ATLAS ITk Pixel Detector

An Overview

Leonardo Vannoli

On behalf of the ATLAS Collaboration

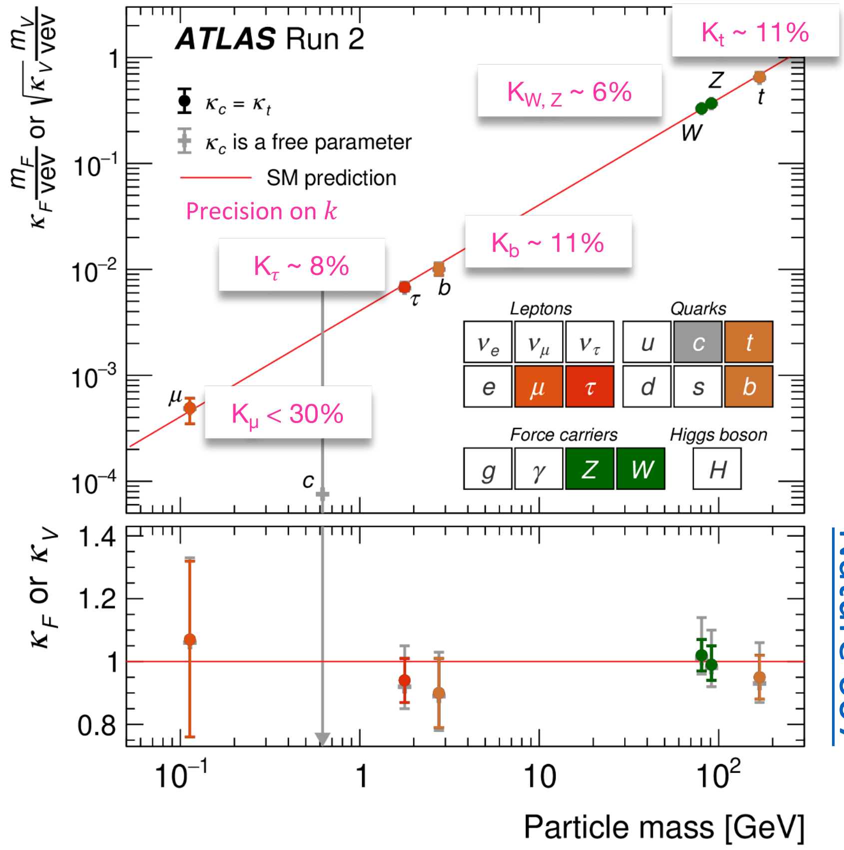
ATLAS EXPERIMENT

Corfu Workshop on Future Accelerators – April 26, 2023

Università di Genova

More Luminosty? Why?

The luminosity increase will expand the discovery power, in the Higgs physics too



Precision on k

$K_t \sim 11\%$

$K_{W,Z} \sim 6\%$

$K_b \sim 11\%$

$K_\tau \sim 8\%$

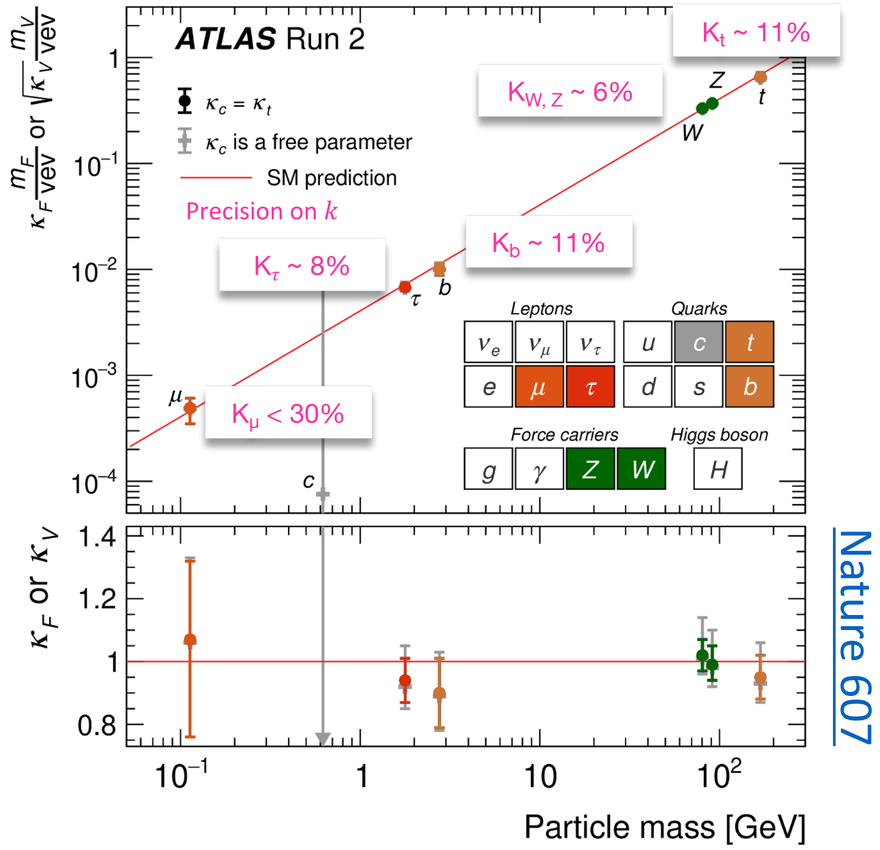
$K_\mu < 30\%$

Nature 607

- The Higgs coupling are measured with a precision under 12%

More Luminosty? Why?

The luminosity increase will expand the discovery power, in the Higgs physics too



Precision on k

$K_t \sim 11\%$

$K_{W,Z} \sim 6\%$

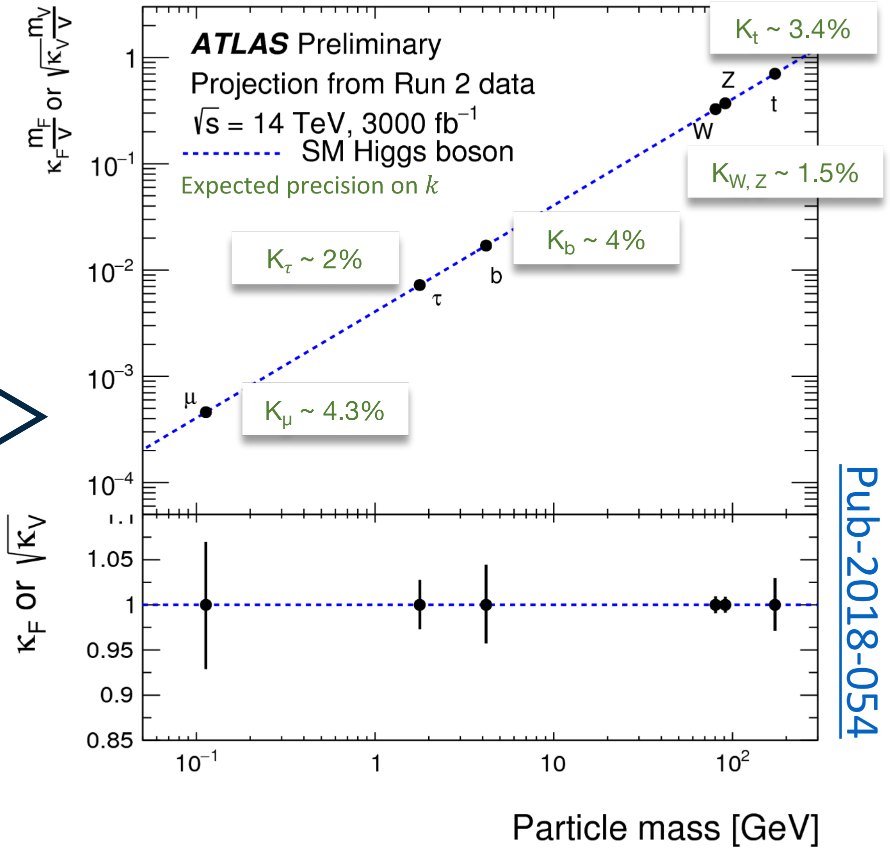
$K_b \sim 11\%$

$K_\tau \sim 8\%$

$K_\mu < 30\%$

Nature 607

Projection after ~3000 fb^{-1}



Expected precision on k

$K_t \sim 3.4\%$

$K_{W,Z} \sim 1.5\%$

$K_b \sim 4\%$

$K_\tau \sim 2\%$

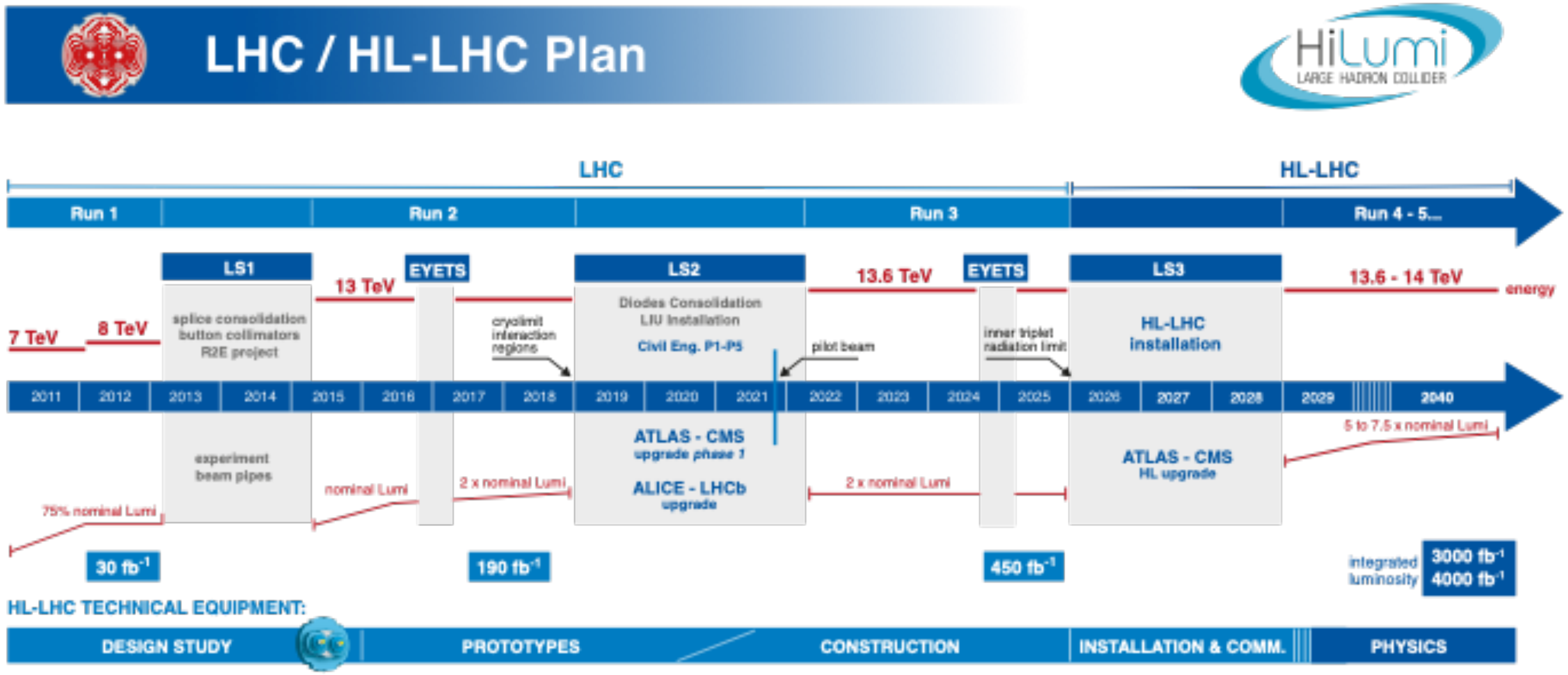
$K_\mu \sim 4.3\%$

Pub-2018-054

- The Higgs coupling are measured with a precision under 12% → with HL-LHC few percent.
- Higgs self-coupling not observed yet
- Precision measurements will rely critically on robust performance of the tracker detector

The High-Lumi Schedule

Run 3 will finish at the end of 2025 and HL-LHC will be installed in 3 years from 2026

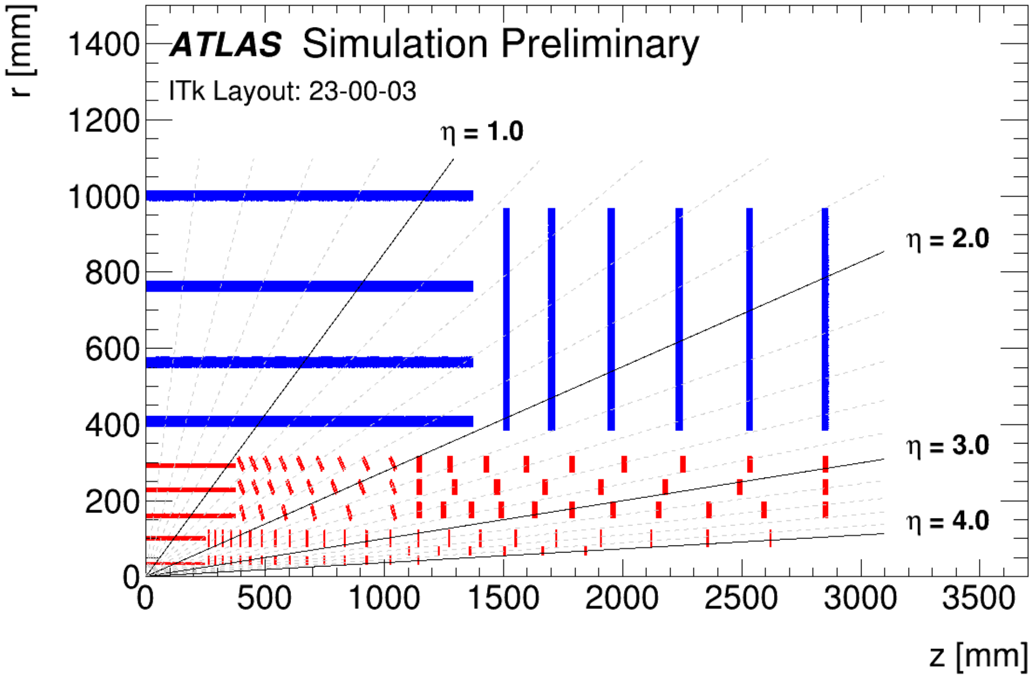


- Luminosity will be increased up to a factor of 7.5 to the LHC nominal luminosity value
    - Average multiple pp collisions (pile-up) will increase to $\langle\mu\rangle = 200$
- The integrated luminosity on the whole HL-LHC operative period will be 4000 fb^{-1}
    - Increased radiation damage by a factor of ~10

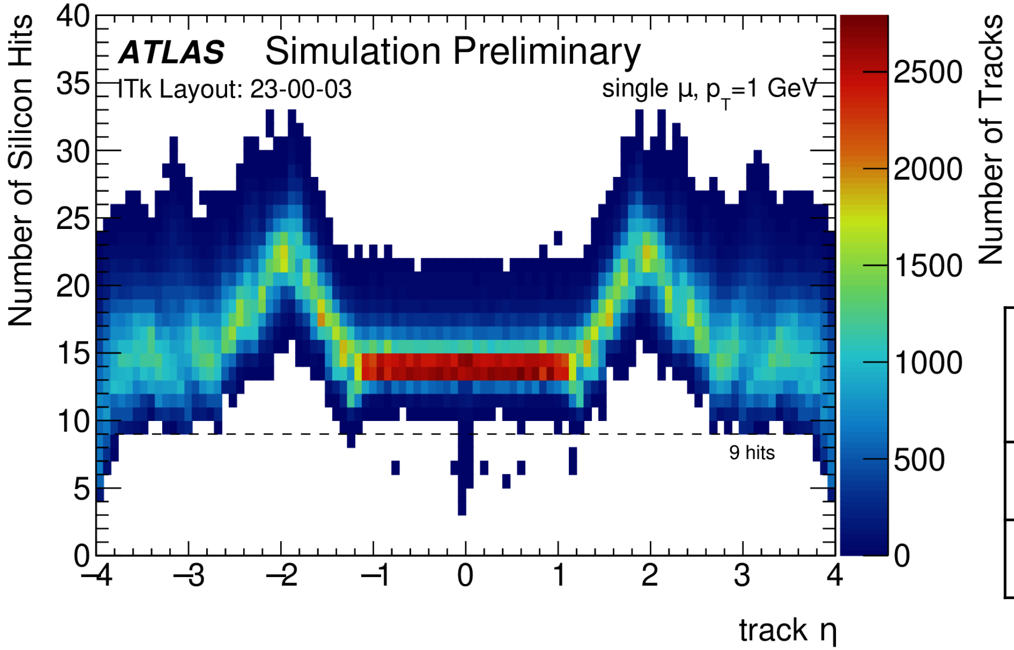
The Inner Tracker Upgrade

A new ATLAS Inner Tracker (ITk) to face the extreme environment of HL-LHC

- A pixel detector surrounded by a strip detector.
  - Strip: 4 layers (barrel) and 12 disks (endcaps)
    (see the talk of Andrea Garcia Alonso)
  - Pixel: 5 Layers (barrel) and many disks (endcaps)
  - With a coverage up to |η| = 4, ITk will provide at least 9 hits per tracks



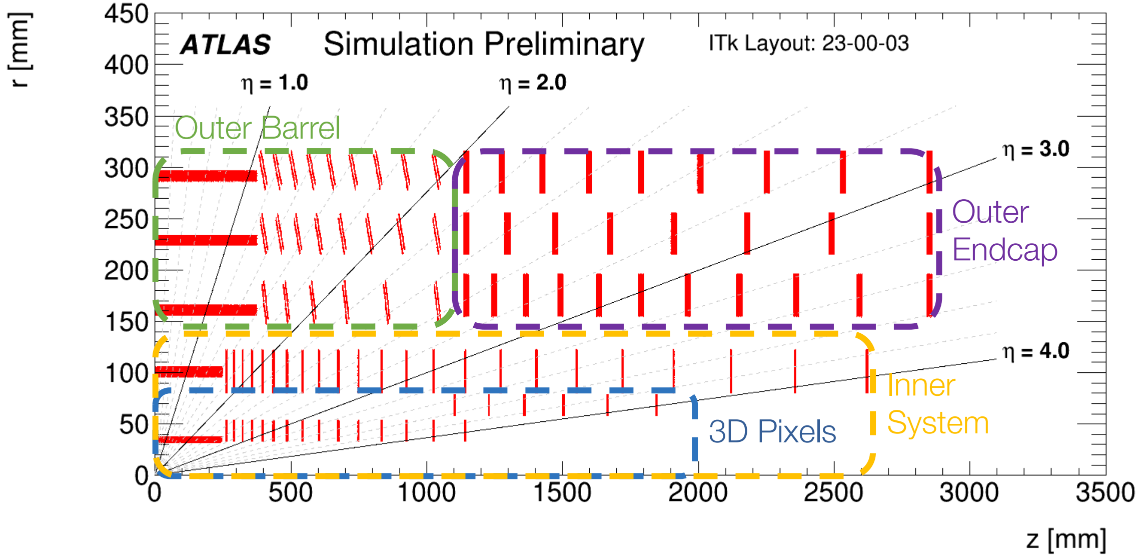
ATL-PHYS-PUB-2021-024

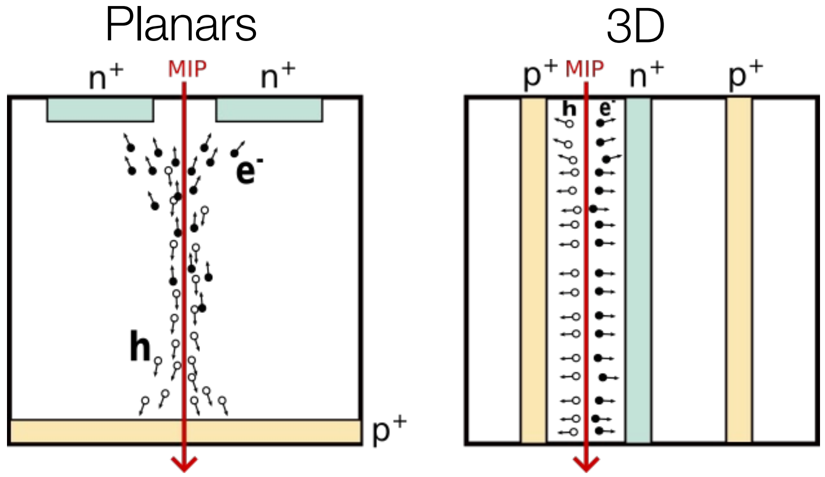


Detector	Eta Coverage	Strip (m^2)	Pixel (m^2)	Pixel Ch.	Pixel Modules
ATLAS ID	$|\eta| < 2.5$	61	1.9	92×10^6	2.0K
ITk	$|\eta| < 4$	165	13	5.1×10^9	9.2K

The ITk Pixel Detector

Three Pixel subsectors: the replaceable Inner System, the Outer Barrel and the Outer Endcap

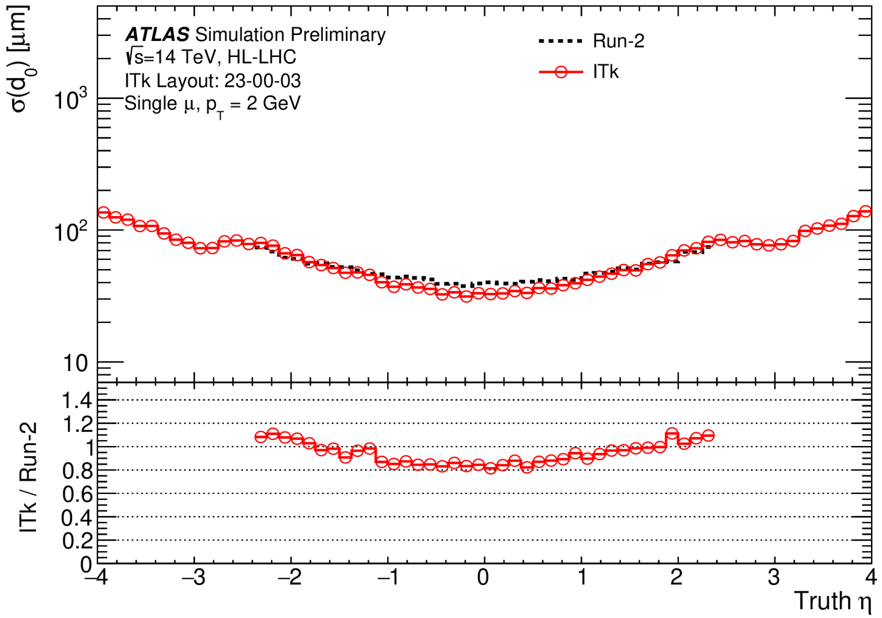


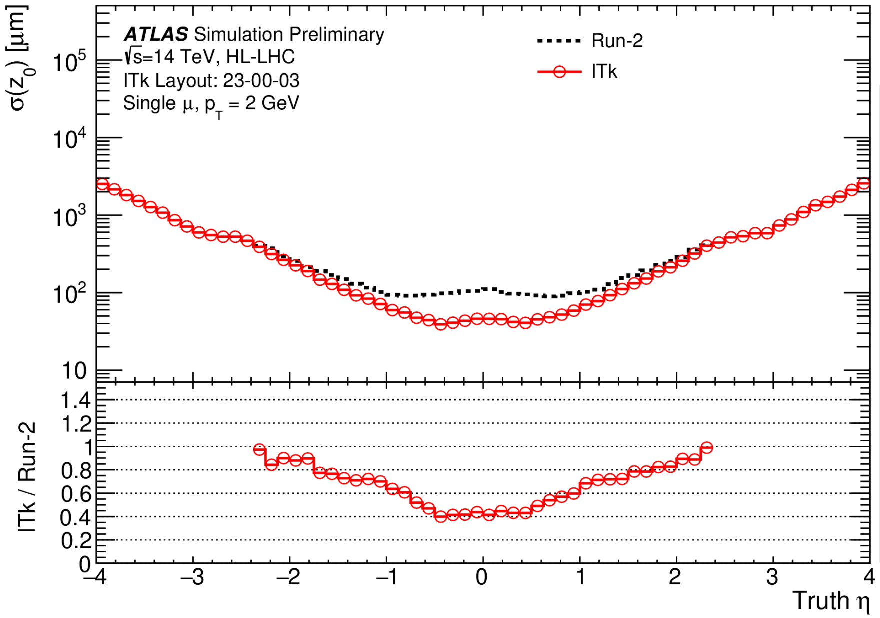


System	# layers	Sensors Types	# modules	Dimension m^2	Module Types	Total Fluence $10^{15}n_{eq}cm^{-2}$
Inner System (replaceable)	2 Layers barrel + rings	3D (L0)	2600	2.4	Triplets	13 (@ 2000 fb^{-1})
		Planar (L1)			Quads	9.2 (@ 2000 fb^{-1})
Outer Barrel	3 layers + inclined rings	Planar	4772	6.94	Quads	2.3 (@ 4000 fb^{-1})
Outer Endcap	3 layers of rings	Planar	2344	3.64	Quads	3.1 (@ 4000 fb^{-1})

ITk Expected Performance

Track parameter resolutions generally improved with ITk





ATL-PHYS-PUB-2021-024

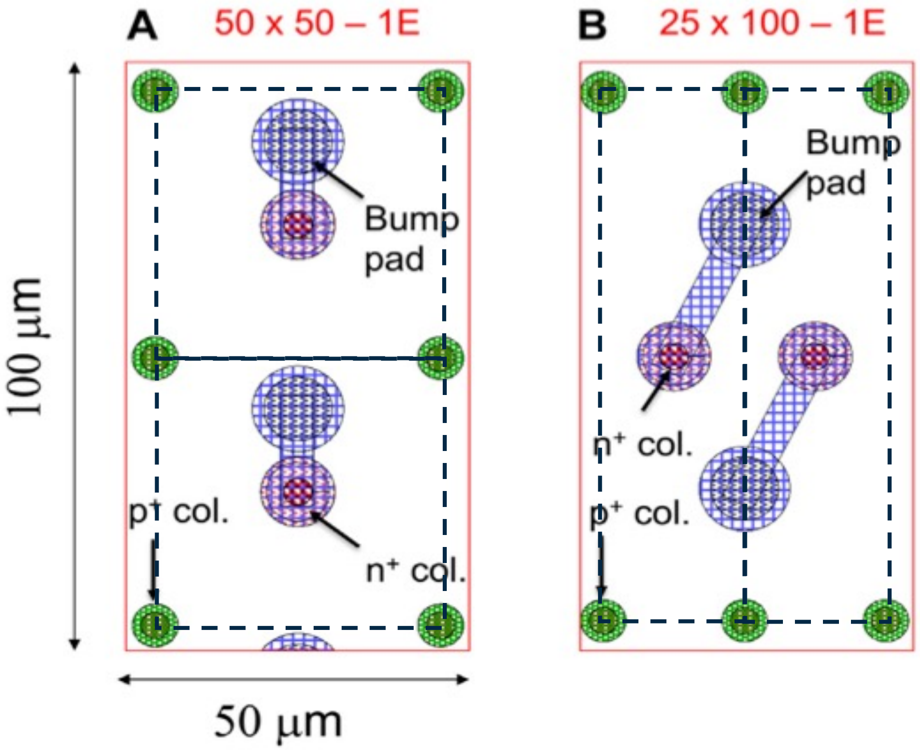
- Transverse impact parameter (d_0) resolution is similar (slightly improved) to the ID performances during Run2

- Longitudinal impact parameter (z_0) resolution is better than the ID performance by a factor of 2, due to the lower pixel pitch in the L0 (25x100 μm^2)

Two 3D Sensors

In the L0 of ATLAS ITk pixel 3D sensors will be adopted, 25x100 and 50x50 µm^2

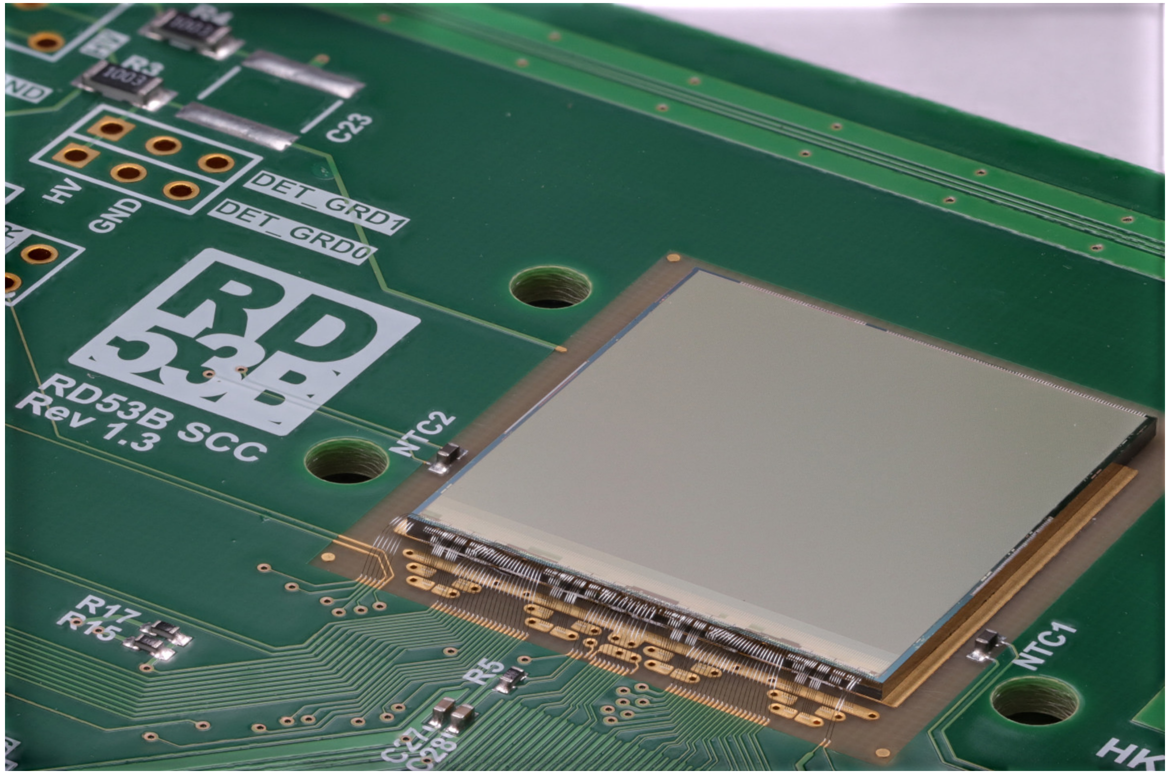
- 3D pixel cells will be two different sizes:
  - 25 x 100 µm^2 in the barrel
  - 50 x 50 µm^2 in the endcap
- The production of the 3D pixel sensors is done by to 3 different foundries
  - FBK (Italy) e SINTEF (Norway) - 50 x 50 µm^2
  - CNM (Spain) - 25 x 100 µm^2 (FBK as backup)
- The pre-production is almost concluded for the three vendors:
  - FBK: 50 x 50 µm^2 (Summer 2021), 25 x 100 µm^2 (summer 2022)
  - SINTEF: 50 x 50 µm^2 (February 2022)
  - CNM: 25 x 100 µm^2 (March 2023), under test



A Single Readout Front-End

The chip ITkPix will be used on the whole ITk pixel subsystem

ATLAS-PHOTO-2021-045-1

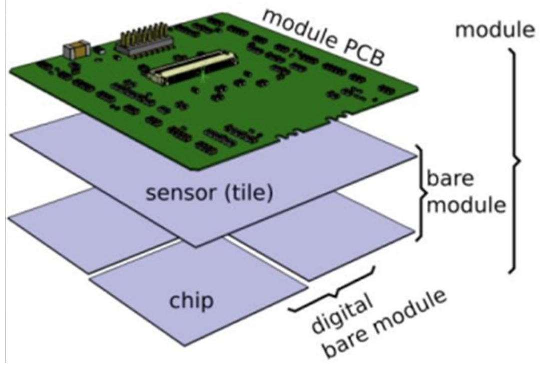


- Developed by RD53 Community
  - The Chip building blocks are in common by CMS and ATLAS, with slightly differences.
  - ITkPixV1.1 is the ITk pre-production chip
  - ITkPixV2 was submitted last March, will be equipped on modules from 2024

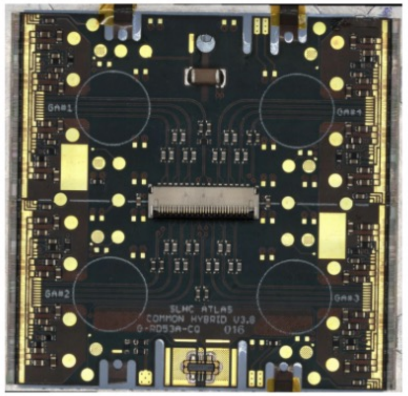
- The ITkPix main feature:
  - 65 nm CMOS, 2x2cm^2 area
  - 384 x 400 pixels (50 x 50 μm^2)
  - Power: 0.56 W/cm^2
  - Rad-hard > 1 Grad
  - Threshold: 1000e (σ = 30e)
  - Noise: 40e

The ITk Pixel Modules

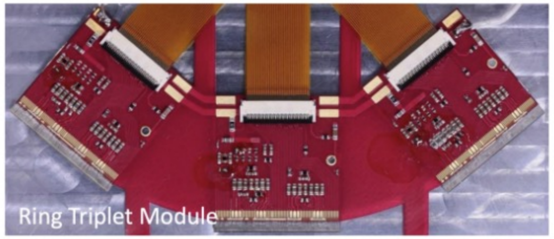
The Module is: Sensor + ASIC + Flex circuit



Quad module



Ring triplet module



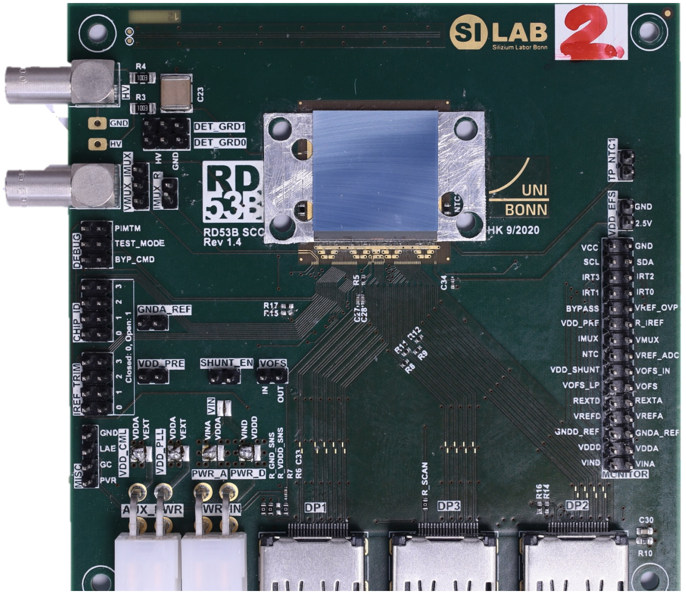
Barrel triplet flex

- Sensor + ASICS: bare module via Hybridization at external vendor.
- Bare module + Flex circuit: module via assembly at ITk institutes.
- The module configurations:
  - Quad module: one large single planar sensor bump bonded to four front-ends.
  - Triplet module: three single-chip and 3D sensor modules connected to one flex for the first layer only
- Good process in prototyping and pre-production hybridization phases:
  - HPK: 20 prototypes
  - IZM: 50 prototypes from 3D FBK and Sintef and HPK sensors
  - Leonardo: firsts 3D 25x100 μm^2 already delivered
- Production will start in 2024, ~9000 modules in 2 years in 20 assembly sites:
  - Sites Qualification: about 20-25 institutes located over the world are currently qualifying for the procedures of module assembly and test.

The Pre-production Modules Characterization

8 Single Chip Cards assembled with pre-production FBK 3D sensors and chip ITkPixV1.1 in Genova

- 4 modules are tested in beam line:
  - 2 tested before irradiation to PS and SPS
  - 2 tested after irradiation:
    - Irradiated at Bonn to $1\times10^{16} n_{eq}/cm^{-2}$
    - Re-Irradiated at IRRAD (CERN) up to $1.9 \times 10^{16}\ n_{eq}/cm^2$
    - The modules were tested at SPS

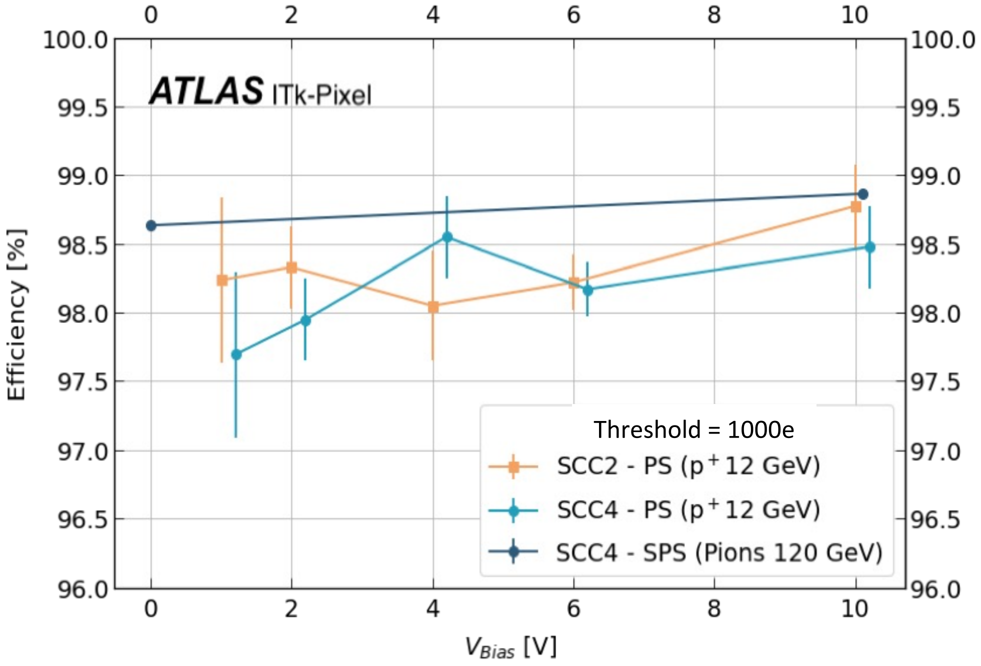


Sensor #	TB facility pre-irradiation	Irradiated at	Fluence	TB facility Post-irradiation	Note
W12-G (SCC2)	CERN PS & SPS	IRRAD	up to $1.7 \times 10^{16}\ n_{eq}/cm^2$	-	FE damaged
W12-M (SCC3)		Bonn + IRRAD	up to $1.9 \times 10^{16}\ n_{eq}/cm^2$	SPS	
W12-N (SCC4)	CERN PS & SPS				Used as RF
W12-J (SCC5)		Bonn + IRRAD	up to $1.9 \times 10^{16}\ n_{eq}/cm^2$	SPS	

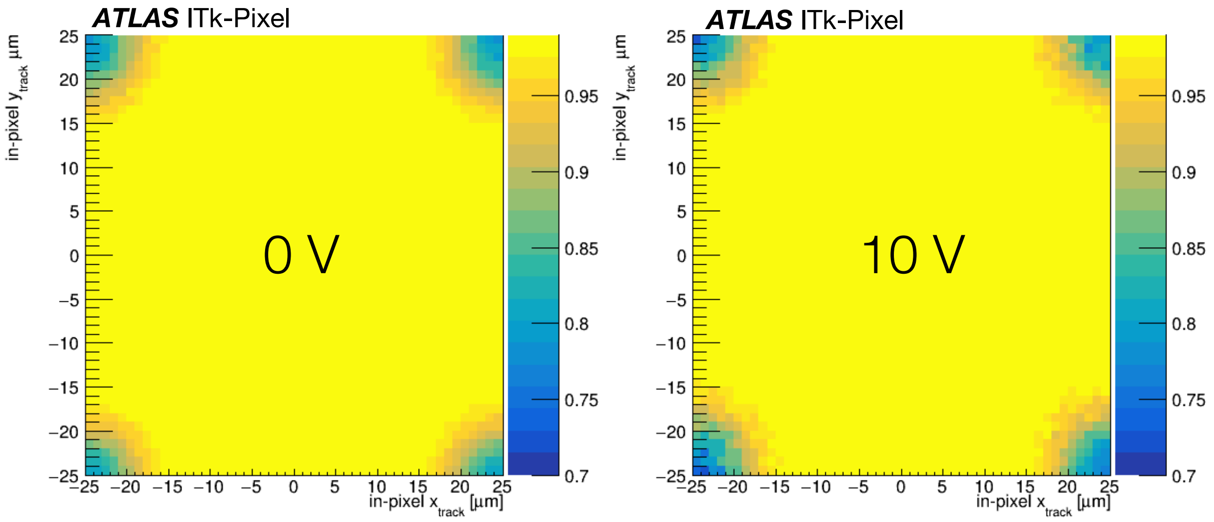
Sensors Test and Efficiency

Not-irradiated pre-production module with FBK 3D sensors and chip ITkPixV1.1

- PS: proton beam at 12 GeV
- SPS: pion beam at 120 GeV
- The modules were placed perpendicularly to the beam
  - Ave. Efficiency = 98.7 ± 0.1% at 0 V bias
  - Ave. Efficiency = 98.9 ± 0.1% at 10 V bias
- Results are compatible with the results obtained with RD53A prototype (FBK 3D sensor 50x50 μm^2) at DESY



PLOT-ITKD-2022-04

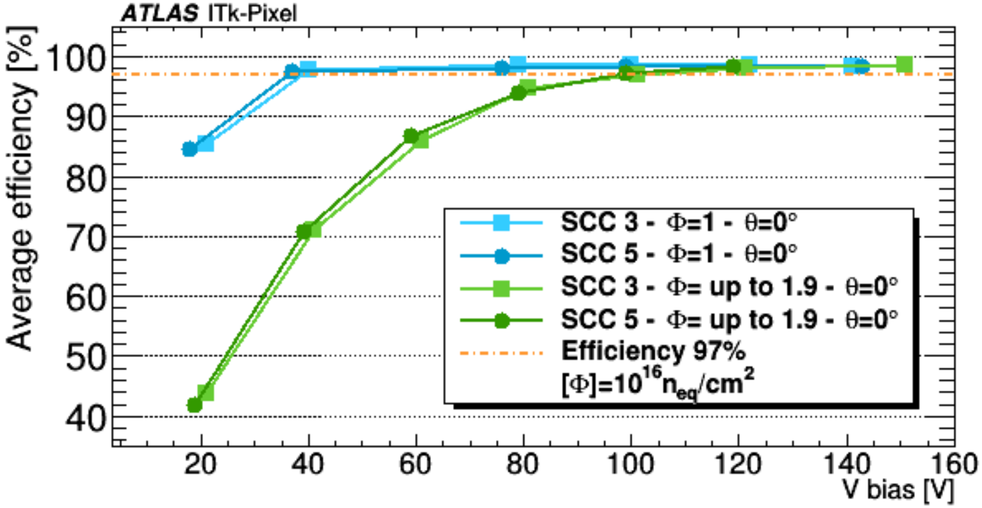


- Local Efficiency of single pixel cell:
  - In the central area: efficiency over 99%
  - On the corners the efficiency is lower (~75%) because of the p$^+$ columns implanted there

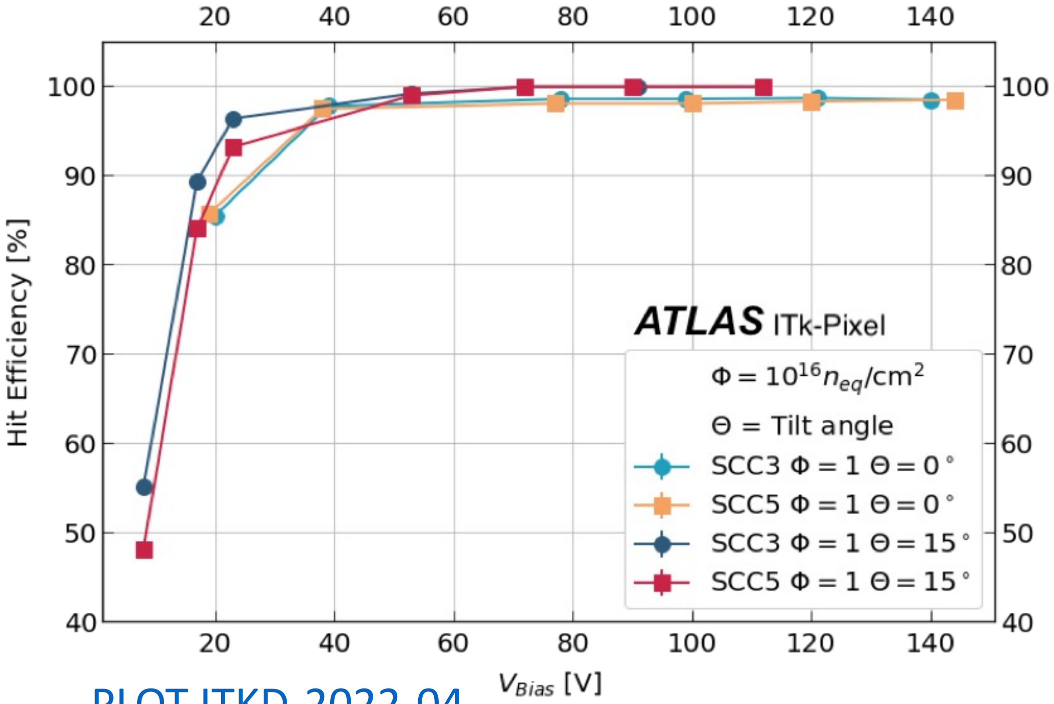
Sensors Test and Efficiency

Post-irradiation pre-production module with FBK 3D sensors and chip ITkPixV1.1

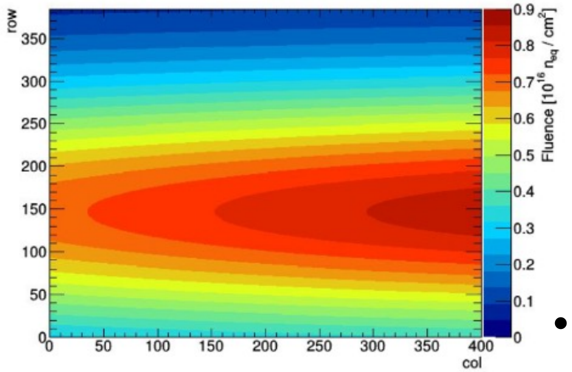
- Modules irradiated at Bonn:
  - Uniform fluence $\phi = 1 \times 10^{16}\, n_{eq}/cm^2$
  - Modules were tested perpendicularly ($\theta = 0°$) and titled ($\theta = 15°$) w.r.t. the beam
  - Ave. Efficiency > 97% a 40 V bias



PLOT-ITKD-2022-05



PLOT-ITKD-2022-04



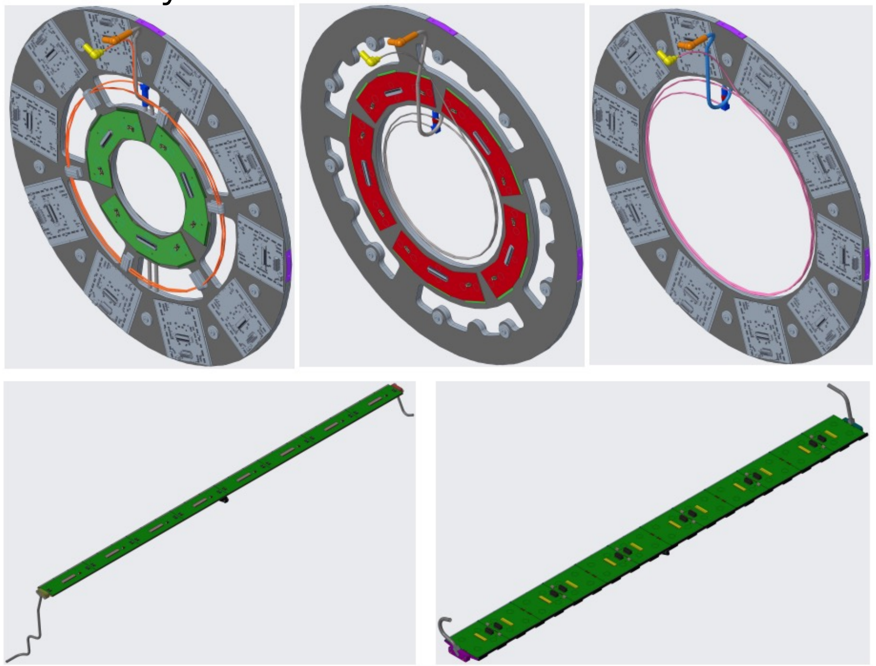
- Modules re-irradiated at IRRAD:
  - Not uniform fluence, up to $\phi = 1.9 \times 10^{16}\, n_{eq}/cm^2$
  - Ave. Efficiency ~97% a 120 V bias
- Operability window:
  - Efficiency ≥ 97%
  - Voltage < 170 V

The Local Supports

Local support prototypes using carbon fibre and carbon foam to minimize mass and maximize thermal performance

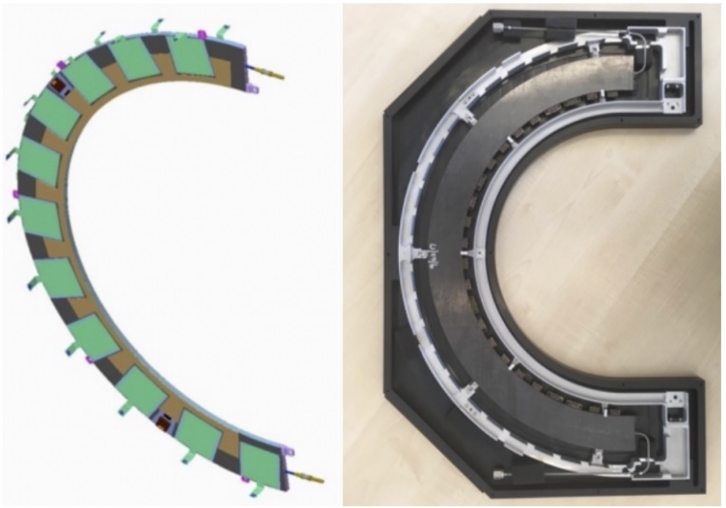
- Different geometries optimized for the various layers and regions of the pixel detectors:
    - Inner system: two layers of staves and double-sided rings in the endcaps
    - Outer Barrel: three layers of longeron and inclined rings
    - Outer Endcap: three layers of endcap rings composed by 2 half-rings (HR)

Inner System



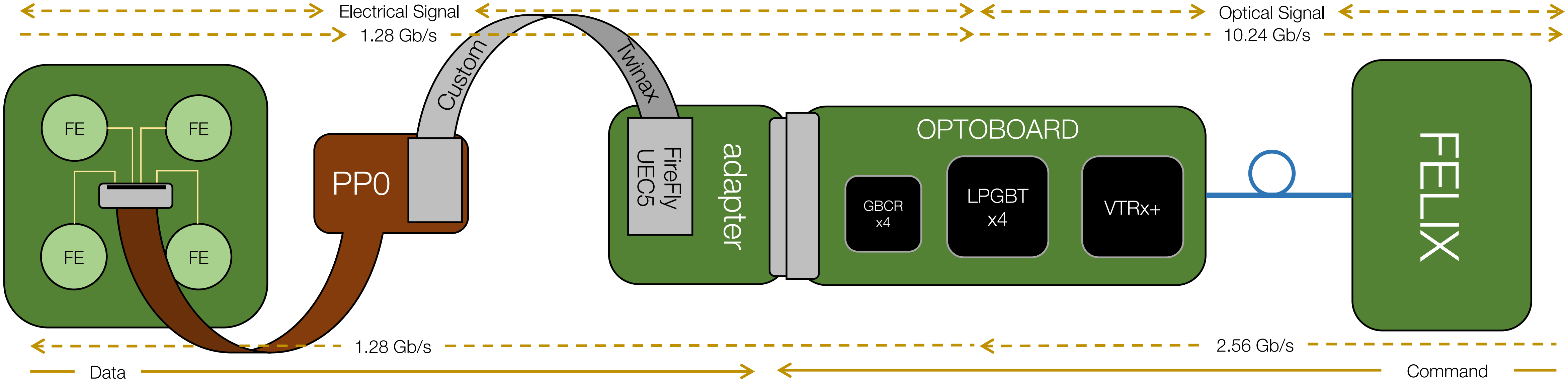
Outer Barrel

Outer Endcap



Data Transmission

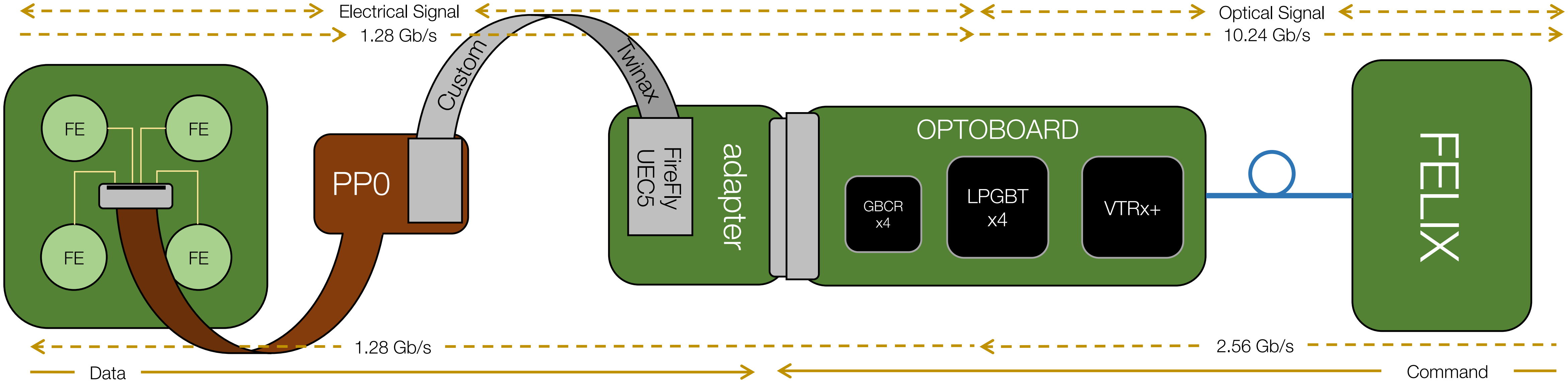
The data services scheme



- A kapton/copper flex hoses the Front-Ends
- The PP0, a ZIF cable, is connected to the flex
- Over 6 meter custom Twinax Cable transmits data via electrical signal
- Via a FireFly connector the Twinax is connected to the Optoboard. The board houses 4 Gigabit Reciver Chips, one for each LpGBT and a VTRx+ chip to aggregate and convert electrical signal to optical
- The optical signal goes out from the detector to FELIX, the off detector board.

Data Transmission

Optical based data transmission to share up to 6 modules on one single optical link

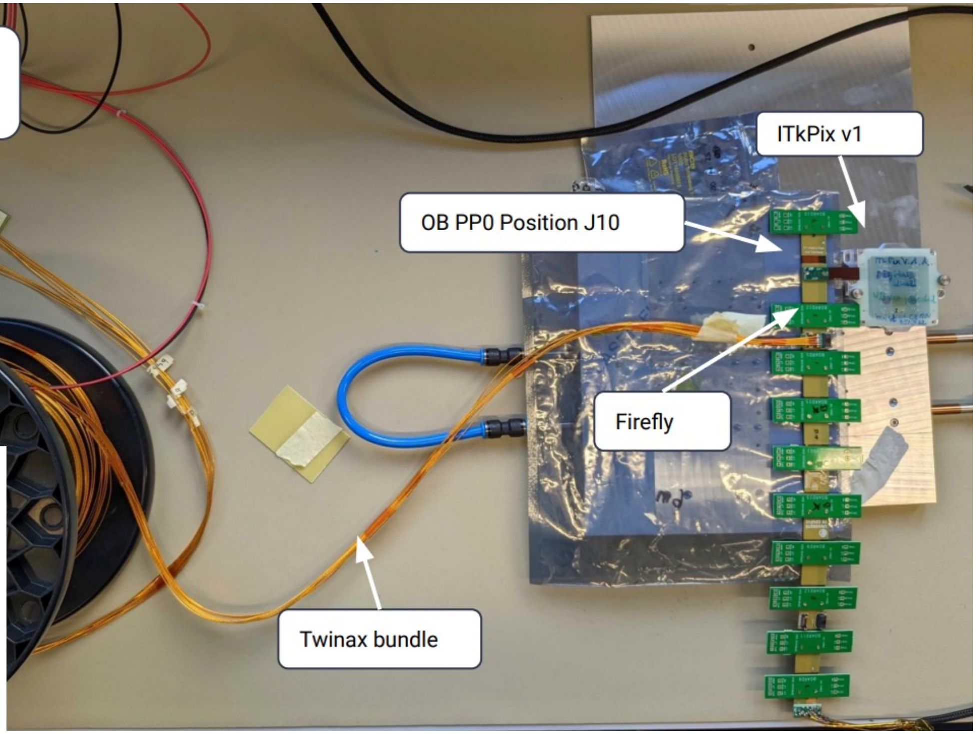


- To reduce material the links are shared on all layers:
  - Readout from FE-chip at 1.28 Gb/s with up to 4 links per chip depending on position in pixel system
  - Data links are up to 6 per lpGBT coming from 1-6 modules depending on detector region to share a single 10.24 Gb/s long data fiber per lpGBT
  - CMD links (down-link) are one 2.56 Gb/s link per lpGBT fanout out to 1-6 modules depending on detector region
- The system test with its final components will be presented at loaded local supports PRR, next Oct. 2024

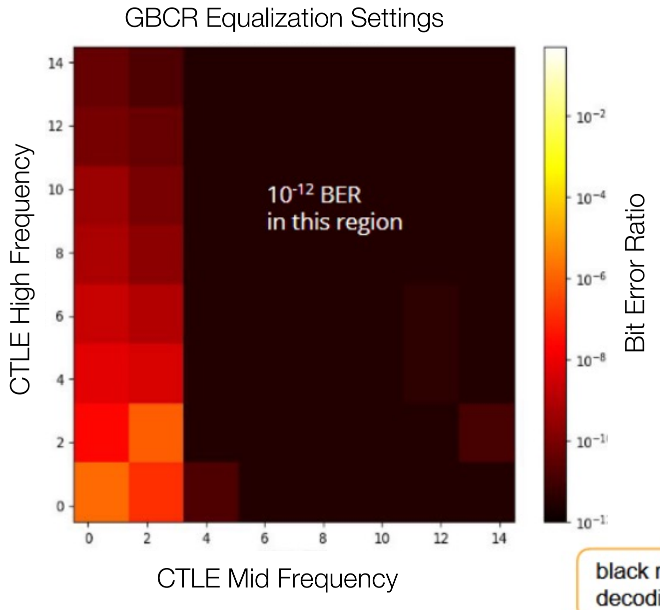
The ITk System Test Setup At Bern

A detector-like data transmission chain functioning

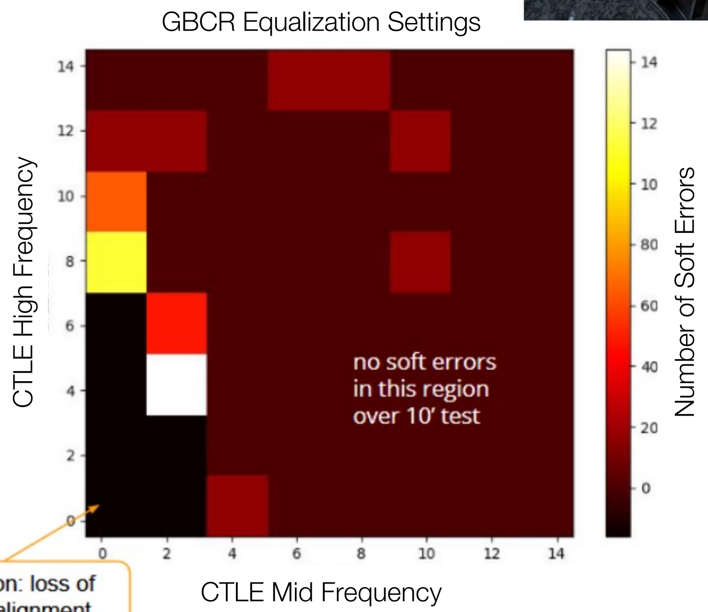
- Scan of the 95% CL limit Bit Error Ratio (BER) varying the settings of the equalizer of the GBCR
- New Felix feature: Soft Error Counter
- The results are encouraging



Optoboard v3.0 connected to Twinax termination board



10^{-12} BER in this region



no soft errors in this region over 10′ test

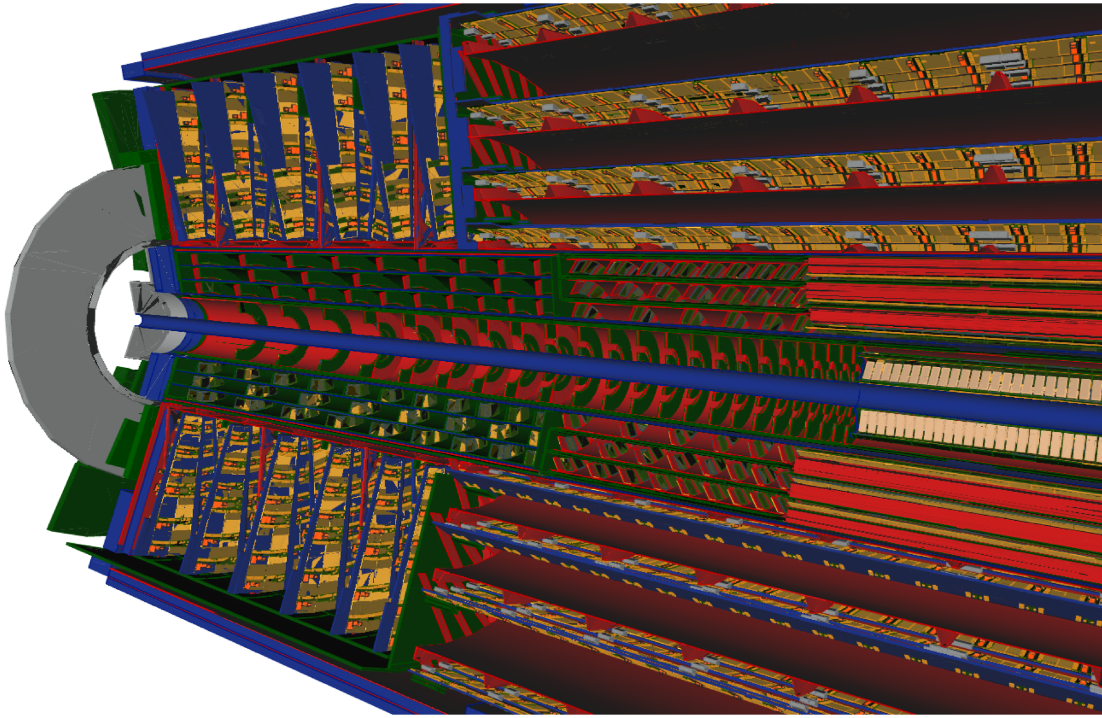
black region: loss of decoding alignment

- Optoboard v3.0
- Termination board (prototype)
- Samtec Twinax bundle
- Outer Barrel PP0
- ITkPix V1 module with pigtail

Summary and Conclusion

The ATLAS ITk is an all silicon detector, composed by strips and pixel, to cope with the luminosity increasing with HL-LHC

- The main features of the ITk detector:
  - Increased acceptance up to η ~ 4
  - A number of points per track higher than 9
  - High granularity
  - Radiation hardness with minimized material budget.
- The Pixel system is finalizing an extensive prototyping phase and recently moving to pre-production and production.
  - System tests and demonstrators for all sub-systems
  - Finalized production version of readout chip, services, loading and integration procedures.
  - Production will start by the end of 2024!



Backup

Status of the Project

Specification reviews and preliminary design reviews are complete

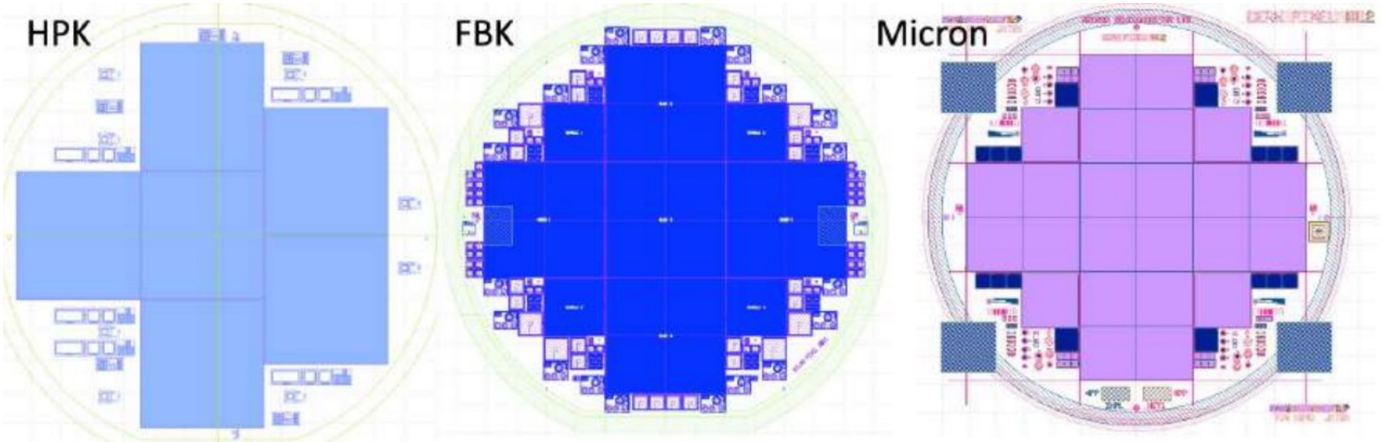
R&D			Pre-Production	Production
Specification Review	Preliminary Design Review (PDR)	Final Design Review (FDR)	Production Readiness Review (PRR)	Production Advancement Review (PAR)

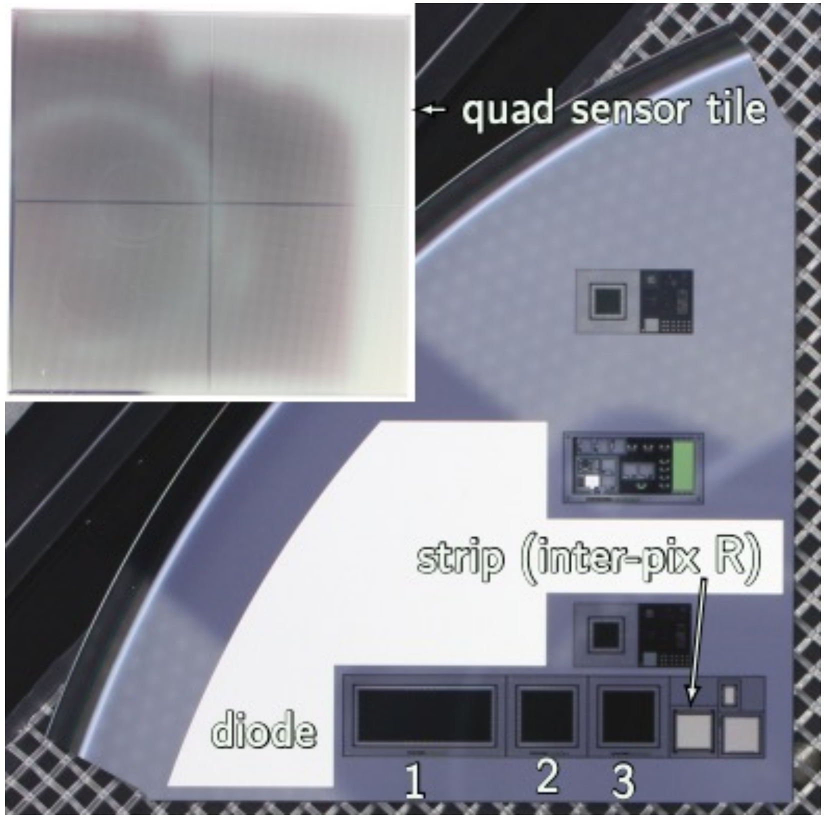
- Completing FDR phase
  - Services, Loaded Local Supports and Global Mechanics & Integration FDRs to be completed in the next months
  - ASIC FDRs MOPS (pixel monitoring chip) and GBCR (data transmission) FDRs will be completed in the next few months
- Pre-production Phase
  - Sensors have completed pre-production except for (25x100μm2 CNM sensors)
  - Pre-production of hybridization has started with initial prototyping phase to verify designs
  - Pre-production of bare local supports is close to completion (early 2023)
- Production phase
  - FE-ASIC ITkPixV2 production will start with an engineering run in March 2023

Planar Sensors

Planar sensors pre-production is completed with about 800 quad sensors

Thickness	Pixel Pitch	Position	Vendor	Bias Structure
150 µm	50 x 50 µm^2	L2-4	HPK	poly-Si
		R2-4	Micron	Punch-Through
100 µm	50 x 50 µm^2	L1	Micron	Punch-Through
		R1	FBK	None



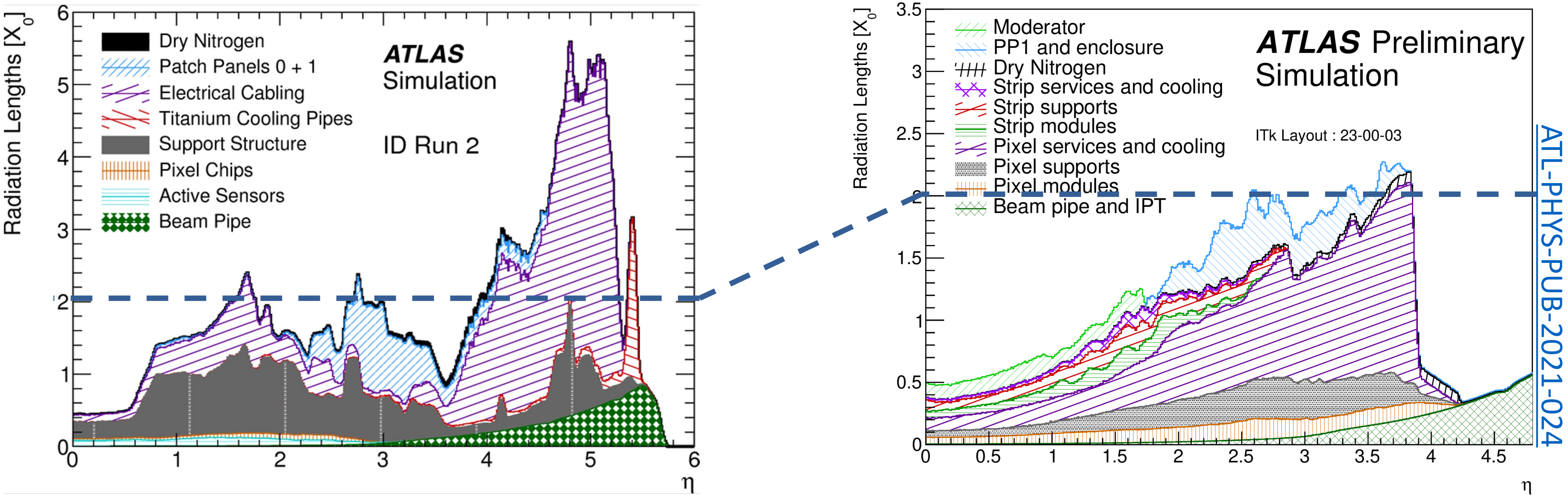


HPK test structure, Micron sensor tile

The Material Budget

Lower material budget than ATLAS ID, using:

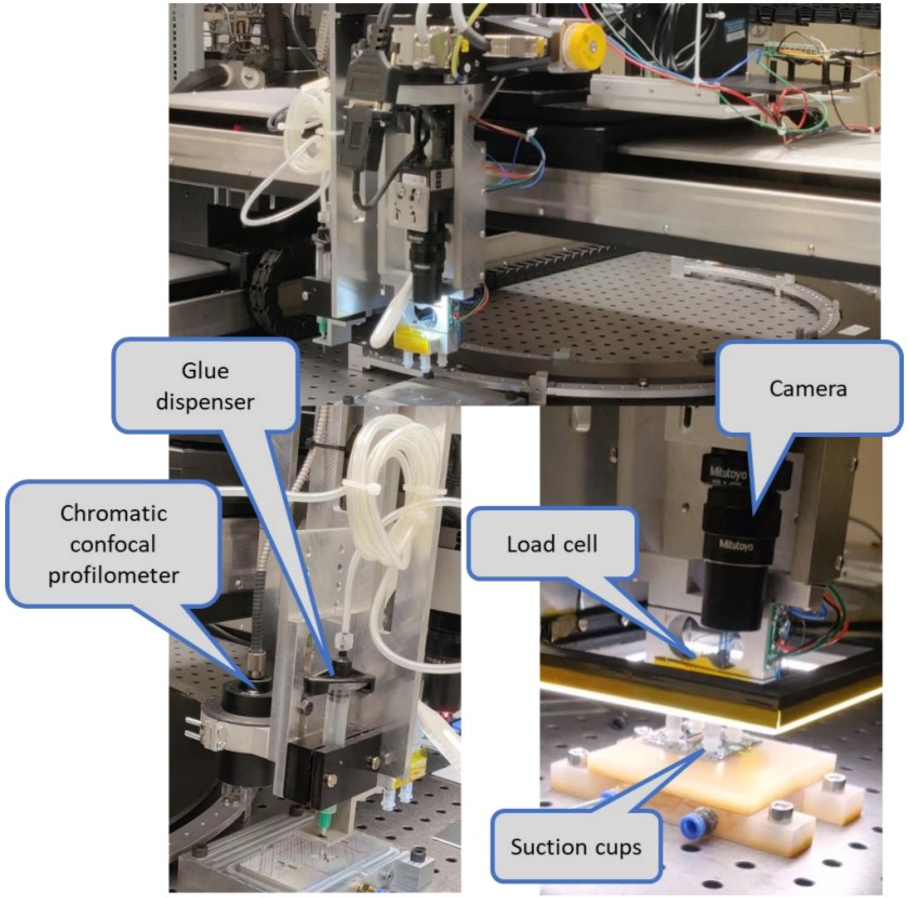
- CO2 cooling with thin titanium pipes
- Advanced powering: serial powering for pixels
- Carbon structures for mechanical stability and mounting
- Optimise number of readout cables using data link sharing (command link sharing being considered)
- Material distribution required for performance and radiation level studies



The Outer Endcap HR Loading Procedure

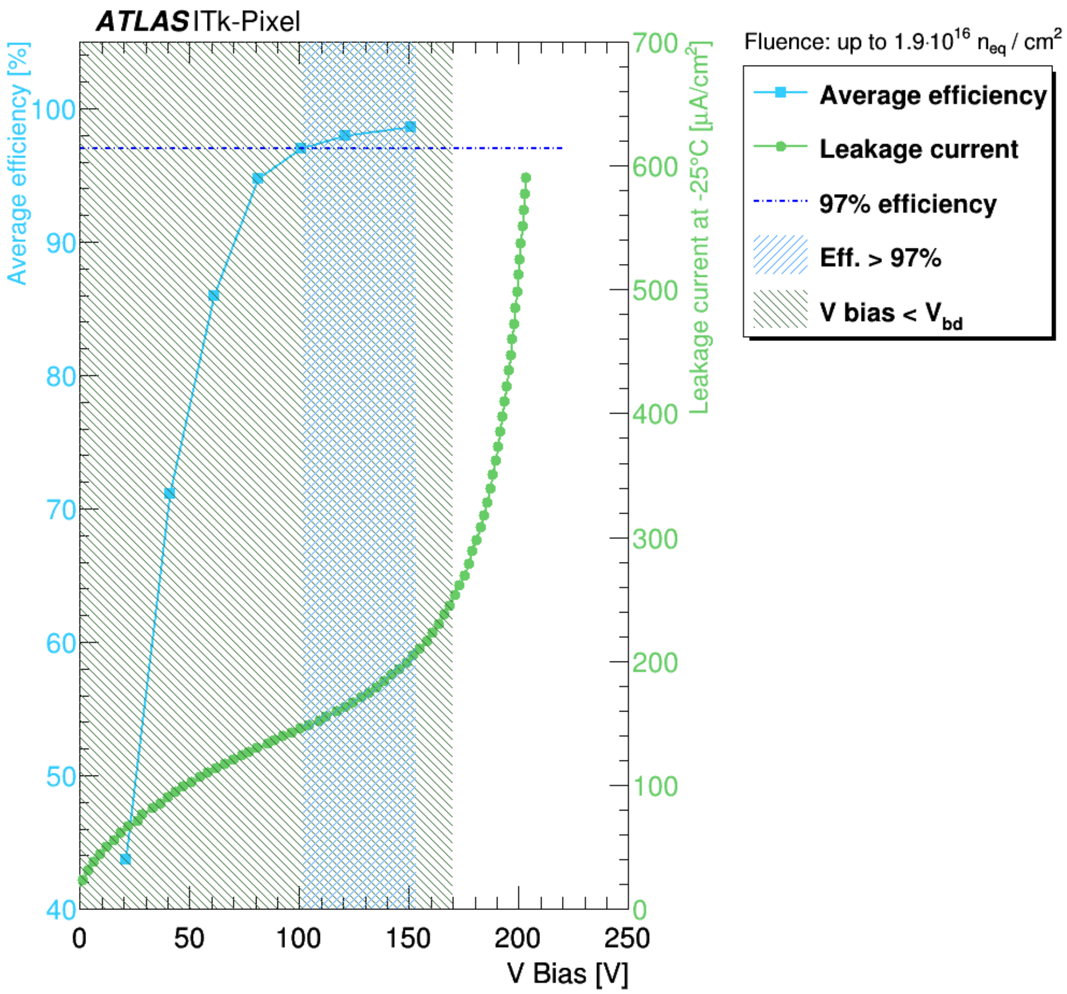
Italian and UK sites are handling the outer endcap local support loading

- Italian sites procedure
  - PI gantry (Physik Instrumente) with x, y, z and theta stages and honeycomb optical breadboard
  - The glue is deposited on the HR by the gantry, using a disposable syringe.
  - 4 suction cups handling the module that is picked-up and placed on the local support
- UK sites procedure
  - In RAL a custom Aerotech linear motor gantry is used
  - Glue is dispensed from a syringe mounted on the gantry
  - A pick-up jig is use to pick-up the models and place on the local support
  - The loading technique at Oxford is similar to that employed by RAL
  - The gantry picks up so-called “bridge tools”, with which it will lift and place modules on a halfring that stay with the positioned module until the glue cures.



Operability Window

An efficiency > 97% when the module is under the break down voltage of ~150 V



- The operability window is defined by high efficiency (> 97 %) and bias voltage below the breakdown: ~100 V to ~170 V bias
- Leakage current I ~ 150 µA/cm² and power dissipation 15 mW/cm² @ 100 V bias (scaled at -25°C) for SCC3