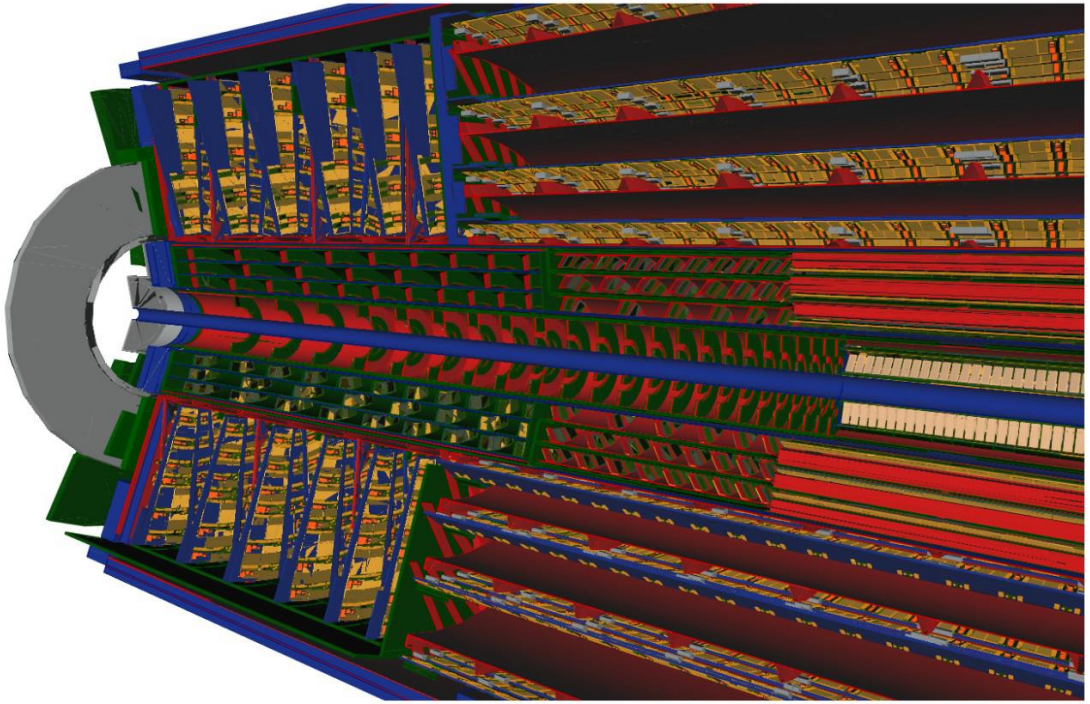
The ATLAS ITk Strip Detector System for the Phase-II LHC Upgrade

Sergio Díez Cornell (DESY) on behalf of the ATLAS ITk Collaboration



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ICHEP 2022 BOLOGNA

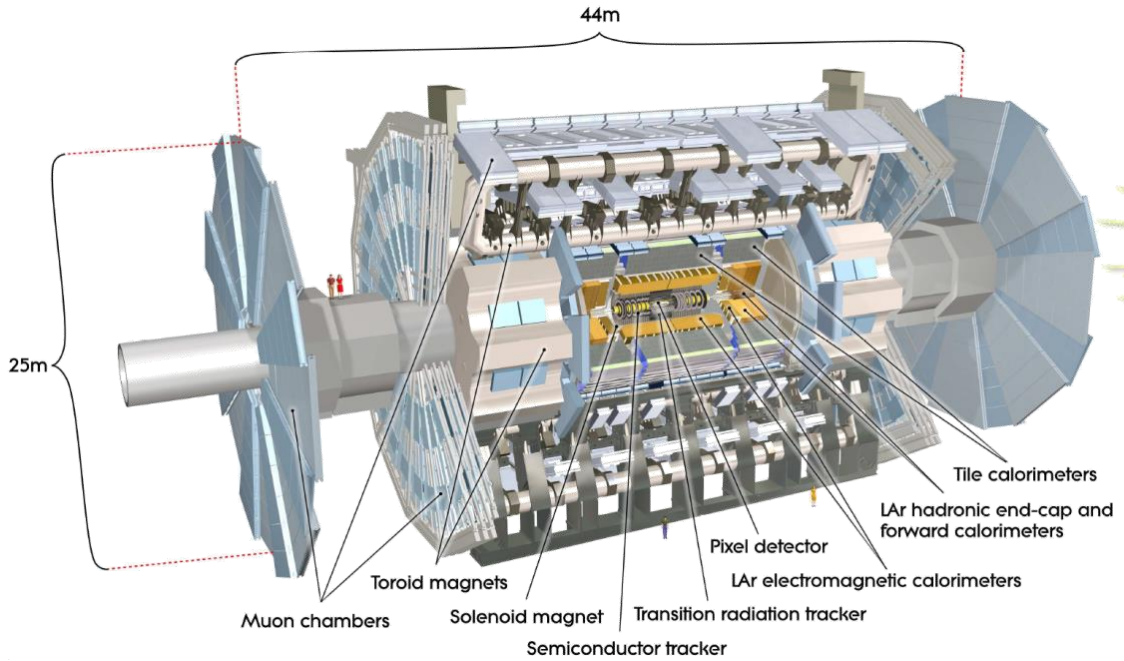
HELMHOLTZ

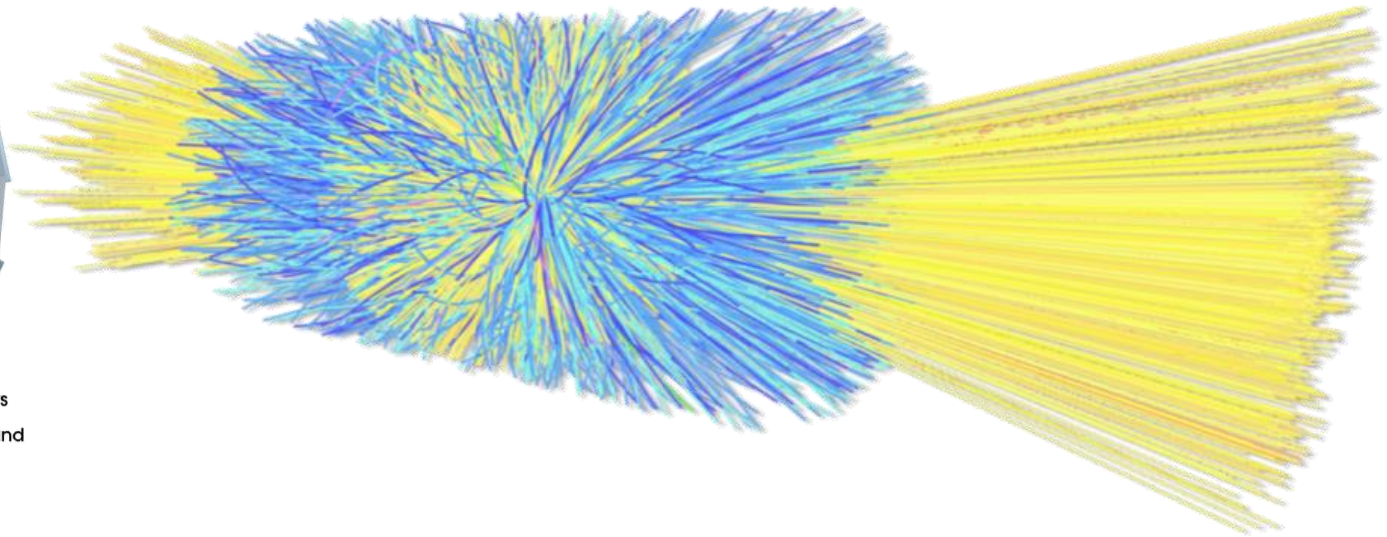
ATLAS ITk

DESY.

Collisions at the HL-LHC

Increasing the luminosity tenfold





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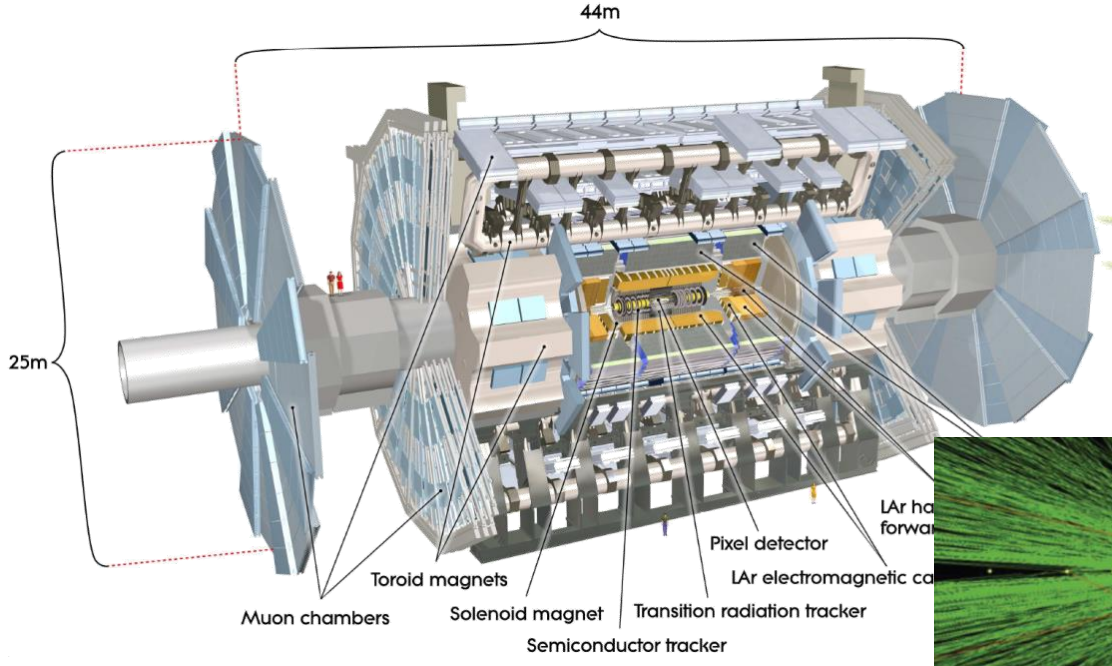
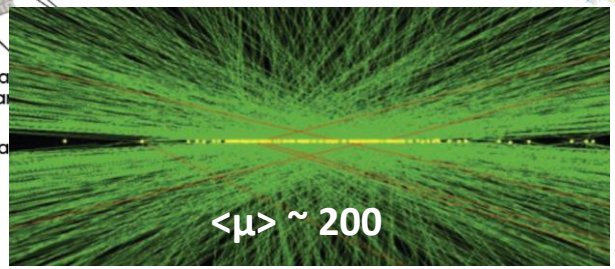
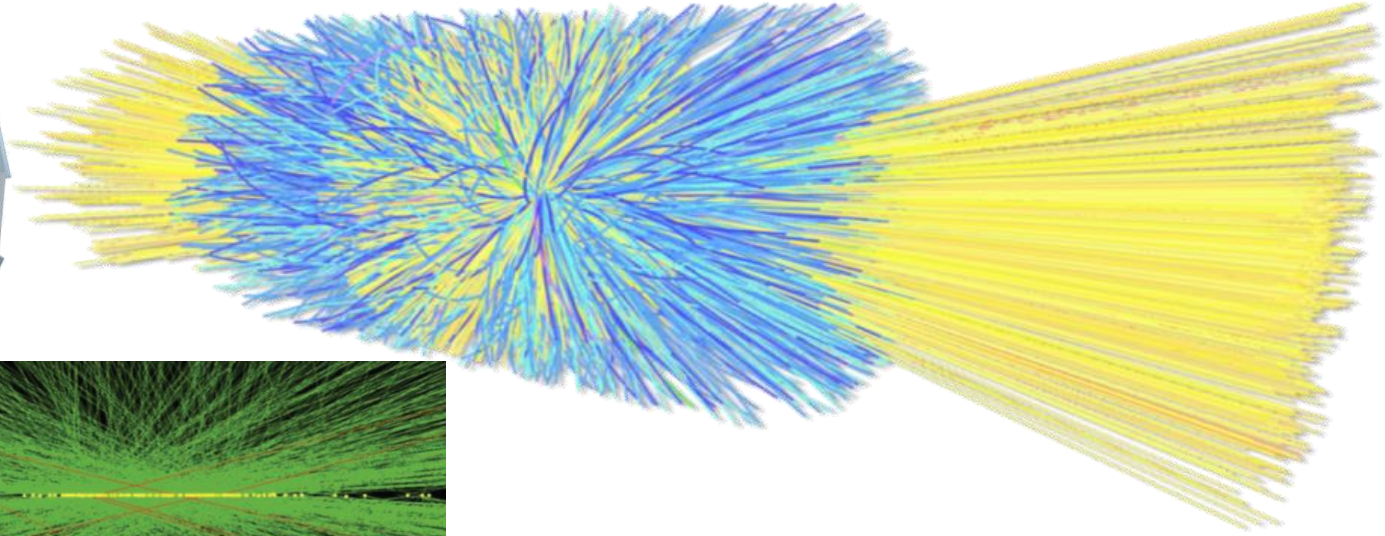




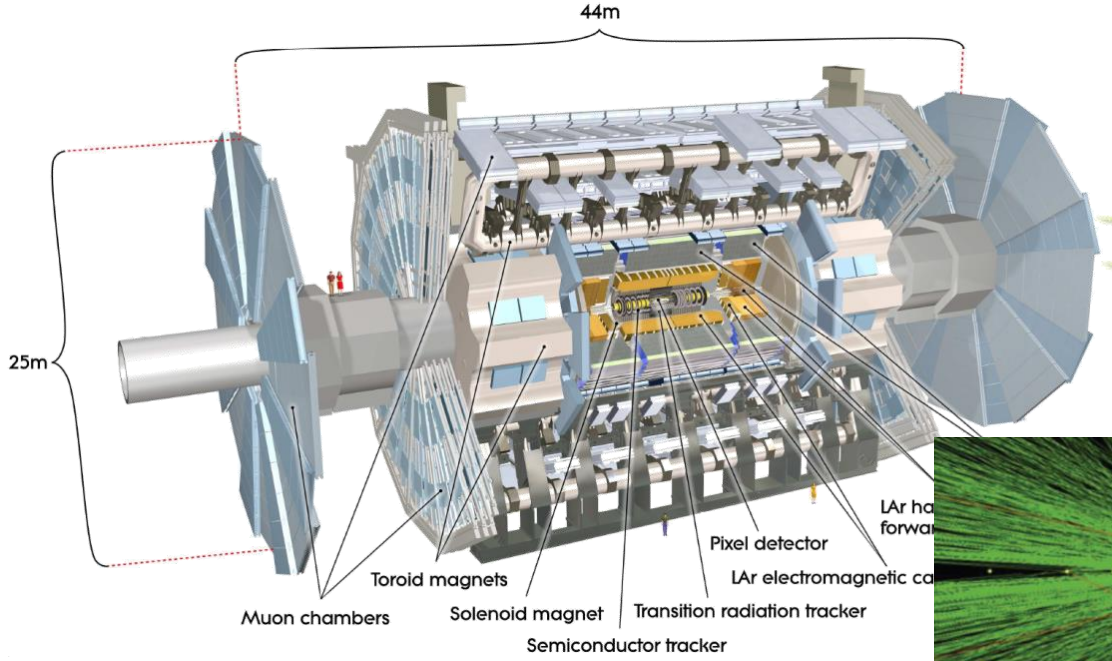


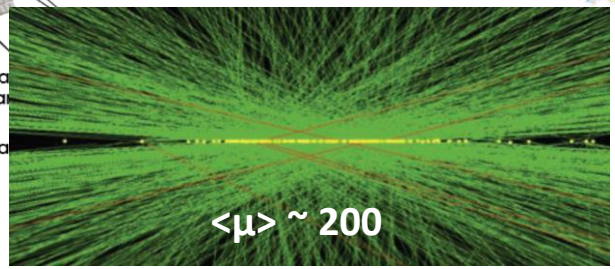
Increased instantaneous luminosity
$7.5x\ 10^{34}\ cm^{-2}s^{-1}$
and pp interaction per bunch crossing
<μ> ~ 200

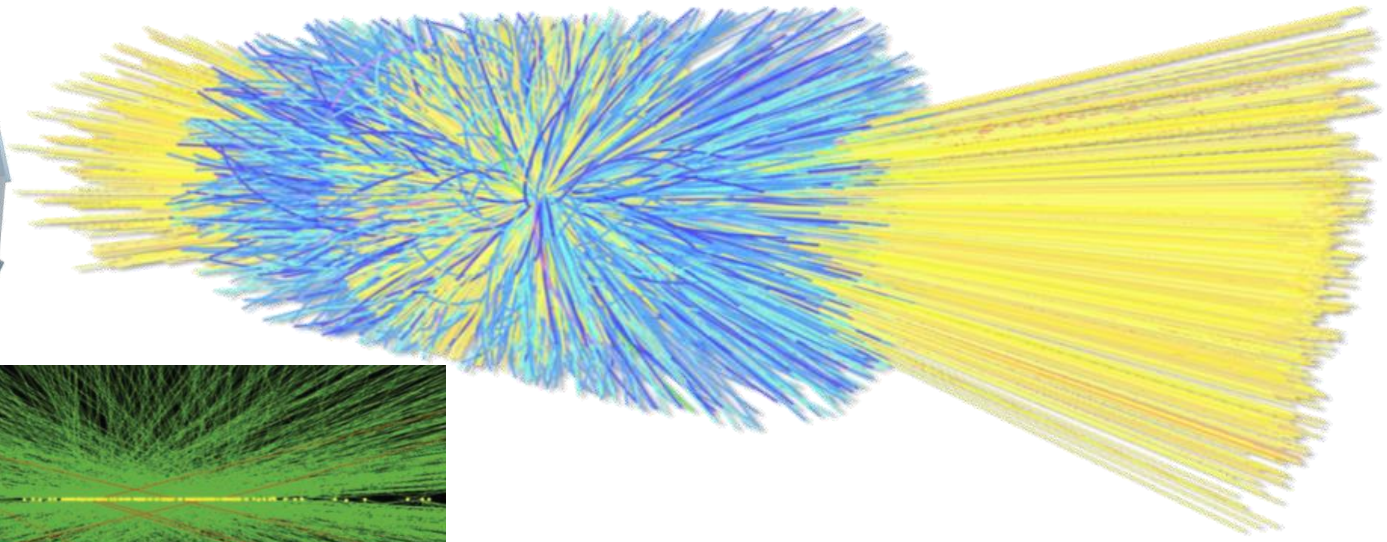
Increased integrated luminosity
3000- 4000 fb^{-1}

Collisions at the HL-LHC

Increasing the luminosity tenfold







Increased instantaneous luminosity
$7.5x\ 10^{34}\ cm^{-2}s^{-1}$
and pp interaction per bunch crossing
<μ> ~ 200

Increased integrated luminosity
3000- 4000 fb^{-1}

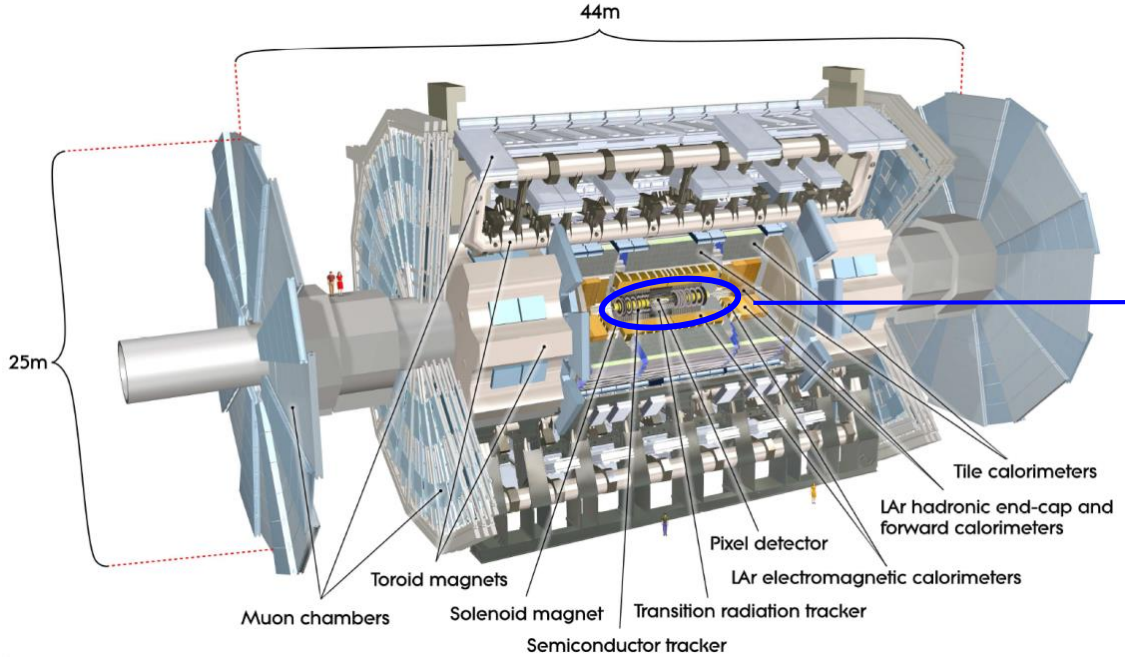
Higher data rate

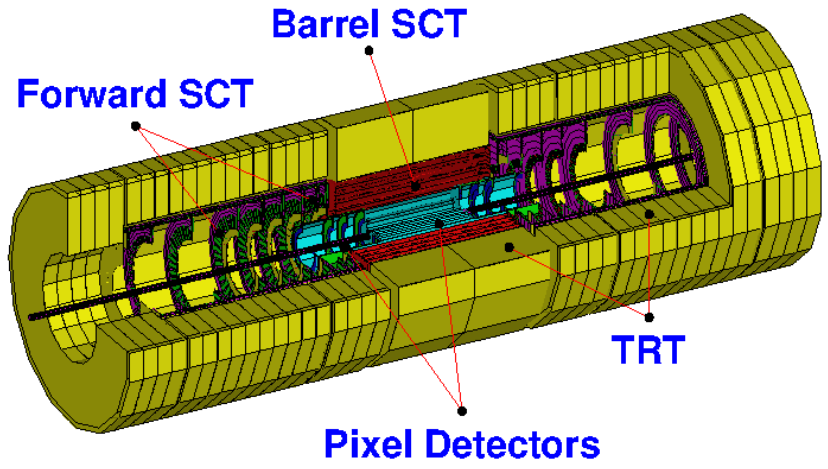
Increased detector occupancy

Increased radiation environment

The new silicon tracker

Replacing the old Inner Detector by a new all-silicon Inner Tracker (ITk)





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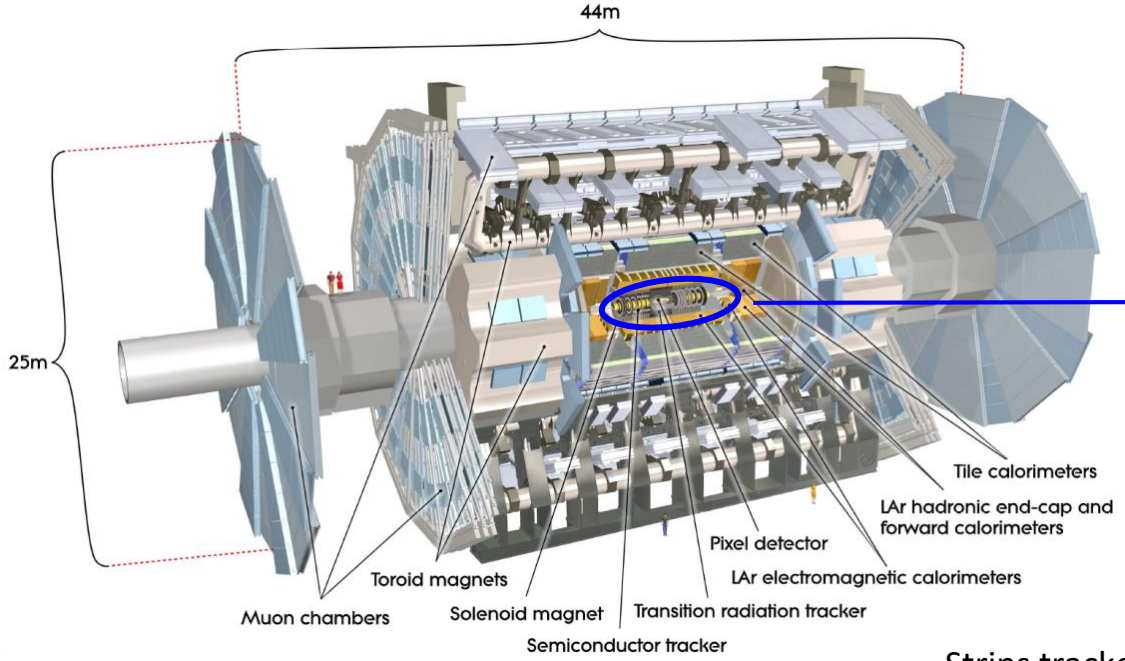
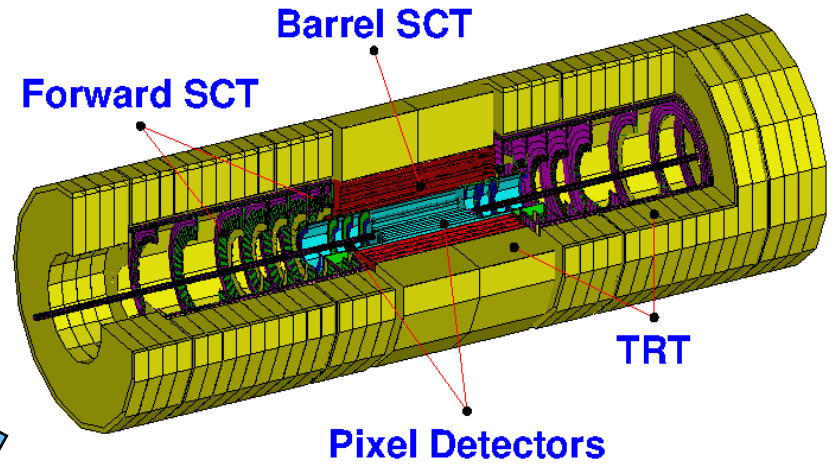
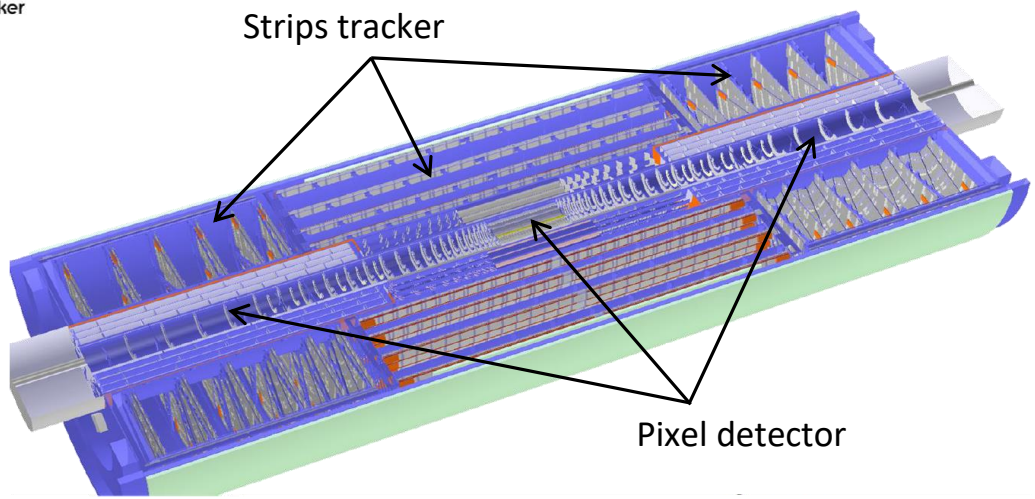






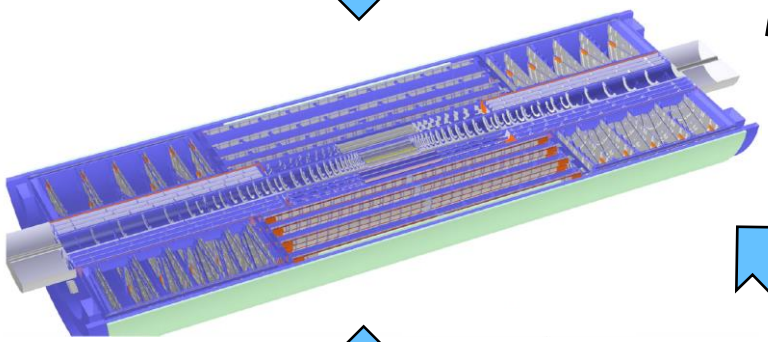
Goals and challenges of the ITk

Layout goal: Maintain or improve resolution and particle identification performance of current ID

High speed

Radiation tolerant

High granularity



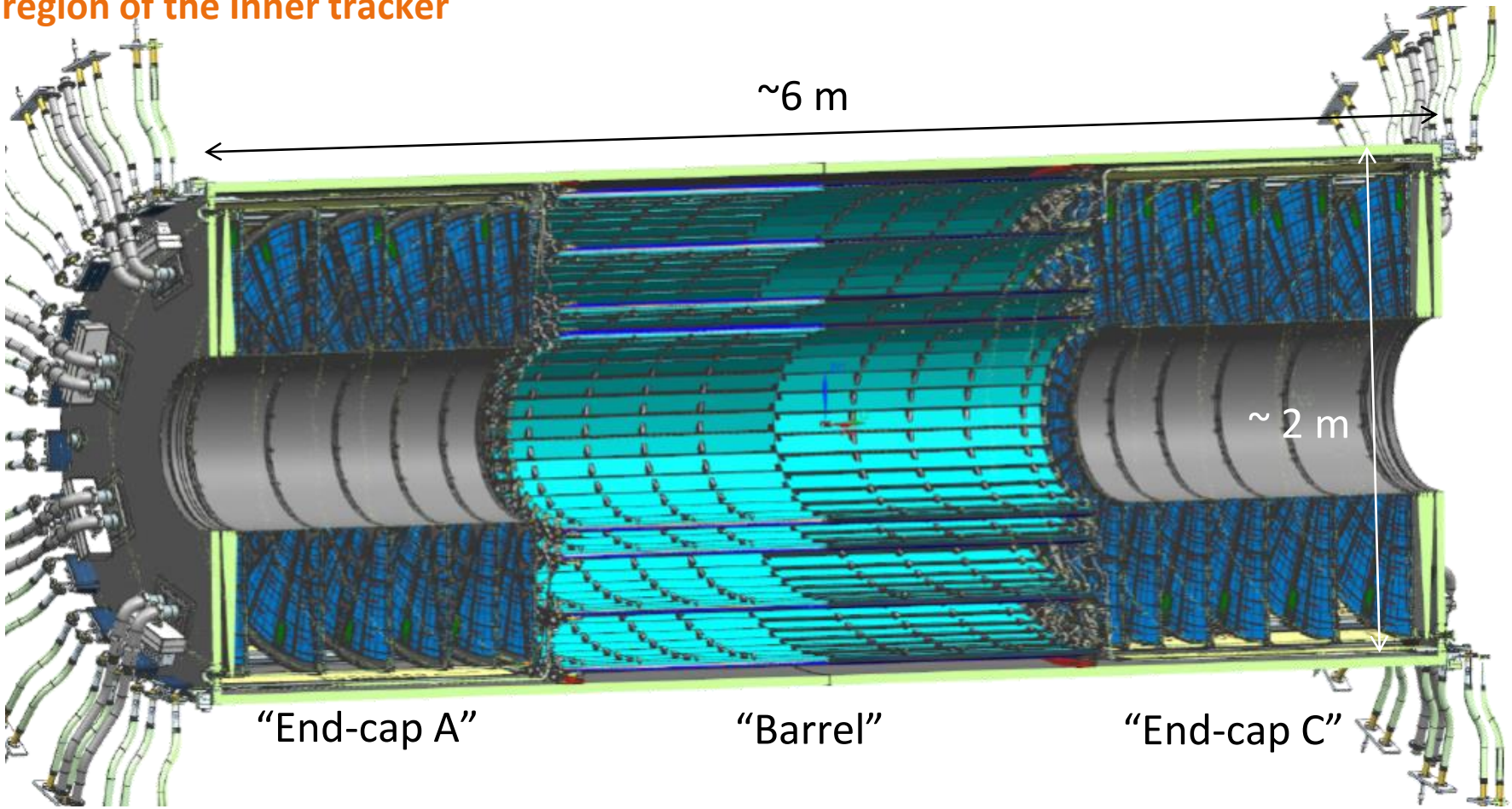
Low cost

Low mass

Low power

The strips tracker

The outermost region of the Inner tracker

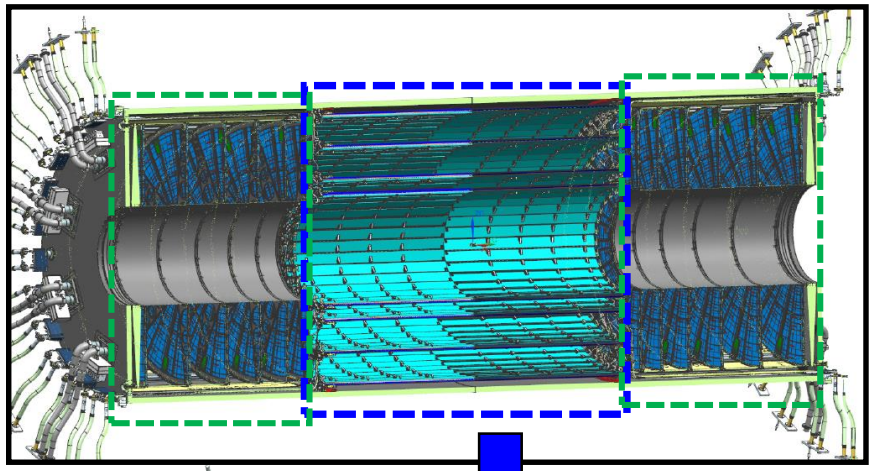


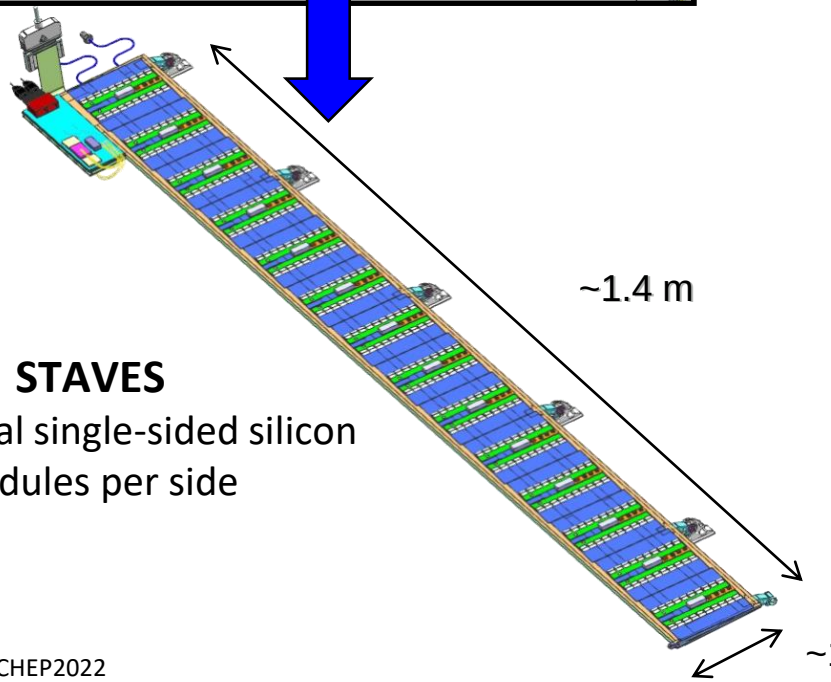
4 barrel cylinders, 6 EC disks per side

180 m^2 of silicon, 15584 silicon “modules”, 60 M channels

The strips tracker

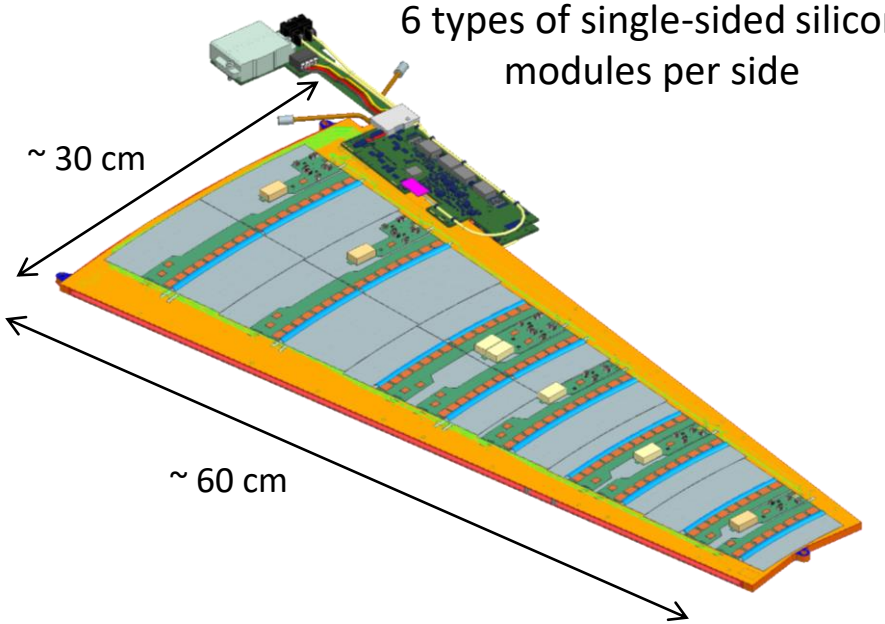
“Stave” and “petal” concept





STAVES
14 identical single-sided silicon modules per side

PETALS
6 types of single-sided silicon modules per side

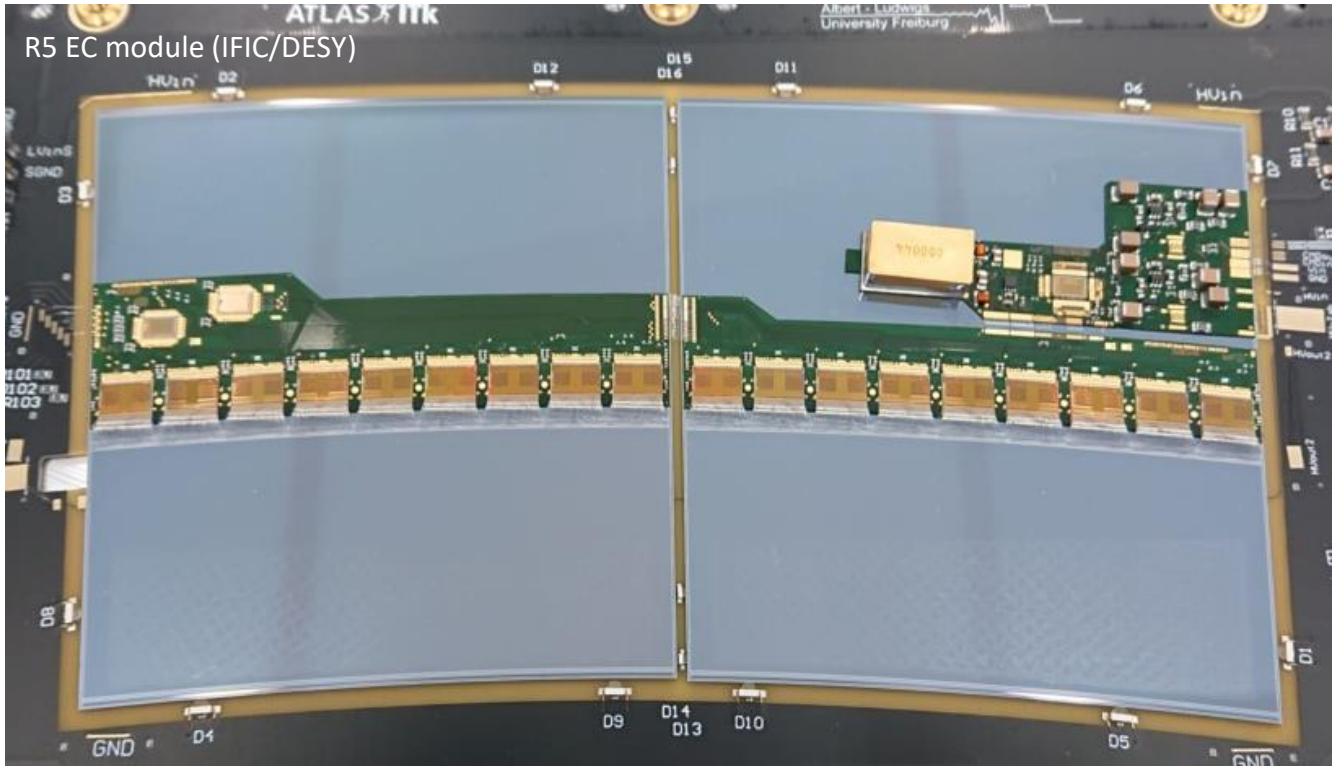


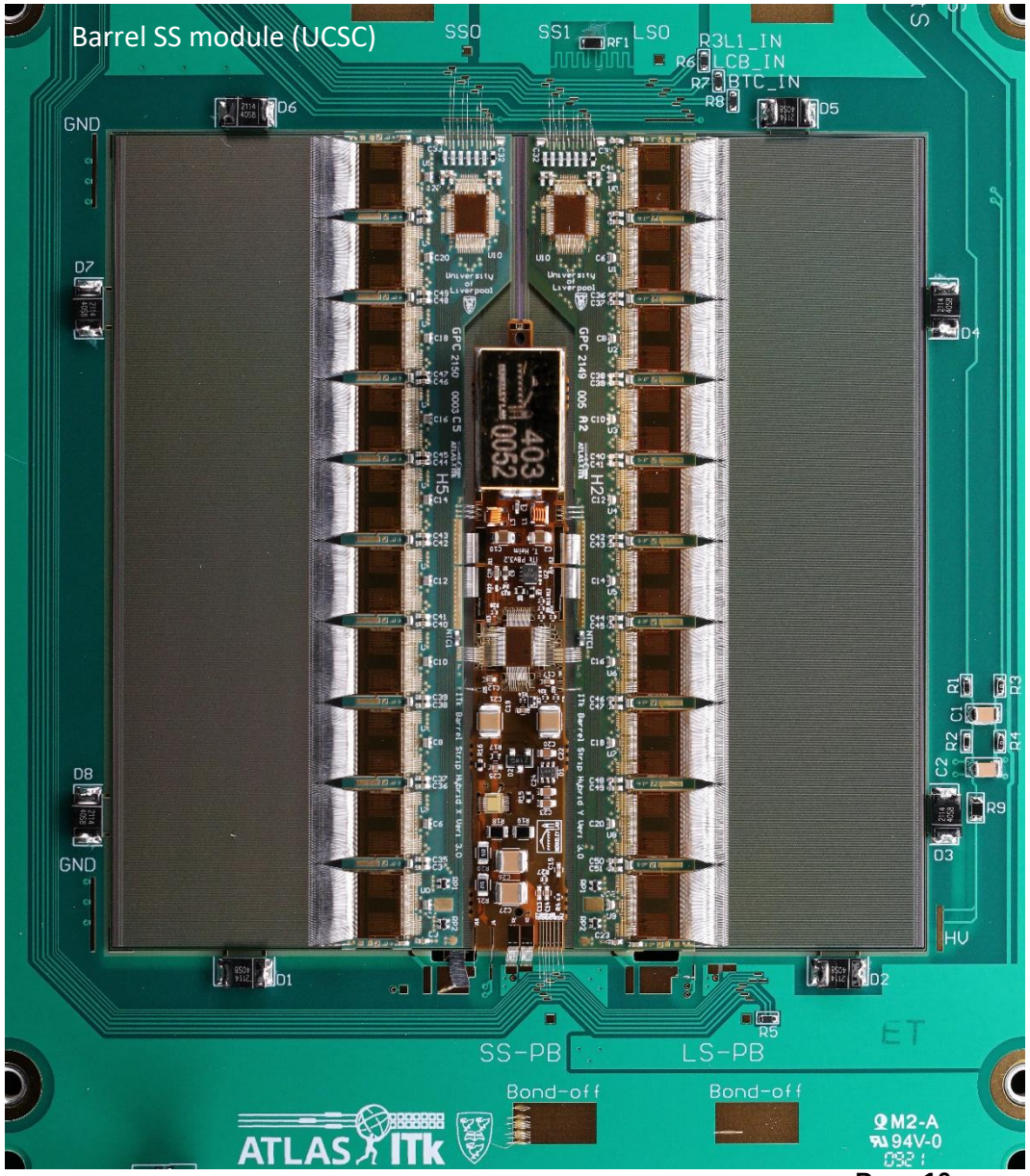
Carbon fiber “sandwich” structures supporting multiple strip silicon modules inside the tracker

Modules are directly glued onto the structures

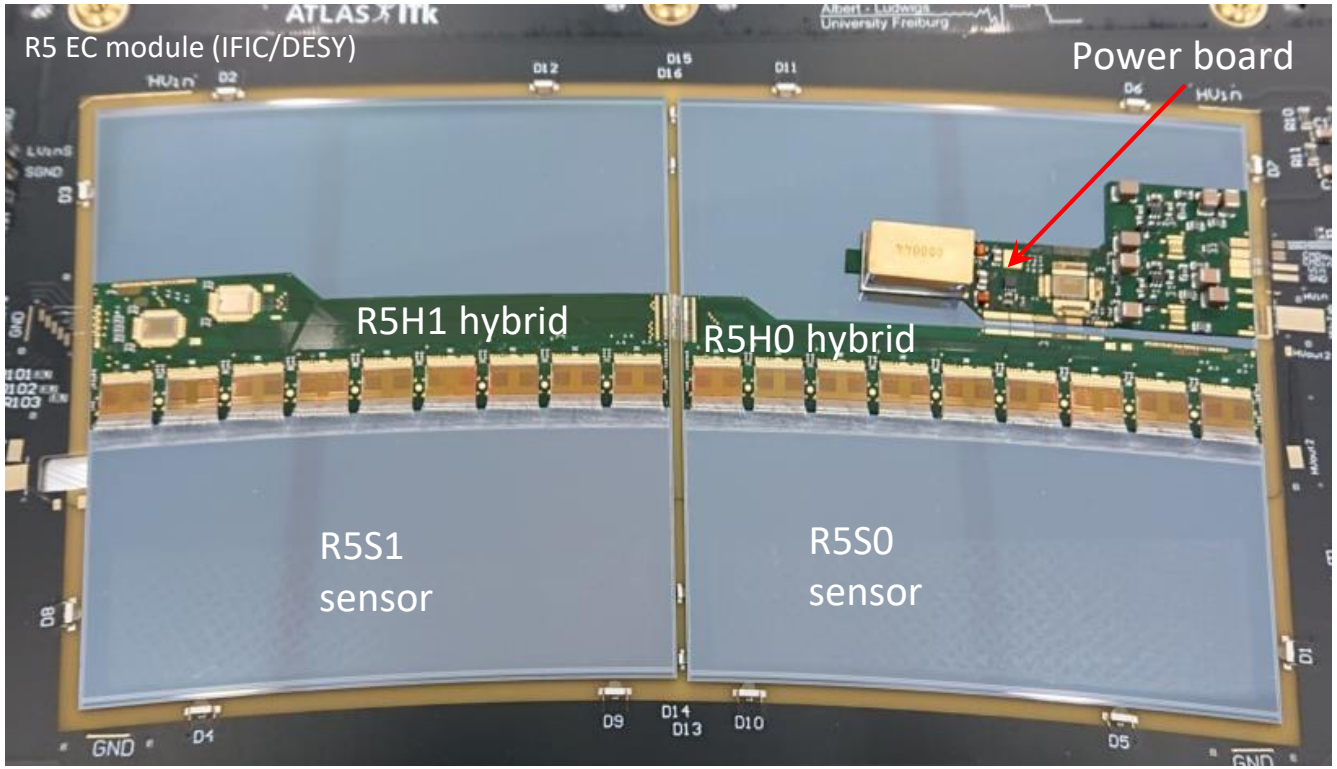
Single power/data cable per stave/petal side

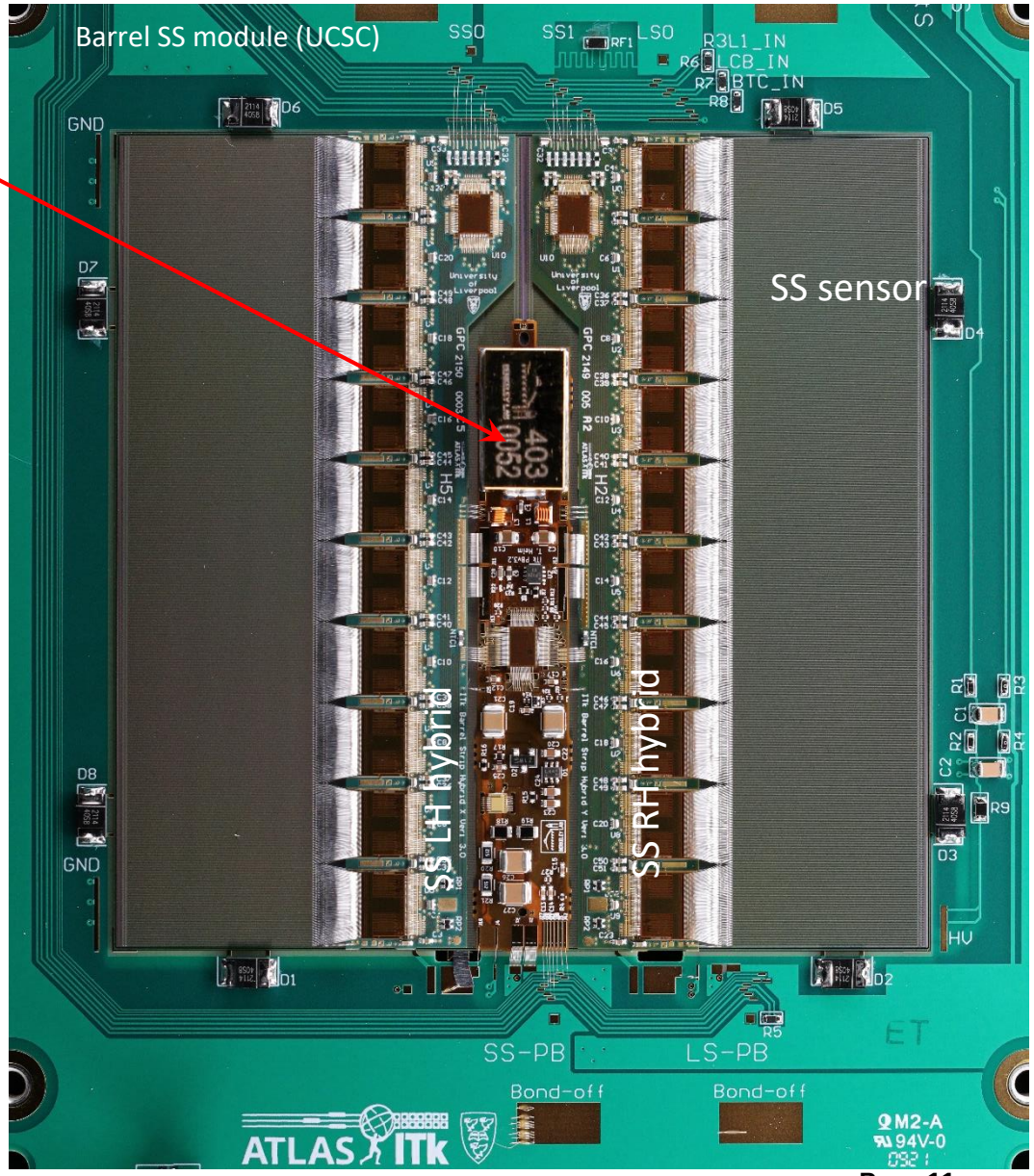
The strips modules





The strips modules





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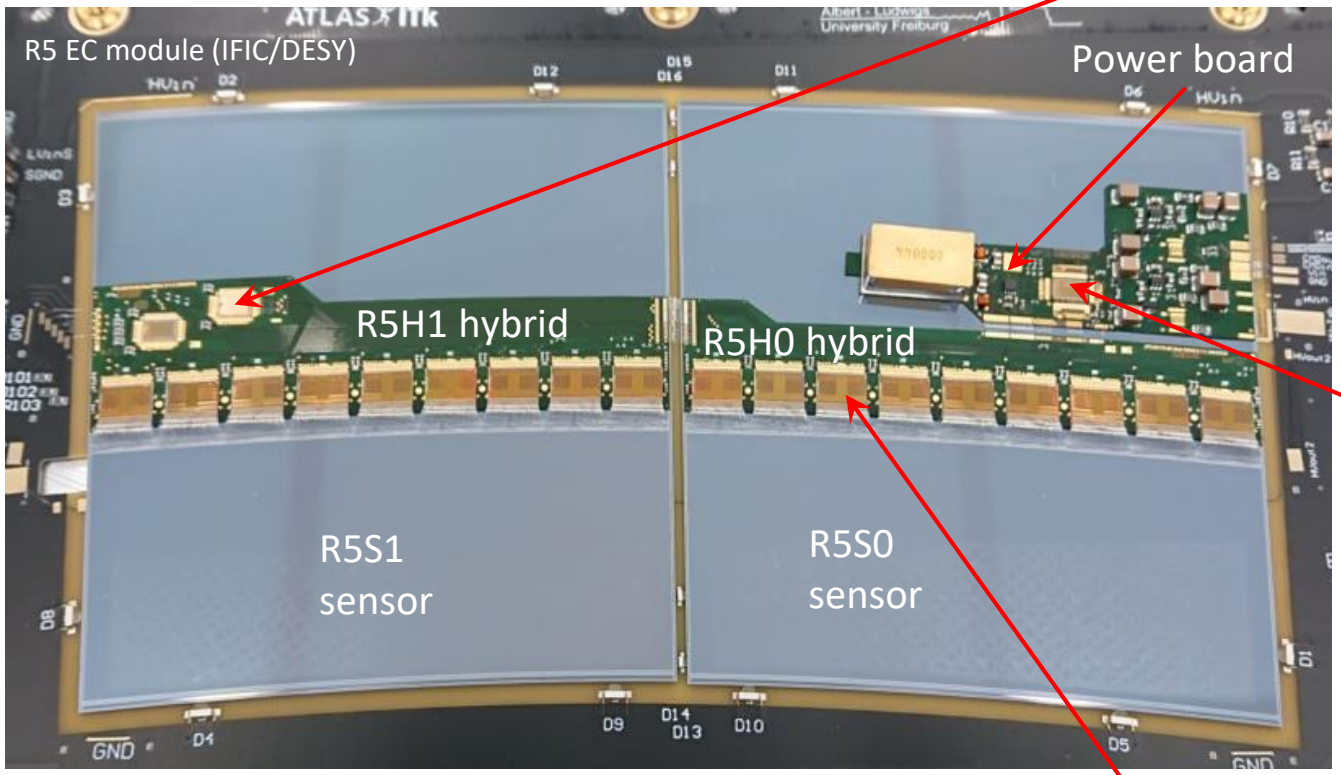
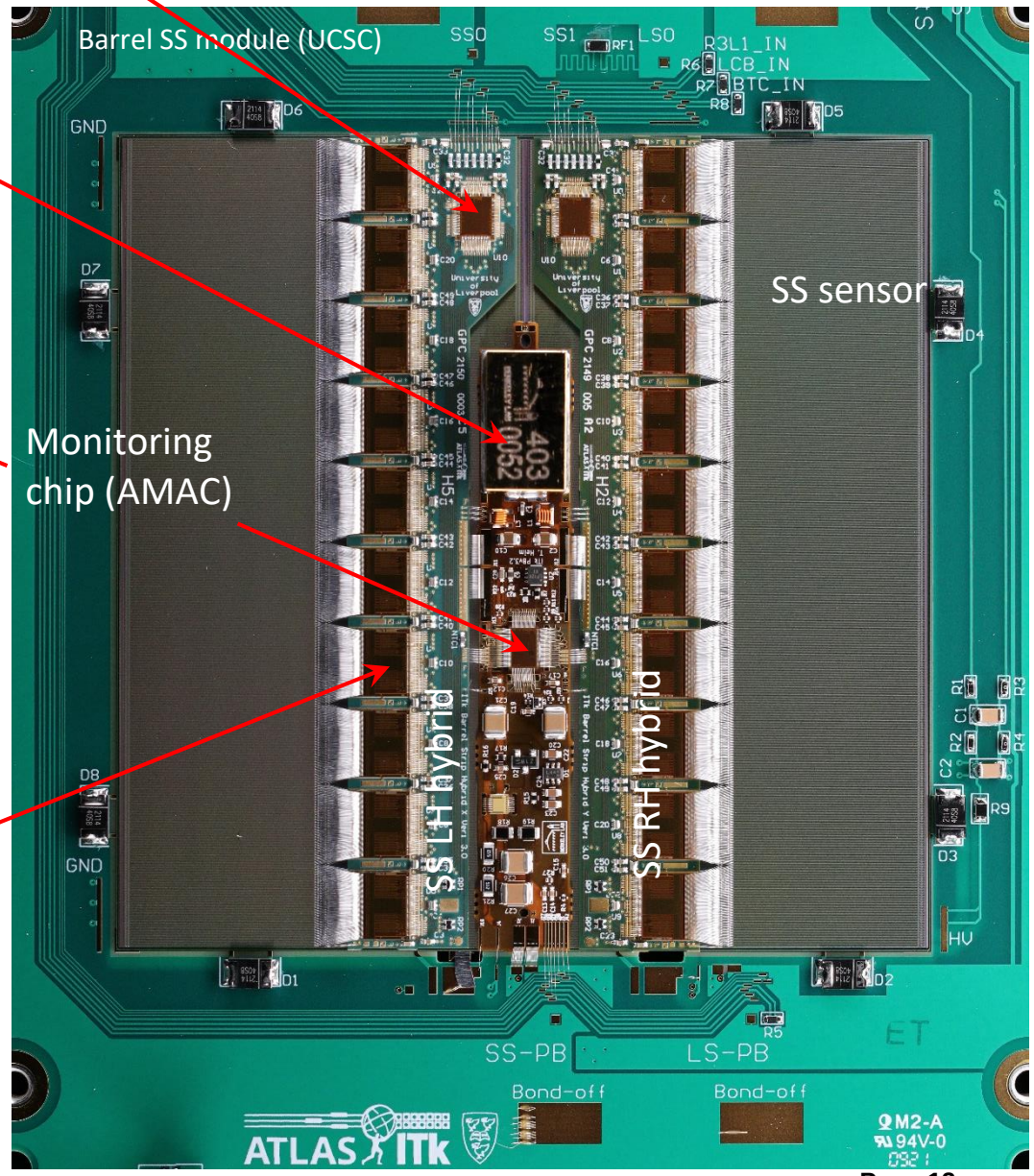


Hybrid controller chips (HCCs)

Front-End chips (ABCStar)



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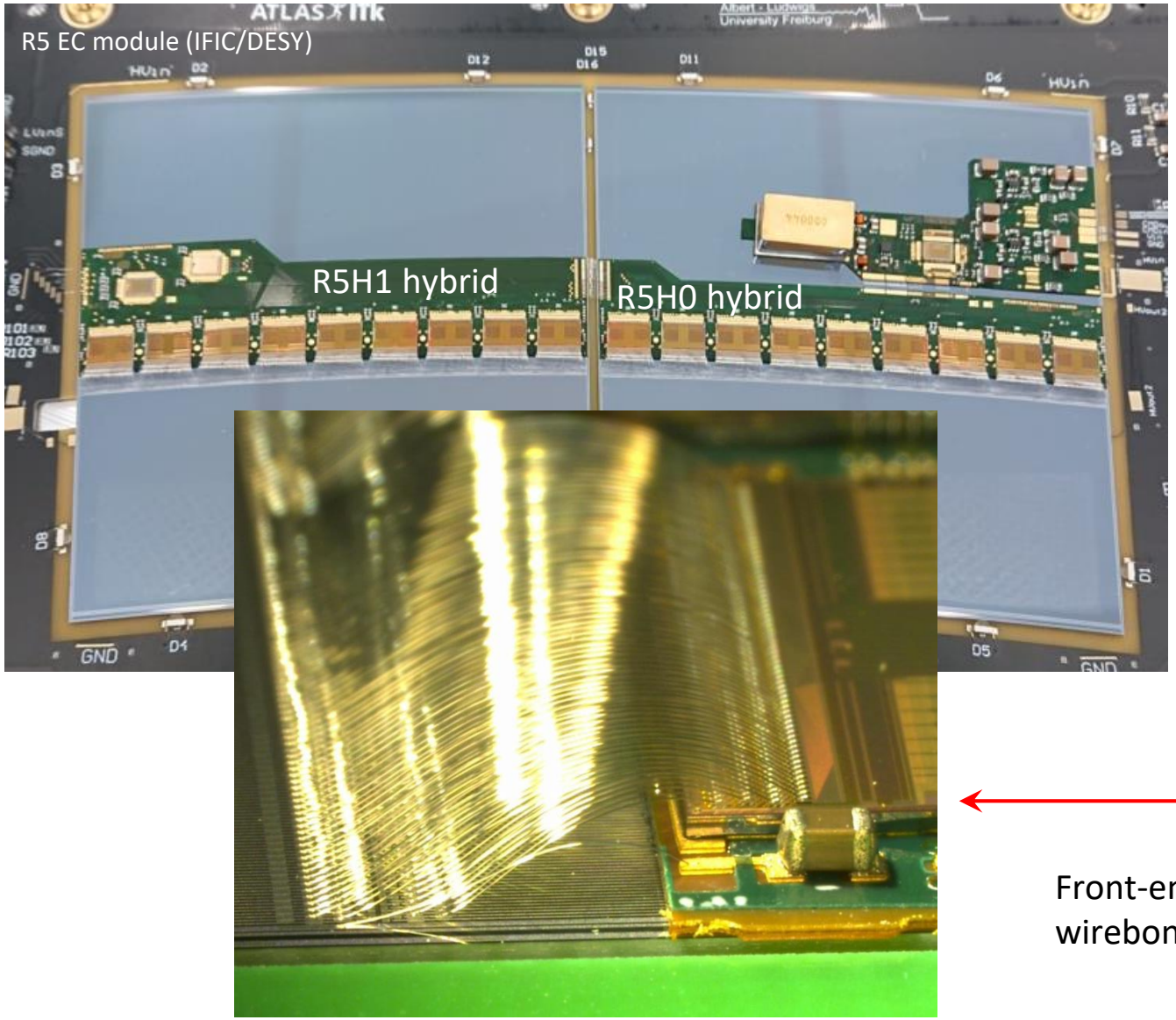
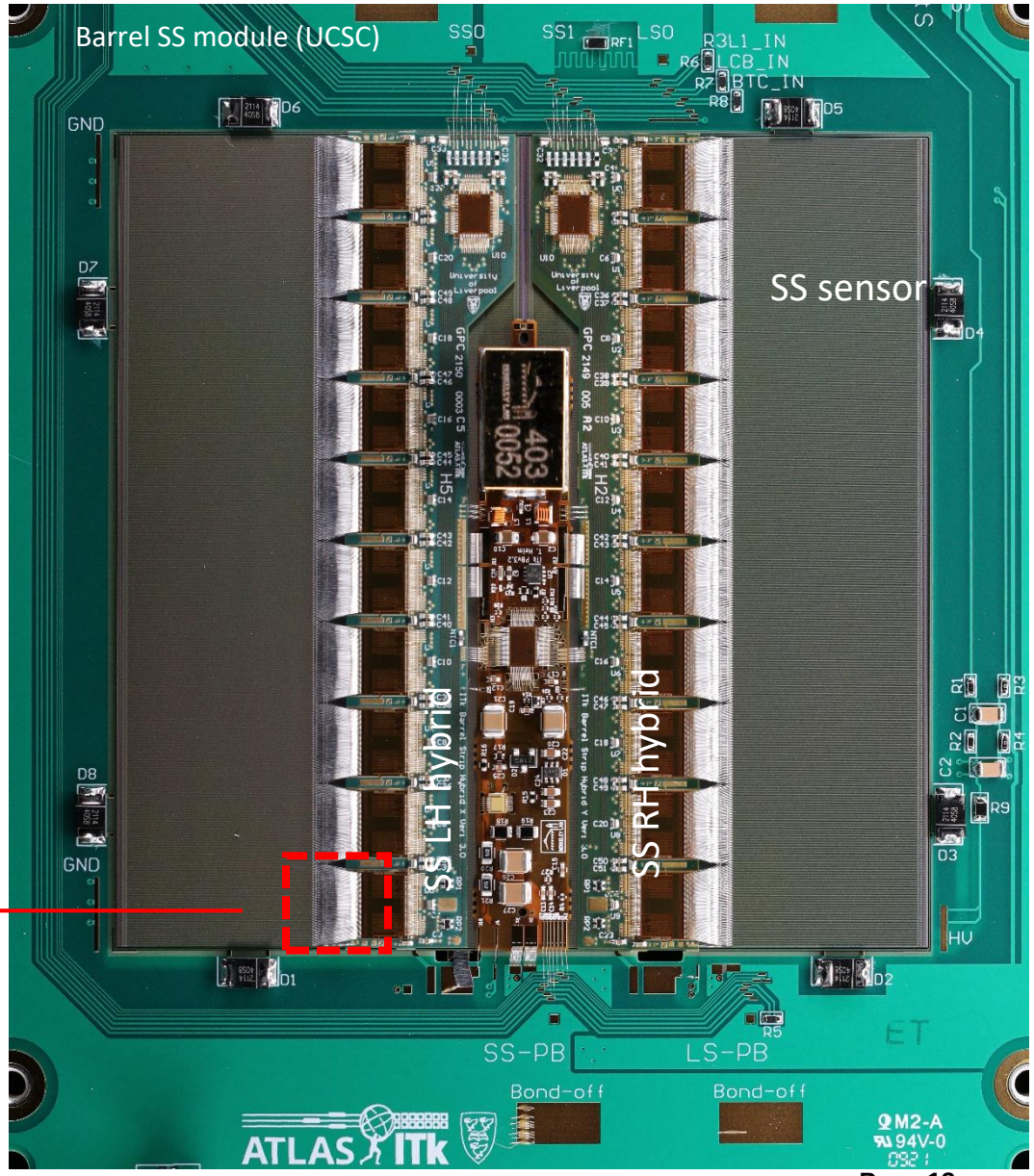


Front-end wirebonds



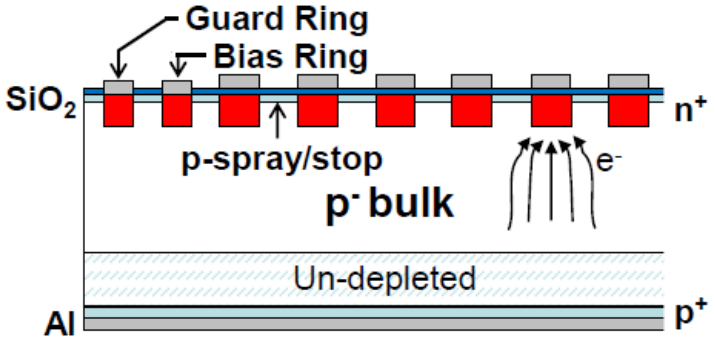
ITk Si microstrip sensors

n+ strips in p-type FZ substrate ("n-in-p")

Faster and more rad-hard than p-in-n

Good signal even under-depleted

Well established technology (HPK)



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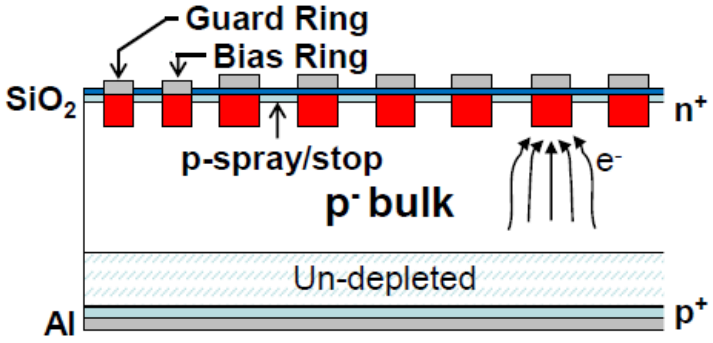
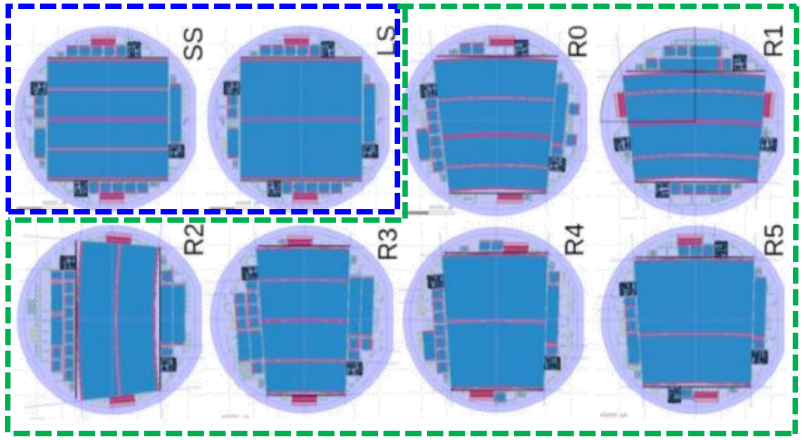
- 6" wafer technology (~10x10 cm²)
- Spatial resolution ~ 20 µm (75µm pitch)
- Time resolution ~ 3 ns



2 barrel flavors: SS (4x~2.5 cm), LS (2x~5 cm)



6 endcap flavors: R0 to R5

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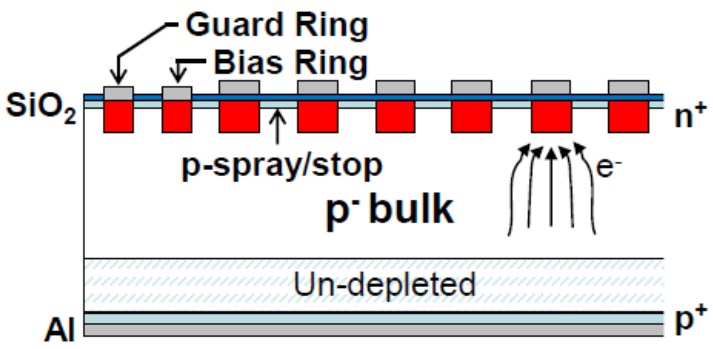
Time resolution ~ 3 ns

Radiation hardness well understood over the years

Sensors meet specifications after irradiations



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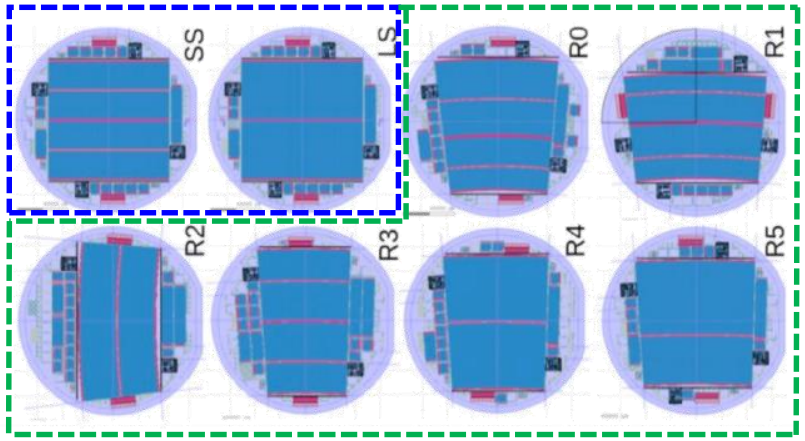

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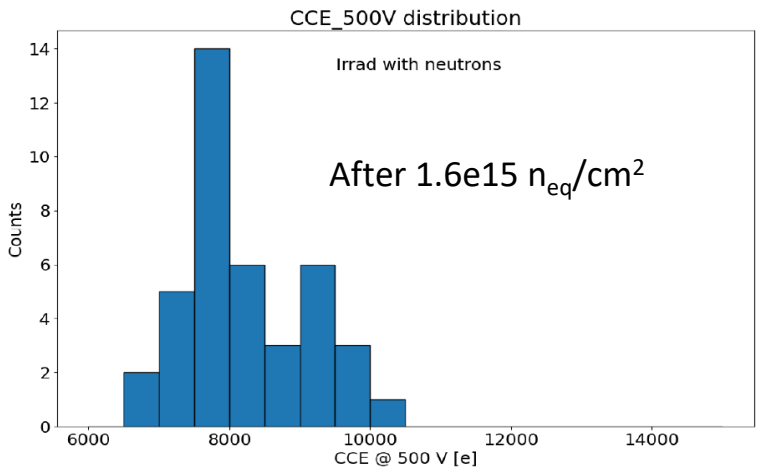


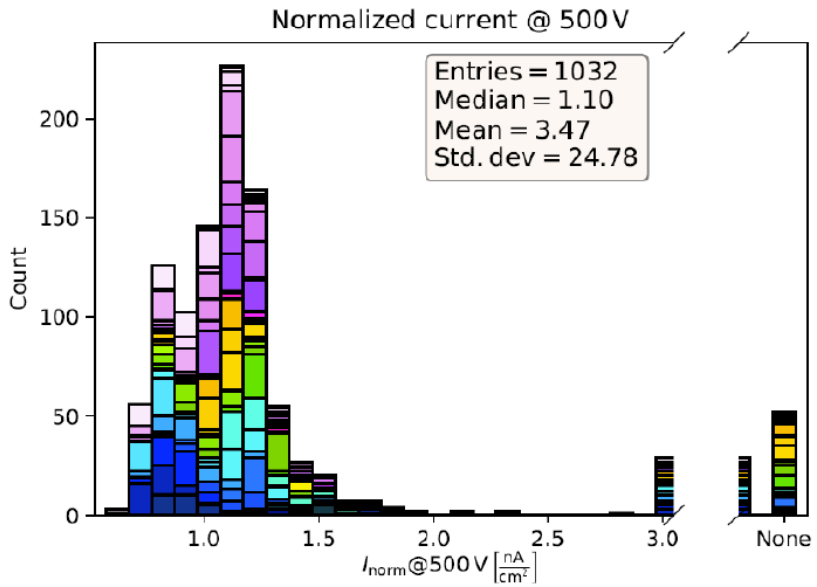
Sensor production

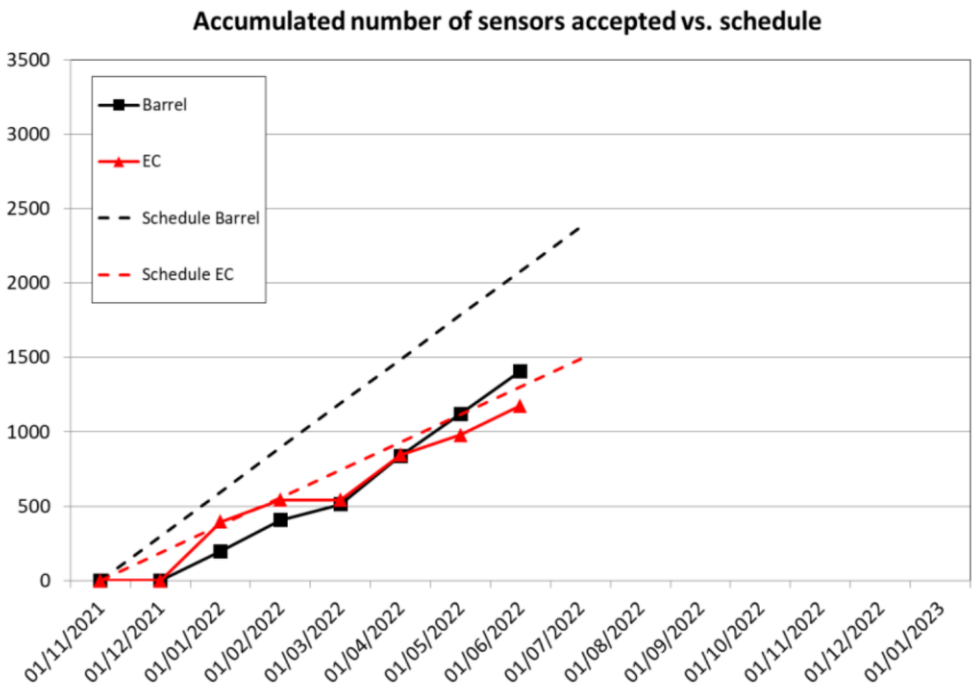
Sensor is in the middle of production phase

Initial slow ramp-up expected, also due to pandemic

13% sensors “ready for modules”, typical rejection rates ~ 3-4%

Significant acceptance tests and QC/QA effort, building up statistics





Readout and control electronics

A single chipset for all module flavors

130 nm CMOS (Global Foundries)

Old, but consolidated technology node

Cost-effective

Technology continuity guaranteed

ABCStar	HCCStar	AMAC
Front-end chip **Binary** readout	On-hybrid digital interface chip	On-module monitoring and control chip

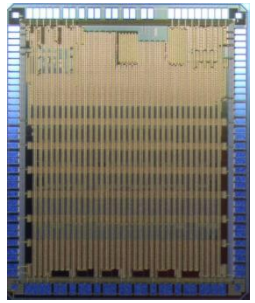
Radiation-hard by design:

Enclosed layout transistor geometry to mitigate total dose effects

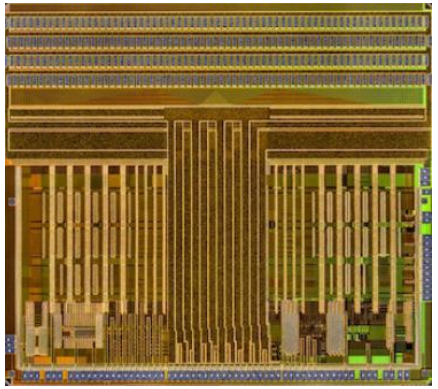
Triplication logic to mitigate Single Event Upsets (SEUs)
→ "Majority wins"

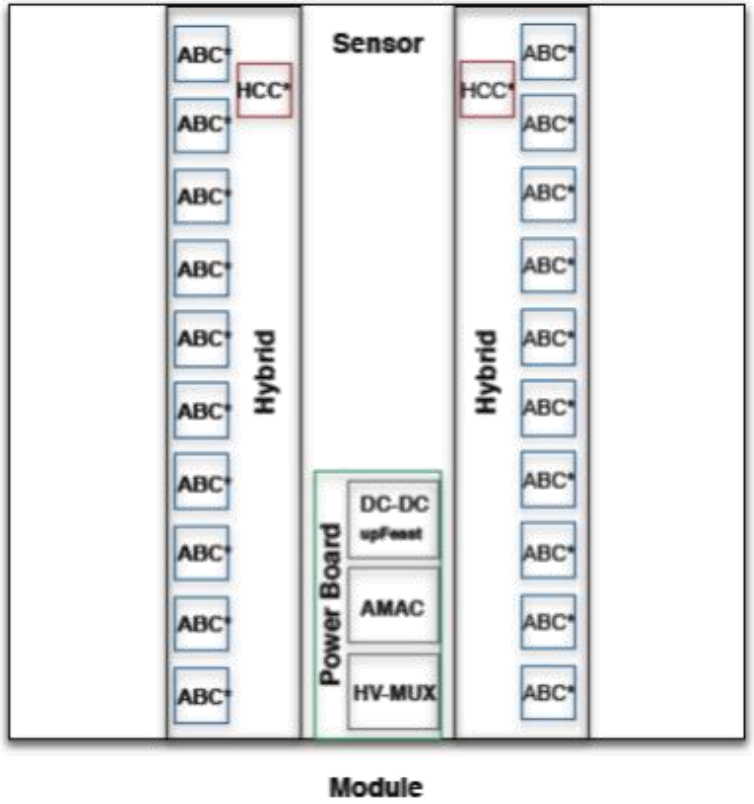
AMACStar

HCCStar



ABCStar





ASIC production

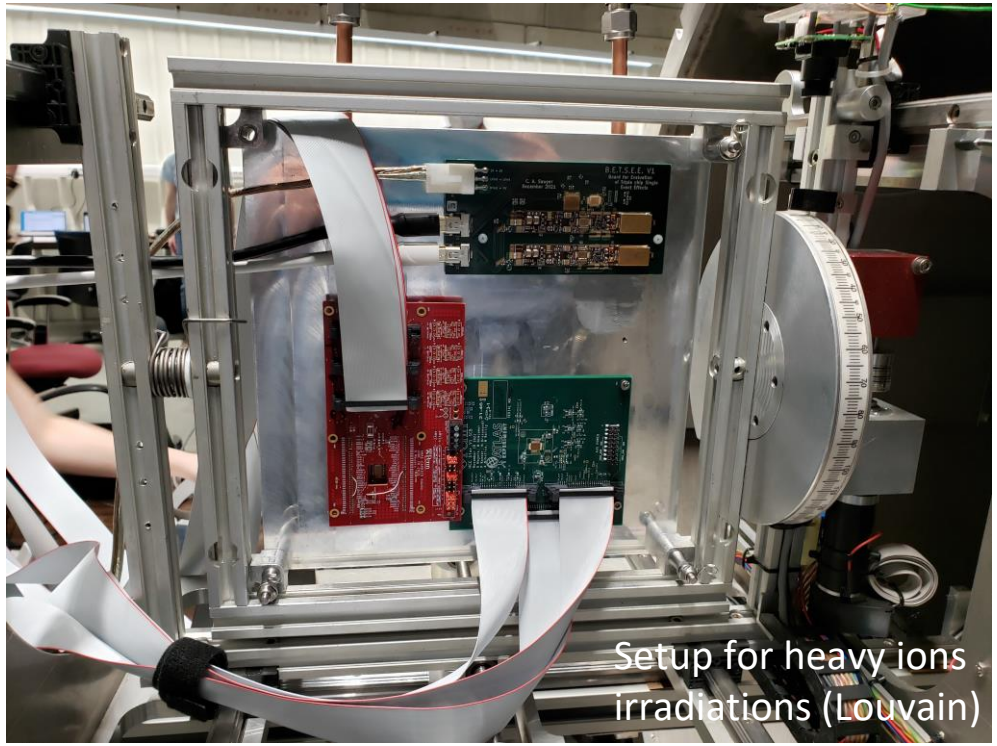
ABCStar in production, HCCStar and AMAC about to start

1/3 of ABCStar wafers delivered

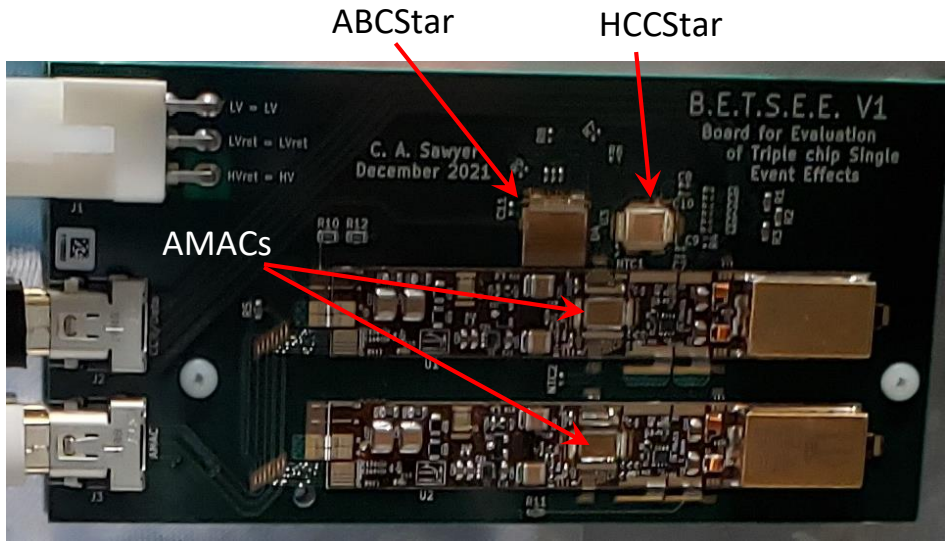
HCCStar and AMAC pre-production finalized

Ambitious acceptance and QA/QC program in place, including wafer probing, dicing, pre-irradiation of ASICs, and extensive SEE testing

	Barrel	Endcap	PP2	Total chips needed	Wafers needed
Pre-Production					
ABCStar	10,159	6,248	0	**16,407**	**35**
HCCStar	1,016	783	0	**1,799**	**4**
AMAC	672	392	265	**1,329**	**3**
Production					
ABCStar	196,282	117,608	0	**313,890**	**668**
HCCStar	19,629	14,713	0	**34.342**	**62**
AMAC	14,447	7,357	2,218	**24,022**	**50**



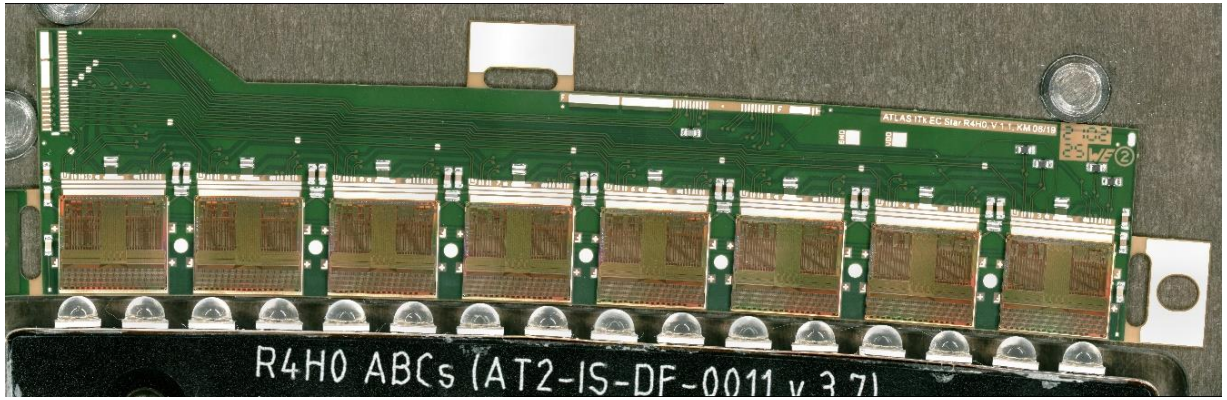
Setup for heavy ions irradiations (Louvain)

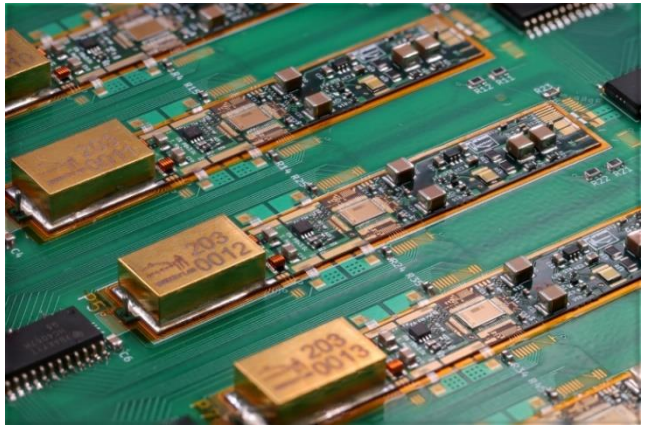


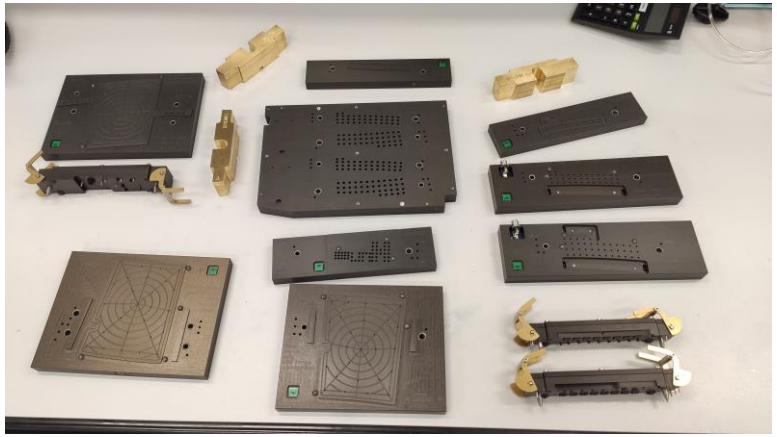
BETSEE board

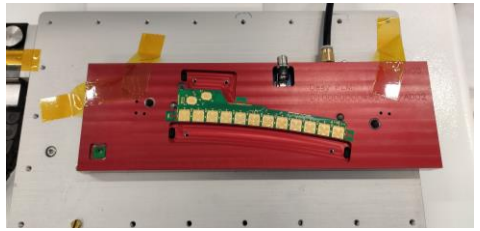
Module building

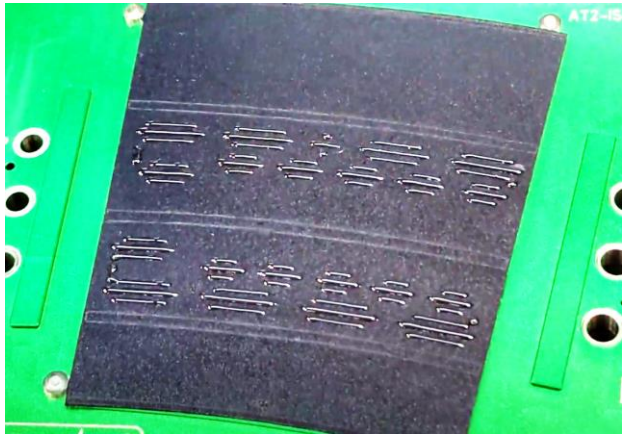
Putting everything together









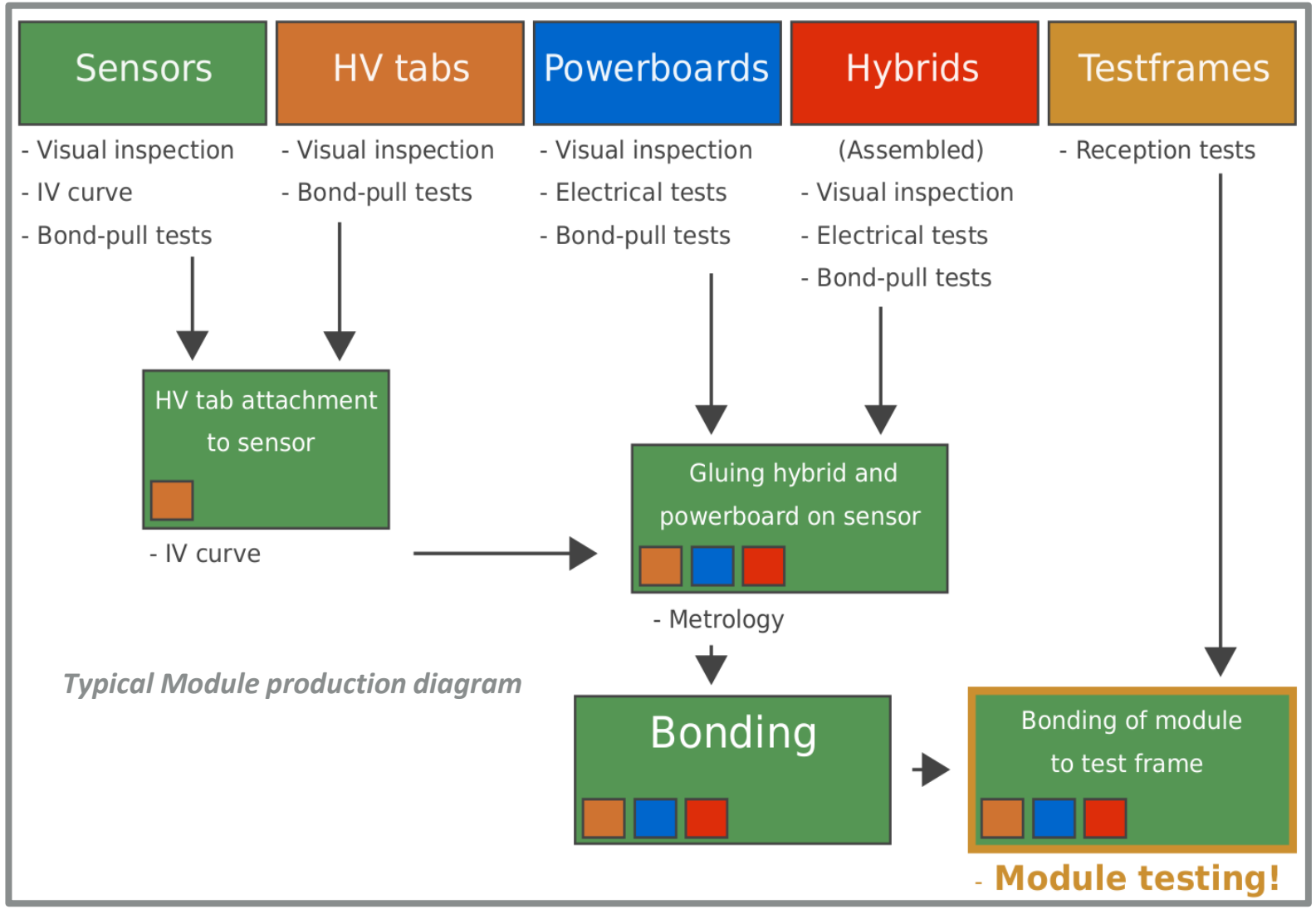


Dedicated effort on panelized production, harmonized tooling and procedures to avoid learning curves for different module types

Automation of glue dispensing to maximize reproducibility

Module building

An “industrial” production



Typical Module production diagram

~ 25 module building sites distributed in 6 clusters and 4 continents

- **Reception tests of components**
- **Assembly**
- **Functionality tests**
- **Quality control (QC) and quality assurance (QA)**

→ each is a small production line!

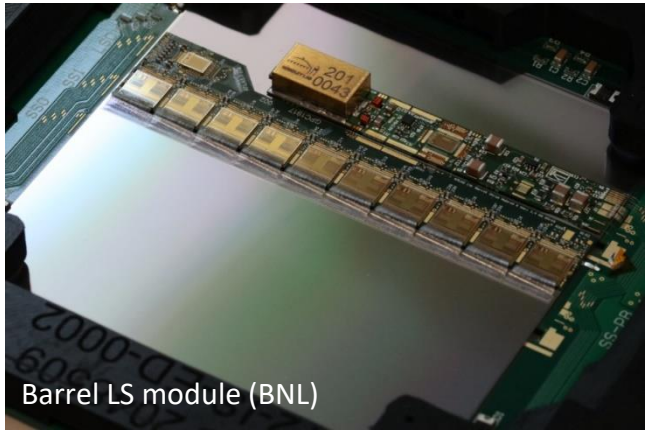
Module production

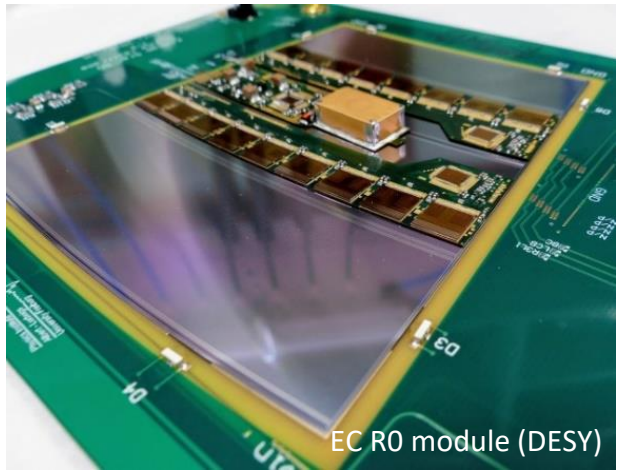
Module effort in pre-production phase

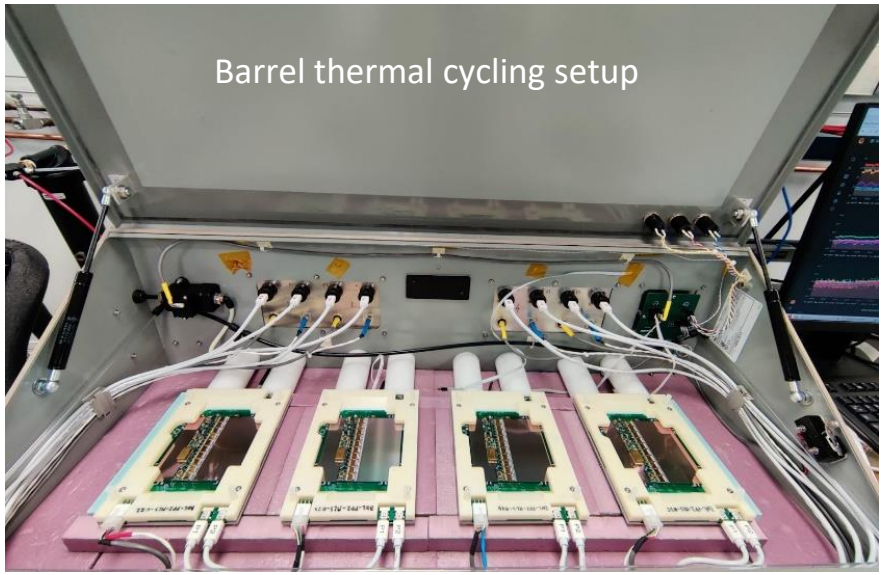
First pre-production B items ("final" chipset and flexes) showing up

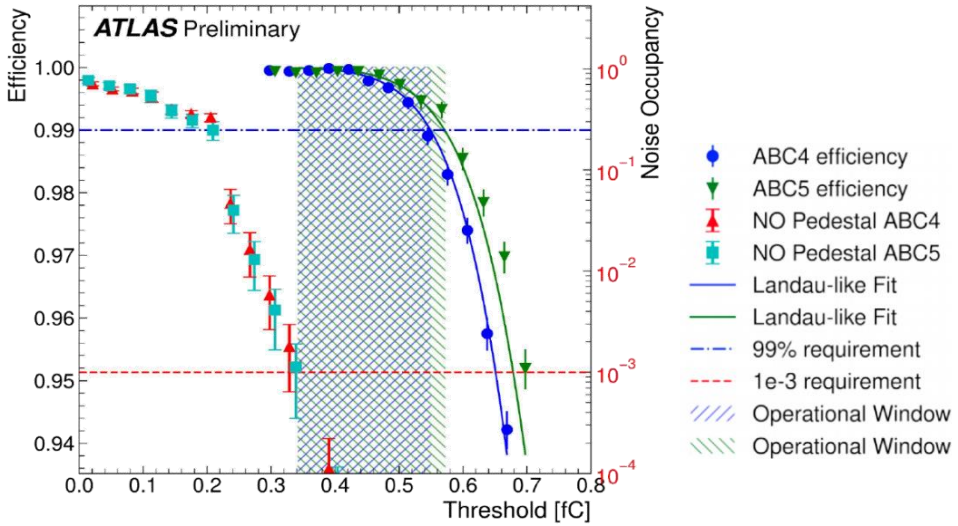
Extensive site qualification process across all sites

QC and QA program: metrology, electrical performance, thermal cycling, test beam experiments,…


Barrel LS module (BNL)


EC R0 module (DESY)


Barrel thermal cycling setup



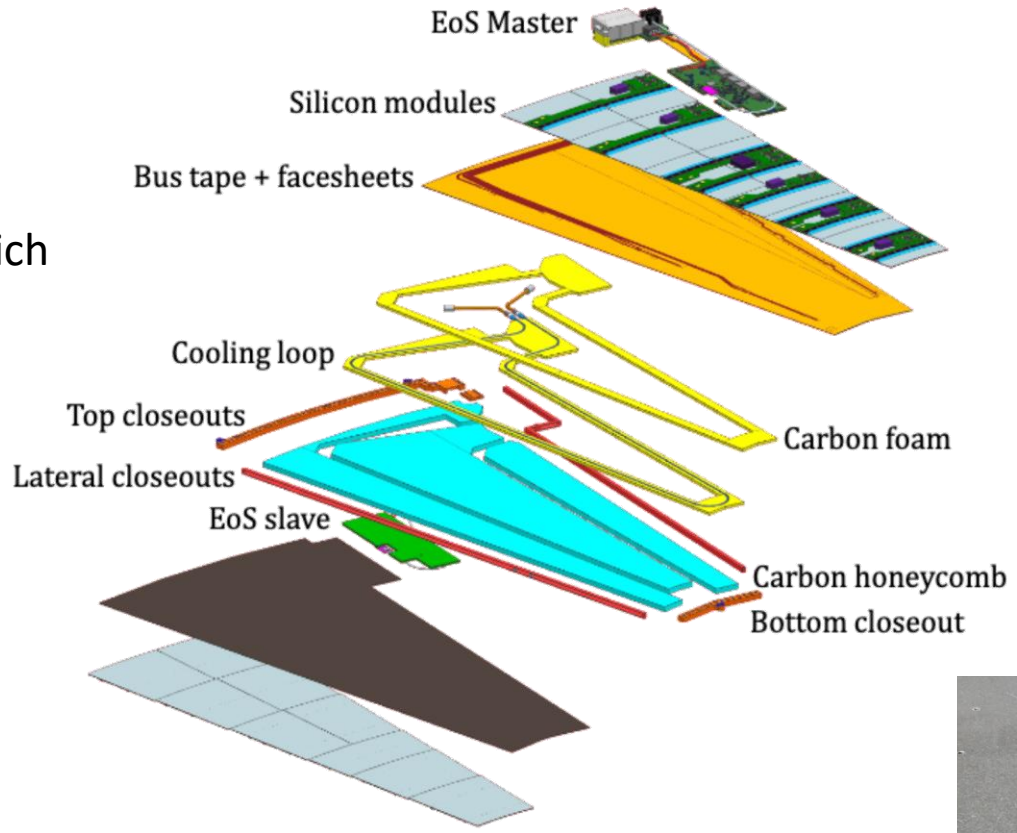
Barrel SS module eff/NO curve

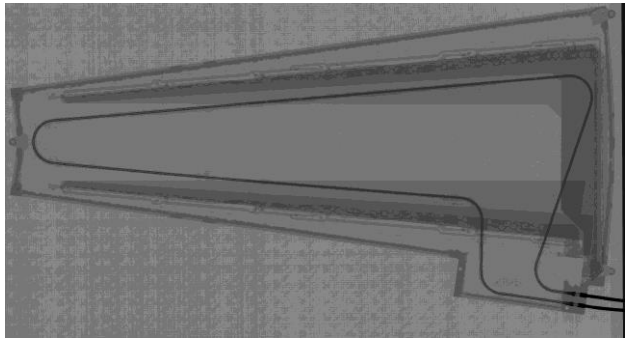
Low mass support structures

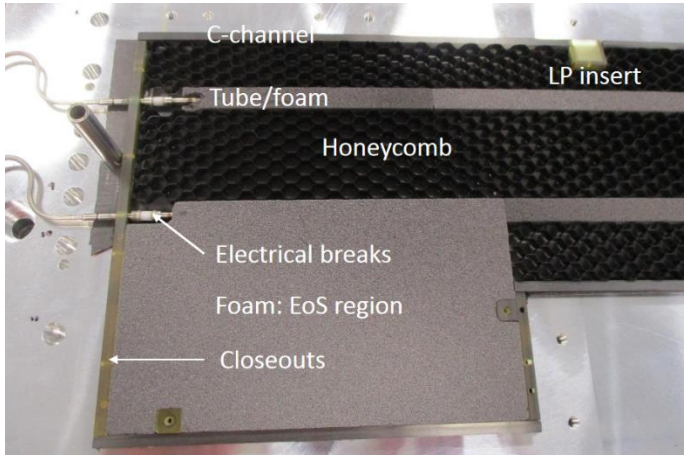
Minimize material, optimize performance

Stave and Petal "cores": carbon fiber-based sandwich structures with embedded cooling

- ✓ Rigidity and stability
- ✓ Mechanical precision
- ✓ Thermo-electrical performance
- ✓ Low mass

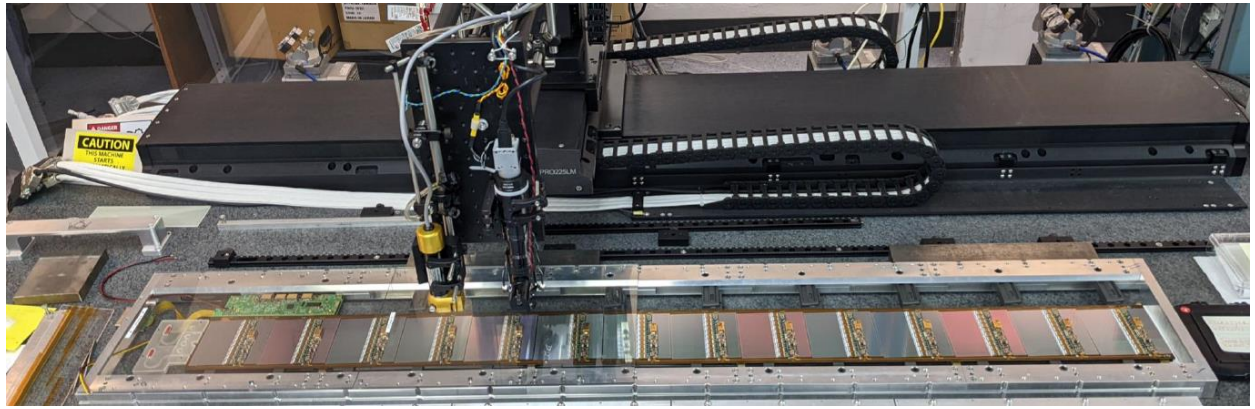


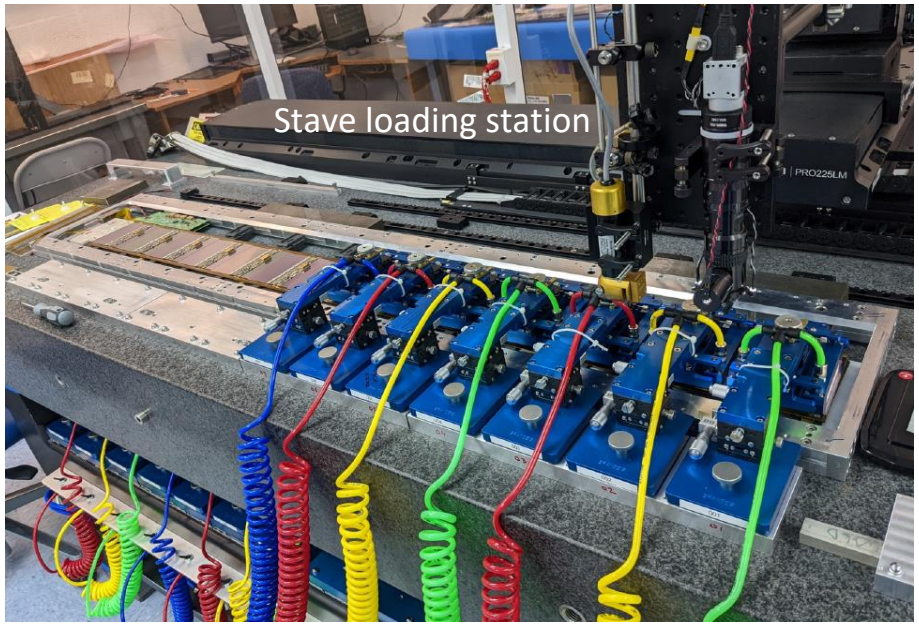


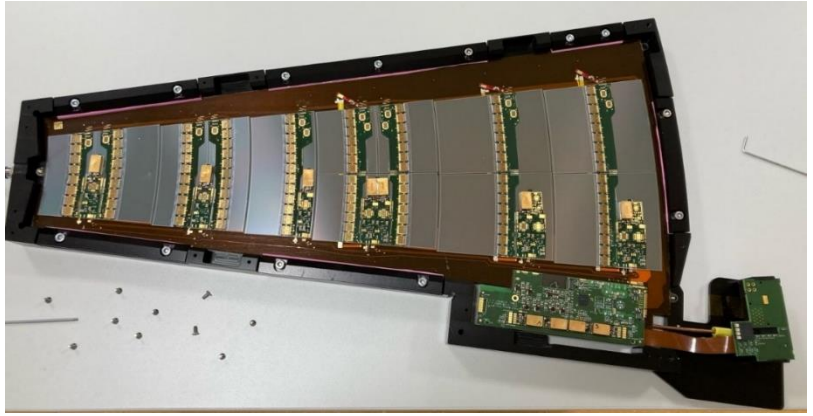


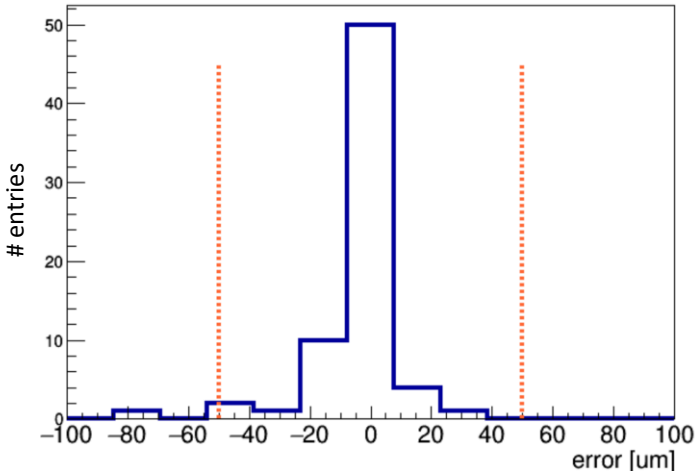
Fully loaded stave and petal structures

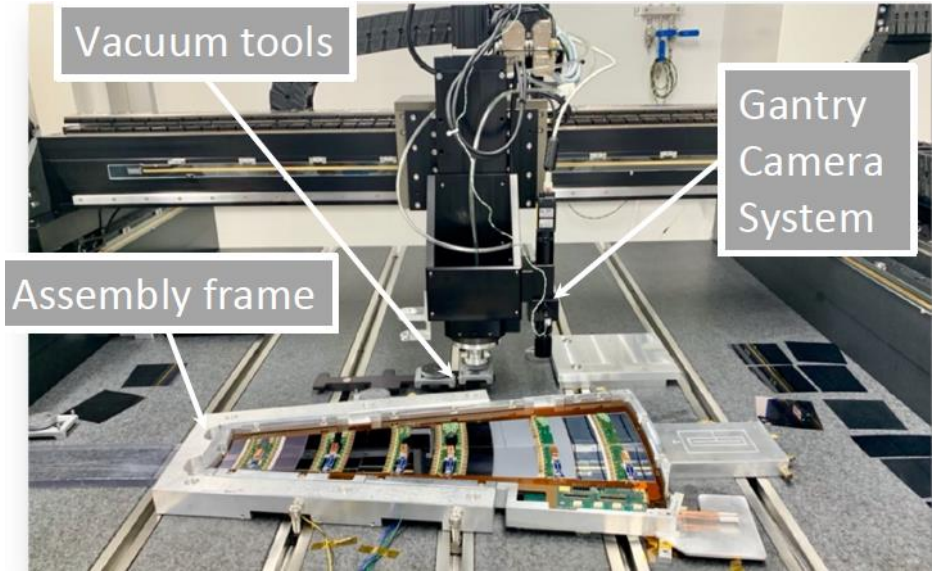
Manual and automated approaches for barrel and endcap







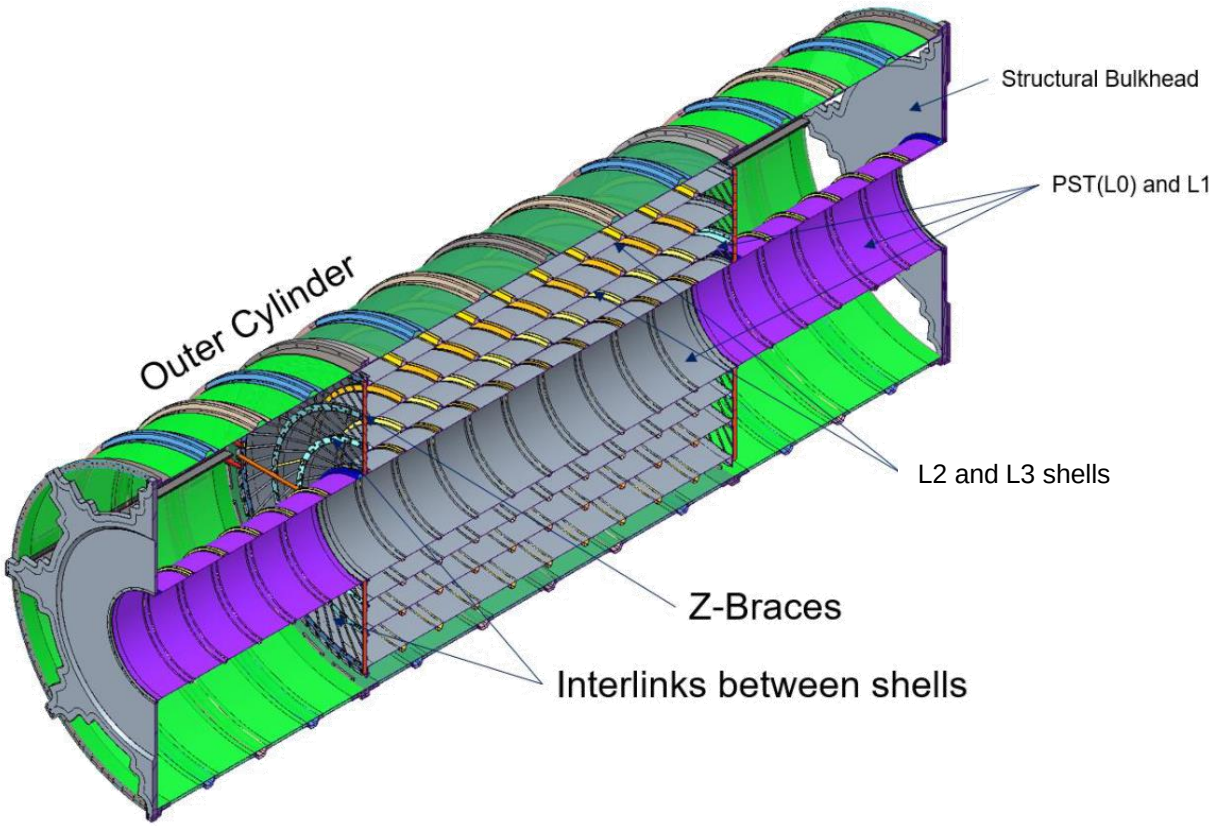


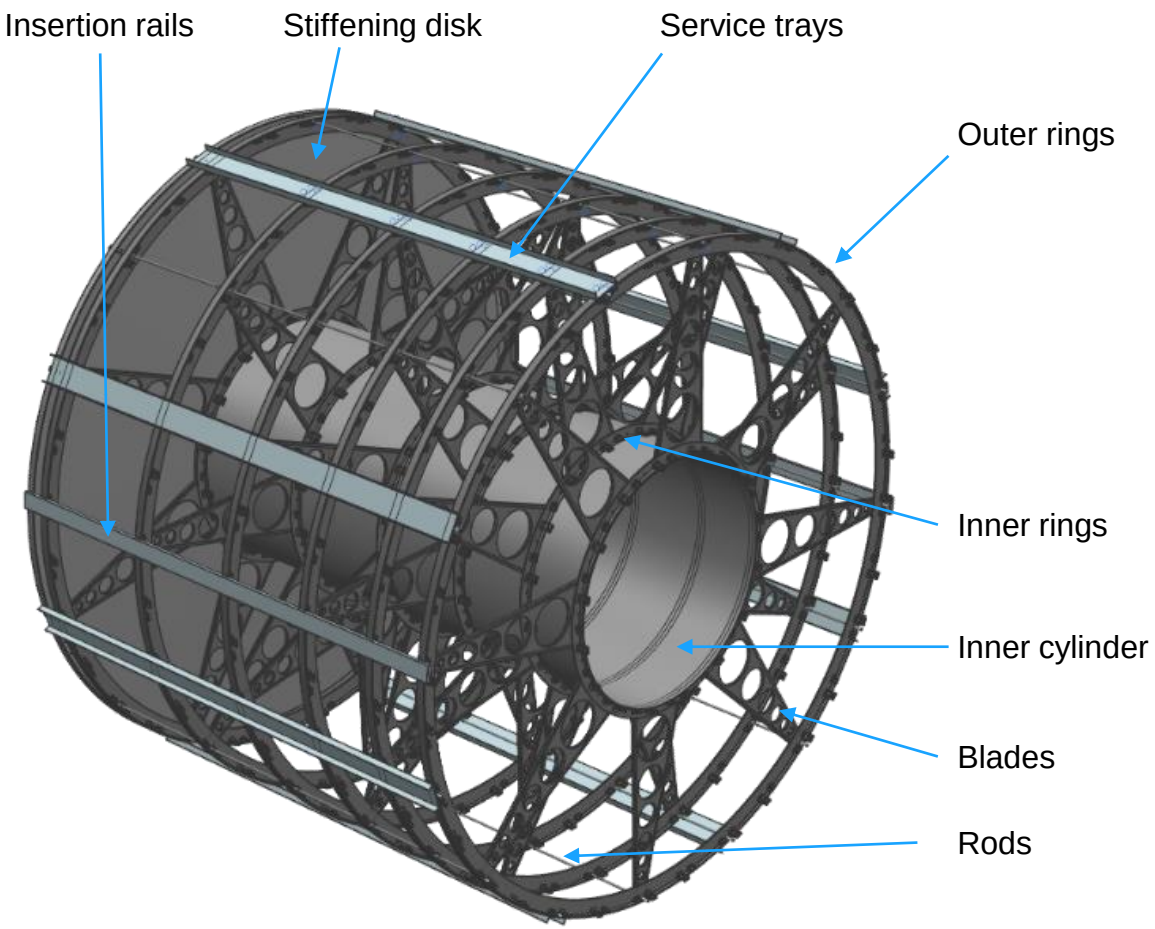


Petal loading gantry

Global structures

A skeleton for the staves and petals





Global structures mostly made out of CFRP or CFRP sandwiches

Modular electrical and cooling services

Low mass, low cost, low power

Where are we?

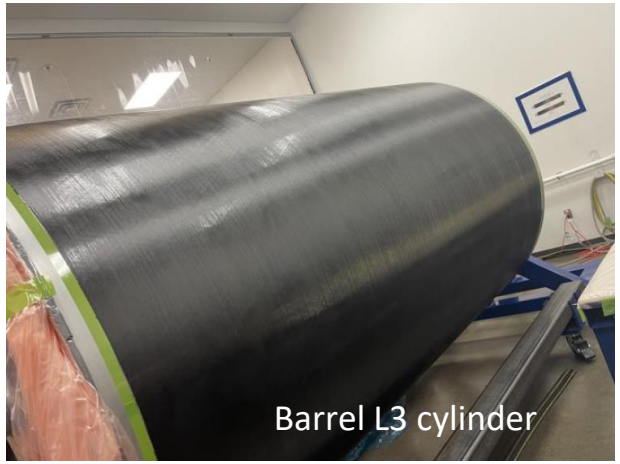
Pre-production is in full swing

Infrastructures and tooling ready

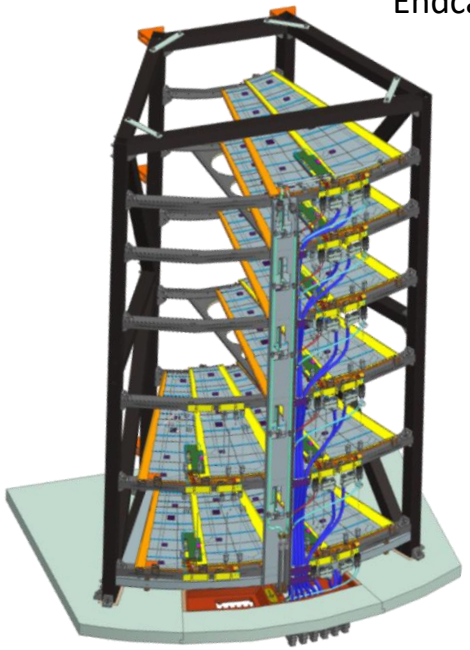
Production processes finishing qualification

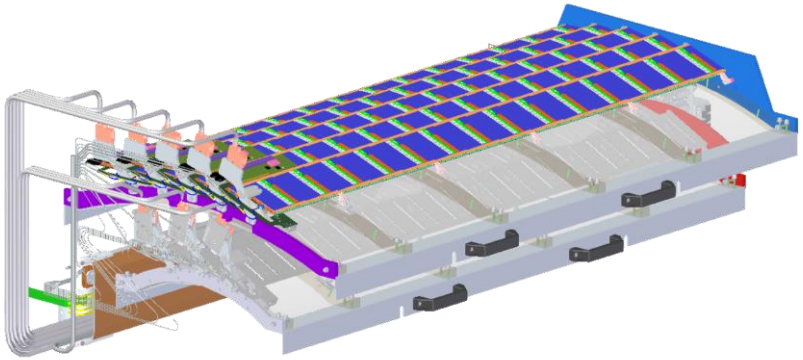
Sensors, ASICs and global structures already in production

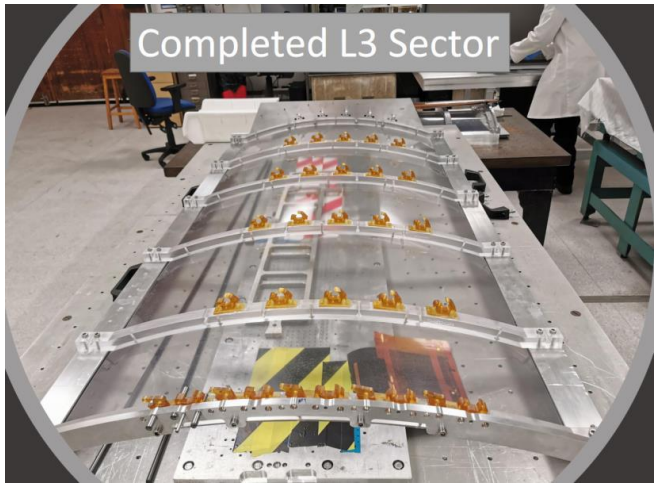
System test structures in construction
→ Realistic test benches for the years to come!



Endcap System Test setup



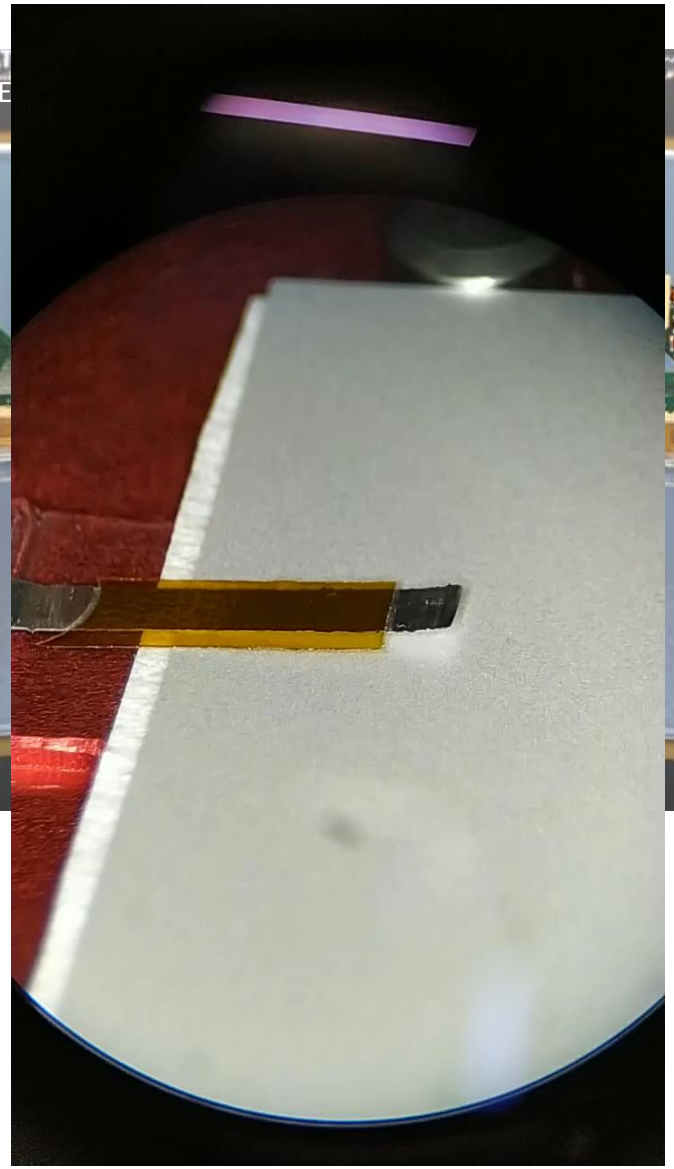




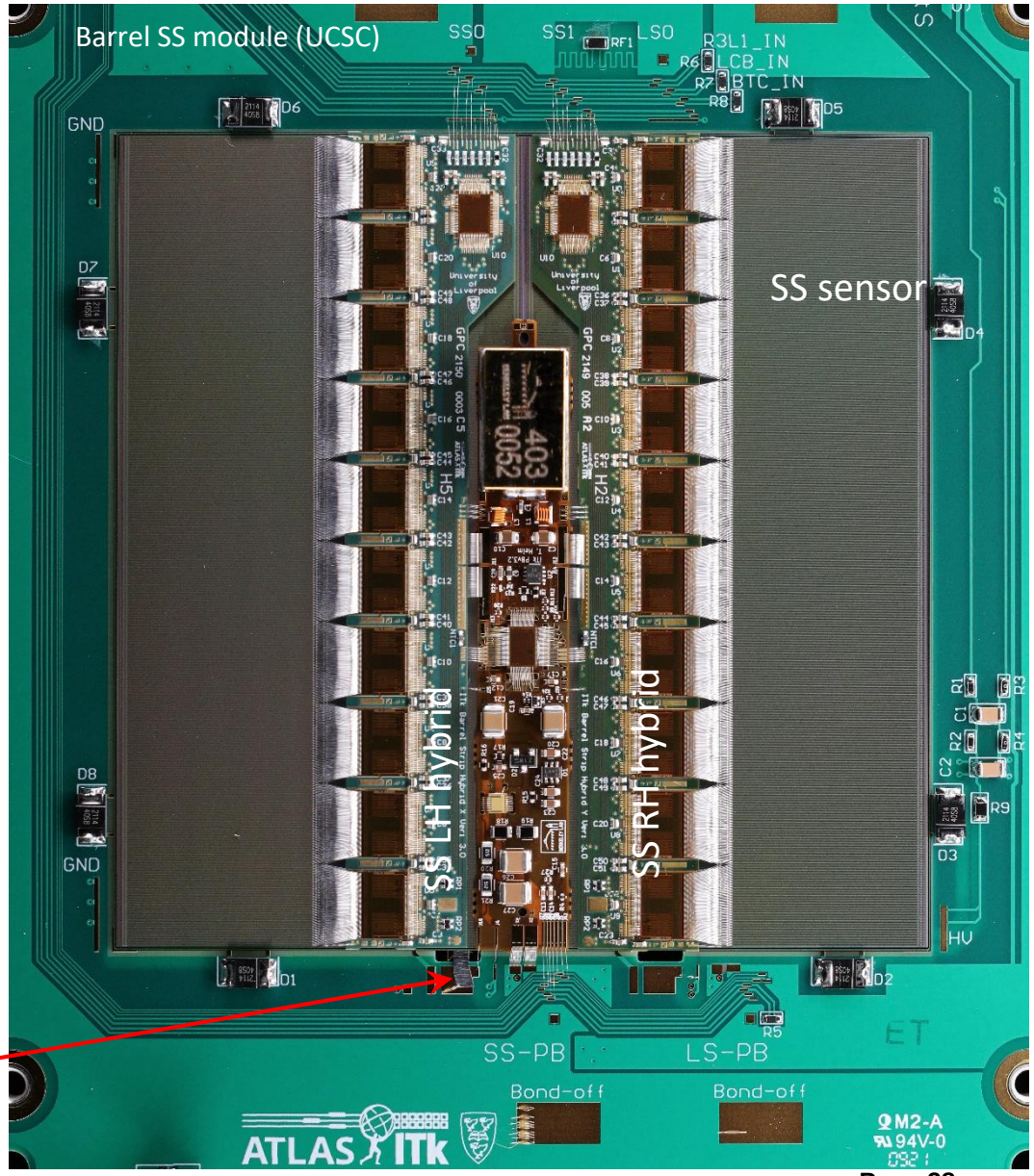
Barrel System Test setup

Thank you

The strips modules



HV tab



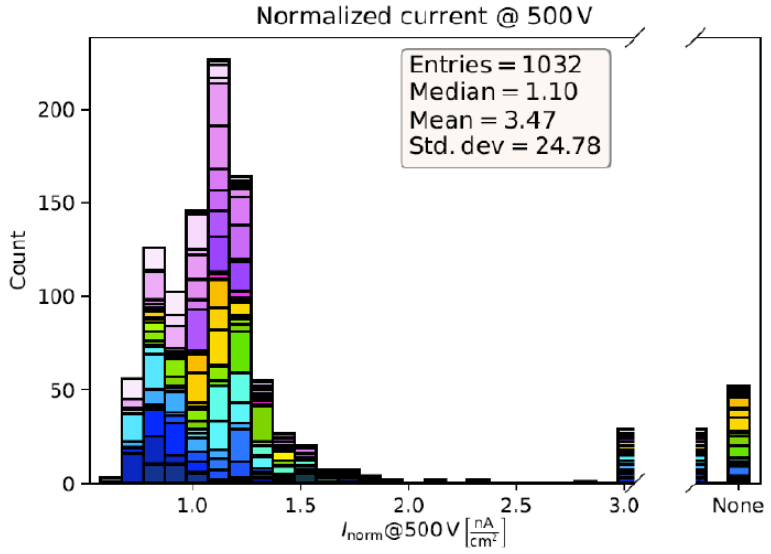
Sensor production

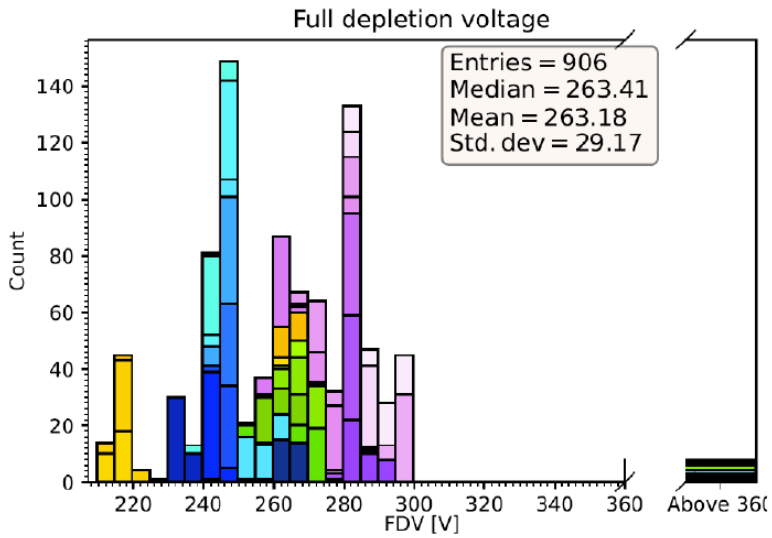
Sensor is in the middle of production phase

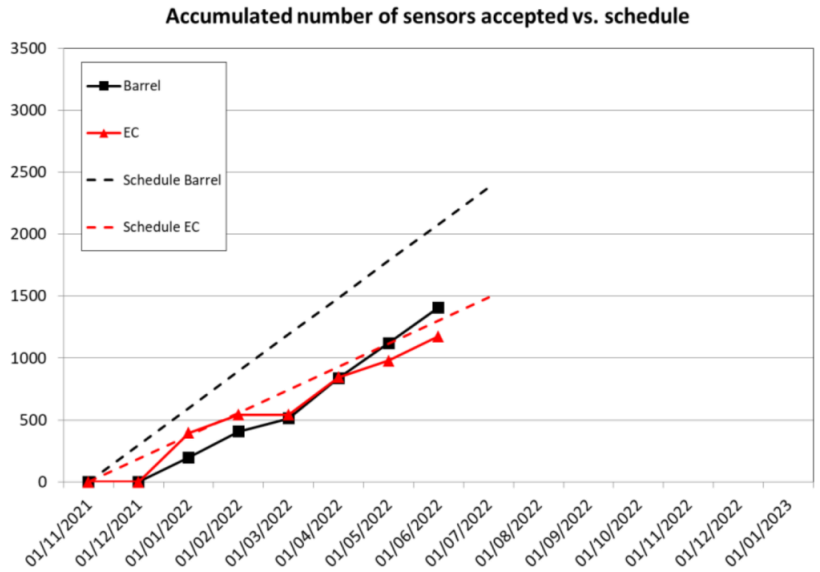
Initial slow ramp-up expected, also due to pandemic

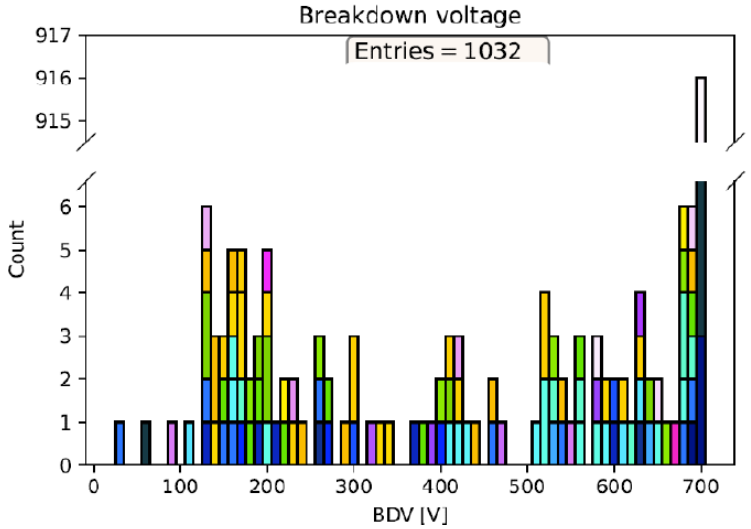
13% sensors "ready for modules", typical rejection rates ~ 3-4%

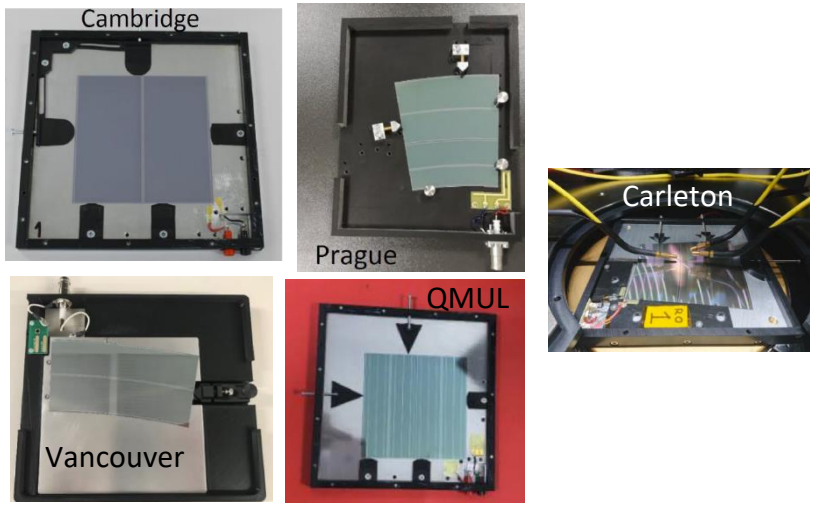
Significant acceptance tests and QC/QA effort, building up statistics





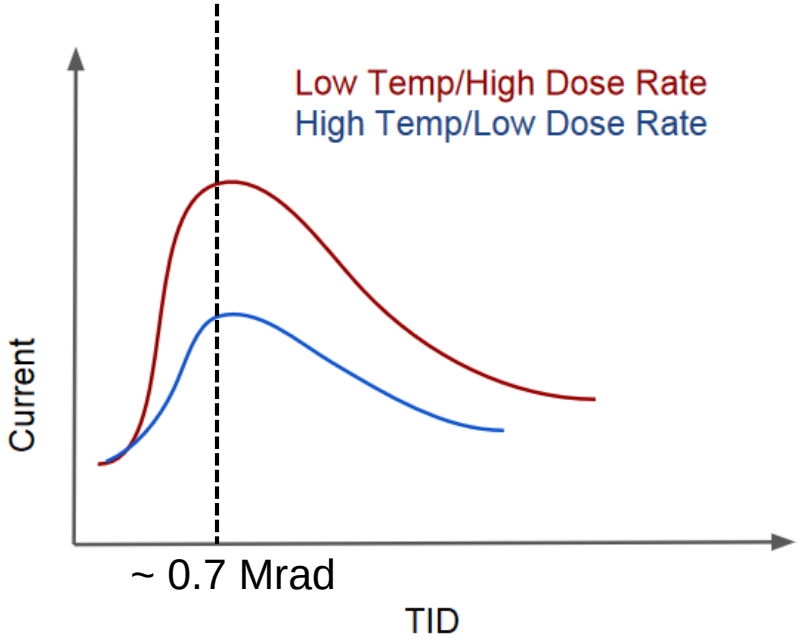


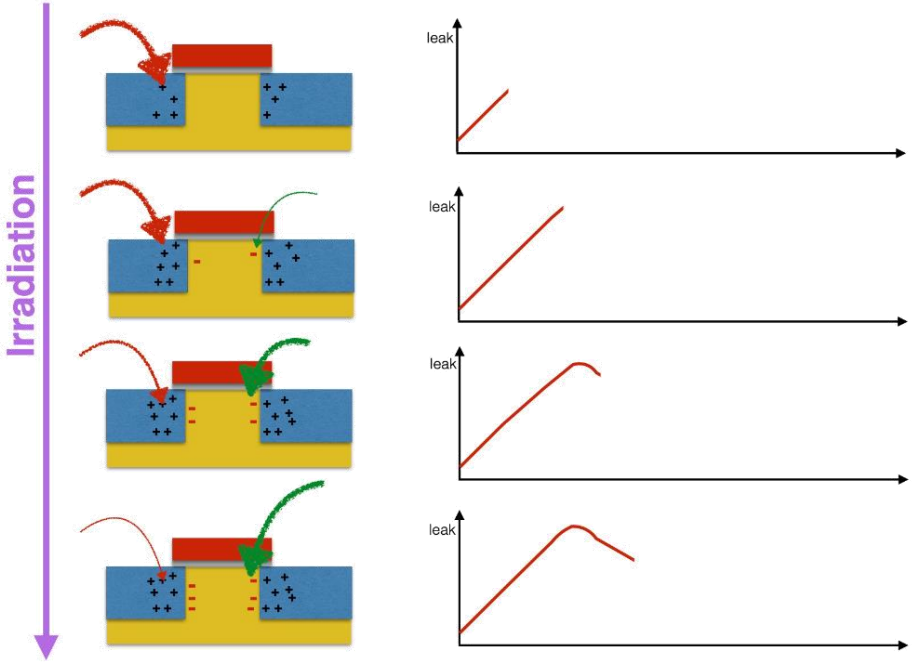




The TID “bump”

Unexpected effect at low ionizing doses on 130 nm CMOS technologies





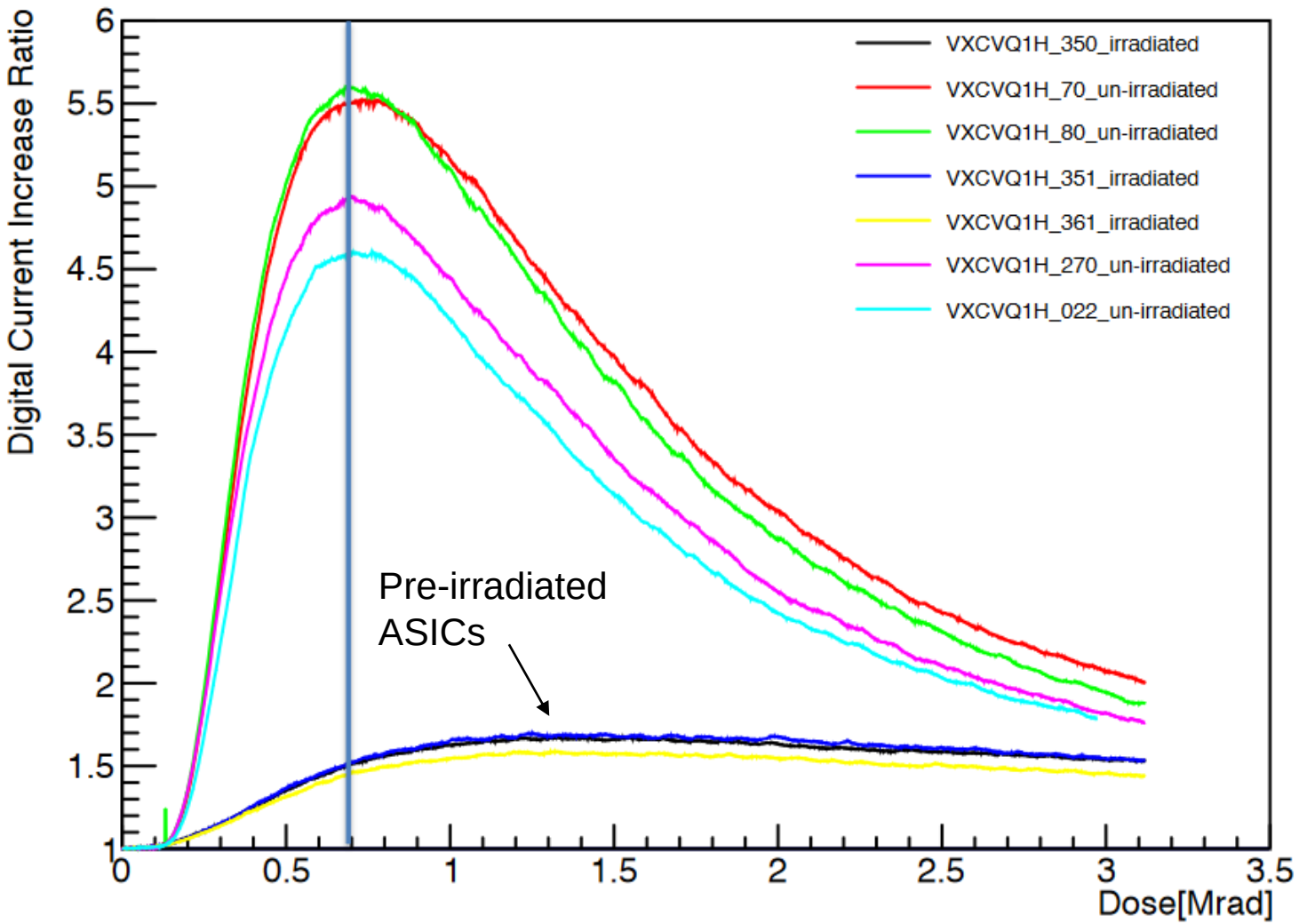
Very significant effect on power consumption at the early stages of the detector

Digital currents recover after a few Mrad

The TID “bump”

An unexpected solution for an unexpected problem

Chipset dies are pre-irradiated up to ~ 5 Mrad even before module construction

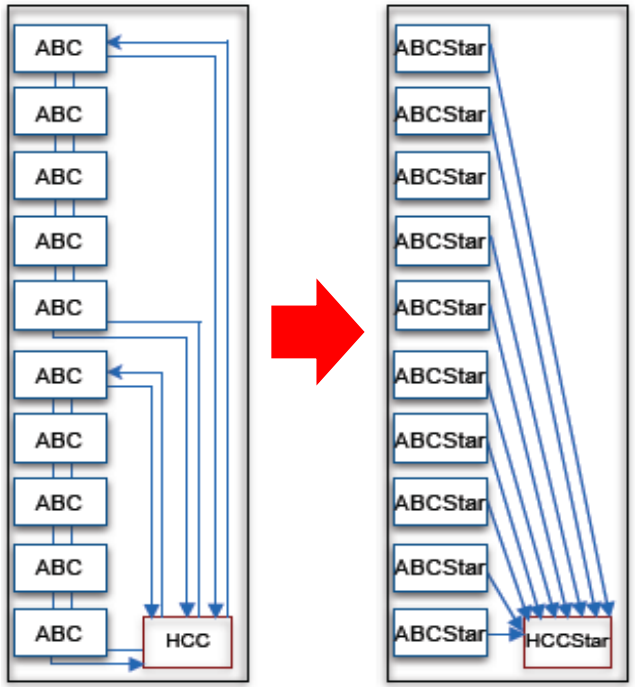


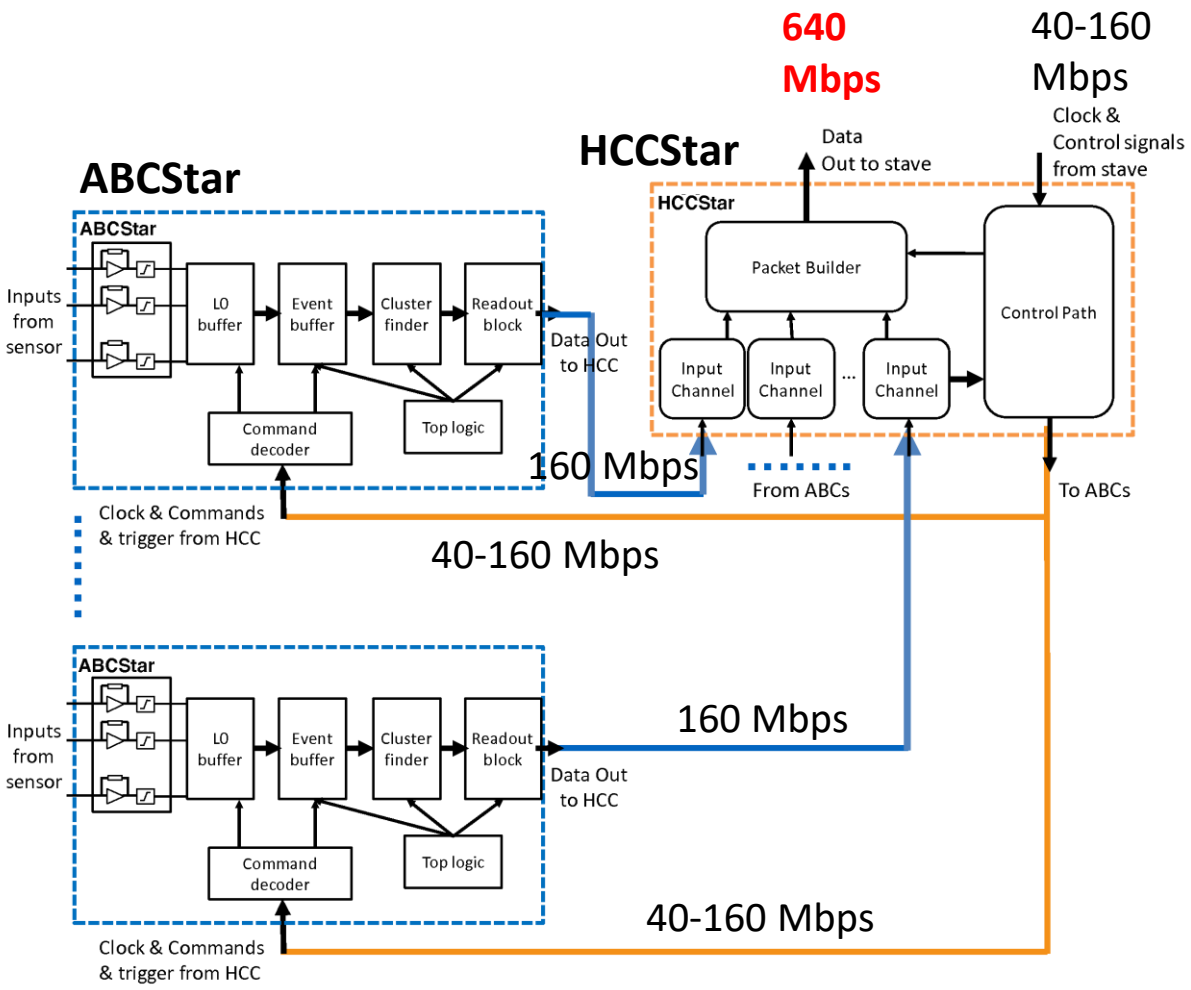
High speed electronics

Coping with 1MHz trigger rates

The STAR architecture

640Mbit/s downlinks from each hybrid controller chip





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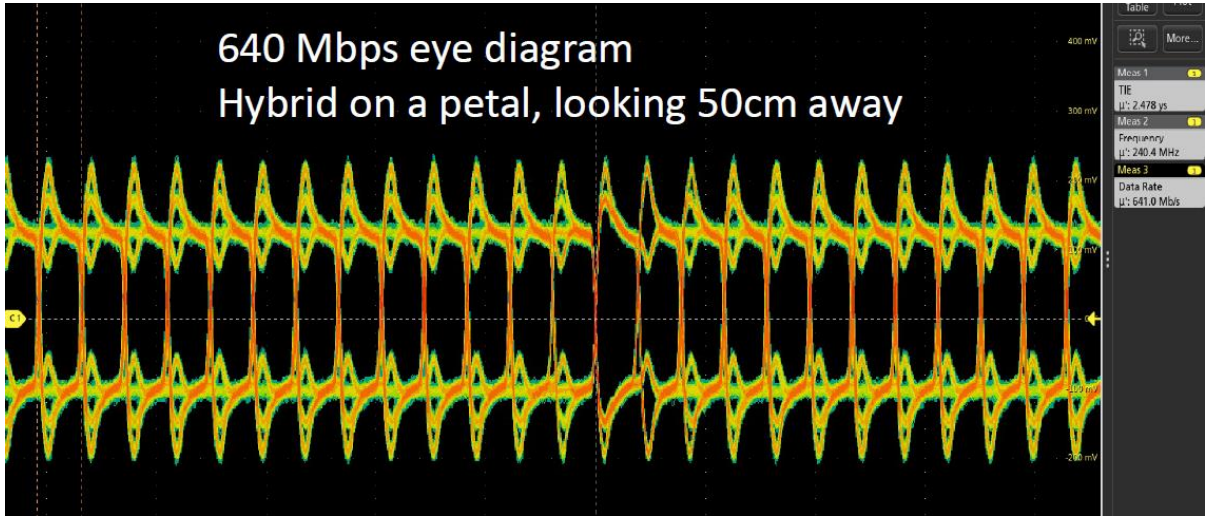
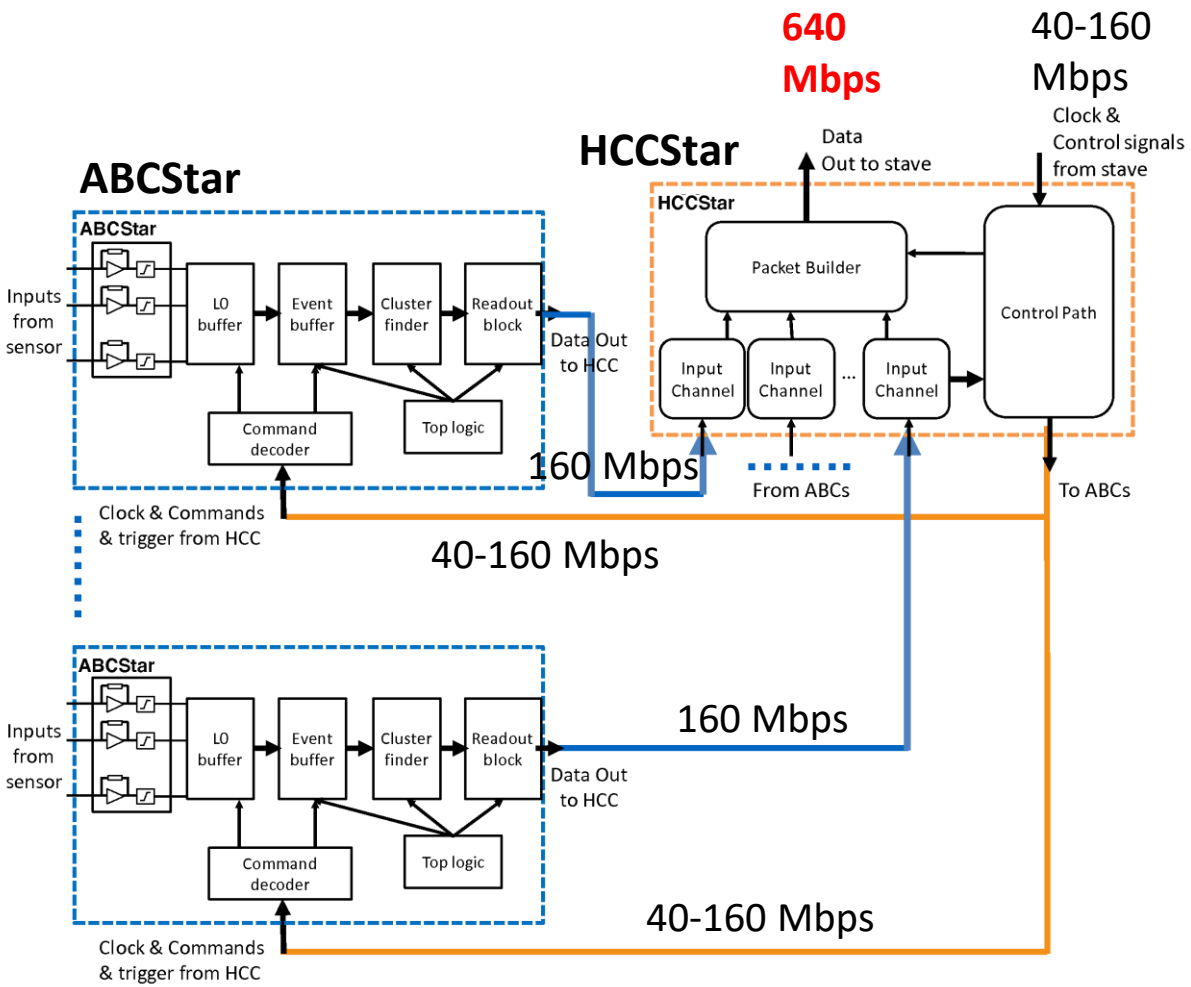
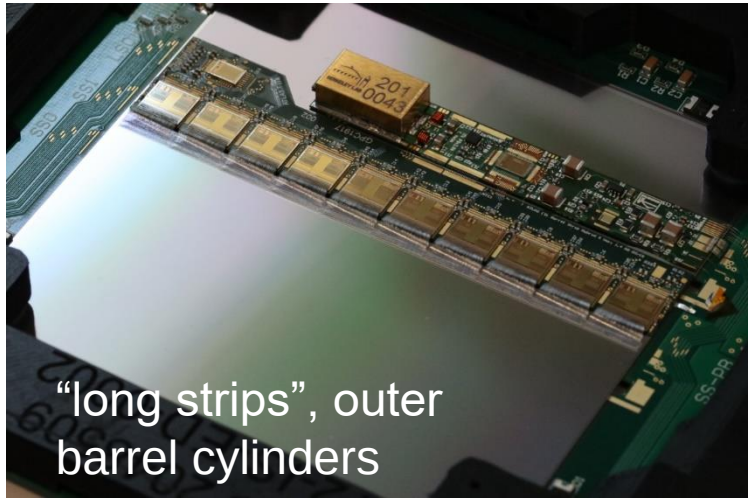
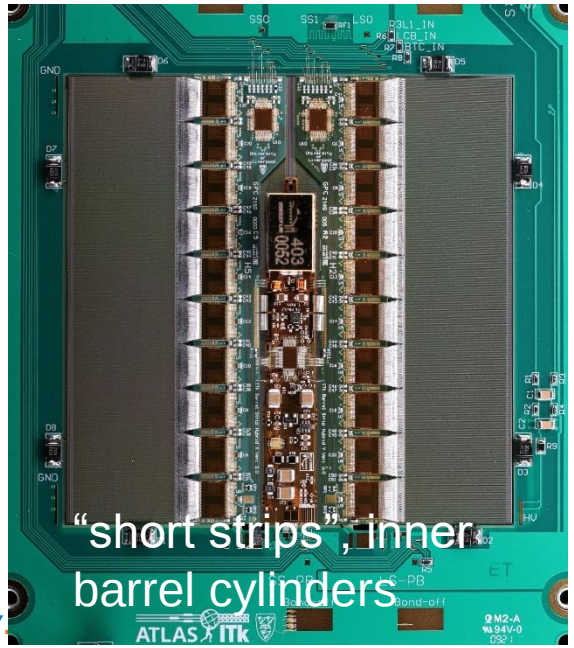


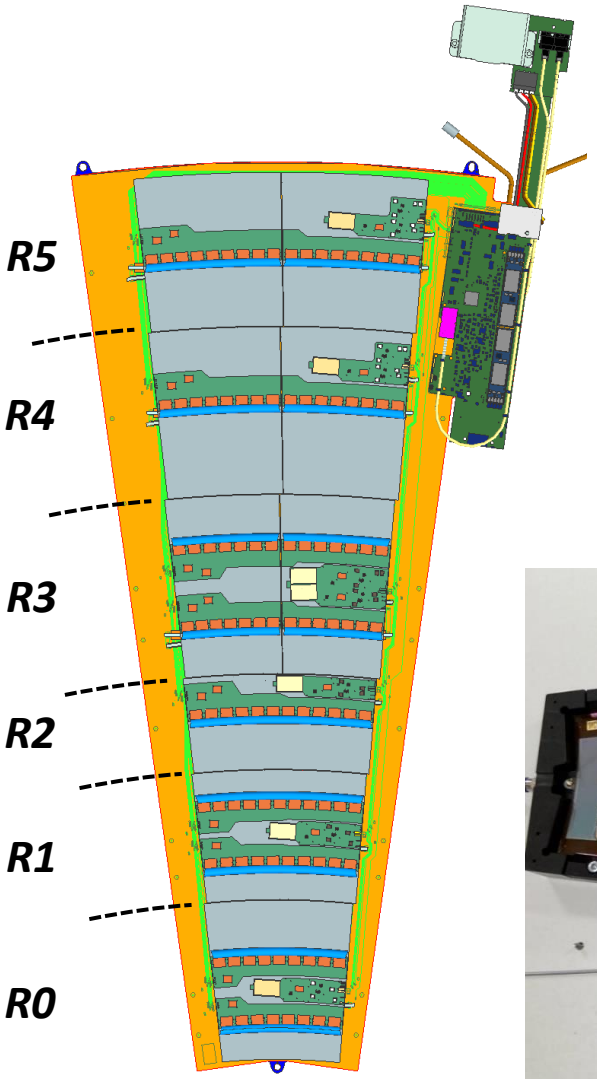


Module flavors

2 module flavors in the barrel, 6 in the ECs







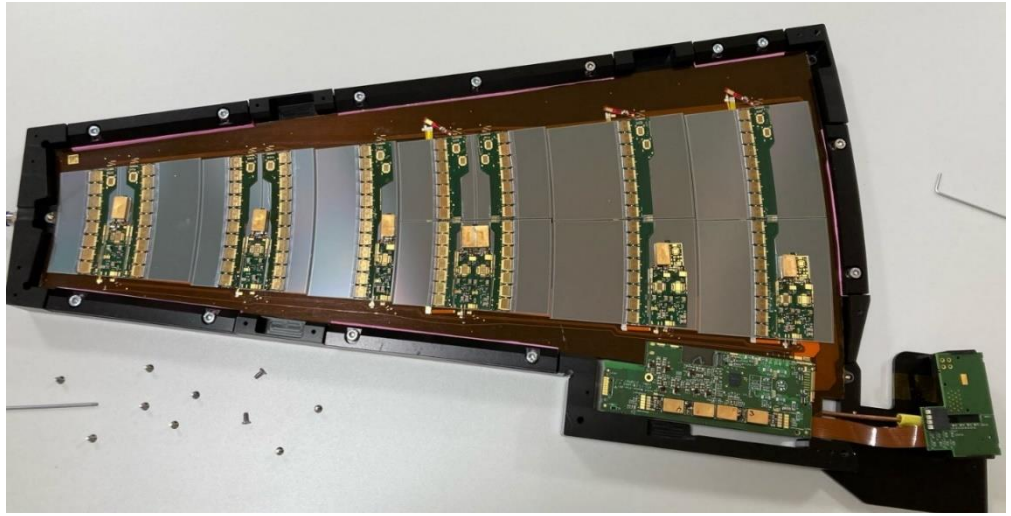
Strip lengths chosen to cope with occupancy

75 µm average pitch

20 mrad stereo angle built into the petal

IP pointing strips for optimal ϕ resolution

Trapezoidal-like shapes to maintain uniform strip length



Module building

Site qualification

	Step Number	Qualification Step	Status	Ready for Review?	Review Status
HV Tab Attach	1.1	Bonding Procedures	Needs Development	No	Not Reviewed
Sensor Reception	3.1	Sensor Reception	Qualification Ready	Yes	Passed
	3.2	Sensor Storage	Qualification Ready	Yes	Passed
	3.3	Sensor I-V	Review Docs Incomplete	No	Not Reviewed
PB Reception	6.1	PB Reception	Qualification Ready	Yes	Passed
	6.2	PB E tests	Requires Parts	No	Not Reviewed
	6.3	PB Vis Insp	Qualification Ready	Yes	Passed
	6.4	PB Storage	Qualification Ready	Yes	Passed
Hybrid Assembly/Testing	8.2	Storage + shipping of glue	Qualification Ready	Yes	Passed
	8.3	Assembling hybrids	Qualification Ready	Yes	Passed
	8.4	Glue weight measurements	Qualification Ready	Yes	Passed
	8.5	Bonding procedures: hybrids	Review Docs Incomplete	No	Not Reviewed
	8.6	Metrology: hybrids	Qualification Ready	Yes	Passed
	8.7	Visual inspection: hybrids	Qualification Ready	Yes	Passed
	8.8	Hybrid Burn-In	Requires Parts	No	Not Reviewed
	8.10	Hybrid Storage	Qualification Ready	Yes	Passed
	8.11	hybrid QC: single panel testing	Review Docs Incomplete	No	Not Reviewed
Hybrid Reception	10.1	Reception tests: hybrids	Qualification Ready	Yes	Passed
	10.2	Storage of hybrids	Qualification Ready	Yes	Passed
Module Assembly/Testing	11.1	Storage of modules	Qualification Ready	Yes	Passed
	11.2	Cleaning module jigs	Qualification Ready	Yes	Passed
	11.4	Storage + shipping of glue	Qualification Ready	Yes	Passed
	11.5	Removing hybrids from panel	Review Docs Incomplete	No	Under Review
	11.6	Module Assembly	Requires Parts	No	Not Reviewed
	11.7	Metrology: modules	Requires Parts	No	Not Reviewed
	11.8	Bonding procedures: modules	Requires Parts	No	Not Reviewed
	11.9	Visual inspection: modules	Qualification Ready	Yes	Passed
	11.10	Module Thermal Cycling	Requires Parts	No	Not Reviewed
	11.11	Single module Electrical Tests	Requires Parts	No	Not Reviewed
General	13.1	Cleanroom standards	Qualification Ready	Yes	Passed
	13.2	ASIC Compliance & Handling	Qualification Ready	Yes	Passed
	13.3	Bond Pulling Procedures	Qualification Ready	Yes	Passed

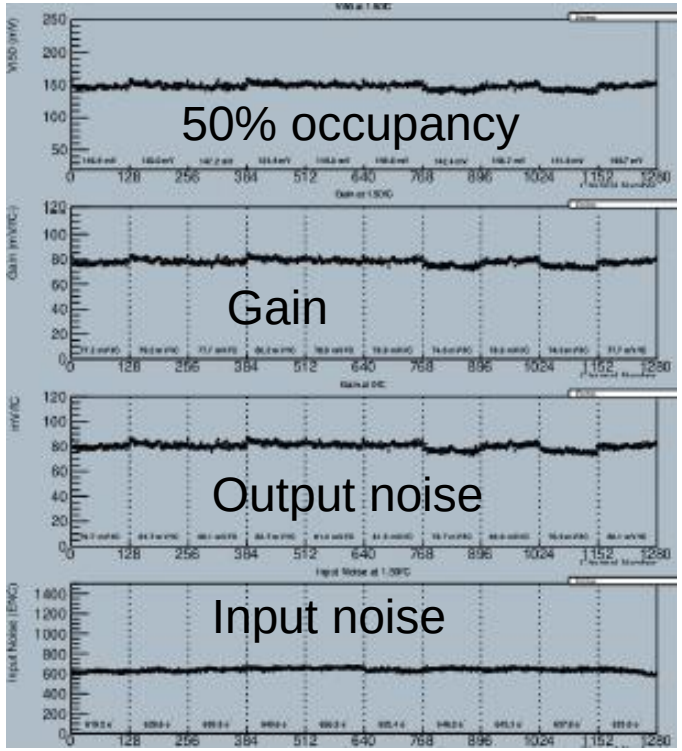
Module production

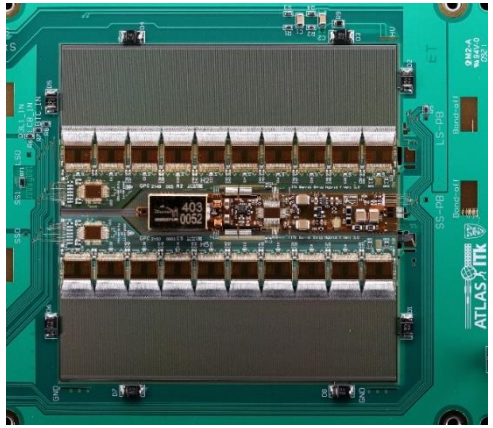
Module effort in pre-production phase

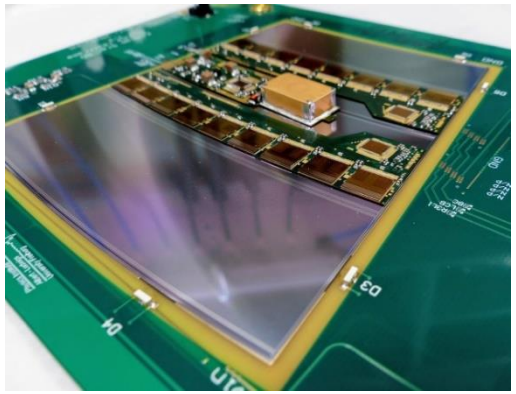
First pre-production B items ("final" chipset and flexes) showing up

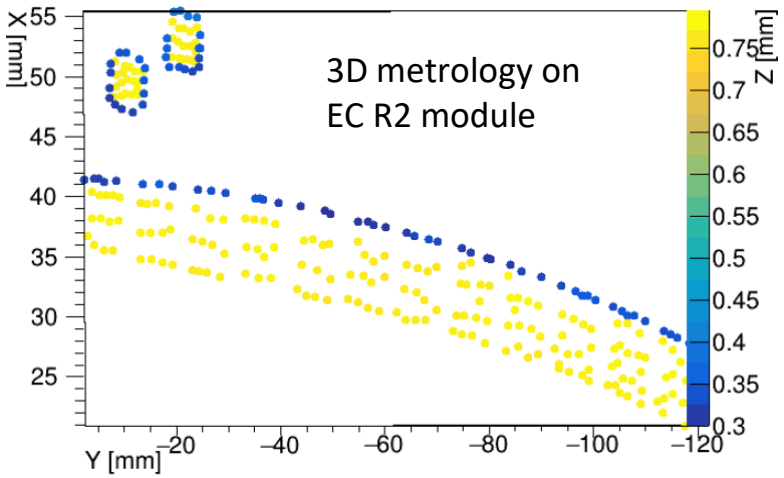
Extensive site qualification process across all sites

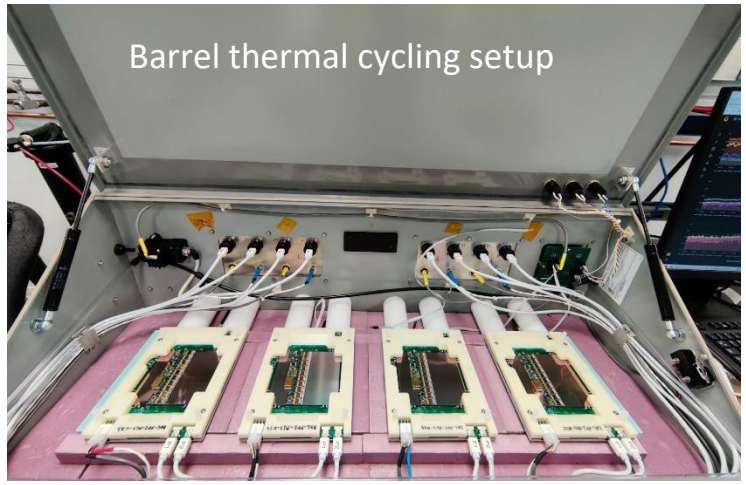
QC and QA program: metrology, electrical performance, thermal cycling, test beam experiments,…

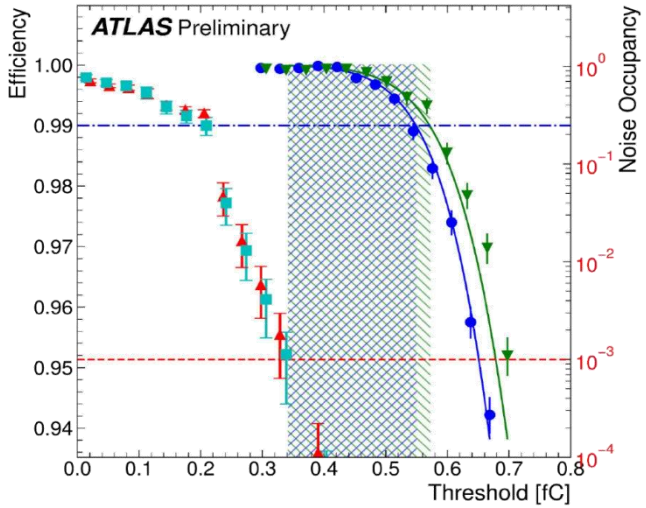








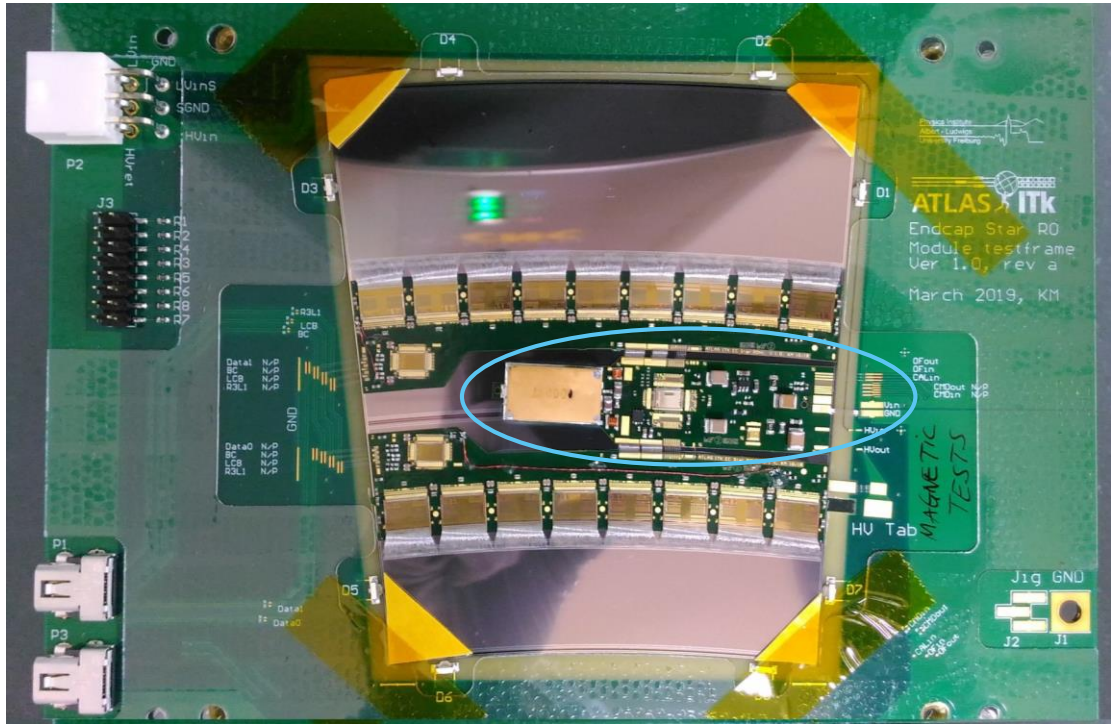


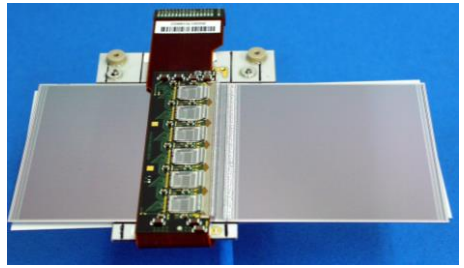


Barrel SS module eff/NO curve

Low power

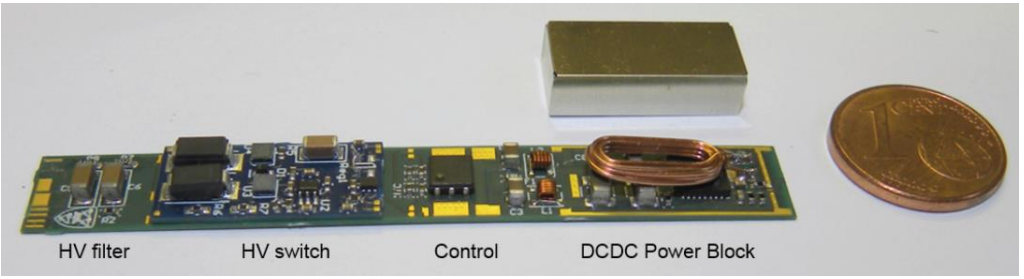
Minimizing power dissipation and cable losses

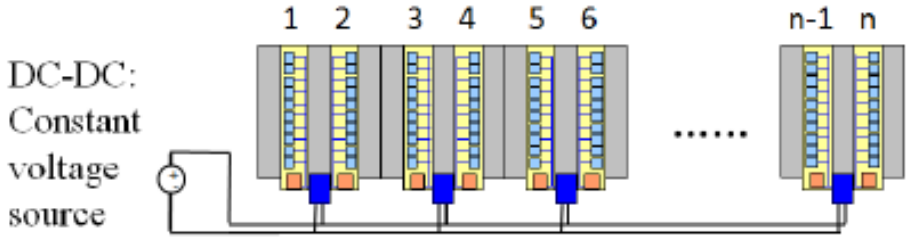




~65 W per petal
(~57k readout channels)
→ 1.1 mW/ch
…in one cable

~5.1 W per SCT module
(~ 1.5k readout channels)
→ 3.3 mW/ch
…in one cable





Power board:

Buck DC-DC converter with switch power transistors

LV and HV control circuitry and monitoring

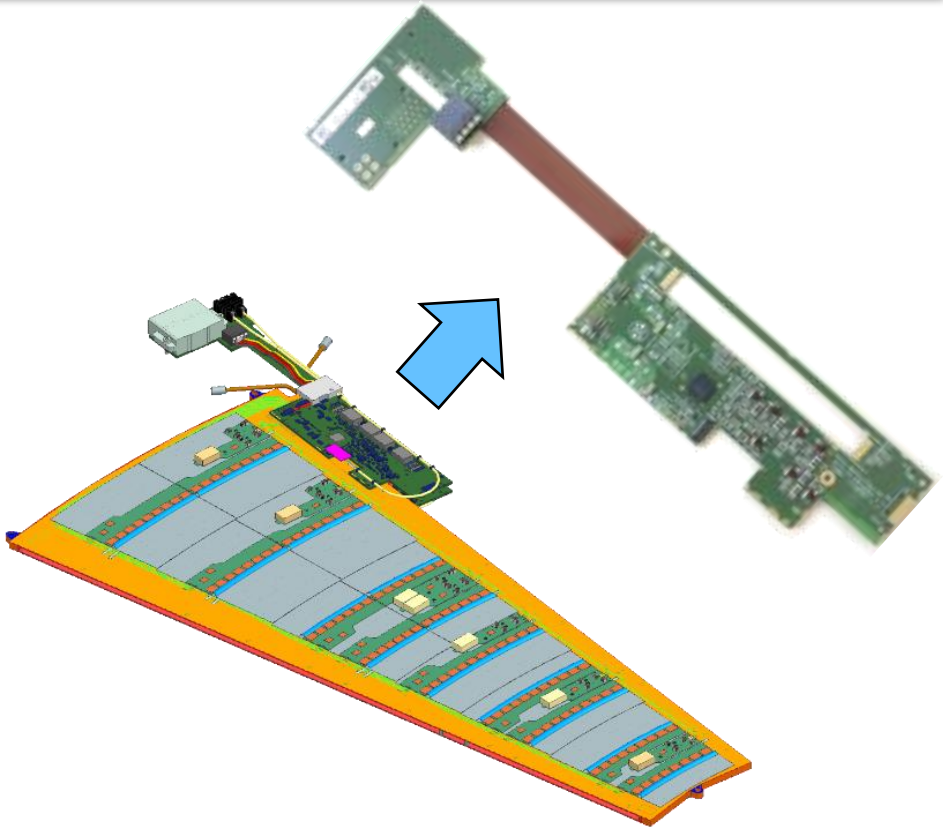
“End of Substructure” (EoS)

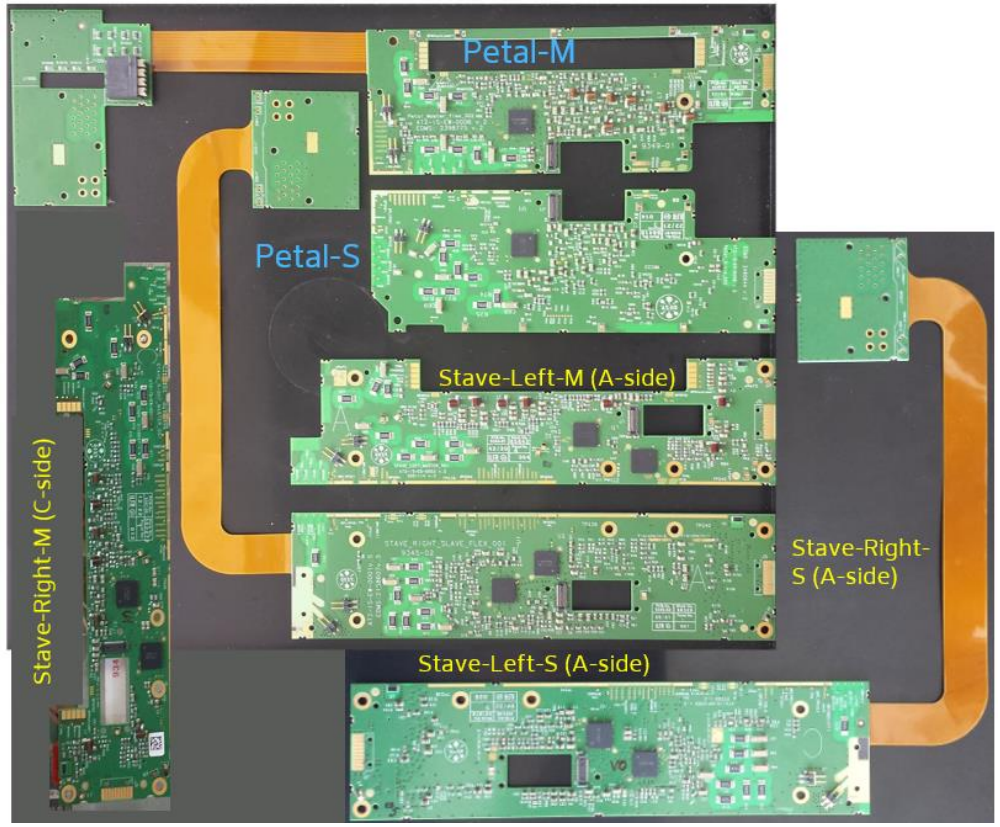
Data concentrator boards to the outside world

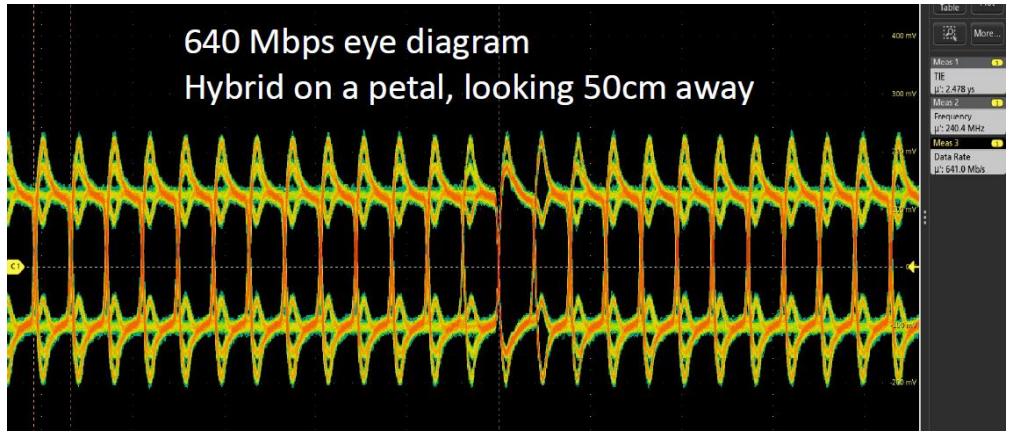
lpGBT: 10GBit/s transceiver, data aggregator

VTRX+: rad-hard optical link + fiber

All main flavors produced at least once



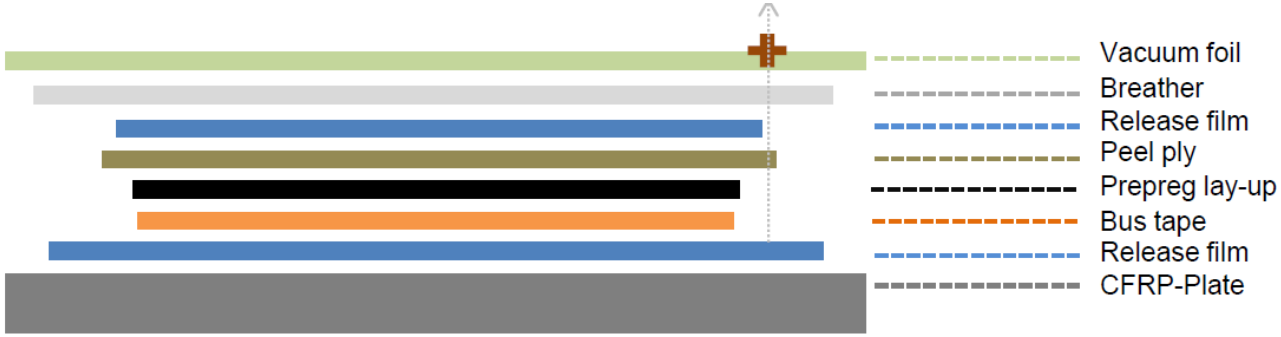


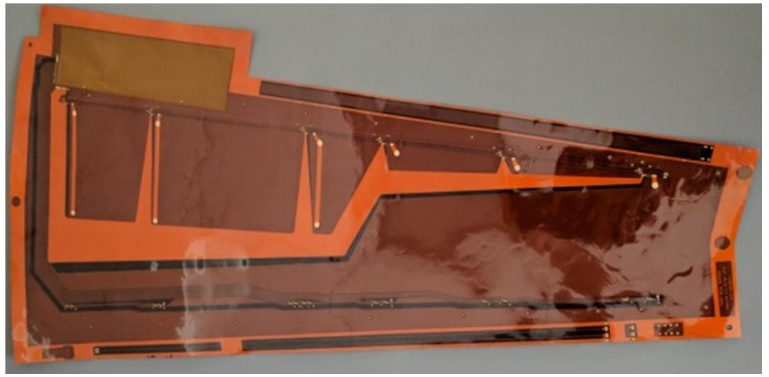


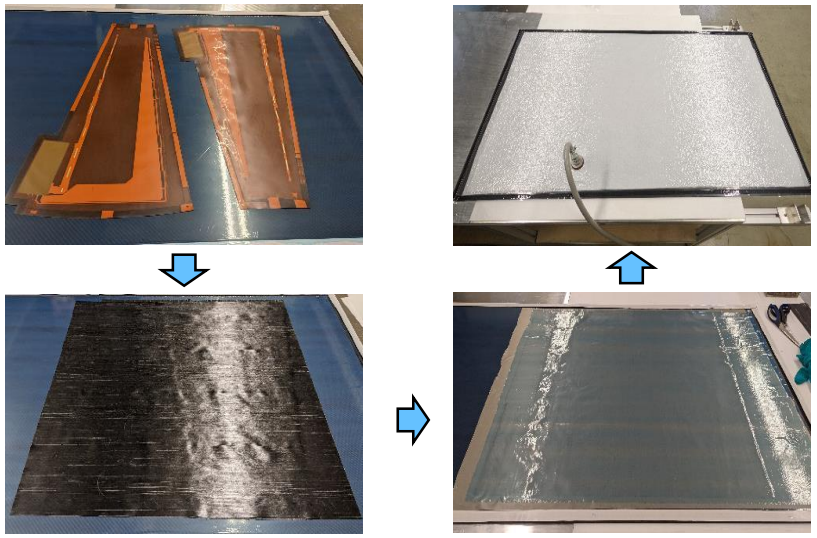
Carbon fiber facesheets

Bus tapes co-cured with CFRP pre-preg

185 µm thick







Optimized for 640 MHz differential signals

Co-cured together in autoclave with lay-up of K13C2U/EX1515 CF pre-preg