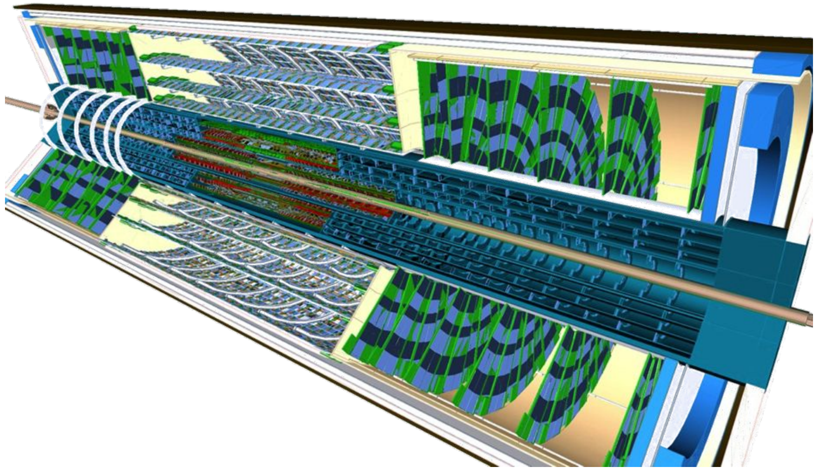
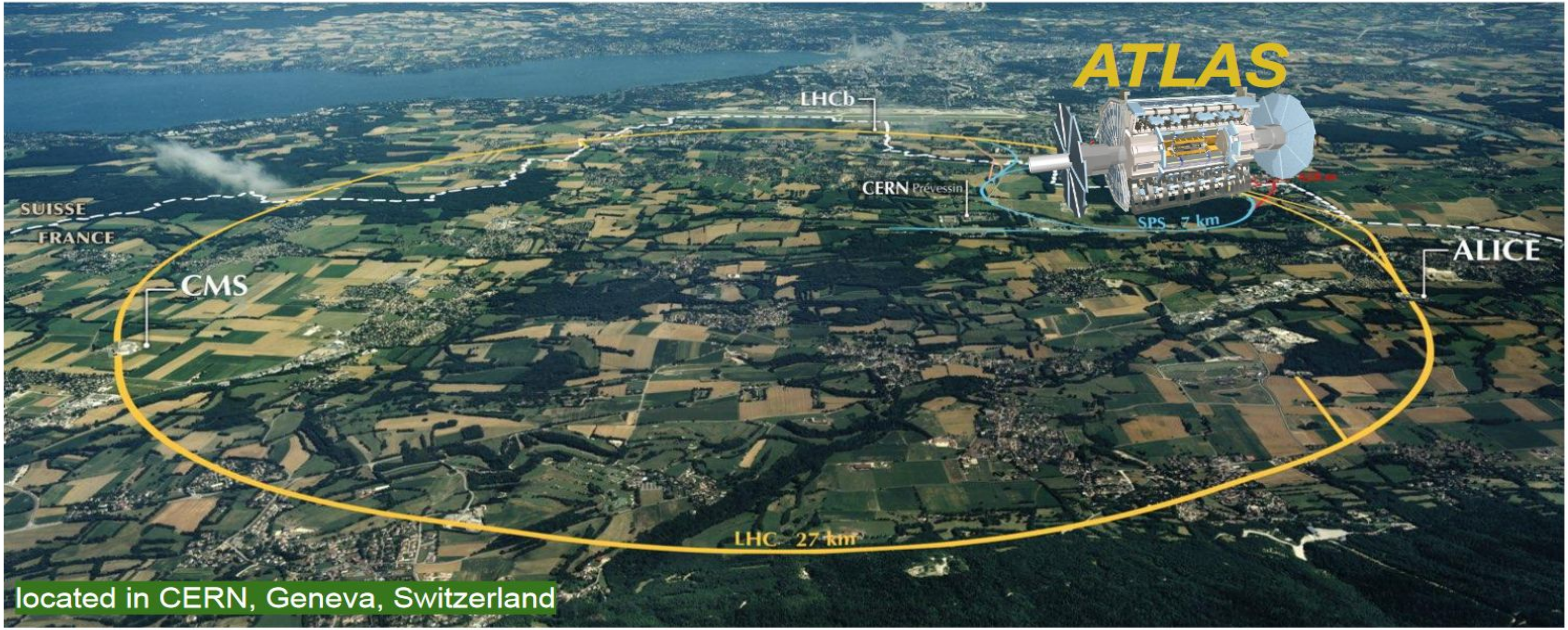
ATLAS Upgrade Phase-II: ITk-Strips



Carles Solaz on behalf of the ATLAS ITk Collaboration

Introduction

The ATLAS experiment at the LHC



located in CERN, Geneva, Switzerland

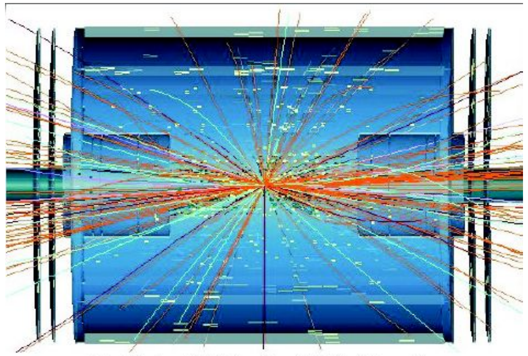
ATLAS Phase-II Upgrade: Why an upgrade?

- Number of collisions from 20 to 200 per beam crossing
- Track multiplicity about 10.000 (~700 for the LHC)

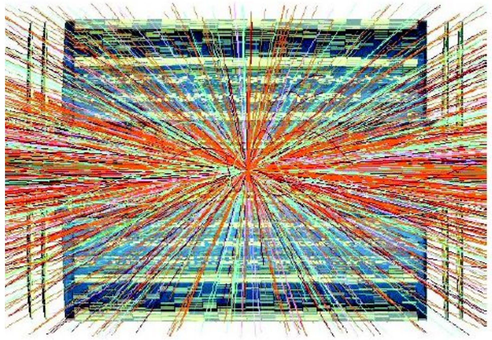
→

Current tracker limitations

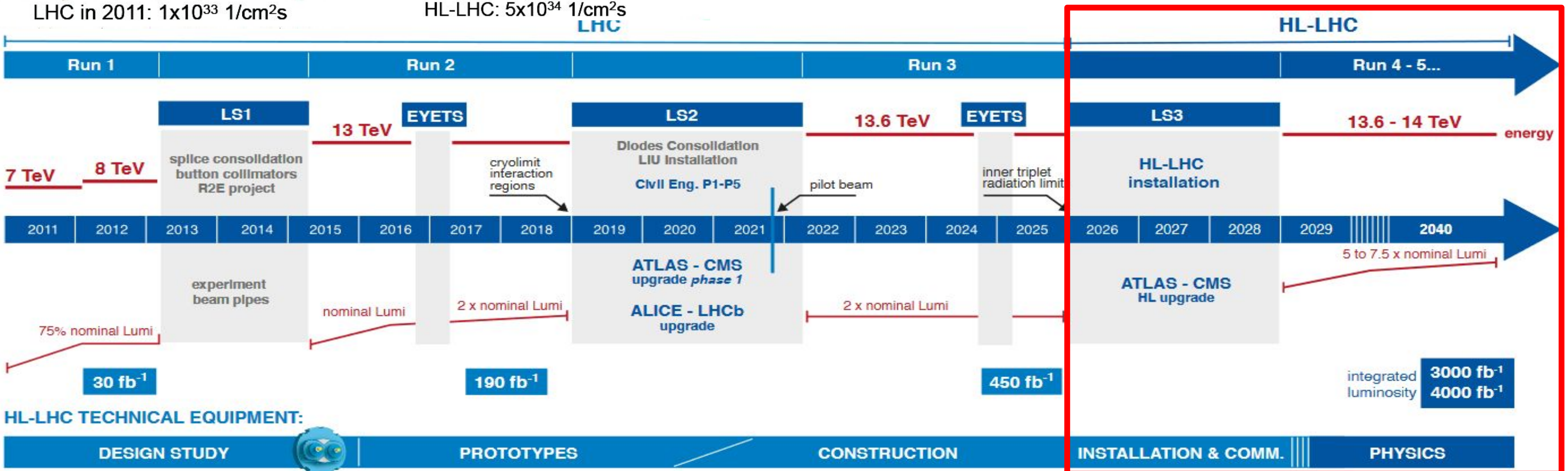
- Radiation damage in Strip and Pixel: designed for 400 pb-1 [PIX], 700 pb-1 [SC
- Too large occupancy in TRT
- High granularity required: deal with 140-200 pile-up events



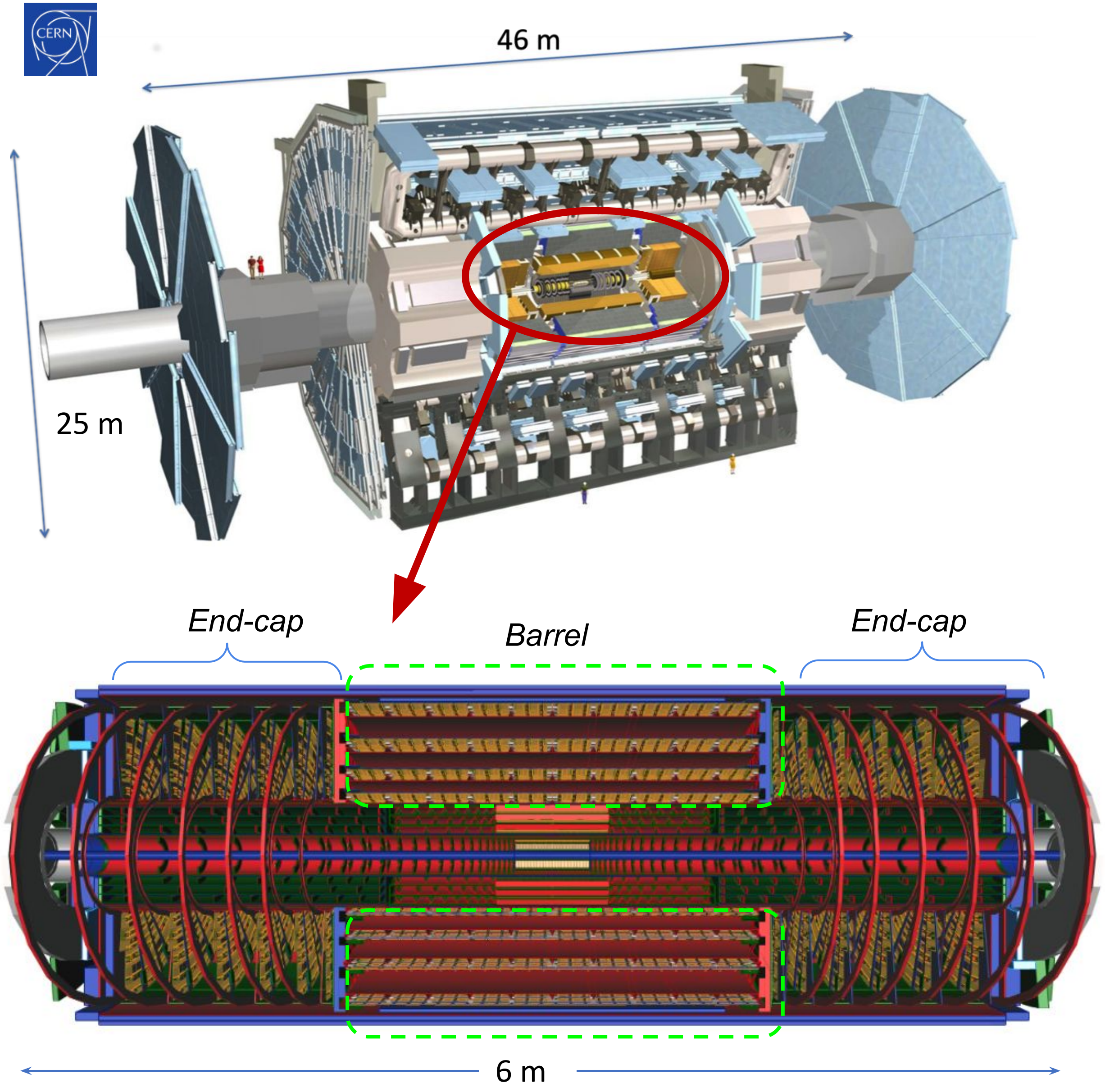
LHC in 2011: 1x10^{33} 1/cm^{2}s



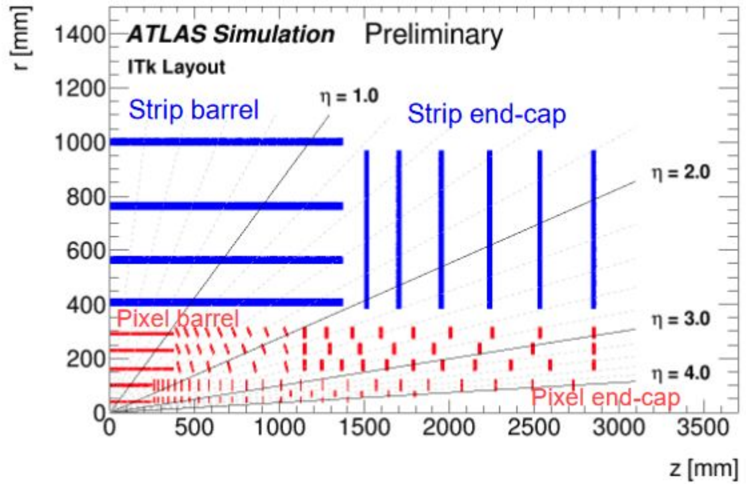
HL-LHC: 5x10^{34} 1/cm^{2}s



ITk – The new ATLAS Inner Tracker



- Full replacement of the present ATLAS Inner Detector with Inner Tracker (ITk).
- Goals:
  - Radiation tolerance at planned levels.
  - Higher trigger rate.
  - High granularity.
  - Low mass.
  - Low power.
  - Contained cost.



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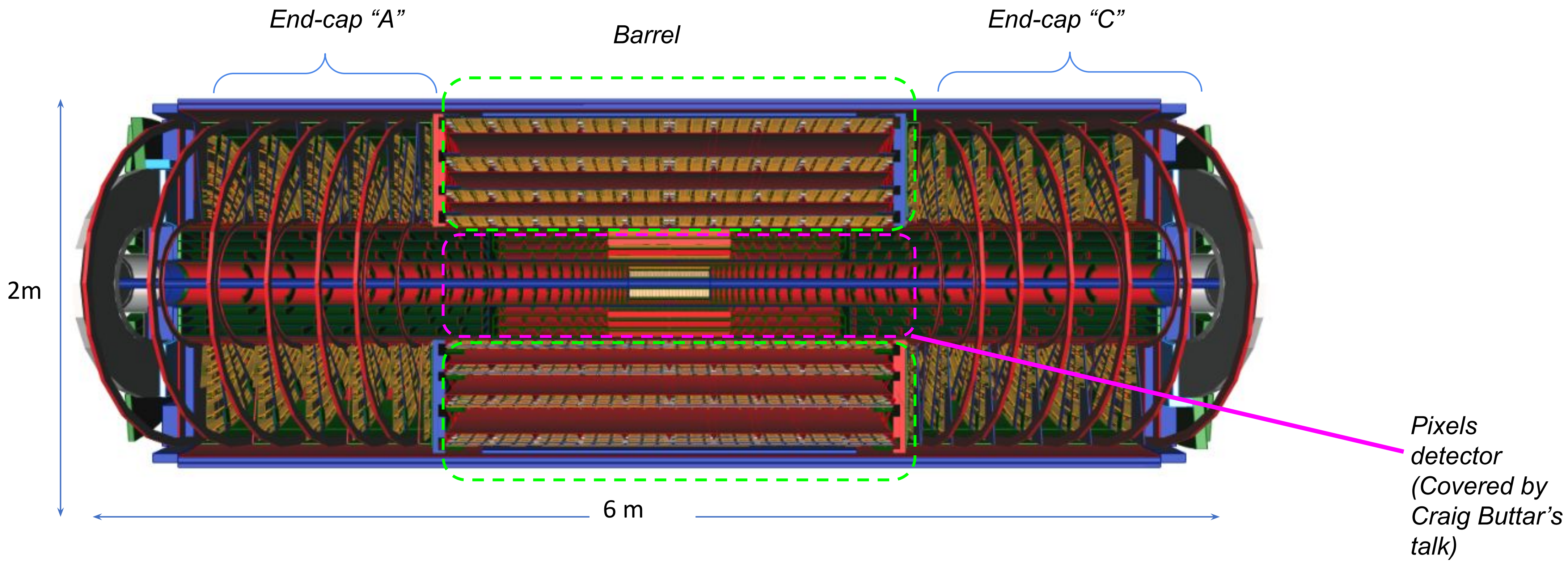
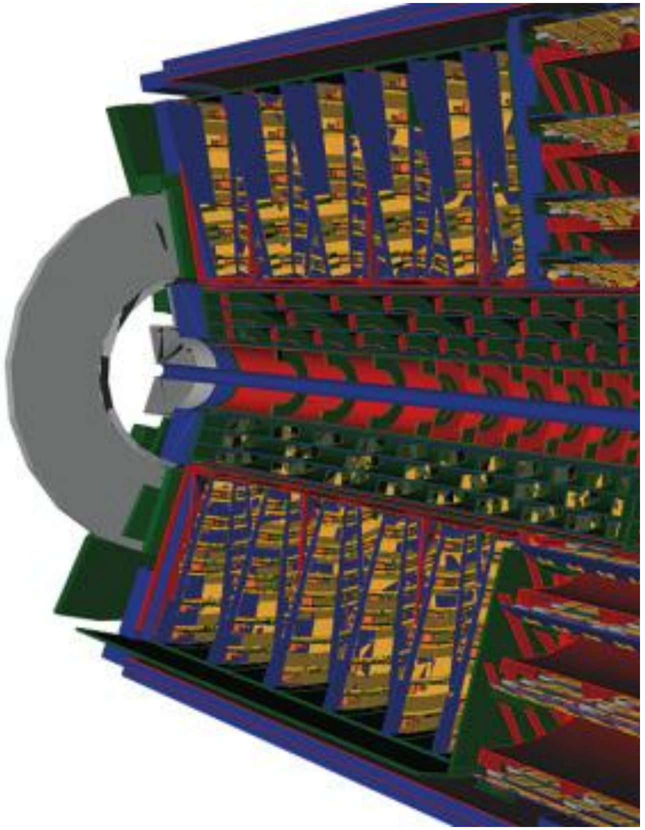


Pixels detector (Covered by Craig Buttar's talk)

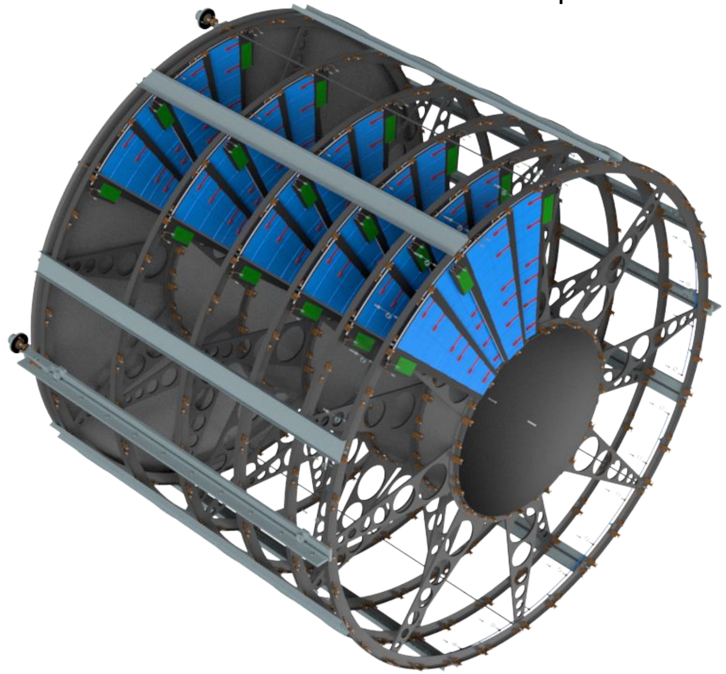
- ITk is full silicon: strips and pixels
- ITk-Strips has:
  - ~165 m^2 of silicon micro-strip sensors
  - ~16 k silicon sensor modules
  - ~60 M channels
- ITk-Strips formed by:
  - 6 End-cap disks per side
  - 4 barrel cylinders
- Barrel and End-cap
  - Same architecture and technology

16th Pisa Meeting on Advanced Detectors

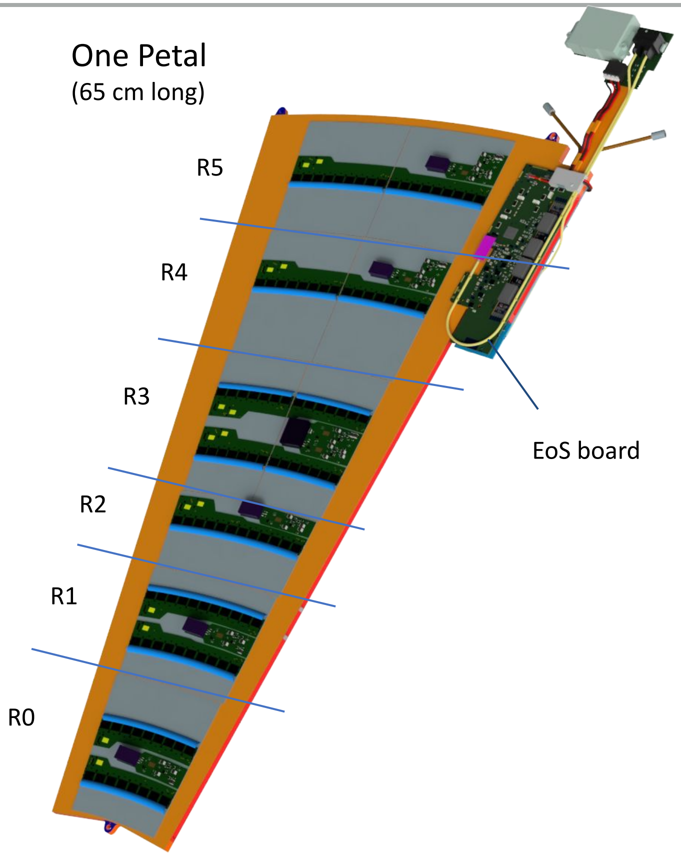
ITk – End caps



One End-cap



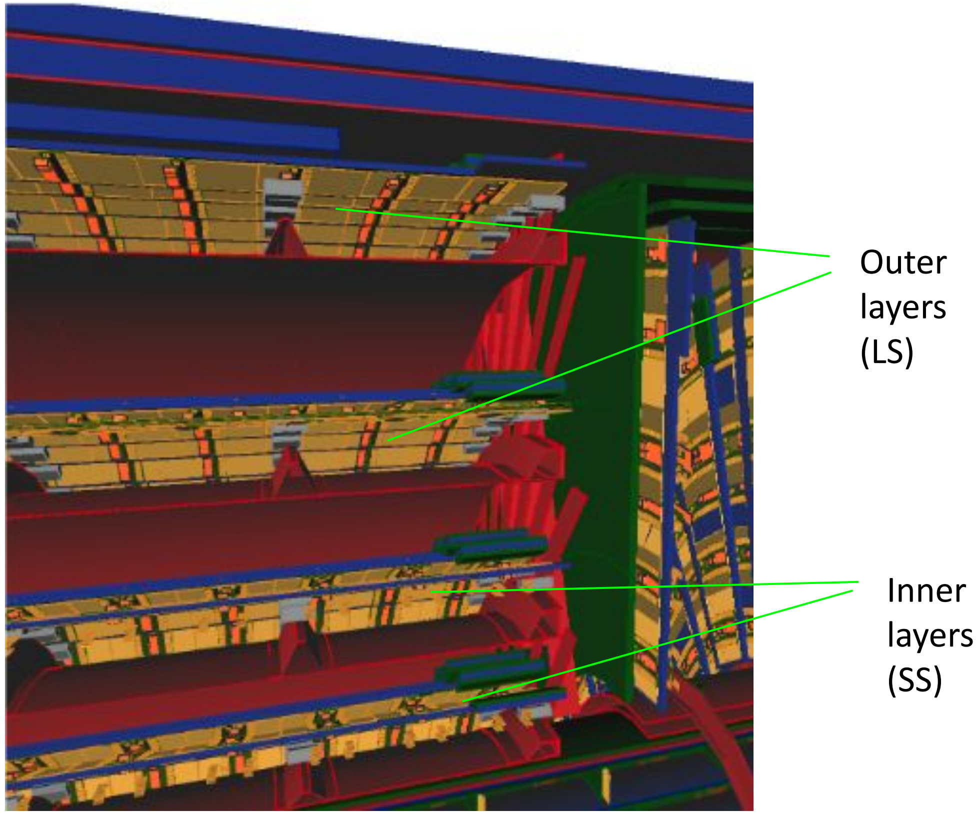
One Petal
(65 cm long)

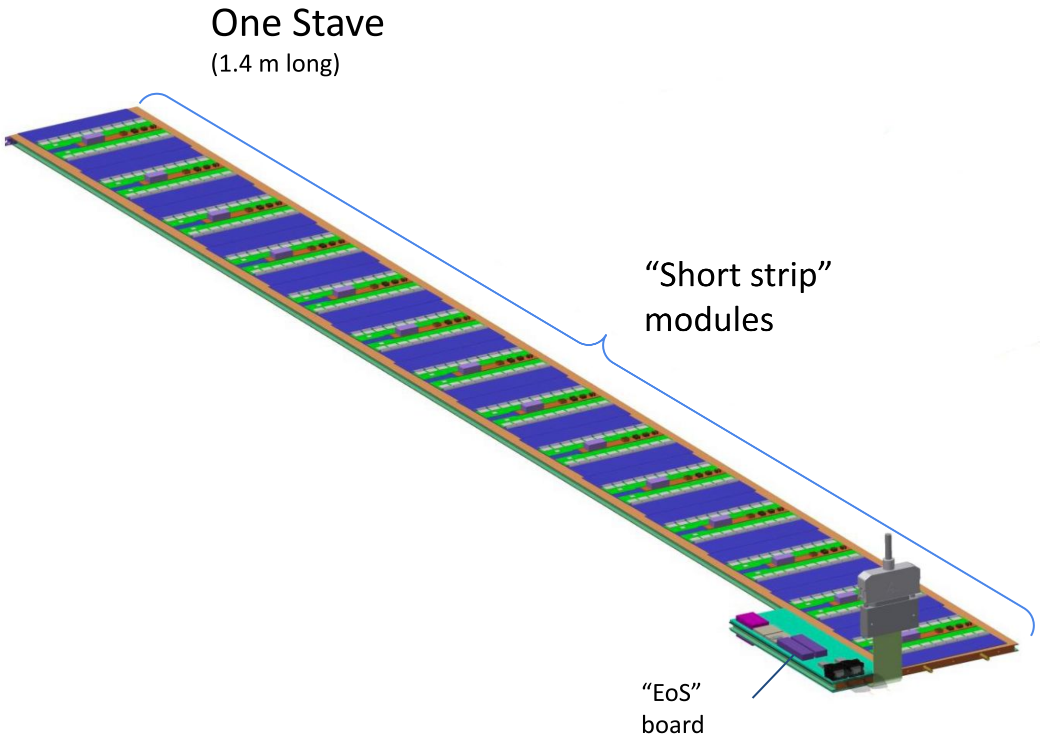


- 2 End caps
  - 6912 silicon modules
  - 384 “petals”
- 6 disks each, populated with “petals” on both sides

- Each petal populated with 6 strips modules on each side
- Due to shape, 6 flavours of modules needed
- “EoS” board provides optical link to the off-detector electronics and receives power for the petal

ITk – Barrel





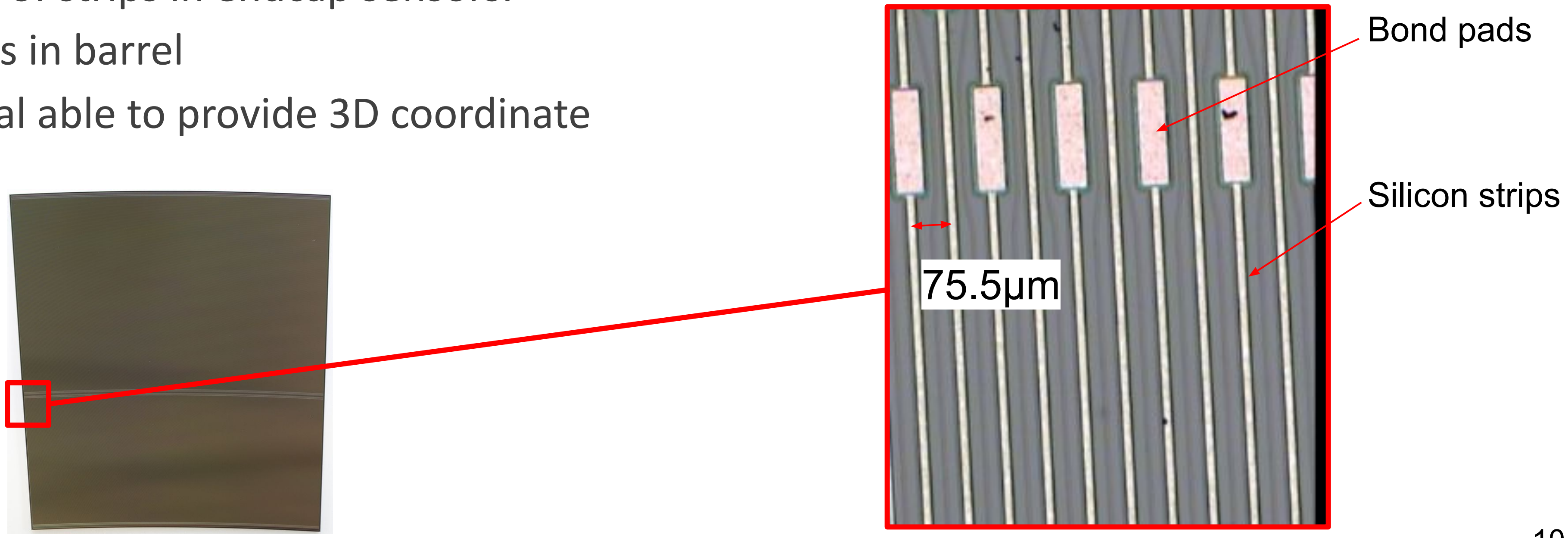
- 4 layers of “staves” in longitudinal position
  - 10976 silicon modules
  - 392 staves
- Outer staves are of “Long-strip” type and inner of “Short-strip” type.

- “Short-strip” double channels vs “Long-strip”
- Each stave 28 silicon modules (14 each side)
- 2 flavours of silicon modules needed (one per stave type)

What is in the detector?

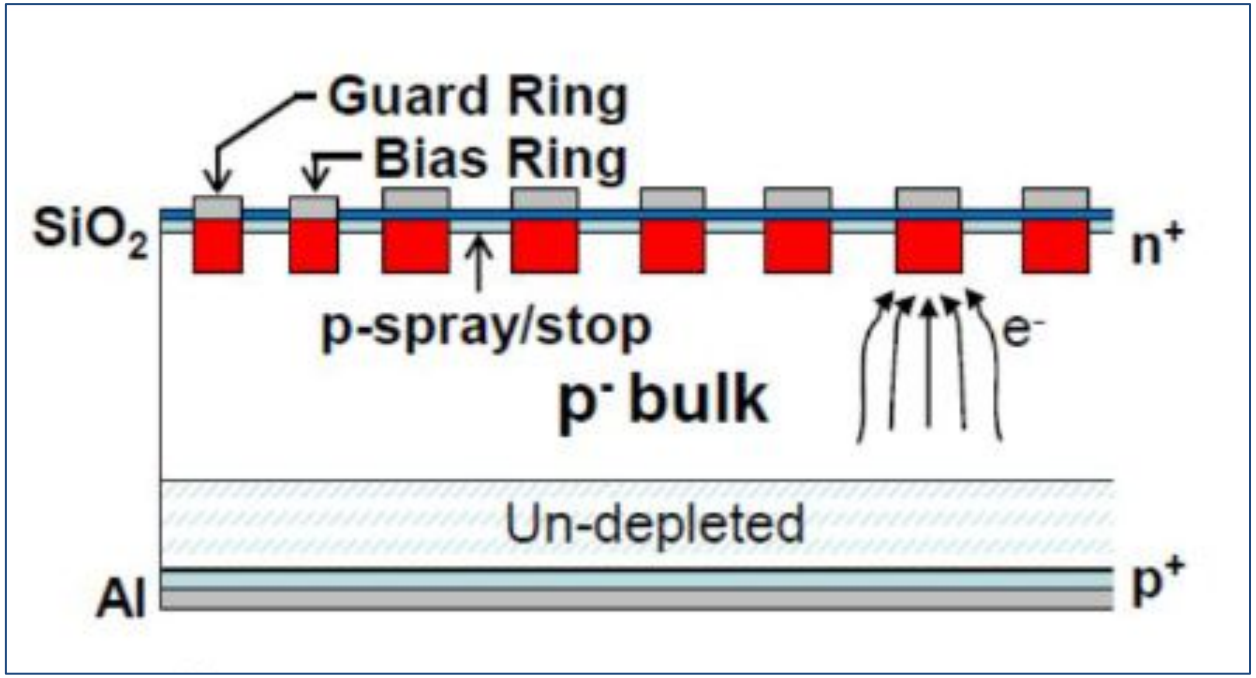
Sensors

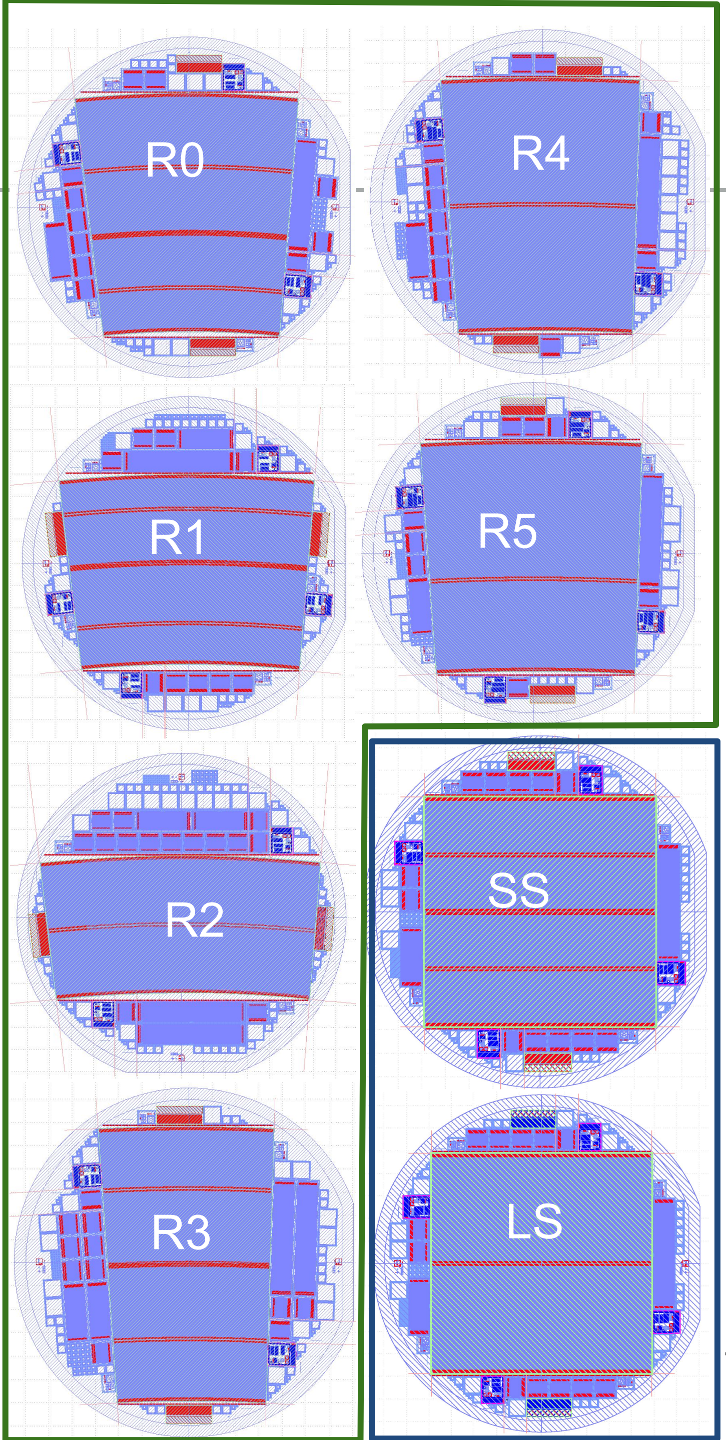
- Why silicon strips?
  - Need to cover a vast area
  - Want to reconstruct particle traces
  - Strips are long, but strips form a reticule with the sensor in the opposite side of the petal/stave
    - Staggered position in petals/staves
    - Stereo annulus of strips in endcap sensors.
    - Rotated sensors in barrel
    - Each stave/petal able to provide 3D coordinate



Sensors

- 6” wafers, ~300 um thick by Hamamatsu Photonics (HPK)
- n^+- in- p float zone (FZ).
  - Better speed and radiation hardness than p-in-n.
  - Can still be used under-depleted.
- 8 different types: 2 barrel, 6 end-cap.





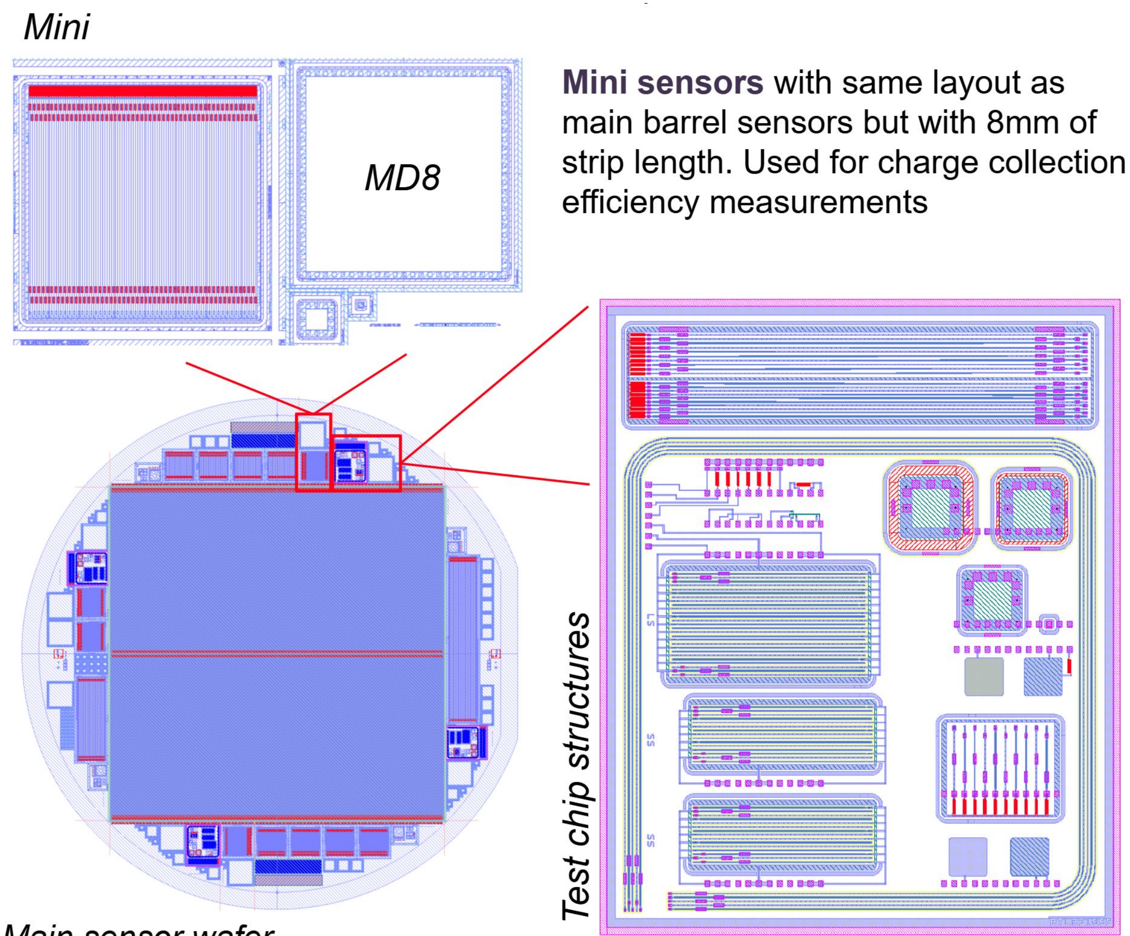
Sensors

- Almost 3 years in production.
- Production sensors received: 15358 (73.8% of total production)
- Very low rejection ratio <5% (rejected sensors will be re-delivered)

- 10 QA institutes
  - Different mini sensors and test structures
  - Tests on irradiated and non-irradiated samples
    - Bias resistance
    - Full depletion voltage
    - Breakdown voltage
    - Interstrip capacitance
    - Interstrip resistance
    - Field oxide capacitance
    - Field oxide thickness
    - Flat-band voltage
    - Coupling capacitance
    - PTP voltage
    - Implant and metal sheet resistance

Poster: *Study of radiation effects in the test structures of ATLAS18 ITk strip sensor caused by CERN-PS 24 GeV/c protons* (Igor Mandić)

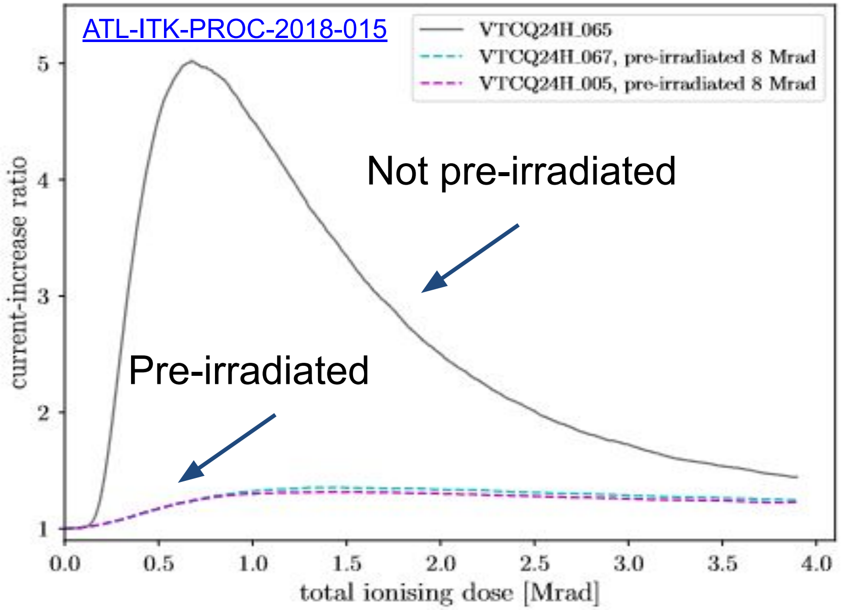
- 7 QC institutes
  - Test all full-size sensors from a batch
    - Metrology
    - Visual inspection
    - Visual capture
    - IV
    - CV
    - I stability
    - Strip test



Mini sensors with same layout as main barrel sensors but with 8mm of strip length. Used for charge collection efficiency measurements

ASICs

- Use of custom ASICs (ABCStar, HCCStar and AMACStar)
  - ○ Use established and understood 130nm technology.
  - ○ Radiation-hard
    - ■ Enclosed layout transistor geometry (analog part) to mitigate total dose effects.
    - ■ Mitigation of Single Event Upsets:
      - Triplication logic and flip-flops as well as reset and clock trees
      - Voting system
    - ■ Pre-irradiated to avoid TID bump (much higher power consumption at the beginning of detector life due to radiation).



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ASICs

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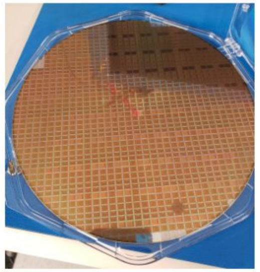
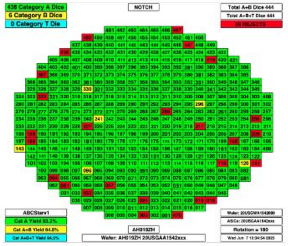
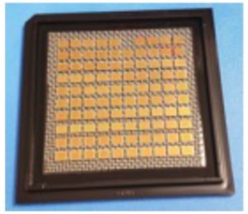
All chips already manufactured and progressing in production chain.

	Manufacture	Probe	Dice	Pre-irradiate	Distribute
Current progress	107%	98%	68%	62%	6%
	Silicon wafers of chips are manufactured by the foundry in lots of 25 wafers.	Each chip on each wafer is probed: needles connect to the chip to power and exercise its functions. Chips are graded based on test results.	Our dicing vendor thins the wafers down to 300µm, then dices (cuts) the wafer into chips. The chips are placed in special containers: gelpacks.	As a treatment to improve chip performance, the chips are irradiated using gamma to 5Mrad.	Based on requests from Production Management and Modules co-ordinators, chips are sent to institutes that build hybrids, powerboards and Patch Panel 2 (PP2).
	Batch size: 25 wafers Delivery: 25-100 wafers	Batch: 25 wafers (ABC) 15 wafers (HCC+AMAC)	Batch: 25 wafers (ABC) 15 wafers (HCC+AMAC)	Batch: varies in time 80 - 150 wafers equivalent	Batch: 3 months of stock, varies by site, see backup slides for details





Probing is our Quality Control



ASICs

QC happens in the probing

- Shorts and power supplies
- Communications including register reads and writes
- Tuning of Low Drop-Out regulators (LDOs)
- Programming the non-volatile eFuse (permanent chip identifier)
- Calibrate and analog circuits and, including the Digital to Analogue Converters (DACs) used to tune it and ADCs.
- Digital tests that verify the digital logic of the chip

QA happens after dicing or pre-irradiation

- Post-dicing metrology
- Bond pull tests
- X-ray TID tests

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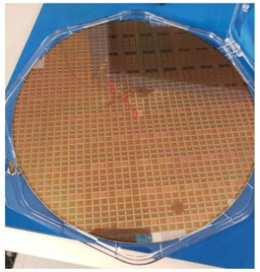

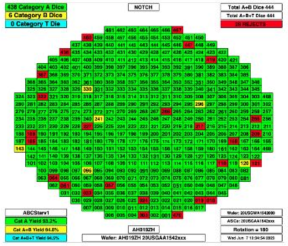

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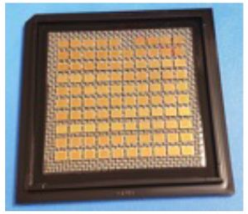
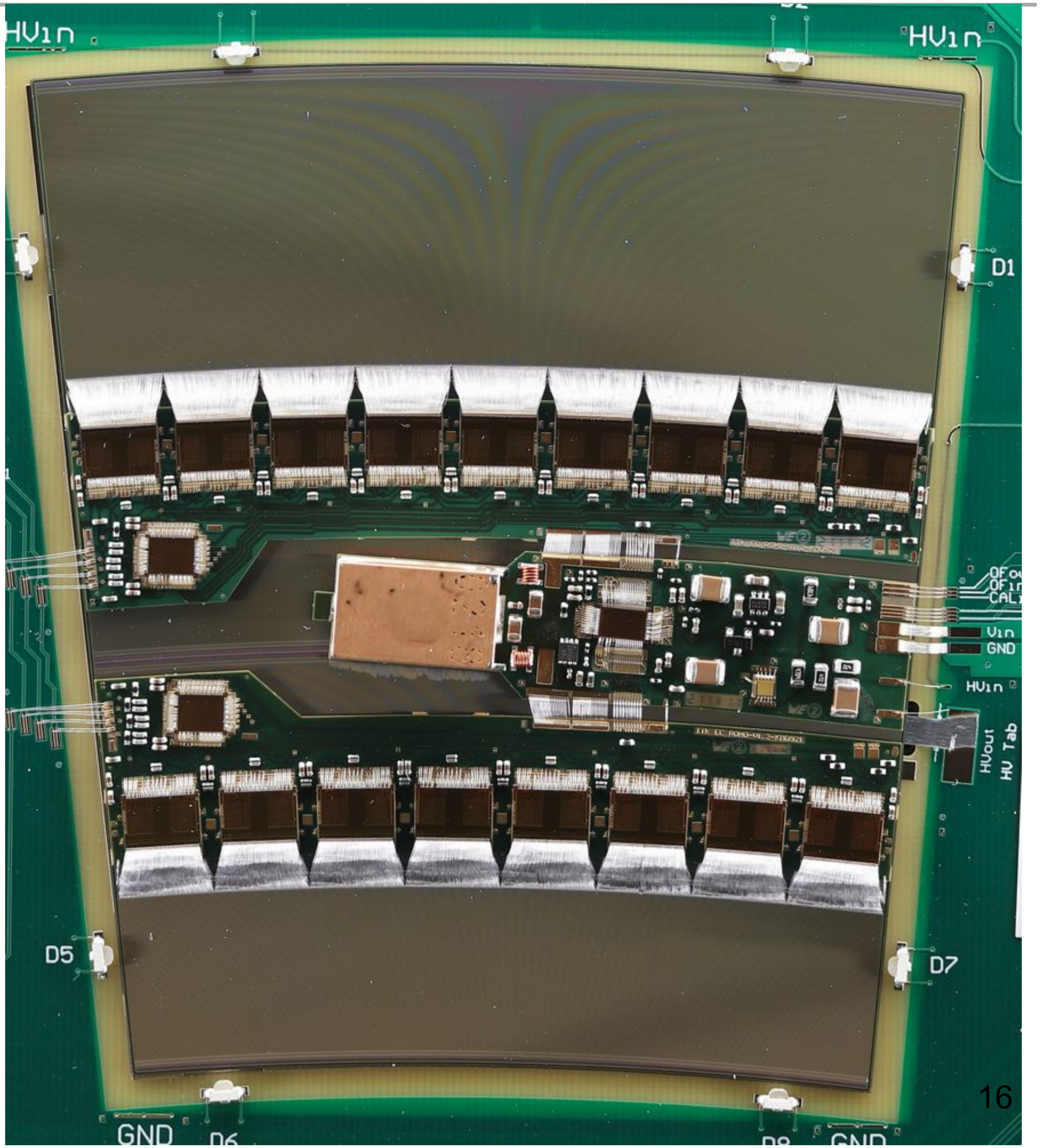


Modules

- Same philosophy for all modules in ITk-Strips
- Formed by:
    - Silicon strips sensors
    - “hybrids” readout electronics
        - Front-end ASICs (ABCStar)
        - Communications and control ASICs (HCCStar)
    - “Power-board”
        - DCDC conversion for low voltage
        - Provides bias high voltage monitoring and management
        - Monitors bias current and temperature of hybrids and power board
        - Shield box avoids EMI pickup



R0 silicon module

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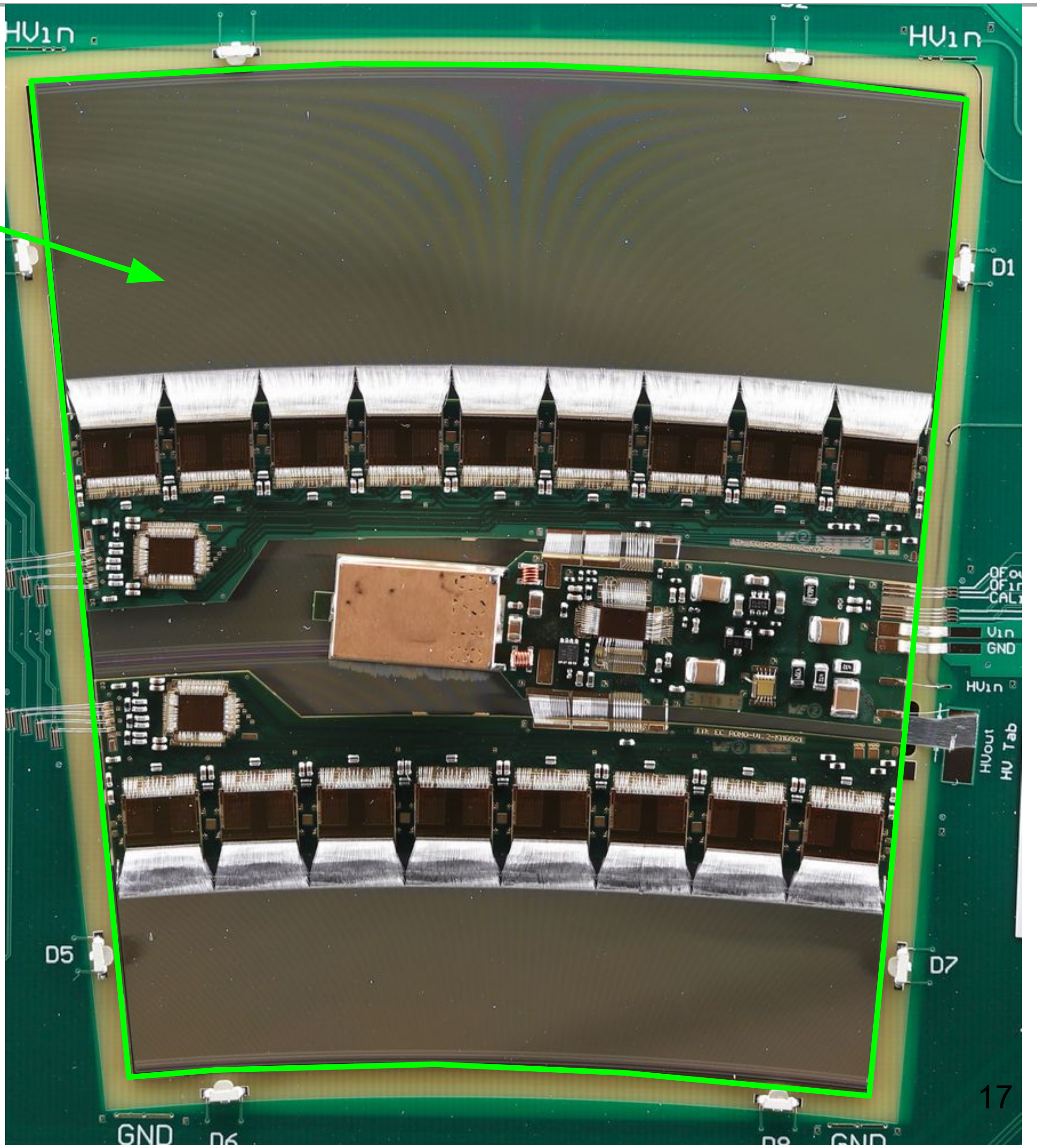

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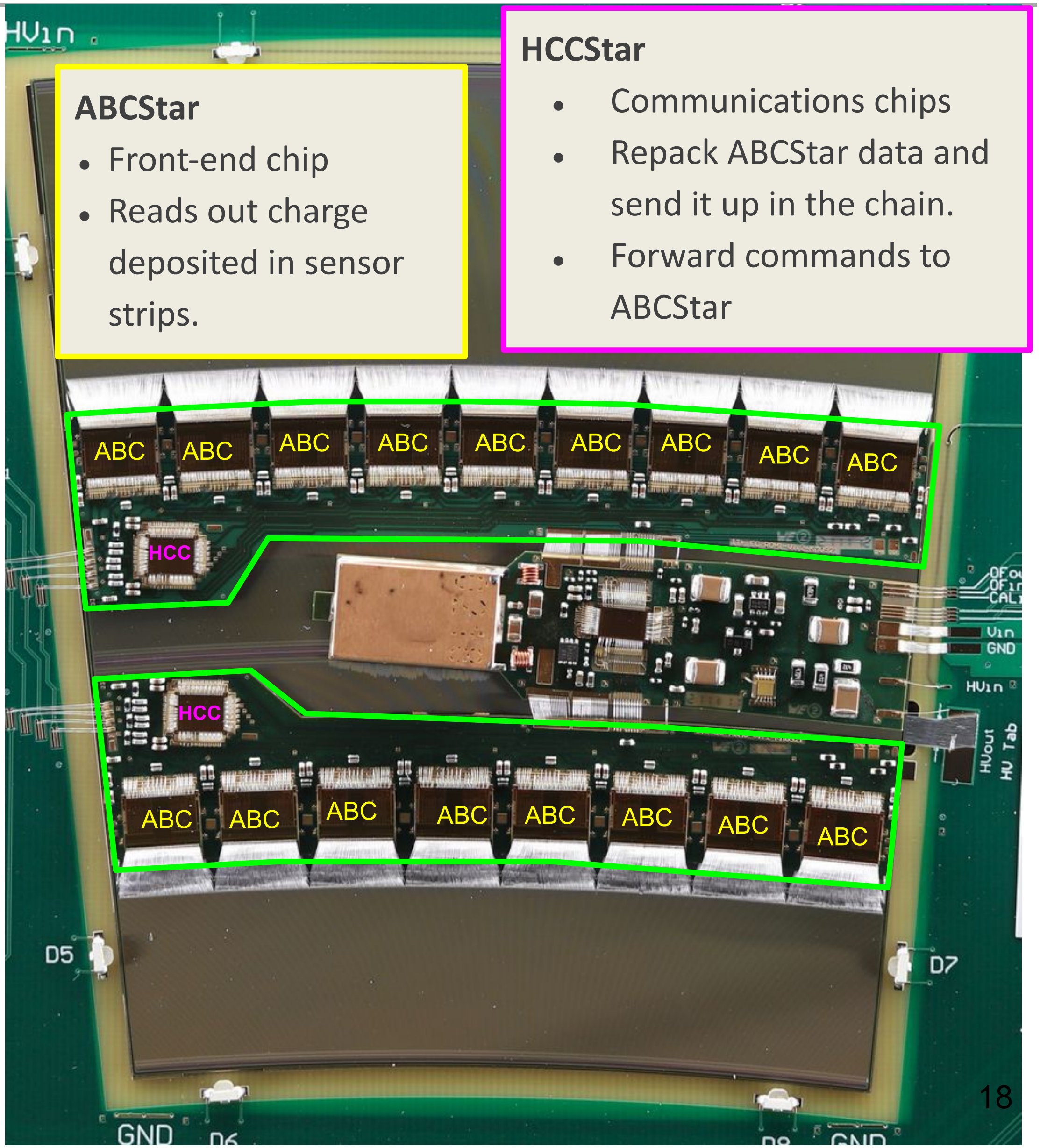

ABCStar

- Front-end chip
- Reads out charge deposited in sensor strips.

HCCStar

- Communications chips
- Repack ABCStar data and send it up in the chain.
- Forward commands to ABCStar

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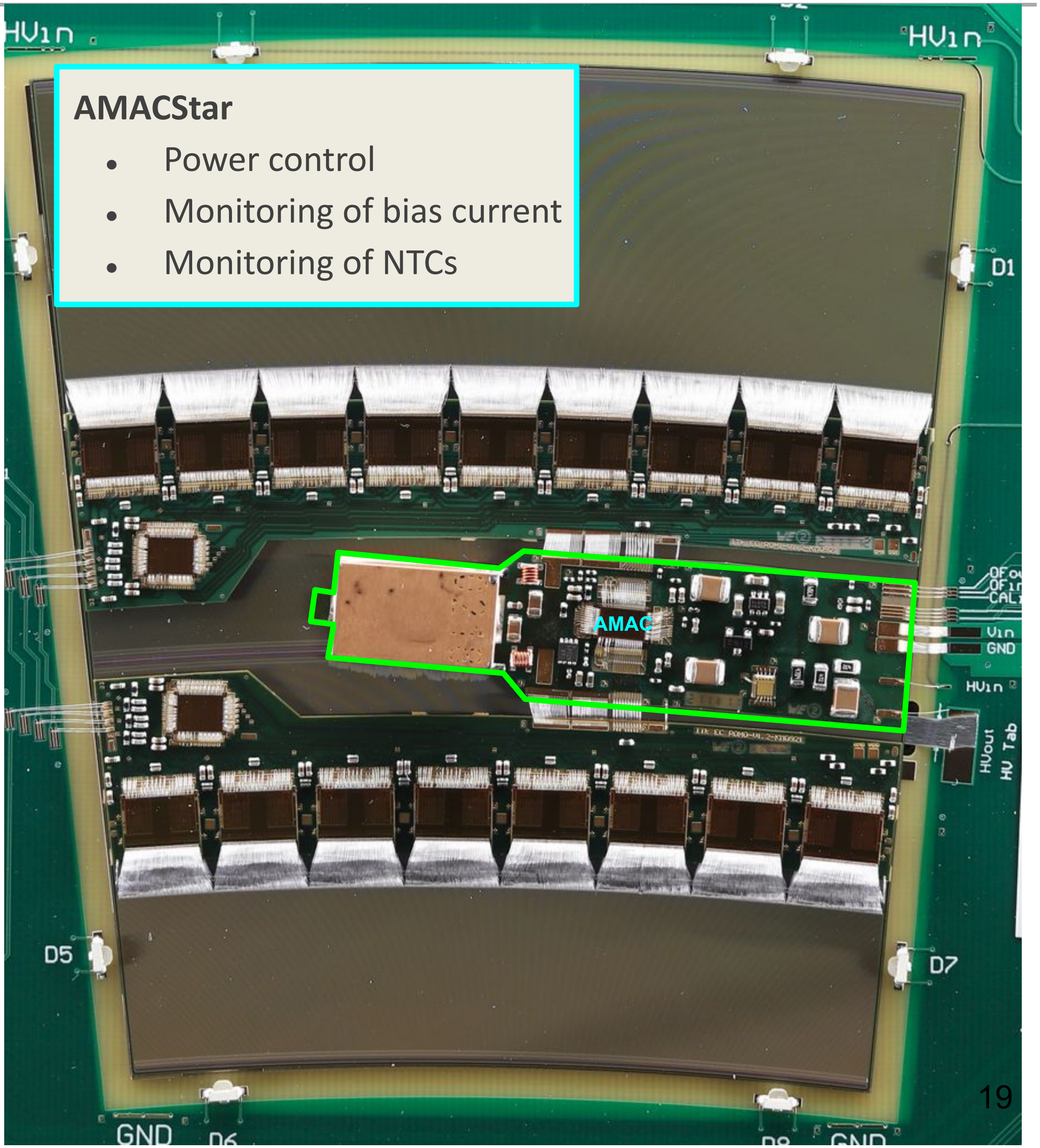
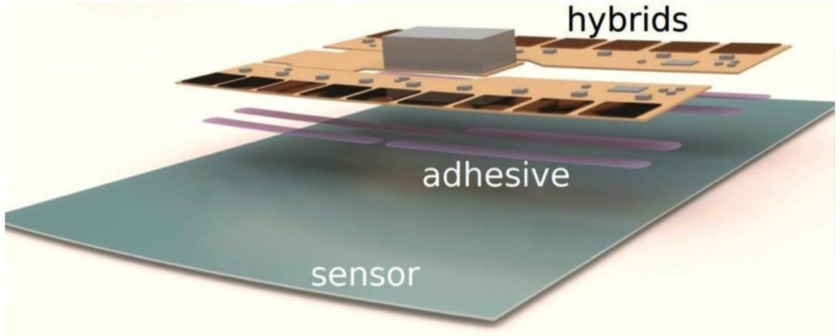
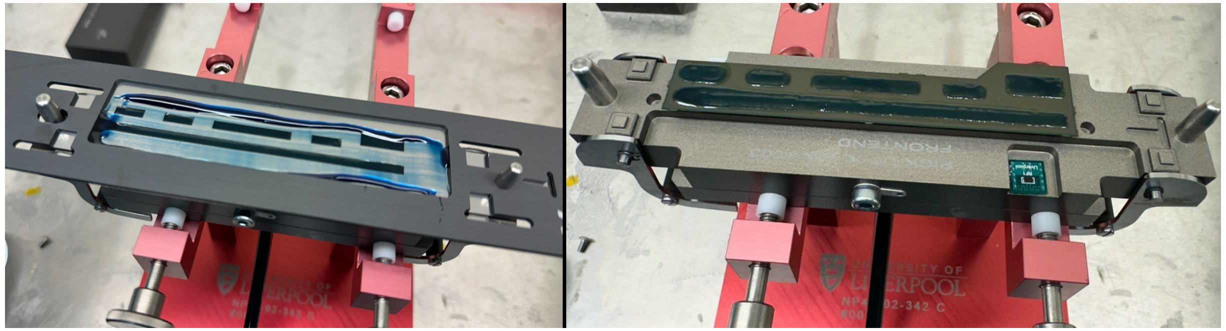


AMACStar

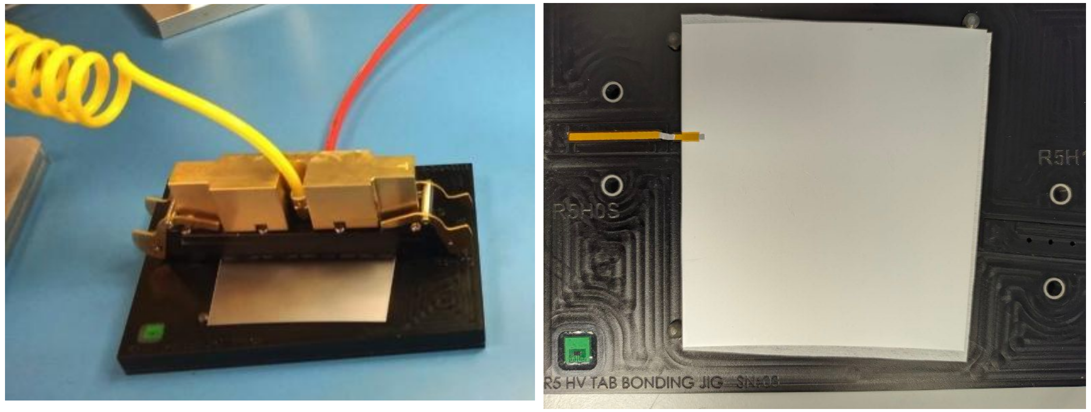
- Power control
- Monitoring of bias current
- Monitoring of NTCs

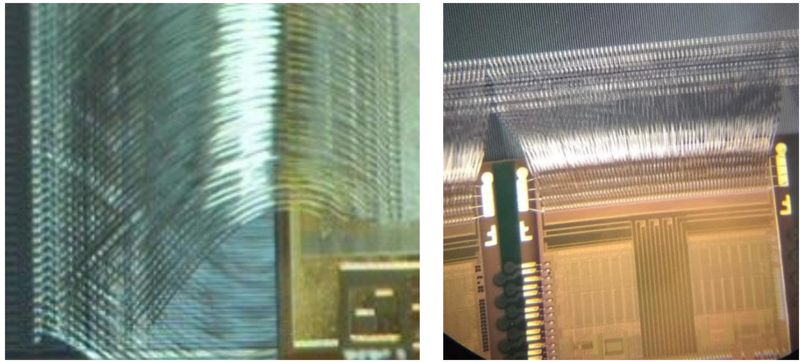
Modules





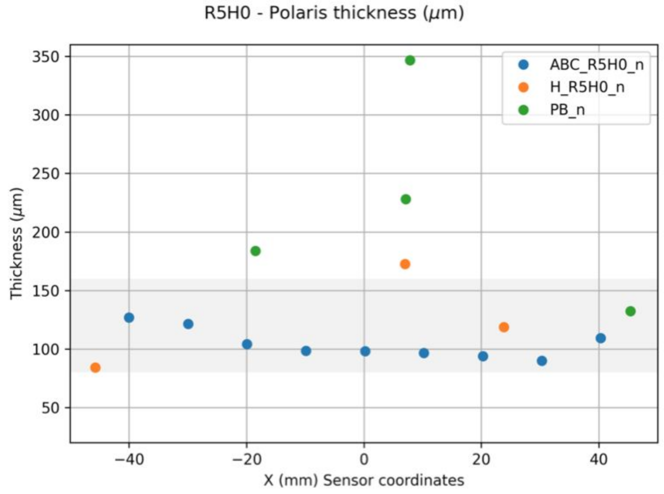
- **Precision assembly** (tens of µm accuracy) to
  - Guarantee good heat dissipation
  - Reduce stray capacitance between F-E and sensor
  - Avoid glue seepage on bias rings
- High precision custom tooling





- **Electrical connections** provided by wire-bonding
  - Each module around 1.5 m of wire.
- Sensors are tab-bonded on the back side for bias connection

Modules: QC

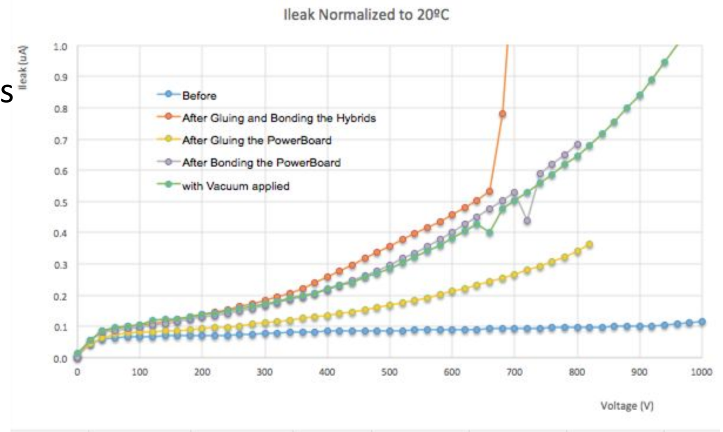


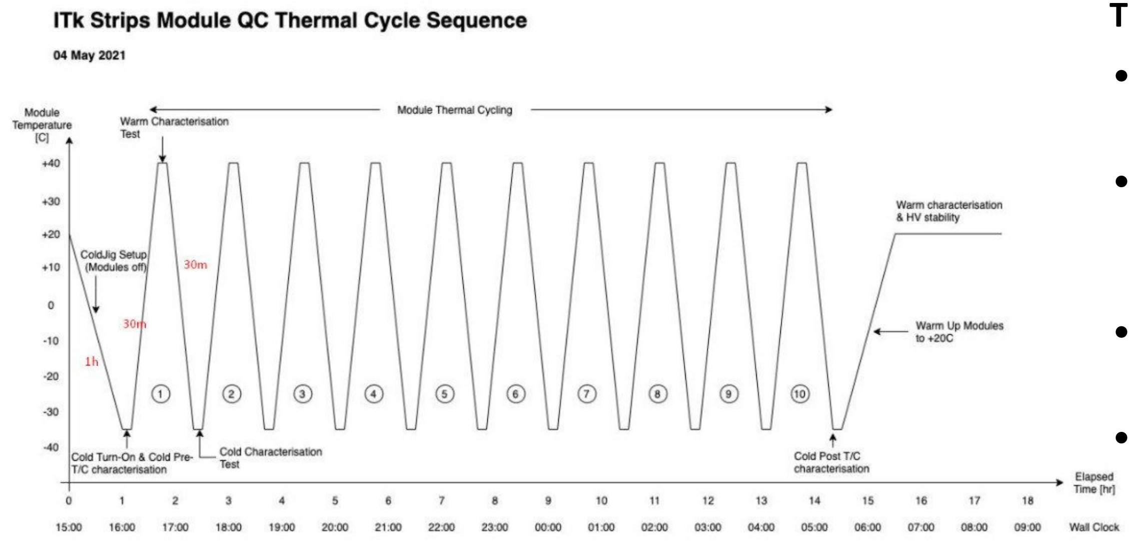
Metrology

- Ensure X,Y,Z precision of the assembly.
- Bow of sensor in specs

IV curves

- Measure IV of the sensors in the different stages of assembly
- Ensure there's no early breakdown



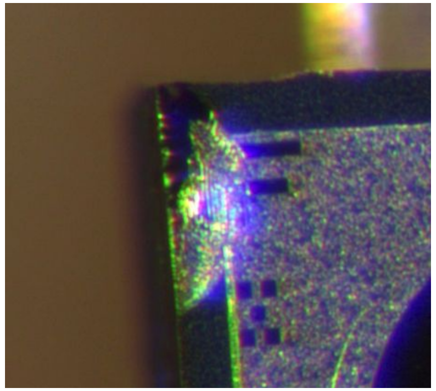


Thermal cycles

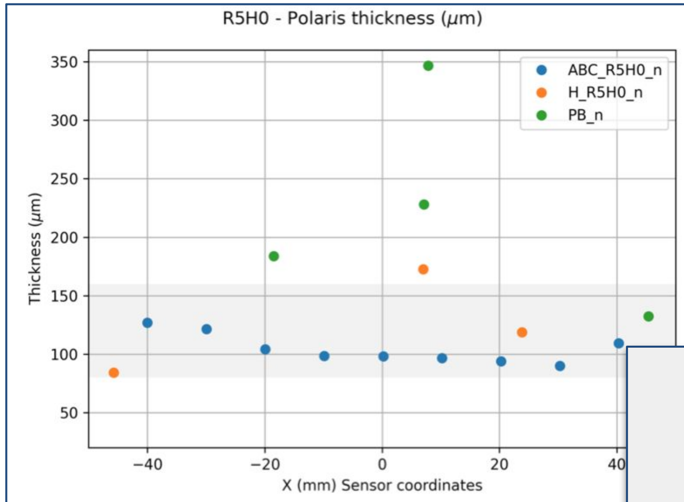
- Electrical tests with internal circuitry and biased sensor
- Prove that the electronics survive to changes of temperature
- Also prove they can operate at -35ºC (nominal working temp.)
- 10 cycles from 20ºC to -35ºC with electrical tests at each target temperature

Visual inspection and pictures

- After each step to catch damage and improve handling and procedures



Modules: QC



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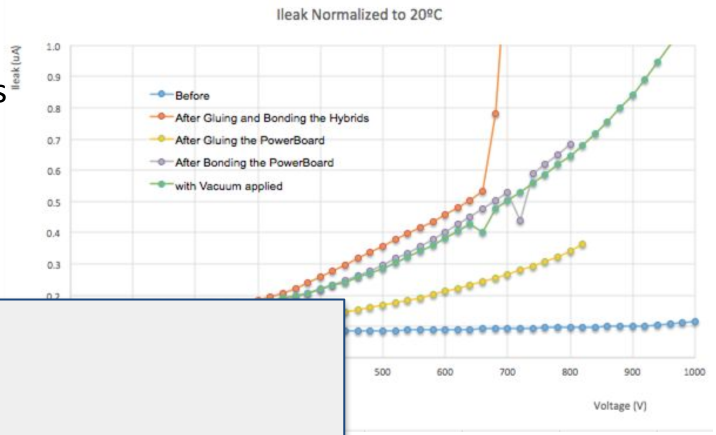
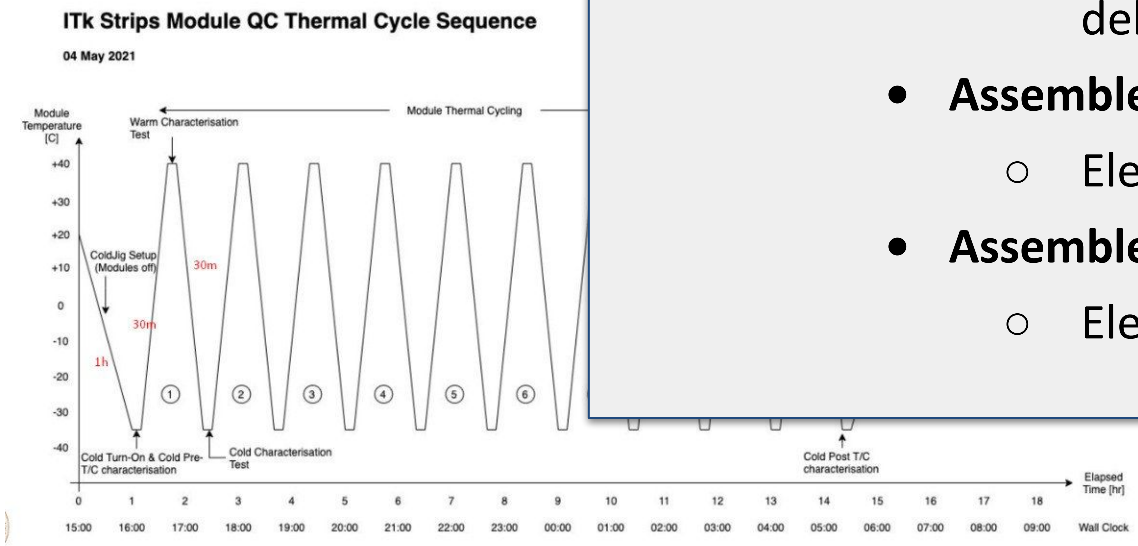


Many more QC tests!

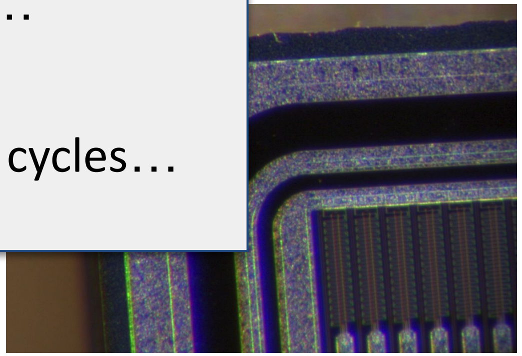
- **PCBs**
  - Visual inspection, pull-tests, delamination…
- **Assembled hybrids**
  - Electrical performance, burn-in…
- **Assembled power boards**
  - Electrical performance, thermal cycles…



ºC with electrical tests at each target temperature

nd pictures

to catch damage and ng and procedures



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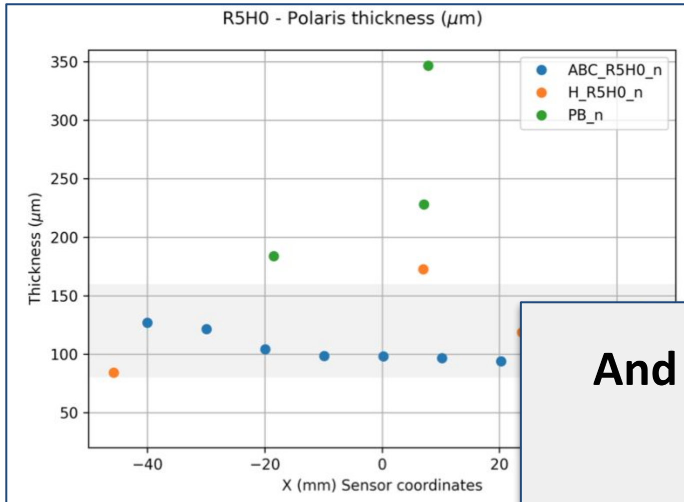

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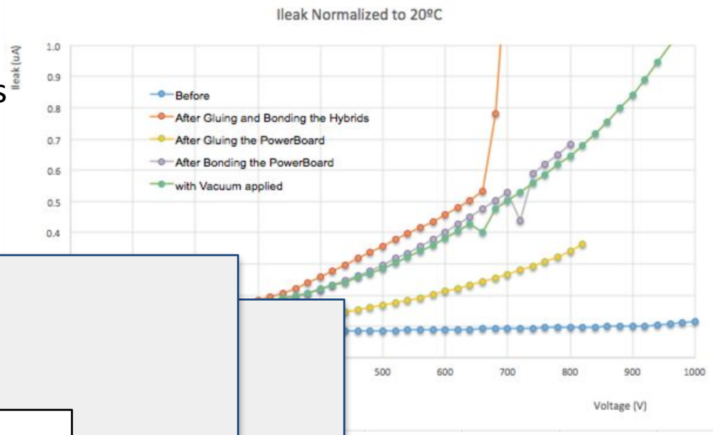


And QA!

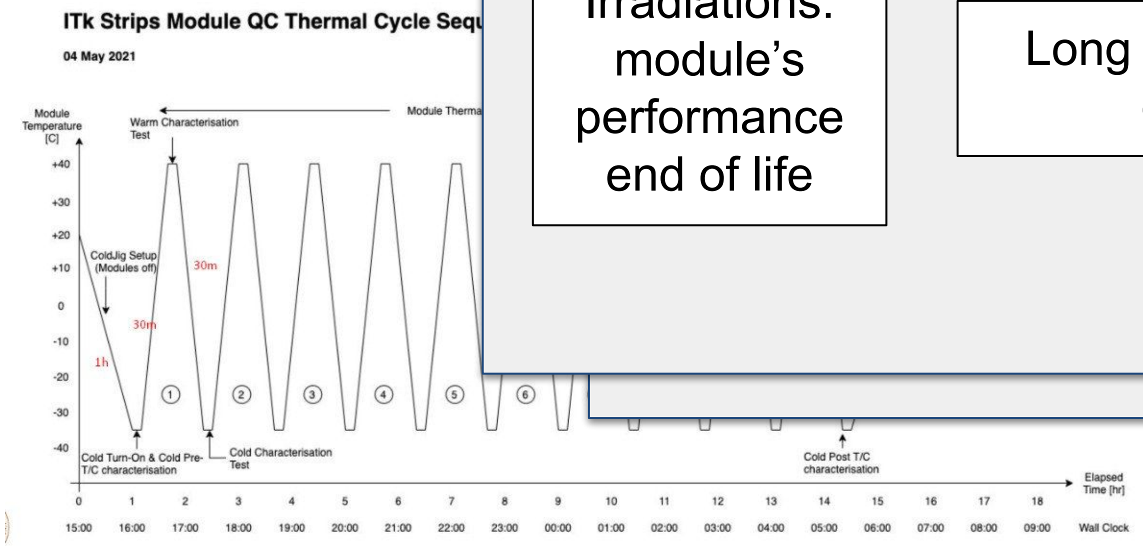
Test beams

…

Irradiations: module's performance end of life

Long term thermo cycling

Long term testing



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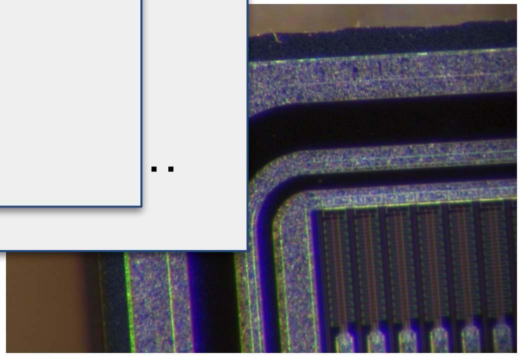
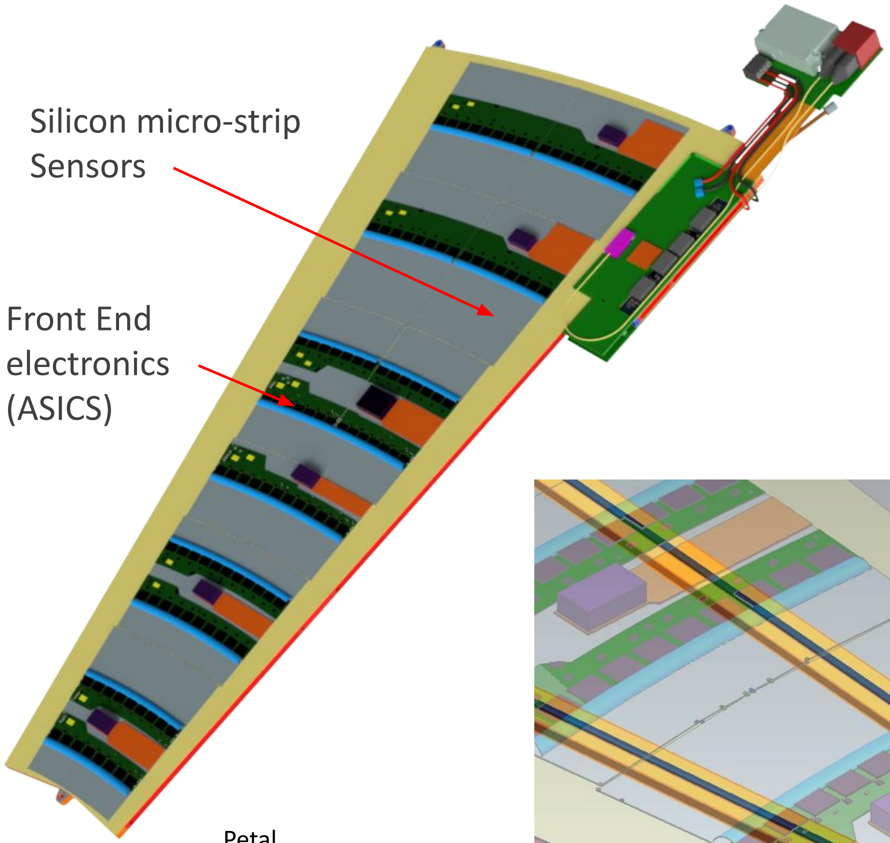


Local support structures: staves and petals

Very low mass support structures

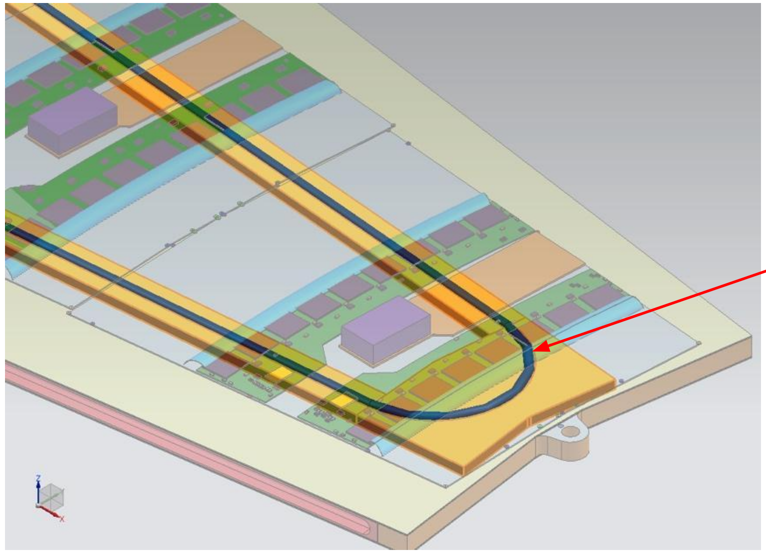
- Minimise materials and optimise heat dissipation.
- Rigidity and stability
- High mechanical precision (flatness, dimensions, fitting structures)

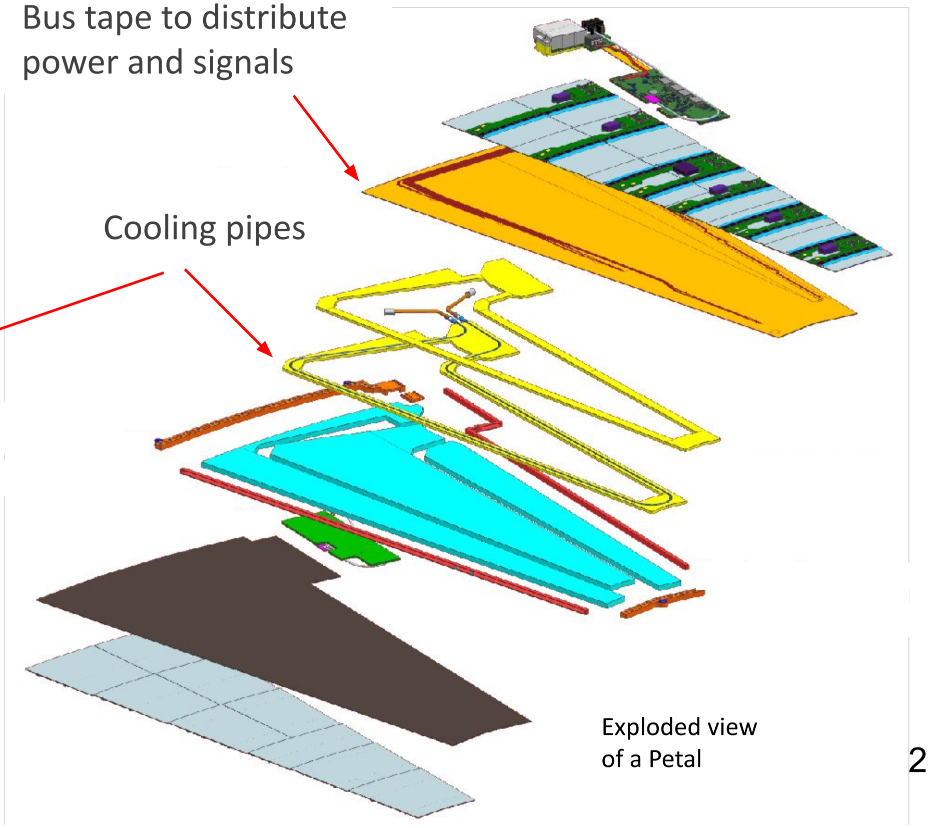


Silicon micro-strip Sensors

Front End electronics (ASICS)

Petal





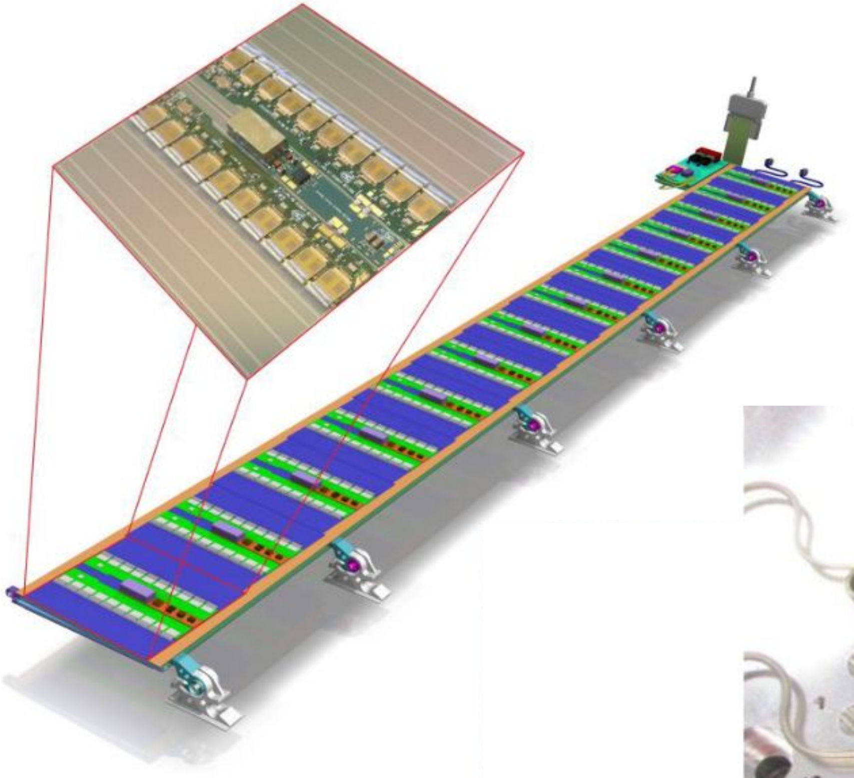
Bus tape to distribute power and signals

Cooling pipes

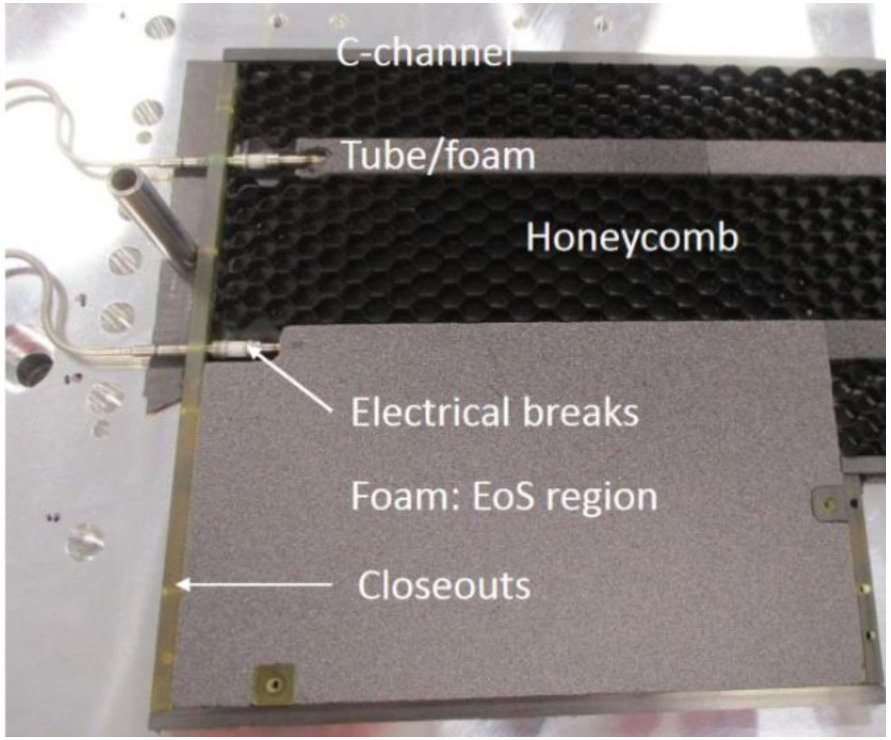
Exploded view of a Petal

Local support structures: staves and petals

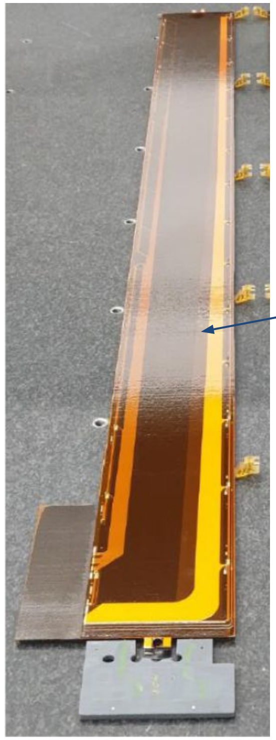
- Titanium pipes circulate CO2.
- Sandwich of carbon fibre foam filled with “honeycomb” carbon fibre.
- Space between pipes and honeycomb filled with carbon foam.
- Ceramic electrical breaks isolate electrically from cooling ground.
- Giant flex PCBs co-cured on top of carbon fiber “covers”.



SS stave



Inside of a stave core



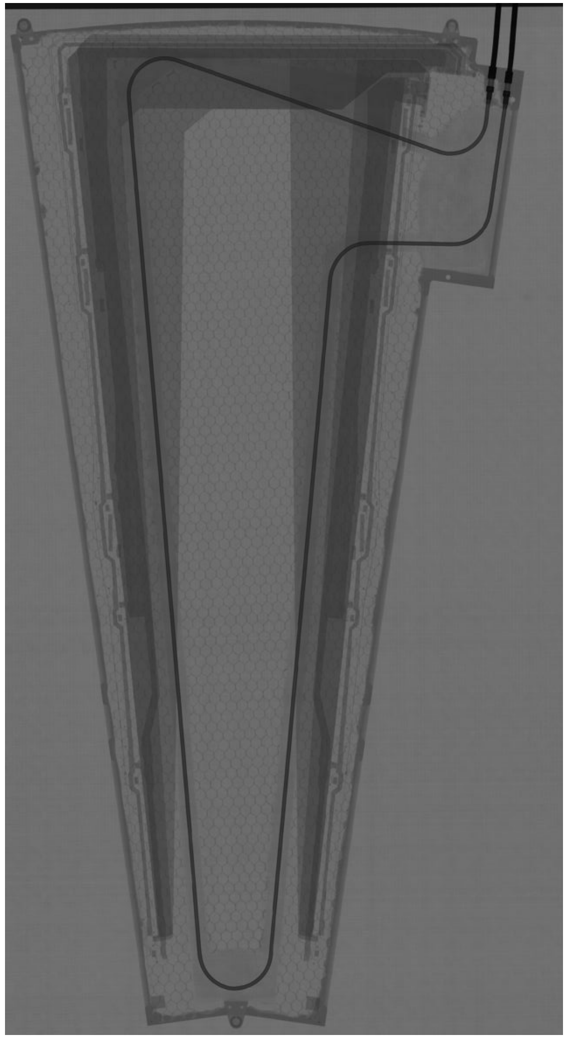
In brown /gold “Bustape” giant flex PCB

Finished stave core

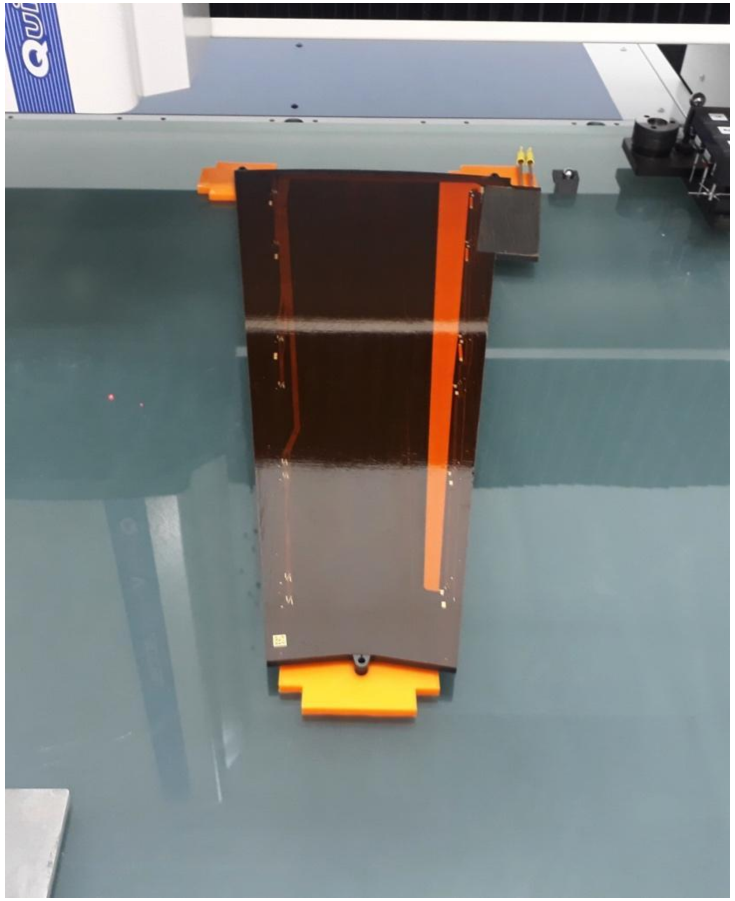
QC of local supports

Many other QC tests done to the “bus tape” flex PCB

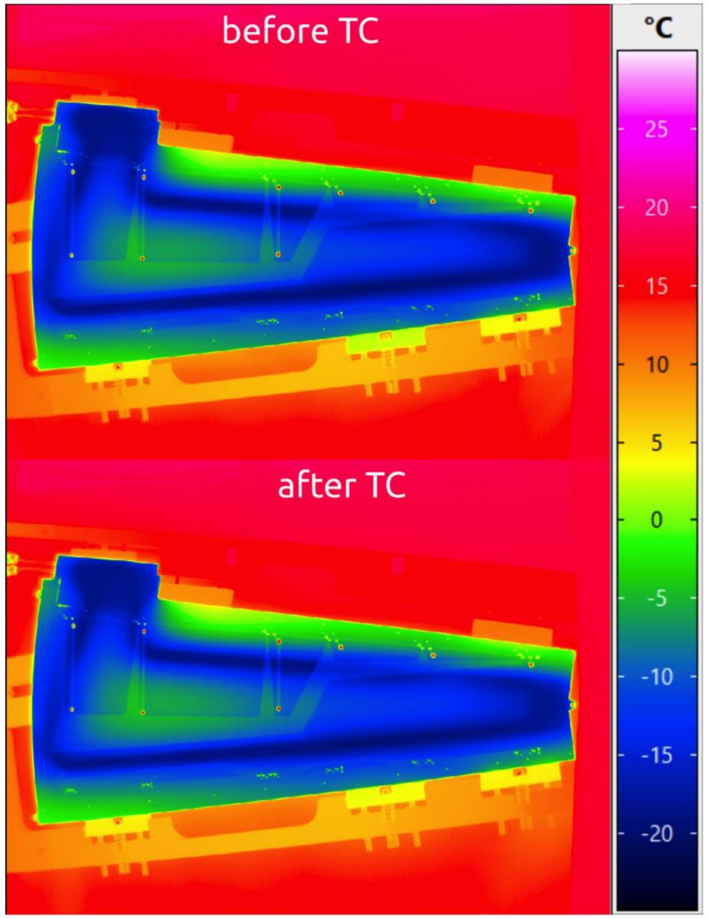
X-ray scan



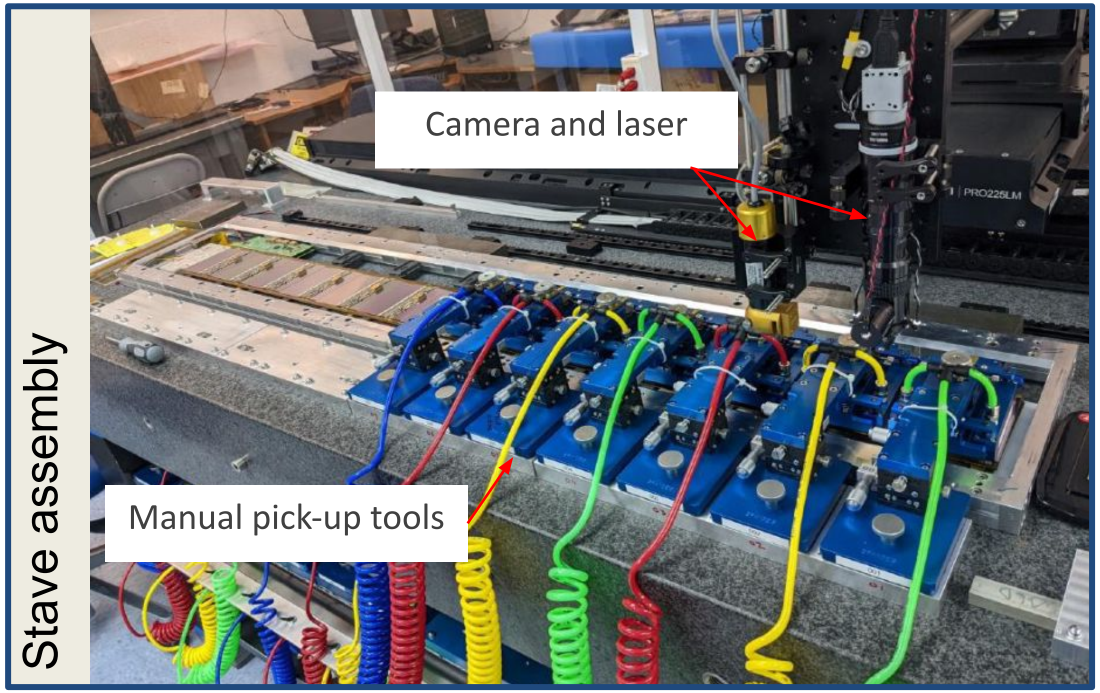
Metrology

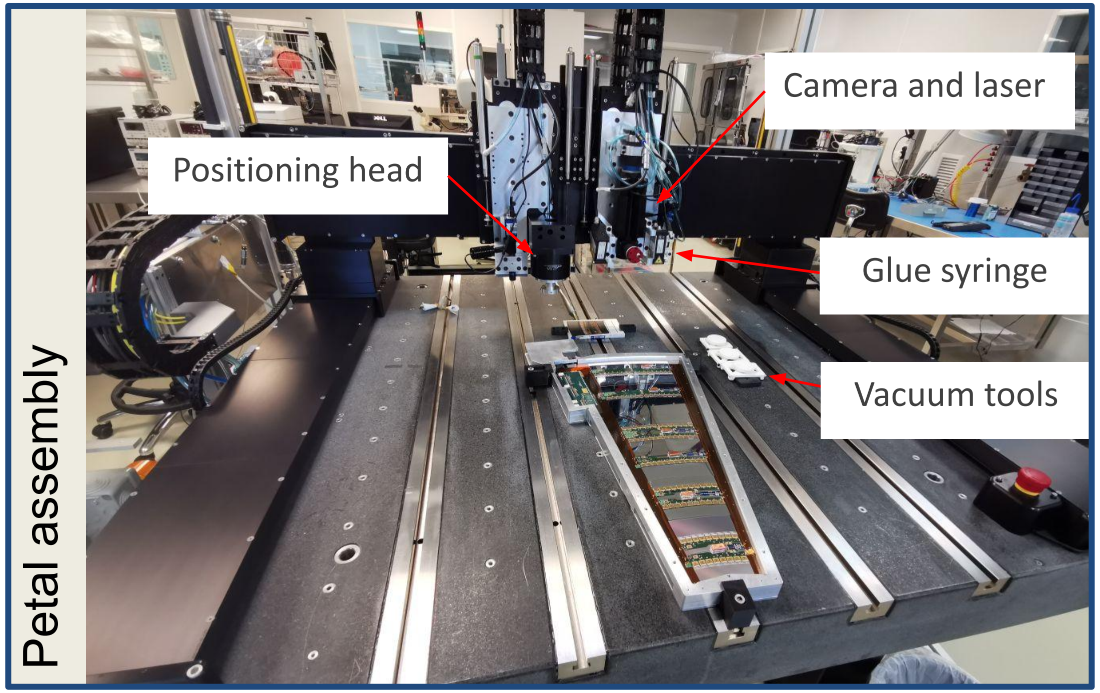


Thermal cycling + Infrared image



Local supports – Module loading



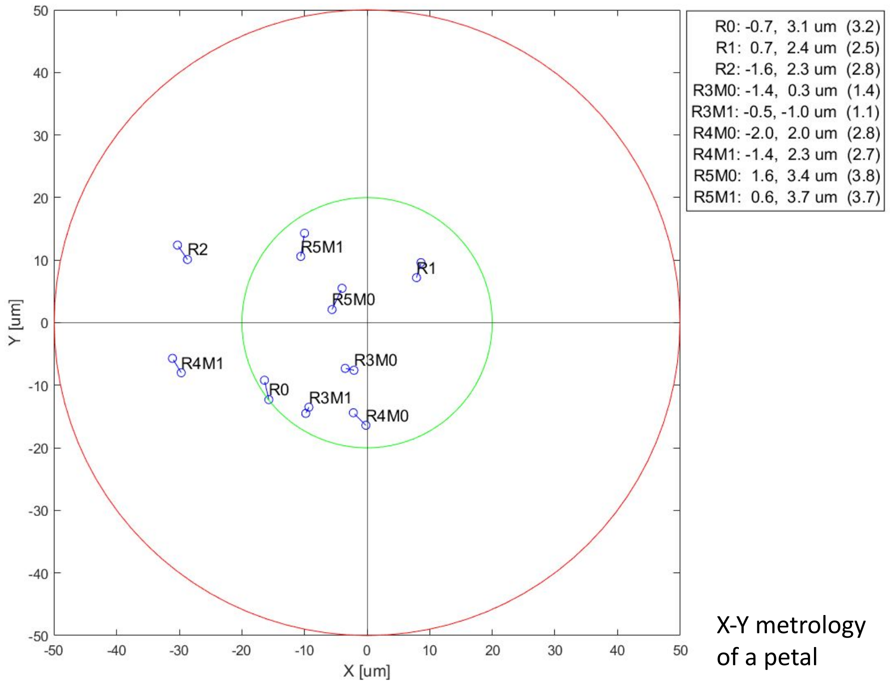


Modules are glued on the cores with a huge custom glue dispenser (gantry).

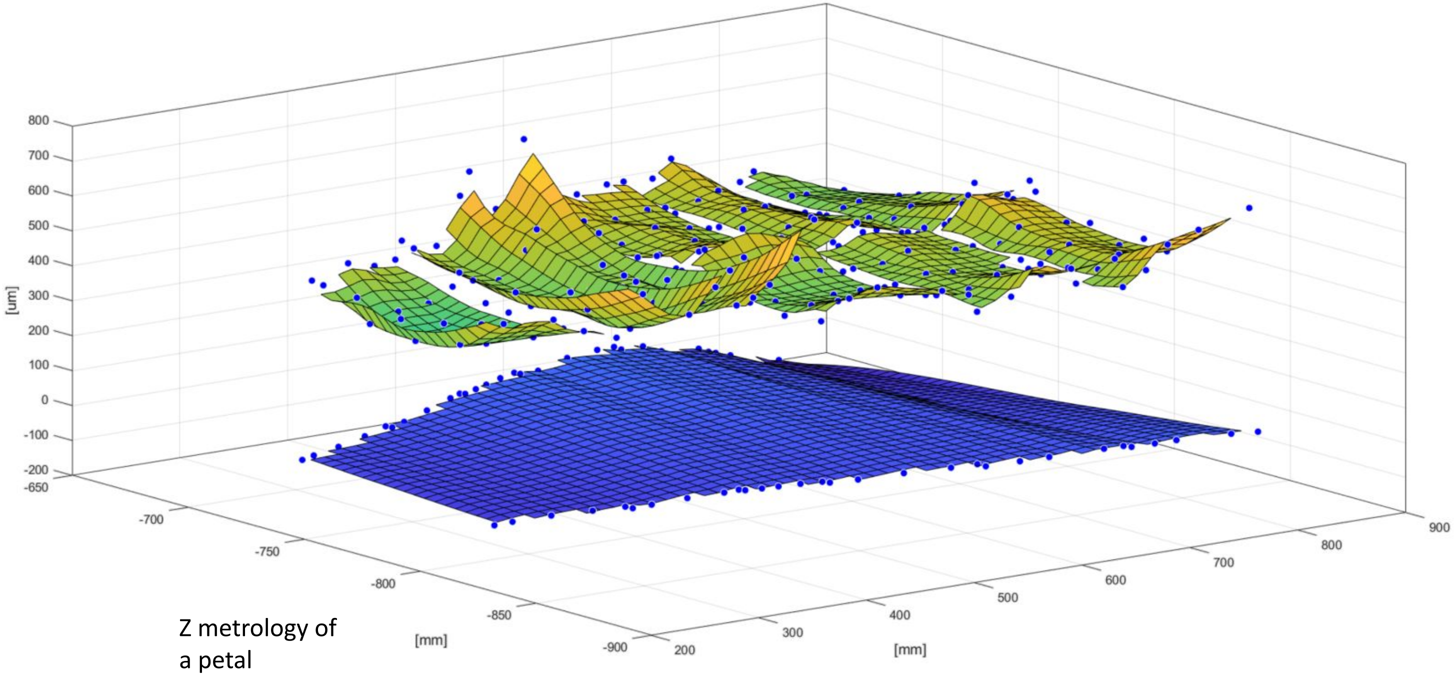
- In the staves using manual pick-up tools for positioning modules.
- In the petals using the gantry as a very large pick&place machine.
- Accuracy better than 50µm.

Gantry does metrology

Loaded petals and staves QC



X-Y metrology of a petal



Z metrology of a petal

- Metrology of the module position (X,Y) is done with optical camera and pattern recognition.
- Metrology of Z is done with laser system.

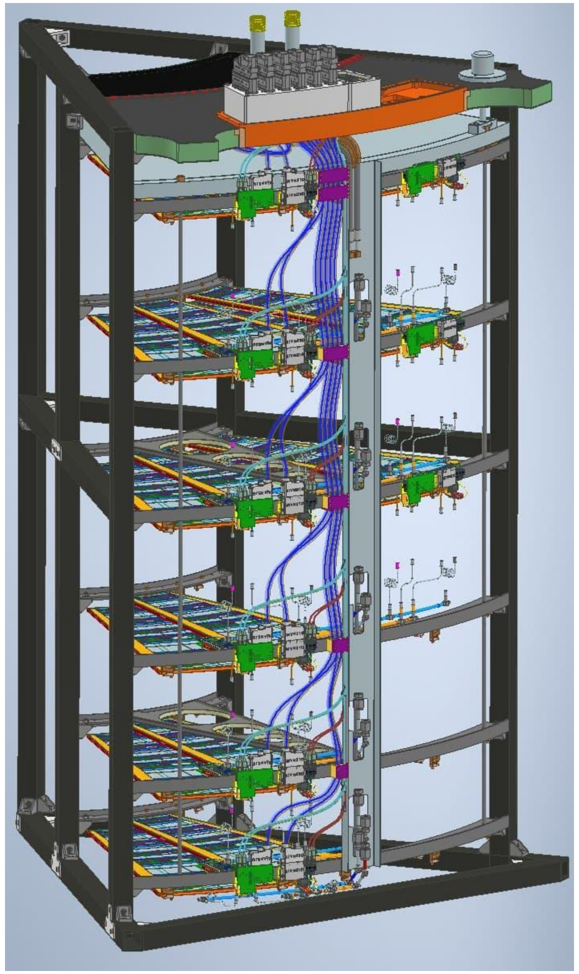
- Fully loaded petals and staves have to be bonded, electrically tested and operated at -35 °C **as part of the QC**.
  - Electrical performance is evaluated.

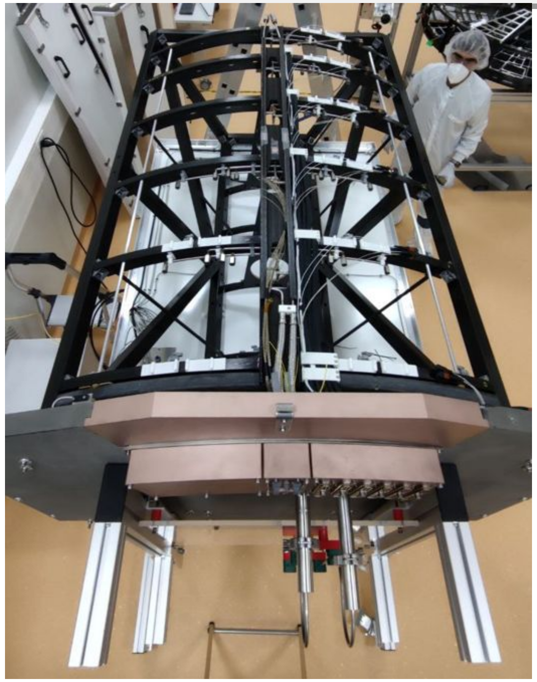
System test

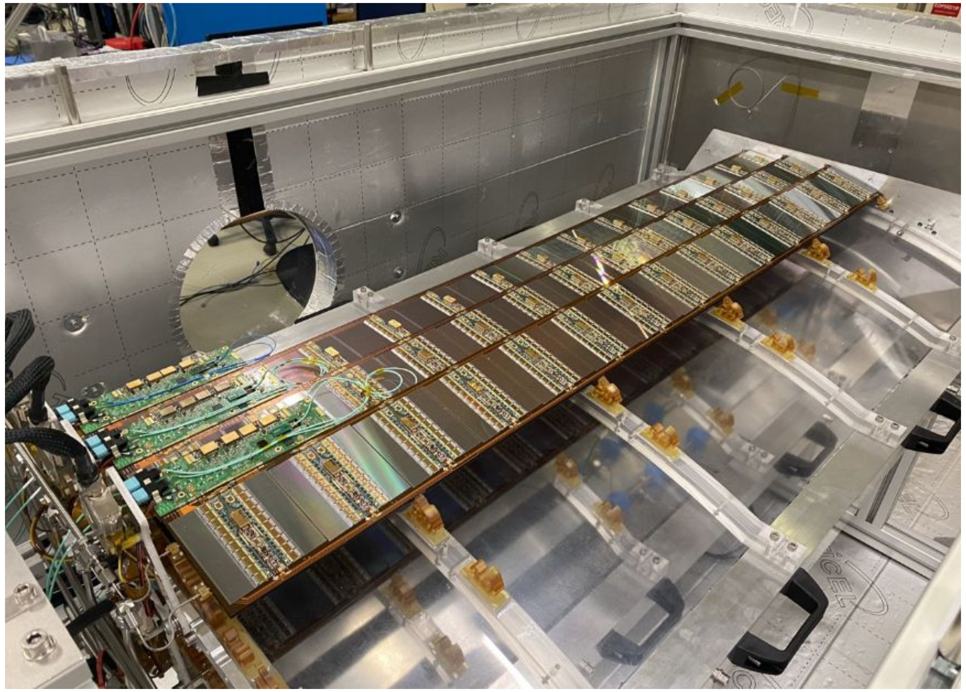
Poster: *Overview of the ATLAS ITk Strip System Tests (Sergio Diez)*

Realistic mockups of a section of the full system

- Barrel up to 8 staves, End-cap up tp 12 petals.
    - Those petal/staves won't go in the real detector.
- Test structures that represent most challenges that allow practicing/verifying
    - Petal/stave insertion
    - Pipe bending and welding
    - Cooling
    - Multi petal/stave readout with detector readout system
    - Services/patch panel
    - Power chain



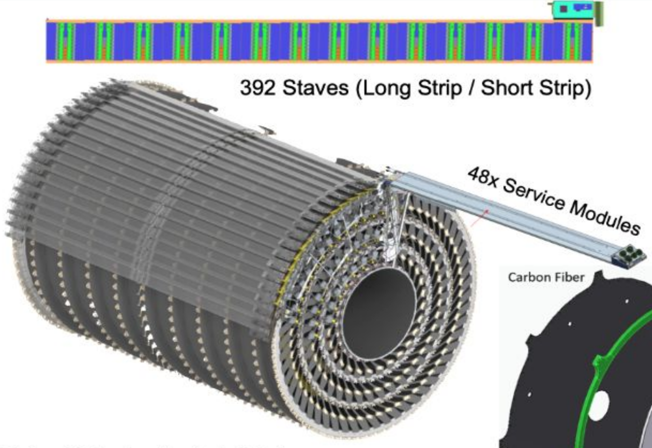




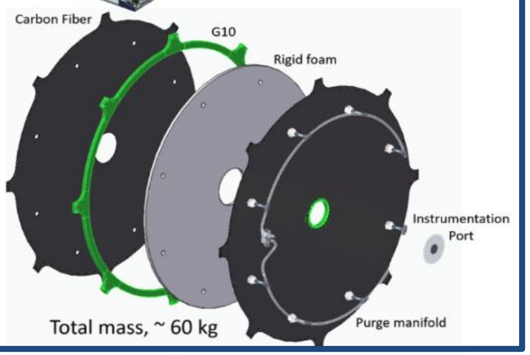
Global structures and integration

Staves barrel

Barrel insertion @CERN



- Outer Cylinder (not visible)
- 4 support cylinders
  - pre-dressed with stave locking brackets

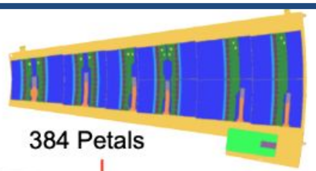


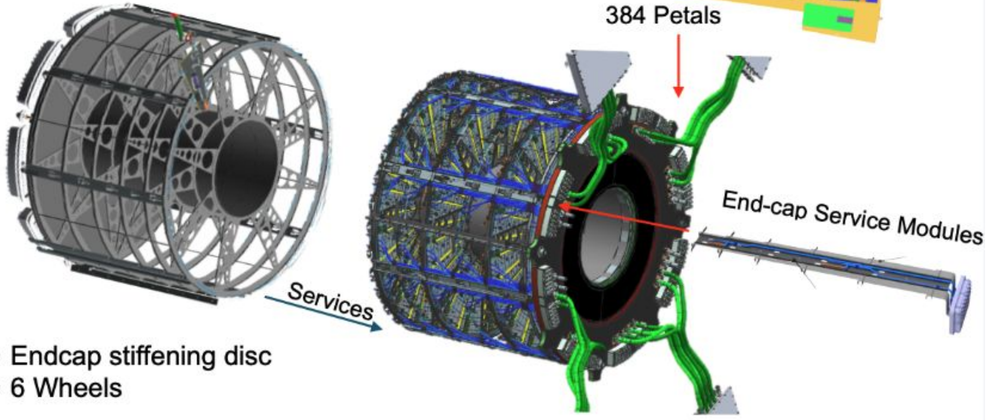
Barrel outer cylinder

- Support cylinder L3 delivered
- L2 and outer cylinder in preparation

Petal End caps

End cap integration @DESY and Nikhef

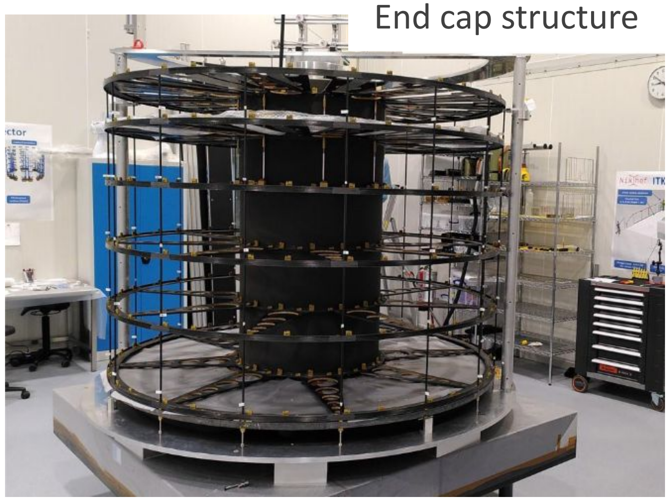




- Endcap stiffening disc
- 6 Wheels

The ECs are combined with **Final Bulkhead** and all services before petal insertion

End cap structure



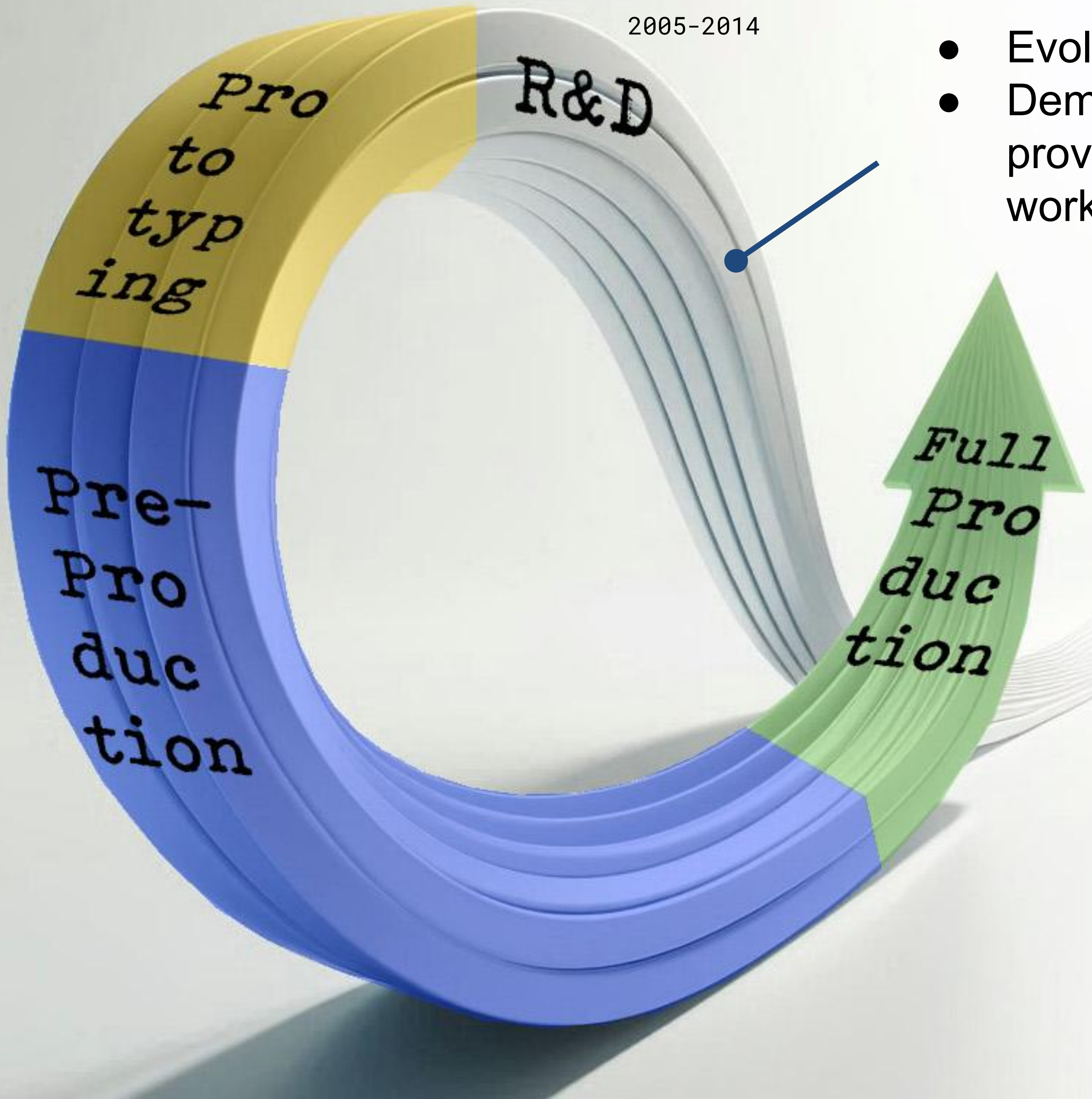
- Both End cap skeletons built and checked
- Services/pipes being installed
- Both bulkheads in hand

ITk-strips in production

The ITk-Strips in production

- The ITk-strips production takes place in ~60 institutes in 14 countries in Europe, Asia, America and Oceania.
- Organised in 6 production clusters
  - 2 Barrel: UK-China and US.
  - 4 End-cap: Canada, Germany1+Australia, Germany2, Spain+Czekia+Scandinavia.
  - Organised around petal/stave assembly sites.
  - Central activities outside the clusters structure.

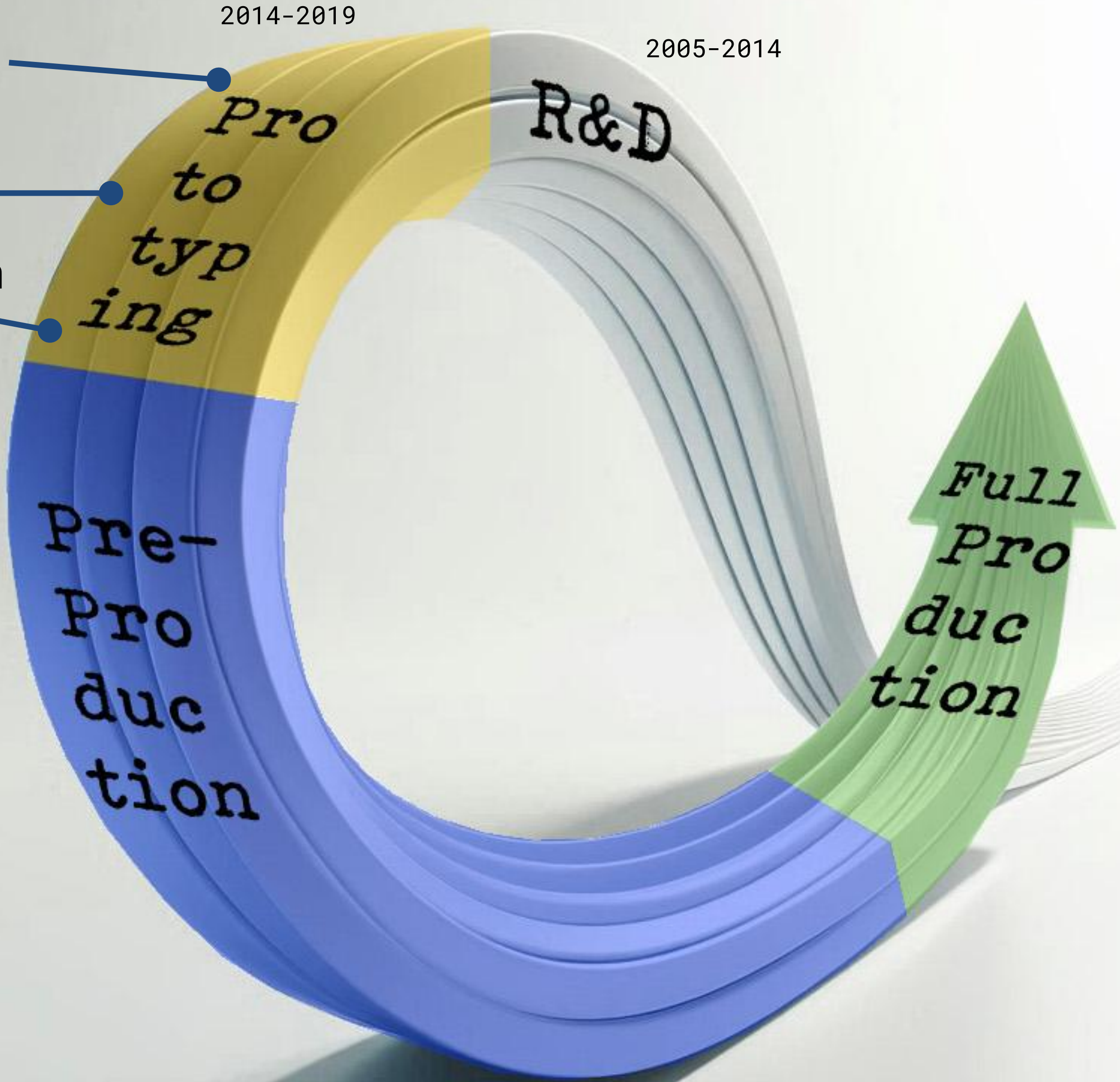
From prototyping to full production



- Evolved the concept
- Demonstrated some ideas and proved that the chosen ones worked

From prototyping to full production

- Verified design choices
    - ○ Non final parts
- Assembly and test procedures
- Started site qualification



From prototyping to full production

- Verified design choices
    - Non final parts
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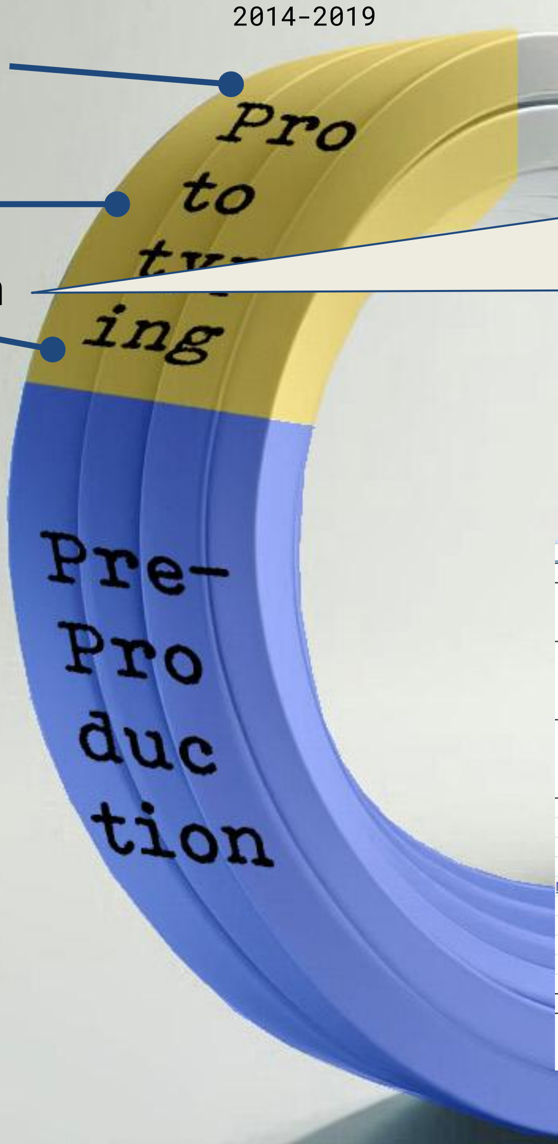
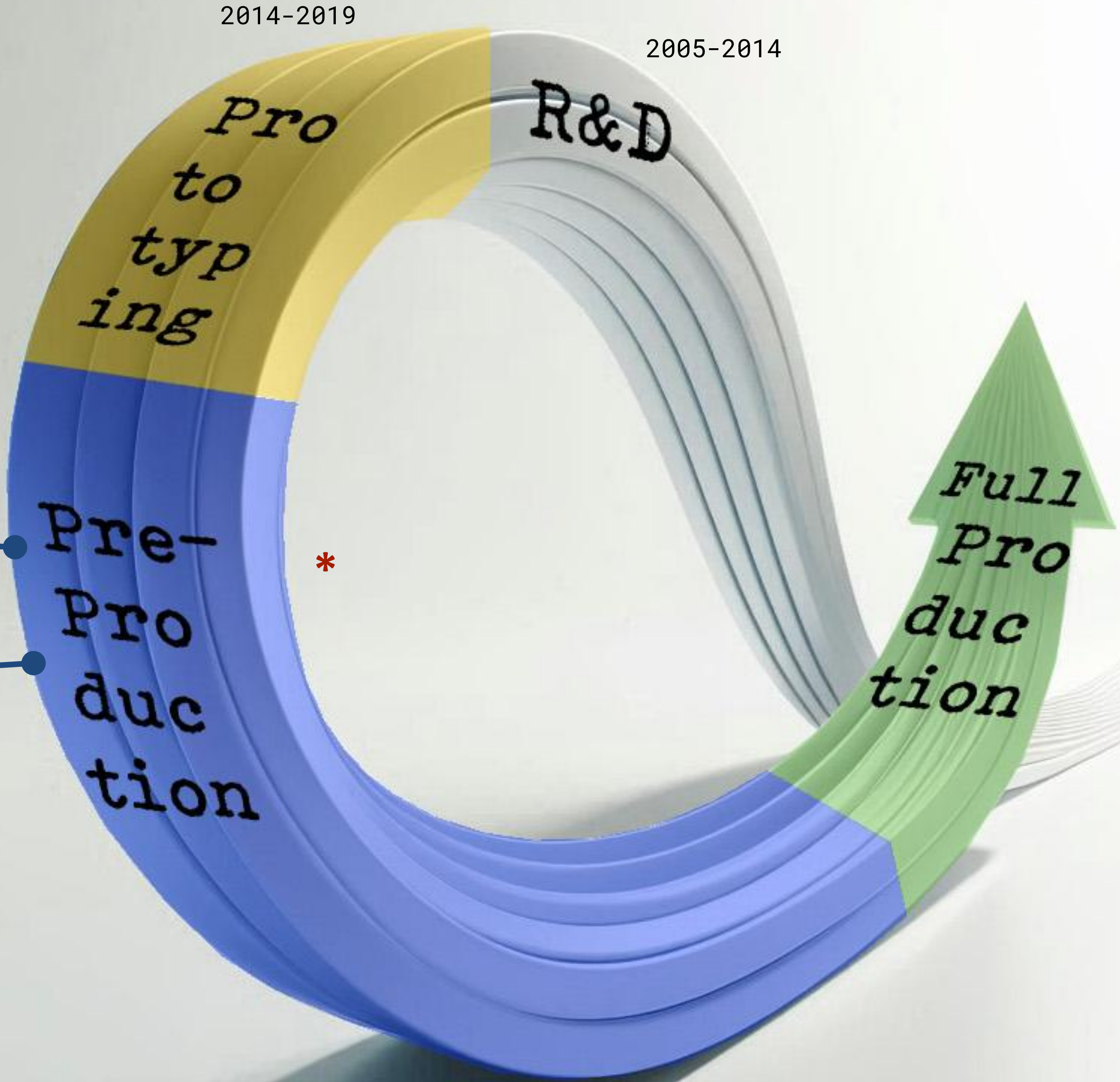
- Started site qualification



- Break tasks down in steps.
- Sites prepare documents that are reviewed online.
- Most sites fully qualified already

Block	Step Number	Qualification Step	Status	Ready for Review?	Object Swapped	Document Link	Video link	DB Entry	Review Status
HV Tab Attach	1.1	Bonding Procedures	Qualification Ready	Yes	No	HV tab attach			Passed
Sensor Reception	3.1	Sensor Reception	Qualification Ready	Yes		3.1 Sensor Reception			Passed
	3.2	Sensor Storage	Qualification Ready	Yes		Steps 3.2,6.4,8.10,11.1 TUDO General storage			Passed
	3.3	Sensor I-V	Qualification Ready	Yes		TU-Dortmund: 3		https://uuapp.plu	Passed
PB Reception	6.1	PB Reception	Qualification Ready	Yes		Reception Steps at TU-Dortmund			Passed
	6.2	PB E tests	Requires Parts	No					Not Reviewed
	6.3	PB Vis Insp	Qualification Ready	Yes	Not needed	Visual Inspection		https://uuapp.plu	Passed
	6.4	PB Storage	Qualification Ready	Yes		Steps 3.2,6.4,8.10,11.1 TUDO General storage			Passed
Hybrid Reception	10.1	Reception: hybrids	Qualification Ready	Yes		Reception Steps at TU-Dortmund			Passed
	10.2	Storage of hybrids	Qualification Ready	Yes		Steps 3.2,6.4,8.10,11.1 TUDO General storage			Passed
	8.7	Visual inspection: hybrids	Qualification Ready	Yes		Visual Inspection		https://uuapp.plu	Passed
	8.11	hybrid QC: single panel testing	Qualification Ready	Yes	No	8.11 Single pane	video-link		Passed
Module Assembly/Testing	11.1	Storage of modules	Qualification Ready	Yes		Steps 3.2,6.4,8.10,11.1 TUDO General storage			Passed
	11.2	Cleaning module jigs	Qualification Ready	Yes	Not needed	TUD Site Qualification			Passed
	11.4	Storage + shipping of glue	Qualification Ready	Yes	Not needed	Step 11.4 TUDO Storage of Glue (Sensor to Hybrid)			Passed
	11.5	Removing hybrids from panel	Qualification Ready	Yes		11.5 Removing h	https://cernbox.c	link	Passed
	11.6	Module Assembly	Qualification Ready	Yes	No	11.6 Module Assembly			Passed
	11.7	Metrology: modules	Qualification Ready	Yes	Yes	11.7 Metrology: Modules			Under Review
	11.8	Bonding procedures: modules	Qualification Ready	Yes	No	11.8 Bonding Procedures: Module		link	Passed
	11.9	Visual inspection: modules	Qualification Ready	Yes		visual inspection		link	Passed
	11.10	Module Thermal Cycling	Needs Development	No					Not Reviewed
	11.11	Single module Electrical Tests	Qualification Ready	Yes		11.11 Single Module Testing			Passed
Module Shipping	12.1	Shipping modules	Qualification Ready	Yes	Yes	12.1 Module Shi	https://cernbox.c	https://uuapp.plu	Passed
General	13.1	Cleanroom standards	Qualification Ready	Yes	Not needed	Step 13.1 TUDO Cleanroom Standards			Passed
	13.2	ASIC Compliance & Handling	Qualification Ready	Yes	Not needed	Step 13.2 TUDO ASIC compliance			Passed
	13.3	Bond Pulling Procedures	Qualification Ready	Yes		13.3 Bond pulling procedures			Passed

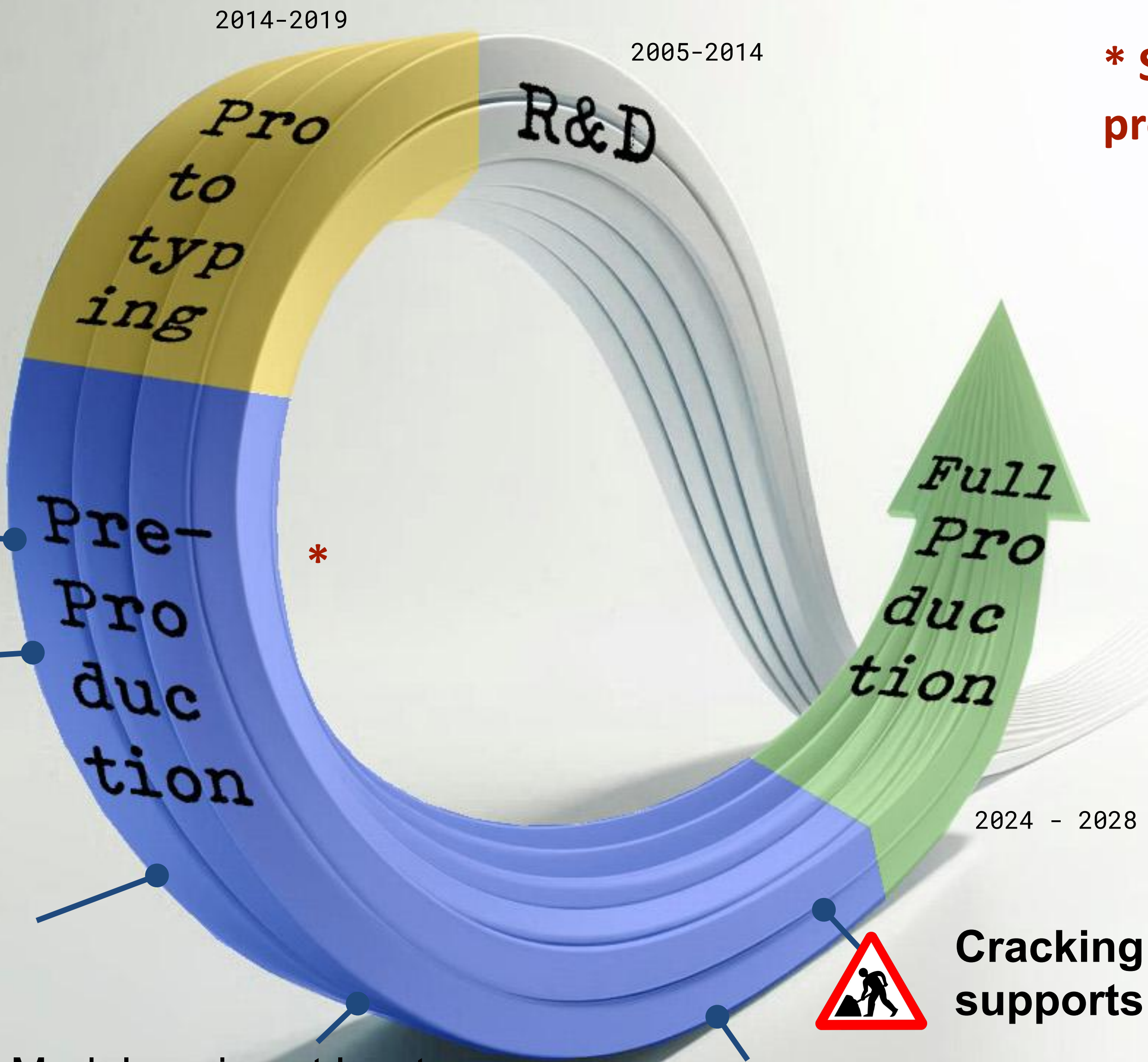
From prototyping to full production



*** Some activities already in production**

- Design verification with final parts
- Finished site qualification

From prototyping to full production

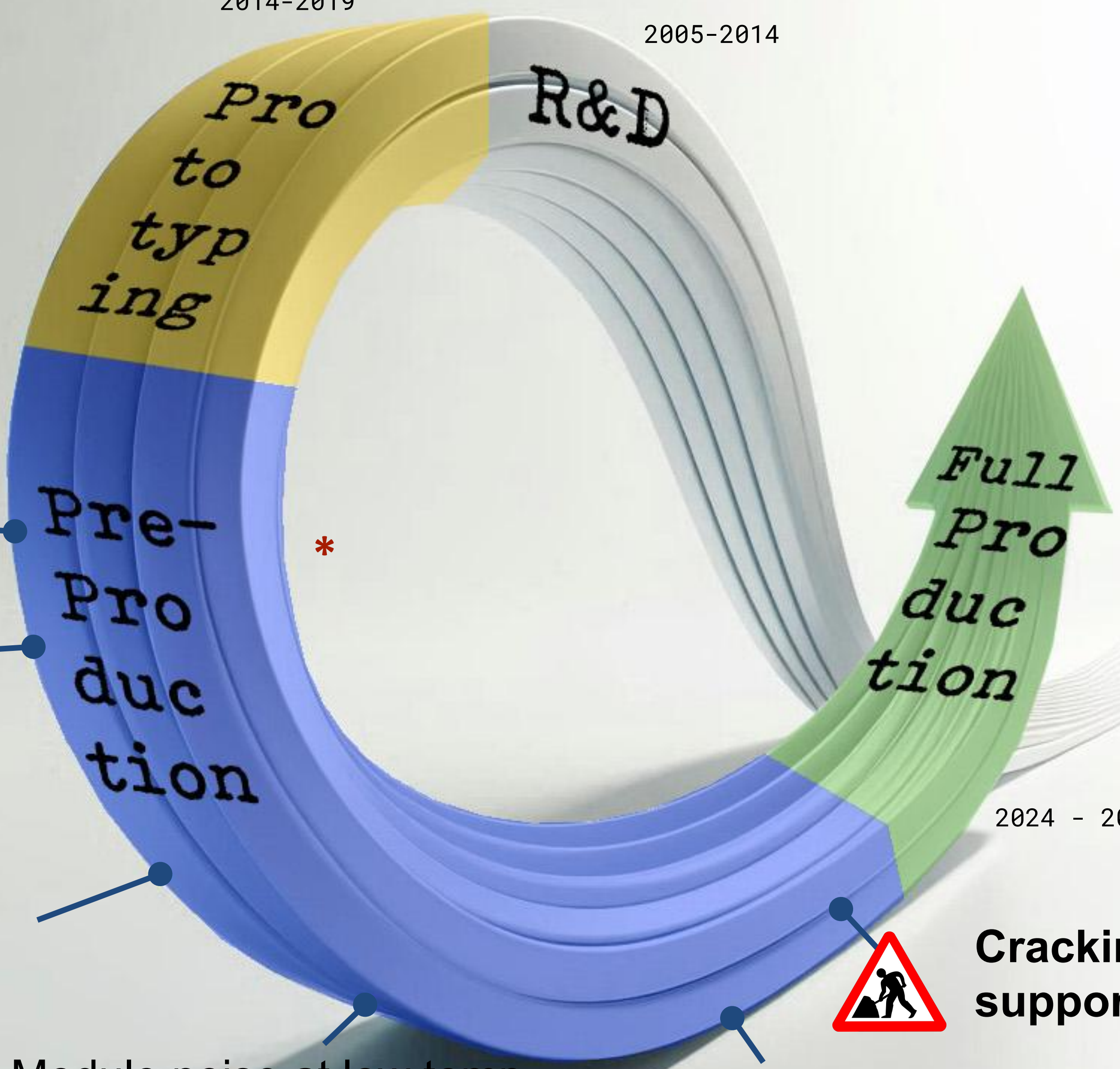


*** Some activities already in production**

- Design verification with final parts
- Finished site qualification
- New technical problems found
  - ✓ Power board excess noise
  - ✓ Module noise at low temp
  - ✓ Barrel cores and bustapes

Cracking modules in local supports at low temp

From prototyping to full production



2014-2019

2005-2014

2019-2024

2024 - 2028

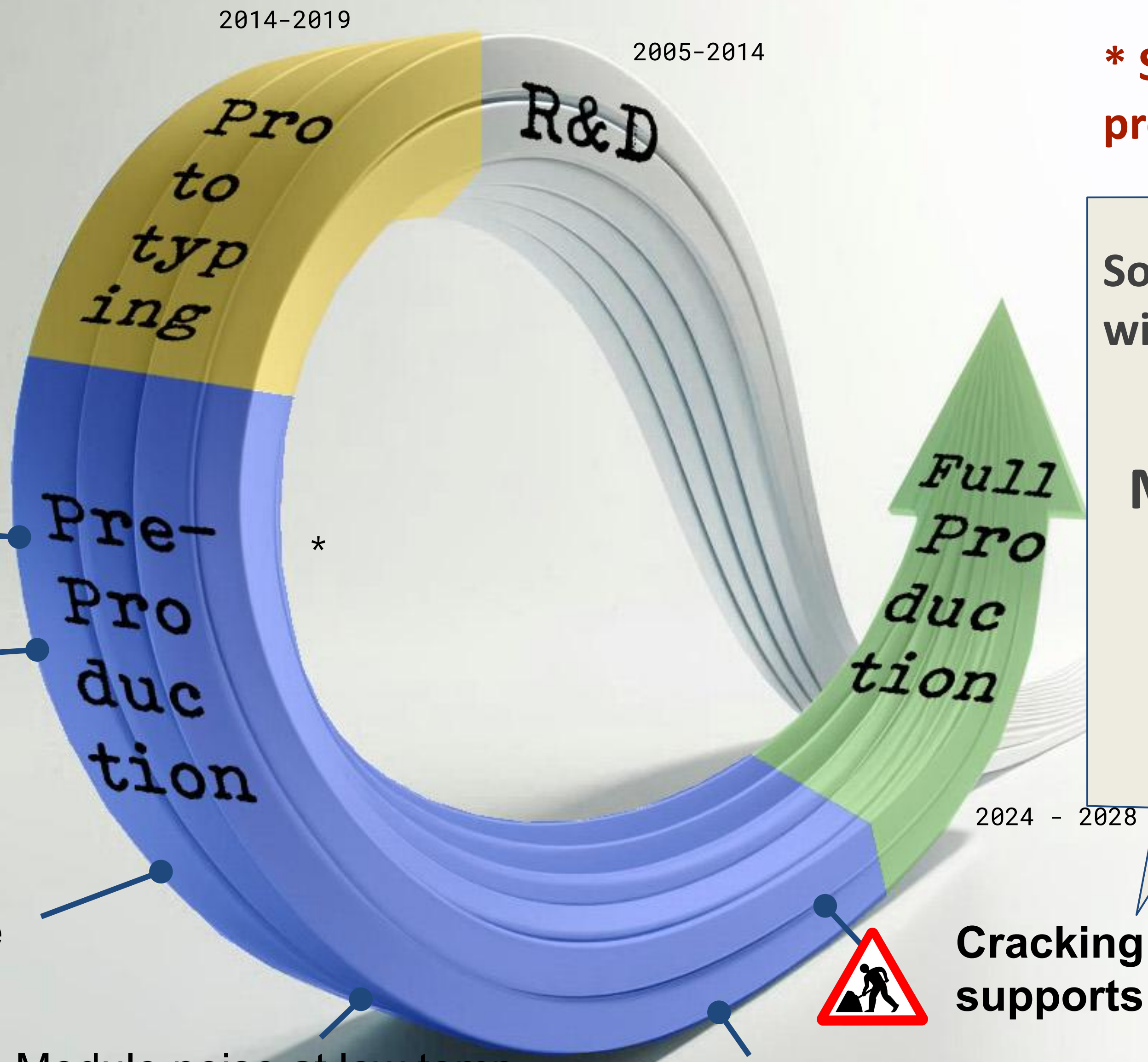
*** Some activities already in production**

- Design verification with final parts
  - Finished site qualification
    - New technical problems found
      - ✓ Power board excess noise
      - ✓ Module noise at low temp
      - ✓ Barrel cores and bustapes

Cracking modules in local supports at low temp

Poster: *Fighting cold noise and early breakdown on the ATLAS ITk strips tracker* (Sergio Diez)

From prototyping to full production



- Design verification with final parts
  - Finished site qualification
    - New technical problems found
      - ✓ Power board excess noise

✓ Module noise at low temp

✓ Barrel cores and bustapes

*** Some activities already in production**

Solving “module cracking” will release

Module production

⇓

Stave/Petal production

Cracking modules in local supports at low temp

Summary

- Building the new ATLAS Inner Tracker for the operation at the LHC is a very challenging task
    - Harsh environment.
    - Complex detector.
    - Many assembly and QA /QC sites in many countries.

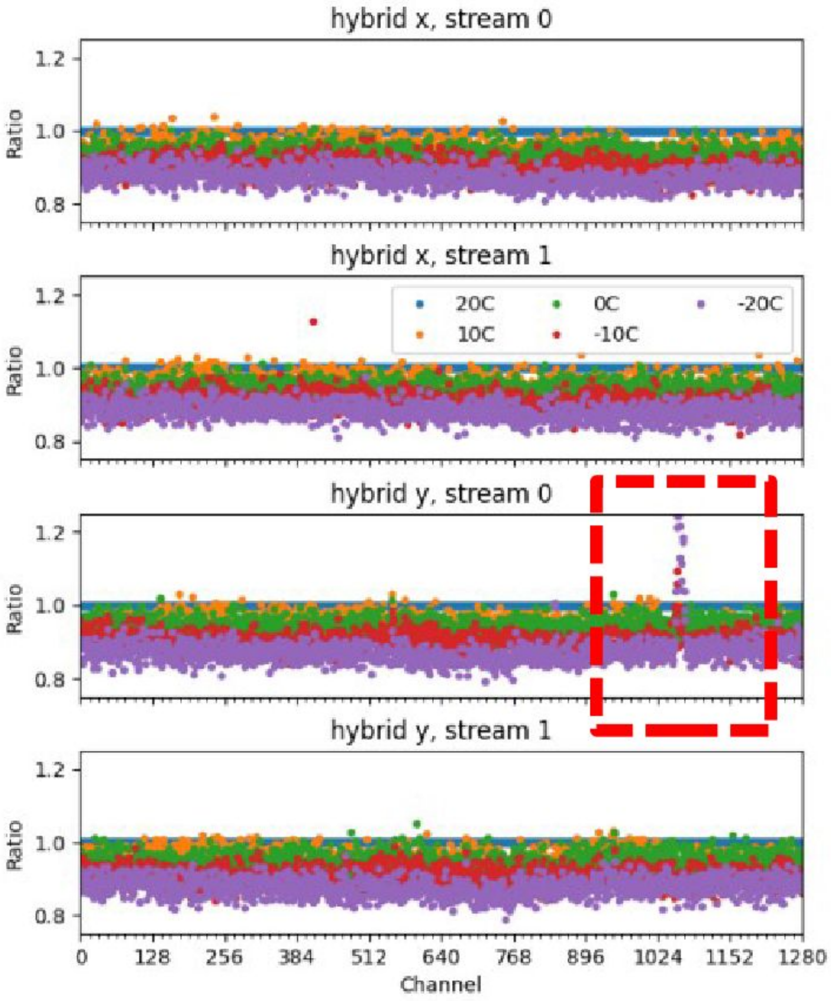
- After almost 20 years since we started R&D, having gone through prototyping and pre-production, we are confident that the ITK-Strips detector will satisfy its expected performance.

- Pre-production of higher-level assemblies (modules, petals, staves) is about to finish and we target starting **full** production this year.

Backup

Cold noise

- Observed in Pre-Production modules.
- Modules showed good noise performance at room temperature.
- Cooling down to -35C produced noise peaks in electrical test.
- More pronounced for colder temperatures.
- Not always in same location, but clustering in certain areas.
- Not on every module.
- Cold noise magnitude depends on flavour of module.



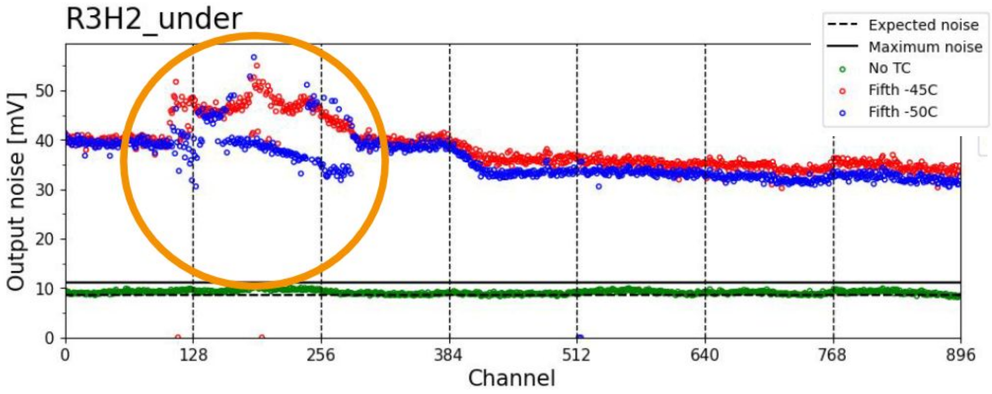
- Current baseline module glue **removes cold noise** from End-cap modules and and barrel long-strip while reduces dramatically cold noise in barrel short-strip.
- Effect related to vibration of capacitors on power board. Coupling mechanism to sensor/front-end still not understood.

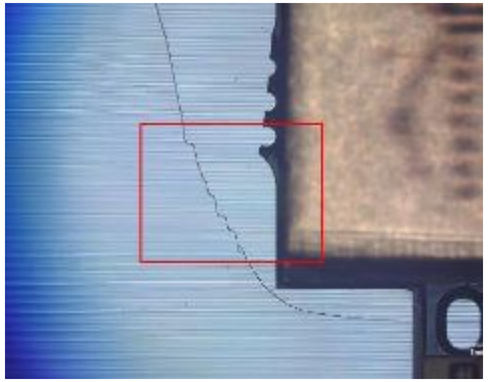
Cold noise

- While effect of cold noise is only present in Short-strip modules (that will only be produced after the full production of Long-strip modules) and having proved that we can operate with low levels of cold noise
  - Studies to understand and mitigate the problem continue. New theory being investigated with high prospect.
  - Need to evaluate together with “cracking” mitigation strategies.

Cracking

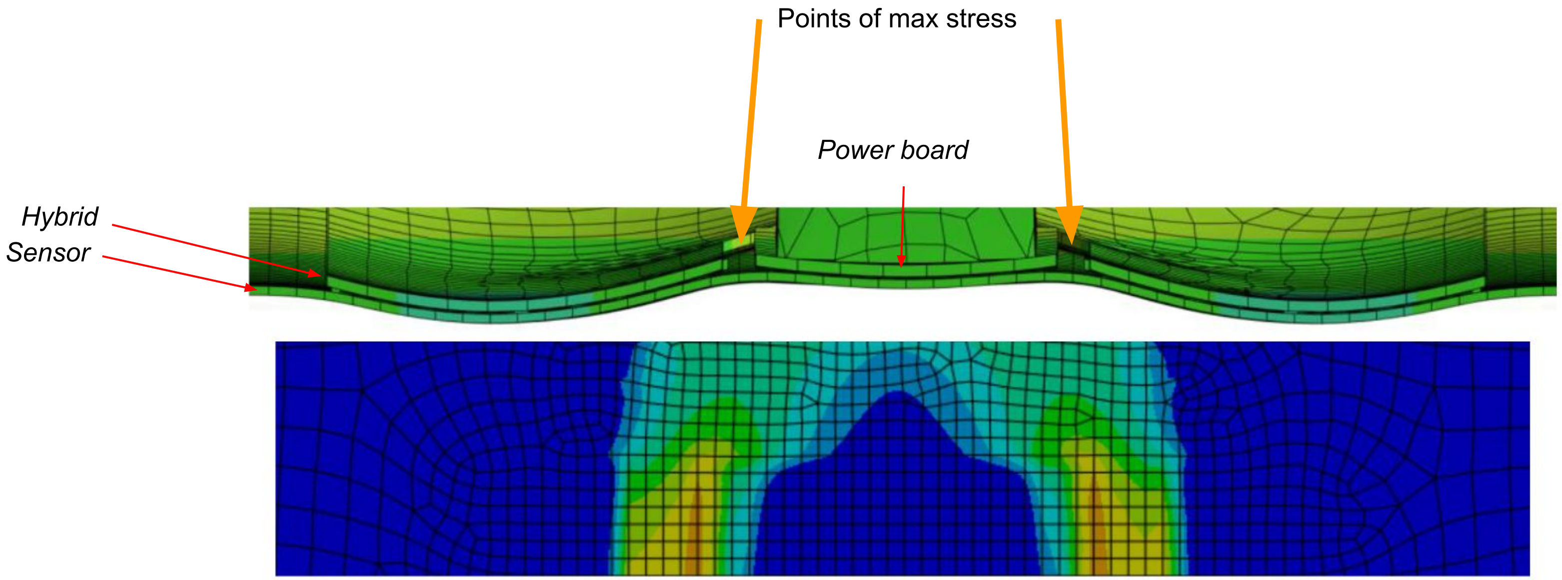
- During Pre-Production some modules glued to local supports showed:
    - Early breakdown after going cold in petal/stave QC.
    - Most have high or low noise channels associated with the location of the crack.
    - Physical cracks only visible sometimes.
- Cracks seen normally near the power board or between hybrid and power board.
- Cracks caused by mismatch in coefficients of thermal expansion (CTE) of electronics, glues and sensor.

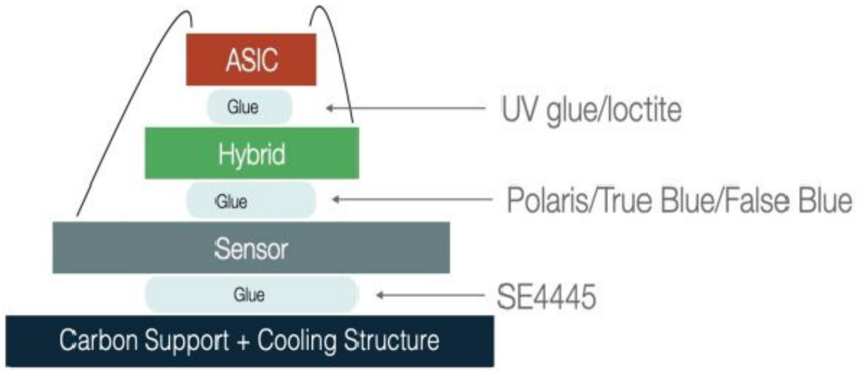




Cracking

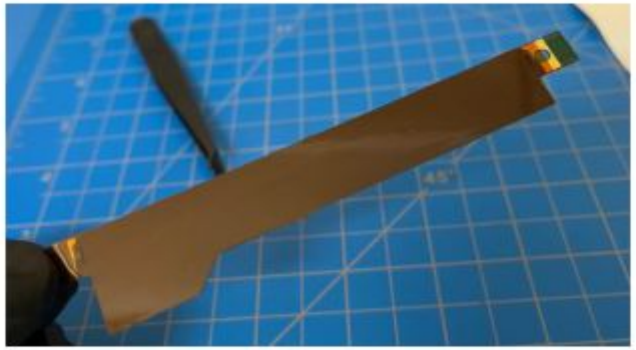
- Cracks caused by mismatch in coefficients of thermal expansion (CTE) of electronics, glues and sensor.
- Localized stress accentuated by the usage of a high modulus (“stiff”) glue (TrueBlue) above the sensor vs. a low modulus (“soft”) glue (SE4445) below the sensor





Cracking

- Huge effort put in solving cracking. A dedicated task force focused on the problem.
- First priority right now since will unlock full production.
- Using simulations to understand the problem and to point to most effective mitigation strategies.
- Extensive empirical tests carried out to demonstrate different mitigation strategies.
- Current motivation strategies under evaluation:
    - Change SE4445 to Hysol (glue under sensor): increasing stiffness and optimising glue pattern to mitigate built-in stress.
    - "Interposers": additional layer between PCBs and sensor that absorbs stress.
    - Increase gap between hybrids and power boards.
    - Thinner hybrids in the barrel.



Kapton interposer glued to the bottom of a hybrid

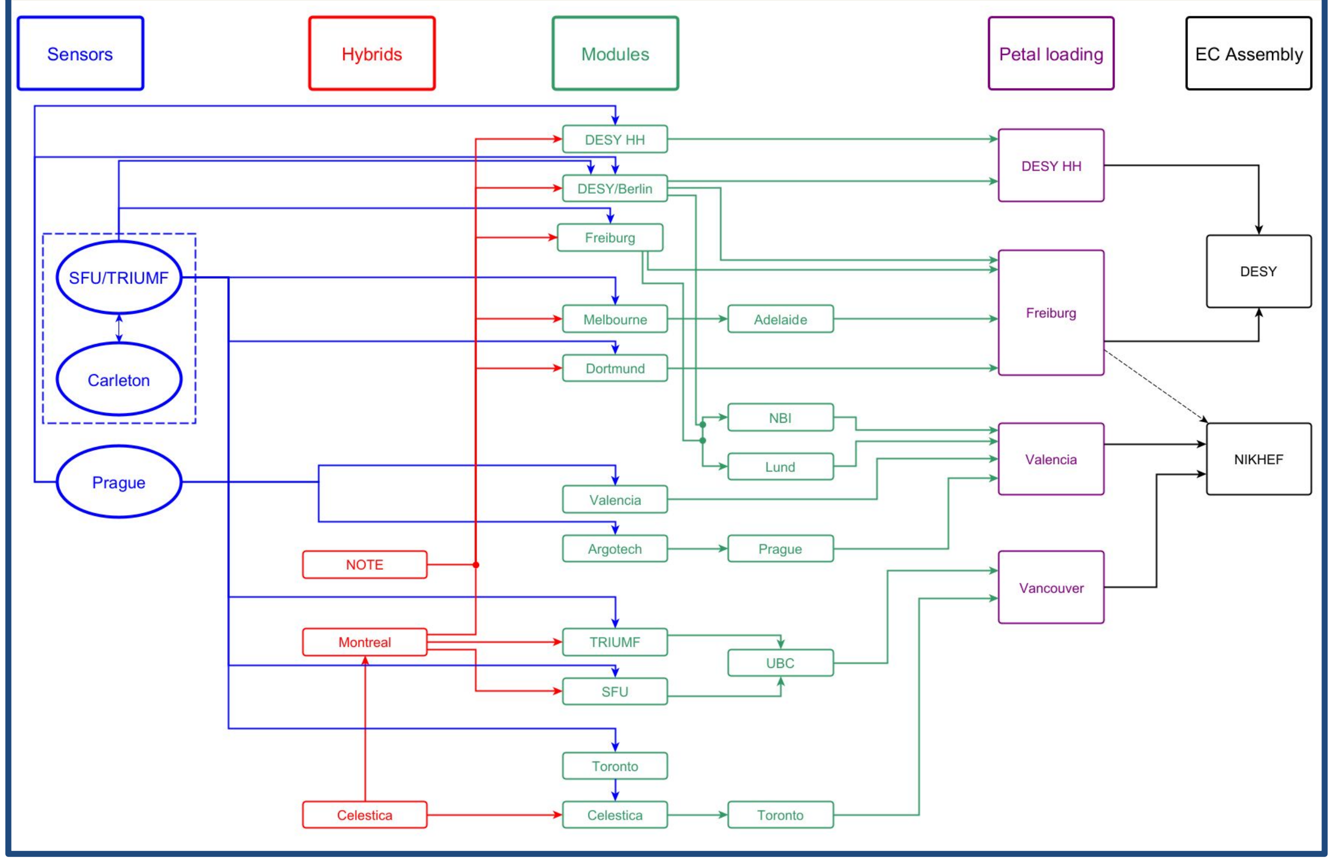
QA/QC

- **QA** identifies defects in **process** used to make the product
- Its **goal** is to assure that the fault won't happen in the final product.
- It is a **proactive** process.
- It is **focused** on the **process**.
- Test can be made on other structures

- **QC** identifies defects in the **finished products.**
- Its **goal** is identifying and discarding faulty products.
- Is a **reactive** process
- It is **focused** on the **product**
- Tests are made on the final products

The ITk-Strips in production

End-cap production flow



Sensors

Hybrids

Modules

Petal loading

EC Assembly

SFU/TRIUMF

Carleton

Prague

NOTE

Montreal

Celestica

DESY HH

DESY/Berlin

Freiburg

Melbourne

Dortmund

Valencia

Argotech

TRIUMF

SFU

Toronto

Celestica

Adelaide

NBI

Lund

Prague

UBC

Toronto

DESY HH

Freiburg

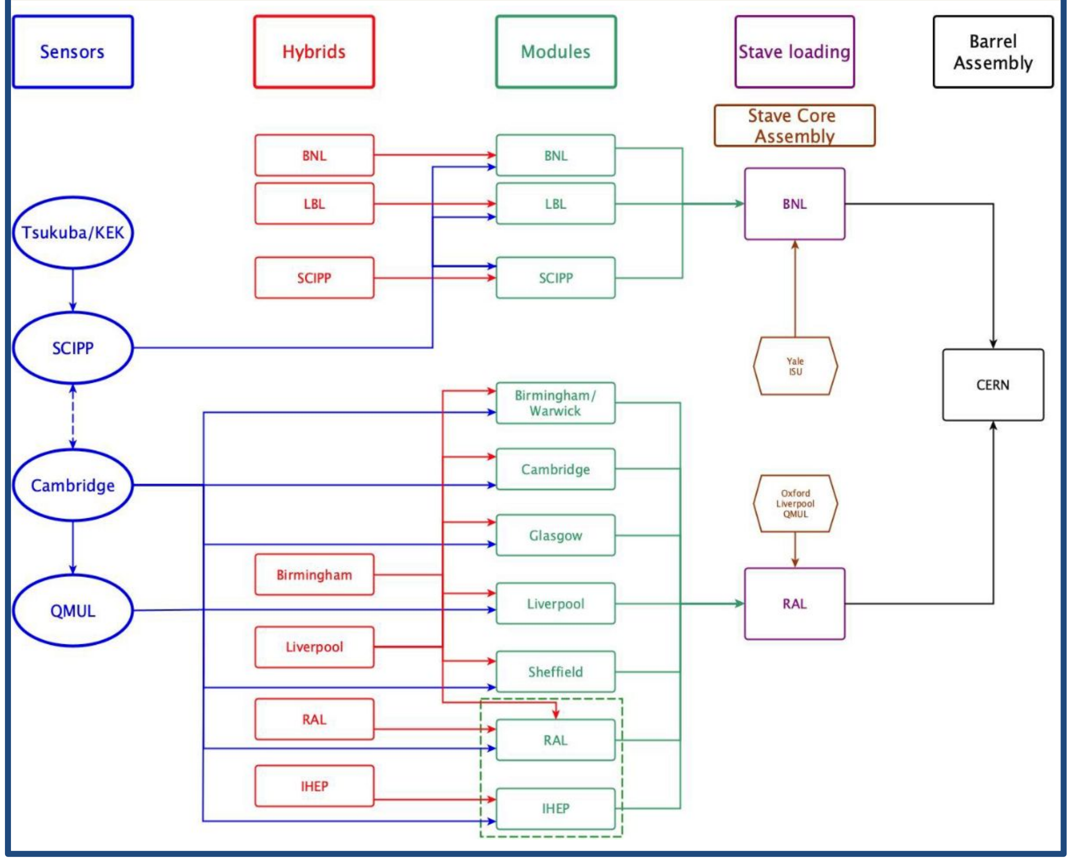
Valencia

Vancouver

DESY

NIKHEF

Barrel production flow



Sensors

Hybrids

Modules

Stave loading

Barrel Assembly

Stave Core Assembly

Tsukuba/KEK

SCIPP

Cambridge

QMUL

BNL

LBL

SCIPP

Birmingham

Liverpool

RAL

IHEP

BNL

LBL

SCIPP

Birmingham/ Warwick

Cambridge

Glasgow

Liverpool

Sheffield

RAL

IHEP

BNL

Yale ISU

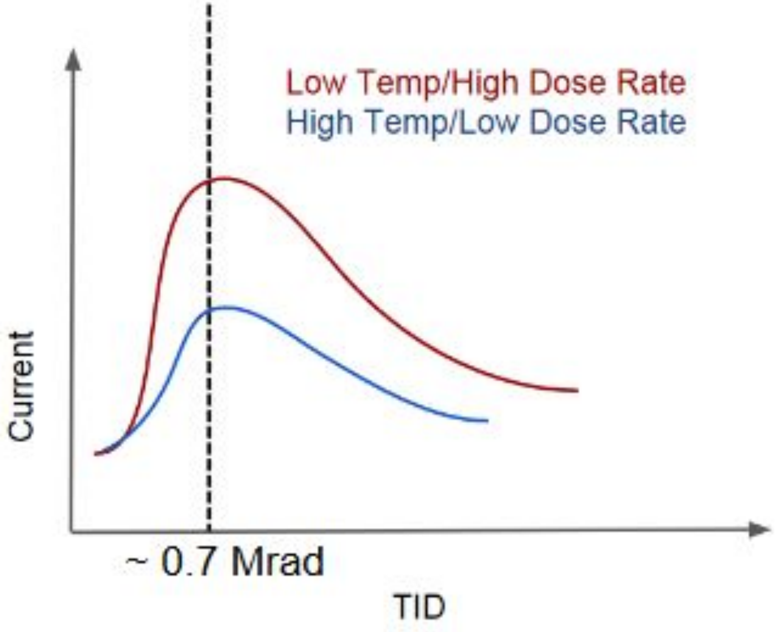
Oxford Liverpool QMUL

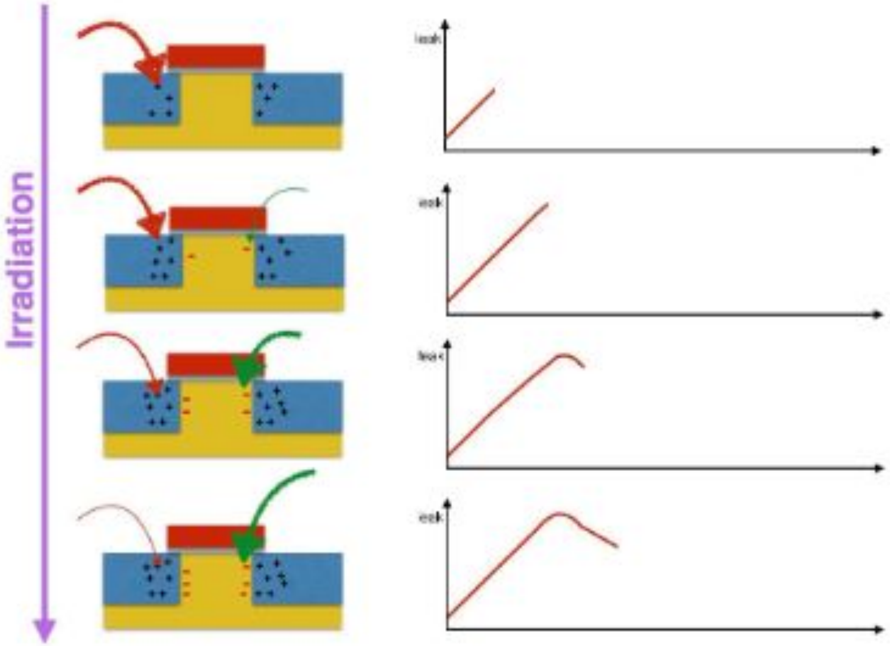
RAL

CERN

Simplified production flows for the End-cap and the barrel.

The TID bump



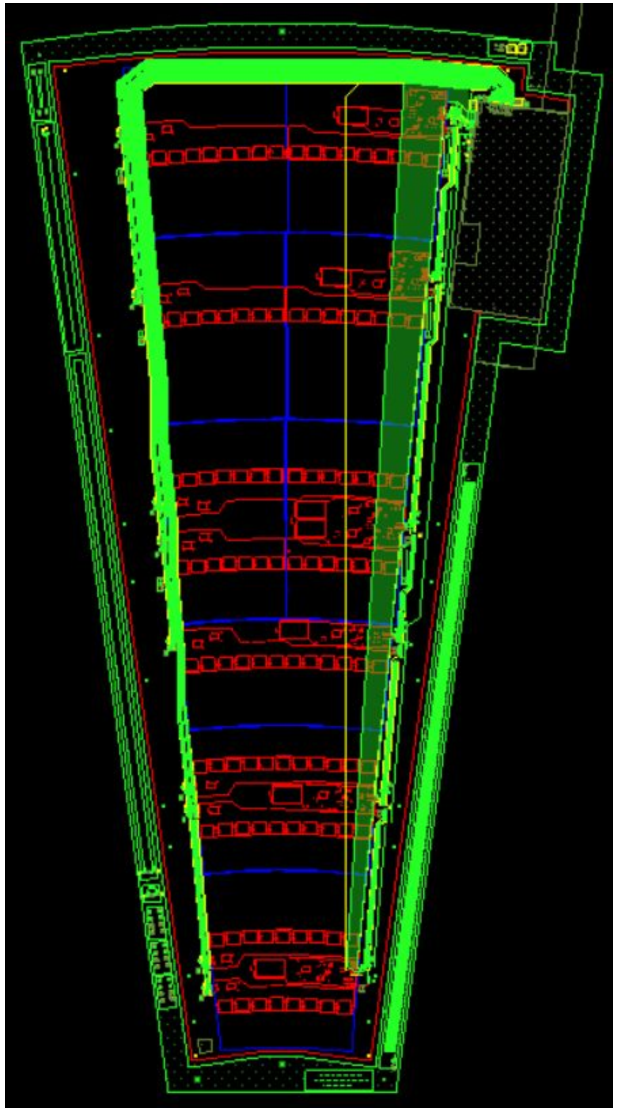


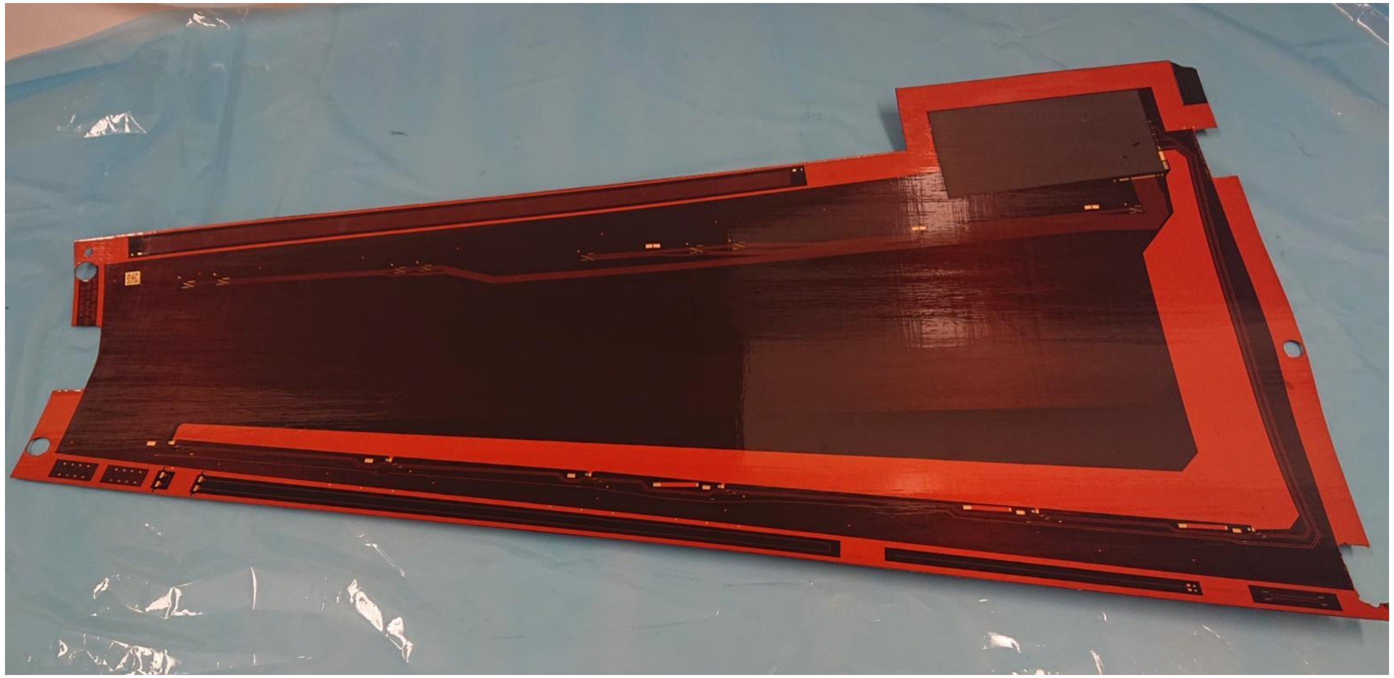
Very significant effect on power consumption at the early stages of the detector

Digital currents recover after a few Mrad

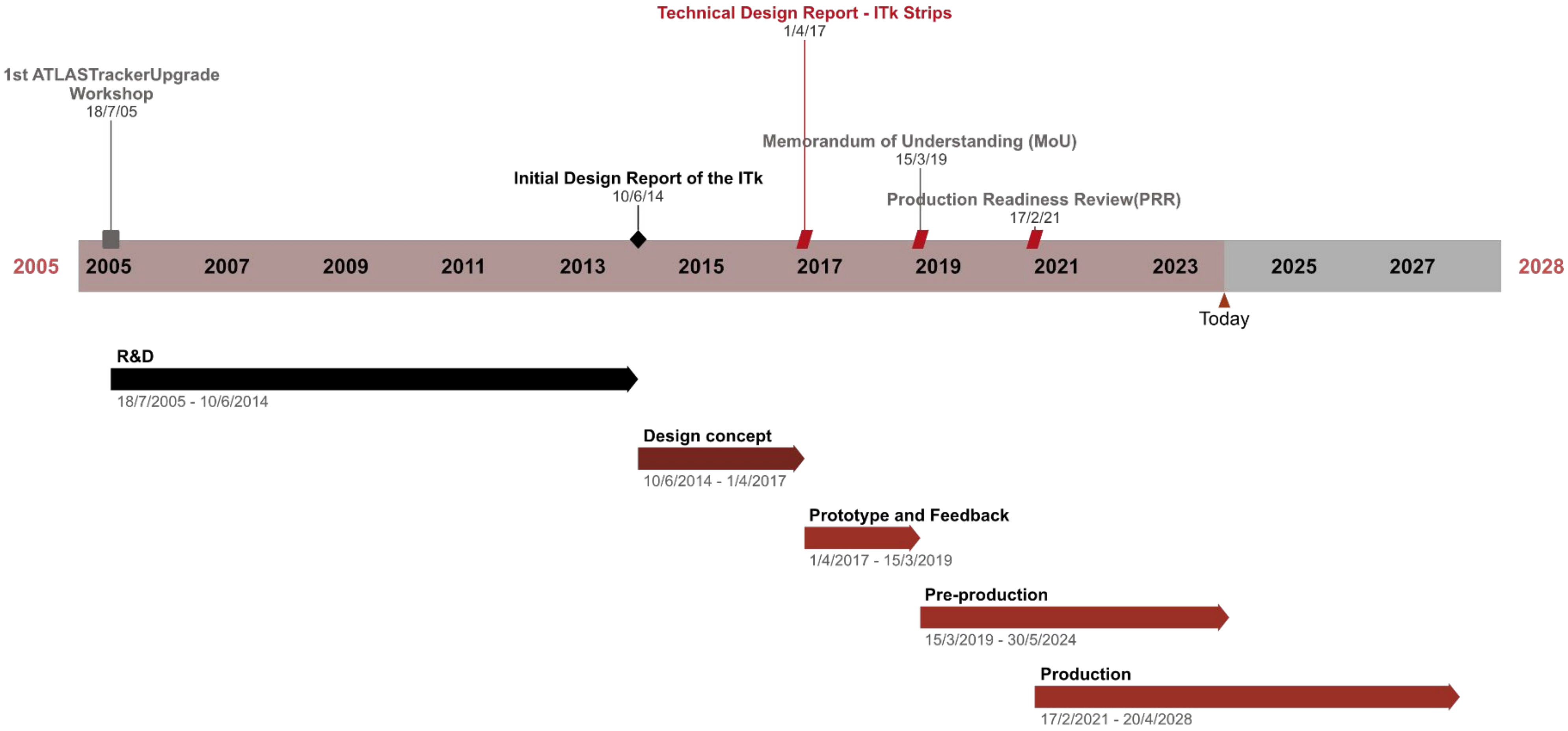
Bustapes

The different signals and voltages get to the modules in the petal via the traces on a polyimide tape (bustape) which is co-cured with the carbon fiber pre-pregs that make the petal facing, where modules are glued onto.





The ITk-Strips in production



Technical Design Report - ITk Strips
1/4/17

1st ATLASTrackerUpgrade Workshop
18/7/05

Memorandum of Understanding (MoU)
15/3/19

Initial Design Report of the ITk
10/6/14

Production Readiness Review(PRR)
17/2/21

R&D
18/7/2005 - 10/6/2014

Design concept
10/6/2014 - 1/4/2017

Prototype and Feedback
1/4/2017 - 15/3/2019

Pre-production
15/3/2019 - 30/5/2024

Production
17/2/2021 - 20/4/2028