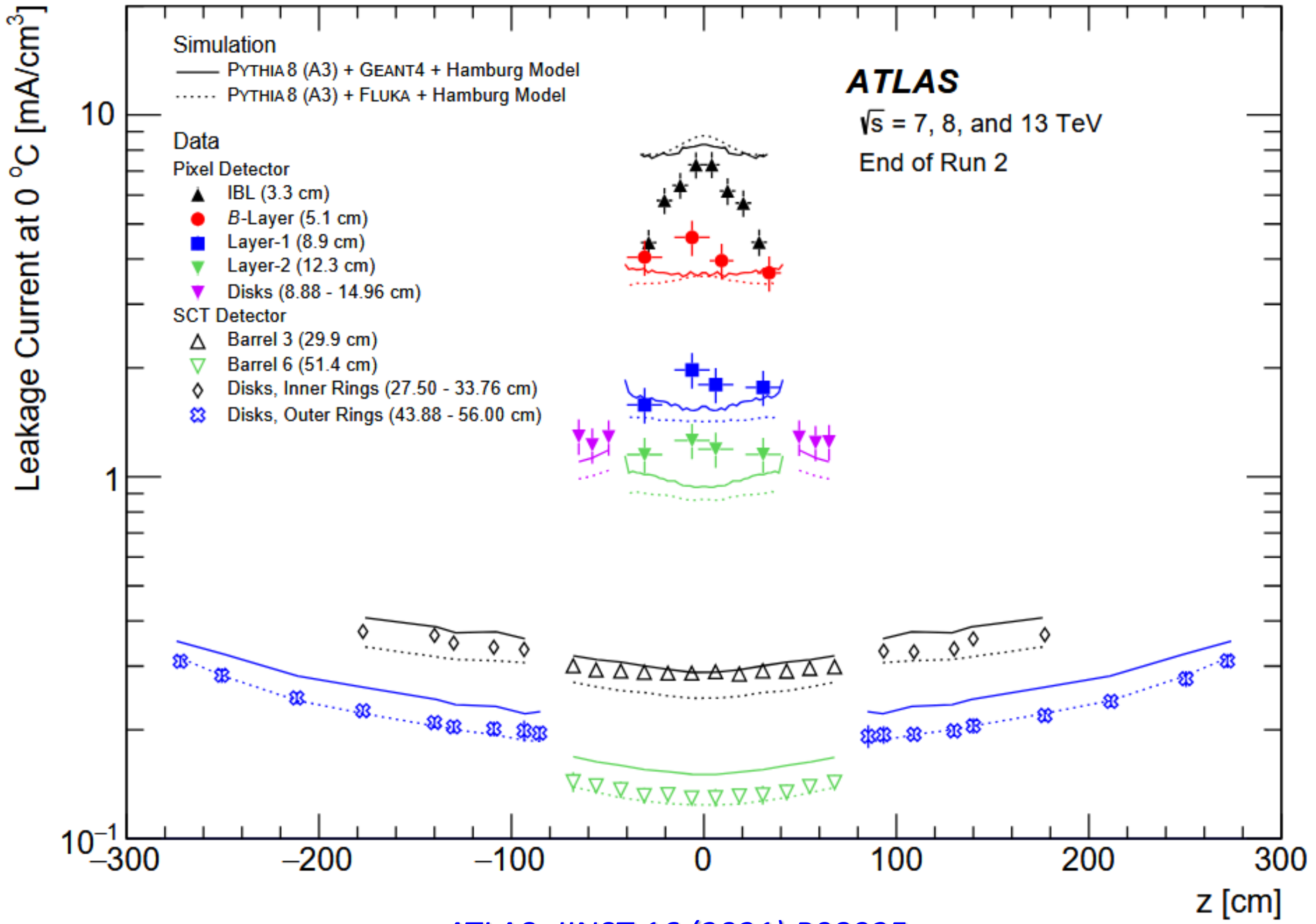




- Performed HV scan with different HV setting in April 2024
  - Set five HV points: 100 V, 150 V, 200 V, 250 V, 350 V (operation HV)
- Measurement successful
  - Derivatives of the fitted functions provide good estimate of the charge distribution
    → First time that we measured charge distribution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

■ Leakage current at ID

- Leakage current at ID well agrees with predictions within ~ 10%
  - The predictions are based on simulated radiation fluences
  - An exception is for IBL, which shows a significant discrepancy at the large z region



ATLAS, JINST 16 (2021) P08025