The ATLAS Strip Detector System for the High-Luminosity LHC

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On behalf of the ATLAS ITk Strip Community

Instrumentation for Colliding Beam Physics

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Albert-Ludwigs-Universität Freiburg

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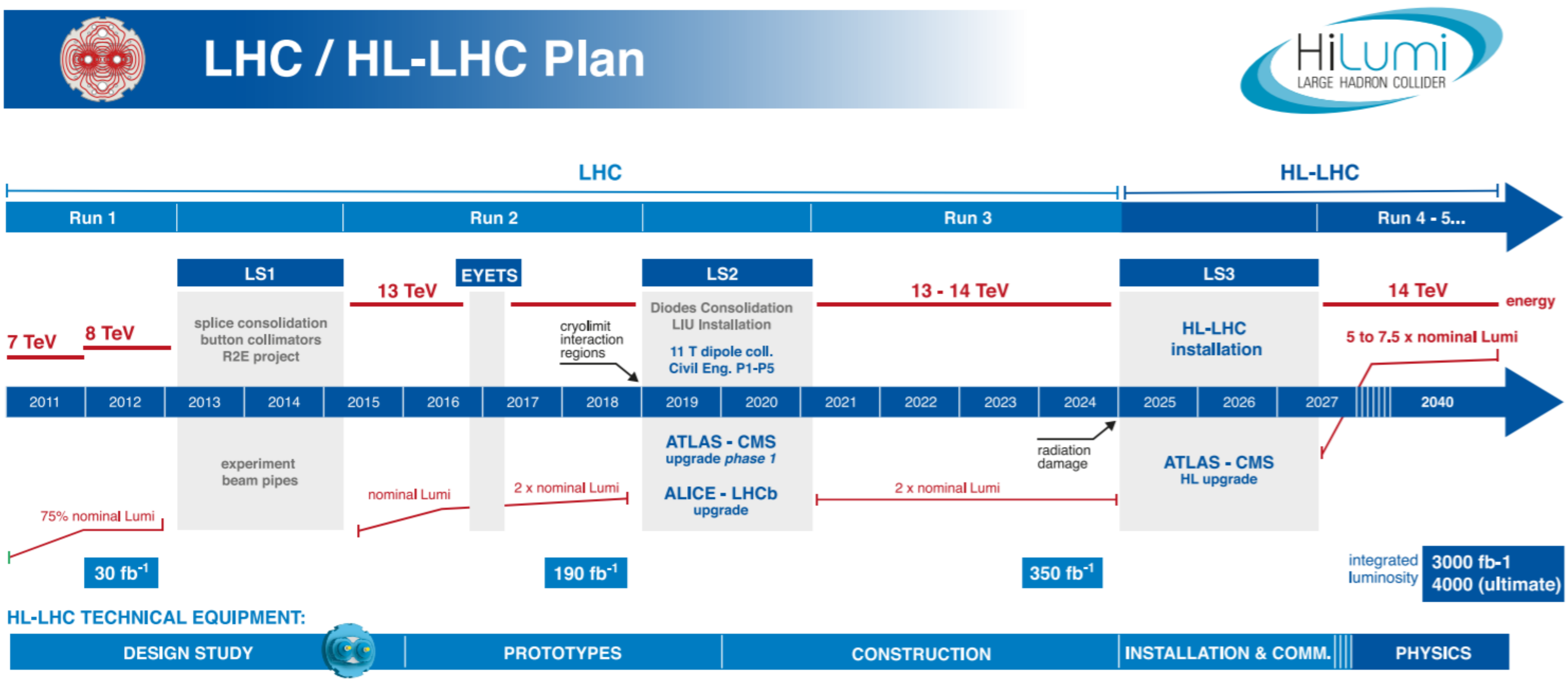
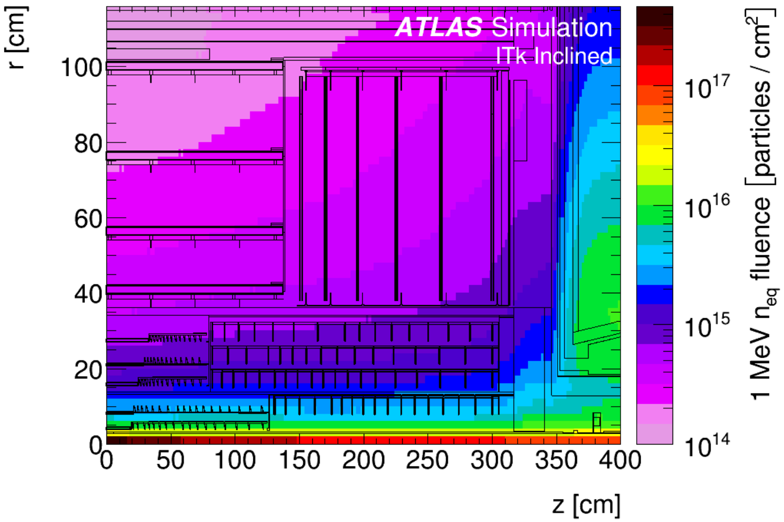
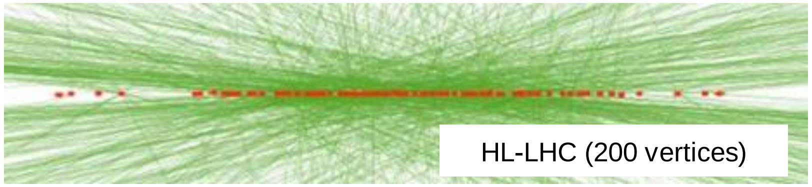
Future of the LHC

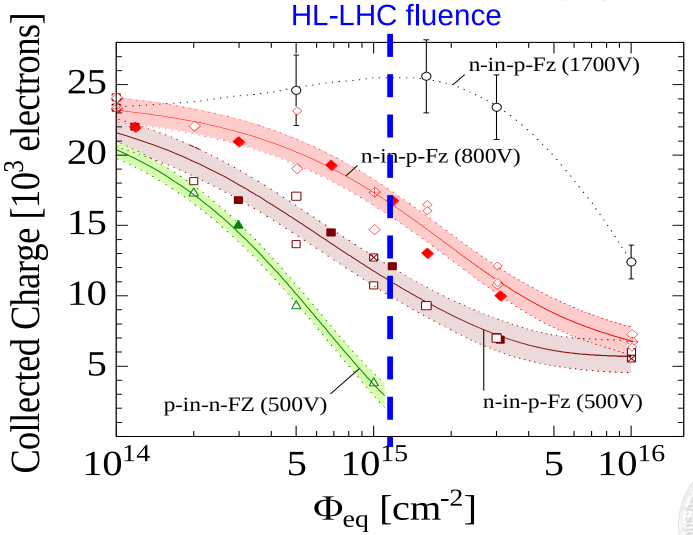


ATLAS upgrade. Why?

- HL-LHC $\mathcal{L}_{int} \sim 4000\ \text{fb}^{-1}$
  - Requires increased radiation hardness
- Pile-up from ~ 50 to ~ 200
  - Requires increased granularity to maintain the current performance
- Faster readout, higher data bandwidth
- Increase $|\eta|$ coverage of tracking to 4

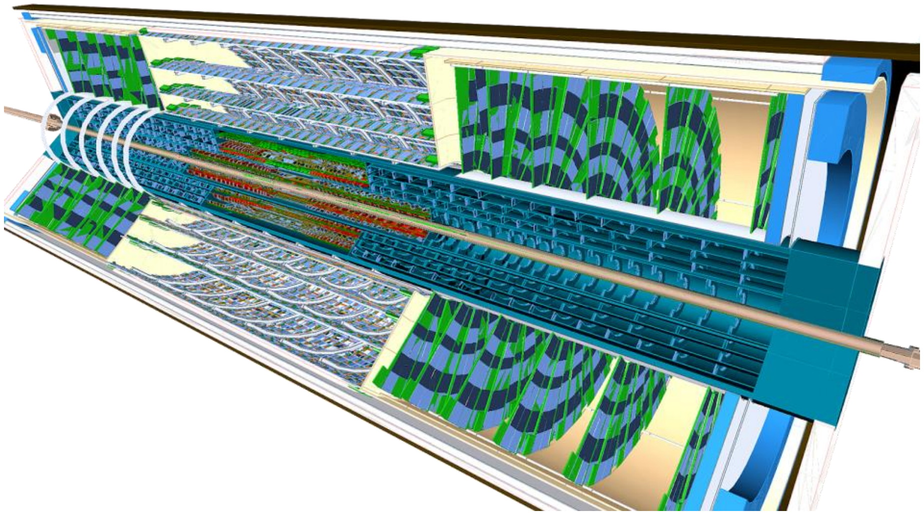






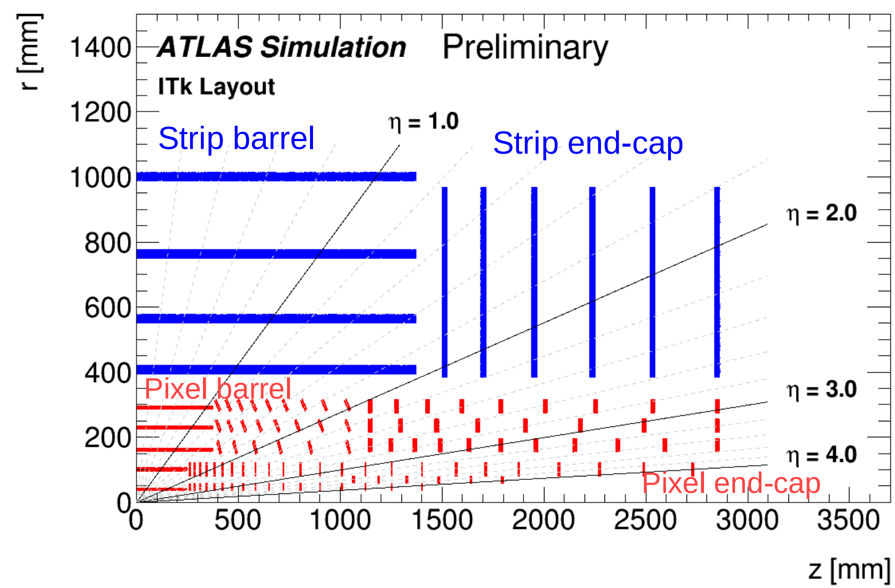
New all-silicon Inner Tracker (ITk)

ATLAS ITk Strip Detector



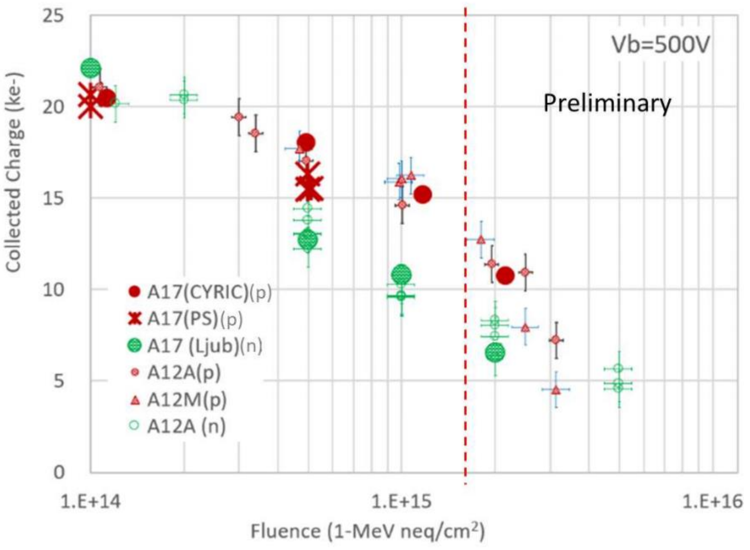
- ITk Detector
  - All-silicon tracking detector
  - Pixel and strips
  - Total area of silicon ~180 m^2
  - 10 times the current number of readout channels

- ITk Strip
  - Barrel and end-caps follow same design philosophy
  - Single-sided modules on both sides of a carbon support structure



ITk Strip Sensor

- ~300 μm thick n^+-in-p float zone (FZ) silicon sensors
- Required to be radiation tolerant up to
  - $1.6 \times 10^{15}\ n_{eq}/cm^2$
  - 81 Mrad
- Bias voltage 100 – 500 V (depending on radiation damage)

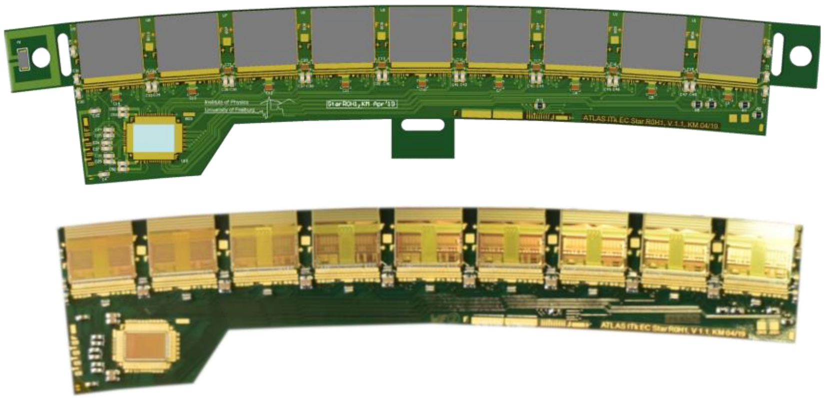


Barrel	End-cap
Rectangular $\sim 97 \times 97\ mm^2$ Parallel strips	Trapezoidal shape ($R - \phi$ coverage) Radial strips
pitch $75\ \mu m$ 2 designs (Short Strips, Long Strips) Strip length 4 rows $24\ mm$, 2 rows $48\ mm$	pitch 70 – 81 μm 6 designs R0-R5 Strip length 15 – 60 mm

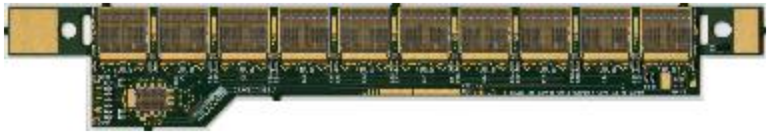
Hybrids, Front-End

- Hybrids
  - 4 layer Kapton PCB
  - Front-end ASICs (ABCStar)
    - Binary hit determination
    - Stores events until requested
  - Aggregation ASIC (HCCStar)
    - Communicates with up to 640 Mbits
    - Clock-control-readout requests are provided to all ABC
- Powerboard
  - Converts 11 to 1.5 V for hybrids
  - Autonomous monitor and control chip (AMAC)
    - Measures temperatures, voltages, currents
    - Controls LV, power states, switch off HV

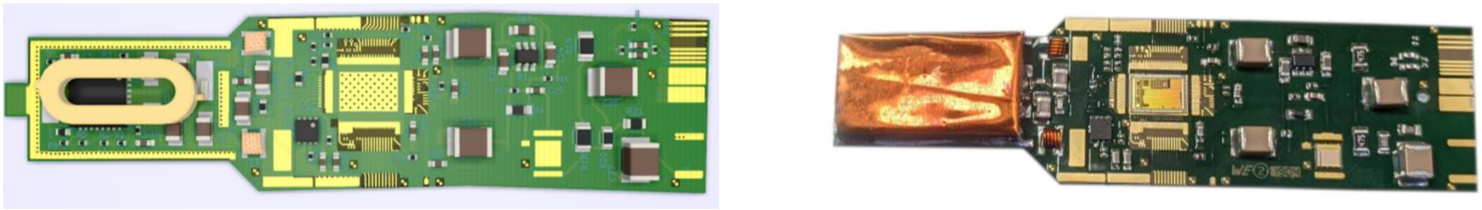
R0 End-cap hybrid: Curvature follows sensor geometry



Barrel hybrid



End-cap powerboard

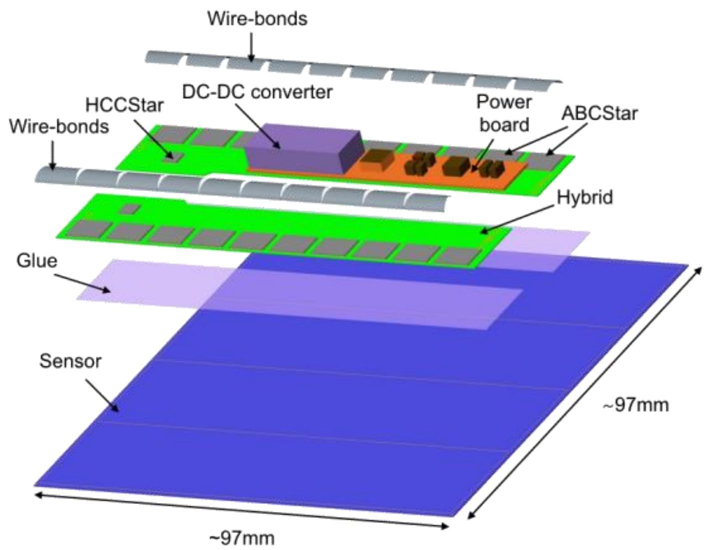


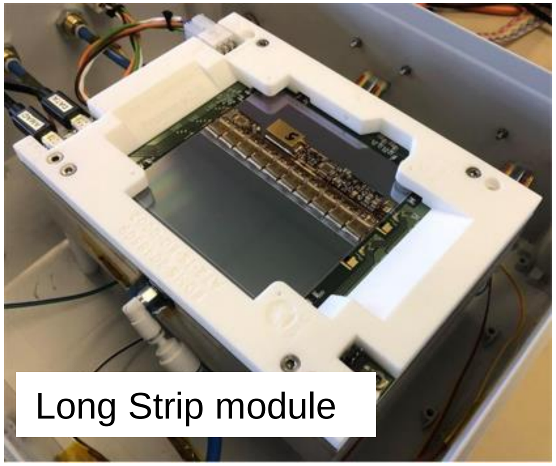
ITk Strip Module

- Silicon sensor
- Hybrids and powerboard glued directly on the sensor
- Wire bonds for connections (25 μm aluminium)
- Modules glued and wire-bonded to stave/petals

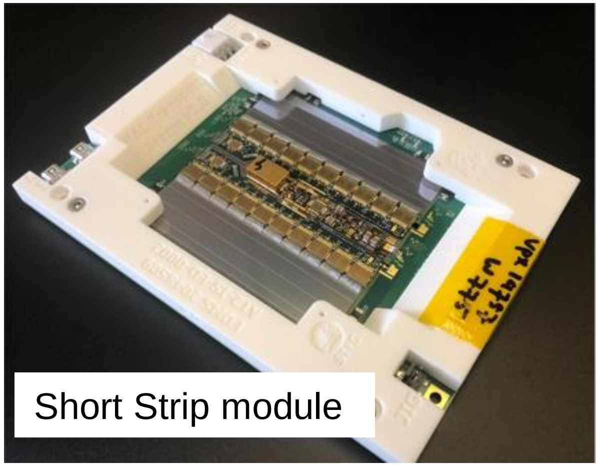
17,888 strip modules required (barrel + end-cap)

Module design following mass production scheme with dedicated tools for module assembly

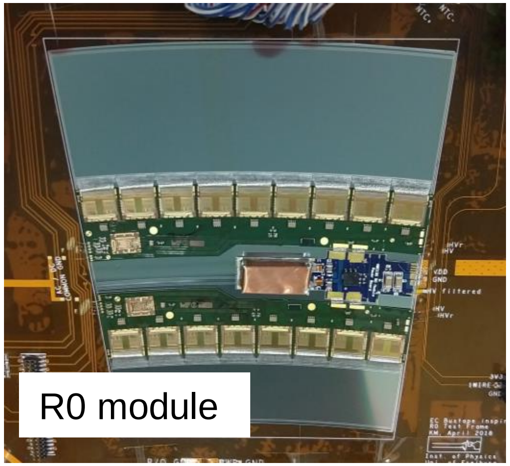




Long Strip module



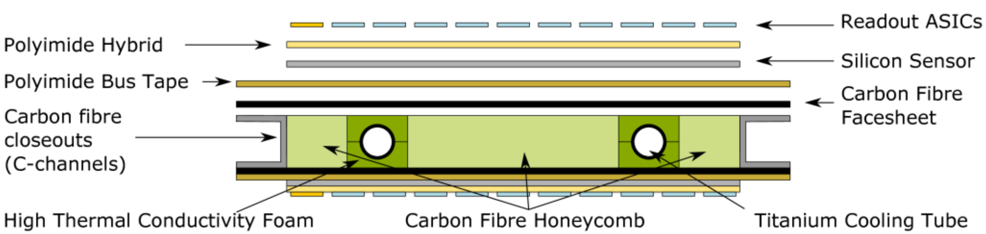
Short Strip module



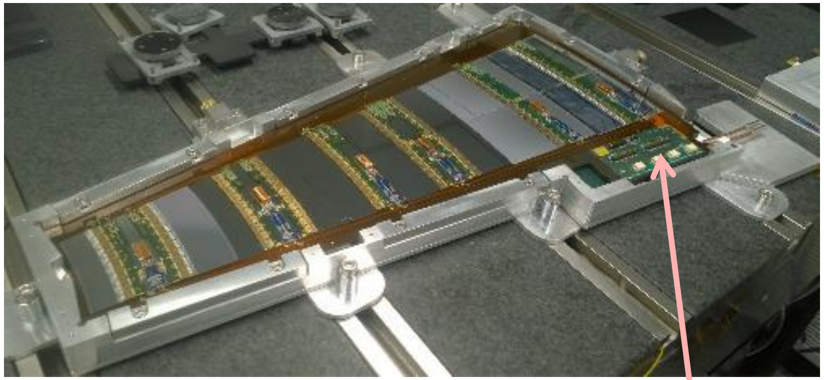
R0 module

ITk Module Support

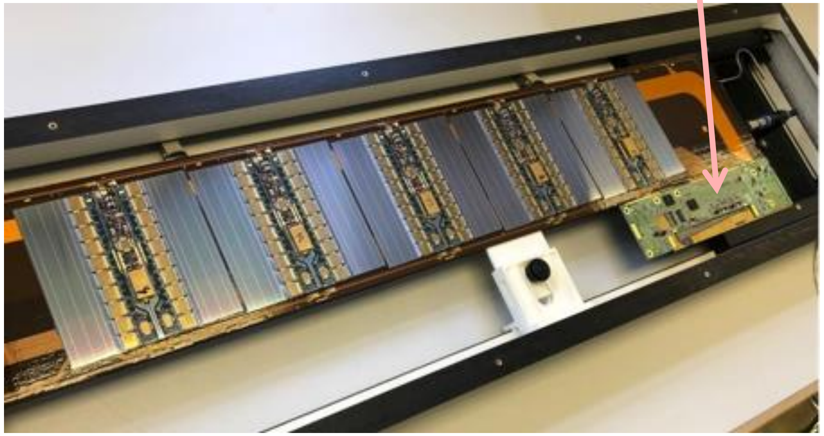
- Mechanical support (low-mass carbon-fiber)
  - Staves (Barrel) and Petals (for the End-Caps)
  - Common electrical, optical and cooling services
- Cooling via embedded Titanium tubes with evaporative CO_2 cooling (at -35°C)
- Copper/kapton co-cured bus tape (power, TTC, data, detector control system)
- Interface between staves and petals with the off-detector electronics through the End-Of-Substructure Card (EoS)



End-cap loaded support structure (petal)

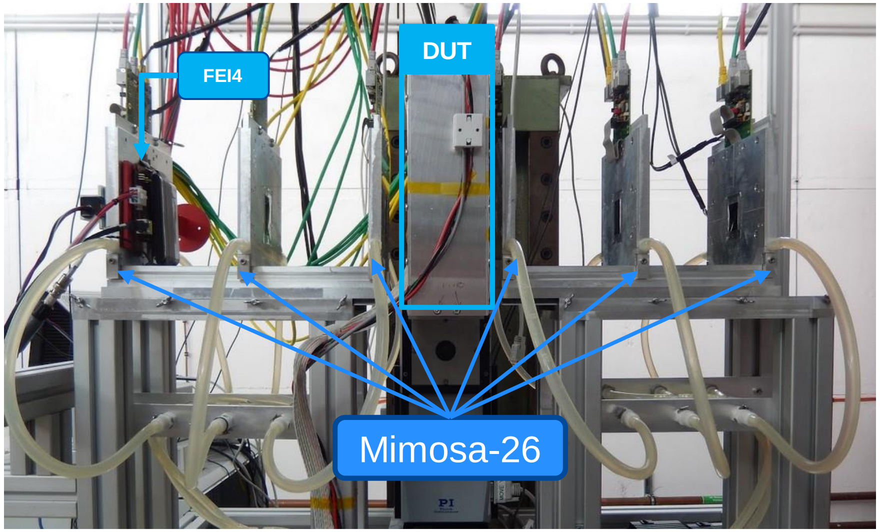


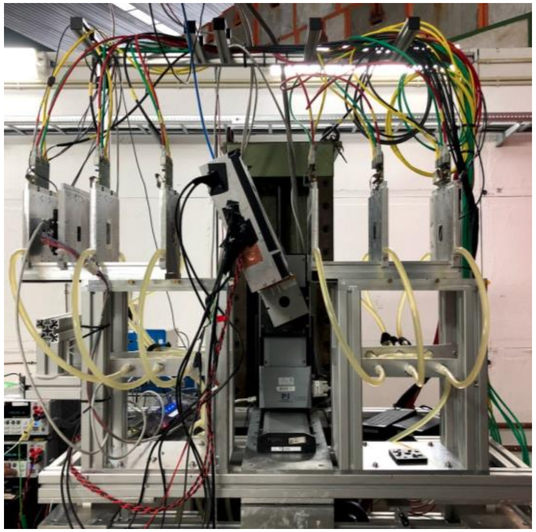
EoS Card on an “ear” of the support structures



Barrel loaded support structure (stave)

Module testing at test beams





- 4.4 GeV electron beam @DESY
- 120 GeV Pion beam @CERN SPS
- EUDET-type telescope resolution:
  - 5-10 µm @DESY
  - 3-5 µm @CERN
- Track time tagging from telescope with USBPix system with FE-I4 chip.
- Dry ice cooling box used for irradiated modules

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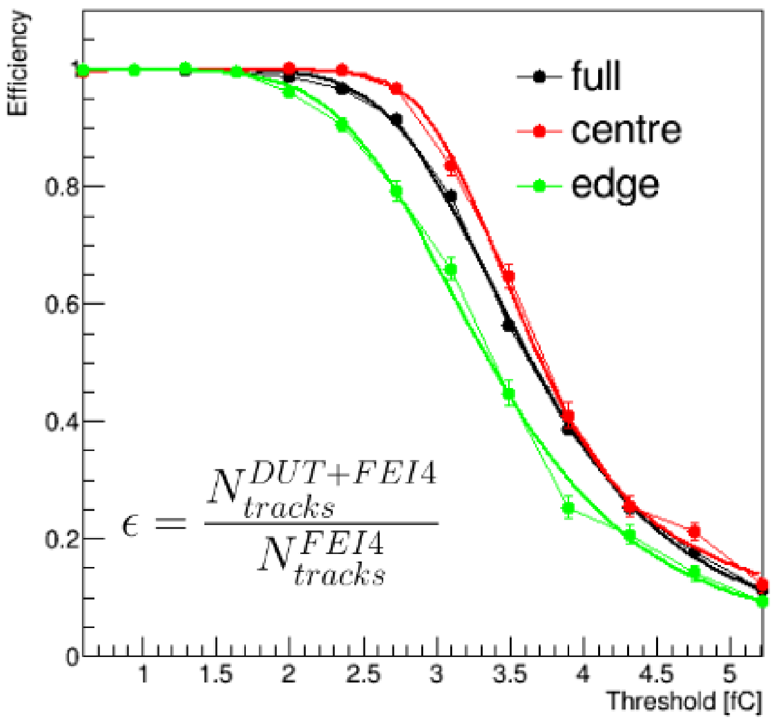
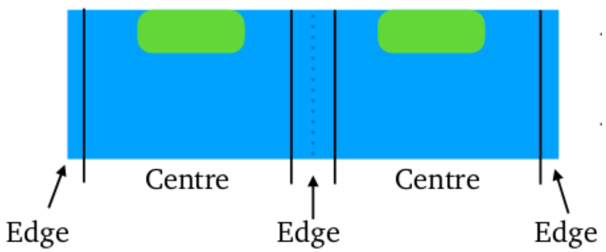
Module testing. Long Strip

- Module built using ATLAS17LS sensor and ABCStar chipset
  - Strip pitch 75 μm
  - Implant size 16 μm
  - Aluminum strip 22 μm





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

- Binary readout → infer charge collection in leading strip from threshold scan
- Edges shown:
  - lower median charge → charge sharing

Median Charge (fC)	Full	Center	Edge
Perpendicular to the beam	3.65	3.72	3.37

Module Testing. Irradiated Long Strip

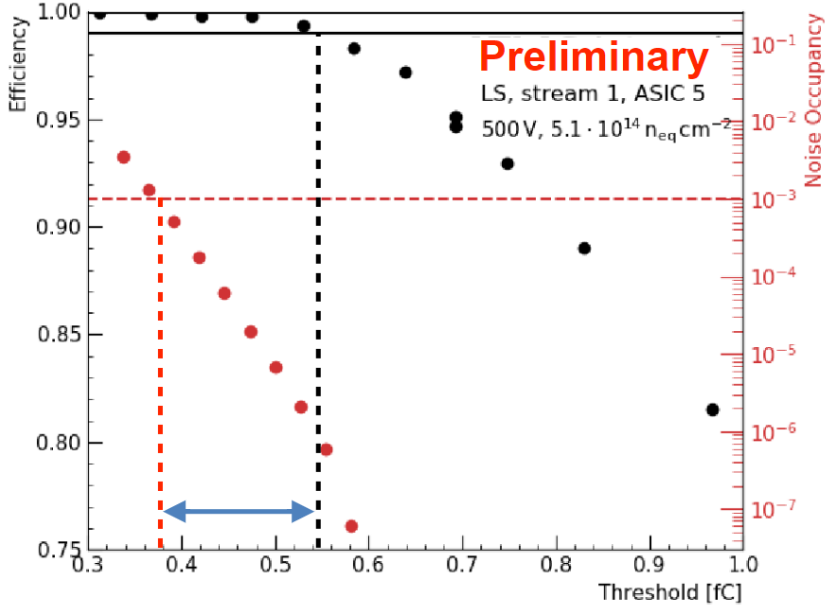
- Testing of irradiated modules performance at the “end-of-life” expected fluence in the HL-LHC is a key point of the ATLAS upgrade project

ITk requirements:

Efficiency	$> 99\%$
Noise-occupancy	$< 0.1\%$
Signal-to-noise ratio	> 10

Proton irradiated sensor to $\mathbf{5.1 \times 10^{14}\ n_{eq}/cm^2}$

Gamma irradiated hybrids to $\mathbf{25\ Mrad}$



Between $\sim 0.37 - 0.55$ fC
Signal-to-noise ratio 15.9

Requirements are satisfied!

Module Testing. Irradiated R0

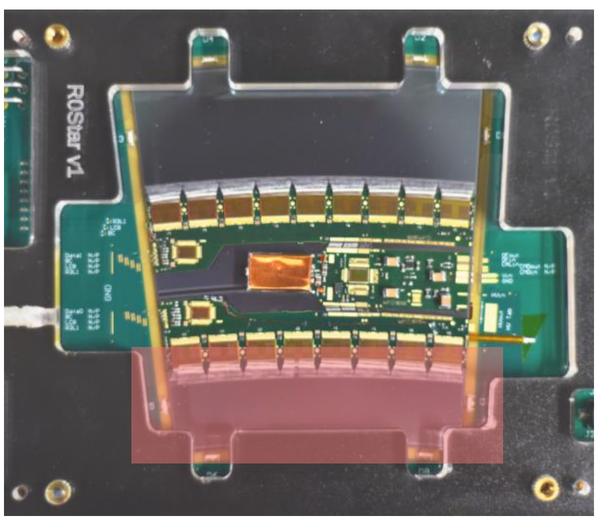
- Testing of irradiated modules performance at the “end-of-life” expected fluence in the HL-LHC is a key point of the ATLAS upgrade project

ITk requirements:

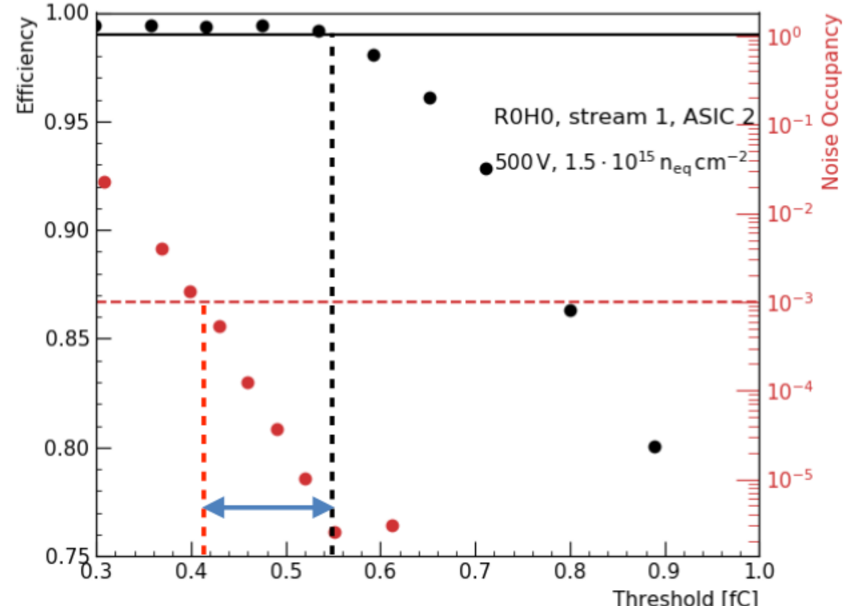
Efficiency	$> 99\%$
Noise-occupancy	$< 0.1\%$
Signal-to-noise ratio	> 10

Proton irradiated sensor to $\mathbf{1.5 \times 10^{15}\ n_{eq}/cm^2}$

Gamma irradiated hybrids to $\mathbf{35\ Mrad}$



Innermost segment in endcap

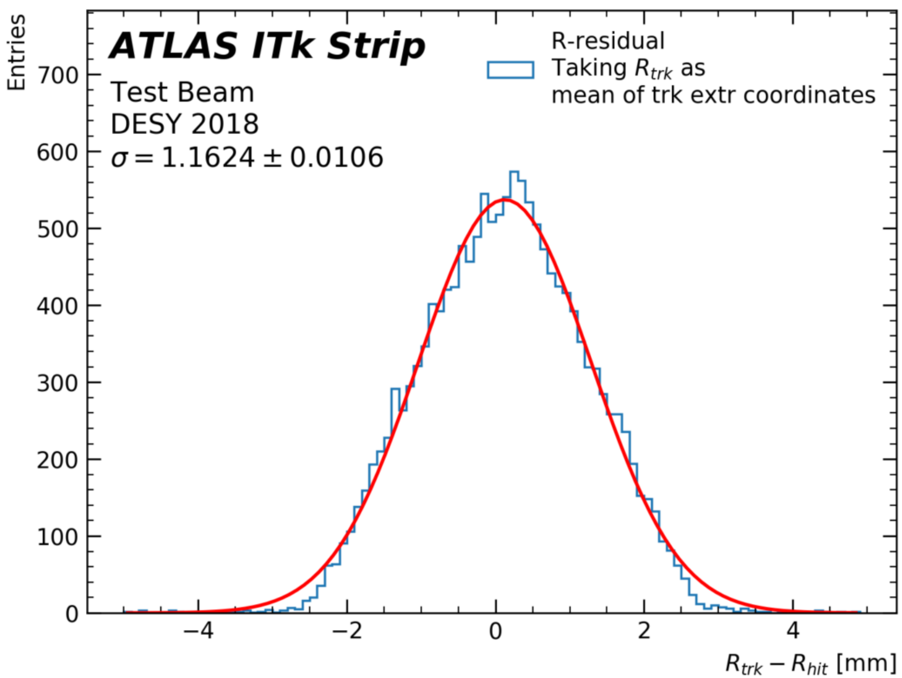


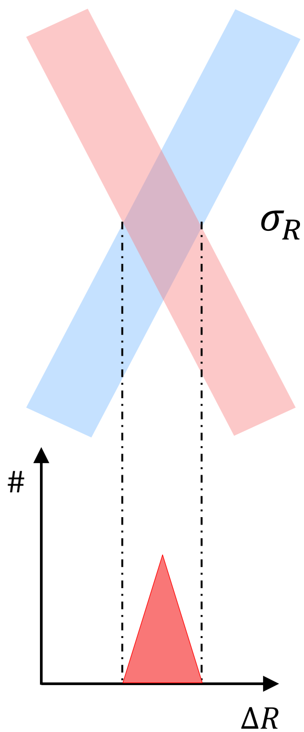
Between $\sim\mathbf{0.4 - 0.55\ fC}$
Signal-to-noise of 11.7

Requirements are satisfied!

Module testing. Double-sided R0

- First double-sided ITk module prototype
- Stereo angle allows reconstruction of space points
  - Expectation for resolution of ITk strip detector: $540\ \mu\mathrm{m}$ in direction “along" strips
- Stereo angle α below nominal - 31 instead of $40\ \mathrm{mrad}$. Only two layers at test beam





$$\sigma_R = \frac{p}{\sqrt{24}\sin\phi/2} \approx 1.1\ \mathrm{mm}$$

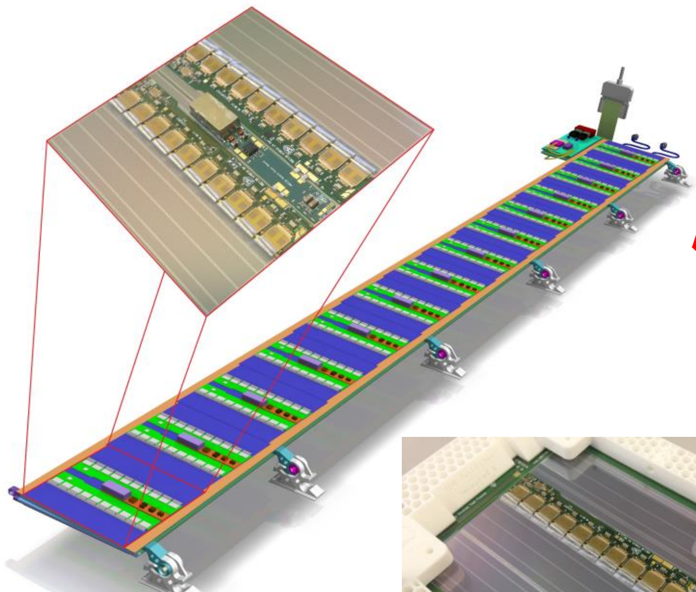
Summary and conclusions

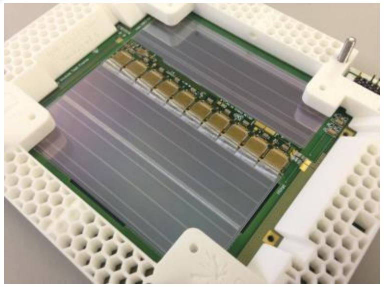
- Results from sensor, readout, and module testing are well within the specification
- Irradiated modules prove:
  - Operational requirements of efficiency and noise occupancy of the ITk strip detector are satisfied
- After 15 years of designing, building prototypes, and testing we are confident the ITk Strip detector will be able to deliver the desired performance under the HL-LHC conditions
- Preproduction starts this year
  - Plenty of production components to test
- More that 20000 modules to build during production

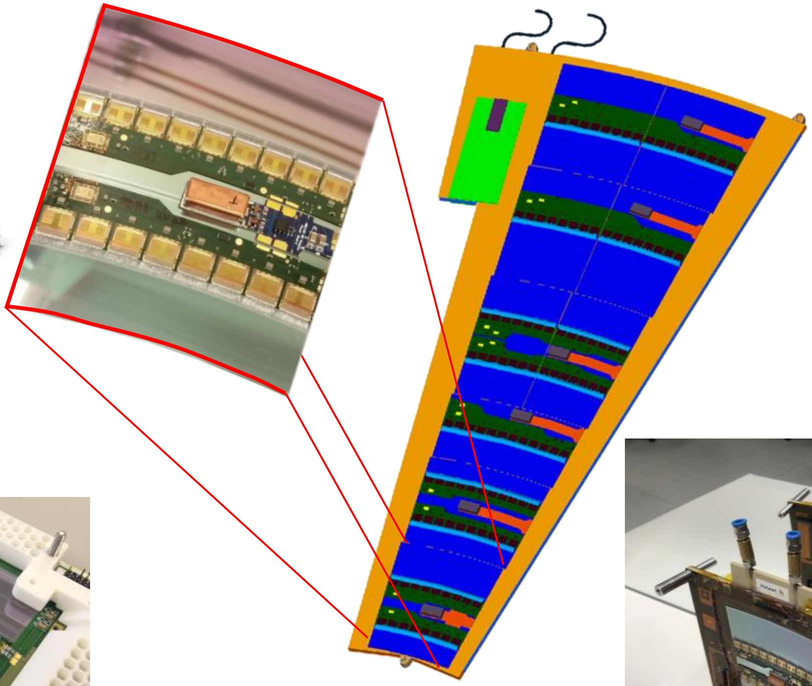
Thanks

Backup Slides

- 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

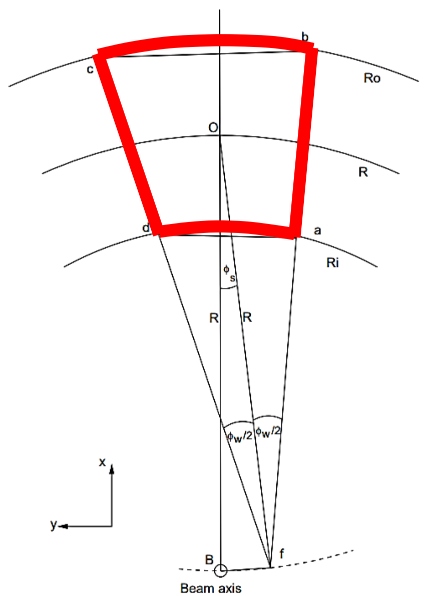






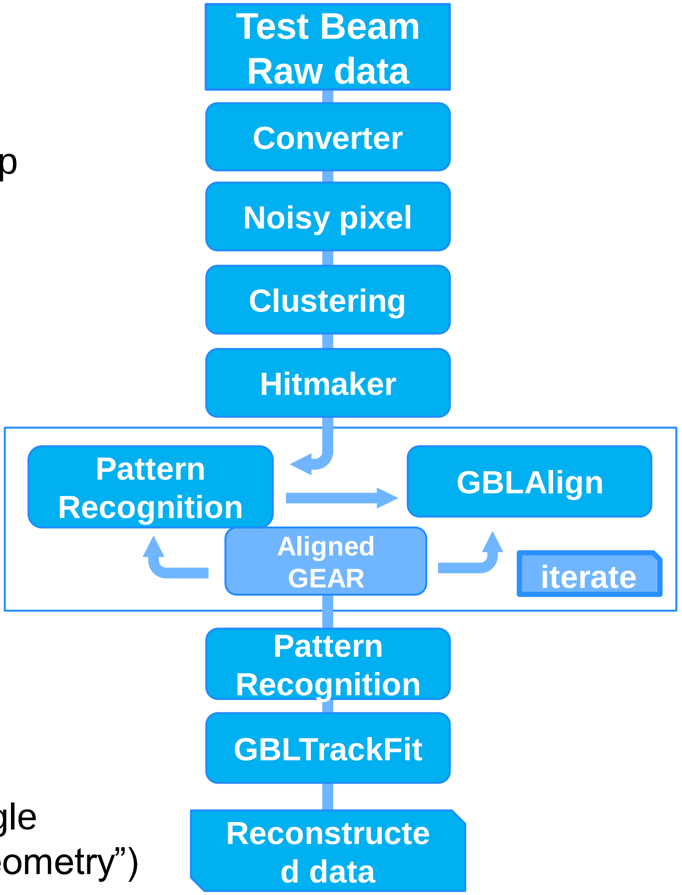
Data Reconstruction and Analysis

- 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

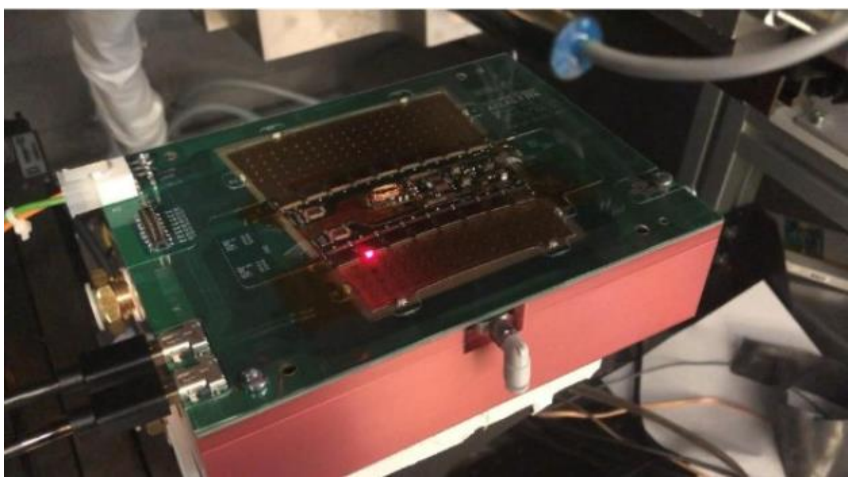
- Have in-sensor stereo angle implementation ("radial geometry")
- Custom EUTelescope modifications

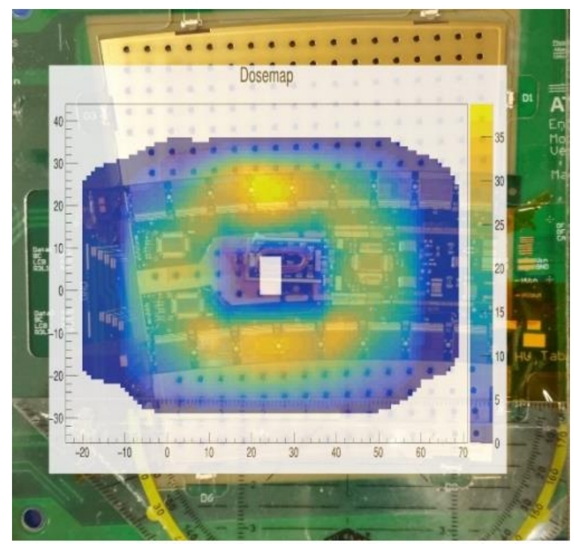


Irradiated ITk Strip Modules

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





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

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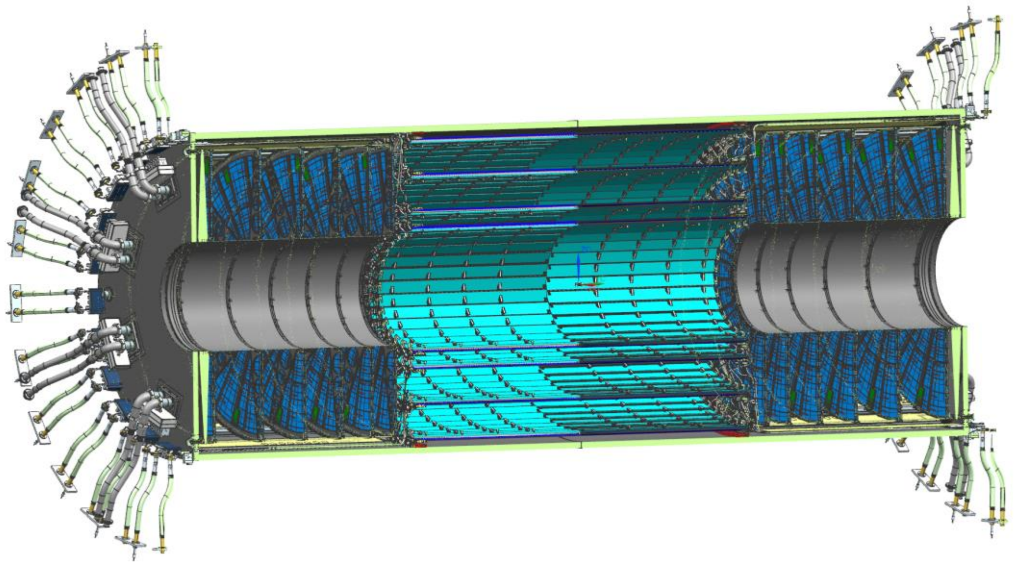
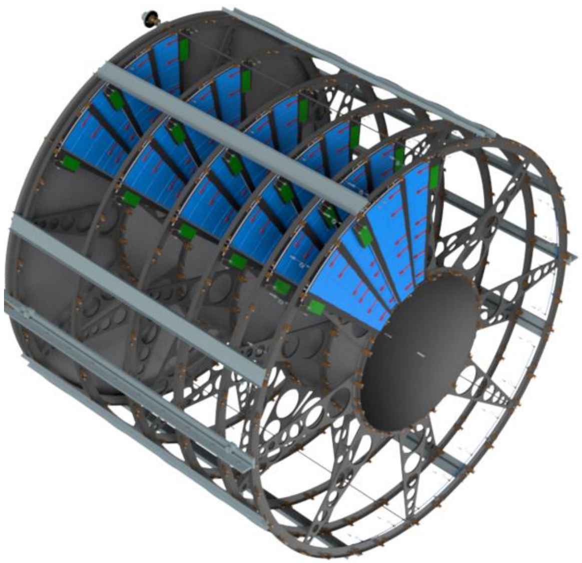
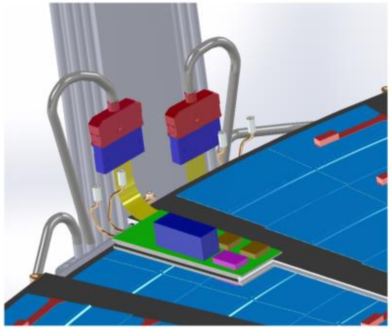
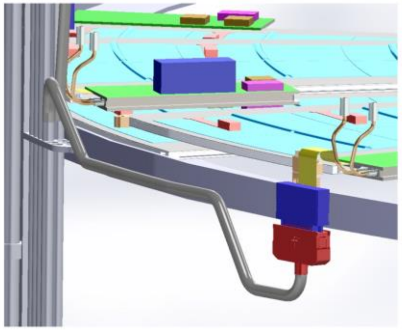
ITk Module Global Support



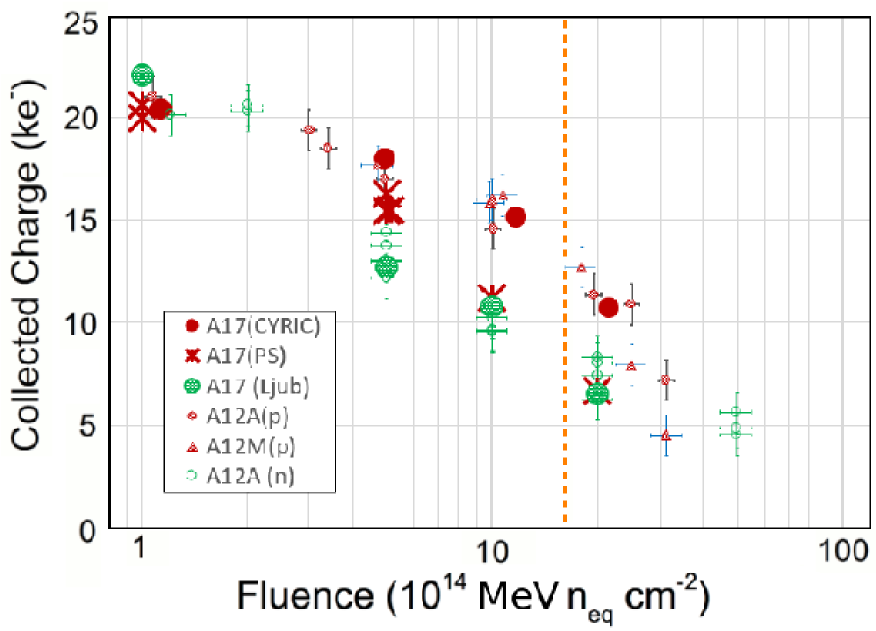


- Cylinders in barrel and disks in end-cap region provide structural support for insertion of staves and petals, respectively
- Services (cooling lines and cables) via interface at end of structures.





ITk Sensor Irradiation Tests



- Full-sized sensors have undergone an extensive irradiation (protons, neutrons, pions and gammas) tests at the expected end-of-life dose $2 \times 10^{15}\ \mathrm{n_{eq}}\ /\mathrm{cm}^2$ and $70\ \mathrm{Mrad}$
- At expected fluence still signal larger than 10,000 electrons compared to expected noise values of below 1,000 electrons
- Signal-to-noise ratio within design specification
- Good agreement for neutron and fair for proton irradiation between averaged results of A12 and A17 sensors

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!

Stereo Annulus Geometry of EC Sensors

- Stereo angle directly implemented in the sensor (20 mrad)
- Non-parallel strips
- No stereo angle implementation in module assembly required (total 40 mrad)