The ATLAS ITk detector for HL-LHC

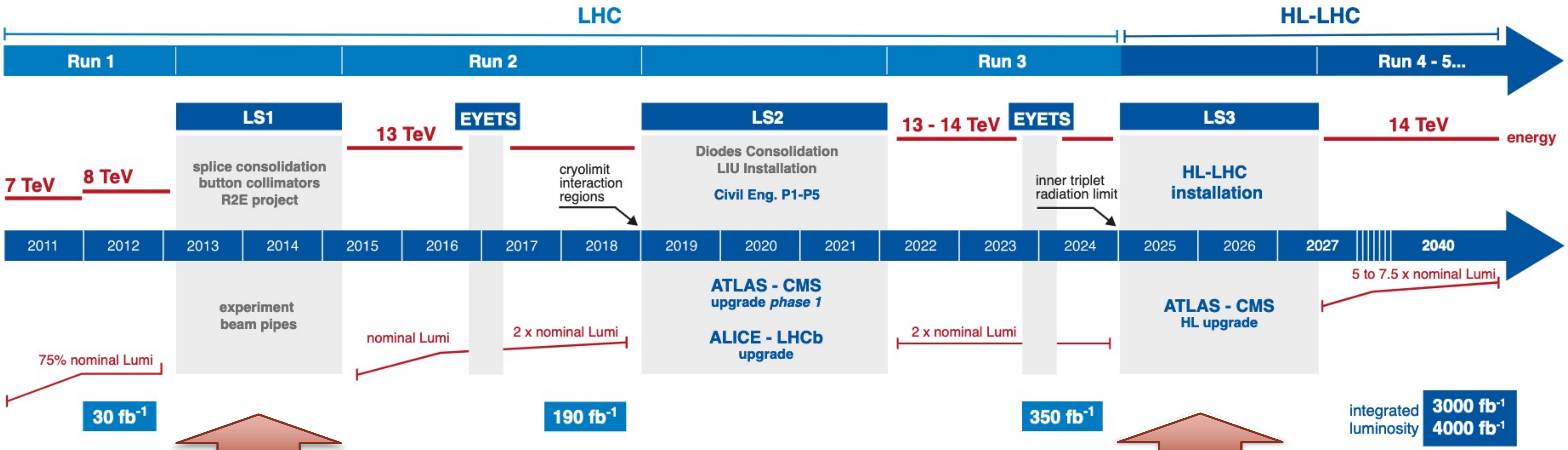
Vertex 2021

The 30th International Workshop on Vertex Detectors

Giovanni Calderini

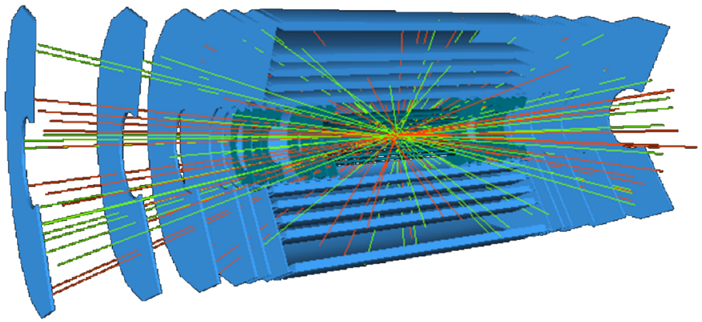
on behalf of the ATLAS ITk Collaboration

Introduction: the upgrade of the LHC



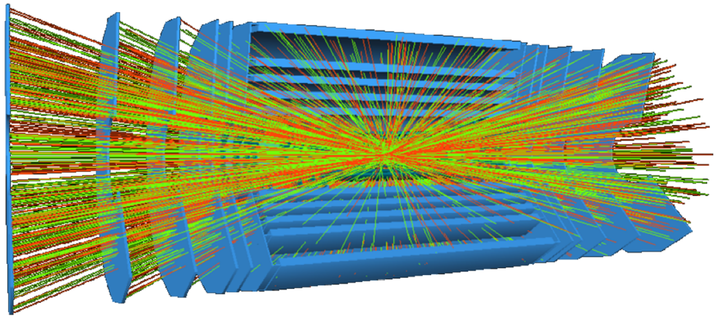
Inner Detector (ID): Pixel+Strip+TRT upgraded by IBL

“Phase II”: full inner detector replacement (Pixel+Strip)



LHC

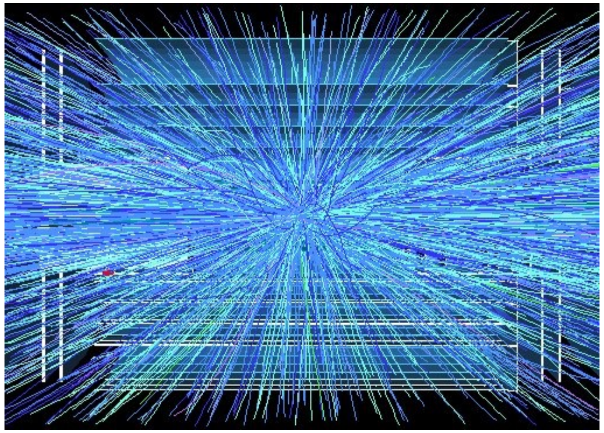
19 - 55 Pile-up events



High Luminosity LHC (HL-LHC)

140-200 Pile-up events

After Run 3 the present Si tracking detector would not be adequate any more



Instantaneous conditions

- pileup and high event rate
- increased occupancy

● higher granularity sensor

● SEE-robust, faster readout

● Redundant tracking for combinatorics

- *Peak luminosity:* 5-7.5 x 10^{34} $cm^{-2}s^{-1}$ → ~x5-7
- *Average pile-up:* up to <μ> ~200 → ~x5
- *Integrated luminosity:* 4000 fb^{-1} → ~x10
- Requested *radiation hardness: up to* 2x10^{16} n_{eq}/cm^2→ x20
- *Higher hit rate*

Integrated effects

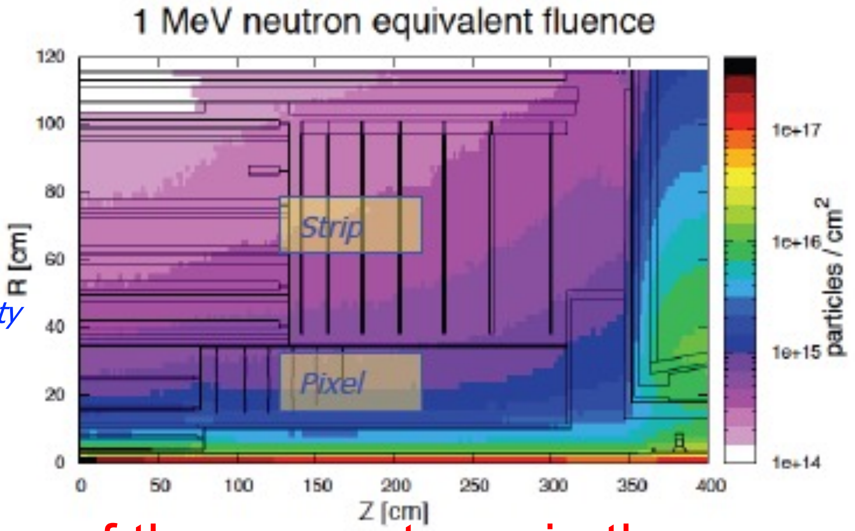
(radiation dose)

- leakage current
- change in operation voltage
- reduced charge collection

High particle fluences up to

- *1.2*10^{16} n_{eq}/cm^2 for pixel*
- *1.0*10^{15} n_{eq}/cm^2 for strip*

Requested Additional 1.5 Safety factor.



● rad-hard components

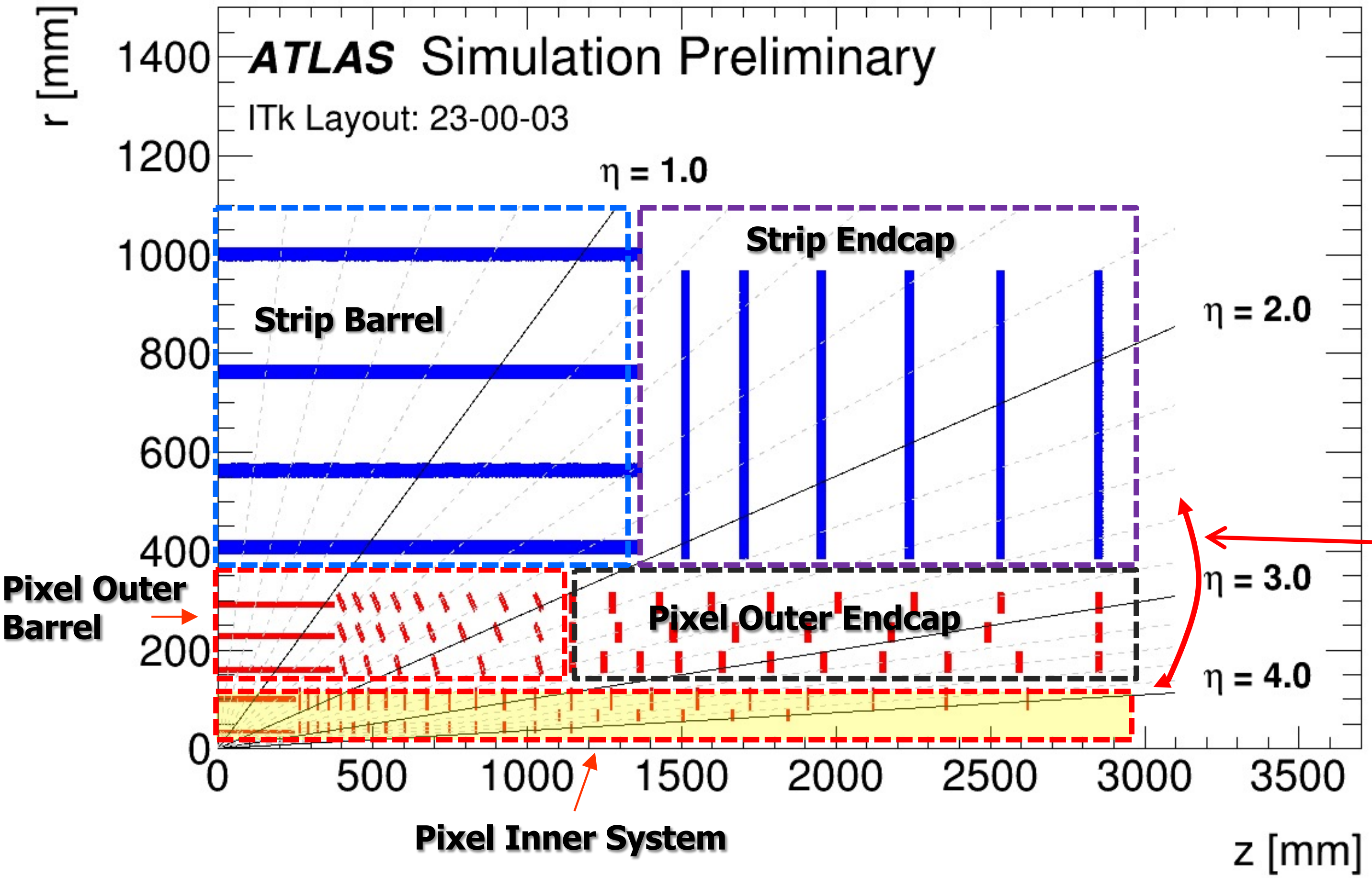
● thin sensors (partial depletion)

New tracker with similar or better performance of the present one in the new more challenging conditions

Layout of the ITk detector

All-silicon detector in 2T magnetic field.

- Strip subsystem covering up to $|\eta| < 2.7$ with 4 Barrel layers 6 End-cap disks
- Pixel subsystem covering up to $|\eta| < 4.0$ with 5 Barrel layers + endcap rings
- Possibility to replace the two innermost pixel layers
- Innermost layer radius finalized at 34/33 mm (B/EC, was 39/36)



Pixel Outer Barrel

Pixel Inner System

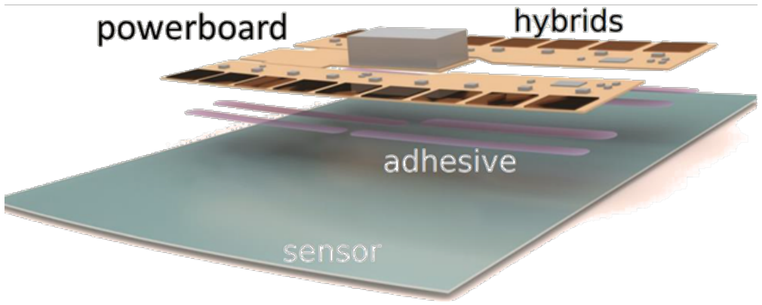
Tracking extension coverage from 2.5 to 4

Numerology and scale

	Surface [m^2]	# Channels	# modules
Pixel	13	5.1 G	9.2 k
Strip	165	60 M	18 k

Large Strip system compared to current SCT system in Run 2

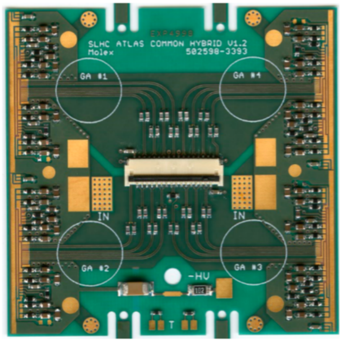
- ~10x channels,
- ~3x size (~10 x 10 cm^2)
- ~5x modules

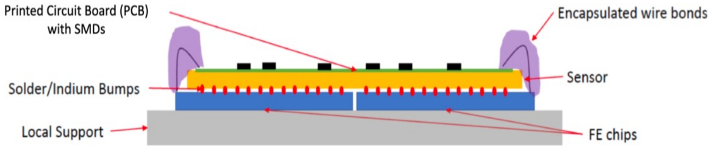


Modules loaded on Local supports: Barrel Stave or Endcap Petals

Large Pixel system compared to current pixel in Run 2

- ~60x channels,
- ~7x size (~ 4 x 4 cm^2)
- ~5x modules





Example stack up of quad module

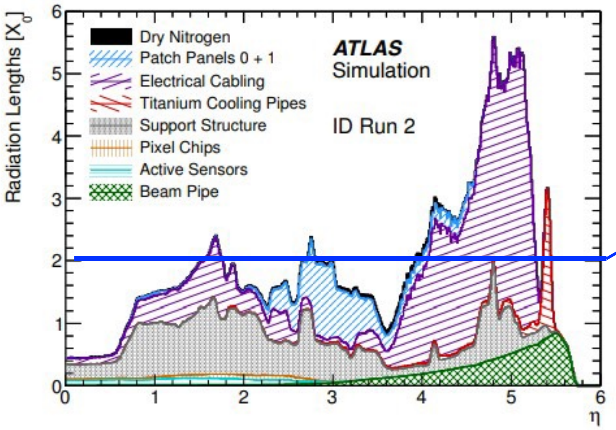
Modules loaded on different structures according to the subsystem

Material Budget

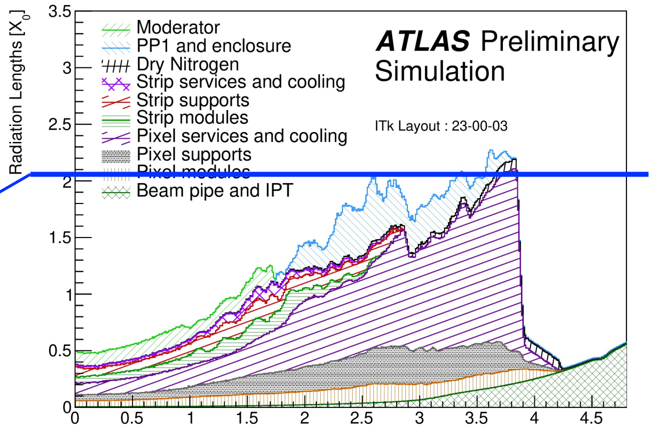
In spite of increased surface and complexity, quantity of material reduced with respect to the present system

- **Pixel:** Thinned sensors and FE, Serial powering, inclined region in the Outer Barrel, increased readout speed
- **Strip:** DC-DC powering and data transmission with optical links and lpGBT
- **Common (Pixel and Strip):** Light structures, cooling designs optimized as well as material choice wrt the requirements

  (precision, stability, contain the thermal run away, …)



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/UPGRADE/CERN-LHCC-2017-021/



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/

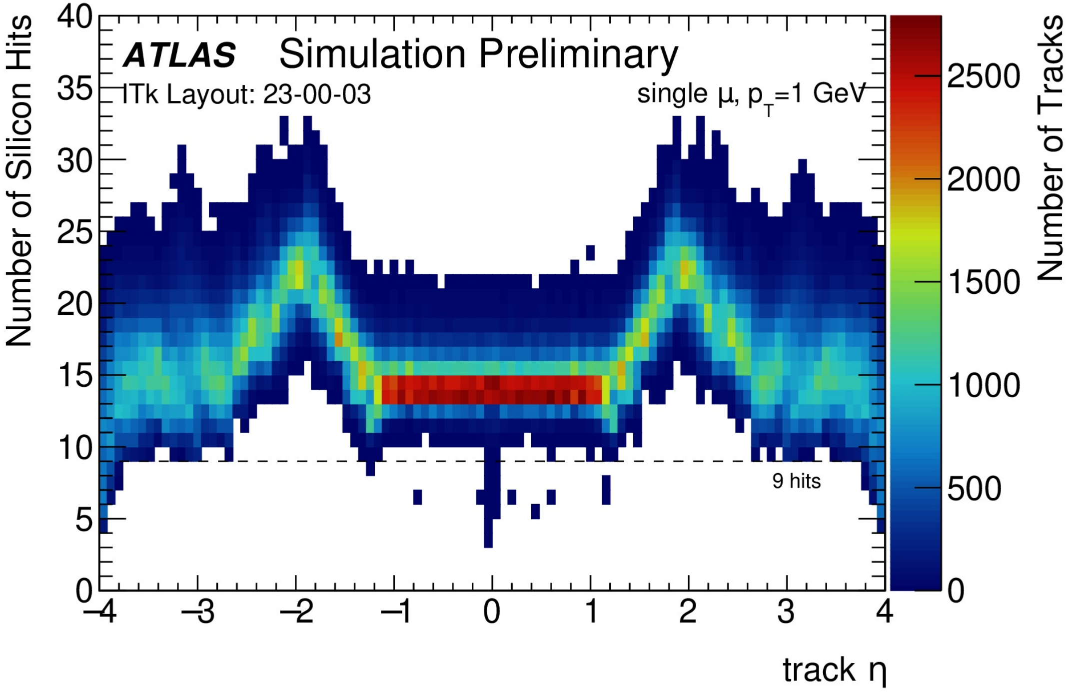
Reduced material budget versus current ID in Run 2.

→ Minimize effects of multiple-scattering and energy losses before outer detectors.

Tracking Performance

Large improvement in performance for the same conditions

- Improved granularity
- Reduced quantity of material, less multiple scattering
- Better hermeticity and more hits on track

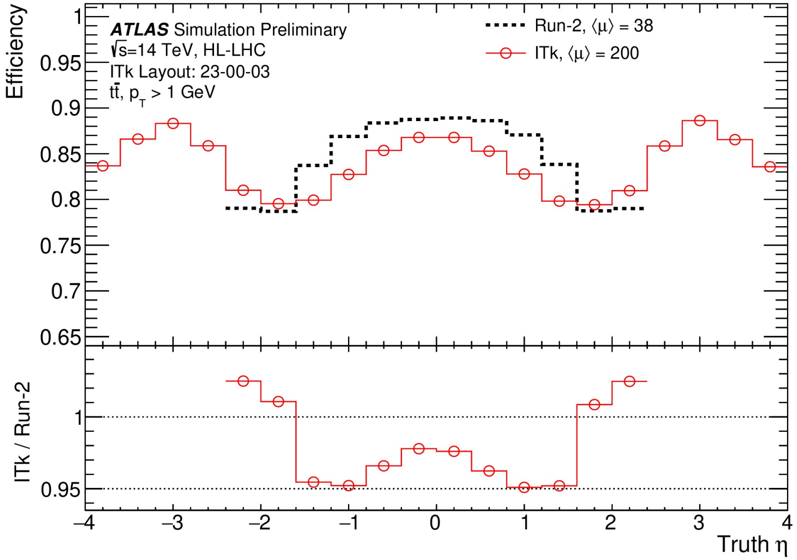


ITk provides at minimum **9 hits** in the barrel and **13 hits** in the forward or all particles with $p_T > 1$ GeV within $|z_{vertex}| < 150$ mm

Redundancy is very important to clean combinatorics in reconstruction

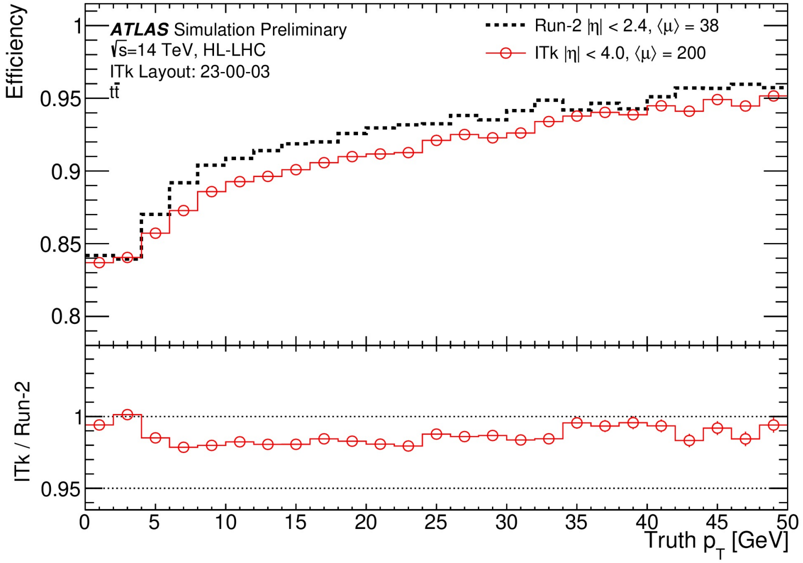
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024

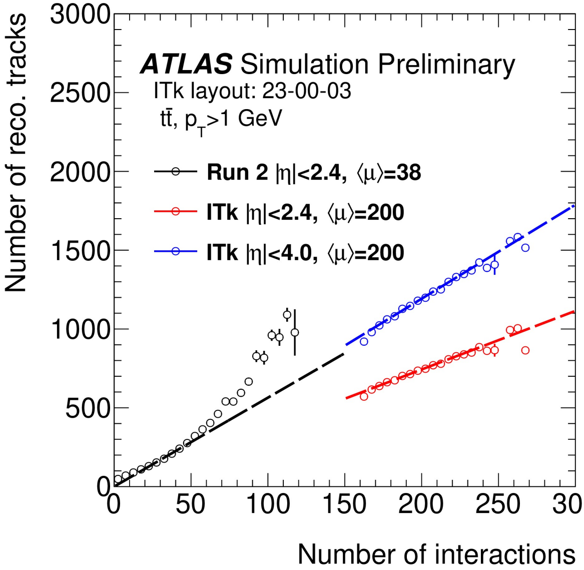
Reconstruction efficiency



Tracking efficiency at 5x pileup wrt Run2

- Similar performance in the barrel
- High efficiency (over 85%) also at high η
- Improves the **fake rate over Run2 ID,** even considering a 5x increase in pile-up.





Number of reconstructed tracks follows nicely the number of interactions

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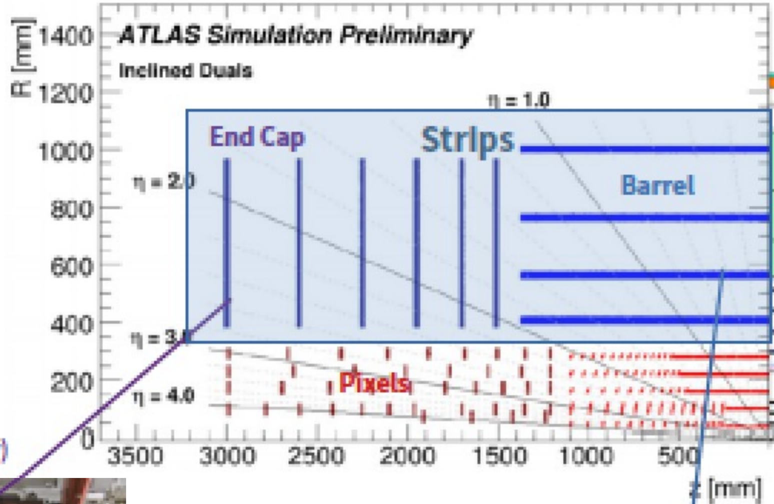
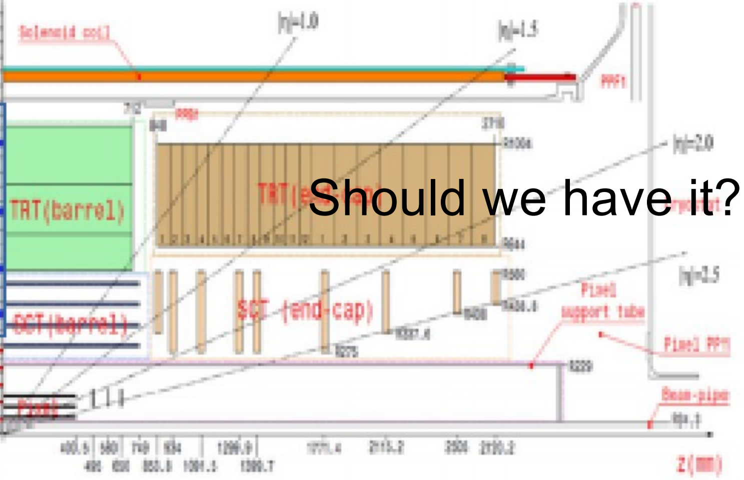
ITk Strips

The Inner Tracker

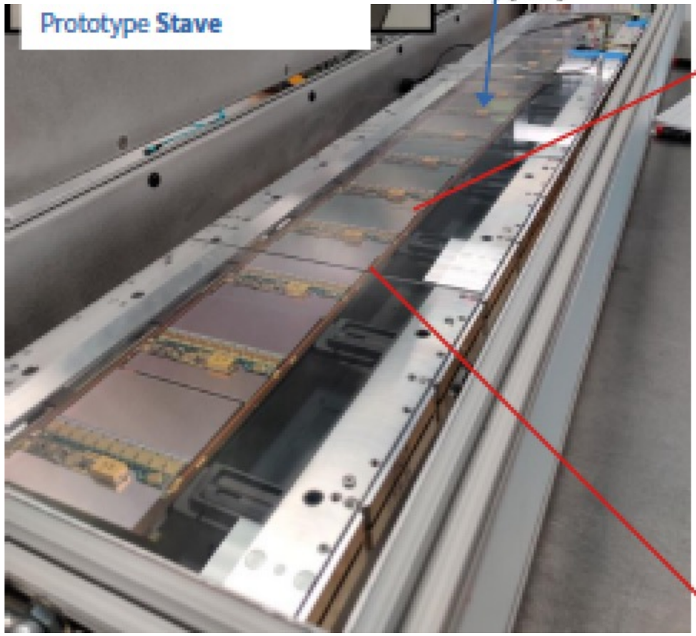


The current detector

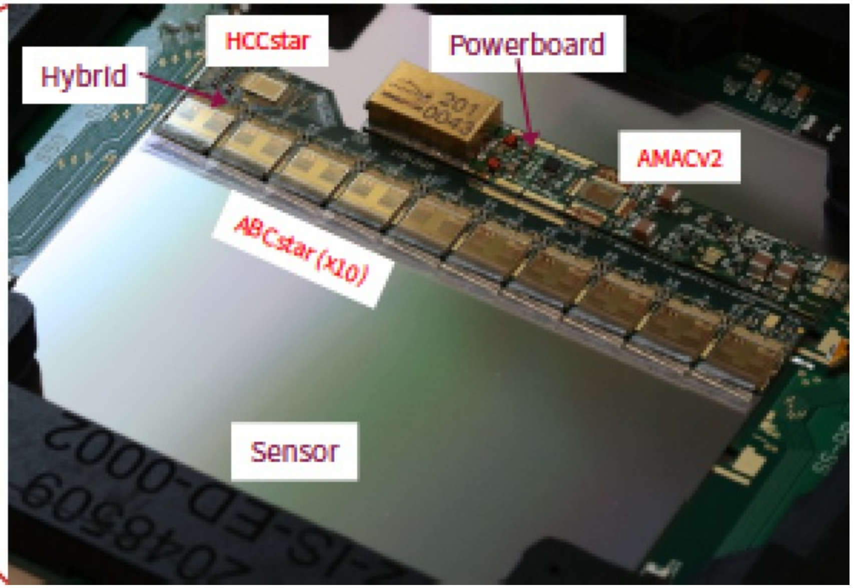


Should we have it?

End Cap
(ring geometry)



Prototype **Module**

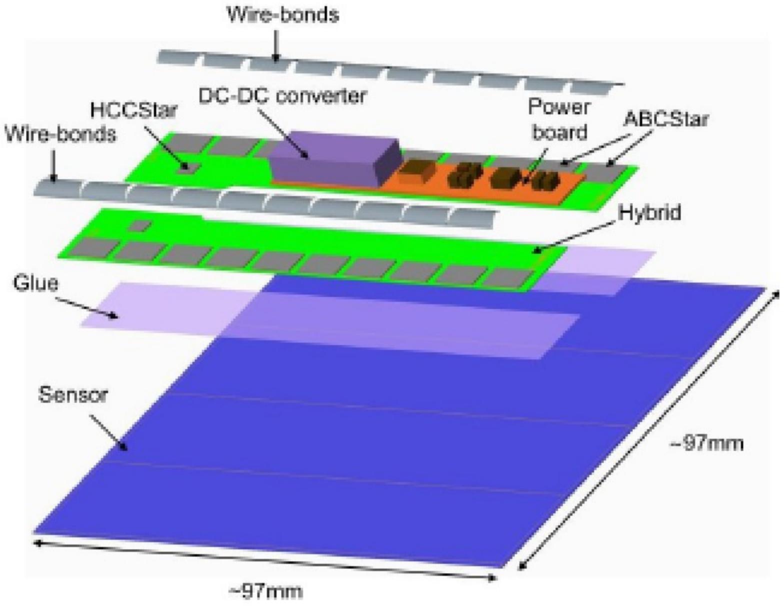


ITk strips module

Basic building block

- Variations based on sensor geometry
- Barrel/endcap difference is shape
- Modularity design aimed at mass production with industry standards
- Assembly and testing in multiple sites

2560 or 5120 channels/module



Parallel powering scheme

- ~14 modules per LV channel
- 11V → 1.5V on-module DC/DC conversion
- ≤ 4 modules per HV channel
- On-module power control and monitoring

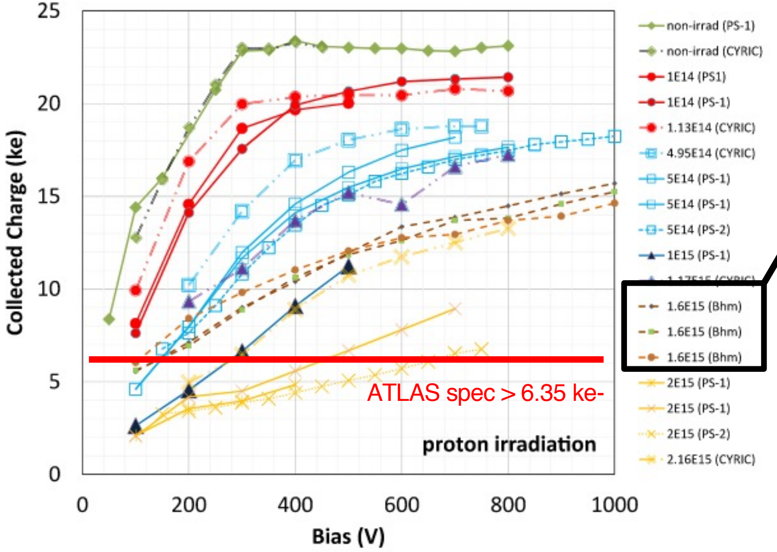
Assembly includes:
Precision placement and gluing of ASIC-to-PCB and PCB-to-sensor
Wirebonding: each FE ASIC has 256 bonds in four rows (x10/20 FE's per module)

ITk strips sensors

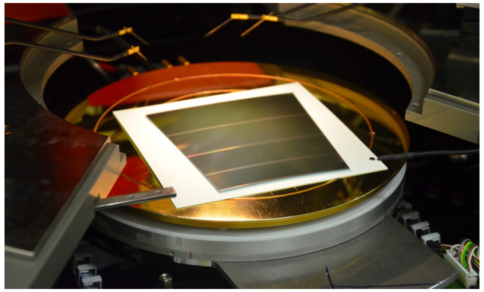
- n-in-p float-zone 320µm thick sensors
- 75.5 µm strip pitch (barrel)
- One sensor / wafer plus mini-sensors and test structures
- 8 sensor types (2 for barrel, 6 for endcap)
- bias voltage: -100V to -500V

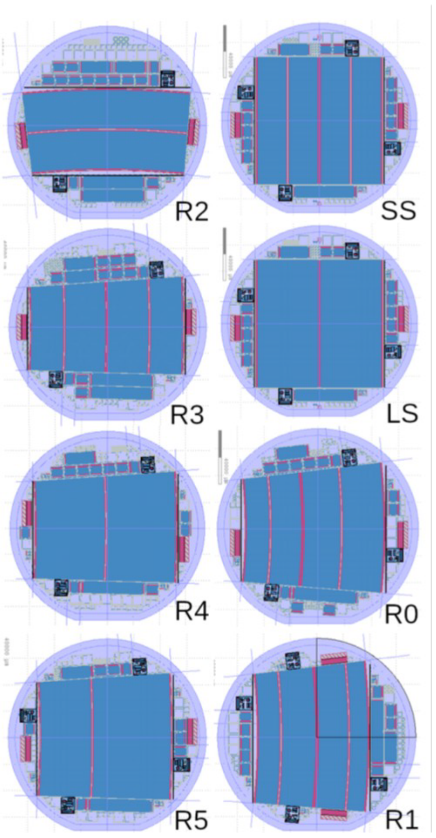
Preproduction delivered
Production Readiness Review (PRR) passed
First production batch delivered

Nucl. Inst. Meth, A 983 (2020) 164422

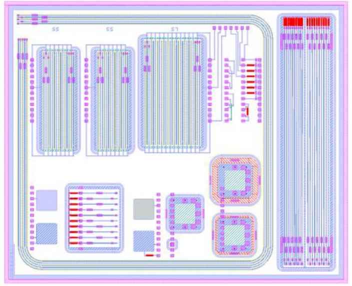


Max expected + safety:
1.6 x 10^{15} n_{eq}/cm^2



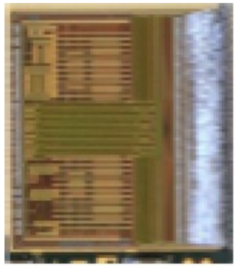


SS, LS are barrel
Rx are endcap petals



Strip readout front-ends

https://arxiv.org/pdf/2009.03197

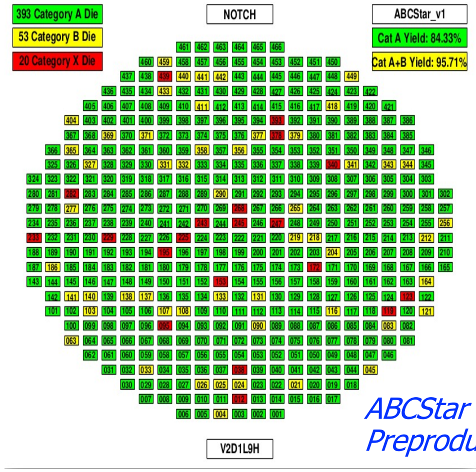


HCCStar (Hybr. controller)
- connects 10x ABC to stave
- SEE mitigation
- Preprod submitted, chip expd late November

AMACStar (Power control and environmental monitoring)
- on the same wafer as HCC
- Preprod submitted

ABCStar (front-end chip)
- binary readout
- preproduction available
- First prod wafers in 01/2022

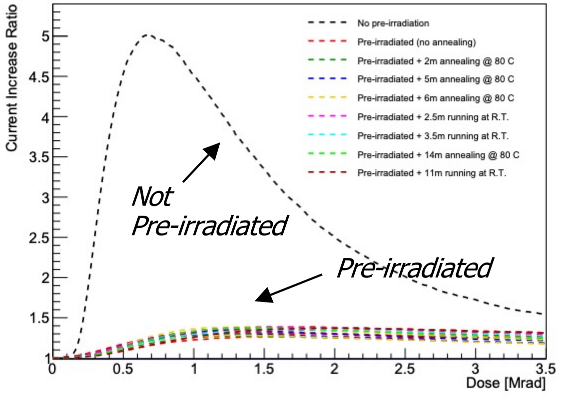
All chips made in 130 nm



ABCStar wafer probing Preproduction

- Extensive testing in simulation for all chips
- Current increase after first step of radiation.

  Pre-irradiation of ASICs baselined (up to where?).
- All three chips were extensively modified to improve SEE protection, including from measured effects.
  - Feature sets for HCCStar and AMACStar reduced to increase area available for triplicated logic.
  - HCCStar die size was increased as well



Strip modules construction

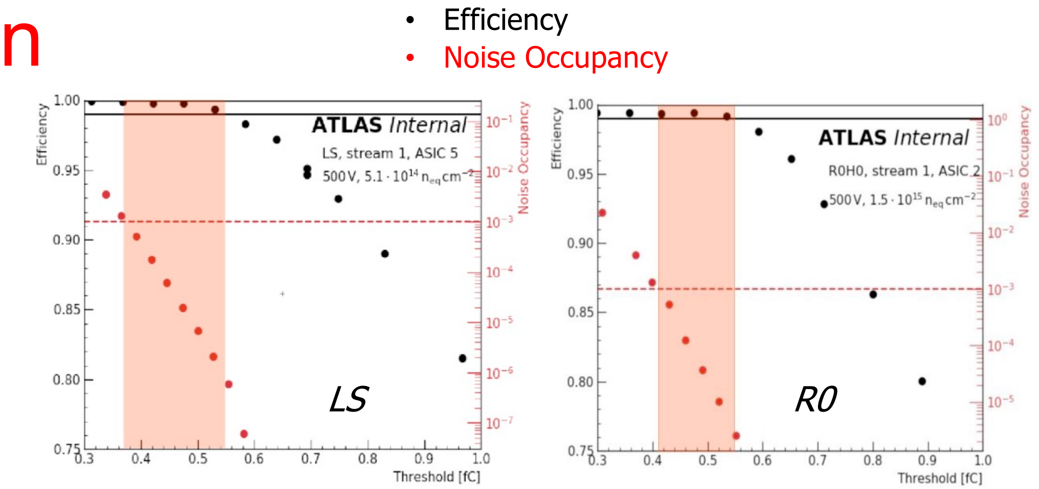
- Successful campaigns at DESY test beam facility of irradiated modules to the end-of-life
    - First results show clear operating windows meeting >99% efficiency, <0.1% noise occupancy requirement
    - New results coming soon

- Preproduction and site qualification
    - will demonstrate we can produce 18000 modules
    - Defined 10% of the actual production
    - ~20 assembly sites across 4 continents

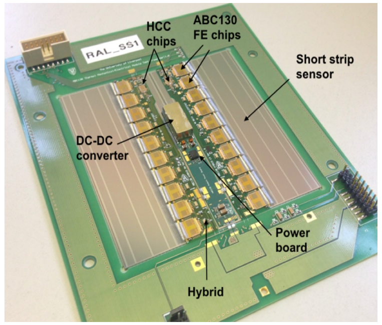
- Organized in two stages
    - Pre-production A: ~20% of pre-prod

      Sensors, flex and ABC but prototype HCC
    - Pre-production B:

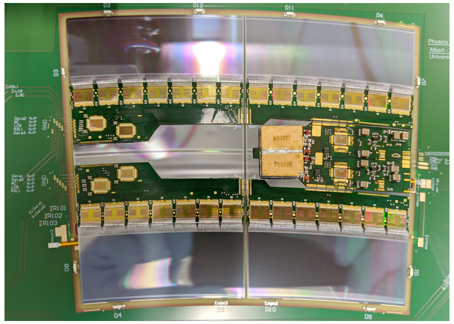
      Using final components

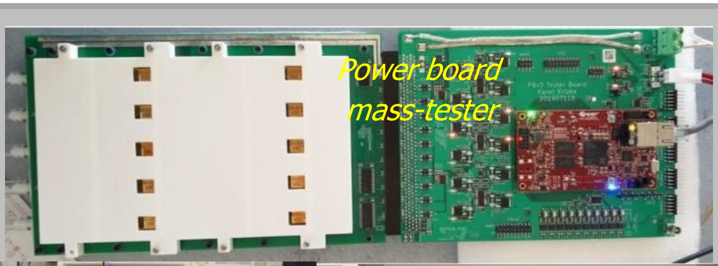


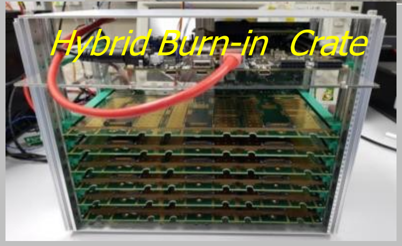
Barrel module

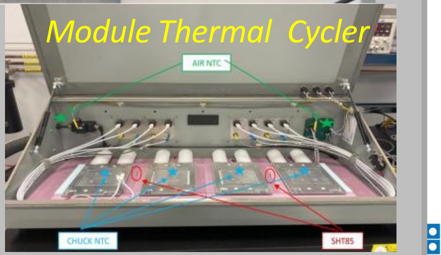


EndCap module









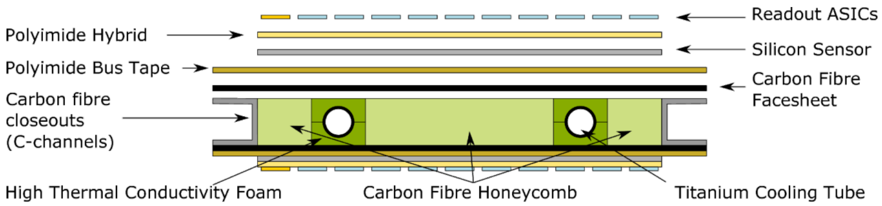
Strip Local Supports

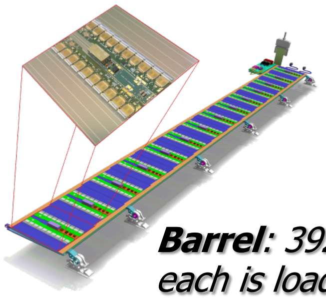
- Carbon-fiber composite structures with co-cured copper bus tapes have modules glued on top of both sides with a stereo angle between them.
- Polyimide bus tapes for data, clock, command and power between modules and end-of-structure cards (EoS).
- EoS cards service the lpGBT and VTRX+ links to the outside world.

- Loading of modules to better than 40 μm accuracy with gantry systems.
- Tests include thermo-mechanical studies, stress tests and thermal cycling, electrical test.

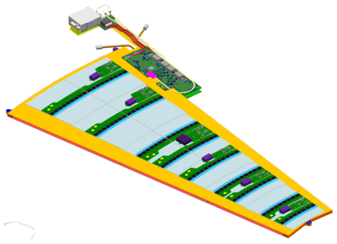
- Existing prototypes used for system tests
  - 1 x LS stave; 1x SS half-stave; 1 x petal
  - another LS and SS stave to be built

Final Design Review passed, ready for preproduction

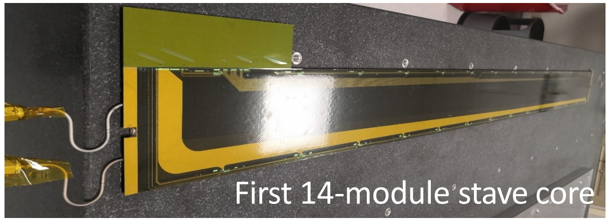




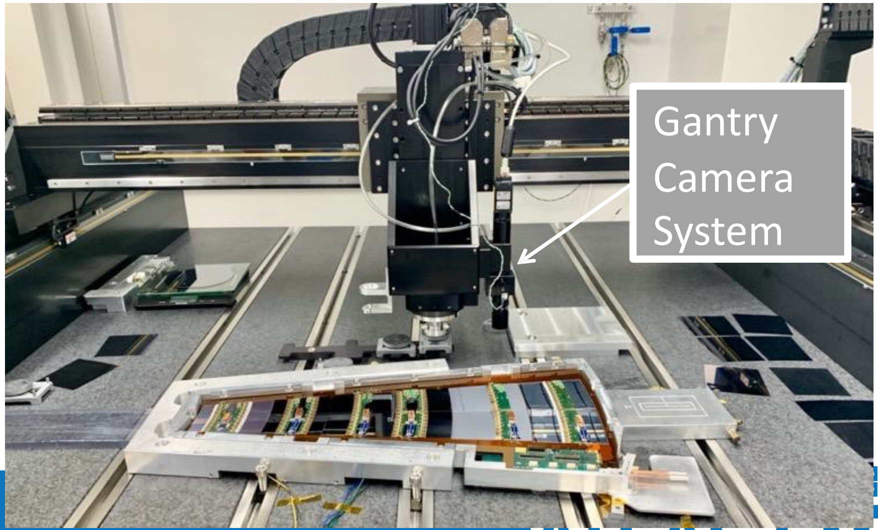
***Barrel**: 392 Staves, each is loaded with 28 modules. Length ~140 cm*



***Endcap**: 384 Petals, each is loaded with 18 modules. Length ~60 cm*



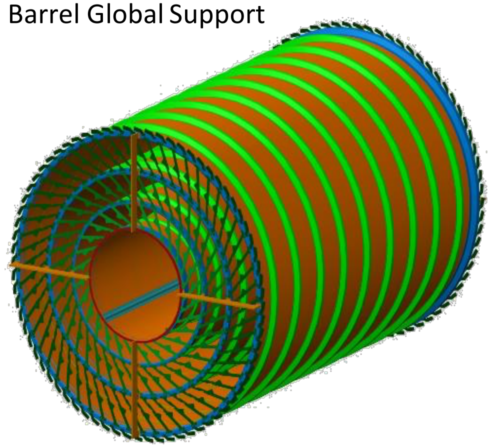
First 14-module stave core



Strip Global Mechanics

After some initial delay related to fire regulations, elements started to be produced

Barrel Global Support

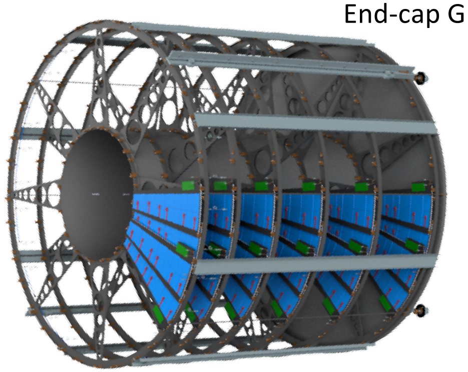


For barrel: carbon cylinders for each layer in which staves are inserted. The outermost one will be delivered in March 2022

Shell flanges prototypes are available

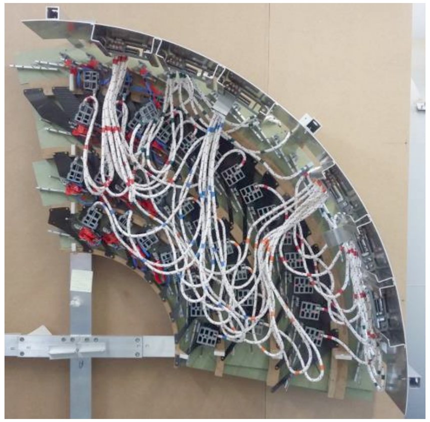
For endcaps: carbon wheels with blades for each disk mounted in endcap structure.

End-cap Global Support



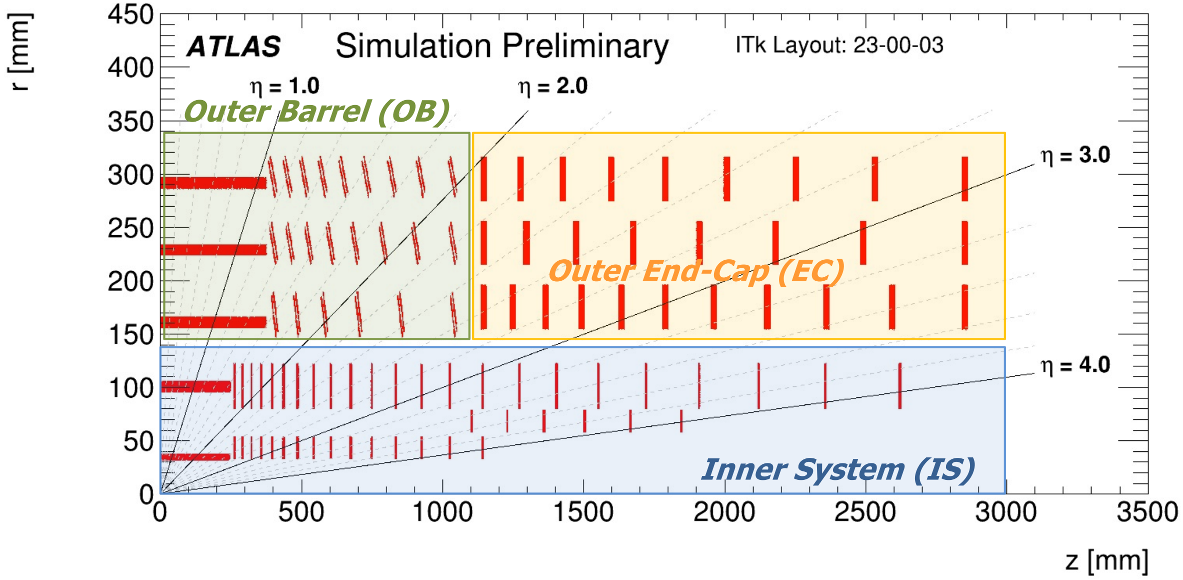
Prototype Wheels (w/ blades)

Mockup of services, interlinks and end flanges

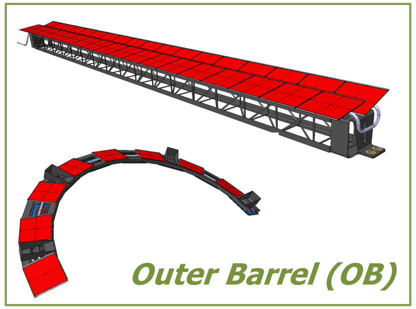


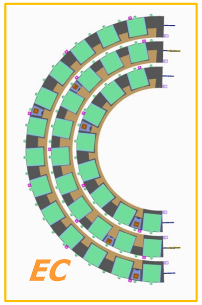
Loaded local support structures (staves and petals) are end insertable including cooling and cabling.

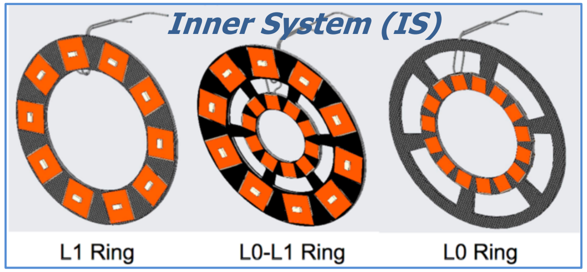
ITk Pixel Overview



Local supports







Inner system can be replaced at 2000 fb^{-1}

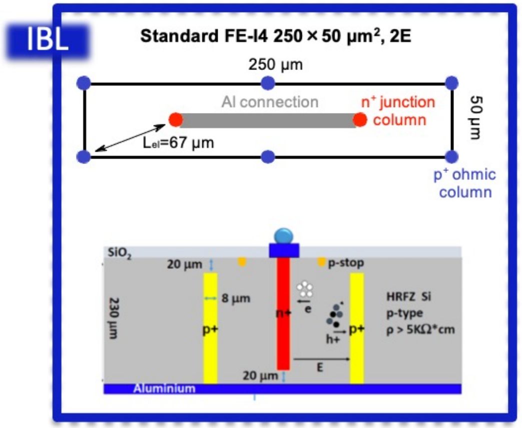
Outer system need to survive to 4000 fb^{-1}

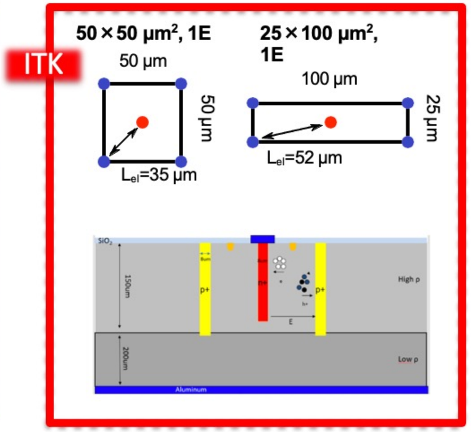
Layer	Sensor Type	Thickn. [μm]	Sensor Size [μm²]	Module Type	Module installed	Replace-ment	Fluence w/ SF [1e15 n_{eq}/cm^2]
L0 barrel	3D n-in-p	150	25x100 1E	Triplet	288	Yes	18
L0 rings	3D n-in-p	150	50x50 1E	Triplet	900	Yes	18
L1	Planar n-in-p	100	50x50	Quad	1160	Yes	4
L2-4	Planar n-in-p	150	50x50	Quad	6816	No	4-1

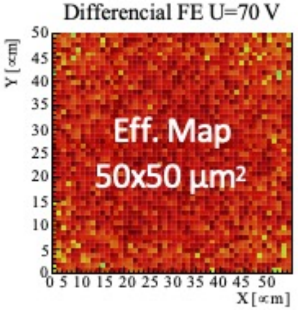
Pixel 3D sensors

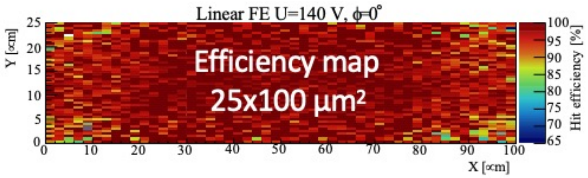
The 3D sensors are already used in the ATLAS innermost pixel layer (IBL)

- New single side technology
    - Conductive support wafer (Si-Si)
    - Both electrode types etched on the same side
- Thinner active substrate
    - 150 µm instead of 230 µm
    - Reduce cluster size and data rate
- Small pixels (improved occupancy and resolution
    - Flat barrel: 25x100 µm^2
    - Rings: 50x50 µm^2
- Superior radiation hardness (@1e16 n_{eq}/cm^2)
    - High efficiency: >97%
    - Low operational bias voltage: 80-140V
    - Low power dissipation <10mW/cm2 (@-25°C)
- 3 Vendors selected by Market Survey
- Pre-production runs finished at one vendor
- Good yield and electrical measurements
- The other vendors will deliver at end of 2021

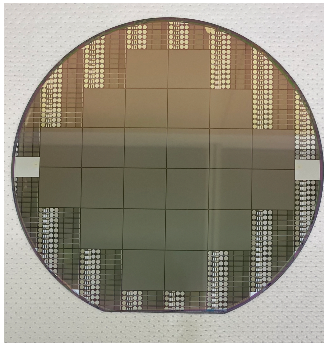




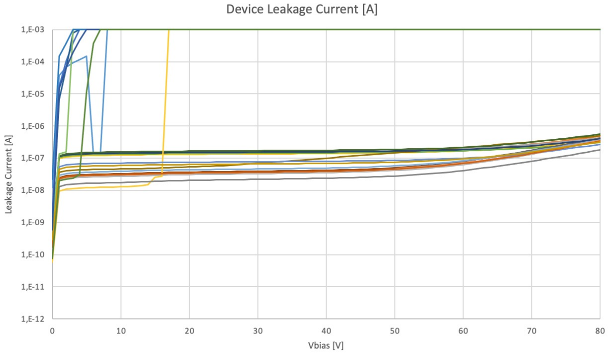




FBK ATLAS 3D 2021



> 65% yield!



Pixel Planar sensors

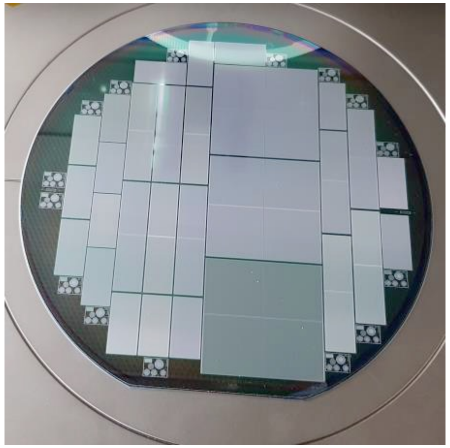
The present pixel system uses n-in-n planar sensors

IBL is 200um thick sensors with 50x250 μm^2 pixels

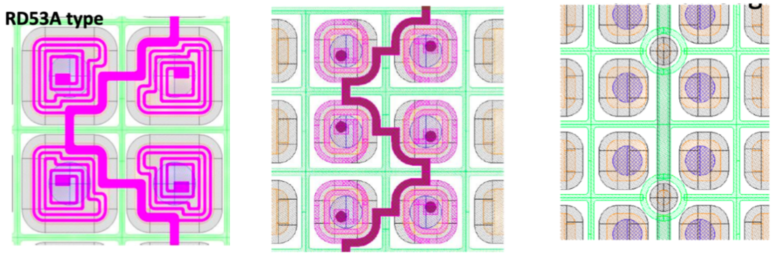
ITk will use n-in-p (single-side process), 50x50 μm^2 pixels

150 μm thick sensors for the outer layers;

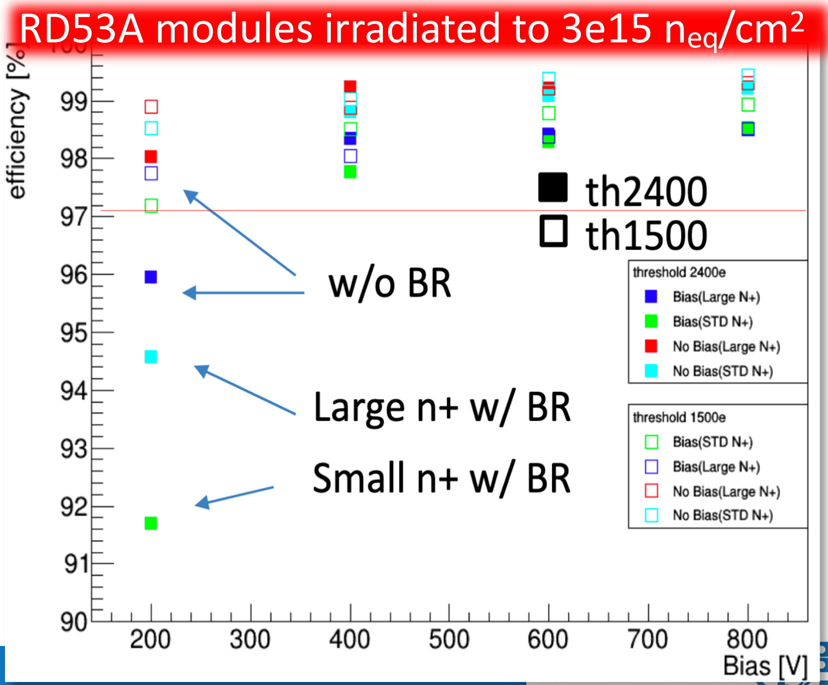
100 μm for the inner Layer-1



- Required performance
  - Hit efficiency >97%
  - Max bias voltage at end of life ($5x10^{15} n_{eq}/cm^2$)
    - 600 V for 150 μm active thickness
    - 400 V for 100 μm active thickness
- Five vendors qualified in Market Survey
  - Long and complex program of qualification with irradiations and test-beam characterization
  - Contracts in preparation with some of the vendors
- Final design frozen
  - Different biasing solution allowed
    - Punch through (PT)
    - Bias Rail (BR) and bias resistor
    - Temporary Metal (TM)



RD53A modules irradiated to 3e15 n_{eq}/cm^2



ITkPixV1 readout chip

See presentation of Maria Mironova later today !

Present RD53A large prototype in 65 nm

- Common ATLAS and CMS R&D
- Small pixel size: 50 x 50 µm²
- Three different Analog Front End (FE)
- Integrated shuntLDO regulators for serial powering

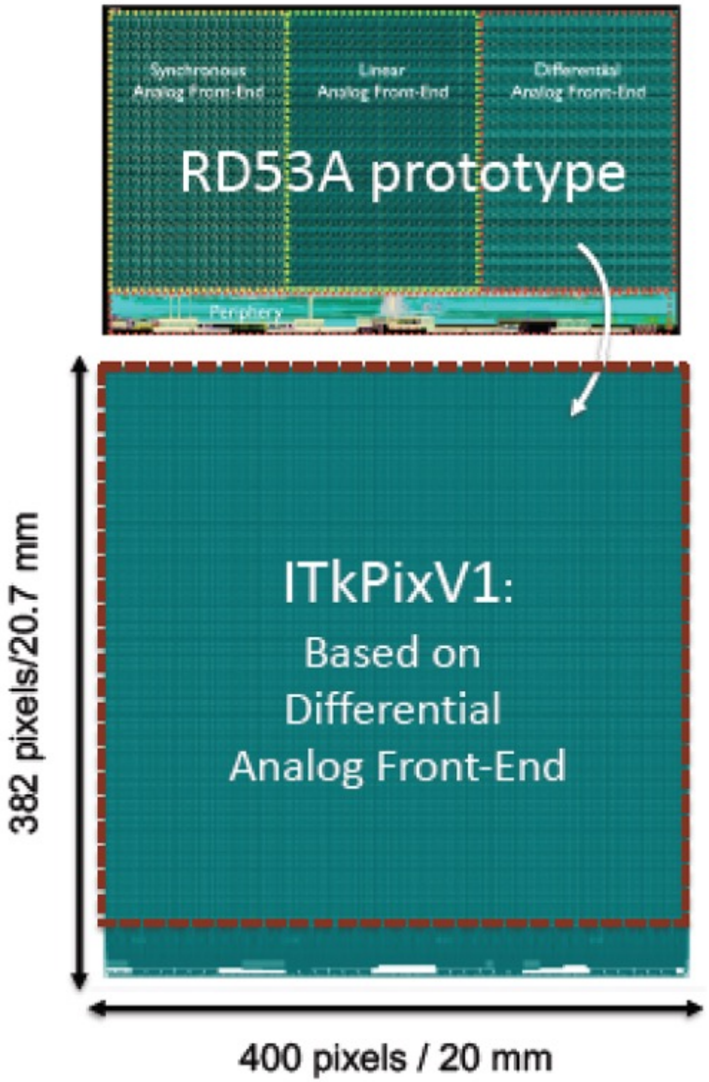
Full size chip ITkPixV1 (and ITkPixV1.1)

- Produced in 65 nm technology
- Radiation hard > 5 MGy, 10^{16} n_{eq}/cm^2
- Single Event Effects (SEE) hardened
- In time threshold < 1 ke
- Trigger rate: 1 MHz
- High hit rate: 3 GHz/cm2
- Improved shuntLDO design for serial powering
- Data format including compression
- Command forwarding

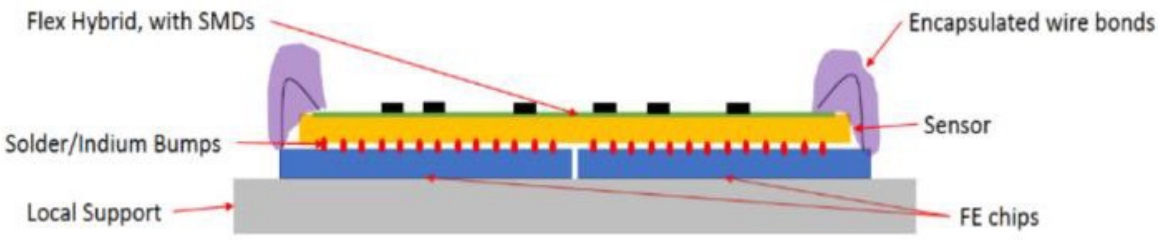
Prototyping and preproduction finished

(being used for modules and component qualification)

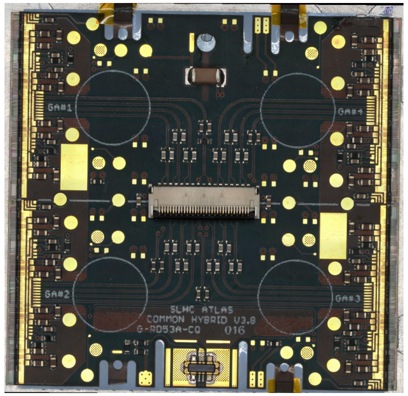
Production of ITkPixV2 foreseen Q1 2022



Module design

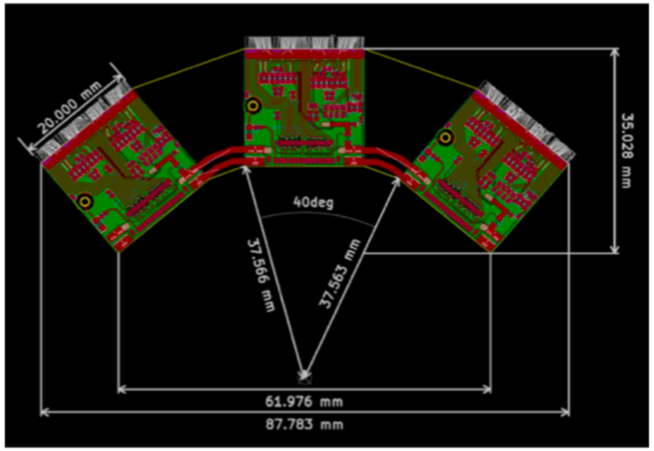


Layer 1-4 Quad



LinearTriplet Flex (Layer-0 barrel)

Ring Triplet Flex (Layer-0 rings)



Quad module (layers 1-4: barrel and rings)

- 1 large single sensor bump bonded to 4 readout chips
- Common design for all outer layers, just difference in pigtail
- Longest Serial Powering (SP) chain of 14 modules

Pseudo Triplets (innermost layer and rings)

- 3 single-chip bare modules connected to the same flex
- Power and ground in parallel + 1 data connector
- Limited space for services -> Serial Powering is essential
- Longest SP chain in L0: 5 SP units in endcap rings

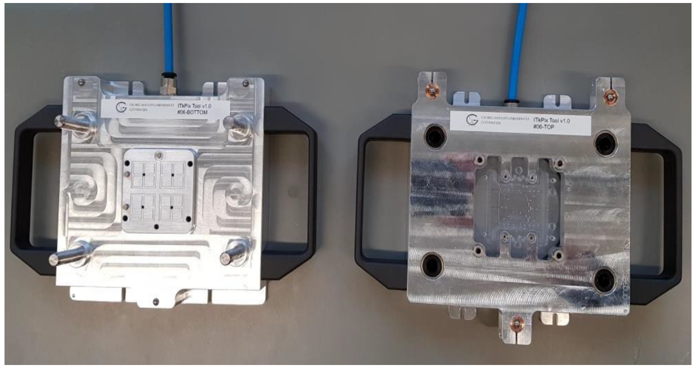
Parylene protection

- Reinforce bonds and to avoid corrosion
- Prevent discharge between sensor and front-end

Pixel modules construction

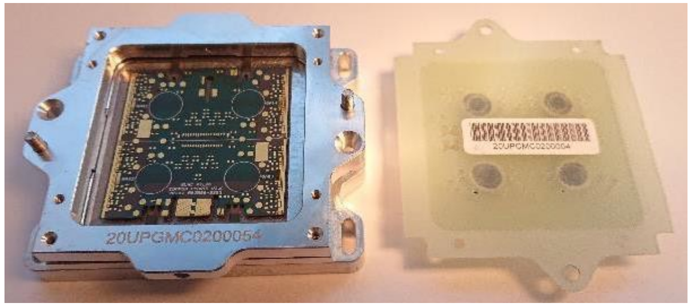
Hybridization

- Market survey of vendors running for different process steps: bump deposition, UBM, flip-chip.
- Program of quality assurance to validate the bump and assembly quality

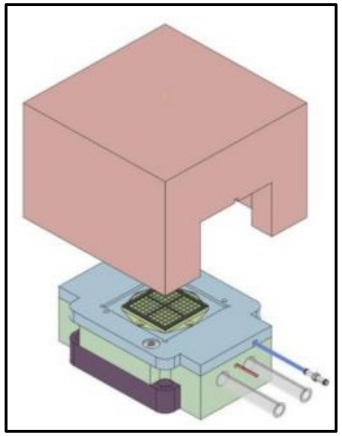


Flex-Hybrid design

- Designs for common flex hybrids finished
- Optimization of Cu layer thickness



About 20 laboratories, merged in clusters, have developed the experience to build modules



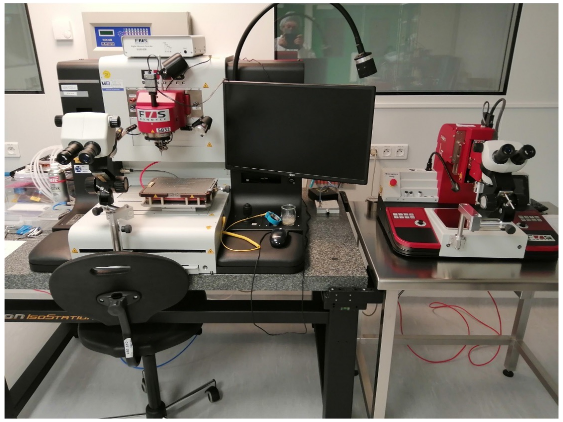
Extensive studies have been done using a program of~250 RD53A module prototypes

- Optimization of assembly jigs and tooling
- Procedure of flex cleaning
- Optimal glue deposition
- Wire-bonding

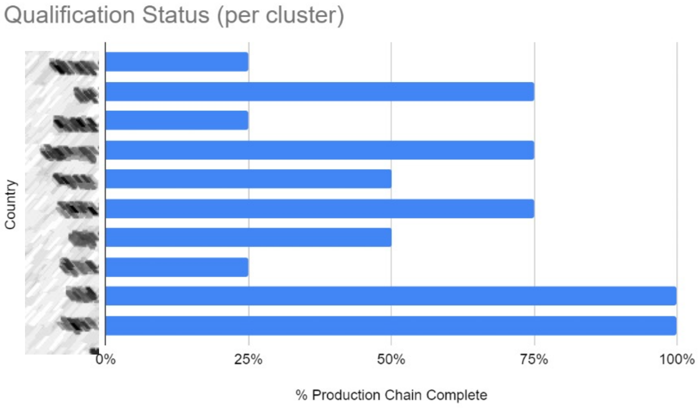
Construction readiness

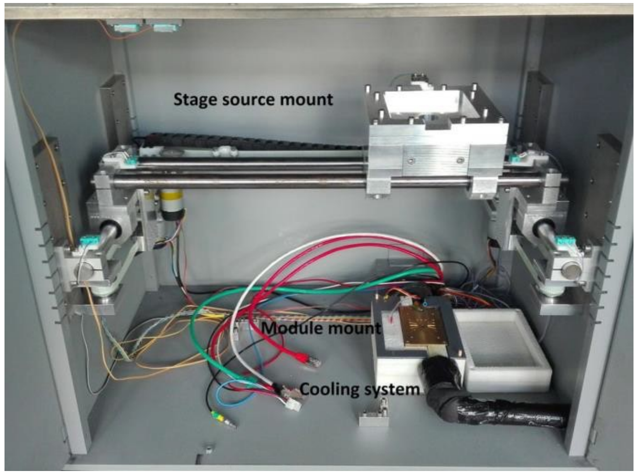
Qualification procedure for assembly and testing in the different sites and clusters

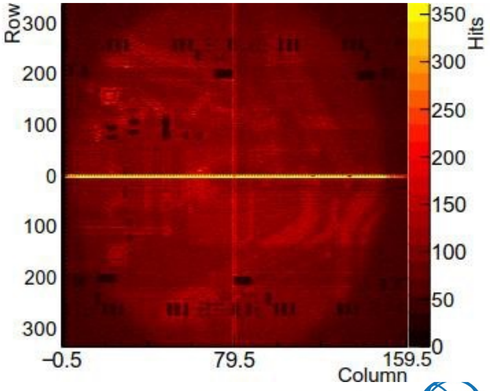
- Metrology
- Assembly and gluing
- Wire-bonding
- Parylene deposition and masking
- Testing and QA infrastructure
- Database interface



Quick progress in site the qualification status





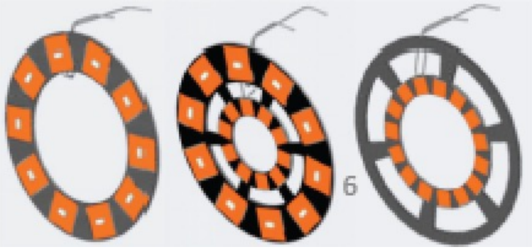


Local supports

Inner system:

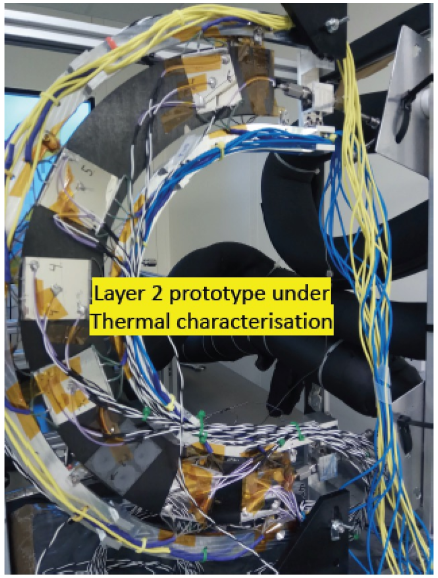
Barrel staves and coupled rings

Endcap: 2 additional flavors of rings



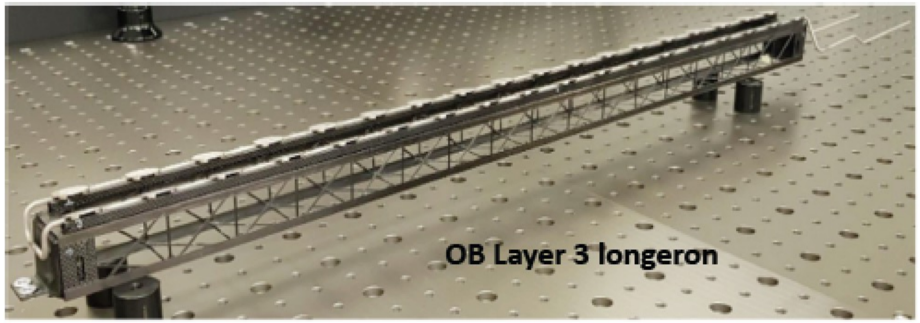
Outer Endcap:

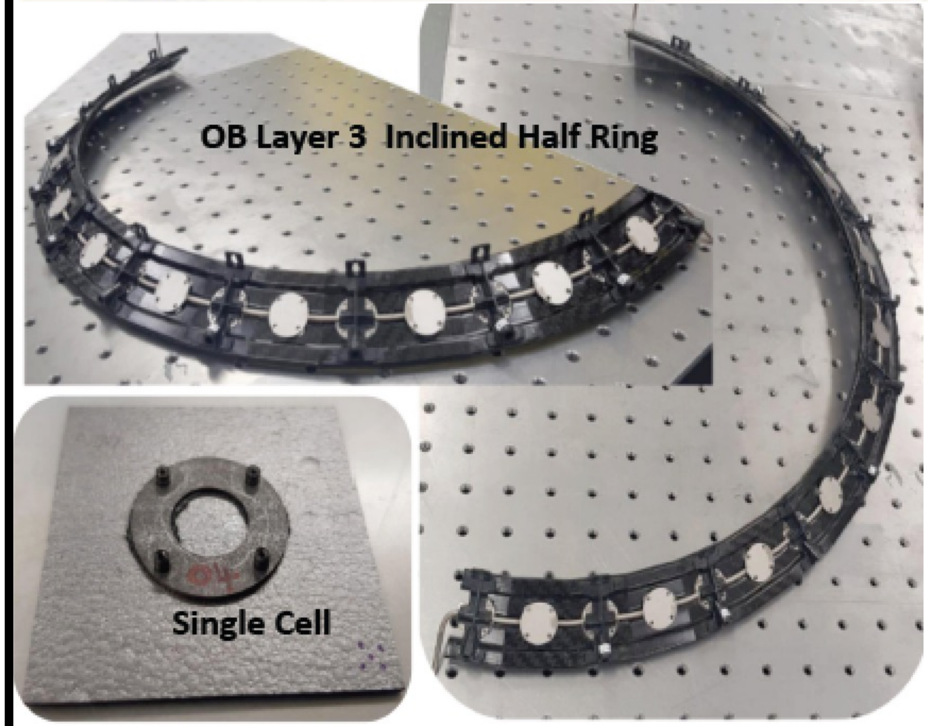
Double sided half rings



Outer Barrel:

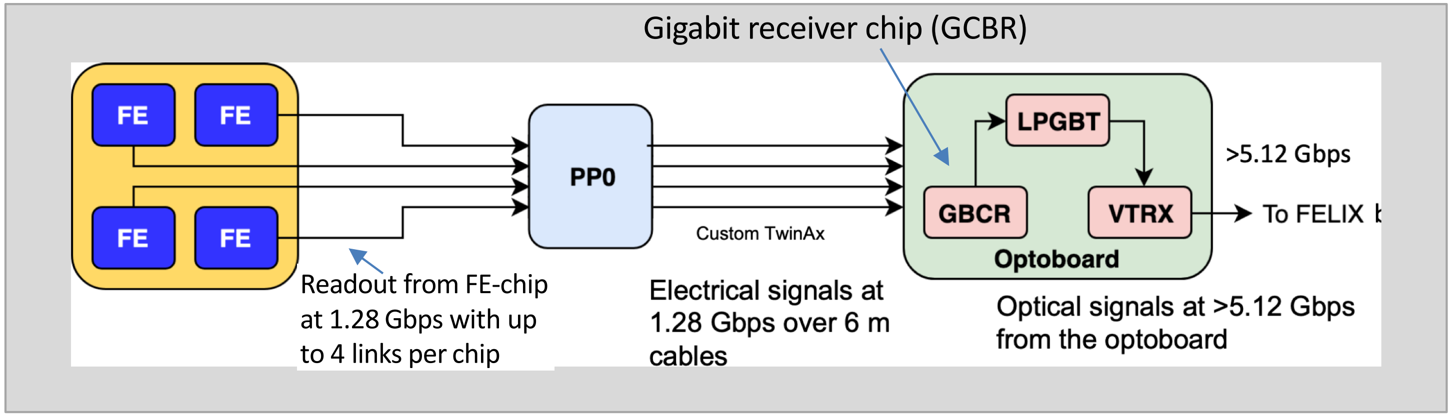
Longerons and inclined half rings





Modular approach for the local support, it allows total re-workability by replacing single cell

Pixel Data Transmission



Gigabit receiver chip (GCBR)

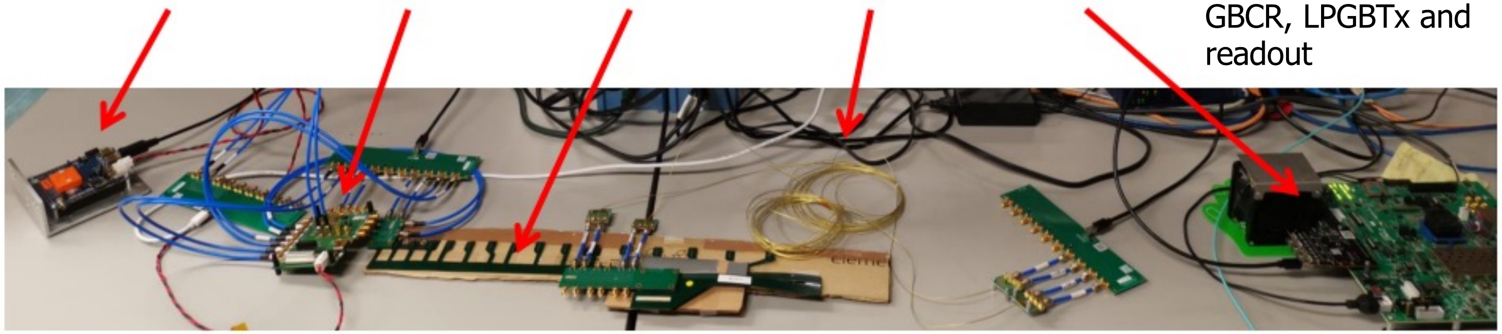
Readout from FE-chip at 1.28 Gbps with up to 4 links per chip

Electrical signals at 1.28 Gbps over 6 m cables

Optical signals at >5.12 Gbps from the optoboard

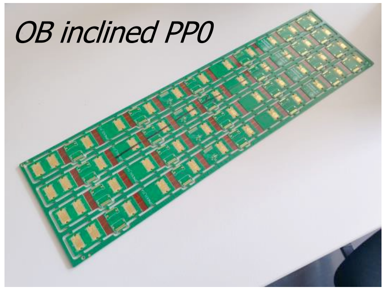
RD53a + Rd53b_cdr + Flex + 6m Twinax+ DAQ

FPGA used to simulate GBCR, LPGBTx and readout



- Results are encouraging (BER < 0.2e-12, spec is 1e-12) and studies continue as components become available
  - Included over summer GBCR v2
  - Use ITkPixV1, will improve on RD53A+RD53B CDR
  - Include final connectors and terminated cable
- System test will evolve but current system is already a realistic test

Optoboard



OB inclined PP0

Pixel Demonstrator Program

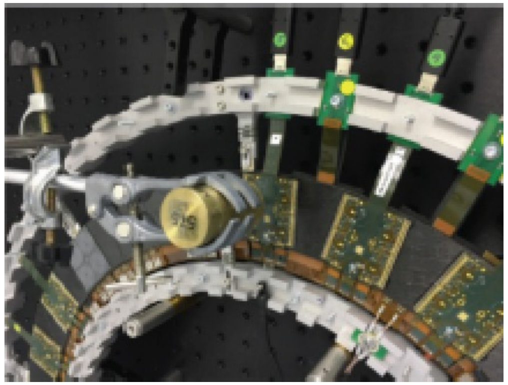
- **Simulations validated with demonstrators**

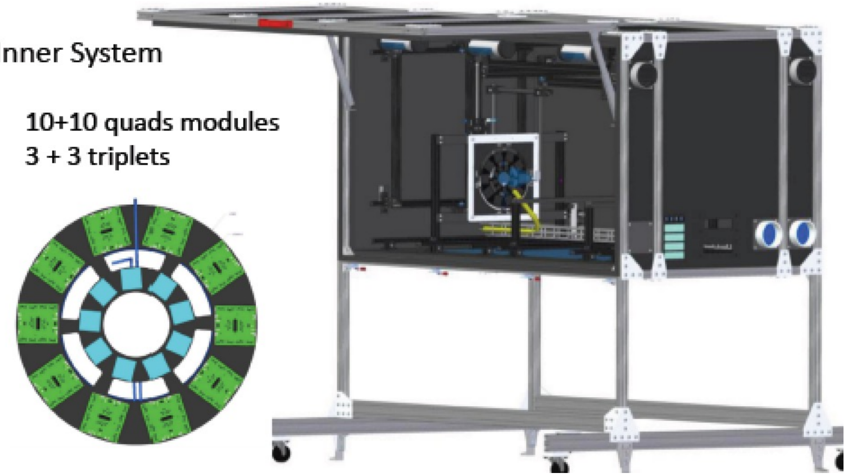
  (FE-I4 used, RD53A modules coming)

- **Endcap system tests with FE-I4-based prototypes**
  - **Ring-0**: 12 module ring structure (2 SP chains)

- **Outer barrel demonstrator programme**
  - Thermal and electrical prototypes
  - Full size prototype (1.6 m) with 7 quads and 1
    - 6 serial powering chains with electrical modul

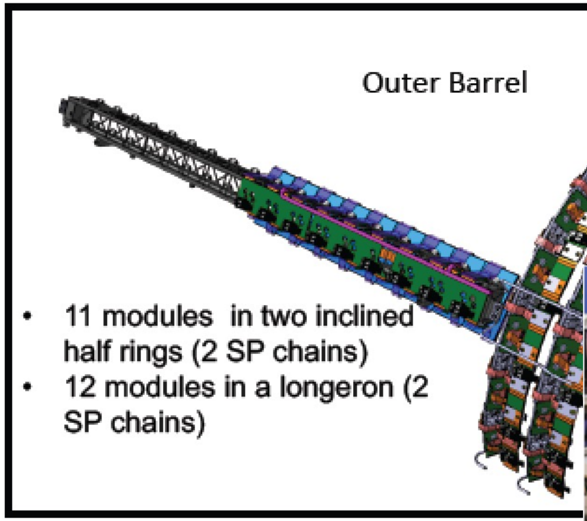
Outer endcap FE-I4 demonstrator





Inner System

- 10+10 quads modules
- 3 + 3 triplets



Outer Barrel

- 11 modules in two inclined half rings (2 SP chains)
- 12 modules in a longeron (2 SP chains)

Conclusions

The ATLAS ITk is moving from the R&D phase to a construction mode

A number of Final Design Reviews have already been passed and pre-productions started

- The Strip system is starting the preproduction for several parts of the system
  - Several issues solved between the readiness for preproduction and the actual start.
  - A lot of in-depth has been gained from the work leading to the Final Design Reviews
- The Pixel system has started more recently the preproduction of some components
  - 3D and planar sensors, FE chips on their way
  - Some last parameter has been fixed, such as the L0 radius or the pitch of the pixels
- Some of the procurements are very complicated
  - huge preparation time necessary and several negotiations with companies

Very important to freeze specs as soon as possible in the project

- The project has accumulated some delay with respect the original plan.
  - COVID has impacted the schedule directly and indirectly (example: testbeams, irradiation campaigns) but this seems now to have stabilized
  - Actions have been taken to catch up some time in the schedule (for instance, factorizing the review of some components from the main one)

The system seems now be sailing in more calm waters