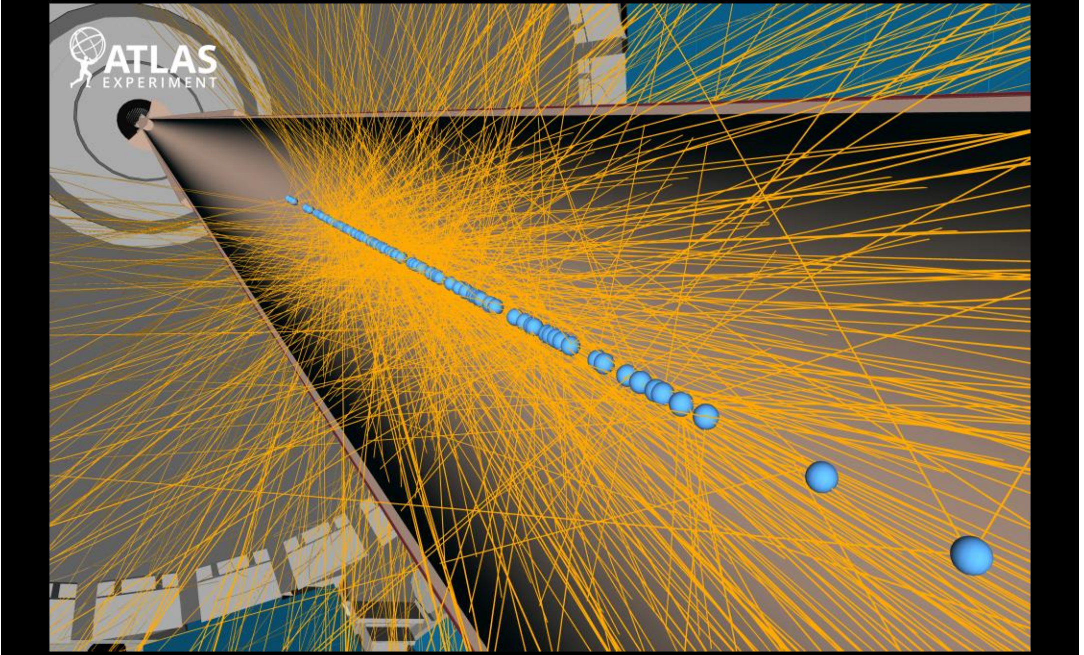
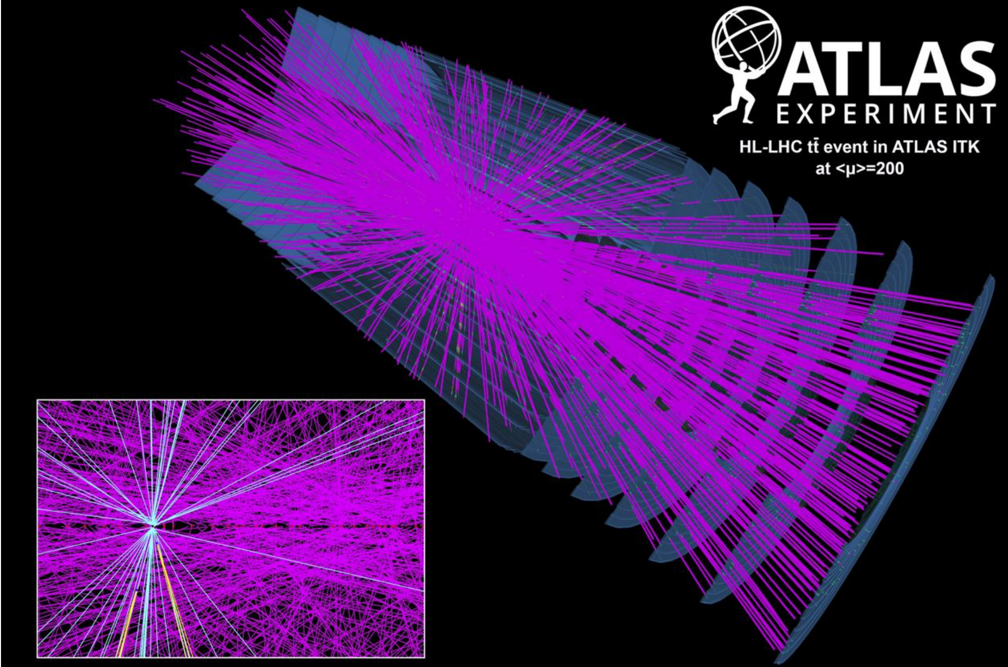




THE ATLAS ITK PIXEL DETECTOR: STATUS AND ROAD MAP

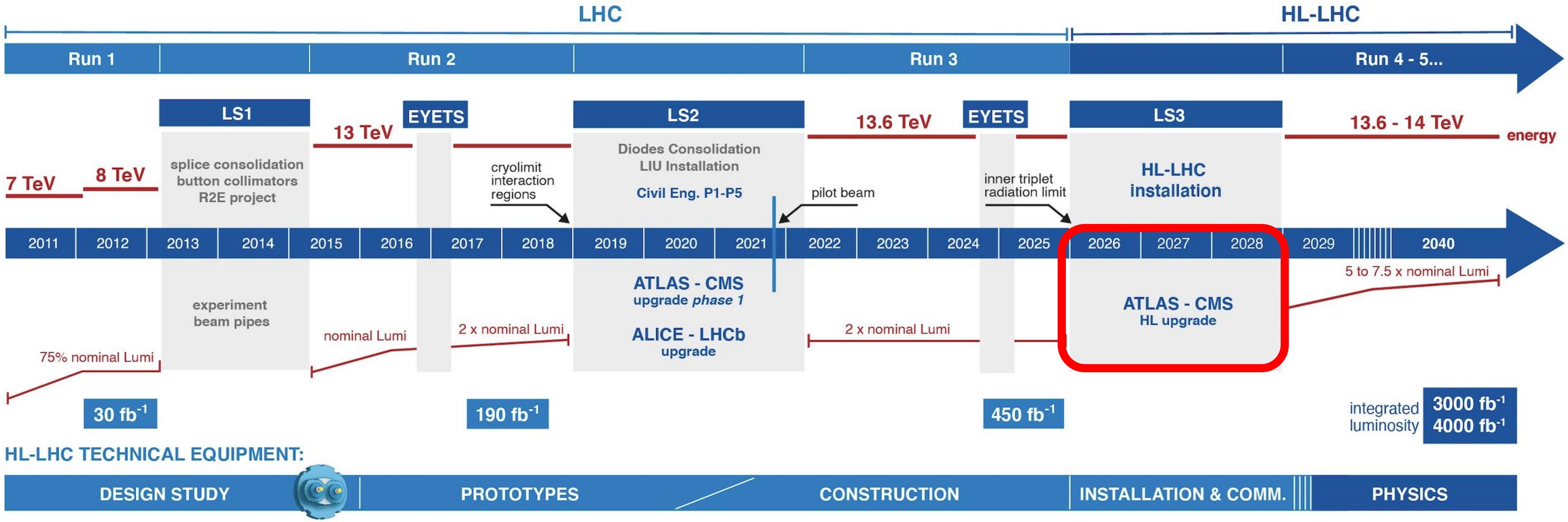
M. Ressegotti (University and INFN Genova)
On behalf of the ATLAS ITk Pixel Collaboration

ICNFP 2024
26 August – 4 September 2024,
Orthodox Academy of Crete, Kolymbari, Crete, Greece

HL-LHC CHALLENGES

HL-LHC: after 2026 luminosity up to 5-7.5 10^{34} cm^{-2} s^{-1} (up to 3.5 times Run-2 peak luminosity)

- 4000 fb^{-1} integrated luminosity in 10 years: more statistics to study rare physics processes
- Pile-up collisions increase from 20-50 (~48 in current Run-3 data) to **150-200**
  - **challenging for tracking, pattern recognition, requires higher readout rates**
- Higher radiation environment: damage scales approx. linearly with luminosity (**~x10 damage increase**)
  - **radiation-hard detectors needed**



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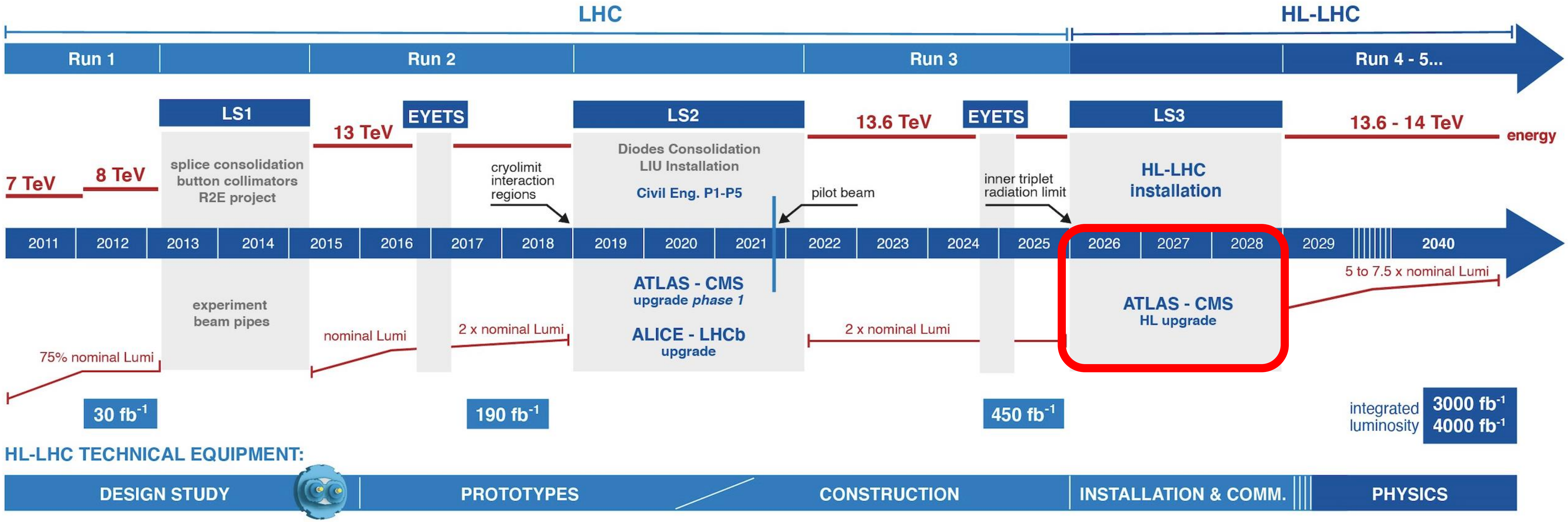
- 4000 fb^{-1} integrated luminosi are physics processes
- Pile-up collisions increase fro **150-200**
  - **challenging for tracking** **readout rates**
- Higher radiation environmen luminosity (**~x10 damage increase**)
  - **radiation-hard detectors needed**

The current inner detector:

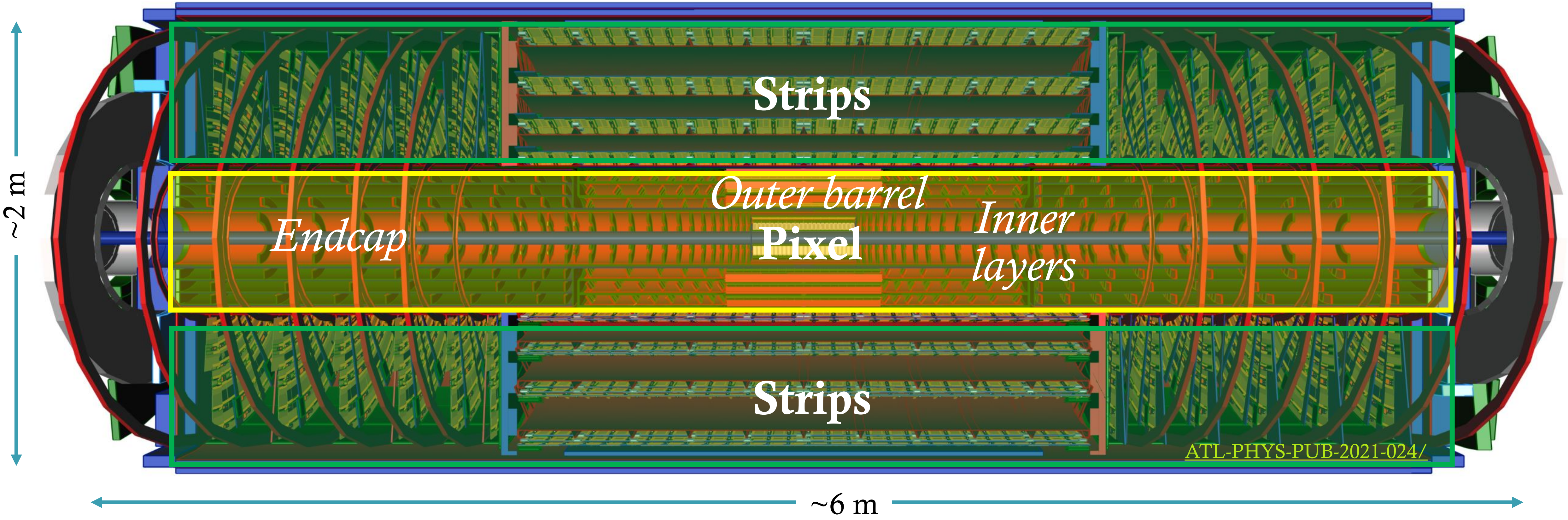
- can't operate during HL-LHC
- will be replaced with a new all-silicon tracking detector: **the ITk**



THE ATLAS ITK

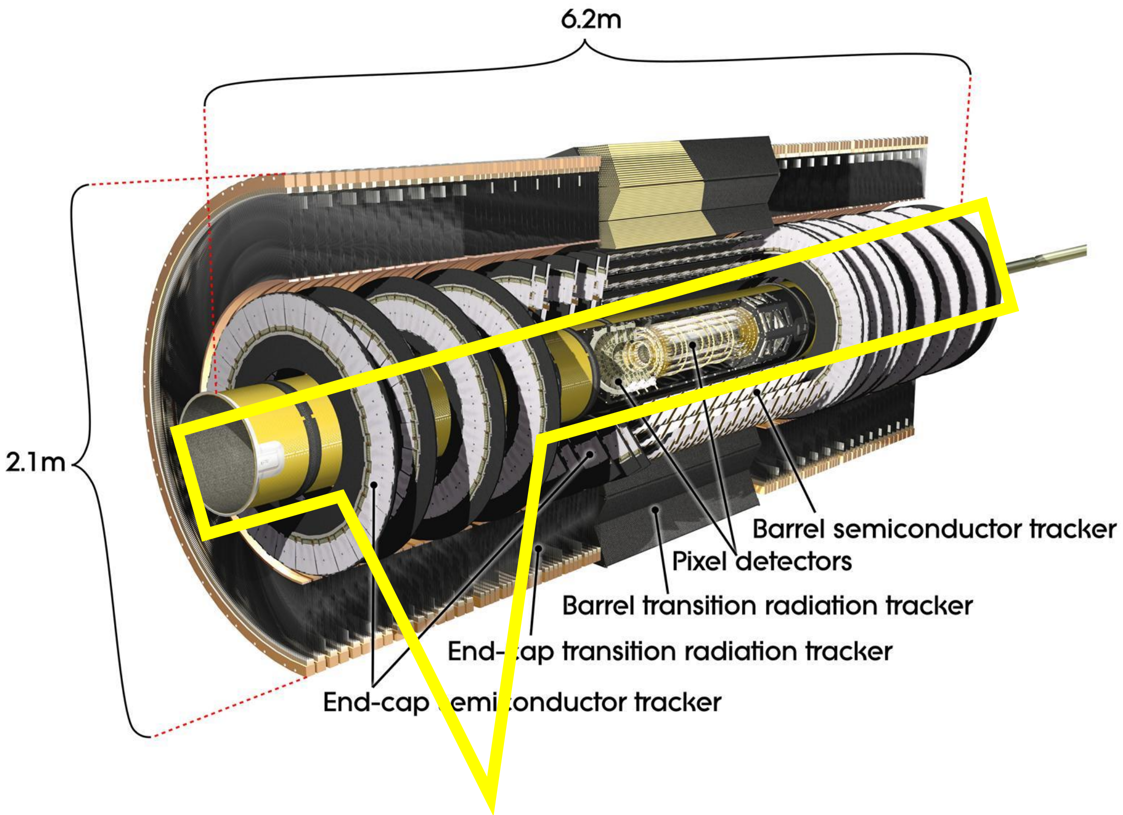
- All-silicon tracking detector
- Increased granularity to keep occupancy <1%
- Minimized material budget: low mass mechanics and cooling, serial powering
- Increased radiation hardness
- Increased trigger rate

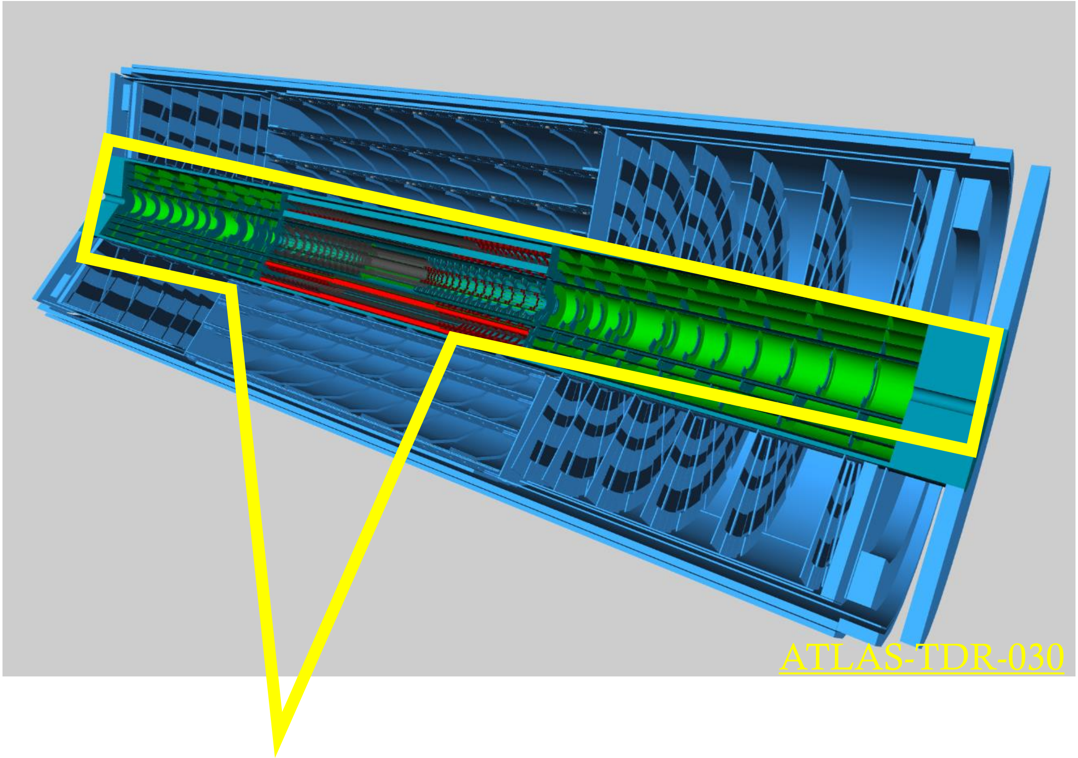
- Innermost part: Pixel detector
- Outermost part: Strip detector (see Emily's talk)



ATL-PHYS-PUB-2021-024/

THE ATLAS ITK PIXEL DETECTOR




ATLAS-TDR-030

Current pixel detector:

~92M pixels
~2000 modules
~1.9 m^2 active area
|η|<2.5

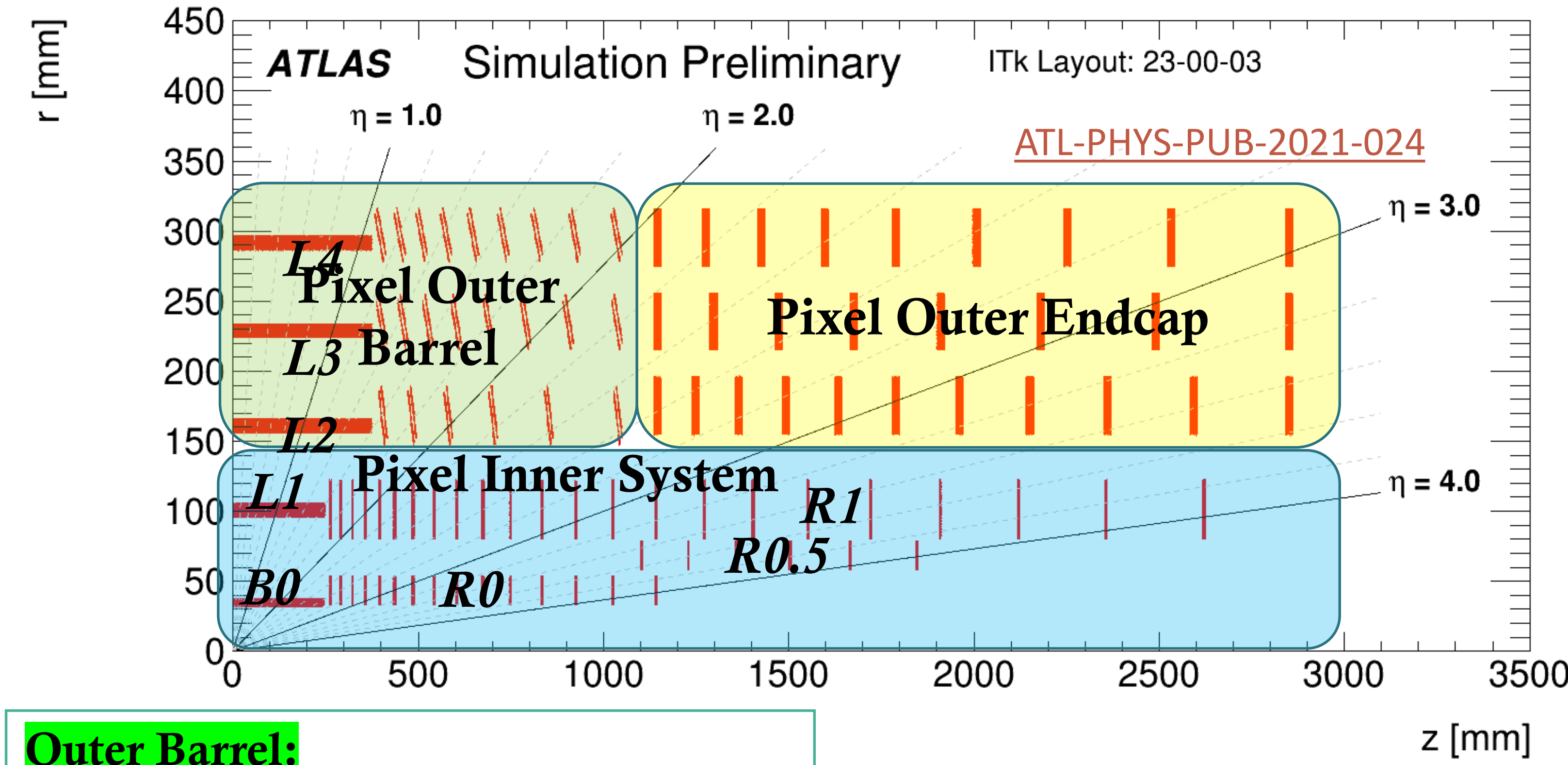
The new ITk Pixel detector:

~5G pixels
~9,400 modules
~13 m^2 active area
|η|<4

THE ITK PIXEL LAYOUT

The ITk Pixel detector:

- 5 layers of Pixel detectors:
  - **L2, L3, L4**: Planar n-in-p sensors (150 μm)
  - **L1, R1**: Planar n-in-p sensors (100 μm)
  - **L0 (B0, R0, R0.5)**: 3D sensors



Inner System:

- 2400 modules on flat staves and rings
- 396 3D triplet modules in L0
- 1160 planar quad modules in L1
- **2.4 m^2**
- expected fluence up to **9.2e15 n$_{eq}$/cm^2** and 7.3 MGy **@2000fb^{-1}**
- will be **replaced** after 2000 fb^{-1} (1.5 safety factor on max fluence)

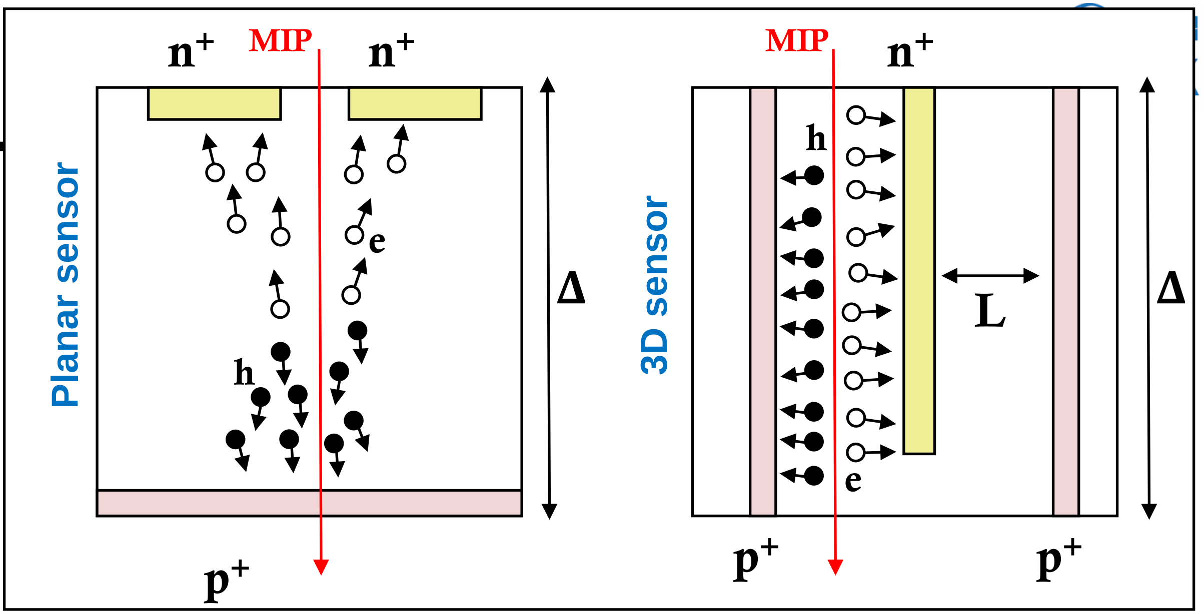
Outer Barrel:

- 4772 quad modules
- 3 layers
- **6.94 m^2**
- Flat staves (longerons) and inclined rings
- down to 34 mm from collisions
- expected fluence up to **2.3e15 n$_{eq}$/cm^2** and 1.7 MGy @4000fb^{-1}

Outer Endcap:

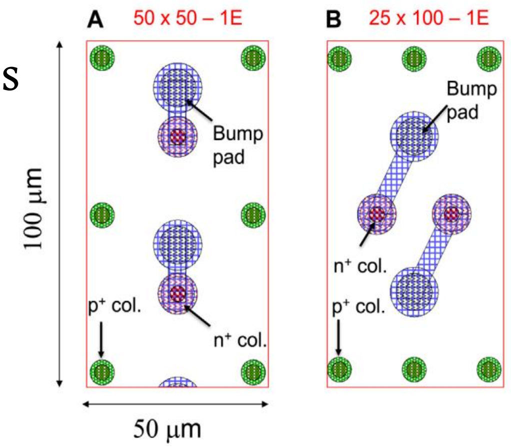
- 2344 quad modules
- 3 layers of rings
- **3.64 m^2**
- expected fluence up to **3.1e15 n$_{eq}$/cm^2** and 3.5 MGy @4000fb^{-1}

PIXEL SENSORS



- Planars (L1-L4)
  - Simpler production process than 3D
  - 100 μm and 150 μm sensor thickness for different radiation hardness
- 3D sensors (L0) – **more radiation hard** → closest to beam
  - Higher electric field for the same applied voltage → low depletion voltage
  - Smaller drift time → fast response
  - Smaller electrode distance (e-h path length) → less trapping probability → improved radiation hardness
- 3D sensors in ITk:
  - single-sided 3D-1E sensors → thinner columns
  - 250 μm thickness (150 active + 100 support)
  - **50x50 μm^2** pixel cell in endcaps (~4000 cm^2)
  - **25x100 μm^2** pixel cell in barrel (~400 cm^2)

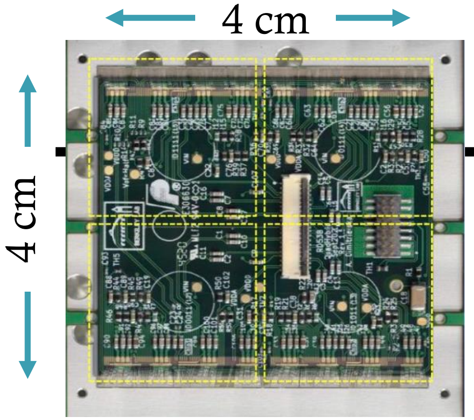
ITk Pixel 3D sensors 1E design



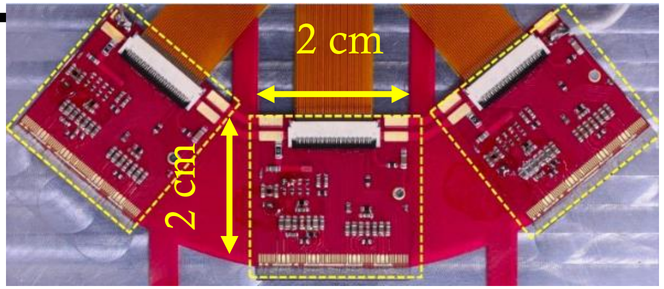
Type	Produced by
planar 100 μm thick	MICRON (UK), FBK (Italy)
planar 150 μm thick	MICRON (UK), HPK (Japan)
3D 50x50 μm^2 cell	FBK (Italy), SINTEF (Norway)
3D 25x100 μm^2 cell	FBK (Italy)

HYBRID PIXEL MODULES

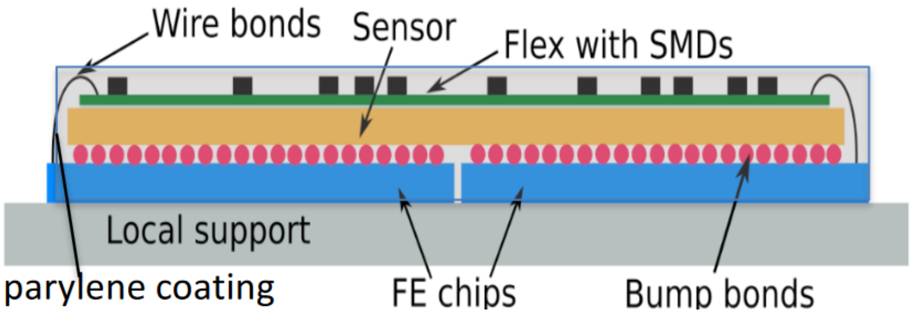
- **Hybrid detector:** FE chip connected to the sensor by *bump-bonds*
- **Module:**
  - Triplet module: 3 (2x2 cm^2) sensors, each one with a FE chip
  - Quad module: 4 FE chips attached to 1 (4x4 cm^2) sensor
  - **Flexible printed circuit** (FPC) for connections to LV, HV, DCS, data
  - FE chip **wire-bonded** to the FPC
- **Hybridisation:**
  - 4 hybridisation vendors needed to hybridize the required number of modules
  - Technical issues:
    - Chipping and debris from dicing of FE-chips
    - Difficulties in handling large area sensors (4x4 cm^2) for some vendors
  - ~400 quads and 100 3D single modules delivered so far (evaluation, pre-production)



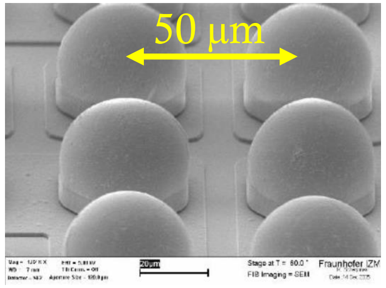
quad module



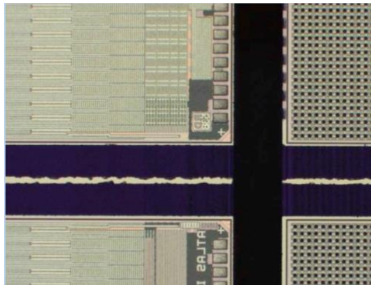
triplet module



module



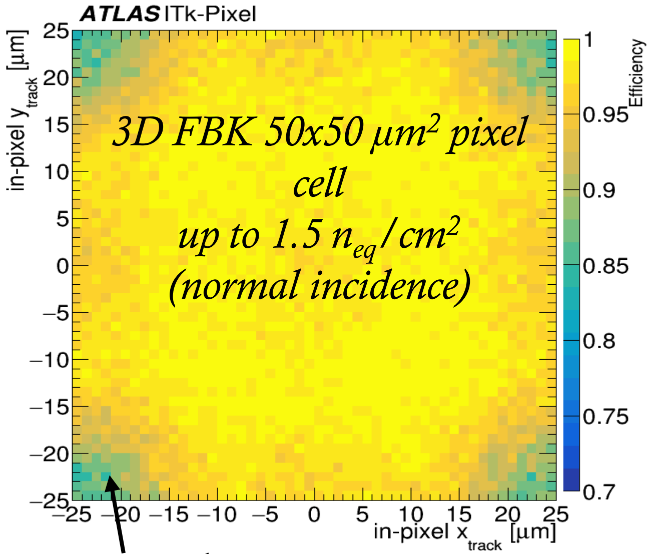
bumps



blade dicing

SENSOR PERFORMANCE

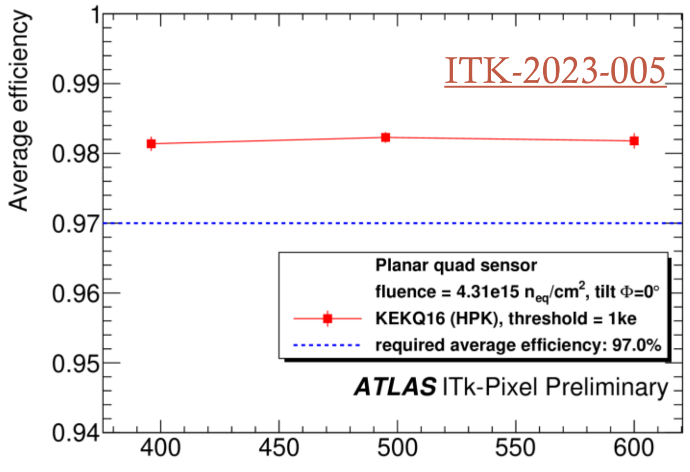
- Test beam results: some pre-production modules tested with beam before and after irradiation
  - **Modules tested so far meet ITk requirements**
    - **3D (FBK and SINTEF): >96% (97%) efficiency** for normal (tilted 15°) incidence after irradiation
    - **Planars (HPK, FBK): >97% efficiency**
    - Results for MICRON upcoming (being irradiated and tested this year)
  - First modules with **ITkPixV2 chip** (unirradiated) available this summer for test beams



3D FBK 50x50 μm^2 pixel cell
up to 1.5 n_{eq}/cm^2
(normal incidence)

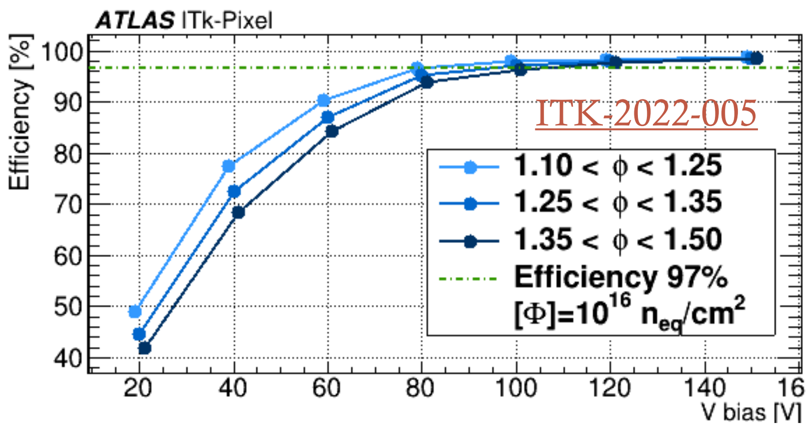
p+ column

ITK-2022-005



ITK-2023-005

Irradiated HPK (planar)



ITK-2022-005

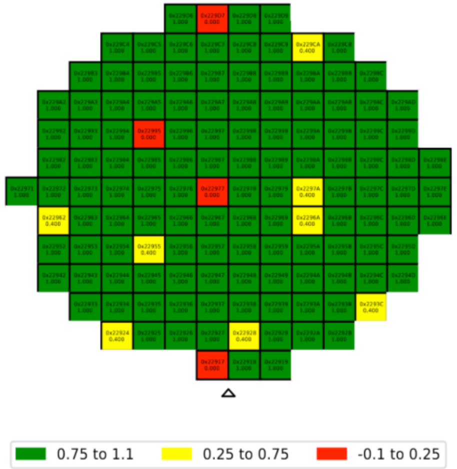
Irradiated 3D FBK
50x50 μm^2 pixel cell

FE-CHIP: ITKPIXV2

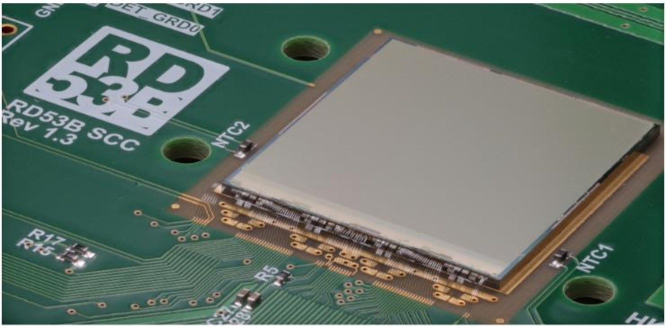
- RD53 collaboration: development of FE readout chip in TSMC65nm common for ATLAS and CMS pixel detectors
- Several pre-production modules successfully tested with version 1.1
- Final ITkPixV2 submitted in March 2023
  - Wafer probing yield ~90% in first 100 wafers
  - First modules for testing in these months

Size and layout	Area 2x2 cm^2, 50x50 µm^2 pitch, 152800 pixels per chip
Hit rate	3 GHz/cm^2
Trigger rate	1 MHz with 12.8 µs latency
Data rate	Up to 5.12 Gbit/s per chip (up to 4 data links 1.28 Gb/s per chip)
Dense environment	Threshold down to ~600 e, cluster charge redout with ToT
Radiation environment	500 Mrad rad. tolerance, SEE hardening in V2, leakage current compensation
Services optimization	Merging of chip data module (reduce nr. of data links), shuntLDO for serial powering (reduce amount of services)

Wafer probing yield map

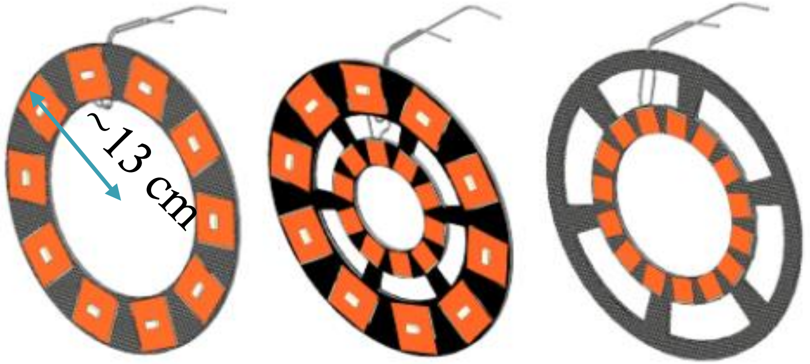


ITkPixV1 chip on Single Chip Card (SCC)

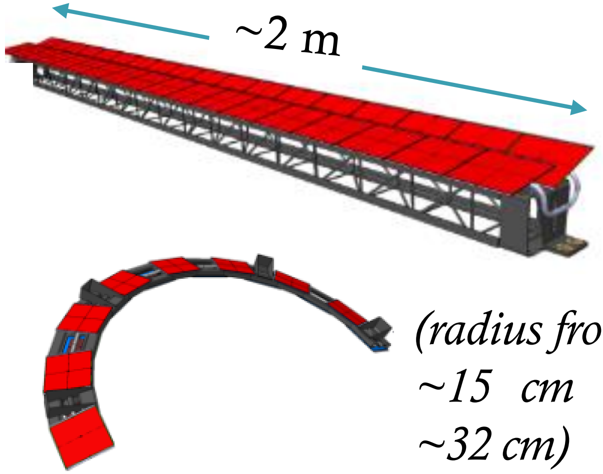


LOCAL SUPPORTS AND MATERIAL BUDGET

- Stable low-mass supports for modules and services
- Thermal performance: interface between module and cooling pipes
- Production of parts underway
- Longerons and half-rings (also inclined in outer barrel)
- Reduced material for reduced impact on tracking, radiation levels, data rates on downstream detectors:
    - CO2 cooling with thin titanium pipes, low-mass carbon structure
    - Thin sensors (100-150µm) and FE-chips (150µm)
    - Serial powering of modules for reduced cabling
    - Data link sharing to optimize number of readout cables

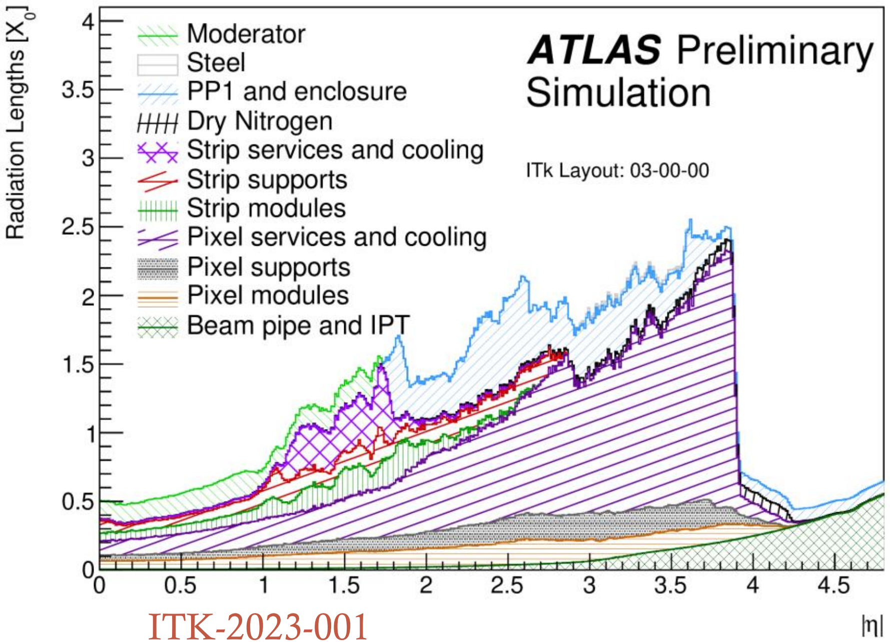


Inner system endcap rings (radius from ~5 cm to ~13 cm)



(radius from ~15 cm to ~32 cm)

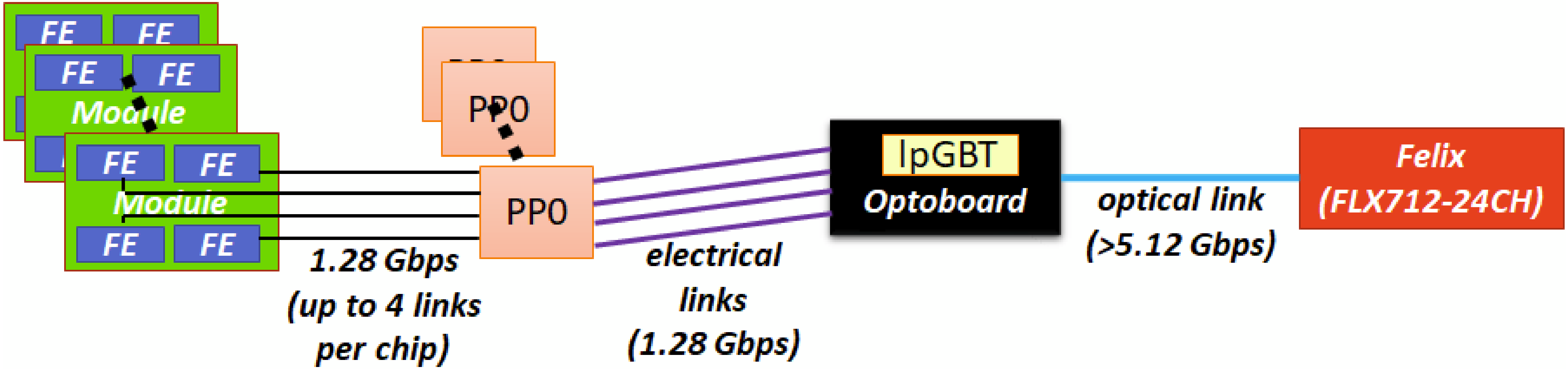
Outer barrel longeron and inclined half-ring



ITK-2023-001

DATA TRANSMISSION

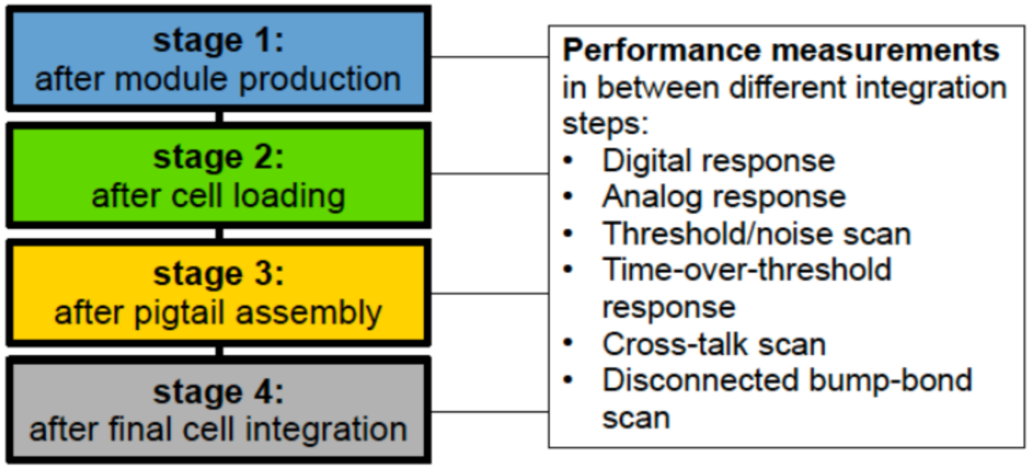
- Data uplinks per FE chip up to 4×1.28 Gbps (data aggregation on FE chip) [now: current inner detector at 160 Mbps]
  → number of links per chip depends on module location
- Data through kapton/copper flexes to PP0 on the local support (LS)
- From PP0 to optoboard (off the LS) electrical signals (1.28 Gbps) on Twinax cables ~6 m long
- Optoboard performs conversion to optical (lpGBT), then optical singlas fed from/into a Felix board (data decoding, distribution of timing signals, sending commands, …)



SYSTEM TESTS

- **Loaded Local Supports (LLS)**: fully functional detector unit, consisting in modules glued onto the bare local supports (mechanical structures and cooling), with services for biasing, control signals and data transmission from modules to the back-end
- **System tests:**
  - Intermediate step between individual prototypes and LLS
  - Validate the design of LLS mounted with realistic mechanical structures, services and readout
  - Help with the development of infrastructures like cooling, interlock, Detector Control System (DCS), powering
  - Test data transmission with the full chain, comparison before/after loading

System test sites	
Inner System	SLAC
Outer Barrel	CERN
Endcaps	Liverpool



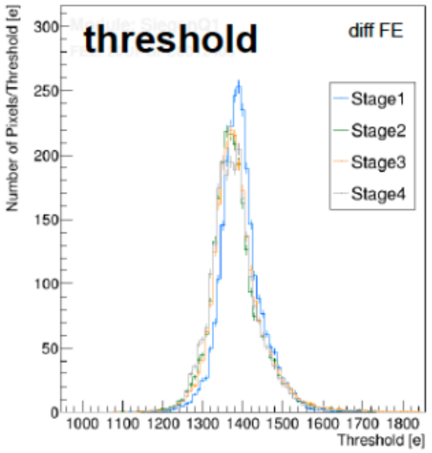
stage 1: after module production

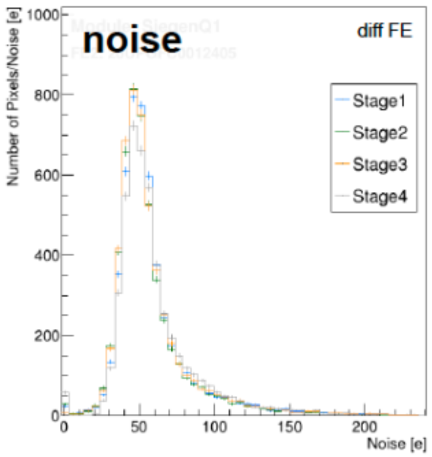
stage 2: after cell loading

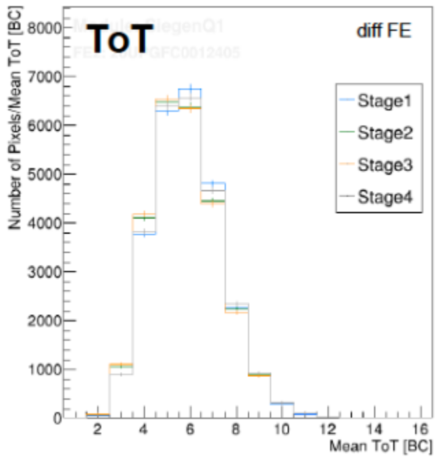
stage 3: after pigtail assembly

stage 4: after final cell integration

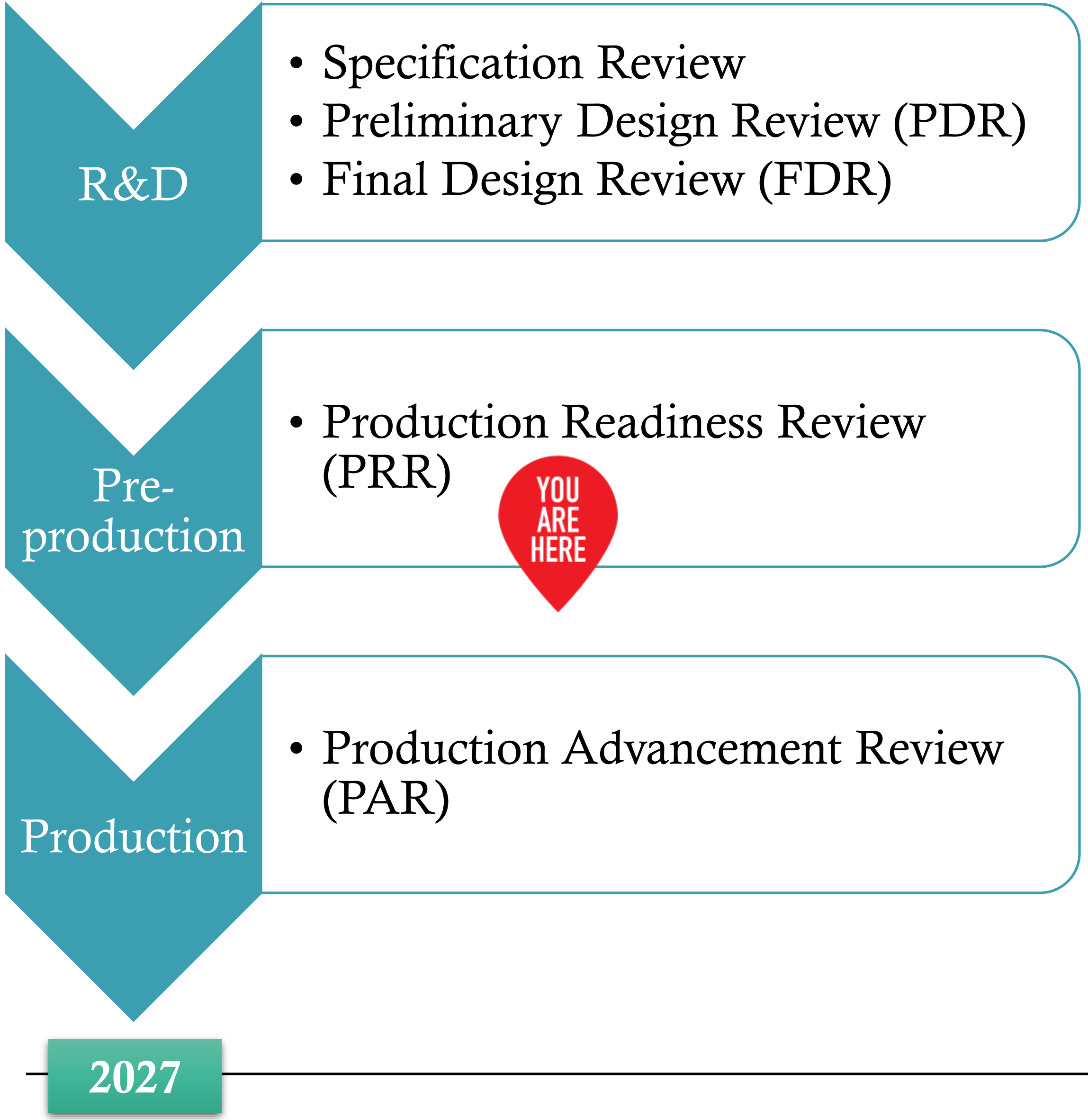
Performance measurements in between different integration steps:
- Digital response
- Analog response
- Threshold/noise scan
- Time-over-threshold response
- Cross-talk scan
- Disconnected bump-bond scan







STATUS AND ROADMAP



- Specification Review
- Preliminary Design Review (PDR)
- Final Design Review (FDR)

- Production Readiness Review (PRR)

- Production Advancement Review (PAR)

- **R&D phase mostly completed**
  - PDR and prototyping completed ✓
  - Last FDRs ongoing
- **Pre-production phase ongoing**
  - 3D and planar sensors pre-production completed ✓
  - FE-ASIC pre-production completed ✓
  - Remaining pre-production (hybridisation, module assembly, services, bare local supports and power supplies) ongoing or upcoming
  - Most PRRs ongoing or upcoming
- **Major tenders** completed and **contracts** in place for planar and 3D sensors, FE chips, hybridisation, power supplies

SUMMARY

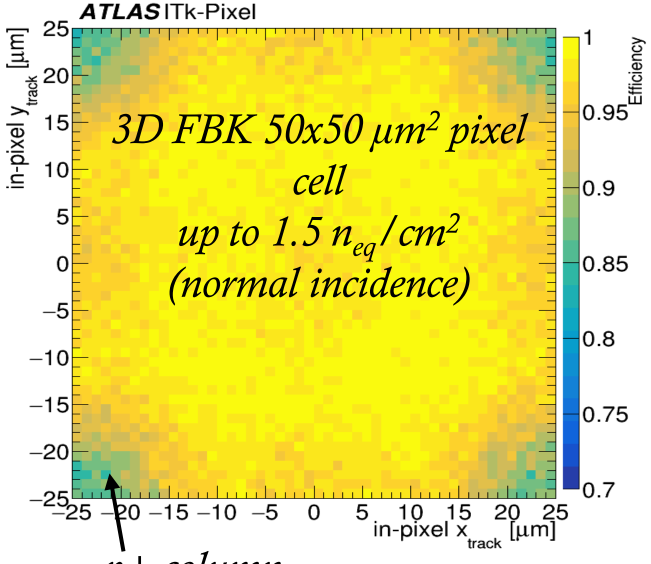
- After 2026 the HL-LHC will pose harsh operational conditions requiring to replace the current inner detector with a new all-silicon tracking detector, the ITk
- The ITk Pixel detector:
  - Increased granularity, radiation hardness and trigger rate, minimized material budget
  - Will use hybrid planar n-in-p sensors 100 and 150 μm thick and 3D sensors in layer closest to beam (radiation hard)
  - Final version of the radiation hard FE chip (ITkPixV2) submitted in March 2023
  - Data transmission up to 4x1.28 Gbps per chip, electrical converted to optical
  - Pre-production modules tested in test beams so far (3D FBK and SINTEF, planar HPK and FBK sensors) meet requirements after irradiation
  - System tests ongoing or being commissioned to validate the design of Loaded Local Supports:
  - Currently the ITk project is concluding the pre-production phase, plan to end the production phase by 2027

THANK YOU FOR THE ATTENTION

BACKUP

SENSOR PERFORMANCE

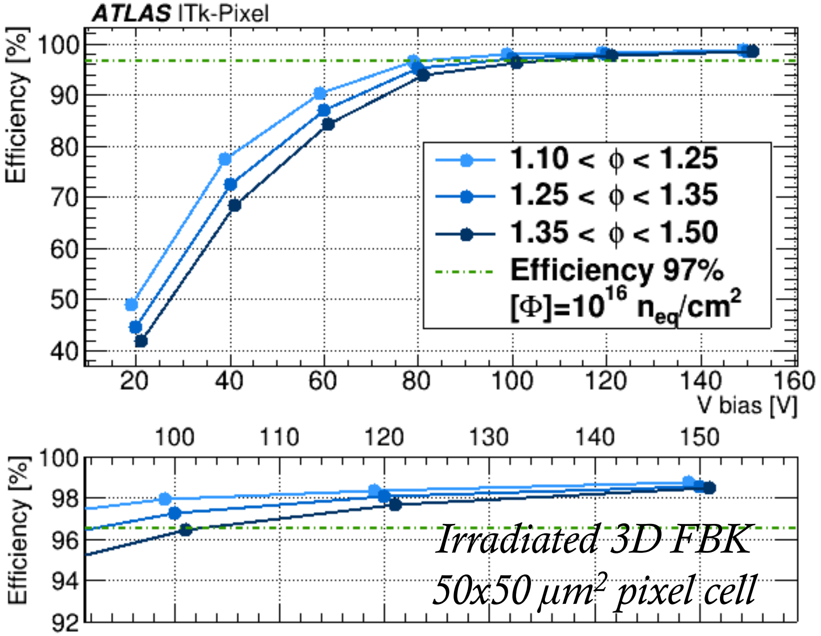
- Test beam results: some pre-production modules tested with beam before and after irradiation
  - **Modules tested so far meet ITk requirements**
    - **3D (FBK and SINTEF): >96% (97%) efficiency** for normal (tilted 15°) incidence after irradiation
    - **Planars (HPK, FBK): >97% efficiency**
    - Results for MICRON upcoming (being irradiated and tested this year)
  - First modules with **ITkPixV2 chip** (unirradiated) available this summer for test beams



3D FBK 50x50 μm^2 pixel cell up to 1.5 n_{eq}/cm^2 (normal incidence)

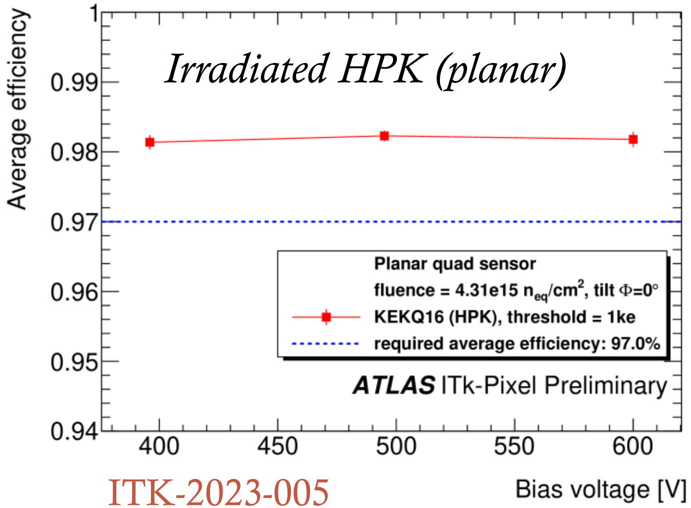
p+ column

ITK-2022-005



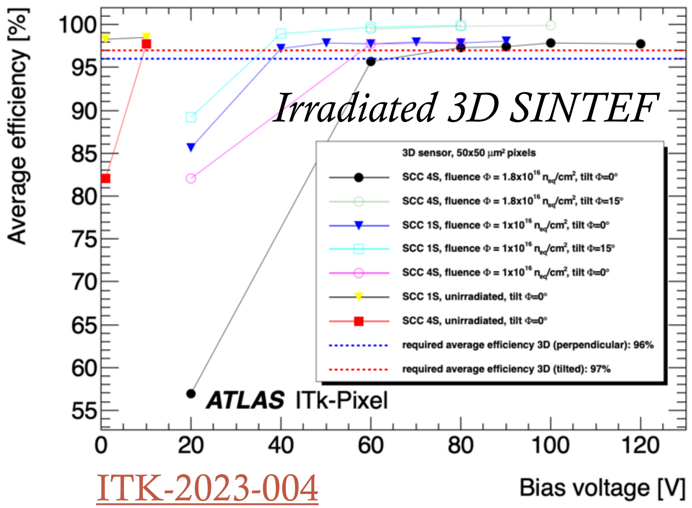
Irradiated 3D FBK 50x50 μm^2 pixel cell

ITK-2022-005



Irradiated HPK (planar)

ITK-2023-005



Irradiated 3D SINTEF

ITK-2023-004

TESTING

- Module qualification:
  - Thermal cycling: between -45°C and +40 °C to verify bump-bondings, followed by check of disconnected bumps
  - Electrical Quality Control (QC): verify that the readout chips meet the electrical specifications
  - Sensor Quality Control: measurement of leakage current vs bias voltage
  - Functional tests: pixel-threshold tuning and tests to check bump-bonding quality
- System tests

SUMMARY (1/2)

- After 2026 the HL-LHC will pose harsh operational conditions requiring to replace the current inner detector with a new all-silicon tracking detector, the ITk
  - Increased granularity, radiation hardness and trigger rate, minimized material budget
- The ITk Pixel detector:
  - Will use hybrid planar n-in-p sensors 100 and 150 µm thick and 3D sensors in layer closest to beam (radiation hard)
  - Sensor production distributed across 4 vendors, hybridization distributed across 4 vendors
  - Final version of the radiation hard FE chip (ITkPixV2) submitted March 2023, high wafer probing yield (~90%) in first 100 wafers

SUMMARY (2/2)

- Production of local supports underway, reduced material budget
- Data transmission up to 4x1.28 Gbps per chip, electrical converted to optical
- Pre-production modules test in test beams: 3D (FBK and SINTEF) and planar HPK, FBK sensors meet requirements after irradiation
- System tests ongoing or being commissioned to validate the design of Loaded Local Supports:
  - Mechanical structures, cooling, services, readout and full data transmission chain, interlock, Detector Control System, …
- Currently the ITk project is concluding the pre-production phase, plan to end the production phase by 2027

PERFORMANCE

- Simulated tracking performance

ABSTRACT

At the High luminosity LHC, the expected instantaneous luminosity of up to 7.5 x1034 cm-2 s-1, a facto 7.5 larger with respect to the nominal LHC one, and the integrated luminosity increase by a factor 10 impose severe challenges for the ATLAS detector. The radiation is expected to reach unprecedented values, with non-ionizing fluence of 1e16 neq/cm2 and ionizing dose of 5 MGy. To cope with the resulting increase in occupancy, bandwidth, and radiation damage, the current ATLAS Inner Detector will be replaced by an all-silicon Inner Tracker (ITk), composed by a strip and a pixel system. The ITk Pixel Detector will consist of five-barrel layers and a number of rings resulting in about 13 m2 of instrumented area with silicon hybrid detectors with angular coverage extended up to |eta| = 4. The silicon hybrid detectors are modules composed by thin planar or 3D silicon sensors bump bonded to novel front-end ASICS and featuring radiation hardness. A fine segmentation enables the requested low occupancy. The data from the modules will be driven form the front-end chip to the opto-electrical conversion system with high-speed transmission parallel lines running at 1.28 Gb/s per data link. Tracking performance will be improved due to the reduced amount of material, thanks to light carbon fiber structures, CO2-based cooling with thin Ti tubes walls, data link sharing and a novel serial powering scheme. The ITk pixel detector will operate at around -35 C and is designed also to sustain the expected large number of temperature cycles during its lifetime.

In this contribution, an overview of the ITk pixel detector project will be shown, from the design and the expected performance to prototyping, testing and qualification of the various components. The future challenges to overcome in the next years will be also presented.