UNIVERSITY OF BIRMINGHAM

The ATLAS ITk Detector System for the Phase-II LHC Upgrade

L. Gonella on behalf of the ATLAS collaboration

15th Pisa Meeting on Advanced Detectors

22 May 2022

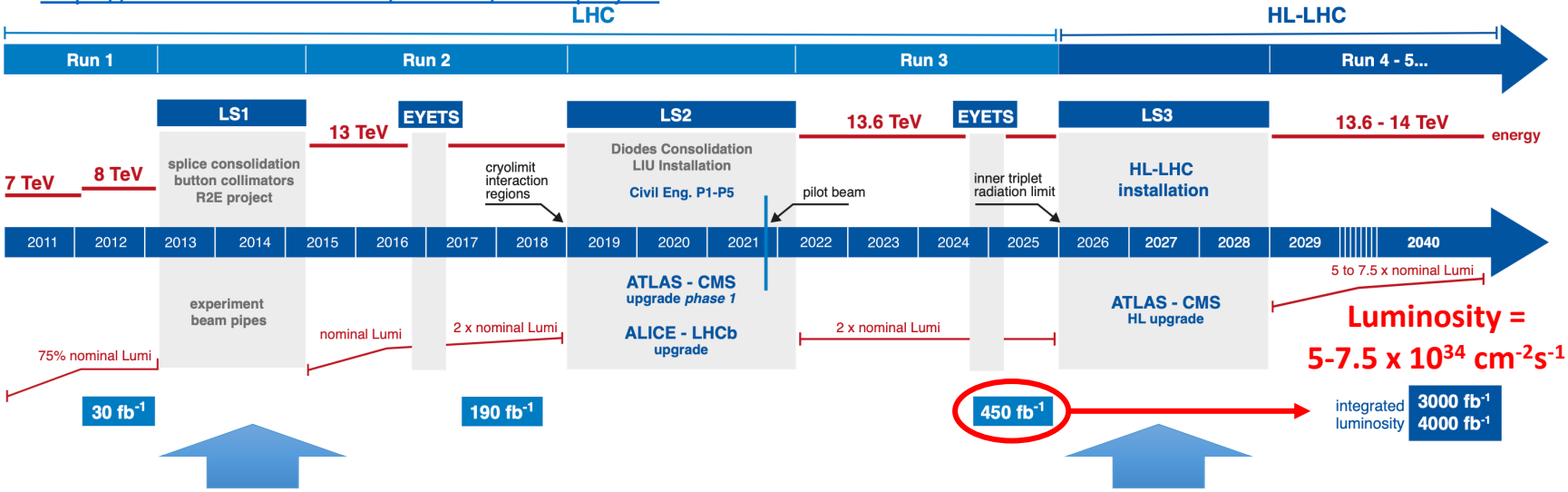
ATLAS ITk

High Luminosity LHC Upgrade

LHC / HL-LHC Plan

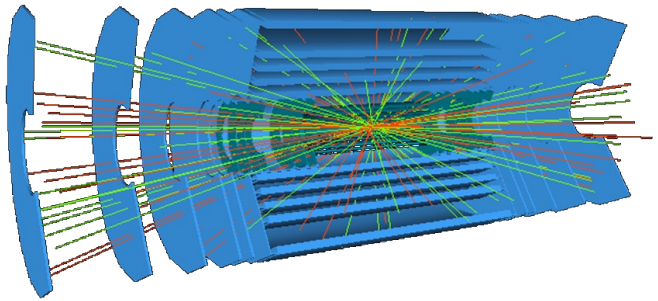
HiLumi LARGE HADRON COLLIDER

https://hilumilhc.web.cern.ch/content/hl-lhc-project



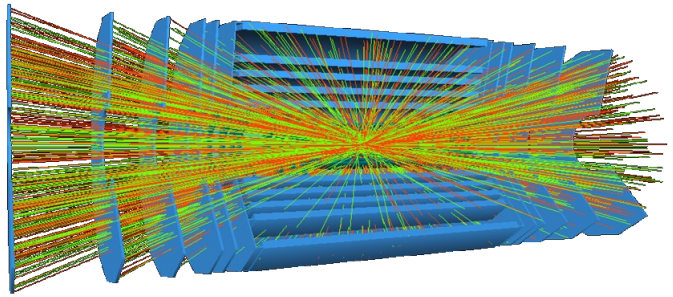
LHC: Inner Detector (ID) system, TRT (gas detector) + Strips + Pixels (with new Insertable B-Layer)

HL-LHC: New all-silicon **Inner Tracker (ITk)**, Strips + Pixels



LHC:
19 – 55
pile up events

HL-LHC:
140 – 200
pile up events



Tracking Challenges at the HL-LHC

- The ITk has to meet the HL-LHC challenges while maintaining (or improve upon) the tracking performance of the ATLAS ID.

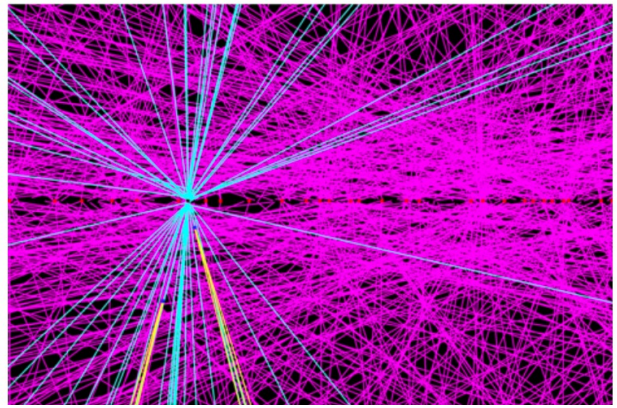
- Instantaneous conditions
  - Pile up, high event rate, increased occupancy.

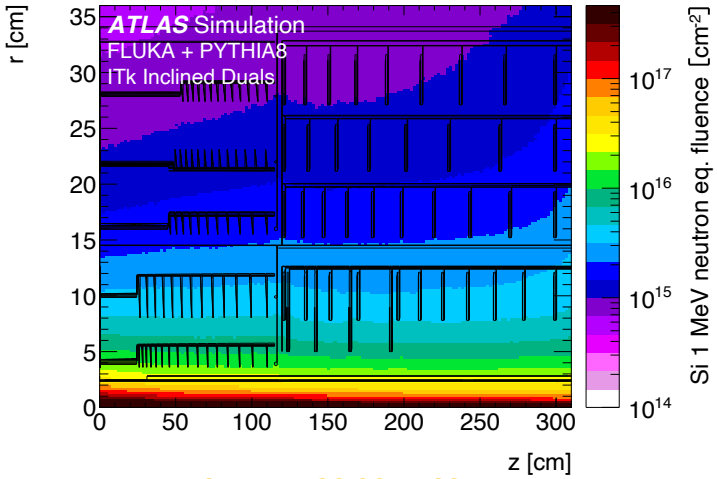
→ *Higher granularity sensor; SEE-robust, faster readout ASICs; redundant tracking for combinatorics.*

- Integrated effects
  - Particle fluence up to 2 x 10^{16} $n_{eq}cm^{-2}$ in the pixel region and 1.6 x 10^{15} $n_{eq}cm^{-2}$ in the strip region.
  - Total Ionizing Dose (TID) up to 10 MGy in the pixel region.

→ *Radiation hard technologies.*

$t\bar{t}$ event @ 140 avg. pileup





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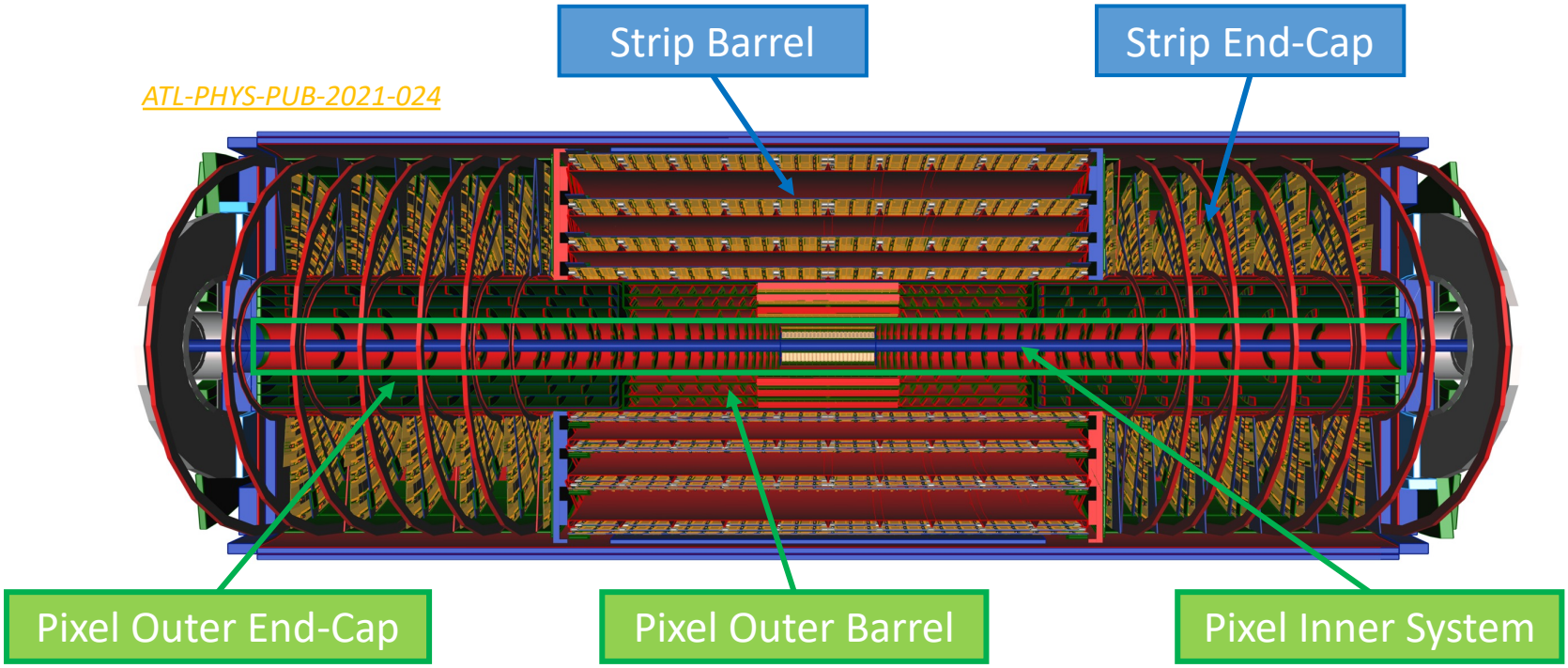
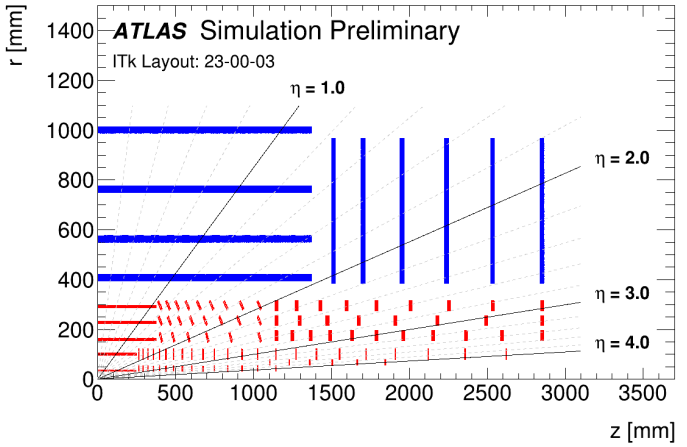
The ATLAS Inner Tracker - ITk

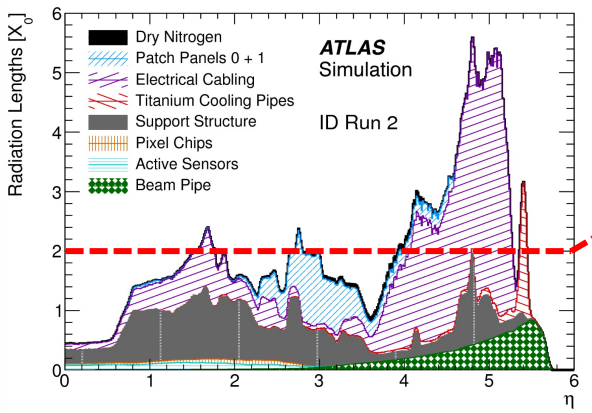


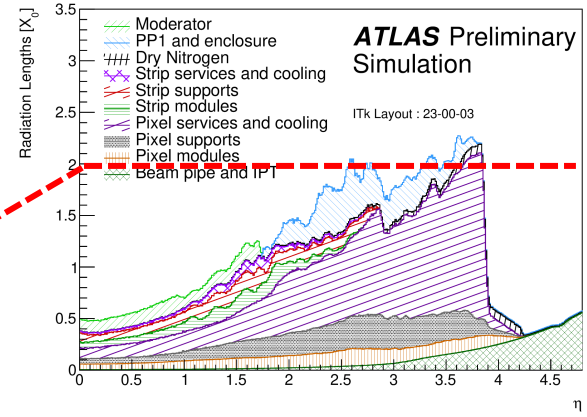
ITk (ID)	**Area (m^2)**	**# Modules**	**# Channels (M)**
Pixels	13 (1.6)	9164 (2000)	5100 (92)
Strips	165 (61)	17888 (4088)	60 (6.3)

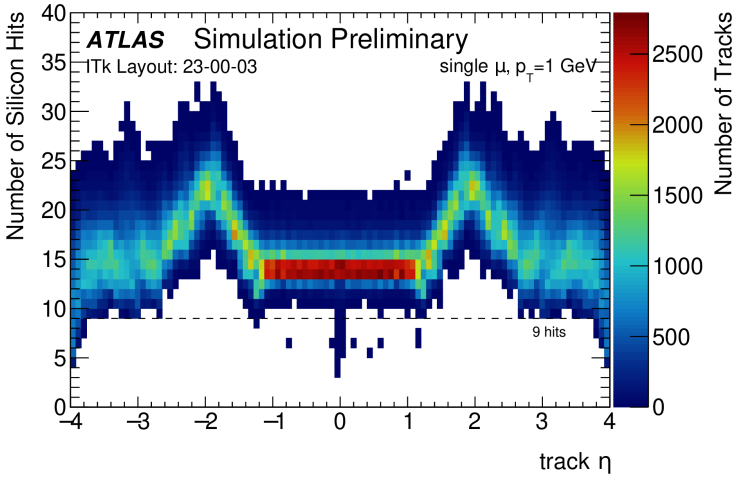
ITk Layout

- Extended coverage up to eta 4 with at least 9 space points per track.
  - 4 strips barrel layers, 2x 6 strips end-cap disks.
  - 5 pixels barrel layers (flat + inclined), novel pixel ring structure.
- Lower material budget than ATLAS ID.
  - Evaporative CO2 cooling system with titanium pipes.
  - Carbon structures for local supports.
  - Optimised number of readout cables using link sharing.
  - Innovative Serial Powering (SP) scheme in the pixels.









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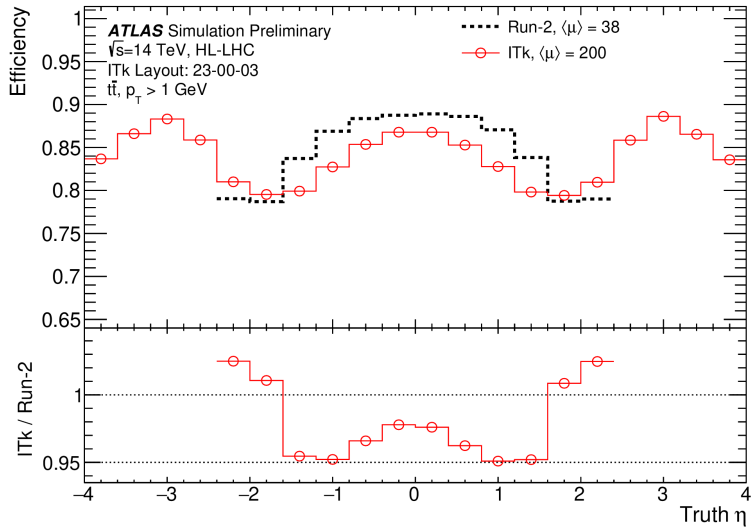
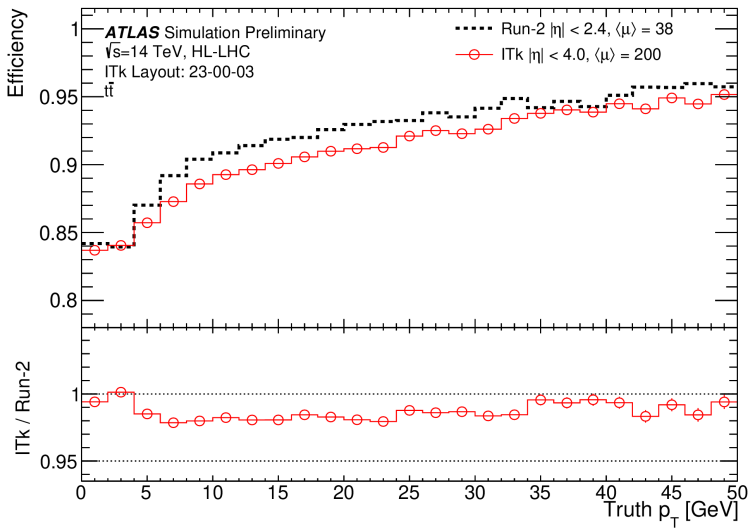
Example of Tracking Performance

- Tracking efficiency at 200 events pileup (ITk @ HL-LHC) vs 38 (ATLAS ID @ Run-2).
  - Similar performance to Run-2 in the barrel.
  - Improved efficiency over 85% at high-eta.





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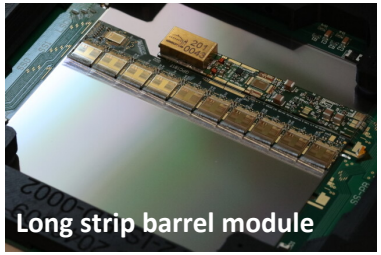
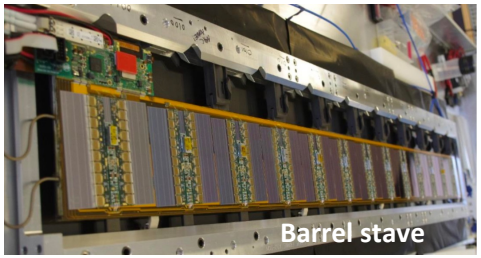
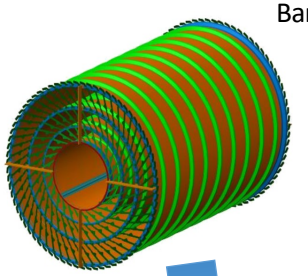
More results on ITk performance in these posters:
- Expected tracking and readout performance of the ATLAS Phase-II Inner Tracker Upgrade - Daniela Bortoletto.
- Expected reconstruction performance with the new ATLAS Inner Tracker at the High-Luminosity LHC - Marianna Testa.
And on general ITk detector operation and safety aspects on these posters:
- An environmental monitoring and control system for the ATLAS Outer Barrel QC and Integration - Nicola Pacifico
- The ITk interlock hardware protection system - Susanne Kersten

ITk Strips Detector Overview





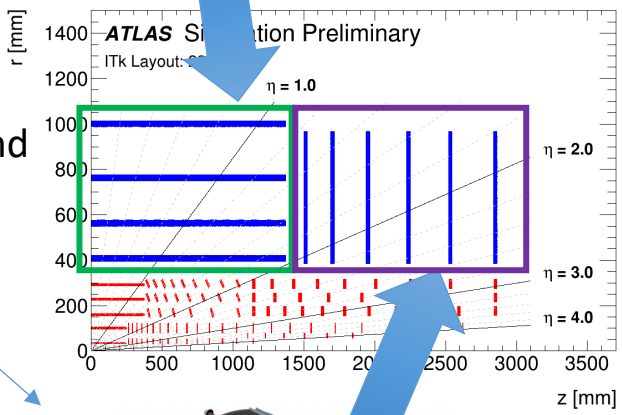
Barrel Global Support

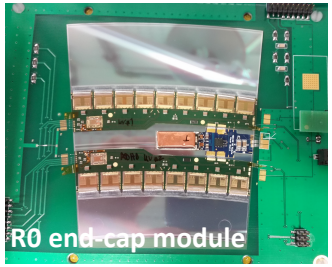


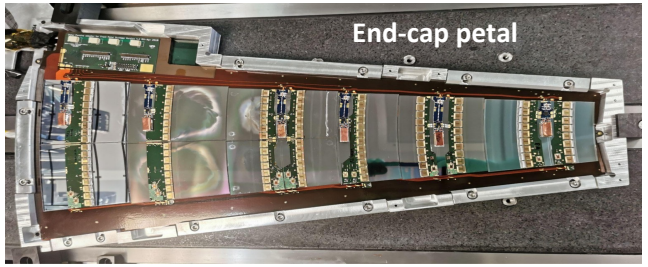
Modules
Basic building block.

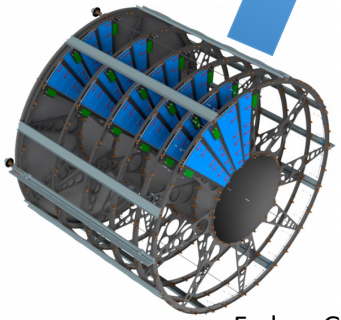
Global mechanics
Carbon cylinders for staves and carbon wheels for petals.

Local Supports
Barrel staves, end-cap petals. Modules loaded on two sides with small stereo angle to provide 2D measurements.







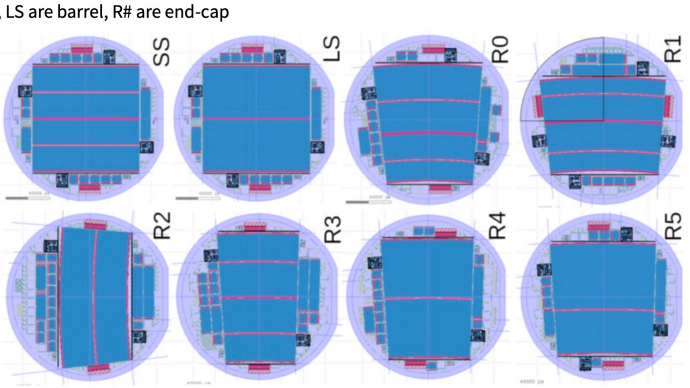


Endcap Global Support

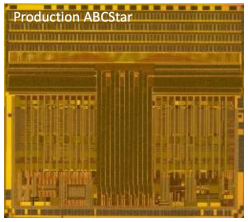
ITk Strips Modules

- Different module flavours based on sensor geometry for barrel (short and long strips) and end-caps (R0, …, R5).

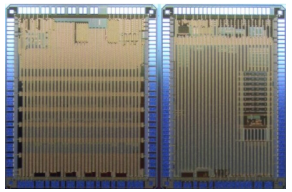
- Common modular design: sensor + hybrid + powerboard.
  - Hybrid: (up to 12) strips binary readout chips (ABCStar) and up to 2 controller chips (HCCStar).
  - Powerboard: HV switch and filter, LV DC-DC converter, Monitor and control chip (AMAC).

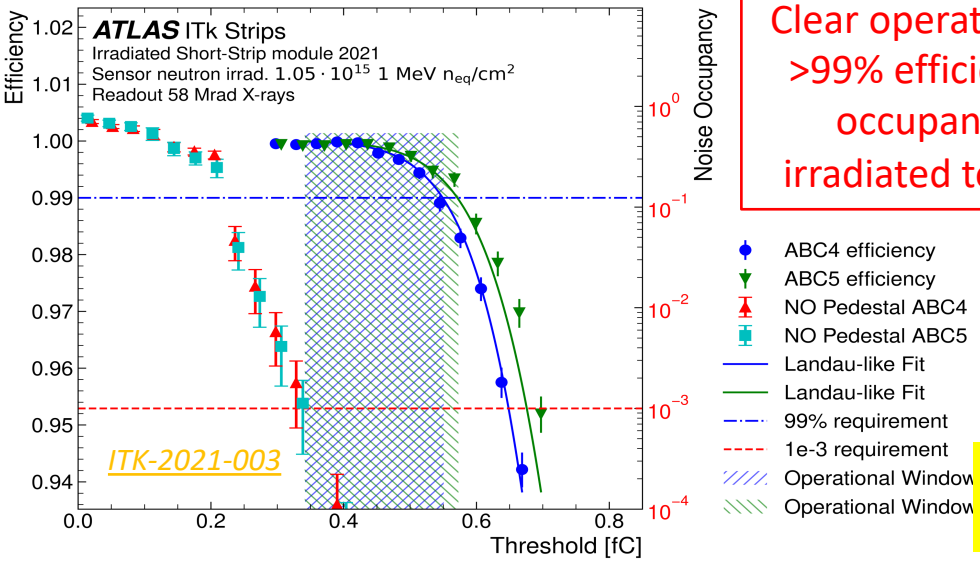


ABCStar

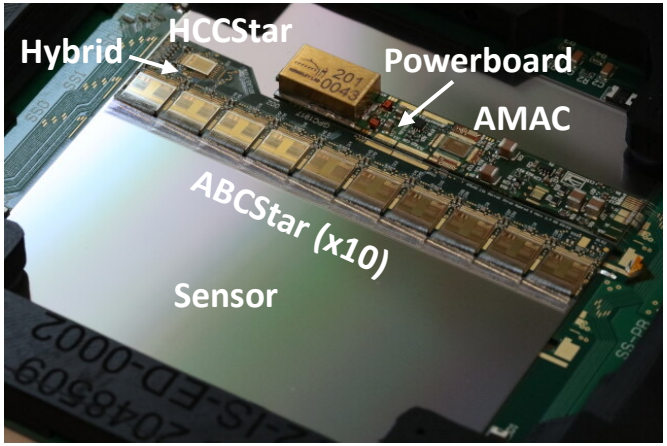


HCCStar + AMACStar





Clear operational window with >99% efficiency, <0.1% noise occupancy for modules irradiated to end-of-life dose.



Four posters on ITk strip sensor characterisation (Jiri Kroll; David Rousso; Xavi Fernandez-Tejero; Vera Latonova).

ITk Strips Module Production

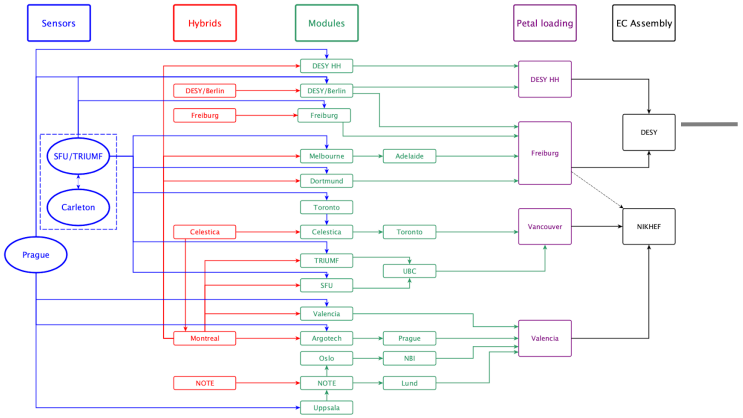
- Global effort with 11/20 assembly and testing sites for barrel/endcaps to build 17888 modules in 3 years
  - Including yield 20625 to be built.
  - Extensive QC/QA procedures on all components and on the modules.

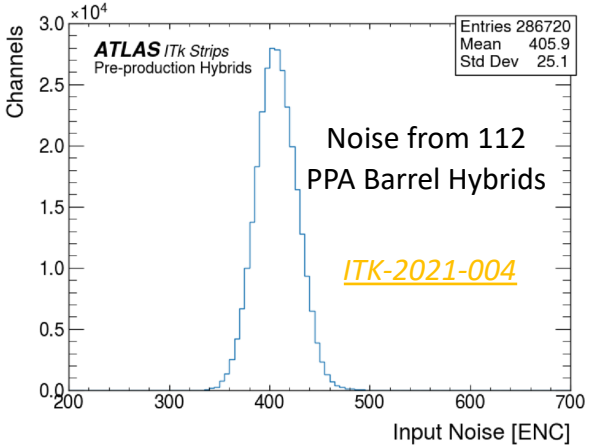
- All sites undergoing site qualification to setup and verify full assembly, bonding, storage/shipping, electrical/QC testing, DB upload procedures; 72% completed.

- Module Pre-Production (PP) well underway.
  - Build ~1000 modules to demonstrate readiness for full production.
  - PP-A with PP sensor and ABCStar, else prototype components, almost completed.
  - PP-B modules with all PP parts starting.
  - Production Readiness Review in Sept 2022.

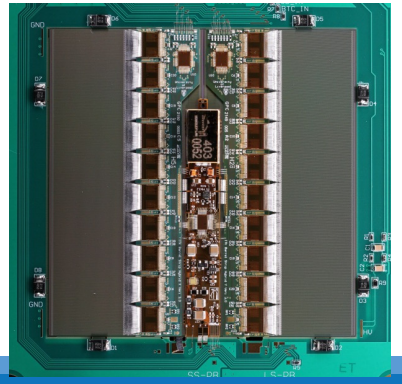
Production to start in Q4 2022

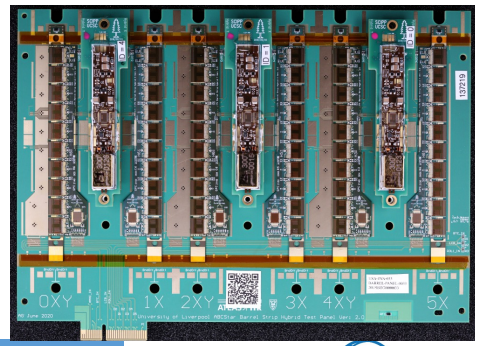
End-cap overall part flow





First PPB module and hybrids



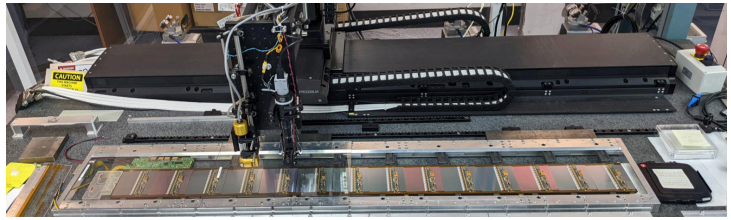


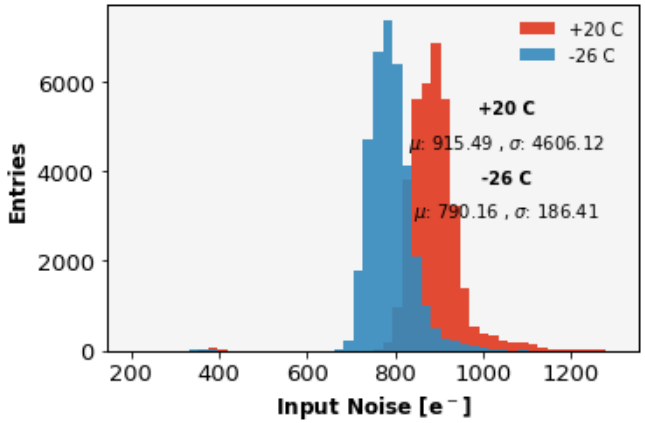
ITk Strips Support Structures

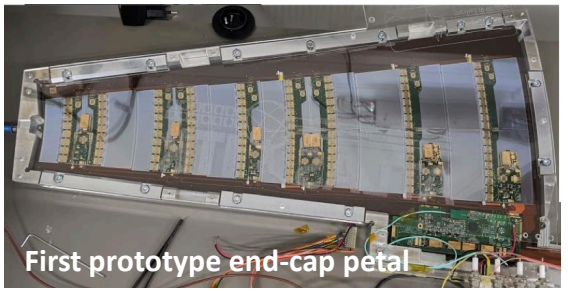
- Local support structures
  - Carbon-fiber composite with integrated electrical and cooling interfaces.
  - Co-cured polyimide/copper bus tapes, EOS card (data links & power).
  - Pre-production of both staves and petals ongoing.
  - First pre-production stave loading ongoing, one side fully assembled, preliminary results on noise performance as expected.

- Global mechanics parts are in production, most elements nearing completion in end-cap.

First PP-A barrel stave (one side)



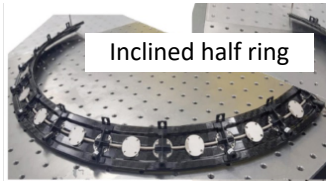


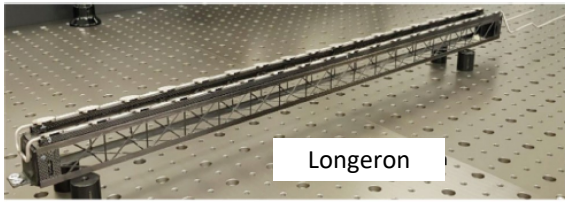


See poster session: Electrical performances of pre-productions staves for the ATLAS ITk Strip Detector Upgrade - Punit Sharma

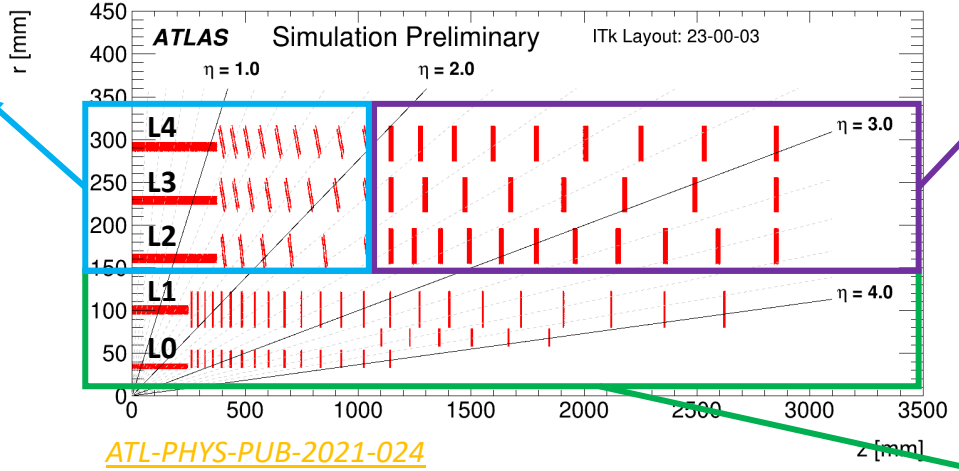
ITk Pixels Detector Overview

Local supports: Different designs to support flat and inclined module mounting.





Outer Barrel (OB)



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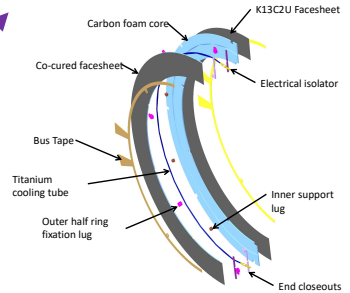
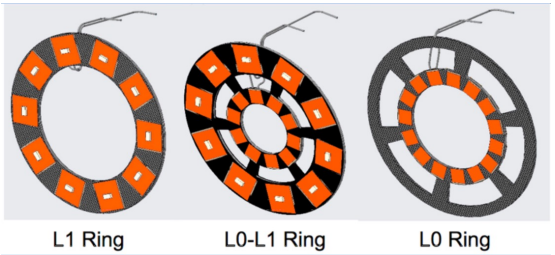
Outer End-Cap (EC)



Inner System (IS)



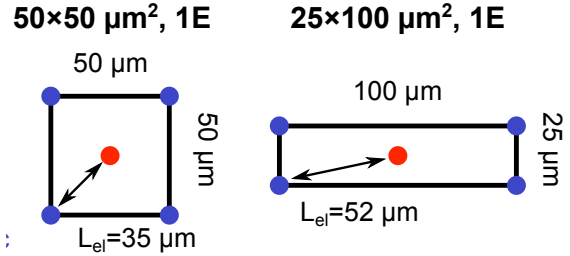
Modules: two main module types, quad & triplet.
(Variations of pixel size and sensor thickness within each type)

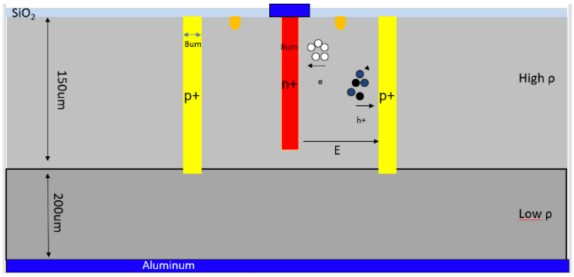
Layer	Module type	Sensor type	Sensor thickness [um]	Pixel size [um^2]
L0 barrel	Triplet	3D n-in-p	150	25x100
L0 rings	Triplet	3D n-in-p	150	50x50
L1	Quad	Planar n-in-p	100	50x50
L2-4	Quad	Planar n-in-p	150	50x50

IS to be replaced after 2000fb^{-1} to reduce radiation damage.
L0 placed 34 mm from beam pipe.

ITk Pixels 3D Sensors

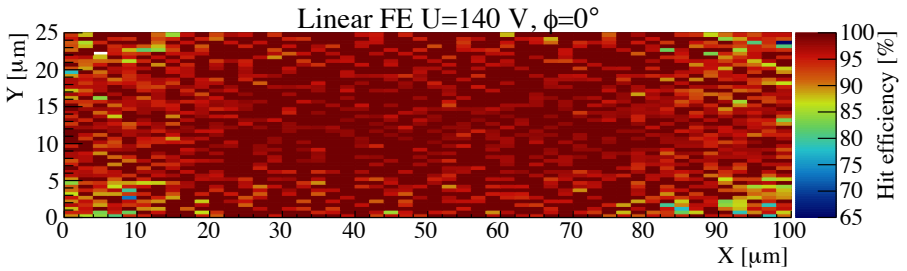
- 3D sensors with new single-side technology.
  - Thin active substrates (150 µm) → Reduced cluster size and data rates.
  - Small pixels → Low occupancy, improved impact parameter resolution.

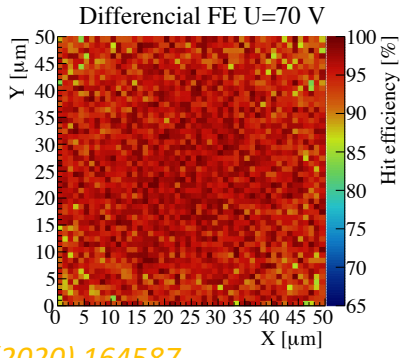




- Efficiency >96-97% at 1.6 x 10^{16} n_{eq}/cm^2.
  - Bias <150V, power < 40 mW/cm² (at -25C).
  - Measured on prototypes. Irradiation of PP sensors starting.

In pre-production





NIM A 182 (2020) 164587

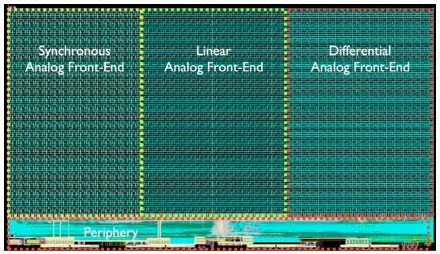
ITk Pixels ASIC

- New Front-end ASIC in 65 nm CMOS technology.
  - Common ATLAS and CMS R&D.

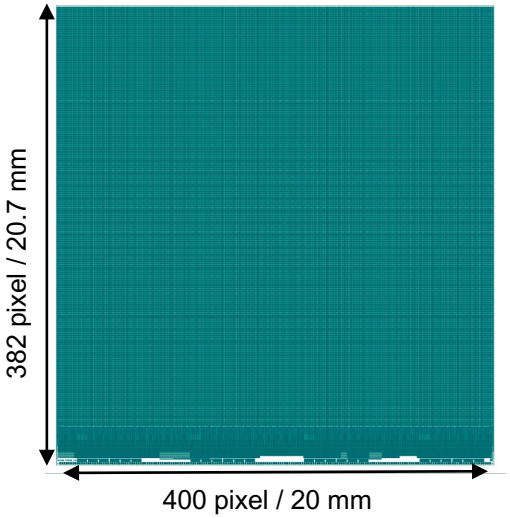
- RD53A: large prototype.
  - Small pixel size: 50 x 50 μm^2.
  - Three different Analog Front End (FE).
  - Integrated shuntLDO regulators for serial powering.

- Full size chip ITkPixV1/V1.1/V2.
  - Radiation hard above 5 MGy (10^{16} $n_{eq}cm^{-2}$), SEE hardened.
  - Trigger rate: 1 MHz.
  - High hit rate: 3 GHz/cm^2.
  - Improved shuntLDO design for serial powering.
  - Data format including compression.
  - Command forwarding.

RD53A prototype



Full size chip ITkPixV1/V1.1/V2



ITkPix V1 in pre-production.
ITkPix V2 submission in June.

ITk Pixels Modules

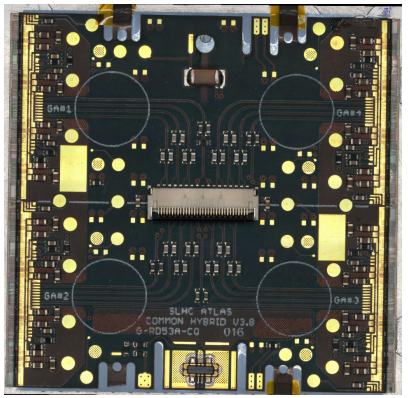
- Module = Sensor + ASIC + flex circuit.
  - Hybridization: bump bonding of sensor to ASICs.
  - Flex attachment.
  - Parylene protection deposition: reinforce bonds, avoid corrosion, prevent discharge between sensor and front-end.

- Quad module: one large single sensor bump bonded to four ASICs.
- Triplet: three single-chip modules connected to one flex.

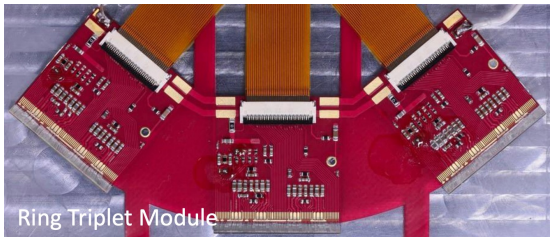
- More than 200 RD53A module prototypes built.
- First prototype modules with ITkPixV1/1.1. becoming available.

- Module pre-production starts Q3-22.
- Module production starts Q3-23.
  - 2 years, 9000 modules, approx. 20 assembly sites.

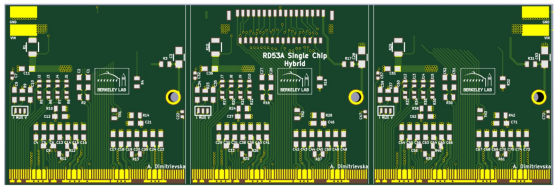
Quad module



Ring triplet module



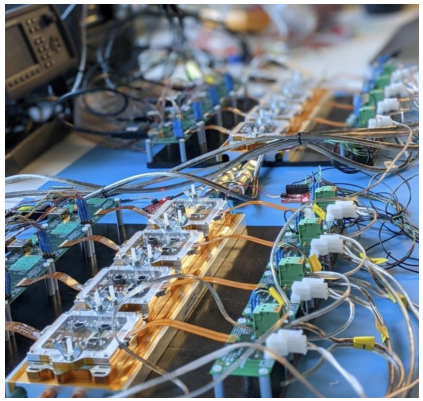
Barrel triplet flex



See poster session: Module development for the ATLAS Phase II Pixel Inner Tracker - Abhishek Sharma

ITk Pixel Demonstrators

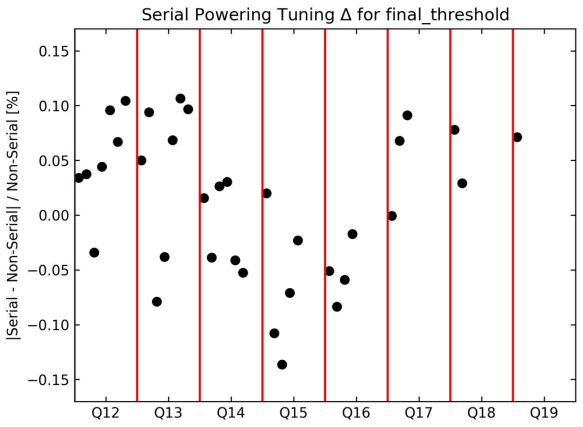
- Early programme of pixel system demonstrators with ATLAS IBL FE chip (innermost ID layer) for OB and EC.
- Demonstrators programme now moving to RD53A modules → all the subsystems are building loaded supports in view of the pre-production.
- Serial Power chain tests with RD53A modules.
  - Quad and irradiated single chip modules.
- IS rings and staves partially loaded, testing ongoing.
  - R0/1 ring, 1 side fully loaded, 3 ring triplets, 10 quads.
  - L0 stave, 1 side fully loaded, 1 side partially loaded, 4+4 linear triplets.
  - L1 stave, 1 side fully loaded, 1 side partially loaded, 6+6 linear triplets.



8-module serial power chain

R0/1 demonstrator with RD53A modules

Quad module minimum threshold operation versus powering option



See poster session: ATLAS ITk Pixel demonstrators - Jonathan Thomas Taylor

Conclusion

- A new tracking system is being developed by the ATLAS experiment for the HL-LHC to cope with increased particle multiplicity and radiation levels.

- The new all-silicon Inner Tracker (ITk) provides large acceptance, a large number of points per track, high granularity and radiation hardness with minimised material budget.

Strips and pixels detectors have demonstrated the required functionality for tracking is maintained up to end-of-life dose.

- The Strip system is progressing through pre-production and production has started for several parts (sensors, ASIC, global mechanics).

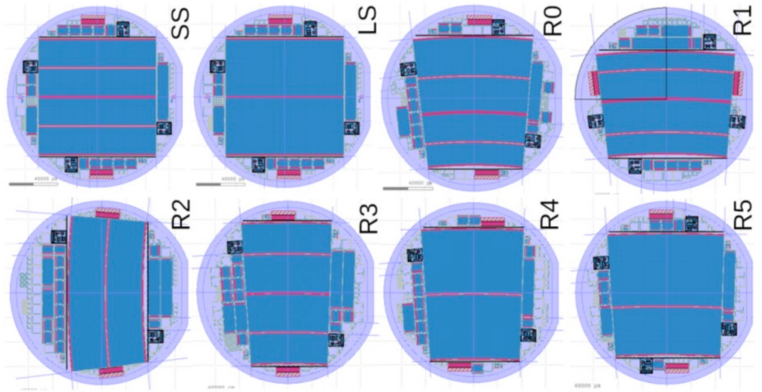
- The Pixel system is finalising an extensive prototyping phase and has recently started pre-production of some components.

Backup slides

ITk Strips Sensor

- 320 µm thick float zone n-in-p silicon.
- 8 sensor geometries.
  - 2 for the barrel, 75.5 µm strip pitch.
  - 6 for the end-caps, 70 to 80 µm pitch.
  - One sensor/wafer + test structures.

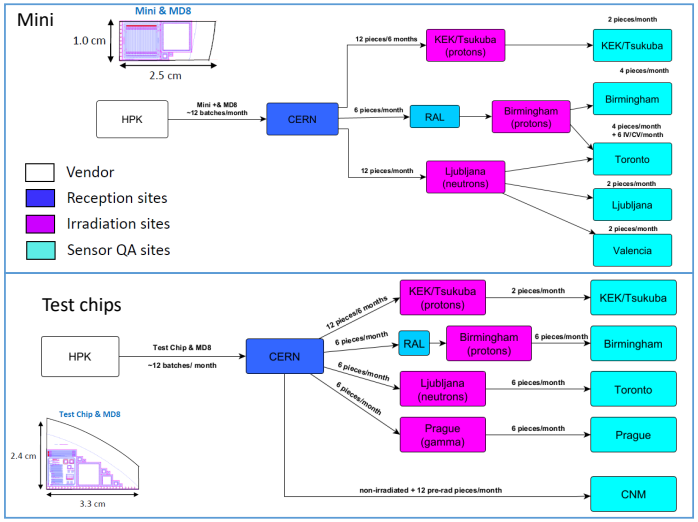
SS, LS are barrel, R# are end-cap



- First production batch delivered August 2021.
  - 17% of production sensors delivered.
  - 40/114 batches approved so far, 1 rejected after QC/QA.
  - 4 months acceptance testing period.

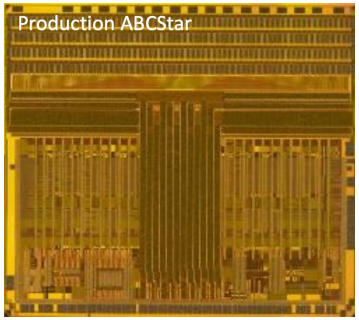
- Extensive QC on main sensor and QA on test structures.
  - 7 QC and 7 QA testing sites.
  - QA irradiations with neutrons, protons, gamma rays.
  - ~ 500 production QA pieces (108 batches) irradiated and tested.

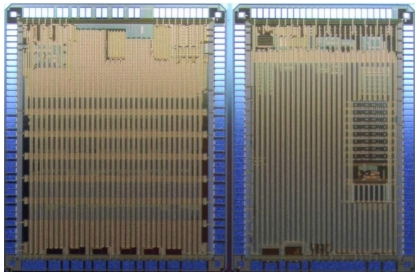
QA test structures distribution for irradiation and testing



ITk Strips ASICs

- Three custom developed ASICs in 130 nm technology.
- Pre-production version of all three ASICs extensively modified to improve SEE protection.
  - Tested in heavy-ions and protons with excellent performance.
  - Pre-production ABCStar with triplication enabled had no measured Single Event Upset (SEU).
- ABCStar
  - Wafer probing at two sites, including one industrial partner.
  - Pre-production completed with yield ~92%, dicing and distribution to hybrid assembly sites ongoing.
  - Production started, received ~30% of first batch.
- HCCStar/AMAC
  - Produced on same wafers, one probing site.
  - Pre-production delivered, yield well above 90%.
  - PRR in June, production to start Q3-2022.





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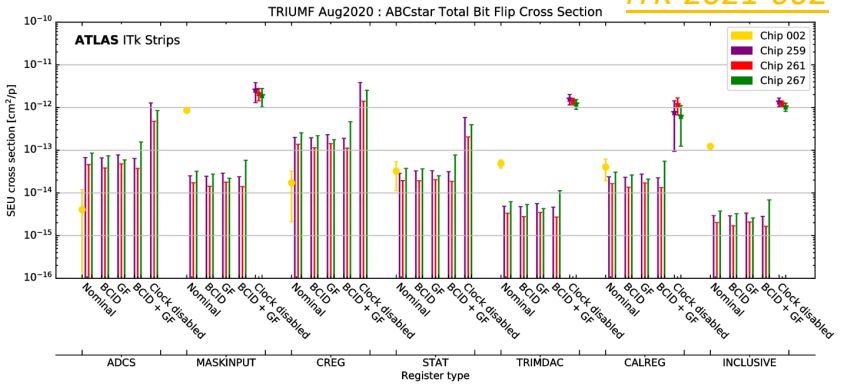

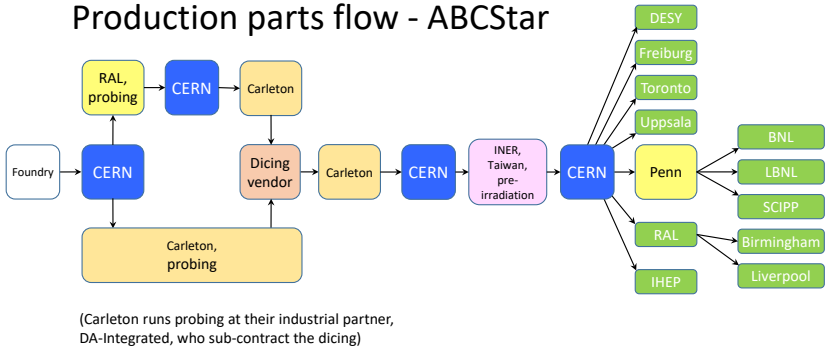

(Carleton runs probing at their industrial partner, DA-Integrated, who sub-contract the dicing)

ITk Pixels Planar Sensors

- Thin n-in-p planar n-in-p sensors technology (single-side process) with 50x50 µm^2 pixel cells.
  - 150 µm for the outer layers, 100 µm for the Layer-1 (more rad-hard).

- Different testing solution employed.
  - Punch through (PT).
  - Bias rail and bias resistor (BR).
  - Temporary Metal (TM).

- Performance required.
  - Hit efficiency >98%.
  - Bias voltage at 5e15 n_{eq}/cm^2 up to:
    - 600 V for 150 µm active thickness.
    - 400 V for 100 µm active thickness.

- Pre-production ongoing for both thicknesses.