University of Glasgow | Department of Physics & Astronomy

ATLAS EXPERIMENT

Testbeam evaluation of heavily irradiated silicon strip modules for ATLAS Phase - II Strip Tracker Upgrade

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On behalf of the ITk Strips Testbeam group

Outline

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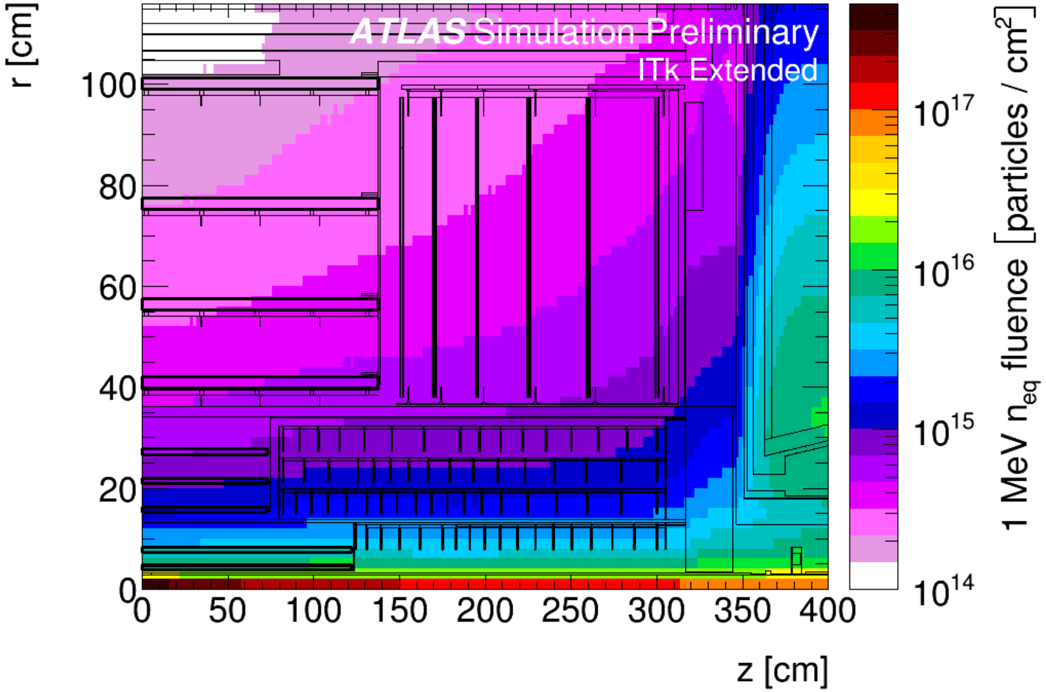
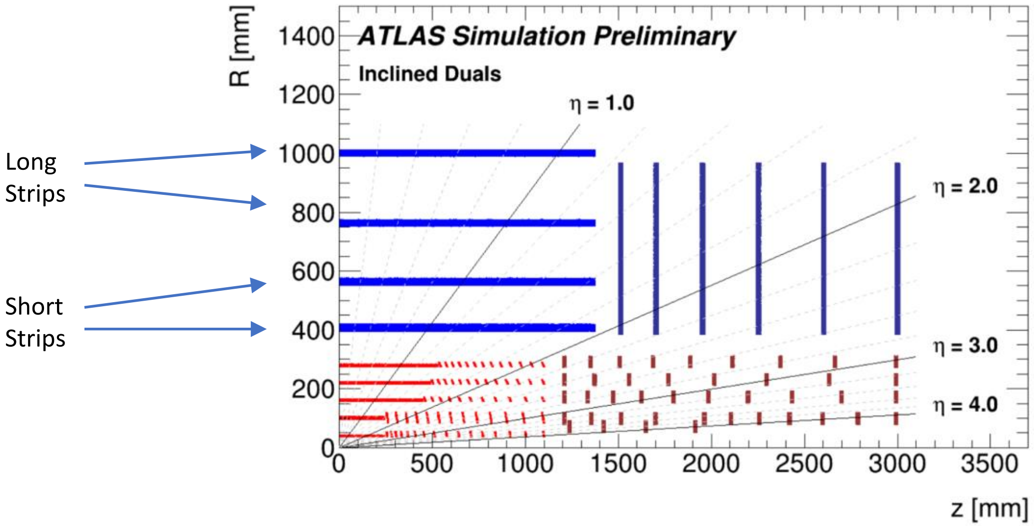
ATLAS ITK

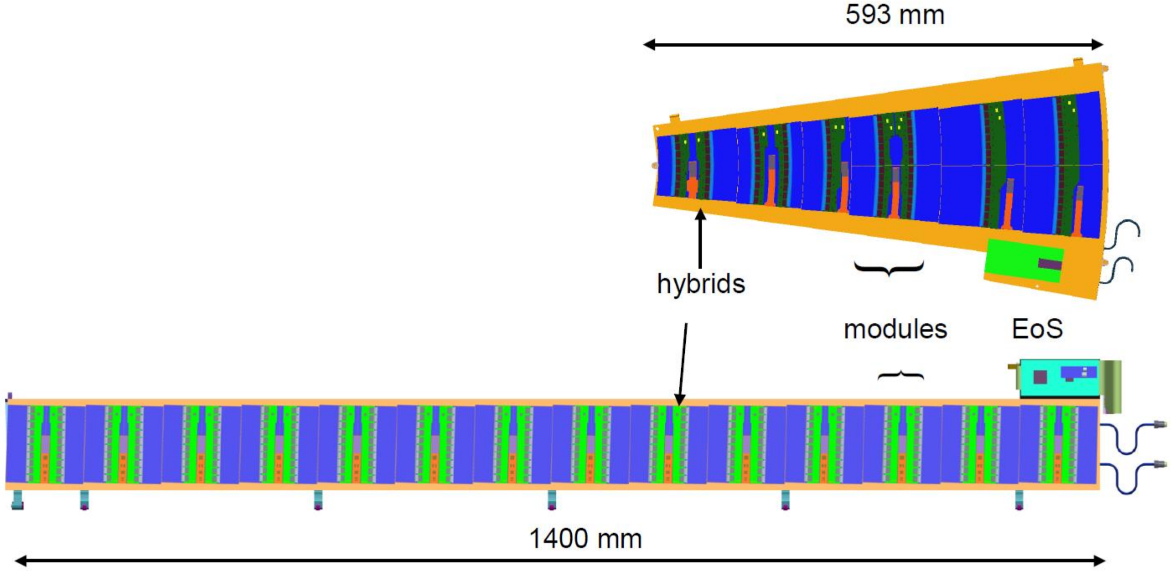
- An Upgrade of the Large Hadron Collider (LHC) to the High Luminosity-LHC foreseen in 2026
- Luminosity of up to $7.5 \times 10^{34} cm^{-2} s^{-1}$
  - Triggering with high rate & large event sizes
- Up to 200 simultaneous interactions per bunch crossing
  - Limit occupancy to 1%
- High particle fluences
  - Radiation hardness of up to 1.2×10^{15} neq/cm^2 (Strips) required
- Low material budget



ITk Strips System

- The new inner tracker (ITk) will be an all Si Tracker system
  - 2T magnetic field, ~6m long, ~1m radius & up to |η|=4
- 5 Central and multiple Forward pixel layers
- 4 Central and 6 Forward strip layers
  - Strips make ~165m² of Silicon, with >60M channels
  - Central (Barrel) region made of Staves (14 Modules/per side)
  - Forward (End-cap) region made of Petals (18 Modules/per side)

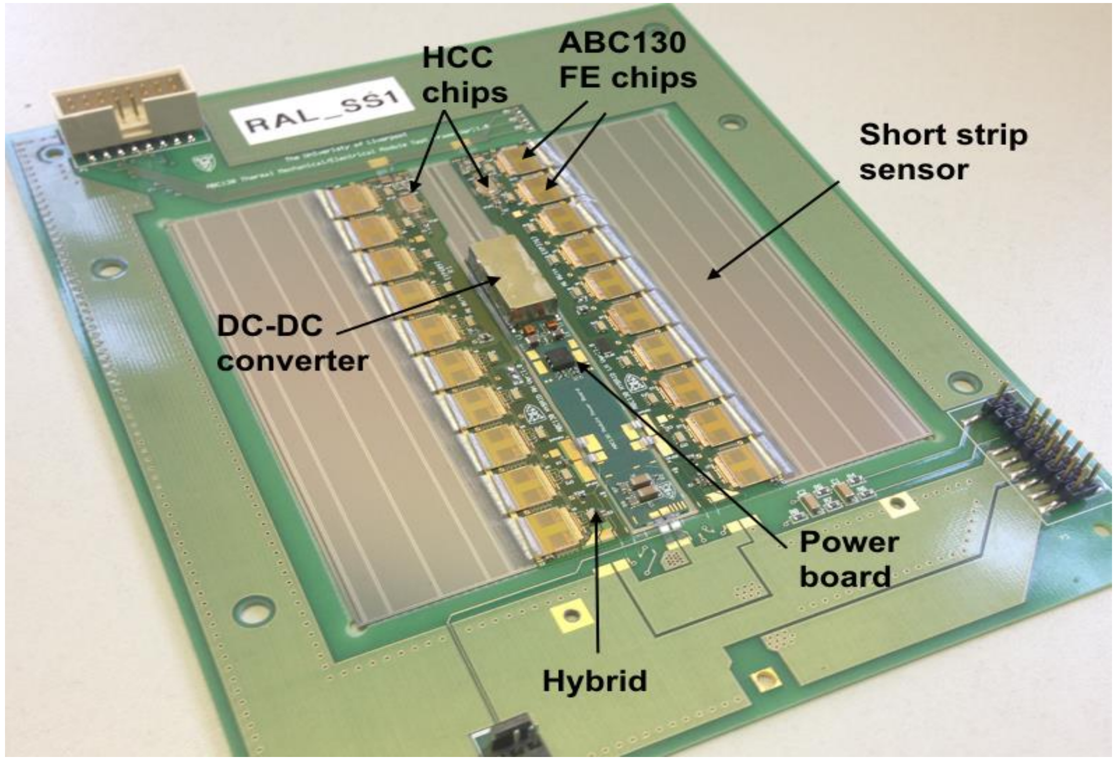




Silicon Strip Barrel Modules

Silicon Barrel Modules consist of:

- 320µm thick n-in-p float zone Si sensors
  - Use of ATLAS12 developed by the ATLAS ITk Strip Sensor collaboration and produced by Hamamatsu Photonics.
  - 74.5µm strip pitch, with strip lengths of 23.9mm
  - Full size is approximately 97 x 97mm^2
  - Bulk Resistivity measured to be **~2.5 kΩ cm**
    - Depletion Voltage ~ **365V**
- Binary readout chips (ABC130) and hybrid controller chips (HCC)
  - Glued & wire bonded to a hybrid
  - Data transfer on hybrid at 320 Mbit/s
- Hybrids are glued to the surface of the Si sensor
  - Wirebonds connect FE ASIC channels to Si strips
- DC-DC powering for increased power efficiency



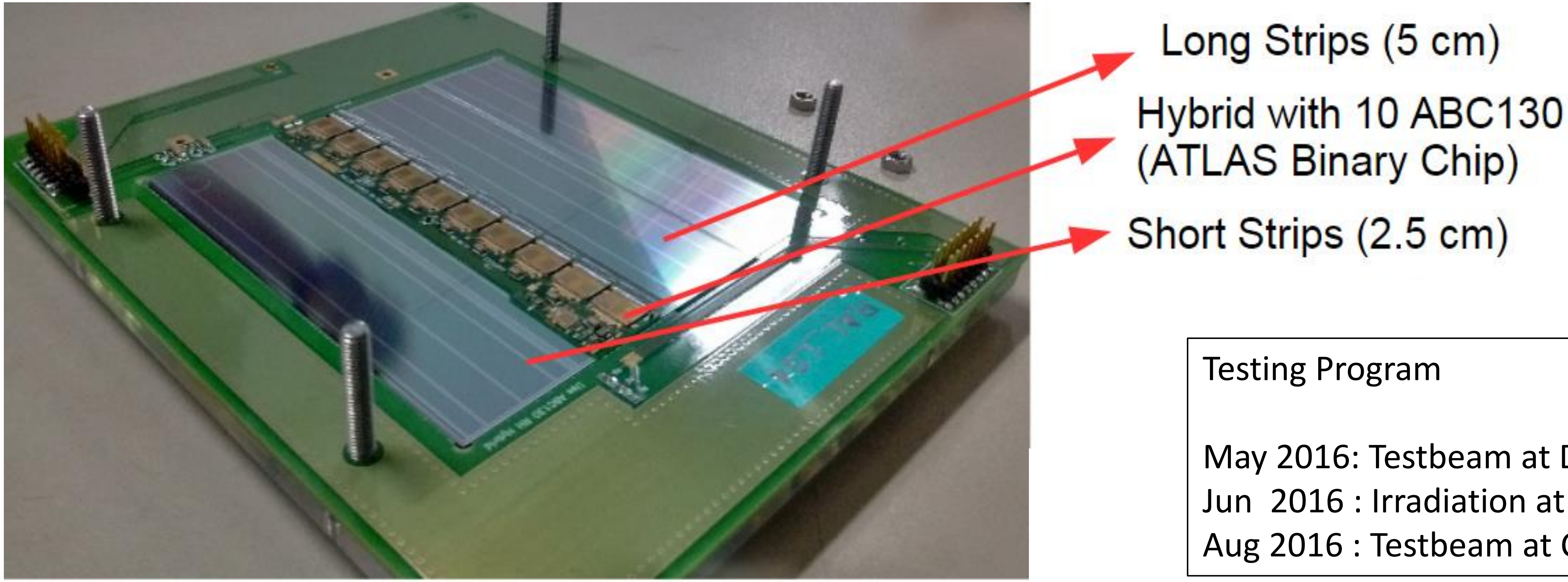
More info on Poster 'Prototype Strip Barrel Modules for the ATLAS ITk Strip Detector' (Peter Phillips)

Motivation for Irradiation Studies

- It is critical to study the performance of Strip modules after being irradiated to accumulated fluences expected at the end of HL-LHC operation
    - Was highlighted to be important to show for the ITk Strips TDR
- The maximal expected fluence for the Strip detectors is $1.2\text{x}10^{15}\text{neq/cm}^2$
    - Includes a safety factor of 1.5
- The requirements at end of life are:
    - Efficiency > 99%
    - Noise Occupancy < 10^{-3}
    - Signal-to-noise Ratio > 10
- **Therefore strips modules were constructed to compare testbeam results before and after irradiation**

Modules Under Test

- 2 Barrel Modules were constructed for testing both Short and Long Strips
  - Long strips formed by wire bonding 2x Short strip channels together

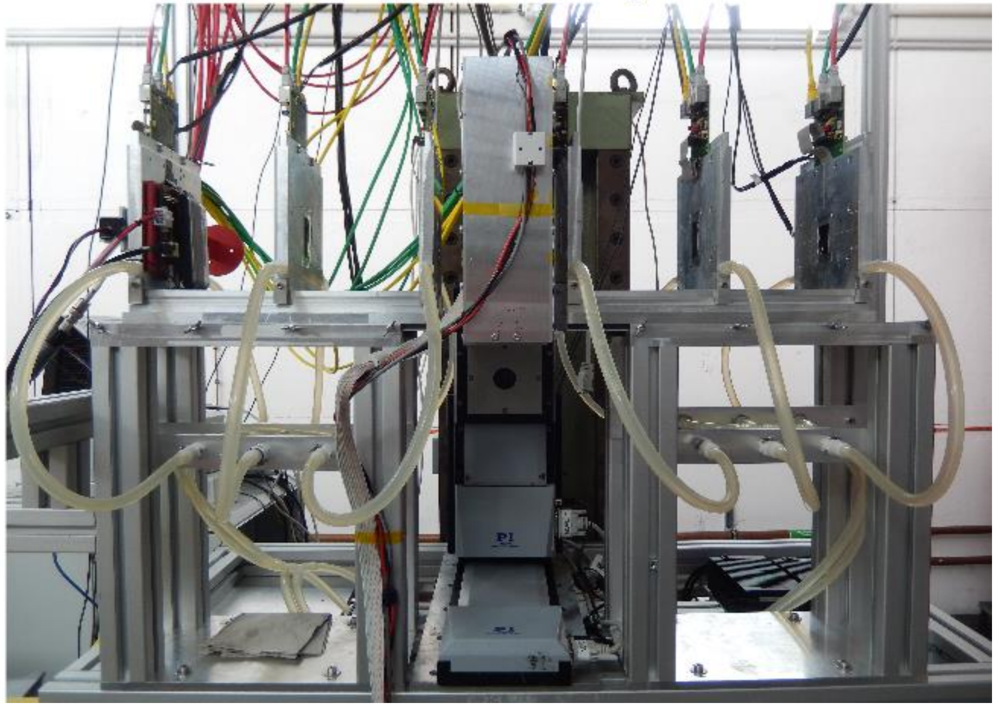


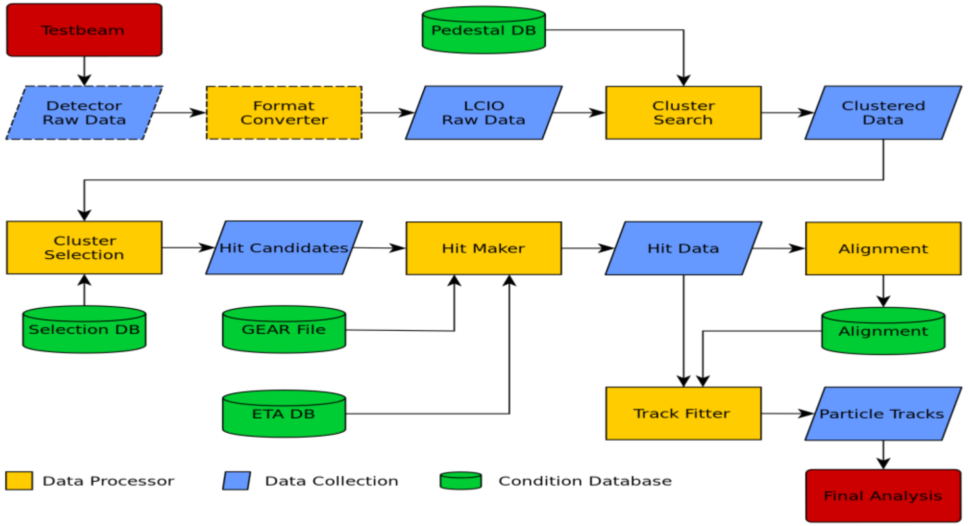
Testing Program

May 2016: Testbeam at DESY
Jun 2016 : Irradiation at CERN IRRAD
Aug 2016 : Testbeam at CERN SPS

Testbeam

- Testbeams took place at DESY (4.8GeV e^-) & CERN (120GeV π)
  - Both use the EUDET style Telescope
    - ~ 3μm pointing resolution
  - 6 planes of Mimosa26 CMOS APS
    - 18μm pitch and 50μm thick
  - FE-i4 pixel detector implemented for timing resolution (25ns)
- ITk Strip DAQ system integrated with telescope DAQ
  - 300 Hz Readout
- Tracks of particle reconstruction using software
  - EUTelescope
  - Alignment of tracks performed using General Broken Lines (GBL) Algorithm
- Analysis performed comparing resolved tracks to hits on the DUT
  - Residuals
  - Hit Efficiency
  - Cluster Size





Results: Non- Irradiated Module

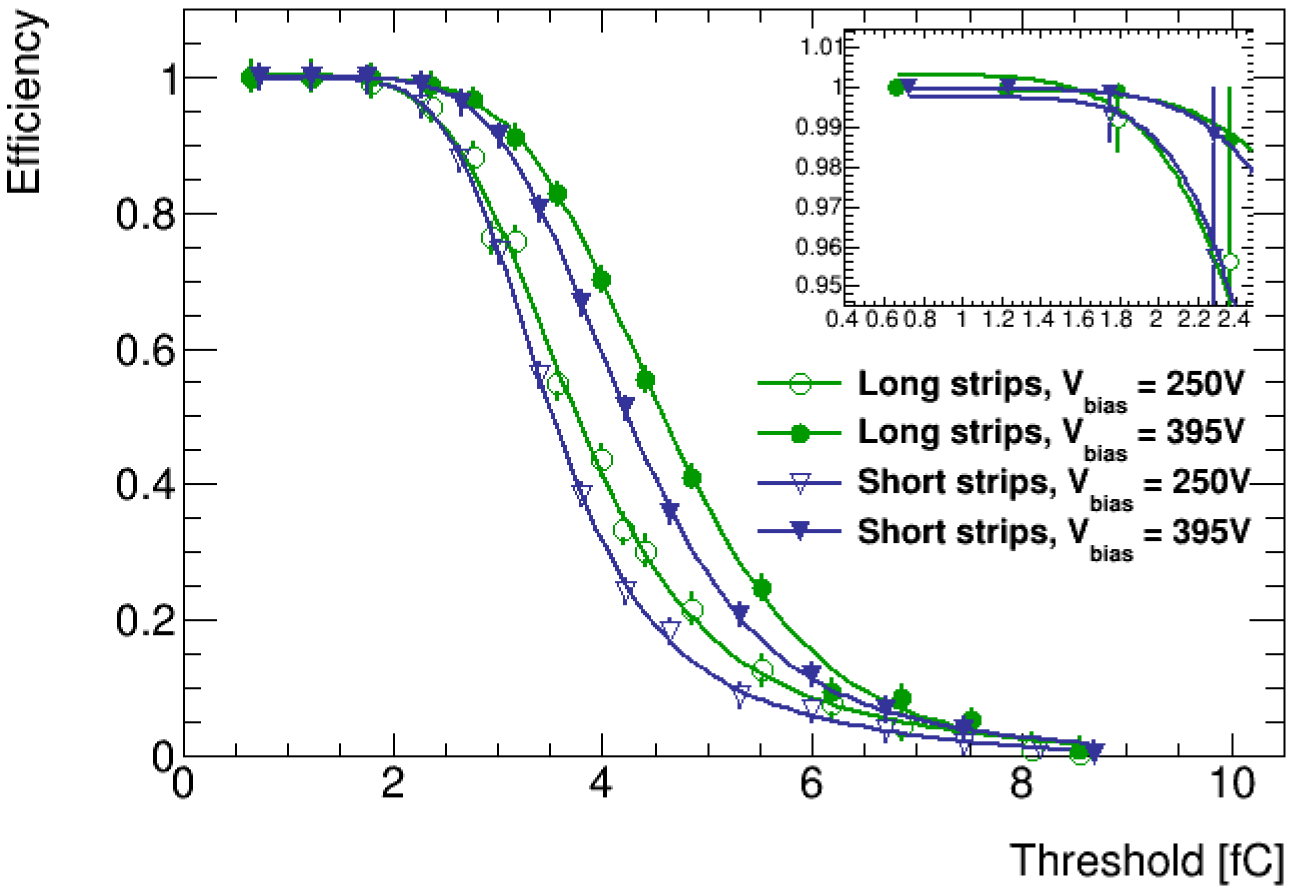
- Beam was positioned in both Long and Short Strip areas of the sensor
- Data sets were taken for a range of threshold settings
- Use tracks reconstructed after timing and position resolution cuts
    - Reject tracks with chi² > 8 (8) or 5 (6)

- Efficiency calculated as

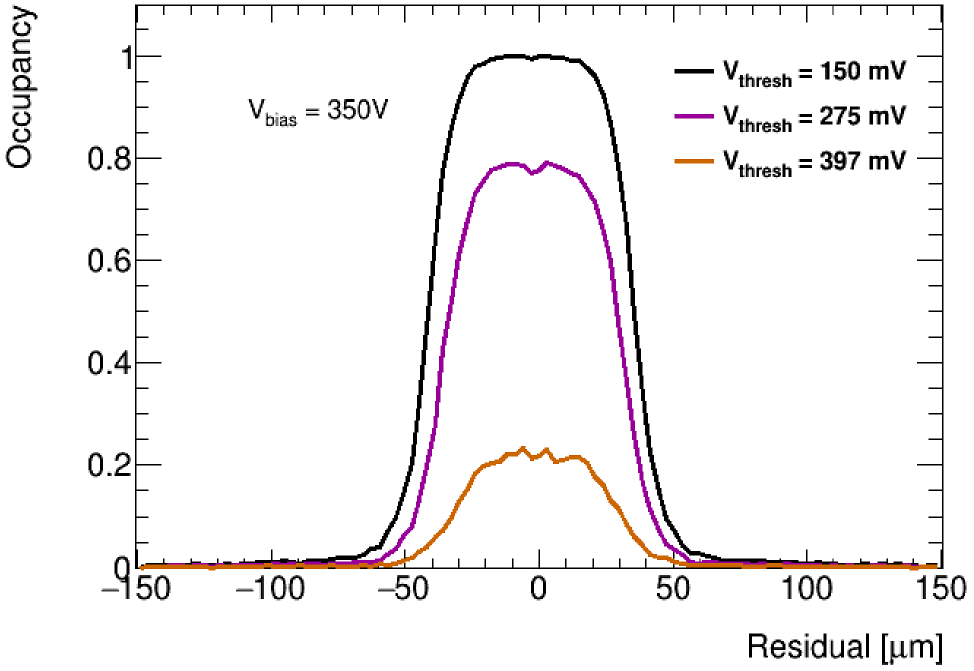
$$\epsilon = \frac{\text{tracks with telescope + DUT Hit}}{\text{tracks with telescope Hit}}$$

- The efficiency curves were then evaluated for the long-strip and short strip regions at two different bias voltages.

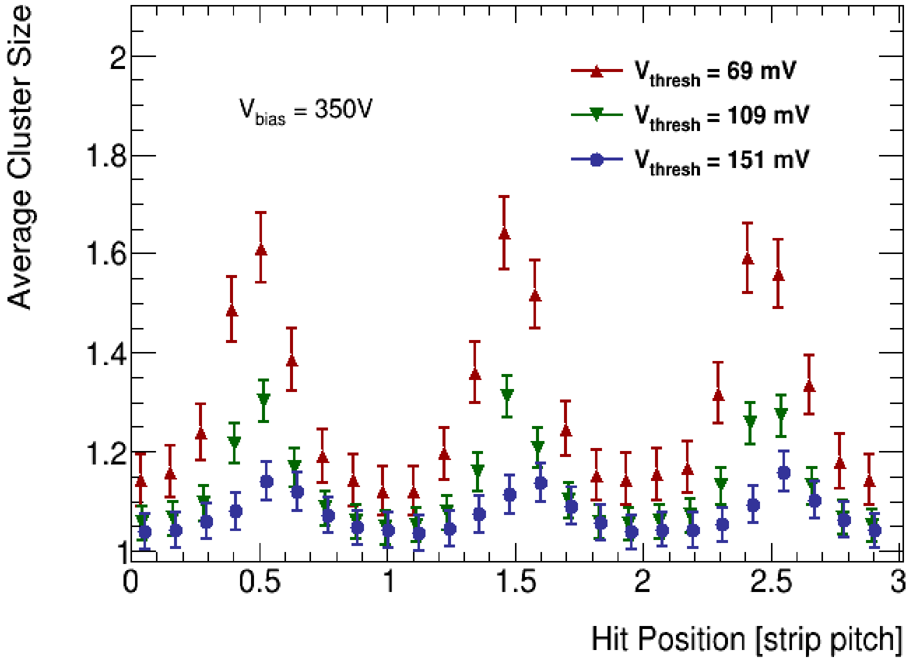
- Increase in sensor bias leads to greater charge collection



Results: Non- Irradiated Module



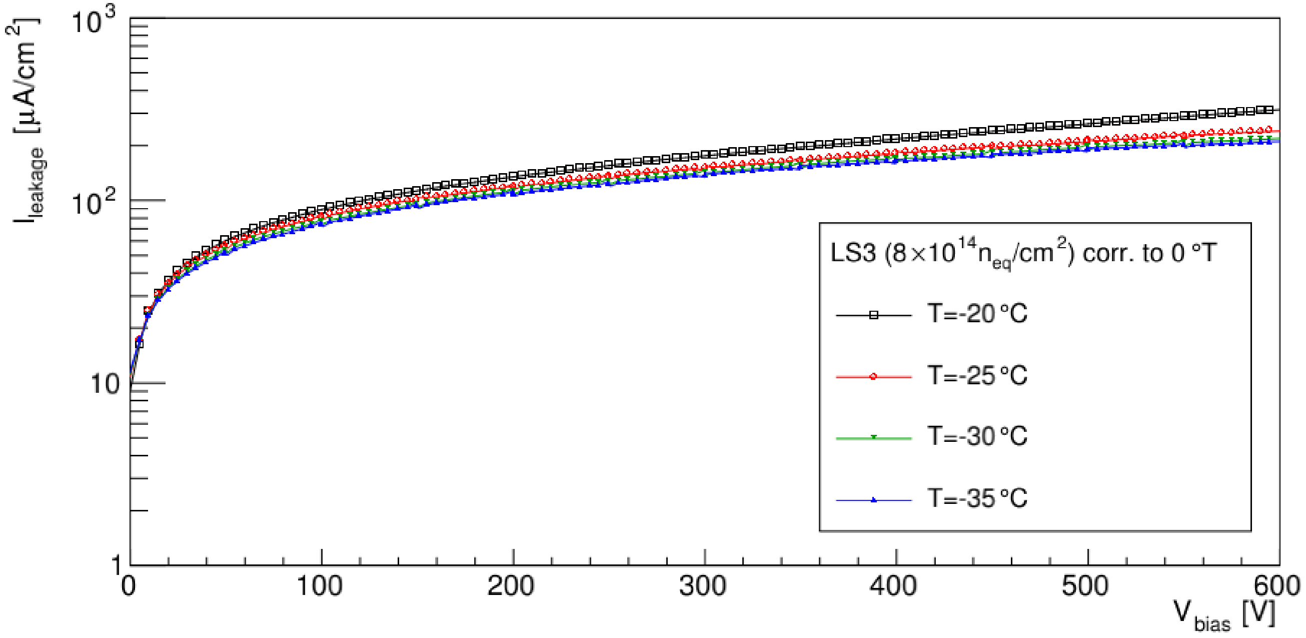
The hit occupancy as a function of the residual (distance from the extrapolated track position on the strip sensor to the strip registering a hit) shows a flat efficiency in the centre region of the strips.



Charge sharing increases near the edge of the strips can be seen looking at the average cluster size for lower thresholds.

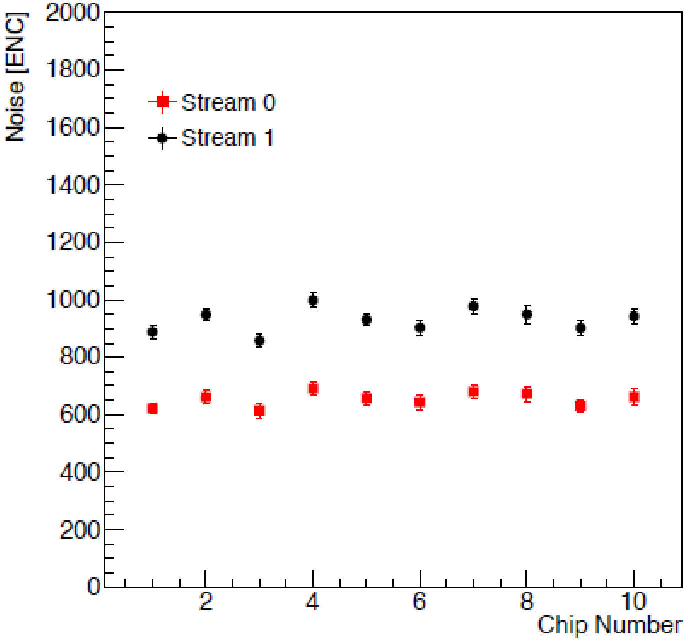
Proton Irradiation of Barrel Module

- A Barrel Module was then irradiated at the 6 Proton Synchrotron with 24 GeV protons resulting in both ionising (TID) and non-ionising energy loss (NIEL) damage.
- The module was cooled to -20°C
- Sensor unbiased but with chips powered, configured and clocked throughout the irradiation period of 19 days
- The final dose received by the module was calculated to be **8x10^{14}neq/cm^{2}** and **TID=37.2 Mrad**
- The module was fully operational and had I-V characteristics taken at a range of temperatures



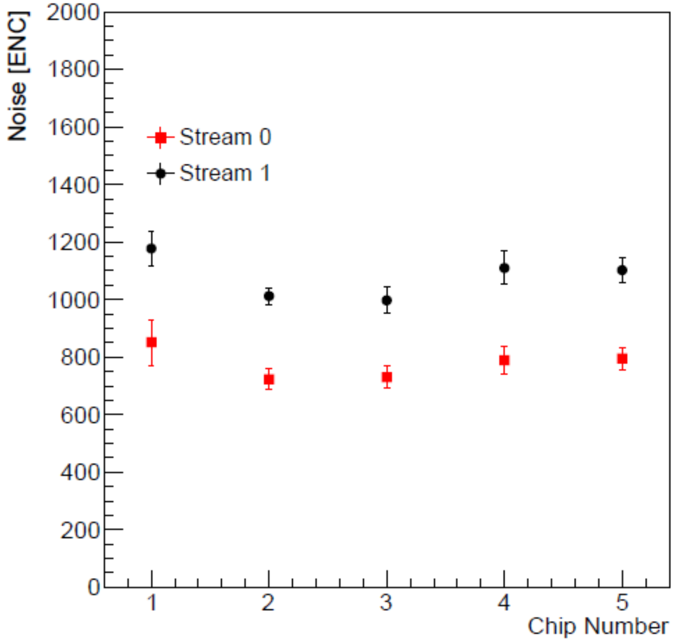
Results: Non Irradiated v Irradiated Module Noise

- Measurements of noise and gain were performed using the internal calibration circuit of the ABC130
- Shown below is the input noise in e$^-$ ENC and averaged per read-out chip for (left) a non irradiated module and (right) five ABC130 of the irradiated module at a bias voltage of 600 V.



🟥 Short Strips

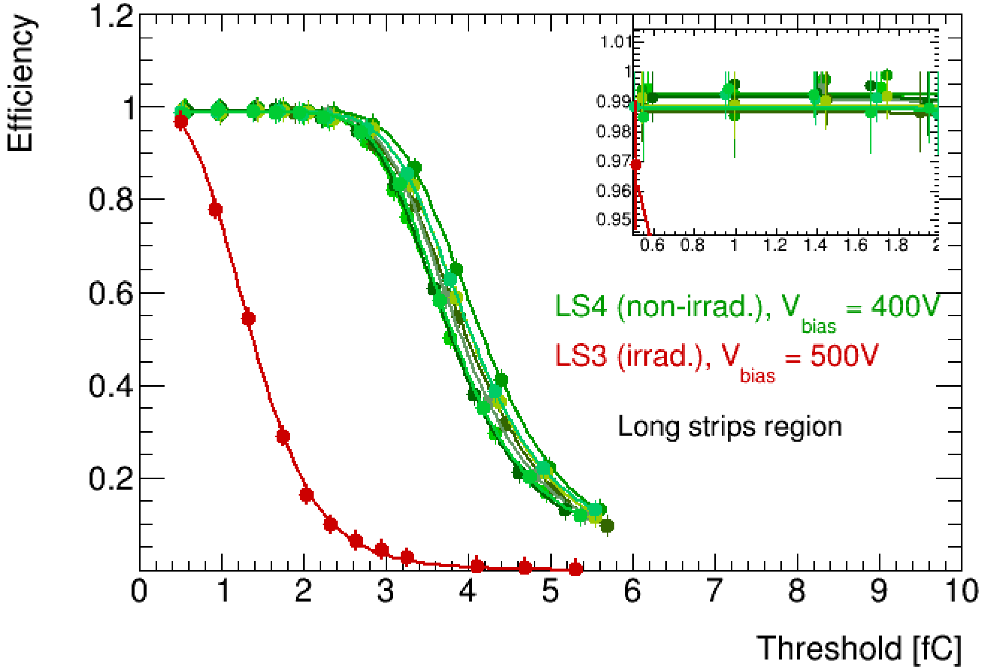
⬛ Long Strips

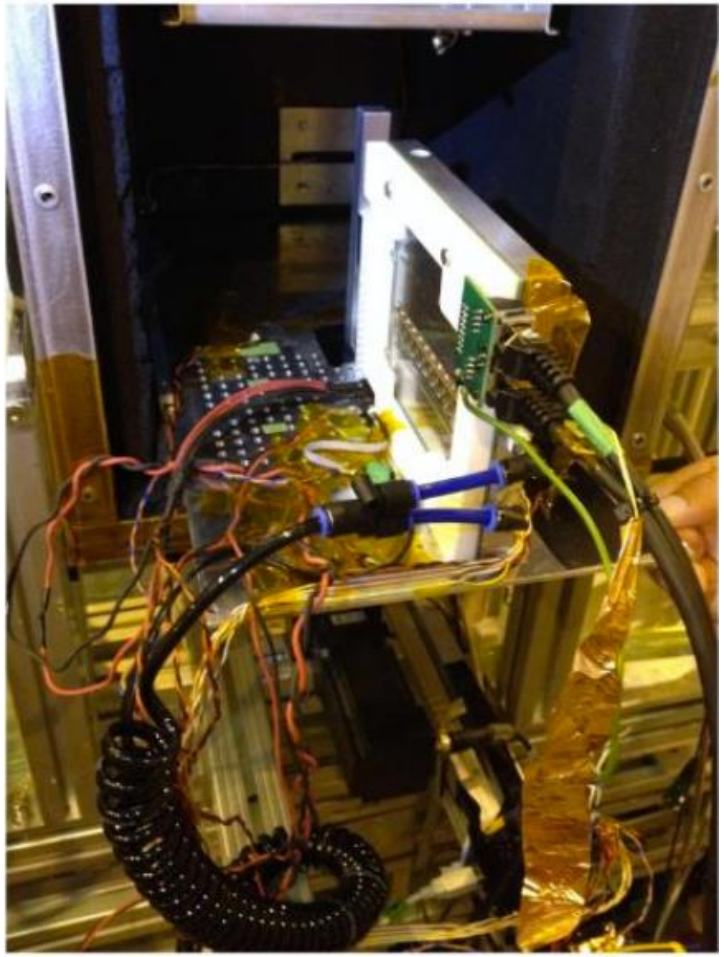


- For the irradiated module both strip types exhibit an increased noise which is consistent with expectations from previous ABC130 single chip irradiations and strip length

Results: Irradiated Module

- The testbeam at CERN allowed a comparison to be made between the performance of efficiency before and after irradiation to 8x10^{14} neq/cm^2
- As expected, the charge collection is reduced significantly after irradiation.

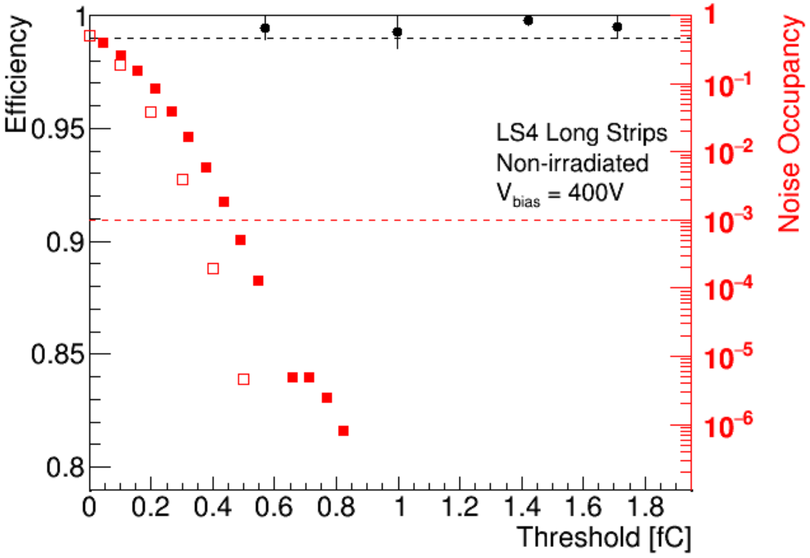


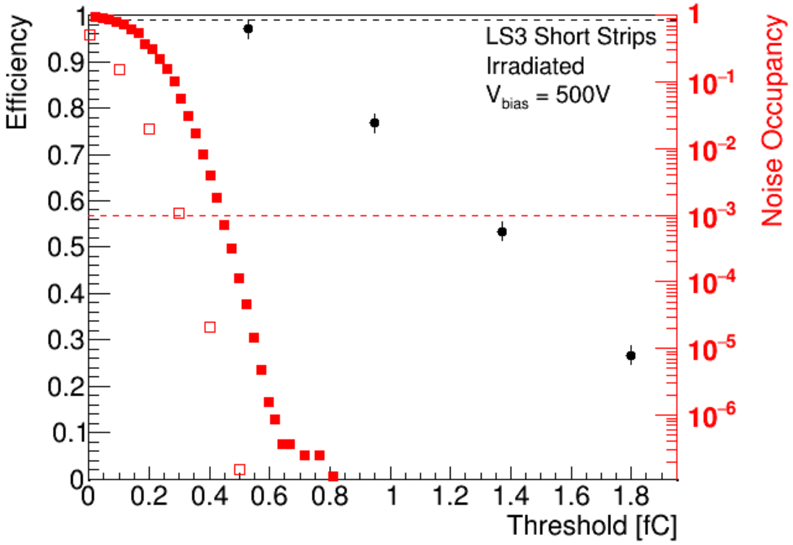


Module under test at CERN SPS:
Module operated in Cold Box at -35°C
(Sensor at -15°C)

Signal to Noise: Pre and Post Irradiation

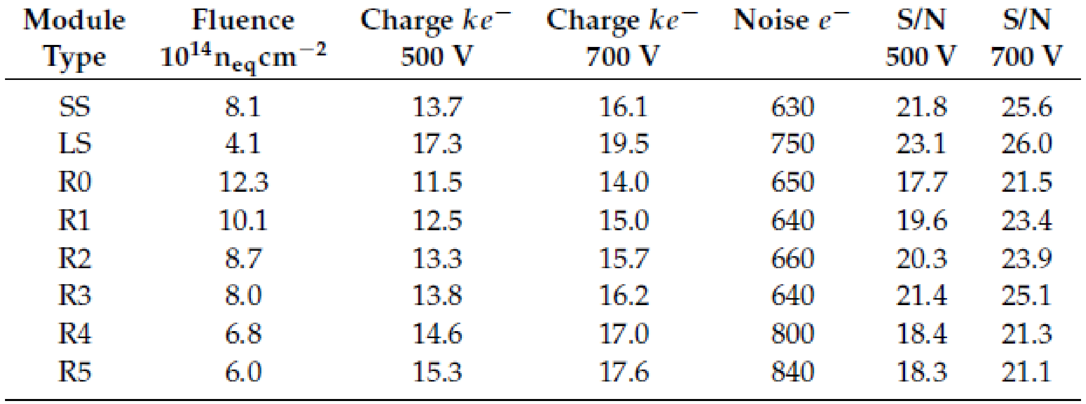
- Shown below is the **signal efficiency** compared to the **noise occupancy** for modules (irradiated and irradiated) studied at the CERN test beam.
- The combination of the lower substrate resistance of the ATLAS12 sensor and lack of annealing after irradiation means that the signal measured at test beam is lower than expected at the end-of-life with production grade sensors.
  - **However there is a working threshold ~0.5fC**
- The noise in the prototype chips ABC130 is larger than expected in the final design of the production chip ABCStar.
  - White Squares □ show expected Noise Occupancy with new ABC* chipset





Expected End of Life Performance

- Estimate the S/N for all Strip layers using testbeam data and noise measurements
- Assumptions:
  1. Noise increase after irradiation seen in the prototype chip ABC130 will be eliminated in the production chip ABCStar through the use of enclosed layout transistors in the critical regions of the front-end
  2. Production sensors have a resistivity closer to ATLAS07 sensors

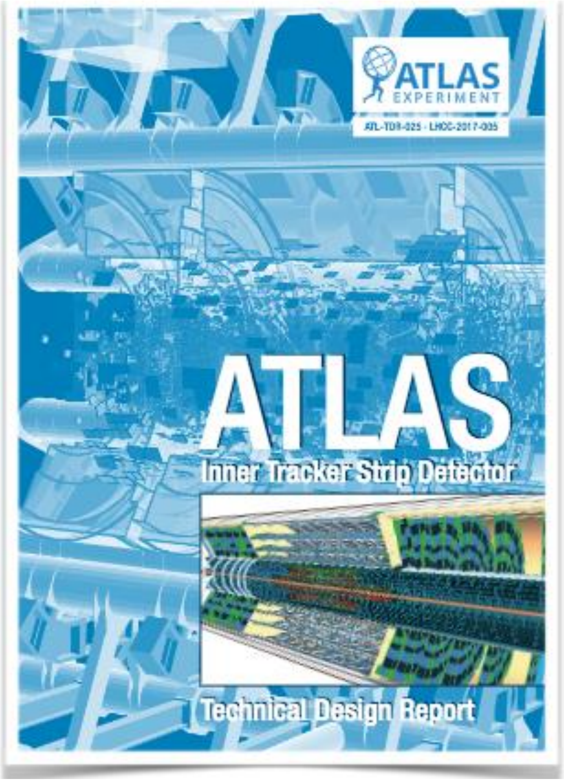


Module Type	Fluence $10^{14} n_{eq} cm^{-2}$	Charge ke^- 500 V	Charge ke^- 700 V	Noise e^-	S/N 500 V	S/N 700 V
SS	8.1	13.7	16.1	630	21.8	25.6
LS	4.1	17.3	19.5	750	23.1	26.0
R0	12.3	11.5	14.0	650	17.7	21.5
R1	10.1	12.5	15.0	640	19.6	23.4
R2	8.7	13.3	15.7	660	20.3	23.9
R3	8.0	13.8	16.2	640	21.4	25.1
R4	6.8	14.6	17.0	800	18.4	21.3
R5	6.0	15.3	17.6	840	18.3	21.1

For the nominal 500 V bias operation, all modules meet the 10:1 signal-to-noise requirements

Conclusions

- Prototype ITK Strip Barrel Modules with ATLAS12 sensors have been successfully constructed and evaluated at testbeam
- Post irradiation ($8x10^{14}$ neq/cm^2 & TID=37.2 Mrad) the module was fully functional, with all components of the module are operational after the irradiation, allowing for full electrical characterization
- Post irradiation test beam results show Long and Short strip modules have a working region satisfying
  - Efficiency > 99%
  - Noise Occupancy < 10^{-3}
  - Signal-to-noise Ratio > 10
- Results are expected to improve with
  - Production ABC* readout chips
  - Increased resistivity of production sensors



Phase-II ITk Strip TDR approved May 2017

A.A. Affolder[22], X. Ai[13,25], P.P.Allport[2], J.-H. Arling[8], R.J. Atkin[4], A. J. Blue[10], L.S. Bruni[1], I. Carli[18], G. Casse[16] , L. Chen[13,25,29], A. Chisholm[6], K. Cormier[26], W. Cunningham[10], P. Dervan[16], S. Diez[8], Z. Dolezal[18], J. Dopke[21], E. Dreyer[24], J. Dreyling-Eschweiler[8], C. Escobar[12], V. Fabiani[17], V. Fadeyev[22], J. Fernandez-Tejero[7], C. Fleta[7], A. Gabrielli[15], B. Gallop[21], C. Garcia Argos[9], A. Greenall[16], I.M. Gregor[8], G. Greig[24], F. Guescini[27], K. Hara[28], M. Hauser[9], Y. Huang[13,25], R.F.H. Hunter[5], J.S. Keller[5], C.T. Klein[3], P. Kodys[18], U. Koetz[8], T. Koffas[5], Z. Kotek[19], J. Kroll[19], S. Kuhn[6,9], S.J. Lee[5], Y. Liu[13,25], K. Lohwasser[23], L. Meszarosova[18], M. Mikestikova[19], M. Minano Moya[12], R. Mori[9], B. Moser[9], K. Nikolopoulos[2], R. Peschke[8], G. Pezzullo[6], P.W. Phillips[21], L. Poley[8], M. Queitsch-Maitland[8], F. Ravotti[6], D. Rodriguez[12], E. Rossi[8], A. Rummler[6], C. Sawyer[21], D. Sperlich[11], S. Sullivan[21], J. Suzuki[28], M. Sykora[18], E. Tahirovic[20], O. Theiner[18], J. Thomas[2], Y. Unno[14], S. Wada[28], M. Warren[30], M. Wiehe[9], S. Wonsak[16], M. Wormald[16], K. Wraight[10], N. Zakharchuk[8] & H. Zhu[13,25]

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