Status of the ATLAS ITk Pixel Project

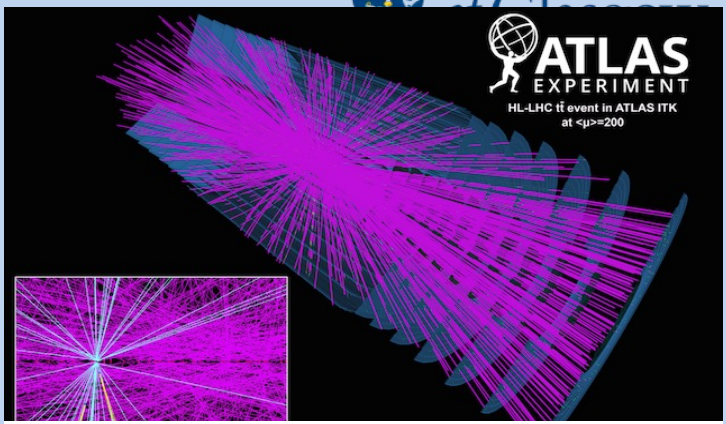
Craig Buttar
On behalf of the ATLAS ITk Pixel Collaboration

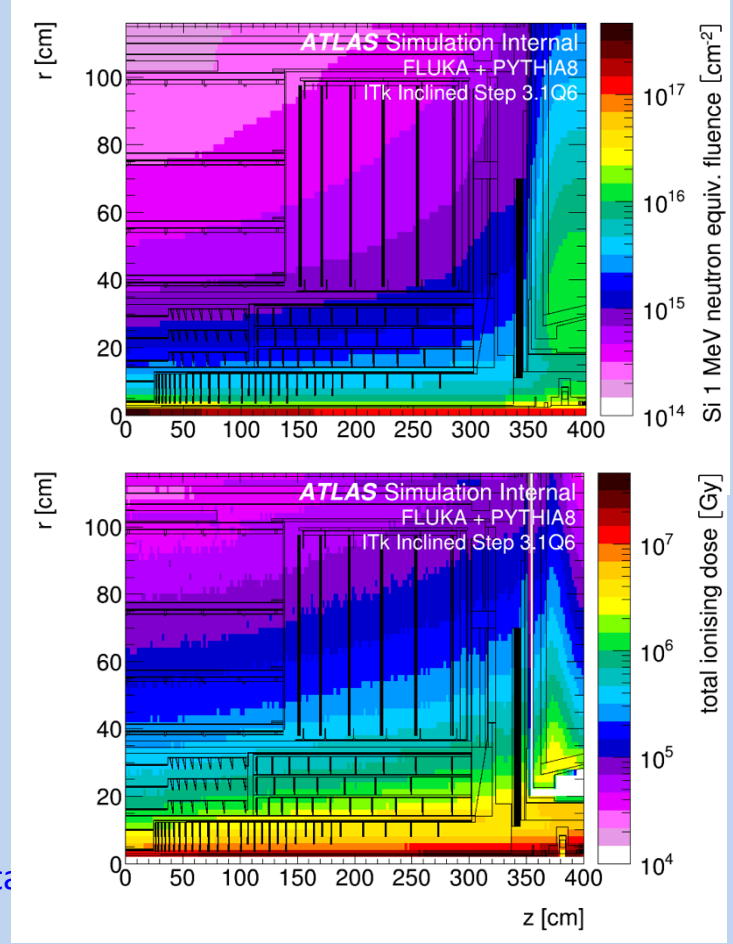
Pixel 2022

Santa Fe December 2022

Increasing LHC luminosity: What are the challenges?

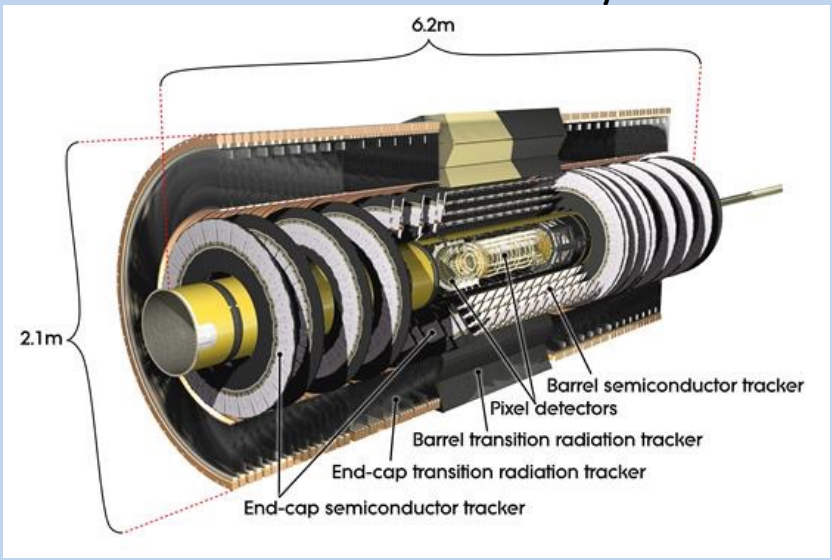
- HL-LHC luminosity ~$7x10^{34}cm^{-2}s^{-1}$
  - About x3.5 times Run-2 peak luminosity
- Increased luminosity → Increased pile-up:
  - Up to 200 pile-up events expected at the LH-LHC compared to ~34 in Run-II data
  - Increased pile-up compromises pattern recognition
  - Increased readout rates
- Increased luminosity → Increased radiation damage
  - Damage scales approximately linearly with luminosity ~x10 increase





ATLAS ITk

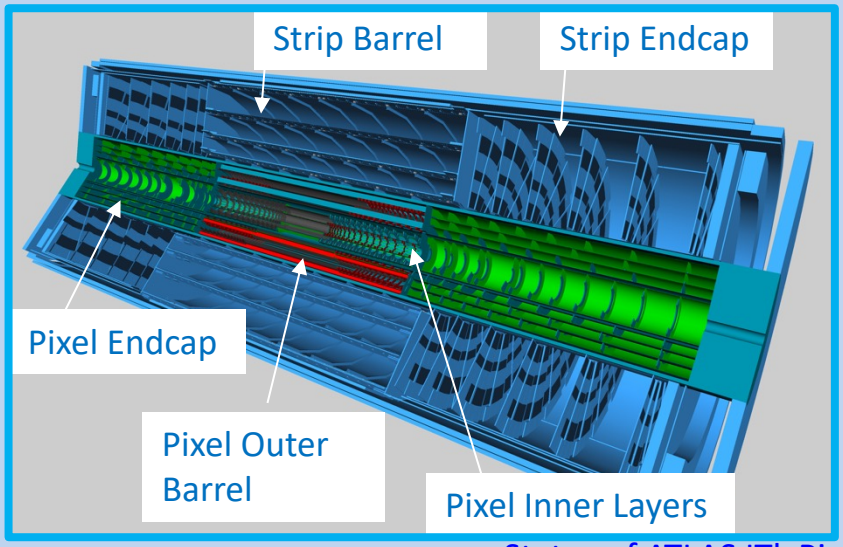
Current Inner Detector System



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

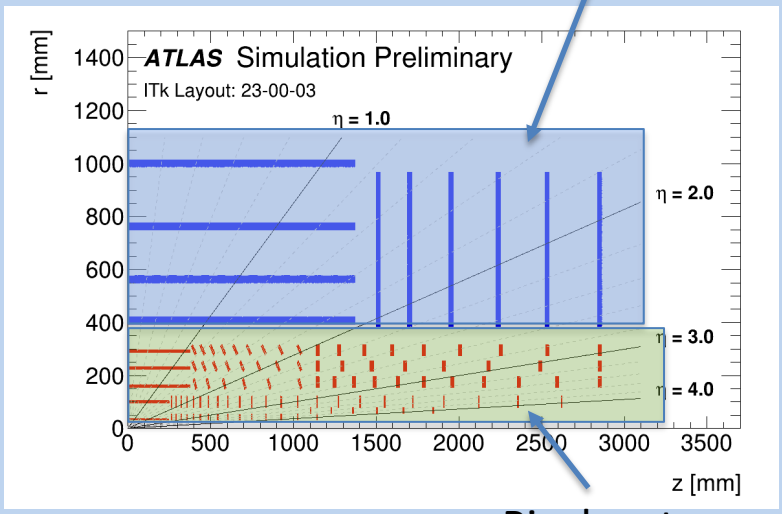
- New tracker
  - Targeting the same or better performance than current Inner Detector
  - Increased granularity to maintain occupancy <1%
  - Low mass mechanics, cooling and serial powering to minimize material
  - Increased radiation hardness

Phase-II Inner Tracker (ITk)



ATL-PHYS-PUB-2021-24

Strip system

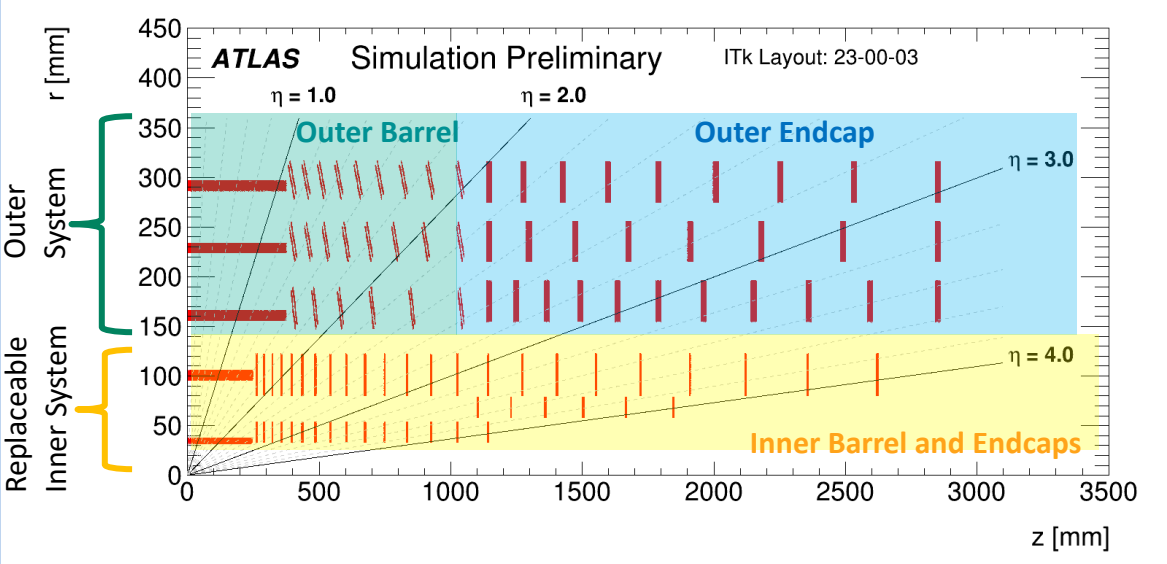


Pixel system

ITk Pixel detector layout

Outer Barrel:
3 layers of flat staves and inclined rings
n-in-p planar quad modules
4772 quad modules, 6.94m^2
2.3x10^{15}n/cm^{-2} 1.7MGy @4000fb^{-1}

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



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

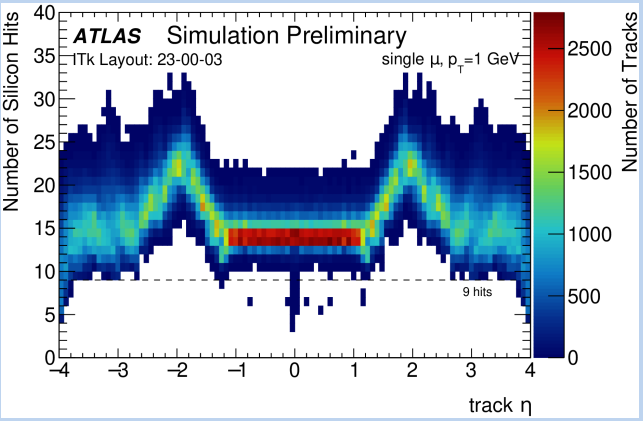
ITk Pixel System
~5G pixels
~9,400 modules
~13m^2 active area

Inner System *Replaceable*
2 layers of flat staves and rings
L0: 396 3D triplet modules and 1160 L1: n-in-p planar quad modules,
2600 modules, 2.4m^2
9.2x10^{15}ncm^{-2} 7.3MGy @2000fb^{-1} (Layer-0 radius=39mm → 34mm)

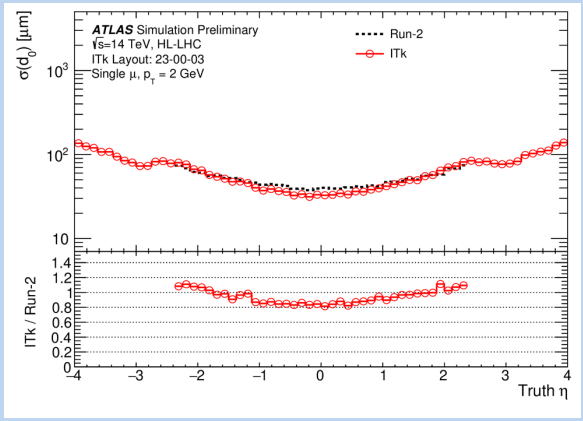
Layout and performance described in ATL-PHYS-PUB-2021-024

Performance

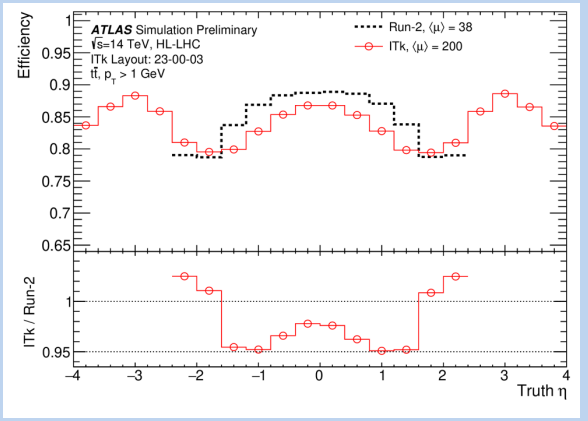
Strips & Pixels



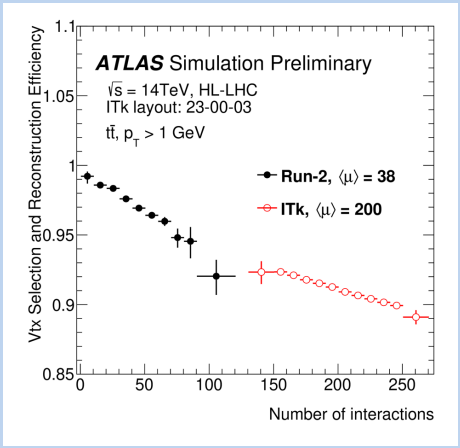
Hits vs eta, vertex reconstruction

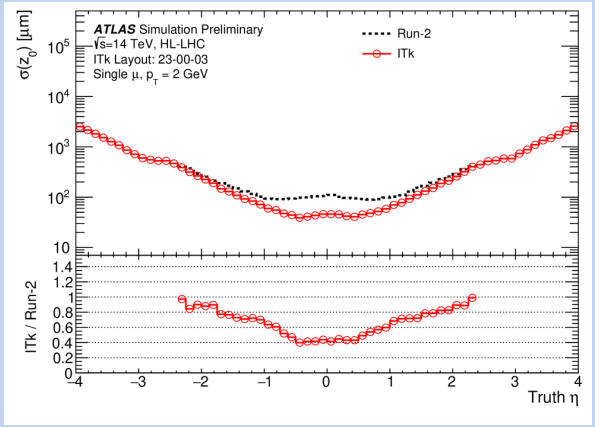


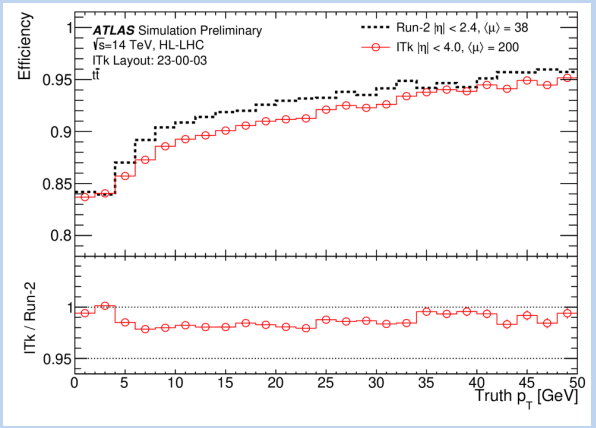
Track d0 and z0 resolution



Track efficiency in ttbar events





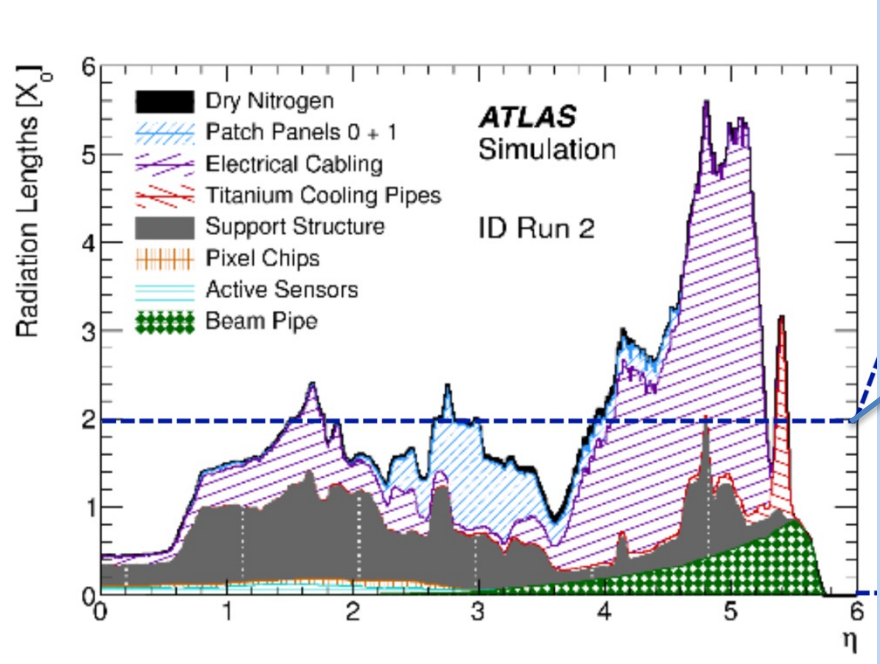


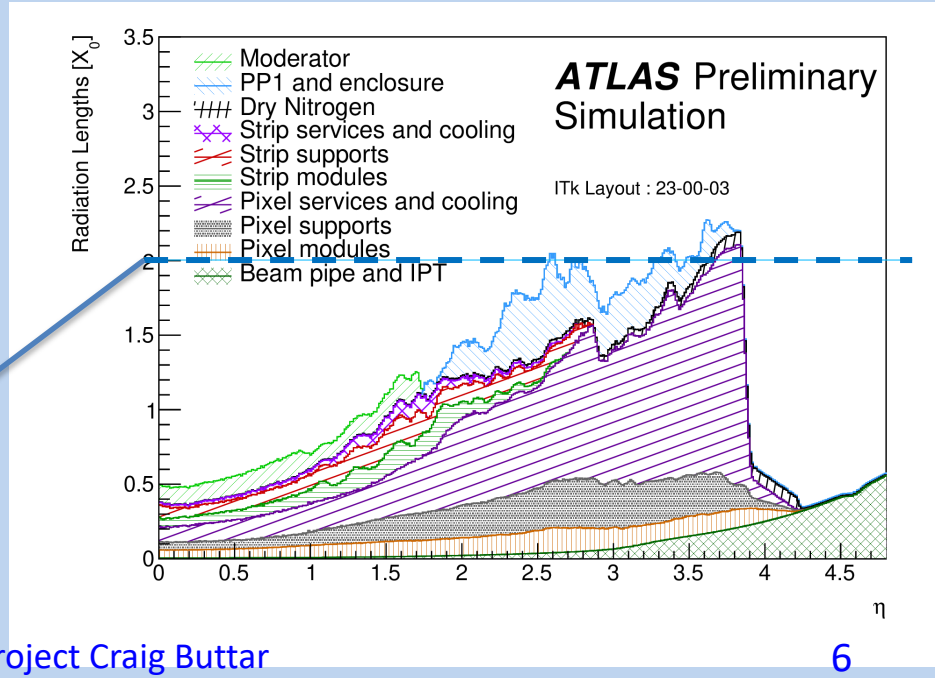
Layer 0 barrel sensors 25x100μm², Layer 0 ring sensors 50x50μm²
Layers 1,2,3,4 sensors 50x50μm²

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

Material

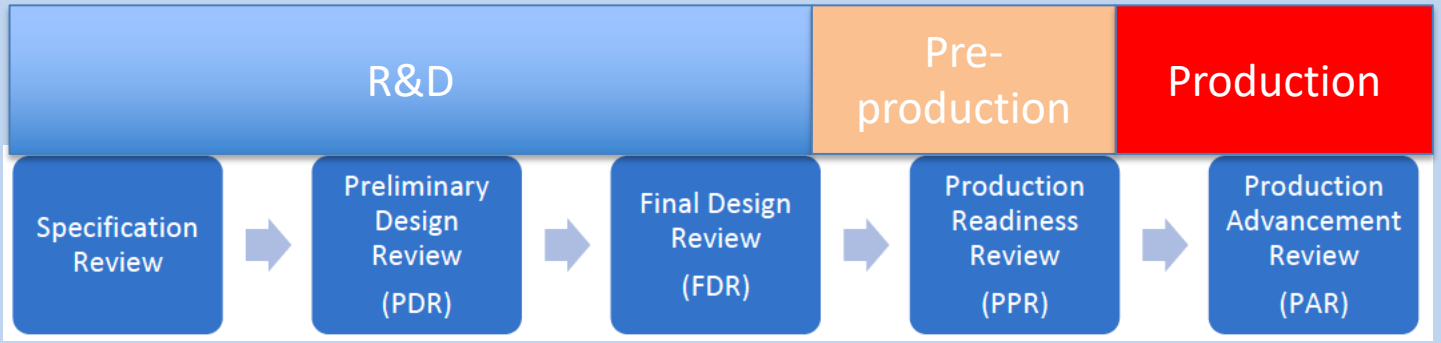
- Reduce material using
  - CO_2 cooling with thin titanium pipes
  - Minimise material in modules using thin Si and FE-chips
  - Advanced powering: serial powering for pixels
  - Low-mass carbon structures for mechanical stability and mounting
  - Optimise number of readout cables using data link sharing
- Material distribution required for performance and radiation level studies





Status of the project

Project Stages

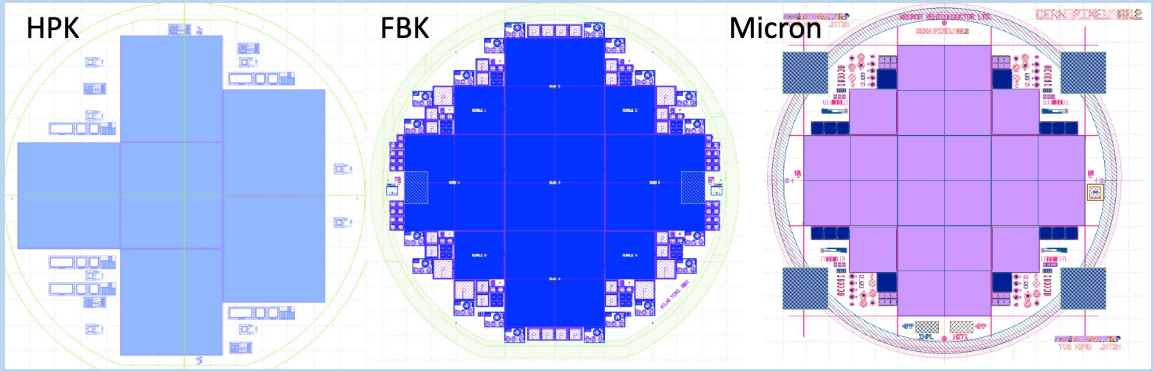


Timeline
Not to scale!

- Specification reviews and preliminary design reviews are complete
- Completing FDR phase
  - Services, Loaded Local Supports and Global Mechanics & Integration FDRs to be completed in the next months
  - ASIC FDRs MOPS (pixel monitoring chip) and GBCR (data transmission) FDRs will be completed in the next few months
- Pre-production Phase
  - Sensors have completed pre-production except for (25x100μm^2 CNM sensors)
  - Pre-production of hybridization has started with initial prototyping phase to verify designs
  - Pre-production of bare local supports is close to completion (early 2023)
- Production phase
  - FE-ASIC ITkPixV2 production will start with an engineering run in March 2023

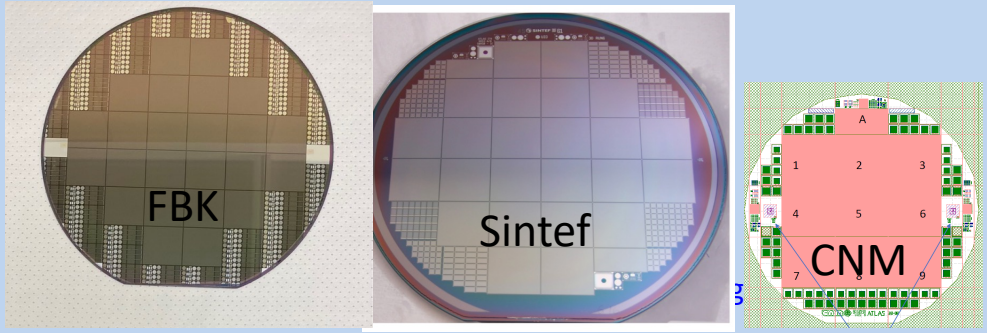
Sensors

- Sensor preproduction
  - Planar sensor preproduction complete about 800 quad sensors from HPK (150μm), Micron (100μm+150μm) and FBK (100μm)

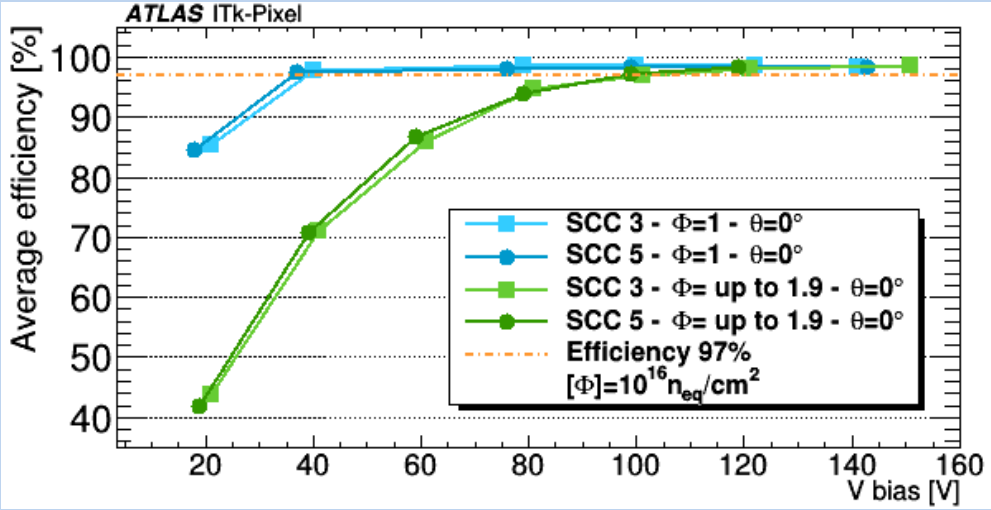


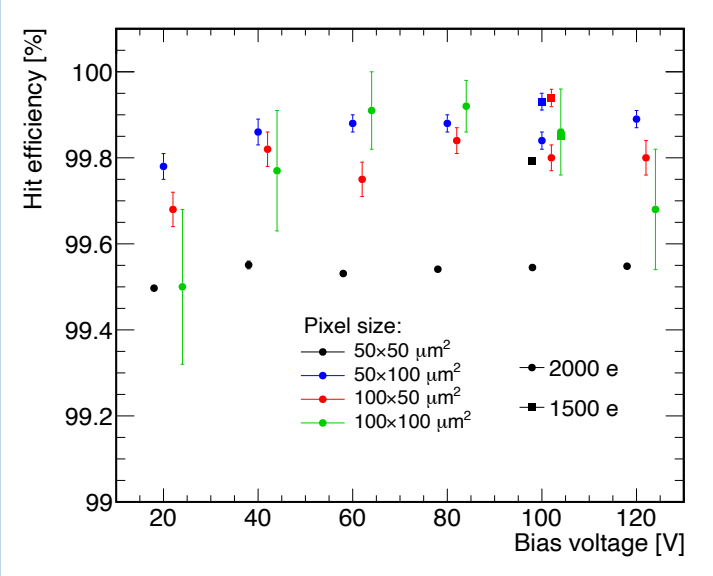
See poster by Yusong Tian "ATLAS ITkPix Pre-production Planar Sensor Level Characterization for the HL-LHC Upgrade"

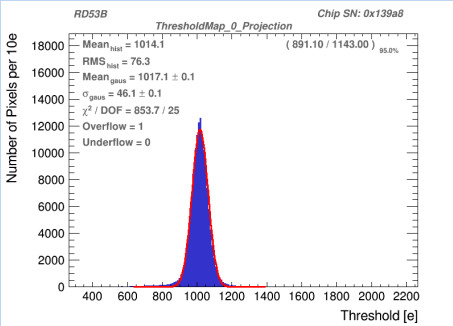
  - 3D sensor preproduction close to complete
    - about 160 50x50μm^2 sensors from FBK and Sintef sensors delivered
    - About 50 25x100μm^2 from FBK delivered, 50 CNM 25x100 μm^2 due January 2023
    - Measured yield found to be higher than assumed 50%



Sensor Testbeam Results







Pixel size [μm²]	Efficiency [%]
50x50	99.545 ± 0.008
50x100	99.84 ± 0.02
100x50	99.80 ± 0.03
100x100	98.63 ± 0.36

Threshold=2000e at 100V

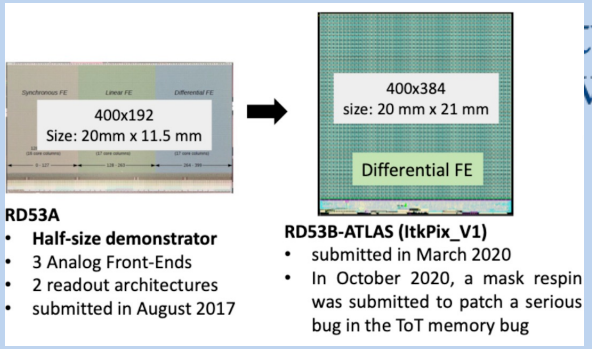
- Irradiated 3D 50x50μm² module with ITkPixV1.1 readout
  - Irradiated to $1x10^{16} n_{eq}cm^{-2}$ at Bonn
  - $+0.9x10^{16}$ $n_{eq}cm^{-2}$ (peak) at PS IRRAD facility
  - Threshold 1000e

- Unirradiated quad-module tested at SPS Four ITkPixV1.1 chips tuned to 2000e
  - Threshold: 1983 ± 43 e
  - Noise: 112 ± 12 e
  - Threshold and noise uniform across surface

See talk by Martina Ressegotti Qualification of the first preproduction 3D FBK sensors with ITkPixV1

FE-chip

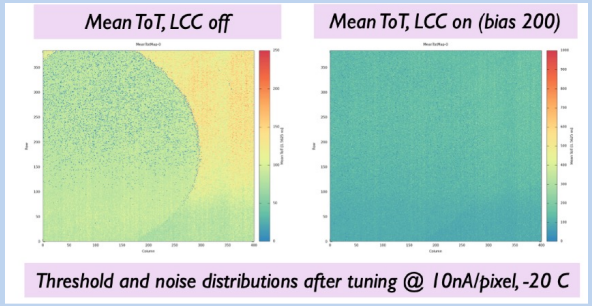
- RD53 Collaboration: joint R&D for ATLAS and CMS ASIC in TSMC 65nm
- Main features for ATLAS
  - 152800 pixels per chip (384 rows per 400 columns)
  - 65nm technology, 50x50 µm2, total area 2x2 cm2
  - Tracking in dense environments
    - Low threshold operation
    - Digital readout with Time over Threshold
  - Radiation environment
    - Low threshold operation
    - Leakage current compensation
    - SEE hardening
  - High data rates for 1MHz data rates
    - 4 data links per chip at 1.28 Gb/s
    - data compression
    - Data rate studies ATL-ITK-PUB-2022-001
  - Optimisation of services
    - Merging of chip data in module
    - Integrated shuntLDO regulator for serial powering
- Submission history
  - RD53A → ITkPixV1 → ITkPixV1.1
  - Final chip ITkPixV2 in final design and verification



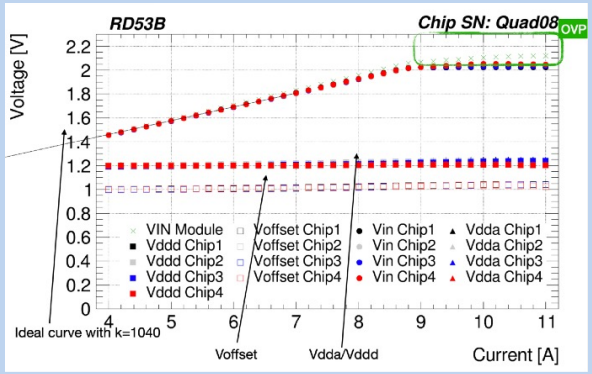
RD53A
- **Half-size demonstrator**
- 3 Analog Front-Ends
- 2 readout architectures
- submitted in August 2017

RD53B-ATLAS (ItkPix_V1)
- submitted in March 2020
- In October 2020, a mask respin was submitted to patch a serious bug in the ToT memory bug

Leakage current compensation



Serial powering

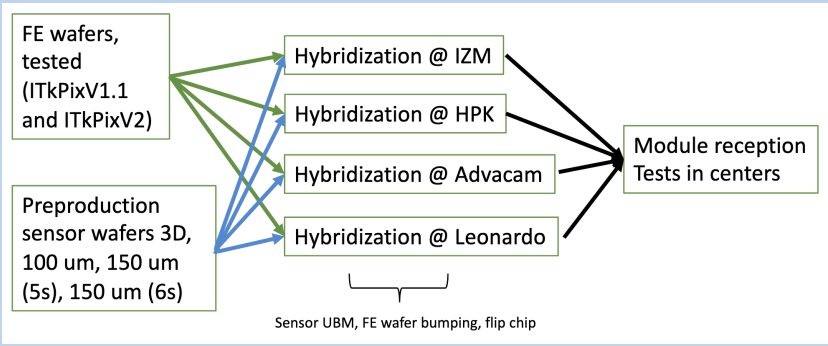


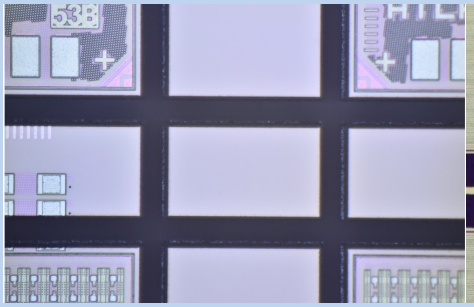
See talk by Jay Chan "Serial powering for ATLAS ITk pixel modules"

Hybridisation

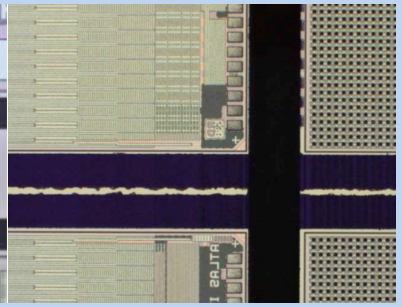
- Hybridisation tender process complete and frame contracts placed with 4 vendors
  - 4 vendors to accommodate the number of modules required
  - 3 solder + 1 indium bump vendor
  - Wide variety of different processing needed due to different sensors
    - 3D requiring thinning and backside metalisation, 5 and 6 sensor planar wafers
  - Technical issues resolved
    - e.g. improved dicing but different for different vendors
  - Pre-production wafers now being delivered

Complex production process





laser pre-grooving and dicing

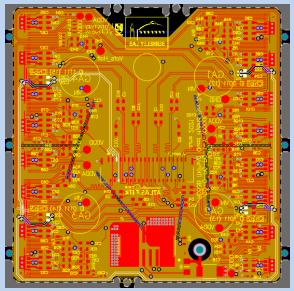


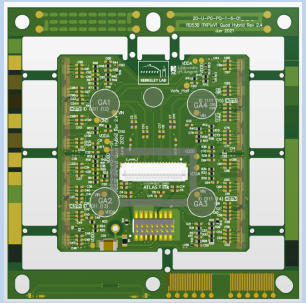
blade dicing

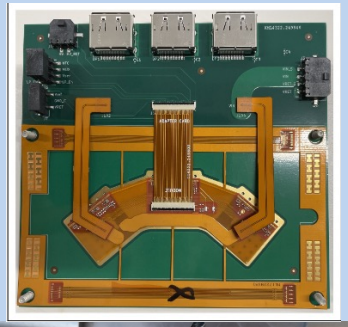
Dicing was shown to be an issue during RD53 programme.
Improved dicing being used by vendors
Initial studies made with dummy wafers give good results
Additional metal free region introduced around seal ring of ITkPix chip for V2 production

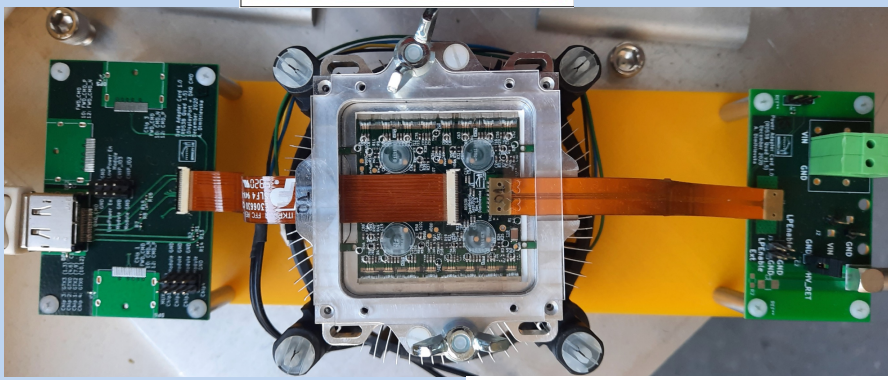
Modules

- Hybrid design challenging
  - Copper content to be balanced between bump—stress (low Cu content required) and low power (high Cu content required) FEA studies indicate that around 35µm effective thickness (taking into account the area)
  - High speed signals and data merging implemented
  - Common hybrid for outer barrel in layers 1-4
  - Triplet hybrids for L0 (R0, R0.5 and linear)
- Bump stress
  - Qualify bump-strength at low temperature and after thermal cycles (-55 (-45) → +20°C) for different vendors
  - cross-check with FEA and shear stress measurement
  - Good results from qualifcation, being followed up in the pre-production
  - Indium bumps need further evaluation

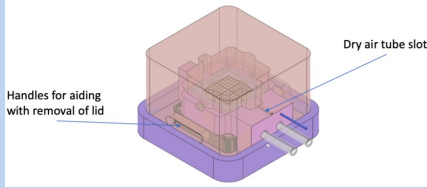








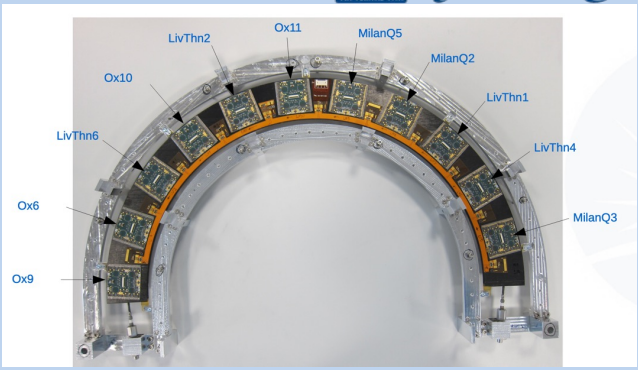
Module carrier and test setup
Carrier interfaces to cooling system



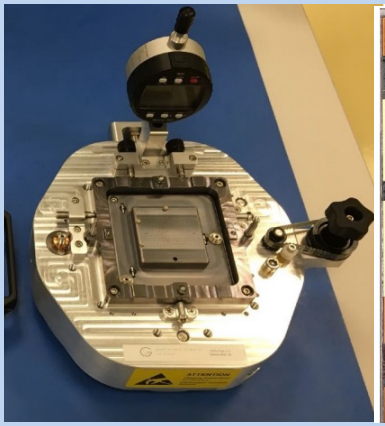
See poster by Jörn Grosse-Knetter "ATLAS ITk pixel module bump bond stress analysis"

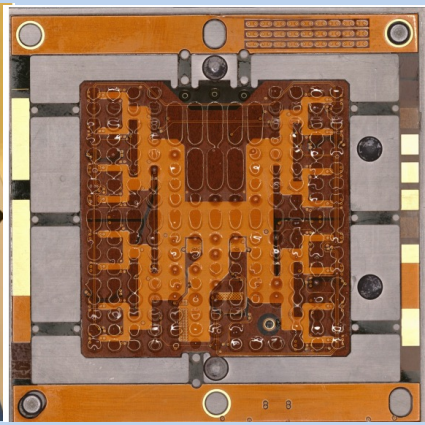
RD53A Module programme

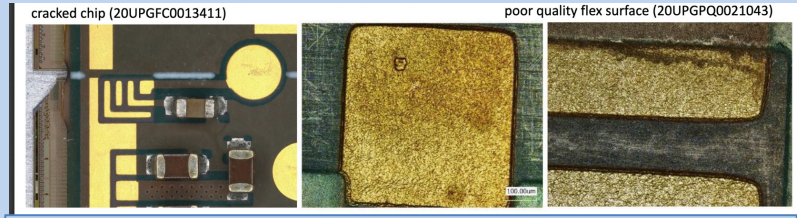
- 31 thick modules assembled and tested for process development
- 109 thin modules assembled and tested for:
  - Outer barrel cell loading
  - Loading on Outer Barrel, Endcap and Inner system local supports
- Exercise production across module sites
  - Site-qualification
- Extensive module QC
  - Electrical readout, metrology, bump-stress, operation at low temperature and burn-in, sensor IVs
- Optimisation of glue coverage
  - maximise coverage and adhesion at edge to avoid delamination
- Experience with tooling led to new tooling design
  - Minimise effect of operator on glue depositon
  - Relaxed the glue thickness specification
- Production revealed quality issues
  - Poor dicing led to cracked chips that did not operate electrically – dicing and hybridization QC improved
  - Poor bond pad quality on flexes made wire bonding diffcicult – improve hybrid QC and also bond-pad layout optimized



Populated endcap ½-ring with RD53A modules from different assembly and testing sites



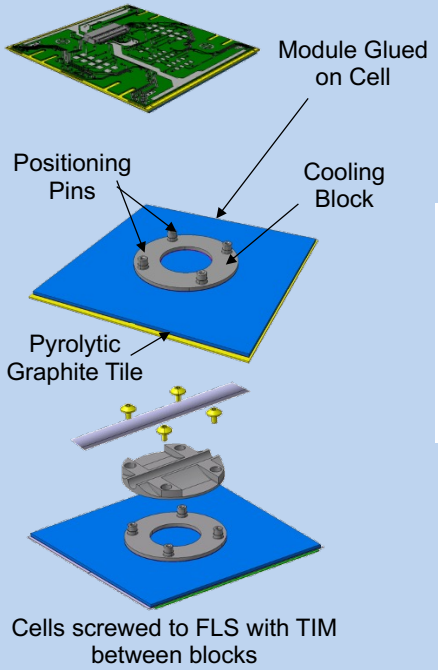


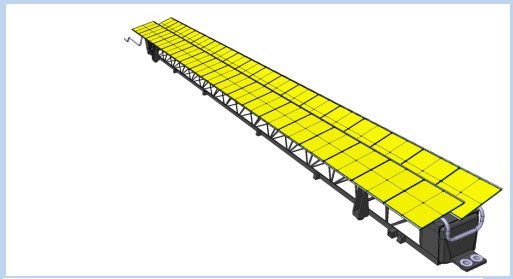


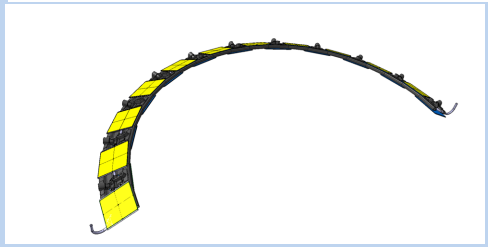
See talk by Dimitris Varouchas "Pixel module assembly for the ATLAS ITk"

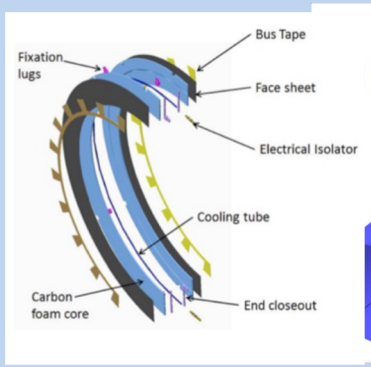
Local Supports

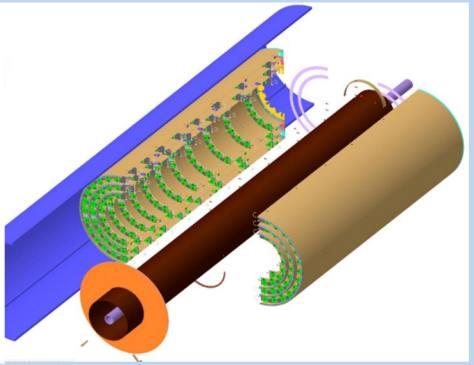
Outer Barrel Module Cells
(Module + PG tile + Cooling Block)

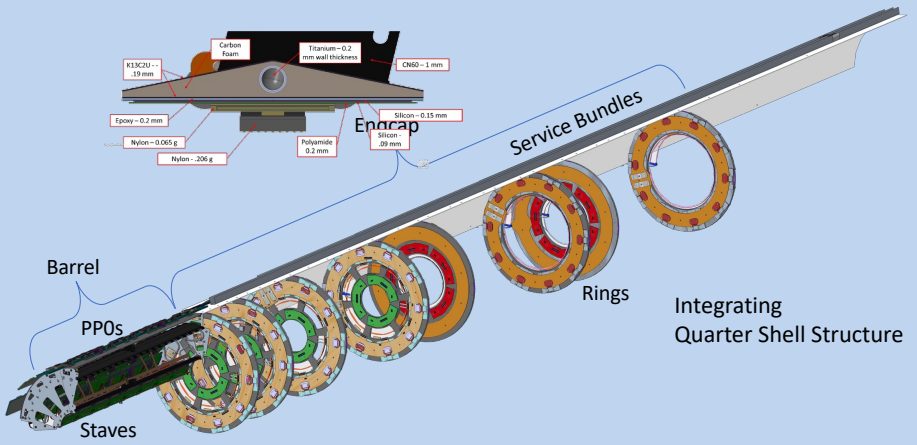








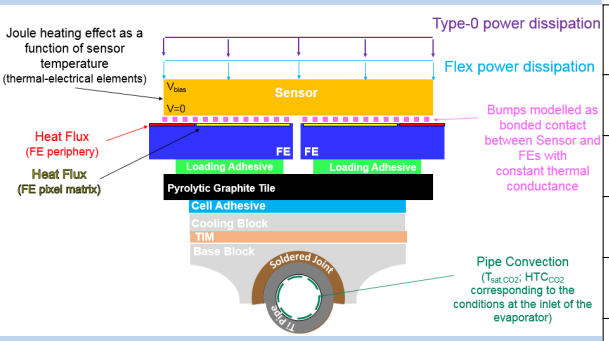




- Local supports provide stable low-mass supports for modules and services
- Critcal element is interface between module and cooling pipes
  - OB modules cooled via cooling cells that interface to the cooling pipe mounted on the CF support
  - Endcap and inner system use CFRP with low-mass foam and embedded cooling pipes

See talk by Owen Shea "Overview on current state of the art pixel mechanics for the upgrade tracking detectors at the ATLAS and CMS experiments "

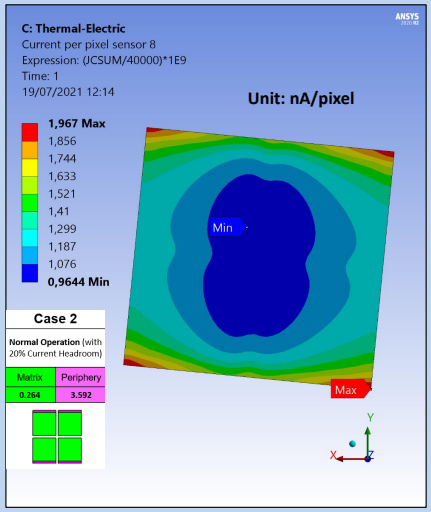
Thermal Management



Outer barrel model

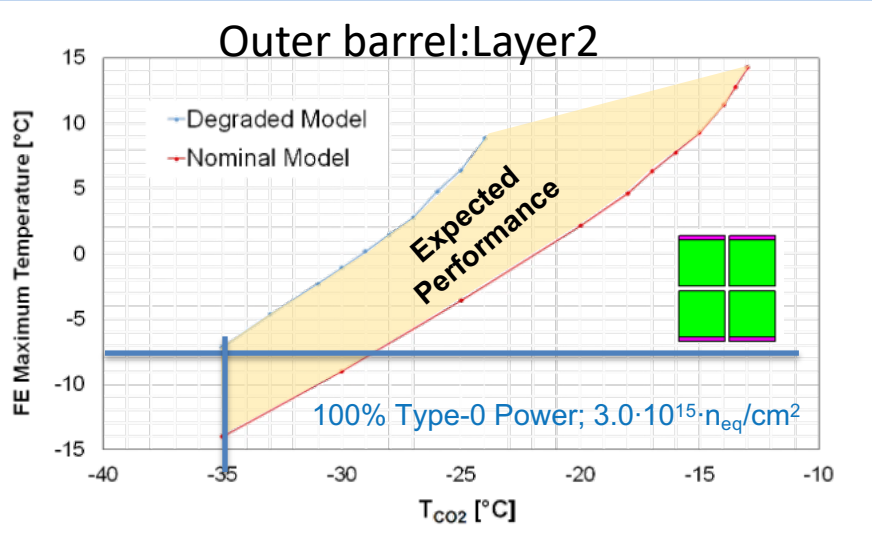
	Case		OS L2 FE Power Dissipation [W/cm2] Matrix	Periphery
1	Homogeneous		0.548	0.548
2	Normal Operation		0.264	3.592
3	No Configuration		0.000	6.411
4	One FE Opened		0.264	6.831
5	No Configuration + One FE Opened		0.000	9.651

Outer Endcap



Current per pixel in the hottest sensor of L-2 Half-Ring, for the five load cases, at $\Phi = 4.59 \cdot 10^{15}\ n_{eq} \cdot cm^{-2}$

See talk by Francisca Munoz Sanchez "Carbon based local supports for the ATLAS ITk-pixel detector"



Layer 2 TFM
Design: 38.8 °Kcm²/W
Degraded: 34.5 °Kcm²/W

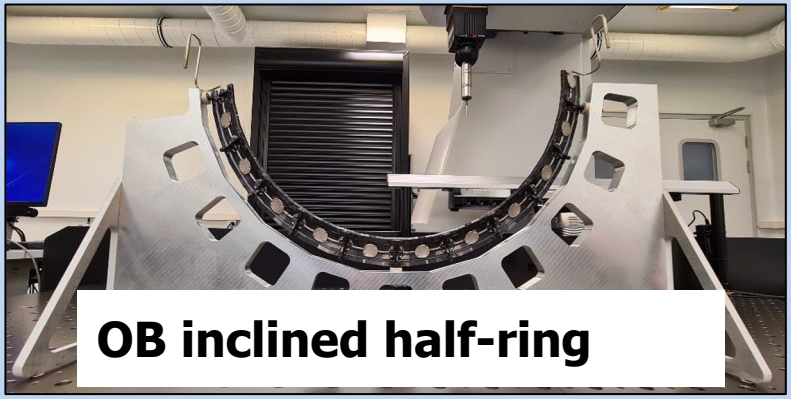
- FEA studies on all three subsystems made to evaluate thermal performance
  - Sensor thermal runaway
  - FE-temperature (<7°C)
  - Pixel leakage current (<10nA into FE-chip)
- Model different power scenarios for FE-chip
  - Include non-uniform power dissipation
- Validated with measurements
- Local supports thermal management within specifications

Mechanical prototypes

Bare local support pre-production for Outer Barrel and Endcap in progress

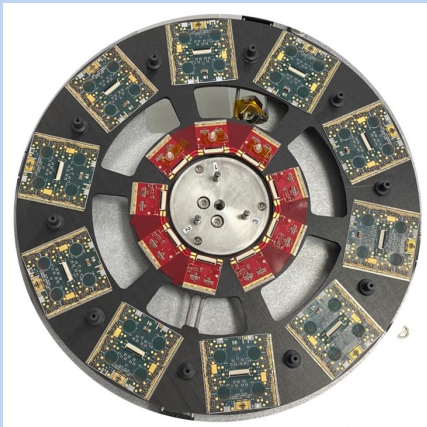
Inner system pre-production about to start

OB longeron



OB inclined half-ring

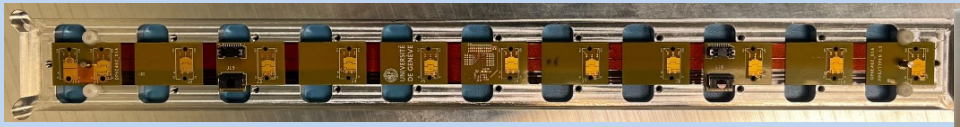
EC half-ring

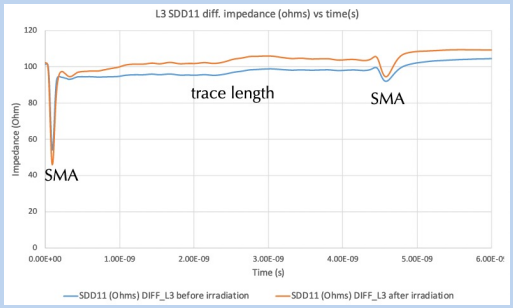


Prototype IS coupled ring

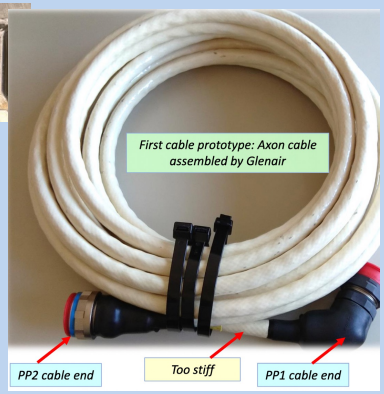
Services

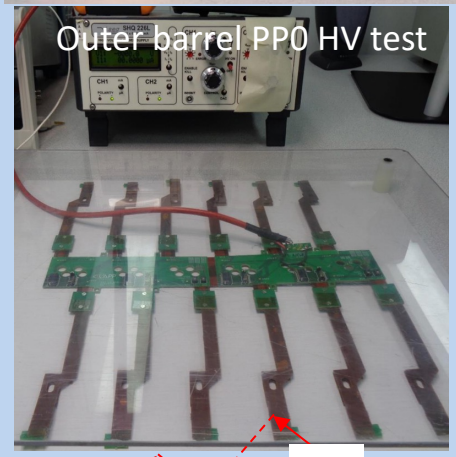
See poster by Richard Van De Wall "High-density high-speed service infrastructure for ATLAS ITk pixel detectors"

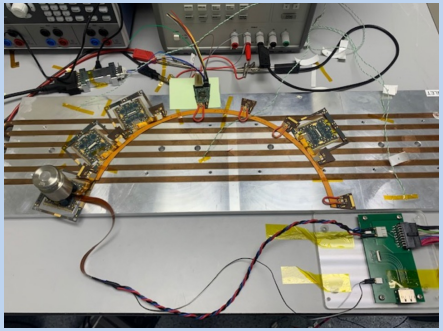




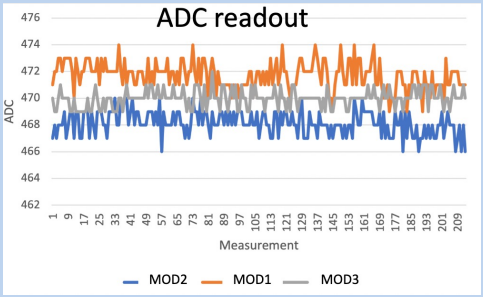
Outer Barrel Inclined L3 PP0
Irradiation results on test coupons show impedance does not change

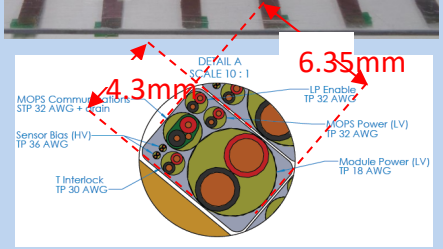


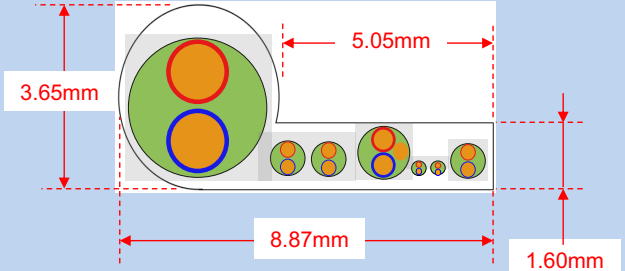




Endcap ring with ring tape & "end-of-stave card"
Module ADCs readout
SP chain powered and modules readout





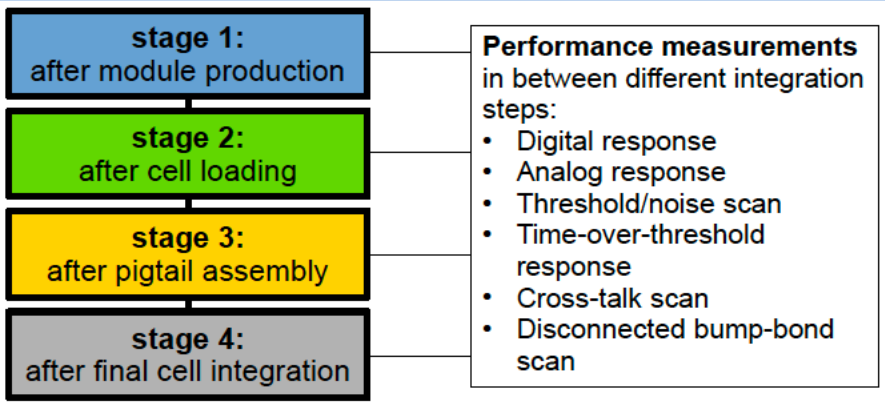


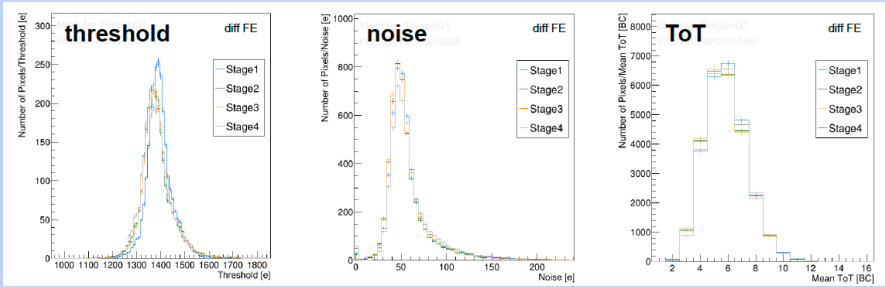
Approximate Dimensions of Woven Bundle

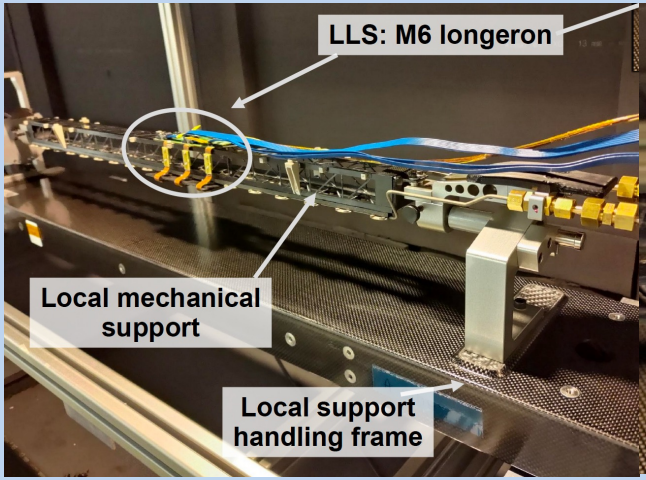
Issues with preparation of type-1 power bundles (HV, LV, Canbus)
First prototypes with ribbonisation did not work well – in discussions with vendor

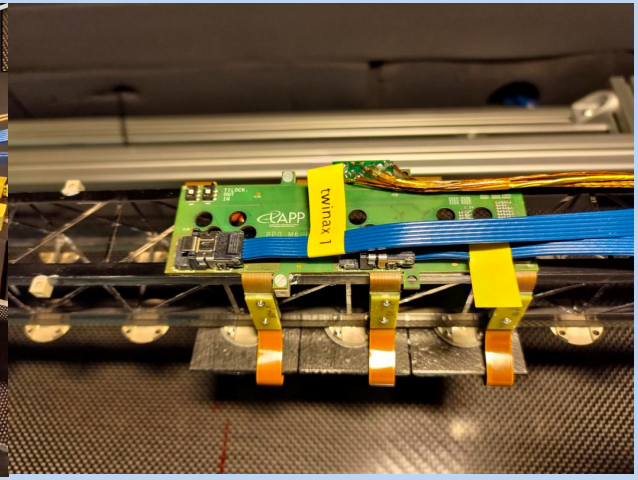
Loaded Local Supports and System test

- Outer barrel module loading and system tests
  - RD53 modules loaded on to cells and thermally tested mounted onto local supoers system test
  - Performance of modules monitored through the loading process









System tests of endcap ½-ring and inner system also ongoing

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
  - Radiation hardness
  - Increased occupancy
  - Low mass
- ITk pixel system has been designed to meet these challenges
  - Smaller pixels
  - Low mass materials
  - Serial powering
- The project is completing the R&D phase and moving to production
  - Large scale production brings a new set of problems
- Moving from development of individual items to a system level
  - Loaded local support system tests are underway, excellent testbed for integration issues