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ATLAS ITk Pixel Detector Overview

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Pixel Detectors for Particles and Imaging,
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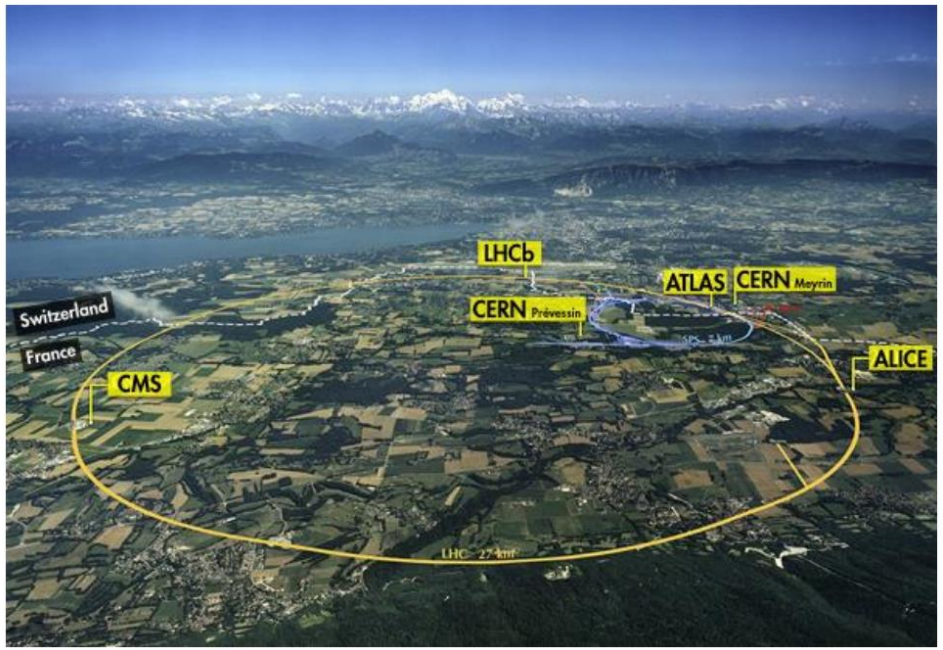
Outline

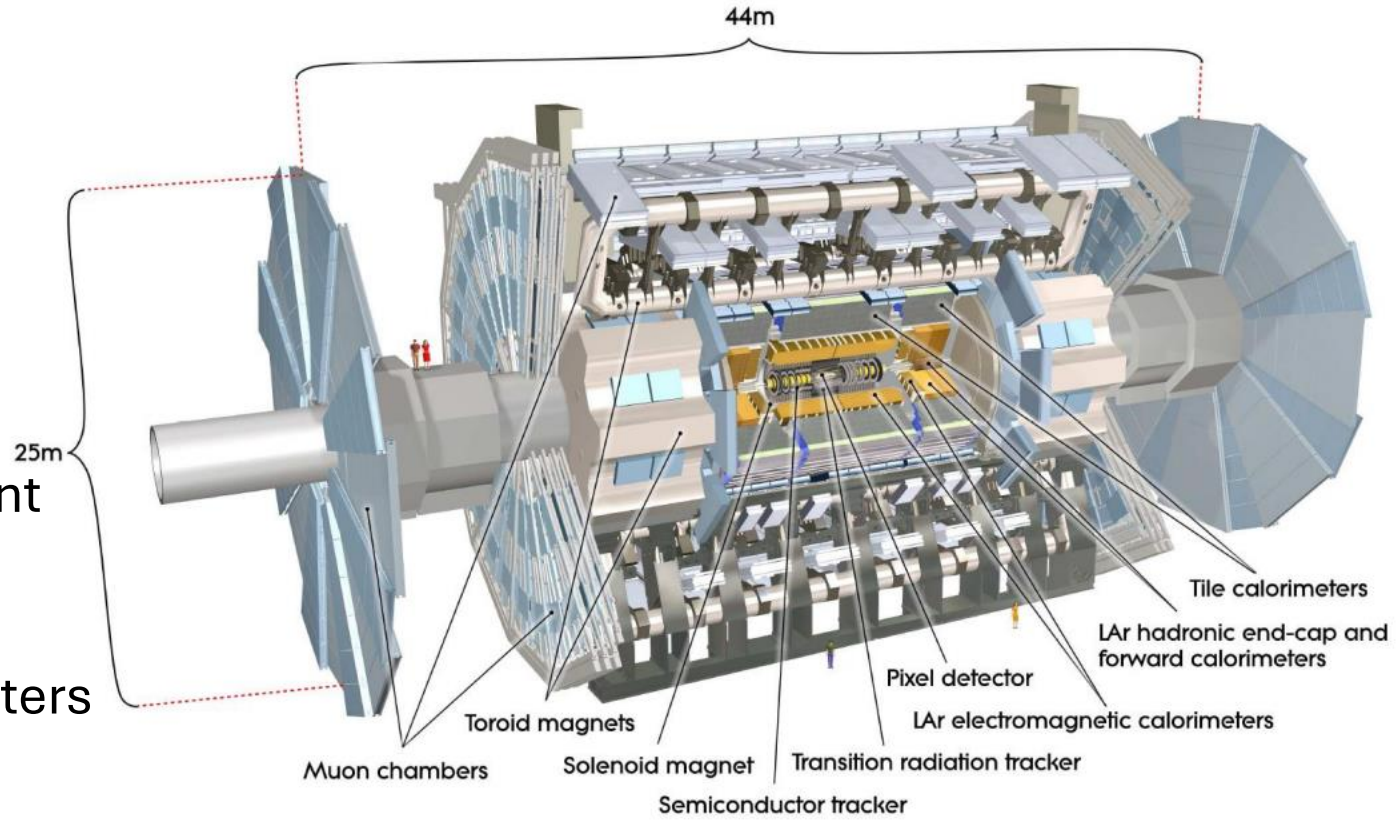
- The ATLAS Experiment and its high luminosity phase
- The new Inner Tracker
- Silicon sensors
- Hybrid modules
- Mechanical structures
- System tests
- Current status
- Conclusions

The LHC and the ATLAS Experiment



The Large Hadron Collider at CERN

- Proton-proton collisions at 14 TeV center of mass energy
- 27 km circonference
- 4 experiments



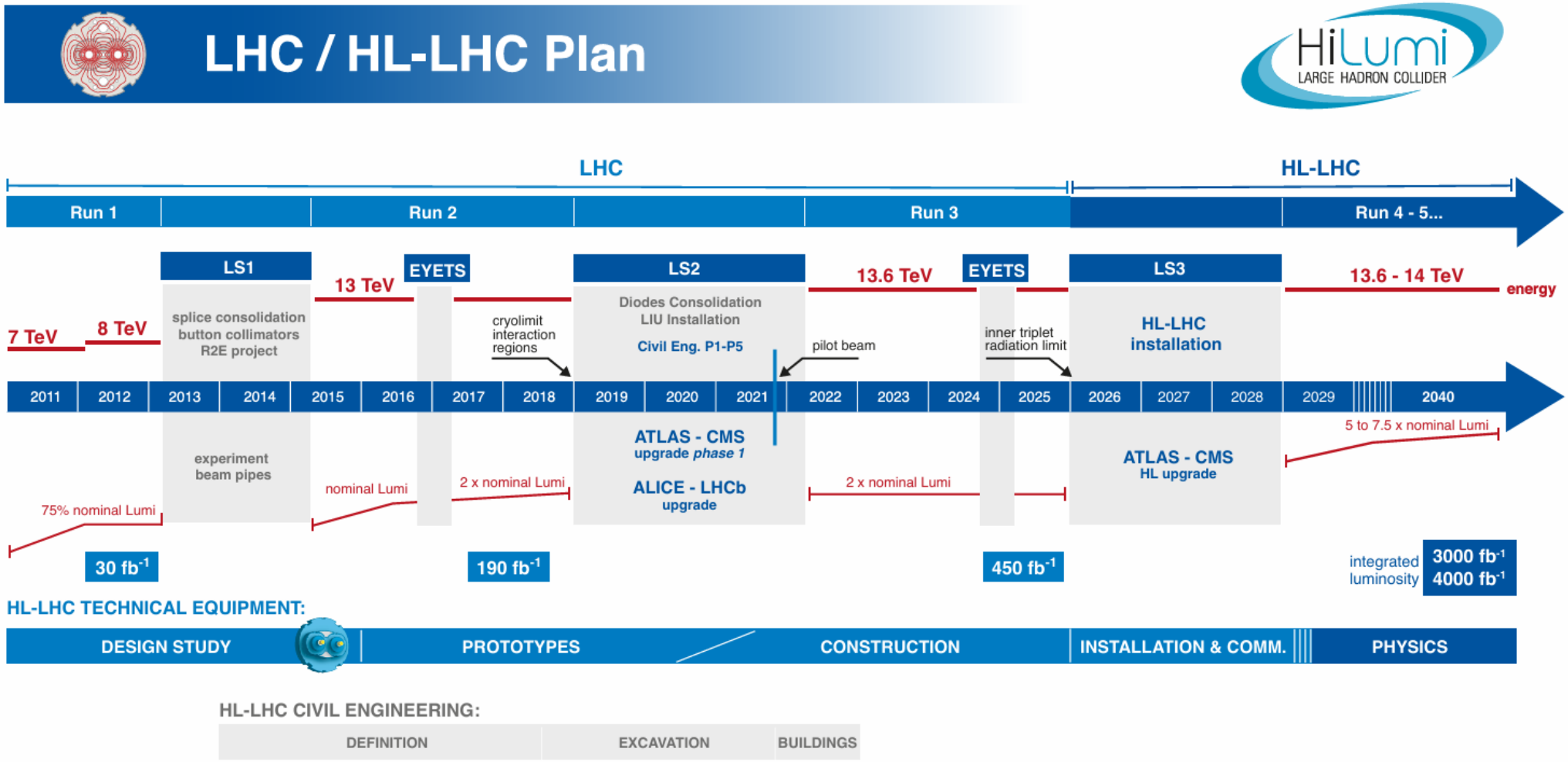
ATLAS

Layered multi-purpose detector in different magnetic fields

- Inner tracking system
- Electromagnetic and hadronic calorimeters
- Muon Spectrometry

The high Luminosity LHC upgrade

https://hilumilhc.web.cern.ch/sites/default/files/HL-LHC_Janvier2022.pdf



Expected increase of the integrated luminosity from 450 fb^{-1} to 4000 fb^{-1}

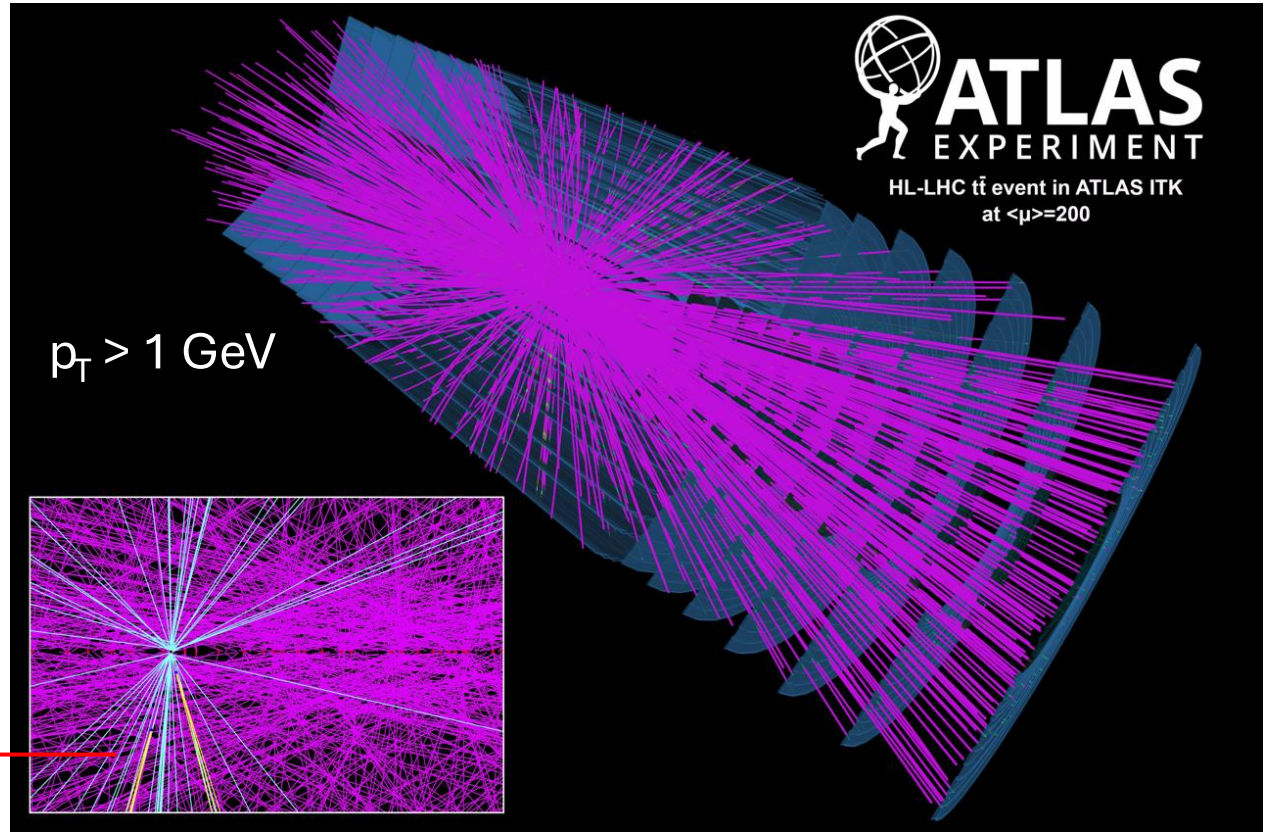
HL-LHC period will start in 2029

The high Luminosity LHC upgrade

number of collisions per bunch crossing

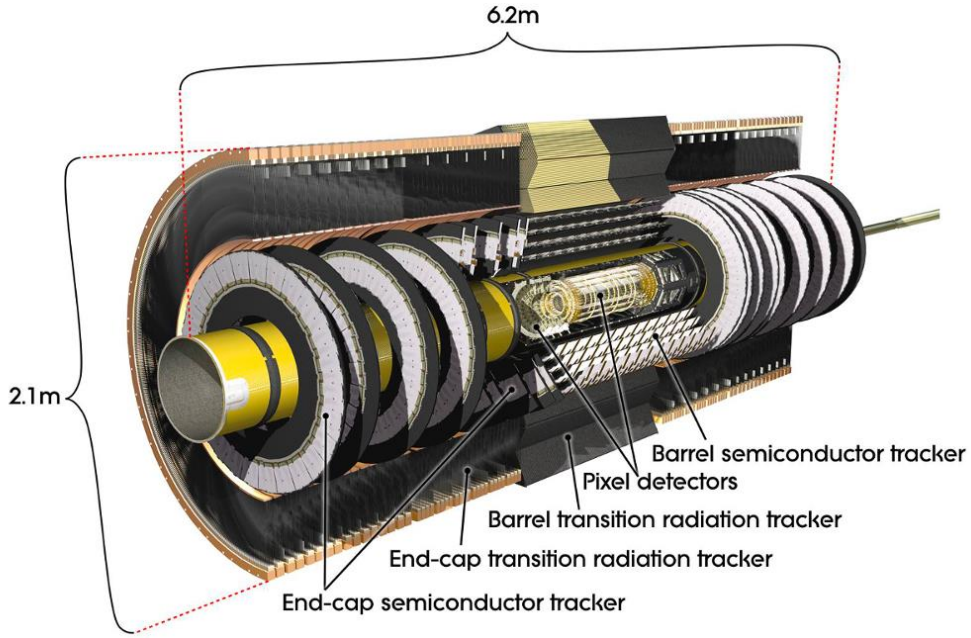
	LHC	HL-LHC (2026)
E	7 - 13.6 TeV	14 TeV
L	2×10^{34} cm^{-2}s^{-1}	7.5×10^{34} cm^{2}s^{-1}
pile-up $< \mu >$	≈ 50	≈ 200

Simulation of a tt event at high luminosity



Tracks from a secondary vertex

The new inner tracker



The current inner detector

- Higher granularity to maintain occupancy lower than 1%
- Irradiation resistance increased 10 times
- Higher bandwidth
- CO_2 cooling system for a lower temperature

Current ID (Pixel, SCT) will degrade and it will be not usable, so we need to replace it with Itk (entirely made of silicon)

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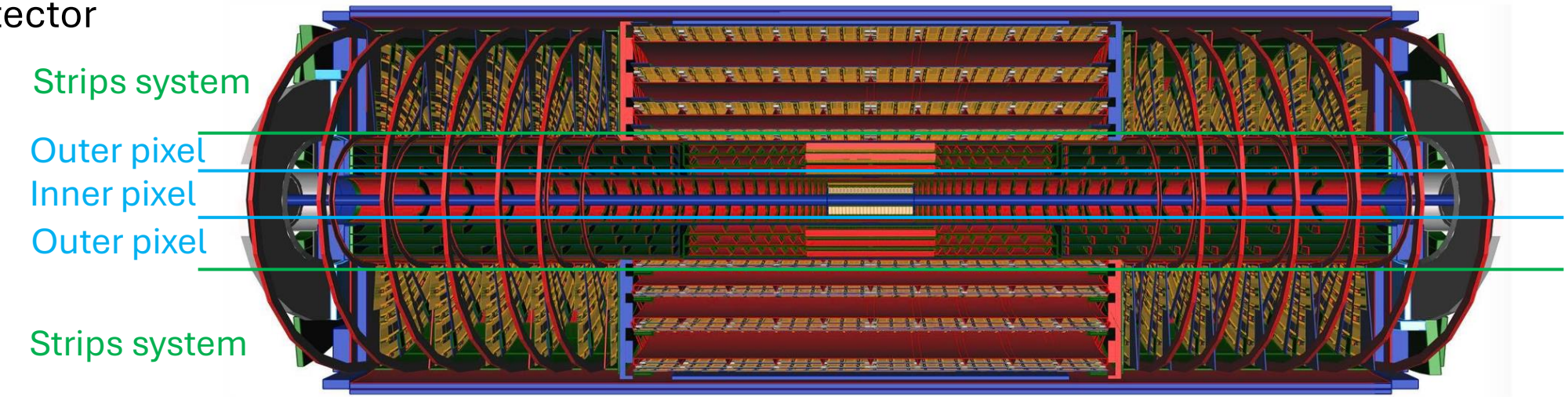
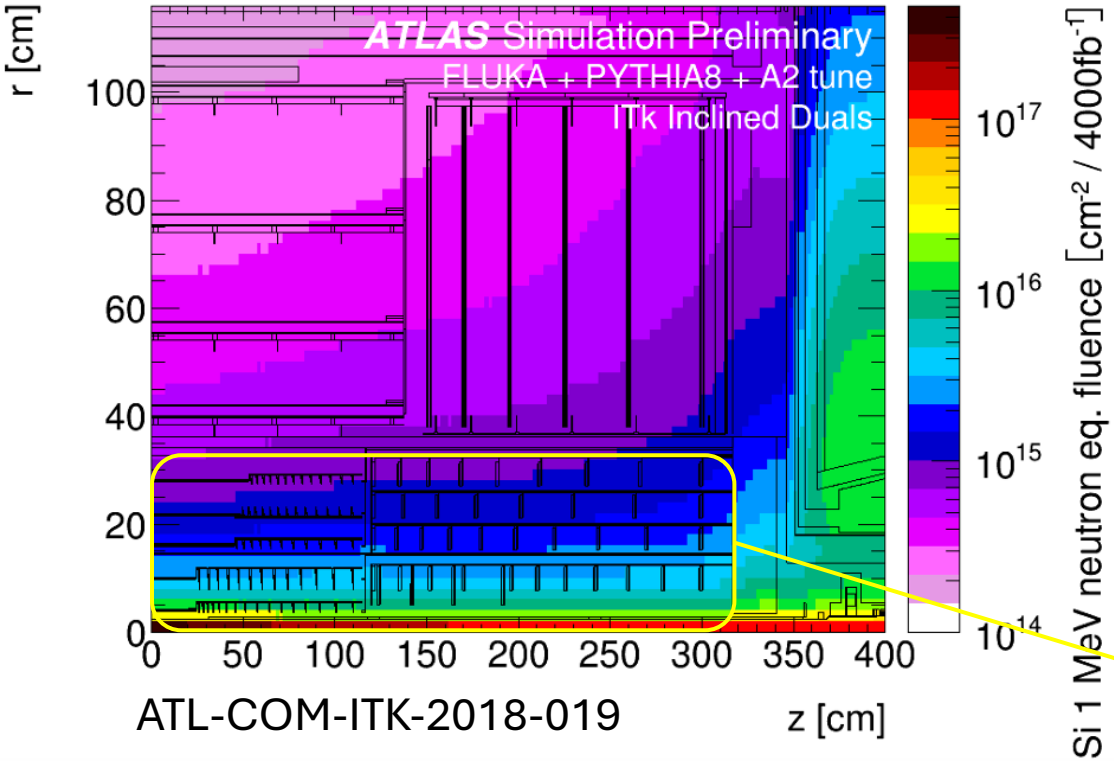


The pixel detector

Requirements for the ITk pixel detector

- Radiation hardness up to 10 MGy (2×10^{16} 1 MeV n_{eq}/cm^2)
- Track recostruction efficiency limits at 99% for muons, 85% for electrons and pions
- Fake rate < 10^{-5}
- Occupancy < 1%
- Readout rate at 1 MHz
- Output bandwidth up to 5.12 Gb/s per FE chip



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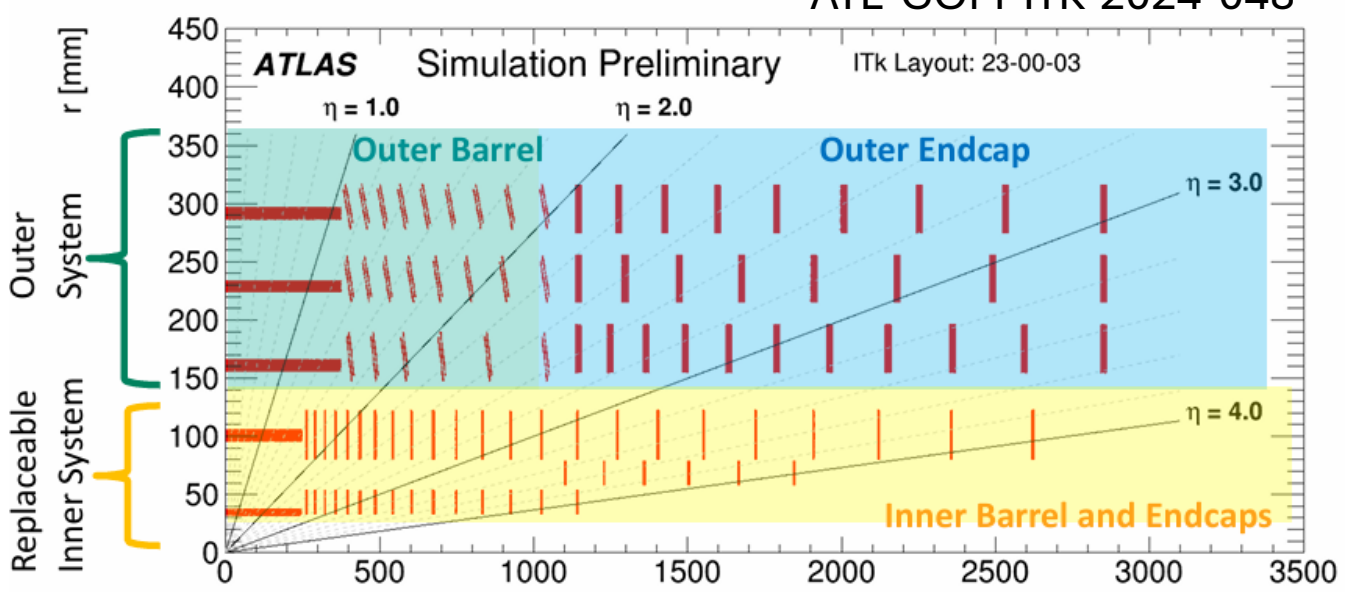


Inner System (to be replaced after 2000 fb^{-1})

From the current pixel system to the ITk pixel system

- Number of pixels from 92M to 5G
- Number of modules from 2000 to 9400
- Silicon pixel area from 1.9 m^2 to 13 m^2
- $|\eta|$ limit increased from 2.5 to 4
- Operation temperature at -15° C to reduce sensor power consumption and radiation damage

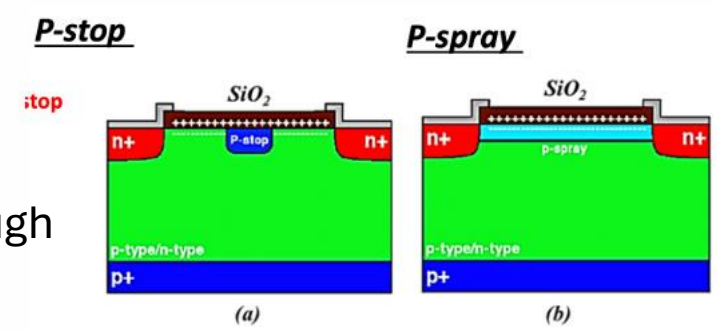
Pixel detector

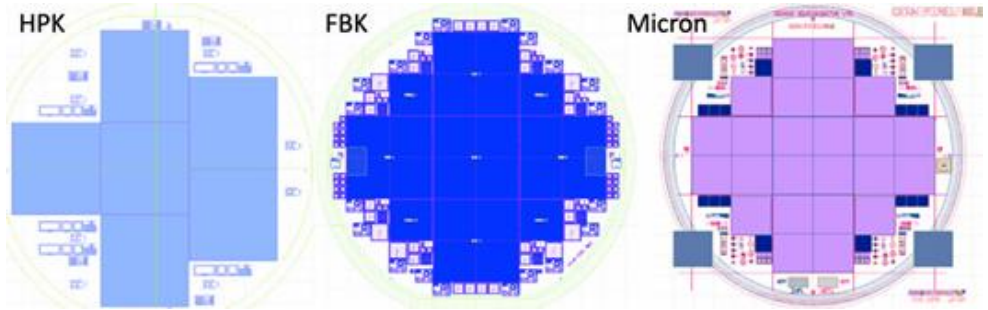
Silicon sensors

Planar sensors

- Thin planar sensors with 100 µm thickness and thick planar sensors with 150 µm thickness
- Radiation hardness to 3.1×10^{15} n/cm^2
- Bias voltage up to 600V (considering radiation effects)
- 50×50µm^2 pixel size
- n-in-p sensor

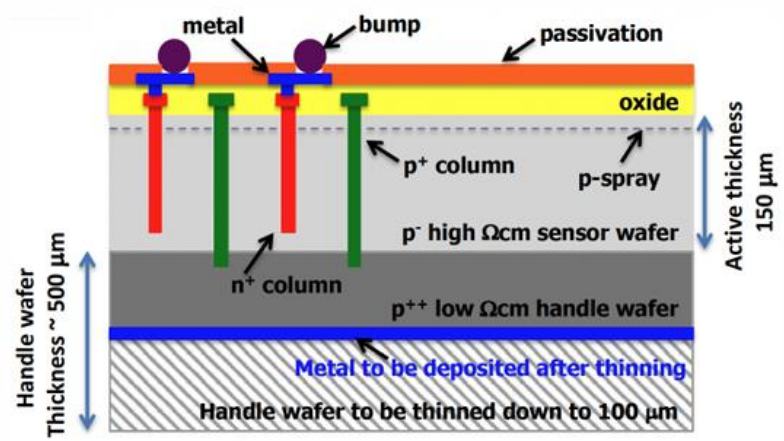
Various design details left up to vendor:
– p-stop vs p-spray insulation
– Polysilicon bias or punch-through
– Guard-ring geometry
Requirements defined on performance

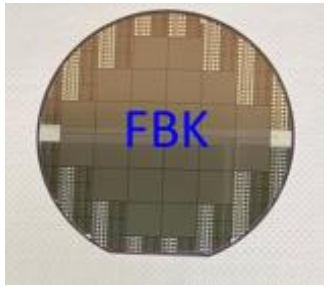


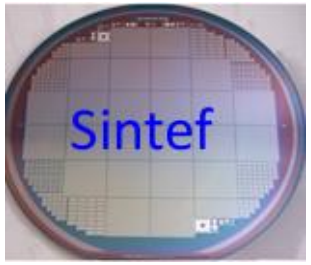


3D sensors

- 150µm thickness
- Radiation hard to ≈ 10^{16} n/cm^2
- Operating voltage < 250V
- 25×100 µm^2 pixel size in the barrel, 50×50 µm^2 pixel size for the rings
- n-in-p sensor



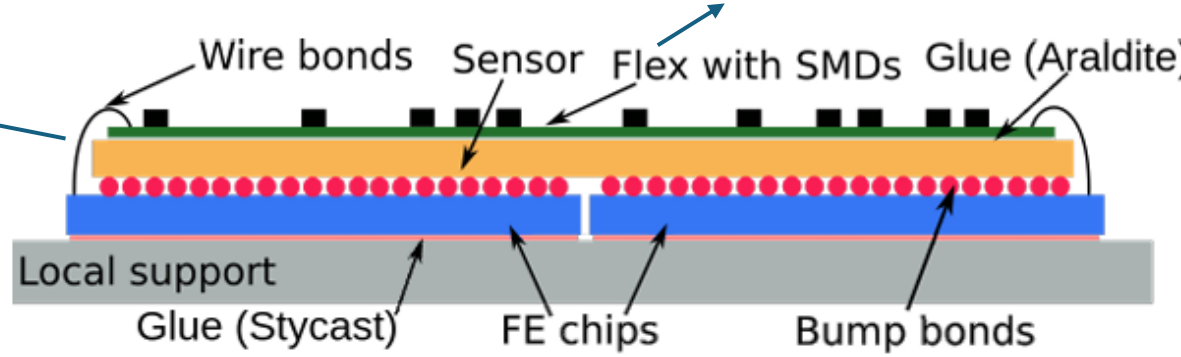




Modules

- Cu/Kapton flex hybrid for connection to power, slow controls and data transmission glued to sensor
- Common flex design for quad leading to modularity for production

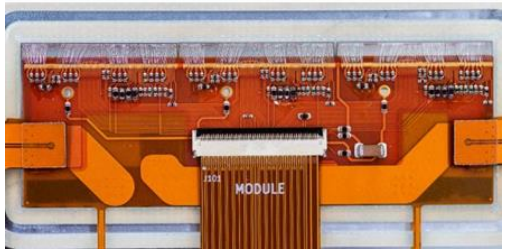
Wire bonds connect the flex to the FE chip



- Serially-powered to reduce cable mass
- Up to 14 modules in a single power chain
- Up to 7A per module

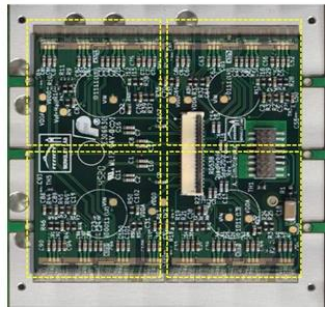
Triplet module

endcap

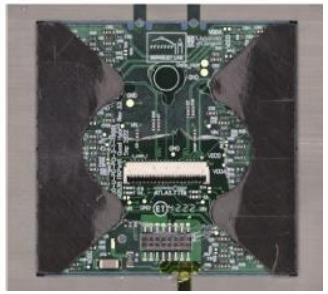


barrel

Quad module



endcap

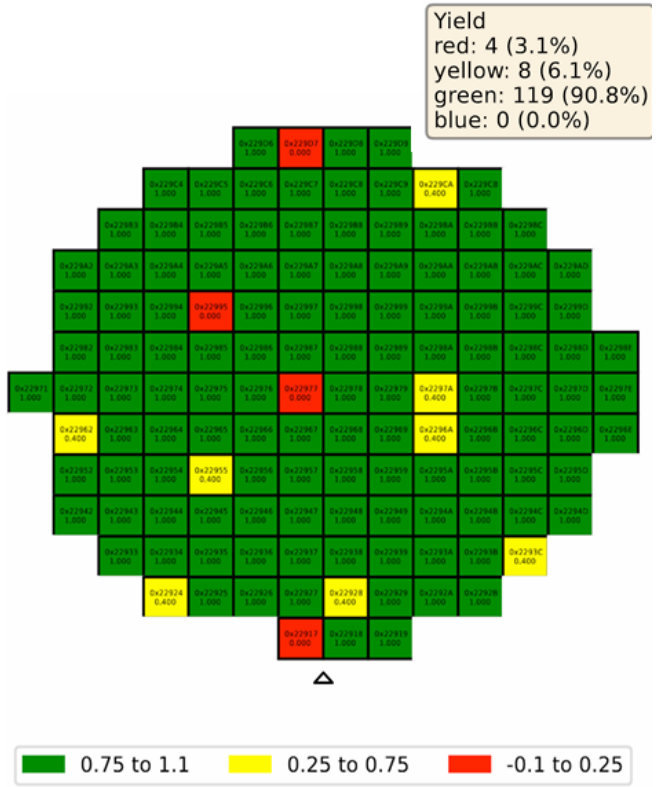


- The final module assembly contains many different materials with different responses to thermal variations
- Detector operational temperature at -35 °C, but variations between -45 °C and +40 °C during the life of the detector induce thermal stresses
- Copper thickness in the flex tuned to dissipate enough power and to avoid inducing thermal stresses at the same time.
- Parylene coating initially only for preventing discharging between chip and sensor, it improves the mechanical resistance.

See L. Cunningham talk

FE chip ITkPixV2

- 152800 pixels (384 rows, 400 columns)
- 65nm technology, 50×50μm^2, total area 2×2 cm^2
- Power 0.56 W/cm^2
- 4 data links per chip at 1.28 Gbps
- Time over Threshold as a measurement of the collected charge
- Threshold at 1000 electrons, noise at 40 electrons
- 40MHz clock with 780 ps phase adjustment
- Data merging: FE readout via another FE
- Chips dicing can induce problem, solved by the laser dicing technique



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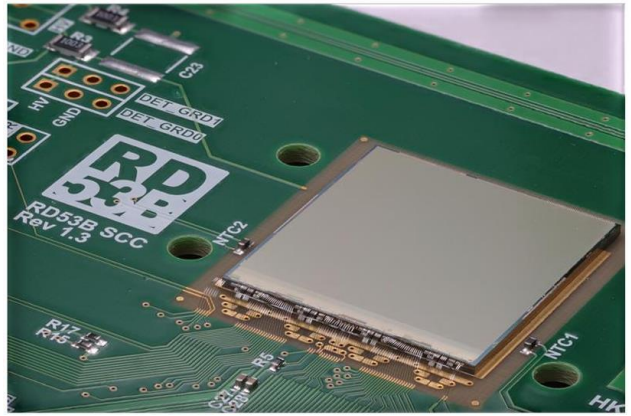


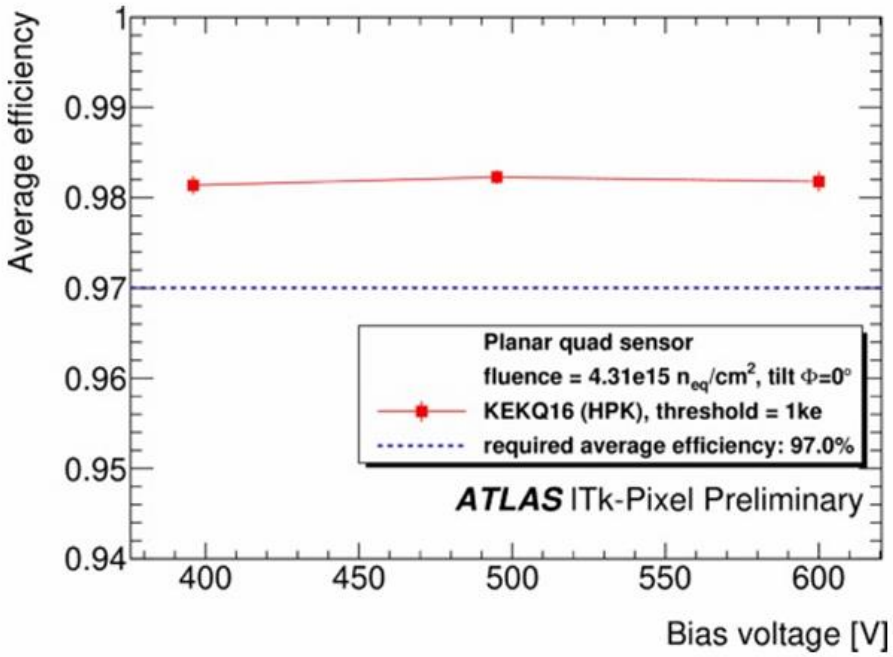
ITkPixV1 on a single chip card

- First 100 wafers of the final 131 chips already probed with a 90% yield (based on digital/analogue functionality and power consumption)
- First modules are under assembly and testing.

See L. Le Pottier talk

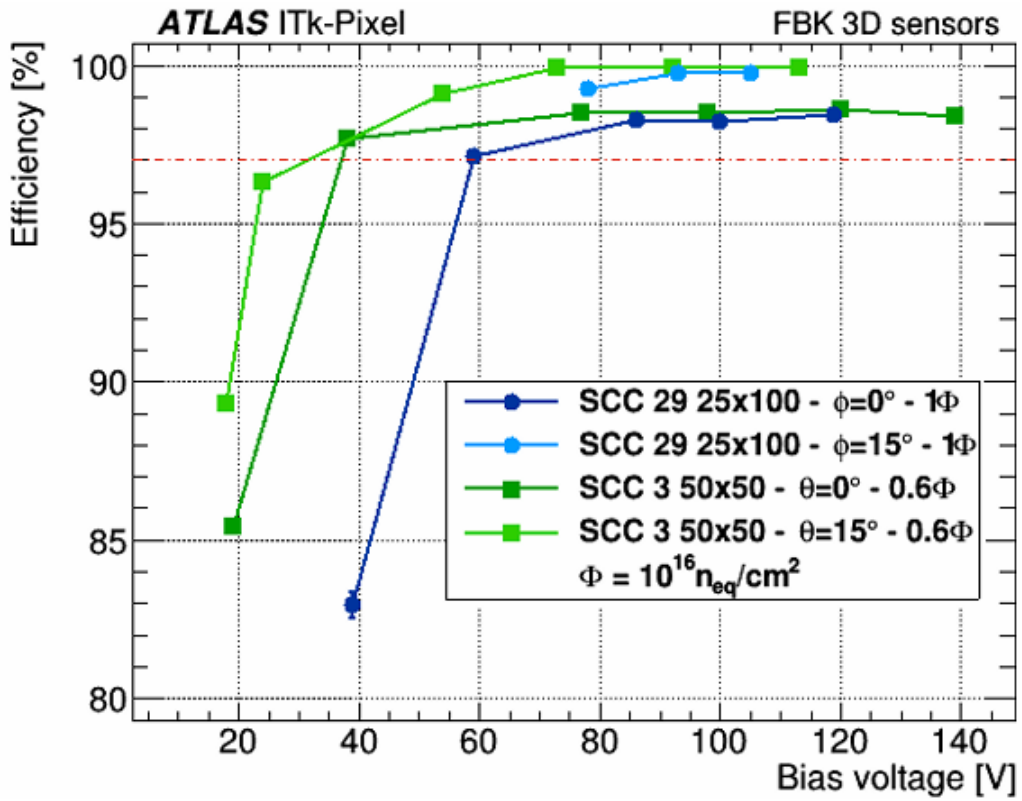
Efficiency after irradiation

ITK-2023-005



Thick planar sensor efficiency after irradiation

ITK-2023-003



FBK 3D sensor efficiency after irradiation

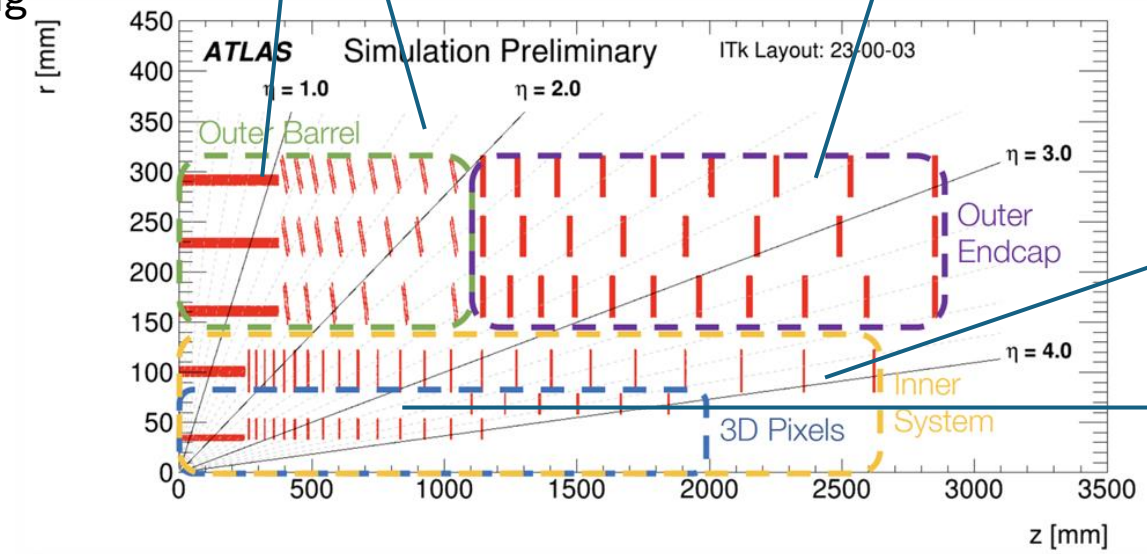
- Sensor preproduction includes qualification in beam test and with irradiated samples
- Hit efficiency > 97% (considering radiation effects)

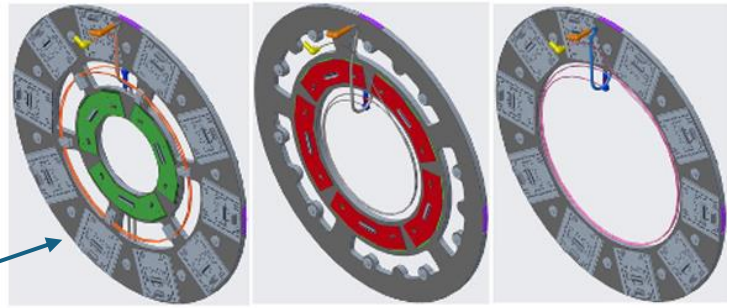
Local supports

Longeron

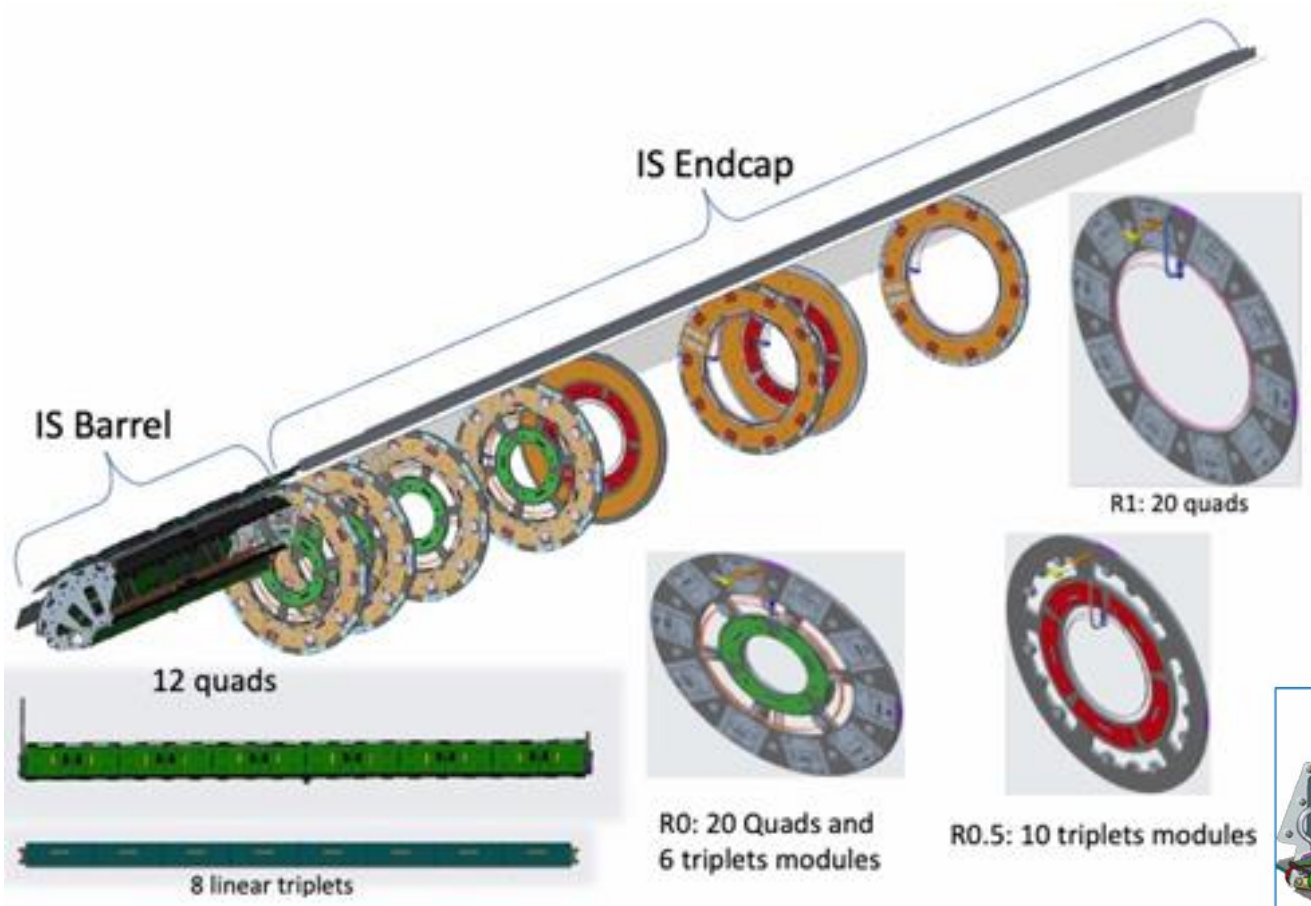
Half ring

- Local support prototypes with carbon fiber and carbon foam to minimize mass, to maximize thermal performance and to provide mechanical rigidity (see L. Cunningham talk)
- Different geometries dependent on the layers and regions of the pixel detectors
- CO_2 cooling system
- OEC and OB local supports already in production
- Thermal, mechanical stresses and irradiation qualification passed
- Modules are glued to supports
- Critical element is interface between module and cooling pipes

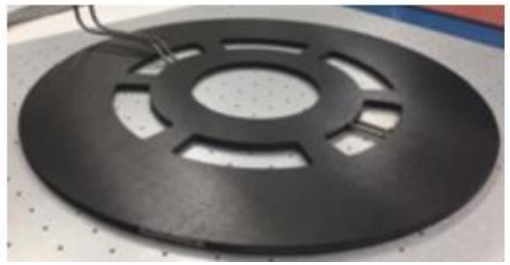




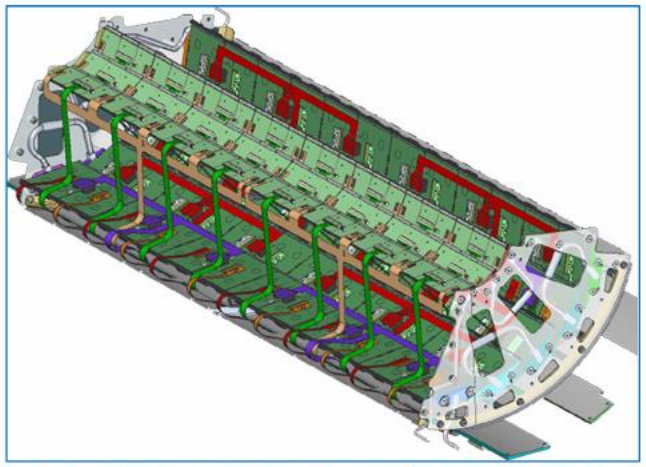
Inner System Global mechanics



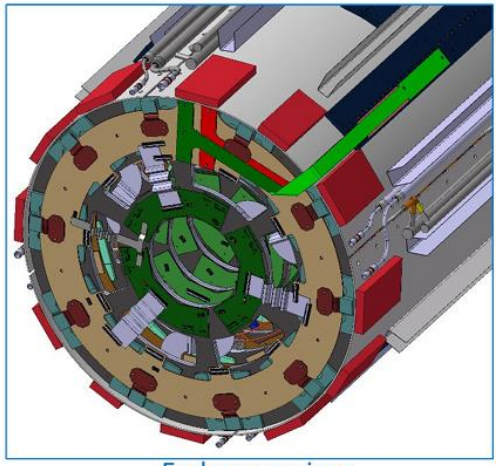
- Global mechanic structures host the local supports and services like power, cooling, data lines
- Half-rings are C-foam/C-fibre “sandwiches” with embedded cooling pipe and fixation lugs
- Cooling feed, exhaust lines and electrical cables run between outer rims of rings and inner surface of cylinder
- The rings and staves of the Inner System are supported by quarter shells
- Each quarter shell holds rings at different positions so that they fit together



Prototype coupled ring



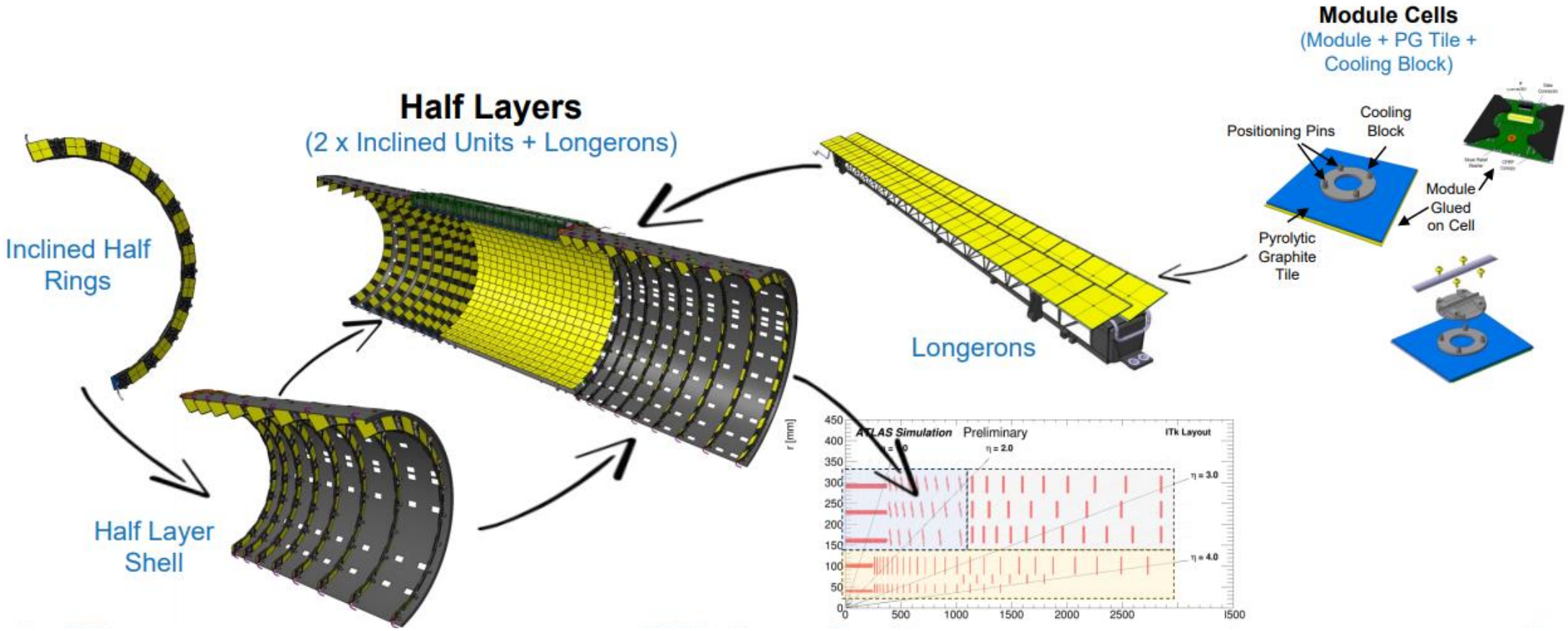
Barrel services running to the outside of the quarter shell



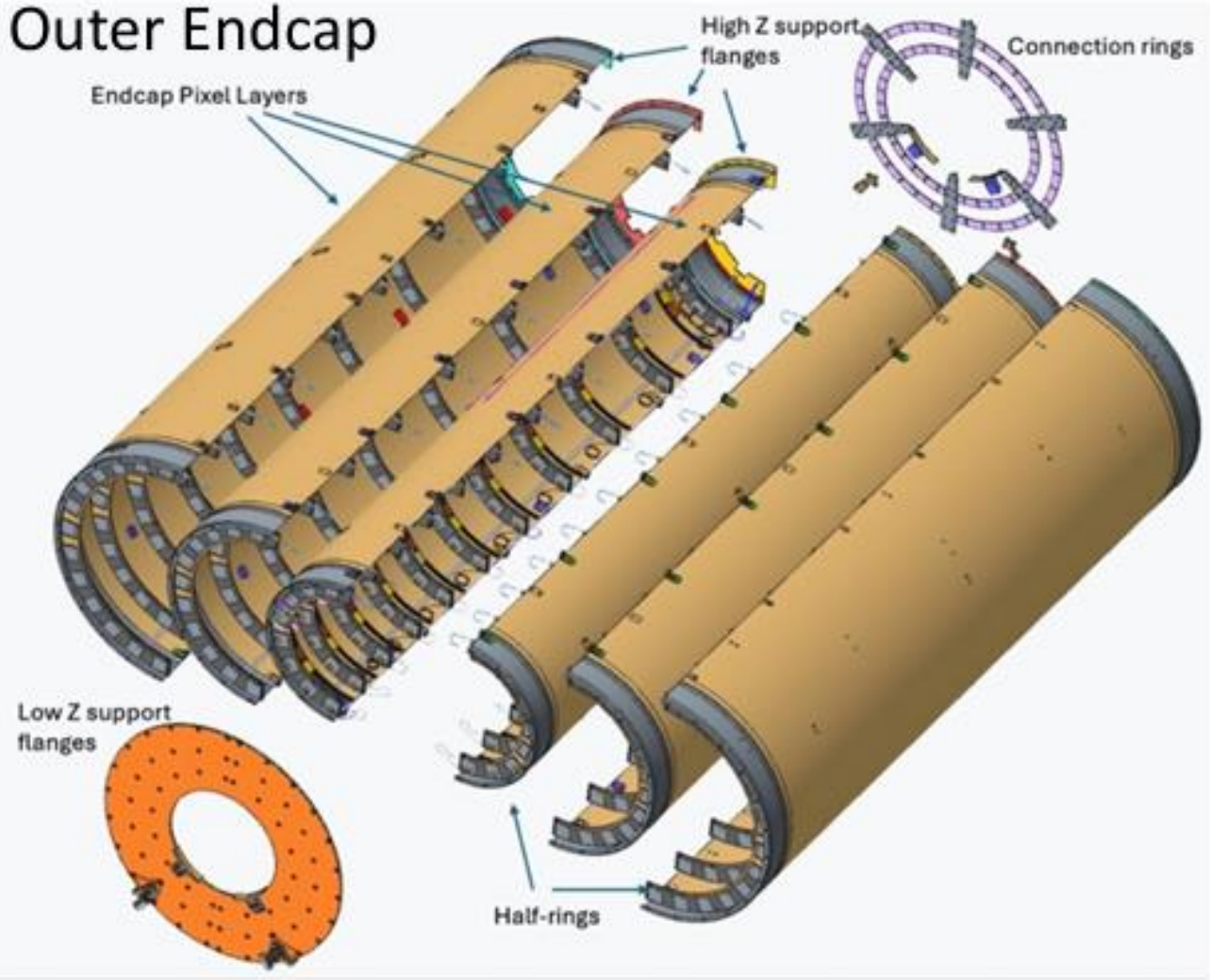
Endcap services

Outer Barrel Global mechanics

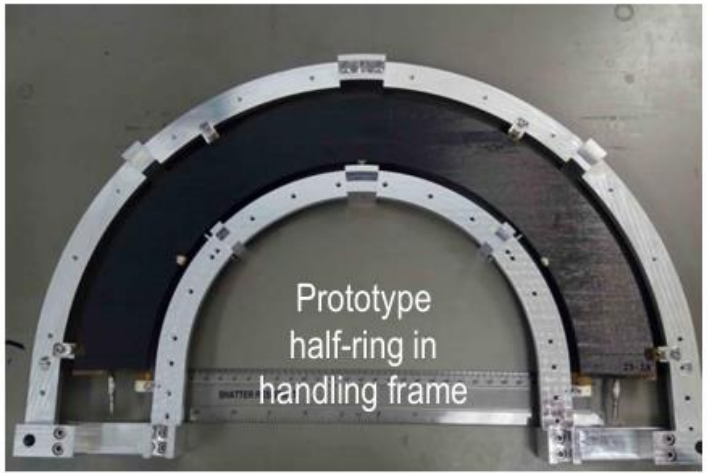
- In the Outer Barrel, modules are mounted on pyrolytic graphite tiles
- Tiles are then mounted on longerons in the flat section, inclined half rings in the inclined section
- Half-layer shells are made of carbon fibre
- Services run out of the shells and along its surface



Outer Endcap Global mechanics

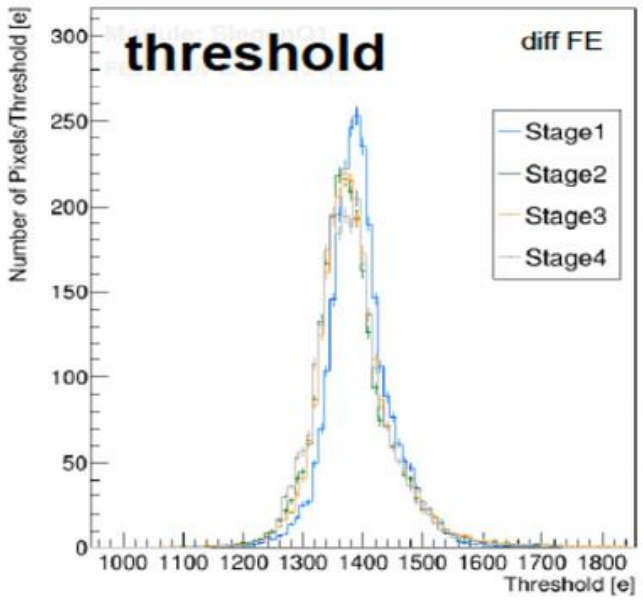


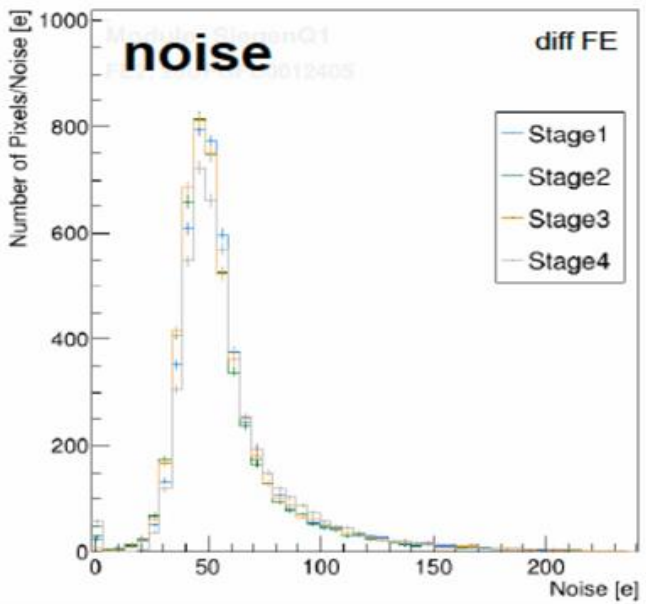
- Half rings are split into 3 layers and they are mounted on the shells
- Carbon fibre half-cylinder shells are between the half rings
- They also support the cooling and electrical services, which run on the interior surface, between the shell and rings
- Electrical services are guided by support rings

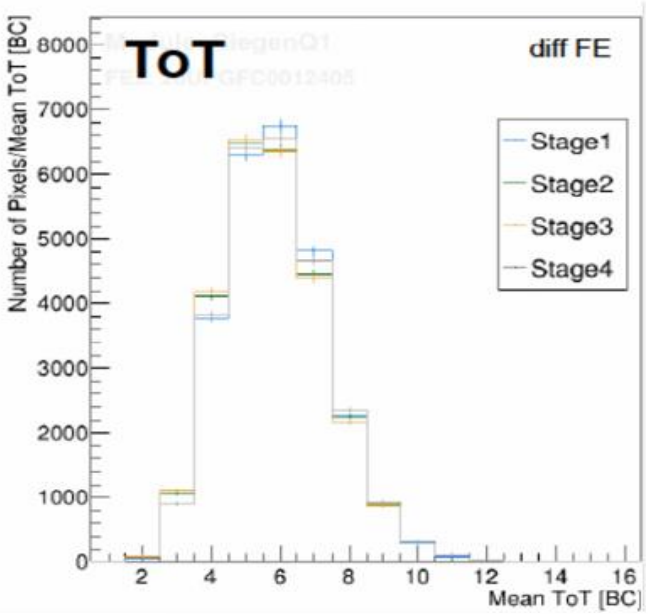


System tests

RD53 prototypes





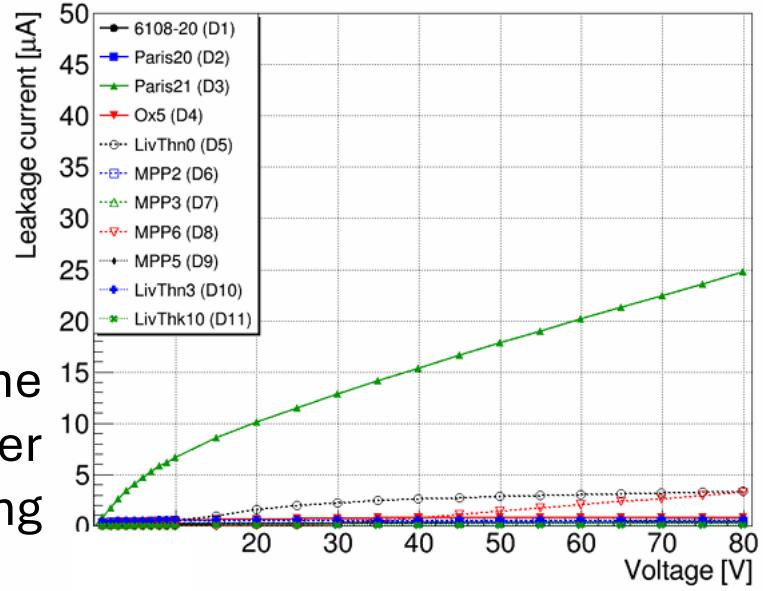


https://cds.cern.ch/record/2899167/files/ATL-ITK-SLIDE-2024-114.pdf

Threshold, noise and ToT after 4 stages:
- module production
- loading on the cell
- pigtail assembly
- integration on the local support

In each stage verification of the performances

Leakage current on the back side of one Outer Endcaps half ring demonstrator



Current status

- Pixel module assembly production start is critical as it feeds into subsequent activities (LLS).
- Areas such as on-detector services and data transmission are critical as they require modules
- Completion at end of 2027

Area	Preliminary Design Review	Prototyping	Final Design Review	Pre-production	Production Readiness Review	Production
Planar Si sensors						
3D Si Sensors						
FE-ASIC						
Hybridization						
Module Assembly						
On-detector Services						
Off-detector Services						
Data Transmission						
Bare Local Supports						
Loaded Local Supports						
Global Mechanics						
Integration						
Power Supplies						

Tenders complete and contracts in place for major components
- Planar sensors
- 3D sensors
- FE chips
- Module hybridization
- Power supplies

- Sensor preproduction covers 10% of total production
- 11000 modules are expected to be produced
- Production of all sensors started
- ~550 modules have been built so far (bump disconnect and/or core column issues)
- Expect modules to start going to loading sites soon (some have already been sent)

Conclusions

- In the high luminosity phase radiation dose will be 10 times greater
- A new inner detector completely made by silicon sensors with extended acceptance (η=4) and higher granularity
- Low mass with carbon structures, serial powering, data merging
- Sensors preproduction completed
- Prototypes and sensors are tested to the high luminosity operation conditions
- First modules already tested
- Production of around 11000 modules (over 2 years in 20 assembly sites, Front-end chips, sensors, some services and local supports) will start soon

Back-up

Current status

- Pixel module assembly production start is critical as it feeds into subsequent activities (LLS).
- Areas such as on-detector services and data transmission are critical as they require modules
- Completion at end of 2027

Outer system quads

Cluster	Modules	Bare SN	Sensor SN	Flex SN	Metrology	Mass	Wirebond	IV	E Summary	Available bare modules
CERN	35	35	35	35	11	12	12	6	8	29
DE	42	42	42	42	28	40	18	12	14	18
FR	54	54	54	54	51	54	39	35	37	2
IT	19	19	19	19	13	13	10	1	5	6
JP	140	137	136	138	1	9	6	1	1	24
UK	15	15	15	15	12	11	10	0	0	29
US	11	11	10	11	4	9	9	2	4	1
Total	**316**	**313**	**311**	**314**	**120**	**148**	**104**	**57**	**69**	**109**

Silicon sensors

- The distance in 3D sensors is usually much shorter than the sensor thickness (more radiation hardness)
- 3D sensors are used in the inner system, planar ones in the outer system