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

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On behalf of the ATLAS ITk Strip Collaboration

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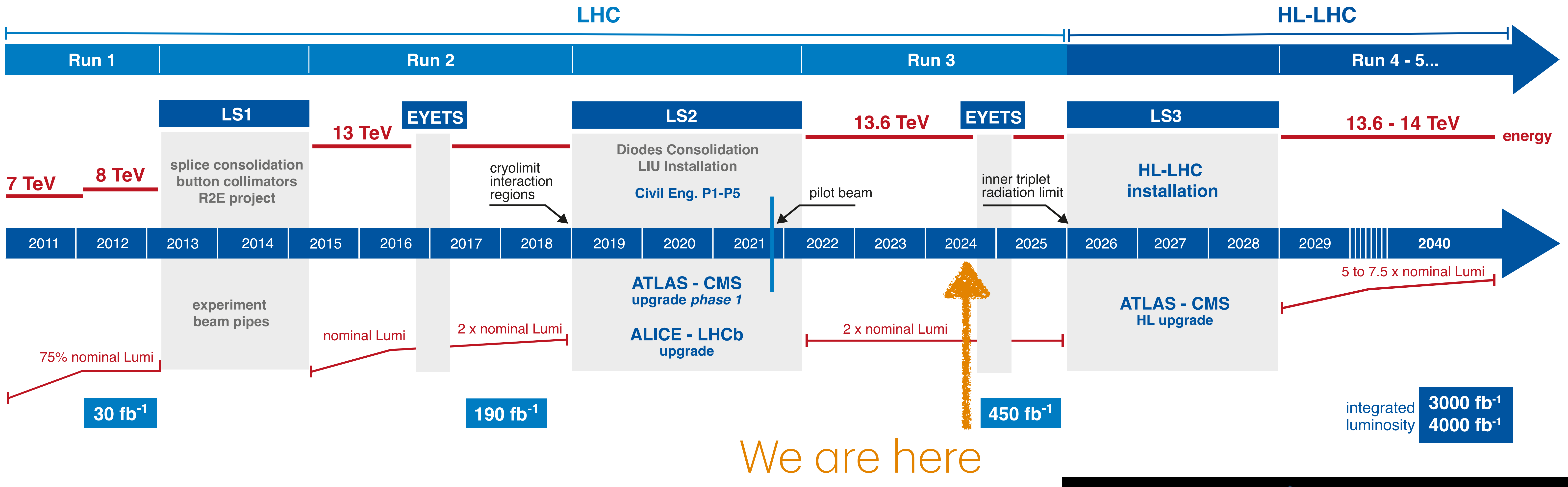
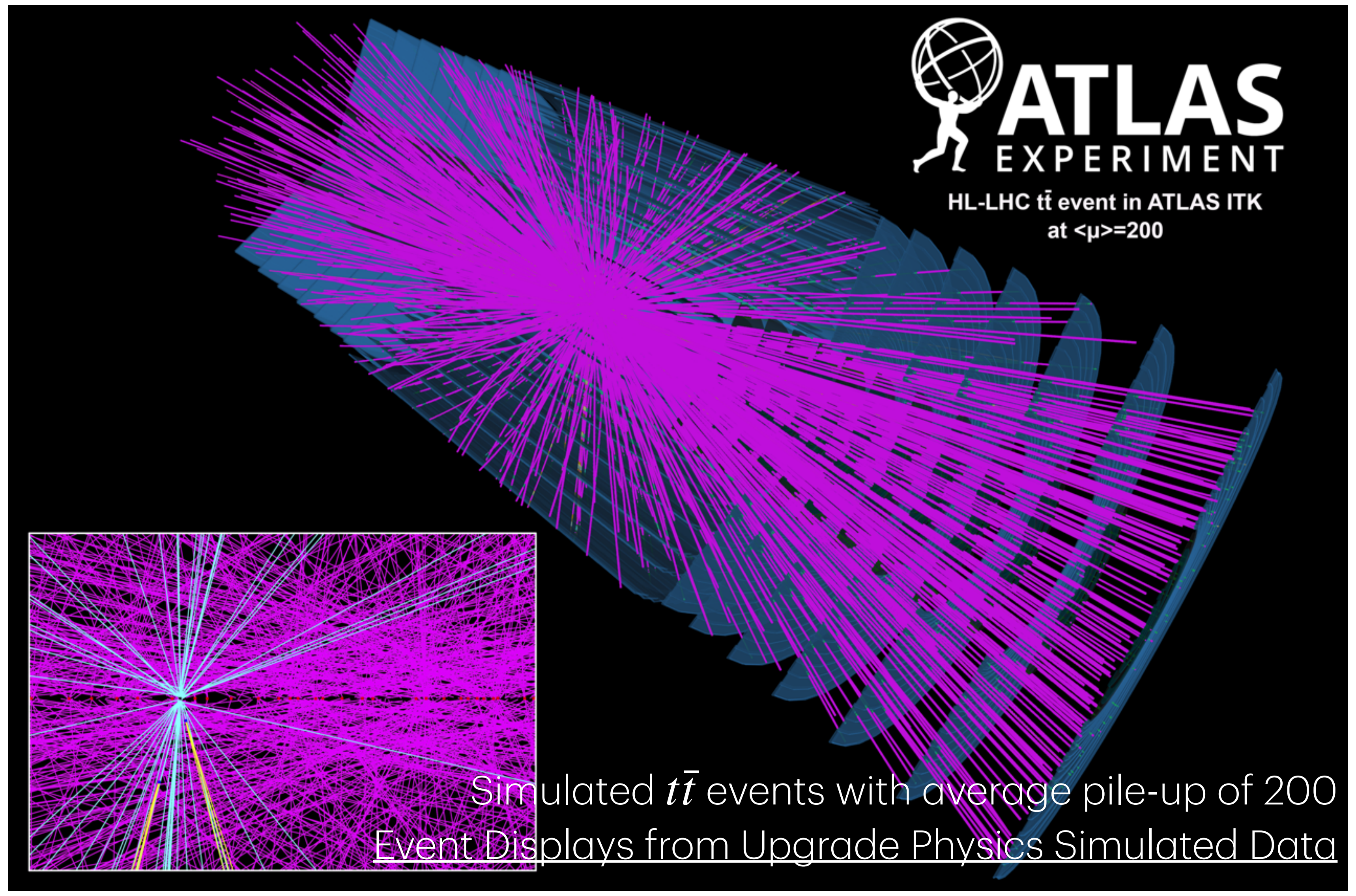
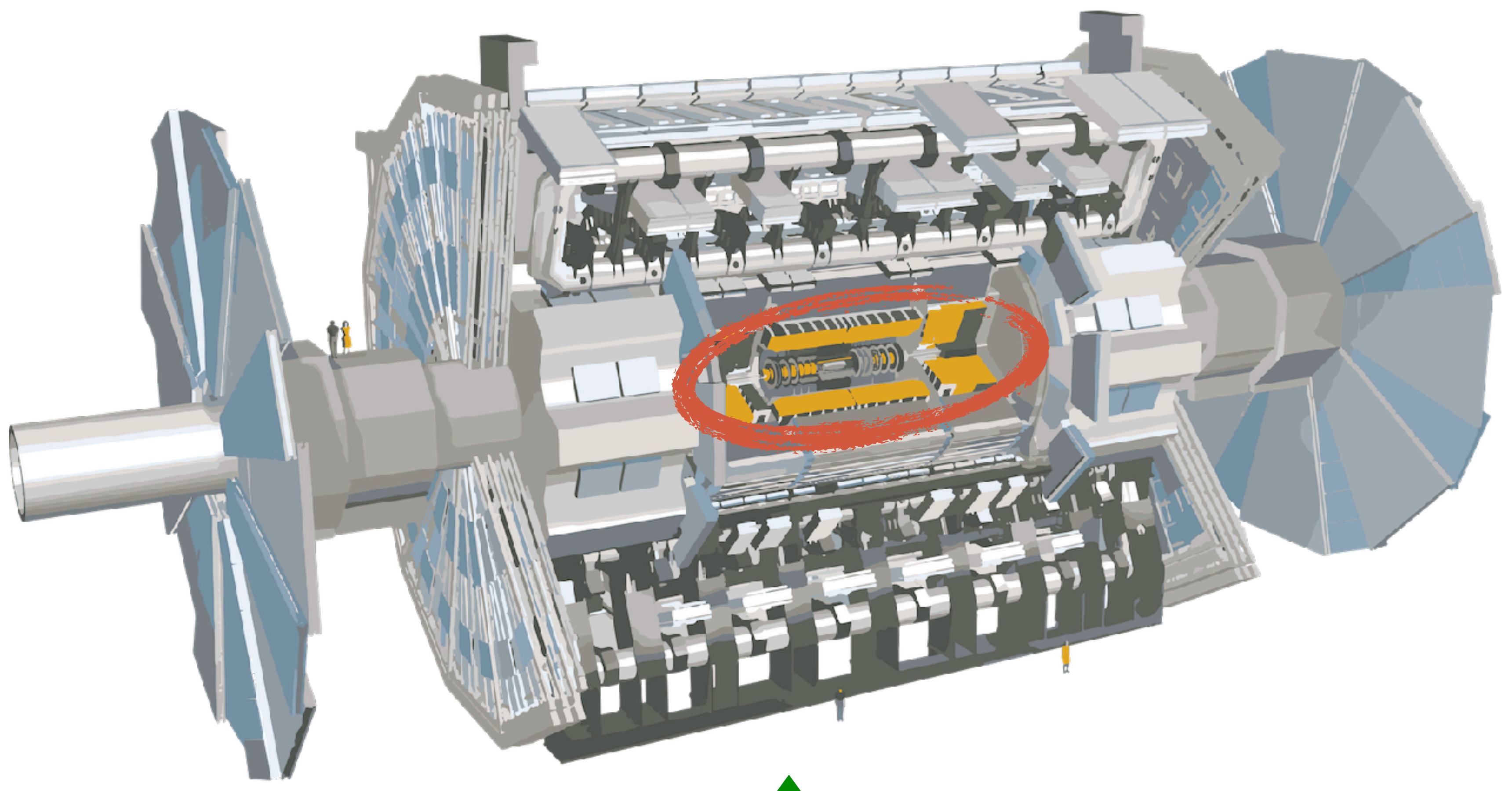
HL-LHC



- **H**igh-**L**uminosity **LHC**
  - An order of magnitude more data than LHC
  - Average overlapping inelastic proton-proton collisions per bunch crossing ("pile-up") up to 200
  - Extremely challenging environment for detectors
- The ATLAS experiment will be upgraded for HL-LHC

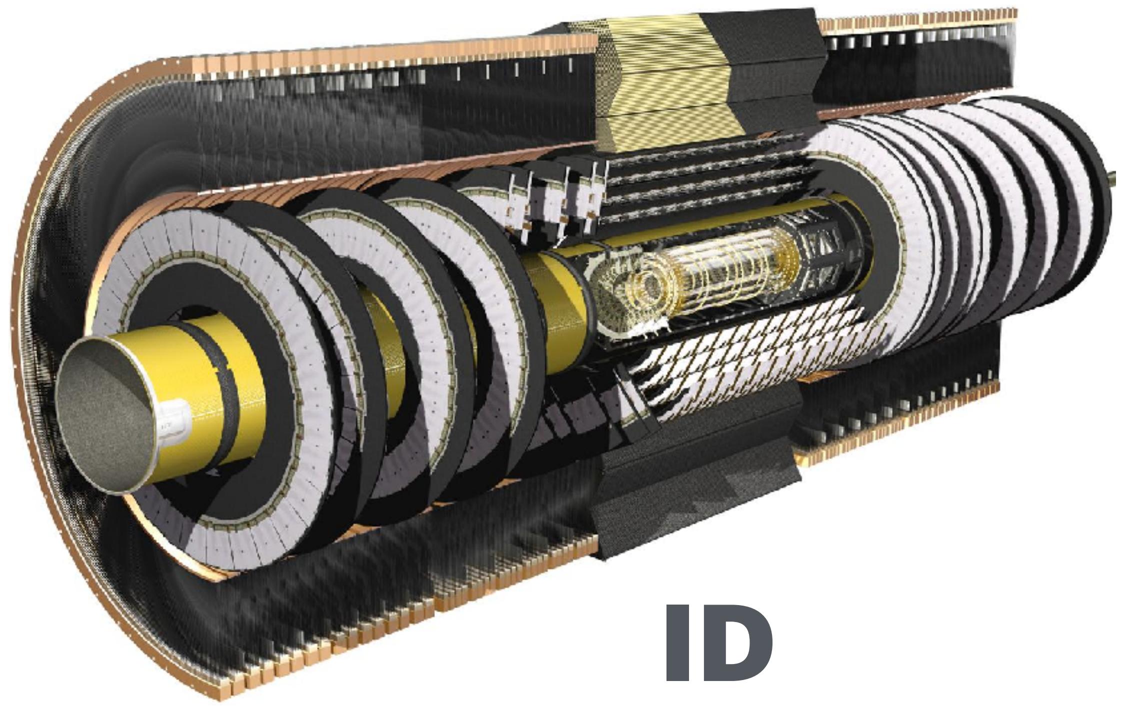


ATLAS Inner Tracker Upgrade

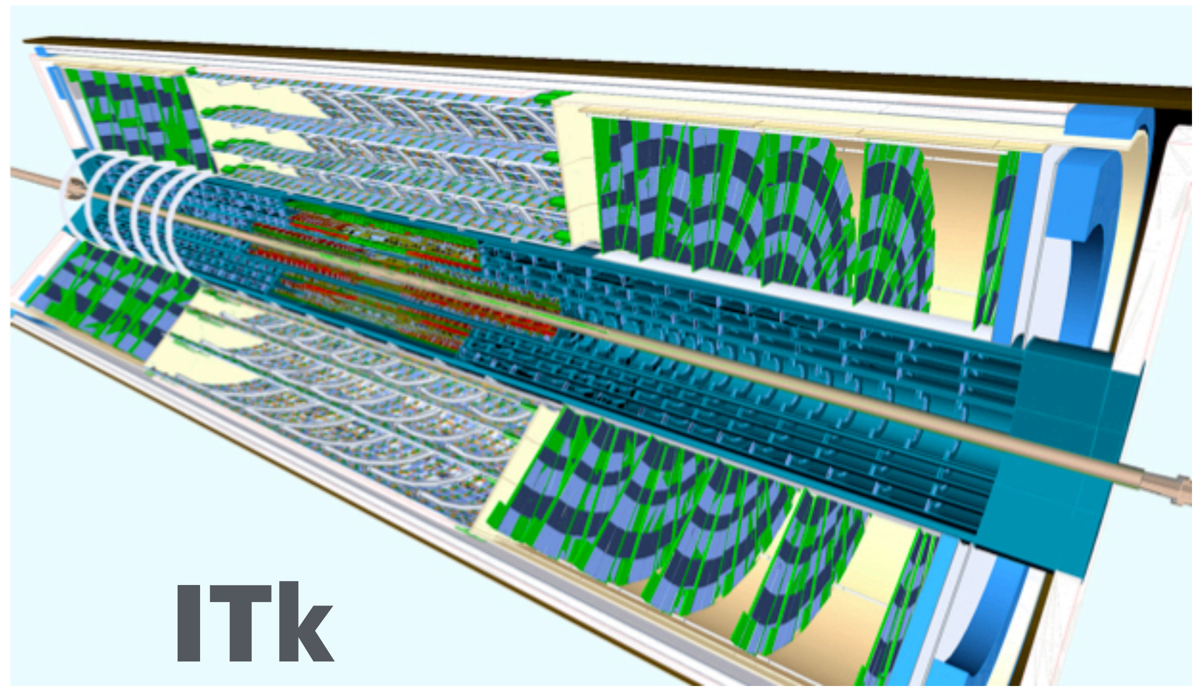


- **ATLAS is replacing its current Inner Detector (ID) with a new all-silicon Inner Tracker (ITk) for HL-LHC**
  - Larger angular coverage: $|\eta| < 4.0$
  - Higher trigger rate: 1 MHz
  - Finer granularity
  - Higher radiation tolerance
  - Less material
  - Similar or better tracking performance in a harsher environment

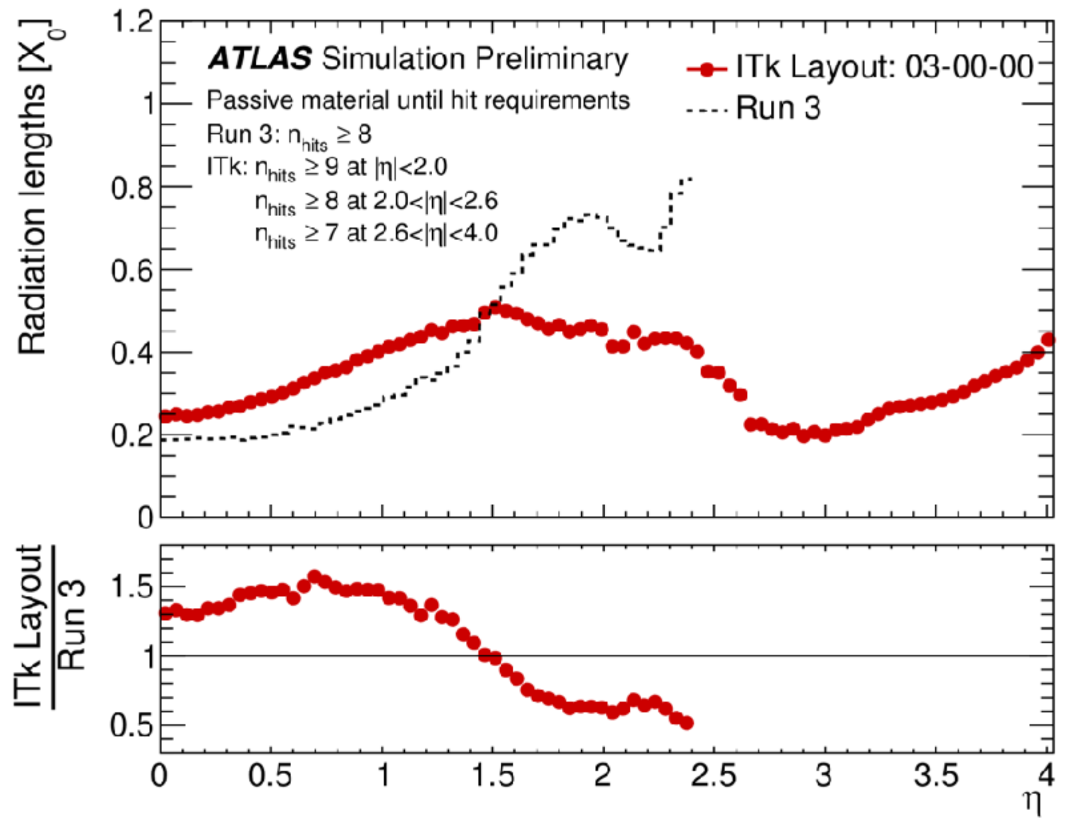
Out



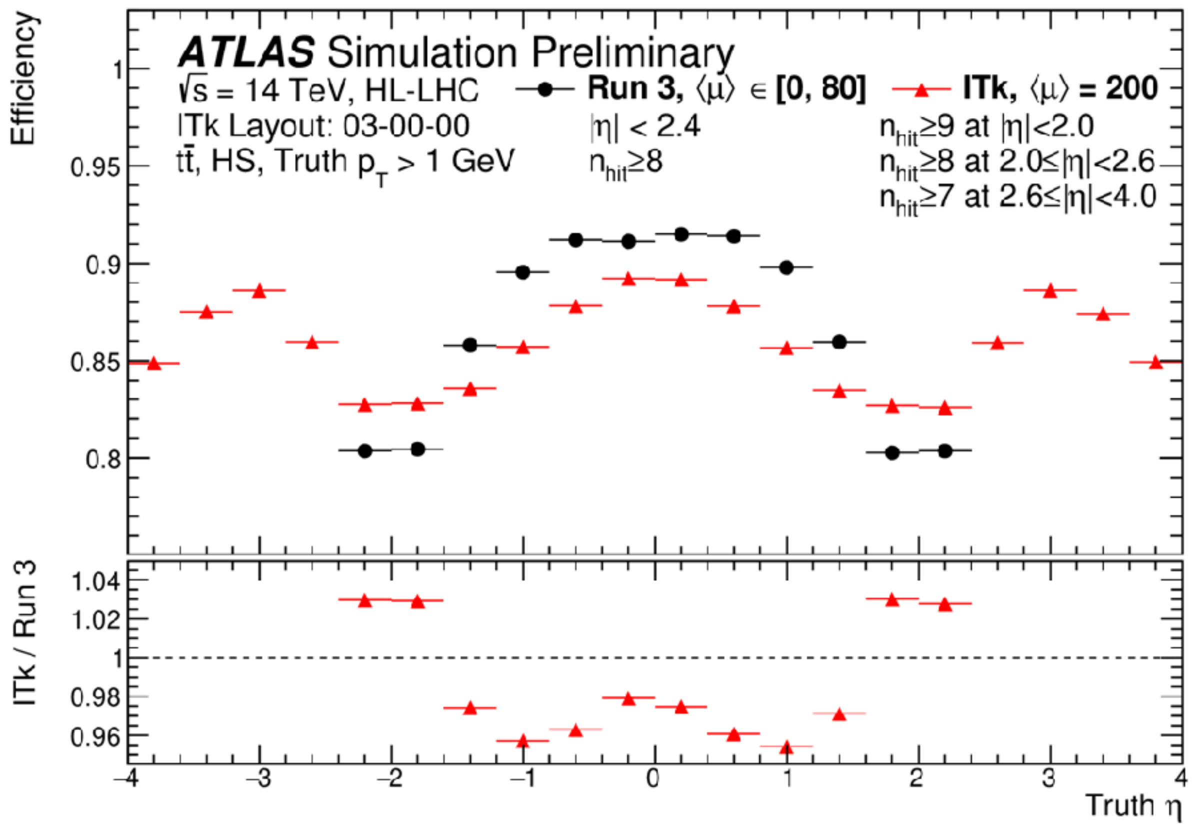
In



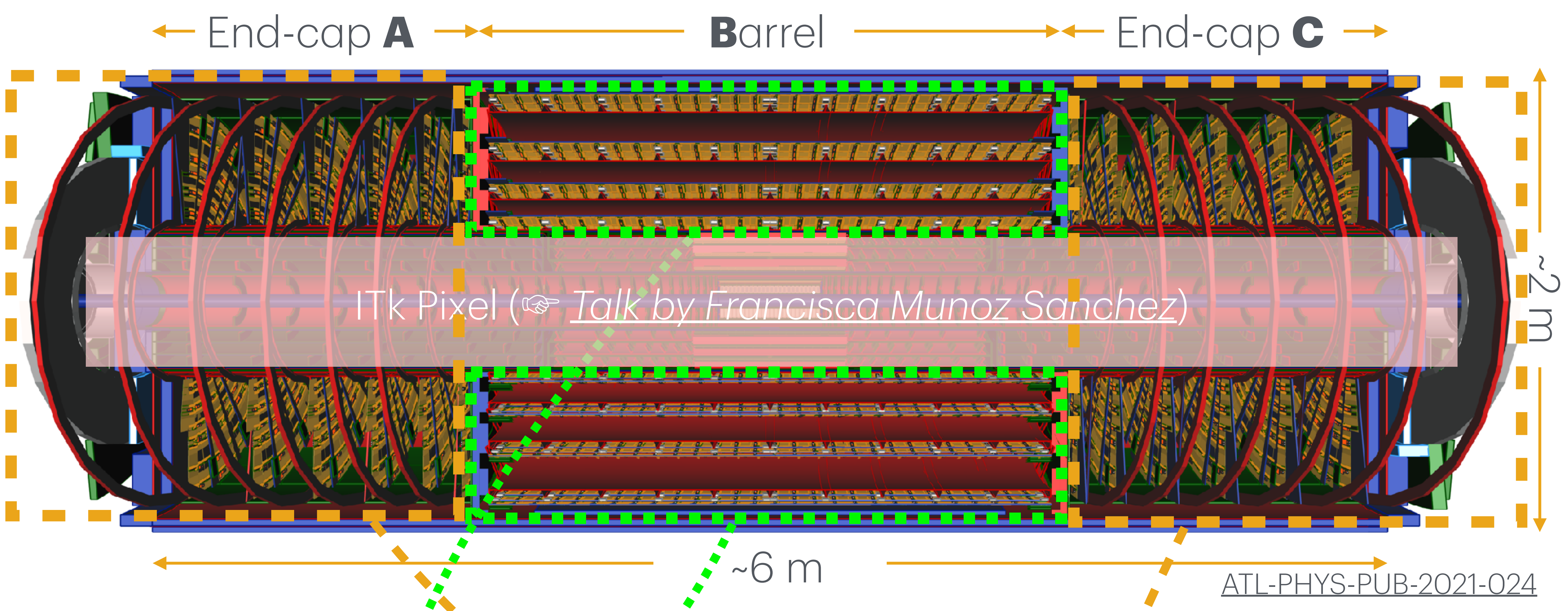
ITK-2023-001

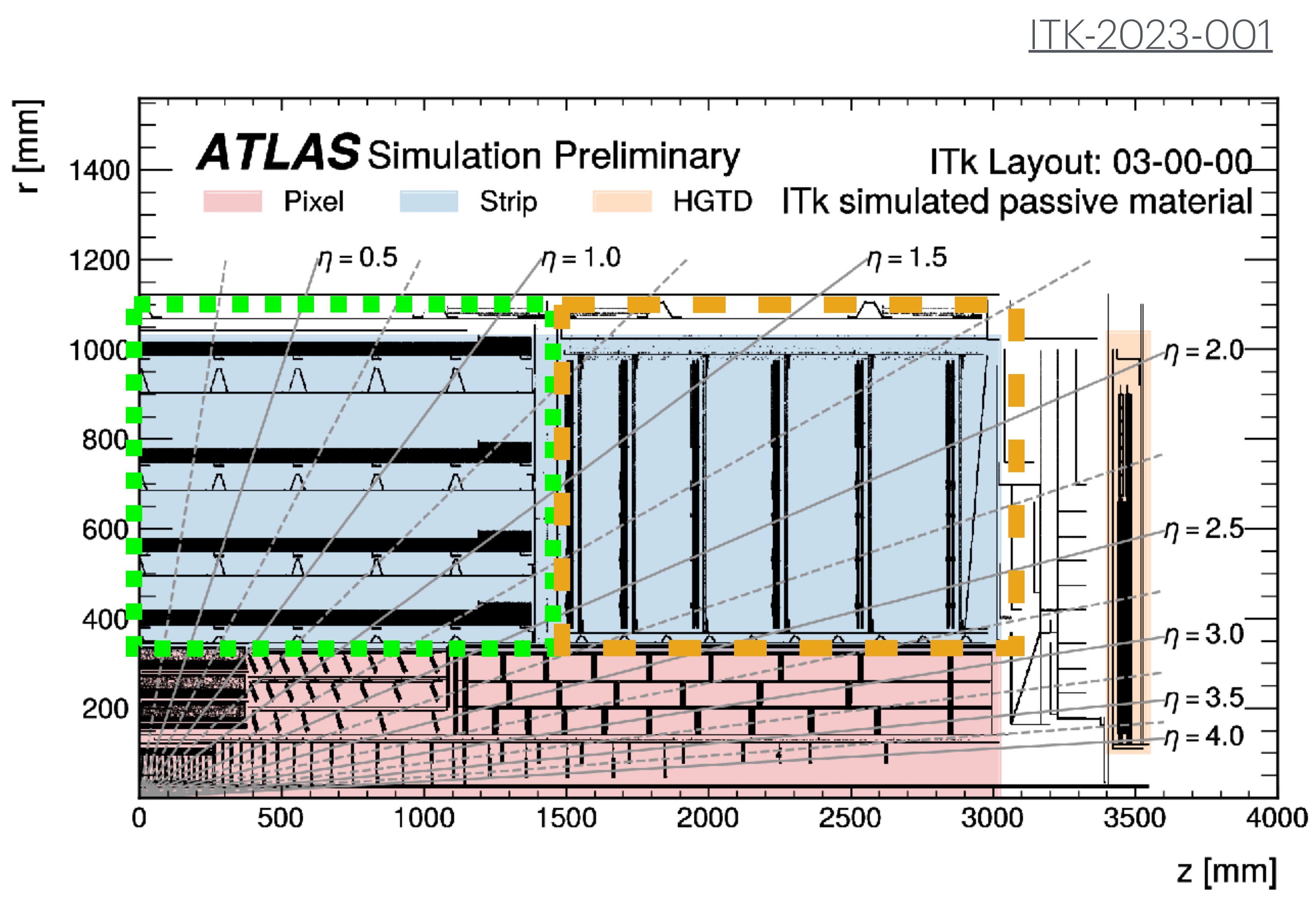


IDTR-2023-05



Inner Tracker Layout



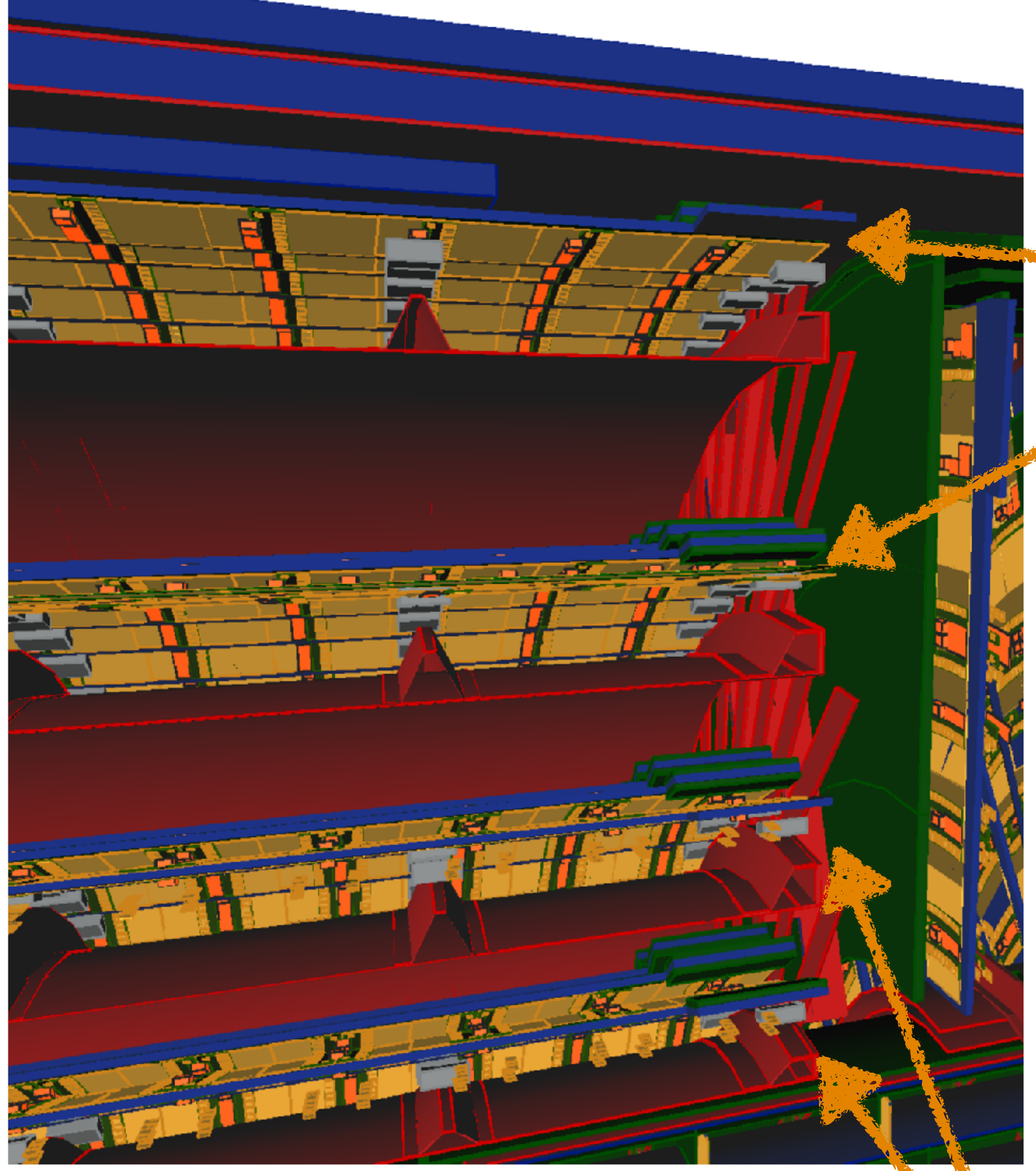


- **ITk Strip Barrel**
  - 4 cylinders
- **ITk Strip End-caps**
  - 6 disks per side

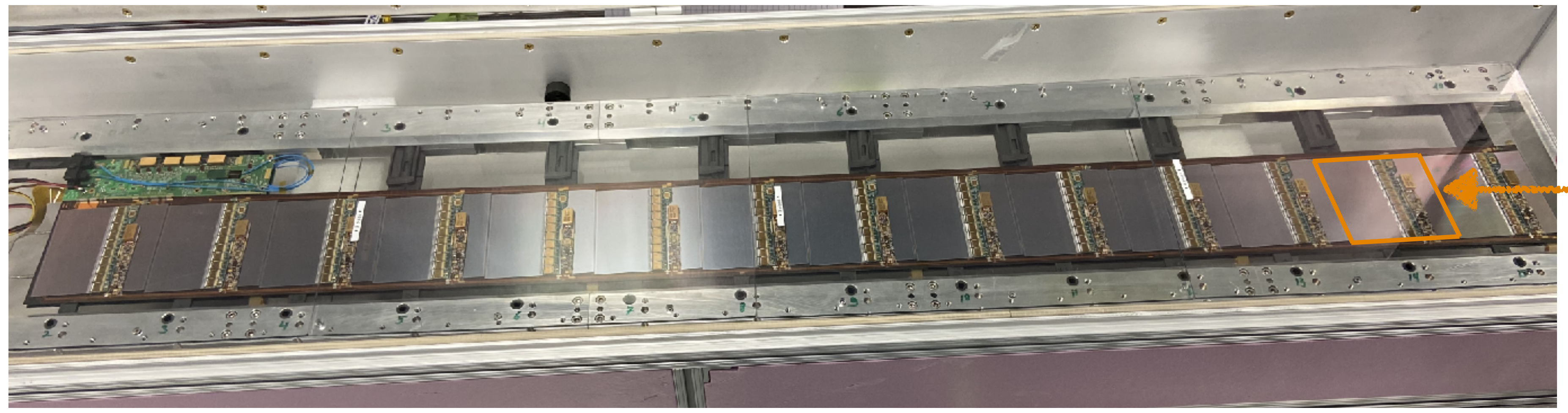
- **ITk Strip detectors**
  - ~165 m^2 silicon area
  - 17888 modules
  - ~60 million readout channels

ITk Strip Barrel

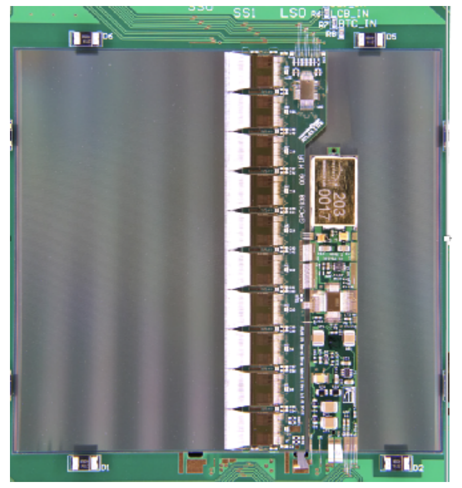
ATL-PHYS-PUB-2021-024



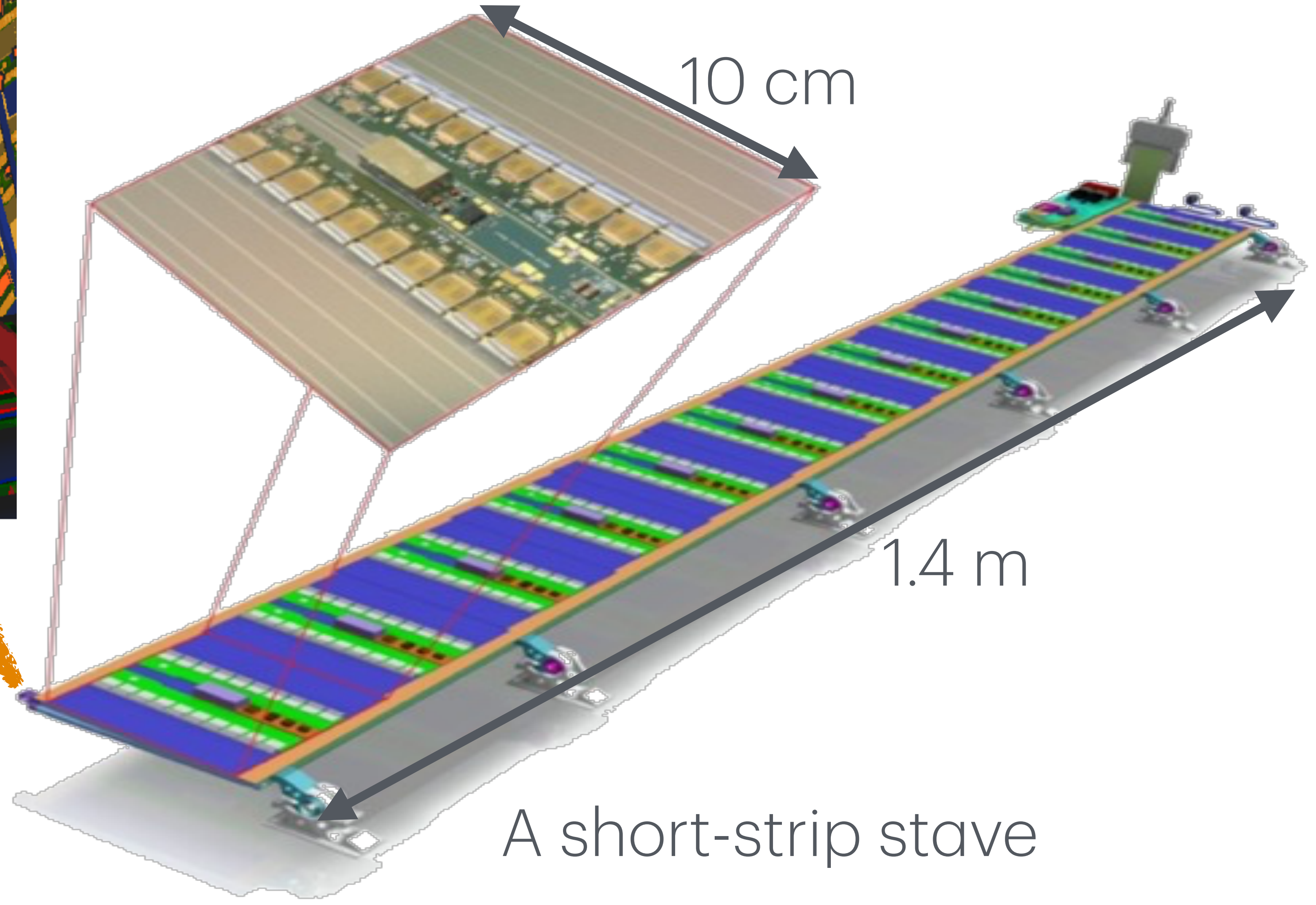
A long-strip stave



A long-strip module



A short-strip module

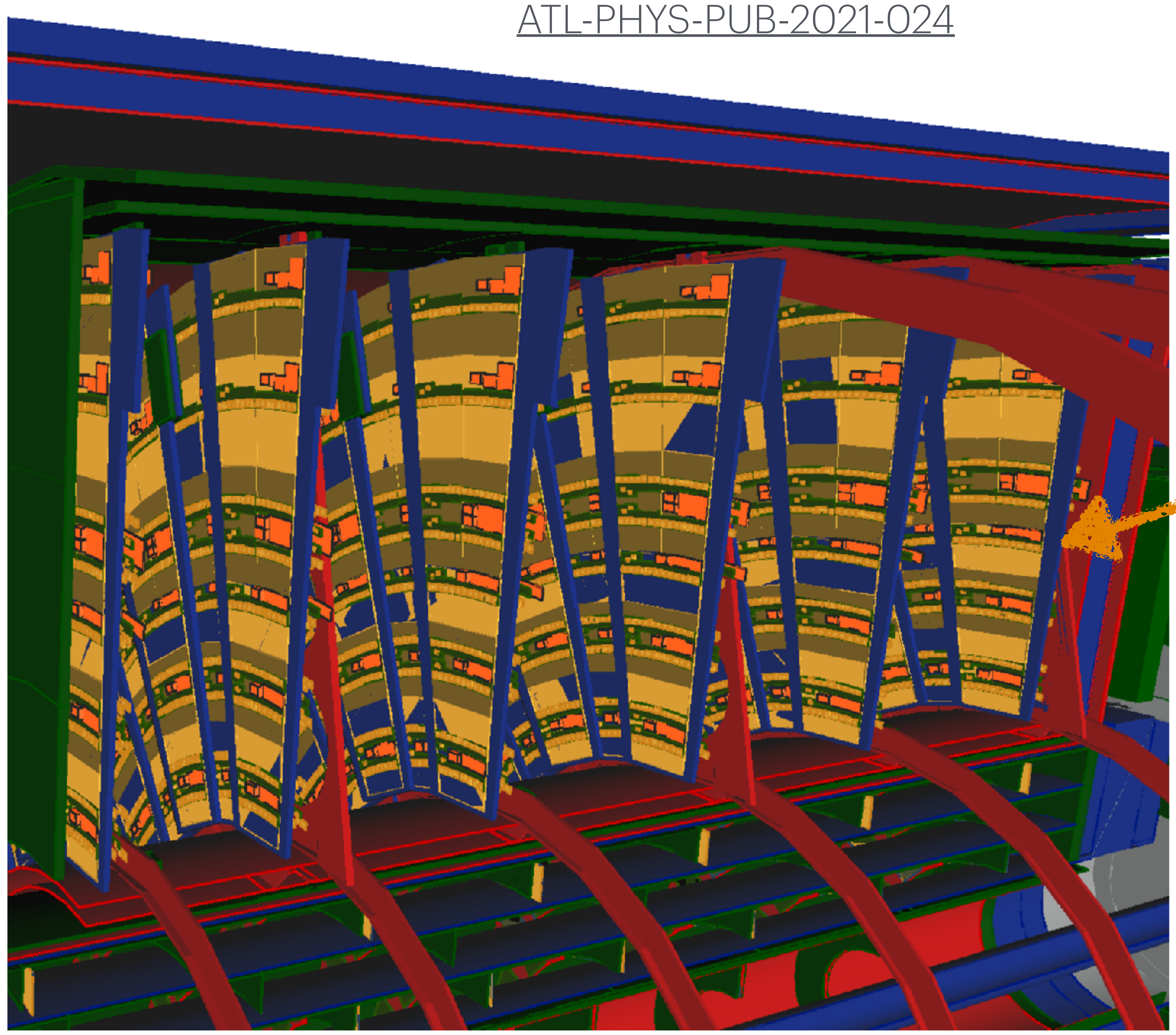


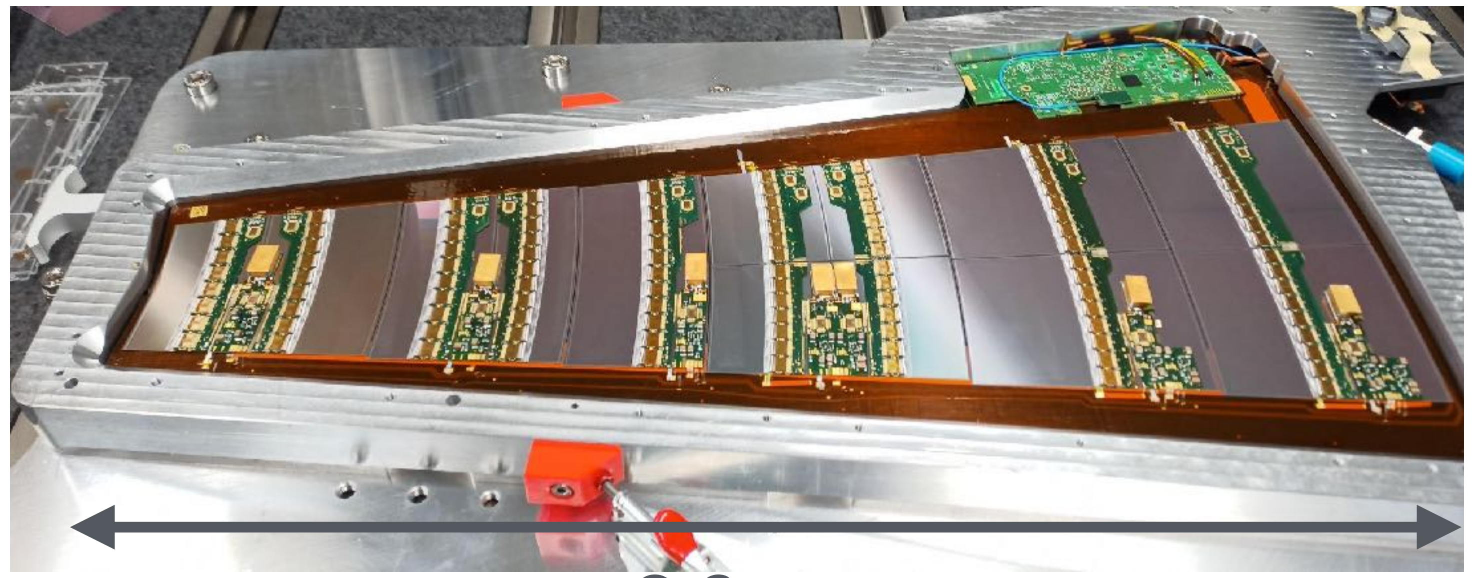
A short-strip stave

- **4 cylindrical layers of “staves”**
  - Outer 2 layers with long strips (LS)
  - Inner 2 layers with short strips (SS)
  - 392 staves in total
- **14 modules on each side of a stave**
  - Different module types for long strips and short strips
  - Modules are rotated around the stave axis by 26 mrad for stereo hits

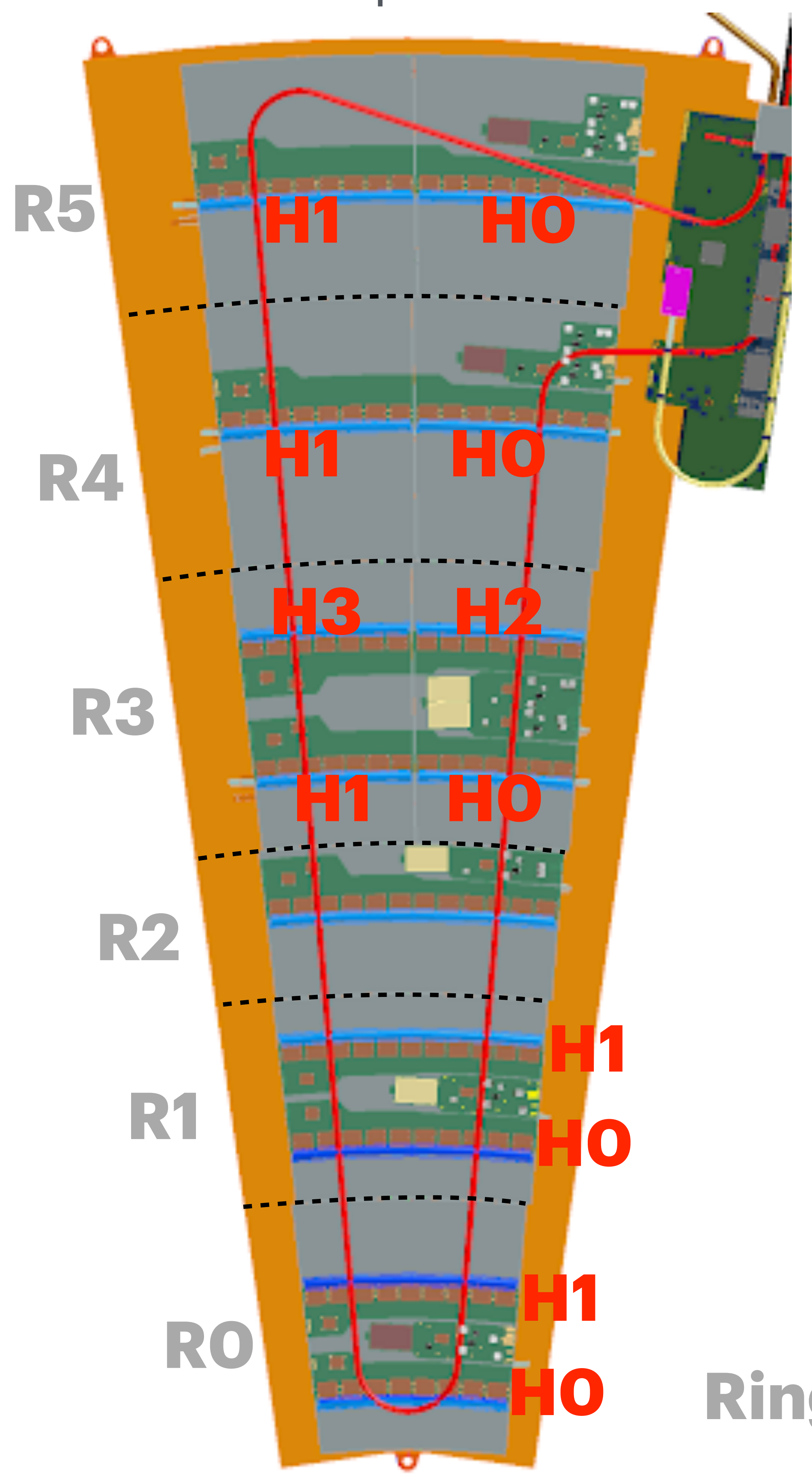
ITk Strip End-cap

ATL-PHYS-PUB-2021-024





A petal



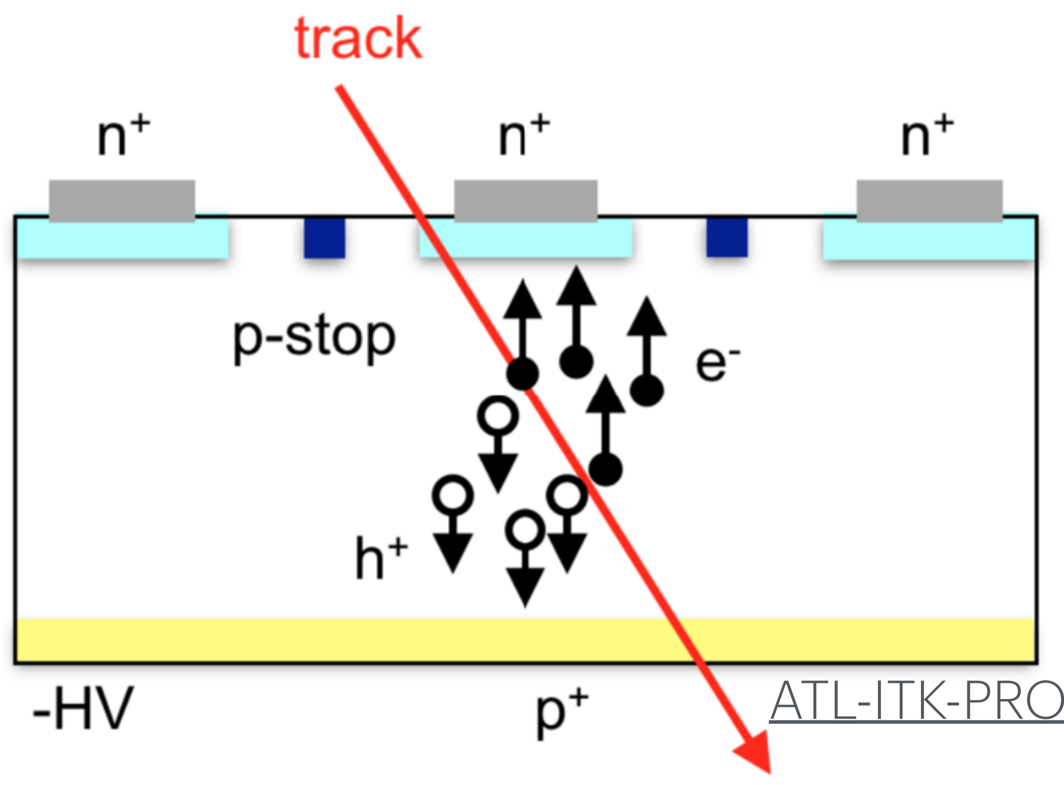
- **6 identical disks on each end**
  - Each disk comprises 32 “petals”
  - 192×2 petals in total
- **6 different types of ring modules on each side of a petal**
  - Built-in stereo angle: strips are rotated 20 mrad around the center of the sensor

Ring module type

Hybrid type

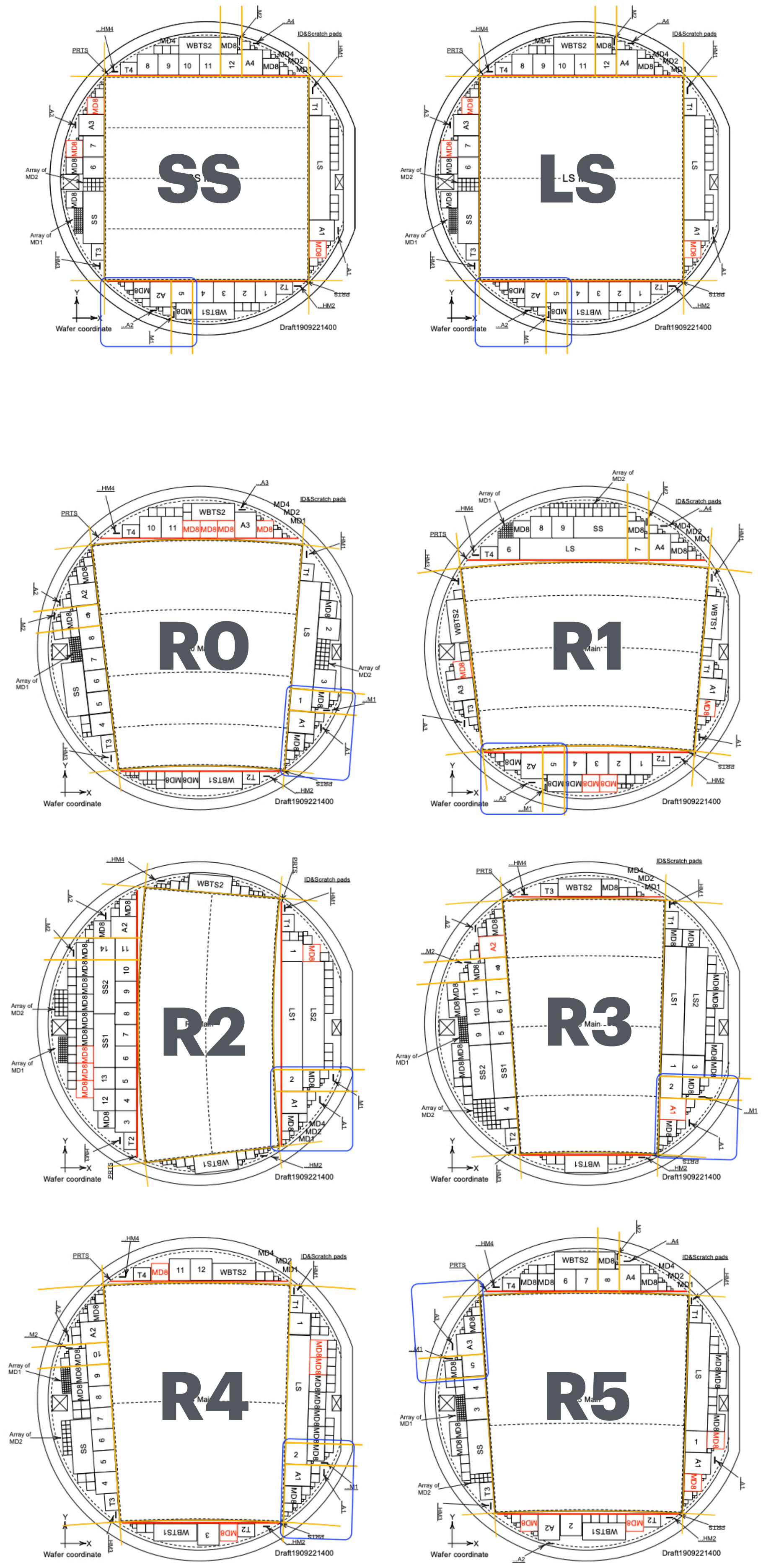
Sensor

- **n⁺-in-p FZ**: n-type implants in a p-type float-zone silicon bulk
    - More radiation tolerant than p-in-n
    - Good signal even under-depleted
    - Faster
- Strips are AC coupled
- **In production since August 2021**
    - Manufactured in 6-inch 320 μm thick wafers
    - As of May 2024, **76.5%** of the total target received (**63.3%** accepted)
    - Recovering the target delivery schedule



ATL-ITK-PROC-2019-003

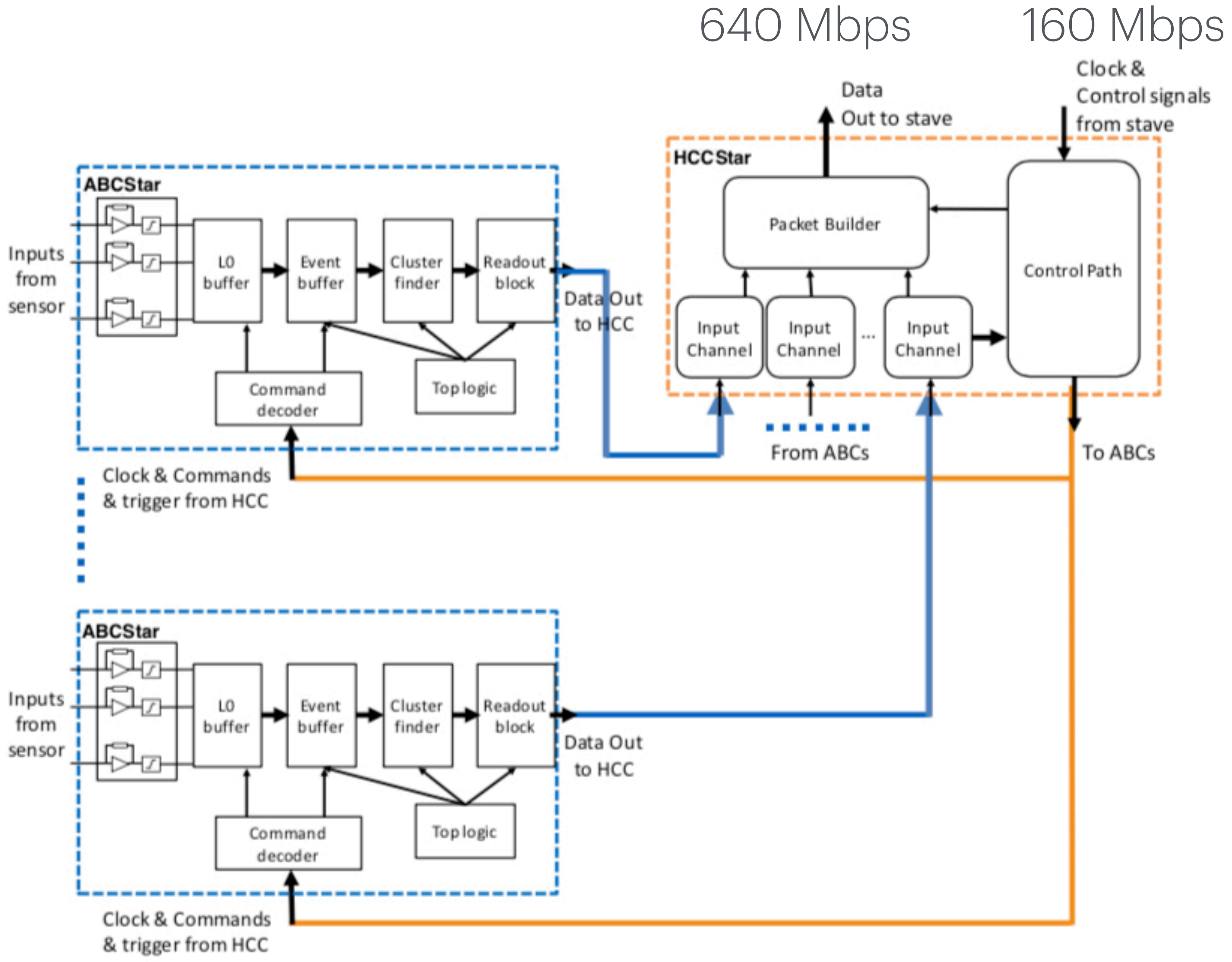
- **Barrel sensors**
    - 2 sensor geometries: **SS** and **LS**
    - Strip length: 2.4 cm for SS and 4.8 cm for LS
    - Strip pitch: 75.5 μm
- **End-cap sensors**
    - 6 sensor geometries: **R0** - **R5**
    - Strip length: 1.5 - 6 cm
    - Strip pitch: 70 - 80 μm



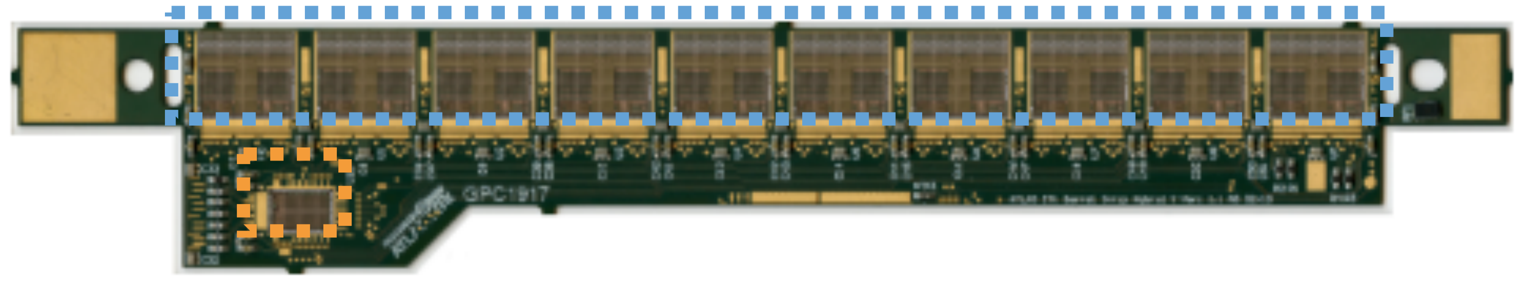
2023 JINST 18 T03008

ASIC

- **ASICs for readout and control**
  - Based on 130 nm CMOS technology
- One chipset for all types of modules
  - The **Star** architecture: point-to-point connections between each ABC and HCC
- Hosted on low-mass flexible PCBs called **hybrid**
  - 2 types for barrels
  - 13 types for end-caps



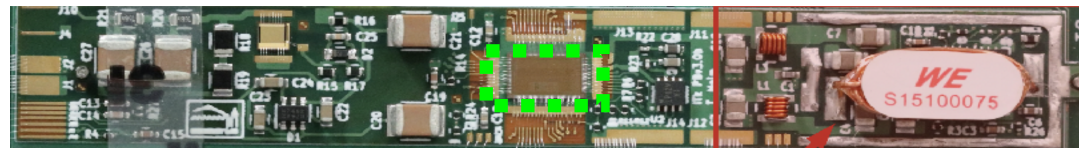
- **ABCStar**: ATLAS Binary Chip
  - Read analog signals from sensors and provide a binary readout per strip
  - Encode hit patterns in clusters



Y barrel hybrid

- **HCCStar**: Hybrid Control Chip
  - Aggregate and send out data packets from ABCStars
  - Send clock and control signals to ABCStars

- **AMACStar**: Autonomous Monitor and Control Chip
  - Module control and monitoring
  - Hosted on the power board

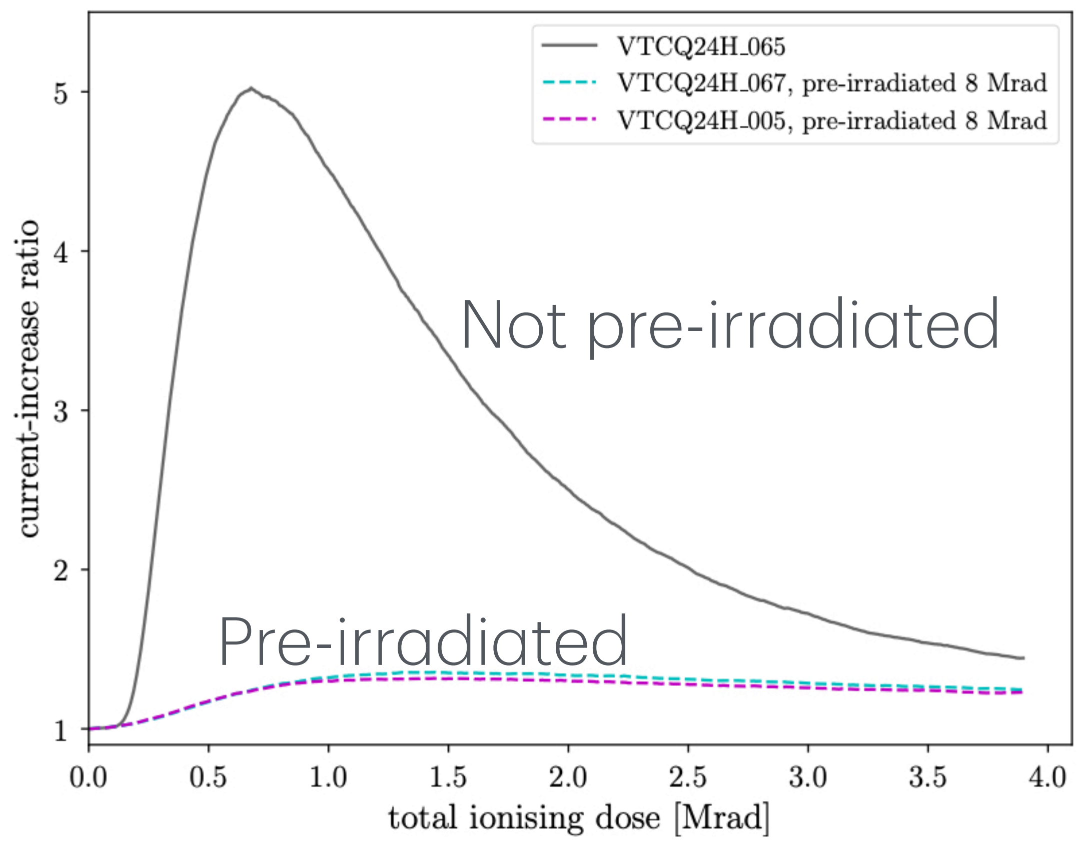


Barrel Power board

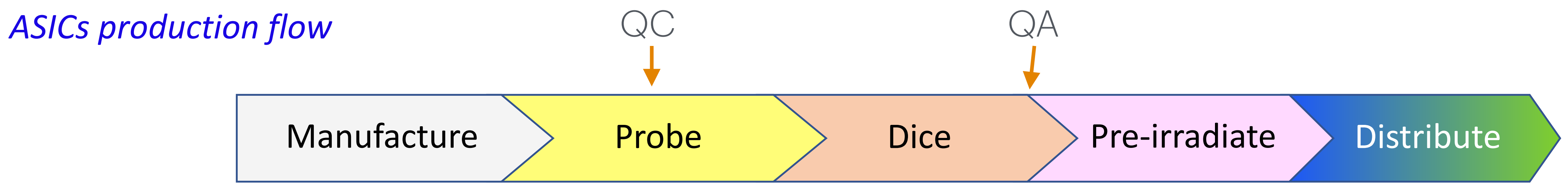
ASIC

- **Triplication** to mitigate **S**ingle **E**vent **E**ffects
  - Triplicating clocks, resets, logic blocks
  - Extensive tests and validations at test beams
- **Pre-irradiation** to mitigate **T**otal **I**onizing **D**ose effect
  - “TID bump”: increased leakage current at the beginning of data taking due to radiation

ATL-ITK-PROC-2018-015



- **ITk Strip ASICs are deep into production**

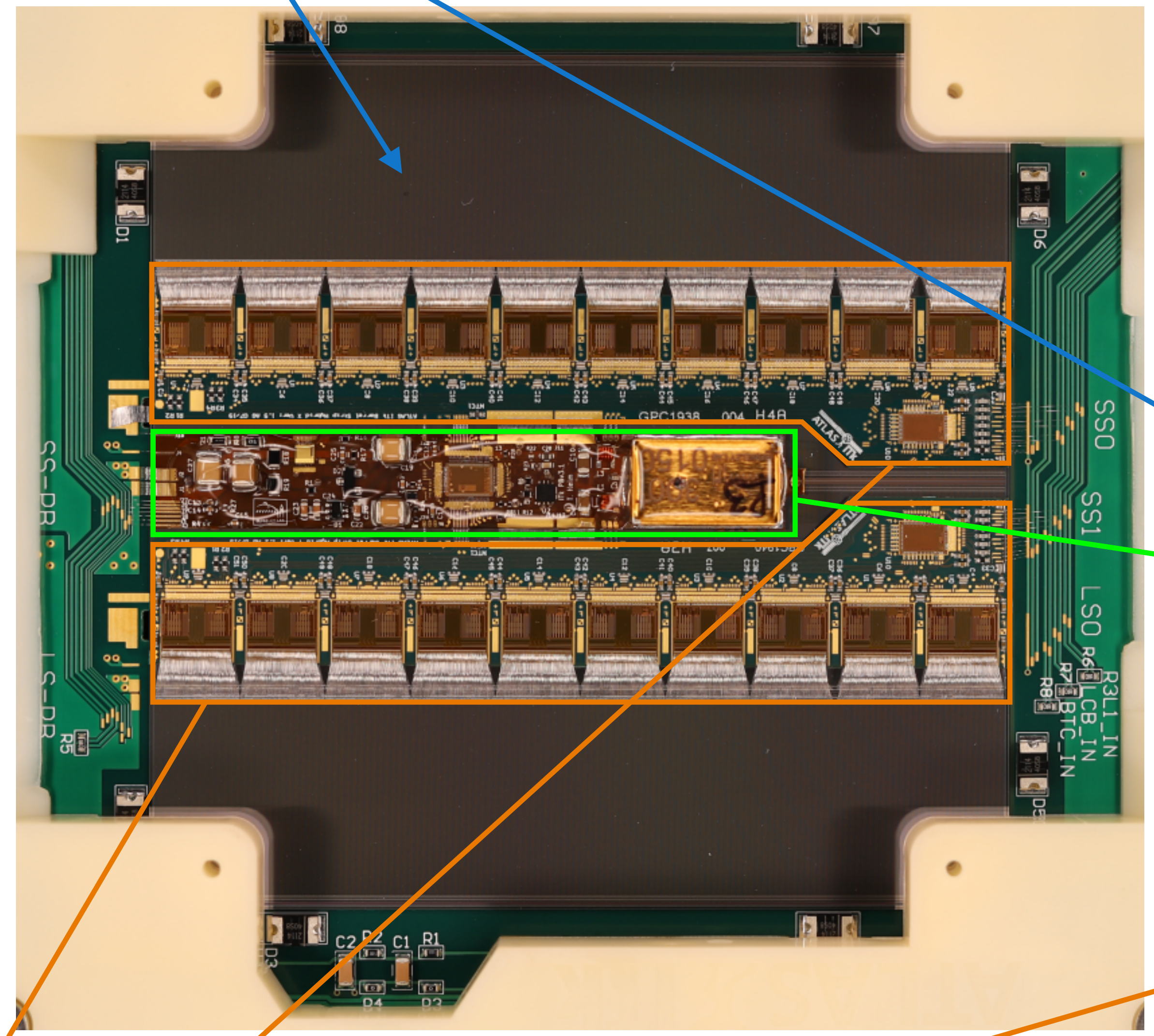


As of June 2024

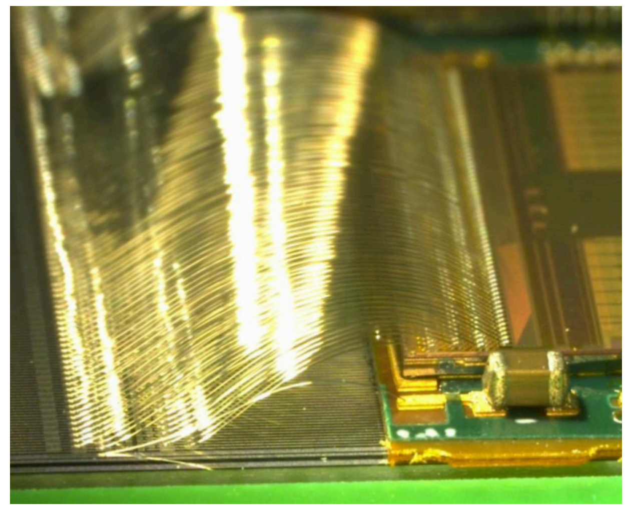
ASIC		Manufactured	Probed	Diced	Pre-Irradiated	Distributed
Overall	%	**106.9%**	**97.6%**	**68.3%**	**62.2%**	**6.2%**
ABCStar	%	**101.4%**	**92.0%**	**59.7%**	**52.5%**	**4.7%**
HCCStar	%	**121.0%**	**107.0%**	**104.5%**	**104.5%**	**5.9%**
AMACStar	%	**166.7%**	**166.7%**	**143.9%**	**43.8%**	**28.6%**
PP2 AMACStar (thinner die)	%	**127.6%**	**127.6%**	**0%**	**Not applicable**	**0%**

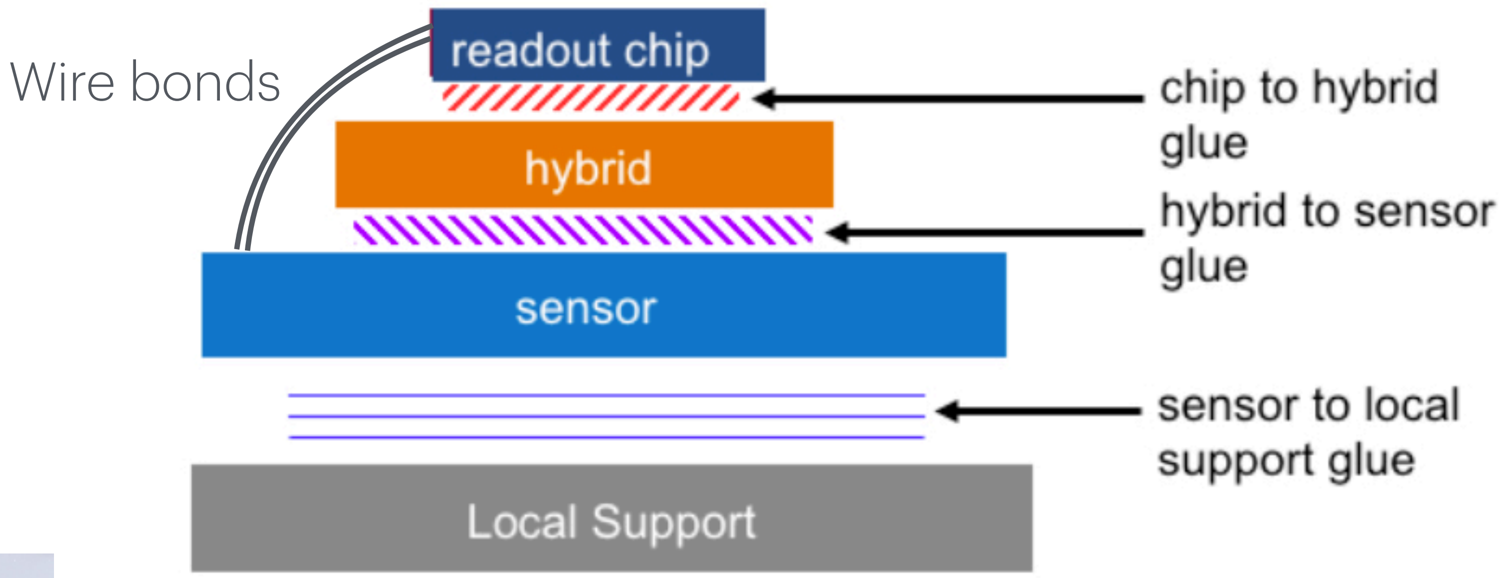
Module

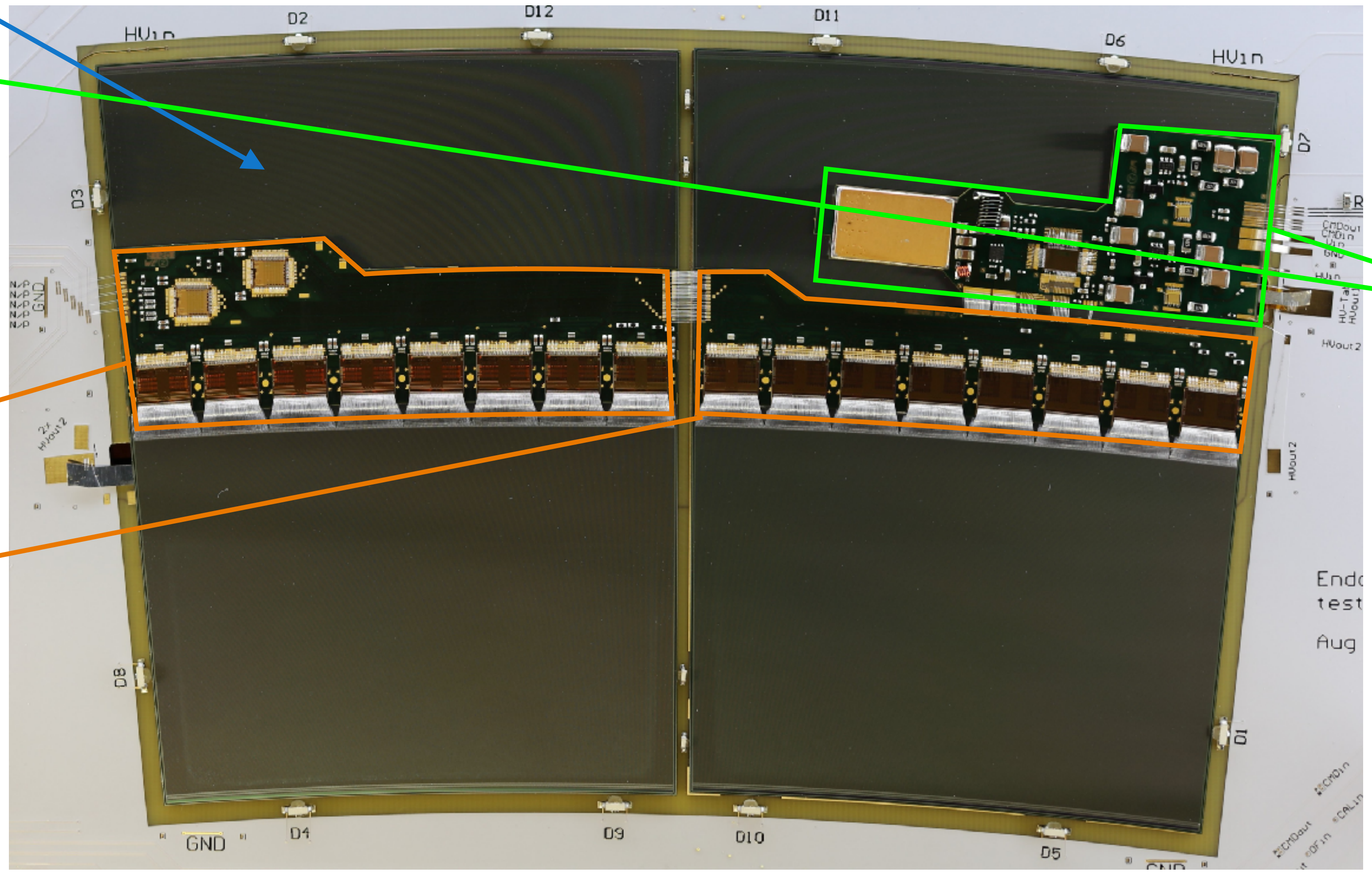
- **Silicon sensors** + **hybrids** + **power board**



A barrel SS module in the test frame







An end-cap R4 module

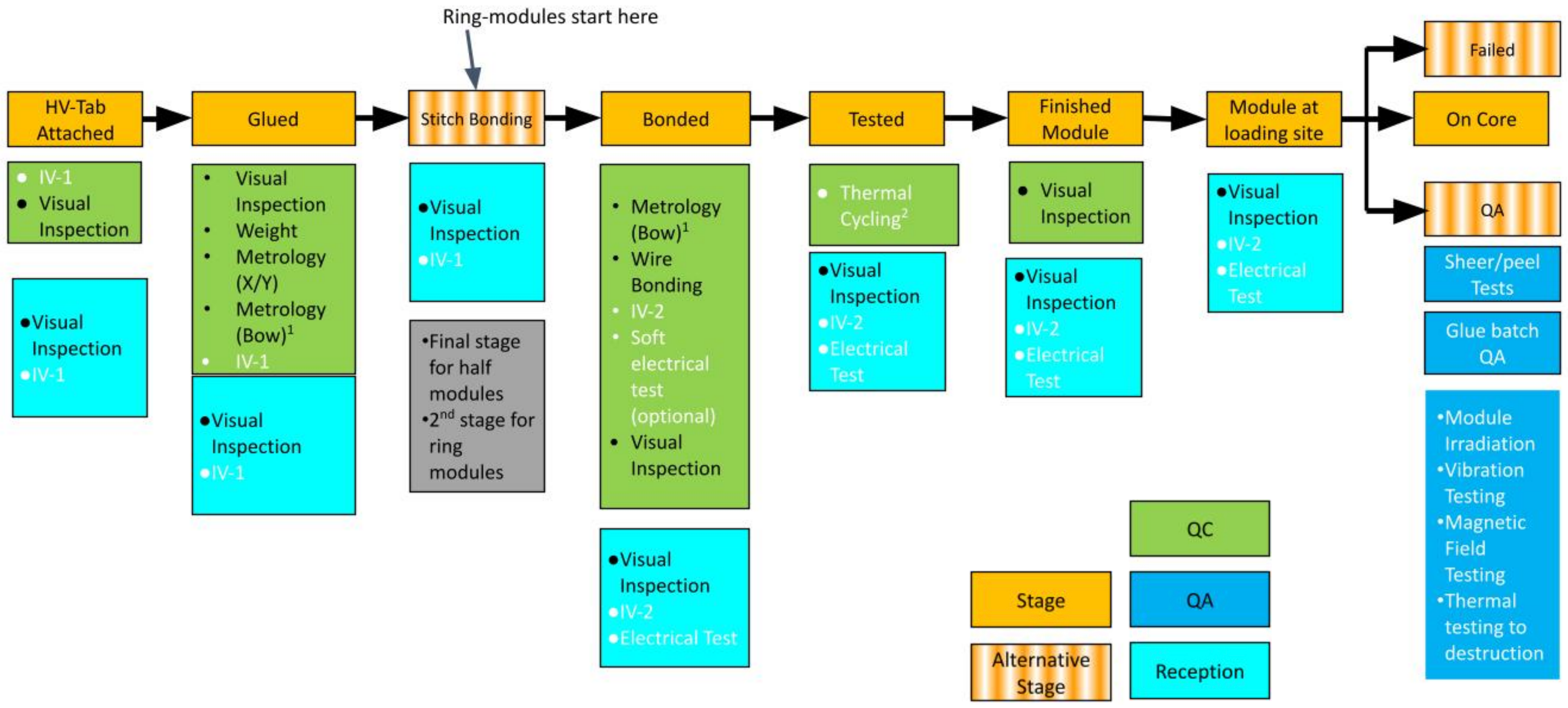
- **Hybrids**
  - Glued directly onto sensors
  - 1 HCC chip + 6~11 ABCs
  - ABC chips are wire-bonded to sensors

- **Power board**
  - Glued directly onto sensors
  - Wire-bonded to hybrids
  - 1 or 2 AMAC
  - High voltage switches for sensor biasing
  - Low voltage DC-DC converters in the shield box

Module

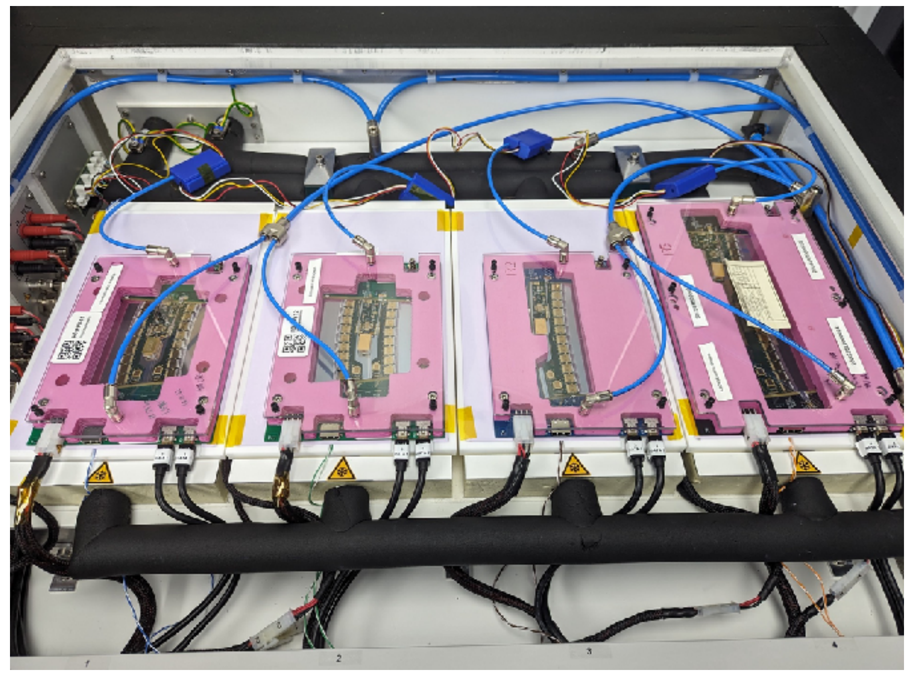
- **Streamlined production**
  - Dedicated high-precision tools for different module types
  - Precision assembly: from sensor positioning to glue thickness
- **Rigorous QC/QA** procedures at every production stage
  - Visual inspections and metrology
  - IV curves
  - Thermal cycling
  - Hybrid burn-in test
- **Towards full production**
  - Nearly all (93%) module sites are now production ready
  - Two technical issues currently under investigation before production can be started
    - "Cold noise" and "sensor cracking"

Module Assembly pipeline



☞ Poster on the module pre-production by Jia Jian Teoh

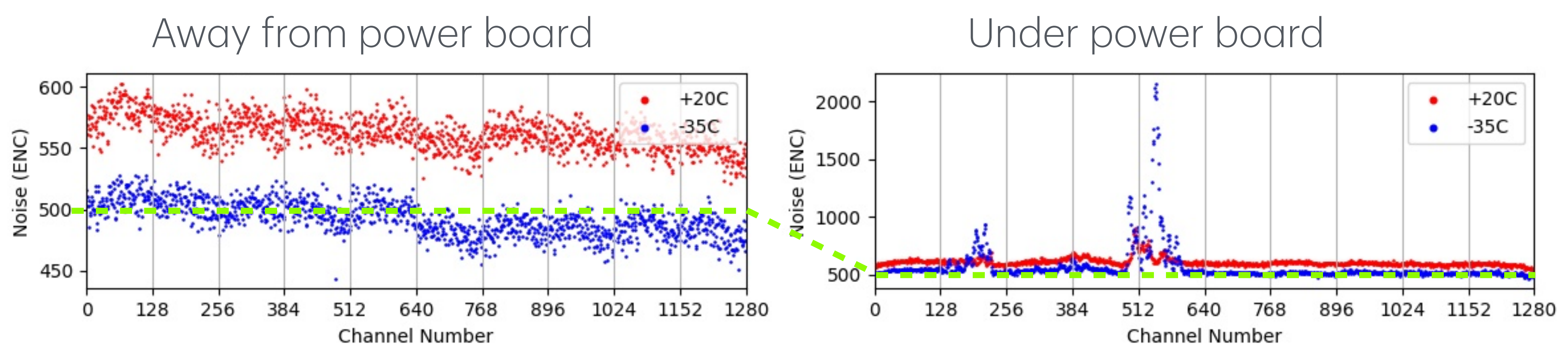
☞ Poster on module performance at test beams by Radek Privara



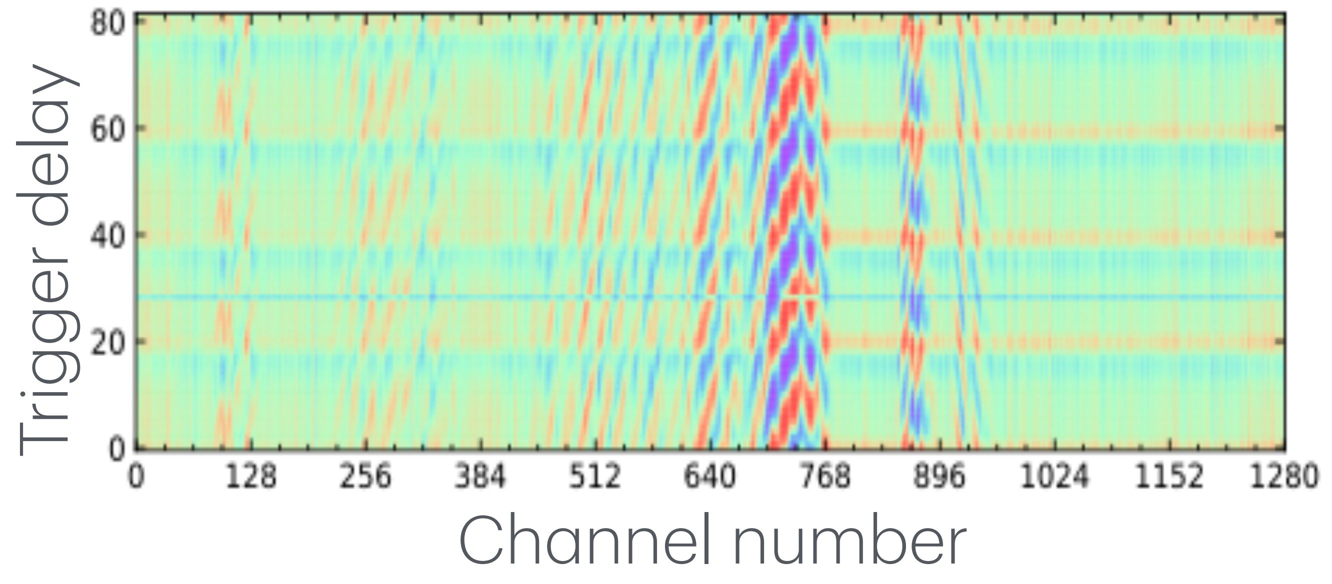
End-cap coldbox

Cold Noise

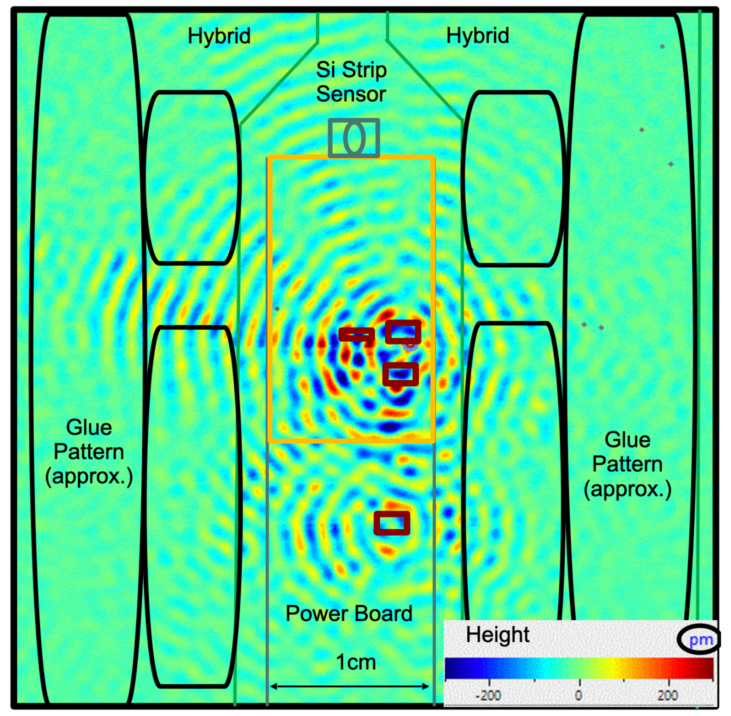
- Observed **clusters of noisy channels around -35 °C**
  - Some remain noisy even when going warm afterwards
  - Noisy channels only in rows of strips below the power board
- **Extensive testing and investigations**
  - **Source identified**: mechanical vibrations
  - How mechanical wave inducing electrical signal under active investigation
- **Mitigations: changing the glue type**
  - No cold noise in the barrel LS modules and EC modules
  - Cold noise reduced but still detectable in the barrel SS modules with the new glue type
  - Impact on the tracking performance due to cold noise on the SS modules under evaluation
- **Cold noise no longer blocks the start of module production**

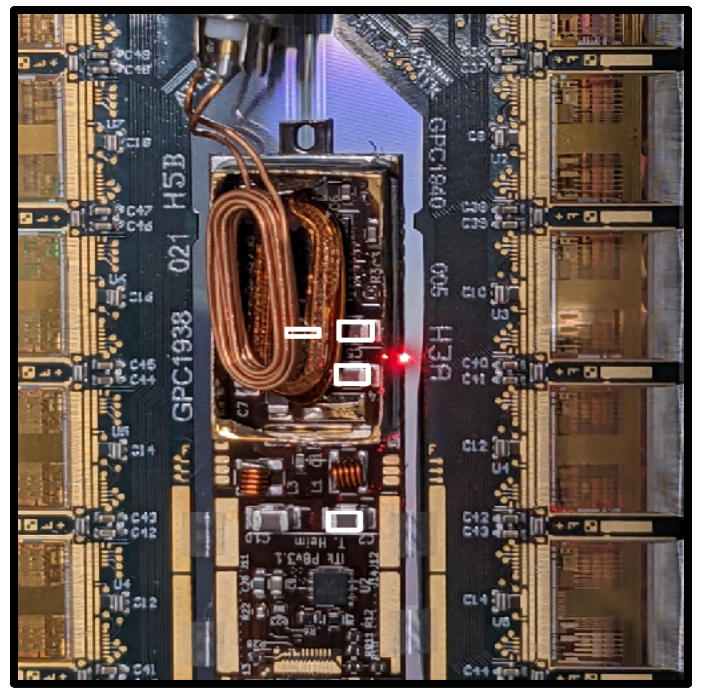


- DC-DC synchronous triggering: cold noise in phase with the 2 MHz DC-DC switching frequency

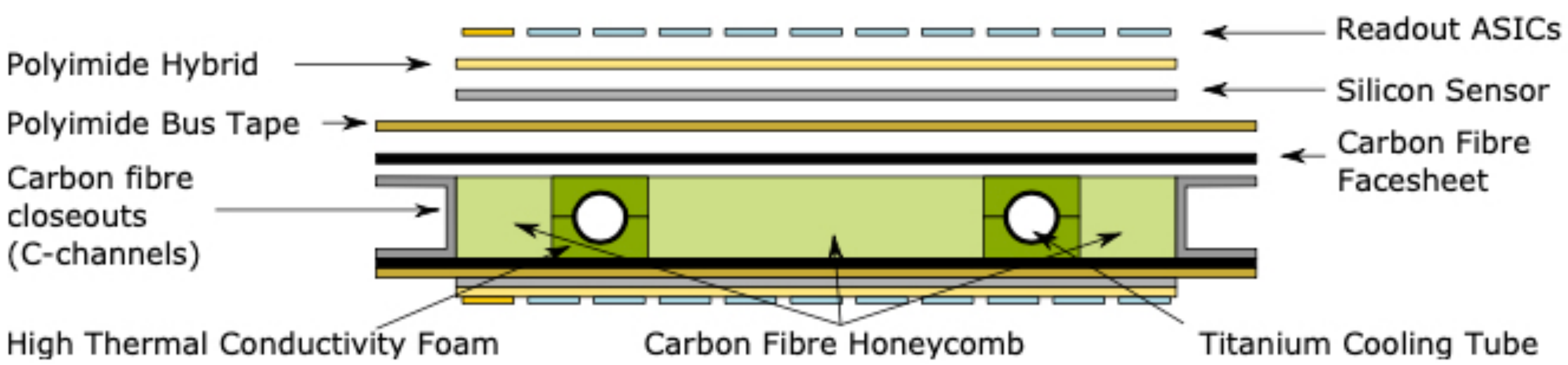


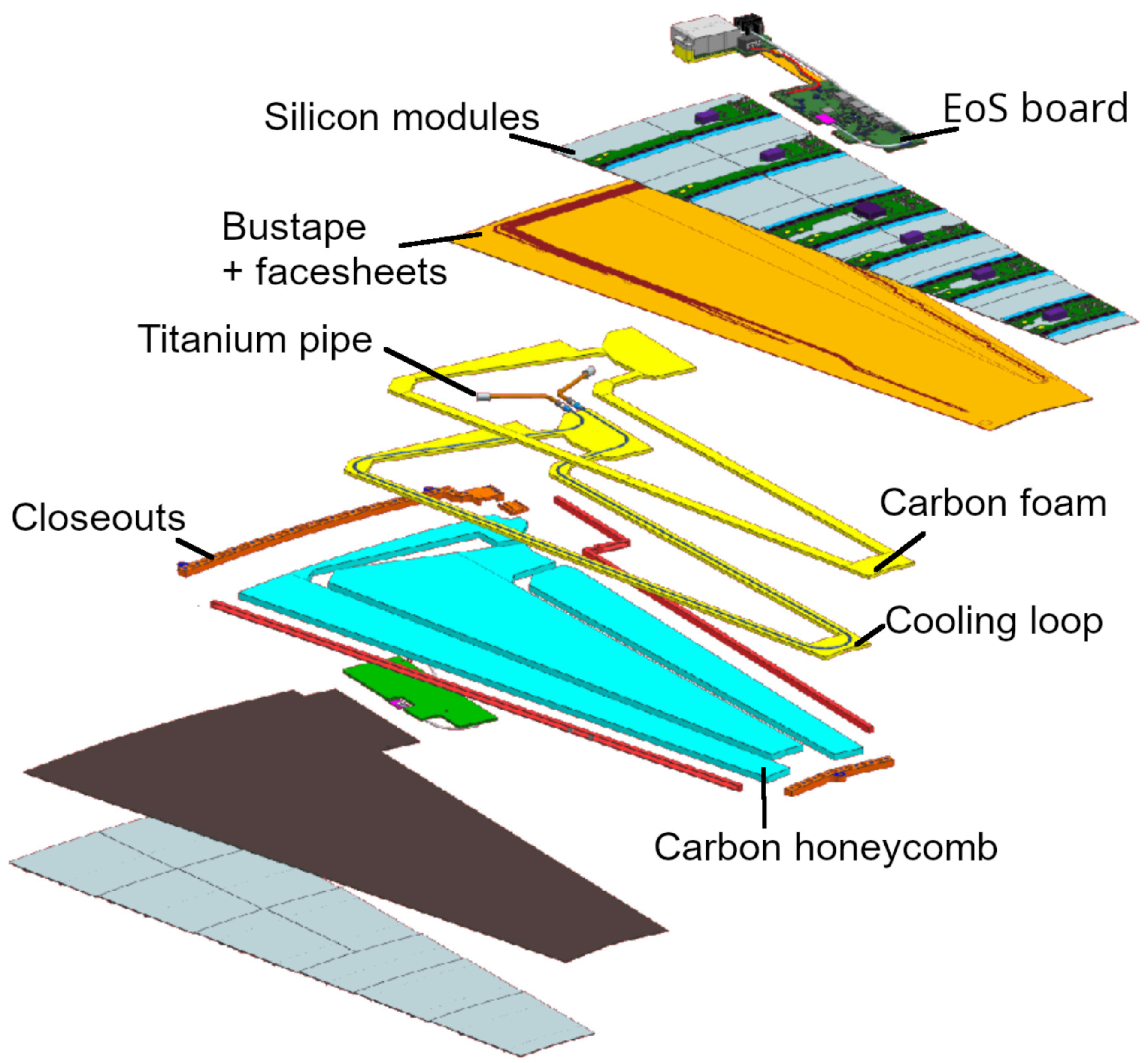
- Laser vibrometer shows mechanical vibrations originating from **capacitors on the power board** and propagating through sensors



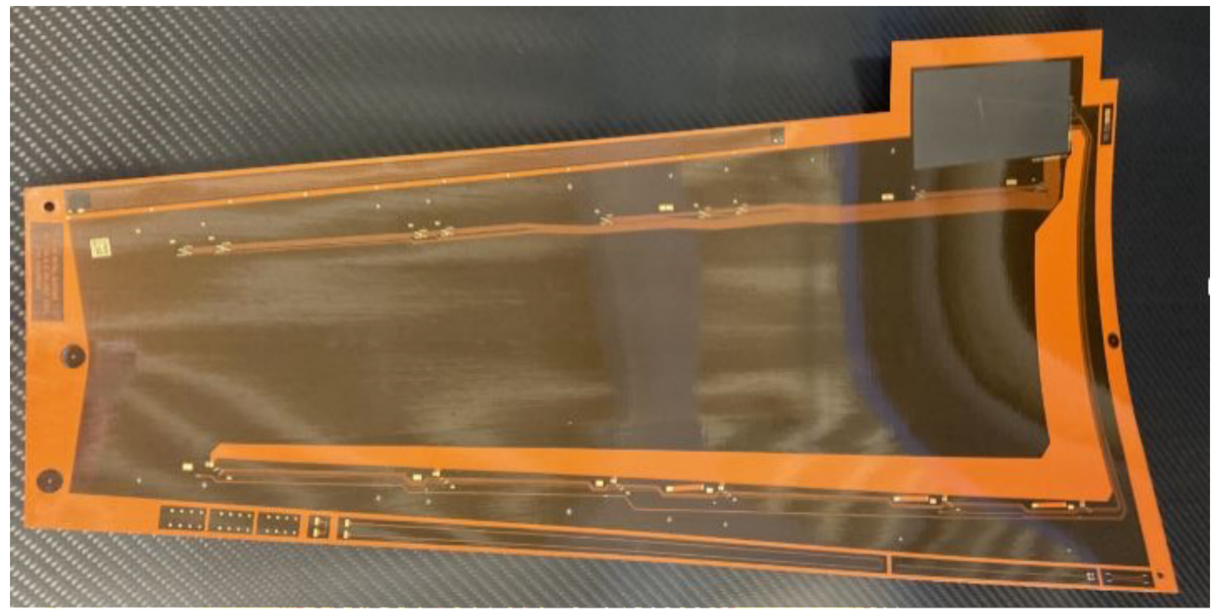


Local support





- **Stave and petal cores**
  - Low mass, good thermal and electrical properties
  - Carbon fibre structures supporting modules and End-of-Substructure (EoS) cards
  - Built-in cooling: titanium pipe circulating CO_2
  - Kapton bus tapes for routing electrical connections
- **Bus tapes and petal cores in production**
- **Stave cores** getting ready for production
  - A local flatness issue under investigation



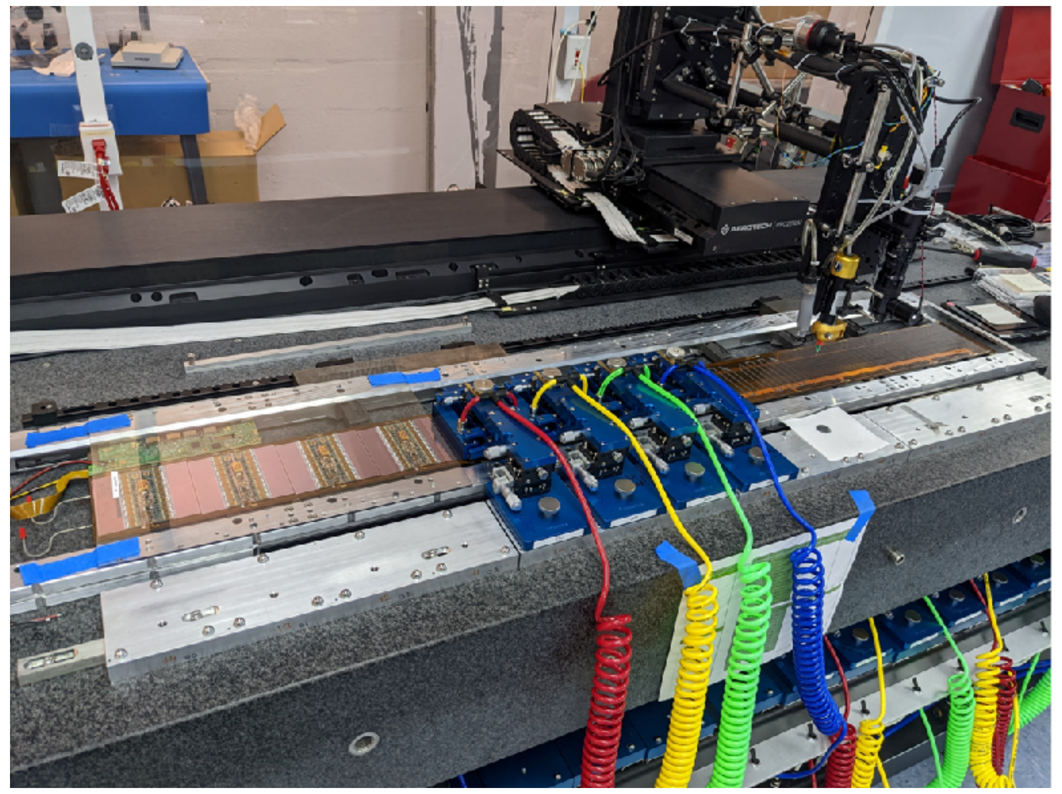
Petal bus tape

Module Loading

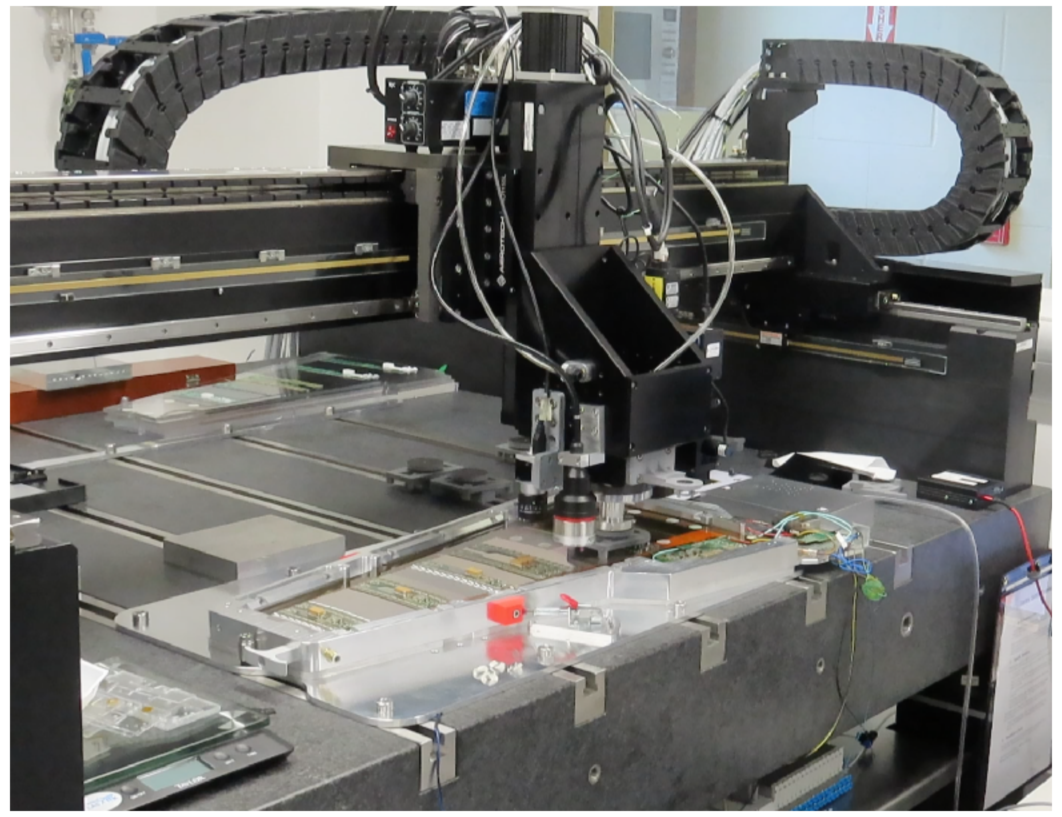
- **Modules are glued to both sides of the core**
  - Using custom gantry
  - Connected to bus tapes via wire bonds
- **Stave and petal QC**
  - Metrology
  - Electrical test
  - Thermal cycling
  - ...

☞ Talk on stave and petal assembly by Bernd Stelzer

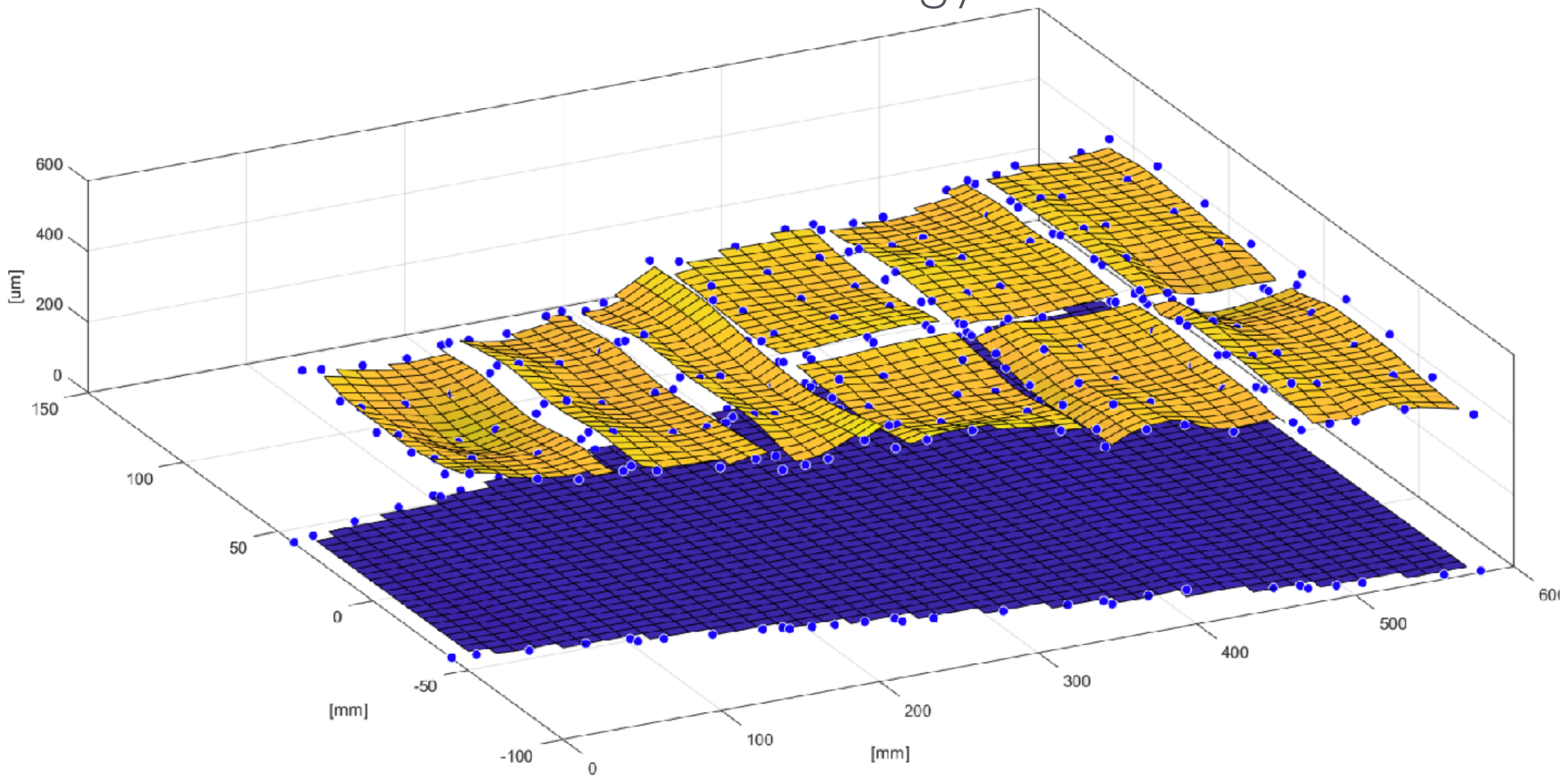
Stave loading station



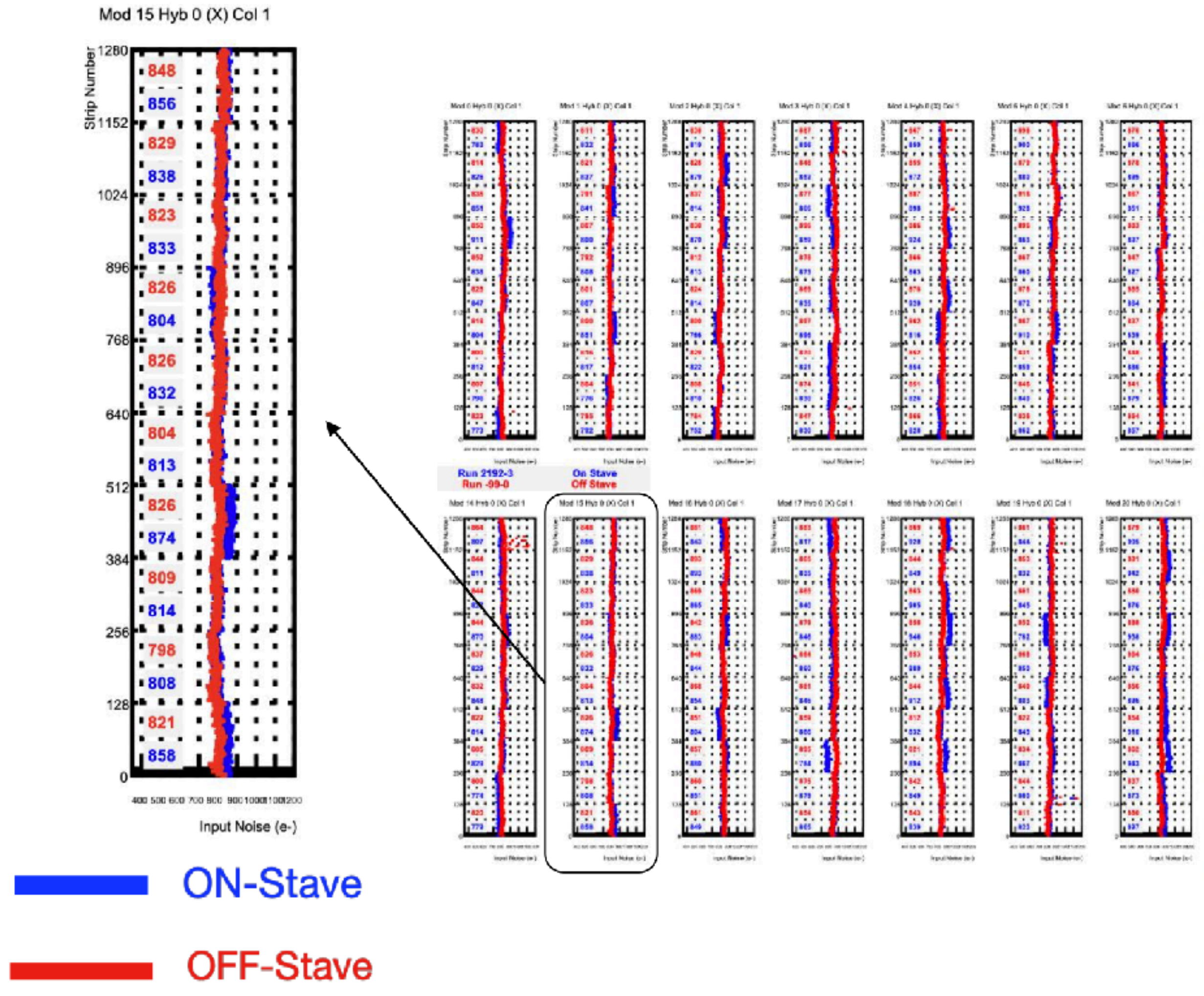
Petal loading station



Petal metrology

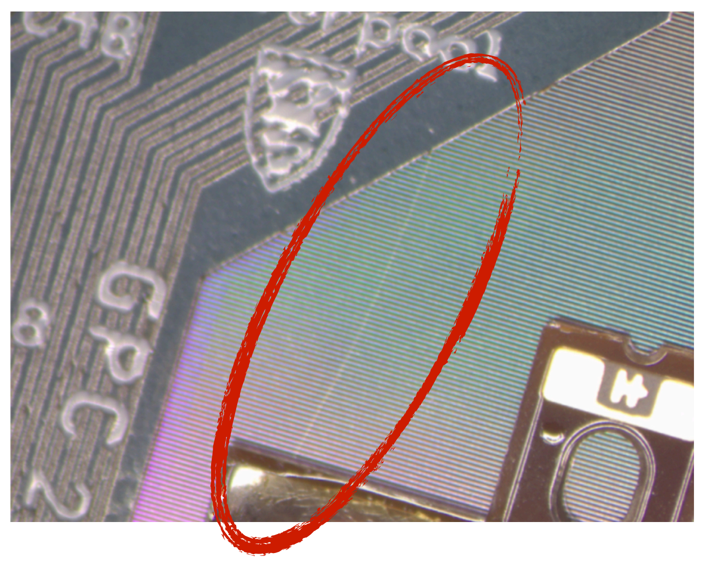


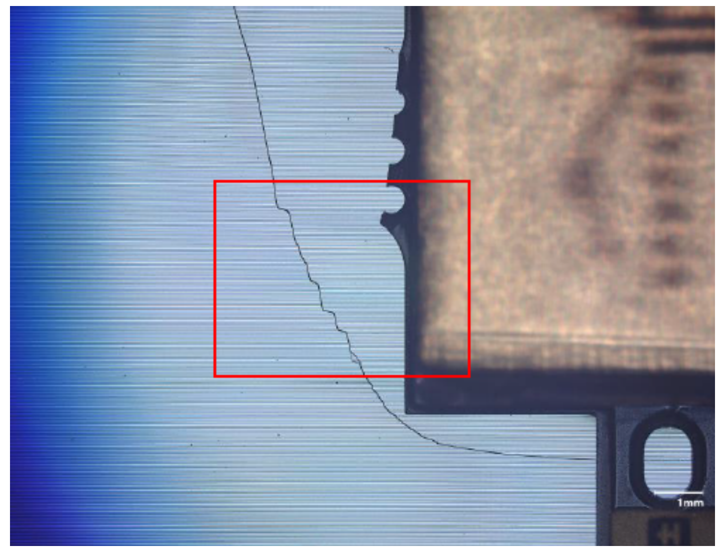
Stave electrical noise tests

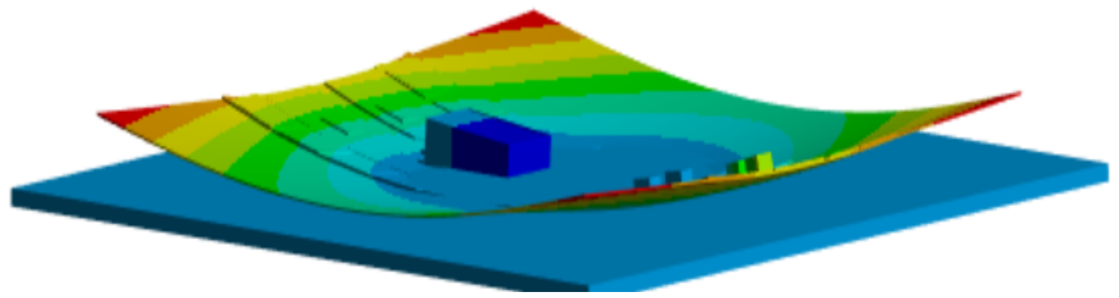


Sensor Cracking

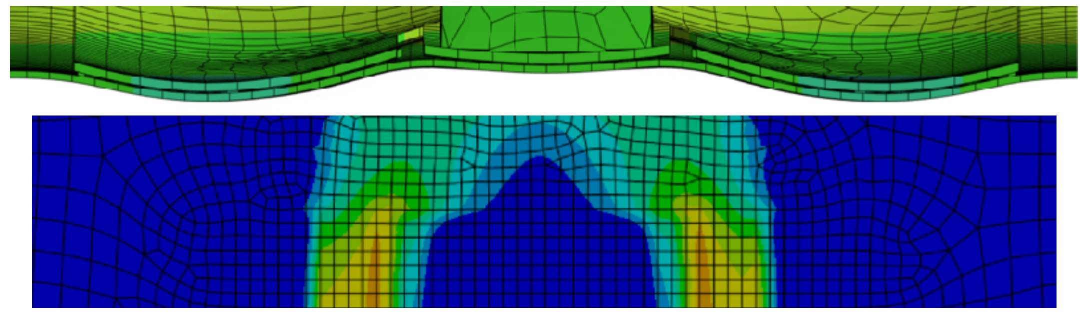
- A fraction (~8%) of sensors had **early breakdown** in stave and petal cold tests
  - Below 500V bias specification (some even below 100V)
  - Only after mounted on staves or petals
  - Cracks typically located around the power board
- **Coefficients of Thermal Expansion (CTE) mismatch** between electronics and sensors causes stress
  - Hybrid/power board flexes curl up more strongly than sensors at low temperature
  - Different stiffness of glue below and above sensors cause localized stress



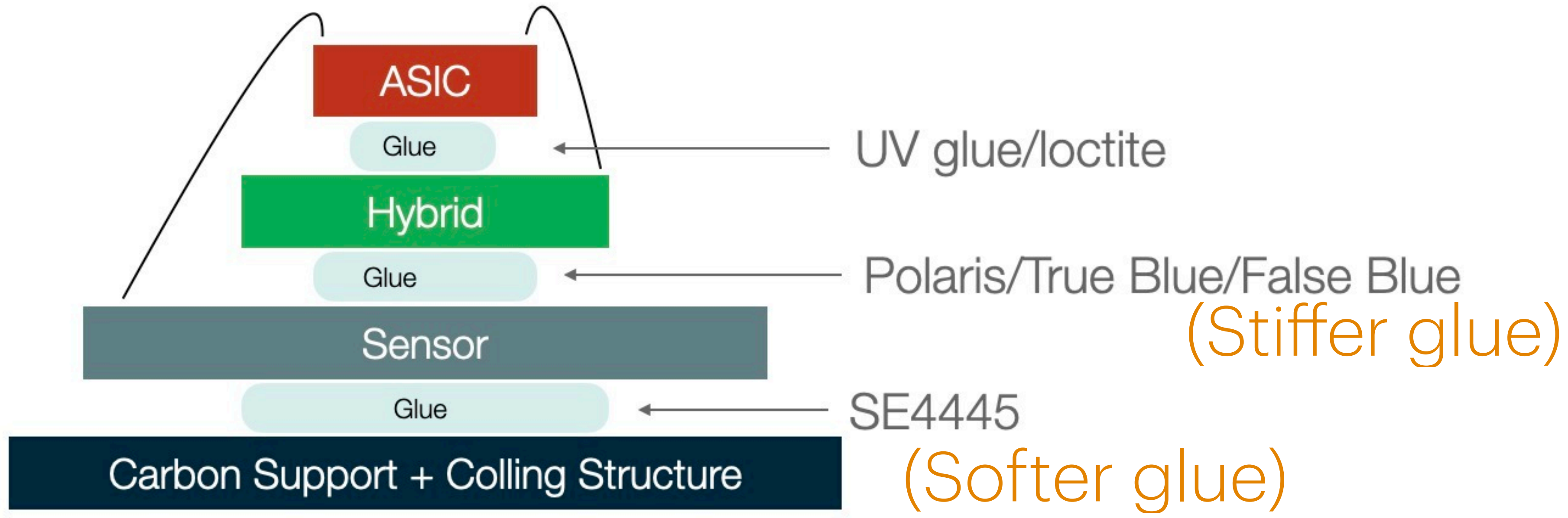


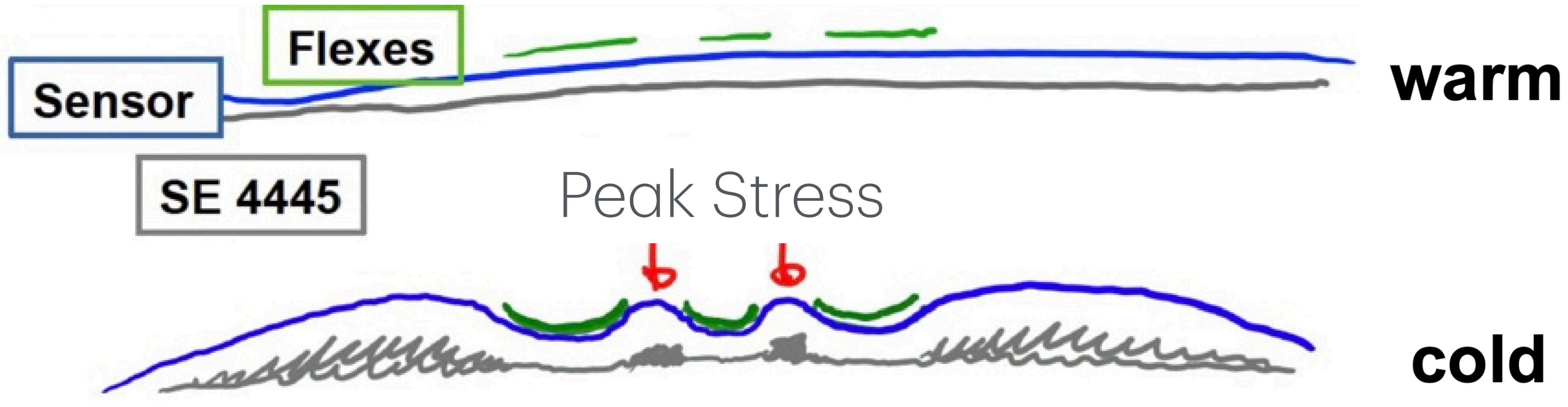


Free sensor



Sensor glued to stave

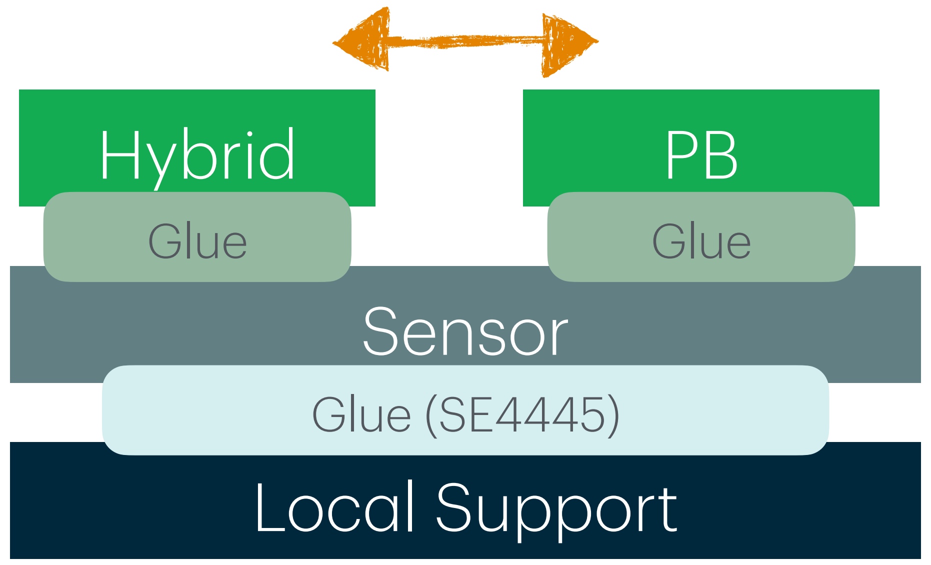


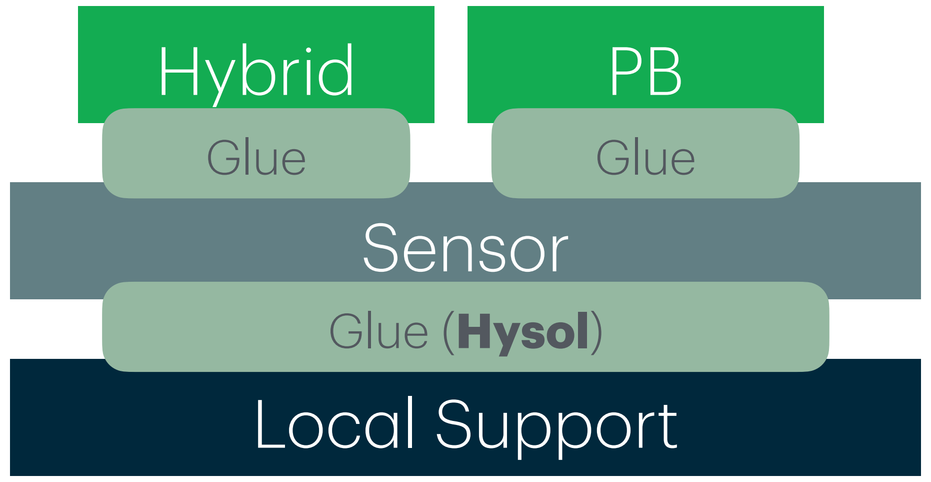


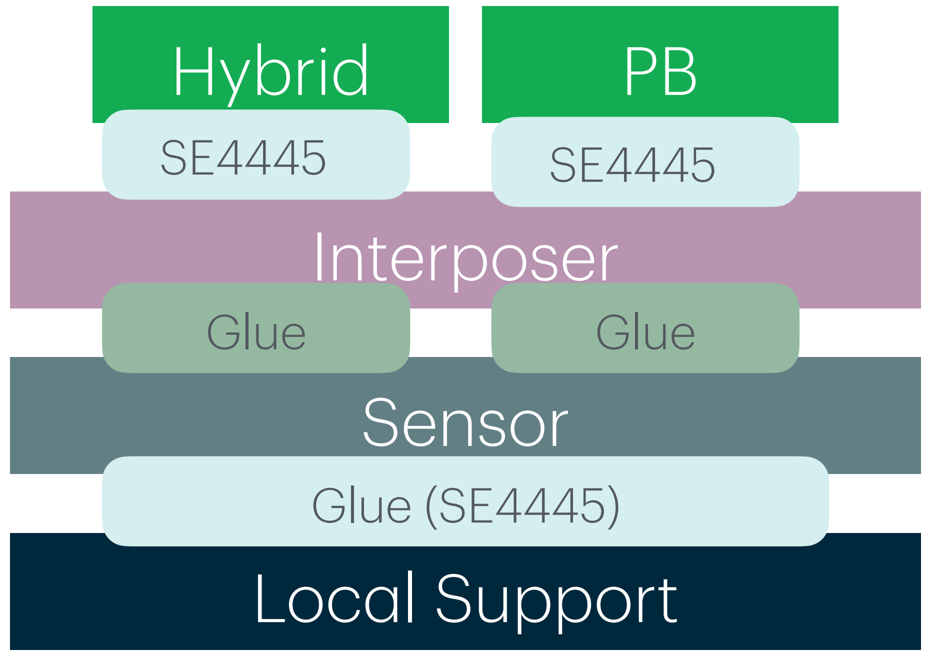
Sensor Cracking

- **Mitigation methods are under development and evaluation**

- "**Wide gap**":
  - Increase gaps between hybrids and power board (PB)
  - Peak stress reduction in simulation: 10-20%
  - Easiest solution among the options
  - Not applicable to all module types though
- "**Hysol**":
  - Use a stiffer glue between sensor and local support to reduce localized stress
    - SE4445 → Hysol
  - Peak stress reduction in simulation: 40-50%
  - Relatively easier solution
- "**Interposer**":
  - Add an additional Kapton layer between hybrid/PB and sensors
  - Peak stress reduction: ~95%
  - Major module design change + additional QC steps
  - **Bonus**: no cold noise observed on SS modules with interposers!





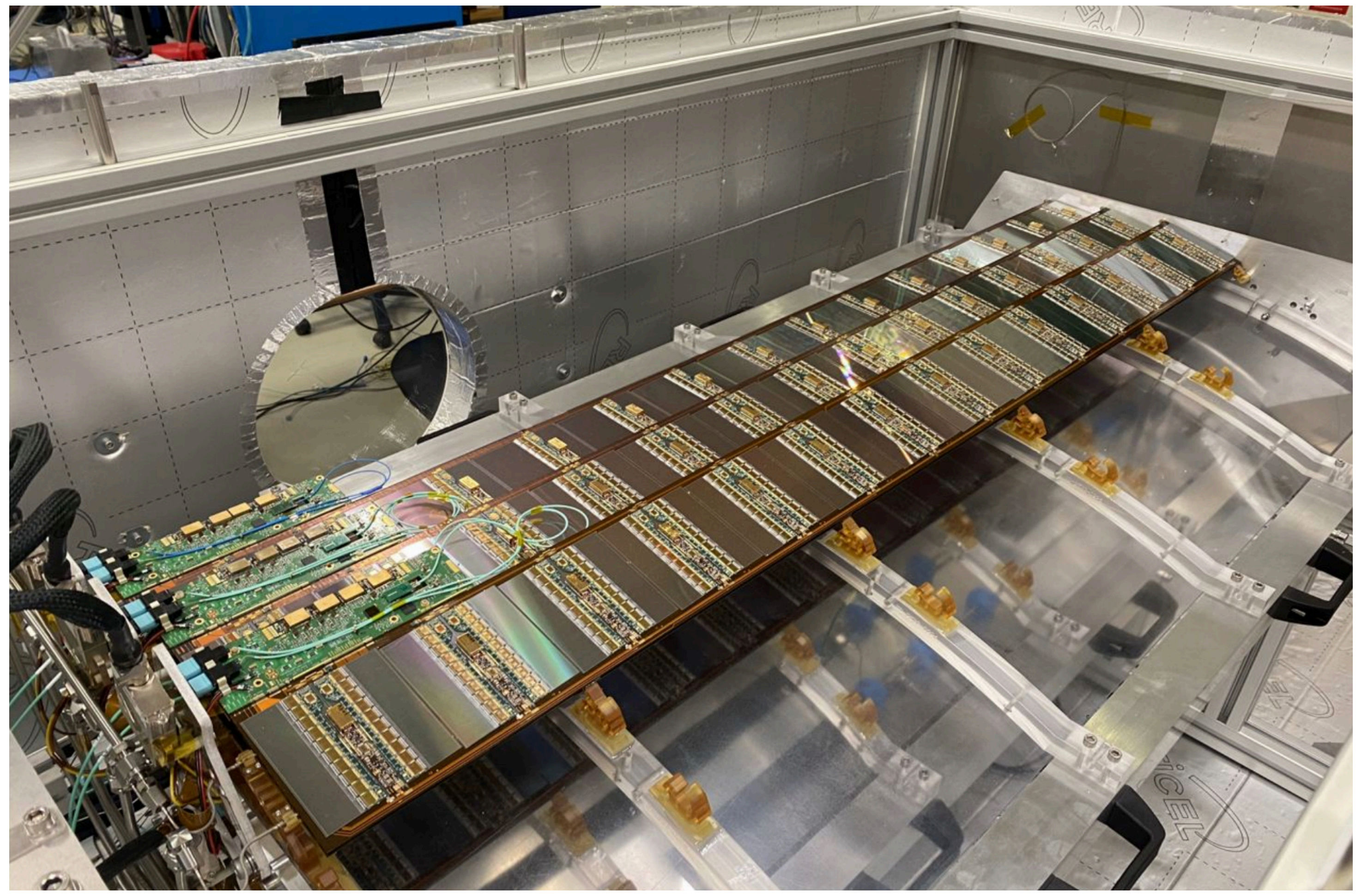


System Test

- **To demonstrate the full-system performance** from pre-production components using the complete service chain
  - Complete **power** chain
  - CO_2 dual-phase **cooling** system
  - Thermal box providing **dry air** and environmental **monitoring**
  - Hardware **interlock**
  - **Readout** chain targeting the final DAQ system
- **Barrel system test @ CERN**
  - Custom barrel support structure to host max. 8 staves
  - Currently populated with 4
- **End-cap system test @ DESY**
  - Realistic end-cap carbon-fiber support structure to host max. 12 petals
  - Currently populated with 1

👉 Poster on the system tests by ZT

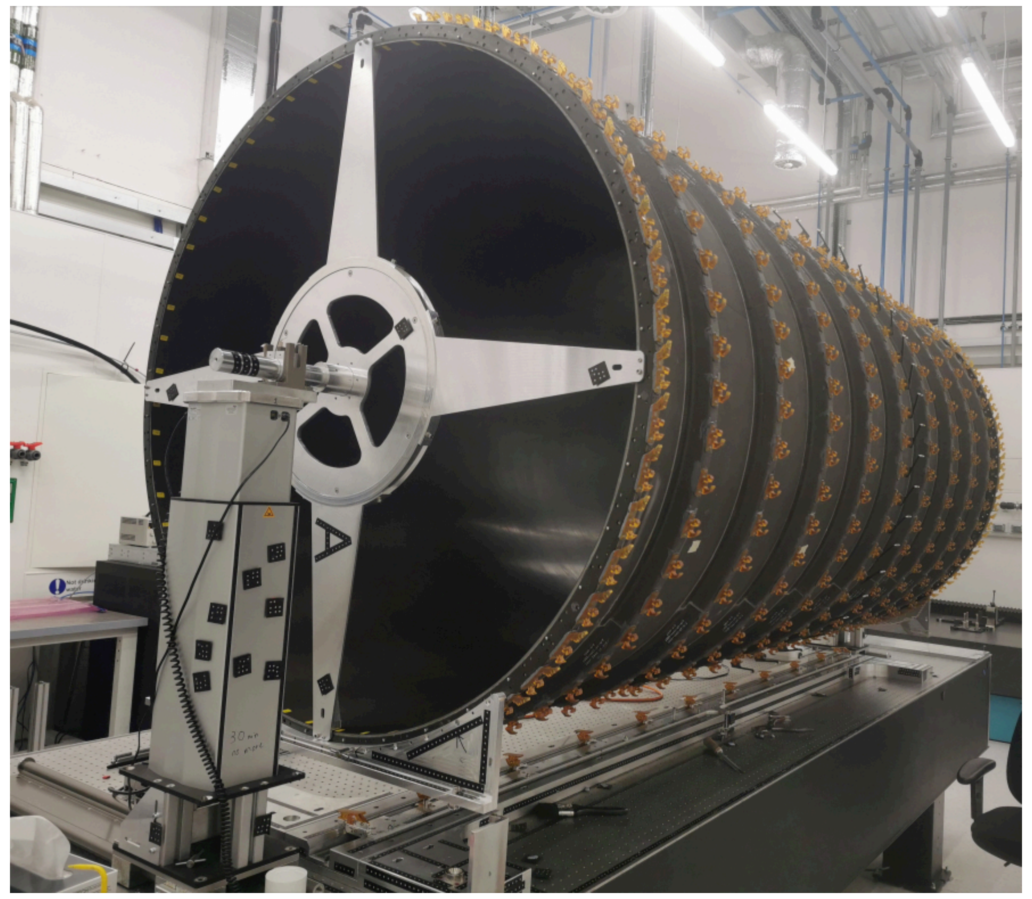
Barrel system test @ CERN



End-cap system test @ DESY

Integration

- Global structures are mostly made out of carbon fiber-reinforced plastic (CFRP)
- The **Outer Cylinder** has arrived at CERN ITk integration area!
- **Four barrel support cylinders**
  - L3 ready at CERN
  - L2 at Oxford in preparation
  - Stave integration @ CERN
- Both **end-cap structures** ready at NIKHEF
  - One is being transported to DESY
  - Petal integration @ DESY and NIKHEF
  - Fully loaded end-caps will be transported to CERN



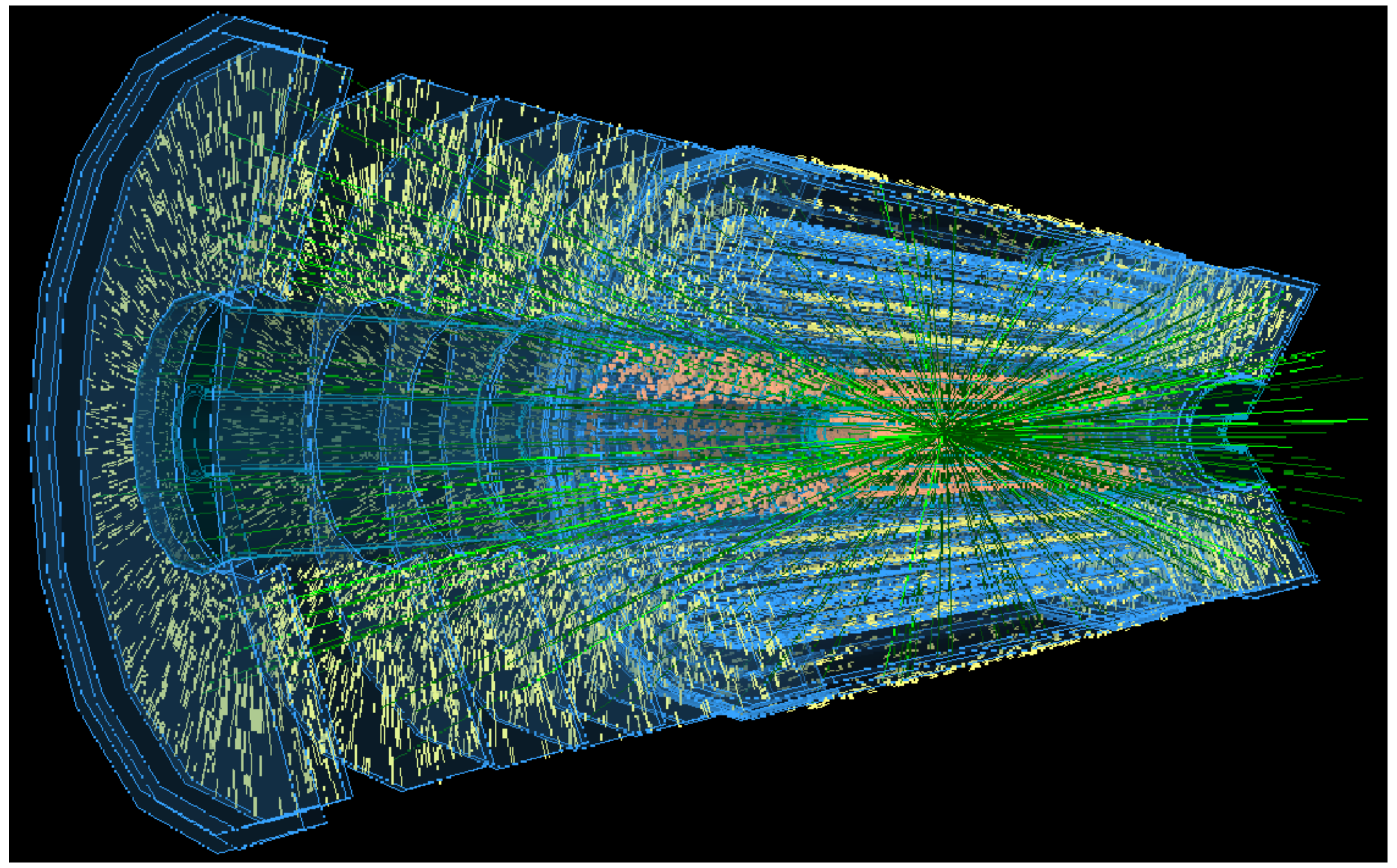
Barrel L2 @ Oxford

Outer Cylinder @ CERN SR1 (June 18, 2024)

End-cap structures @ NIKHEF

Summary

- ATLAS is building an all-silicon **I**nner **T**rac**k**er for the High-Luminosity LHC
  - Designed to operate in a much more challenging environment at the HL-LHC and deliver similar or better tracking performance
- **Building a detector is not easy!** 🙂
  - The ITk Strip team has been through years of prototyping and pre-production.
  - Rigorous QC and QA procedures have been put in place.
  - The production takes place in ~60 institutes in 14 countries all over the world.
  - While some issues identified during the pre-production are under investigation, preliminary mitigation strategies are promising.
- **We are on the verge of full production!**
  - Many components have already been in production and advancing well.



👉 Poster on the ITk production database by Kenneth Wraight

Backup

ITk Strip Components

ATLAS-TDR-025

Barrel Layer:	Radius [mm]	# of staves	# of modules	# of hybrids	# of of ABCStar	# of channels	Area [m^2]
L0	405	28	784	1568	15680	4.01M	7.49
L1	562	40	1120	2240	22400	5.73M	10.7
L2	762	56	1568	1568	15680	4.01M	14.98
L3	1000	72	2016	2016	20160	5.16M	19.26
Total half barrel		196	5488	7392	73920	18.92M	52.43
Total barrel		392	10976	14784	147840	37.85M	104.86
End-cap Disk:	**z-pos. [mm]**	**# of petals**	**# of modules**	**# of hybrids**	**# of of ABCStar**	**# of channels**	**Area [m^2]**
D0	1512	32	576	832	6336	1.62M	5.03
D1	1702	32	576	832	6336	1.62M	5.03
D2	1952	32	576	832	6336	1.62M	5.03
D3	2252	32	576	832	6336	1.62M	5.03
D4	2602	32	576	832	6336	1.62M	5.03
D5	3000	32	576	832	6336	1.62M	5.03
Total one EC		192	3456	4992	43008	11.01M	30.2
Total ECs		384	6912	9984	86016	22.02M	60.4
Total		**776**	**17888**	**24768**	**233856**	**59.87M**	**165.25**