The University of Manchester

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ATLAS ITk

The ATLAS Pixel Detector Upgrade at the High-Luminosity LHC

Jo Pater
The University of Manchester (UK)
Representing the ATLAS ITk Collaboration

VERTEX2023 ▪ Sestri Levante, Italy ▪ 16-20 October 2023

Outline

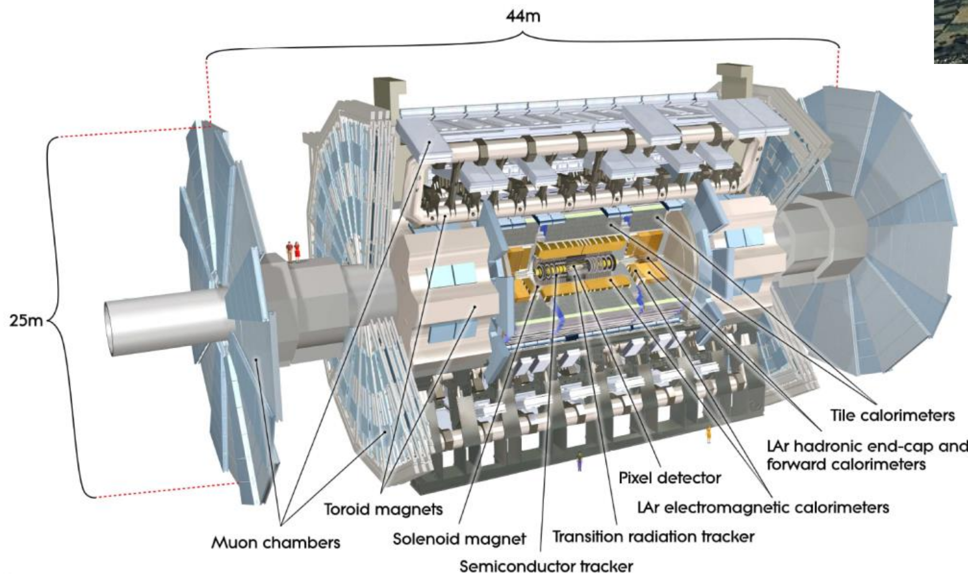
ATLAS ITk

- Introduction:
  - The LHC and ATLAS
  - LHC → HL-LHC and the Phase-2 Upgrades
    - → Requirements for the ATLAS Inner Tracker (ITk)
- The ITk pixel detector:
  - Layout
  - Sensors, FE chips, and Modules
  - Support Structures and Cooling
  - Electrical Services / Data Transmission
- Current Status
- Summary

The LHC and ATLAS

Large Hadron Collider at CERN:

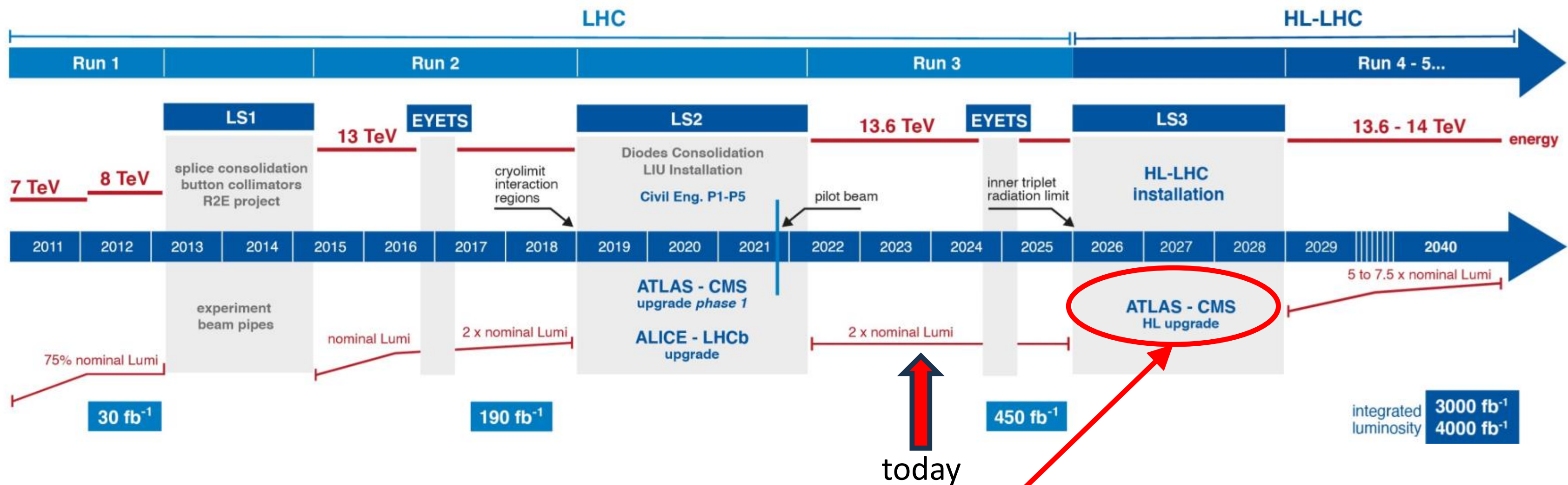
- 27km circumference
- protons and heavy ions
- 4 experiments



ATLAS:

- Layered multi-purpose detector: tracking, calorimetry, muon detection

LHC → HL-LHC



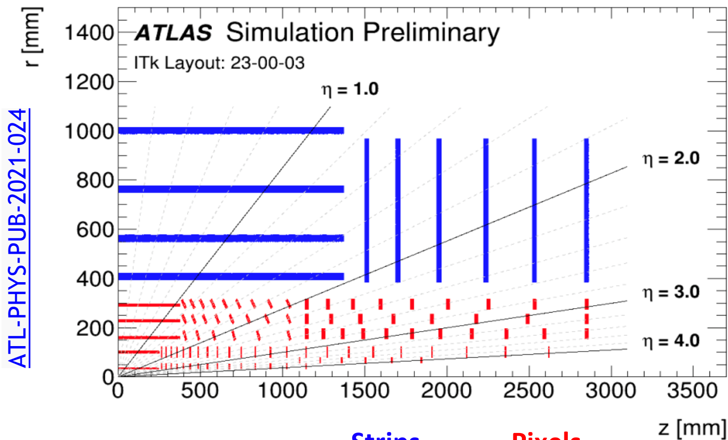
"Phase-II" upgrade of ATLAS in ~2027. Upgraded tracker will need to cope with

- average 200 interactions per bunch crossing
  - Currently ~50
- x5 pileup
- x10 integrated luminosity → x10 radiation damage

→ much higher data rates and occupancies

ITk: The New Inner Tracker

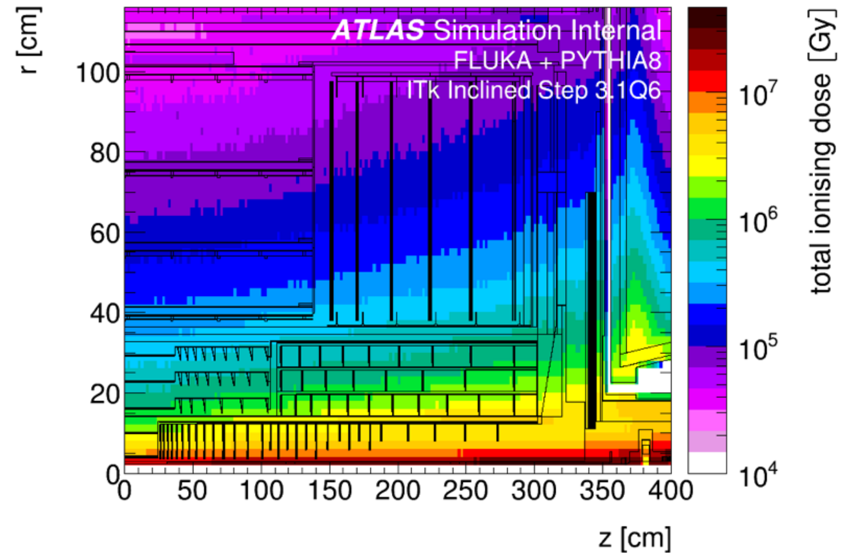
- All-silicon
- Coverage up to |η| < 4
  - ≥ 13 hits / track (barrel)
  - ≥ 9 hits / track (forward)



	Strips	Pixels
Si Area:	160 m^2	13 m^2
# channels:	50 x 10^6	5 x 10^9

ITk Strips at VERTEX2023:

- Design and Construction of the ATLAS ITk Strip Detector (I.Mandić, this afternoon)
- Towards the Construction of the ATLAS ITk Strip Endcap Detector for the HL-LHC Phase-2 (L.Franconi, poster session)
- Gamma Irradiation of ATLAS18 ITk Strip Sensors Affected by Static Charge (M.Mikestikova, Thursday)



Requirements for ITk pixel detector:

- Radiation hardness up to
  - 10 MGy (TID)
  - 2×10^{16} n_{eq}/cm^2
- Track reconstruction efficiency
  - > 99% for muons
  - > 85% for electrons and pions
- Fake rate < 10^{-5}
- Occupancy < 1%
- Robust against loss of 15% of channels
- Readout rate 1 MHz
- Output bandwidth up to 5.12 Gb/s per front-end chip
- Material budget ~ 2.0%X0 per layer

The ITk Pixel Detector

Outer Barrel

Outer Endcaps

Inner System

ATLAS Simulation Preliminary

ITk Layout: 23-00-03

η = 1.0 η = 2.0 η = 3.0 η = 4.0

Flat Barrel Barrel Rings End-cap Rings

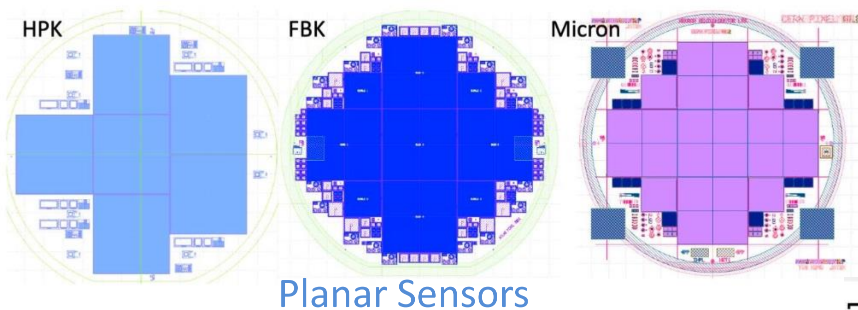
r [mm]: 0, 50, 100, 150, 200, 250, 300, 350, 400, 450

z [mm]: 0, 500, 1000, 1500, 2000, 2500, 3000, 3500

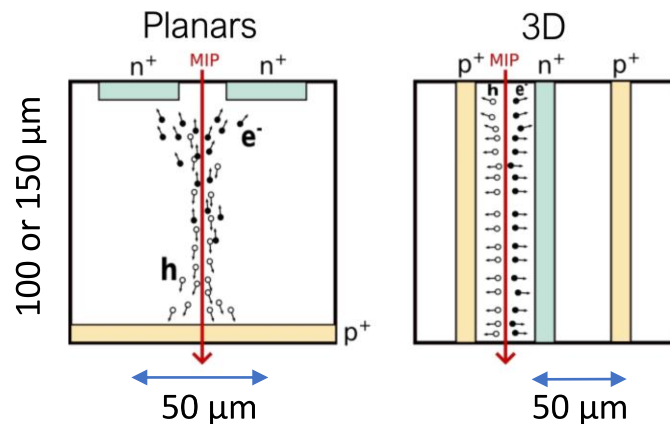
- Three distinct sub-systems with complementary designs
  - Aimed at keeping the silicon ~normal to high-momentum tracks from the interaction point (0,0)
- Work on mechanics and on-detector services is organized in geographical clusters:
    - Outer Barrel: CERN, Switzerland, France, Germany, Japan
    - Outer Endcaps: Italy, UK
    - Inner System: USA
  - Facilitates detailed collaboration
  - Minimises parts flow across borders
    - Some exchanges e.g. UK/Italy, Japan/Europe require careful handling → special logistics group based at CERN
  - Provides local redundancy: we can help each other through temporary problems e.g. equipment failure, personnel problems.

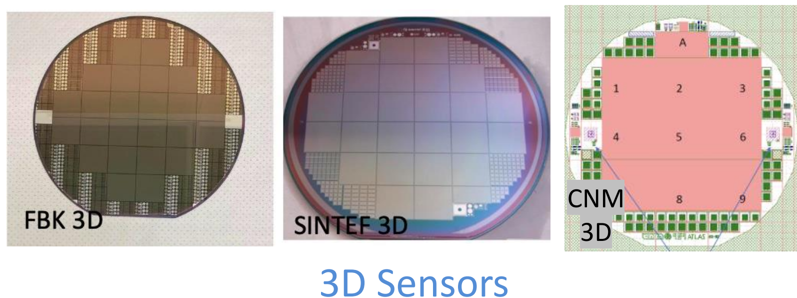
Silicon Sensors

- Sensor production is in progress
  - Following successful pre-production
  - Including tests in beam tests and with irradiated samples

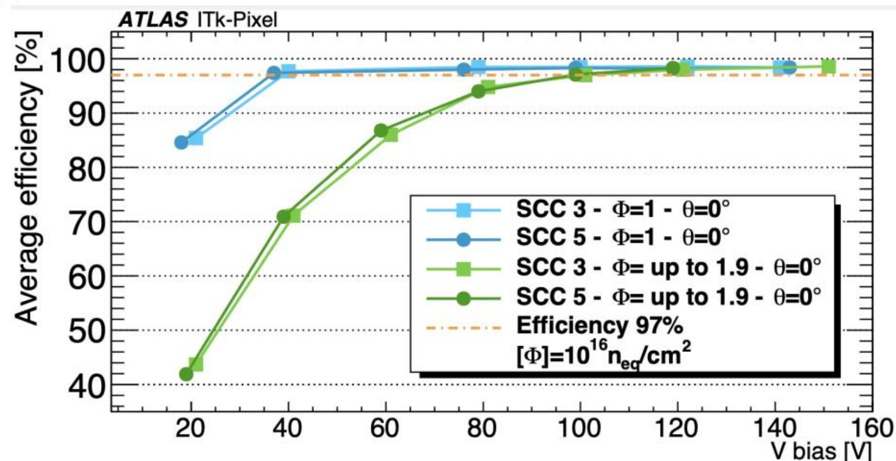


Planar Sensors





3D Sensors



FBK sensor performance after irradiation to 10 and 19 MGy

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2022-005/

ITk Pixel Sensors at VERTEX2023:

- Qualification of Irradiated 3D Pixel Sensors produced by FBK for the Pre-production of the ATLAS ITk Detector (S.Ravera, poster)
- Qualification of irradiated 3D Pixel Sensors produced by Sintef for the Pre-production of the ATLAS ITk Detector (S.Hellesund, poster)

Modules

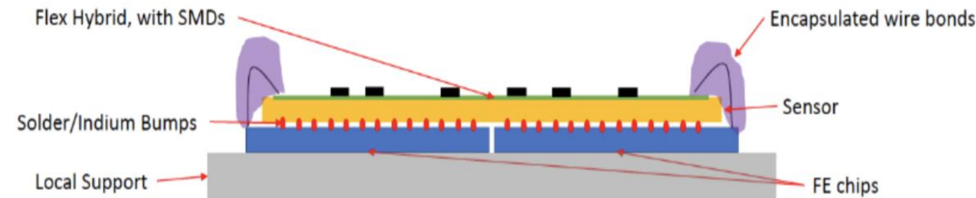
The Front-End Chip

- Developed by the RD53 collaboration
  - Joint ATLAS-CMS effort
    - Rad-hard chip design, software and prototypes
  - 65nm technology
  - Chip size:
    - 400 x 384 (153,600) 50x50 μm^2 pixels
    - 2.0 x 2.1 cm^2
  - Shunt-LDO regulator for serial powering
- Production design completed and submitted in March 2023
- First 100 V2 production wafers now in hand and being tested
  - Main focus of tests are verification of fixes implemented from previous version

ITk Pixel Modules at VERTEX2023:

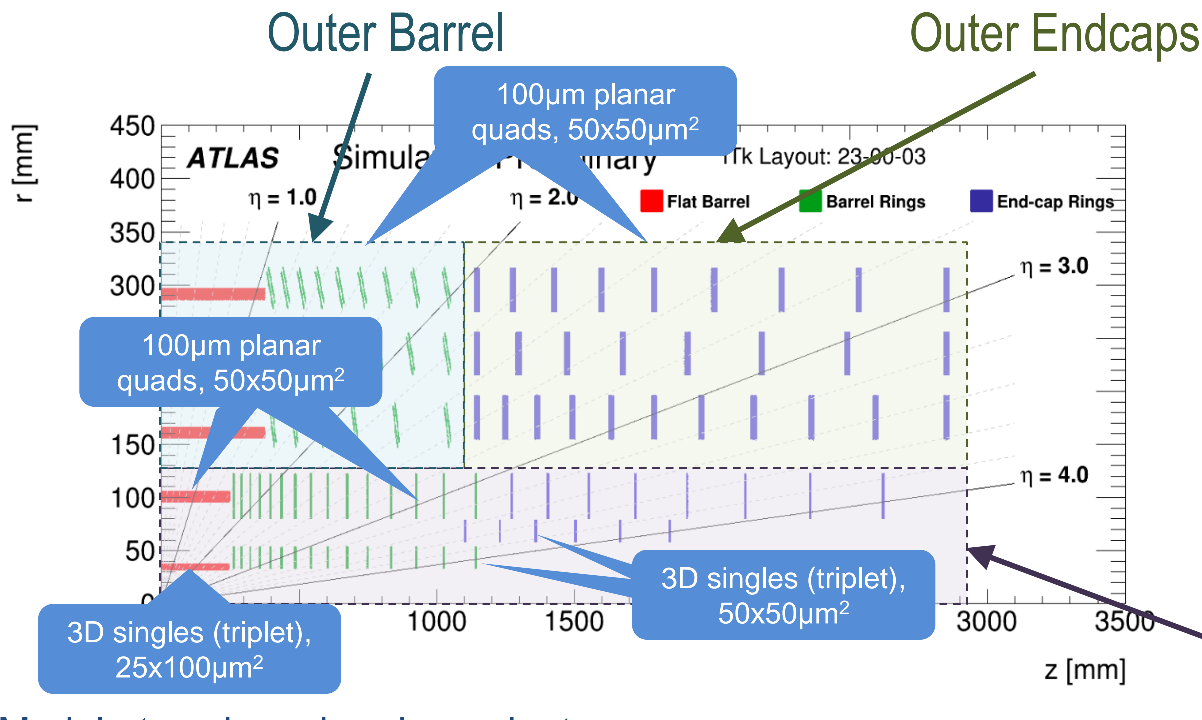
- RD53A/B Pixel Module Assembly and Testing Experience (A.Petrukhin, poster)
- Material Measurement of an ATLAS Pixel Module via Multiple Scattering (B.Moser, poster)
- Characterization of Pixel Detectors with Test Beams for the Inner Tracker Upgrade of the ATLAS Experiment (A.Rummler, Thursday)

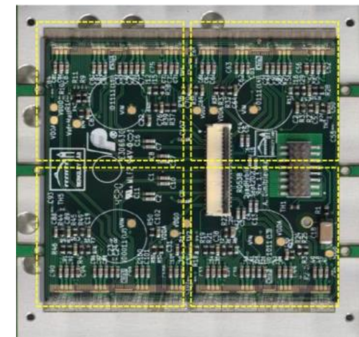
Hybrid Modules



- 1 or 4 FE chips bump-bonded to sensor
  - 4 industrial vendors
- Cu-Kapton flex hybrid glued to sensor
  - Common flex design for quads
    → modularity for production
  - Flex provides connection to power, slow controls and data distribution
    - Wire bonds connect the flex to the FE chip(s)
    - "pigtails" connecting modules to power / monitoring are subsystem-specific
- Serially-powered to reduce cable mass
  - Up to 14 modules in a single power chain
  - Up to 7A per module

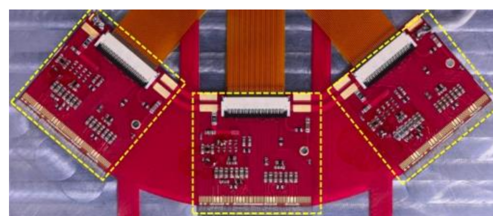
Module Placement





"Quad" module (4 FE chips)

- Module type is region-dependent:
  - Innermost layer ("Layer 0"): 3D silicon
    - Higher radiation tolerance
    - Lower power consumption → easier servicing
    - Pixel size 50x50 µm² or 25x150 µm²
  - Layer 1:
    - 100µm thick planar Si
    - Pixel size 50x50 µm²
  - Layers 2-4:150µm thick planar Si, 50x50 µm² pixels
- Innermost two layers will be replaced at half-lifetime (~2000 fb^{-1})



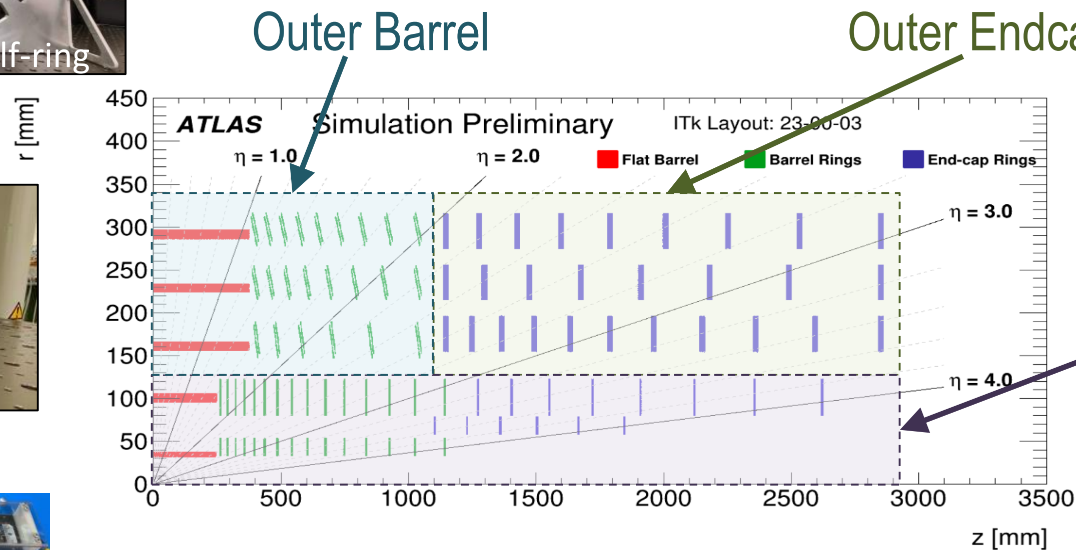
3 Single-chip modules in a triplet

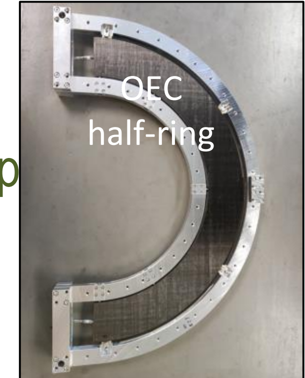
Support Structures

- Support structures are also specialized by region:

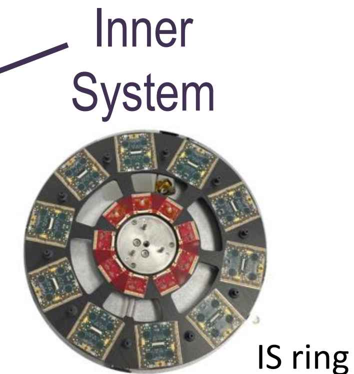
Outer Barrel

Outer Endcap





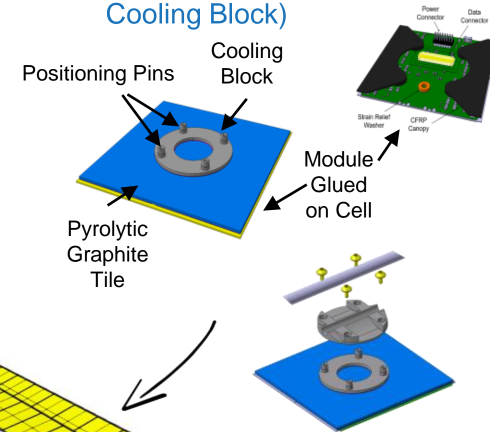
Inner System



- All structures are made of carbon-based materials…
  - Low mass, high stability, high thermal conductivity
- …and cooled by evaporative CO_2 in thin-walled Ti pipes

Outer Barrel Supports

- Modules are glued to pyrolytic graphite tiles, which are then attached to supporting structures with integrated cooling pipes:
  - In the central (low-η) region modules are "flat", on lightweight open structures called "longerons"; adjacent rows of modules overlap in ϕ
  - In the mid-η region, inclined-module layout keeps modules ~normal to high-p_t tracks
  - Services (cooling and electrical) run along the longerons and the ring-support cylinder



Half Layers
(2 x Inclined Units + Longerons)

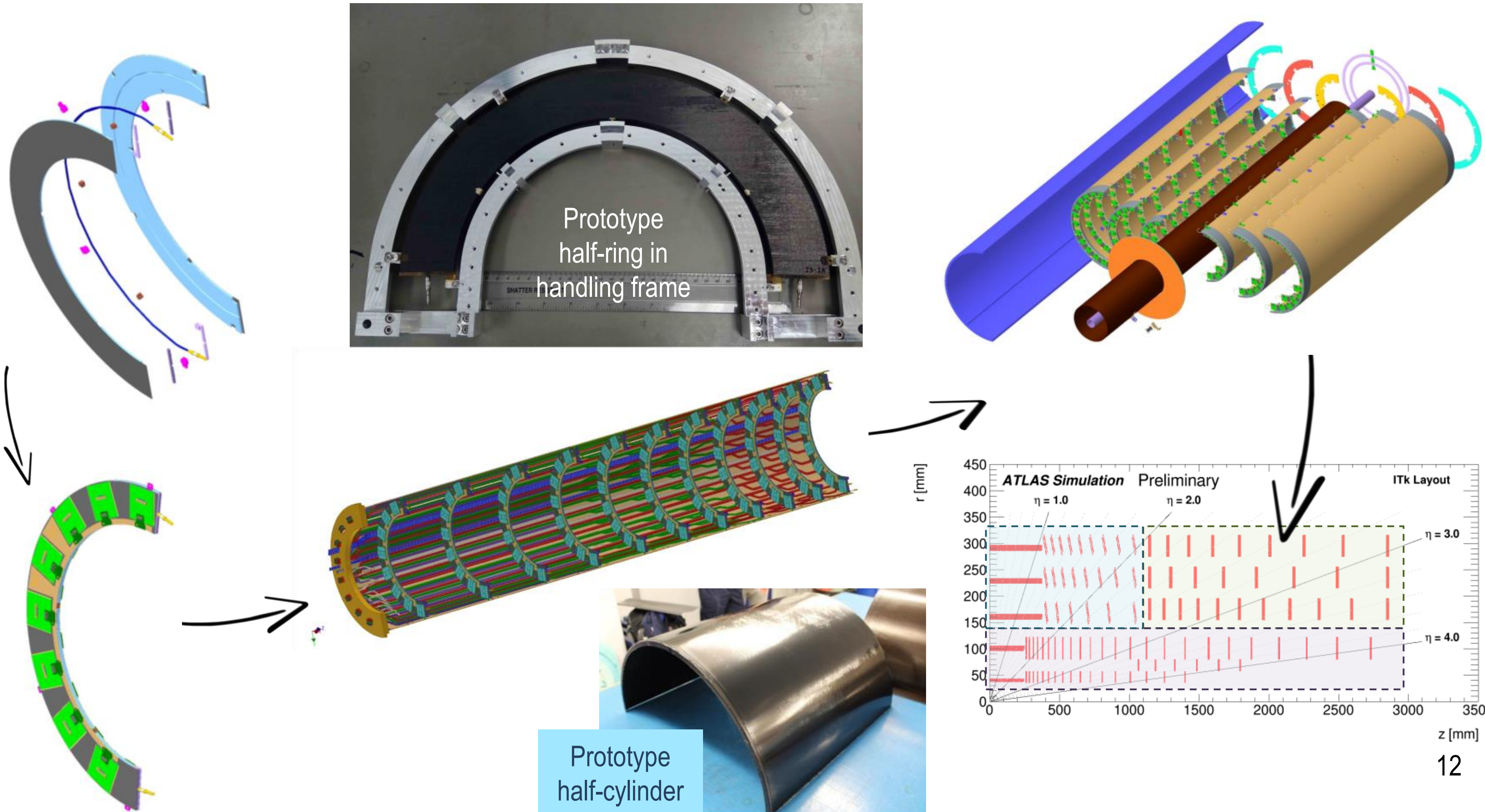
Inclined Half Rings

Half Layer Shell

Longerons

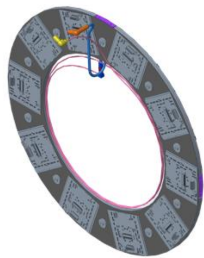
Outer Endcap Supports

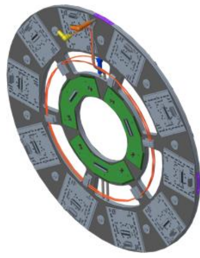
- Single rows of modules on both sides of half-rings ⊥ to beampipe → Φ hermeticity:
  - 3 layers of half-rings loaded into half-cylinders
  - Rings are strategically placed in z to provide hermeticity in η
- Half-rings are C-foam / C-fibre “sandwiches” with embedded cooling pipe and fixation lugs
- Cooling feed and exhaust lines, and electrical cables, run between outer rims of rings and inner surface of cylinder

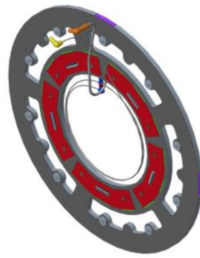


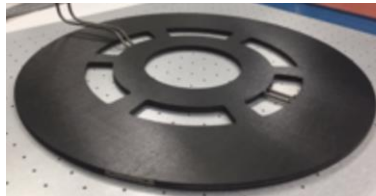
Inner System Supports

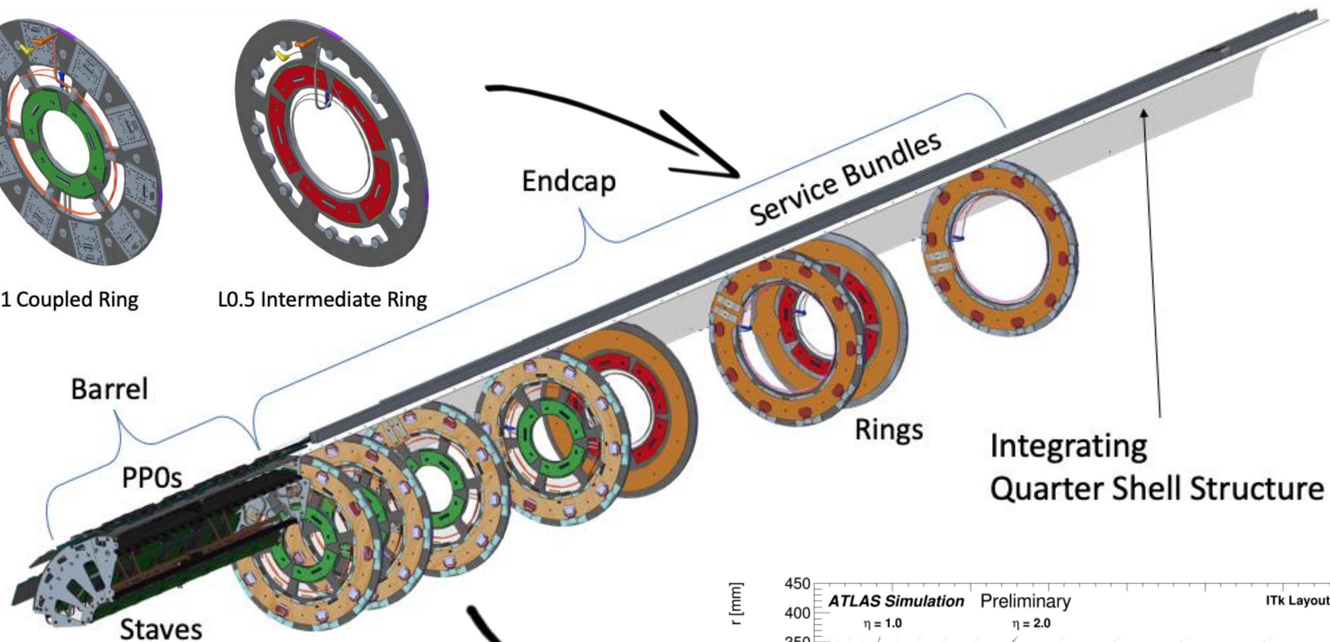
- The inner system will be contained inside an Inner Support Tube and will be replaced once (at ~2000 fb^{-1})
  - Short 2-layer flat barrel + long section of rings (3 types)
  - Cooling feed/exhaust and cables run along the quarter shell
  - Assembled in quadrants – one quadrant shown below

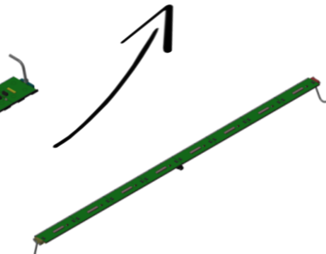


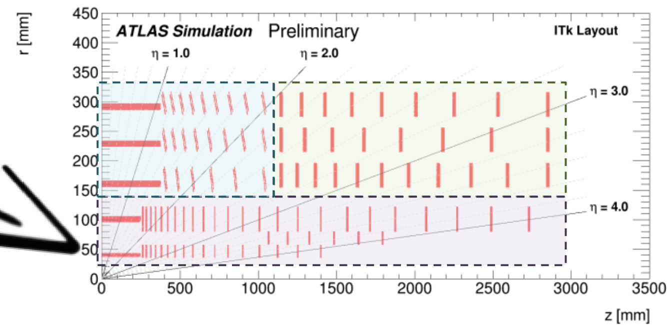





Prototype coupled ring

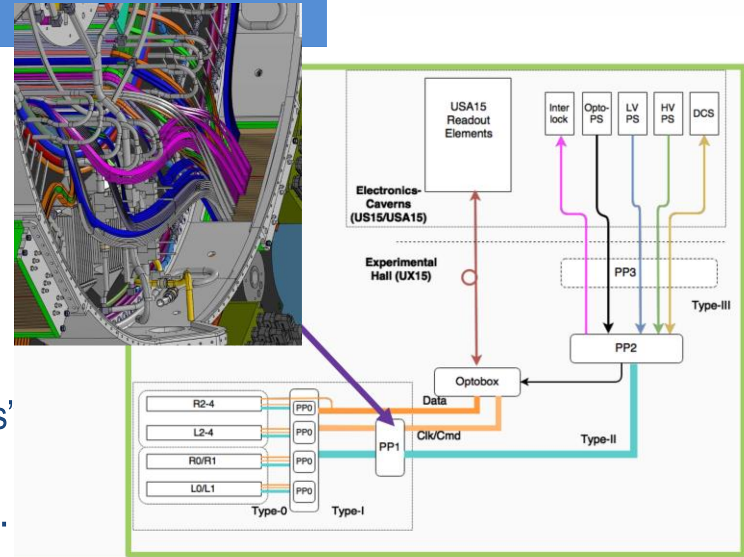


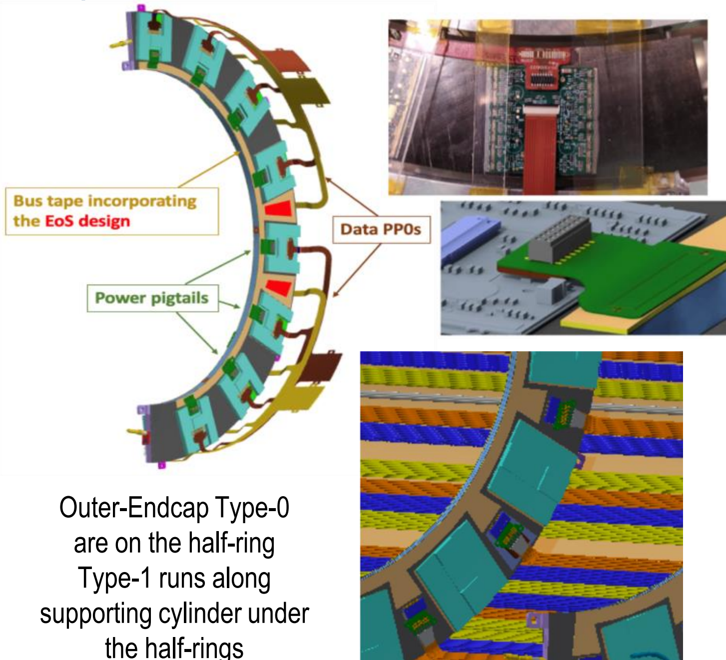




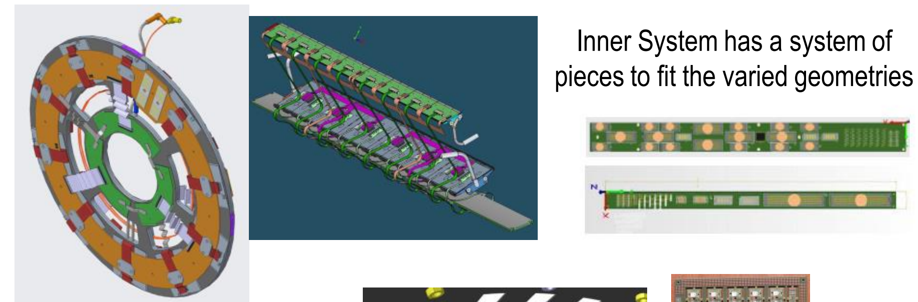
Electrical Services
(power, data, monitoring)

- Local supports hold "PP0s" with connections to modules
- "Type-I" cables carry services into / out of the detector
  - Twisted pairs for HV and monitoring/interlocks
  - Co-ax for LV
  - Data is on twin-ax cables inside the detector with electrical-to-optical conversion outside at "opto-boxes"
    - Accessible, lower radiation
- Successive steps of patch panels, thicker cables … up to services caverns

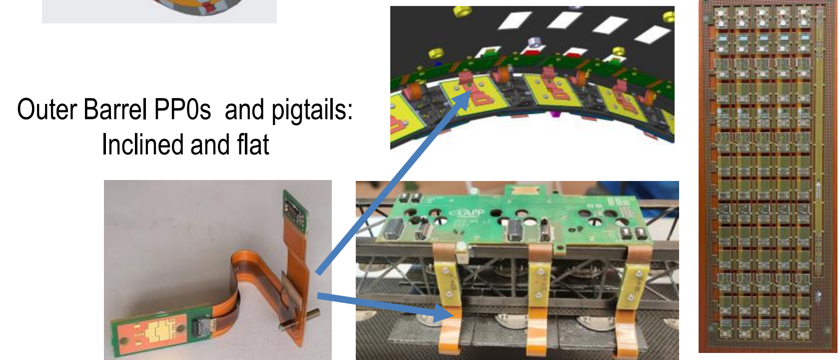




Outer-Endcap Type-0 are on the half-ring
Type-1 runs along supporting cylinder under the half-rings



Inner System has a system of pieces to fit the varied geometries

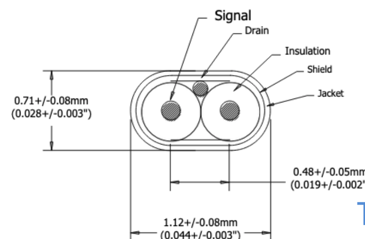


Outer Barrel PP0s and pigtails: Inclined and flat

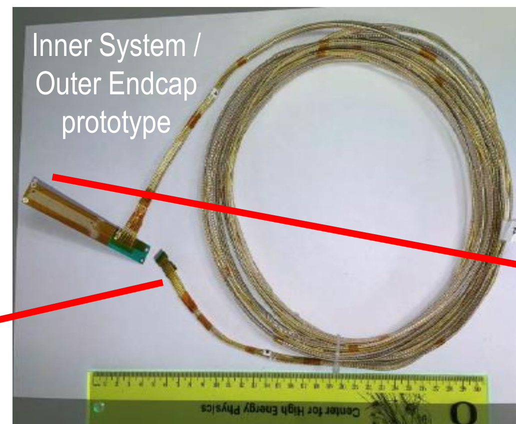
Data Transmission

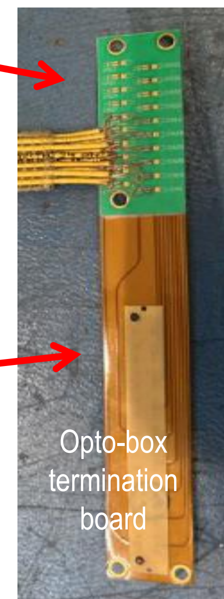
ATLAS ITk

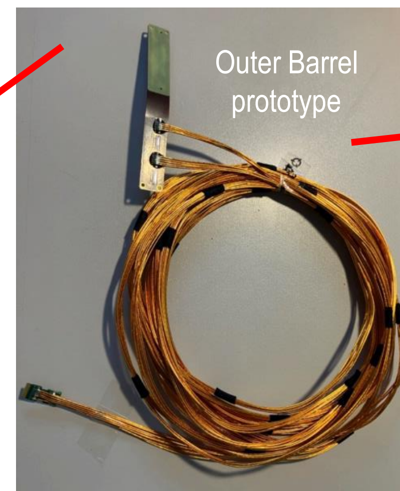
- Twinax cables for high-speed data transmission from local supports to opto-boxes
  - Two vendors with slightly different characteristics
  - Very thin (~1.1 x 0.7 mm^2): extremely limited space and material considerations are balanced with impedance requirements
- Cables can be ribbonized for easier handling
  - Detector end termination:
    - Via Samtec FireFly™ for outer system
    - Direct soldering to PP0 for inner system (not shown)
  - Opto-box end termination: bespoke PCBs

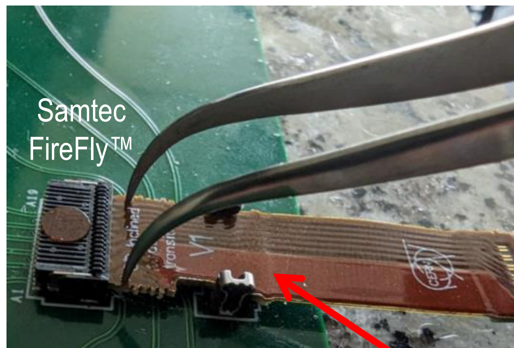


Twinax cross-section (Molex)

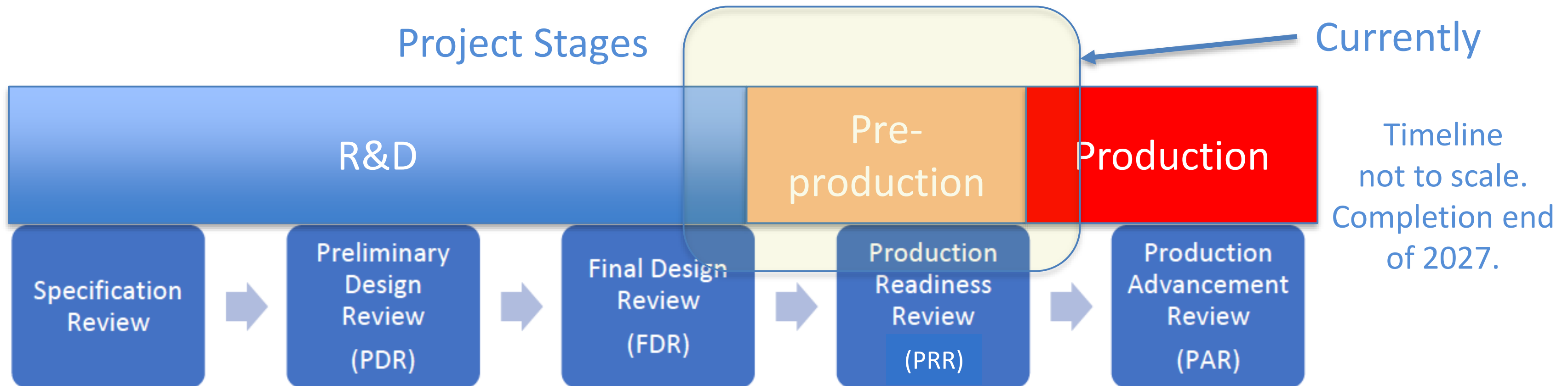








Current Status



Timeline not to scale. Completion end of 2027.

Area	PDR	Prototyping	FDR	Preproduction	PRR	Production
Planar Si sensors	Complete	Complete	Complete	Complete	Ongoing	Ongoing
3D Si sensors	Complete	Complete	Complete	Complete	Ongoing	Ongoing
FE-ASIC	Complete	Complete	Complete	Complete	Ongoing	Ongoing
Hybridisation	Complete	Complete	Complete	Ongoing	Upcoming	Upcoming
Module assembly	Complete	Complete	Complete	Ongoing	Upcoming	Upcoming
On-detector services	Complete	Complete	Complete	Ongoing	Upcoming	Upcoming
Off-detector services	Complete	Complete	Complete	Ongoing	Upcoming	Upcoming
Data Transmission	Complete	Complete	Ongoing	Upcoming	Upcoming	Upcoming
Bare Local Supports	Complete	Complete	Complete	Ongoing	Upcoming	Upcoming
Loaded Local Supports	Complete	Complete	Complete	Upcoming	Upcoming	Upcoming
Global Mechanics	Complete	Complete	Upcoming	Upcoming	Upcoming	Upcoming
Integration	Complete	Complete	Upcoming	Upcoming	Upcoming	Upcoming
Power supplies	Complete	Complete	Complete	Ongoing	Upcoming	Upcoming

Complete / Ongoing / Upcoming

Tenders complete and contracts in place for major components:

- Planar sensors
- 3D sensors
- FE chips
- Module hybridisation
- Power supplies

Summary

- The LHC→ HL-LHC upgrade requires a new tracker (ITk) for ATLAS, with tough requirements.
- Features of the ITk pixel detector:
  - 5-layer coverage to $|\eta| < 4$
  - New FE chip (RD53) and sensor (3D, planar) developments
  - Serially-powered
  - CO_2 cooled
- Individual components have been verified in prototype runs during last two years and most have passed final design reviews
  - Sensors, FE-chips, Outer Barrel local supports in production
  - Module hybridization and assembly, most services in pre-production
  - Remaining activities planning final design reviews in next few months.
- Completion scheduled for 2027

Backup Slides

Material ID → ITk

Material reduction techniques:

- CO_2 cooling with thin-walled titanium pipes
- Minimize material in modules using thin sensors and FE-chips
- Serial powering → fewer cables
- Low-mass carbon structures for mechanical stability and mounting
- Optimize number of readout cables using data link sharing

Below: comparison of material in simulation

- Current ID vs ITk
- Important for performance and radiation-level studies