Brookhaven National Laboratory
Brookhaven Science Associates
U.S. DEPARTMENT OF ENERGY

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

George Iakovidis

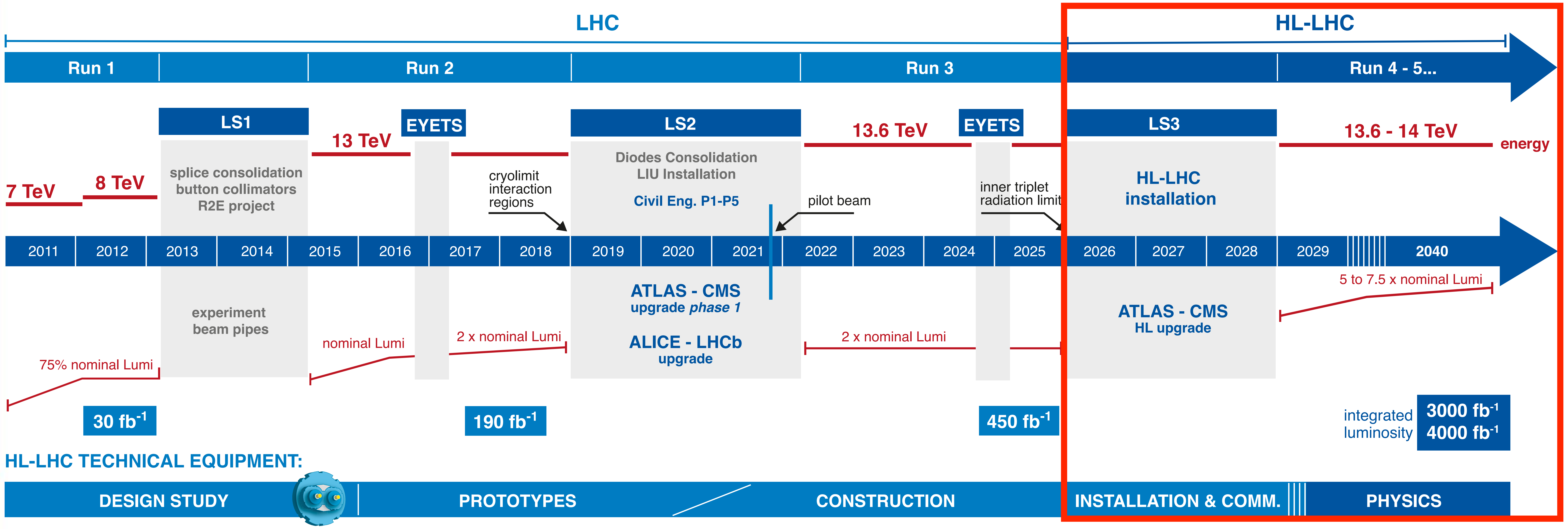
on behalf of the ATLAS ITk Strips community

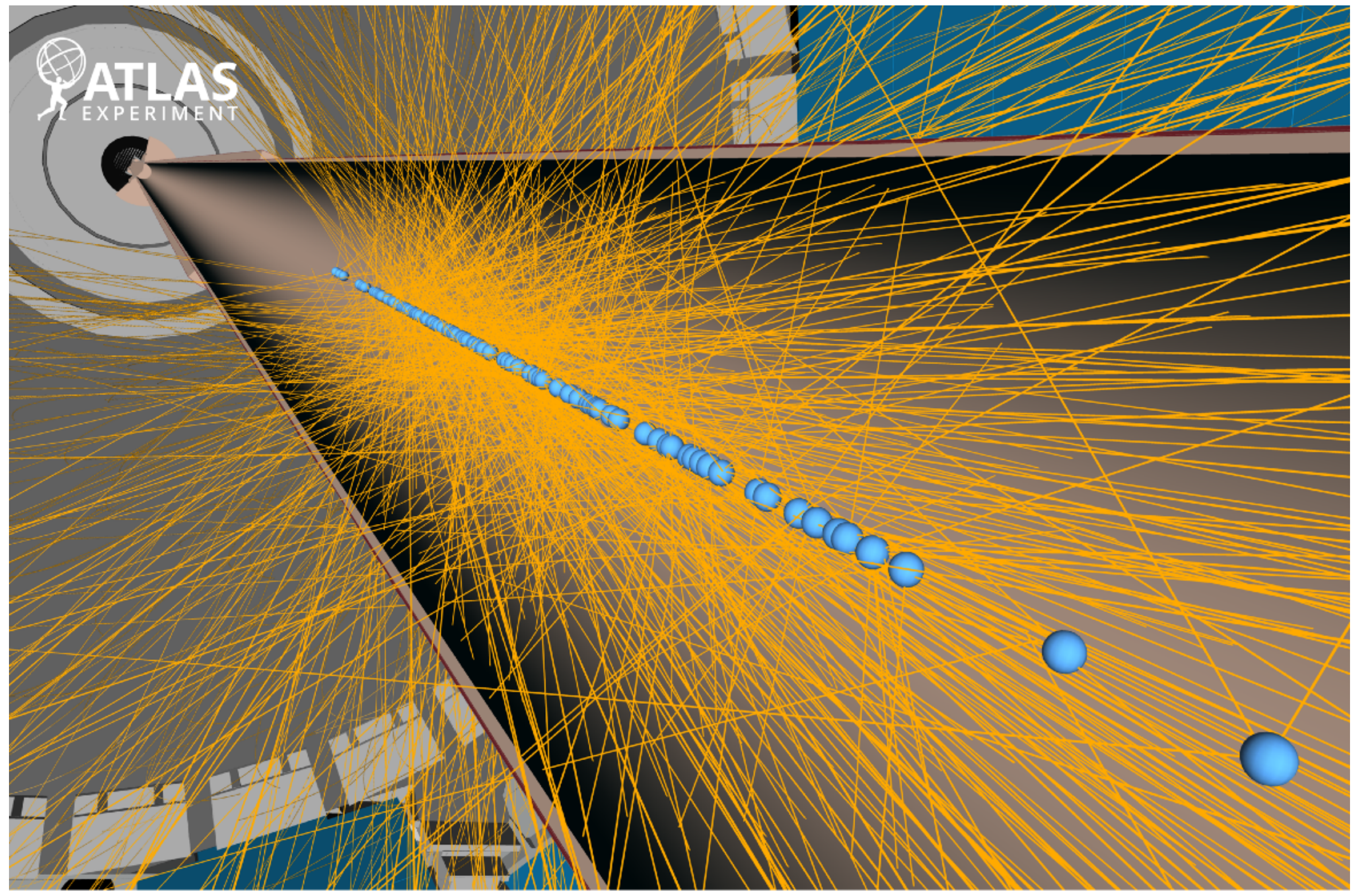
13th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD13)
Dec 3 – 9, 2023 - Vancouver, Canada

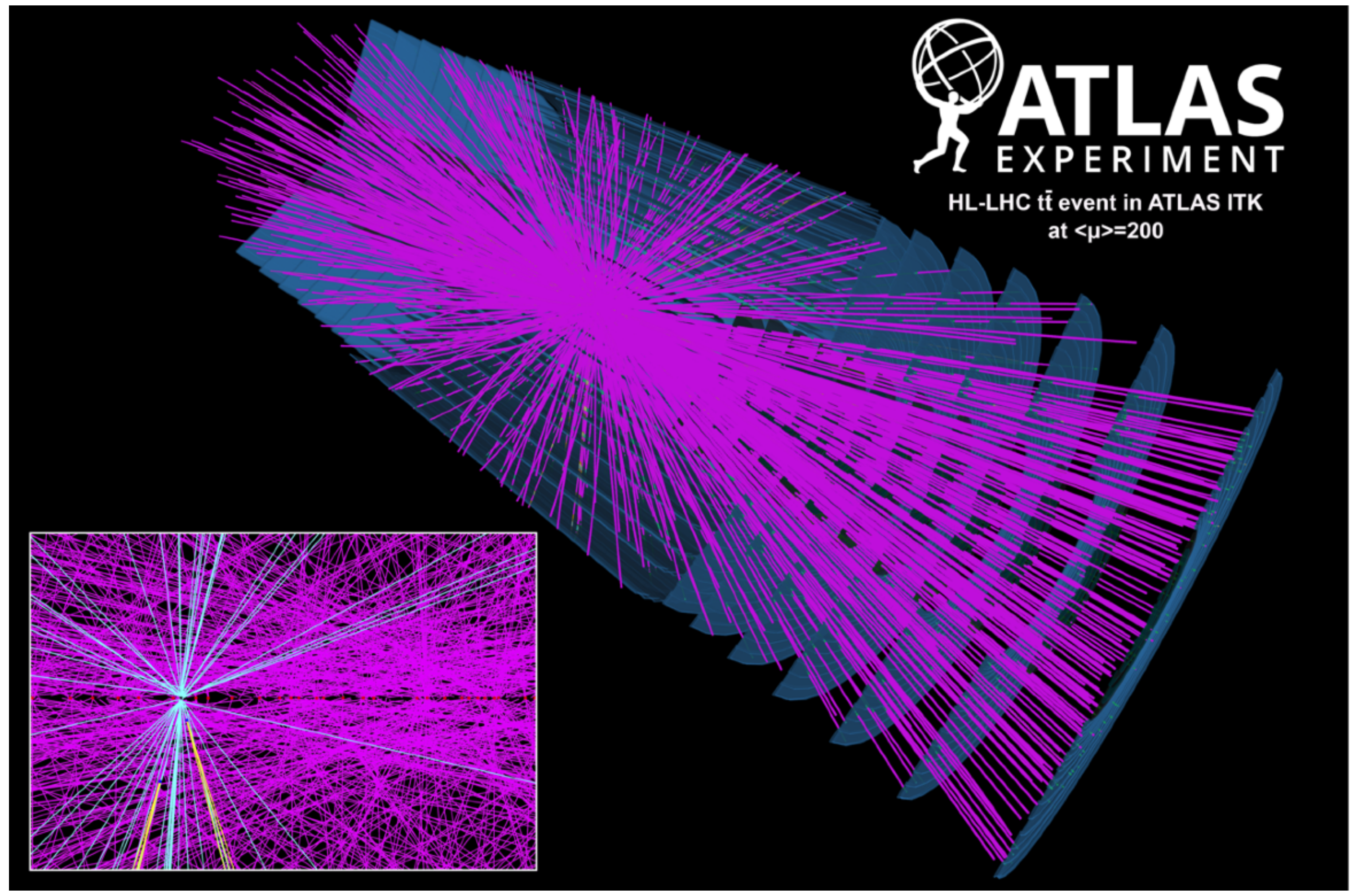
High Luminosity - LHC

High Luminosity **(HL)-LHC** will bring **major** changes to the detector's environment:

- **Luminosity** increase up to $\mathscr{L} = 5 - 7.5 \times 10^{34}\,\mathrm{cm}^{-1}\mathrm{s}^{-1}$
- **Integrated** Luminosity up to $3000 - 4000\,\mathrm{fb}^{-1}$
- Up to 200 inelastic *pp* collisions per beam crossing (**pileup**)
- Increased luminosity → ~10 times higher **radiation**
  - ➡ **Harsh environment** for the tracker



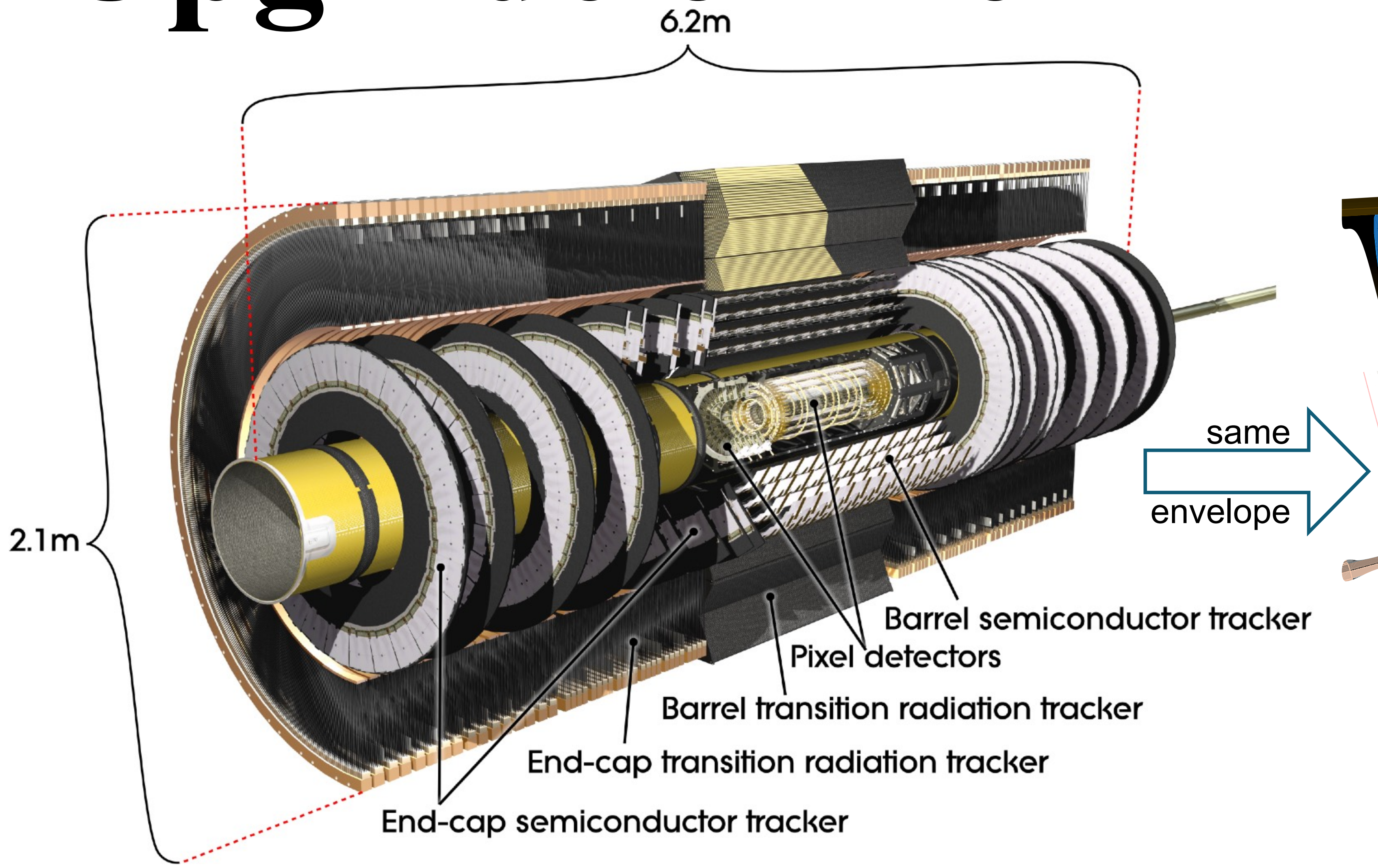


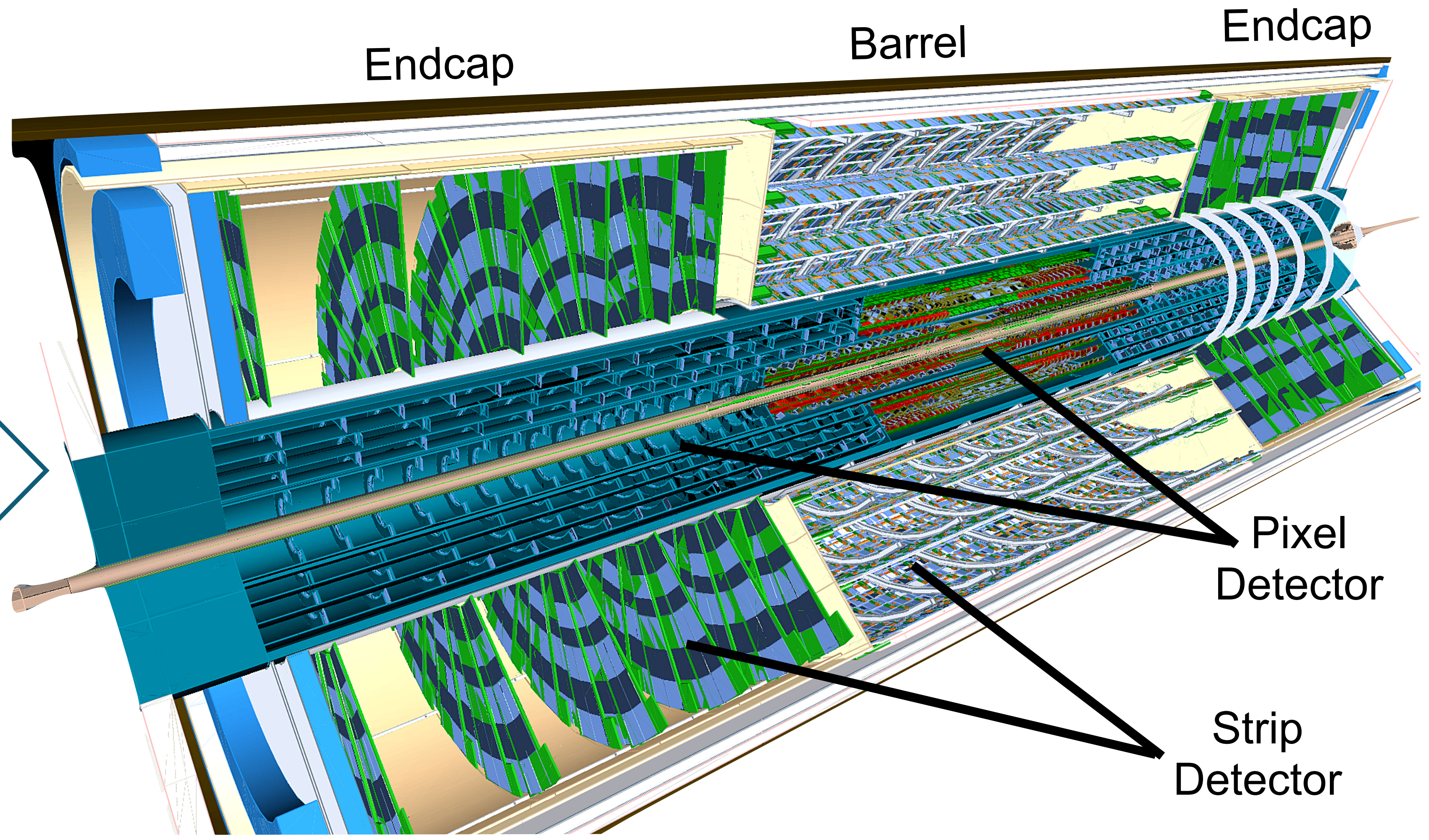


Event Displays from Upgrade Physics Simulated Data

Brookhaven National Laboratory

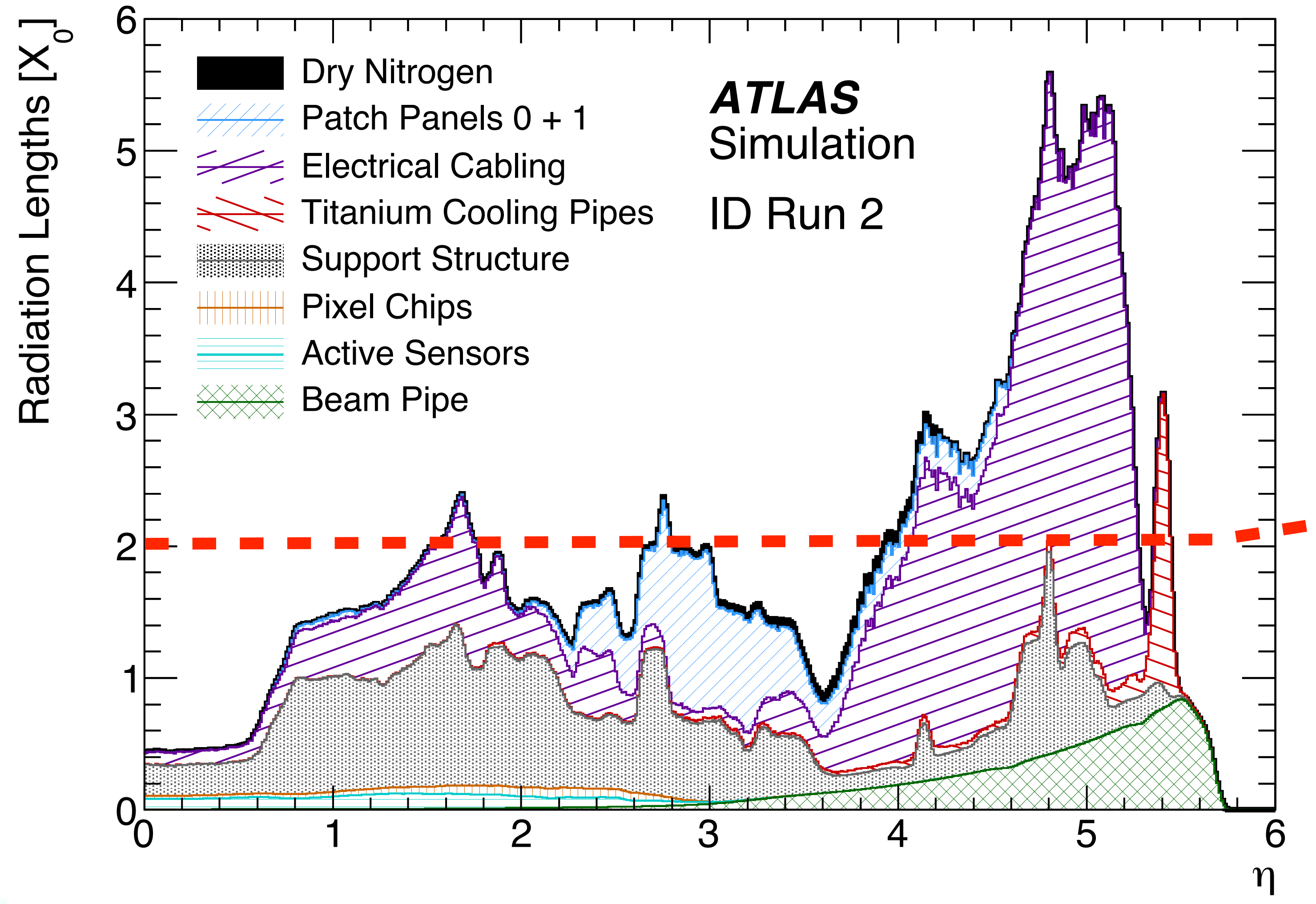
Upgrade of the ATLAS Inner Detector



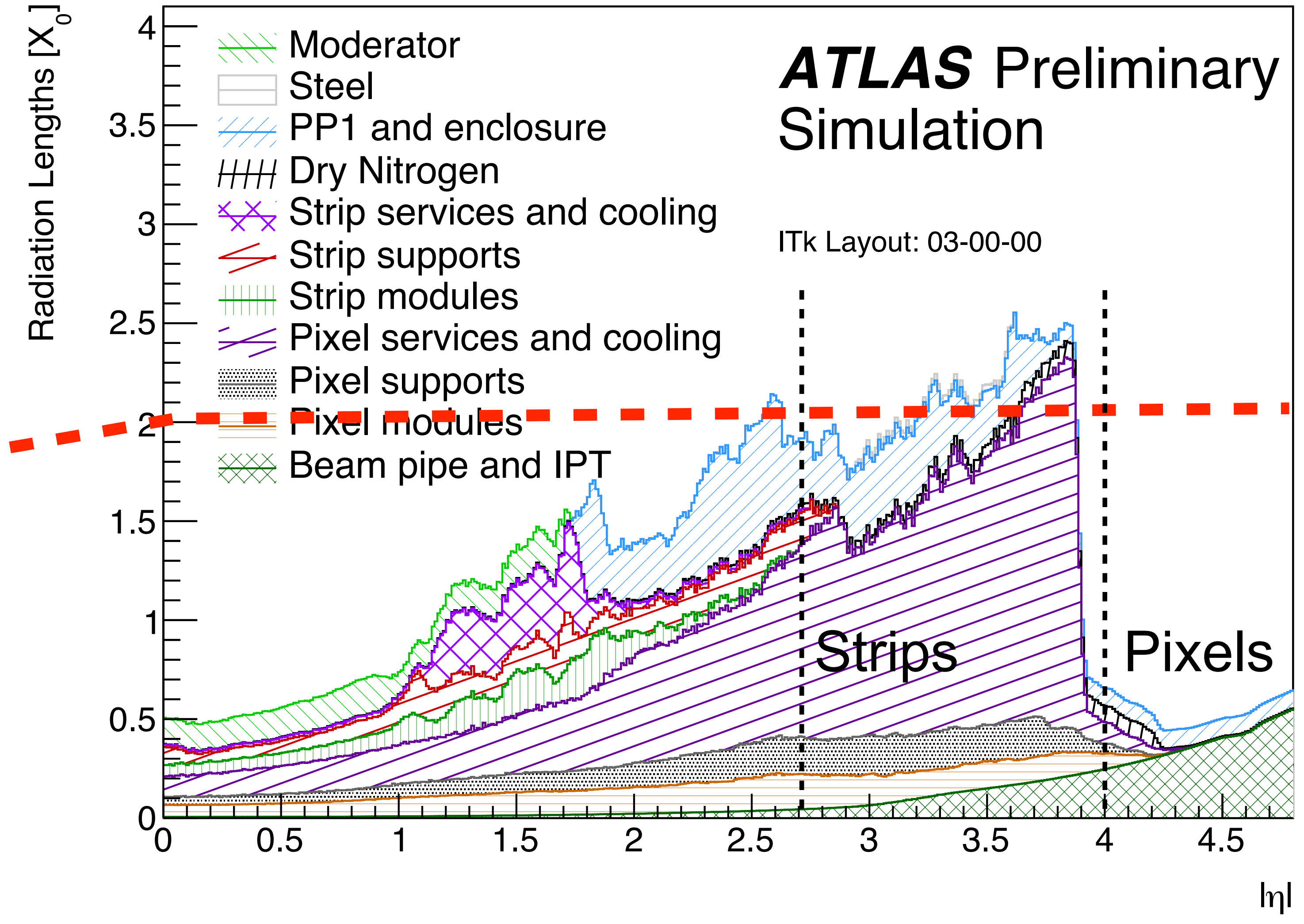


The ATLAS Inner Tracker (**ITk**) to replace the existing Inner Detector

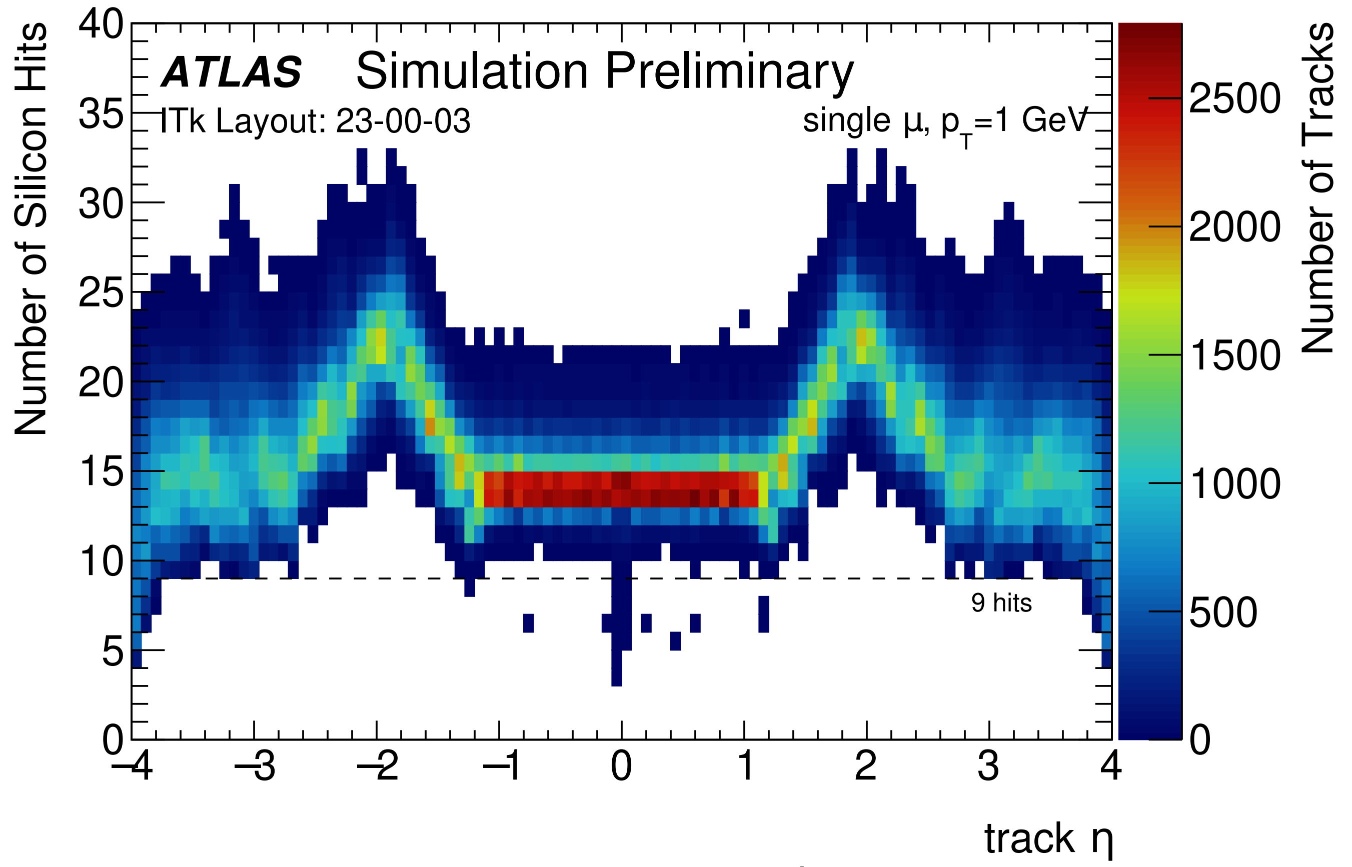
- **All silicon** - Pixels and Strips
- Higher **radiation** tolerance
- Finer **granularity** (# of channels) larger **coverage**
- **Faster** response
- Reduced **material budget**



Current Inner Detector



ITk



Coverage up to $\eta = \pm 4$ with at least 9 space points per track

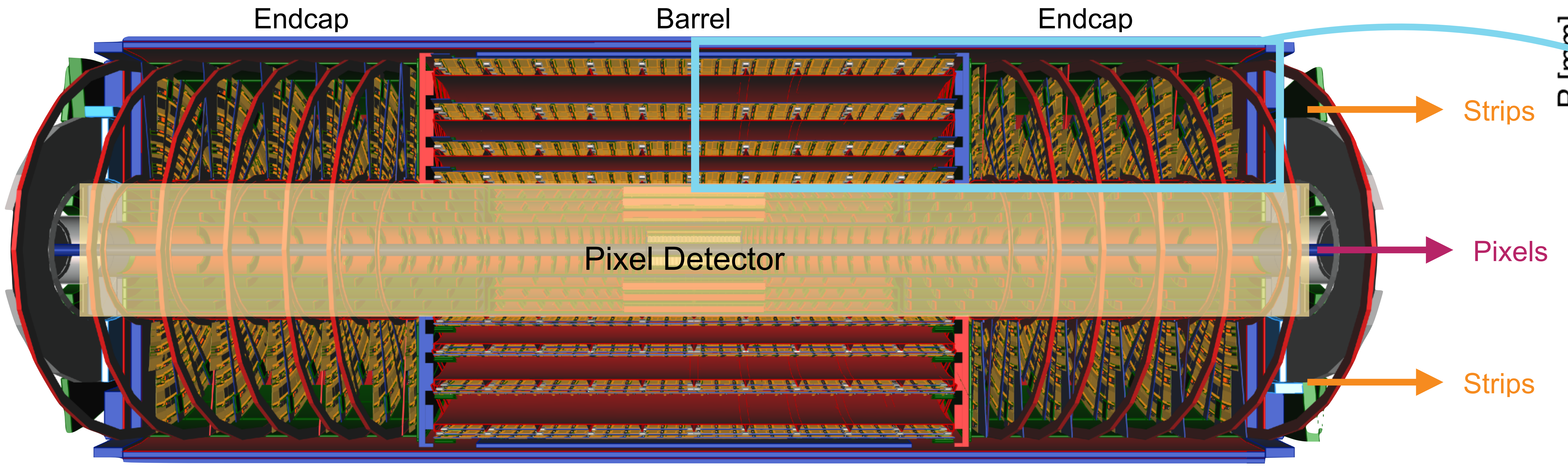
ATLAS-TDR-025

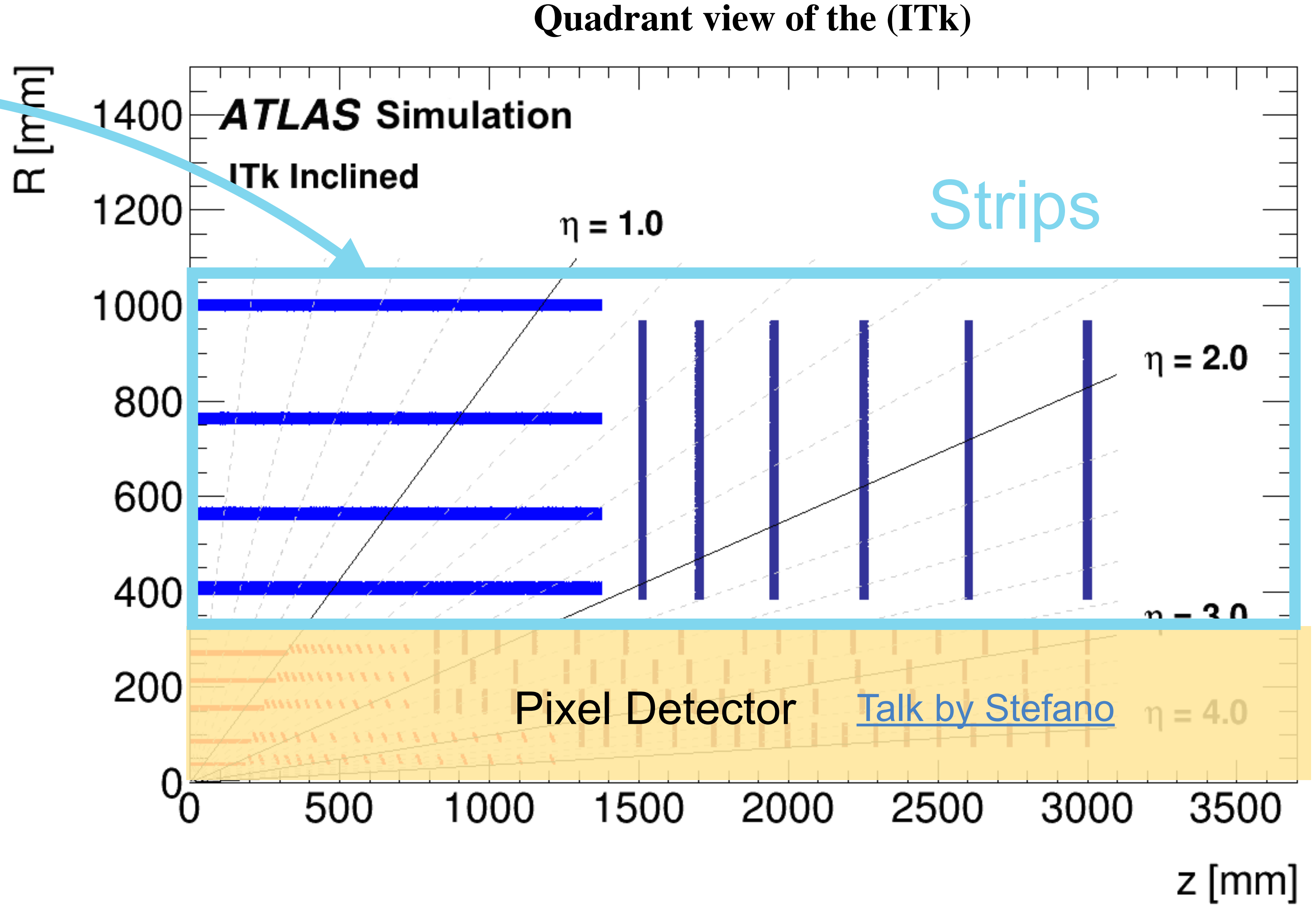
ATL-PHYS-PUB-2021-024

ATL-SOFT-SLIDE-2023-553

Brookhaven National Laboratory

The ITk Strips Layout





Barrel : 4 layers (double sided)

- L3/L2 (outer layers) with long strip (**LS**) staves
- L1/L0 (inner layers) with short strip (**SS**) staves
- Up to $\sim 33\,\text{MRad}$ **dose** and $7.2 \times 10^{14}\, n_{eq}/\text{cm}^2$

Endcap(s) : 6 disks (double sided) per endcap

- Disk0-Disk5: 32 identical petals on each disk
- Variable pitch and length due to geometry
- Up to $\sim 50\,\text{MRad}$ dose and $1.2 \times 10^{15}\, n_{eq}/\text{cm}^2$

Strips	# of Layers	# of Detectors	Surface [m^2]	Channels [M]	Strip Pitch [μm]	Strip Length [mm]
Barrel	4	392 Staves	104.86	37.85	75.5	24.1 - 48.2
Endcap	6	384 Petals	60.4	22.02	69 - 85	19 - 60
Total		**776**	**165.25**	**59.87 M**		

Brookhaven National Laboratory

The ITk Strip Sensors

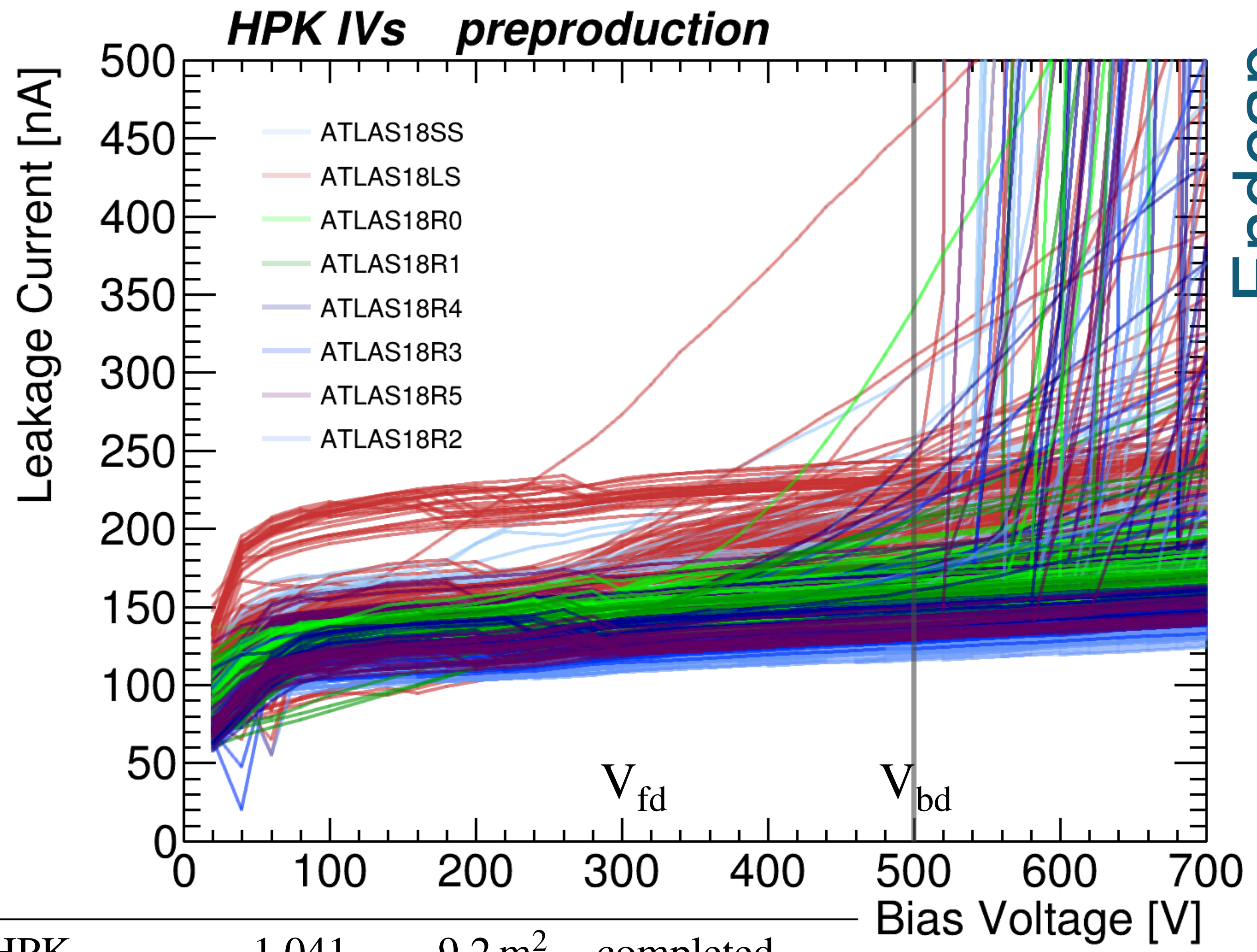
[Poster on Sensor Charachteristics by Javier]

[Talk by Luise on Curing early breakdown in silicon strip sensors with radiation]

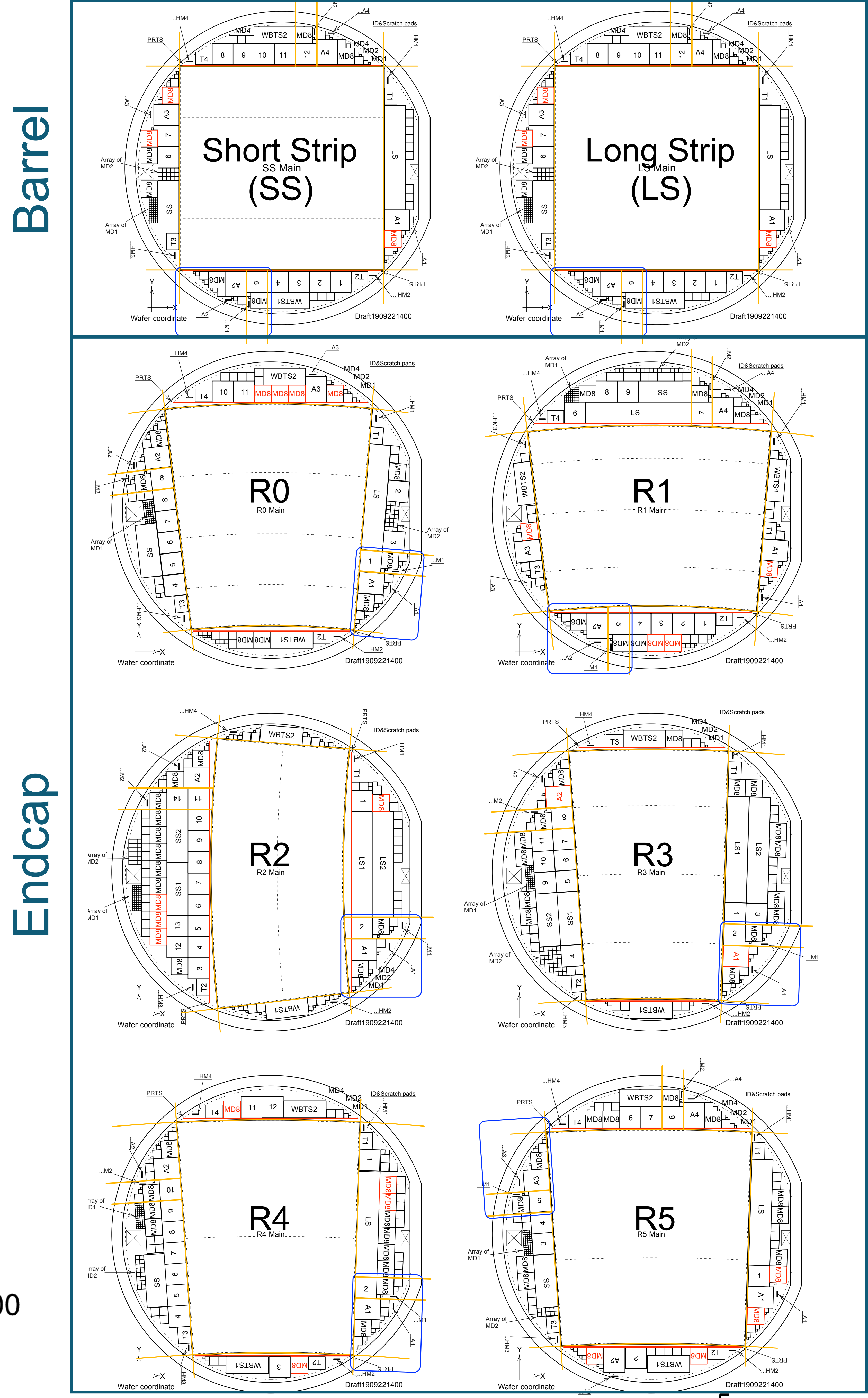
- Silicon: **n-type implants in a p-type** float-zone **silicon** bulk ($n^+ - in - p$) with aluminum AC-coupled **strips**
  - **Produced** by Hamamatsu Photonics K.K. (HPK) in 6-inch, 320 µm thick **wafers**
- 2 **variants** for barrel, 6 variants for endcap(s)
- Miniature sensors, test structures, monitor diodes, and other structures are laid out in the "**halfmoons**"
  - ➡ **Validating** the characteristics/performance of the sensors
- **Operating** bias voltage is set to backplane at −500 V (0 V on n^+) at ~ -30°C

HPK performs **initial tests** against the specifications

- **Visual** inspection edge chipping and scratches
- **Electrical** tests such as Overall capacitance (C-V) and the leakage current (I-V)
- Pre-production (1041 sensors - 5%) showed that **quality** of the sensors "as produced" is **excellent**.



Pre-Production	all 8 types	HPK	1,041	9.2 m^2	completed
Production	all 8 types	HPK	20,800	190.3 m^2	ongoing



Brookhaven National Laboratory

[NIM A 989 (2021) 164928]

[Y. Unno et al 2023 JINST 18 T03008]

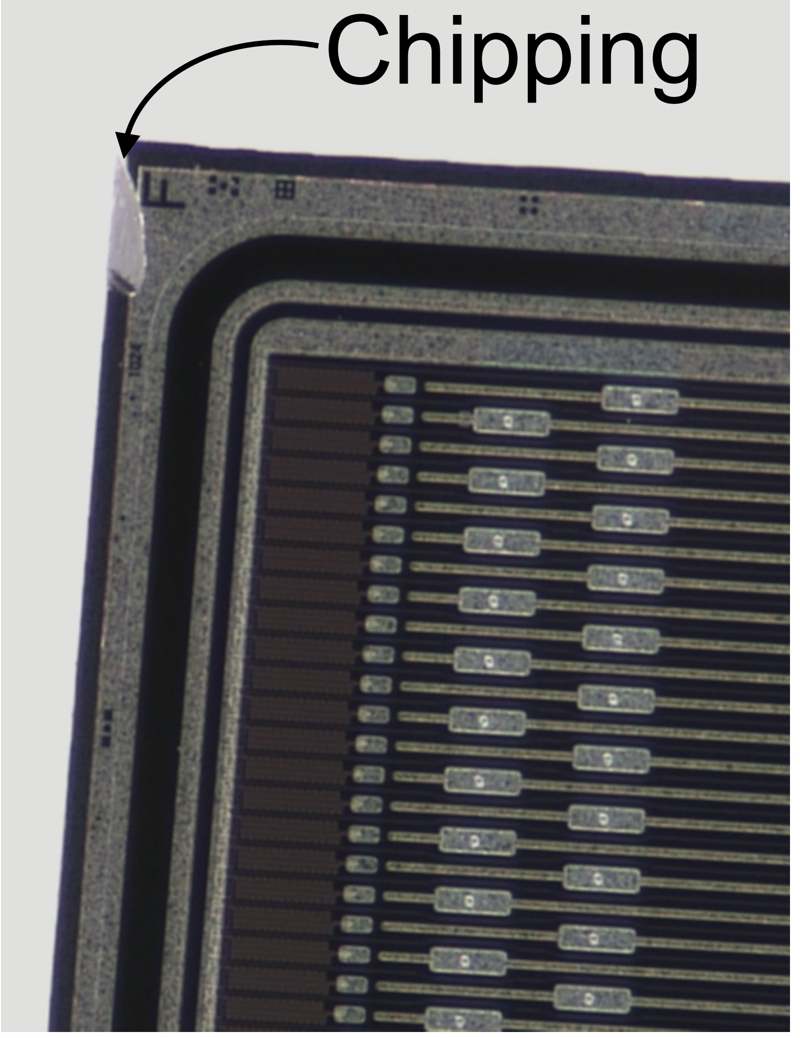
The ITk Strip Sensors - QA/QC

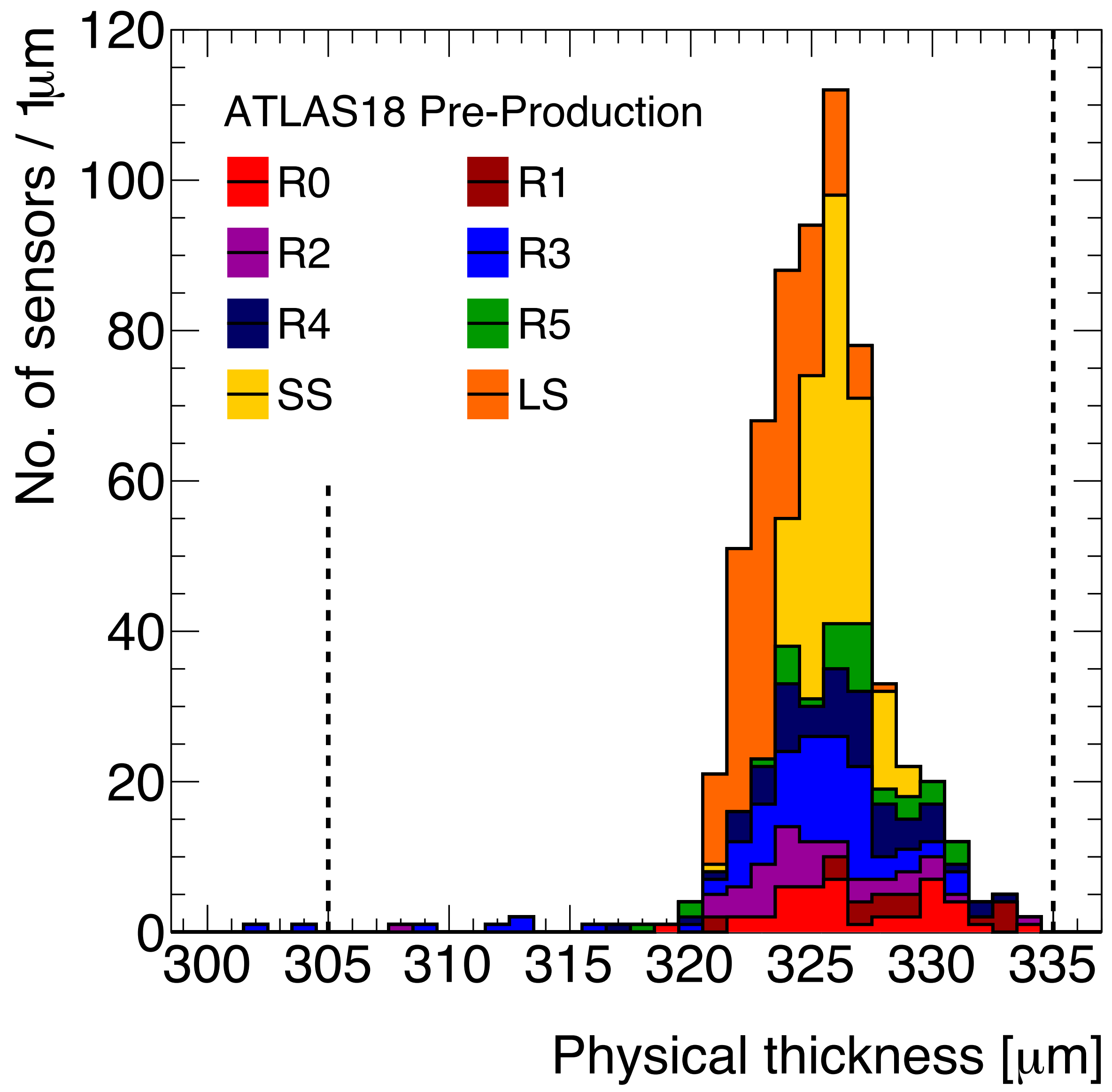
ATL-ITK-PROC-2023-002

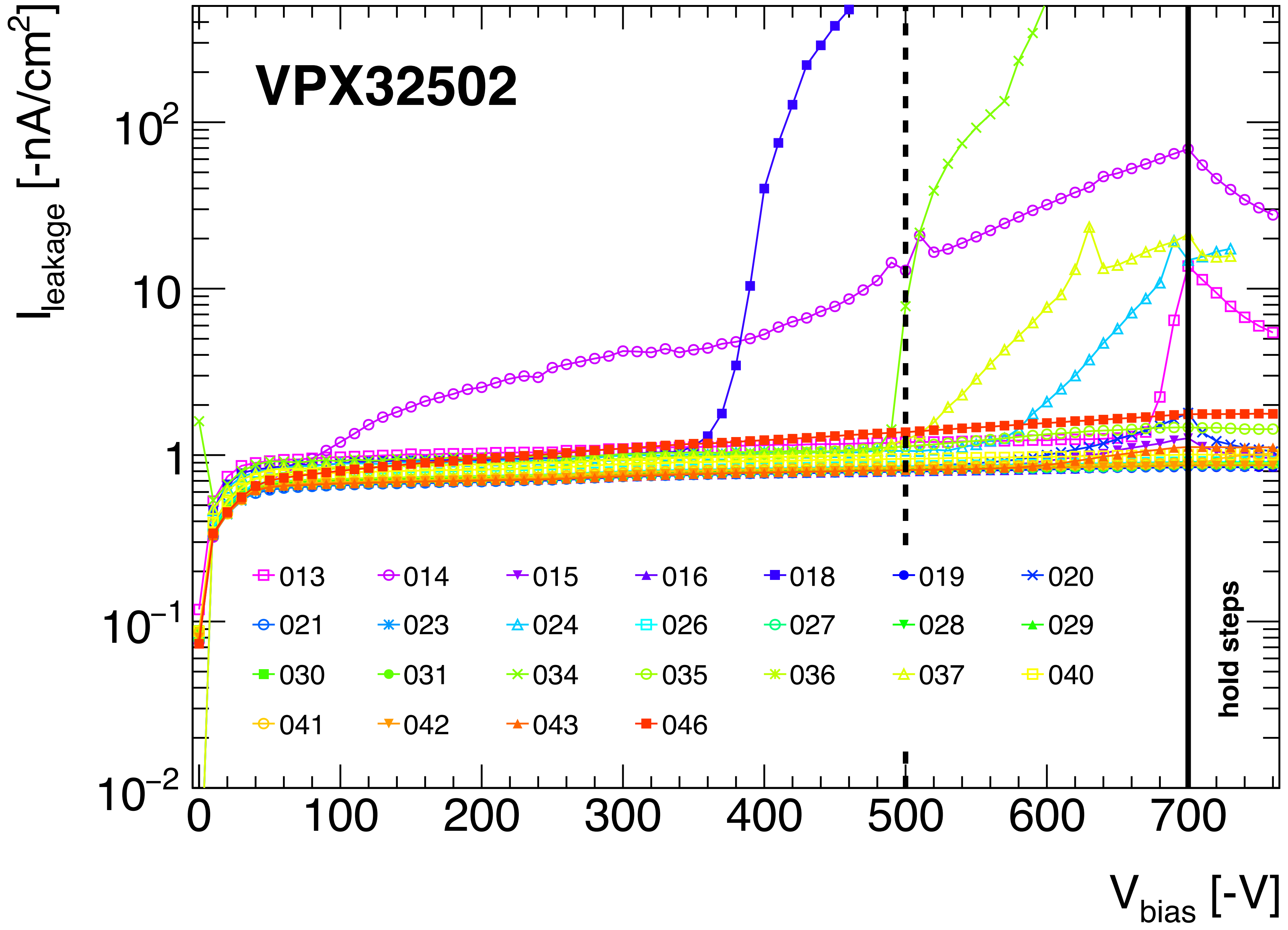
Extensive QA/QC is carried out in several **institutes** for either all sensors or sample of them:

- All Sensors
  - **Visual** inspection, planarity (<1% failures)
  - **IV** ($V_{bias} = 500\,V$ & $I < 0.1\,\mu A/cm^2$) under dry conditions (3.5% failing)
- Subset of sensors:
  - **Thickness** measurement on **test sensors** with calipers (320 ± 15 µm)
  - **Long-term stability** (40h at 400-500 V, 2-5% of sensors)
  - **Full Strip Test**, probing each strip, measure currents and $R_{bias} = 1 - 2\,M\Omega$, $C_{coupling} > 20\,pF/cm$

Poster on Humidity exposure by Vitaliy







QC Test	Vis. Insp.	Metrology	Thickness	IV	CV	LTS	Striptest
Yield (Fails)	99.6% (4)	100%	99.7% (2)	96.5% (36)	100%	99.3% (4)	99% (4)

Talks on QA/QC: by Eric & by Christoph

Posters on QA/QC by Andrew & by Paul

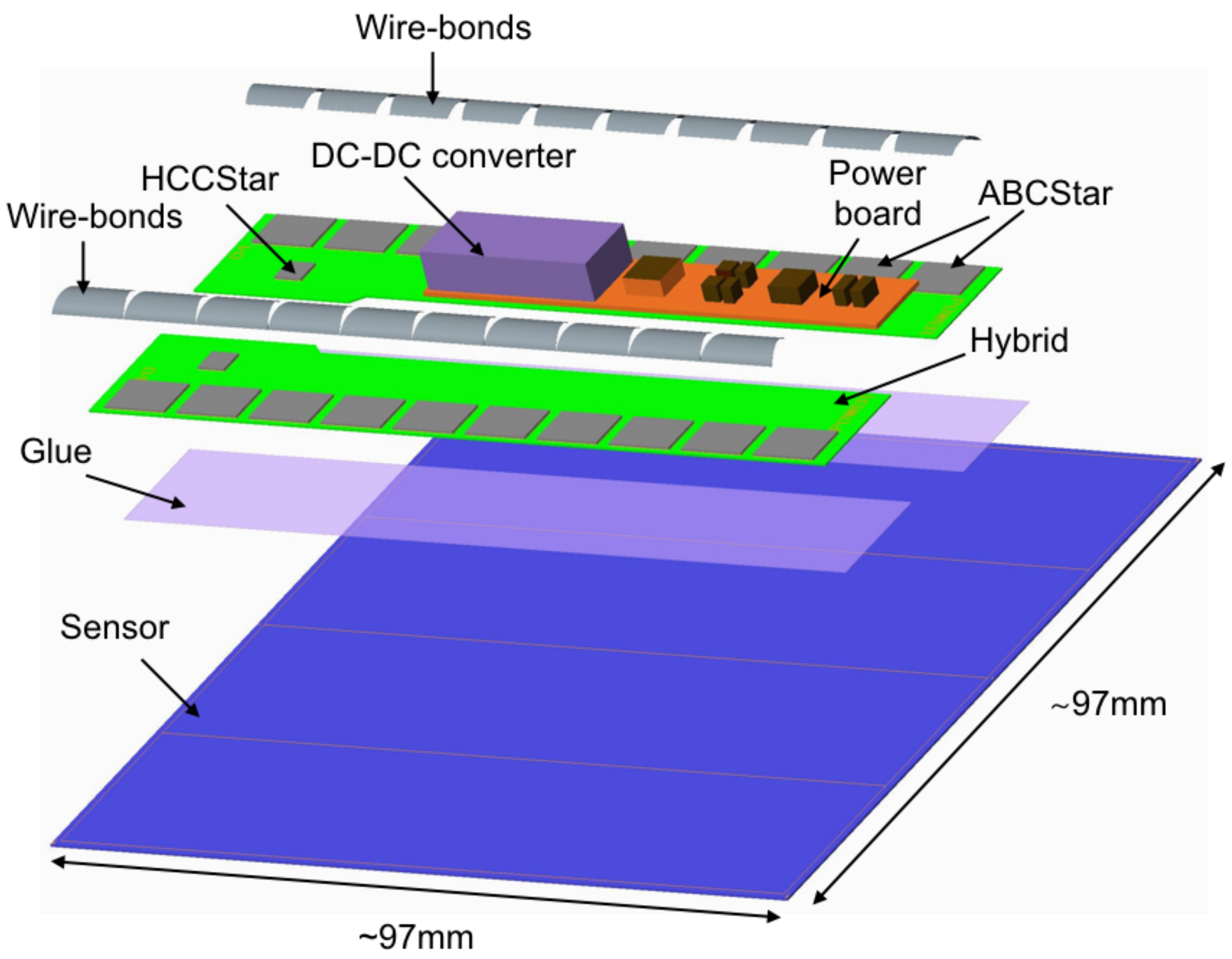
Talk on Sensor recovery by Ezekiel

Brookhaven National Laboratory

The ITk main element: Module

The main detector element in ITk is the **module** which consists from:

- Diced **Sensors**
- **Hybrid** board (glued on the Sensor) consists of **ABCStar** custom frontends and **HCCStar** custom readout ASICs
  - wire-bonded to the sensor
- **Power-board** (glued) which has **AMACStar** ASIC for controls, HV multiplexer, **DCDC** (linPOL12V, bPOL12V - CERN development)
  - wire-bonded to Hybrids



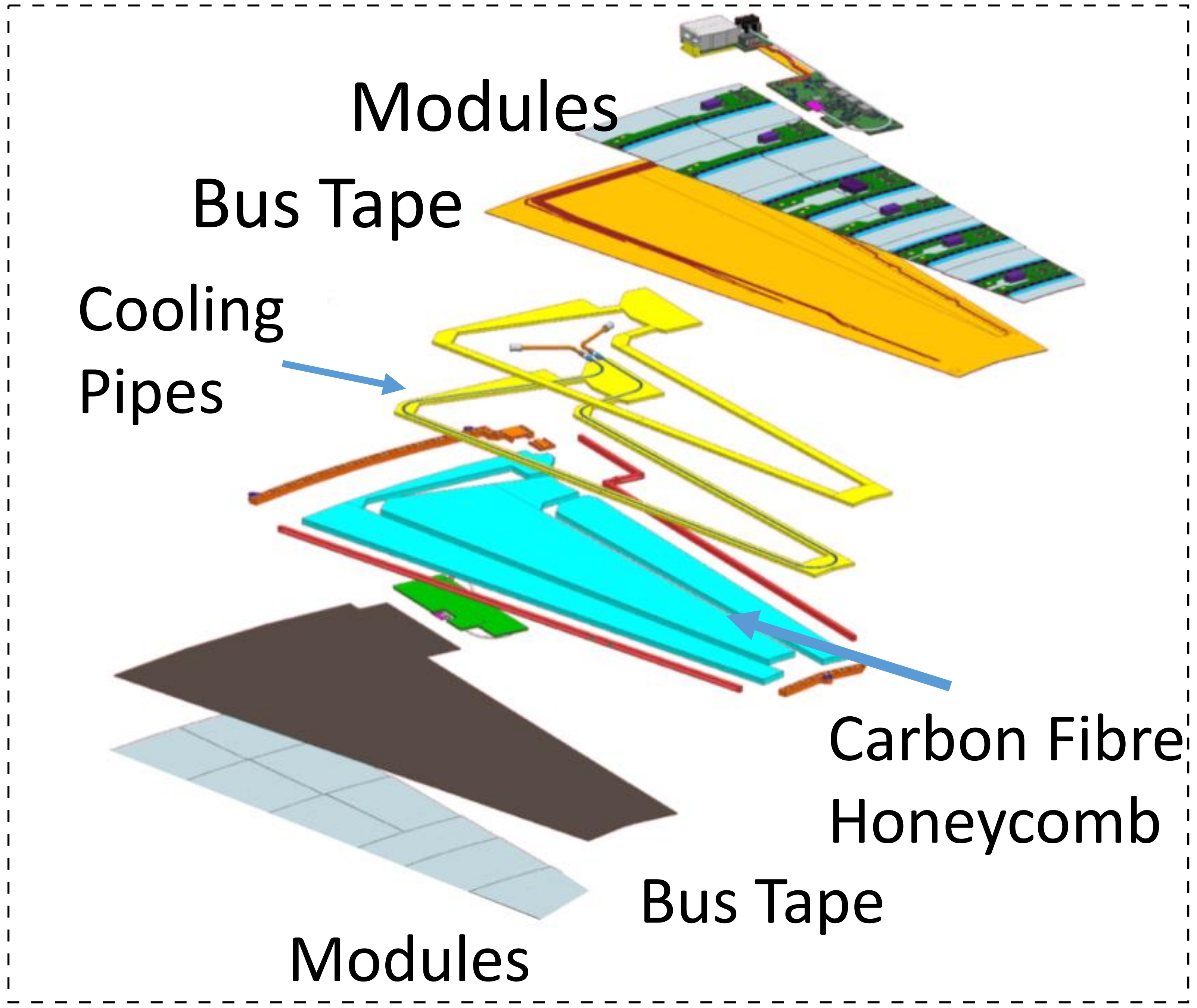
Short strip module exploited view

ATLAS-TDR-025

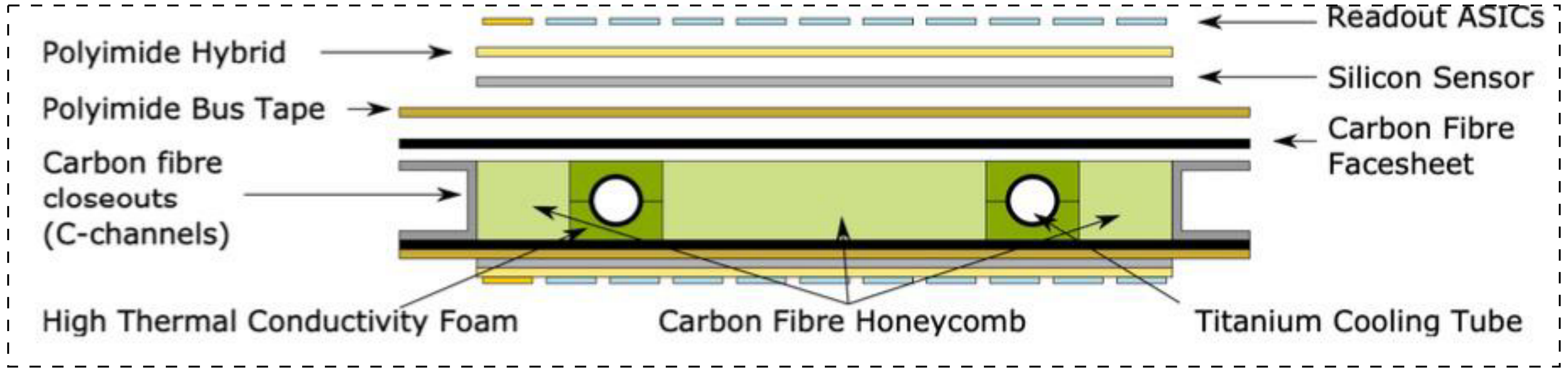
Core supports

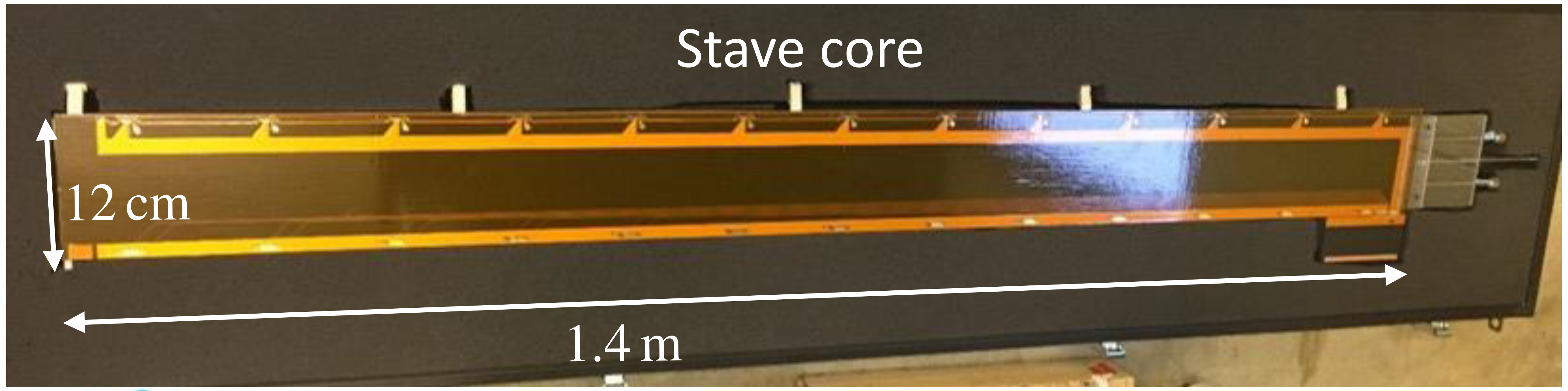
- **Carbon-fibre structures** form the **support** for the modules and the EoS
- Copper on Polyimide (kapton) **bus-tapes** are used to route electrical connections (inc. power)
- **Titanium** pipes used for evaporative CO_2 cooling in highly thermal-conductive carbon-fibre honeycomb - operation at ~ -35°C
- **Modules** are **glued** on either side of the core and **wire-bonded** to bus-tapes

Petal exploded view

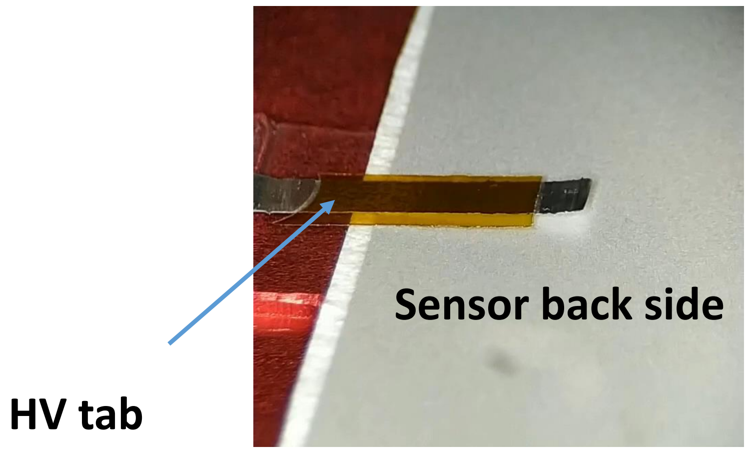


Stave Cross section

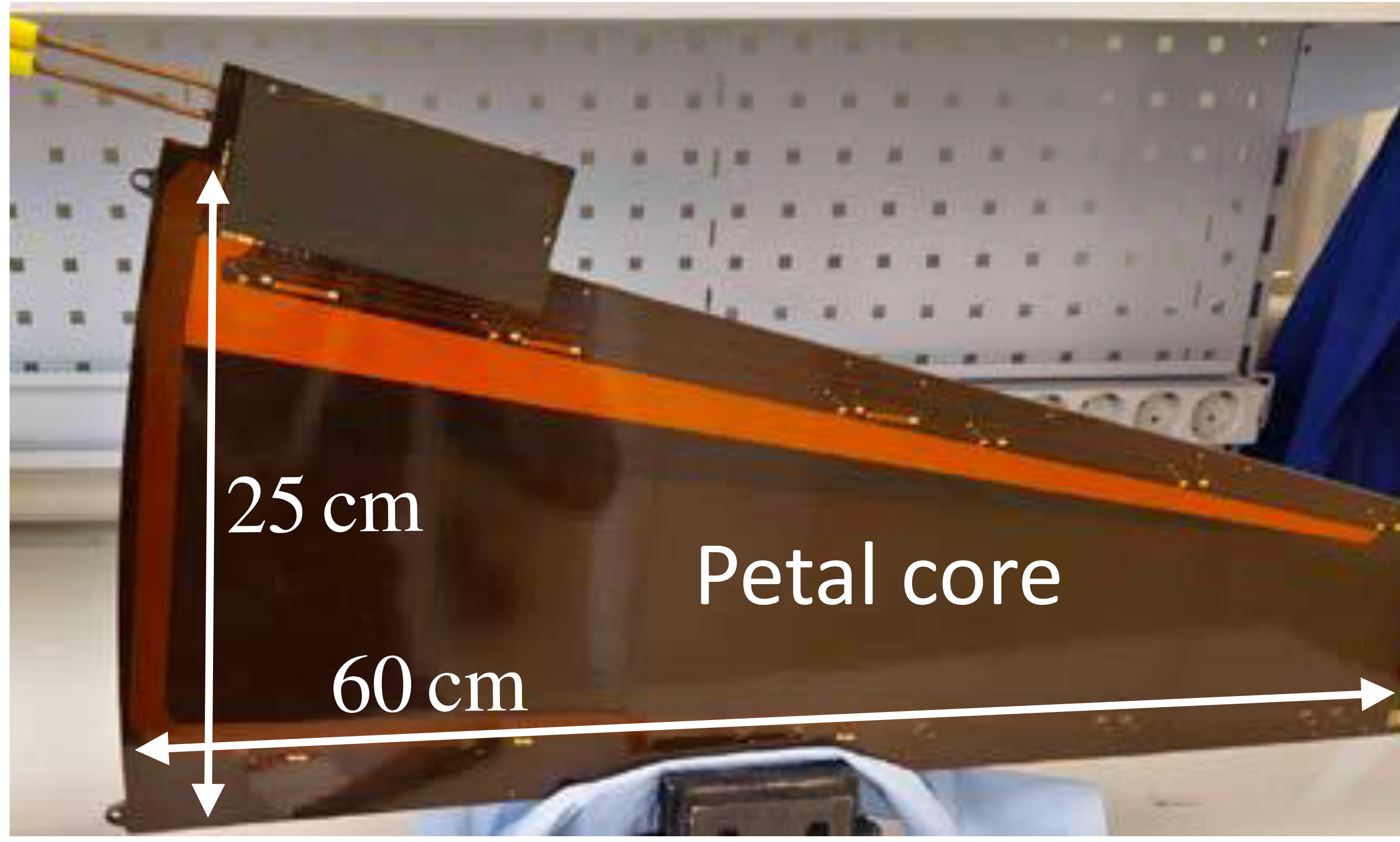




HV on sensor back plane by Tape Automated Bonding (**TAB**) bonding



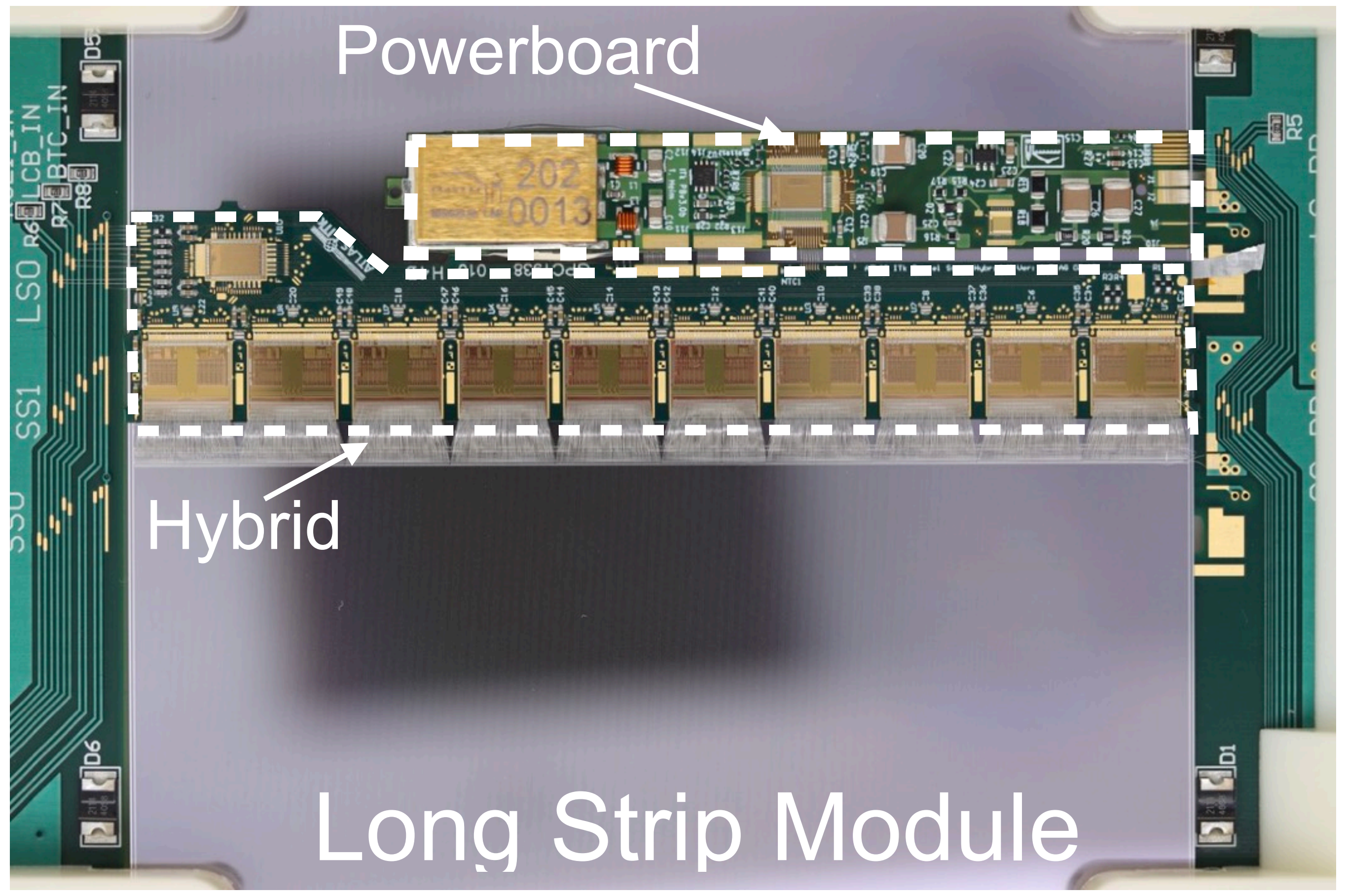
Poster on local support structures by Sergio

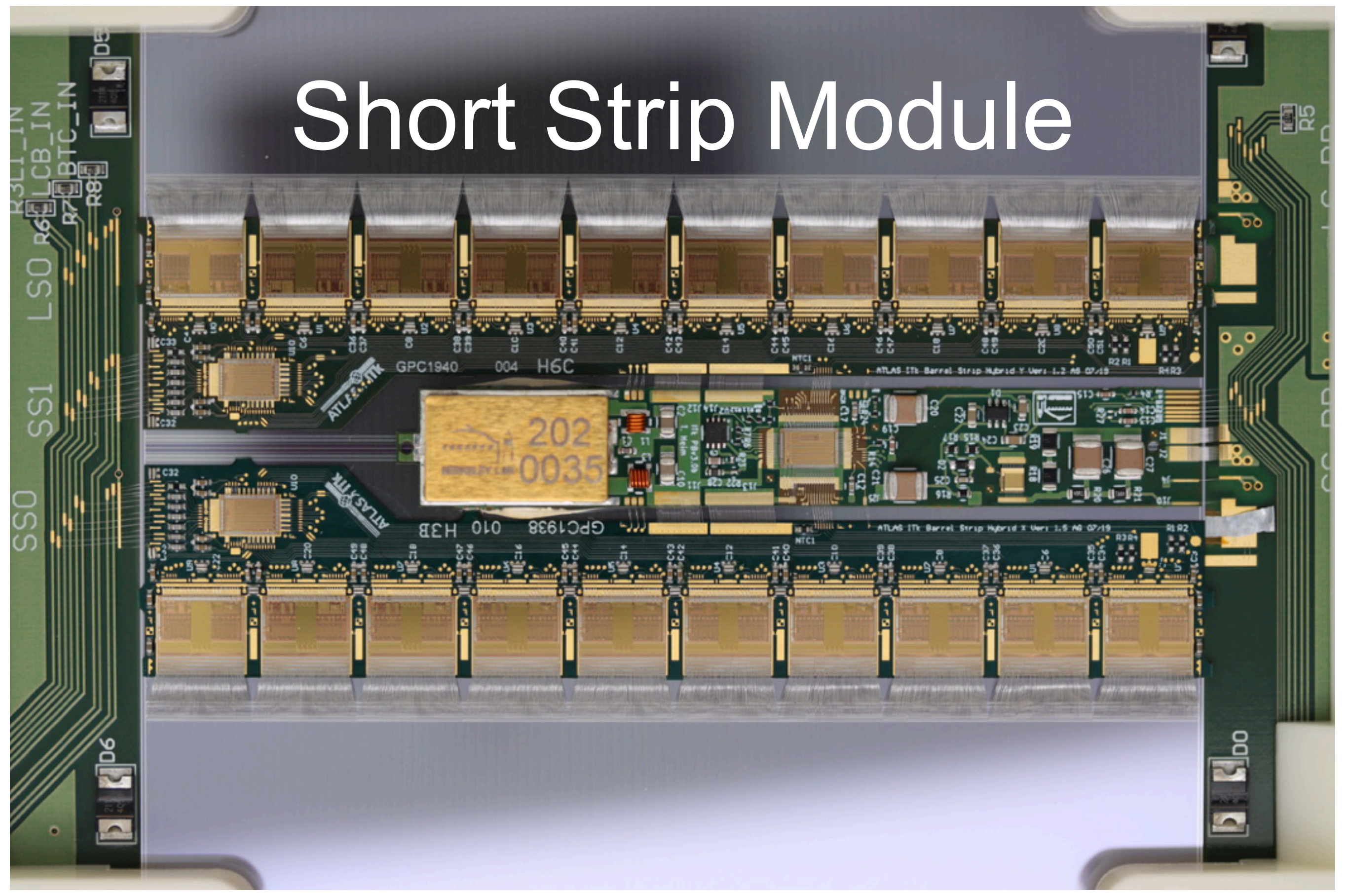


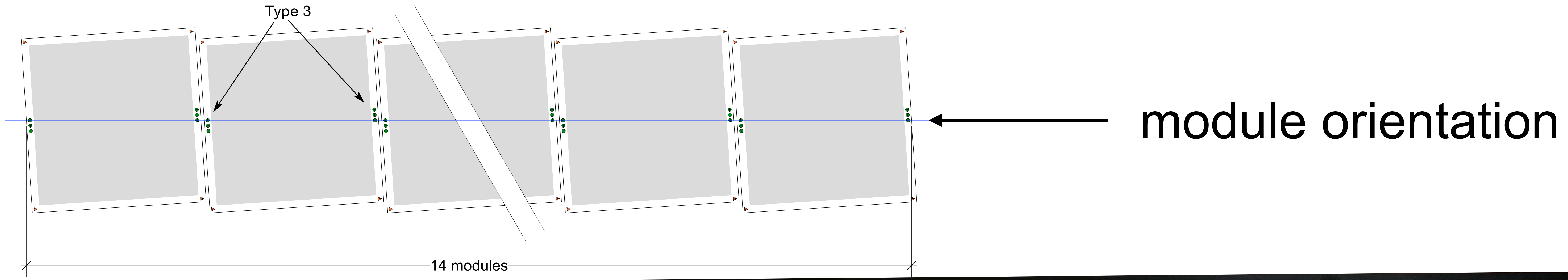
Brookhaven National Laboratory

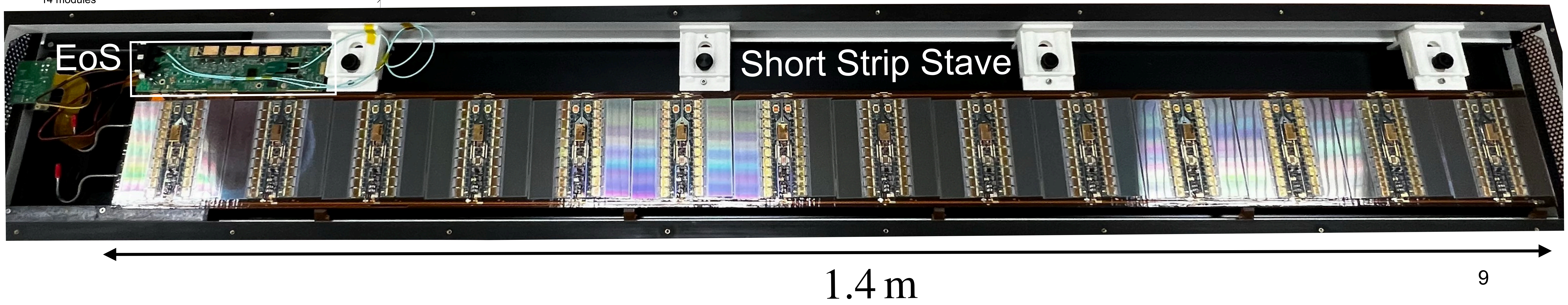
Barrel detectors: Staves

- **Modules** are **loaded** in structure to form **Staves**
- Staves consist of **28 modules** in total, **14 on either side** of the stave **core**
- Modules are **rotated** by 26 mrad to the stave axis to provide **stereo** information
- The End of Substructure (**EoS**) facilitates the communication through the CERN developed ASICs:
  - lpGBT (Low Power GigaBit Transceiver, 65 nm CMOS ASIC)
  - VTRx+: fibre transmitter - receiver (10 Gb/s - 2.5 Gb/s)





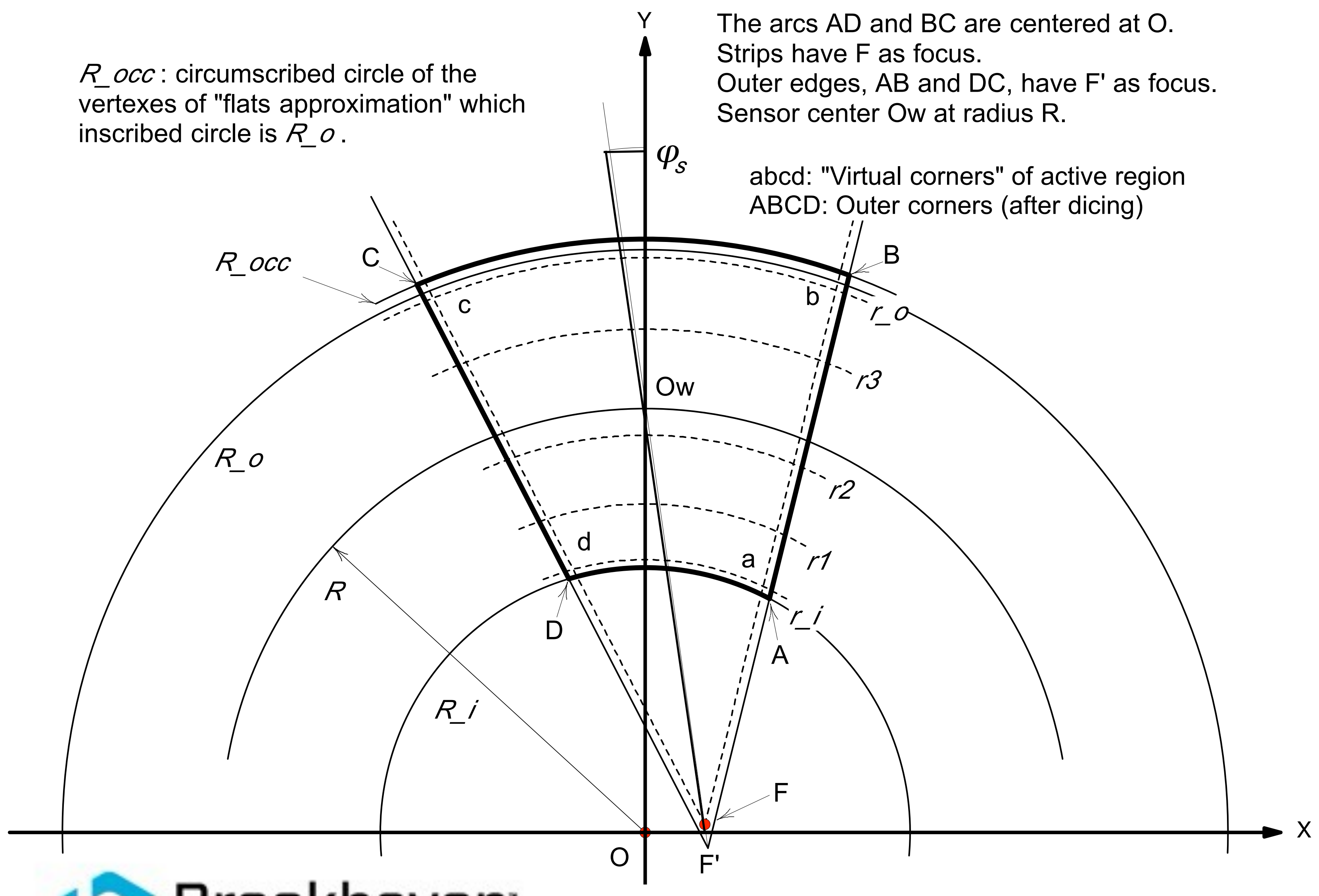


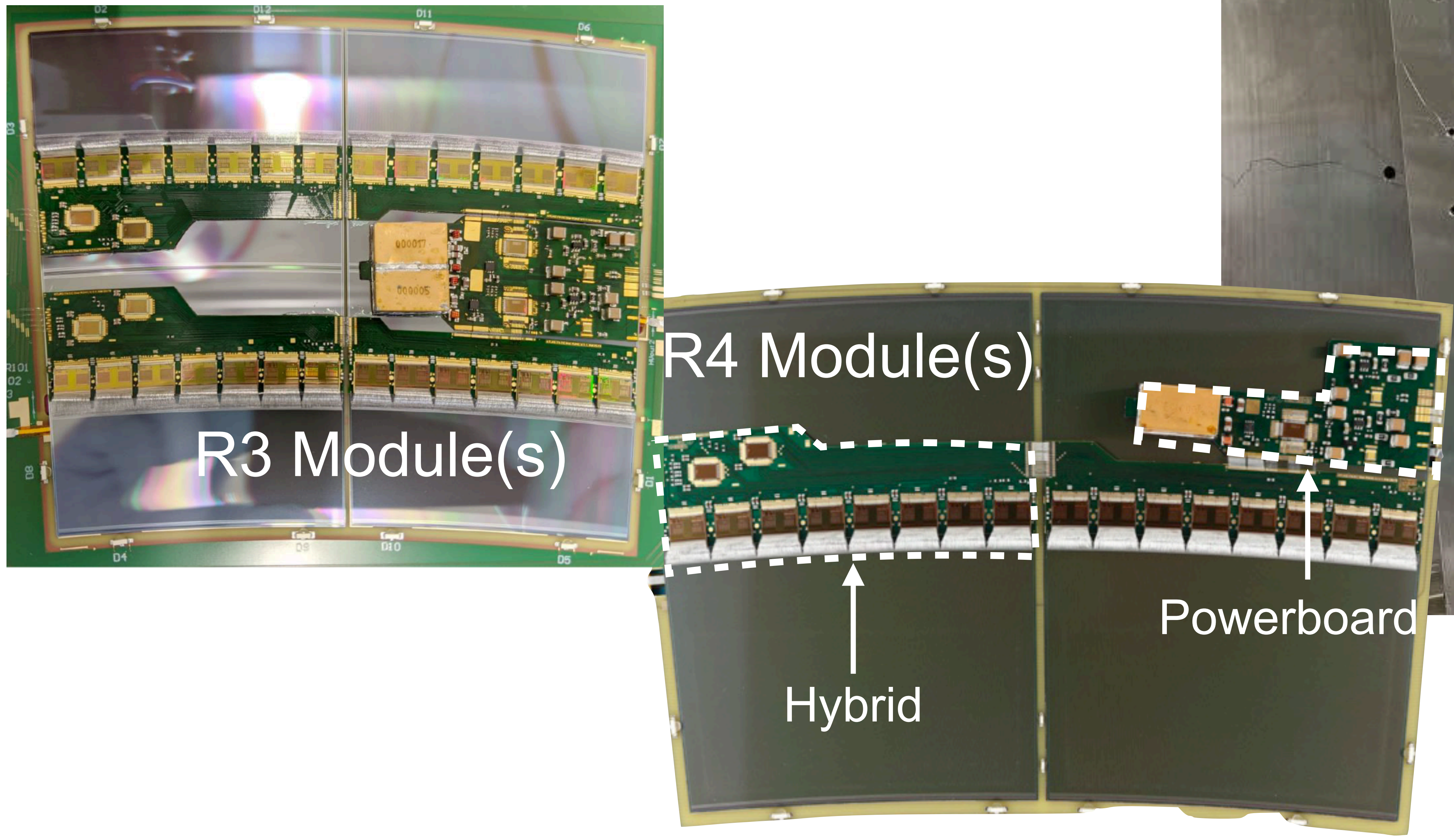


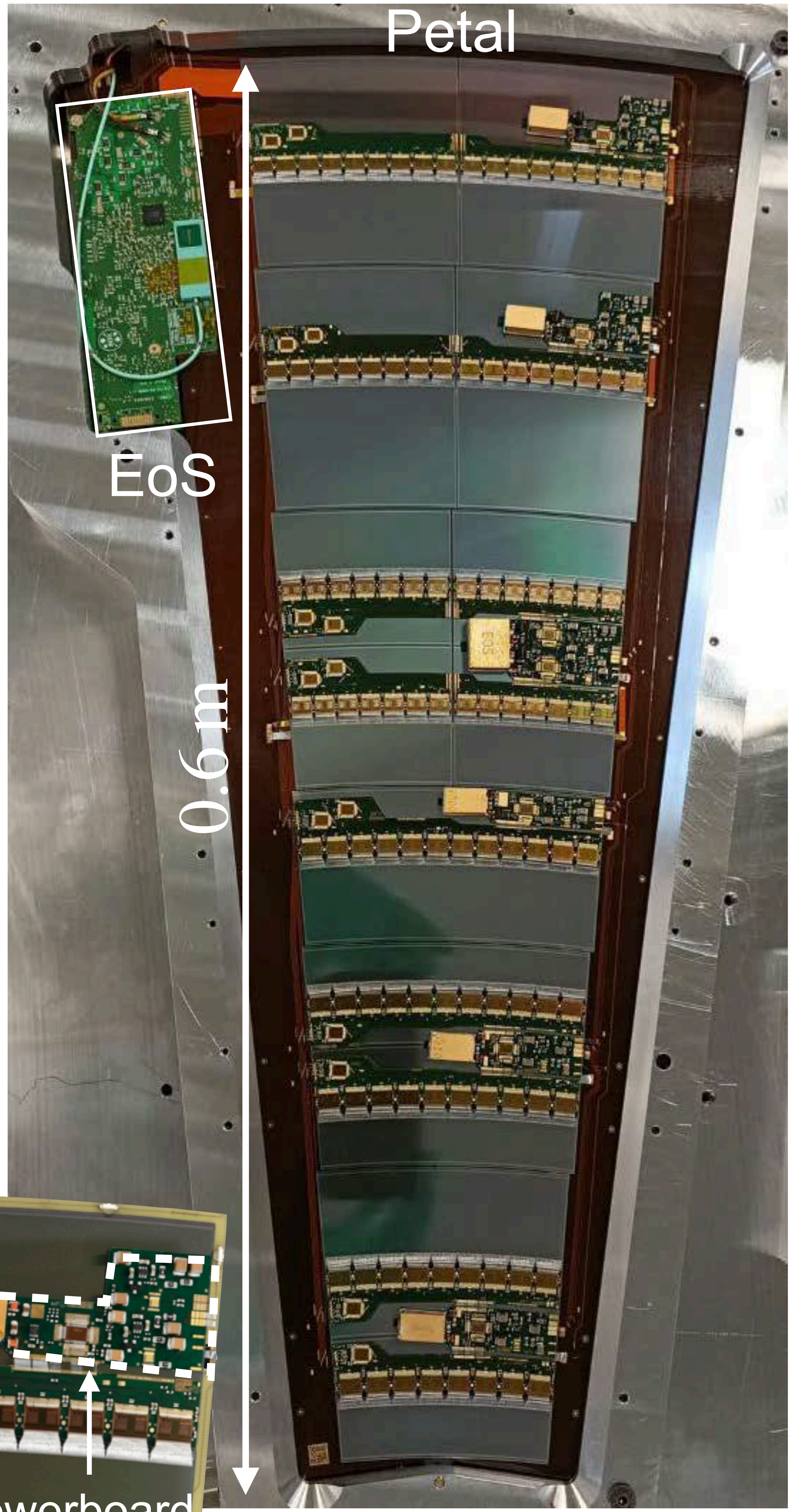
Brookhaven National Laboratory

Endcap detectors: Petals

- In a similar way **Modules** loaded in **trapezoidal** structures form **Petals**
- Petals consist of 6 module **variants** - in total **18 modules**, **9 on either side** of the petal **core**
- Contrary to staves, petals feature strips which are **rotated** by an angle $\phi_s = 20\,\text{mrad}$ around the **center of the sensor** to provide stereo information
- **Petals** have more **variations** of **hybrids** due to the nature of their shape but all the ASICs and the EoS have **identical** to staves functionality

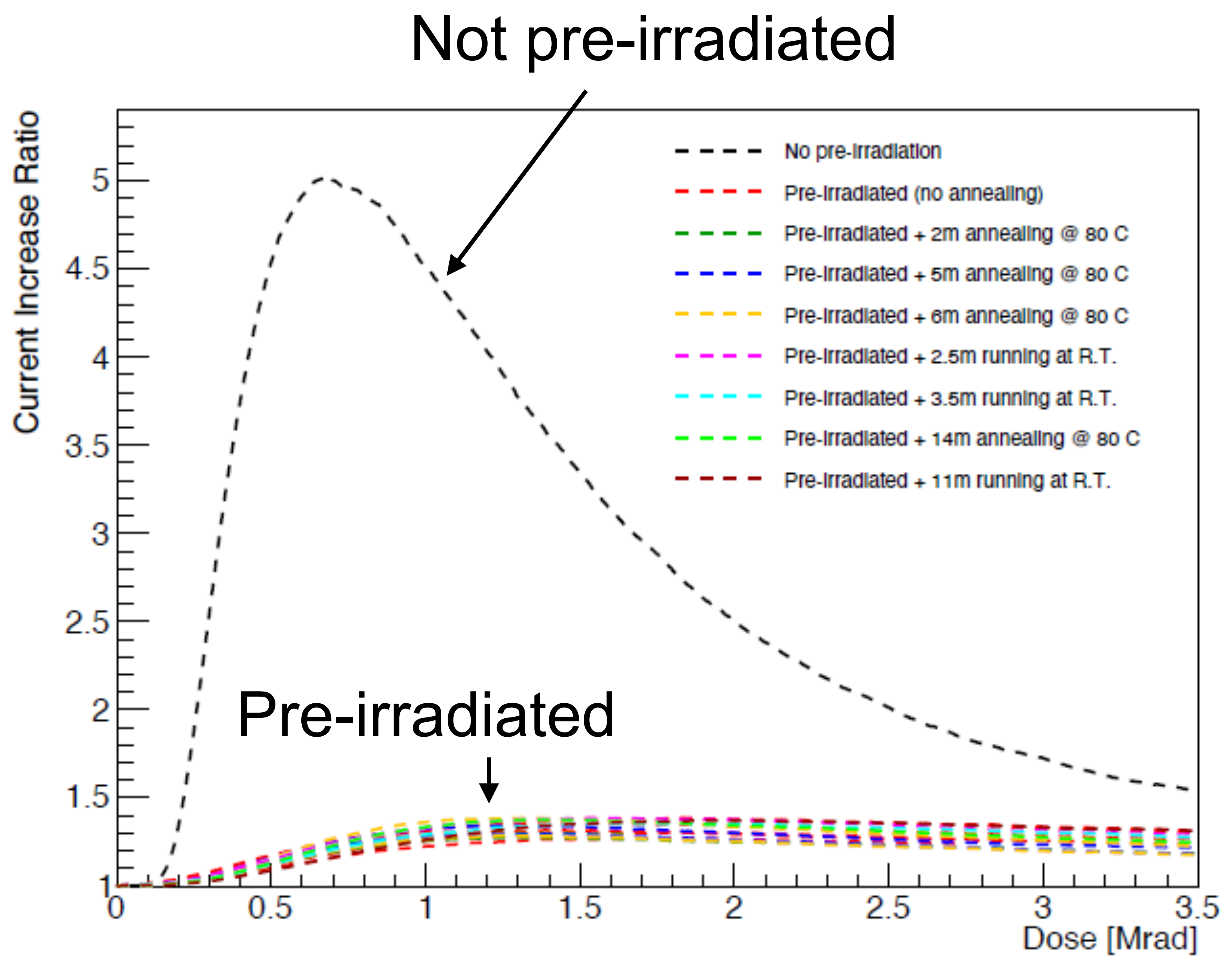


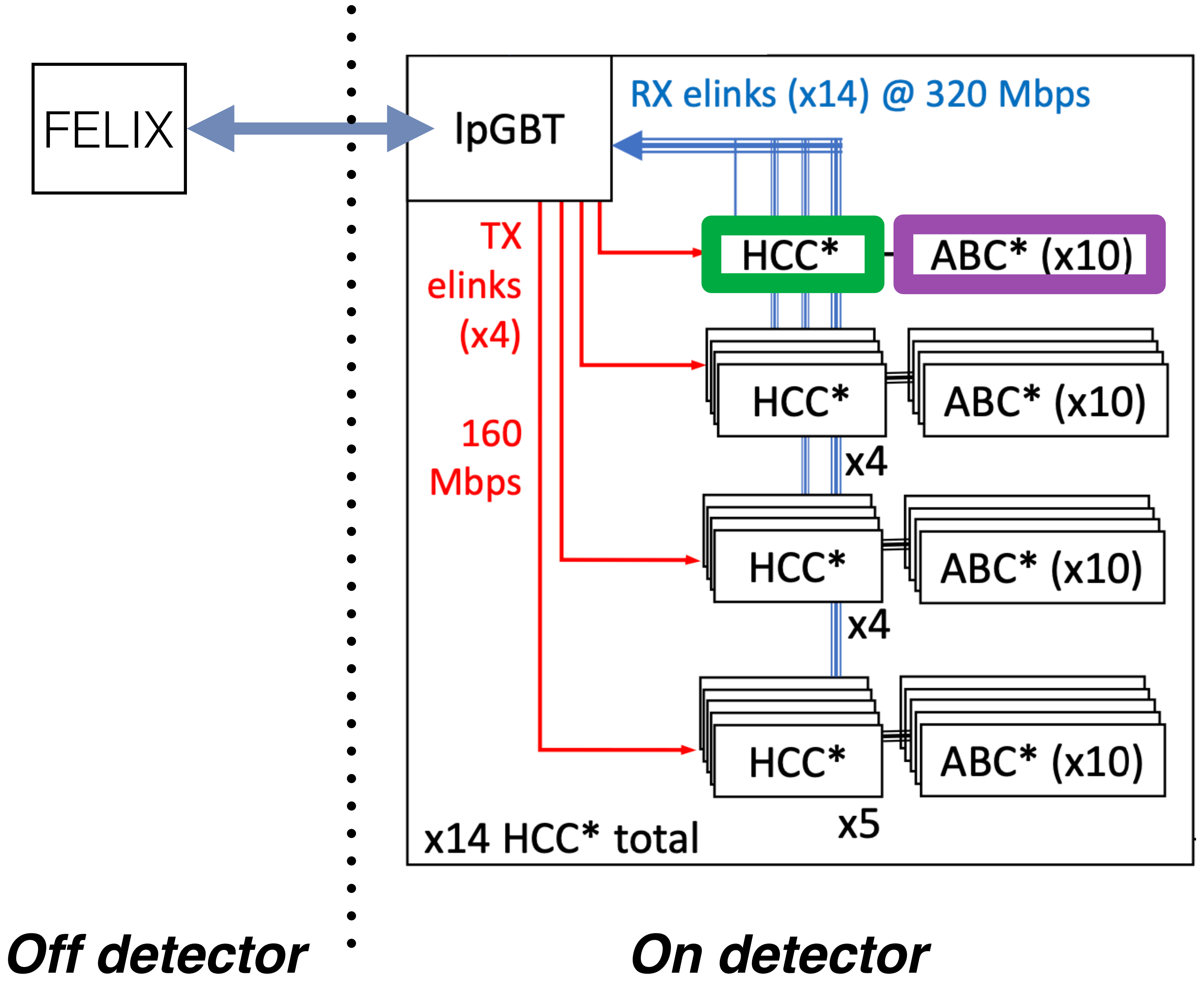




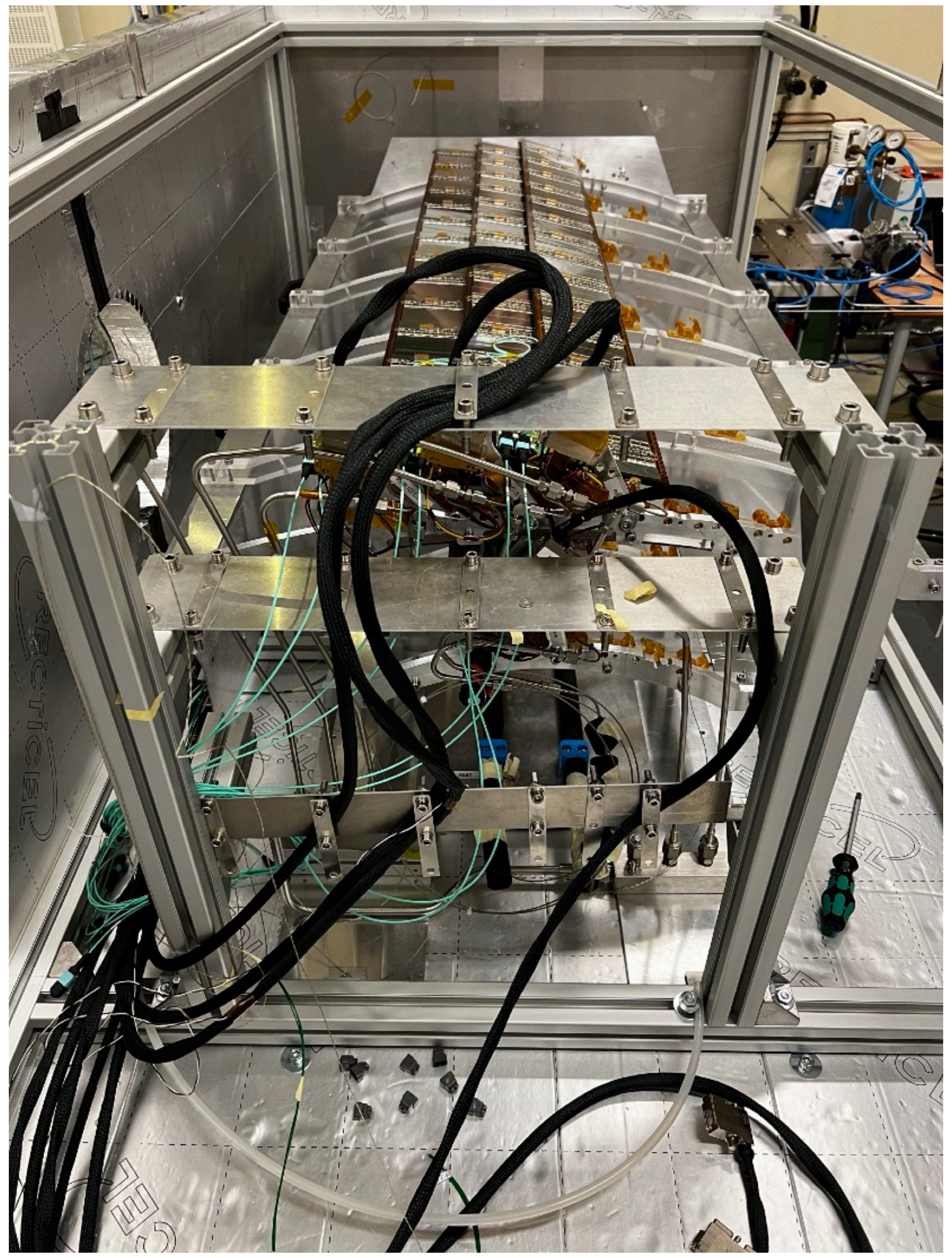
Electronics and Readout

- **All three ASICs** (ABCstar, HCCstar, AMACstar) are produced by Global Foundry (**GF**) in the 130 nm technology [Poster on SEU by Shaogang](#)
- **ASICs are pre-irradiated** to 5 Mrad with ^{60}Co since their current consumption becomes more **uniform afterwards**
- **Performance evaluated** in test beam campaigns and extensive simulations,
- **Readout performance** (1MHz with link occupancy <90%, 6μs latency) and developments studied at dedicated **System test setups**





Barrel System test at CERN



Endcap System test at DESY

[Talk on System tests by Jan](#)

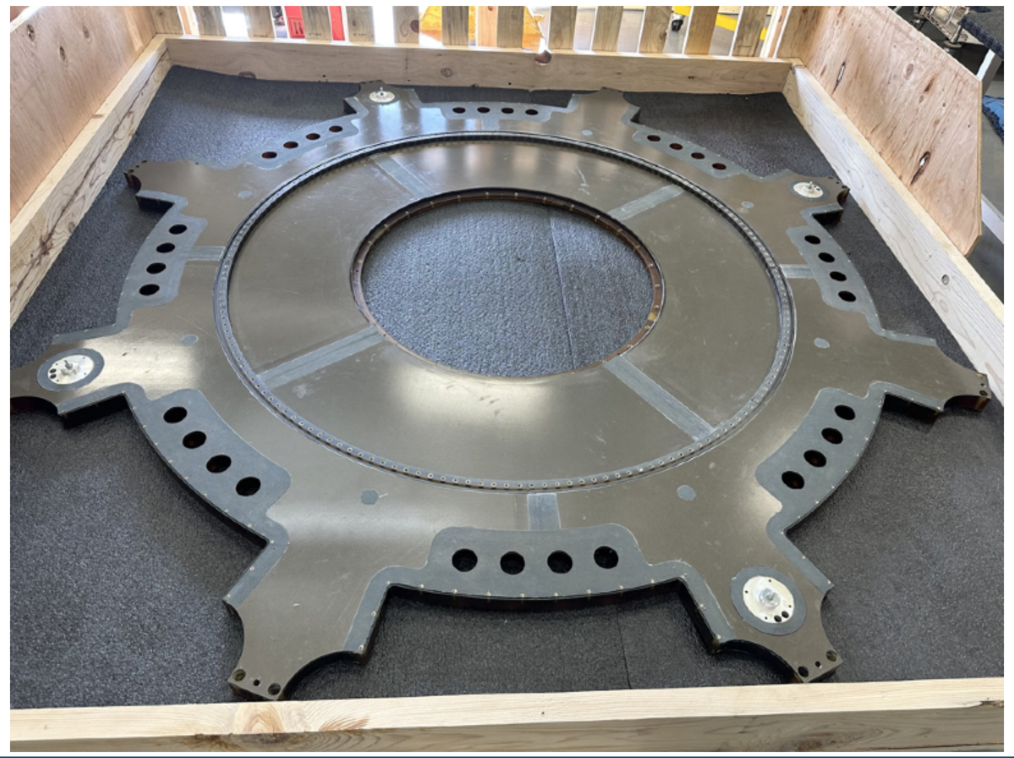
Brookhaven National Laboratory

Structure Highlights

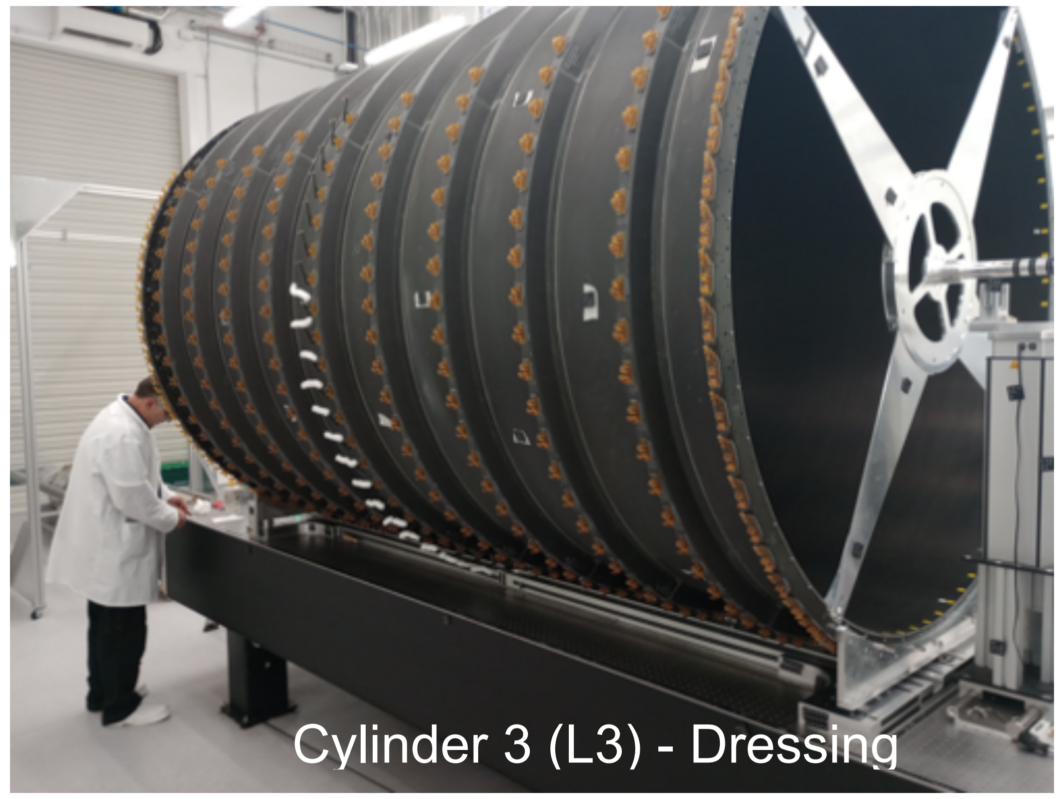
Global

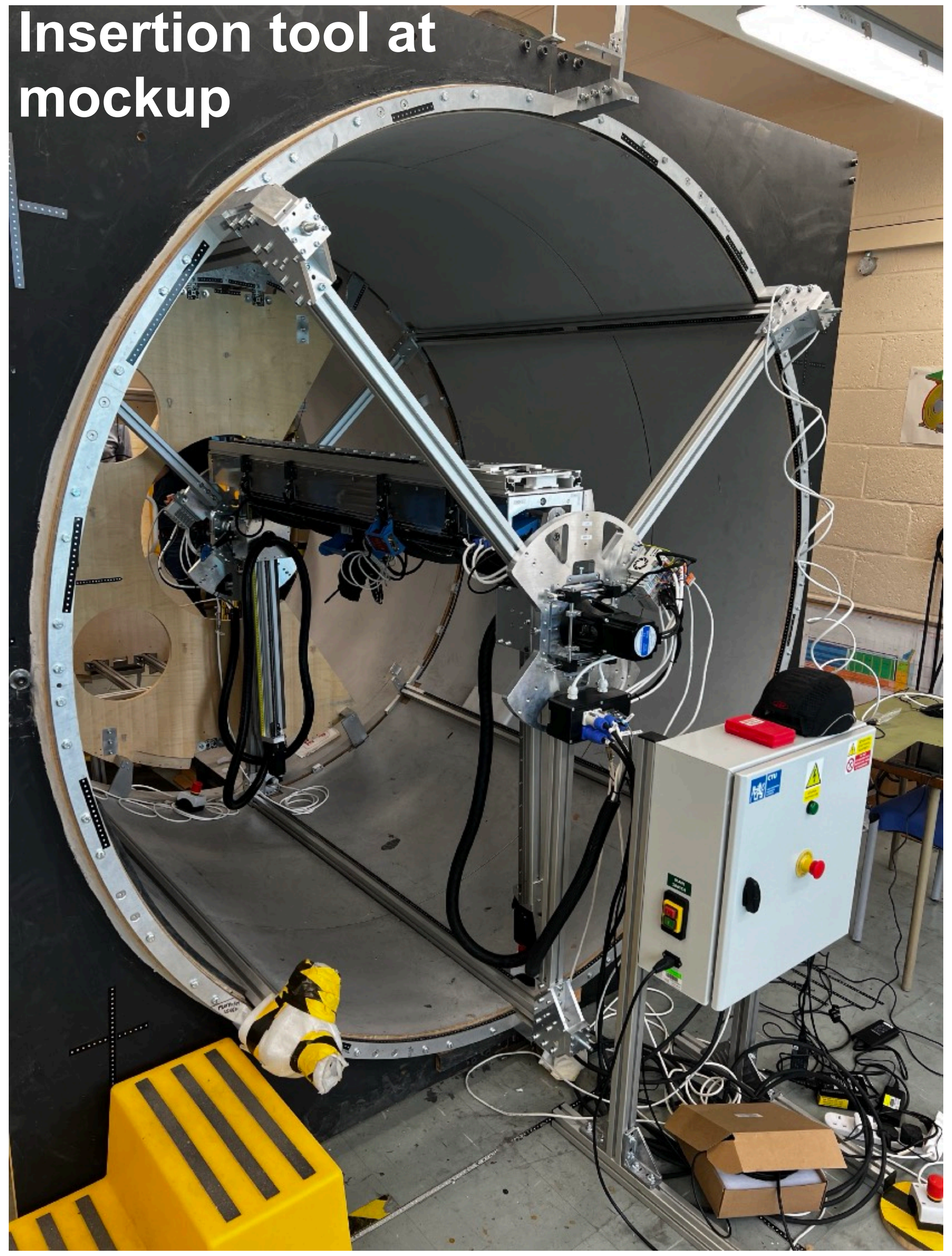
Global Structure :Outer Cylinder (OC)
Hosts the ITk

Bulkheads:
Close the volume on either end of OC

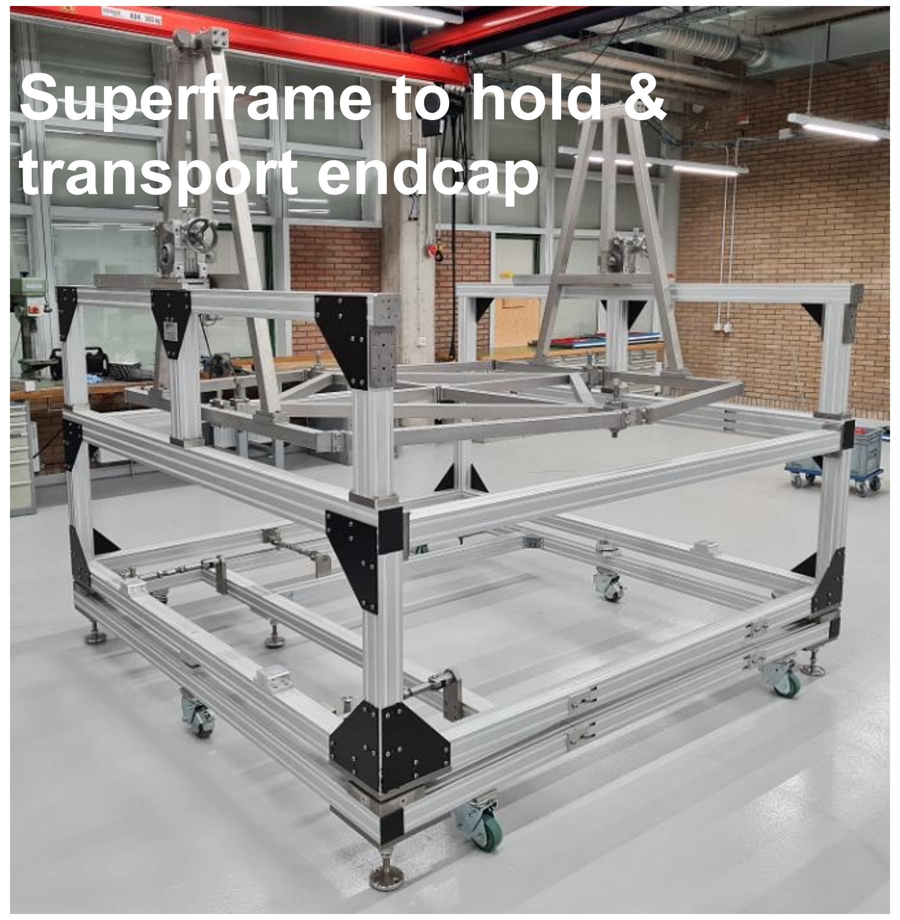


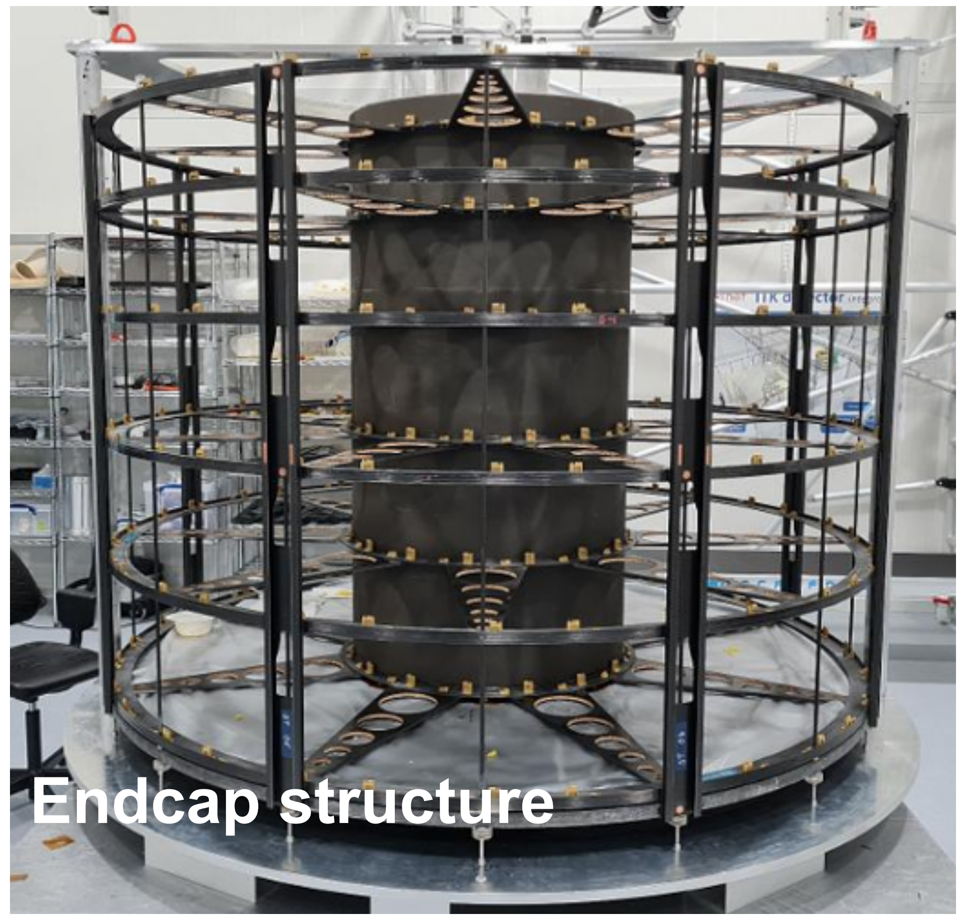
Barrel

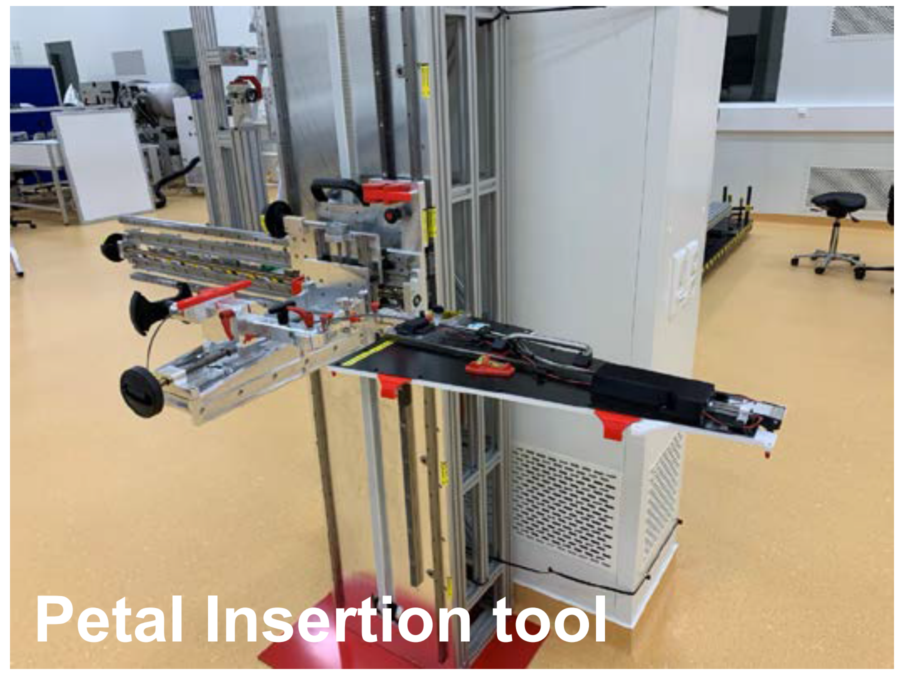




Endcap(s)



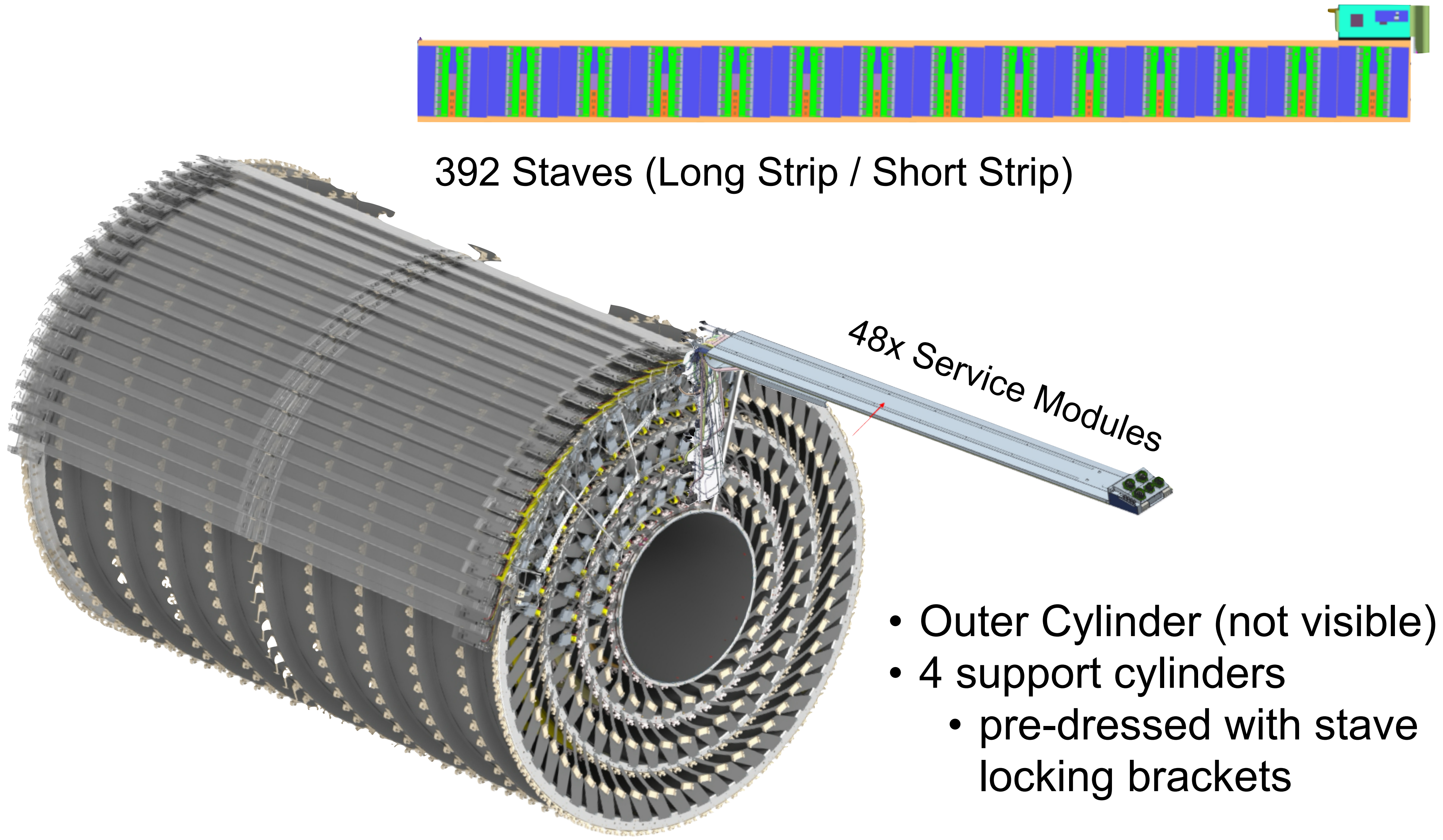




Brookhaven National Laboratory

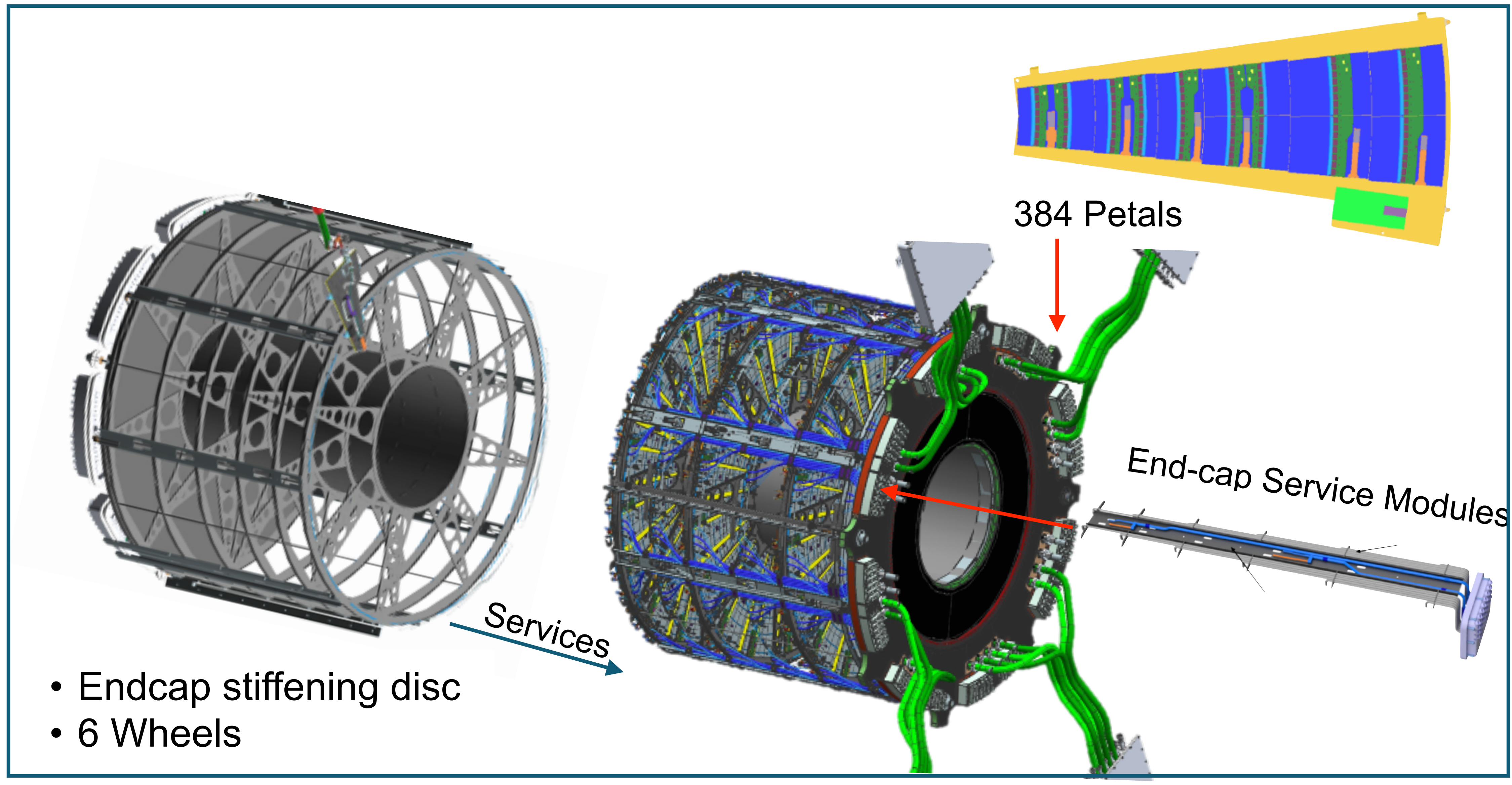
Integration

Barrel Integration at CERN



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

2x Endcap(s) - Integration at DESY, Nikhef

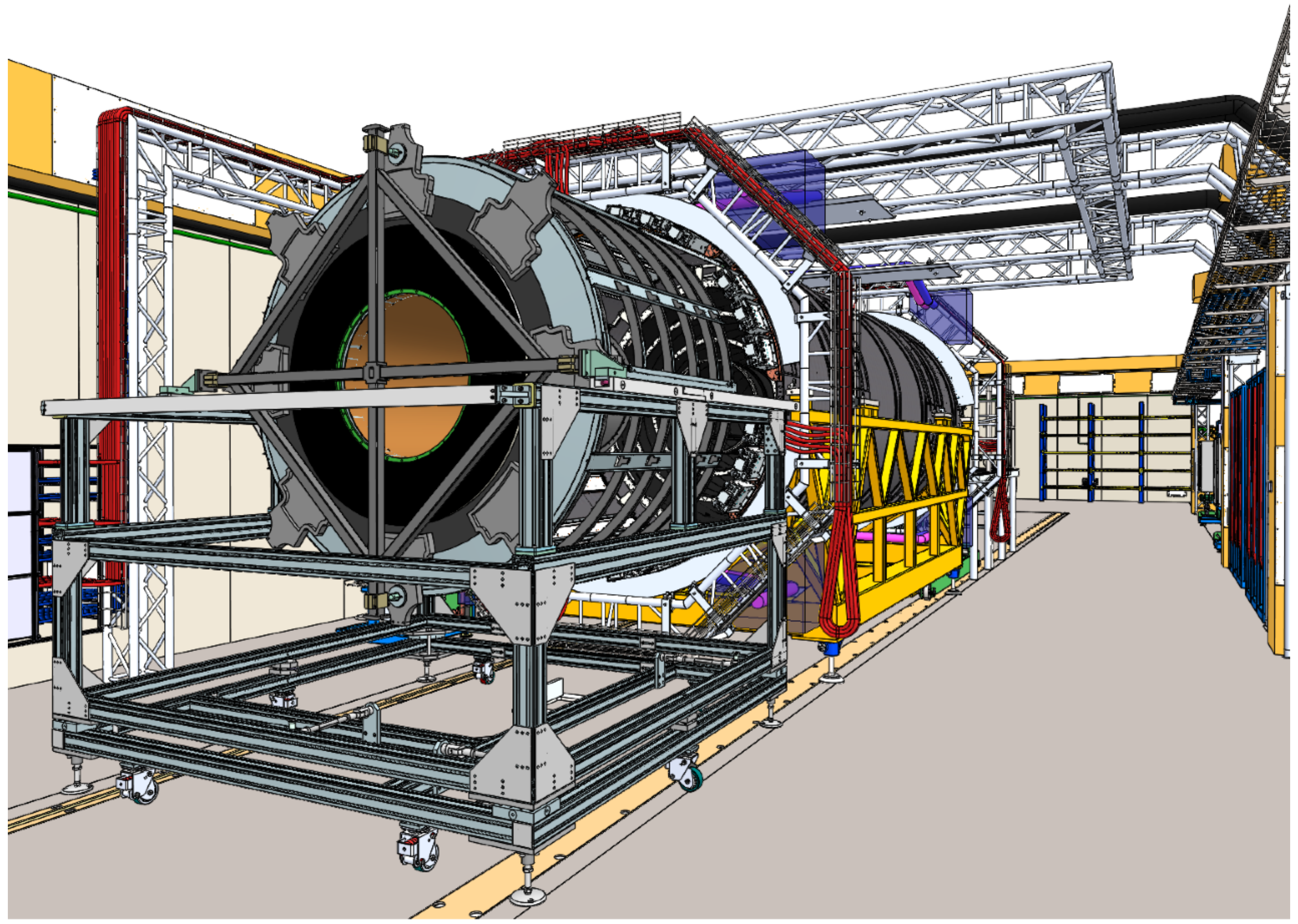


- Endcap stiffening disc
- 6 Wheels

Complete endcaps to CERN

Clean room preparation at CERN

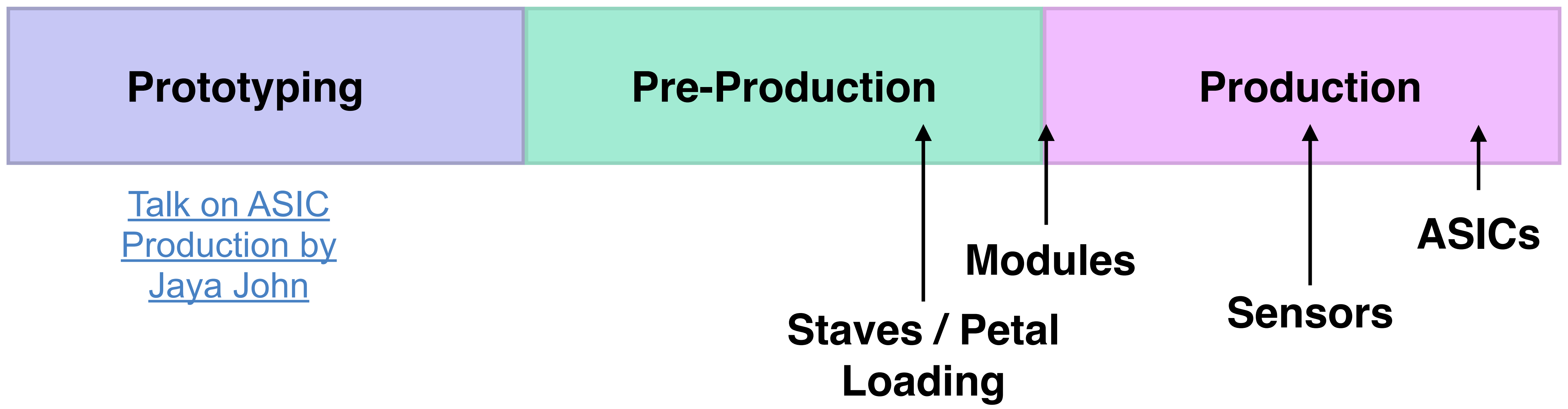
Complete ITk Strips detector

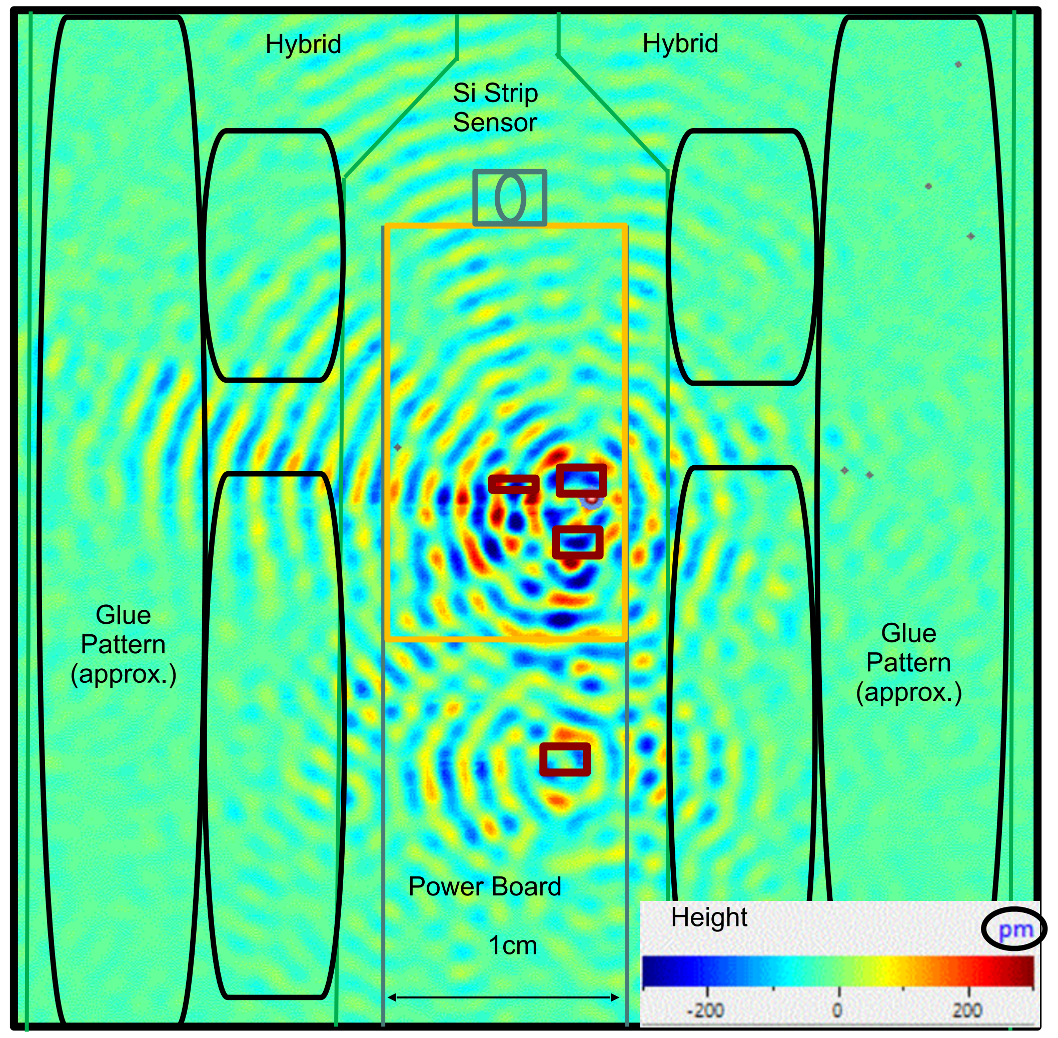


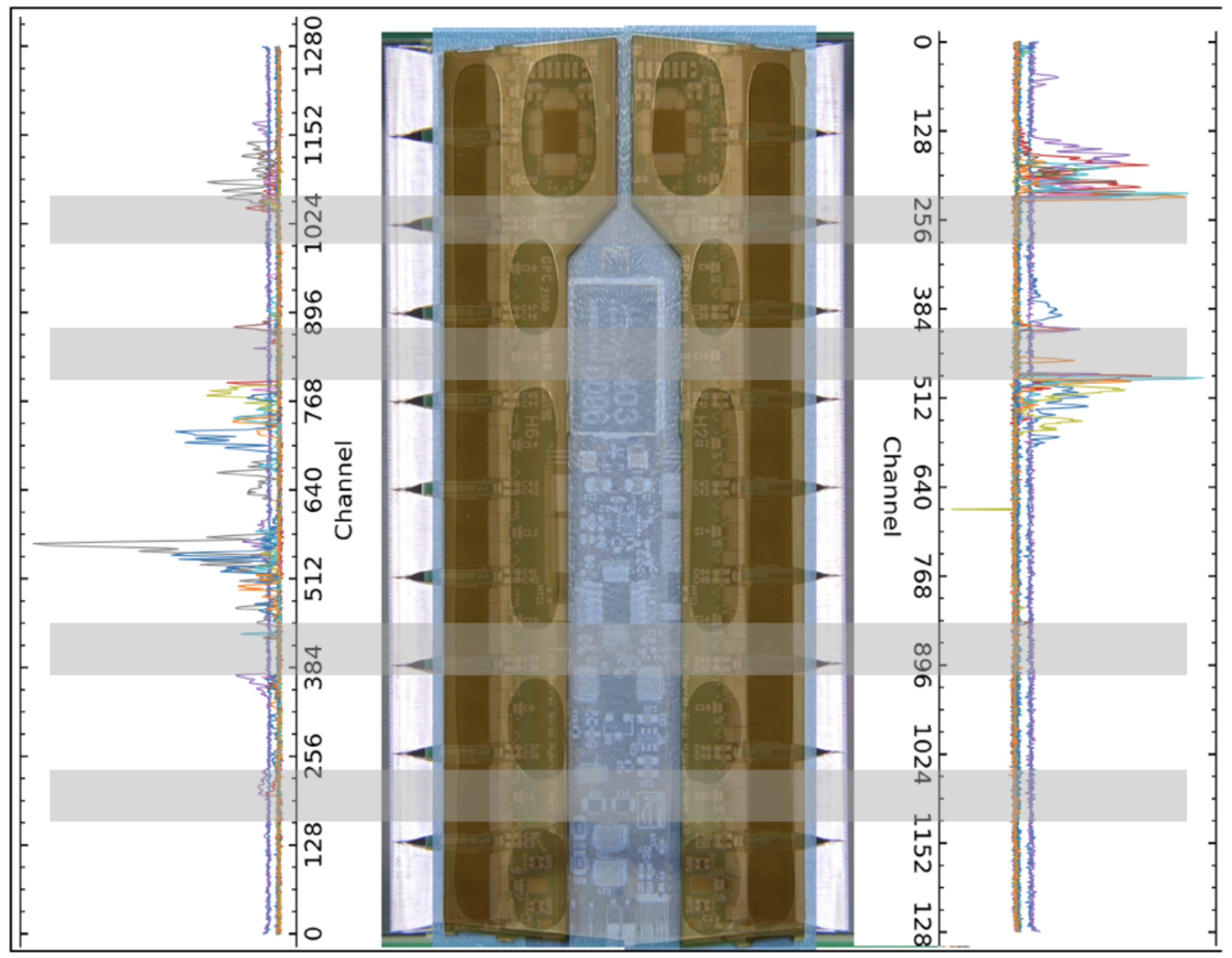
Brookhaven National Laboratory

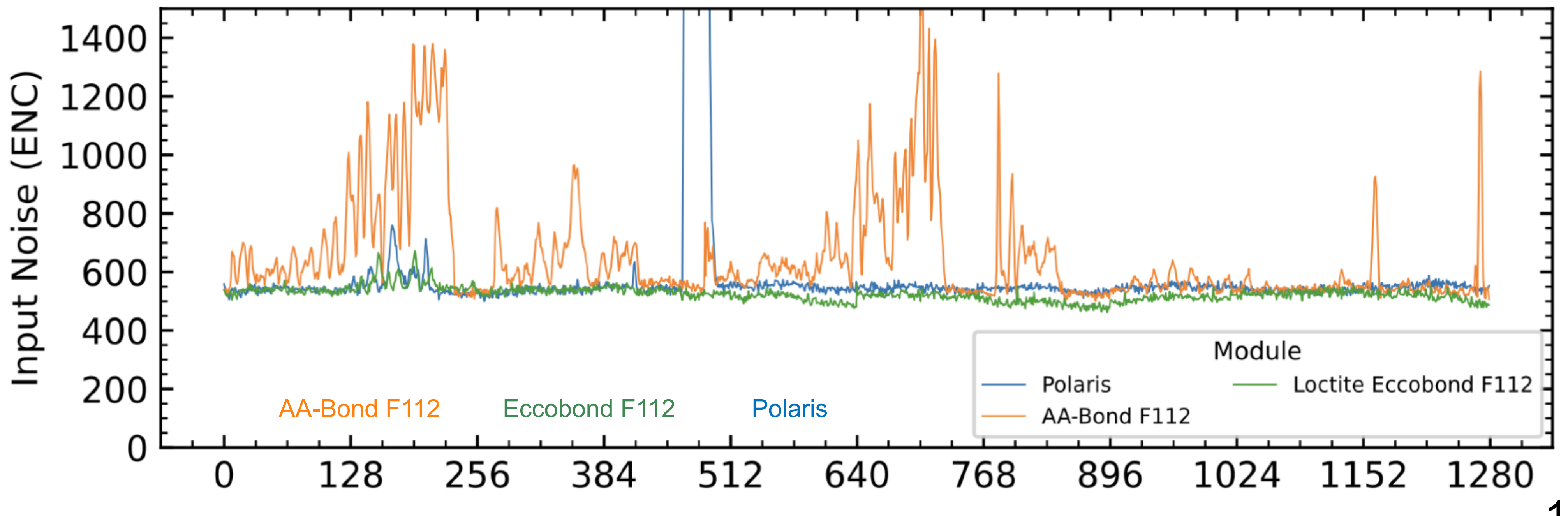
Current status - Towards production

- **Sensor** (>50% delivered) and **ASIC production** (>90% manufactured) running **smoothly**
- **Unfortunately** on May 2022 before modules enter production, a **technical issue** was discovered”
  - **Excessive noise** once at “Cold” temperatures below -20°C a.k.a **“Cold Noise”**
  - **Dedicated studies** tracked down to capacitors in the DCDC domain of the powerboard vibrating at 2 MHz and those **vibrations** traveling across the sensor and coupling back into the sensors
  - By May 2023 a **mitigation** technique was put in place: changing the glue which minimises the noise







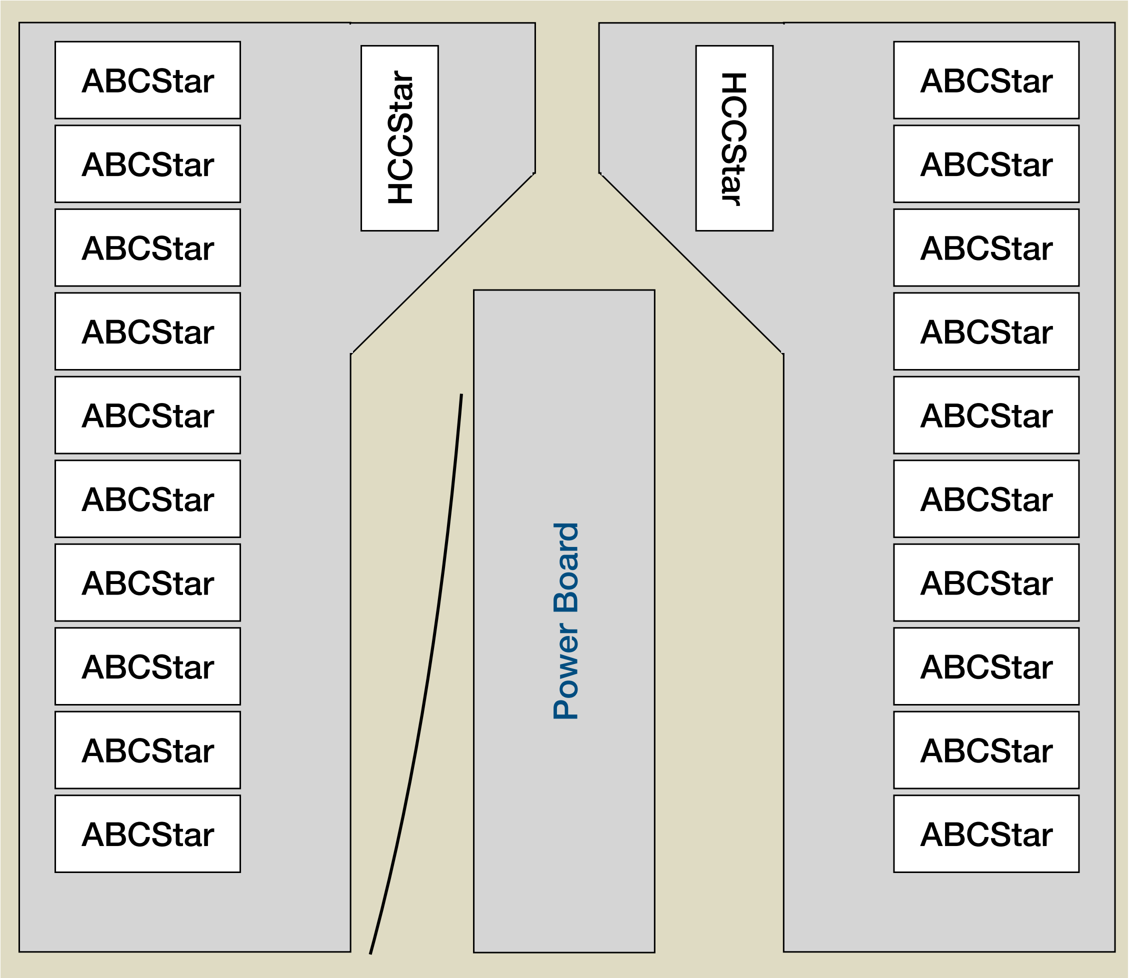


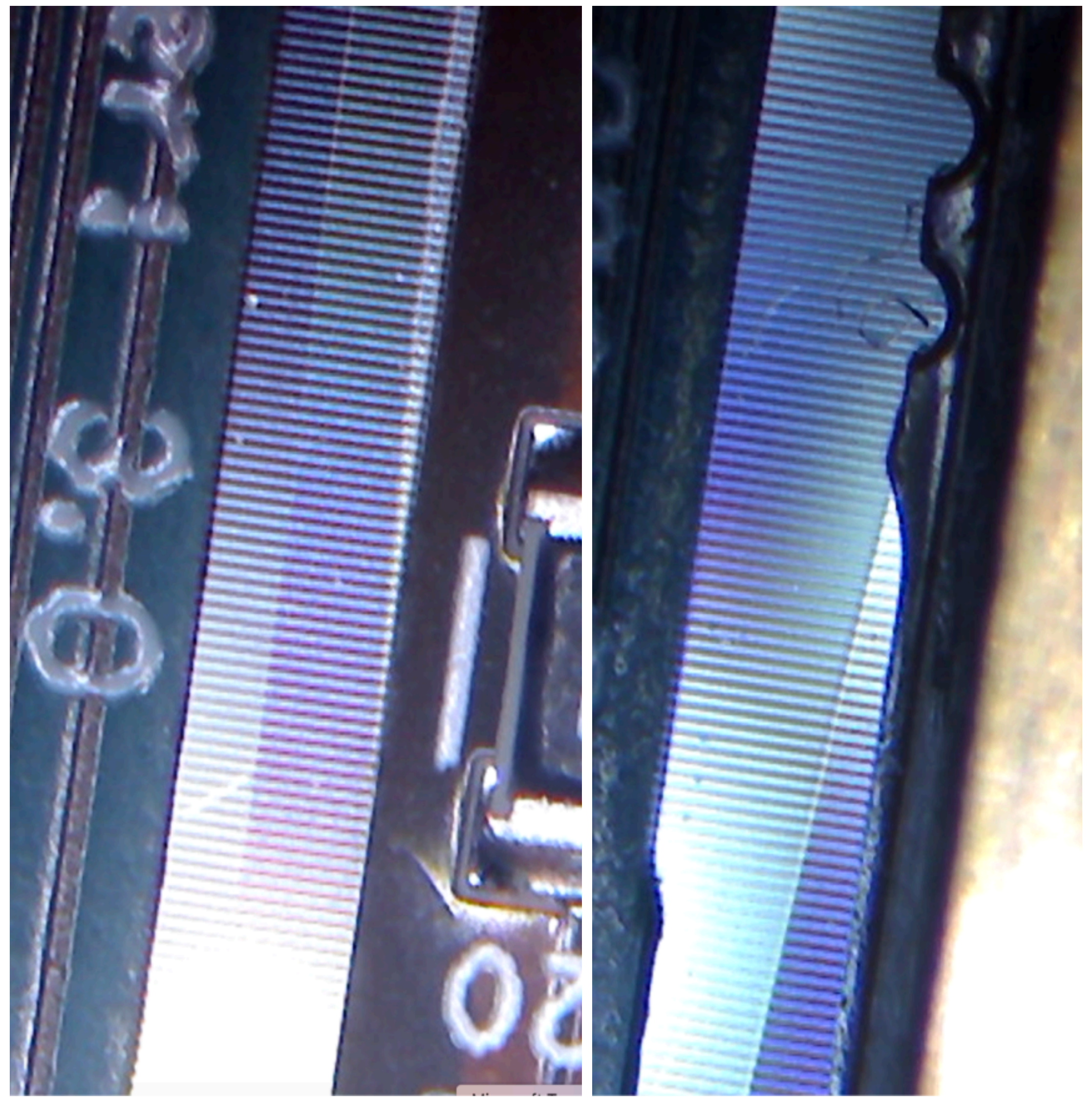
Ian Dyckes and Matthew Kurth, TWEPP 2023

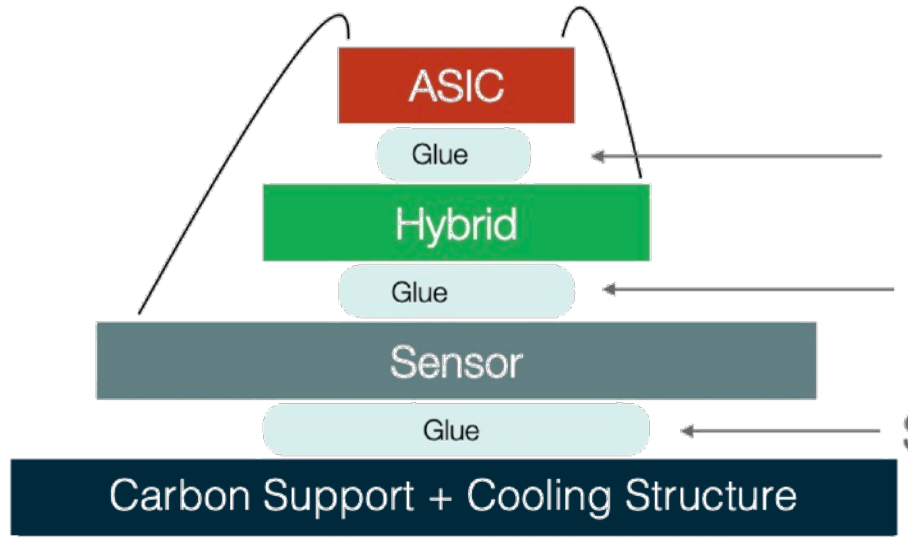
Brookhaven National Laboratory

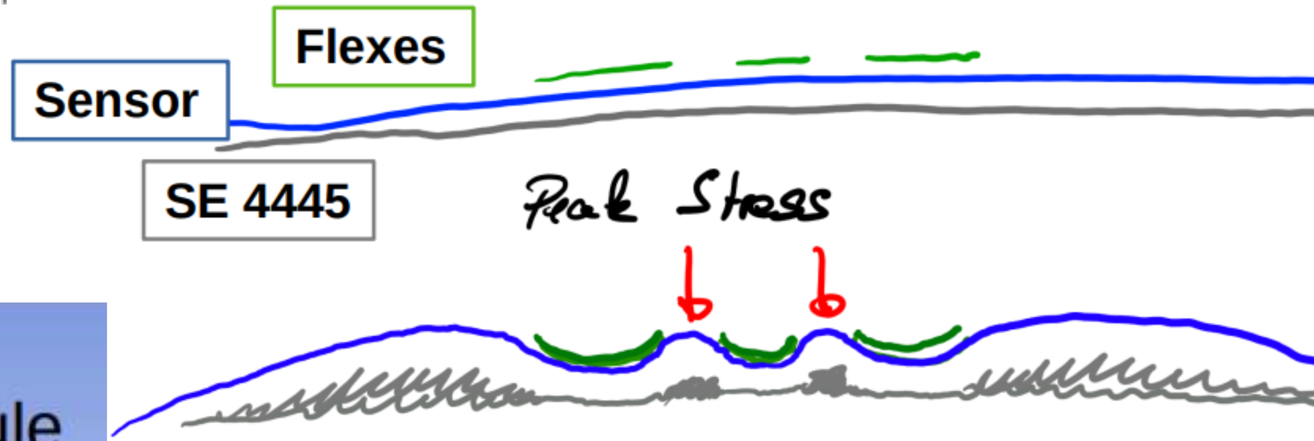
Current status - Sensor cracks

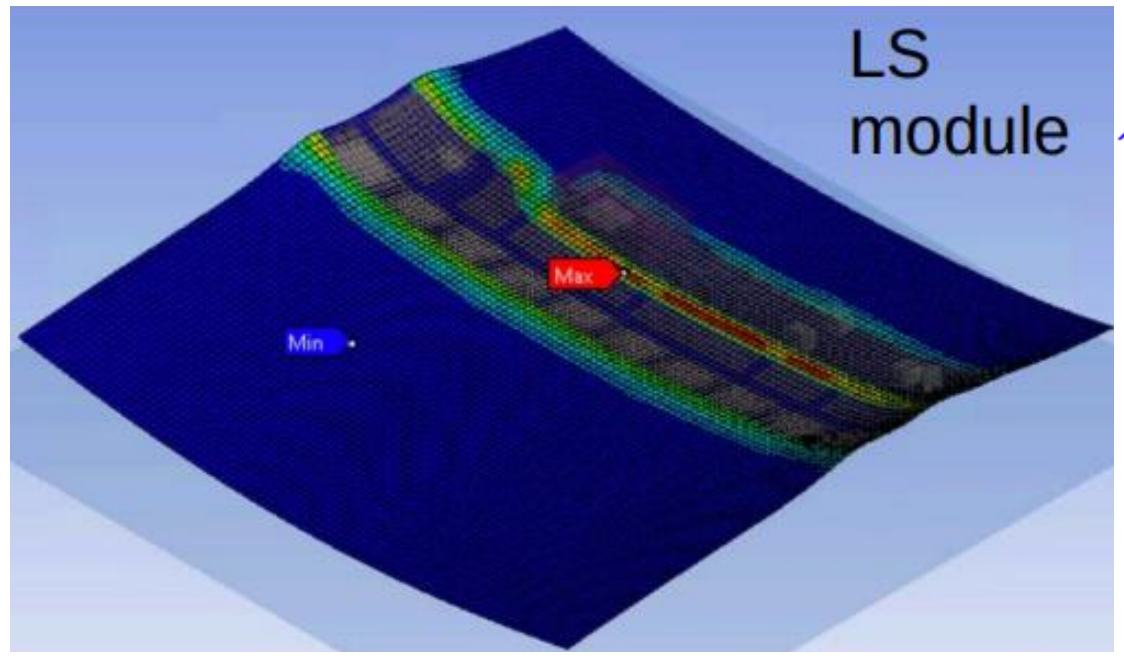
- Although a **mitigation** action has minimised the issue of “Cold Noise” **another technical challenge** was discovered
- In June 2023 we started to observe that we had **higher levels of high voltage breakdown** during **stave** tests than expected
- **Investigations** led to the discovery of **cracking** sensors
- **Studies are ongoing**, FEA simulations indicate the issue is the **CTE mismatch** between hybrids/ powerboards and sensors
  - Issue of different stiffness of the glue below and above the sensor
- Mitigation actions are explored and **<u>studies are ongoing</u>**









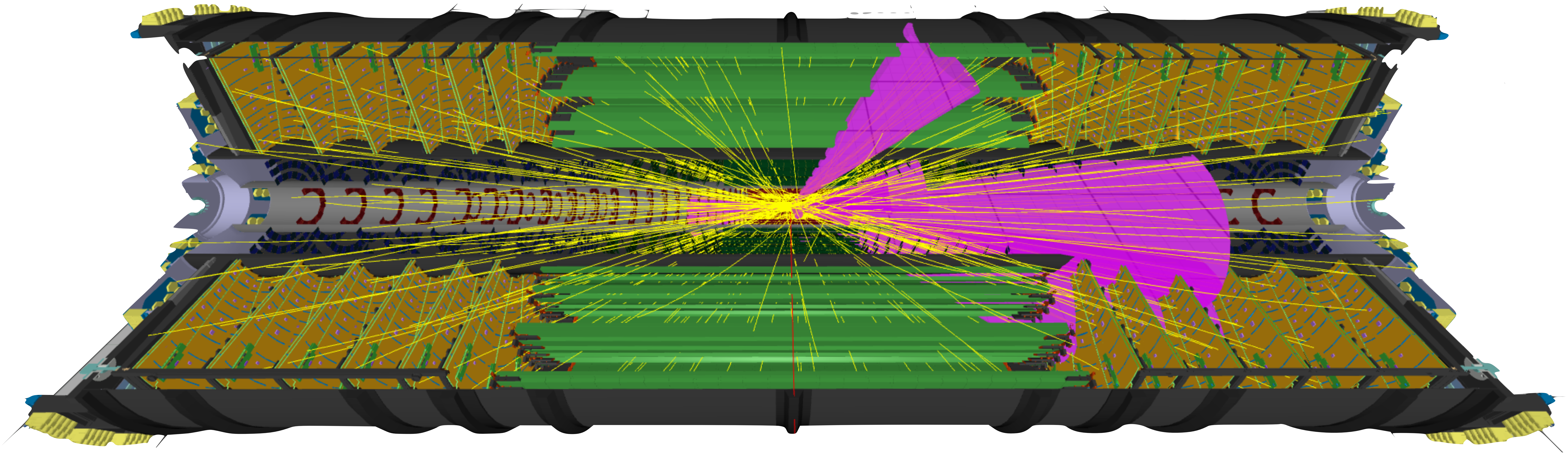


Brookhaven National Laboratory

Summary

- In view of **HL-LHC**, the ATLAS experiment will **upgrade** its complete Inner Detector with an all silicon **Inner Tracker (ITk)**
- ITk is **expected to improve** the ATLAS performance operating under a harsh environment
- The **Strips detector** has been through many years of **design and R&D** with the **pre-production** smoothly ongoing in several areas
- **Major advancements** on the construction of **structures**, **services** and **preparation for integration**
- **Two major technical issues** have derailed the production schedule though:
  - The community is working hard to address and mitigate those issues such that production of Modules can be launched
  - Initial results from mitigation techniques are encouraging

Thanks !



Backup

LHC Long term schedule

Last update: April 2023

Brookhaven National Laboratory

Numbers

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**

Electrical properties common to all types of sensors

Parameters	Initial condition (*1)	Post-irradiation (*2)
Wafer:		
Material	p-type Silicon, float-zone (FZ)	--
Crystal orientation	<100>	--
Resistivity	>3.5 kΩcm	--
Oxygen concentration	1.5x10^16 to 6.5x10^17 (atoms/cm^3)	--
Active thickness (tolerance)	>270 µm	--
Sensor:		
Full depletion voltage (V_{fd})	<350 V	--
Breakdown voltage (V_{bd})	>500 V	>500 V or V_{fd}+50 V
Maximum operating voltage	500 V (at sensor)	←
Leakage current	<0.1 µA/cm^2	<0.1 mA/cm^2
	at 500 V, RH<10%	←
Leakage current stability	<15% at 500 V, RH<10%, 24 hours, after temperature correction (*3)	←
Bad strips	≤8 consecutive, <1% per segment	←
Collected charge (MPV(*4))	>6350 electrons, at 500 V	←
Strip:		
Resistance of n-implant strip	<50 kΩ/cm	←
Resistance of AC-metal strip	<30 Ω/cm	←
AC coupling capacitance (C_{AC})	>20 pF/cm, at 1 kHz	←
Polysilicon bias resistor (R_b)	1.5 ± 0.5 MΩ	1.8 ± 0.5 MΩ
Inter-strip resistance (R_{int})	>10×R_b, at 300 V	← at 400 V
Inter-strip capacitance (C_{int})	<1 pF/cm (*5), at 300 V to its nearest neighbors on both sides, at 100 kHz or 1 MHz (main sensor or mini sensor, respectively)	← at 400 V

Radiation Safety Factors

Layer	Radius [mm]	Maximal Fluence [n_{eq}/cm^2]	Maximal Dose [MRad]
Strips			
Long Strips	762	3.8×10^{14}	9.8
Short Strips	405	7.2×10^{14}	32.5
End-cap	385	1.2×10^{15}	50.4
Pixels			
Layer 0	39	1.87×10^{16}	1268
Layer 1	75	0.59×10^{16}	549
Layer 2	155	0.22×10^{16}	129
Layer 3	213	0.15×10^{16}	87
Layer 4	271	0.11×10^{16}	53
End-cap	80	0.62×10^{16}	477

TDR of ITk Strips

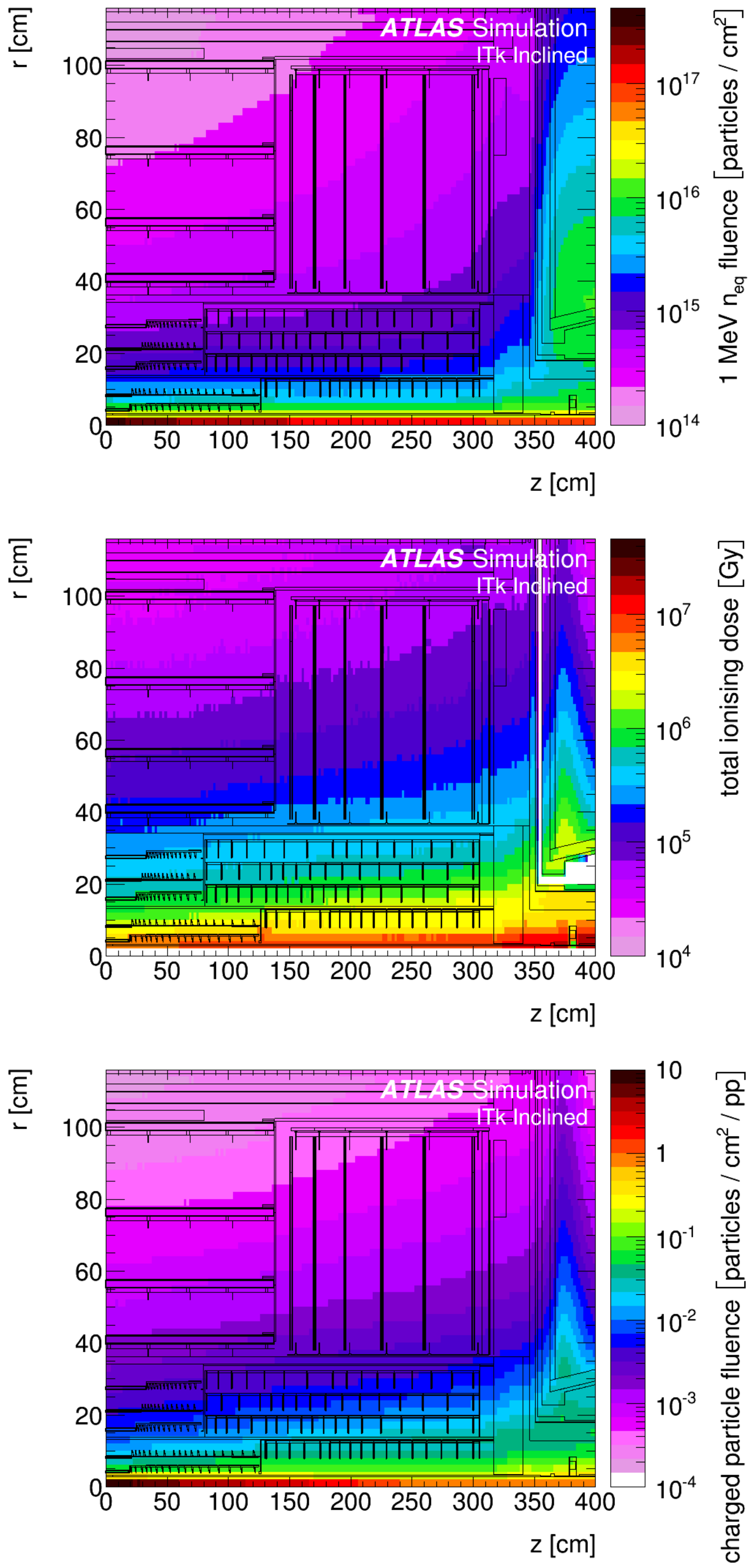
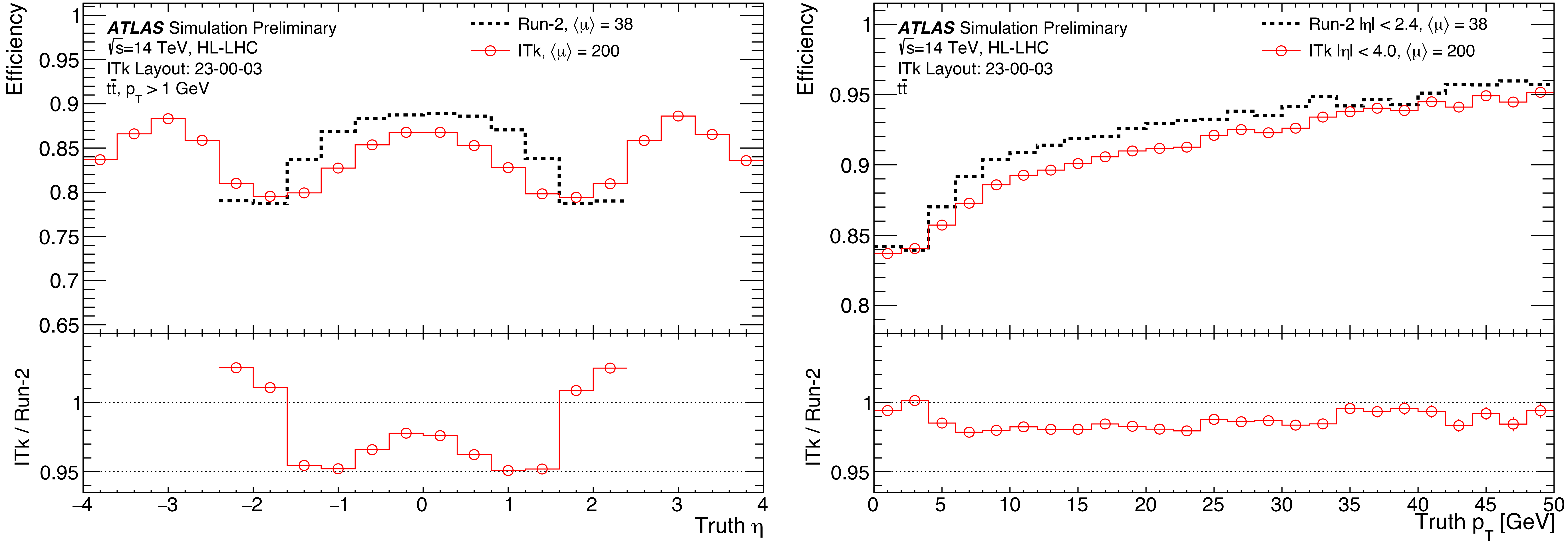


Figure 3.9: The fluence and dose distributions for the ITk layout. **Top**: The 1 MeV neutron equivalent flux. **Middle**: The total ionising dose. **Bottom**: The charged particle fluence.

Brookhaven National Laboratory

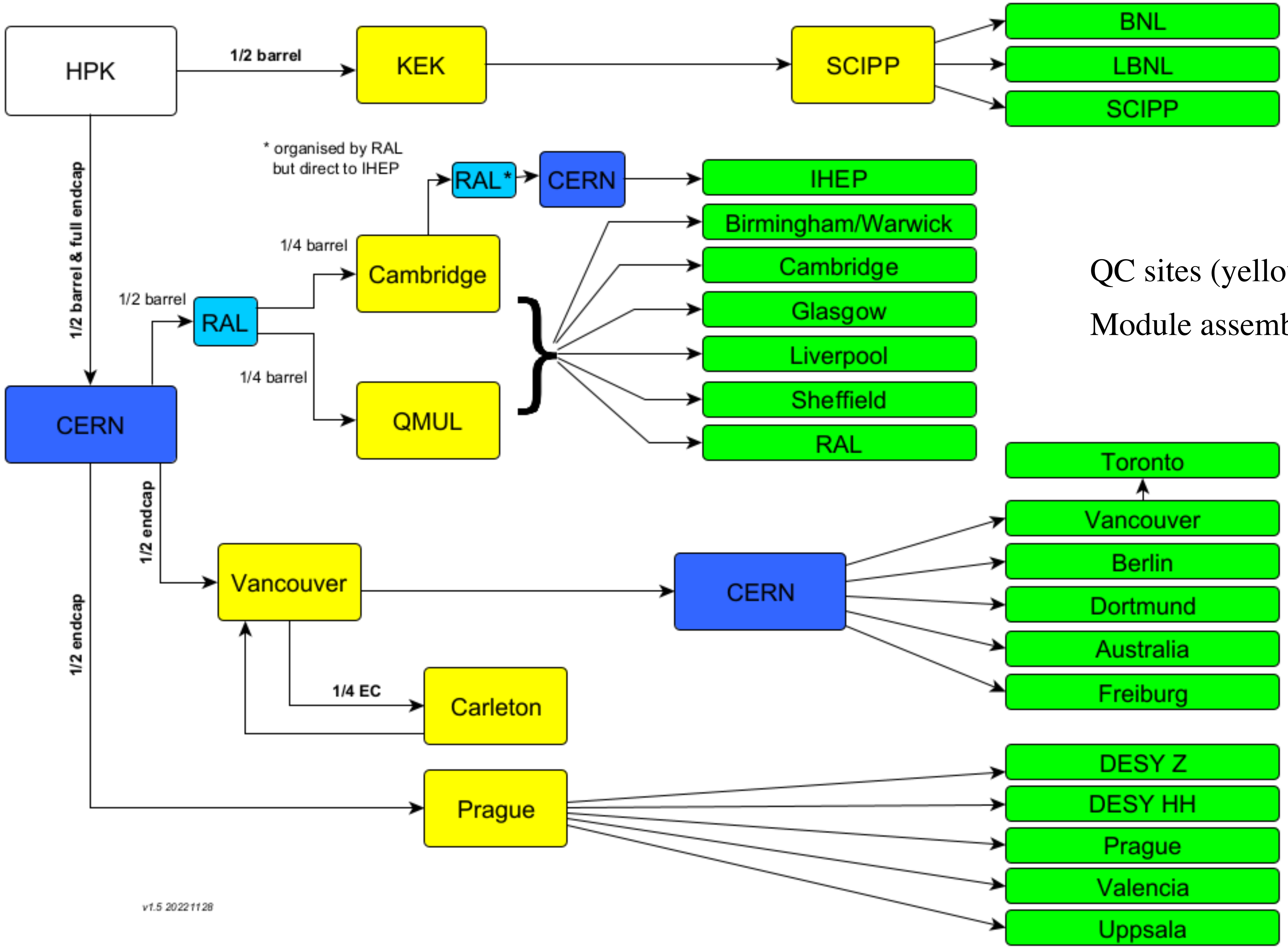
The ITk expected performance



- Tracking efficiency for $t\bar{t}$ events at mean pile-up of 200
- Performance maintain although pile-up 5x more
- Extended performance up to 4 pseudo-rapidity with efficiency >85%

Brookhaven National Laboratory

ITk Strip Sensor part flow and QC procedure



QC sites (yellow)

Module assembly sites (green)

ITk Strip Sensor QC procedures

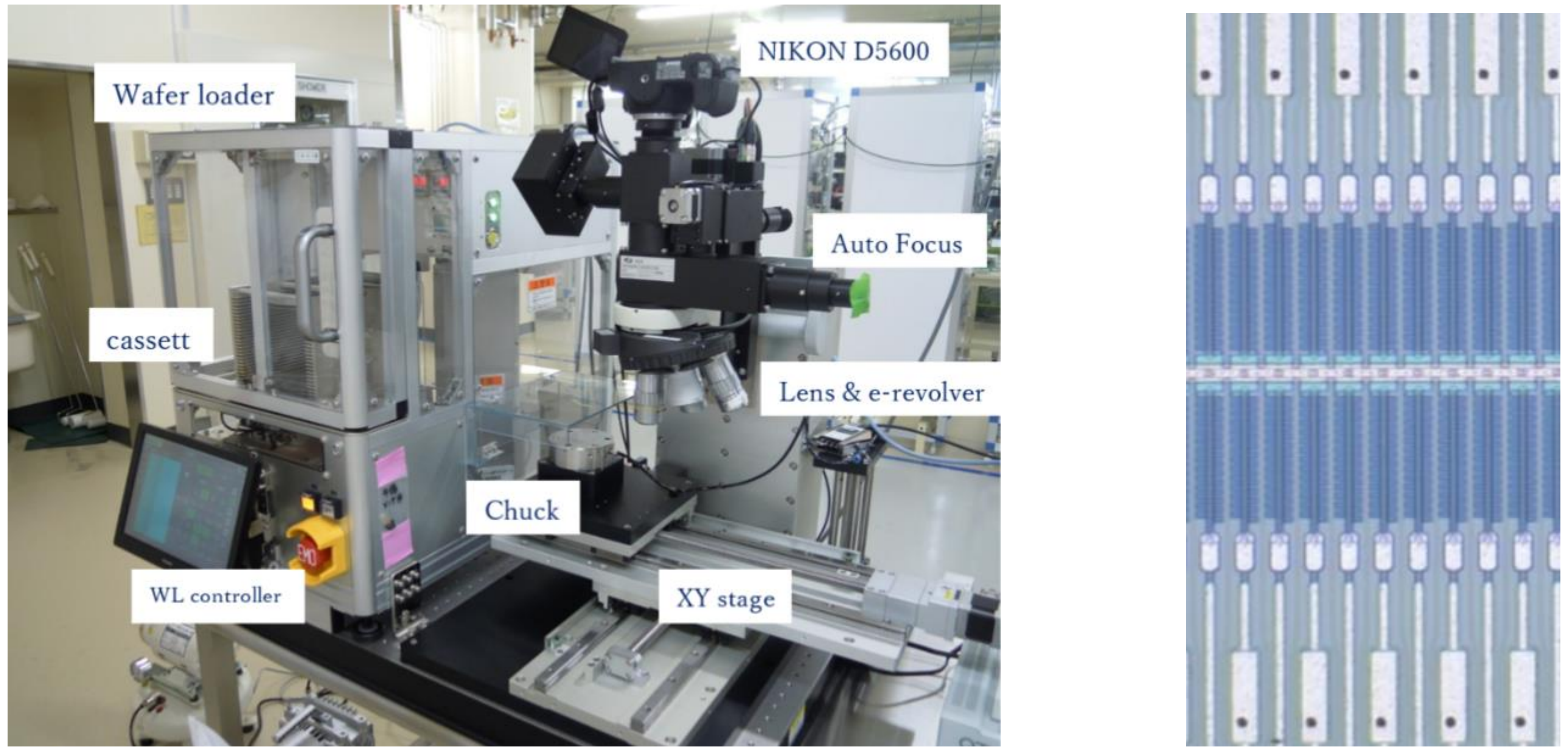


Figure 2. Metrology and Visual Capture setup installed in the clean laboratory of HPK and used by the KEK/Tsukuba QC testing site (left). Evidence of the resolution achieved with this setup (right).

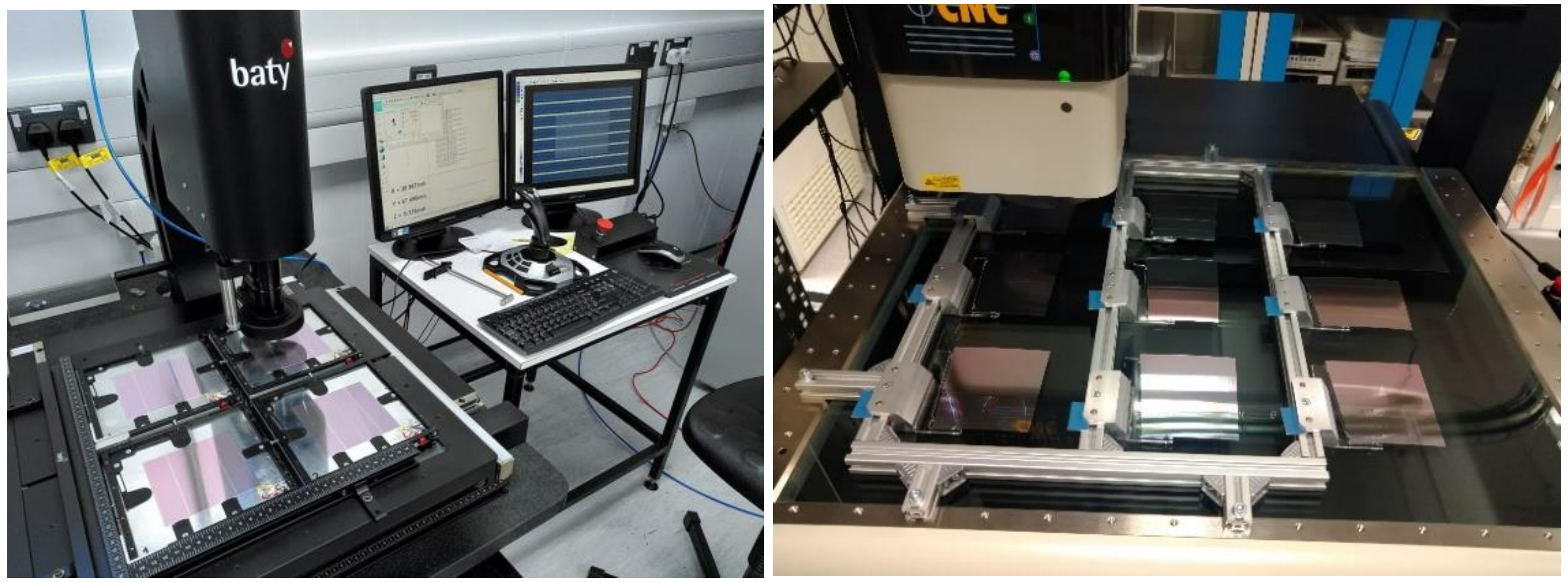


Figure 3. BATY Venture 3030 measurement system installed at University of Cambridge (left) and OGP SmartScope CNC 500 machine used for metrology and Visual Capture tests in Prague (right).

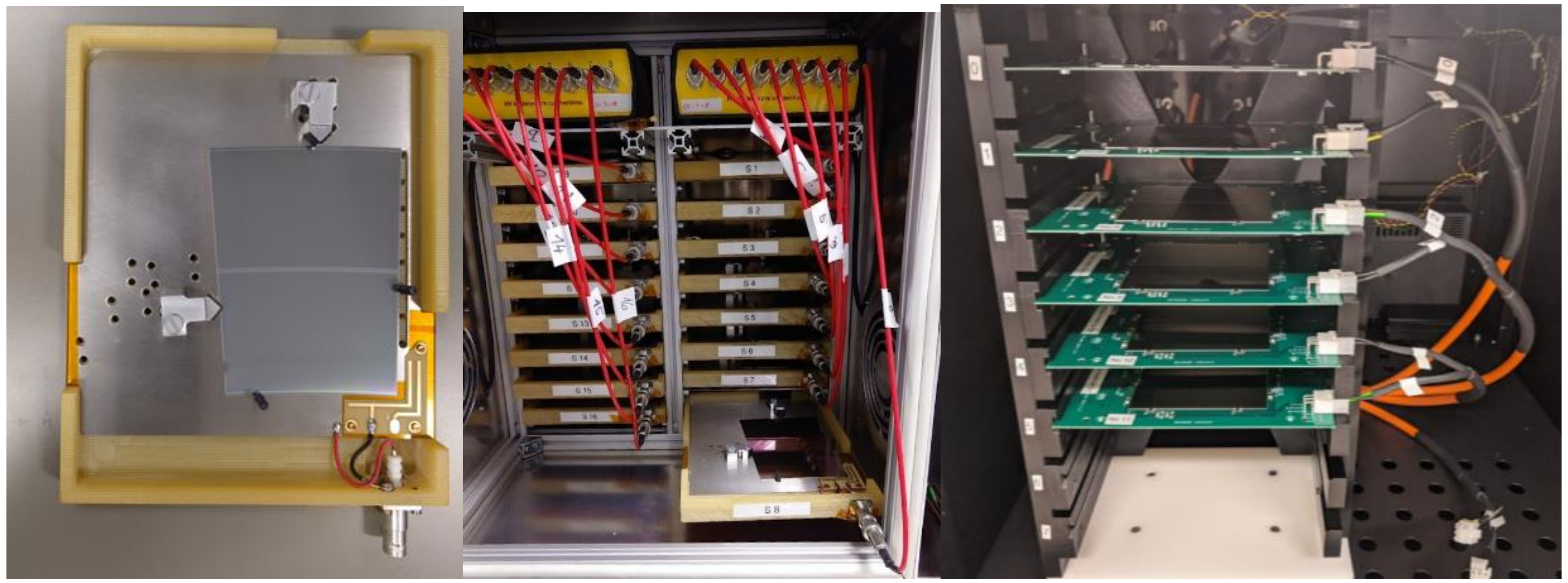


Figure 4. The R4 endcap sensor installed on the jig designed for leakage current stability tests (left). Dry storage cabinets with slots for sensor jigs or module test frames used for the leakage current stability tests in Prague (middle) and SCIPP (right).

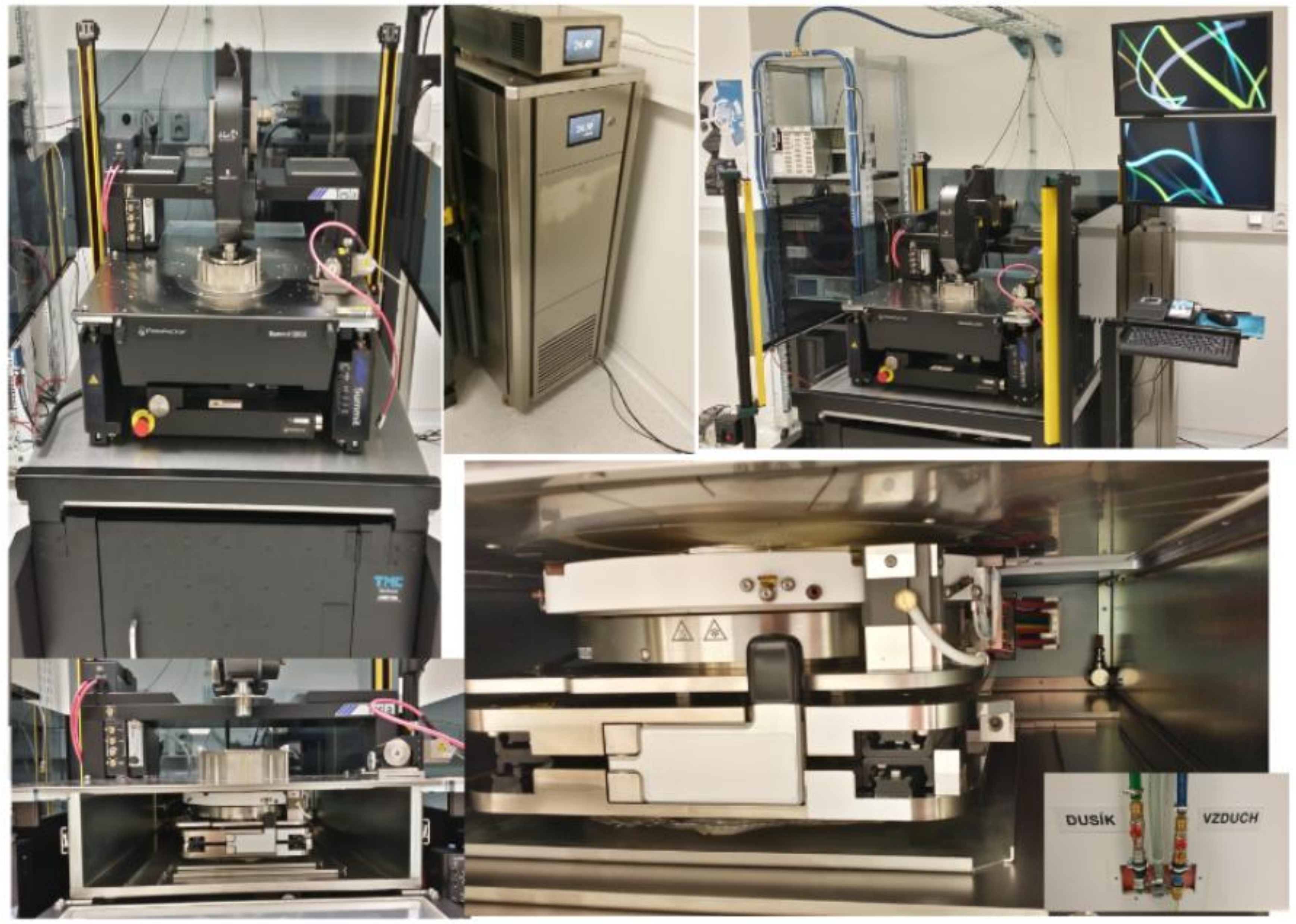
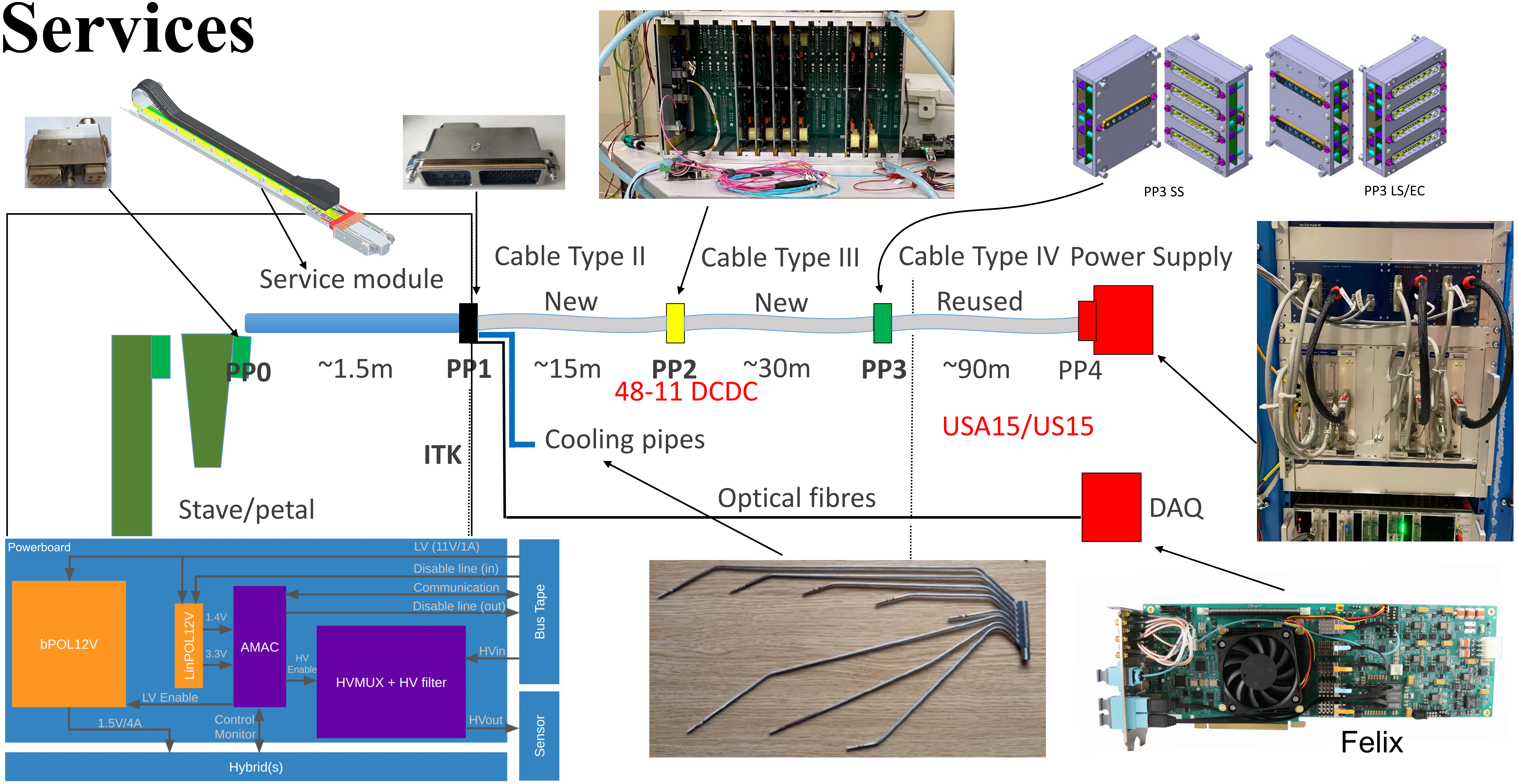


Figure 5. Semi-automatic Probe station Tesla 200mm installed in Prague.

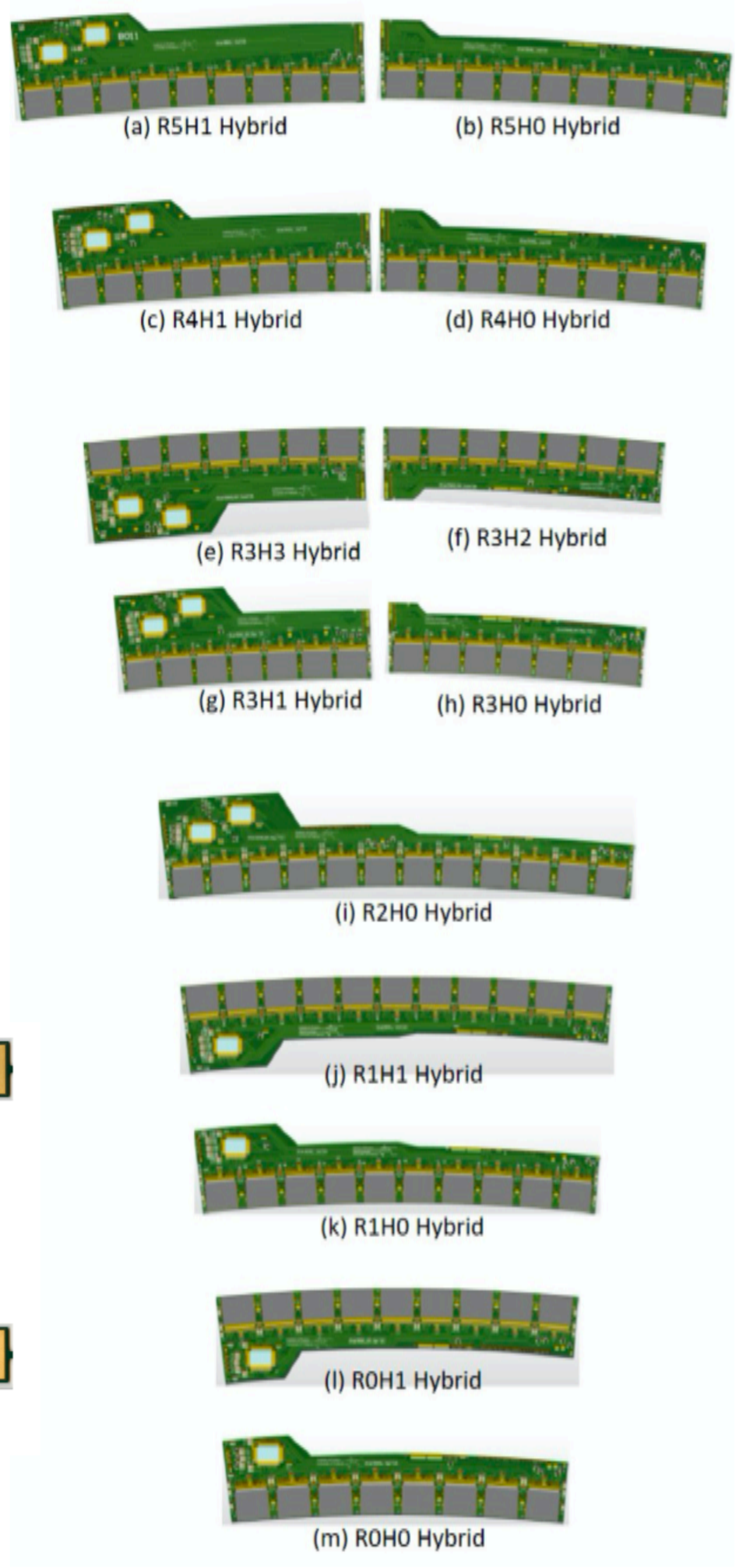
Services

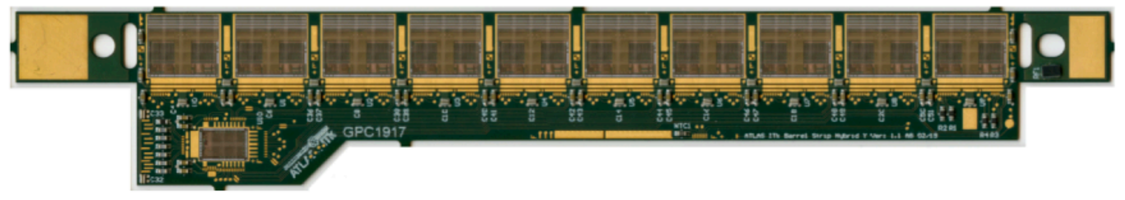


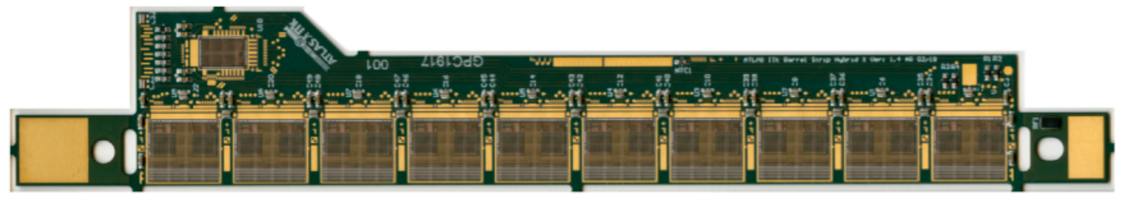
PP3 SS
PP3 LS/EC
Service module
Cable Type II
New
Cable Type III
New
Cable Type IV
Reused
Power Supply
PP0
~1.5m
PP1
~15m
PP2
48-11 DCDC
~30m
PP3
~90m
PP4
USA15/US15
ITK
Cooling pipes
Optical fibres
DAQ
Stave/petal
Powerboard
LV (11V/1A)
Disable line (in)
Communication
Disable line (out)
bPOL12V
LinPOL12V
1.4V
3.3V
AMAC
HV Enable
HVMUX + HV filter
HVin
HVout
LV Enable
1.5V/4A
Control
Monitor
Hybrid(s)
Bus Tape
Sensor
Felix

Hybrids

- ABCStar: ATLAS Binary Chip
- HCCStar: Hybrid Controller Chip




(a) Y barrel hybrid.


(b) X barrel hybrid.