Test beam results for the ATLAS ITk Strip upgrade

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on behalf of the ATLAS ITk Strip Test Beam Group

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Albert-Ludwigs-Universität Freiburg

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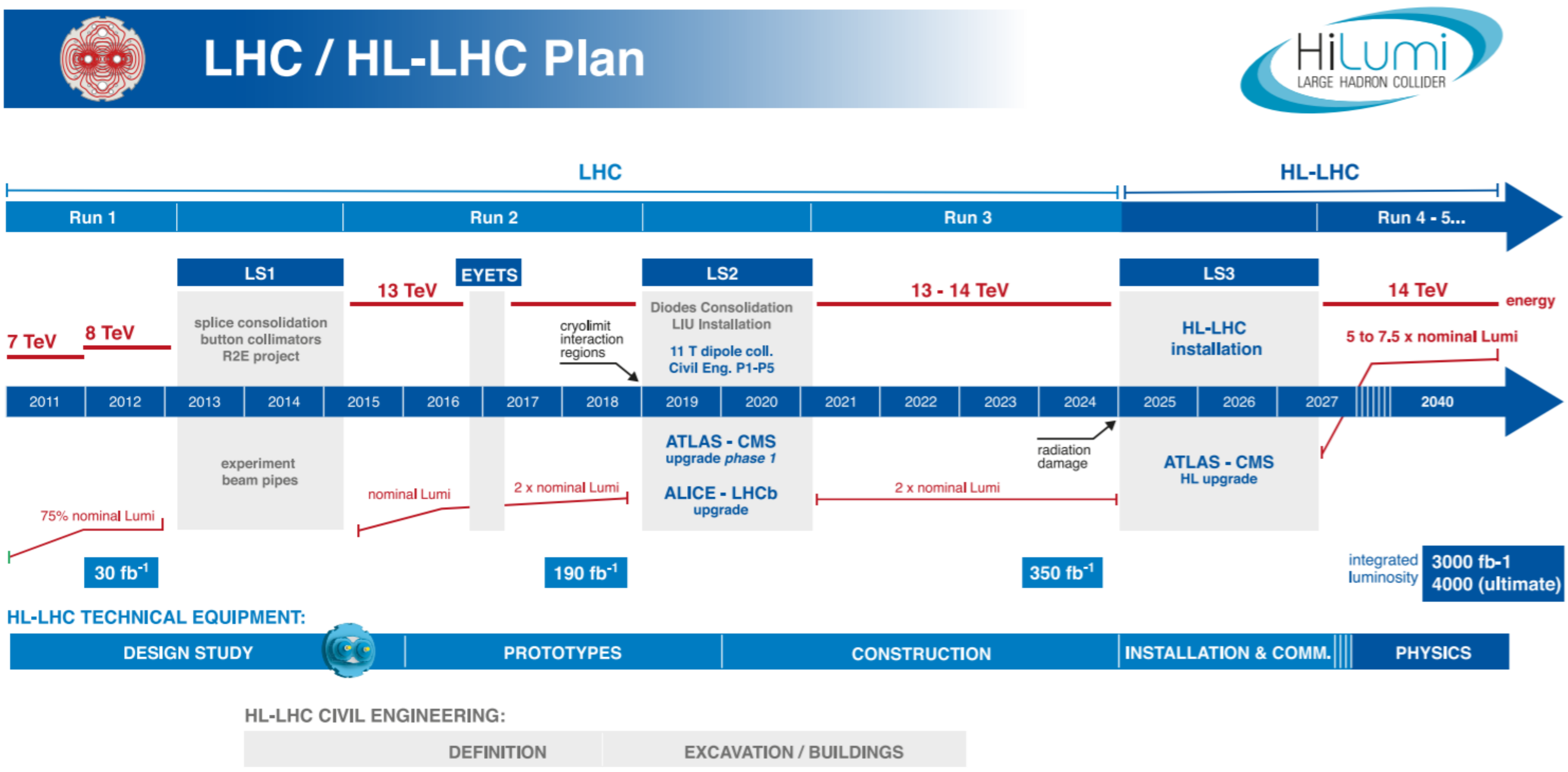
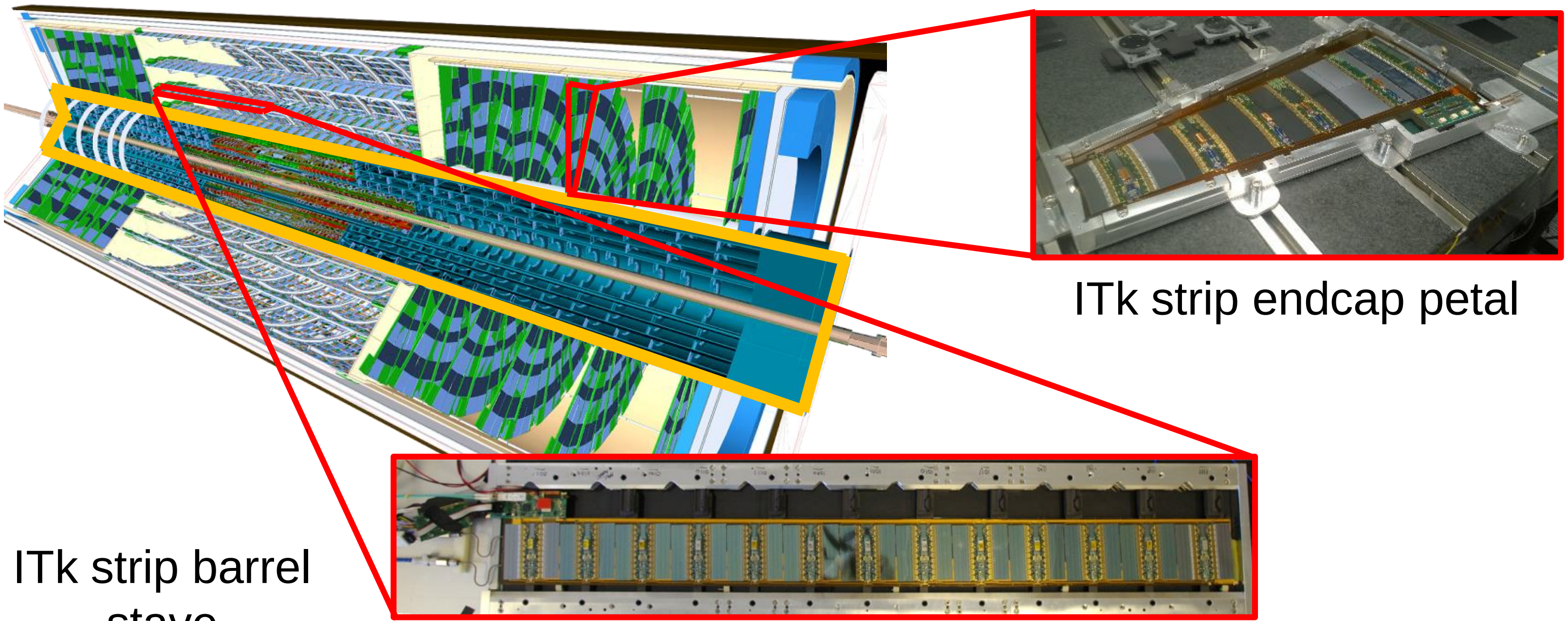
Future of the LHC



ATLAS Upgrade

- HL-LHC $\mathcal{L}_{int} \sim 4000\ fb^{-1}$
  - Requires increased radiation hardness
  - Expected total dose for strip endcap system $10.73 \times 10^{14}\ n_{eq}/cm^2$
- $\langle\mu\rangle$ from ~ 50 to ~ 200
  - Requires increased granularity
- **New tracker during the HL-LHC has to maintain the performance of the present Inner Detector under more difficult conditions. New all-silicon Inner Tracker (ITk)**

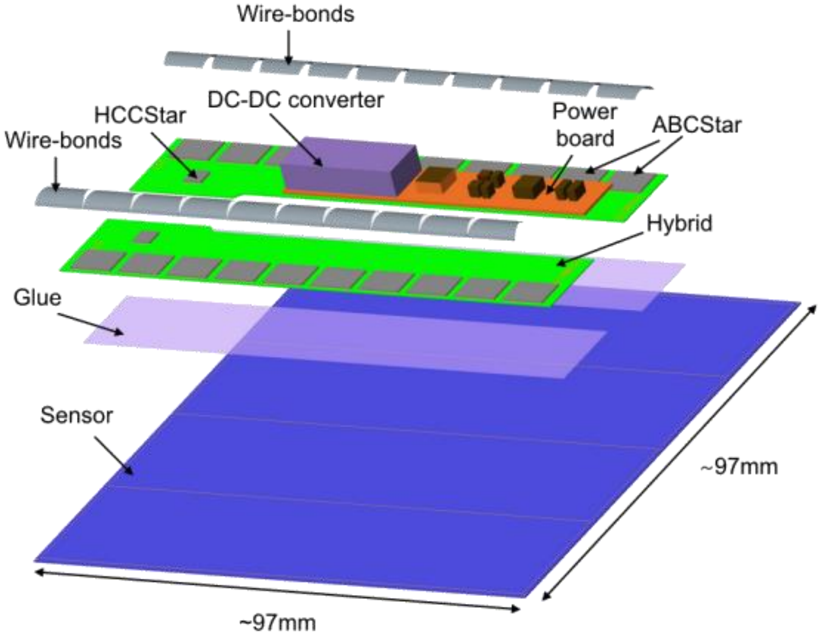


ITk strip endcap petal

ITk strip barrel stave

ATLAS ITk Strip Module

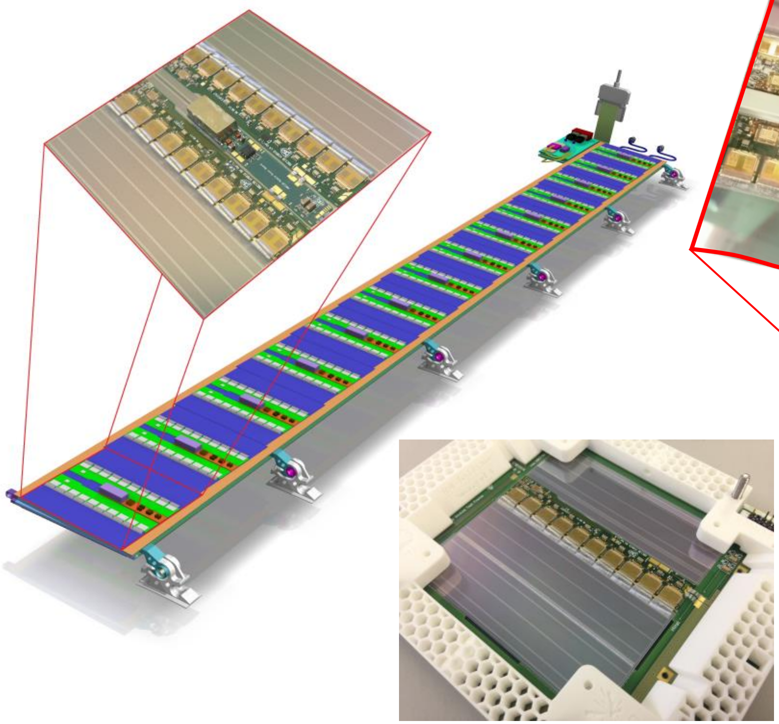
- Silicon Sensor
  - n^{+}-in-p float zone
  - $\sim 300\ \mu m$ thick
  - rectangular (barrel)
  - wedge-shaped (endcaps)
- Low-mass PCB (hybrids)
  - Glued directly on the sensor
- Hybrids host ATLAS Binary Chip (ABC) readout and Hybrid Control Chip (HCC)
  - Both in final version (ABCStar and HCCStar)
- Power board for powering and monitoring of the module
- Pre-production phase of ATLAS ITk strip project starts this year

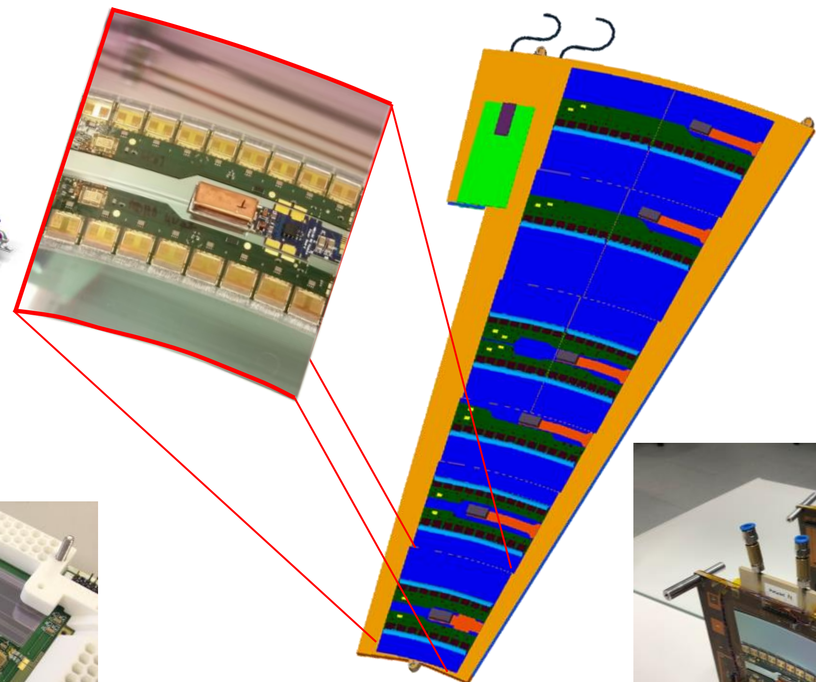


Plenty of production components to be tested in 2020 and 2021 to pass Production Readiness Reviews

ATLAS ITk Strip Modules

- Basic building block of ATLAS ITk Strip detector:
  - Staves for the barrel. Built from long and short strip modules
  - Petals for the endcaps
- Prototyping phase based on long and short strip modules for the barrel and R0 module for the endcap

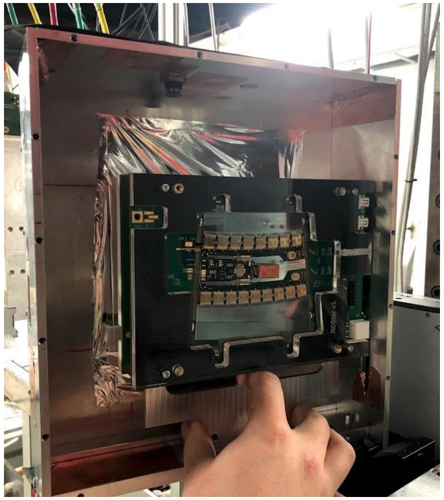




Modules and Test Beams in 2019

- Test beams in 2019 done exclusively with the Star readout electronics (ABCStar, HCCStar, etc.) at DESY II test beam facility
- April 4th - June 6th
  - **Non-irradiated Long Strip** and R0 modules
- June 3rd – 23rd
  - **Irradiated R0 module**
- September 2nd – 15th
  - **Irradiated Long Strip module** and non-irradiated Short Strip module

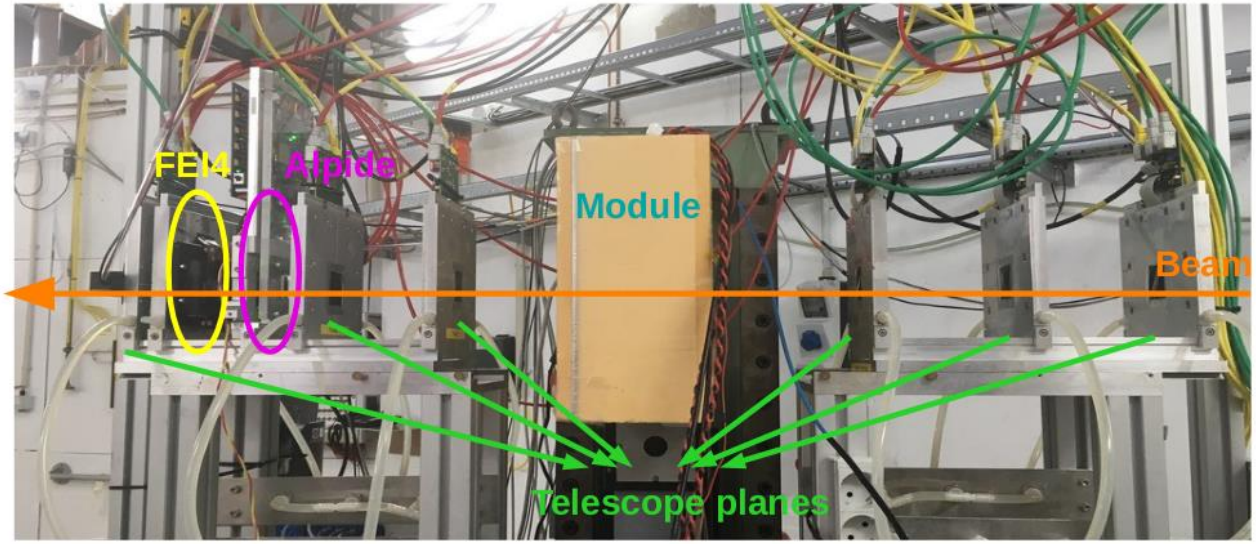
Non-irradiated LS



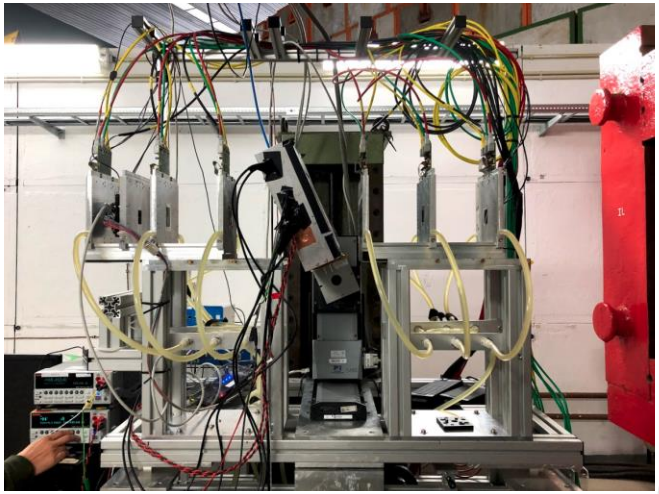
Non-irradiated R0

Irradiated R0

DESY Test Beam Setup

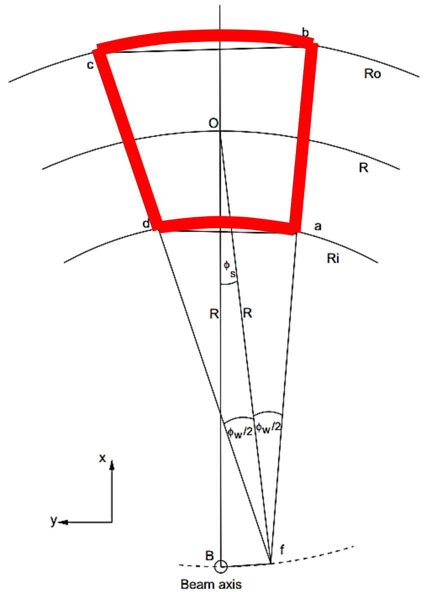


- Electron beam @DESY up to 6 GeV
- EUDET-type telescope: resolution 5-10 µm with our setup
- USBPix system with FE-I4 chip: track time tagging from telescope (April and September TB). Alpide plane used in June and in September for comparison with FE-I4
- Dry ice cooling box used for irradiated modules



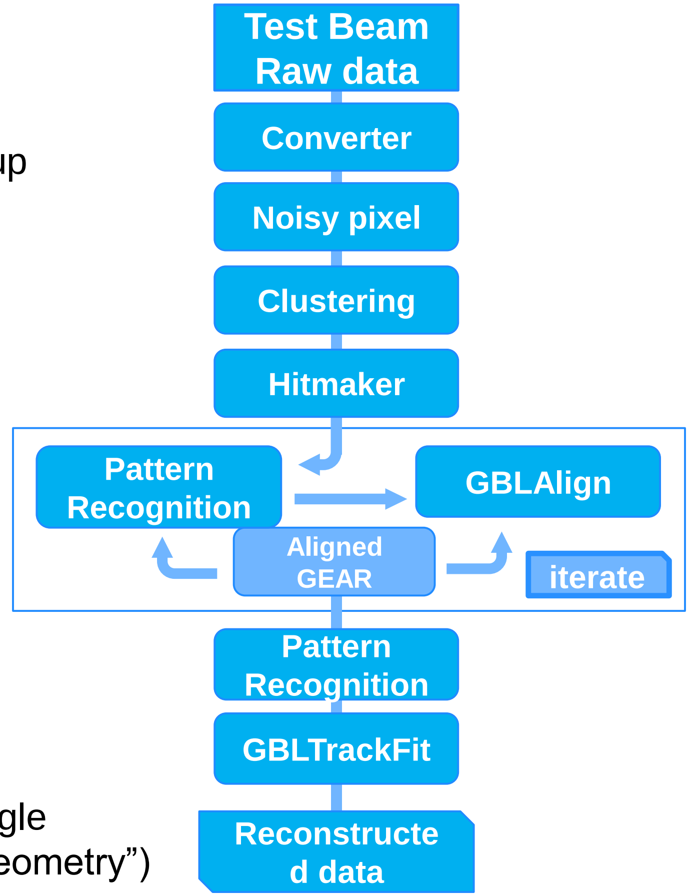
Data Reconstruction and Analysis

- Reconstruction
  - Track reconstruction by EUTelescope software using General Broken Lines algorithm
  - DUT positions in beam not precisely known from the setup
  - Tracks are used to (re)align each new beam impact position
- Analysis
  - Timing window: select particles in phase with $25\ ns$ clock
  - Time matching of hit on timing plane
  - Only good tracks chi2/NDF



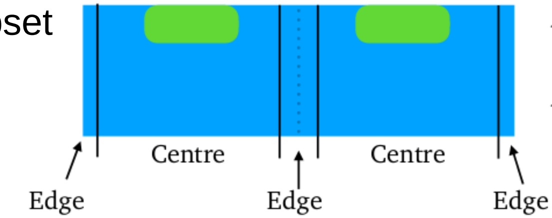
Endcap sensors

- Have in-sensor stereo angle implementation (“radial geometry”)
- Custom EUTelescope modifications

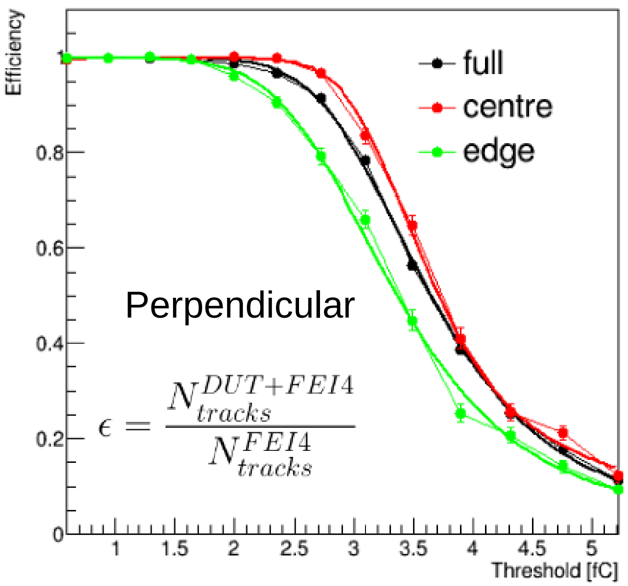


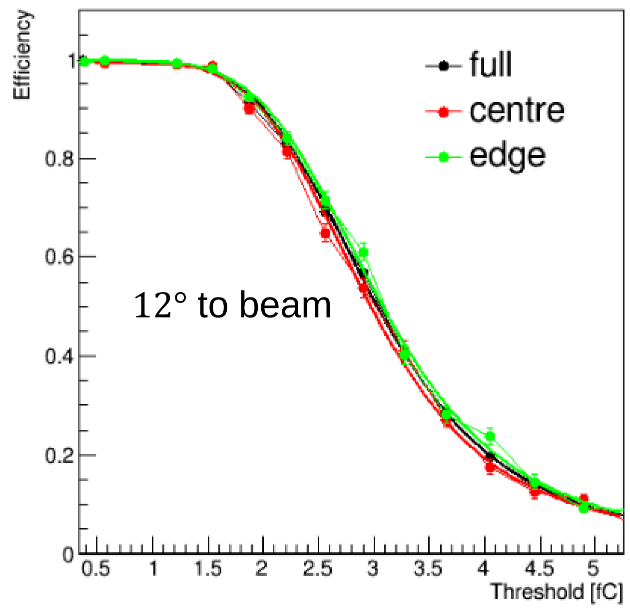
Non-irradiated Long Strip Module

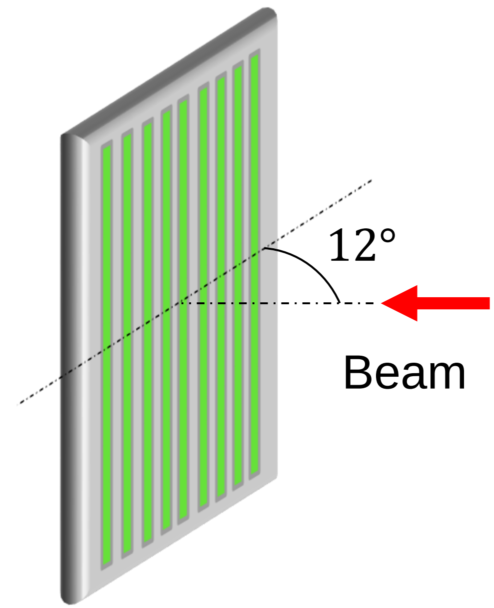
- Module built using ATLAS17LS sensor and ABCStar chipset
  - Strip pitch 75.5 μm
  - Implant size 16 μm
  - Aluminum strip 22 μm



Define an edge of strip/inter-stripregion of 15 μm





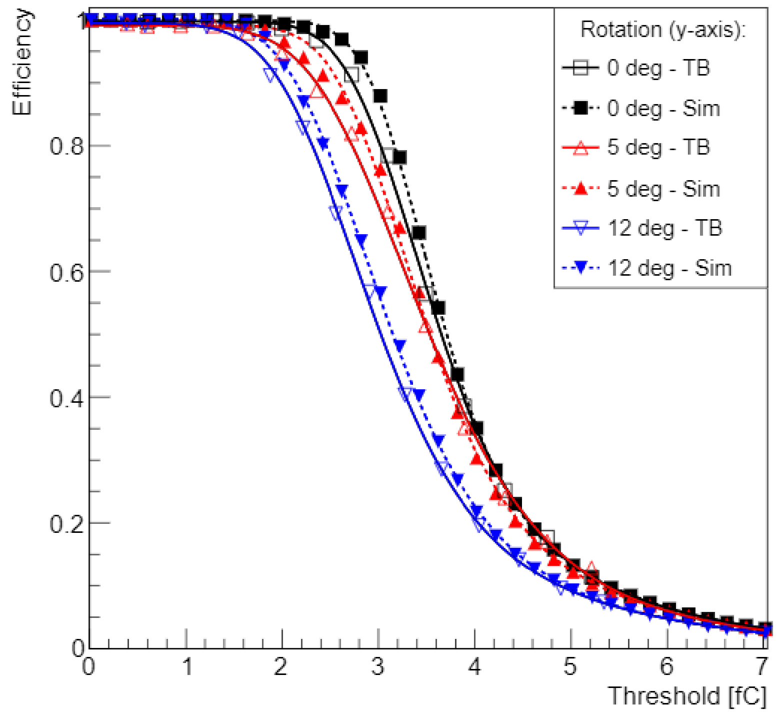


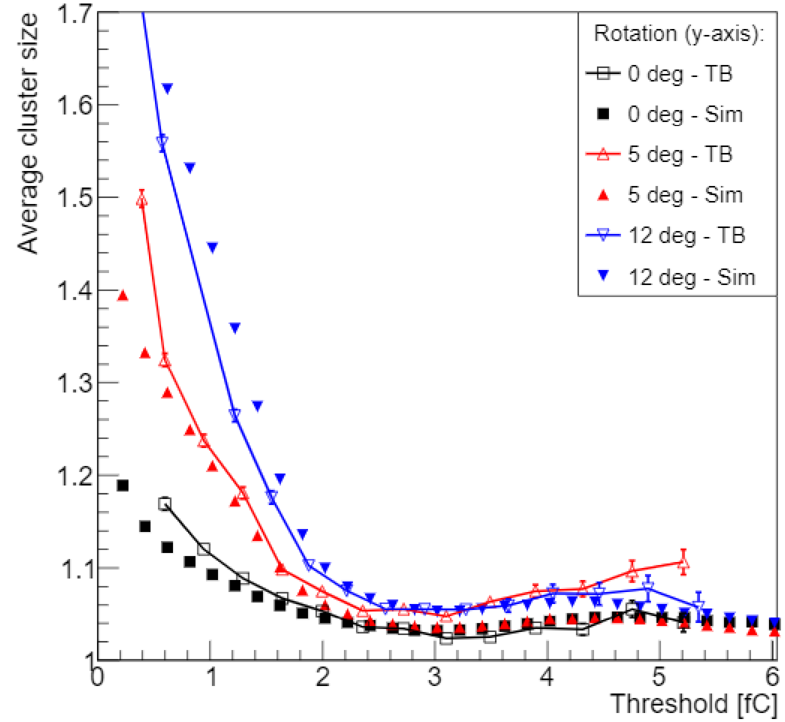
Median Charge (fC)	Full	Center	Edge
Perpendicular to the beam	3.65	3.72	3.37
12° to the beam	3.03	2.97	3.08

- Binary readout → infer charge collection in leading strip from threshold scan
- Charge sharing increases in centre at non-zero angles
- Edges shown:
  - lower median charge → charge sharing

Long Strip. Test Beam vs Simulation

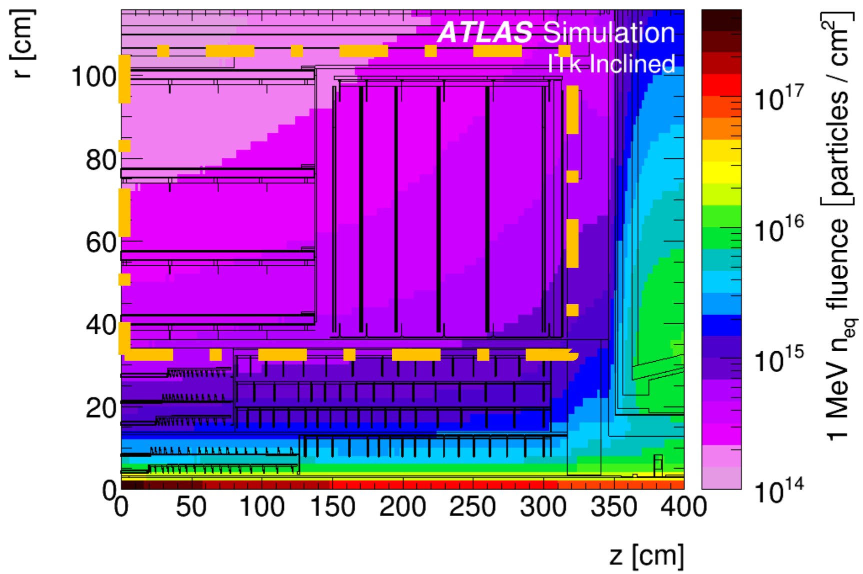
- Simulation of non-irradiated Long Strip Module using Allpix^2
  - Compared efficiencies and cluster size



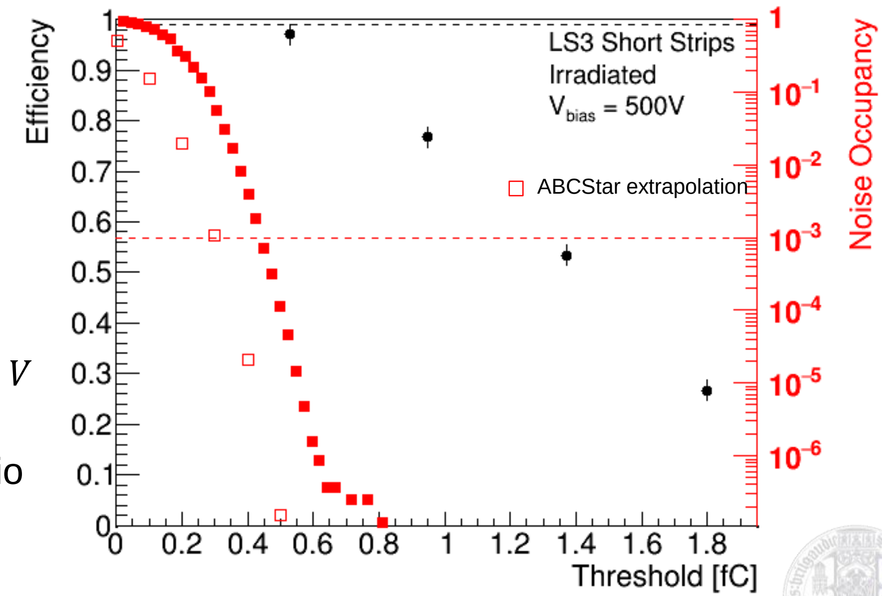


- Good agreement between test beam and simulation for all the efficiencies
- Preliminary result
  - New electric and weighting field maps are work in progress
  - Moving to "TransientPropagation" module of Allpix2

Irradiated ITk Strip Modules



- Testing of irradiated modules performance at the “end-of-life” expected fluence in the HL-LHC is a key point of the ATLAS upgrade project
- ITk requirements:
  - Efficiency $> 99\%$
  - Noise-occupancy $< 10^{-3}$
  - Signal-to-noise ratio > 10

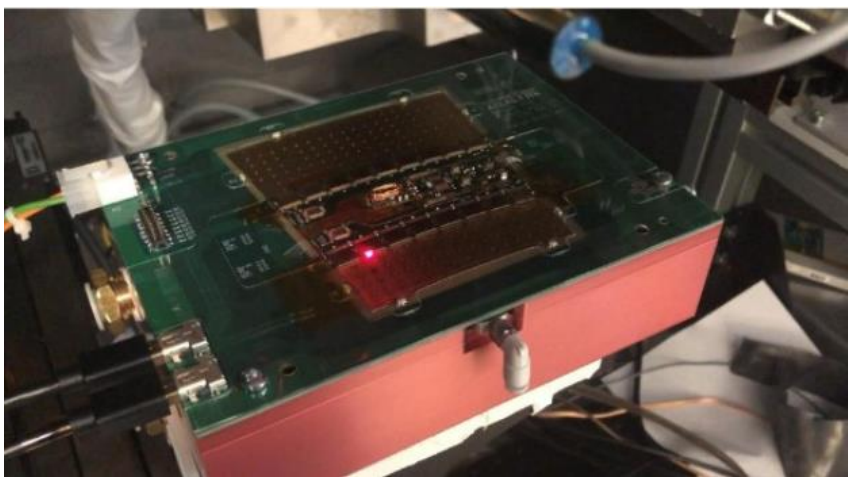


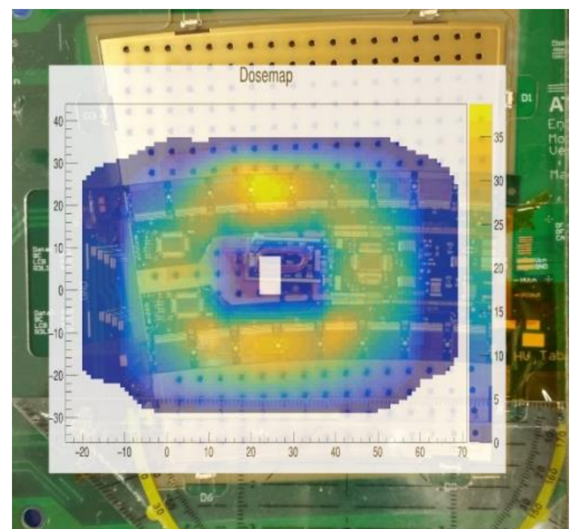
- LS3 module built 2016
  - Baseline for ITk strip TDR
  - ATLAS12 with long strips and ABC130
  - Proton irradiate to $8 \times 10^{14}\, n_{eq}/cm^2$
- No clear operational window for end-of-life for 500 V bias voltage
- TDR estimated sufficiently high signal-to-noise ratio by extrapolating to “Star”-readout chip

Irradiated ITk Strip Modules

- Typical irradiations:
  - Proton and neutron irradiation to the end-of-life fluence including safety factor of 1.4
  - X-ray irradiation of hybrids, chips and power boards

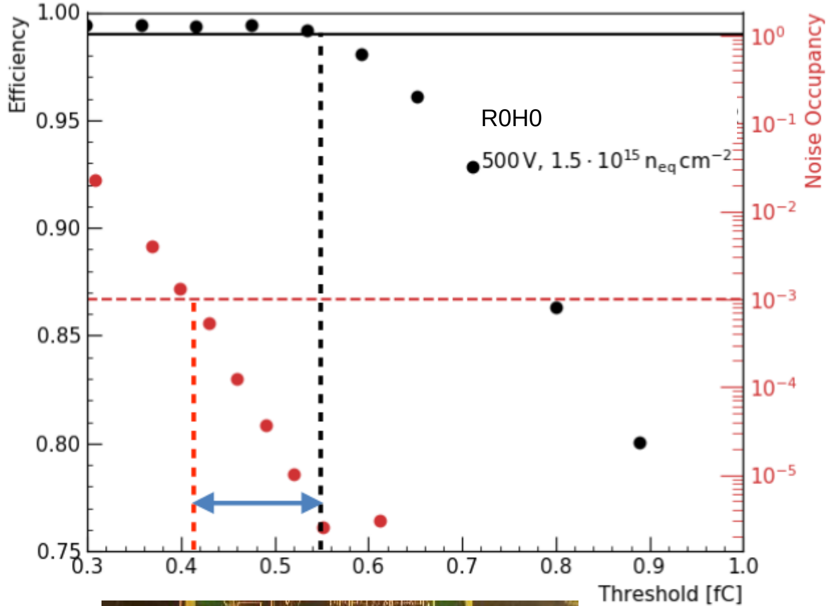
Module	Tested	Proton irradiation† $(10^{14}\, n_{eq}/cm^2)$	X-ray hybrids* irradiation $(Mrad)$
R0	June	15	35
Long Strip	September	5.1	25





† Only silicon sensor
*Fully populated hybrids (ABCStar, HCCStar)

Irradiated R0 Module

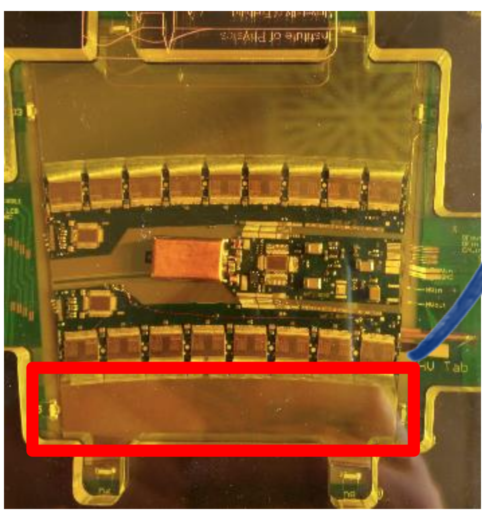


- Noise occupancy measured during test beam. In the lab, NO usually lower (from experience)
- ITk modules requirement: operating window where hit detection efficiency $> 99\%$ and Noise occupancy $< 0.1\%$

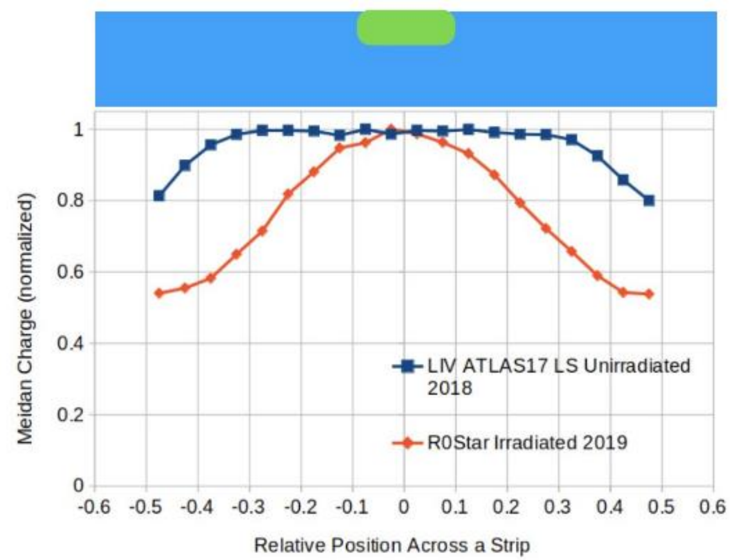
Between $\sim 0.4 - 0.55\ fC$

Requirements are satisfied!

- Increased charge-sharing compared to non-irradiated modules

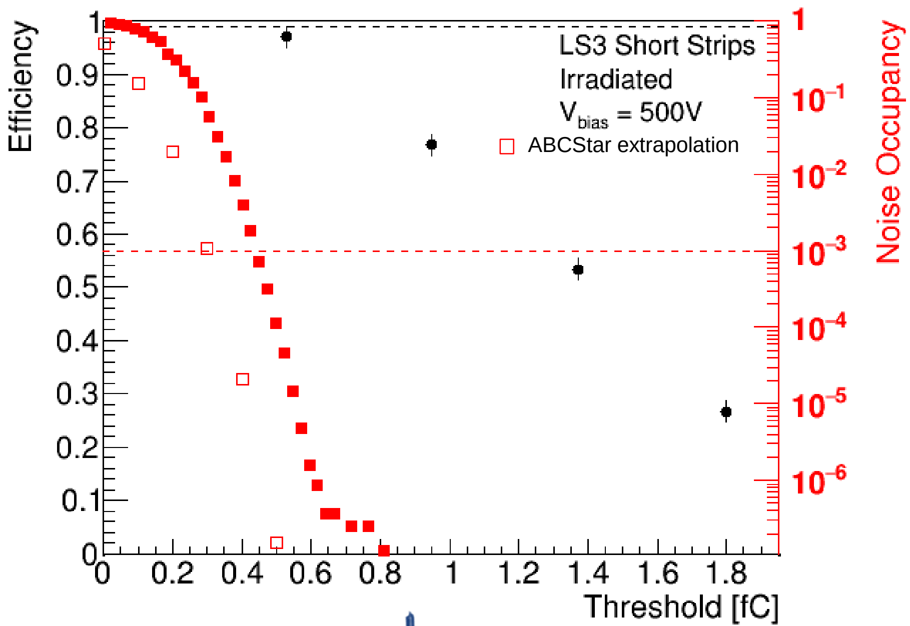


Innermost segment in endcap

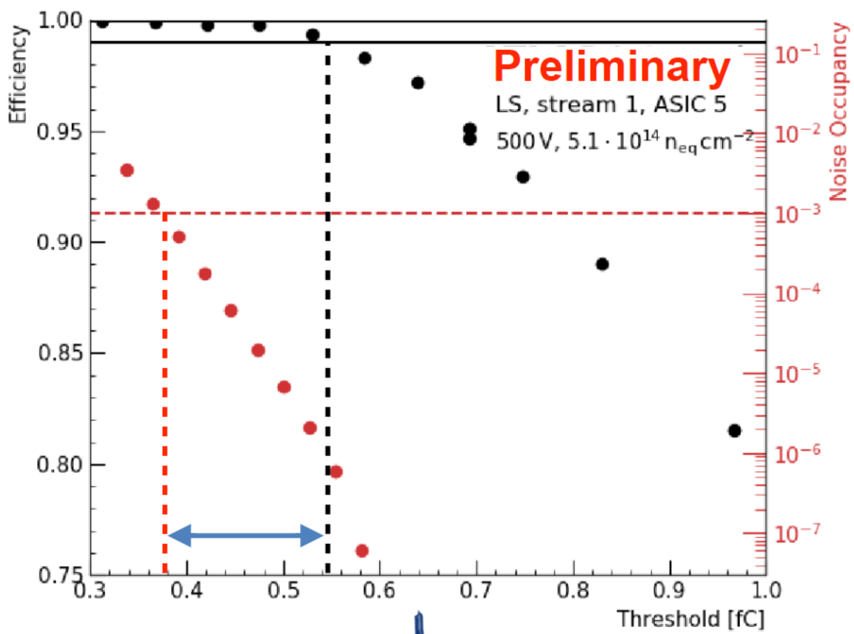


Irradiated Long Strip Module

2017 ITk Strip TDR



June 2019



No clear operational window
Requirements not satisfied

Between $\sim 0.37 - 0.55\ fC$
Requirements are satisfied!

Signal-to-noise ratio

- From experience it has been proven that a signal-to-noise ratio higher than 10 guarantees the existence of an operational window where the efficiency ($> 99\%$) and the noise occupancy ($< 0.1\%$) requirements are satisfied.

Module (ABCStar)	Signal [fC] (e.)	S/N
Unirrad. LS (400 V)	3.28 (20500)	23.8
Unirrad. R0S (400 V)	3.28 (20475)	29.3
Irrad. R0 innermost ring (500 V)	1.65 (9281)	14.8
Irrad. R0 second ring (500 V)	1.71 (9619)	13.2
Irrad. R0 third ring (500 V)	1.80 (10125)	11.9
Irrad. R0 outermost ring (500 V)	1.84 (10350)	11.6
Irrad. LS (500 V)	1.59 (9956)	15.9

It is clear that all the modules with the ABCStar readout chip tested satisfied the requirements!

Summary

- 2019 was a very busy year for the ITk Strip Test Beam group:
  - Three successful test beam campaigns
  - More than 5000 runs of data-taking
  - Tested both, barrel and endcap modules including irradiated ones
- Tracking resolution, hit efficiencies and noise occupancies are within expectation and are well understood
- Results from irradiated modules prove that the operational requirements of efficiency and noise occupancy of the ITk strip detector are satisfied
- 2020 will be a very exciting year for the ITk Strip Test Beam group
  - Study of other endcap geometries
  - Larger scale structures like a petal or several strip layers in series

Summary

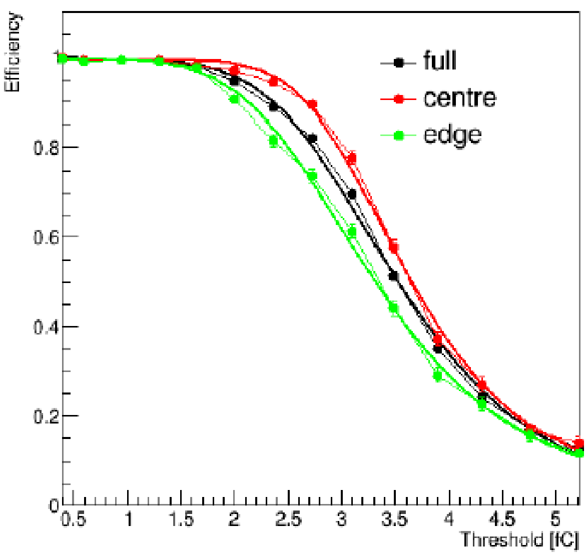
“A successful test beam campaign is not possible without a big team effort”

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 654168

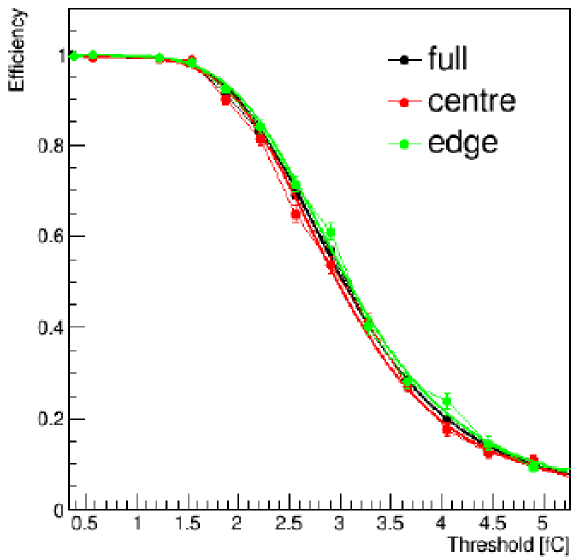
AIDA 2020

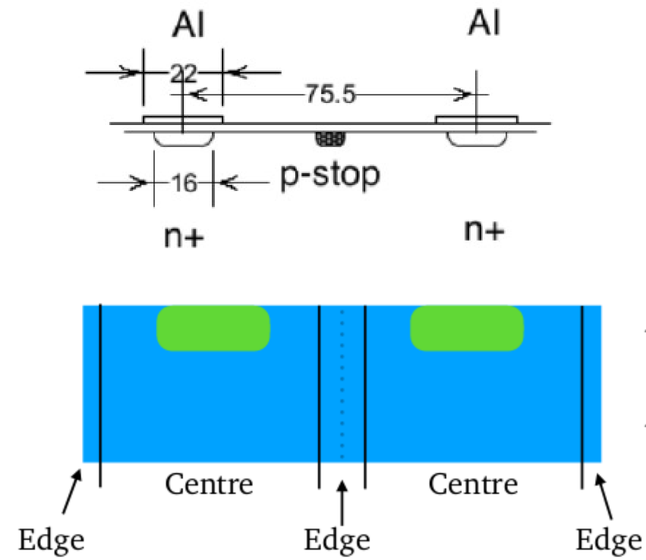
Backup

5 degrees



12 degrees

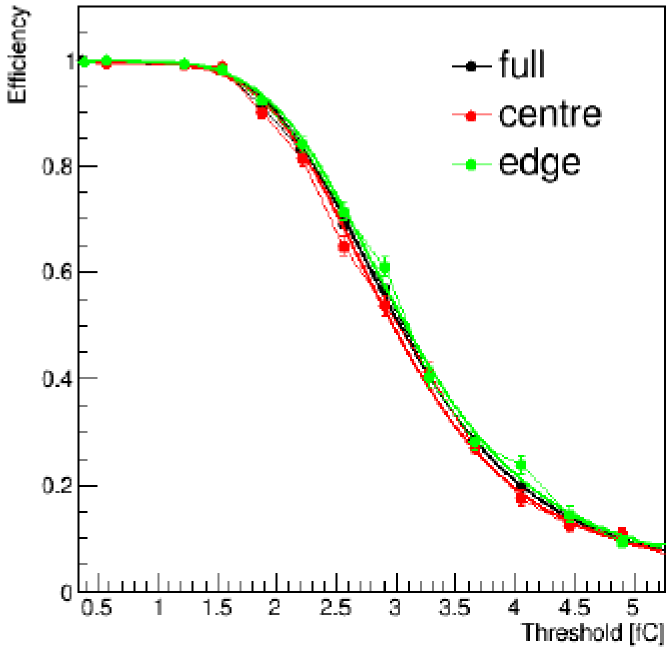


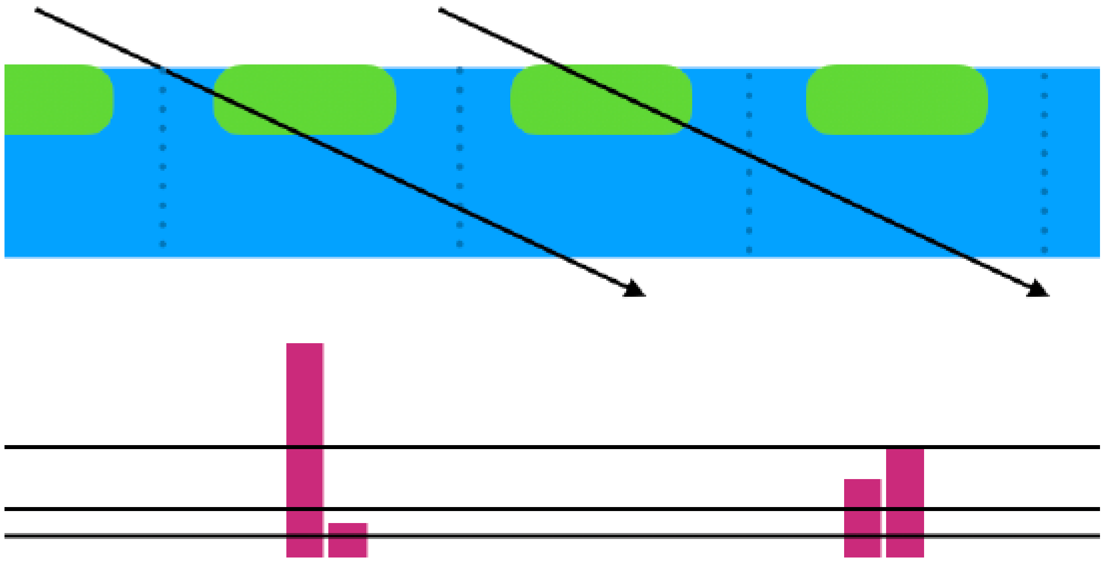


- The edge area is defined as $7.5\ \mu m$ from the edge of a strip
- Total edge area for two neighbouring strips is $15\ \mu m$

Backup

12 degrees





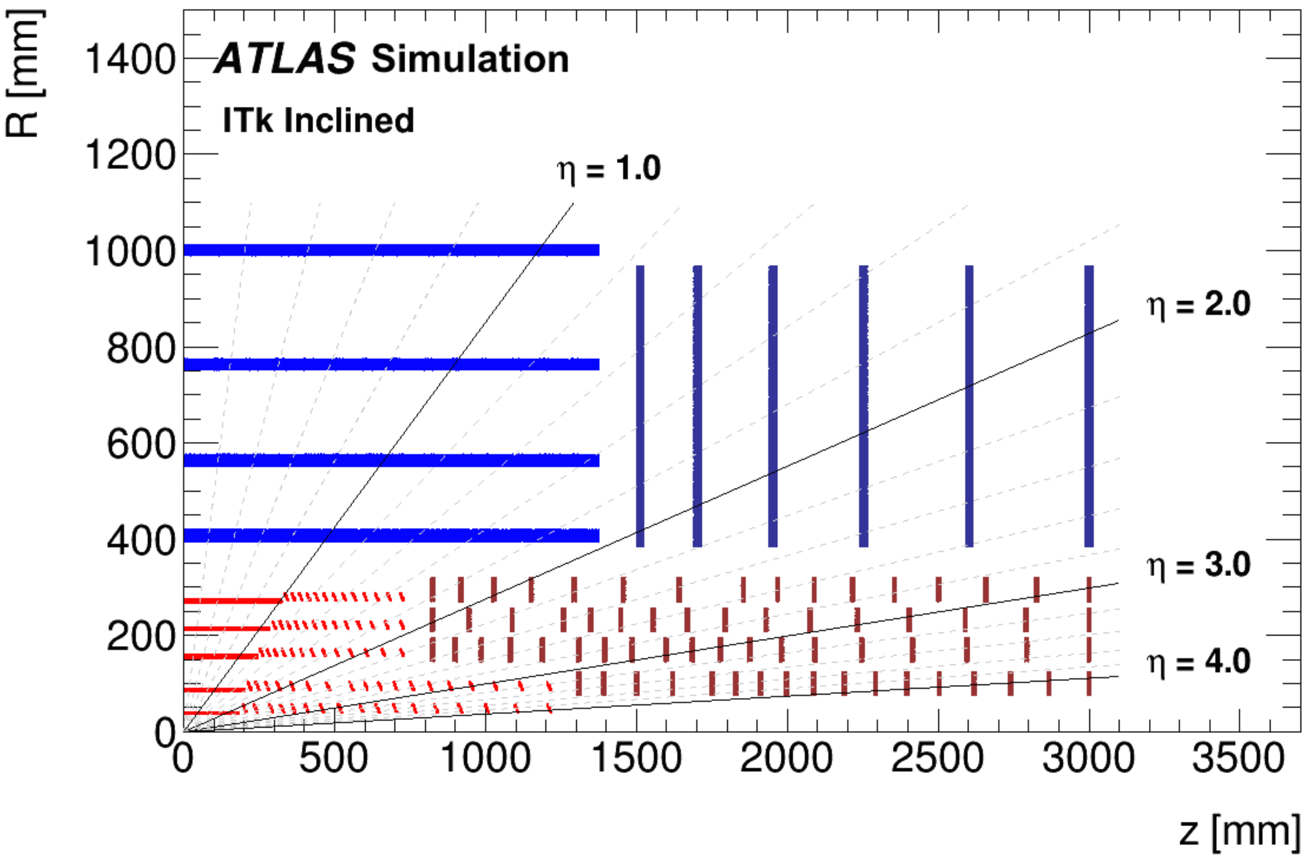
- Two tracks that have identical angles but different incident inter-strip hit positions have different charge divisions between strips
- At large angles, if the track first hits at the edge of a strip the path length could be mostly through one strip and only a small fraction through a neighbouring strip
- If the track hits in the centre of a strip the path could be through 2 strips and the charge division can be more equal
- This leads to the corners being more efficient than the centre of the strip for tracks at a large angle
- Opposite behaviour to perpendicular tracks

Backup

Simulations performed using Allpix2 Framework

- Simulation of a simplified LS module:
  - Every strip is a 10 cm long block of silicon with strip pitch 75.5 µm
  - Sensor thickness is simulated at 270 µm
  - This gives a better agreement with test beam data
  - Active thickness of the HPK 300 µm thick sensor could be anywhere from 270µm upwards — still under investigation
- Simulating 50000 electrons with an energy 4.4 GeV
- Efficiency and Mean cluster size plots are obtained for different track angles to compare with test beam data

Backup



ATLAS Simulation
ITk Inclined
η = 1.0
η = 2.0
η = 3.0
η = 4.0
R [mm]
z [mm]
0
200
400
600
800
1000
1200
1400
0
500
1000
1500
2000
2500
3000
3500