Thermo-mechanical characterization of Petals as Local Support Structures for the ATLAS ITk Strip Detector

Forum on Tracking Detector Mechanics June 2018 València

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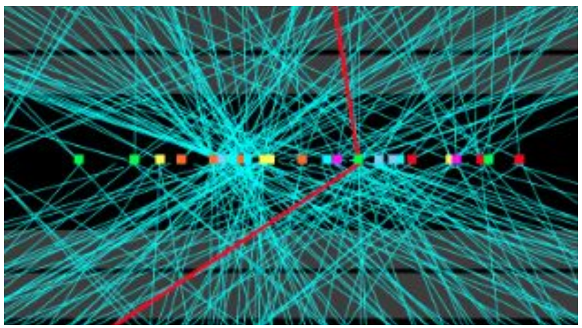
The new ATLAS Inner Tracker for High-Lumi LHC

- **The High-Luminosity LHC program** → **×5 - ×7 nominal luminosity increase**

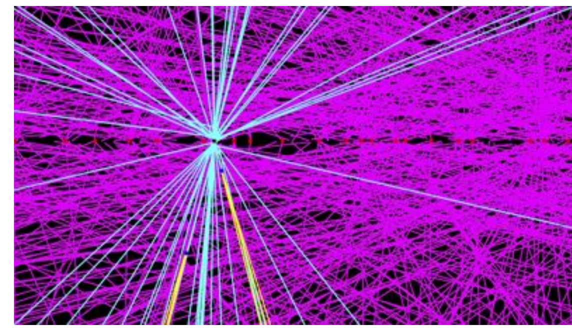
  ↓

  $5 - 7.5 \times 10^{34}\ cm^{-2}.s^{-1}$

- **The pile-up** → average number of proton-proton interaction per bunch crossing



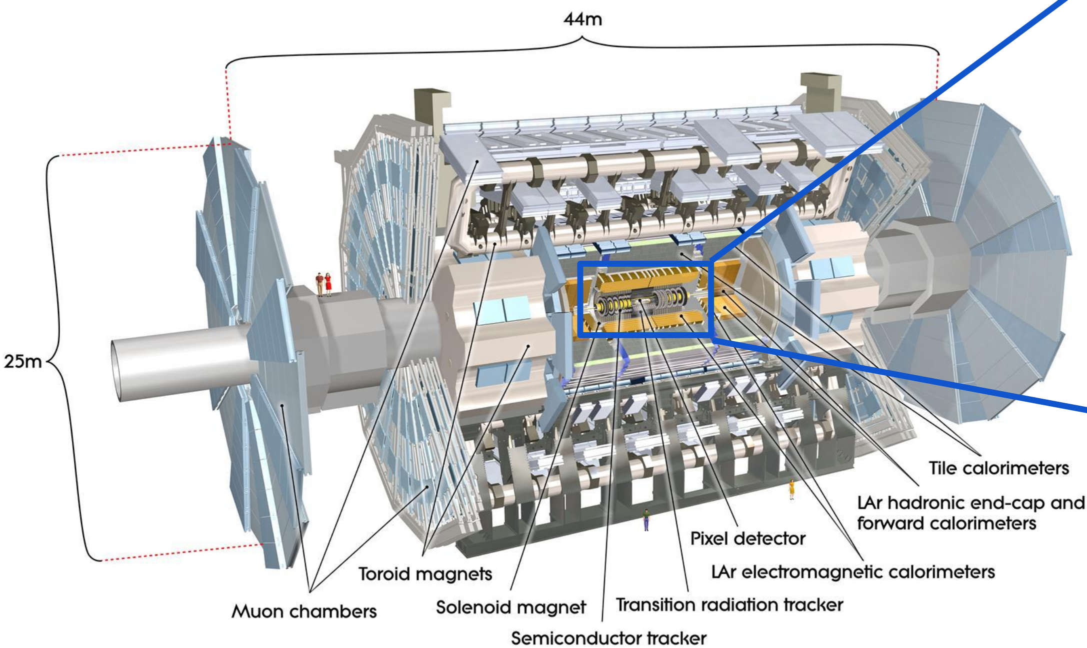
60 (Run II) → 200 (High-Lumi LHC)

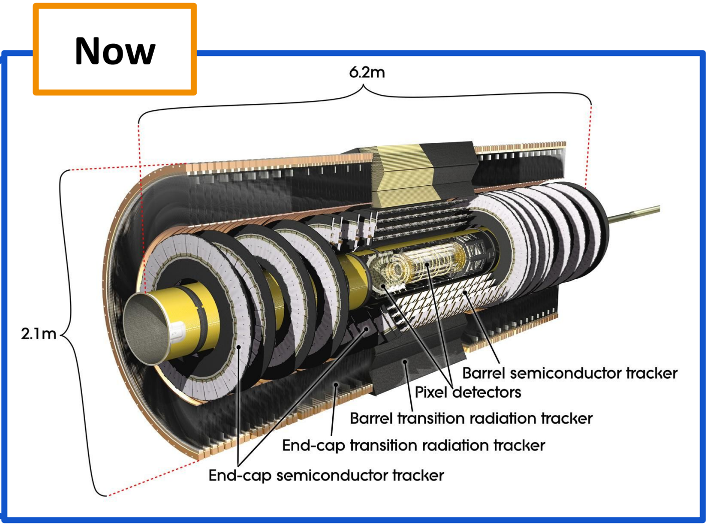


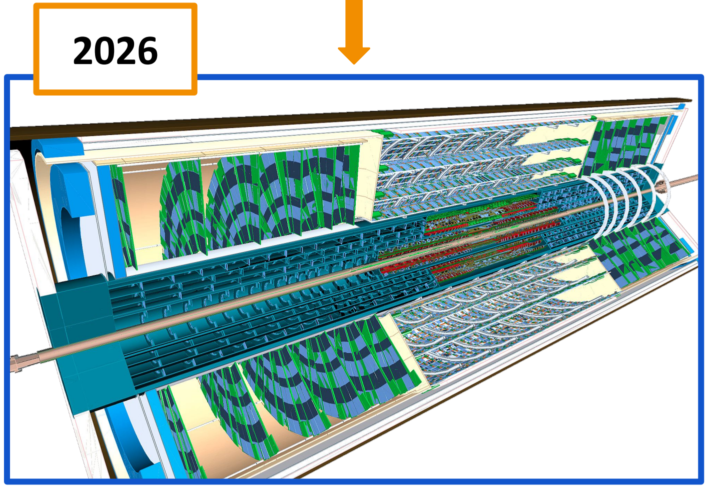
- **Challenges of High-Luminosity LHC on tracking**

Radiation hardness	Granularity	Speed	Coverage
sensors & electronics need to withstand ×10 radiation levels ~ $10^6\ n_{eq}/cm^2$	dense environment maintain occupancy < 1%	fast electronics high bandwidth	expanding eta coverage minimize lower inactive material

The new ATLAS Inner Tracker for High-Lumi LHC





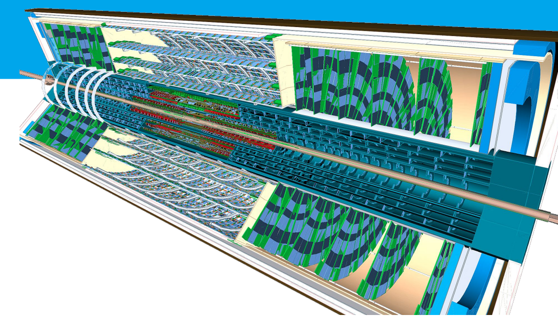


Replacement of ATLAS Inner detector by an **all-silicon tracker**

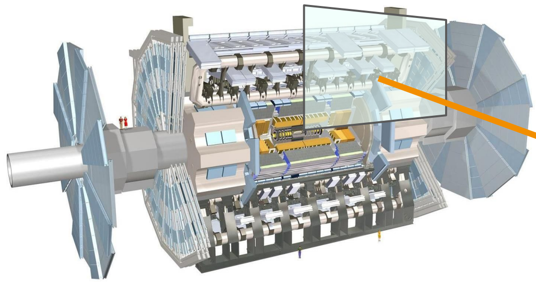
↓

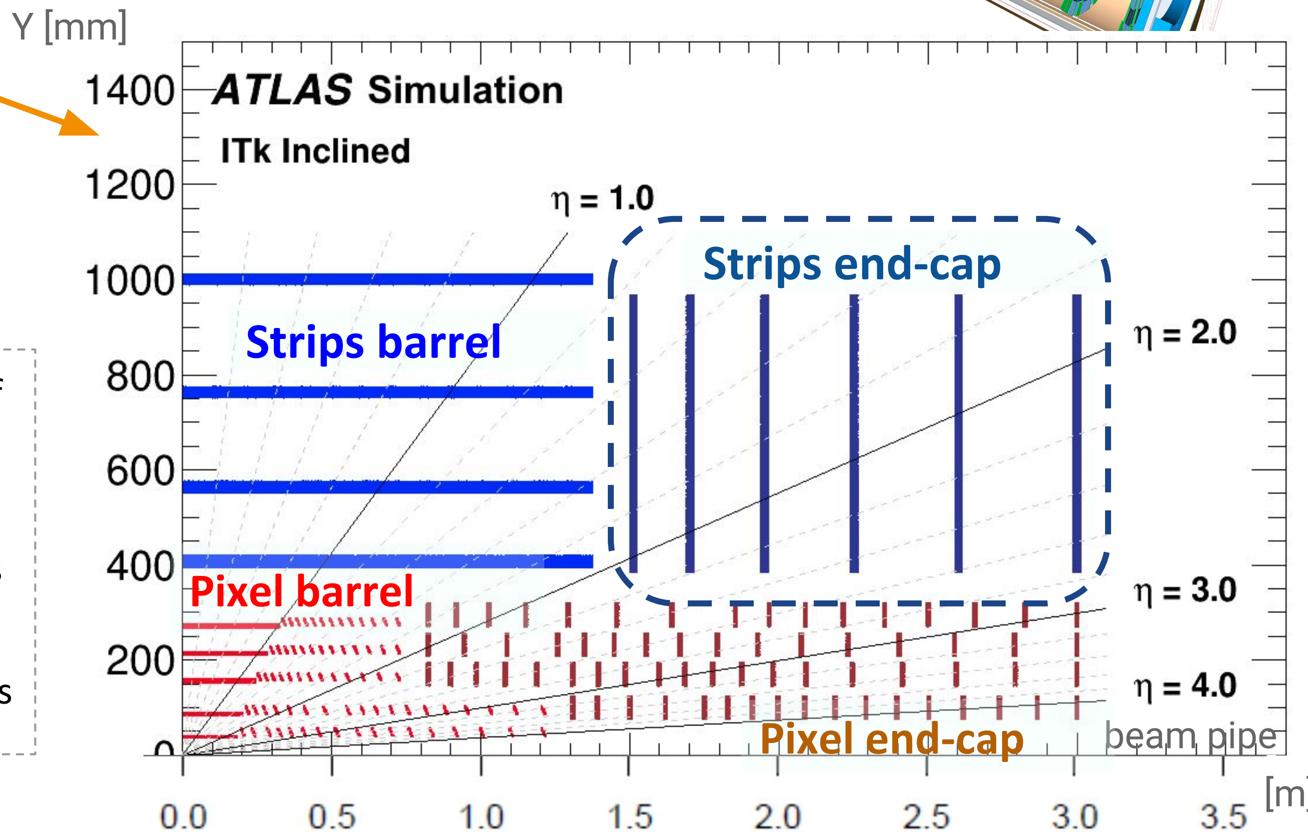
ATLAS Phase II Upgrade

New ATLAS Inner Tracker (ITk)



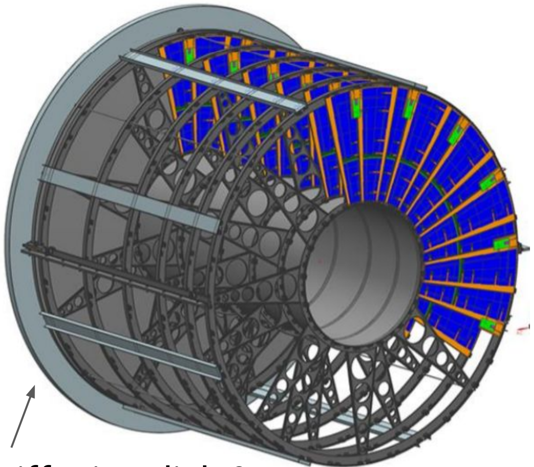
Quarter segment





	Silicon area	Number of channels
Strips	160 m^2	50 millions
Pixel	13 m^2	580 millions

ATLAS Strip end-caps



Stiffening disk & bulkhead

Each end-cap consists of 6 disks

⬇

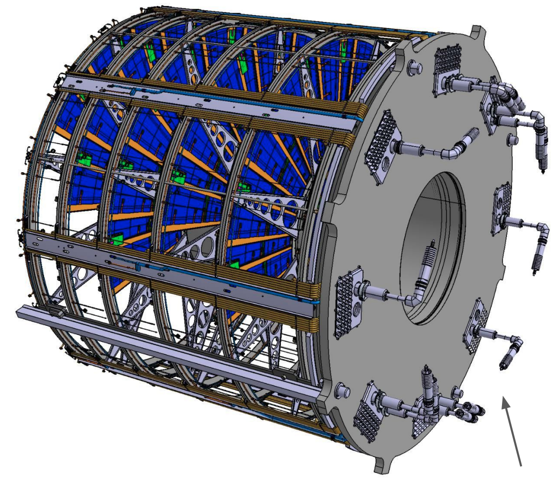
Each disk has 2 layers

⬇

Each layer populated by 16

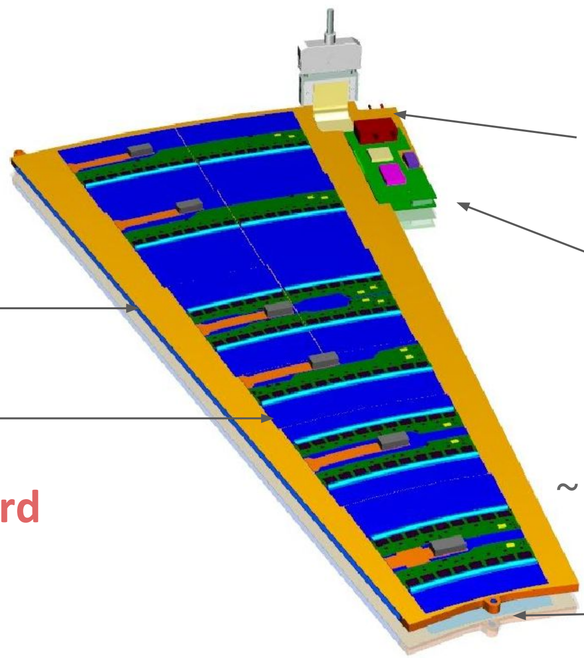
petals

= support structure for modules



Services at outer radii

- the **core** is the base on which strip modules are mounted
- **strip module** = **sensor** + **hybrid** + **powerboard**



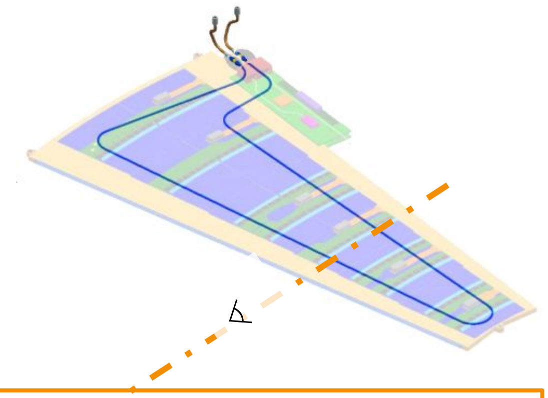
Locator (Zφ position) for kinematic mount

"End-of-substructure" (data concentrator board)

~ 60 cm × 30 cm

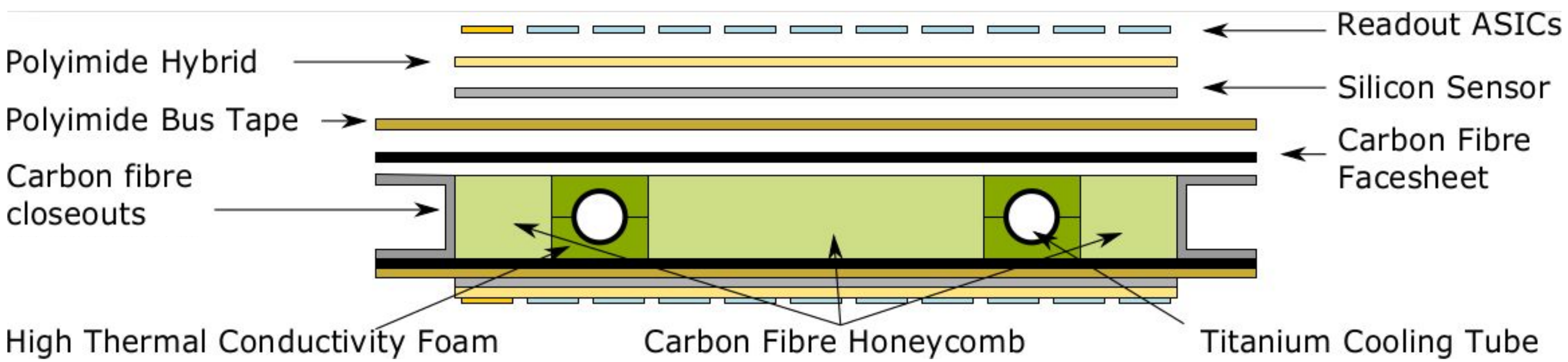
Locator for XYZ position

The petal concept



- Modules directly glued on core
- Core = two face-sheets sandwiching carbon-fiber honeycomb
- Embedded cooling pipes in carbon thermal foam
  - ⇒ short thermal paths (~3 mm) + efficient heat transfer

Cross section



👍 Minimizing material

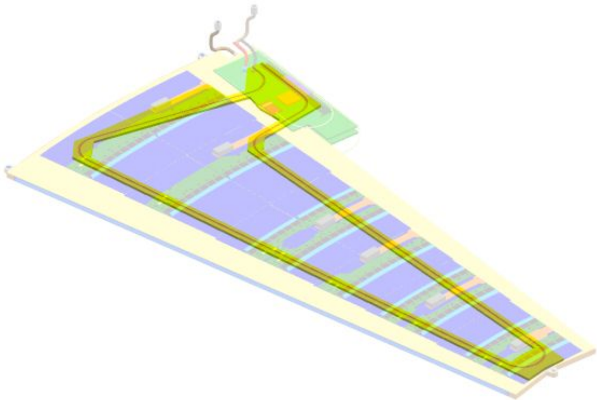
👍 Simplicity for large scale reproducibility

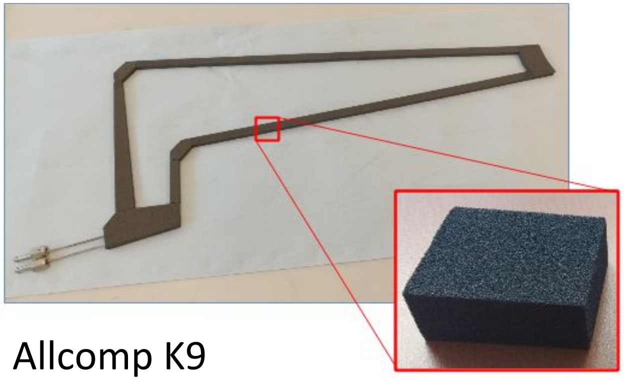
👍 Core and electronic components individually testable before assembly

Petal cores

Petal cores: baseline design

Graphite thermal foam

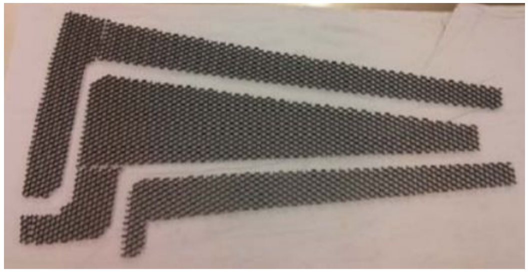




Allcomp K9

0.23 g/cm^3 K = 30 W/(m.K)

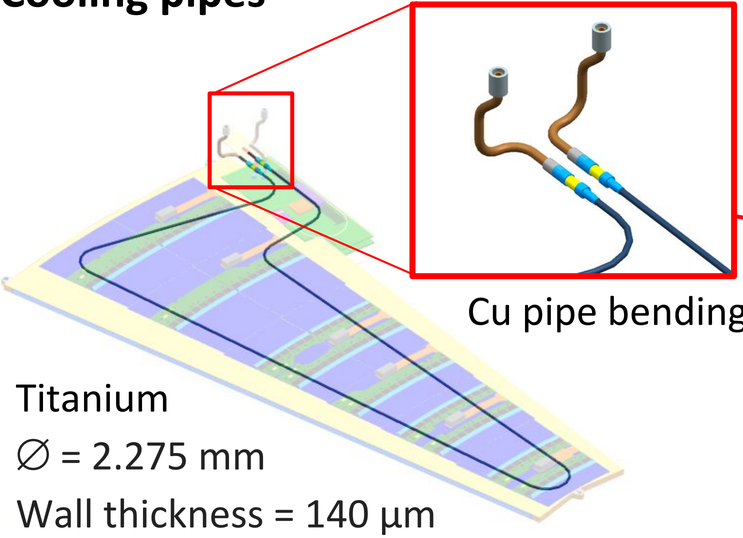
Honeycomb



YSH50A-75 +EX-1515 (1/4)

Density: 0.048 g/cm^3

Cooling pipes



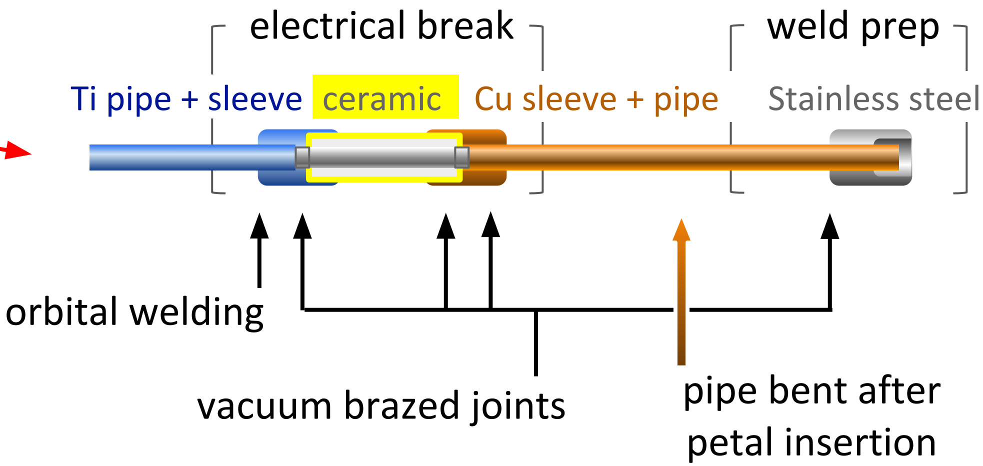
Cu pipe bending

Titanium

∅ = 2.275 mm

Wall thickness = 140 µm

Electrical breaks & welding/brazing joints



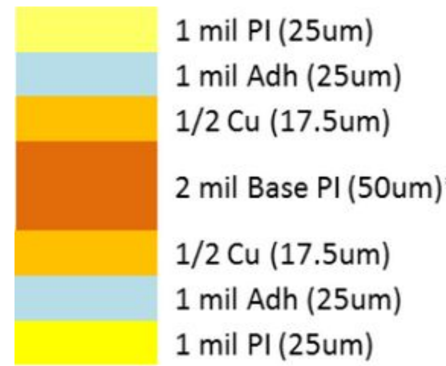
Petal cores: baseline design

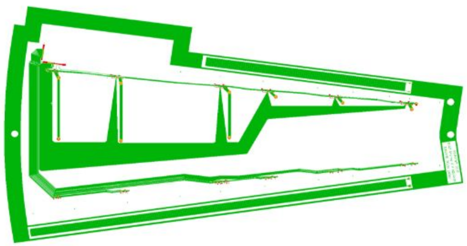
Face-sheet + bus tape co-curing

Flexible low-mass printed circuit

- provides readout + power + control lines to modules
- co-cured to face-sheet material:
  K13C2U + EX1515 resin (0 - 90 - 0) 150 µm thick total

Total thickness: 185 µm



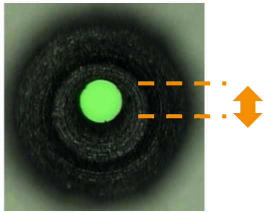


- 84 & 116 µm track-and-gap diff. lines
- design optimized for 640 MHz signals
- gold-plated pads for easier bonding

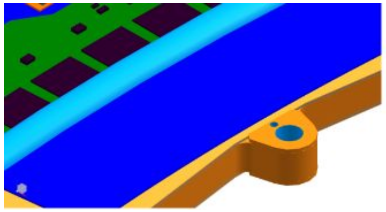
Petal locators

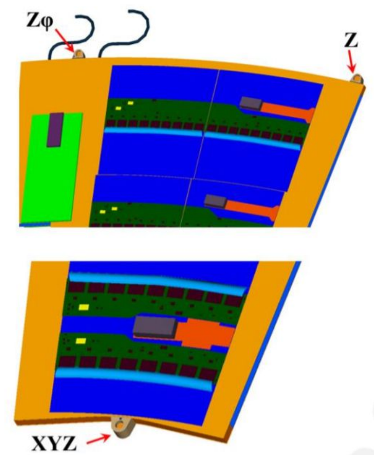
Precision and fiducial holes for kinematic mount

- achieve 20 µm in both Rφ and Z
- material:
  Options currently under study



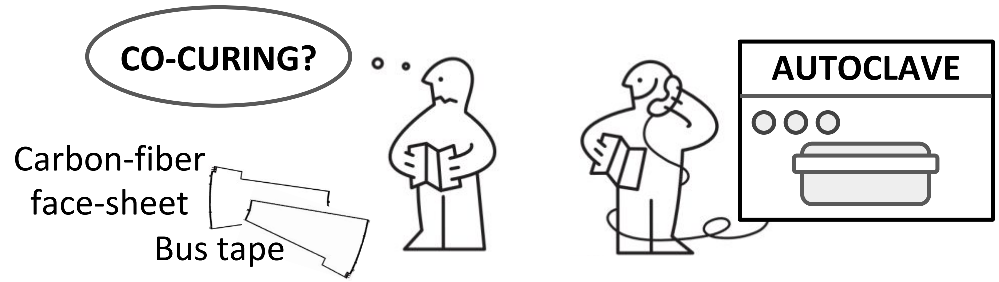
Fiducial holes Ø = 300 µm





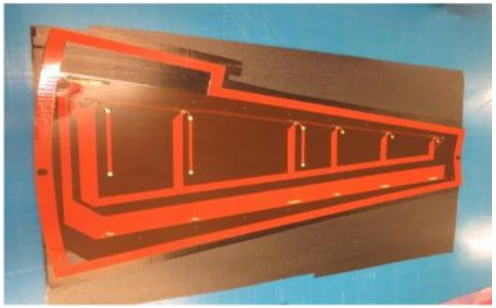
Petal core (baseline): assembly

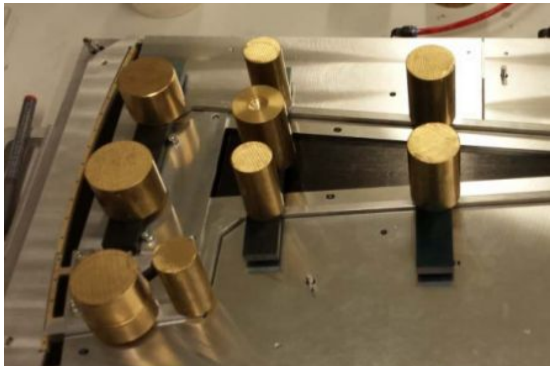
- **Precision tools**
  - accuracy
  - repeatability
  - high throughput

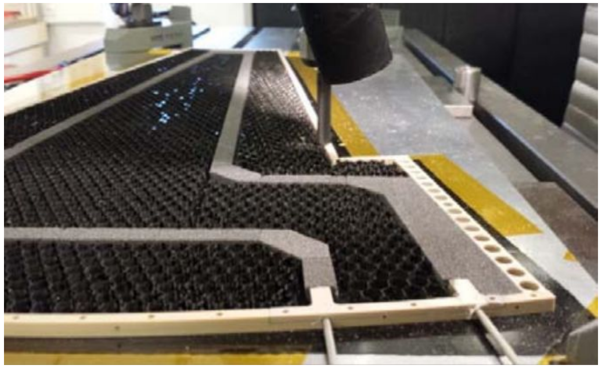


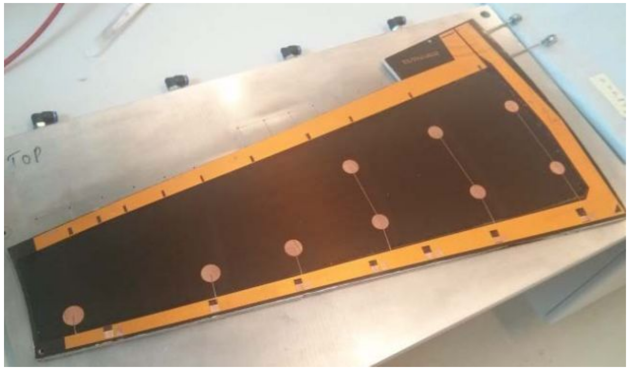
- **Prototypes built at DESY**

Co-cured bus tape to carbon-fiber face-sheet + closeouts + pipe + foam + honeycomb









Petal core: possible industrialization

Petal core from Scientifica International

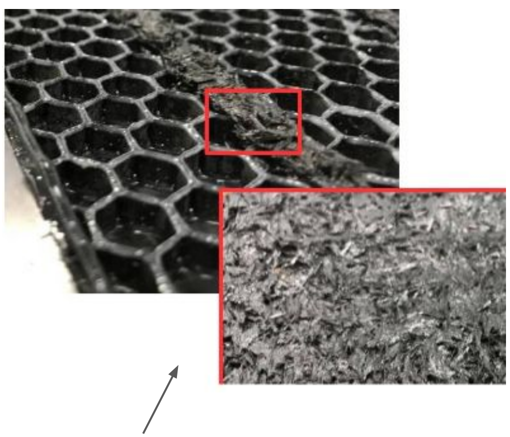
Following the design of the ‘baseline’ except:

SCIENTIFICA

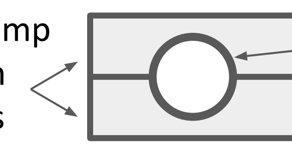
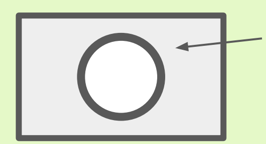
company designing, prototyping, manufacturing precision equipment for science

- Thermal conductive interface: Conductive epoxy putty

No Allcomp foam



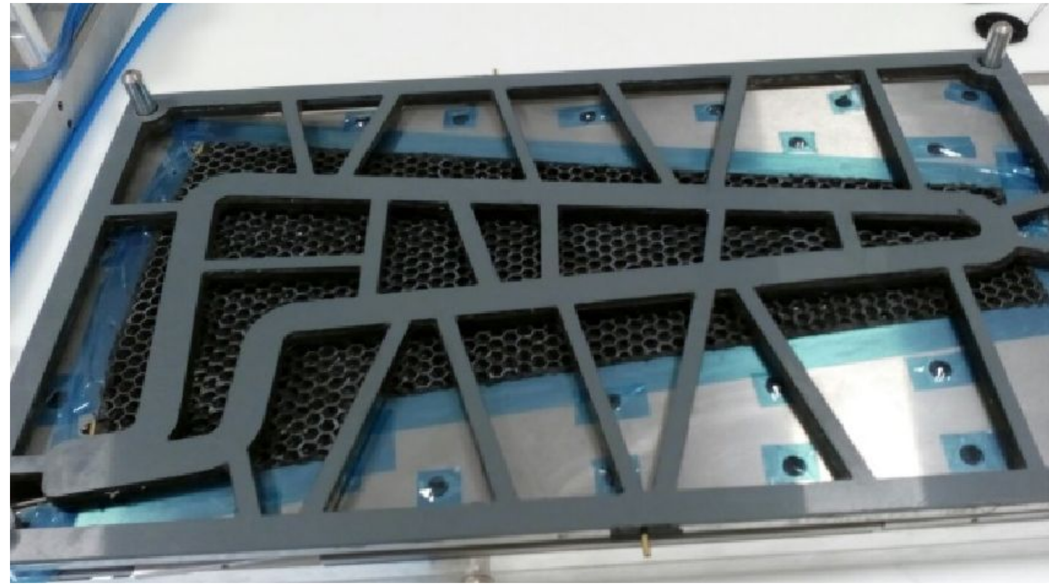
Injected conductive epoxy putty

	Baseline	*Alternative (Scientifica)*
	Allcomp	**Conductive epoxy putty**
	Long manufacturing process (2 days)	👍 Easier & faster manufacturing (1 step)
	Thermal discontinuity Allcomp foam parts  Cooling pipe	👍 no boundaries  epoxy
	👍 low mass (228 g)	heavier (300 g)

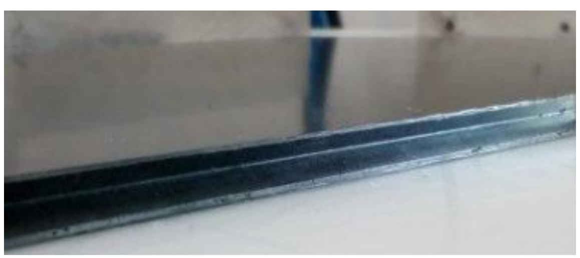
Petal core: Scientifica petal assembly

Manufacturing process simplified

1. Face-sheet on perimetral jig
2. Honeycomb glued with epoxy adhesive lip (thickness unaltered)
3. Bent cooling loop in positioned jig: injection of conductive epoxy putty
4. Closure with second face-sheet (parallelism controlled by jig)
5. Curing at ambient temperature

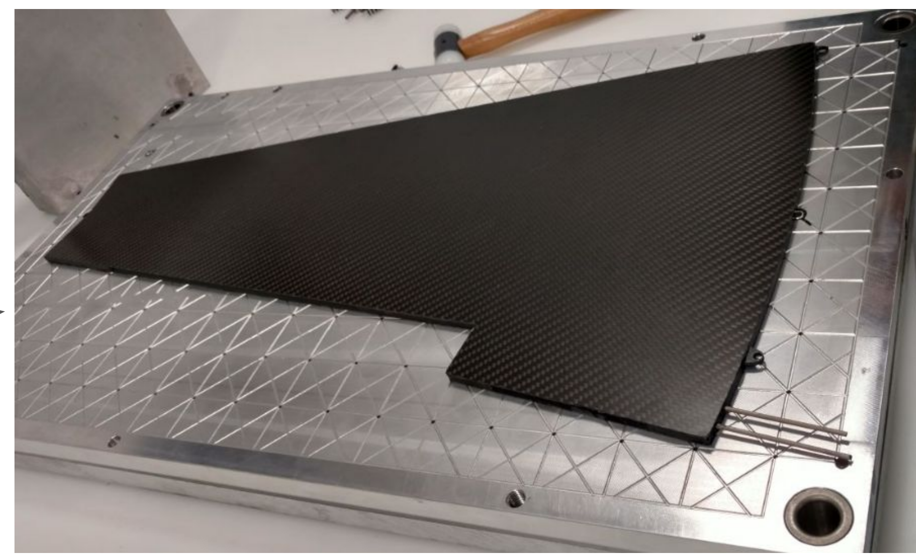


Final results



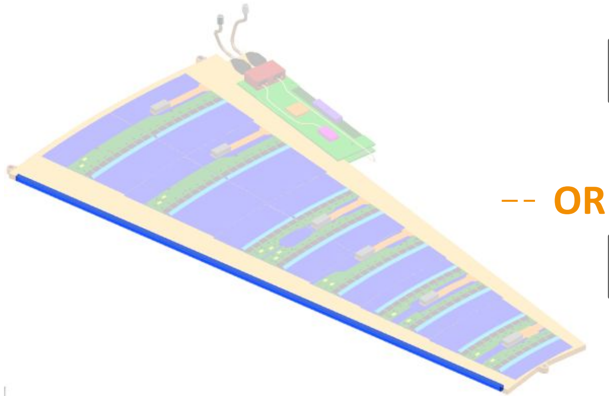
V-shaped closeout "V-Channels"

Finalized core →



Petal core: baseline vs industrialization on closeouts

Lateral carbon-fiber closeouts



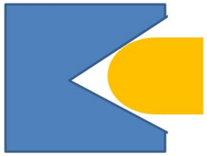
C-channels →

Machined from pultruded T300 + epoxy carbon-fiber rods

OR

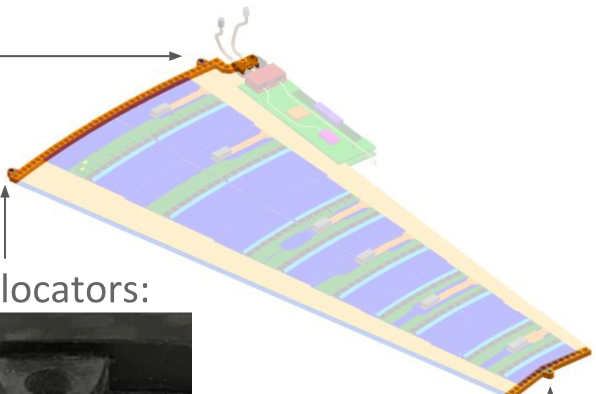
V-channels → Scientifica alternative

- better precision
- less expensive
- more material



Under validation

Top and bottom closeouts



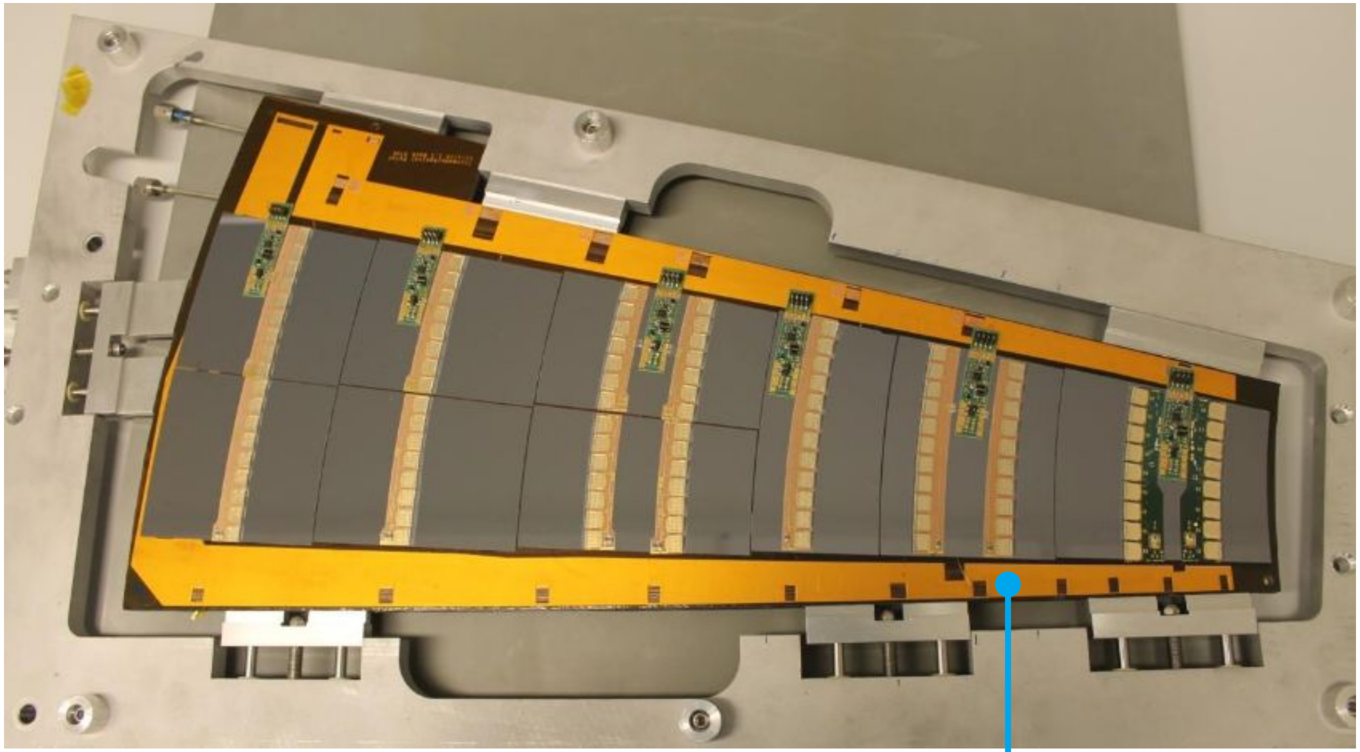
petal locators:

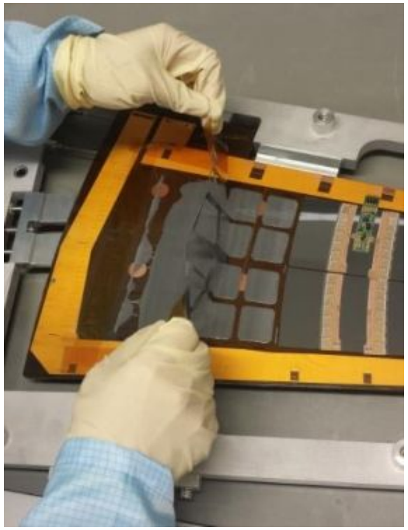
	Baseline	***Alternative (Scientifica)***
	closeouts + locators in Torlon	*closeouts: CF putty, locators: Torlon*

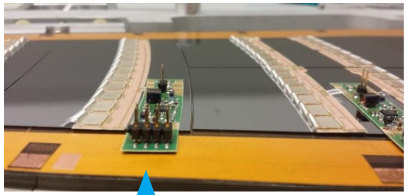
Torlon	Carbon-fiber putty
inhomogeneous CTE	homogeneous CTE
expensive	cheap
easy to machine & glue	tricky to drill precise holes*

** if locators are in CF-putty*

Prototypes: thermo-mechanical petal







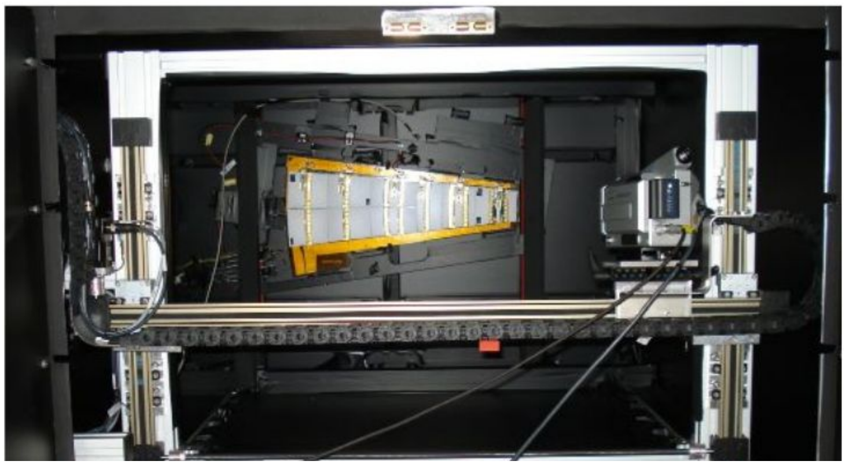
- **Core + modules**
  - real copper power traces
  - blank Si, laser cut (6” wafers, 320 µm thick)
  - dummy FR4 hybrids + glass ASICs with pattern heaters
  - dummy data-lines + shield layers

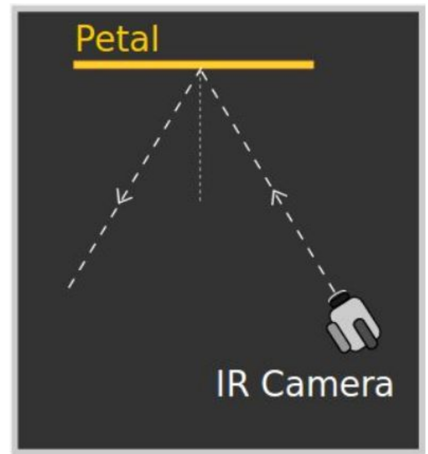
Measurements on core & petal prototypes

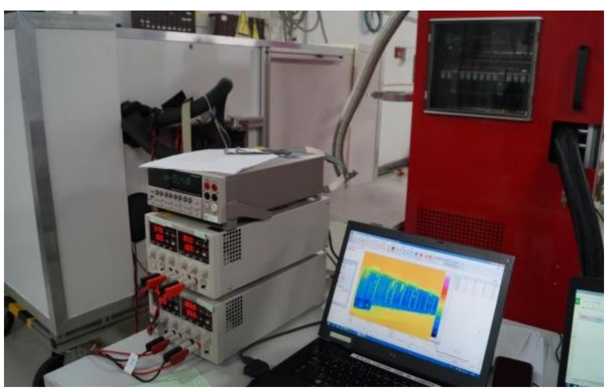
Petal thermal performance

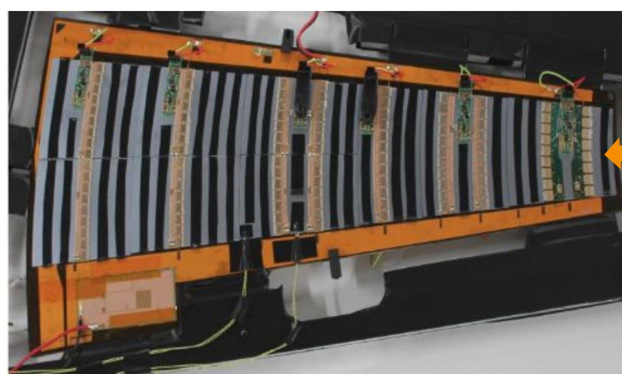
Experimental setup: custom chamber & CO_2 cooling

- Petal vertically inserted in dark chamber with room temperature flushed dry air (RH < 4%)
- CO_2 cooling system 'TRACI' (2-PACL) 100 W → minimum set point P_{CO2} = 13 bar → T_{CO2} ~ -30 °C





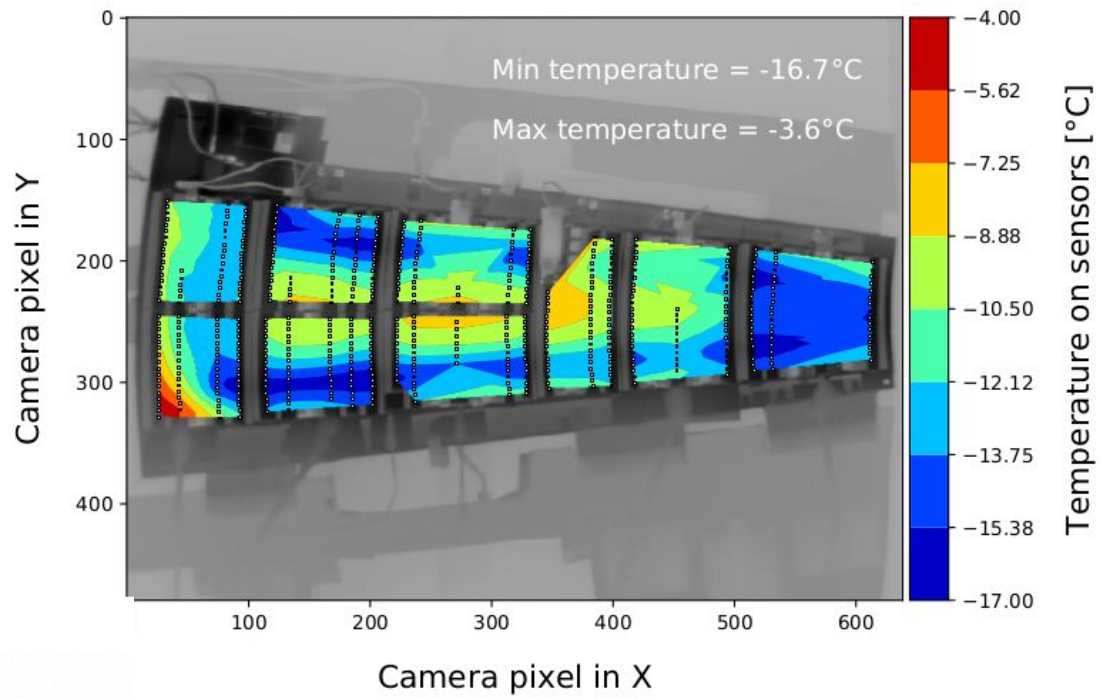




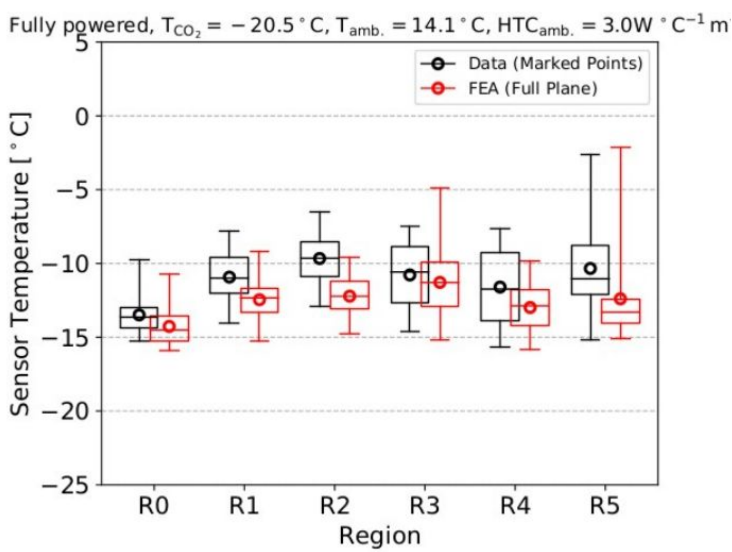
← High-emissive tape stripes on Si sensors to correct temperature read by infrared camera (VARIOcam HR)

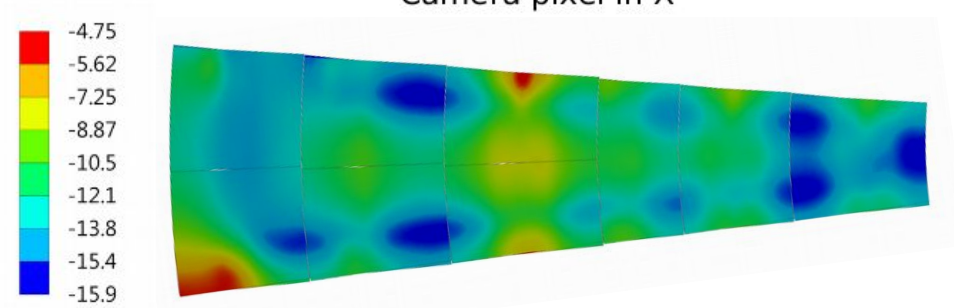
Petal thermal performance: inframetry results

- **Experimental results**
  - achieving a min of -24 °C at outlet TRACI's temperature probes (start of 3 m transfer line)
    $T_{outlet} - T_{inlet} \approx -4°C$
    ⇒ phase transition
  - CO_2 flow ~ 2.6 g/s



- **Comparison with FEA simulations**



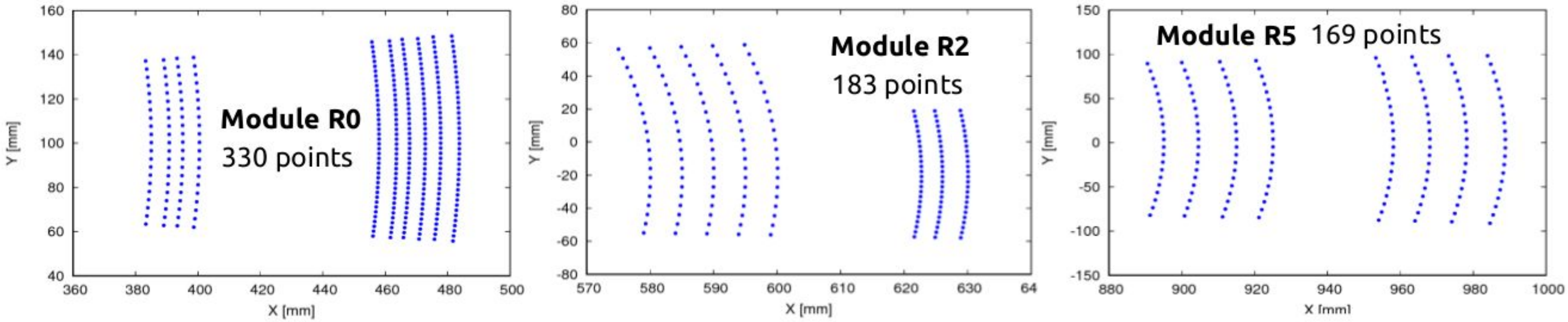


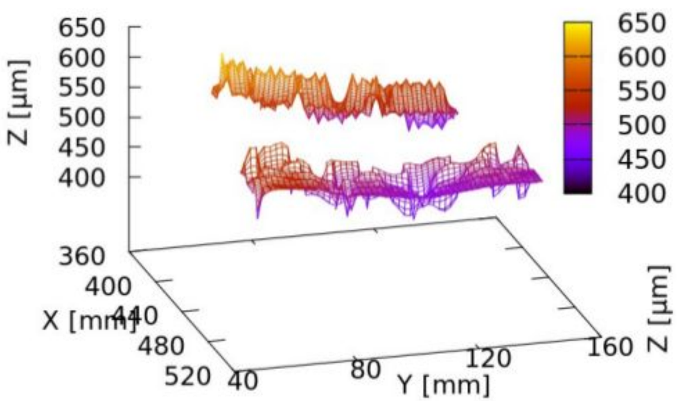
- Good overall agreement within 2.5°C

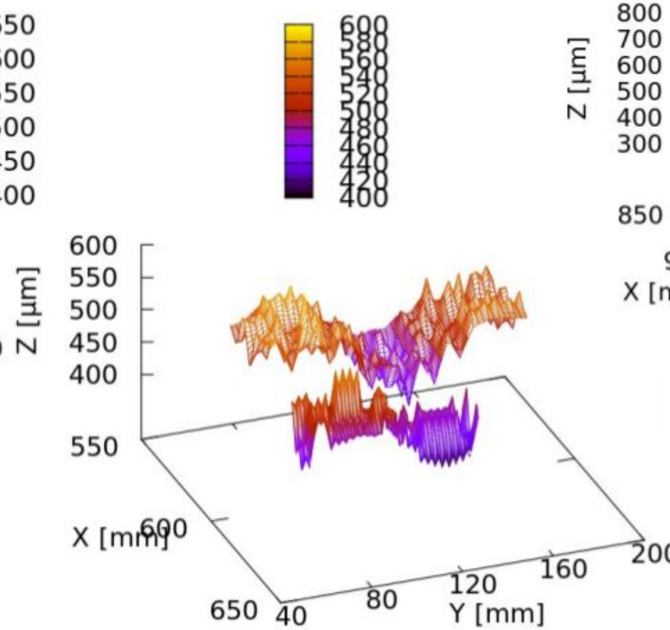
Refining...

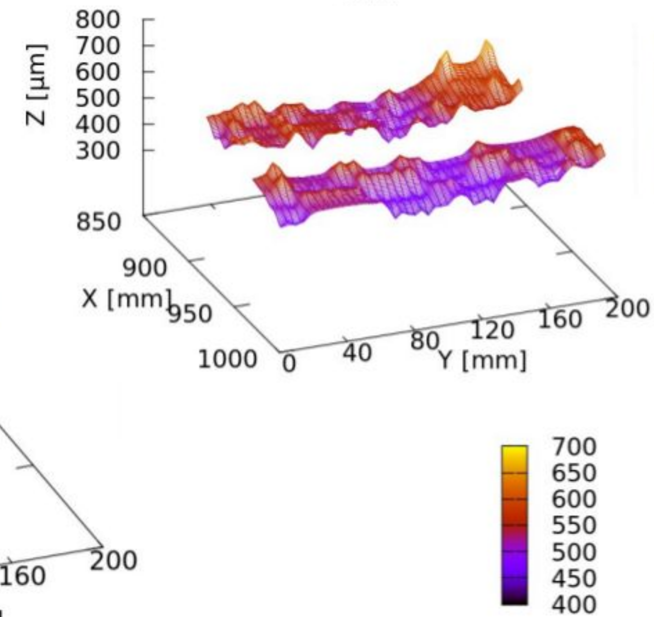
Metrology: sensor bow

- **Inspection** using optical table SmartScope™ Resolution in Δx,y,z = 0.5 µm









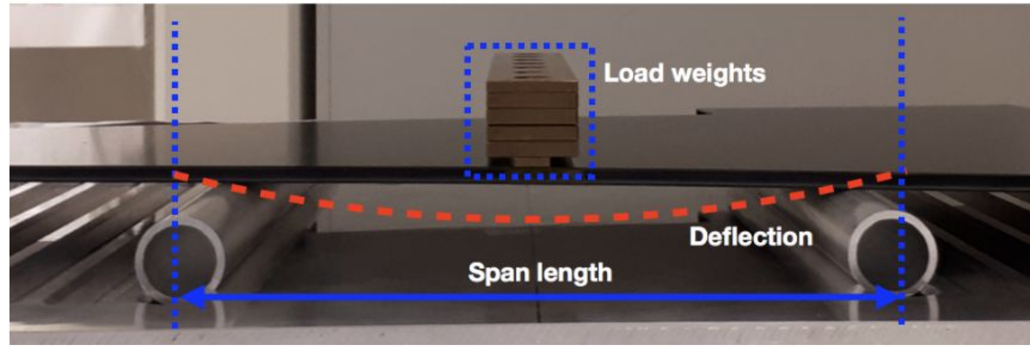
Flatness:

- R0: 151.3 µm
- R2: 165.3 µm
- R5: 203.7 µm

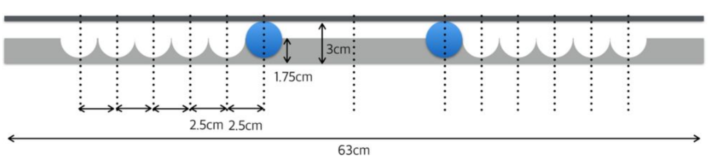
Satisfying for manual gluing. Specs: < 200 µm

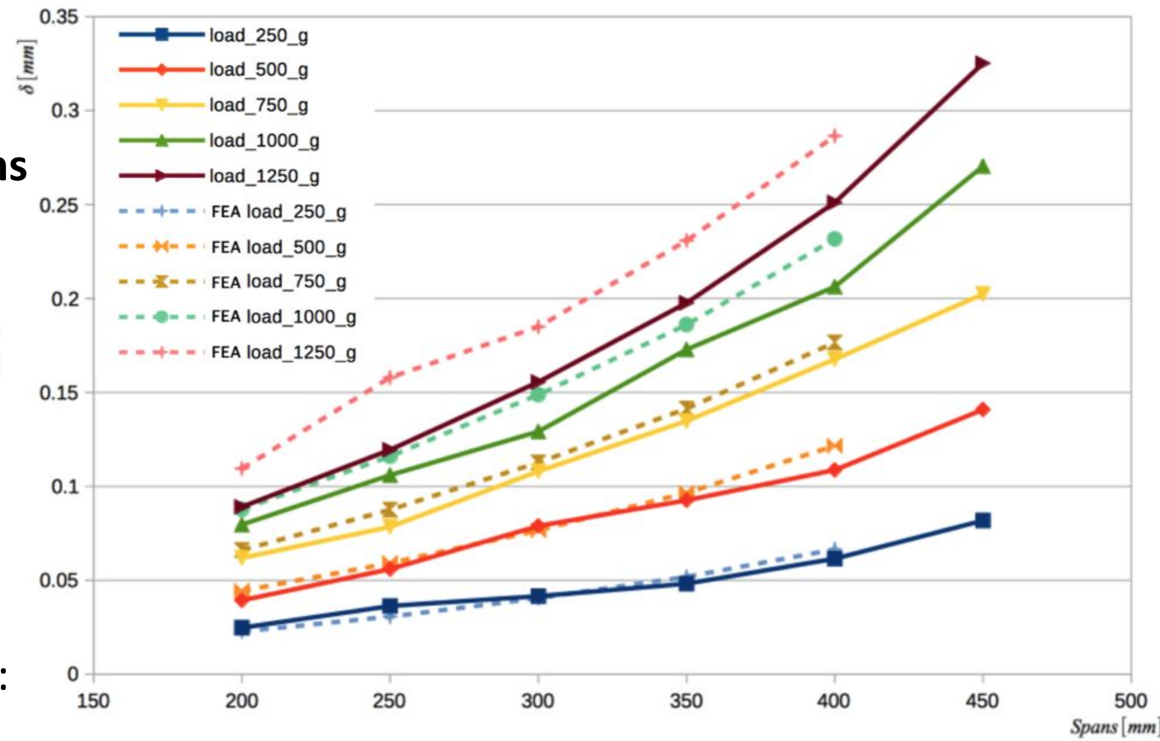
Three point bending test on petal core

- **Experimental setup**
  - petal core on 2 supporting points
  - weight applied in center of mass
  - measuring deflection using optical table (SmartScope CNC™ 670)



- **Results & comparison with FEA simulations**
  - varying span length 20 → 40 cm

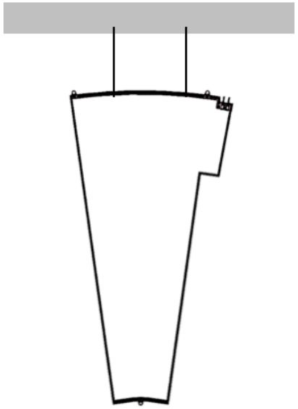




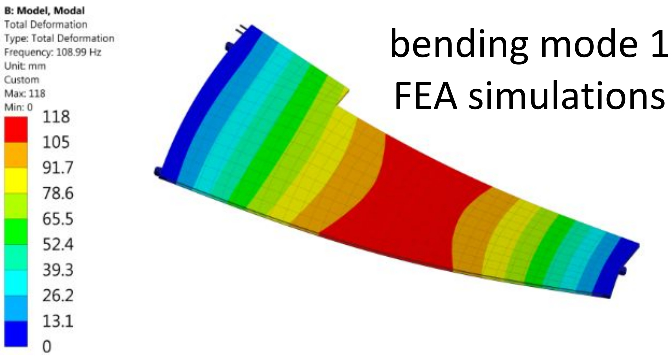
  - reasonable agreements with FEA for loads < 750 g
  - shear + bending elasticity moduli: ⇒ FEA and data matching

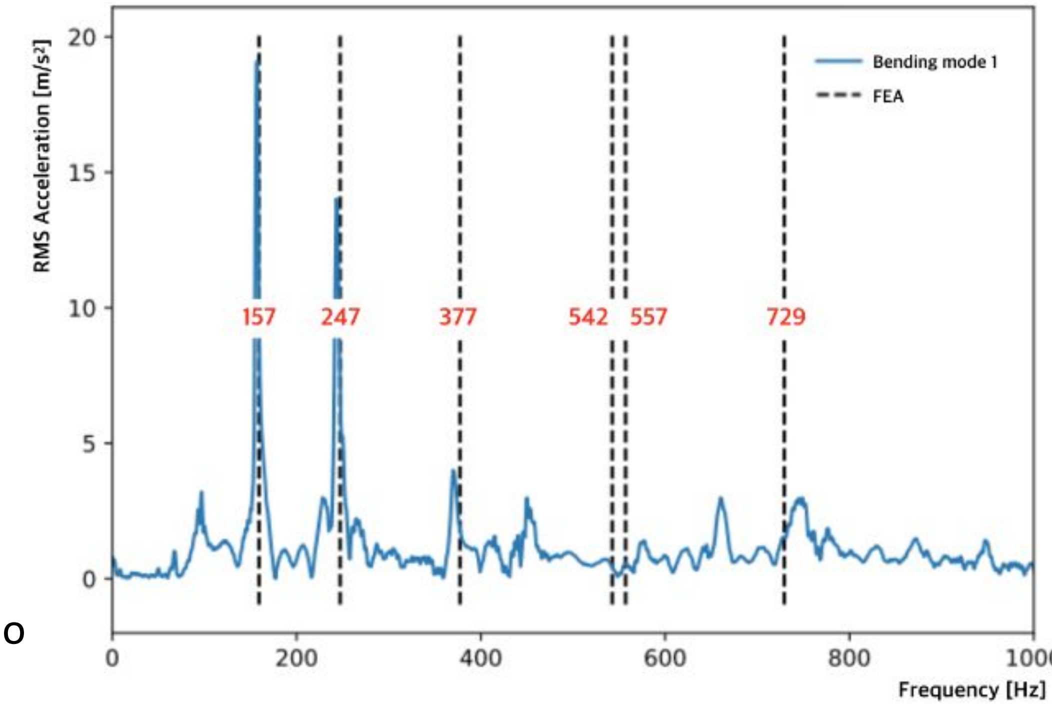
Vibration test on petal core

- **Configuration**
  - tested vertically & horizontally suspended cores
  - 6 hitting points & 6 sensor positions → for ≠ bending & torsional modes
  - impact hammer PCB 086C03 → generating + measuring force
  - piezoelectric sensor (PCB-352C23/NC) → measuring generated frequency



- **Results: modal analysis**



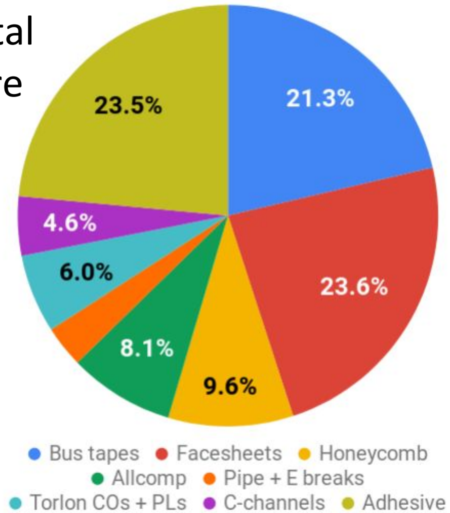


  - good agreement for lower modes
  - higher modes: small signal-to-noise ratio

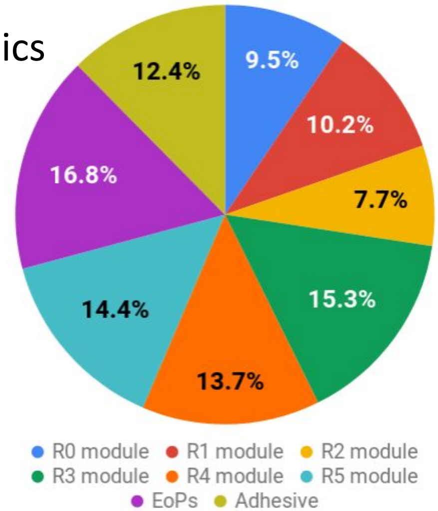
Mass & budget material estimations

Core and petal mass calculations

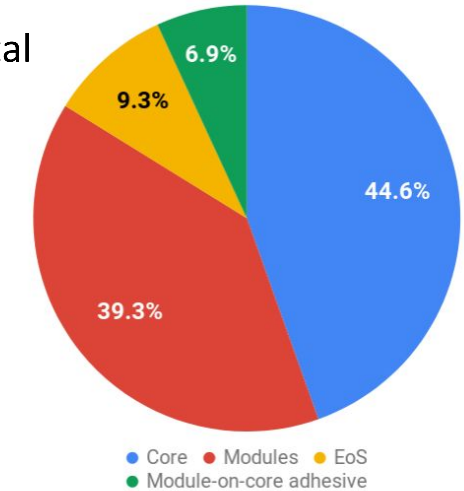
Petal core



Electronics

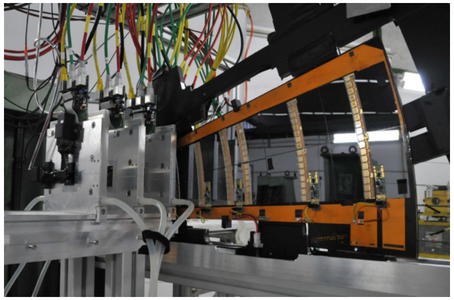


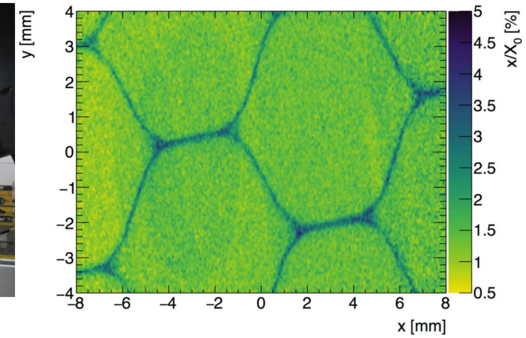
Full petal



Radiation length X_0: material budget

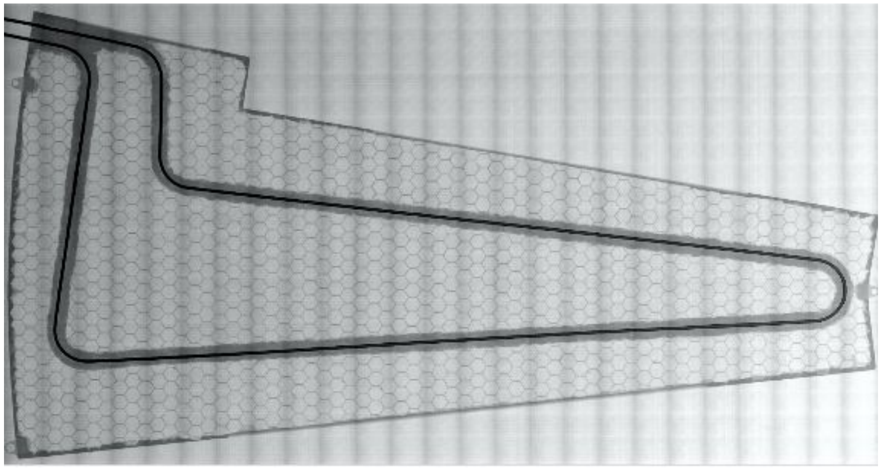
- petal inserted in EUDET-type telescope at DESY
- reconstruction of scattering angles using *General Broken Line* algorithm in EUTelescope
- X/X_0 extracted using Highland formula:
  - → inside honeycomb hole: 1 - 3 %
  - → on the honeycomb: ~4 %





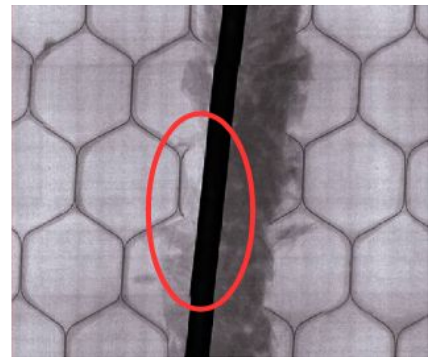
Measurements of core by Scientifica

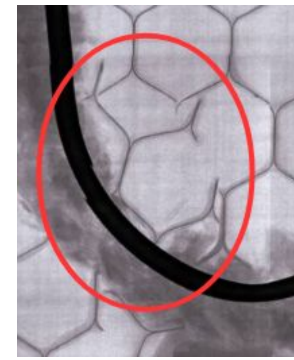
X-rays scans



Qualitative checks on honeycomb and epoxy:

Detection of defects (previous prototypes)

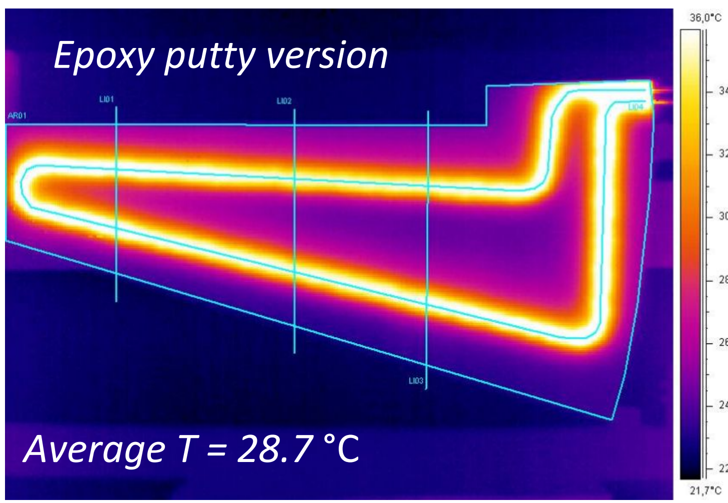


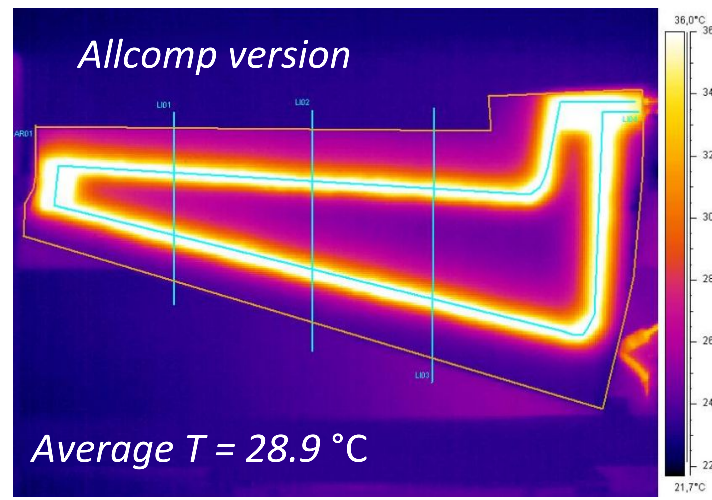


Thermal tests

<u>Fluid:</u> fricofin mixed with distilled water

T = ~38 °C





Towards production

Quality Control & Quality Assurance

Currently in the QC/QA definition phase *discussion workshop last week in Oxford*

Tests split by production steps.

Overview of QC tests for core → petal production

	Reception	Manufacturing	Assembly	Post-assembly
TESTS	Visual inspection Dimensions Weighing	Visual inspection Dimensions Weighing Pressure test Electrical conductivity HV resistance	Visual inspection Dimensions Weighing Pressure test Leak test Electrical conductivity HV resistance	Visual inspection Metrology X-rays Pressure cycle Thermal cycle Pressure drop Thermography → long cycles → rapid cycles
OBJECT(S)	Pre-preg Honeycomb Bus tape Allcomp foam Titanium pipe	C-Channels Co-cured bus tape Half core	Core	Petal

Schedule

Focused on reviews:

- **Local support PDR**

  Preliminary Design Review

  - Validation of the design

- **Local support FDR**

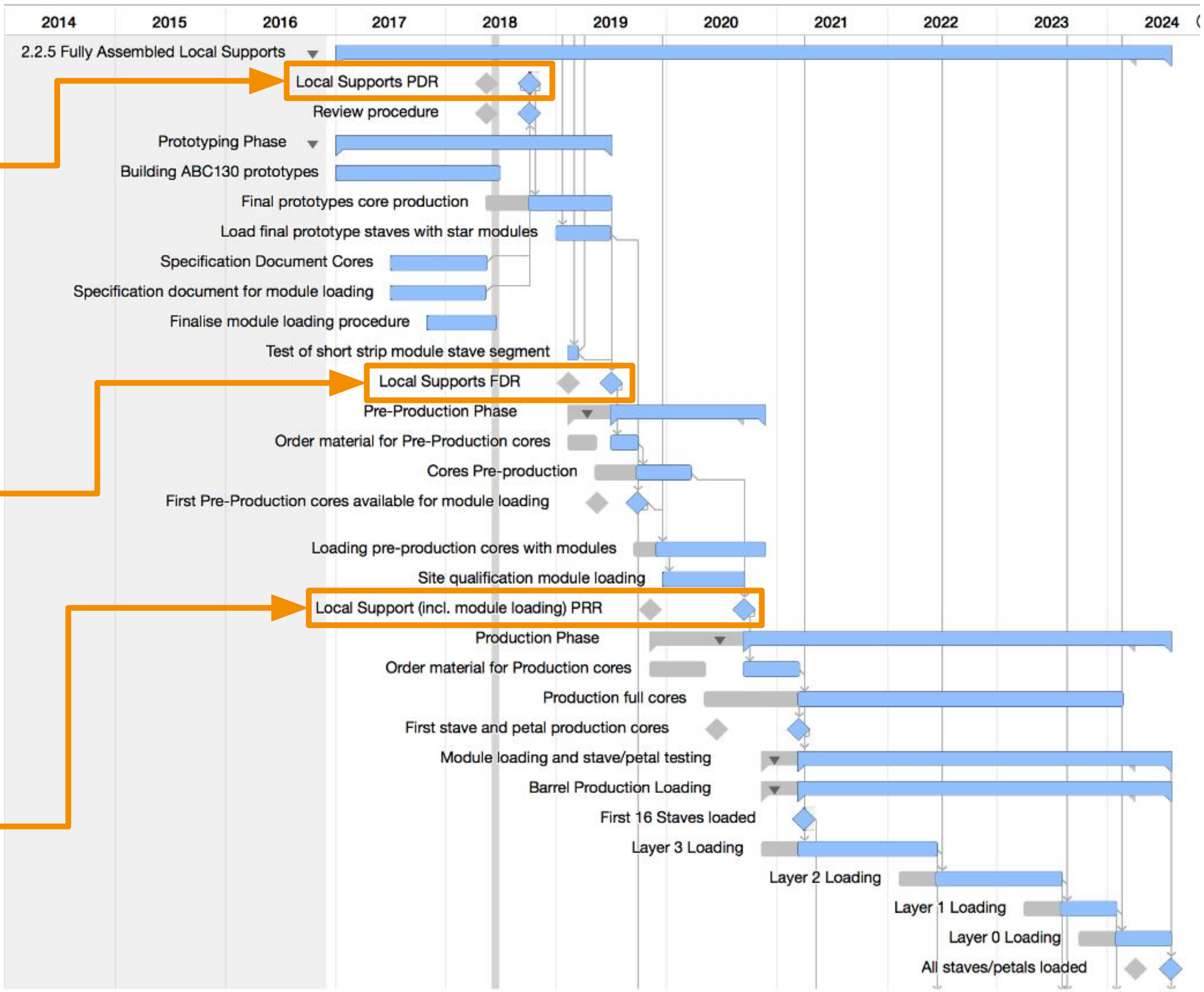
  Final Design Review

  - Start of pre-production (5 % total)

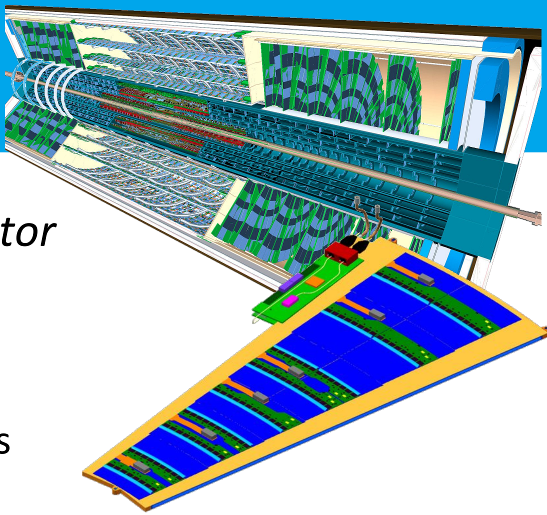
- **Local support PRR**

  Production Readiness Review

  - Green light for final production



Summary



Local support structures for the new ATLAS Inner Tracking (ITk) detector

Design finalized

Prototypes built and design validated:

- Measurements agreeing with FEA simulations → Mechanical tests / Thermal performance
- Several options on possible industrialization of petal cores (Scientifica)
- Design compatible with global structures (interface) + inserting methods

Schedule

Important milestones:

Early october → PDR

2019 Q2 → FDR → pre-production starting

Future work

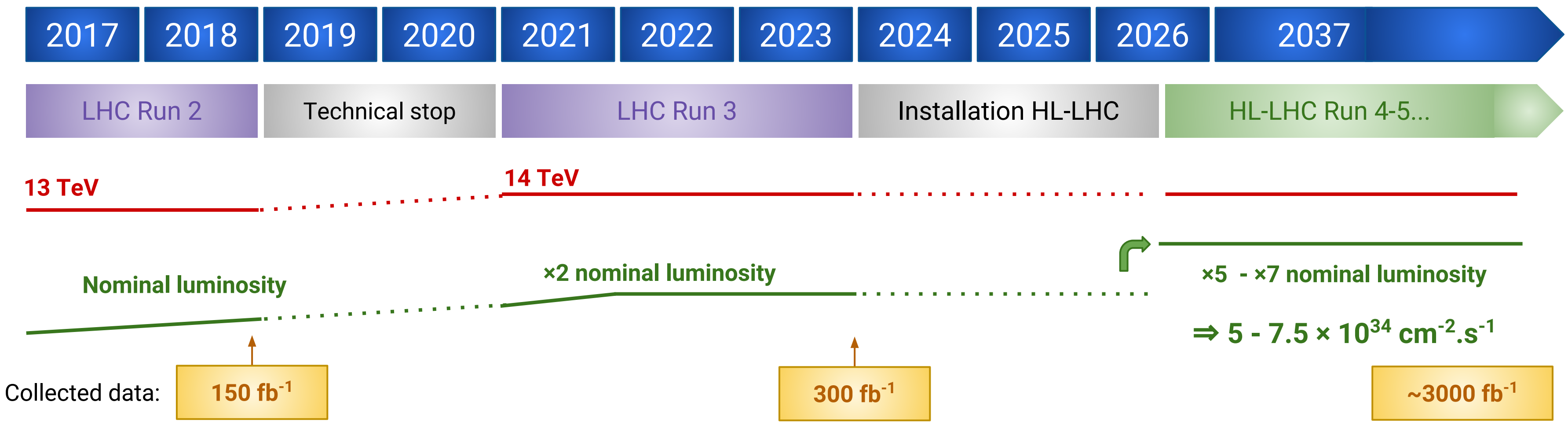
Improving measurements → more precision + better diagnostics

CO_2 properties / checking performance of petal in different orientations, etc

Backups

From LHC to High-Lumi LHC

Schedule



Right now **Peak lumi = 1.7×10^{34} $cm^{-2}.s^{-1}$**

~16 fb^{-1}
2016

≡ order of 100 × 10^{12} (trillions) proton-proton collisions

Need of a decisive increase in luminosity

→ to significantly extend statistical sensitivity to new physics

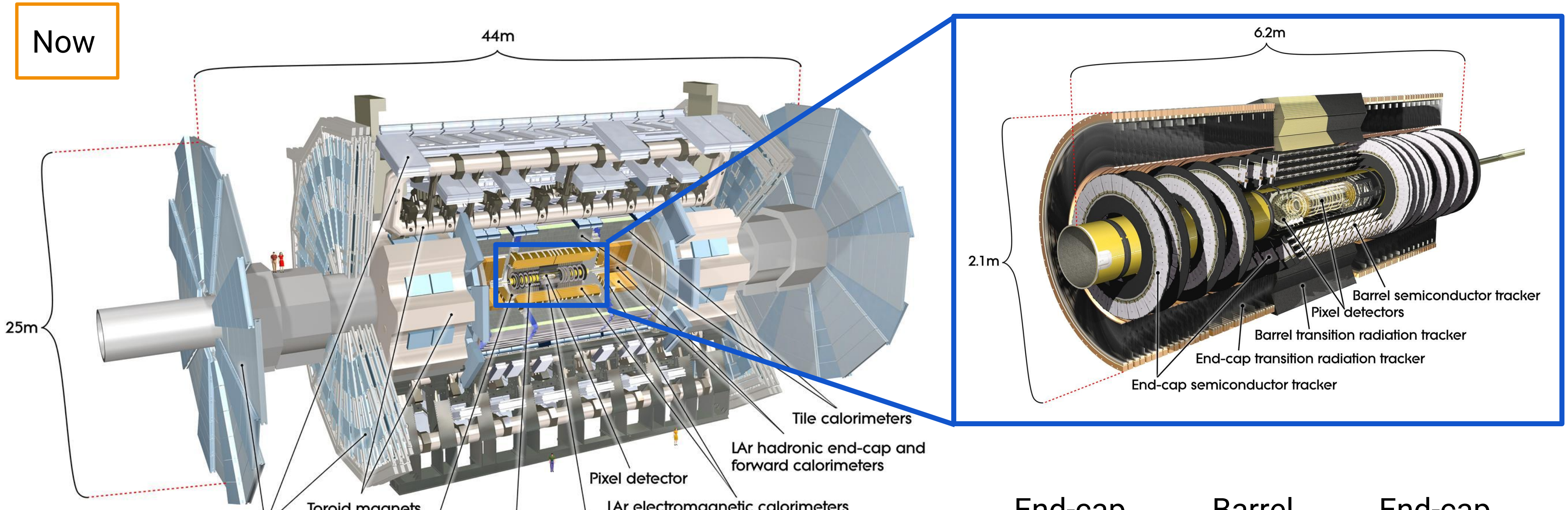
→ to maximize performance for precision measurements

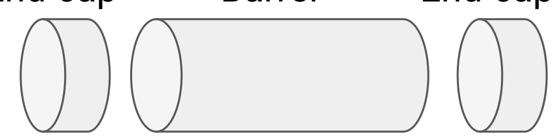
⇒ fully exploit LHC's singular potential

The High-Luminosity LHC program

The Inner Tracker of the ATLAS detector

Now





For HL-LHC

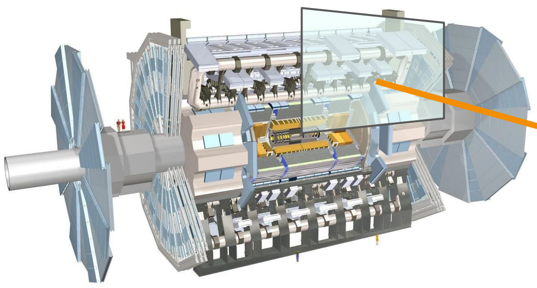
Current inner tracker to be fully replaced by all-silicon tracker **ITk** ⇒ **ATLAS Upgrade (Phase II)**

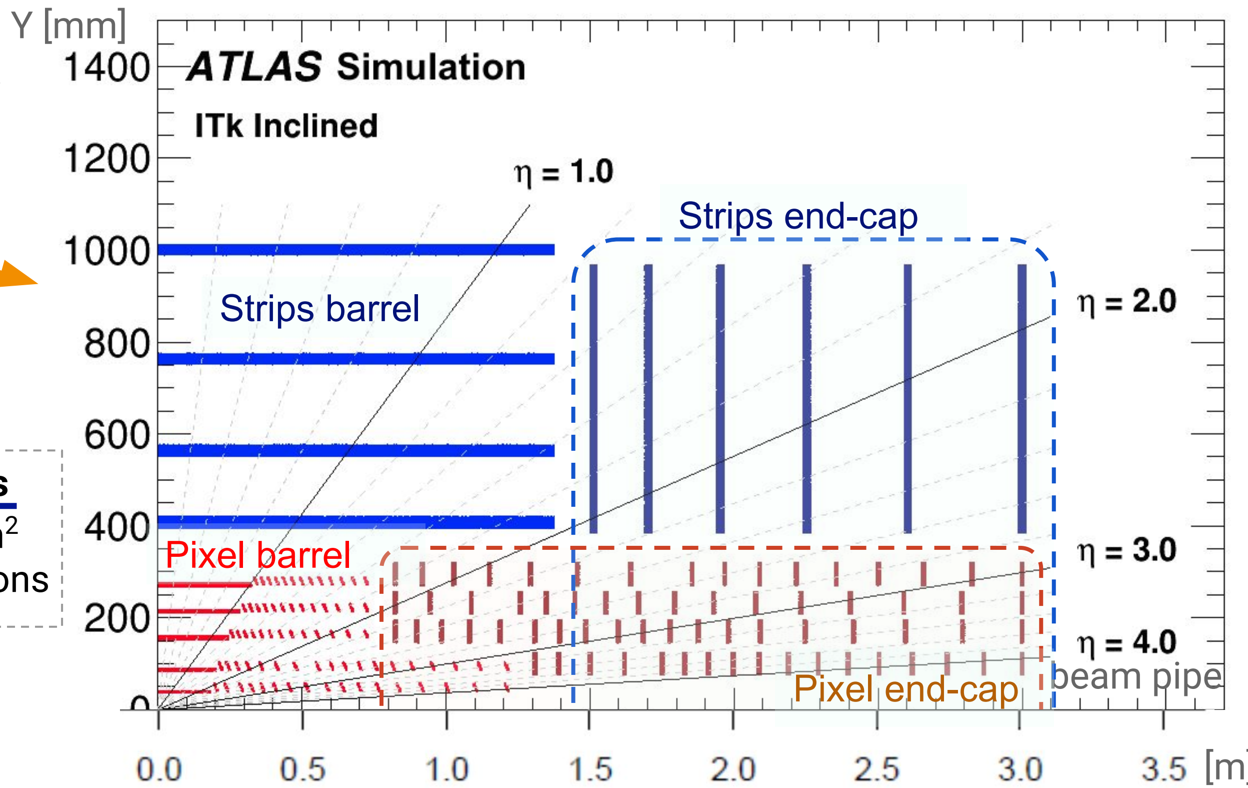
Goals: **Sustain** and **improve** the excellent performance of ATLAS Run 2 in denser environment

Overview of new strip tracker of ATLAS Upgrade II

Overall layout

Quarter segment





	Pixel	Strips
Silicon area	13 m^2	160 m^2
Nb channels	580 millions	50 millions

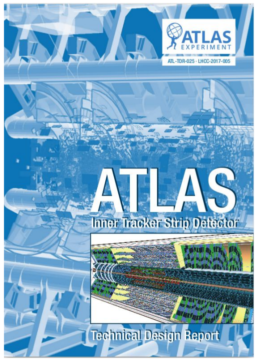
This presentation

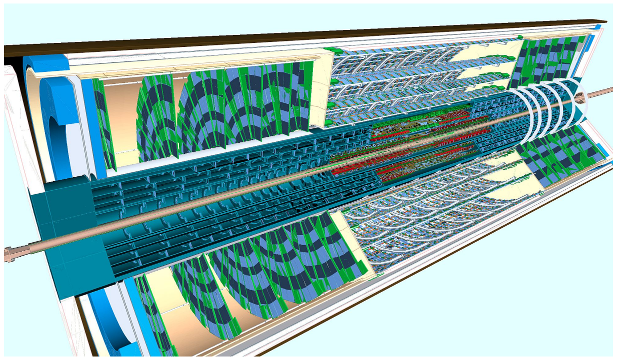
Focus on the strips region of the ITk

sensors > electronics > modules > support structures

For (much) more details:
Technical Design Report, April 2017

https://cds.cern.ch/record/2257755/files/ATLAS-TDR-025.pdf



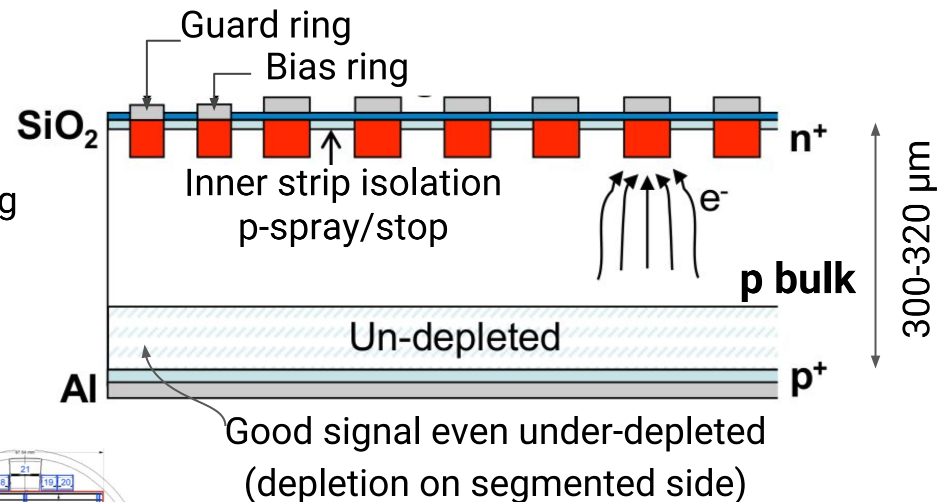


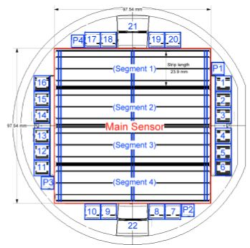
Silicon sensors

Technology

Silicon sensors → n^+-in-p float-zone (FZ) *Now = p-in-n*

- 👍 collects electrons: more & faster signal, less trapping
- 👍 no radiation-induced type inversion
- 👍 single-sided process
  - ⇒ cheap & easy
  - ⇒ more available foundries worldwide
- 👎 sensor edges at bias potential (~700 V)

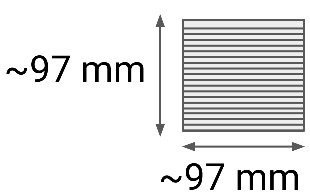


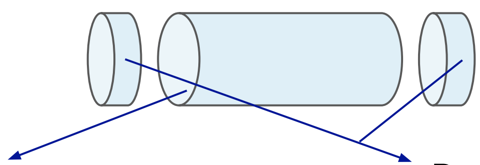


← design based on 6-inch wafer technology

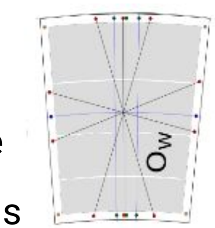
Sensor shapes & pitch

Barrel → rectangular





End-caps → trapezoidal shape for r-Φ coverage

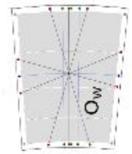
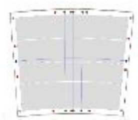
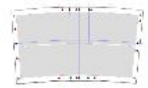
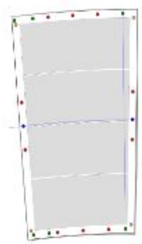


Radial strips pointing to beam axis
⇒ wedge-shaped sensors with curved edges

75.5 µm	**Strip pitch**	60 - 80 µm
Long: 48.2 mm Short: 24.1 mm	**Strip length**	15.1 - 60.2 mm

chosen to balance higher occupancy regions with shortest strips

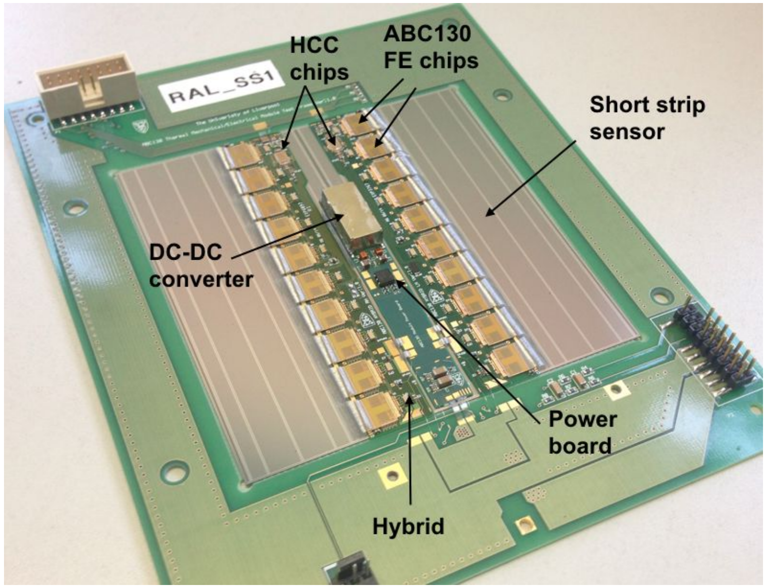
End-cap sensor geometries

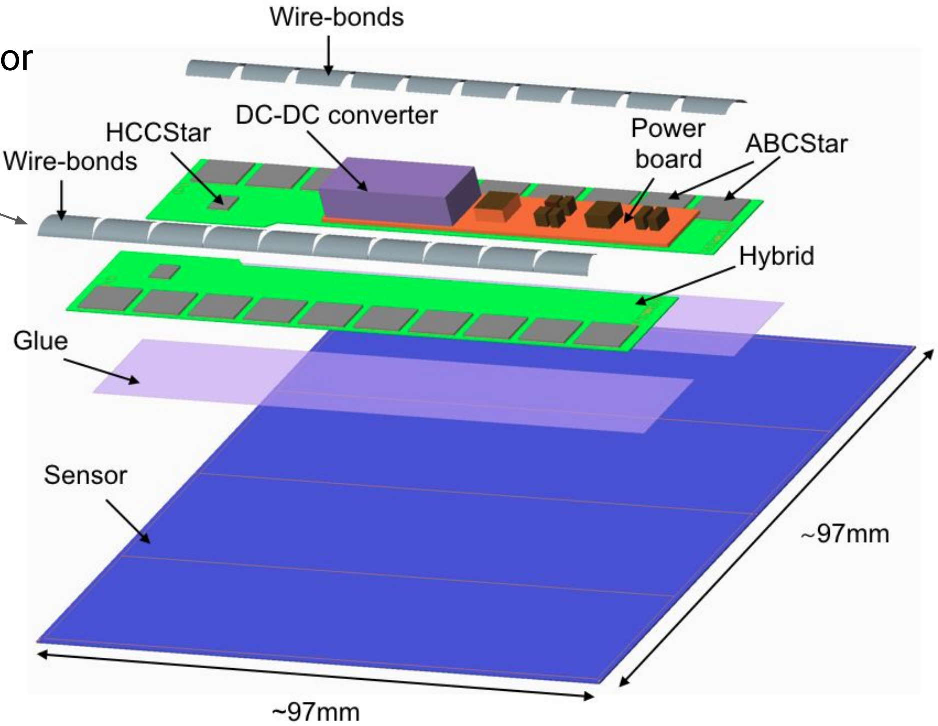
Sensor type	Number of sensors	Shape	Number of rows	Channels per sensor	Min/max pitch (μm)
Short-strips	3808	Square	4	5128	75.5
Long-strips	7168	Square	2	2564	75.5
EC Ring 0	768		4	4360	73.5/84
EC Ring 1	768		4	5640	69/81
EC Ring 2	768		2	3076	73.5/84
EC Ring 3	1536		4	3592	70.6/83.5
EC Ring 4	1536		2	2052	73.4/83.9
EC Ring 5	1536		2	2308	74.8/83.6

Strip Module

= Silicon sensor + hybrid + power board

- **New:** low mass PCB's directly glued on sensor
- Hosting readout electronics
- Connection to strips by wire-bonds





Glue: thermally conductive DCFE4445 adhesive

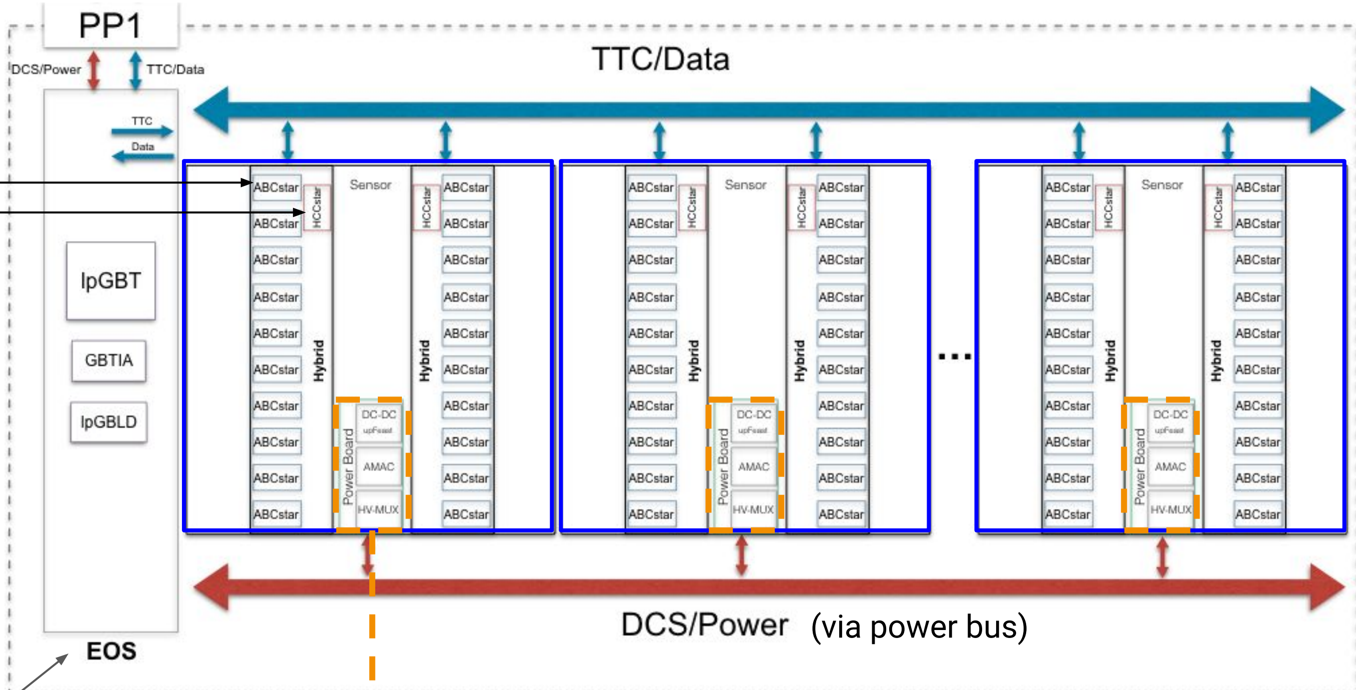
K= 2 W/Km

Total number of modules = 17888 ⇒ designed for mass production

Signals & Electronics

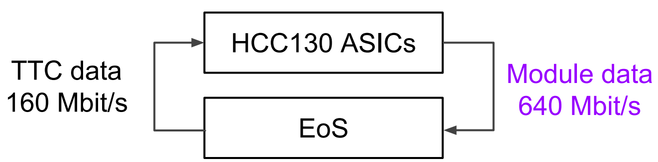
Front-end read-out

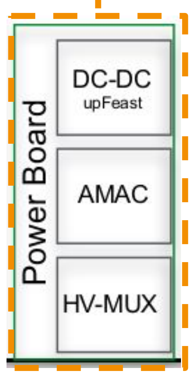
Charged particles through sensor
↓
signal charge
↓
Conversion in hit signal
in ABCStar
binary ASICs using 130nm tech
256 channels
↓
Hybrid Controller Chip
HCCStar
↓
Packed signals sent to End-of-Substructure via bus tapes



Clock & Trigger rates

Baseline: L1 trigger rate = 1 MHz





Power board

← Point of load DC-DC conversion 10.5 V → 1.5 V
radiation-hard "upFeast" chip controls parallel powering

← Autonomous Monitor and Control Chip
local monitoring of current/voltage/temperature
controls HCC, ABC, HV switch

← Multiplexer: controllable switch, allows connection/isolation of individual sensor to single HV line

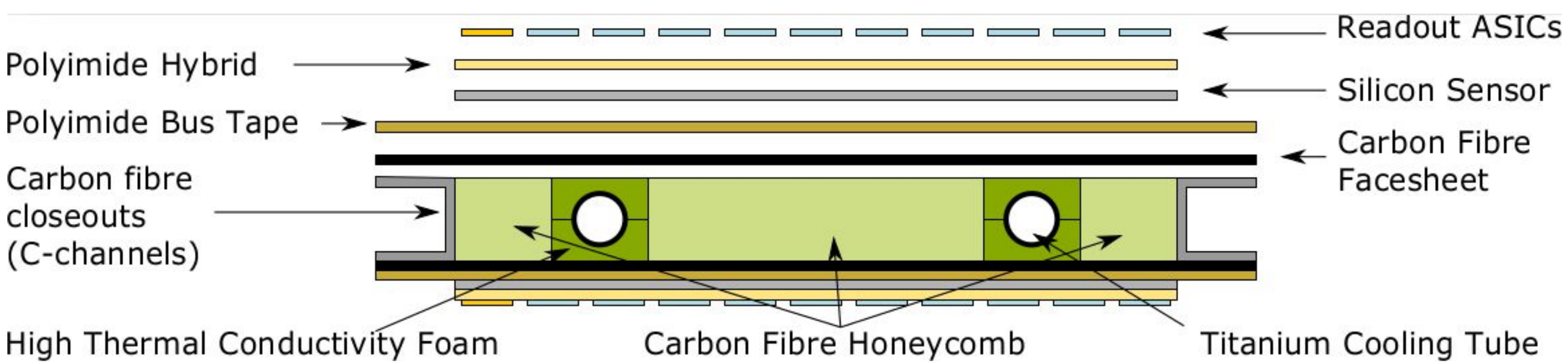
Module support (1/2)

System unit: a sandwich

→ Modules directly glued on both sides of a light carbon-fiber support structure

→ Cooling system embedded (bi-phase CO_2 cooling at -35°C)

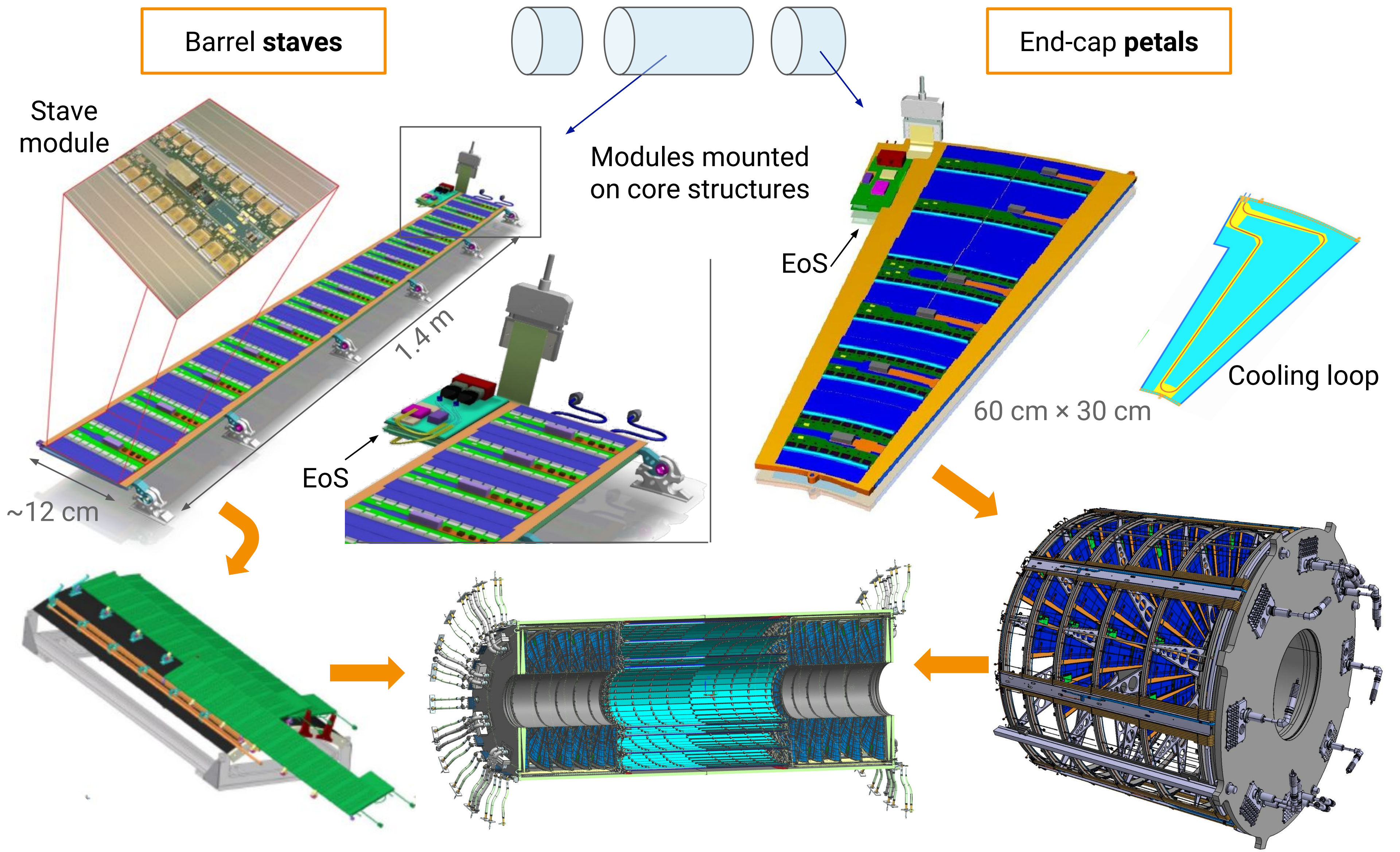
Cross section



- Minimizing material
  - ⇒ short thermal paths ~ 3 mm
  - ⇒ reduced radiation length ~ 2% [x/X_0]
- Simplicity for large scale reproducibility
- Core and electronic components individually testable before assembly

Module support (2/2)

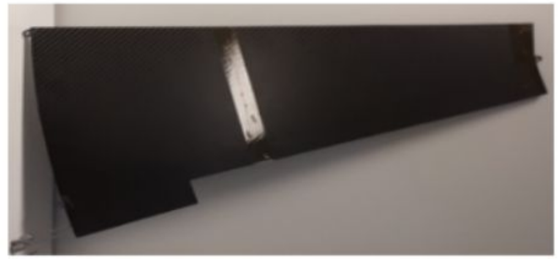
more details in **Ankush's talk** on Friday



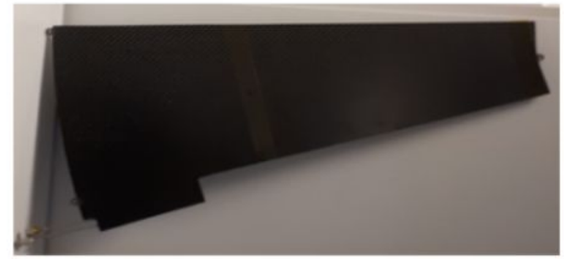
Petal Cores manufactured at DESY

Petal01

(Co-cured TM bus tape included)



Petal02



Petal03

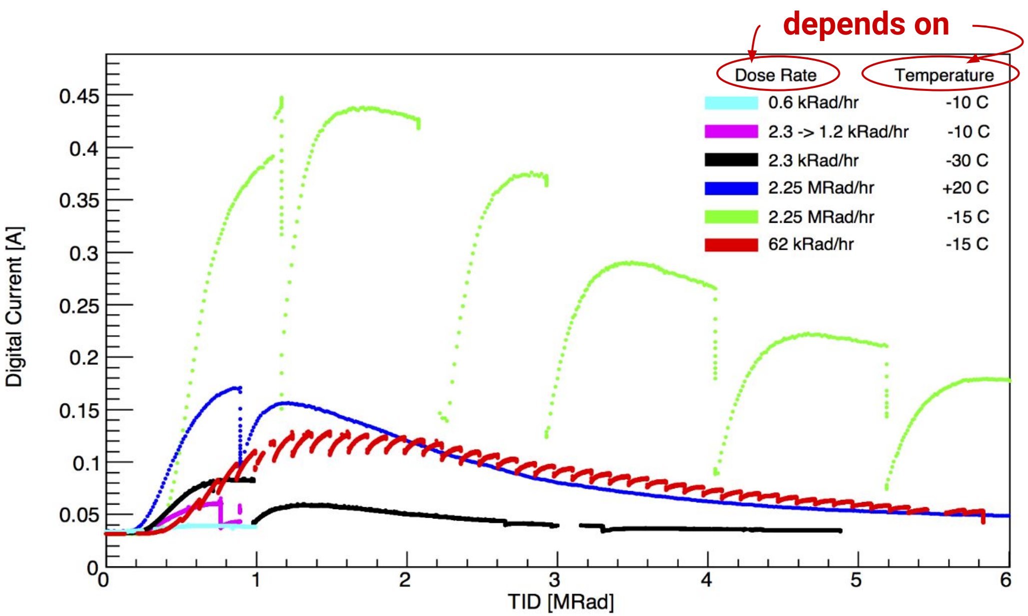
		Petal01	Petal02	Petal03	Sandwich panel
Total thickness [mm]		5.84	5.70	5.70	6.18
Bus tape	material	Polyimide/Cu/Al	-	-	-
	thickness [mm]	0.17			
	Young's modulus [GPa]	2.50			
	Poisson's ratio	0.33			
Facing	material	K13C2U	Woven CF	Woven CF	Woven CF
	layers	0-90-0	0-90	0-90	0-90
	thickness [mm]	0.15	0.25	0.25	0.25
	Young's modulus [GPa]	353*	62	62	62
	Poisson's ratio	0.49*	-	-	-
Honeycomb	material	Nomex C2-4.8-32 (paper)	UCF-328-1/4-3.0 (carbon)	CC-T300-EP1-10-31 (carbon)	CC-T300-EP1-10-31 (carbon)
	cell size [mm]	4.80	5.50	10.00	10.00
	Young's modulus [GPa]	0.16	-	0.17	0.17

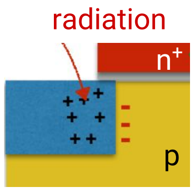
Ongoing R&D

Irradiation tests: TID induced current increase

Total Ionizing Dose (TID) induced current increase

Irradiation with X-rays ⇒ increase of digital current in ABC130 ASIC





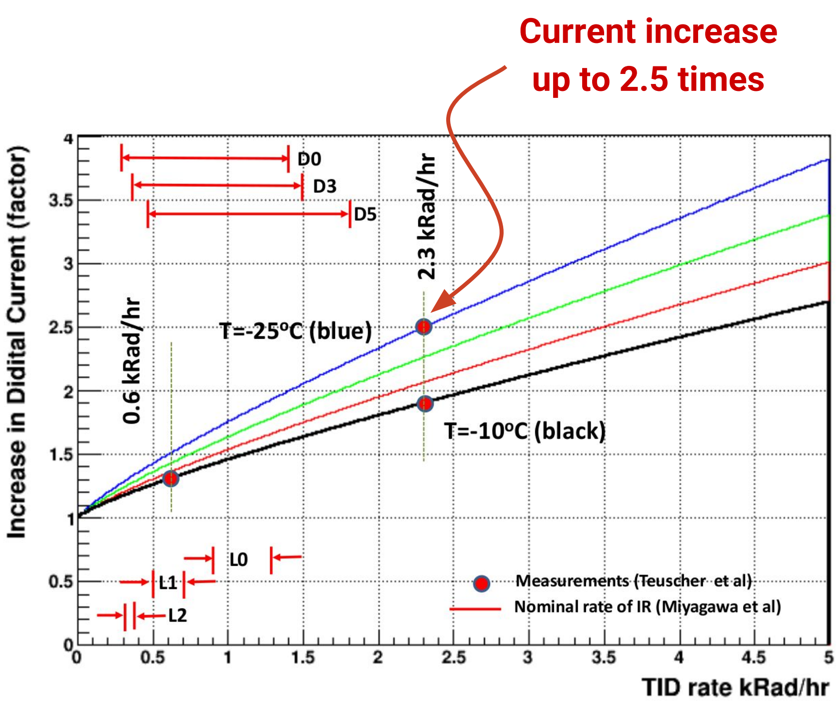
Radiation

⇓

creates trapped charges in oxide

- recovery @ higher doses

F. Faccio and G. Cervelli, Radiation-induced edge effects in deep submicron CMOS transistors, IEEE Transactions on Nuclear Science 52 (2005) 2413–2420.



Intensive studies ongoing to:

→ characterize ⇒ irradiation tests

→ model dissip. power ⇒ P^{dissip} = f(position, fluence)

⇒ feeds FEA simulations

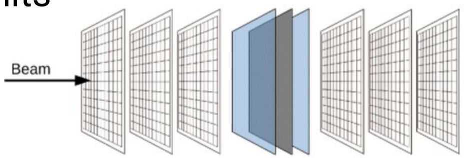
⇒ design and layout of the strip detector is sturdy enough to incorporate this feature

Irradiation tests: testbeam results (1/2)

Comparison of performance before and after irradiation

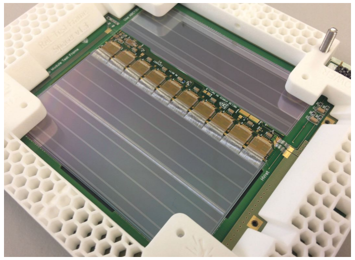
→ miniature sensors irradiated

→ beam tracks matched to strip hits using EUDET-type telescopes (CERN & DESY)

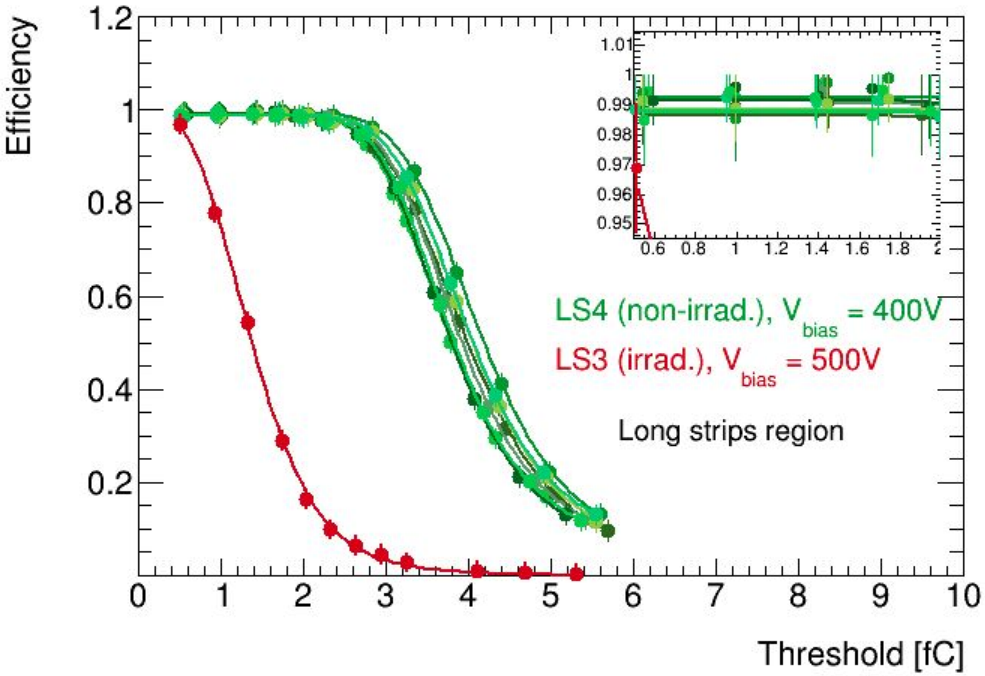


↑ telescope MIMOSA sensors

↓ Long Strip module 4 (LS4)



Threshold scans



Irradiation of Long Strip module 3

→ at CERN Proton Synchrotron

→ 24 GeV protons

- Non-Ionizing Energy Loss: $8 \times 10^{14}\ n_{eq}.\ cm^{-2}$
- Total Ionizing Dose: 37.2 MRad

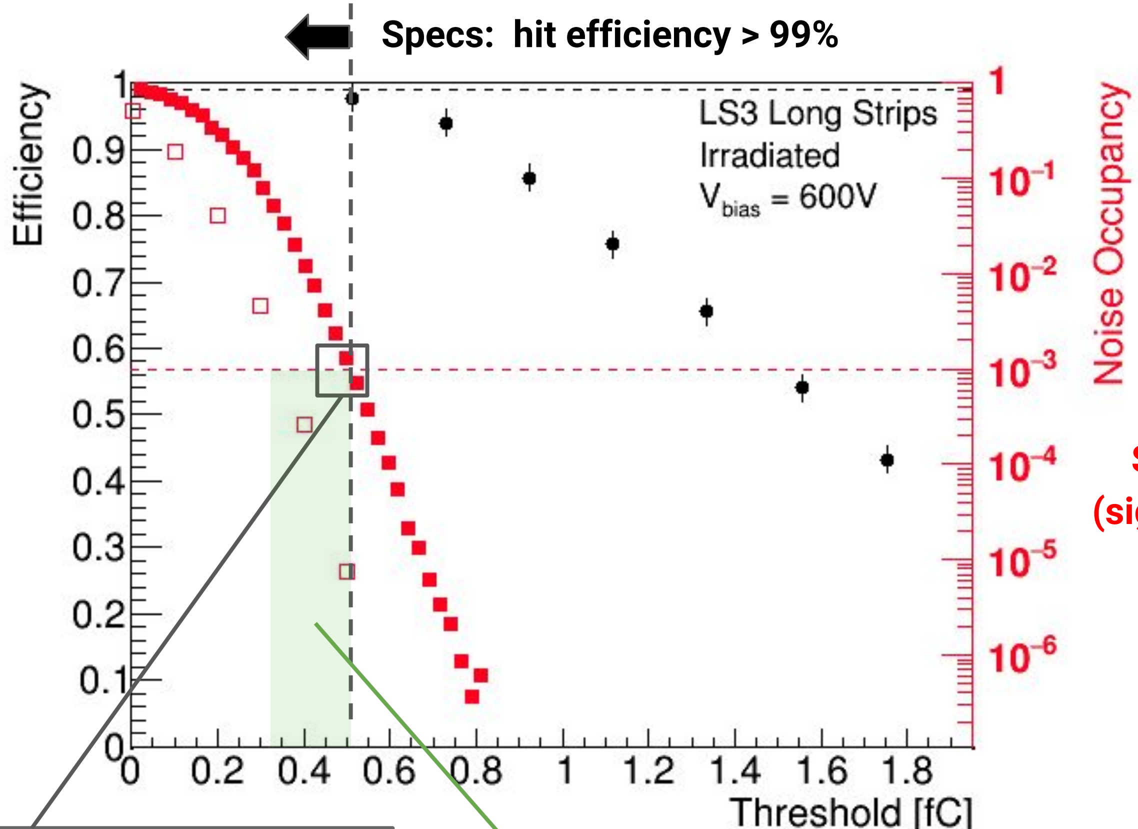
Max level of radiation expected in the strip system

← charge collection reduced after irradiation

Irradiation tests: testbeam results (2/2)

Expected end-of-lifetime performance

Hit efficiency (obtained using track reconstruction of telescope data)



- hit efficiency
- ABC130 noise occ.
- New front-end noise occ.

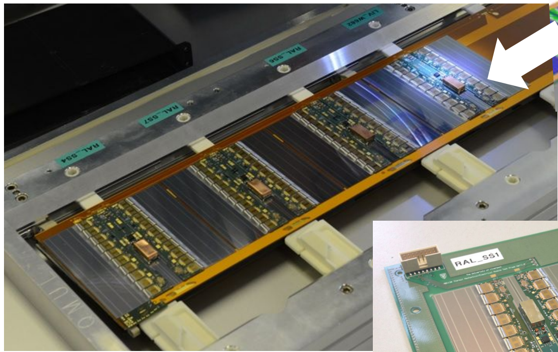
Specs: NC < 10^{-3}
(signal-to-noise 10:1)

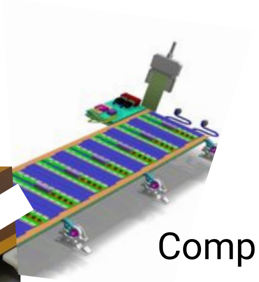
Very small working window with ABC130

Range of thresholds meeting the 2 specs much wider with new front-end stage for ABCStar chip

Prototype characterization

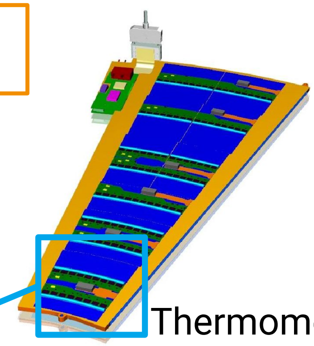
Stave barrel

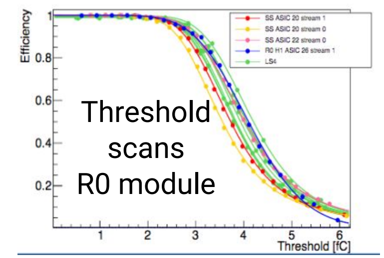




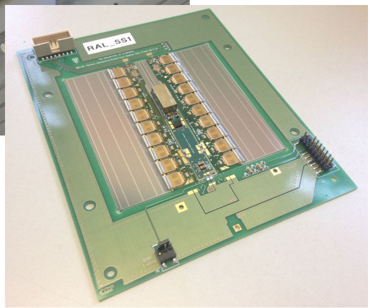
End-cap petal

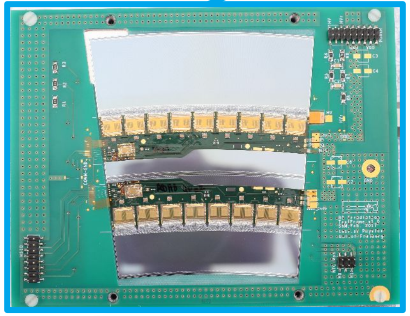
Complete modules currently tested pre/post-irradiation

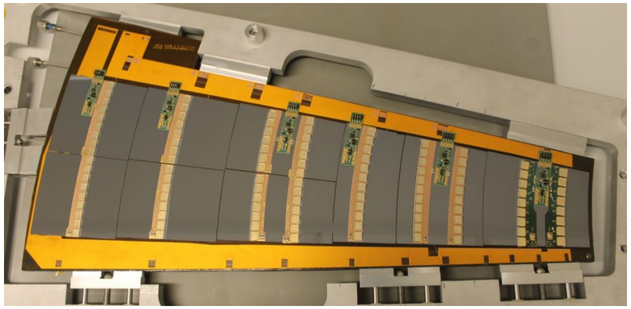


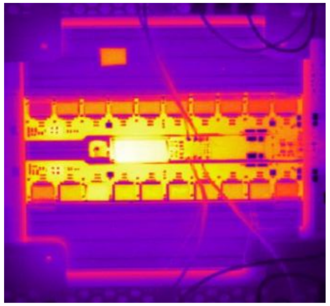


Thermomechanical prototype petal





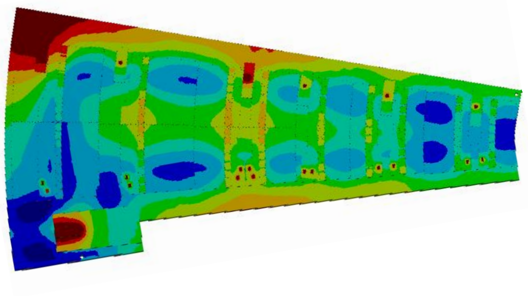


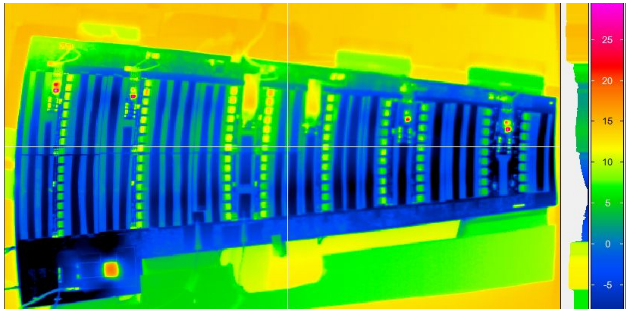


Ongoing tests:

→ metrology
→ readout developments
→ infrared measurements
→ mechanical stress

⇒ comparison to FEA simulations





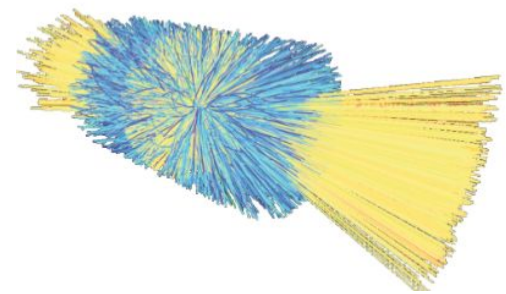
Working on detailed Quality Control & Quality Assurance procedures

On the road to 2026...

Design of the new inner tracker for the upgraded ATLAS detector

Proposed tracker designed to meet the requirements of the High-Luminosity LHC program

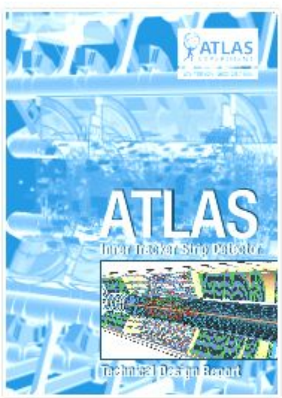
→ dense environment with high levels of radiations
→ coping with 5 times more pile-up: from 40 to 200



Milestones and achievements

Intensive R&D activities performed by numerous institutes within the ITk collaboration

→ strong prototyping effort to optimize stave and petal structures
→ irradiation and testbeam data taking



June 2017 → CERN Research Board approved the Phase-II ITk Strip TDR

Ongoing Research & Schedule

Ongoing tests & simulations to further help reaching desired sensitivity of HL-LHC analyses

End of 2017 → pixel TDR

High-Luminosity LHC requirements

Coverage	→ Expanding eta coverage → Reduce lower inactive material
Speed	→ Fast electronics → High bandwidth
Radiation hardness	→ sensors & electronics to withstand ×10 radiation levels of current inner strip tracker
Granularity	→ dense environment: ~200 collisions/bunch crossing → occupancy < 1%

Edge & multiple strip behaviour

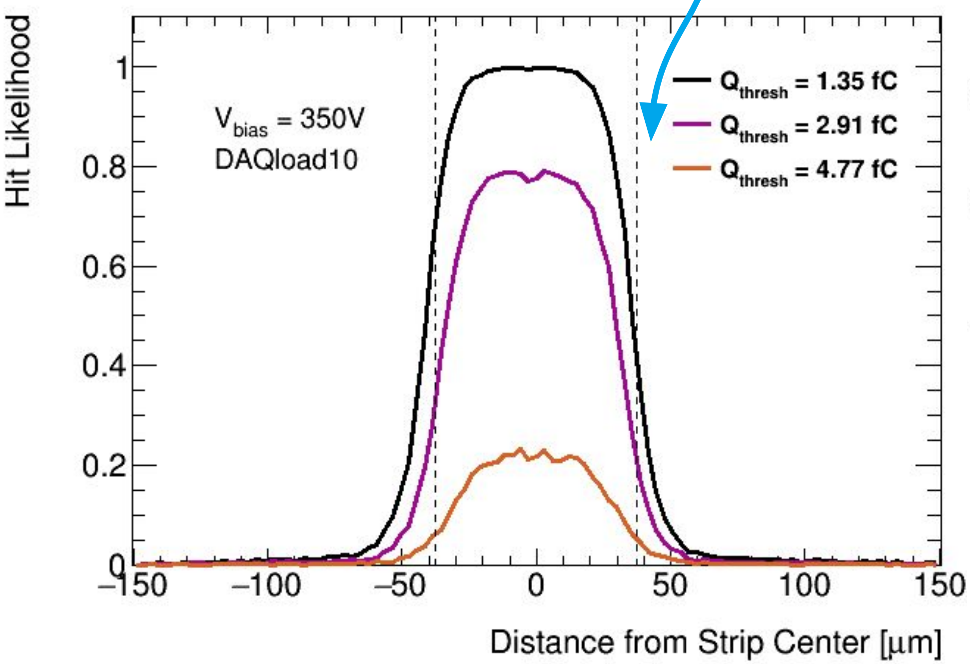
Hit occupancy

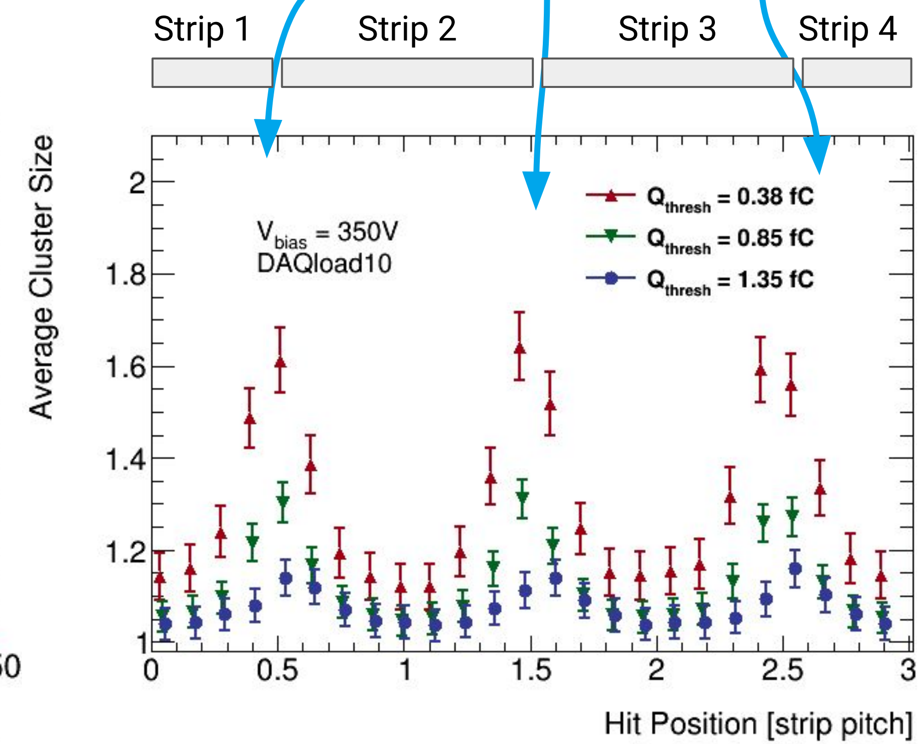
Average cluster size along strips

Flat efficiency,
Consistent with
strip pitch **74.5 μm**

Drop due to charge
sharing between strips

Charge charing highest for electrons
passing in between 2 strips





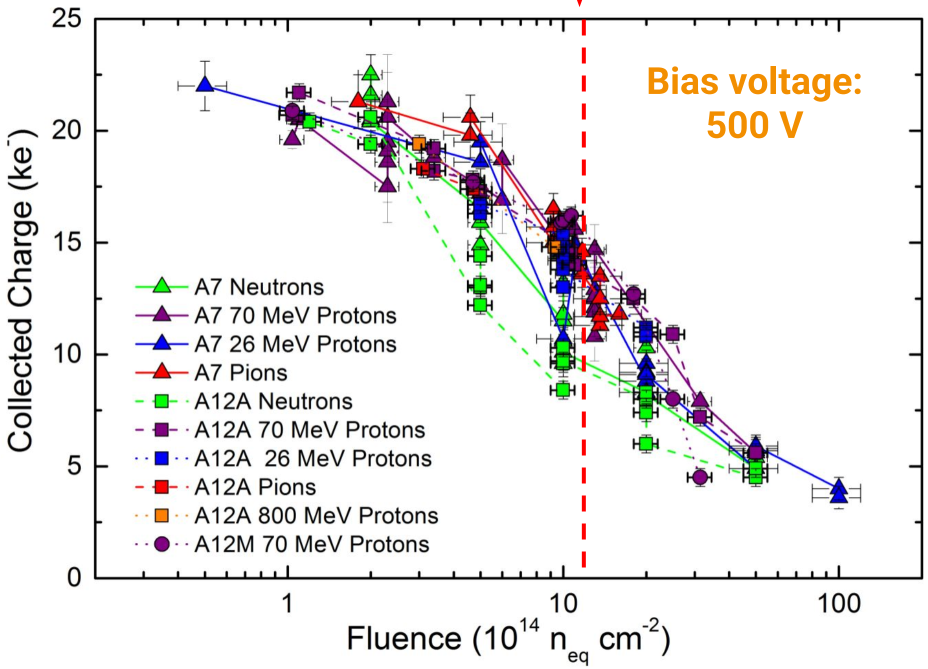
Charge Collection Efficiency after Irradiation

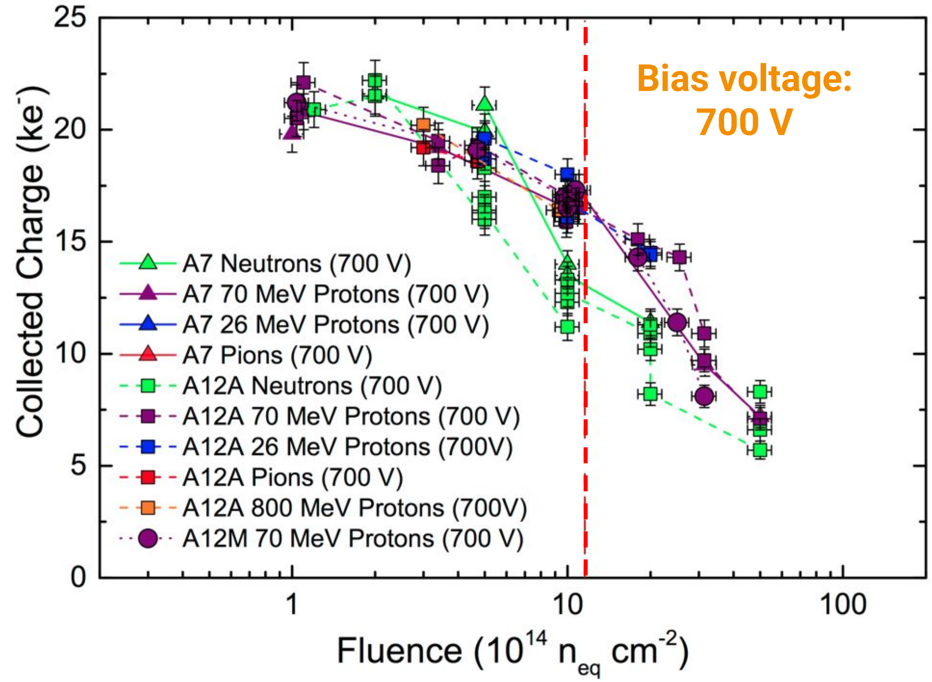
Estimated collected charge vs fluence

Miniature devices irradiated to strip barrel radiation level with neutrons, pions, protons

safety factor

Maximal expected fluence within ITk strip × 1.5



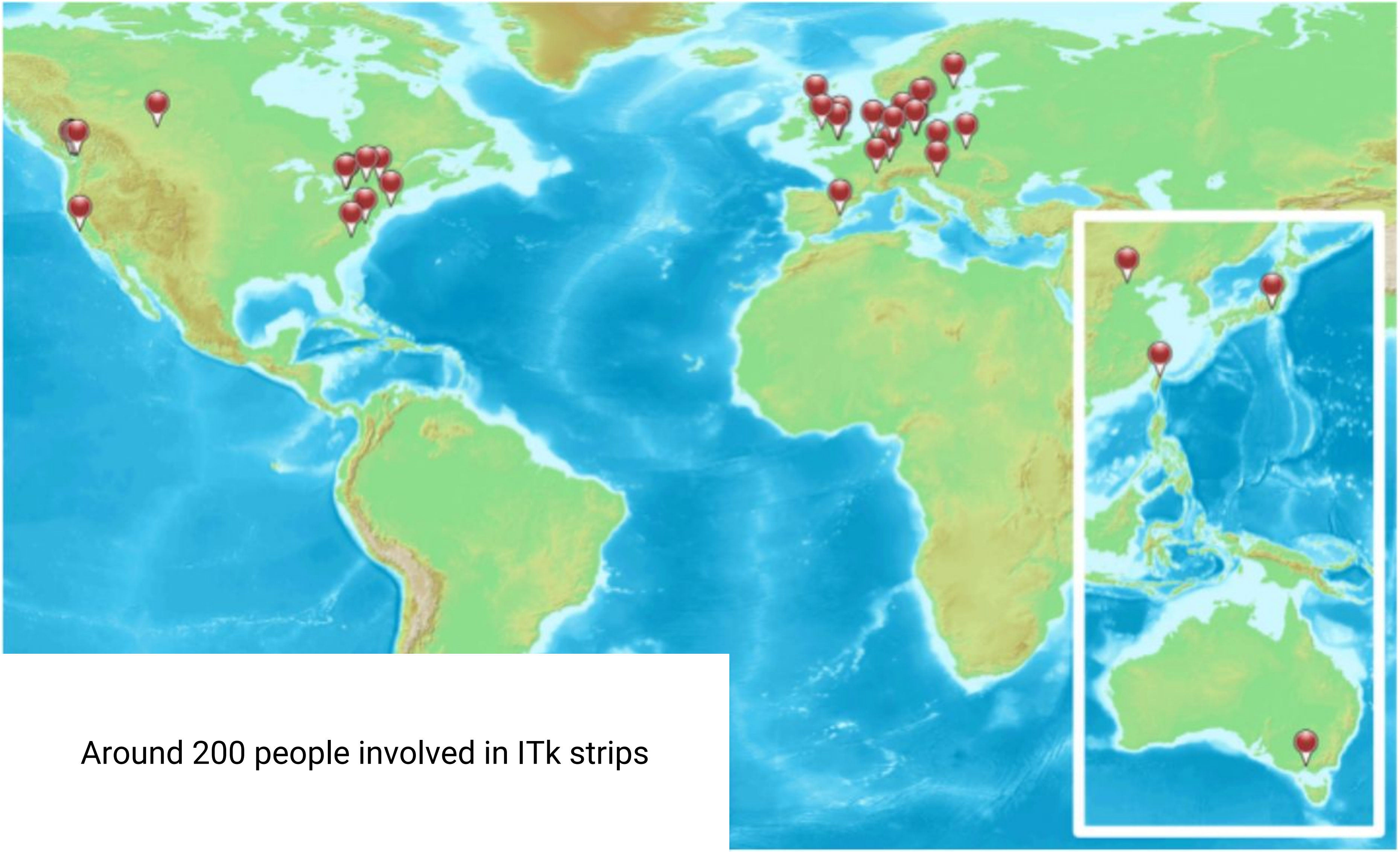


Expected collected charge:

@ 500 V
11.5 - 17.3 ke⁻

@ 700 V
14 - 19.5 ke⁻

ITk strips collaboration



Around 200 people involved in ITk strips