ATLAS ITk Pixel Detector Overview

Anna R Petri* on behalf of ATLAS ITk Pixel collaboration

* INFN Milano

Large Hadron Collider (LHC)

Last update: Oct 2024

LHC | HL-LHC

Run 1 | Run 2 | Run 3 | Run 4 - 5...

LS1 | EYETS | LS2 | LS3

7 TeV | 8 TeV | 13 TeV | 13.6 TeV | 13.6 - 14 TeV energy

splice consolidation
button collimators
R2E project

cryolimit
interaction
regions

Diodes Consolidation
LIU Installation
Civil Eng. P1-P5

pilot beam

inner triplet
radiation limit

HL-LHC
installation

2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2041

experiment
beam pipes

75% nominal Lumi | nominal Lumi | 2 x nominal Lumi

ATLAS - CMS
upgrade *phase 1*

ALICE - LHCb
upgrade

We are here

2 x nominal Lumi

50 pile-up events

ATLAS - CMS
HL upgrade

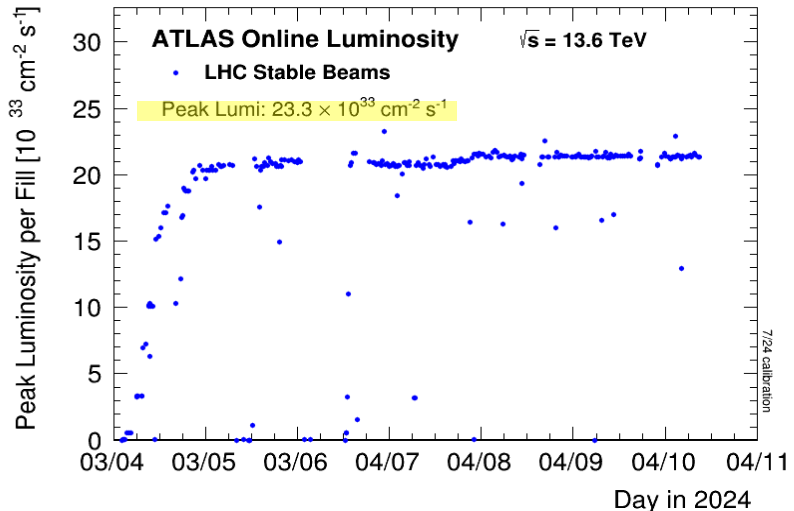
5 to 7.5
x nominal Lumi

200 pile-up events

30 fb^{-1} | 190 fb^{-1} | 500 fb^{-1} | integrated luminosity 3000 fb^{-1} 4000 fb^{-1}

HL-LHC TECHNICAL EQUIPMENT:

https://hilumilhc.web.cern.ch/sites/default/files/2024-10/HL-LHC_October2024.pdf



High-luminosity large hadron collider (HL-LHC) :

- ➢ integrated luminosity: more than 250 fb^{-1}/year
- ➢ instantaneous luminosity expected to be 75 x 10^{33} cm^{2} s^{-1}

Source:https://home.cern/resources/faqs/high-luminosity-lhc / NIMA 1070 (2025) 169978

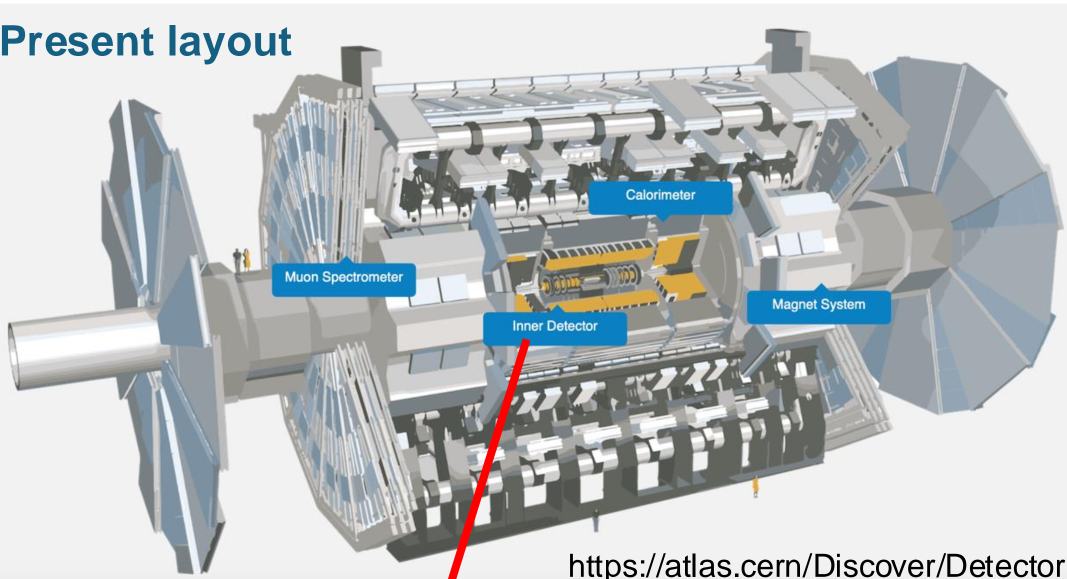
https://atlas.web.cern.ch/Atlas/GROUPS/DATAPREPARATION/PublicPlots/2024/DataSummary/figs/peakLumiByFill.png

ATLAS Getting Ready!

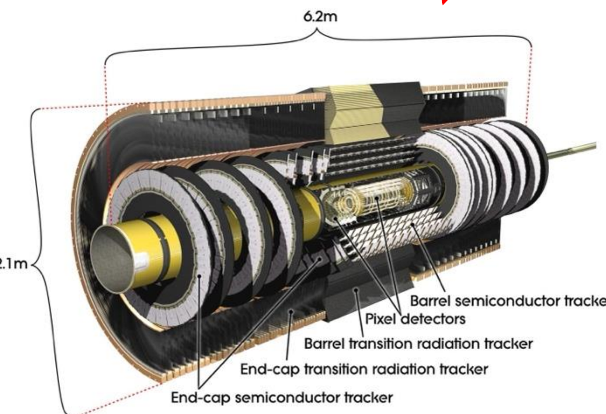
ATLAS ITk

The current innermost detection system of ATLAS is the Inner Detector

Present layout



https://atlas.cern/Discover/Detector



Inner Detector (ID)

Max Acceptance |η| = 2.5

Pixel Detector: 92 million channels

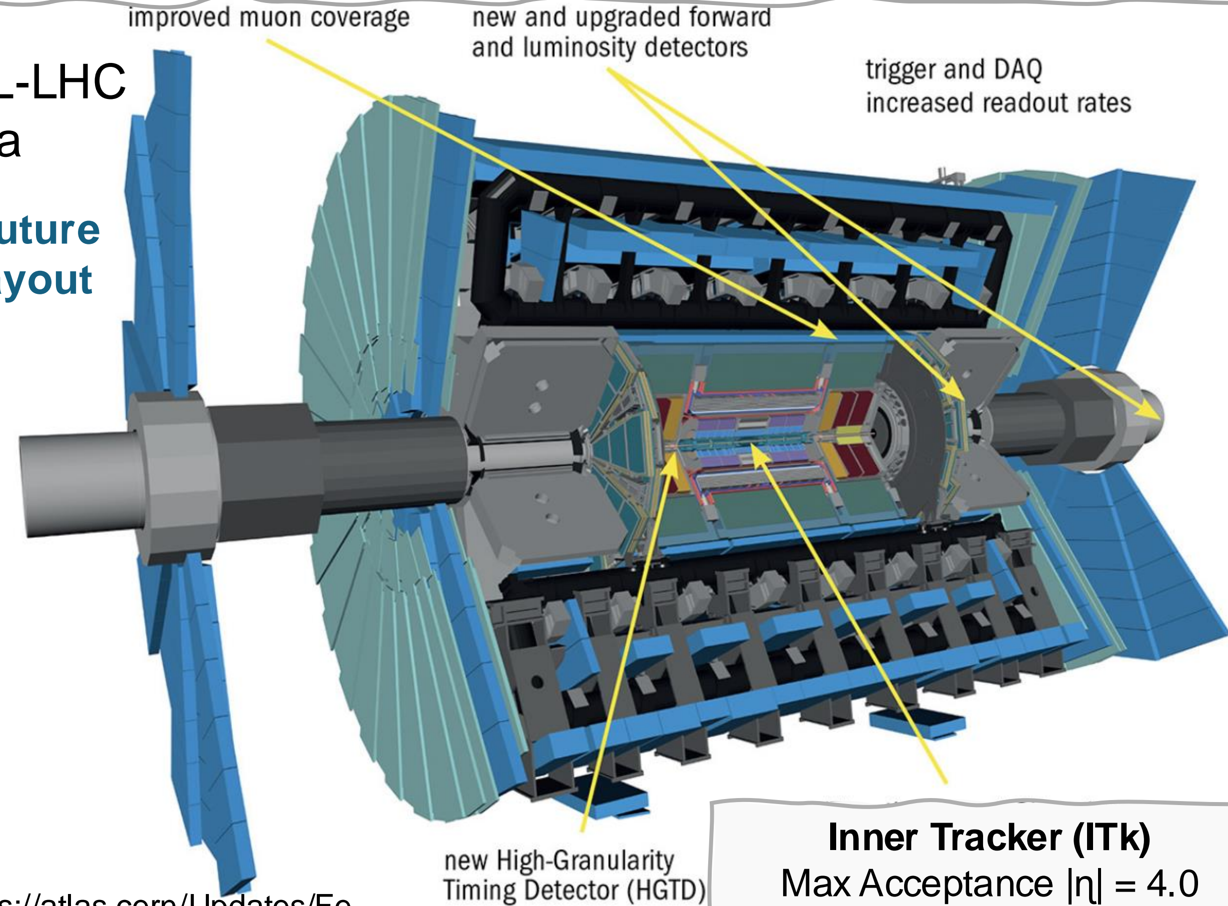
Semiconductor Tracker: 6 million channels

Transition Radiation Tracker: 350.000 channels

https://atlas.cern/Discover/Detector/Inner-Detector

HL-LHC era

Future layout



https://atlas.cern/Updates/Feature/High-Luminosity-ATLAS

ID will be replaced by the all-Si tracker ITk

Inner Tracker (ITk)

Max Acceptance |η| = 4.0

ITk Pixel Detector: 5 billion channels

ITk Strip Detector: 60 million channels

Inner Tracker - ITk

ATLAS ITk

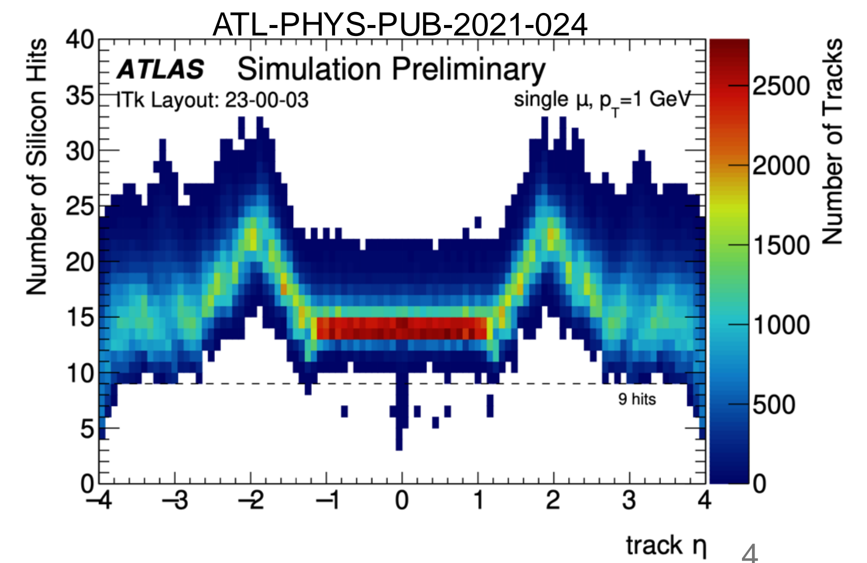
ITk Pixel

ATL-PHYS-PUB-2021-024

ITk Strip

For the ITk Strip, see Katie W. Pass' talk

- Closest to the interaction point
- At least 9 hits/track
- Occupancy kept < 1% thanks to the higher granularity
- Compost of two parts: **ITk Pixel** (this talk) with 5 pixel barrels and rings and **ITk Strip** with 4 strip barrels and strip disks
- Replaceable two innermost layers at half of the lifetime: ITk Pixel Inner System (IS) with Endcaps and Barrels



ITk Pixel

- The ITk Pixel Detector is made of 9400 modules covering 13m^2
- Minimized material budget: low mass mechanics and colling and serial powering
- Radiation hardness up to 10^{16} n/cm^2

Inner System

	L0	L1
# of modules	396	1160
Covered area	2.4 m^2	
Dose for 2k fb^{-1}	7.3 MGy	

Outer System

	Barrel	Endcap
# of modules	4772	2334
Covered area	6.9 m^2	3.6 m^2
Dose for 4k fb^{-1}	1.7 MGy	3.5 MGy

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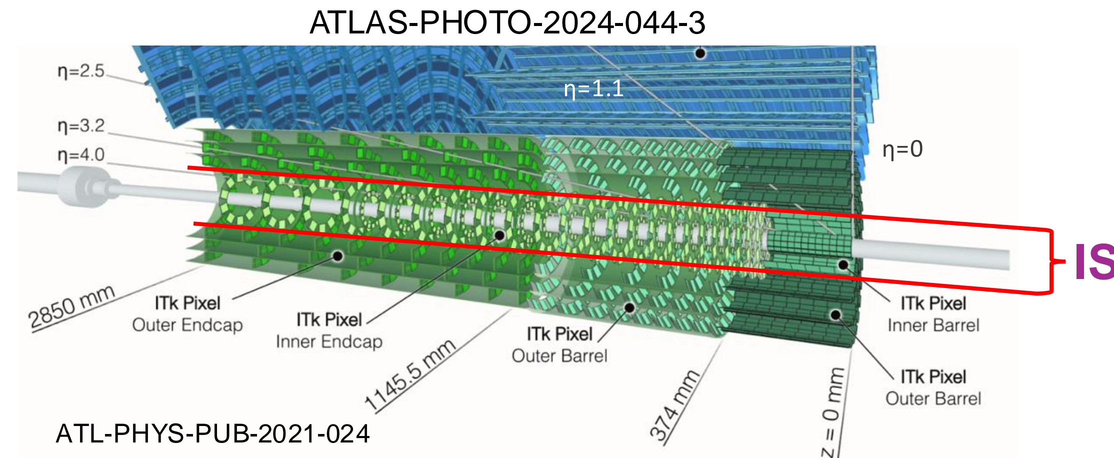
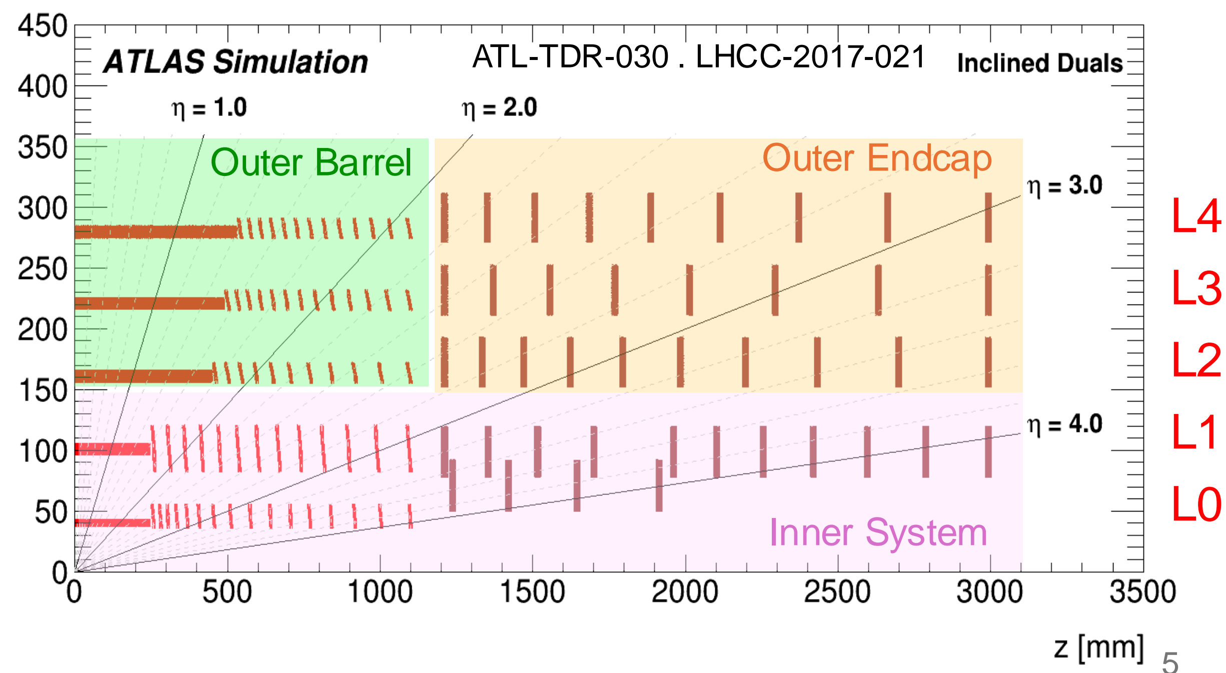
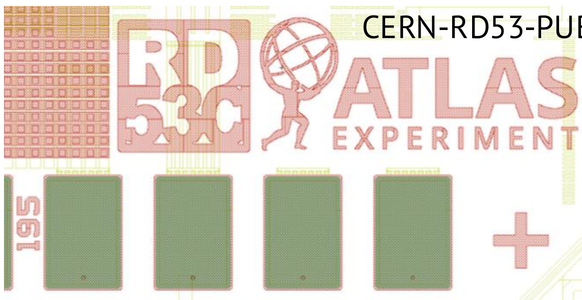






Front-End ASIC

- Developed by the RD53 collaboration
- 65nm CMOS technology
- Common ASIC for ATLAS and CMS, with few differences in:
  - ✓ Pixel matrix
  - ✓ Pixel analog front end
- Production design of the ITkPix v2 is part of the framework RD53C
- Prototype: RD53A
- Pre-production: RD53B = ITkPix v1
- Front-end chip is connected to the sensor via bump bonding

ITKPix V2

- Pixel matrix: 384 rows x 400 columns
- Pixel bump pitch: 50 x 50 μm^2
- Chip dimension: 20 x 21 mm^2
- 4 data link per chip at 1.28 Gbps -> read-out with data compression
- Data merging to reduce quantity of cables
- Shunt-LDO regulators integrated to the front end -> constant current for serial powering the modules

bump

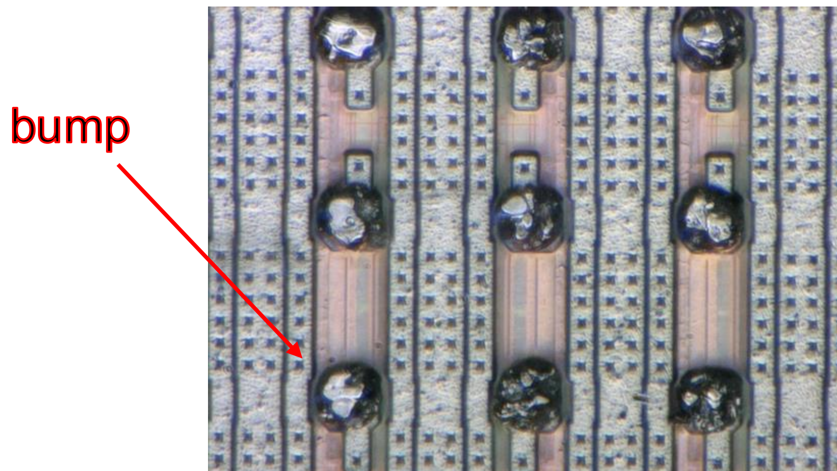
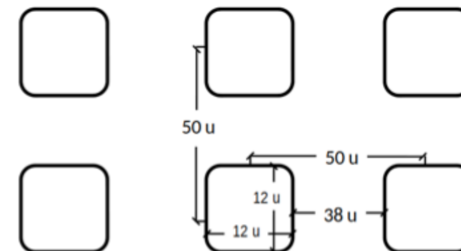


Photo done in Milan of a chip ITkPix V1 with Indium bumps



CERN-RD53-PUB-24-001

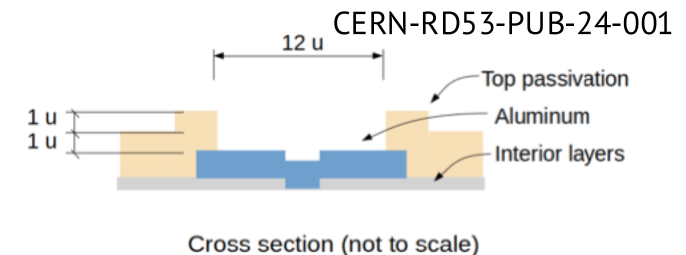


Figure 6: Bump bond pad dimensions. Matrix layout on the left and cross section on the right.

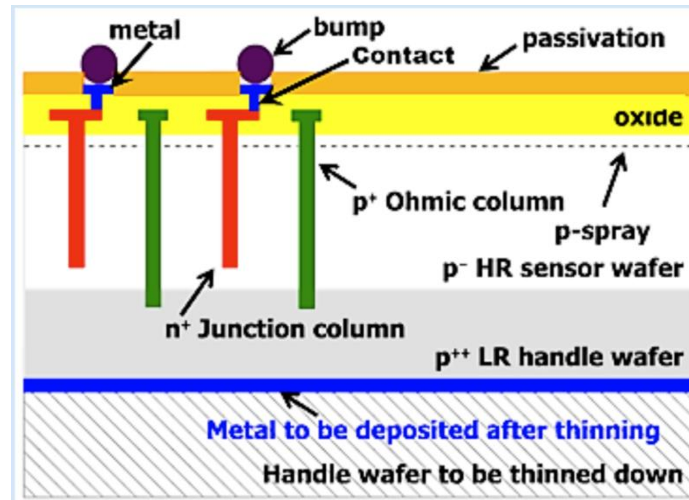
ITk Pixel 3D Sensors

- Single-side technology: both columns, n-type and p-type, etched from the same side
- 150 µm active substrate
- Sensor thickness 250-270 µm
- Dimension: 20 x 20 mm²

- Small pixel cells -> improved radiation hardness

Bump bonded to a 20 x 20 mm² front-end chip: single bare module

- n+ columns used for read out



Y. Tian, ICHEP2024 (poster)

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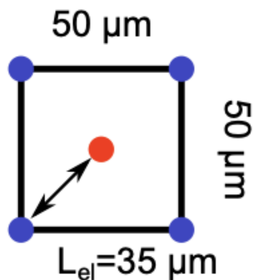
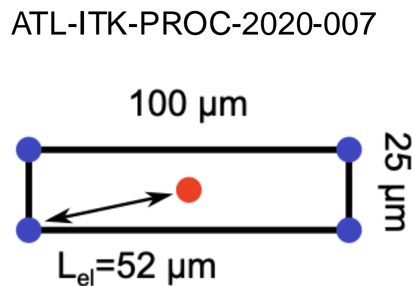
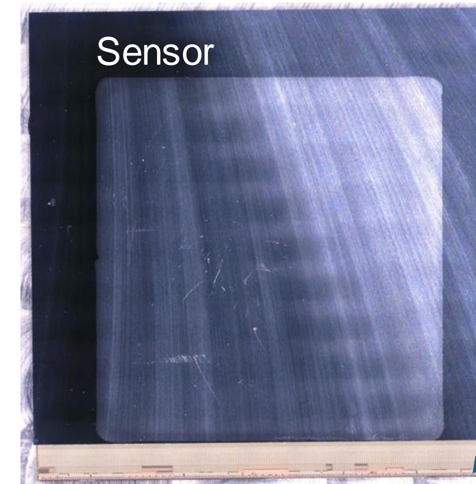


L0 ring



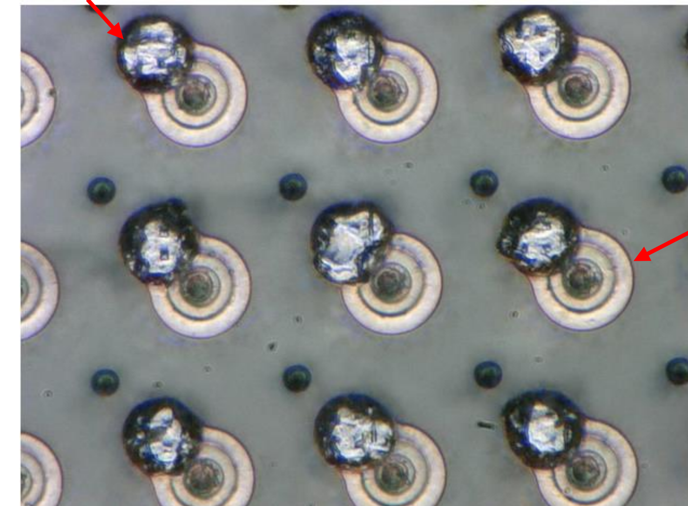
L0 barrel



Front-end ASIC wire-bonding pads

Photos done in Milan of a single bare module ITkPix v1 (top) and a 3D sensor (bottom)

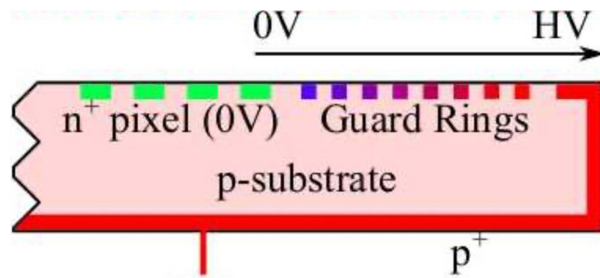
Indium bump on the contact of the n+ column



Location of the p+ column

ITk Pixel Planar Sensors

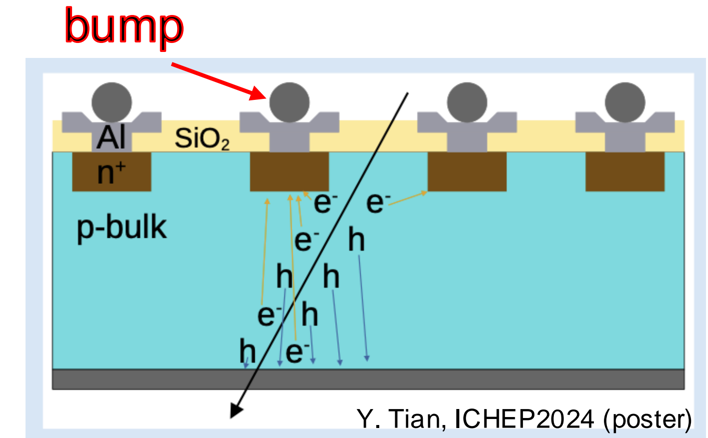
- Planar sensors used in the Outer System + the outer layer of the Inner System (L1-L4)
  - Simpler production process than 3D
  - Lower cost
- Single-side technology: n-in-p



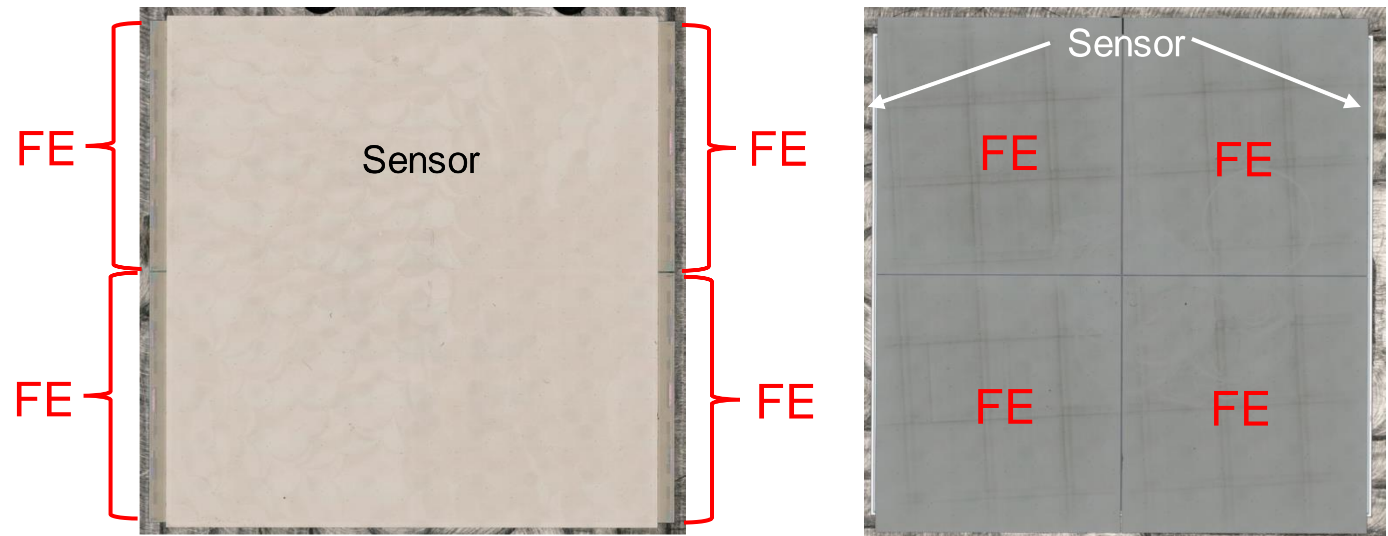
A. Rummler, VERTEX2023 (talk)

- 100 or 150 µm active substrate
- Dimension: 40 x 40 mm^2

Bump bonded to four 20 x 20 mm^2 front-end chips (FE): quad bare module



Y. Tian, ICHEP2024 (poster)



Photos done in Milan of a ITkPix quad bare module ITkPix v2

ITk Pixel Module

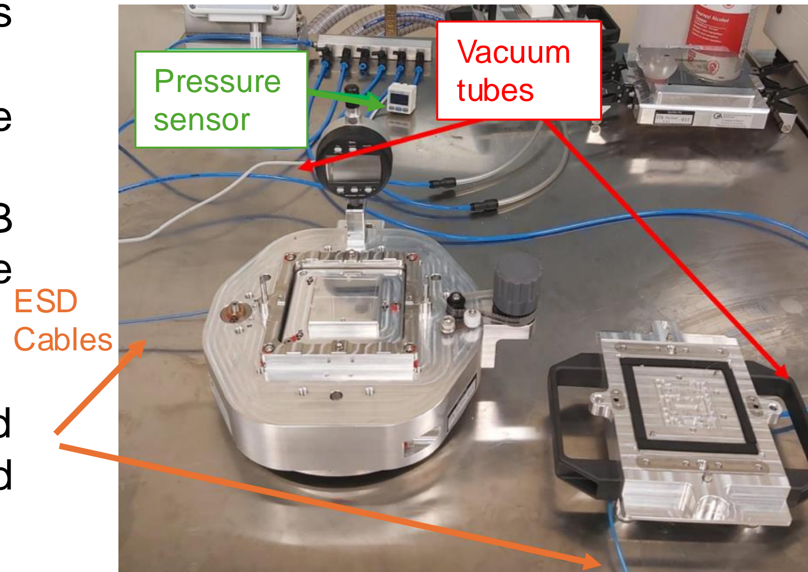
ATLAS ITk

The bare module is assembled to a flexible PCB, which provides connection for power, DCS and data:

- Araldite is applied to the back of the PCB.
- Bare (sensor backside) and PCB are joined together, letting the adhesive curing for at least 8h

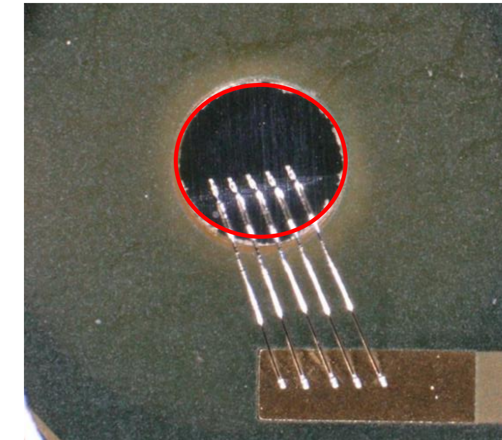
Different techniques and tools are used according to the module flavour and assembling site.

- **Quad**:
  - Common tool produced in Gottingen and used by the sites from the US, Italy, France, Germany, the UK (except Oxford)
  - Japan and Oxford designed and produced their own assembly tool
- **Triplet**: each site developed its own technique and tools

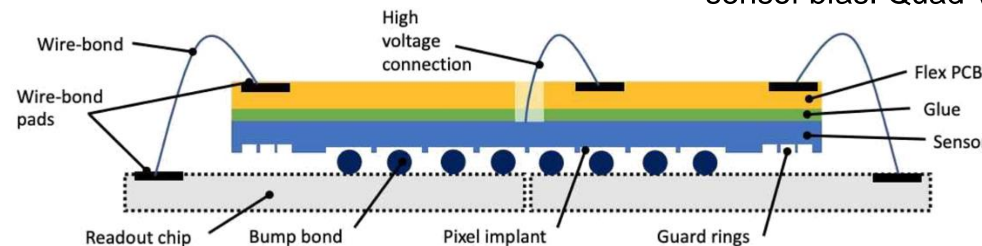


Common Quad module assembly tool . Photo from the Milan setup.

Then, the PCB is connected to the read-out ASIC and to the backside of the sensor via wire bonds.



Wire bond connecting the back of the sensor (inside the red circle) and the PCB, for the sensor bias. Quad V1 from Milan.



A. Rummler, VERTEX2023 (talk)

ITk Pixel Module

QUAD module: Quad bare module + a flexible PCB

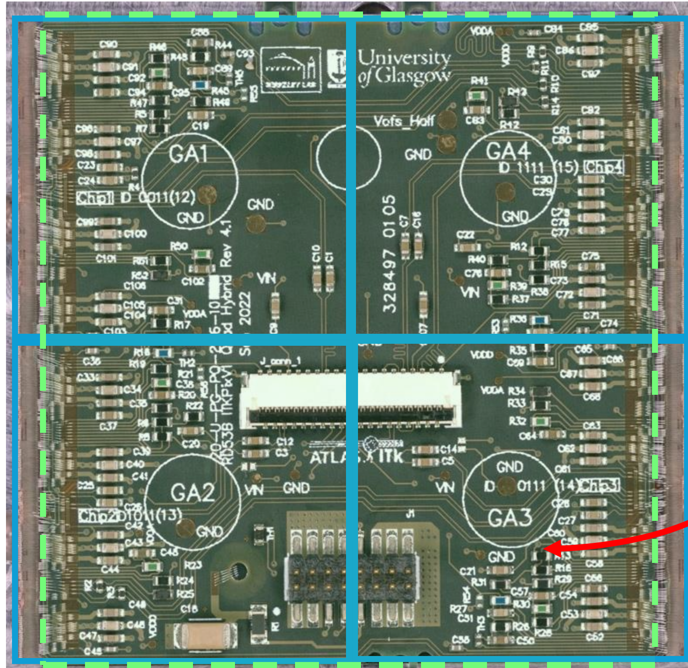


Photo made in Milan of an ITk Pixel quad module v1

Sensor

FE

PCB

TRIPLET module: 3 single bare modules + a flexible PCB

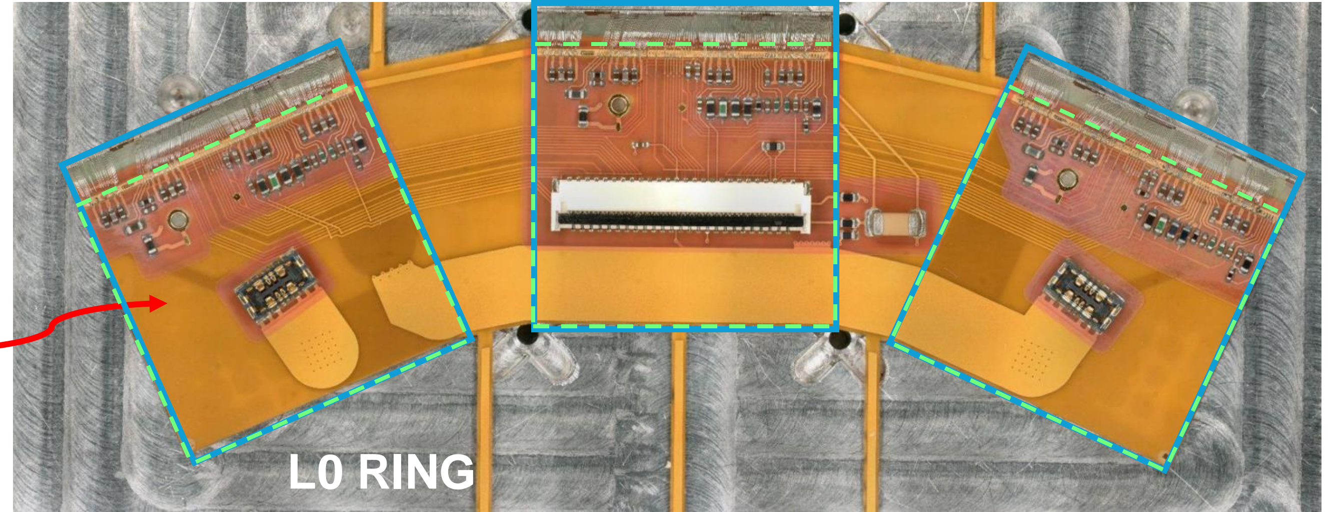
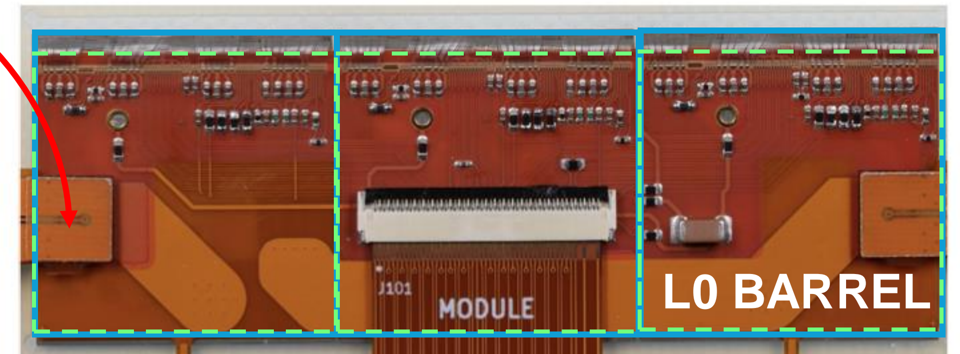


Photo made in Milan of an ITk Pixel triplet module v2 for Ring 0.5

Layer	Module type	Sensor type	Sensor thickness (µm)	Pixel size (µm²)
L0 barrel	Triplet	3D n-in-p	270	25x100
L0 ring	Triplet	3D n-in-p	250	50x50
L1	Quad	Planar n-in-p	100	50x50
L2-4	Quad	Planar n-in-p	150	50x50



NIMA 1063 (2024) 169309

ONLY FOR QUAD MODULES

ITk Pixel Module Coating

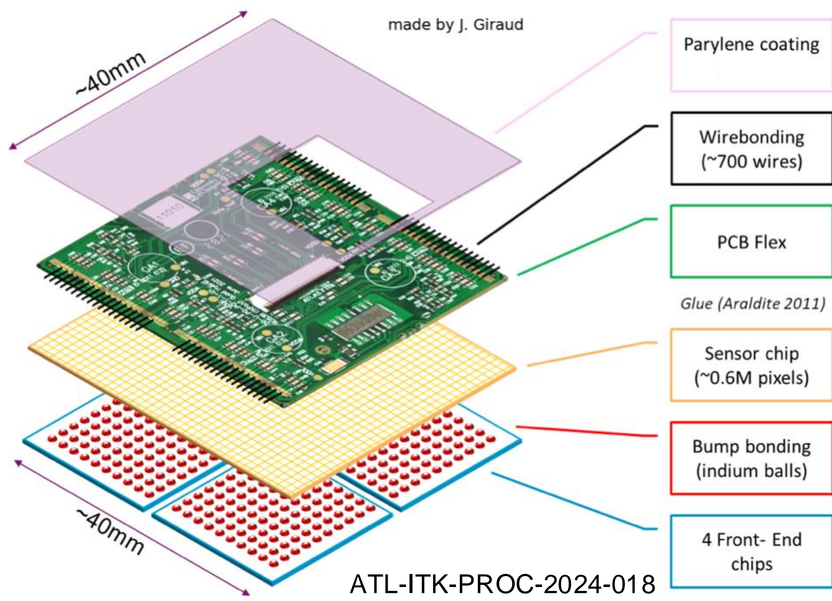
ATLAS ITk

Increasing radiation damage → Higher sensor depletion voltage → Possible spark between sensor and ASIC ground connection →

Coating the module with parylene, around 7-8 μm of this polymer is deposited on both module surface via vapor process

Other benefits

- Mechanical Protection
- Increased wire bond strength



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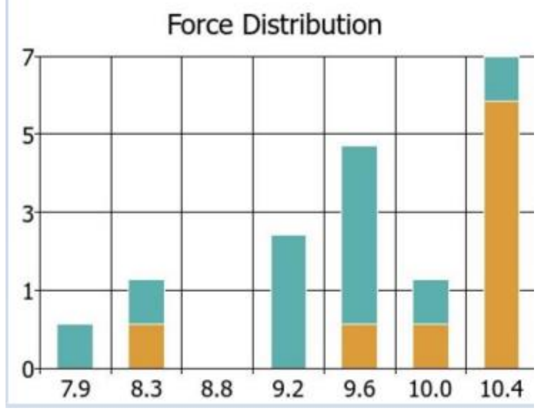
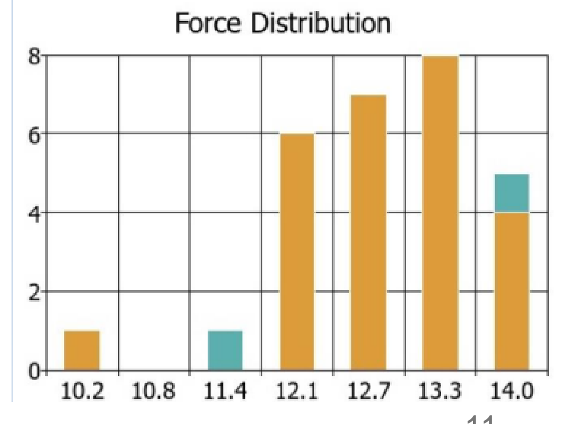




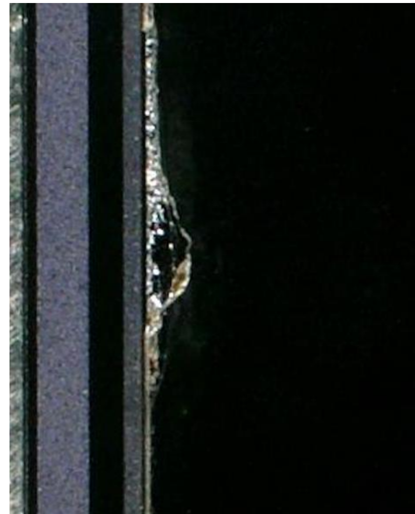
Results from a RD53A quad module in Milan

ITk Pixel Module QC

QC aims the early identification of low-quality modules that should not be part of the detector and are done for all modules in different stages

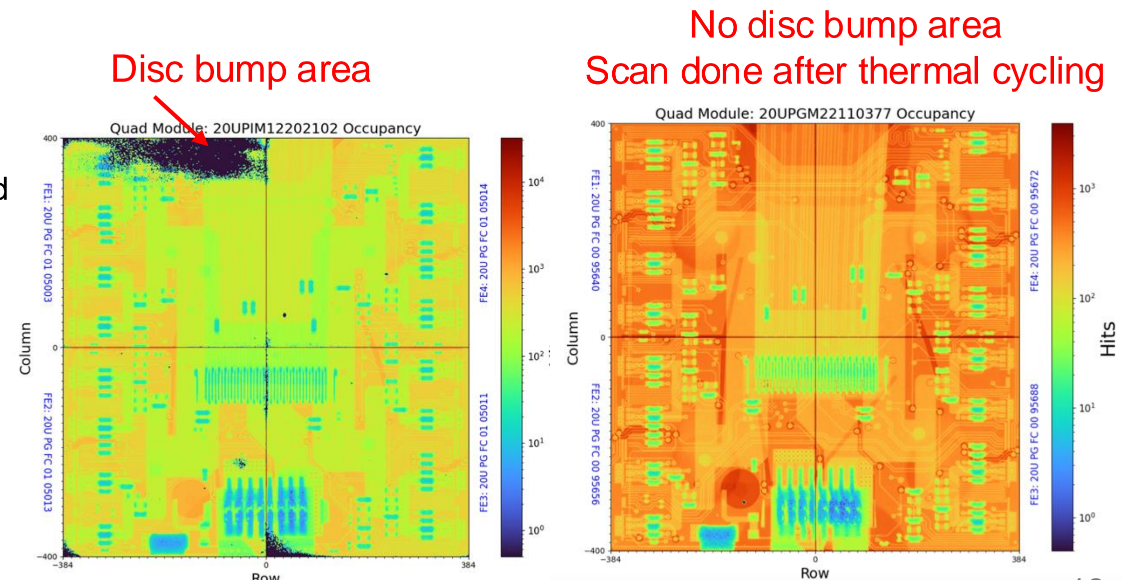
Summary of tests that are part of the QC

- modules XYZ are within envelope requirements
- Visual inspection
- Sensor IV
- Module performance at room and operational temperatures (~ -10°C)
- See digital, analog and time-over-threshold response
- Tune threshold
- Check pixel noise, crosstalk and disconnected bumps



Visual Inspection of an ITkPix v1 module in Milan showing a chipped ASIC border

- The modules are constructed with different materials -> extra stress on the bumps due to the huge temperature gap between assembly (~ +20°C) and the HL-LHC coolant (~ -45°C) .
- To verify their capacity to work under these conditions, all modules are thermally cycled before loading, with 100 cycles between -55°C and +60°C (nowadays +40°C)



X-ray scan of two quad modules v1 assembled in Milan

ITk Pixel Module (PRE)Production

Sensors already in production

PRR of both quad and triplet modules approved with recommendation in November 2024

Module Construction is moving now from pre-production to production

Data from 22 November 2024

ITkPix V1 and V2

Counts

500
450
400
350
300
250
200
150
100
50
0

July September November 2024 March May July September November

Date

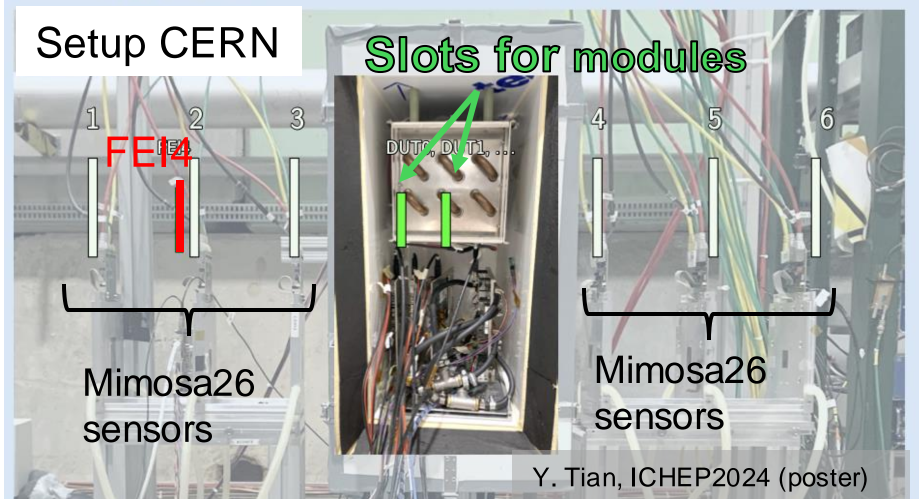
moduleType
L1_QUAD_MODULE
OUTER_SYSTEM_QUAD_...
TRIPLET_L0_RING0.5_M...
TRIPLET_L0_RING0_MO...
TRIPLET_L0_STAVE_MO...

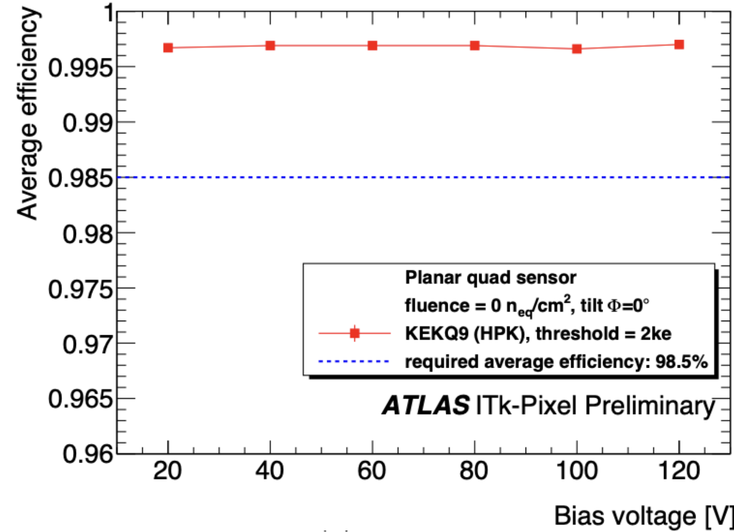
Plots available on:
https://module-qc-statistical-tools-atlas-itkpixel-data-reporting.app.cern.ch

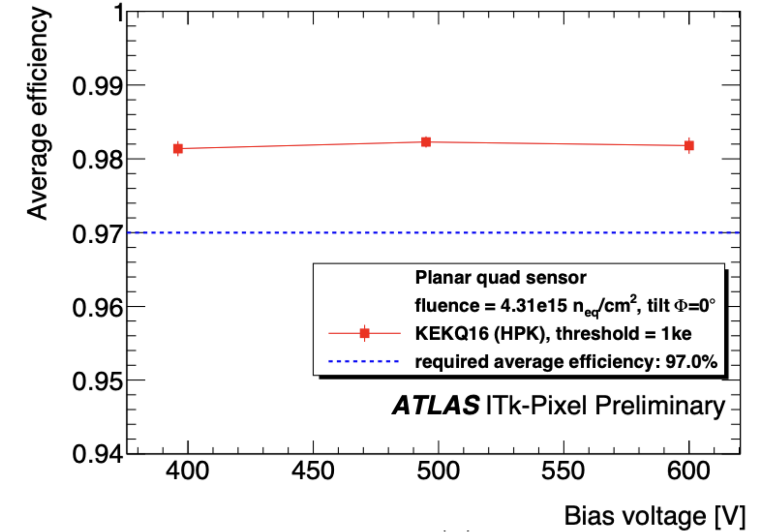
Testbeam

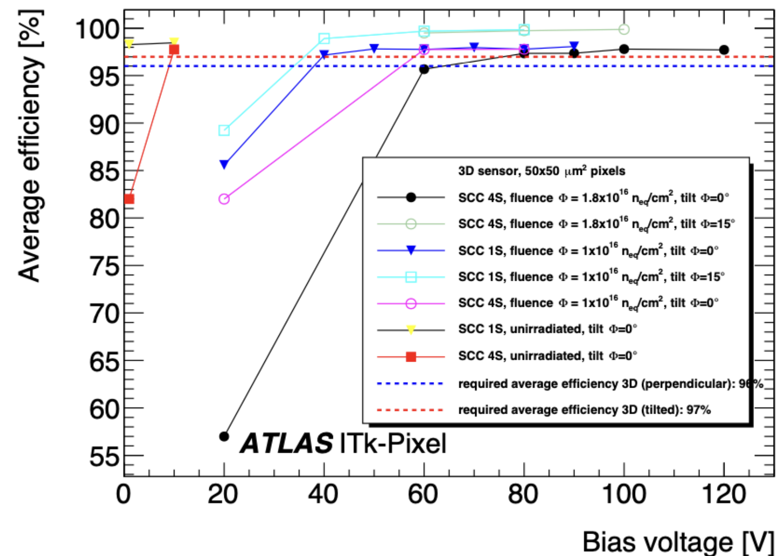
ATLAS ITk

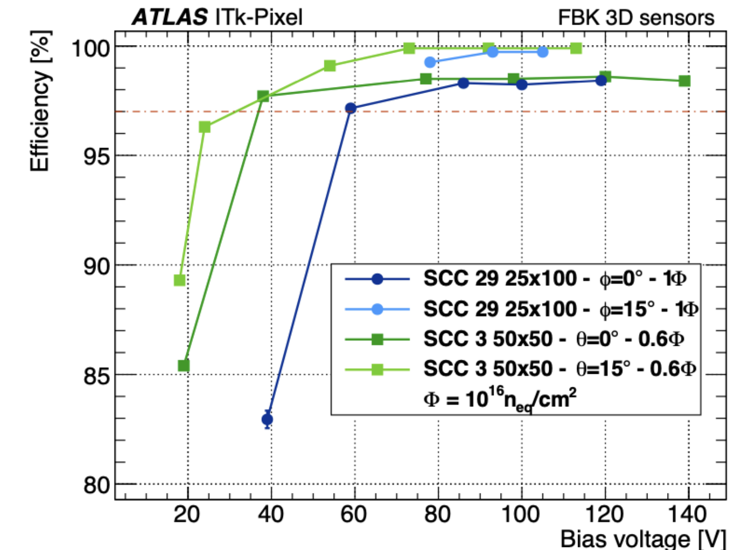
ATL-ITK-PROC-2024-002











- Average efficient of planar (top) and 3D sensors (bottom) unirradiated and irradiated.
- These sensors were assembled to ITkPixV1 chips
- In all cases, it is higher than the efficiency required (dashed lines)

Outer Barrel and Endcap local support already in production

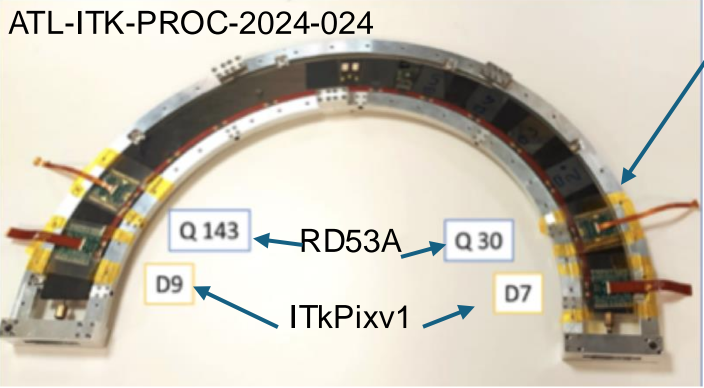
Local Support

Outer Barrel

F. Munoz Sanchez ICHEP 2024

ATL-ITK-PROC-2023-003

Outer Endcap



Modules are glued to the local support

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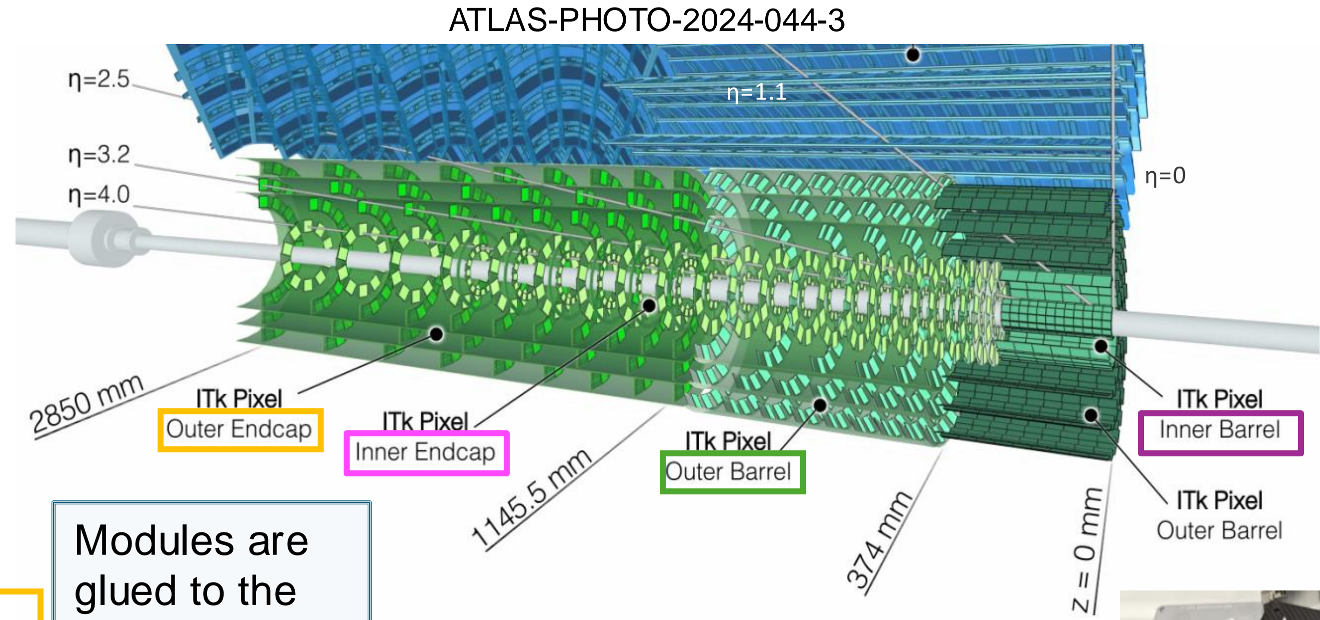

Carbon-based structures that provides mechanical support to the modules + cooling and part of the services

Inner Barrel

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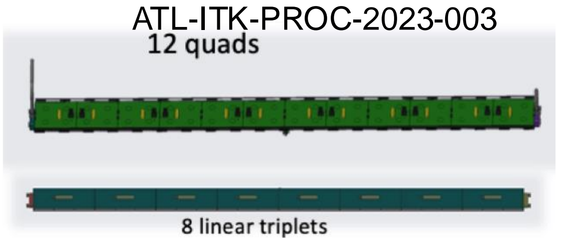
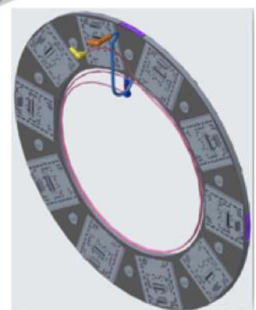


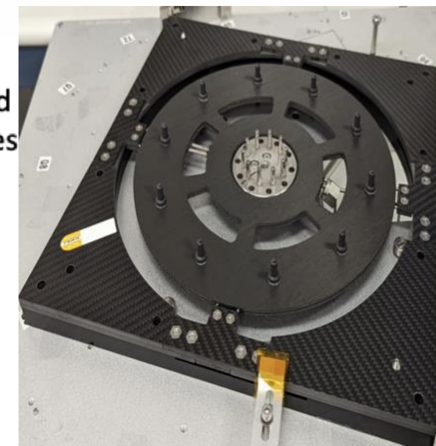
Inner Endcap

ATL-ITK-PROC-2023-003



R1: 20 quads

R0: 20 Quads and 6 triplets modules



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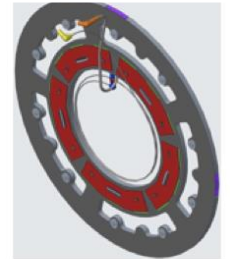
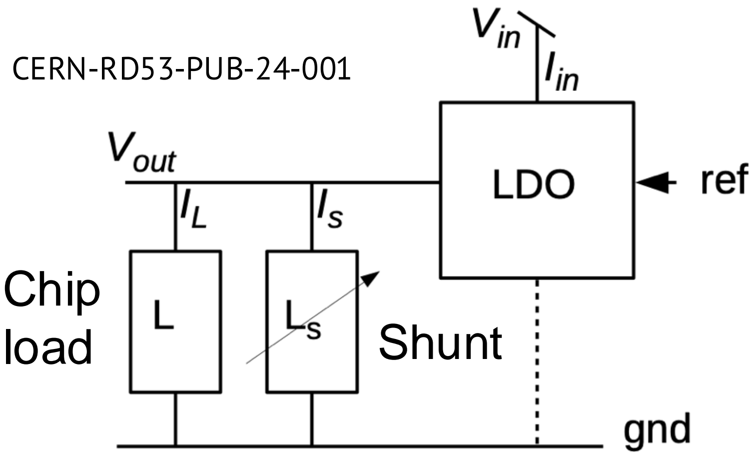
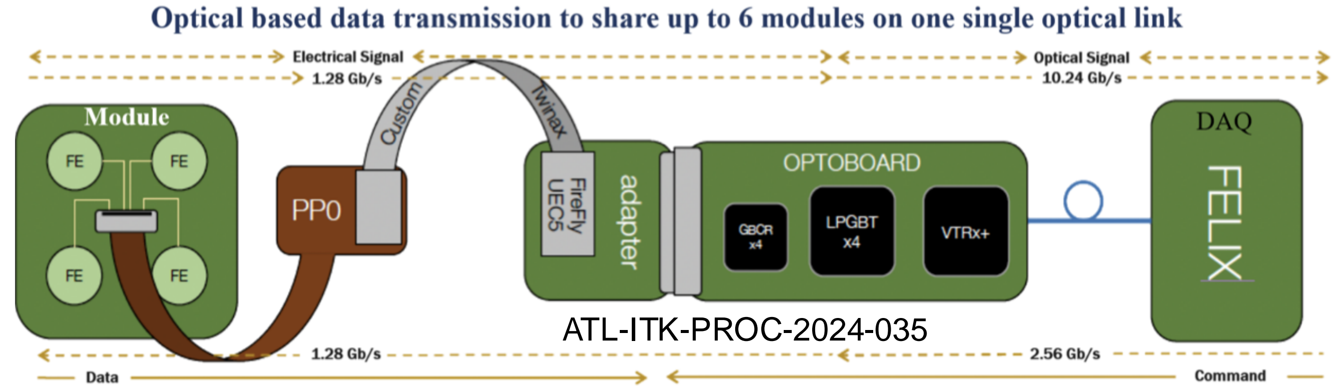


R0.5: 10 triplets modules

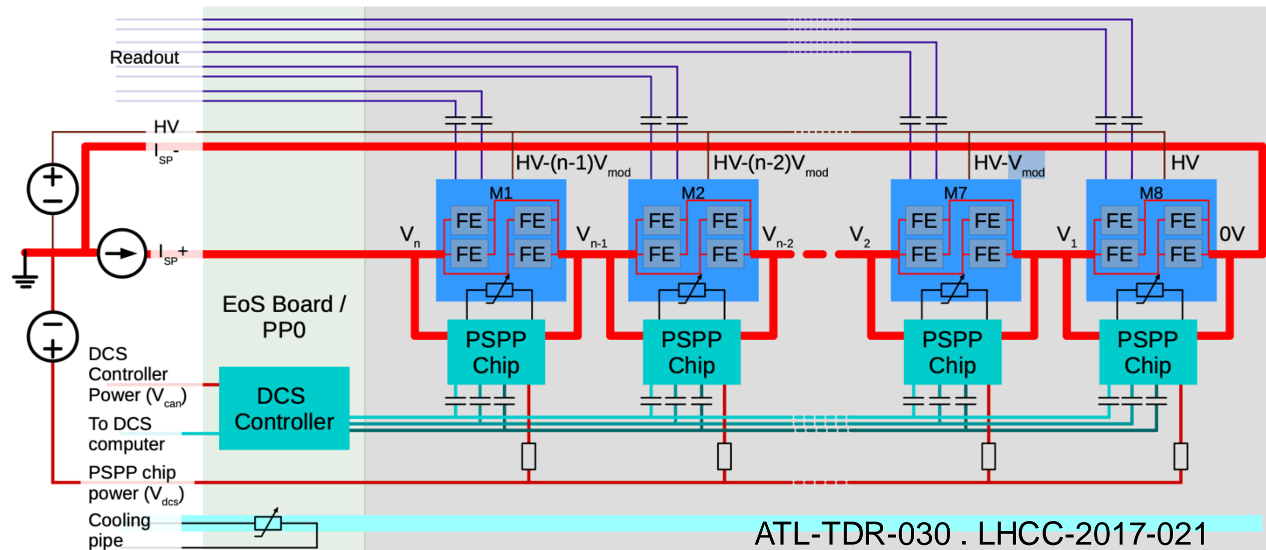
Serial Powering and Data Transmission

Shunt-LDO circuit: chip voltage constant





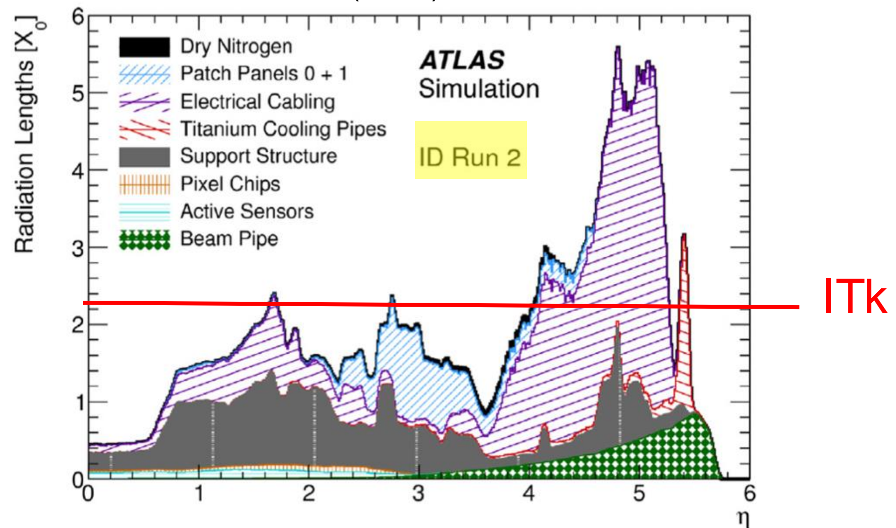
Chips in a module are connected in parallel, but modules are powered in series with constant current



- Module <-> PP0 (on local support) via Kapton/cooper flexes
- PP0 <-> Optoboard on Twinax cables
- Optoboard performs signal aggregation and electrical-to-optical signal conversion
- Optical signal <-> FELIX

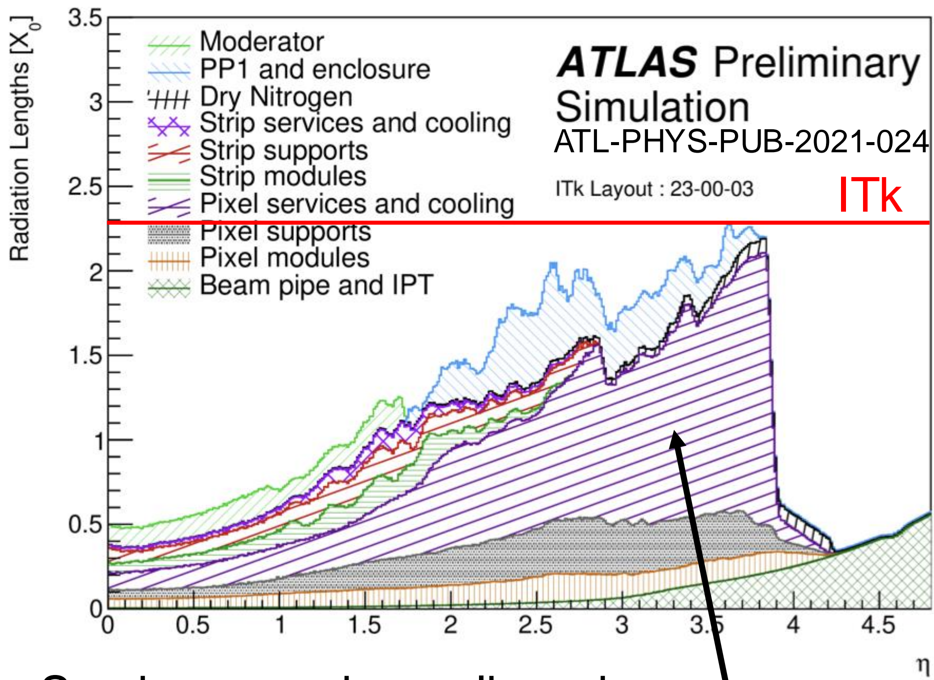
Reduction of cable material

Material Budget ATLAS ITk



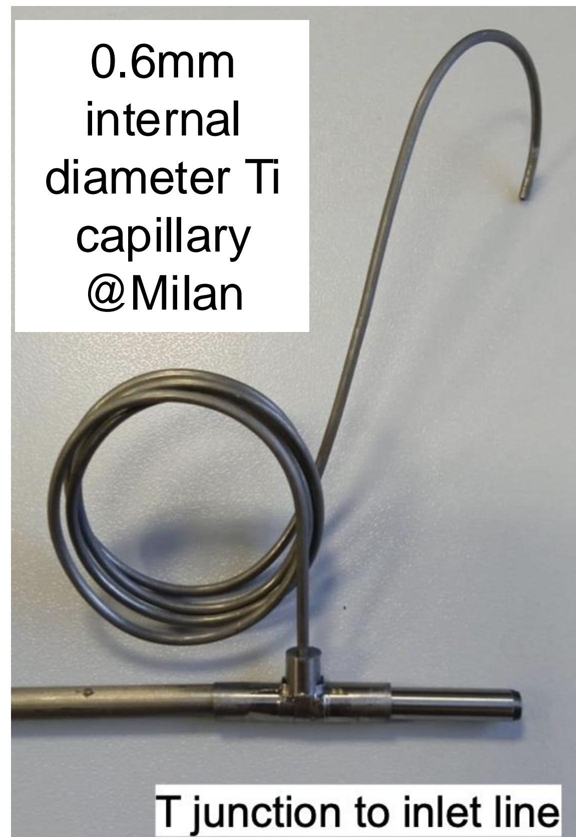
Apart from the use of less cables, also the cooling was proposed to minimize the overall contribution of services to the budget.

- CO_2 cooling
- thin-walled titanium pipes



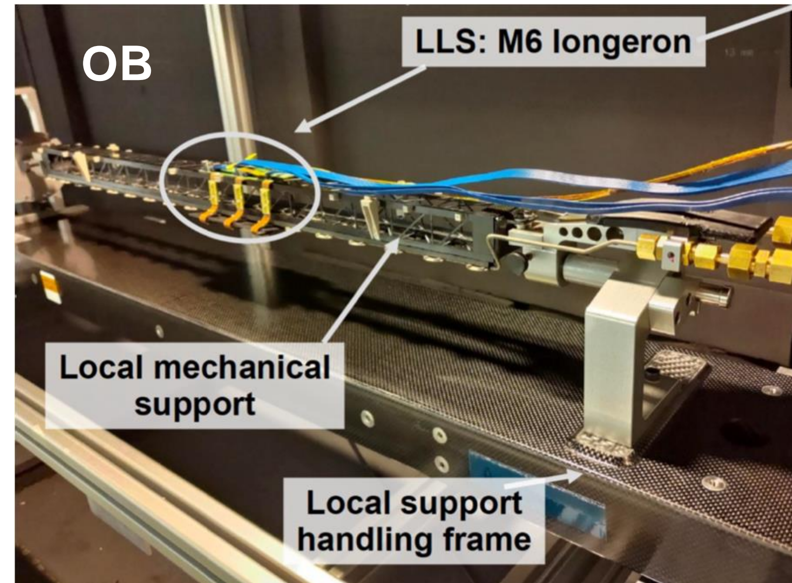
Services and cooling have an important contribution to the ITk material budget.

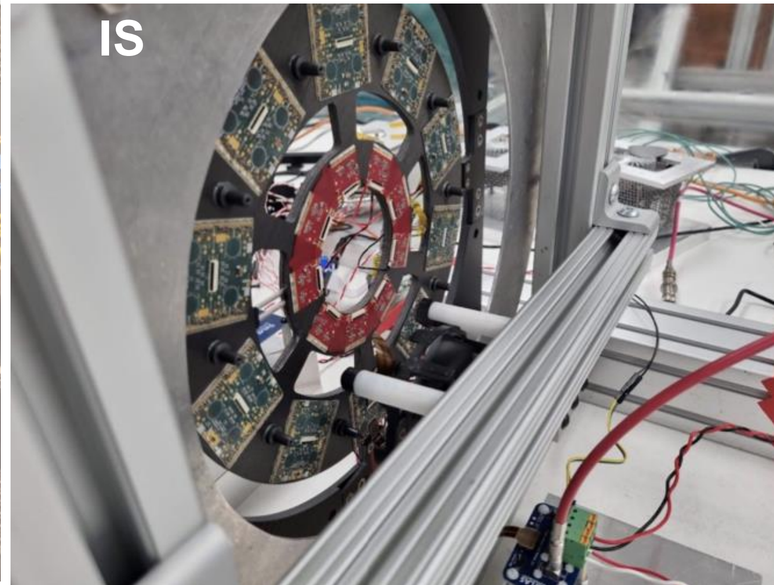
Integration test of L2 cooling system on mockup half shelf @Milan



System Test

ATL-ITK-PROC-2024-035



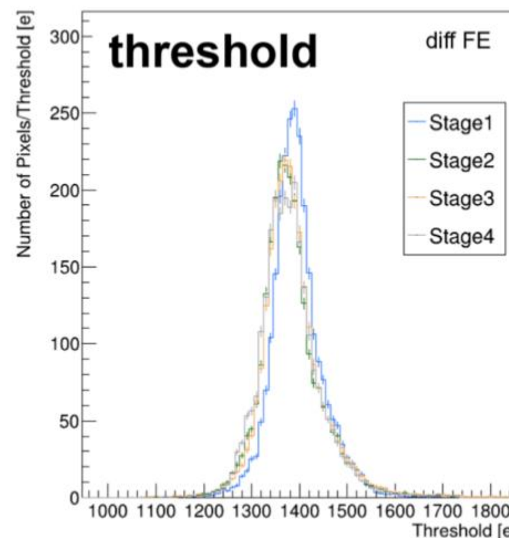


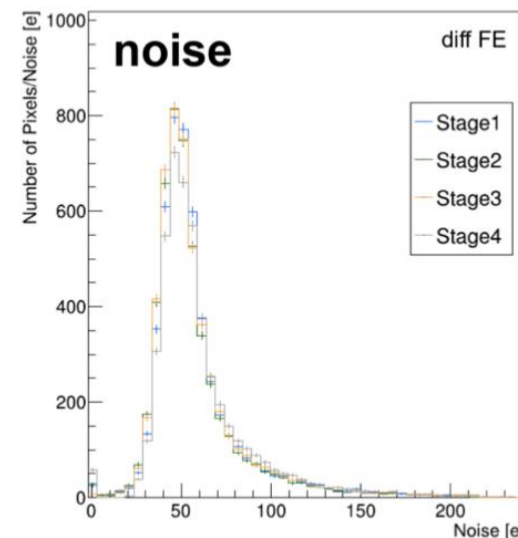
Check the modules performance in different stages. Bottom: A **RD53A** FE of a module on an OB local support

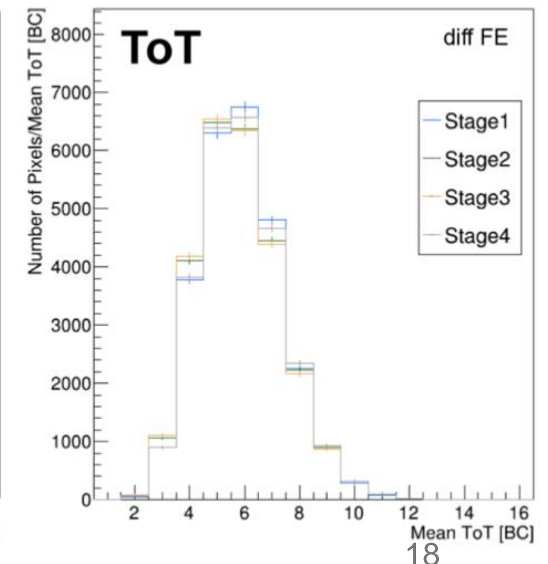
1. Module construction
2. Module Loading on local supports
3. After Pigtail Assembly
4. Integration

Modules are glued to local support, which is mounted in a structure close to the real one, with all services available

- Powering
- Data transmission
- Cooling
- DCS





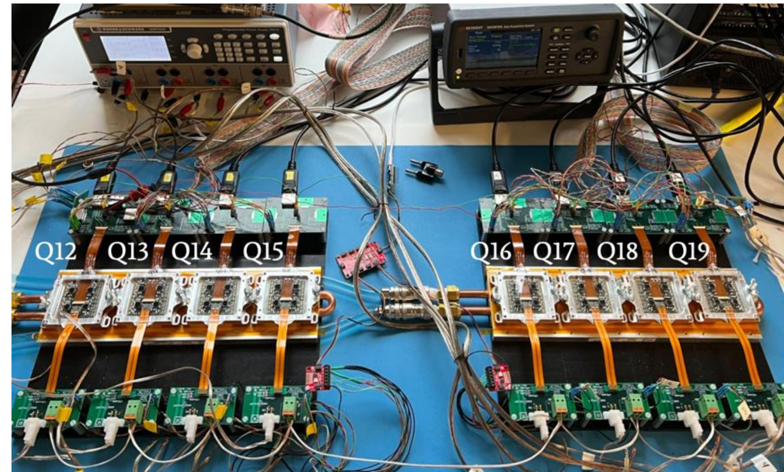


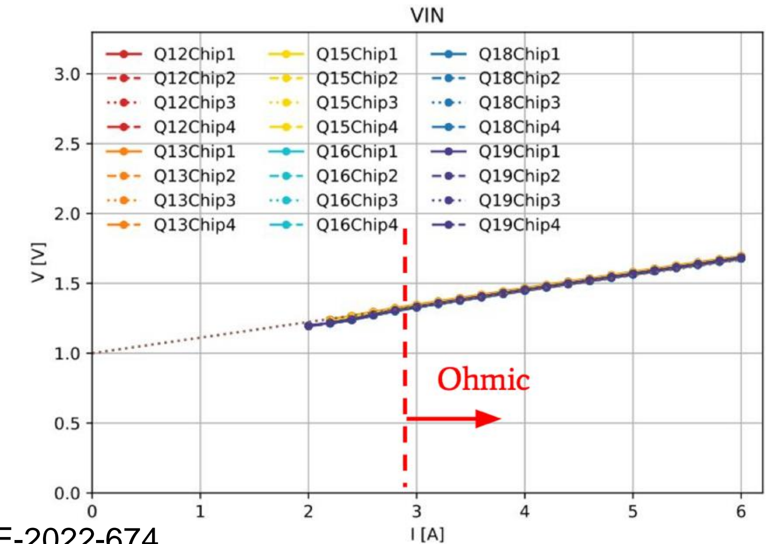
ATL-ITK-PROC-2024-035

ITkPix Early Tests

Next stage is to load ITkPix modules for system test

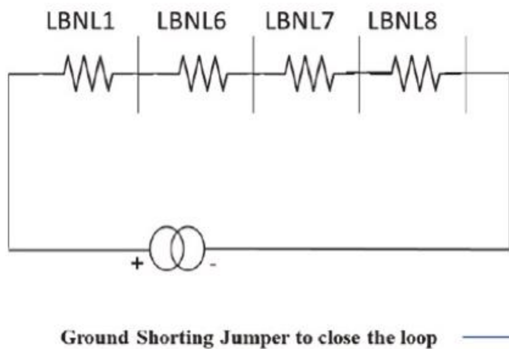
So far, these modules have been used for serial powering tests at Lawrence Berkeley National Laboratory (LBNL)

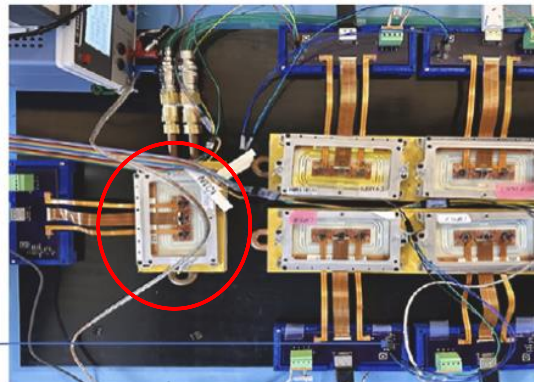




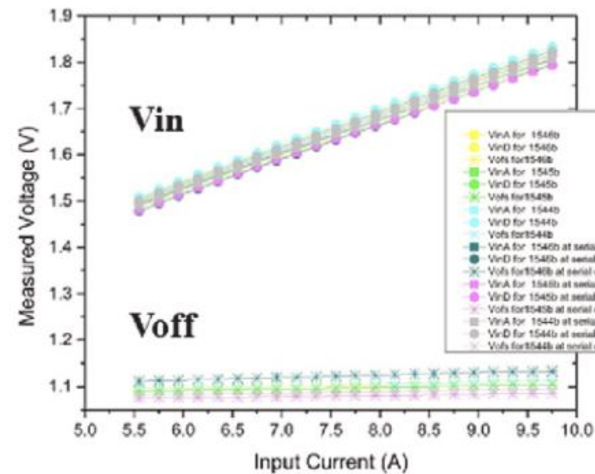
ATL-ITK-SLIDE-2022-674

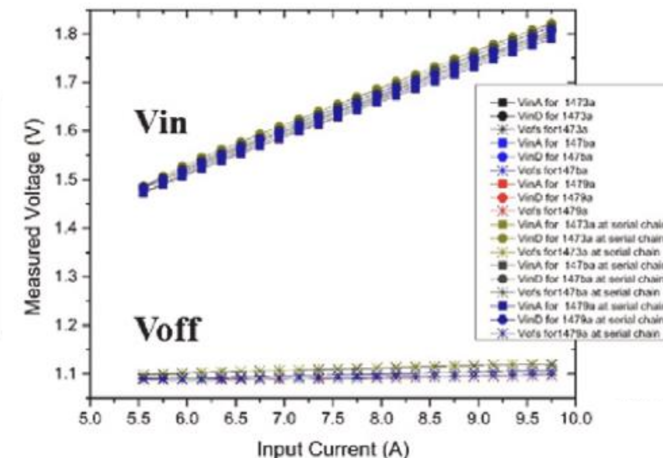
Setup with 8 ITkPix V1 quad modules connected in series. For a certain current, Vin for all chips are the same





4 linear triplet modules connections. The fifth (red circle) is not connected





Voltage per chip as function of the input current for 2 of the 4 ITkPix v1linear triplets powered in series

NIMA 1063(2024)169309

ITk Pixel Status

ATLAS ITk

Challenges during RD53A/B program

- **Gluing highly affected by the operator** -> use of a common tool for quad assembly, which reduced also the overall assembly time
- **Delamination** -> improve of hybridization technique
- **Contamination of flex WB pads**→ visual inspection of those during flex reception QC
- **Parylene on data and power connectors** -> minimized by use of common tooling
- **ASIC chipping during dicing** -> extra metal free area + better dicing technique

Path to completion

- Sensors and ASIC in production
- Modules: just passed Production Readiness Review (PRR)
  - Moving to production once production PCBs are delivered
- Hybridization: 2 out of 4 vendors in production
- Most of the other areas with PRR coming soon

ITk Pixel Detector Completion in 2027

Summary

ATLAS ITk

- The ITk Pixel detector has been designed to replace the Inner Detector of ATLAS for operating in the hasher environment of the high luminosity era of the LHC:
  - Higher granularity
  - Better radiation hardness
  - Higher acceptance

- Most of the activities are in pre-production, getting ready to the Production Readiness Review

- In production
  - Sensors
  - ASIC
  - Outer System local supports
  - 2 hybridization vendors (out of 4)
  - Modules: soon, missing production PCBs

- ITkPix modules are needed in many areas for validation, system tests and demonstrators.

ATLAS ITk

Thank you