The ATLAS ITk Pixel Detector Status and Roadmap

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on behalf of the ATLAS ITk Collaboration

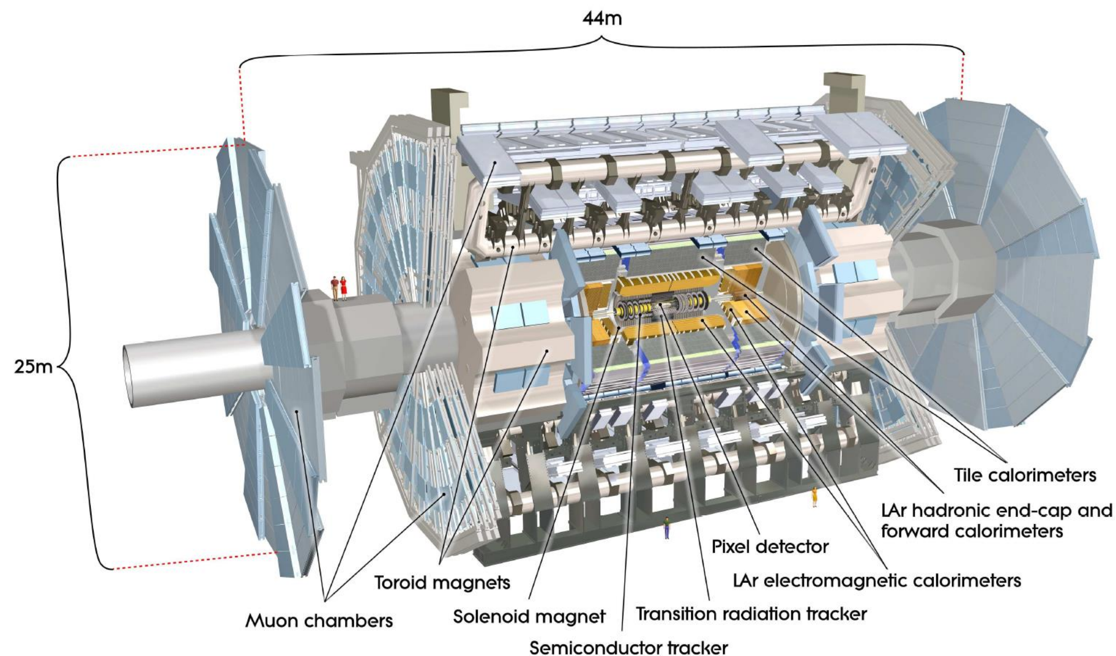
13th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors
HSTD13, Vancouver, Canada, 3-8 Dec 2023

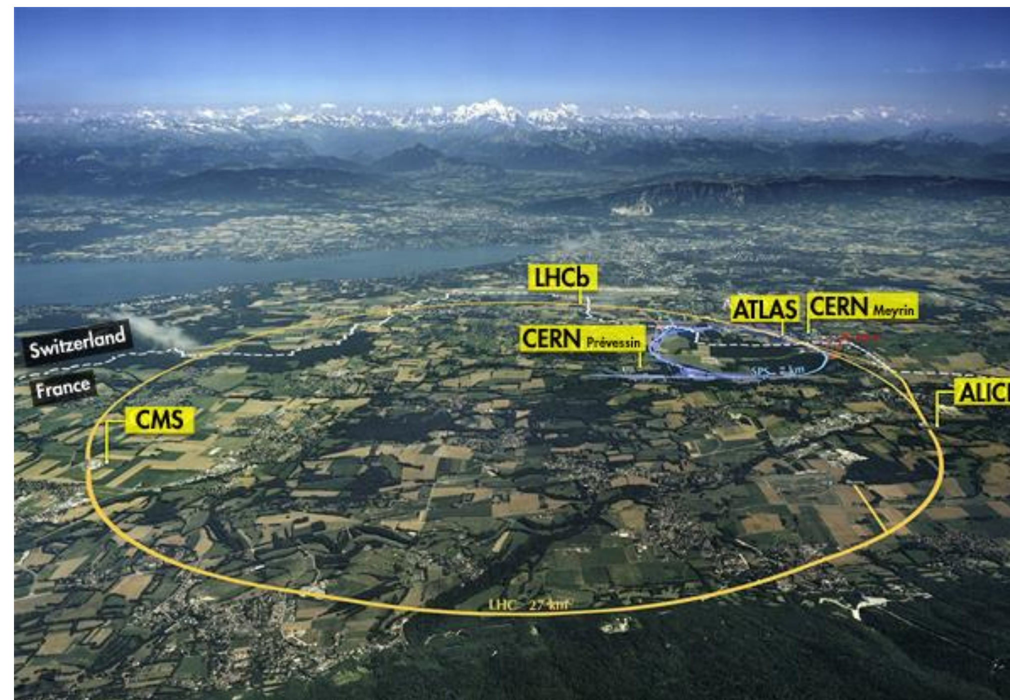
LHC and ATLAS

ATLAS ITk

Large Hadron Collider at CERN

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





ATLAS

Layered multi-purpose detector

- Tracking
- Calorimetry
- Muon Spectrometry

High Luminosity LHC Upgrade

ATLAS ITk

LHC | HL-LHC

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

LS1 | EYETS | LS2 | EYETS | 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 | 2040

75% nominal Lumi

experiment
beam pipes

nominal Lumi

2 x nominal Lumi

ATLAS - CMS
upgrade *phase 1*

ALICE - LHCb
upgrade

2 x nominal Lumi

ATLAS - CMS
HL upgrade

5 to 7.5 x nominal Lumi

30 fb^{-1} | 190 fb^{-1} | 450 fb^{-1}

integrated luminosity: 3000 fb^{-1} / 4000 fb^{-1}

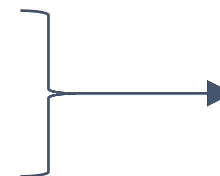
today

Phase-II upgrade of ATLAS in progress in parallel with ongoing Run3 Data Taking

HL-LHC data taking planned to start in 2029 and to accumulate 4000 fb^{-1} (x10 of Run3)

The upgraded tracker will need to cope with

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



much higher data rates and occupancies

ITk – The new Inner Tracker

ATLAS ITk

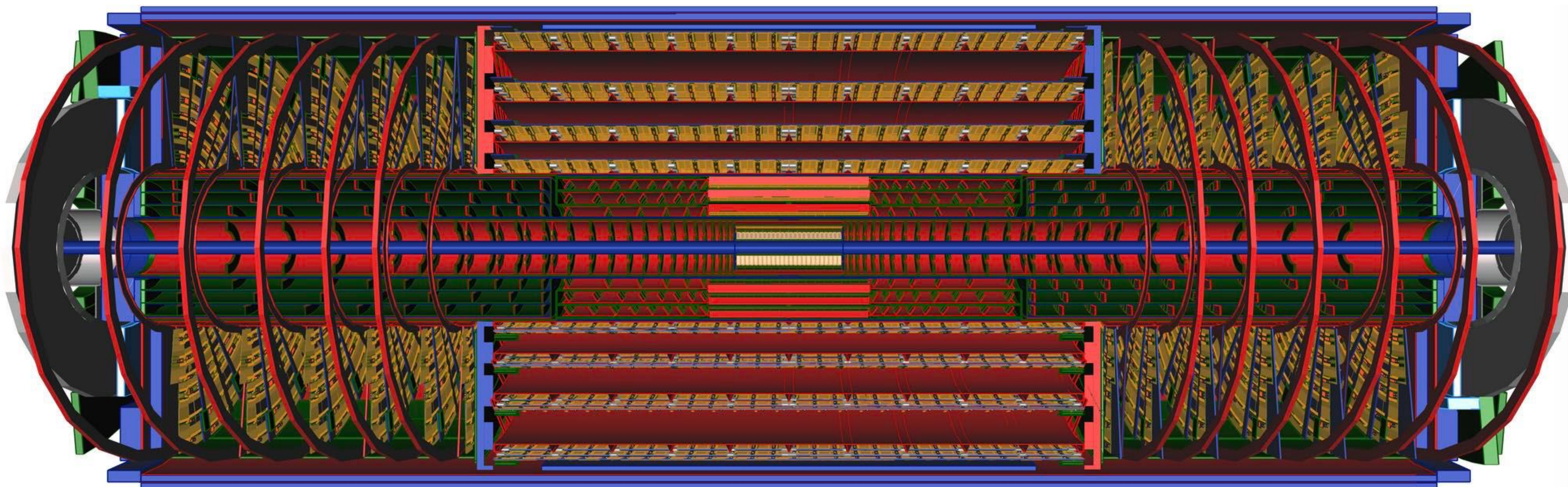
All-silicon

Coverage up to $|\eta| < 4$

- $\geq$ 13 hits / track (barrel)
- $\geq$ 9 hits / track (forward)

The ITk tracker consists of **outer strip tracker** and **inner pixel tracker** to replace current ATLAS “Inner Detector”

- 168 m^2 of silicon strip and 13 m^2 of silicon pixel
- Designed to withstand up to $10^{16}\ n_{eq}/cm^2$ on the innermost pixel layer



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ITk – The new Inner Tracker

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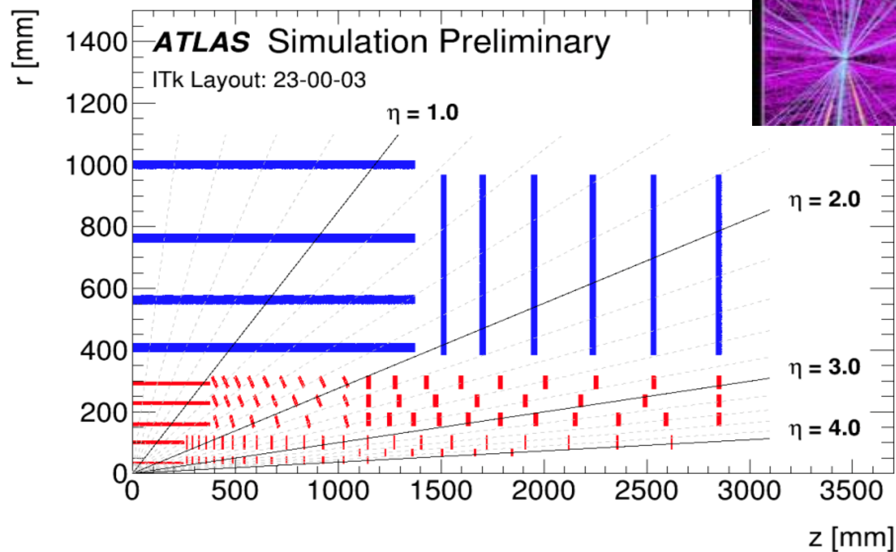
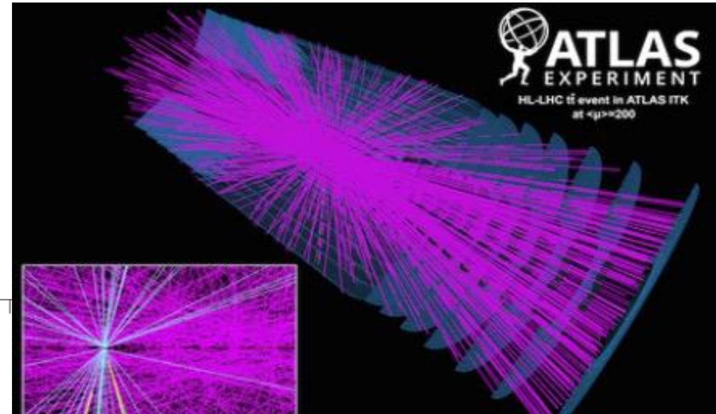
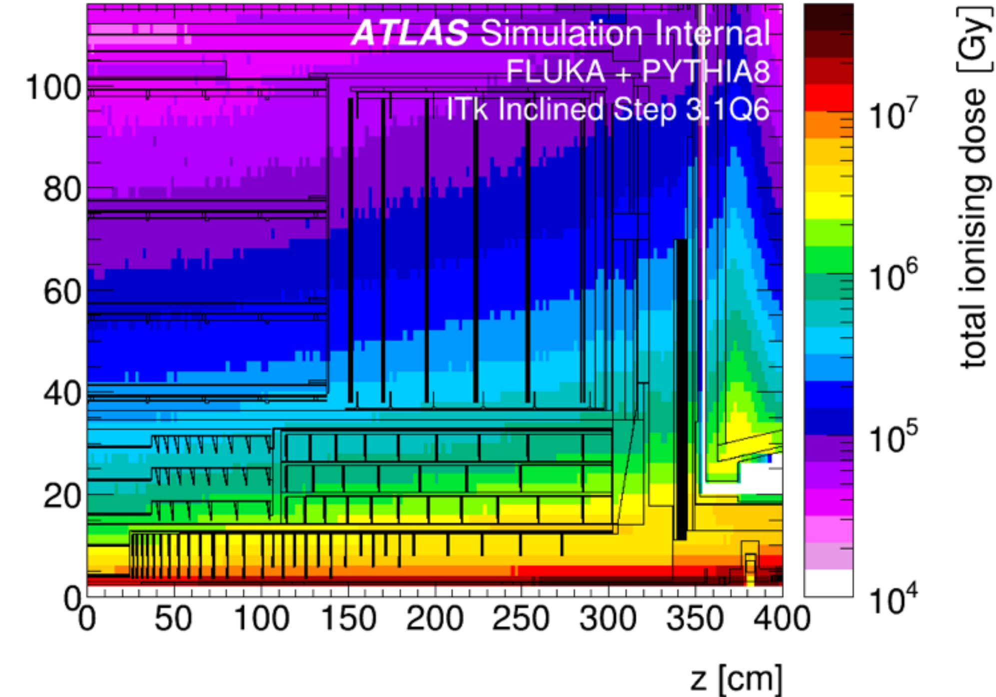


Simulated ttbar event with average pile-up of 200 collisions per bunch crossing





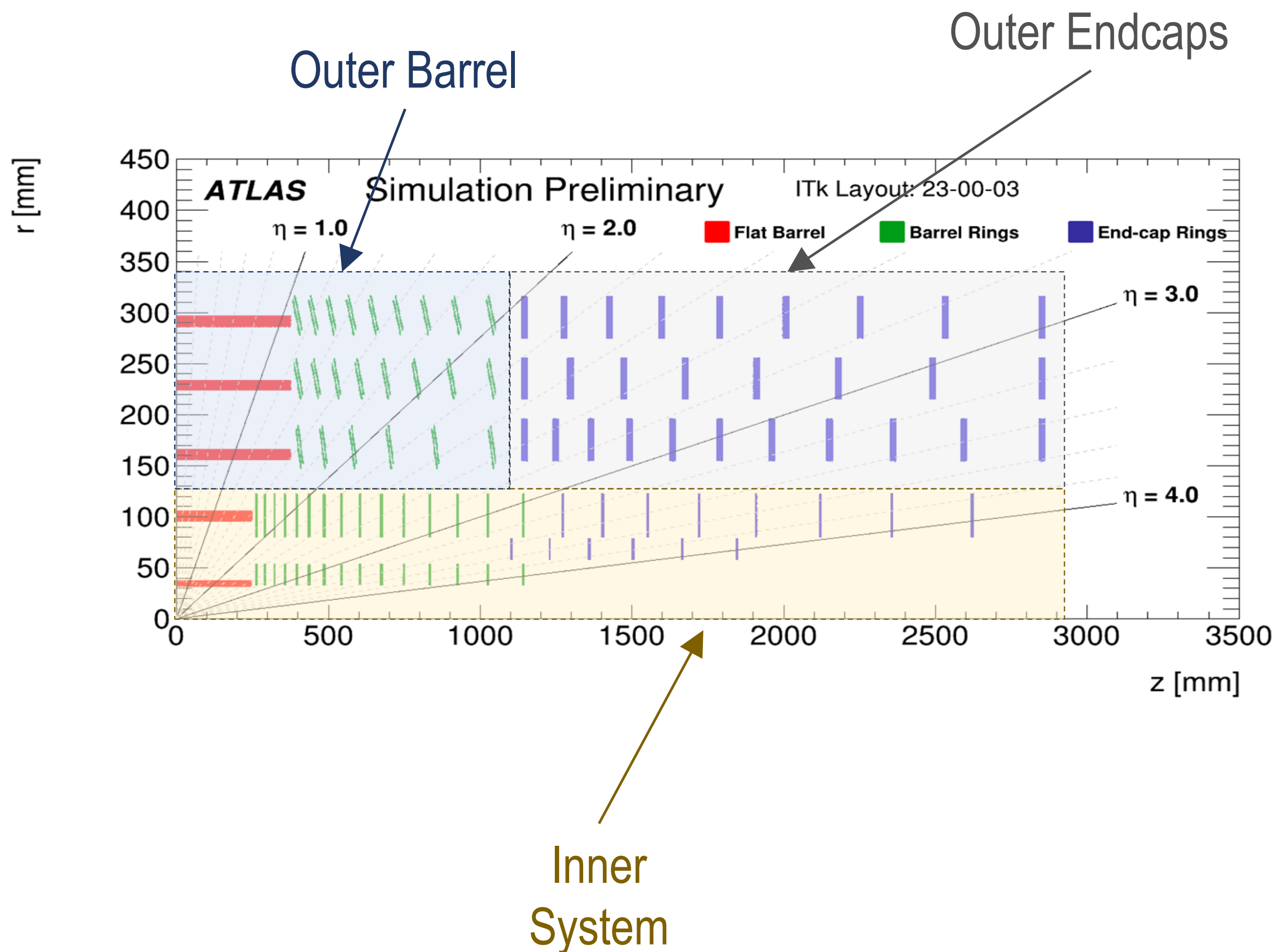
	Strips	Pixels
Si Area:	160 m^2	**13 m^2**
# channels:	50 x 10^6	**5 x 10^9**

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% X_0 per layer

The ITk Pixel Detector

Three distinct sub-systems with complementary designs

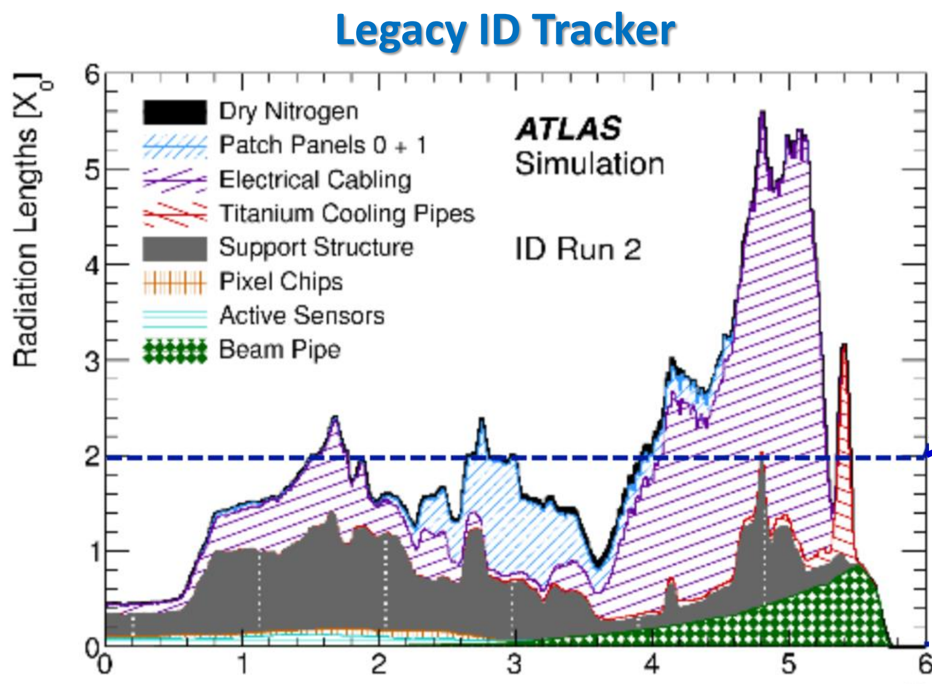


- Aimed at keeping the silicon ~normal to high-p tracks from the interaction point
- Work on **mechanics** and **on-detector services** is organized in geographical clusters
  - Outer Barrel: CERN, Switzerland, France, Germany, Japan
  - Outer Endcaps: Italy, UK
  - Inner System: USA
- Facilitates detailed 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
    - equipment failure
    - personnel problems
    - …

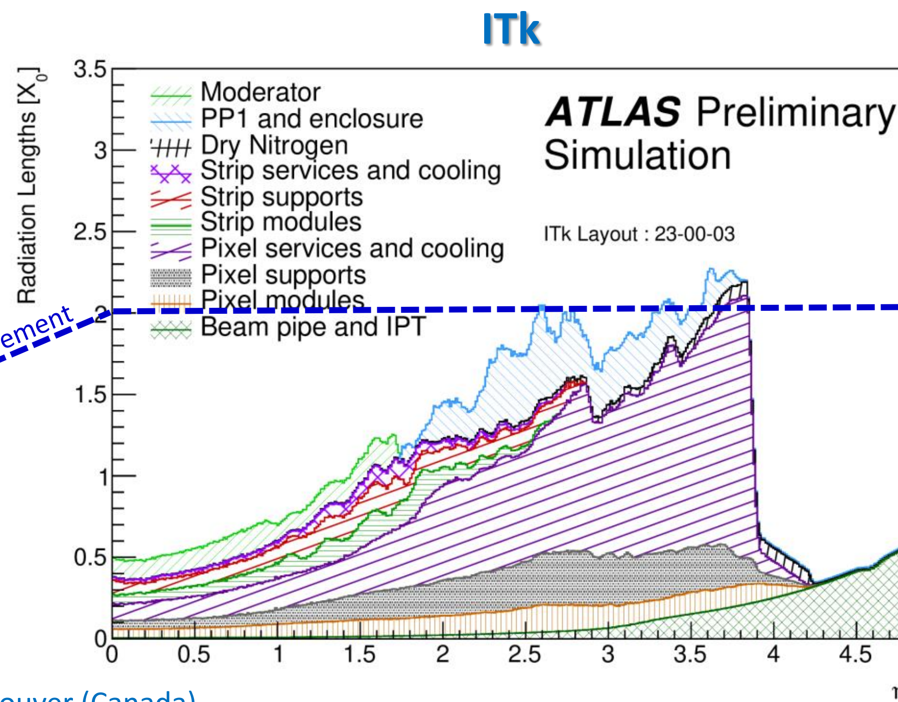
Material Budget

Material reduction strategies

- 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



Factor ~2 improvement



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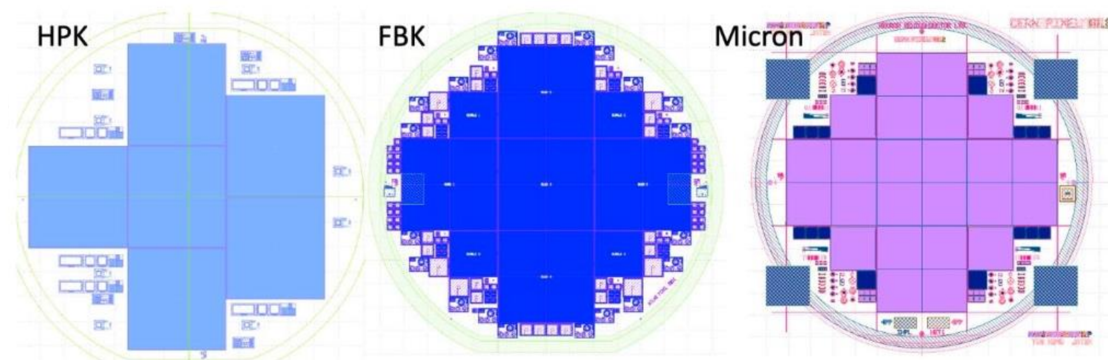
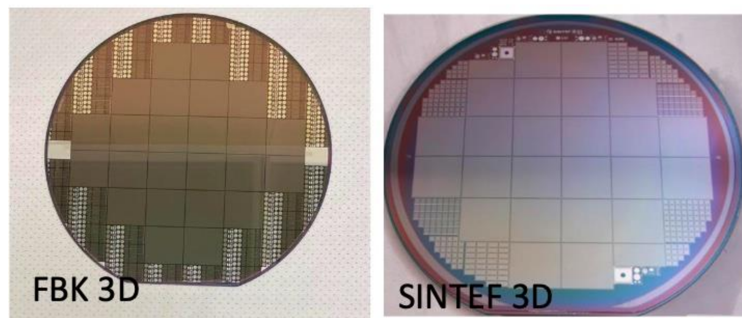
Silicon Sensors

Sensor production is in progress

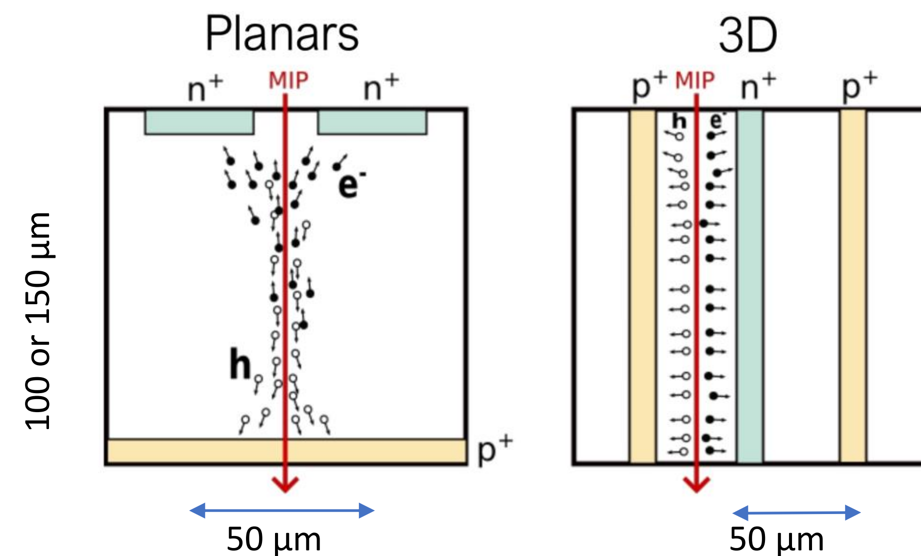
- Following successful pre-production (10% of total)
- Including qualification in beam tests
  and with irradiated samples

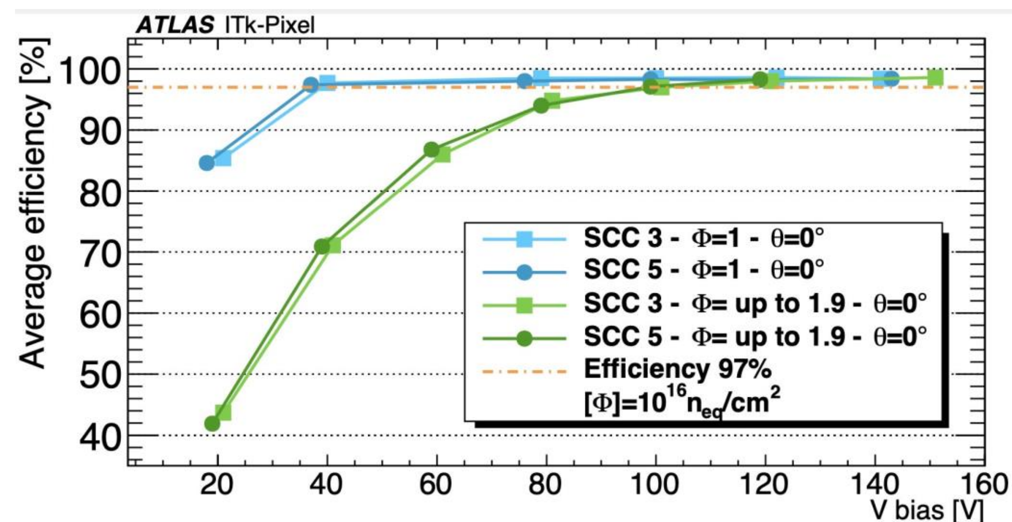


Planar sensors



3D sensors





FBK sensor performance after irradiation to 1.0 and 1.9 $10^{16} n_{eq}/cm^2$

@HSTD13, see:
Christopher Krause "TB perf. of pixel detectors for the ITk Upgrade of the ATLAS exp"

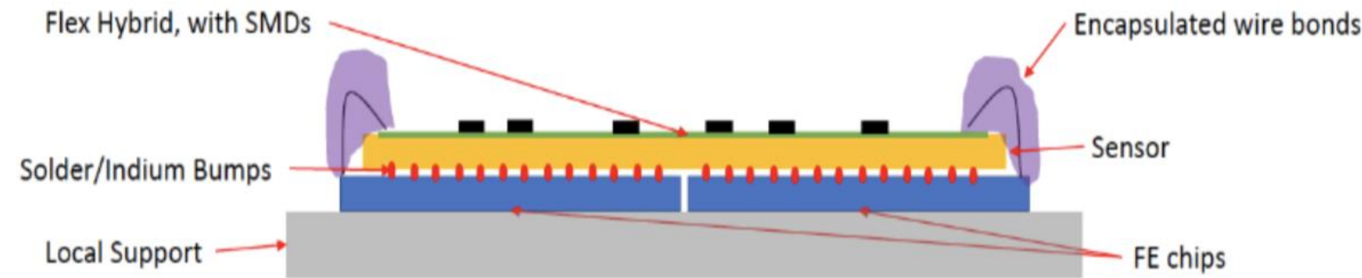
FE chips and Hybrid Modules

@HSTD13, see:
Abhishek Sharma "Module development for the ATLAS ITk Pixel Detector"

The Front-End Chip

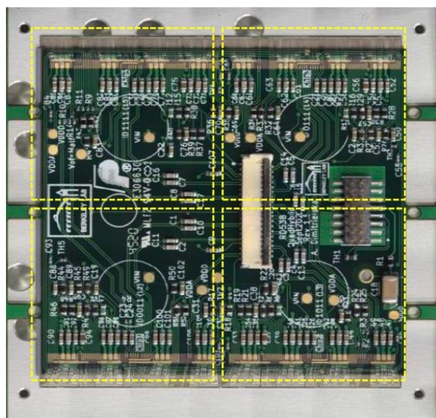
- Developed by **RD53 collaboration**
- Joint effort for ATLAS and CMS
  - common chip design
  - slight difference in FE and matrix size
- Rad-hard chip design, 65nm technology
- Chip size
  - 400 x 384 (153,600) 50x50 μm^2 pixels
  - 2.0 x 2.1 cm^2
- Shunt-LDO regulator for serial powering
- Production design completed and submitted in March 2023
  - Prototyping: RD53A, ITkPixV1
- First 100 ITkPixV2 production wafers now in hand and being tested
- Main focus of tests:
  - verify fixes implemented from previous version

The Hybrid Module

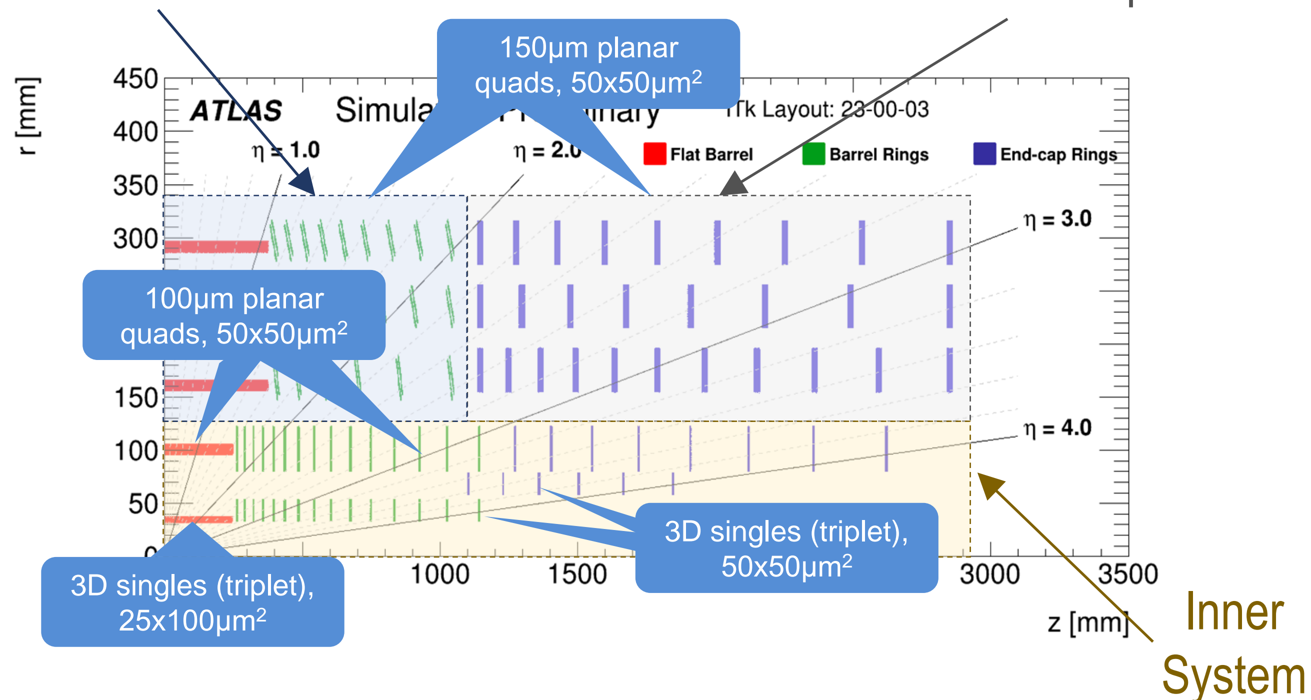


- 1 or 4 FE chips bump-bonded to sensor
  - 4 industrial vendors
- Cu-Kapton flex hybrid glued to sensor
- Common flex design for quads → modularity for production
- Flex provides connection to power, slow controls and data distribution
  - Wire bonds connect the flex to the FE chip(s)
  - "Pigtails" 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



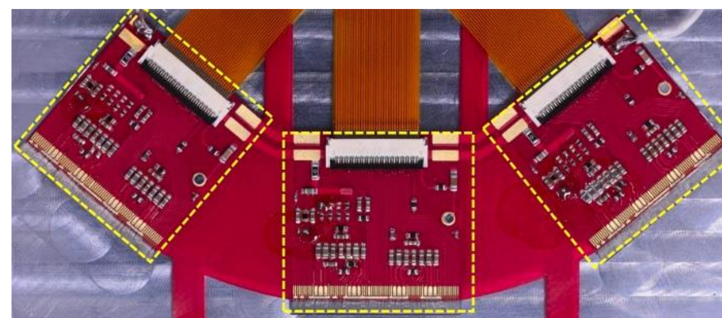
“Quad’ module
(4 FE chips)



Module type is region-dependent

- Innermost layer (“Layer 0”): 3D sensors
  - Higher radiation tolerance
  - Lower power consumption → easier servicing
  - Pixel size 50x50 μm^2 or 25x100 μm^2
- Layer 1
  - 100µm thick planar Si
  - Pixel size 50x50 μm^2
- Layers 2-4
  - 150µm thick planar Si, 50x50 μm^2 pixels

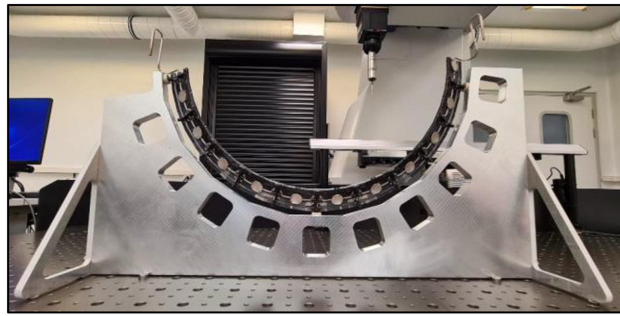
Innermost two layers will be replaced at half-lifetime (~2000 fb^{-1})



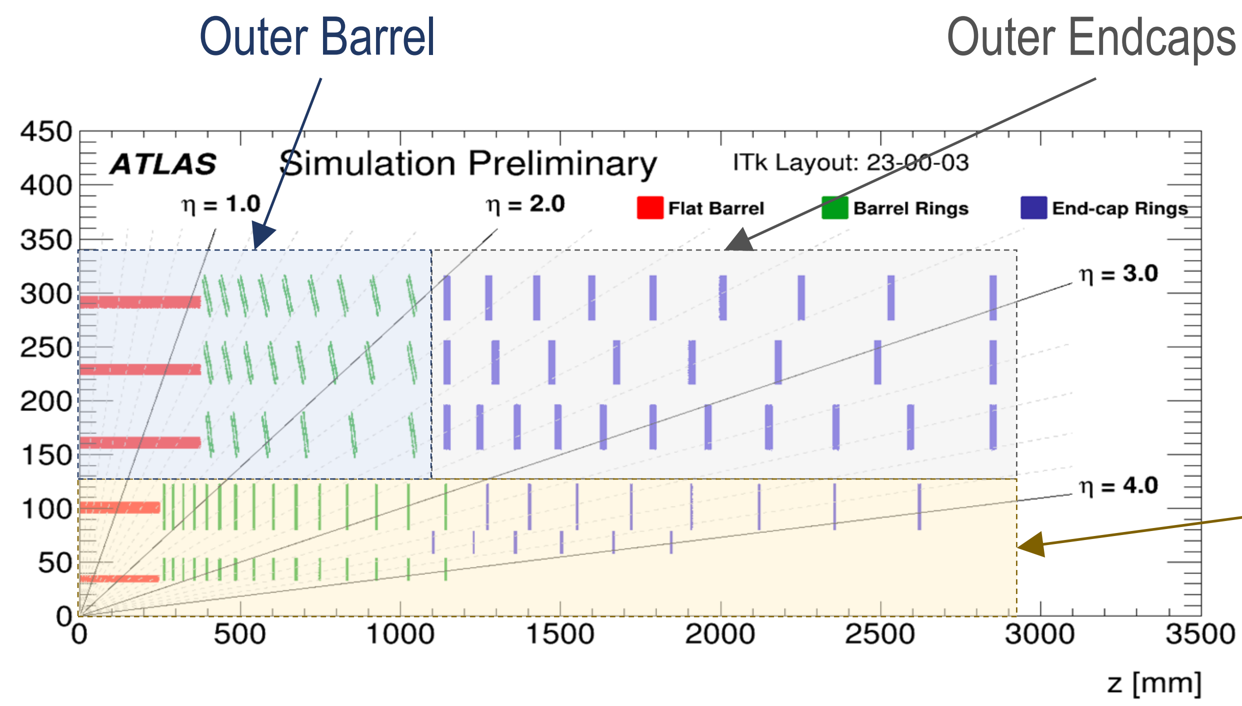
3 Single-chip modules in a “triplet”

Support Structures

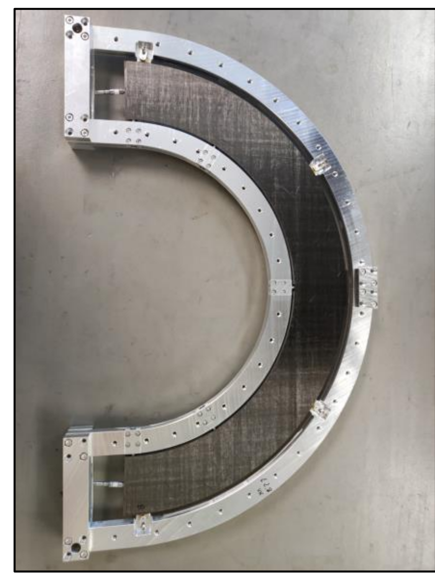
Support structures are also specialized by region


OB inclined half-ring

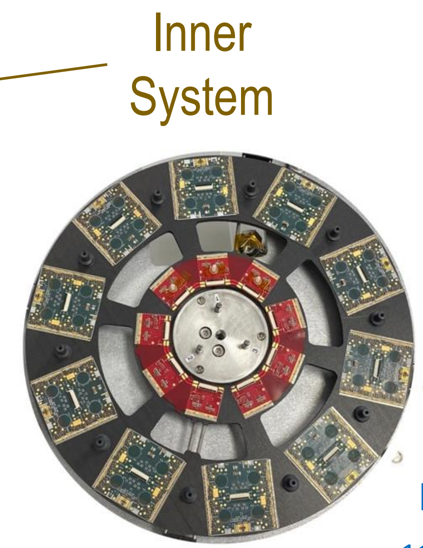
OB longeron



OEC half-ring



Inner System

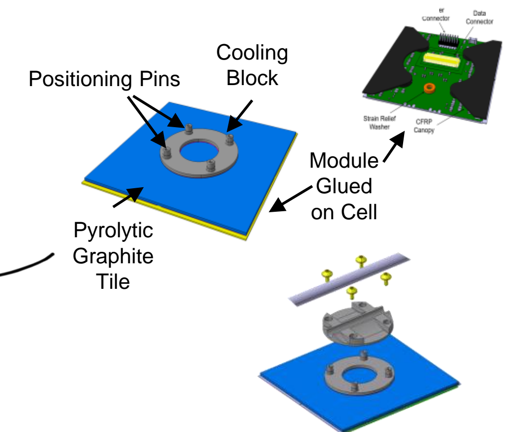

IS ring

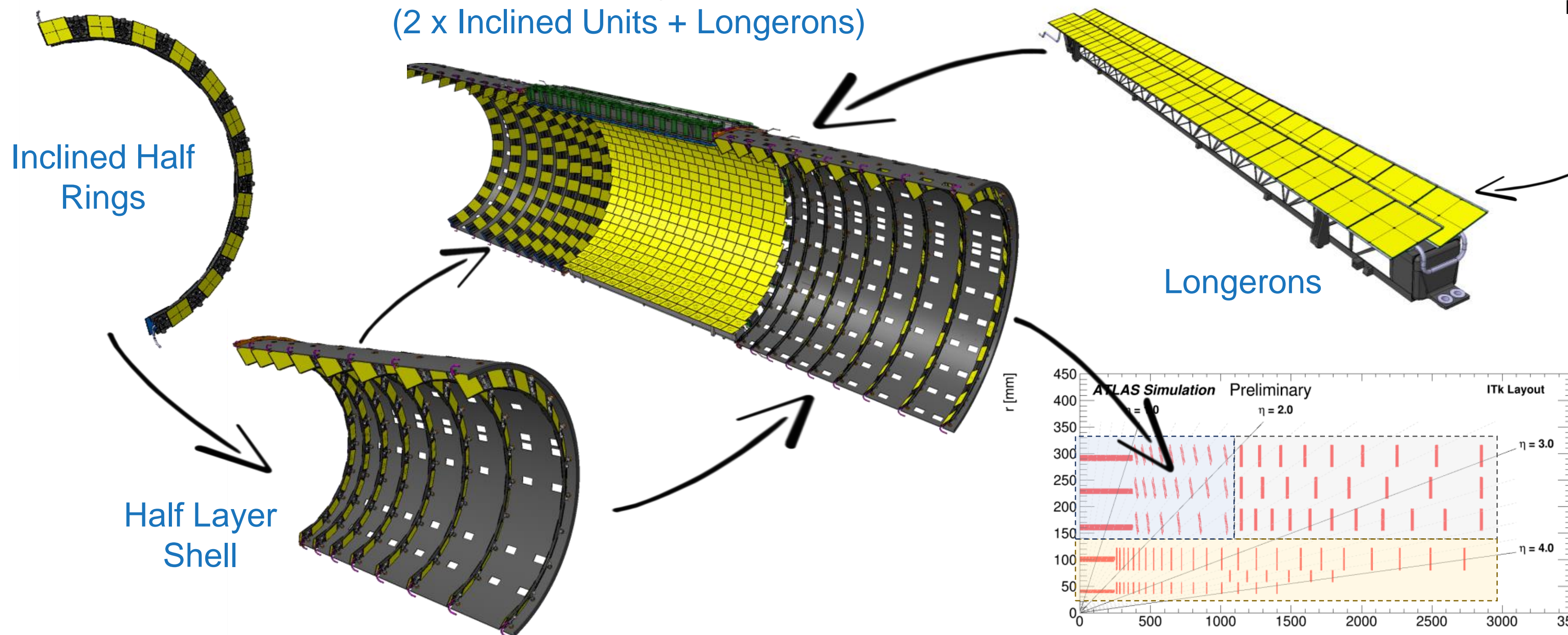
All structures are made of carbon-based materials…
Low mass, high stability, high thermal conductivity
…and cooled by evaporative CO_2 in thin-walled Ti pipes

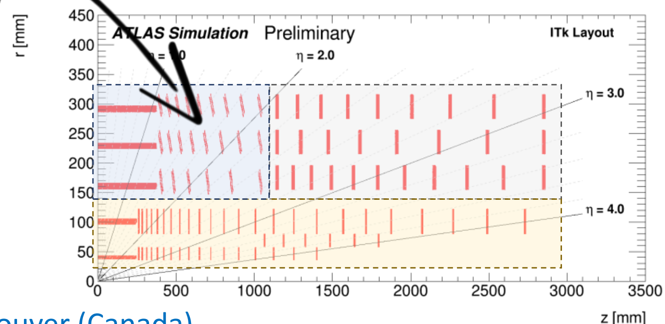
Outer Barrel Supports

Modules are glued to pyrolytic graphite tiles, which are then attached to supporting structures with integrated cooling pipes:

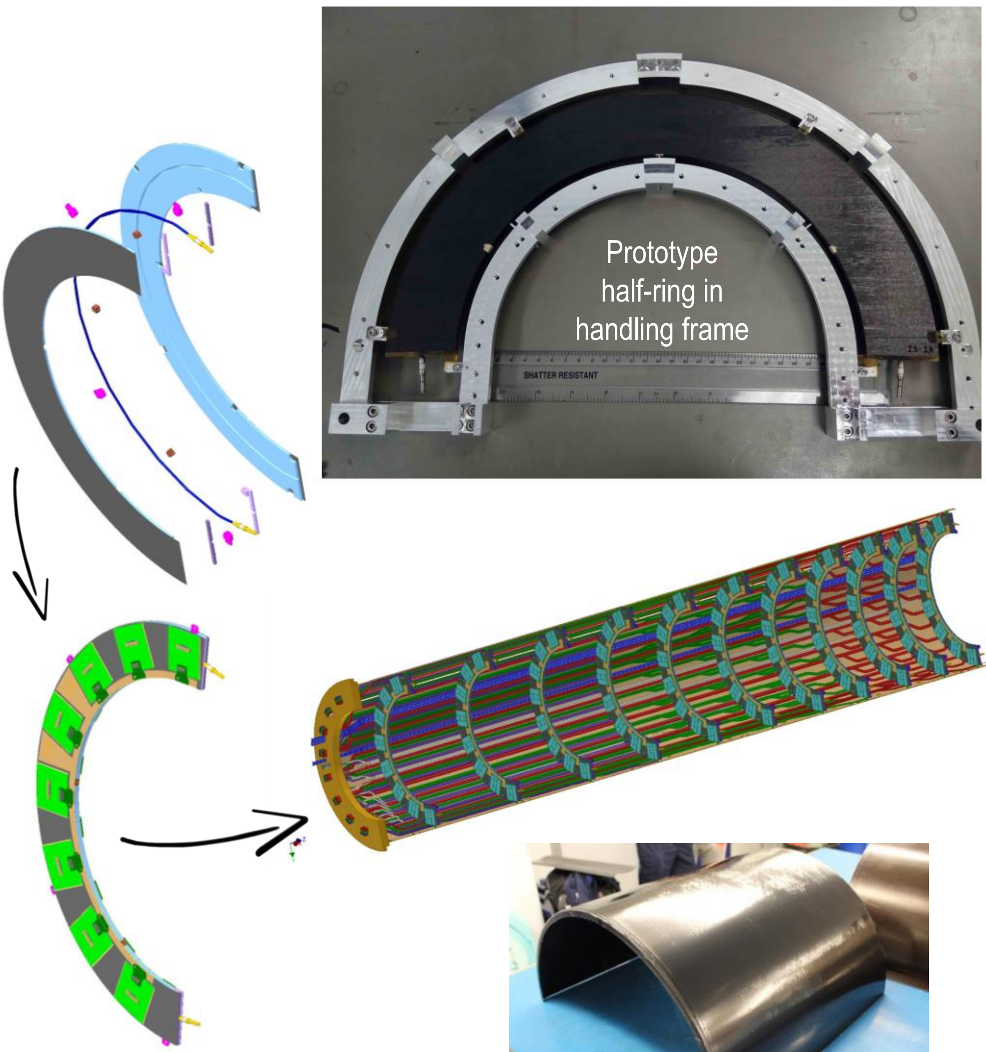
- In the central (low-η) region modules are "flat", on lightweight open structures called "longerons" Adjacent rows of modules overlap in ϕ
- In the mid-η region, inclined-module layout keeps modules ~normal to high-p_t tracks
- Services (cooling and electrical) run along the longerons and the ring-support cylinder





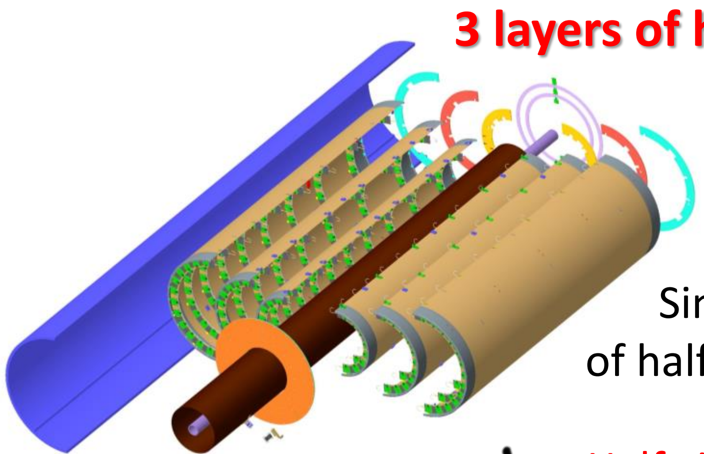


Outer Endcap Supports



Prototype half-cylinder

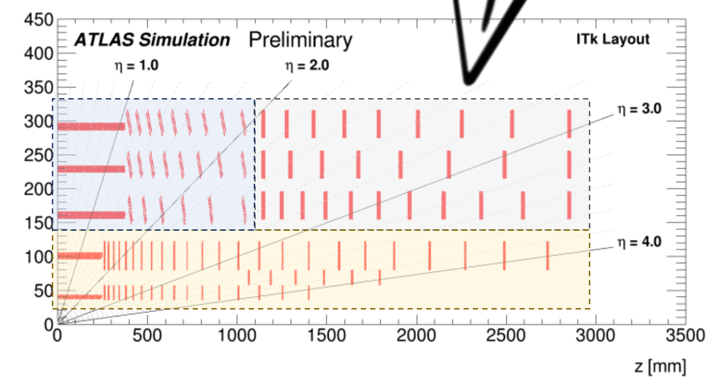
3 layers of half-rings loaded into half-cylinders



Single rows of modules on both sides of half-rings ⊥ to beampipe → Φ hermeticity

Half-rings are C-foam / C-fibre "sandwiches" with embedded cooling pipe and fixation lugs

Cooling feed, exhaust lines and electrical cables run between outer rims of rings and inner surface of cylinder

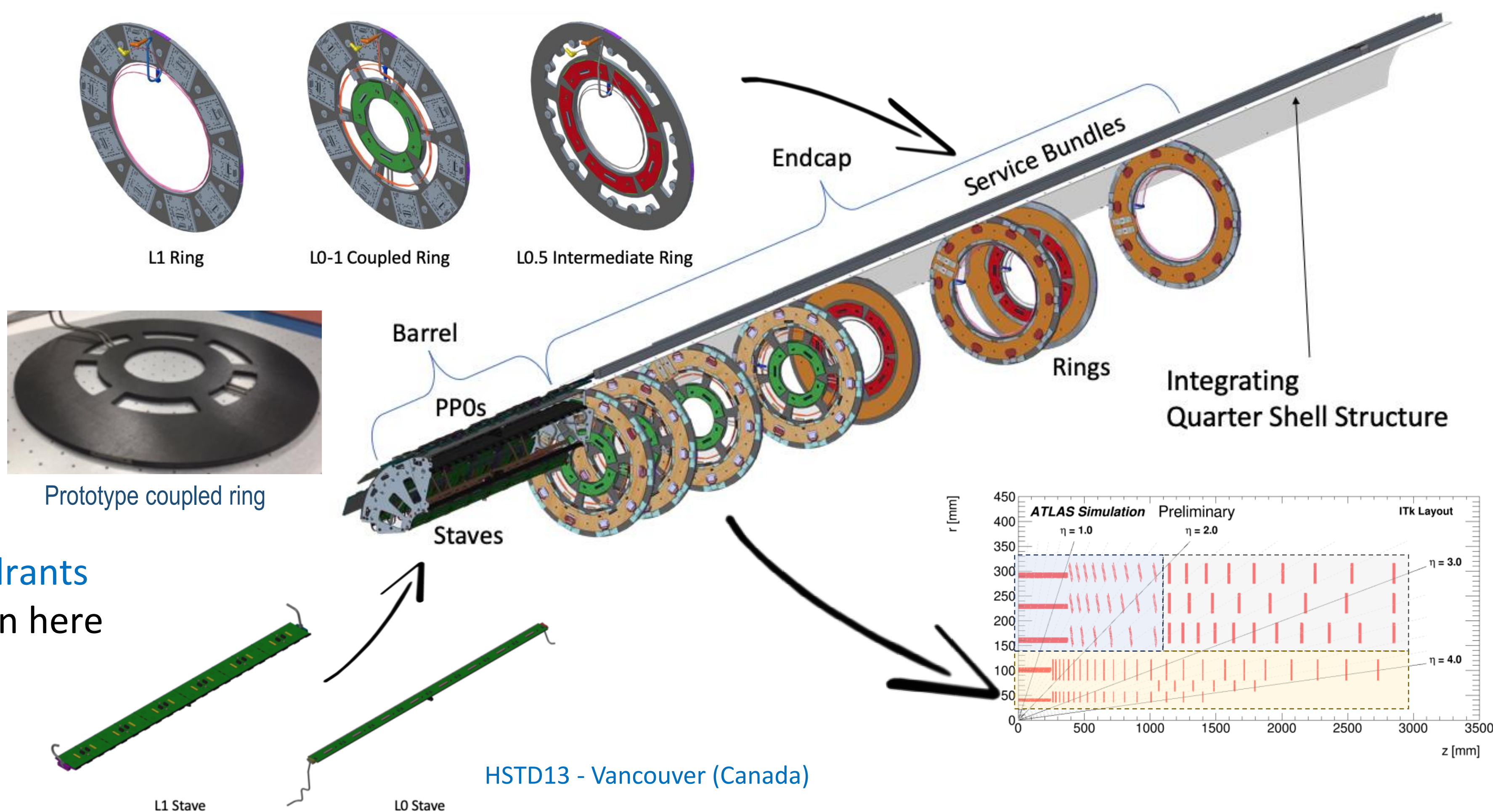


Rings are strategically placed in z to provide hermeticity in η

Inner System Supports

The inner system will be contained inside an Inner Support Tube and will be replaced once (at ~2000 fb^{-1})

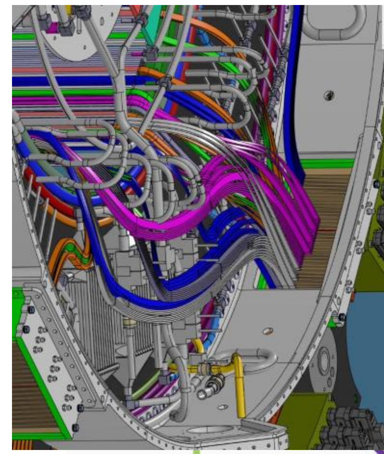
Short 2-layer flat barrel + long section of rings (3 types)
Cooling feed/exhaust and cables run along the quarter shell

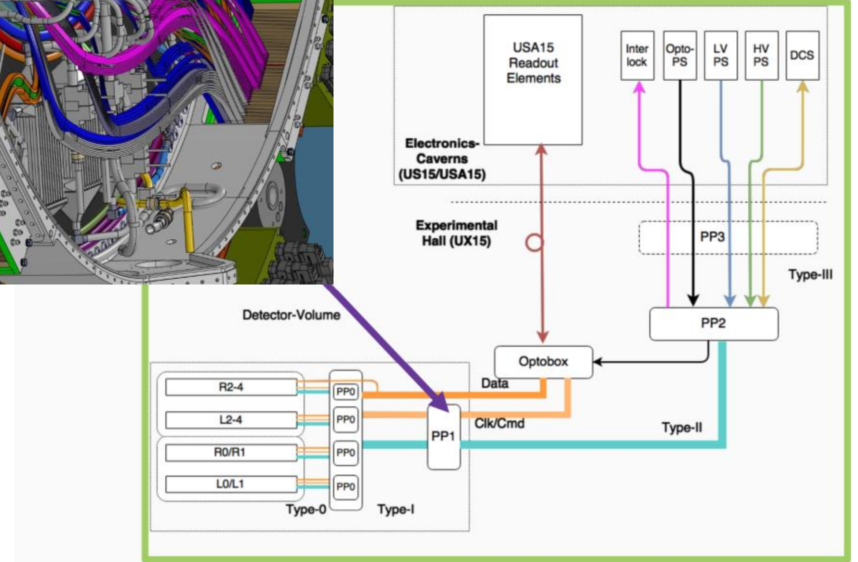


Prototype coupled ring

Assembled in quadrants
one quadrant shown here

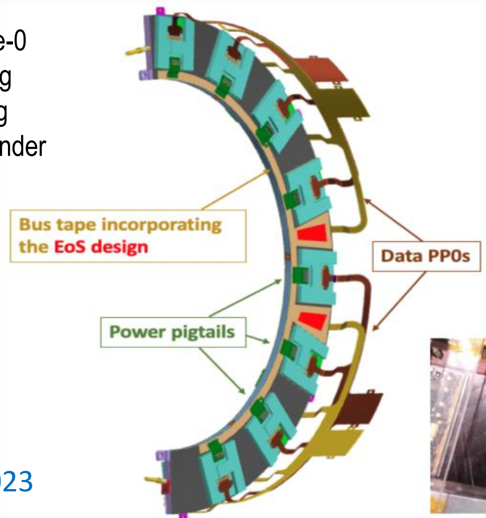
Electrical Services (power, data, monitoring)

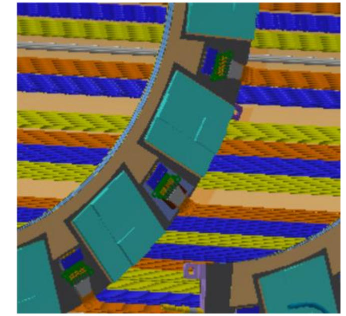


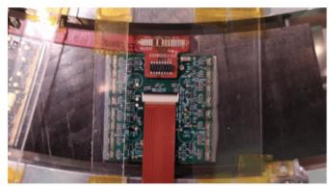


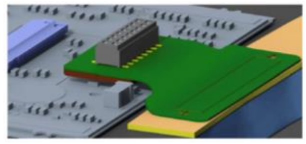
- Local supports hold “PP0s” with connections to modules
- “Type-I” cables carry services into / out of the detector
  - Twisted pairs for HV and monitoring/interlocks
  - Co-ax for LV
  - Data is on twin-ax cables inside the detector with electrical-to-optical conversion outside at “opto-boxes”
   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

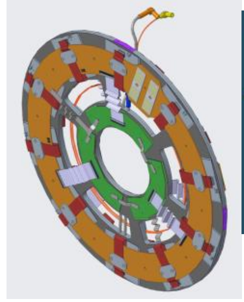
Outer-Endcap Type-0 are on the half-ring Type-1 runs along supporting cylinder under the half-rings

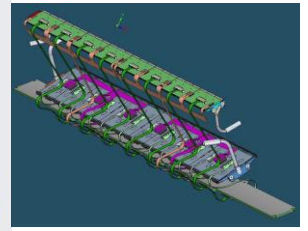




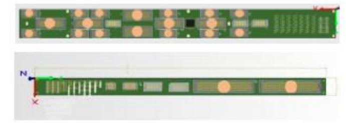




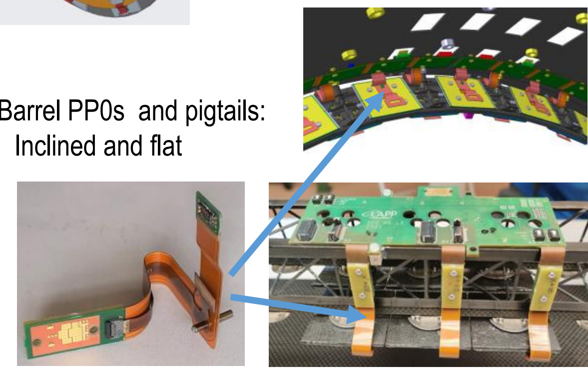


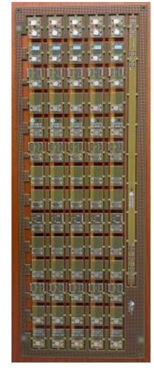


Inner System has a system of pieces to fit the varied geometries



Outer Barrel PP0s and pigtails: Inclined and flat





Data Transmission

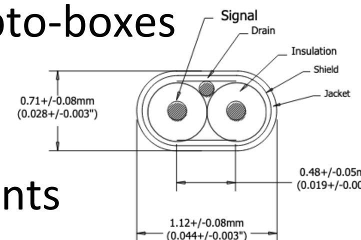
Twinax cables for high-speed data transmission from local supports to opto-boxes

- 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

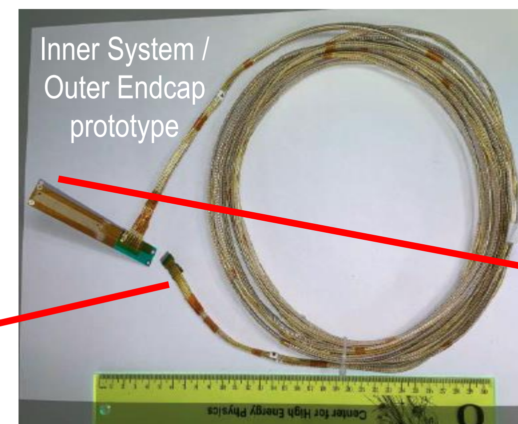
Cables can be ribbonized for easier handling

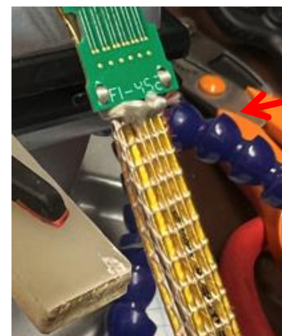
- Detector end termination
  - Via Samtec FireFly™ for outer system
  - Direct soldering to PP0 for inner system (not shown)
- Opto-box end termination: bespoke PCBs

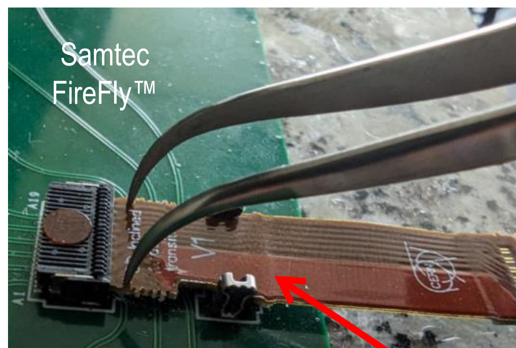
Qualified vendor for ribbonized & terminated cable: Tekdata (UK)

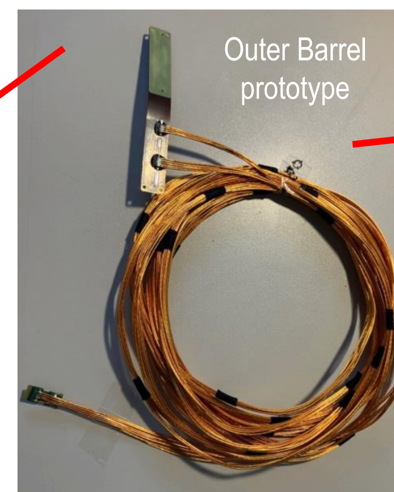


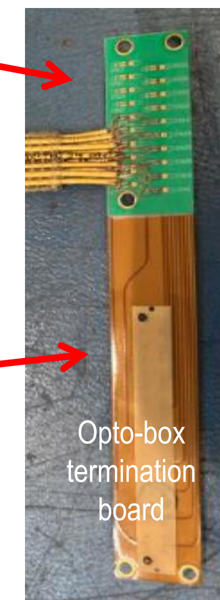
Twinax cross-section (Molex)



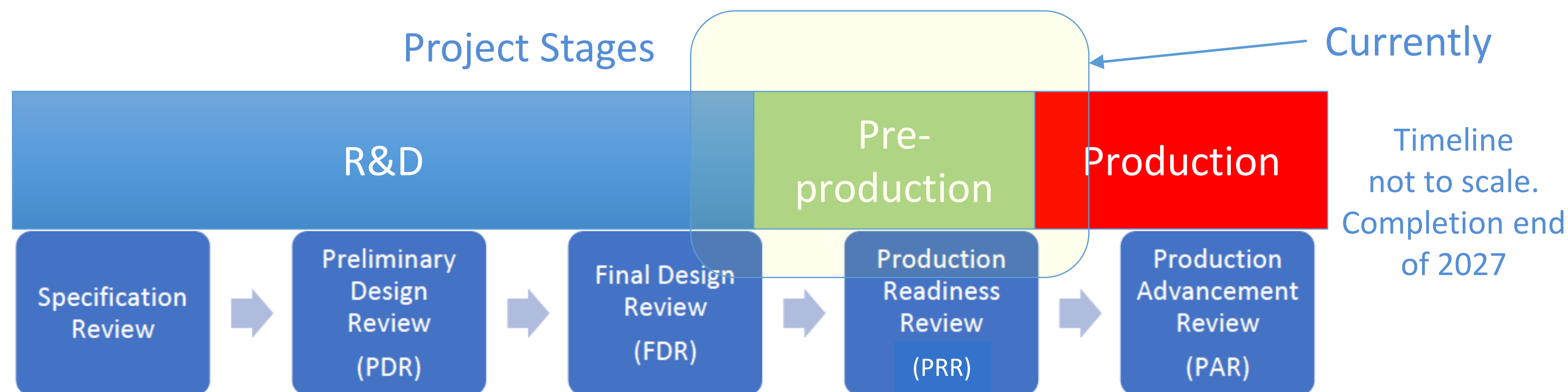








Current Status



Area	PDR	Prototyping	FDR	Preproduction	PRR	Production
Planar Si sensors	Complete	Complete	Complete	Complete	Complete	Ongoing
3D Si sensors	Complete	Complete	Complete	Complete	Complete	Ongoing
FE-ASIC	Complete	Complete	Complete	Complete	Complete	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

Legend: Complete / Ongoing / Upcoming

Tenders complete and contracts in place for major components

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

Major procurements in progress

- Data cables
- Type 1 power cables

Summary

ATLAS ITk

- 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