The ITk pixel detector for the ATLAS Phase-2 Upgrade at HL-LHC

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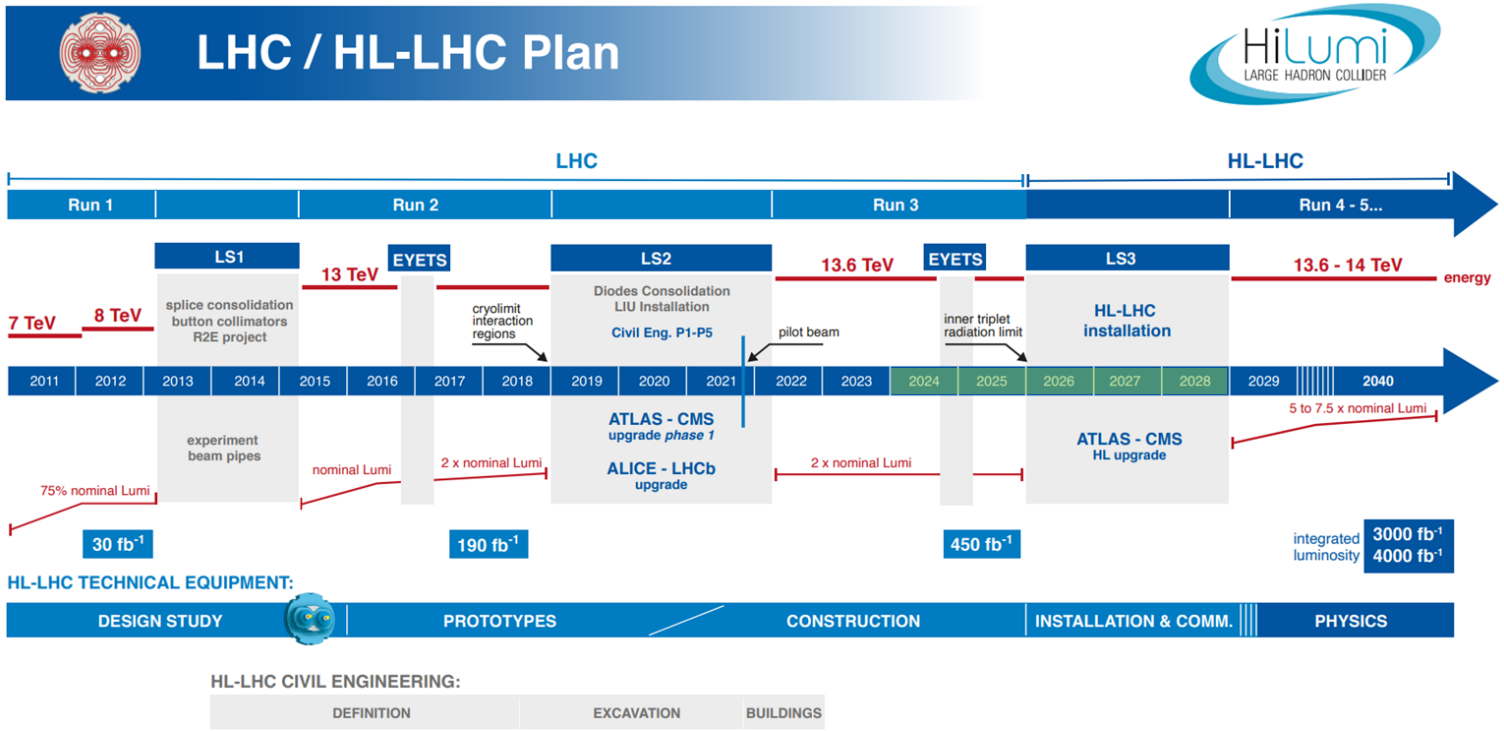
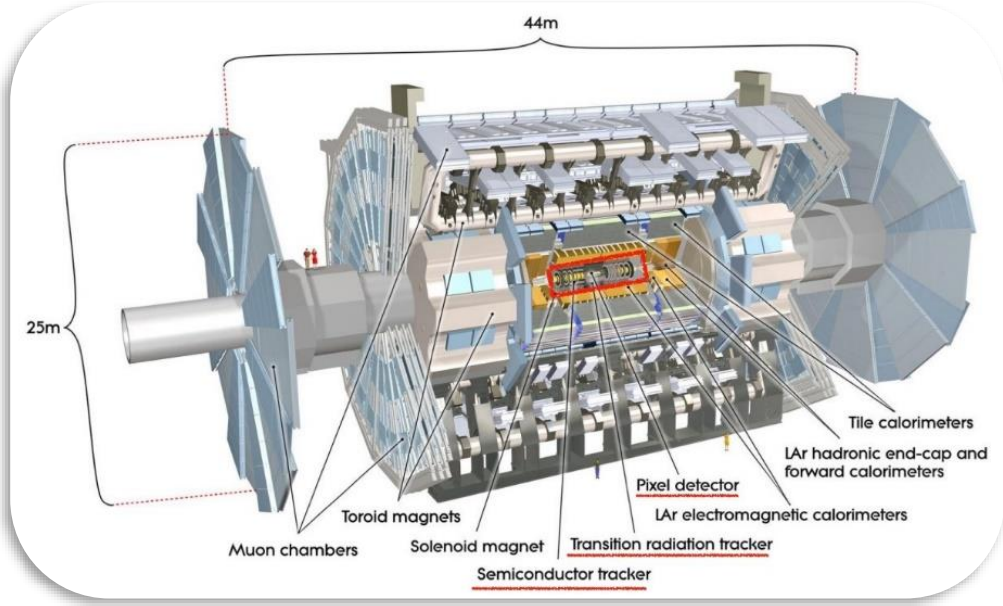
Motivation of Phase-II Upgrade of the LHC

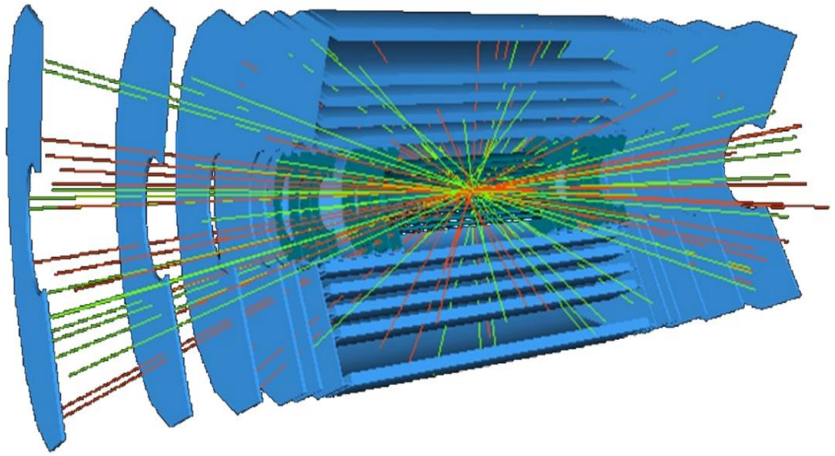


ATLAS experiment



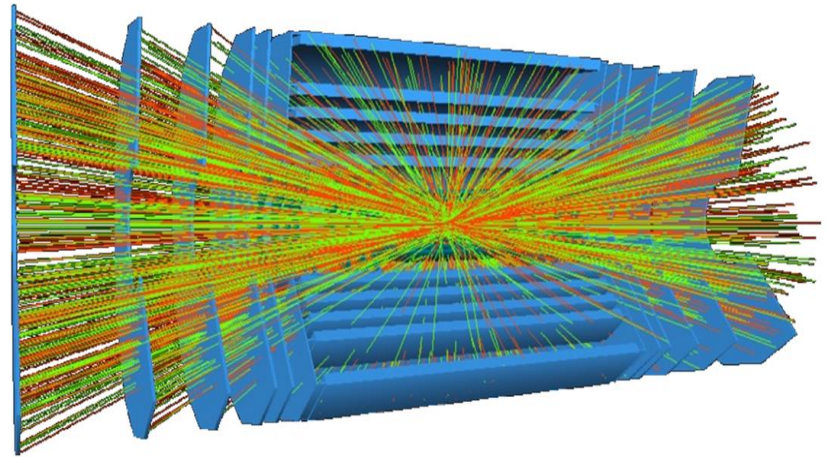
- **Scientific goals:**
  - **Pushing the frontiers of particle physics.**
  - **Exploring the properties of the Higgs boson** with higher precision.
  - **Searching for new particles** and phenomena beyond the Standard Model and etc.

- **The High-Luminosity phase of the LHC (HL-LHC) will provide from 2029**
  - **Proton-proton collisions** with up to **14 TeV** center-of-mass energies.
  - $\int$ Ldt ~4000fb^{-1} of integrated luminosity, an order of magnitude more than current data.



LHC:
19 – 55
pile up events

HL-LHC:
140 – 200
pile up events

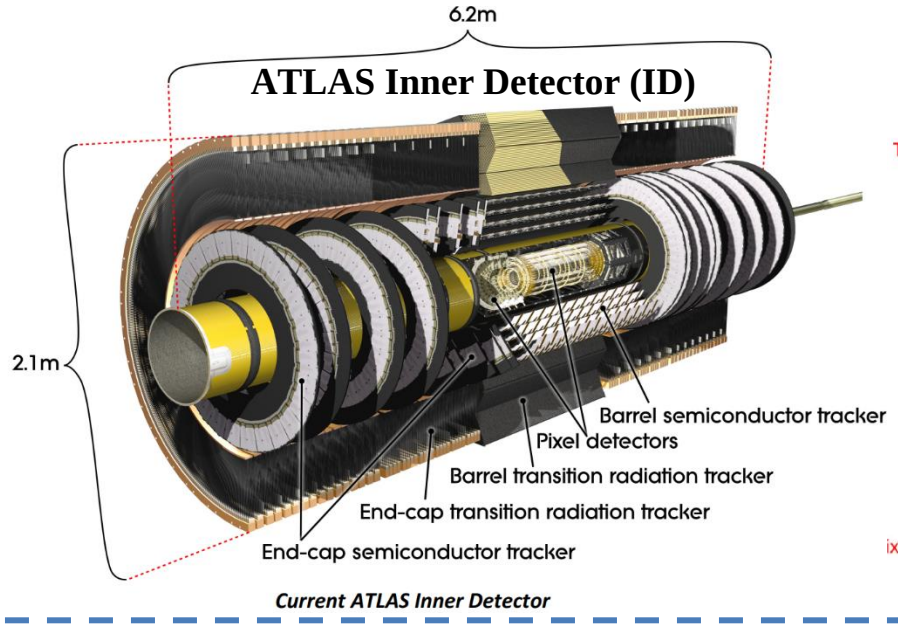


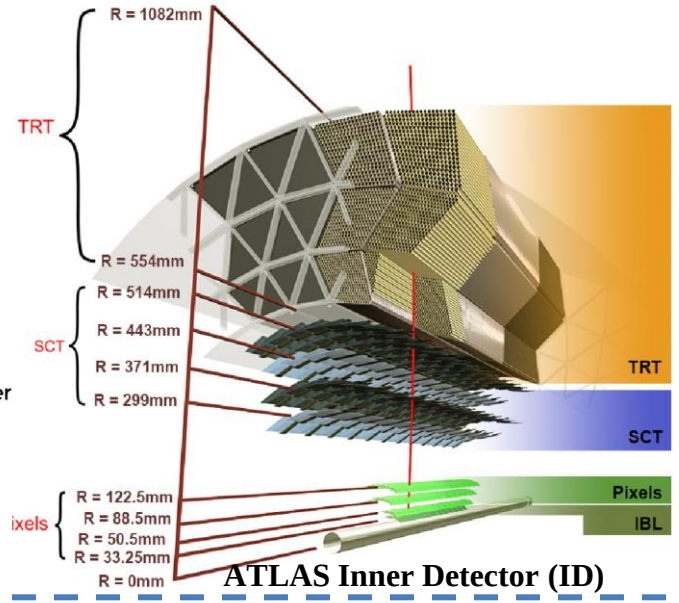
- Instantaneous luminosity x 5-7.5 above the nominal value of 1×10^{34} $cm^{-2}s^{-1}$
  - Increase of additional pp collision per bunch crossing (pile-up) from 33 to 200
  - Increased particle densities
    → **need of increased granularity**
    → **high trigger rate**

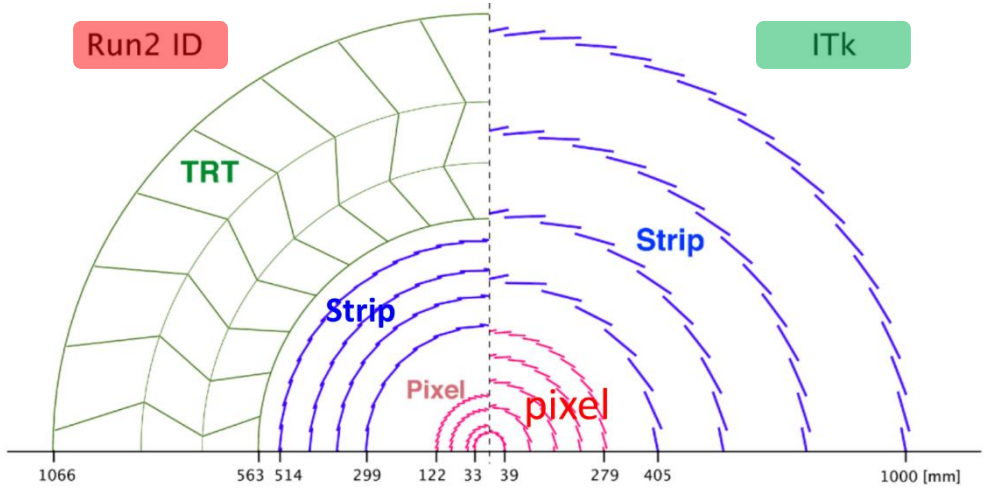
- Integrated luminosity x 10
  - x10 Increased radiation damage
  - Fluence up to 2 x 10^{16} n_{eq}/cm^{-2} and 10 MGy Total Ionizing Dose
    → **need more radiation hard technologies**

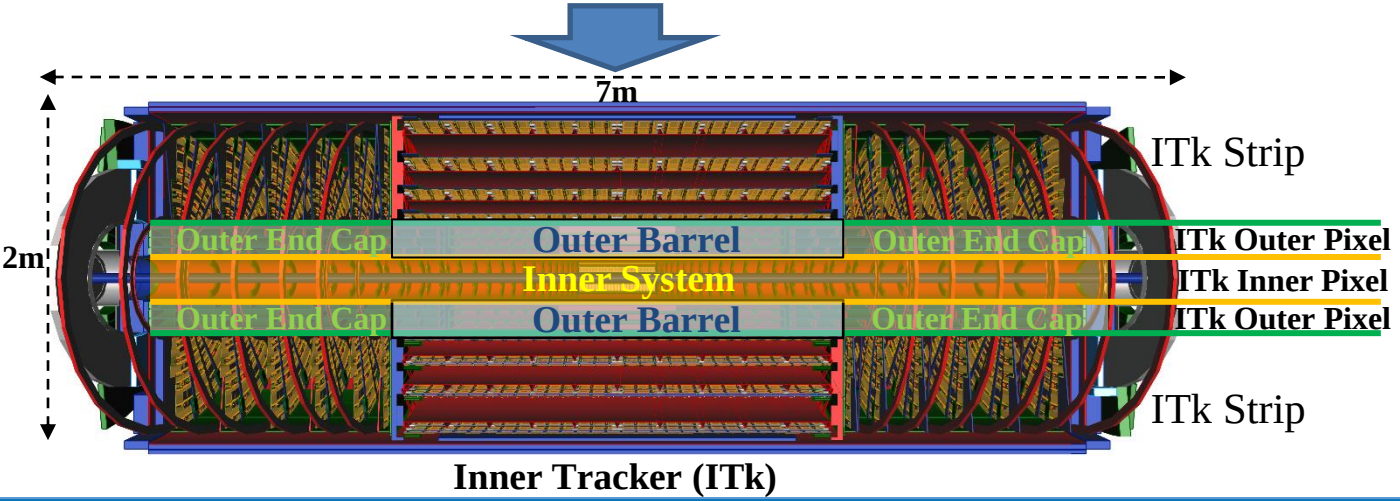
A replacement of the current detector is by far not enough.

Upgrade ID Tracker to ITk







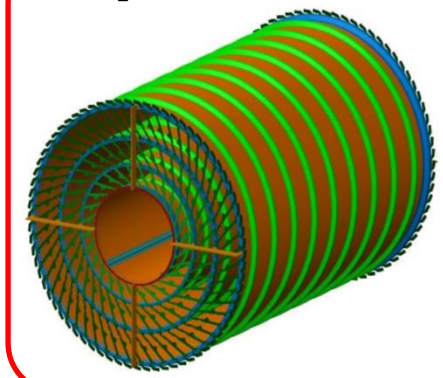


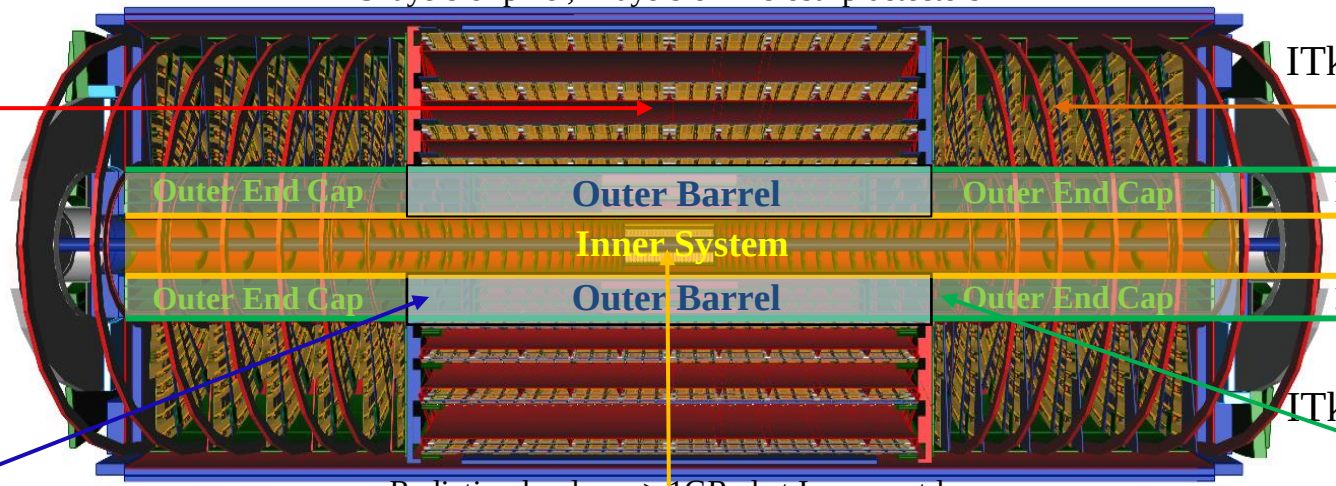
- **The Inner Tracker (ITk) will fill the space of the ID** with a radius of 1 m and a length of 6 m.
- Design of the ATLAS **all-silicon** ITk inner tracker
- ITk is full Silicon based system which is divided Pixels and Strips

ITk sub Detectors

5 layers of pixel, 4 layers of microstrip detectors

Strip Barrel structure





ITk Strip

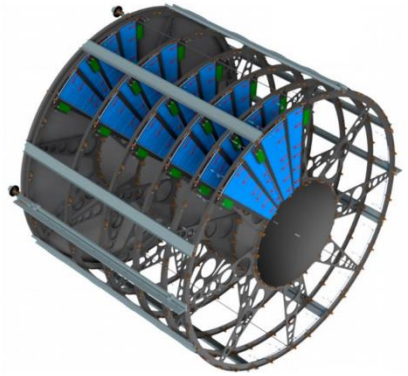
ITk Outer Pixel

ITk Inner Pixel

ITk Outer Pixel

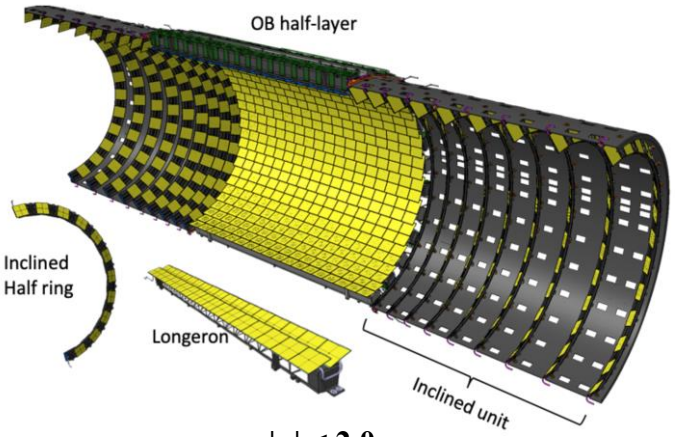
ITk Strip

Strip End-Cap Structure



Radiation hardness > 1GRad at Innermost layers

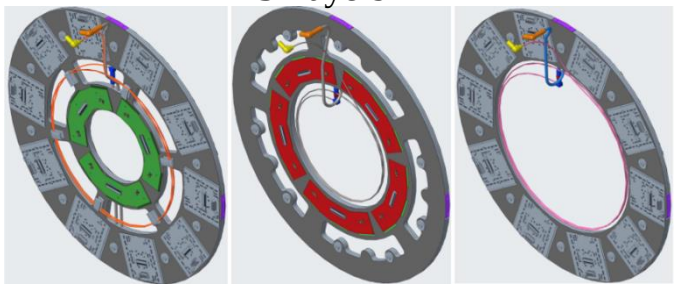
3 Layers



$|\eta| < 2.0$

Outer Barrel (OB)

3 Layers



Outer ring: Planar pixel modules
Inner ring: 3D pixel modules

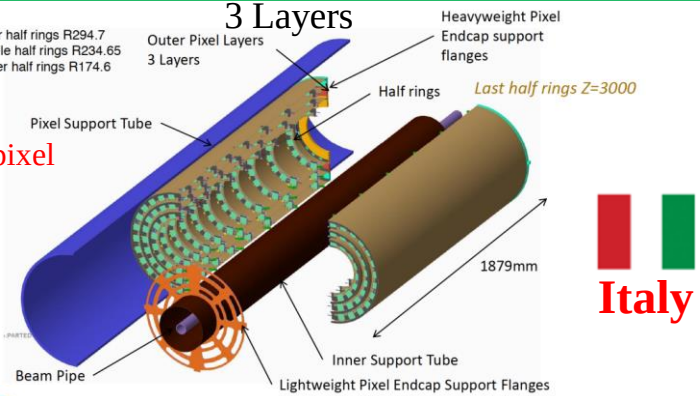
Two layers are designed to be replaceable

Ring prototype

$|\eta| < 2.0$

Inner System (IS)

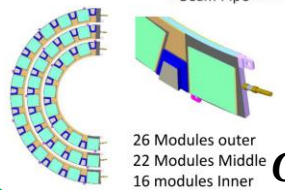
3 Layers



Up to 1172 pixel modules

Italy

Half-Shel and Half-ring with pixel modules

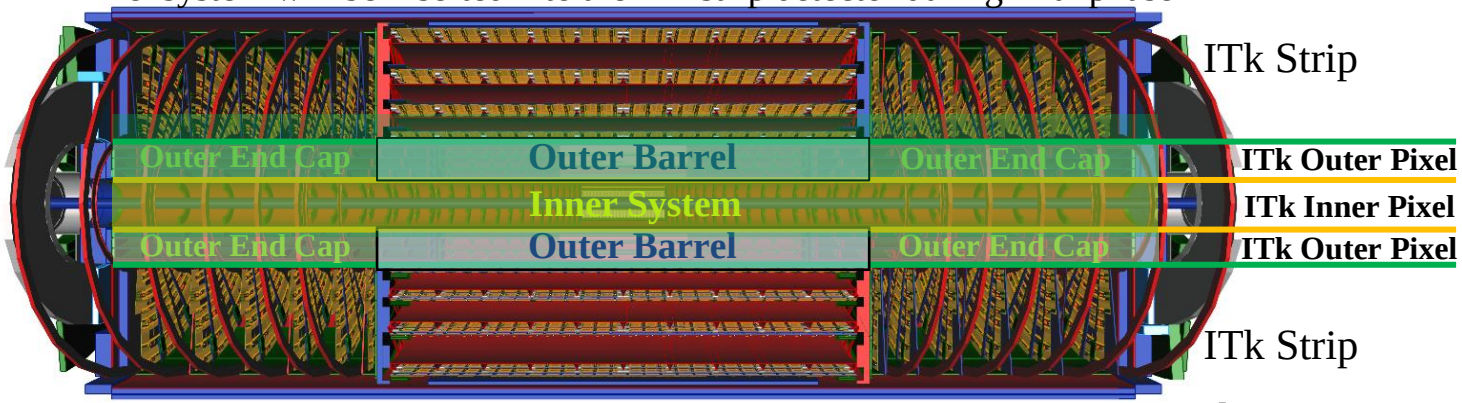


$2.0 < |\eta| < 3.6$

Outer End-Cap (OEC)

ITk Pixel Detectors

Pixel system will be inserted into the ITk strip detector during final phase



Subsystem	Total Pixel Area	1MeV n_{eq} Fluence [particles/cm2]	Total ionizing dose
Inner System	2.4m²	9.2×10^{15} n/cm^{-2}	7.3 MGy
Outer Endcap	3.64 m²	3.1×10^{15} n/cm^{-2}	3.5 MGy
Outer Barrel	6.94 m²	2.3×10^{15} n/cm^{-2}	1.7 MGy

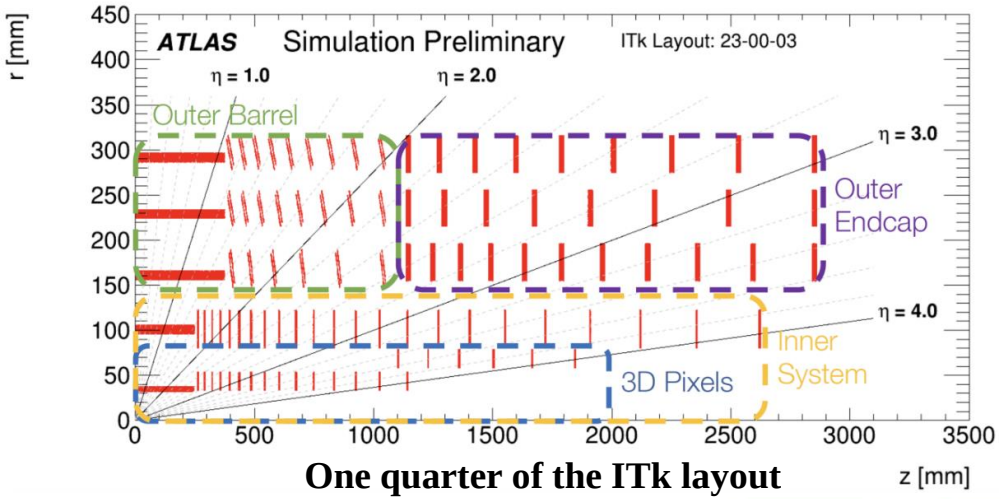
- 5 barrel layers, 2 × 23 inclined disks (**OB**)
- 2 × 28 outer disks (**OEC**)
- 2 × 21 inner disks, 2 × 23 L1 disks, (**IS**)

Upgrade summary

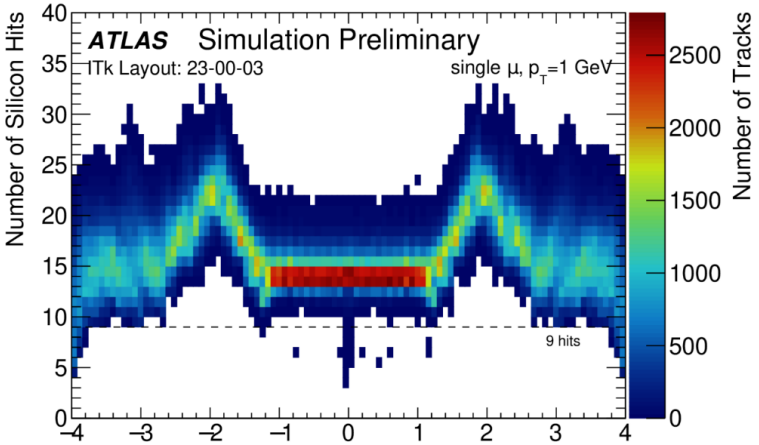
ITk (ID)	Area (m²)	# Modules	# Channels (M)	Pseudo-rapidity |η|	Instantaneous luminosity (L)	Integrated luminosity (∫Ldt)
Pixels	~13 (1.9) ~6.8x	~9700 (2000) ~4.8x	~5100 (92) ~55x	<4 (<2.5) ~2x	7×10^{34} cm^{-2}s^{-1} (1×10^{34} cm^{-2}s^{-1}) ~7x	4000 fb^{-1} (300 fb^{-1}) ~13x
Strips	~165 (61) ~2.7x	~17888 (4088) ~4.8x	~60 (6.3) ~9.5x			

- The ATLAS ITk detector has been designed with **technologies providing higher granularity** (less pixel pitch)**, radiation hardness, readout speed** and low material budget to maintain, or even improve upon, the performance of the current tracking system, while meeting the challenges of operation in the harsh HL-LHC environment.
- This has been achieved through a number of innovations in **cooling CO^2 (with thin Titanium walls), power distribution,** and **readout system**.

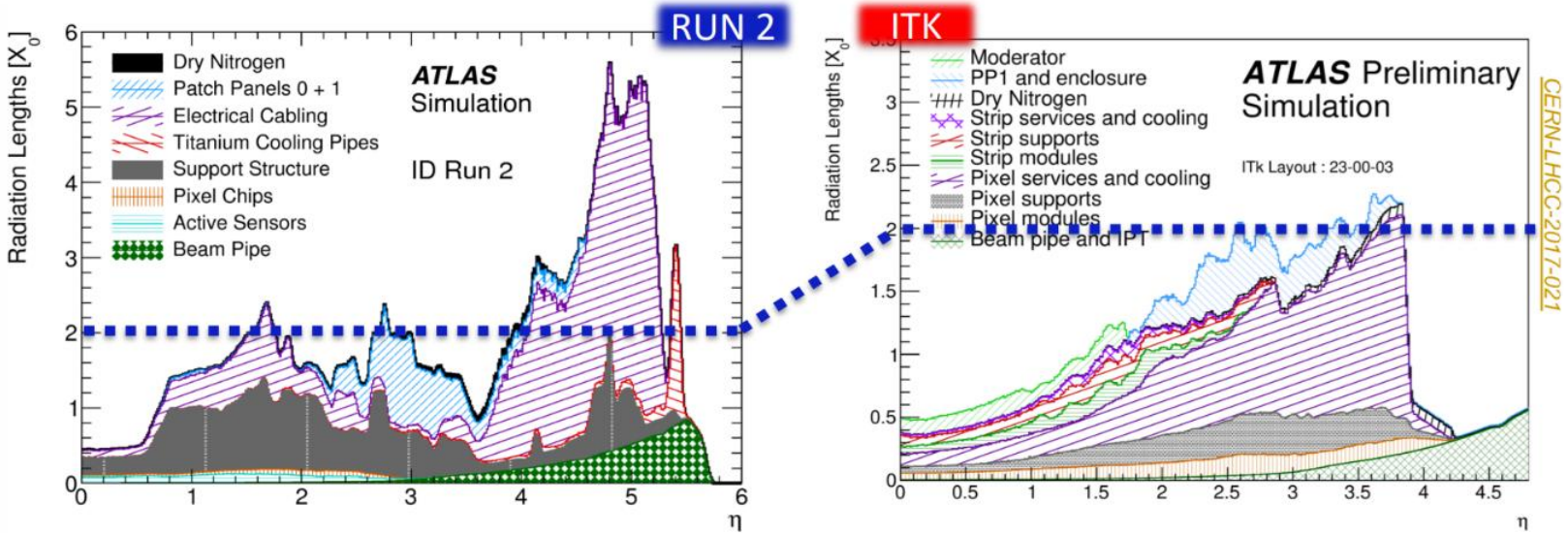
ITk Pixel Detector Performances



One quarter of the ITk layout



Number of hits on a track as a function of η for single muon events with pT = 1 GeV



Low-mass services, to reduce **radiation length** [X0]

- Different sub pixel detectors cover different Pseudo-rapidity ranges.

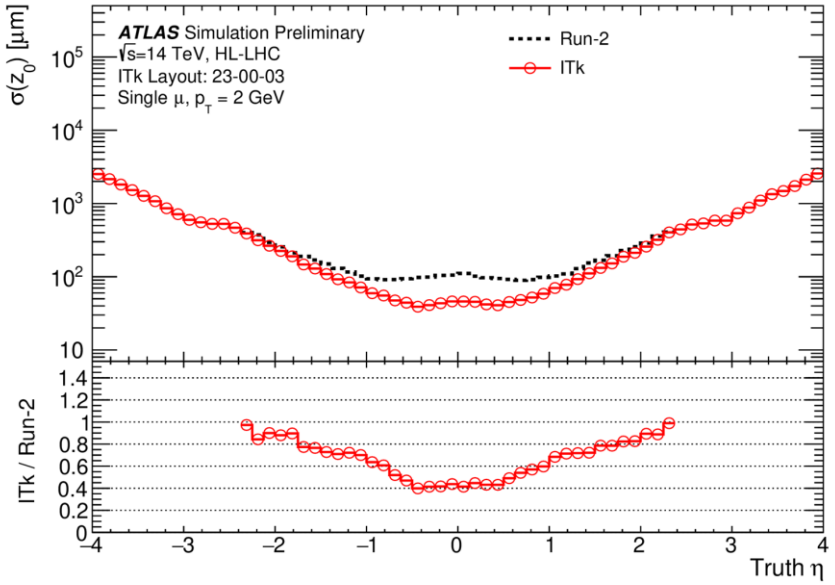
Reduction of material is the key to:

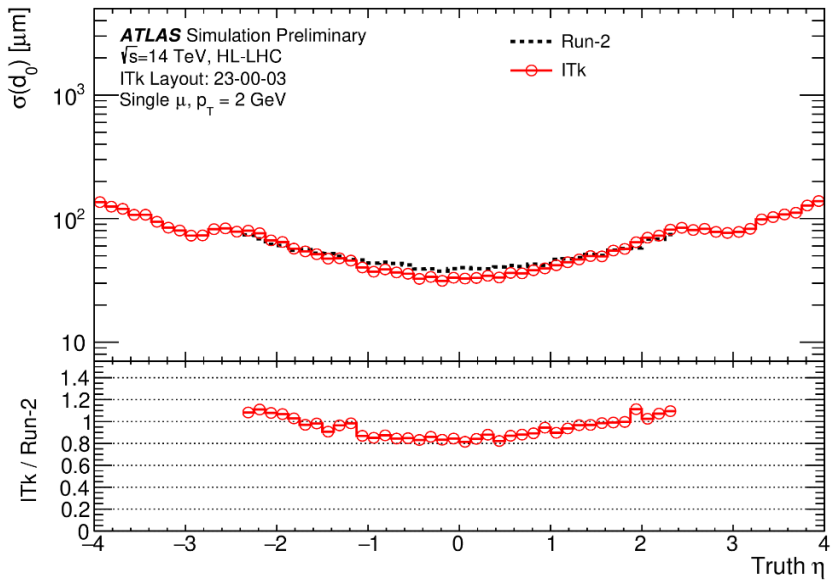
– Resolution for **low momentum particles**

– **Tracking efficiency** (dominated by interaction with the detector)

- Reduction material is done by Carbon fiber structures, thin titanium pips serial powering and data links sharing.
- At least 9 points per track in the barrel region and 13 in the endcaps.
- The Material budget where improved at least factor 2 in ITk detector.

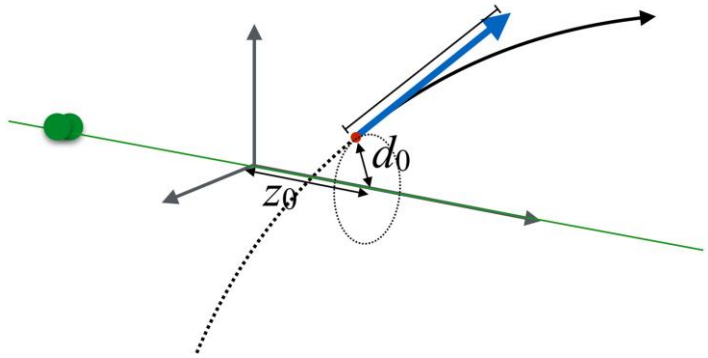
ITk Pixel Detector Performances

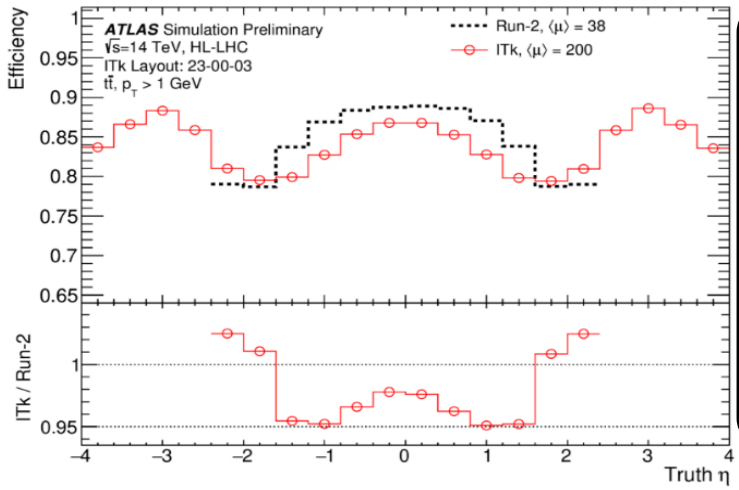




A trajectory of a charged particle in a magnetic field requires five track parameters (q)

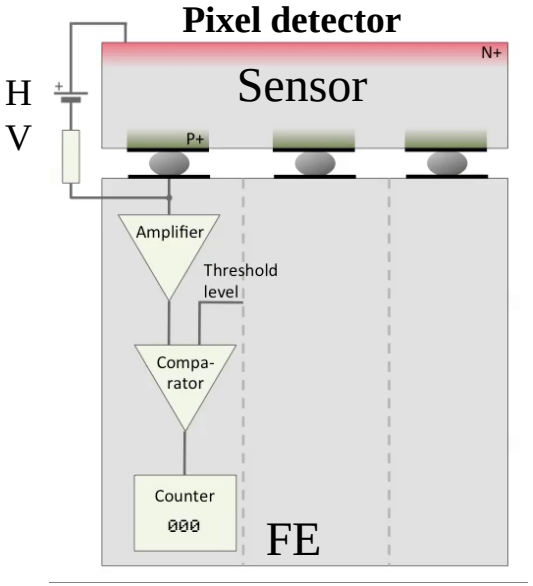
$$\mathbf{q} = (d_0, z_0, \phi, \theta, q/p)$$

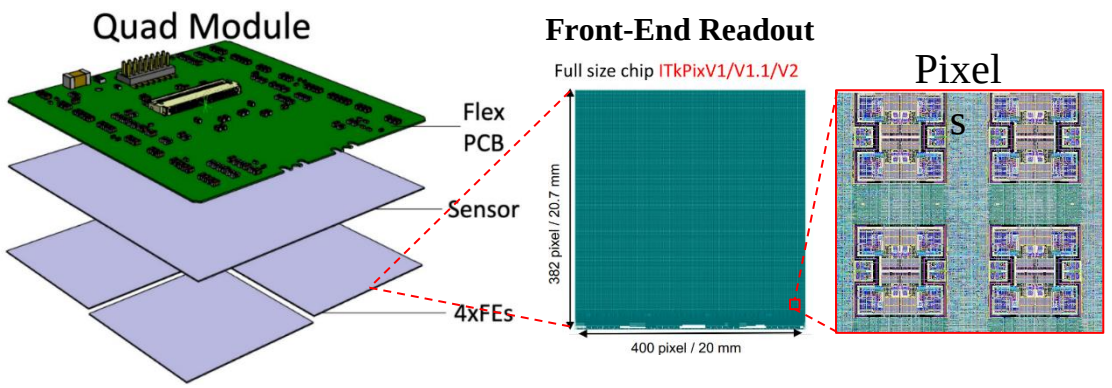


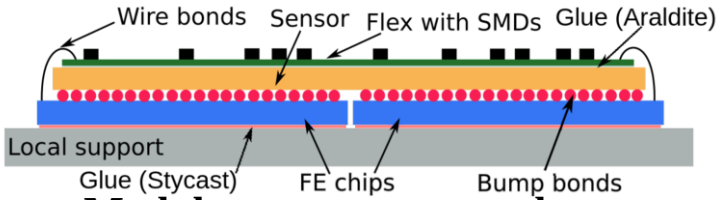


- **Track reconstruction is described by 5 parameters.**
- ITk detector improves reconstruction parameters d0 and z0
  - **d0 resolution** is crucial for long lived particles reconstruction
  - **z0 resolution** is critical for separate pile-up vertices from primary vertex.
- ITk performance similar to ID thanks to smaller **pixel pitch size** and also **material budget**.

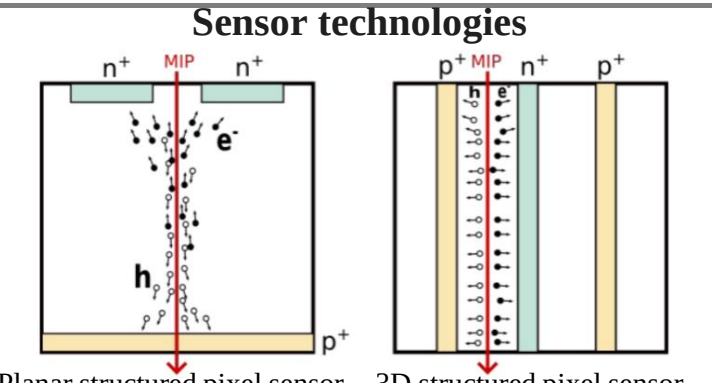
ITk Pixel modules

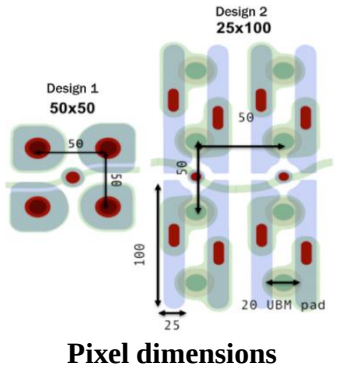




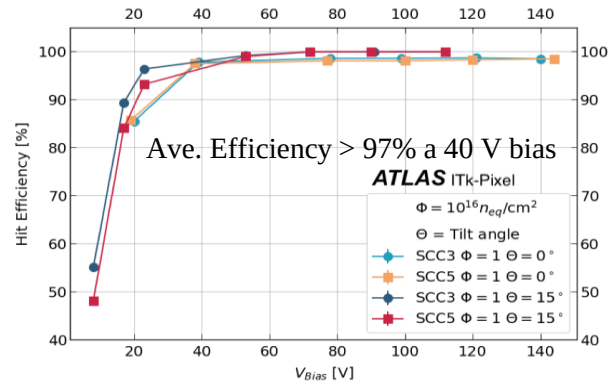


Module components stackup





Pixel dimensions



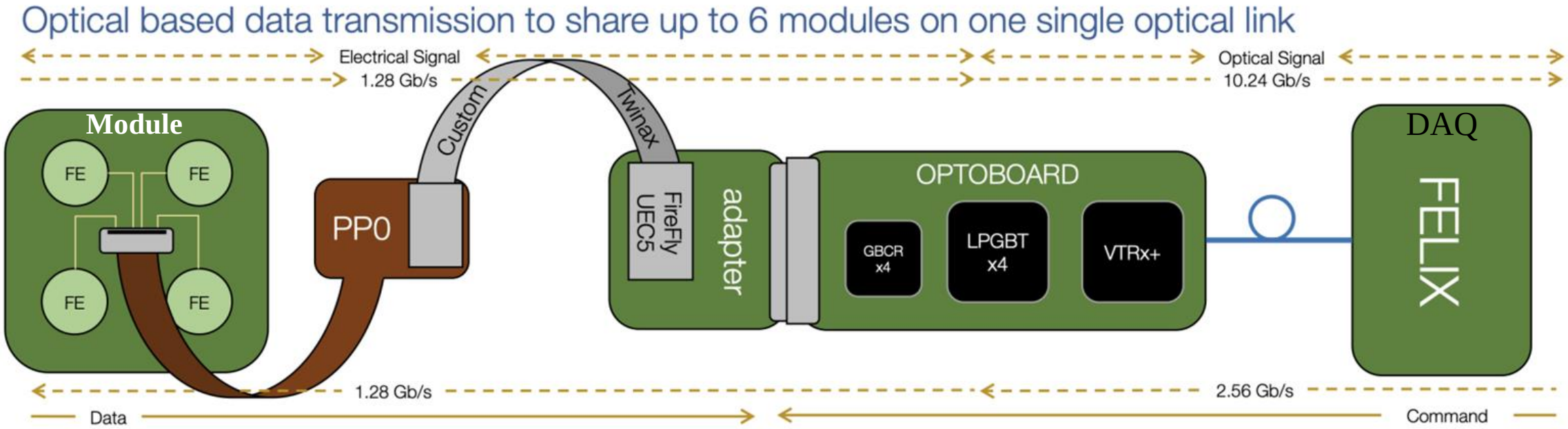
Efficiency v.s. Bias voltage

*"**n-in-p** structured" pixel sensor for radiation hardness*

Layer 0 (100 um) barrel sensors 25x100μm^2, Layer 0 ring sensors 50x50μm^2
Layers 1,2,3,4 (150um) sensors 50x50μm^2
Quad modules (1 sensor 40 x 40 mm; 4 FE ASICs 20 x 20 mm^2)

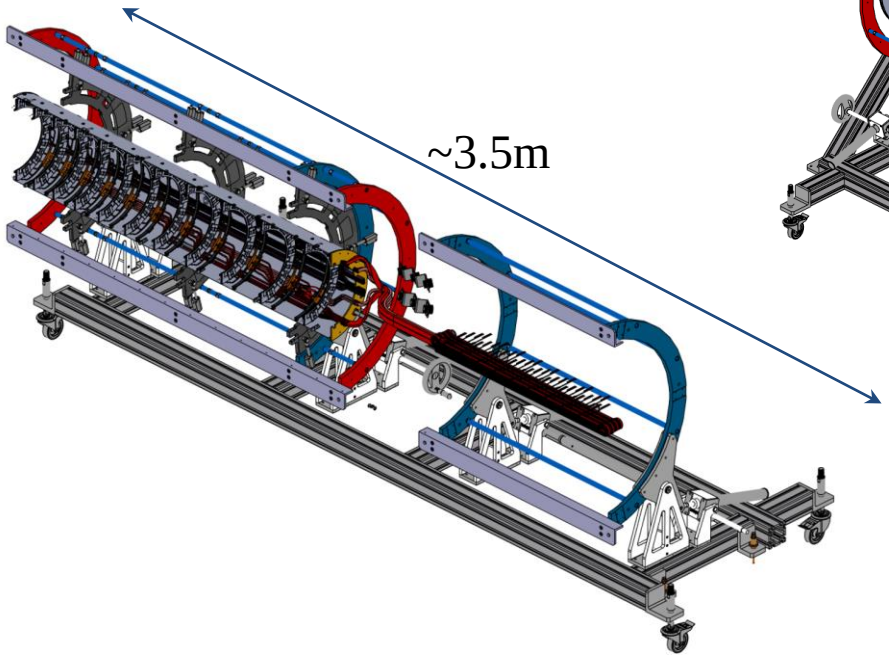
- Sensor and FE Designed by **RD53 collaboration** in 65 nm CMOS technology.
- Pixel modules will be built with **3D and planar sensors** bump-bonded to the **pixel readout ASIC** (Front-End).
- The baseline sensor technologies for the ITk Pixel system **are n-in-p** structured **3D sensors** for the innermost layer and thin **Planar sensors** elsewhere. 3D sensor has less distance between contacts and it has more **radiation hardness** and **low power dissipation**.

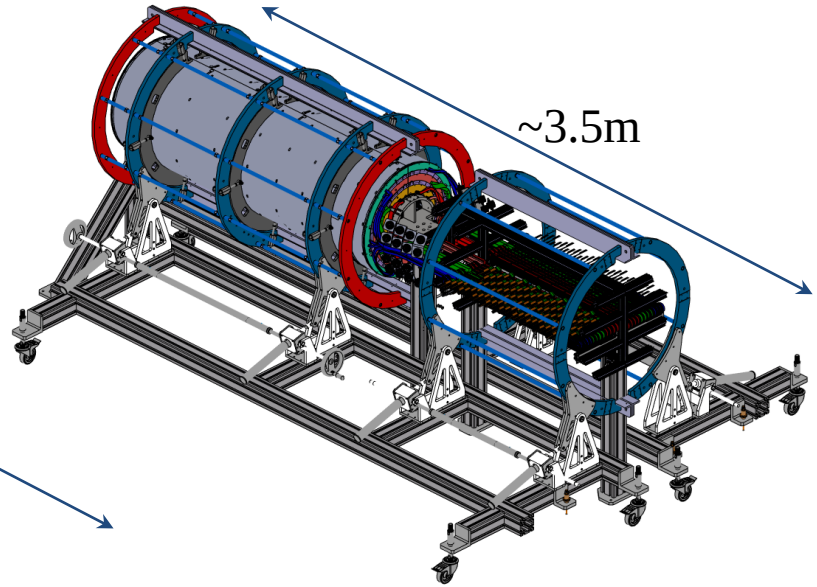
Data transmission

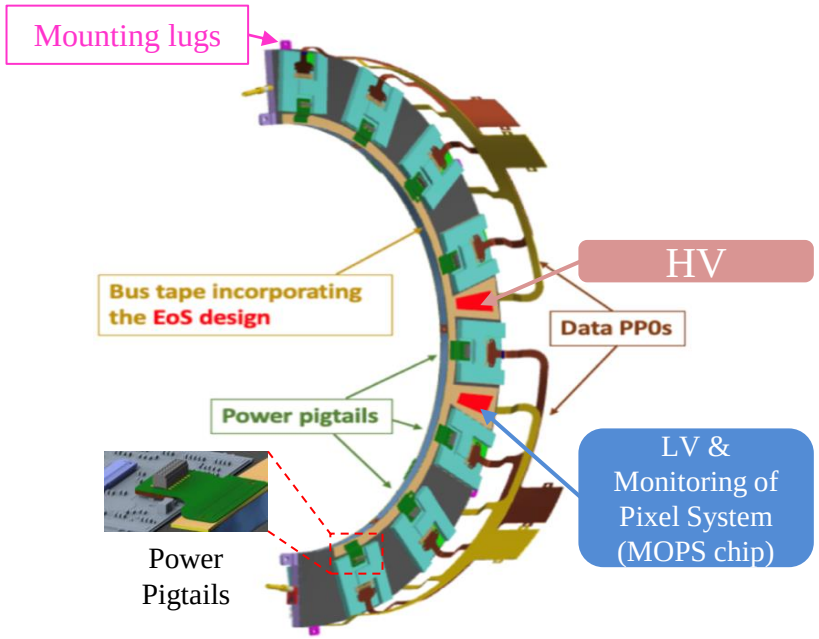


- New The new Detector Readout System include: Gigabit receiver chip (GCBR), low-power Gigabit transceiver (lpGBT) and VTRx+ Which recovers Signal and serialize electrical links and converted to optical links. Up to 10.24Gb/s data transmission speed is available per one optical fiber.
- Each FE has 4 x 1.28Gb/s electrical links.
- Optical links are hosted by The Front-End Link eXchange (FELIX) DAQ interface.

The Outer End-Cap integration at LNF







Ring Layer	# of Rings	SP chain length (# of Quad Modules)	# of Modules / Ring	Total # of Modules
Layer 2	11	8	32	352
Layer 3	8	11	44	352
Layer 4	9	13	52	468
				1172

- Each side of a *loaded* half-ring holds one **serial-powering** chain:
  - 8/11/13 Modules for Layer2/Layer3/Layer4
  - A "bus tape" to deliver power and monitoring to the modules.

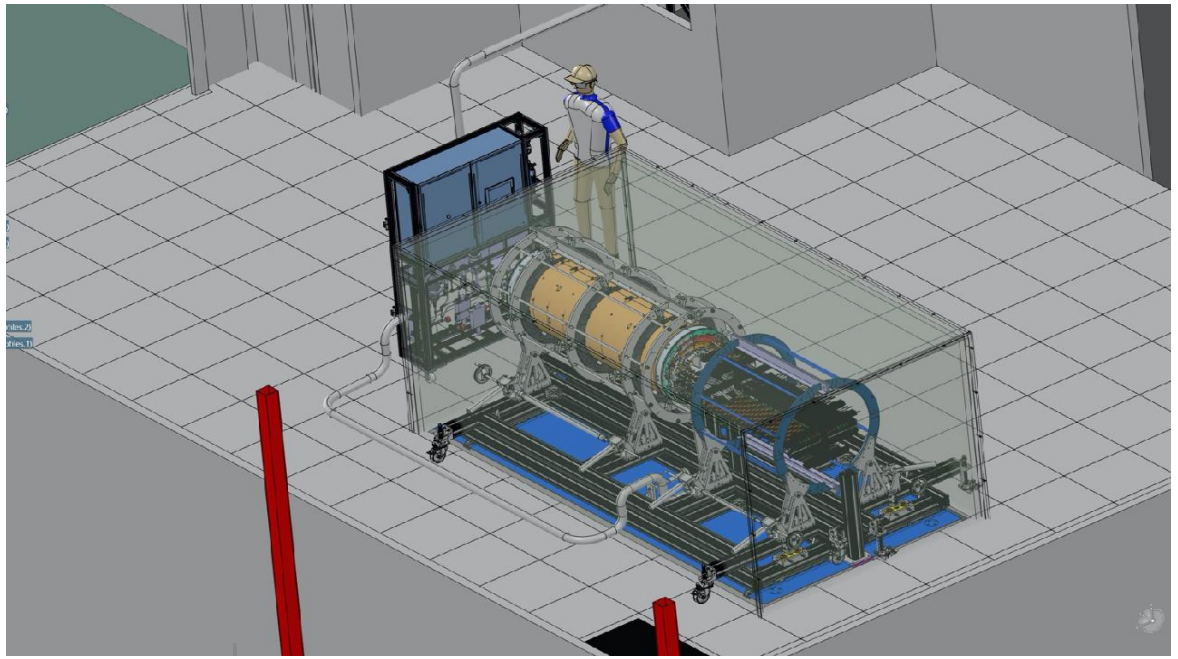
Innovation is not only on the detector side, but also on services.

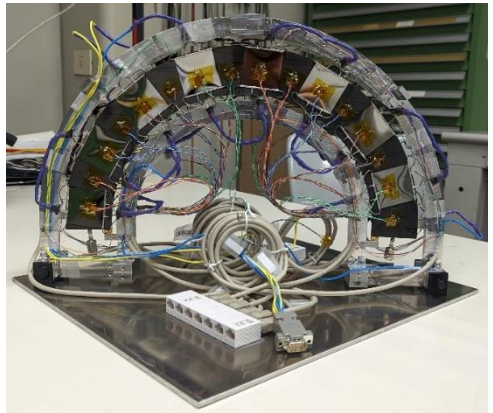
A small diameter titanium pipe is embedded in the HR structure to allow heat removal via a CO^2 cooling system and high thermal conductivity materials, as carbon based composites. The CO^2 evaporation temperature is assumed to be -30 °C.

Clean Room for EC integration at LNF

Clean room renovation project (ISO 6)

Clean room refurbishment at
LNF per OEC assembly





Small demonstration stand with Half-Ring

Large Clean room designed for:

- Mechanical assembly, electrical testing, cooling
- Hosting climate chamber, transfer CO_2 cooling lines, dry air / N_2 distribution
- Currently Frascati is working on prototypes, which need system test.

Summary

- The design and construction of the new ATLAS tracker for the HL-LHC phase poses several challenges to deliver a comparable or even **improved physics performance with respect to the present one**, in the much harsher conditions of the HL-LHC.
- A new all-silicon tracking system is being developed by the ATLAS experiment to cope with increased number of events per bunch crossing, particle multiplicity and radiation levels at the HL-LHC.
- The ITk detector installation will start in 2026 in ATLAS.
- The ITk design provides large acceptance for tracking with at least nine points per track, high granularity and radiation hardness, combined with a low material budget.
- Both strips and pixels technologies have demonstrated the required tracking efficiency up to end-of-life dose.
- ITk production will be a global effort with more than fifty institutes world

Thank You For Your Attention!
Any Questions?