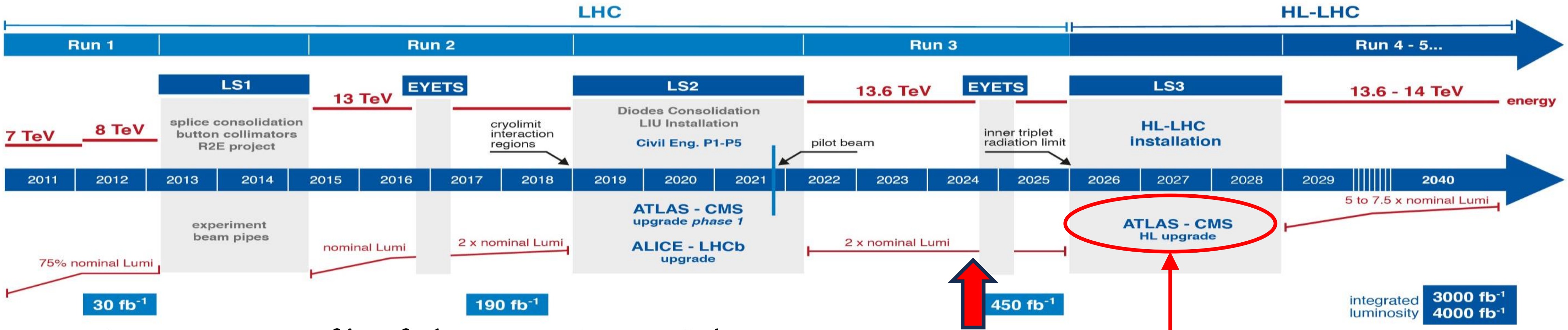
University of Glasgow | Department of Physics & Astronomy

ATLAS Inner Tracker (ITk) modules

Richard Bates

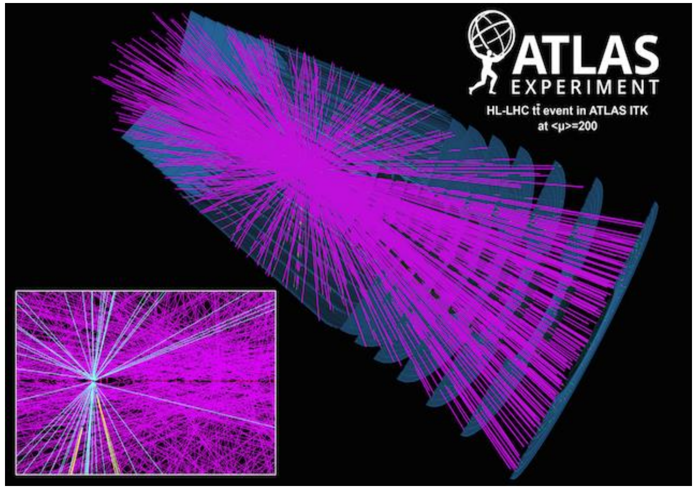
LHC timeline



Today

“Phase-II” upgrade of ATLAS in ~2027

- HL-LHC luminosity ~7x10^{34}cm^{-2}s^{-1} integrated ~3000fb^{-1}
  - ~3.5 times Run-3 peak luminosity
  - ~x5 times integrated luminosity at end of Run-3
- Increased luminosity → Increased pile-up:
  - Up to 200 pile-up events expected at the HL-LHC compared to ~48 in current Run-3 data
  - Increased pile-up compromises pattern recognition and requires higher granularity and higher readout rates
- Increased luminosity → Increased radiation damage
  - Damage scales approximately linearly with luminosity ~x10 increase

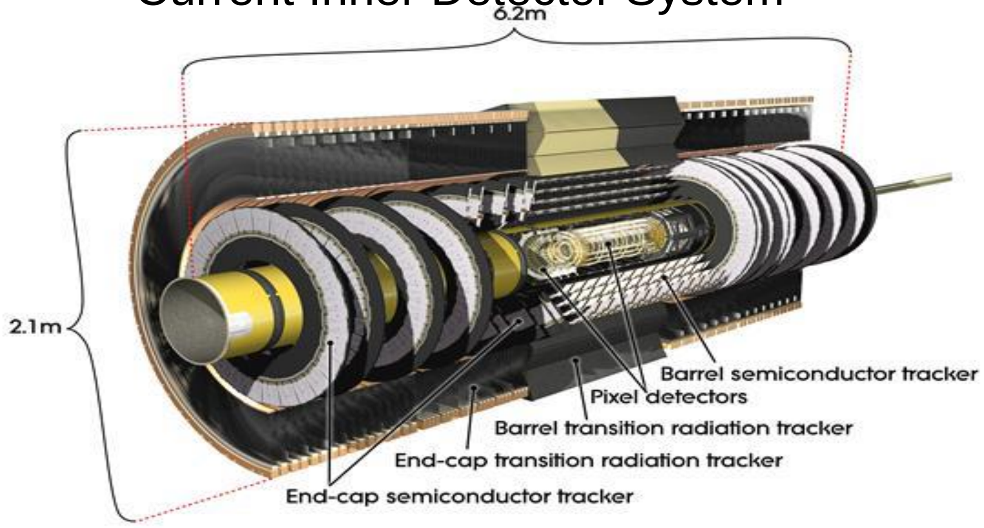


Simulated ttbar events with 200 pileup

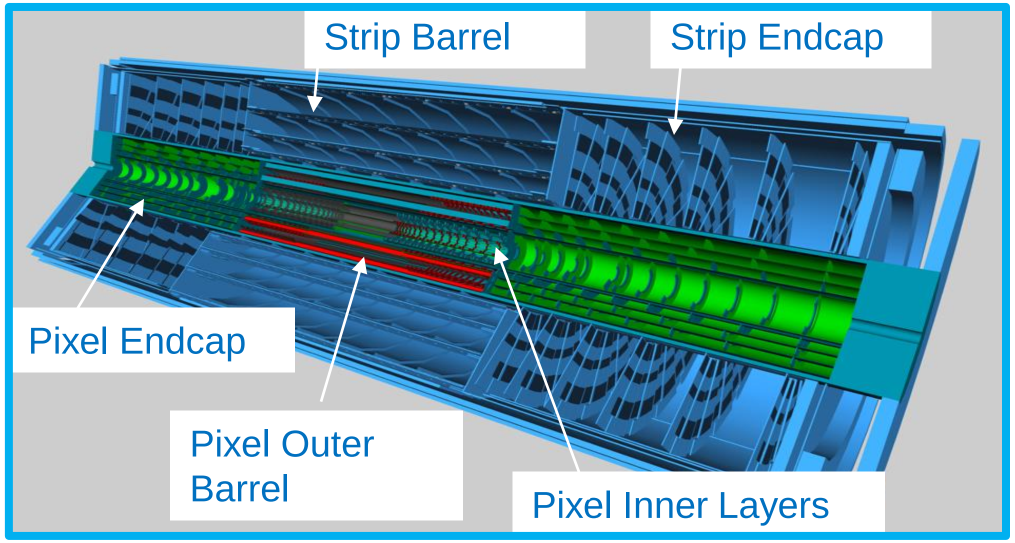
ATLAS public plot

ATLAS Inner Tracker (ITk)

Current Inner Detector System



Phase-II Inner Tracker (ITk)



The current inner detector system will be replaced with a new all-silicon tracking system -- ITk

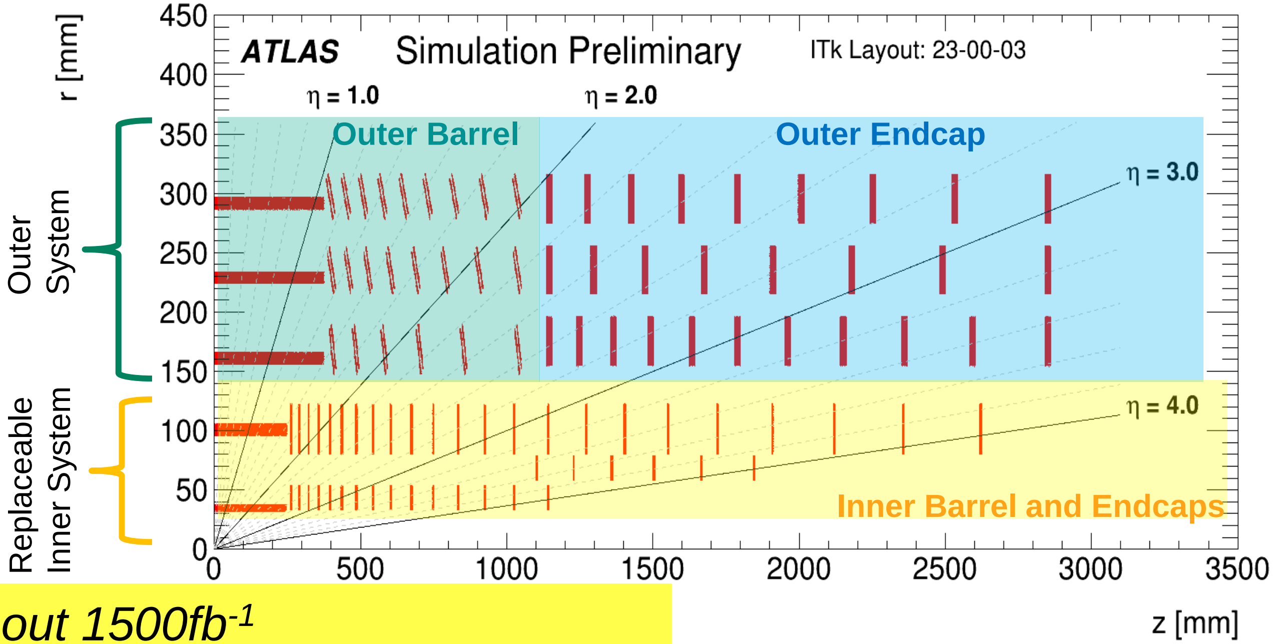
- New tracker
  - Targeting the same or better performance than current Inner Detector
  - Increased granularity to maintain occupancy <1%
  - Low mass mechanics, cooling and serial powering to minimize material
  - Increased radiation hardness

ITk Pixel detector layout

Outer Barrel:
3 layers of flat staves and inclined rings
Si n-in-p planar quad modules
4472 quad modules, 6.94m^2
2.3x10^{15}n/cm^{-2} 1.7MGy @4000fb^{-1}

Endcap:
3 layers of rings
Si n-in-p planar quad modules
2344 modules, 3.64m^2
3.1x10^{15}n/cm^{-2} 3.5MGy @4000fb^{-1}

- 5 layers of pixel detectors
- Layers 0-1 : Inner System (IS)
- Layers 2-4: Outer System (OS)
    - Outer Barrel (OB)
    - Endcaps (EC)



Current pixel system
~92M pixels
~2000 modules
~1.9m^2 active area

ITk Pixel System
~5G pixels
~9,400 modules
~13m^2 active area

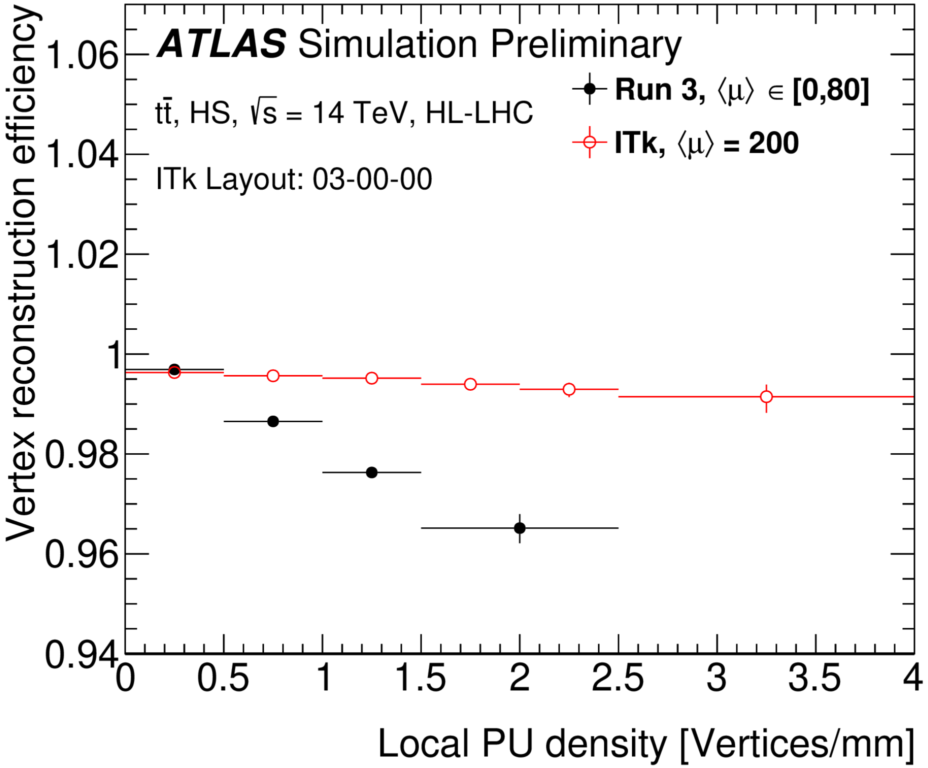
Inner System *Replaced after about 1500fb^{-1}*
2 layers of flat staves and rings
L0: 396 3D Si triplet modules and 1160 L1: n-in-p planar quad modules, 2.4m^2
9.2x10^{15}ncm^{-2} 7.3MGy @2000fb^{-1}

Layout described in
ATL-PHYS-PUB-2021-024

Simulation studies of performance

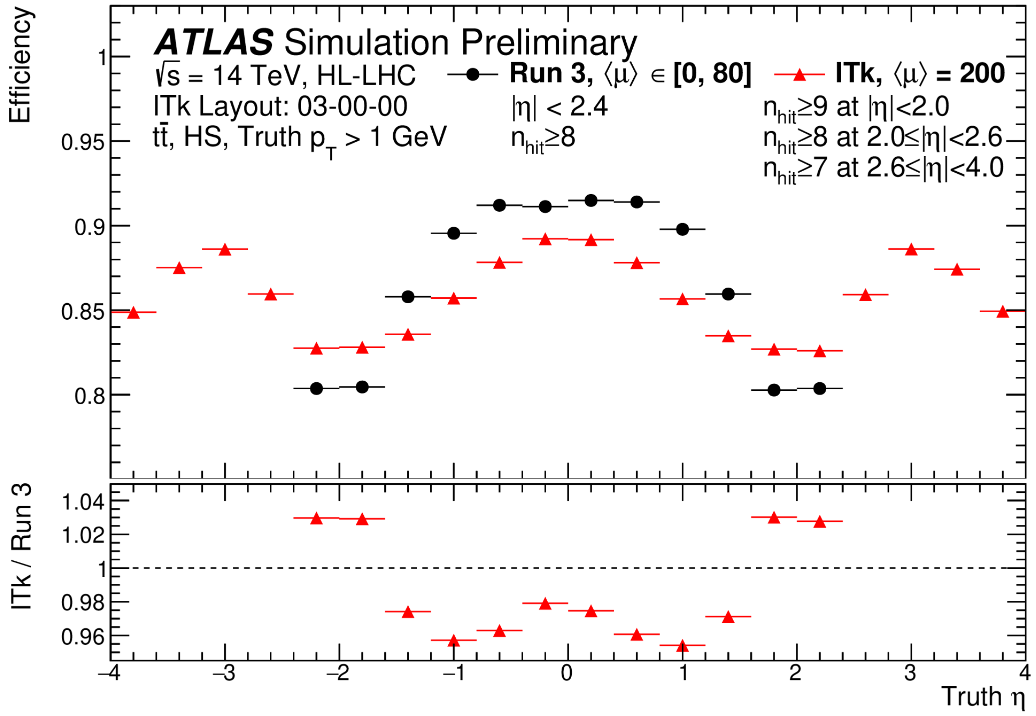
Aim for a performance as good as or better than the current inner tracker

IDTR-2023-05



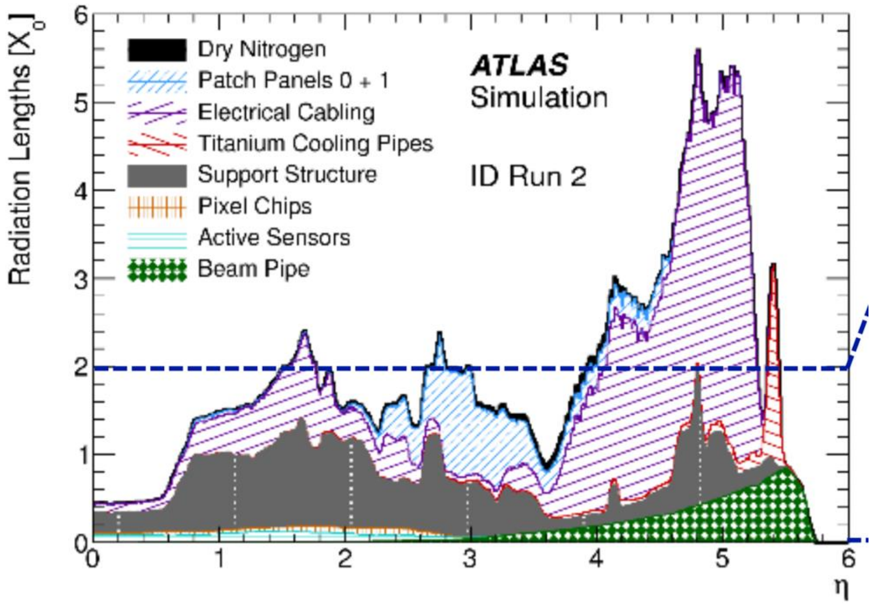
Vertex reconstruction efficiency vs pileup density

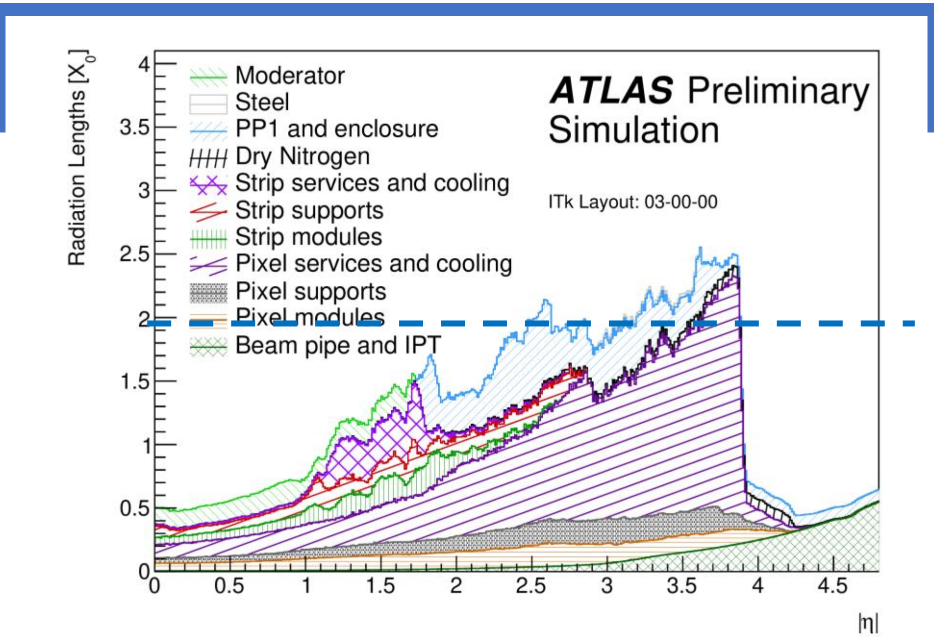
IDTR-2023-05



Track efficiency in ttbar events

Material

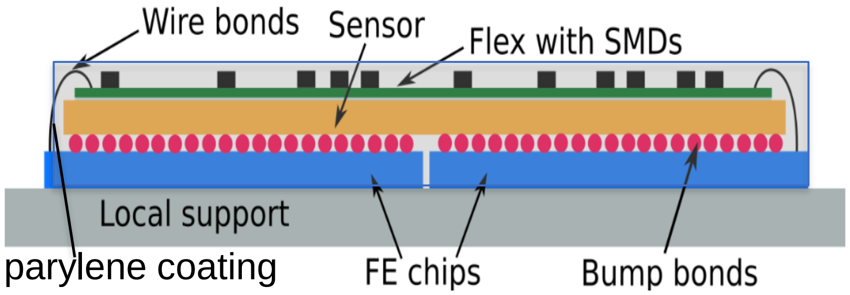




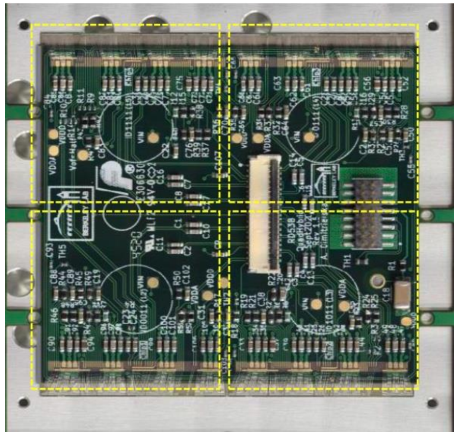
ITK-2023-001

- Material impacts tracking, radiation levels, data rates and downstream detectors such as the calorimeter.
- It is important to minimize the material.
- Reduce material using
  - CO_2 cooling with thin titanium pipes
  - Modules with thin Si sensors (100-150μm) and FE-chips (150μm)
  - Serial powering of pixel modules to reduce cabling
  - Low-mass carbon structures for mechanical stability and mounting
  - Optimize number of readout cables using data link sharing

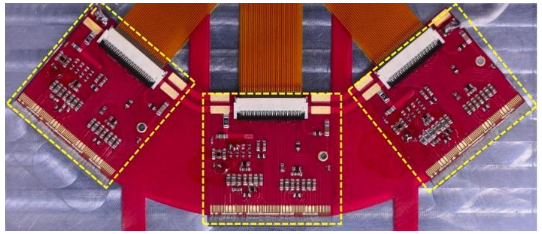
Modules



- 1 or 4 FE chips bump-bonded to sensor
  - Quad modules: 4 FE-chips bonded to 1 sensor
  - Triplet module: 1 FE-chip bonded to 1 sensor
- Cu-Kapton flex hybrid glued to sensor
  - Flex provides connections for power, DCS and data
- Mix of materials with different coefficients of thermal expansion make the module design challenging
  - Modules assembled at. +20°C, but lowest module temperature can be -45°C in the experiments
  - Difference in CTE between Cu and Si leads to thermal stress on the bumps
  - Amount of Cu needs to be carefully balanced between low power requirements and thermal stress on the bumps
  - Qualify bump-strength of solder-based bumps after 100 thermal cycles (-55°C +60°C) for different vendors
  - Good results from qualification, being followed up in the pre-production
  - Indium bumps needs further evaluation



Quad module



Triplet module

Module Flavors: Quads

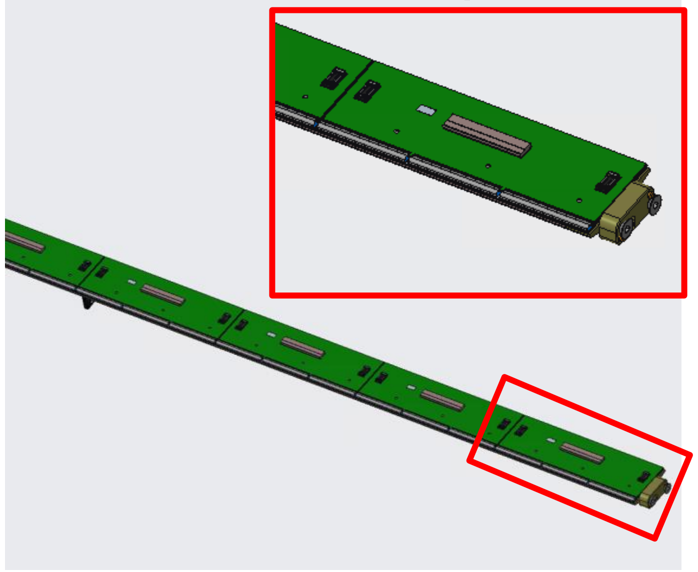
- Quad modules on L1-4
  - L1: 100 um thick sensor
  - L2-4 150 um thick sensor
    - EC modules
    - OB modules with wire bond protection canopy

Slightly smaller in x & y for the L1 modules

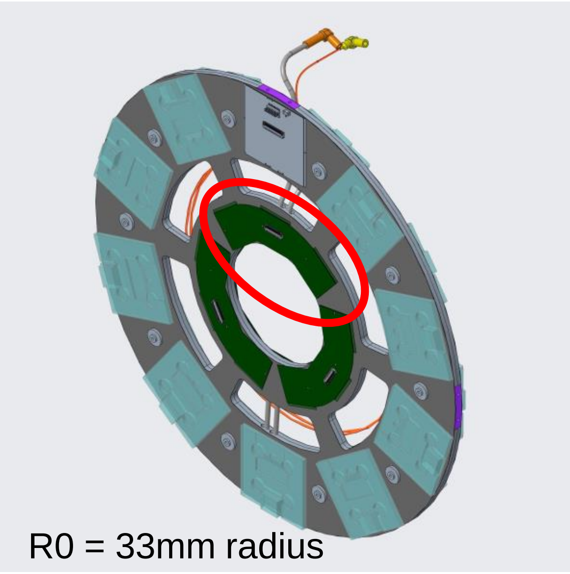
Module Flavors: IS

- Pseudo-triplet modules for L0
  - 3 single bare modules glued to triplet hybrid

Linear Triplet:
12 L0 staves x8 triplets = 96

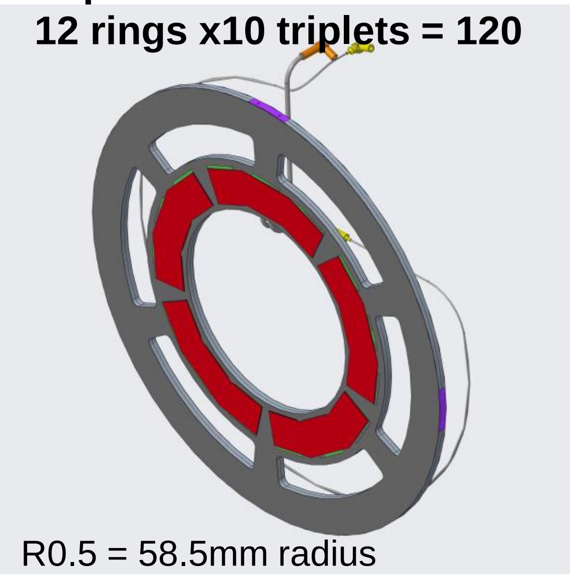


R0 Coupled-ring Triplet:
30 rings x6 triplets = 180



R0 = 33mm radius

R0.5 Intermediate-ring
Triplet:
12 rings x10 triplets = 120



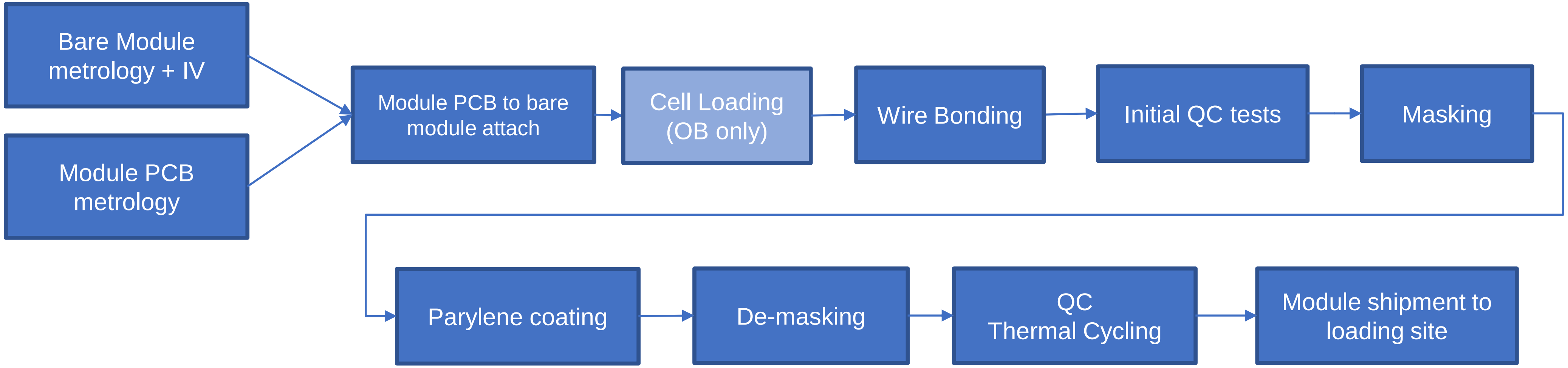
R0.5 = 58.5mm radius

Module Production Numbers

Item	Pre-production	Production	Installed	Yield factor
Module hybrids	**839**	**12370**	**8372**	
L0 – Stave	10	141	96	1.46
L0 – Coupled Rings	18	264	180	1.46
L0 – Endcap Rings	12	176	120	1.46
Common Quad Hybrids	799	11789	7976	1.48
Assembled Modules	**849**	**12011**	**8372**	
L0 – Stave	10	141	96	1.47
L0 – Coupled Rings	18	264	180	1.47
L0 – Endcap Rings	12	176	120	1.47
L1 Quad	120	1690	1160	1.46
L2-L4	683	9740	6816	1.43

Yields from MoU/BoE document and may change

Overview



Bare Module metrology + IV

Module PCB metrology

Module PCB to bare module attach

Cell Loading (OB only)

Wire Bonding

Initial QC tests

Masking

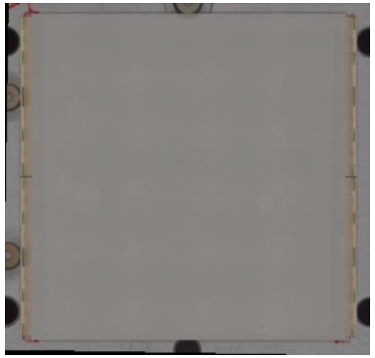
Parylene coating

De-masking

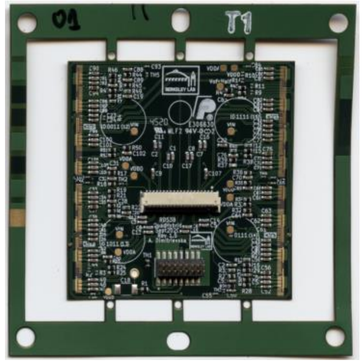
QC Thermal Cycling

Module shipment to loading site

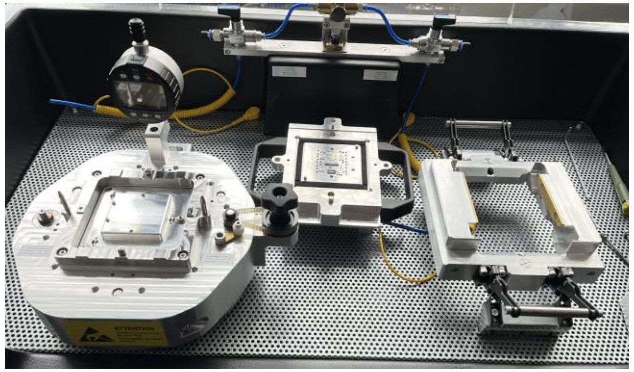
Bare Module



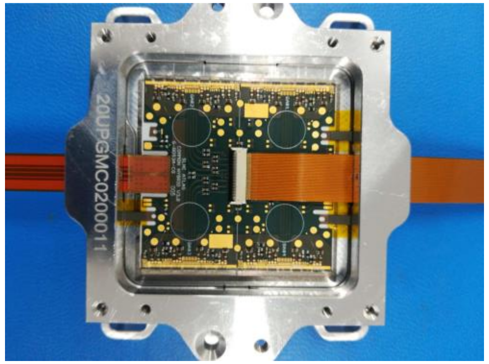
Quad Hybrid



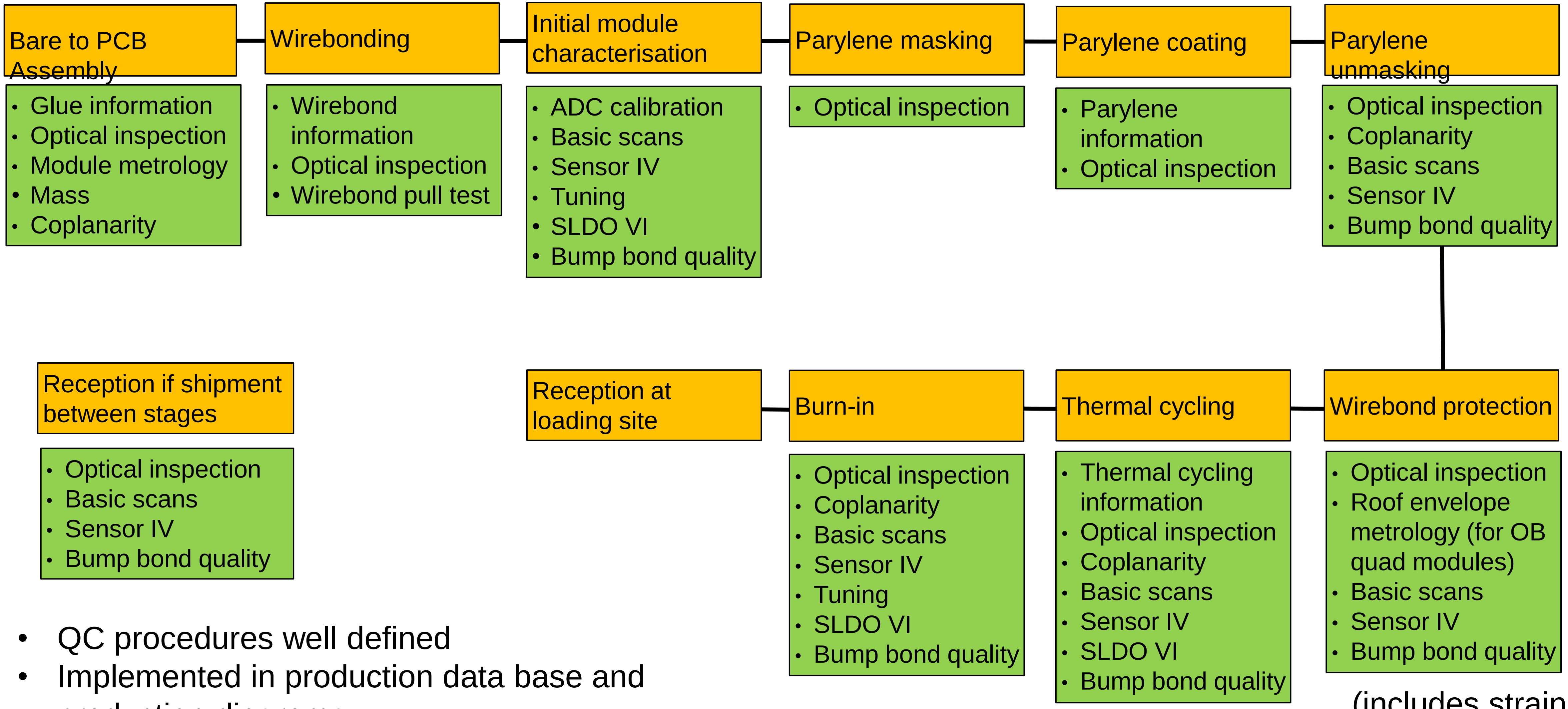
Assembly



Testing



Quality Control



Bare to PCB Assembly
- Glue information
- Optical inspection
- Module metrology
- Mass
- Coplanarity

Wirebonding
- Wirebond information
- Optical inspection
- Wirebond pull test

Initial module characterisation
- ADC calibration
- Basic scans
- Sensor IV
- Tuning
- SLDO VI
- Bump bond quality

Parylene masking
- Optical inspection

Parylene coating
- Parylene information
- Optical inspection

Parylene unmasking
- Optical inspection
- Coplanarity
- Basic scans
- Sensor IV
- Bump bond quality

Wirebond protection
- Optical inspection
- Roof envelope metrology (for OB quad modules)
- Basic scans
- Sensor IV
- Bump bond quality

(includes strain relief)

Thermal cycling
- Thermal cycling information
- Optical inspection
- Coplanarity
- Basic scans
- Sensor IV
- SLDO VI
- Bump bond quality

Burn-in
- Optical inspection
- Coplanarity
- Basic scans
- Sensor IV
- Tuning
- SLDO VI
- Bump bond quality

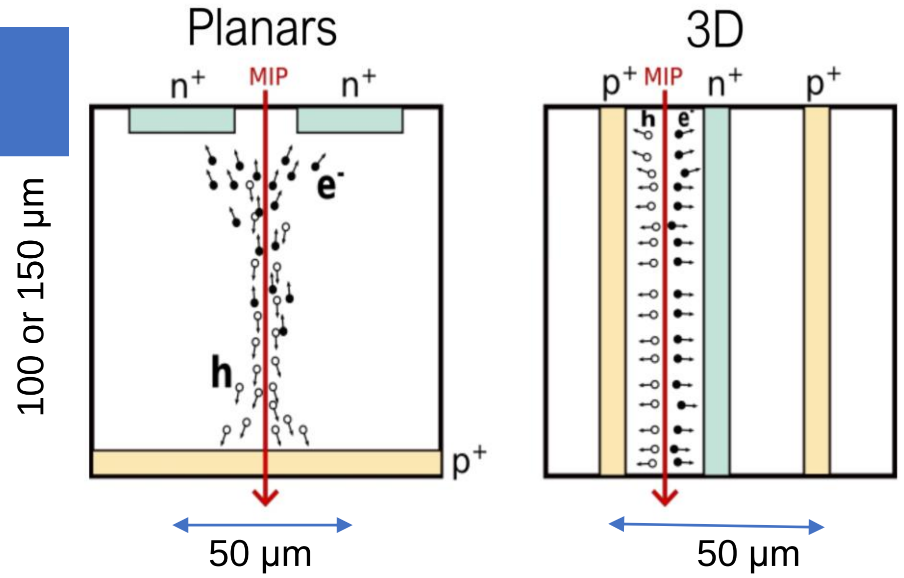
Reception at loading site

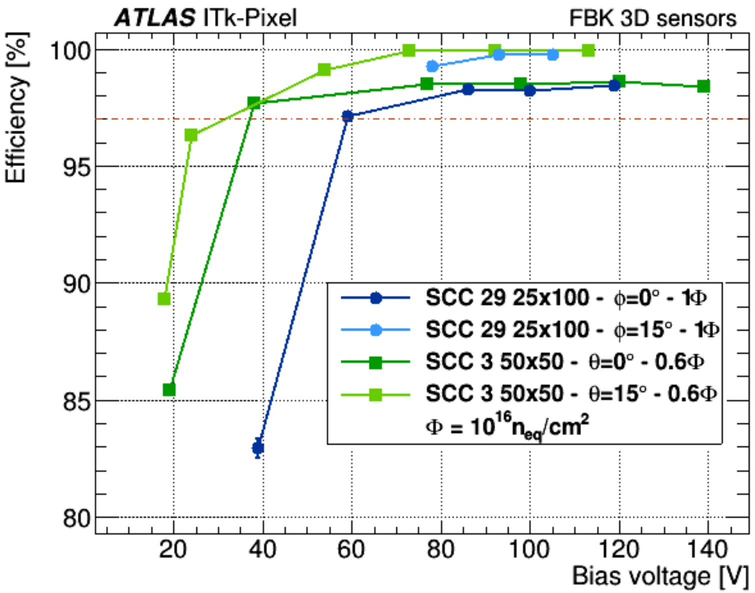
Reception if shipment between stages
- Optical inspection
- Basic scans
- Sensor IV
- Bump bond quality

- QC procedures well defined
- Implemented in production data base and production diagrams

Sensors

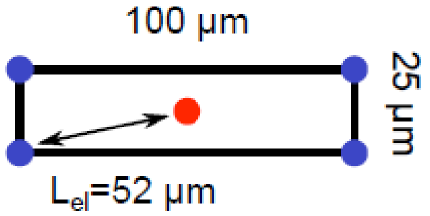
- Improve radiation hardness by:
  - Using thin planar sensor 100+150µm thickness
  - Use 3D sensors in inner layer



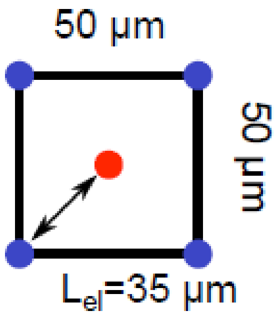


Irradiated 3D 25x100mm^2 & 50x50µm^2 module with ITkPixV1.1 readout irradiated to 1x10^{16}n$_{eq}$cm^{-2}

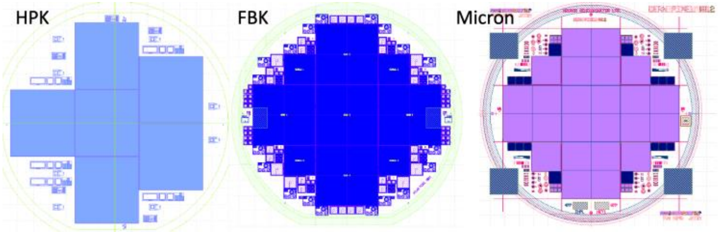
25×100 µm^2, 1E



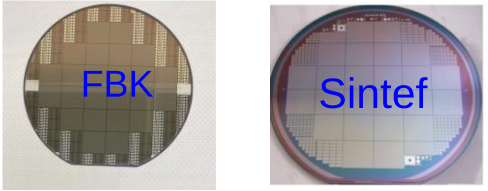
50×50 µm^2, 1E



Planar silicon



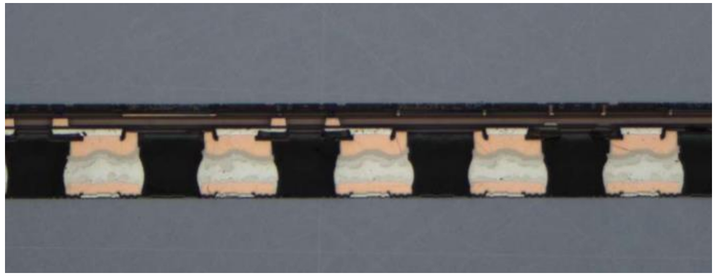
3D sensors



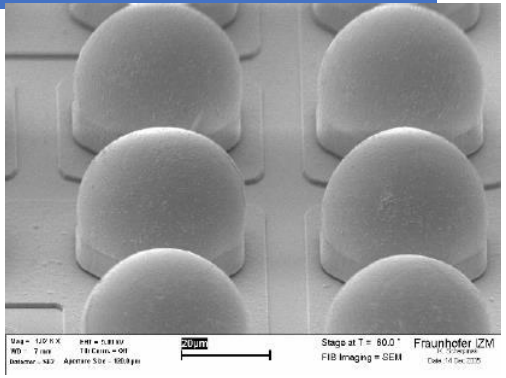
Planar preproduction complete and 3D close to completion

Hybridization

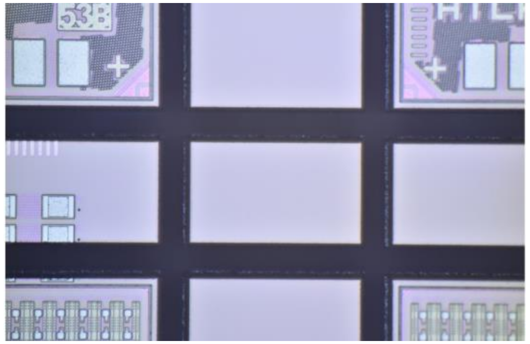
- Number of modules requires 4 hybridization vendors to meet the needed capacity
- Technical issues
  - Dicing of FE-chips can lead to chipping and debris
  - flip-chip of multiple FE-chips to a sensor has caused problems for some vendors
  - Handling the bow of sensors during flip-chip
- Currently, approximately 380 quad modules and 100 3D single modules delivered for technical evaluation and module pre-production



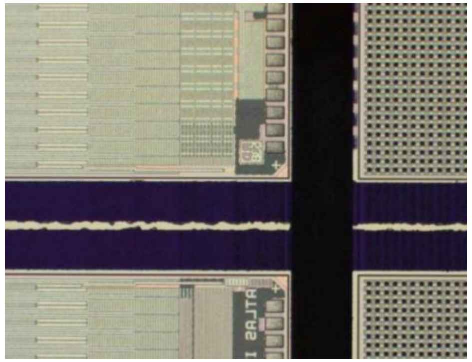
Cross-section of sensor & FE-chip connection



Solder bumps



laser pre-grooving and dicing

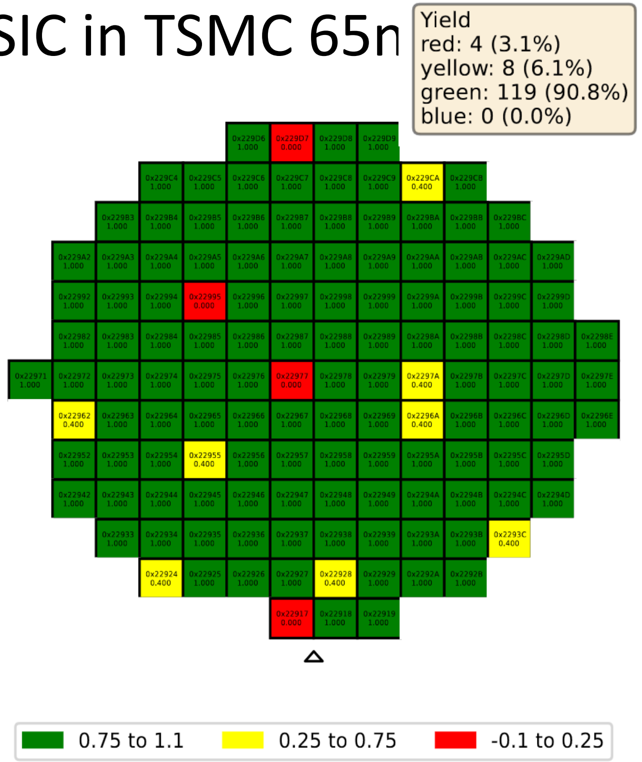


blade dicing

FE-chip: ITkPixV2

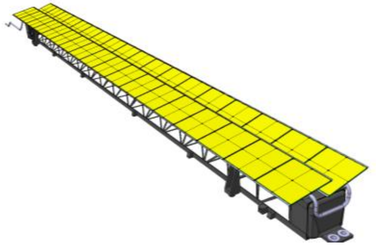
- RD53 Collaboration: joint R&D for ATLAS and CMS ASIC in TSMC 65n
- Main features for ATLAS
  - 65nm technology, 152800 pixels per chip, 50x50 μm^2 pitch
  - Tracking in dense environments
    - Low threshold operation
    - Cluster charge readout using Time over Threshold
  - Radiation environment
    - Sensor leakage current compensation
    - SEE hardening
  - 1.28Gb/s data rates
    - 4 data links per chip at 1.28 Gb/s
    - data compression
  - Optimization of services
    - Merging of chip data in module
    - Integrated shuntLDO regulator for serial powering
- Final chip ITkPixV2 submitted March 2023
  - Wafer probing yield around 90% based on first 100 wafers

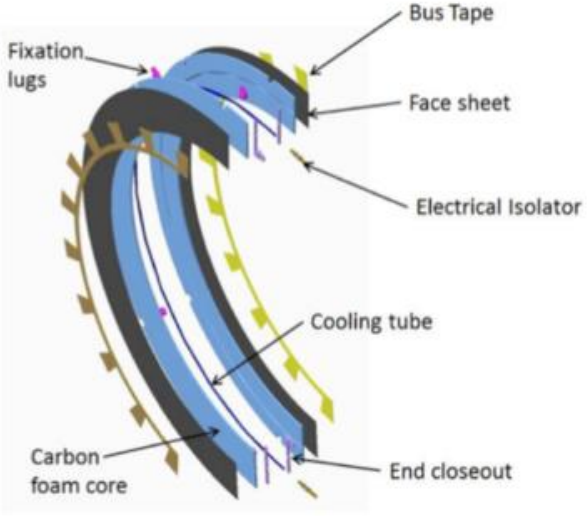
Wafer probing yield map

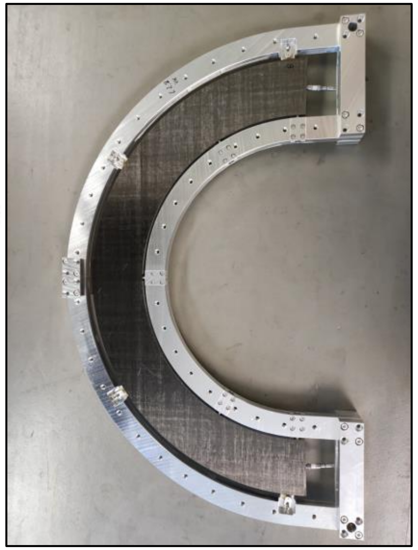


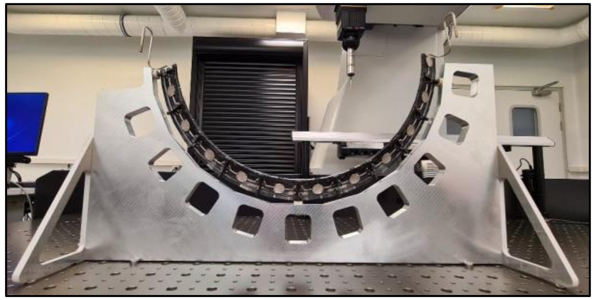
131 chips per wafer
Probing of full wafer takes about 24hrs
Yield map based on test of power, digital and analog functionality

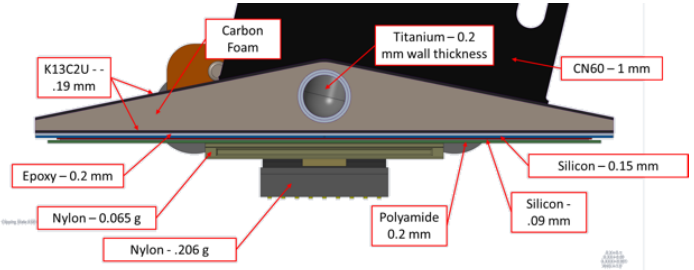
Local Supports

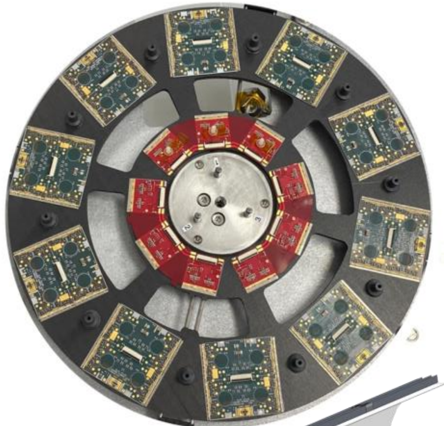




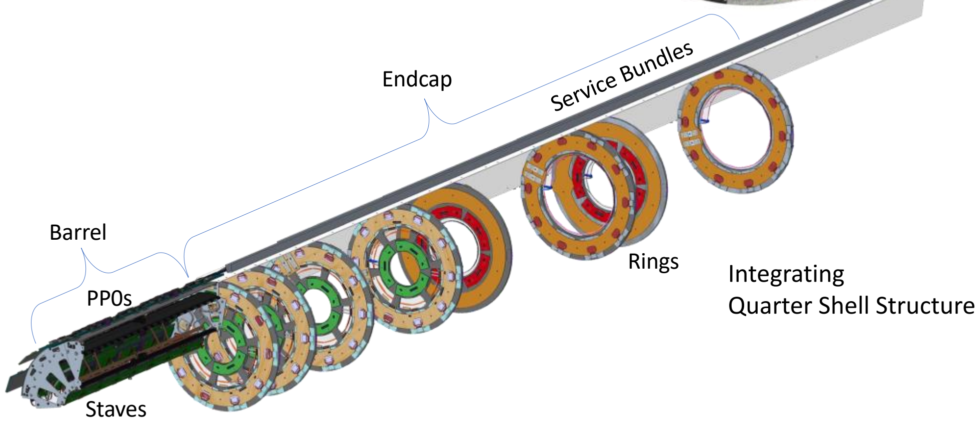








- Local supports provide stable low-mass supports for modules and services
- Critical element is interface between module and cooling pipes
- Production of parts underway



Loaded Local Supports and System test

- Outer barrel module loading and system tests
  - RD53 prototype modules loaded on to cells and thermally tested mounted onto local supoerts system test
  - Performance of modules monitored through the loading process
  - Work on system tests preproduction items in progress

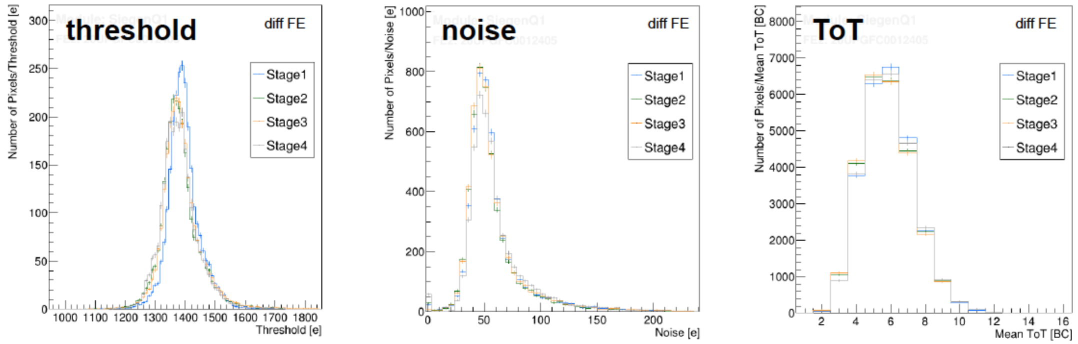
stage 1:
after module production

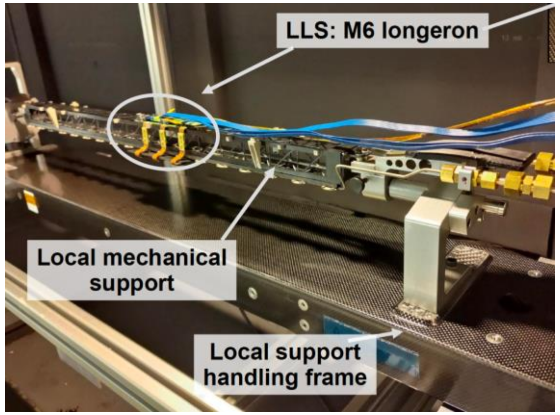
stage 2:
after cell loading

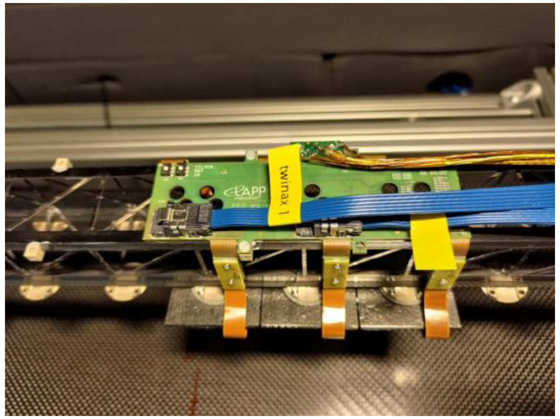
stage 3:
after pigtail assembly

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







Summary

- The ATLAS ITk Pixel detector has been designed to operate in the challenging HL-LHC environment and maintain the performance of the current tracking system
  - Increased radiation hardness
  - Maintain pixel hit occupancy at 1% by increasing granularity
  - Low mass achieved using carbon based mechanics, serial powering and data merging
- The project is now in pre-production
  - Large scale production brings a new set of problems as more sensitive to rare problems
- Moving from development of individual items system level tests
  - Loaded local support system tests are underway, excellent testbed for integration issues

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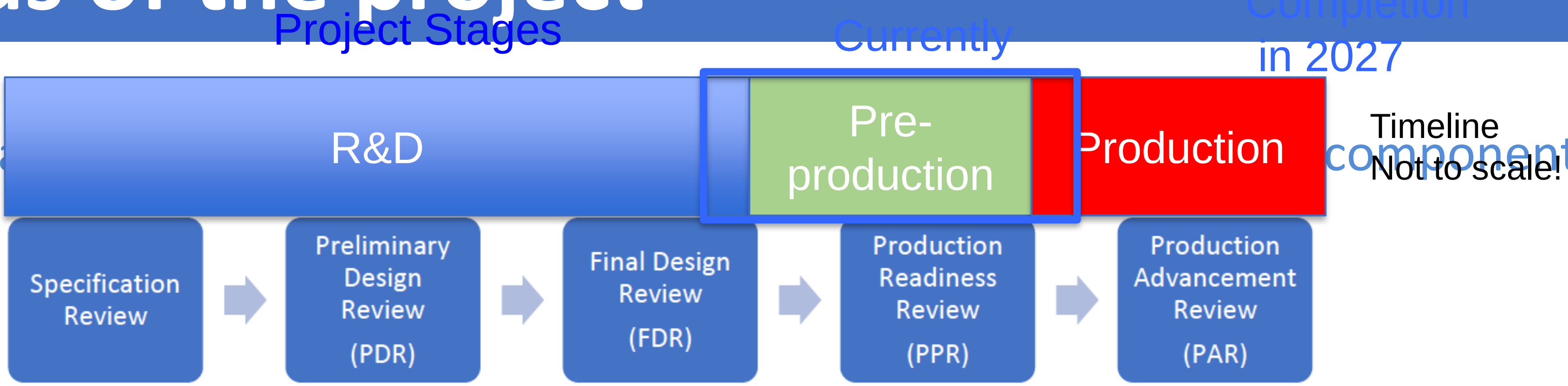
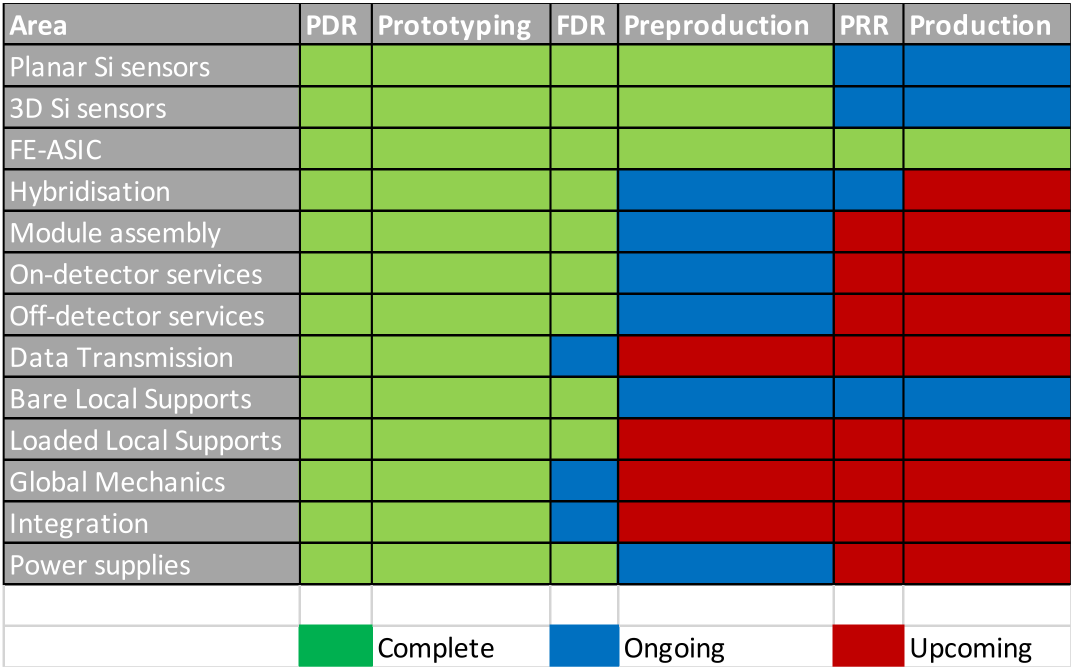
Thank you for your time

Status of the project

Tenders for ma components:

- Planar senso
- 3D sensors
- FE chips
- Module hybridisation
- Power supp





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

🟩 Complete 🟦 Ongoing 🟥 Upcoming