Sensor and Module development for the CMS Phase-2 Tracker Upgrade

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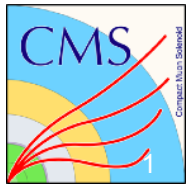
on behalf of the CMS collaboration

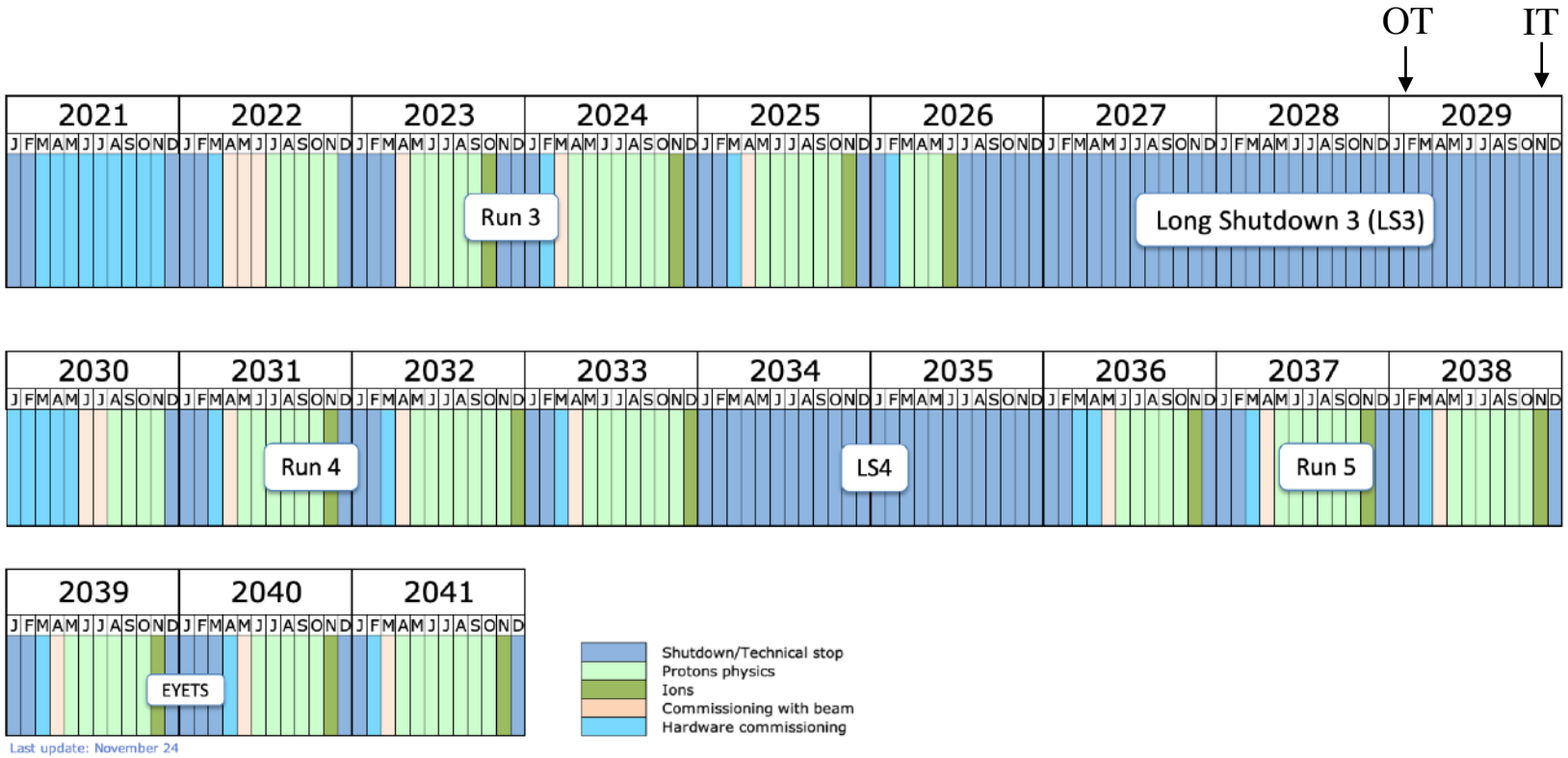
VERTEX 2025

25–29 August



CMS Phase-2 Tracker in HL-LHC

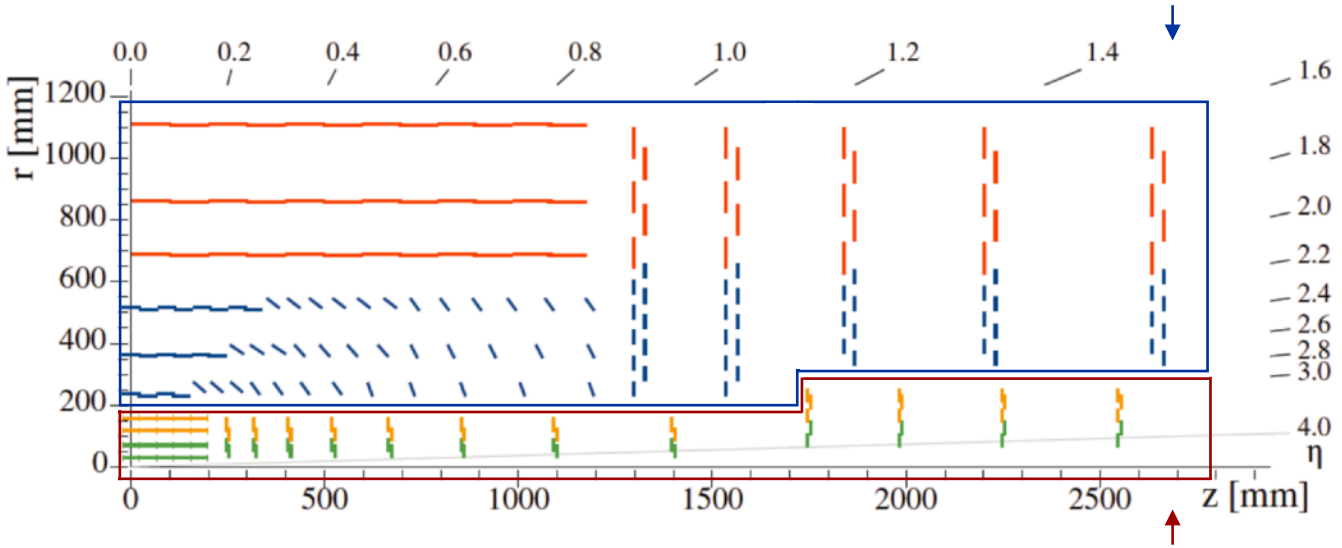
- High Luminosity LHC in 2030
  - Peak luminosity: 5 - 7.5 x 10^{34} $cm^{-2}s^{-1}$
  - Integrated luminosity: 3000 - 4000 fb^{-1}
  - High pileup: 200 events per bunch cross
  - High radiation environment



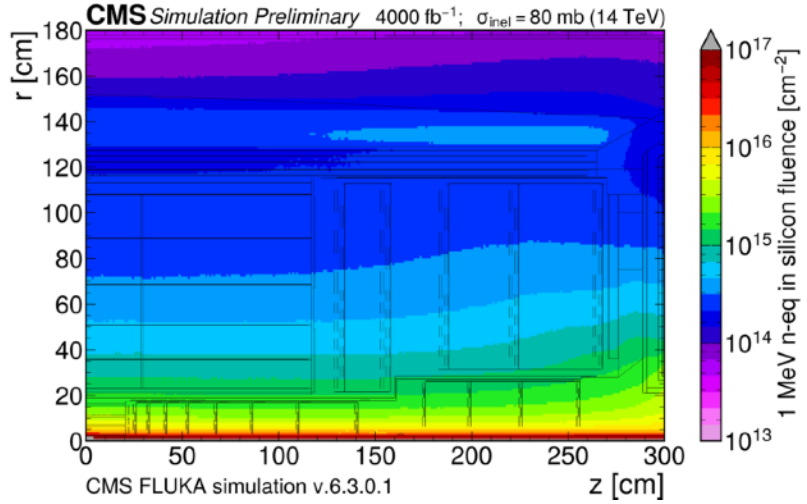
CMS Phase-2 Tracker upgrade

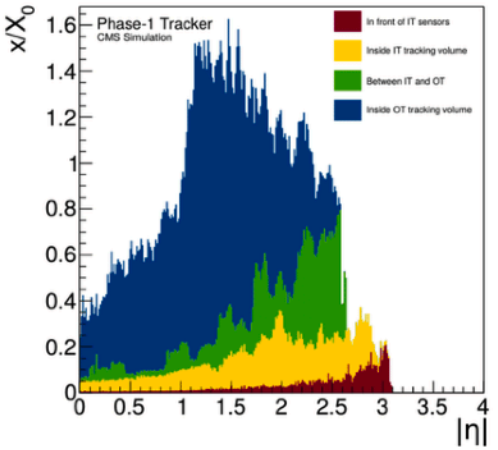
- Increased granularity -> High reconstruction efficiency at increased pile-up conditions
- Extended acceptance from $|\eta| \sim 2.5$ to $\mathbf{|\eta| \sim 4}$
- Reduced material budget
- Radiation level up to ~ 2.3 x 10^{16} n_{eq}/cm^2 (Inner tracker)
- Tracking information to L1 trigger

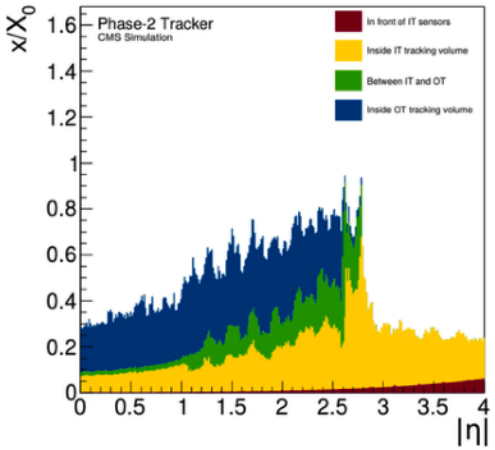
Outer Tracker: Radius > 15 cm , Area 192 m^2 with 1.7x10^8 macro-pixels & 42x10^6 strips



Inner Tracker: Radius < 15 cm , Area 4.9 m^2 with 2x10^9 pixels



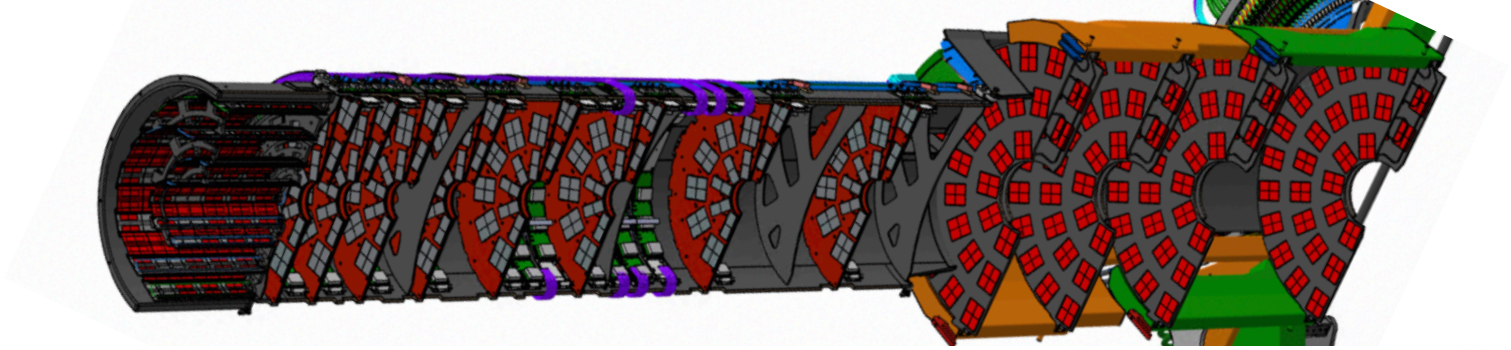


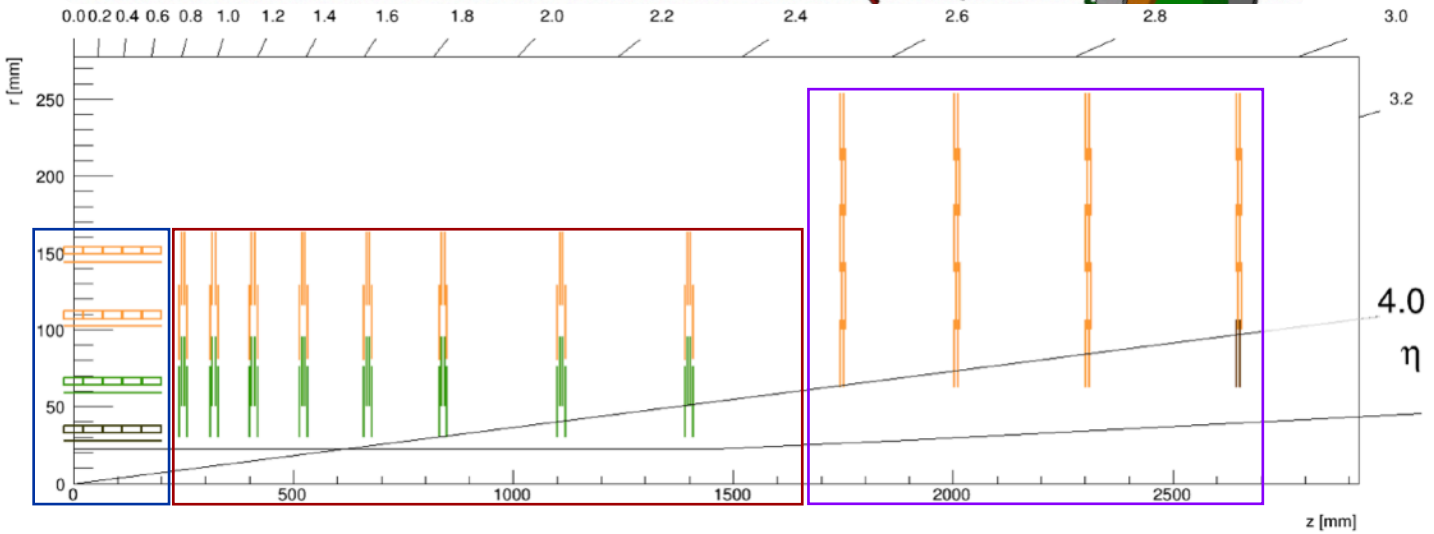


Talk: The CMS Tracker Upgrade for Phase-2: Meeting the Challenges of the HL-LHC by Matteo Magherini

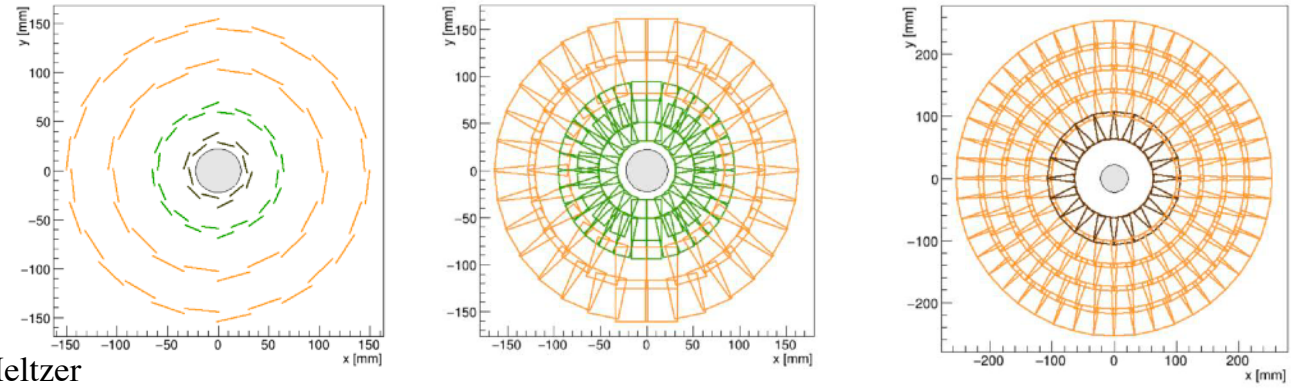
Inner Tracker Upgrade

- Tracker Barrel PiXel (TBPX)
  - 4 layers
  - 756 modules
  - Replaceable innermost layer (3D)
- Tracker Forward PiXel (TFPX)
  - 8 small double-disks on each side
  - 1728 modules
- Tracker Endcap PiXel (TEPX)
  - 4 large double-disks on each side
  - 1408 modules
  - Luminosity measurements, Disc 4, Ring 1: BRIL





TBPX TFPX TEPX

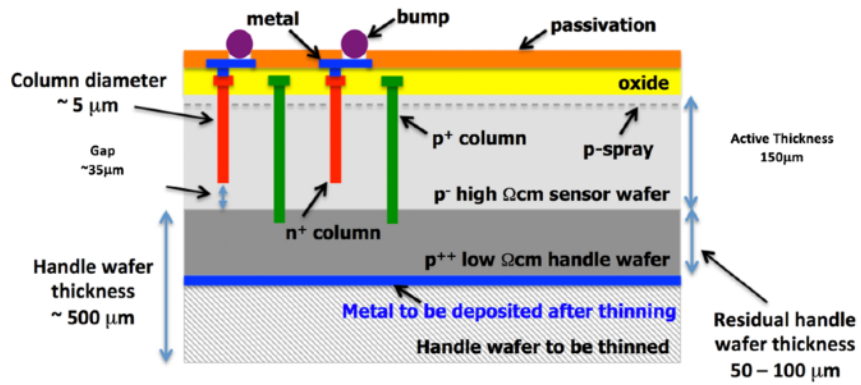


Poster Using the CMS Tracker for BRIL Operations in the HL-LHC by Philip Meltzer

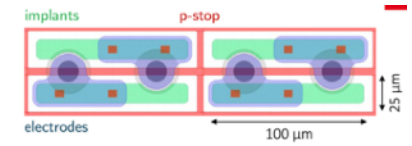
Inner Tracker: Sensors

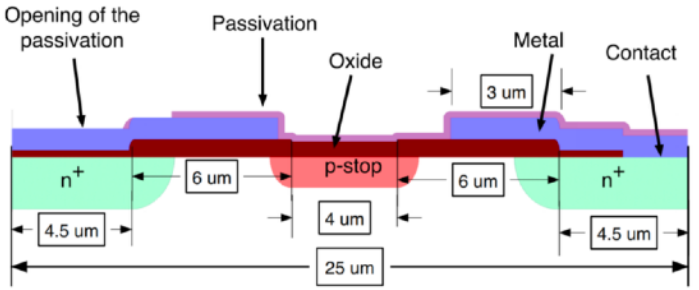
- 3D Si sensors from FBK
  - Only in the innermost layer of TBPX, reduced risk of thermal runaway due to lower power consumption.
  - Hit efficiency > 96% (normal incidence), qualified $\Phi_{eq} = 1.6 \times 10^{16} cm^{-2}$

- Planar Si sensors from HPK
  - n-in-p
  - Minimised cross talk with bitten implant
  - Elongated pixels in the inter chip region, to avoid inactive areas
  - Single-sided processing
  - Hit efficiency > 99%, qualified $\Phi_{eq} = 1 \times 10^{16} cm^{-2}$



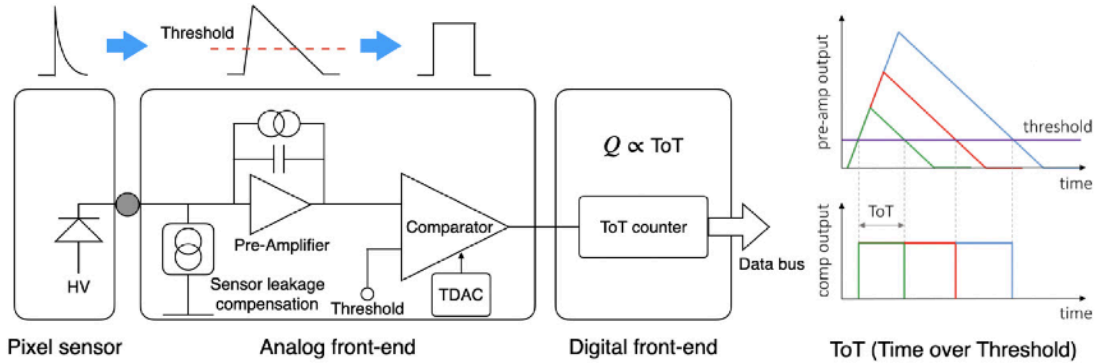
$150\mu m$ active thickness
Pixel size: $25x100\mu m^2$

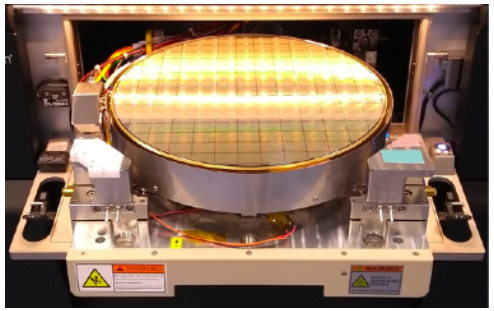


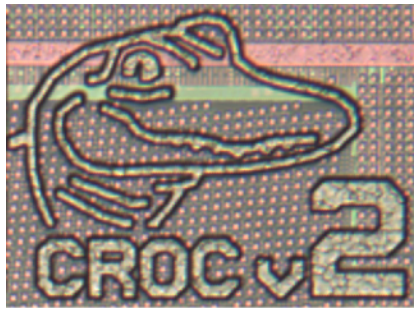


Inner Tracker: CMS Readout Chip (CROC)

- CROC 65 nm CMOS ASIC developed by joint ATLAS - CMS within RD53 Collaboration
- Previous versions:
  - RD53A (half-size, 3 AFE investigated)
  - RD53B - CROCv1 (full size, Linear AFE)
- Final version RD53C - CROCv2:
  - Pixels: 432 x 336, Size 21.6 x 18.6 mm^2, Cell size: 50 x 50 μm^2
  - Linear Analogue Front-End (adjustable threshold <1000 e$^-$).
  - Time-over-Threshold (ToT) measurements at 40MHz
- Radiation tolerance up to 1Grad
- Serial powering via on-chip Shunt-LDO regulators







Inner Tracker: Modules

TBPX Modules

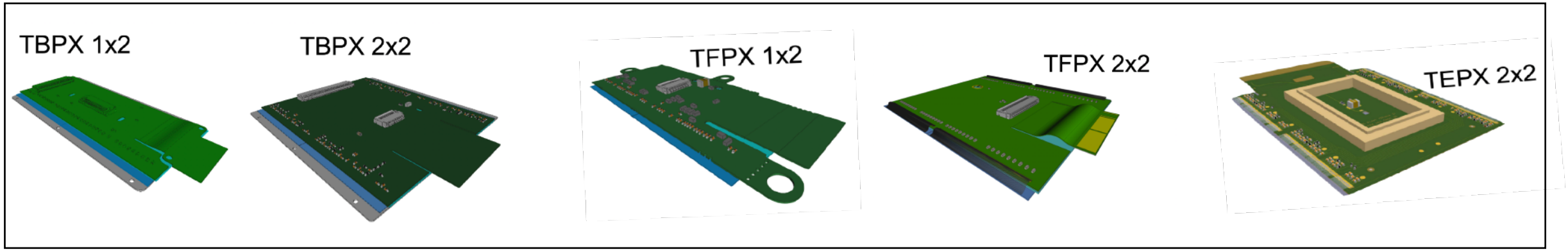
- Planar Double (2 ROCs and 1 sensor)
- Planar Quad (4 ROCs and 1 sensor)
- 3D Double (2 ROCs and 2 sensors)

TFPX Modules

- Planar Double
- Planar Quad

TEPX Modules

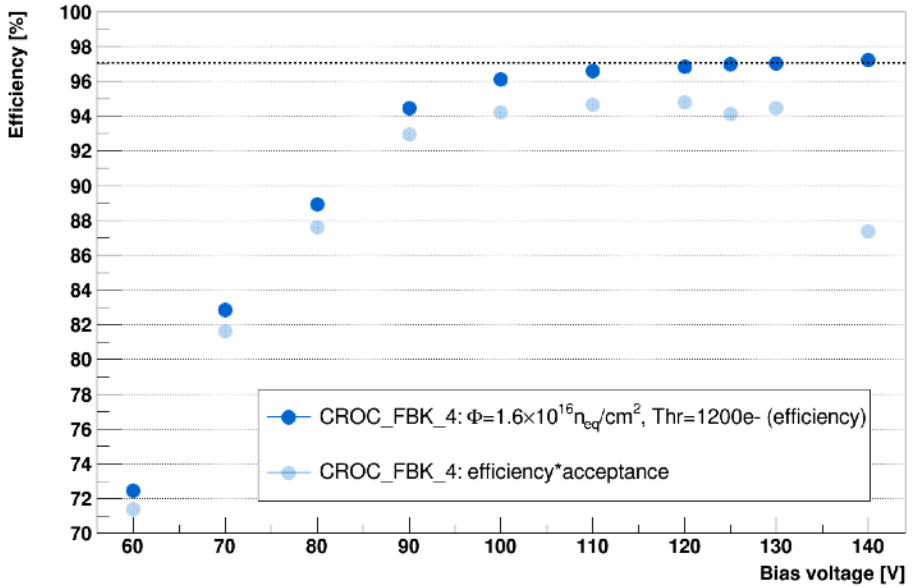
- Planar Quad



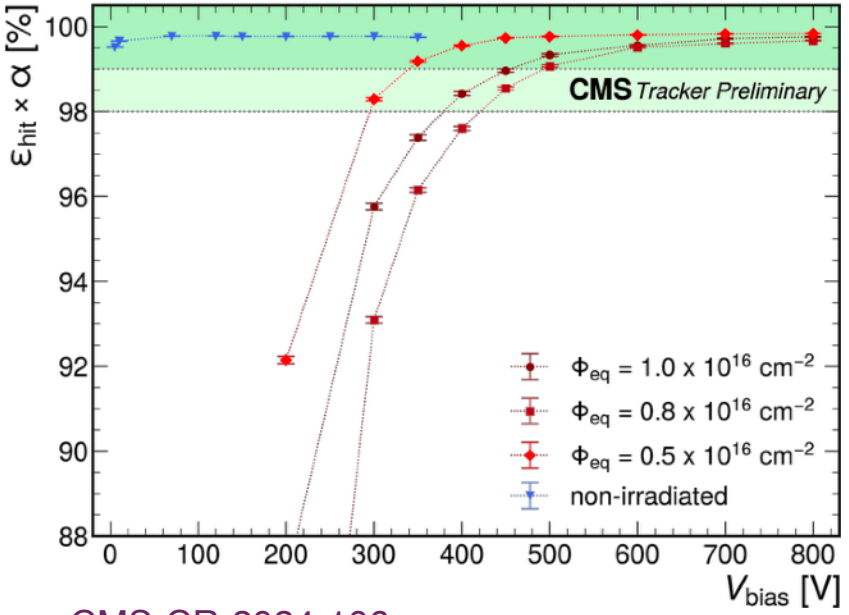
Bi-phase CO_2 cooling -> Operating temperature -35 °C

Inner Tracker: Irradiation studies

- 3D pixel modules
  - $\epsilon_{hit} \geq 96\,\%$ at $\Phi_{eq} = 1.5 \times 10^{16} cm^{-2}$ for $V < 200V$ at normal incidence
  - Within requirements for V > 100V
- Planar pixel modules
  - $\epsilon_{hit} \times \alpha$ non irradiated $> 99\%$
  - $\epsilon_{hit} \times \alpha$ at $\Phi_{eq} \leq 5 \times 10^{15} cm^{-2} > 99\%$ for $V \leq 600V$
  - $\epsilon_{hit} \times \alpha$ at $\Phi_{eq} > 5 \times 10^{15} cm^{-2} > 98\%$ for $V \leq 600V$



CMS-CR-2024/100

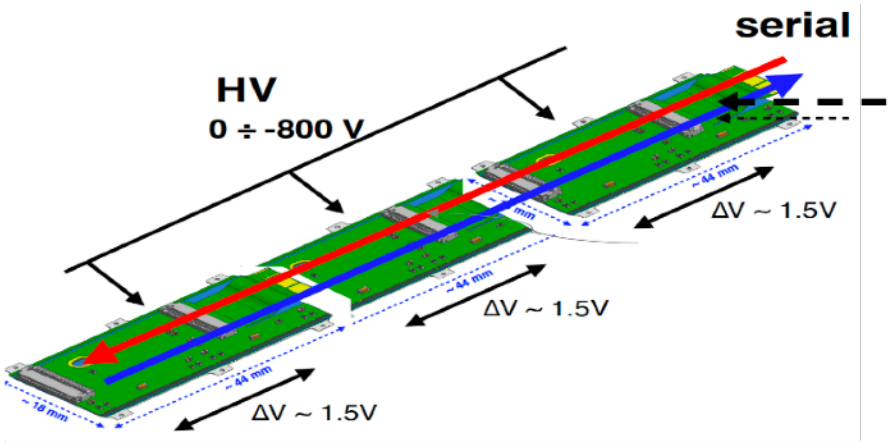


CMS-CR-2024-106

Inner Tracker: Module powering and readout

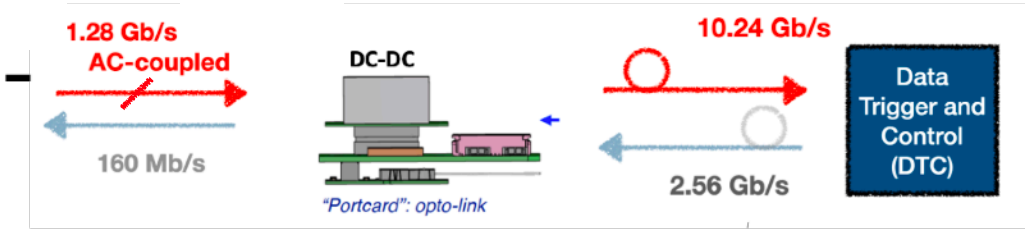
Serial powering of modules

- Low material budget for a 50 kW detector power
- More than 500 power chains
- Up to 12 modules/chain serially powered
  - Chips on each module are connected in parallel
  - HV supply in parallel



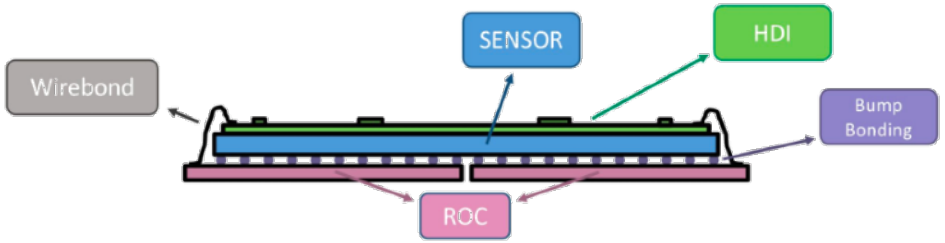
Readout of modules

- E-links from module to lpGBT - up to 6x1.28Gb/s
- Portcards: 3 lpGBTs/ opto-card
- Optical fibers -> between portcards and the Data, Trigger, and Control (DTC) boards.



Inner Tracker: Module production

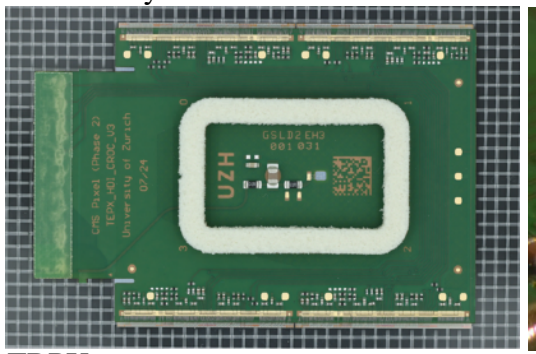
- Sensor bump-bonding to the ROC (bare module)
- Cooling plate attachment to bare module (only for TBPX)
- Airex frame attachment to the HDI (only for TEPX)
- High Density Interconnect (HDI) glueing to the sensor.
- Wire bonding of ROC to the HDI
- Parylene coating (spark protection)
- BURN-IN: 10 thermal cycles -35^{0}C to 40^{0}C



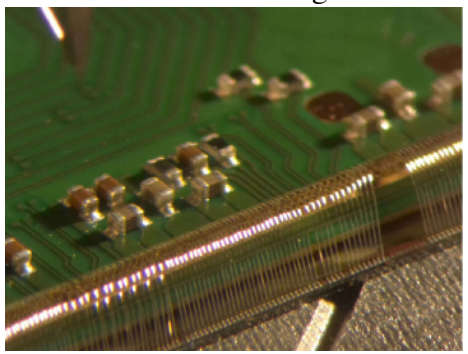
General structure of Inner Tracker module

Poster: Spark Protection for the HL-LHC Upgrade of the CMS Forward Pixel Detector by Peter Kim

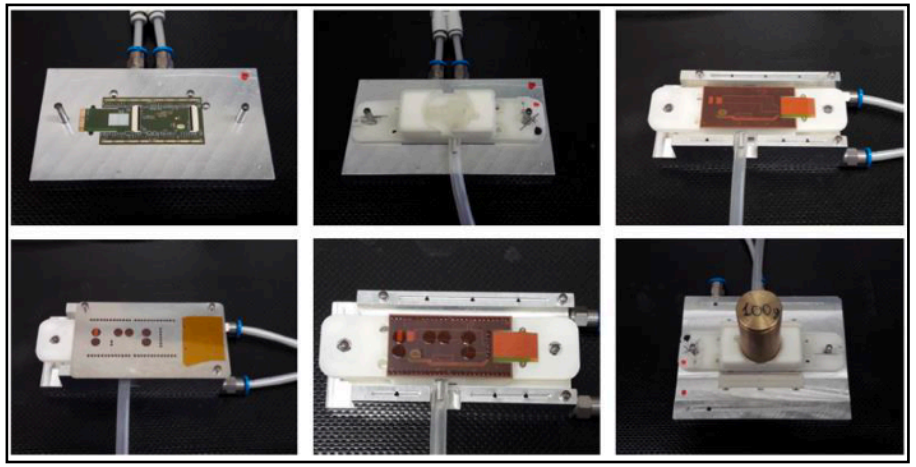
TEPX fully assembled module



ROC- HDI wire bonding

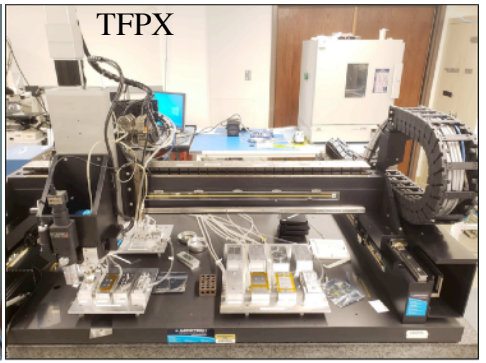


TBPX



TEPX

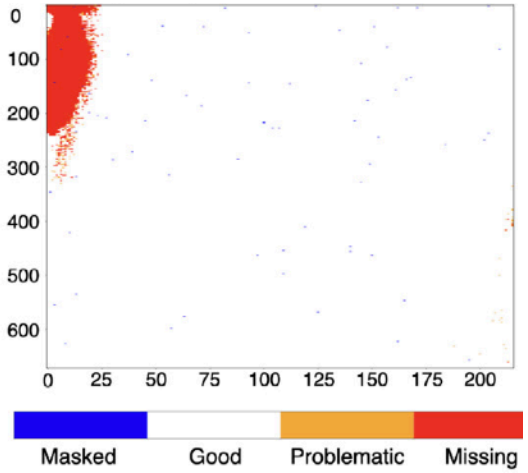
TFPX



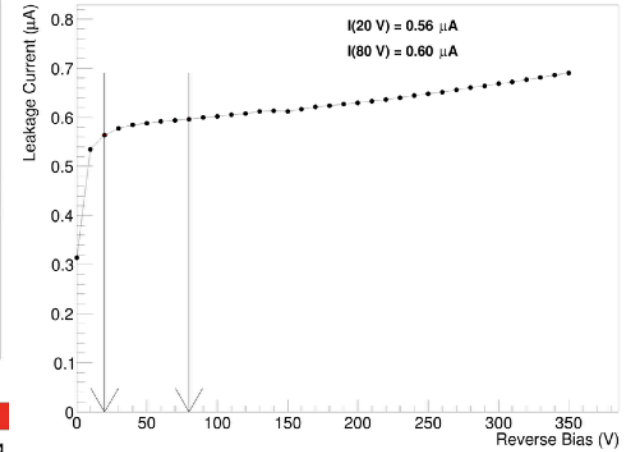
Inner Tracker: Module qualification

- Electrical tests and Visual inspection during assembly
  - SLDO tests (input, digital and analogue voltages of ROC)
  - Sensor I/V curves
  - Threshold tuning, Pixel scans (dead & inactive pixels)
  - Bump connectivity -> Cross talk measurements
- Issues observed during assembly
  - Broken bump-bonds (non optimal bonding jigs)
  - Issues after coating (contamination on connectors, damage in wire bonds). Optimisation of procedures in order to mask critical zones

Missing bumps map with crosstalk



Planar sensor - I/V curve



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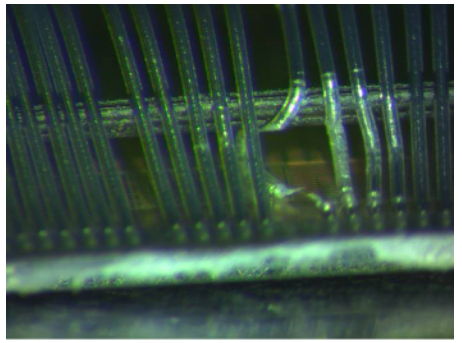
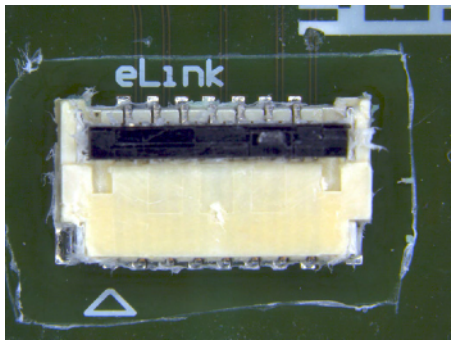


Damaged wirebond



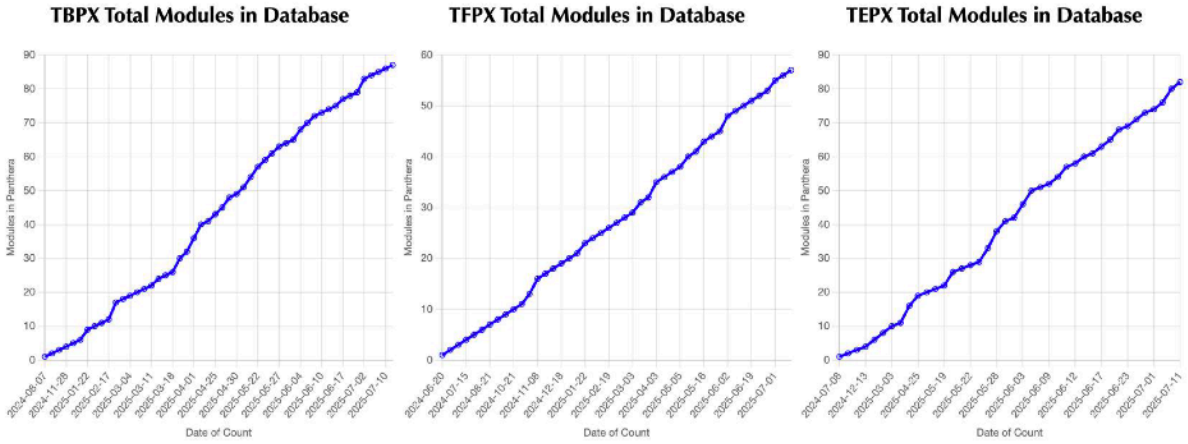
Coating on connector

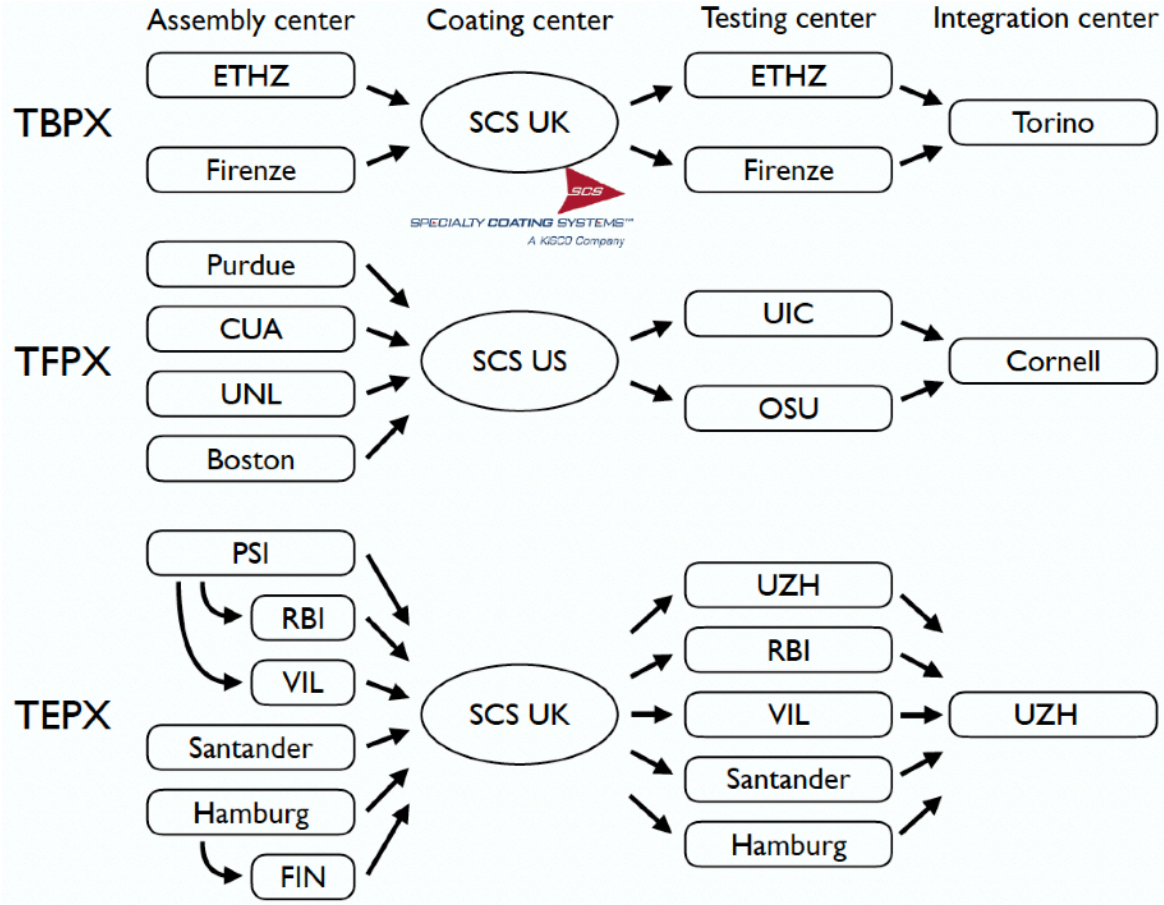
Talk: Readout implementation and testing procedures to characterise the pixel detector modules of the CMS inner tracker for the high luminosity upgrade of LHC by Mauro Dinardo

Poster: Bare Module Testing for the CMS Vertex Detector Upgrade by Jesse Harris

Inner Tracker: Assembly status

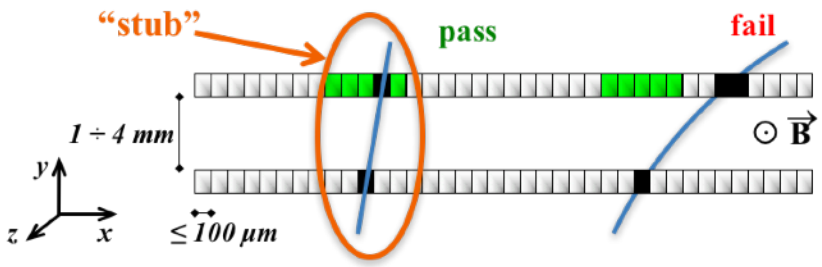
- Module assembly and testing distributed > 10 institutes
- In total 3892 modules required for installation in CMS. More than 6000 modules are planned
- Currently in pre-production -> fall starting production

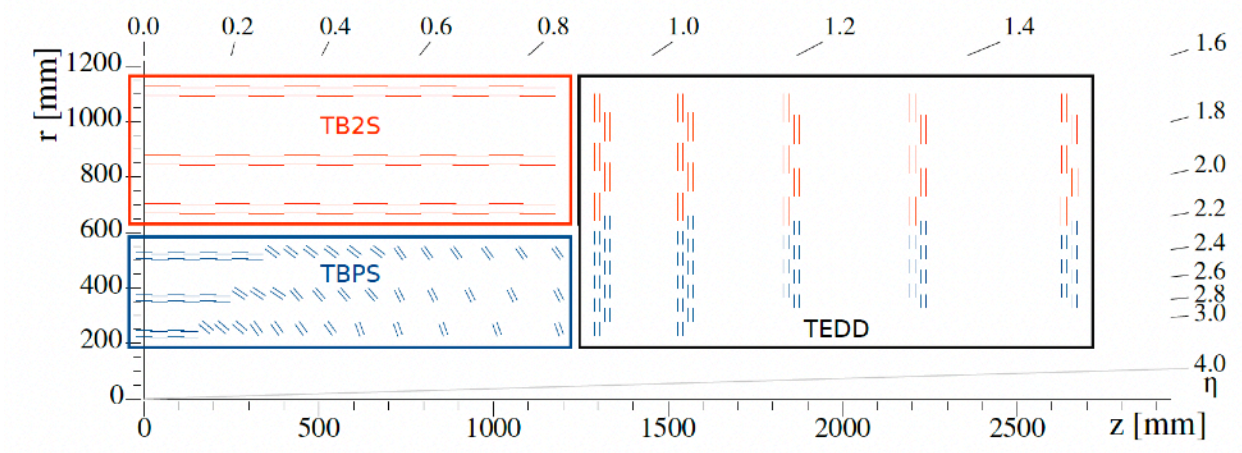




Outer Tracker Upgrade

- Increased granularity -> shorter strips & macro-pixels
- Improved radiation hardness -> n-in-p silicon sensors
- Decrease of material budget
- p_T module concept
  - Correlate hits from 2 closely spaced sensors to form "stubs" $p_T > 2$ GeV
  - Pixel - Strip modules (PS) - Strip - Strip modules (2S)
- Tracker input to the L1 trigger at 40MHz





- Tracker Barrel with 2S modules (TB2S)
- Tracker Barrel with PS modules (TBPS)
- Tracker Endcap Double - Discs (TEDD)

Module type and variant		TBPS	TB2S	TEDD	Total per variant	Total per type
2S	1.8 mm	0	4464	2792	7256	7680
	4.0 mm	0	0	424	424	
PS	1.6 mm	826	0	0	826	5616
	2.6 mm	1462	0	0	1462	
	4.0 mm	584	0	2744	3328	
Total		2872	4464	5960	13296	

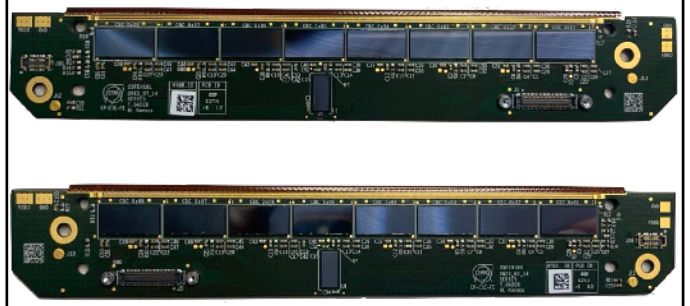
Poster: Progress in the CMS Level-1 Track Finder Data Processing Chain for HL-LHC by Brandi Skipworth

CMS-TDR-014

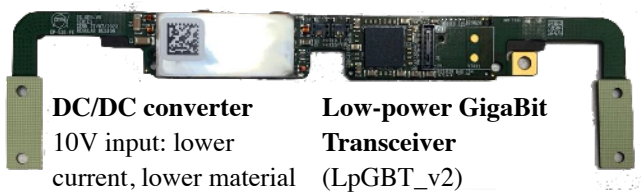
Outer Tracker: Modules - Strip / Strip (2S)

2S Module hybrids

2S Front End Hybrid (x2)

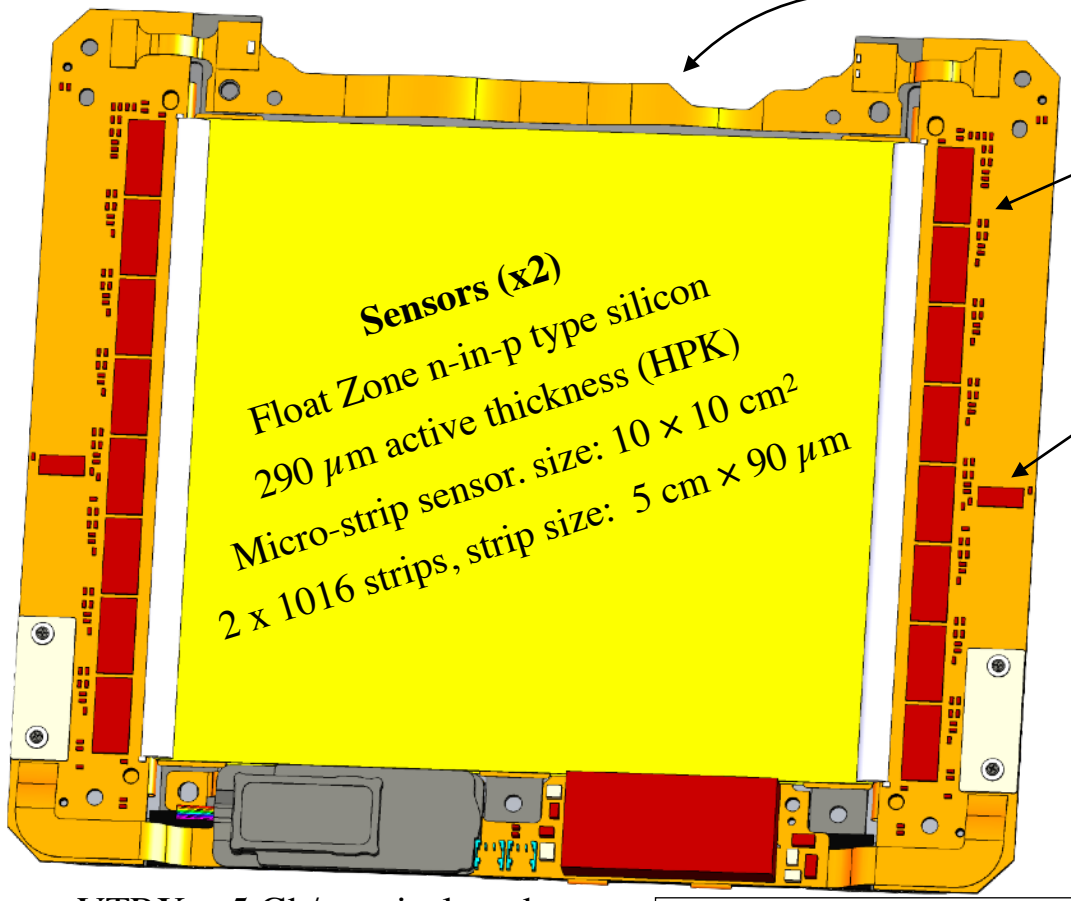


2S Service hybrid



DC/DC converter
10V input: lower current, lower material
bPOL12V , bPOL2V5

Low-power GigaBit Transceiver
(LpGBT_v2)



VTRX+: 5 Gb/s optical readout + Light shield

CMS Binary Chip (CBC) 130nm

8 chips/ Front End Hybrid (FEH)

Readout and stub finding for L1T

Reads out both sensors

254 channels per chip

Concentrator Chip (CIC) 65nm

1 chip/ FEH

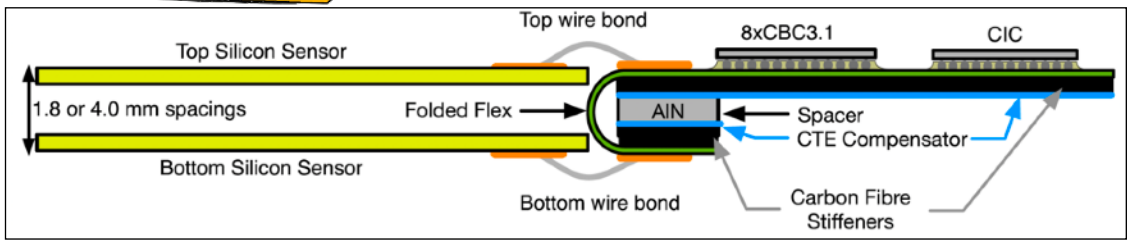
Receives L1 information and serialises the data

2SFEH Spacing variants:

1.8mm

4.0mm

Max fluence at 4000fb^{-1}: 4.9 x10^{14} n$_{eq}$/cm^2



Outer Tracker: Modules - Pixel / Strip (PS)

Short-Strip ASIC (SSA) 65nm

Readout of sensors, 8 / FEH

SSA sends cluster and L1 information to MPA to enable match in space and time

Concentrator Chip (CIC) 65nm

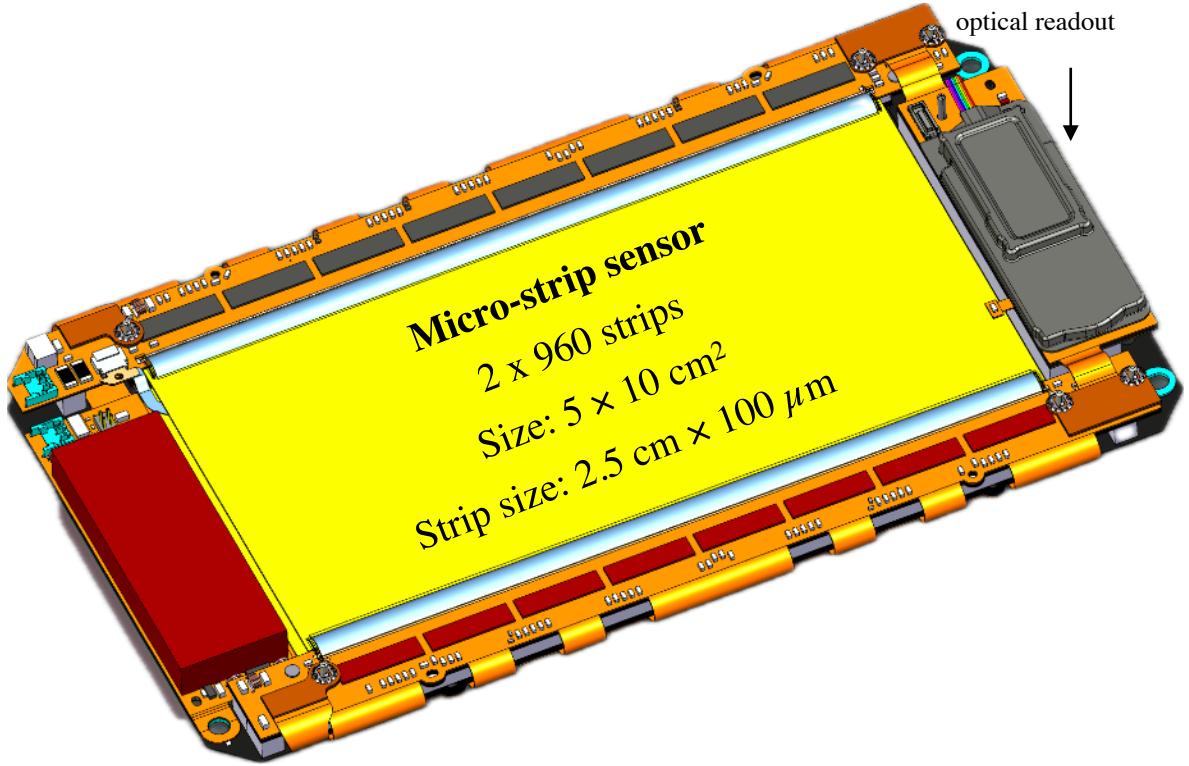
Back side of the hybrid (common with 2S modules), 1 / FEH (back side)

Macro-Pixel ASIC (MPA)

Stub finding

Bump bonded to the sensor

16 / Module



PS Module hybrids

Spacing variants: 1.6mm, 2.6mm, 4.0mm

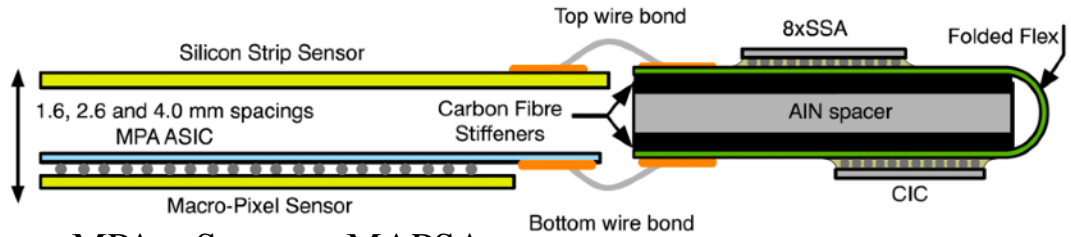
PS Readout Hybrid

2 variants: 10 / 5G, LpGBT_v2

PS Front End Hybrid (x2)

PS Power Hybrid

DC/DC: bPOL12V , bPOL2V5



MPA + Sensor = MAPSA

Macro-pixel sensor

32 × 960 pixels

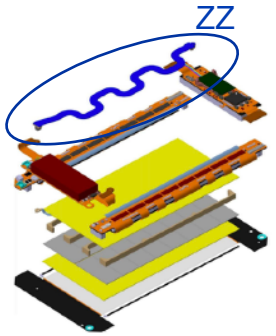
Size: 5 × 10 cm²

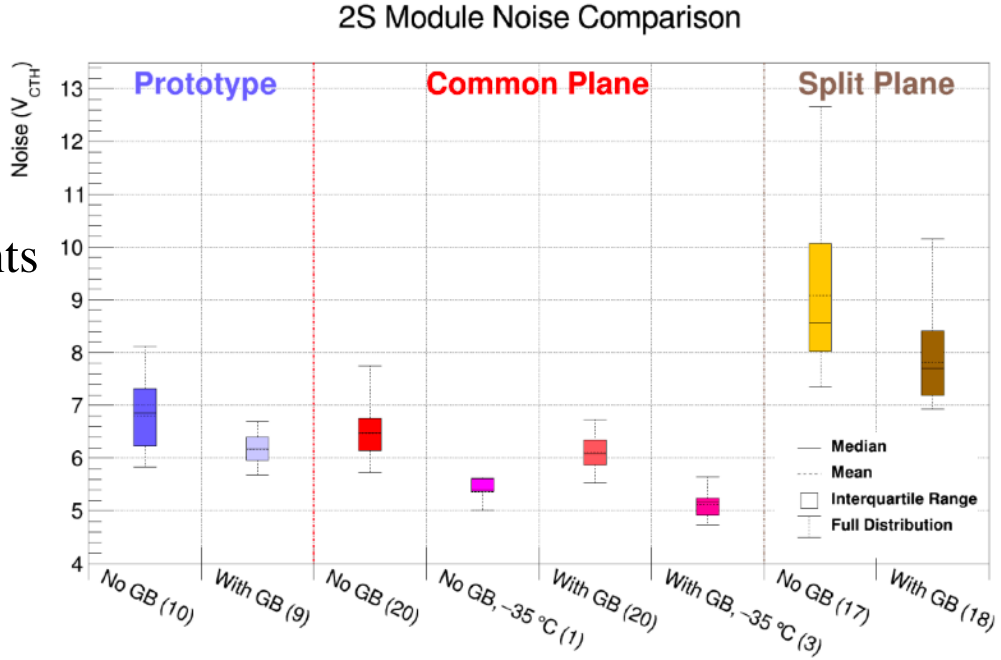
Pixel size: 1.5 mm × 100 μm

Max fluence at 4000fb^{-1}: 1.4 x10^{15} n$_{eq}$/cm^2

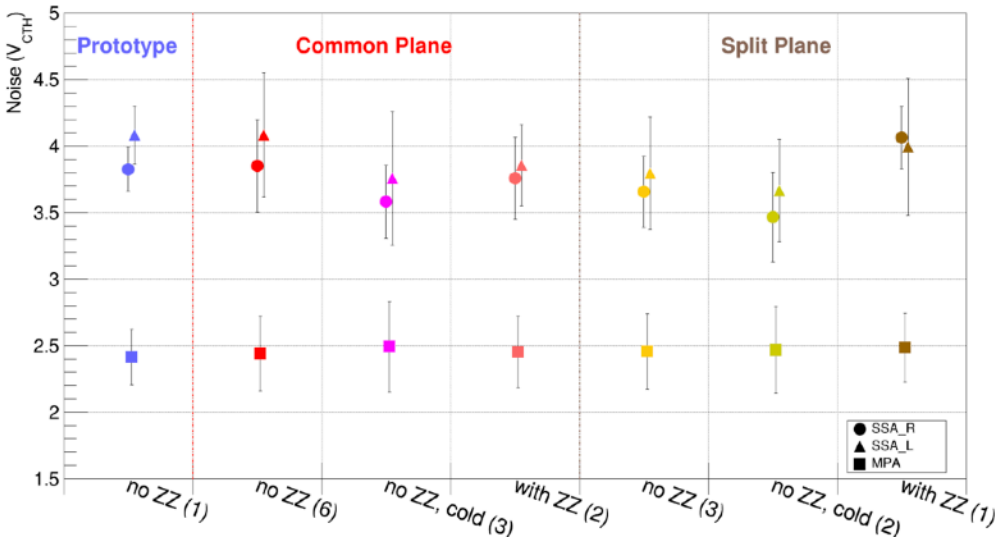
Outer Tracker: Hybrids optimisation

- Grounding optimisation
  - PSPOH & 2SSEH ground: DC outputs and switching power currents
    - Common plane vs Split plane
  - 2S: Ground Balancer (GB) / PS: ZZ connection
  - Final choices:
    - 2S: Common plane with Ground Balancer
    - PS: Common plane with no ZZ connection
- Oscillations in PSPOH at cold -> increased noise
  - Optimisation of the PSPOH DC-DC stage
- Fold over integrity
  - PSFEH cracks in the fold over -> 4 layer -> 5 layer design



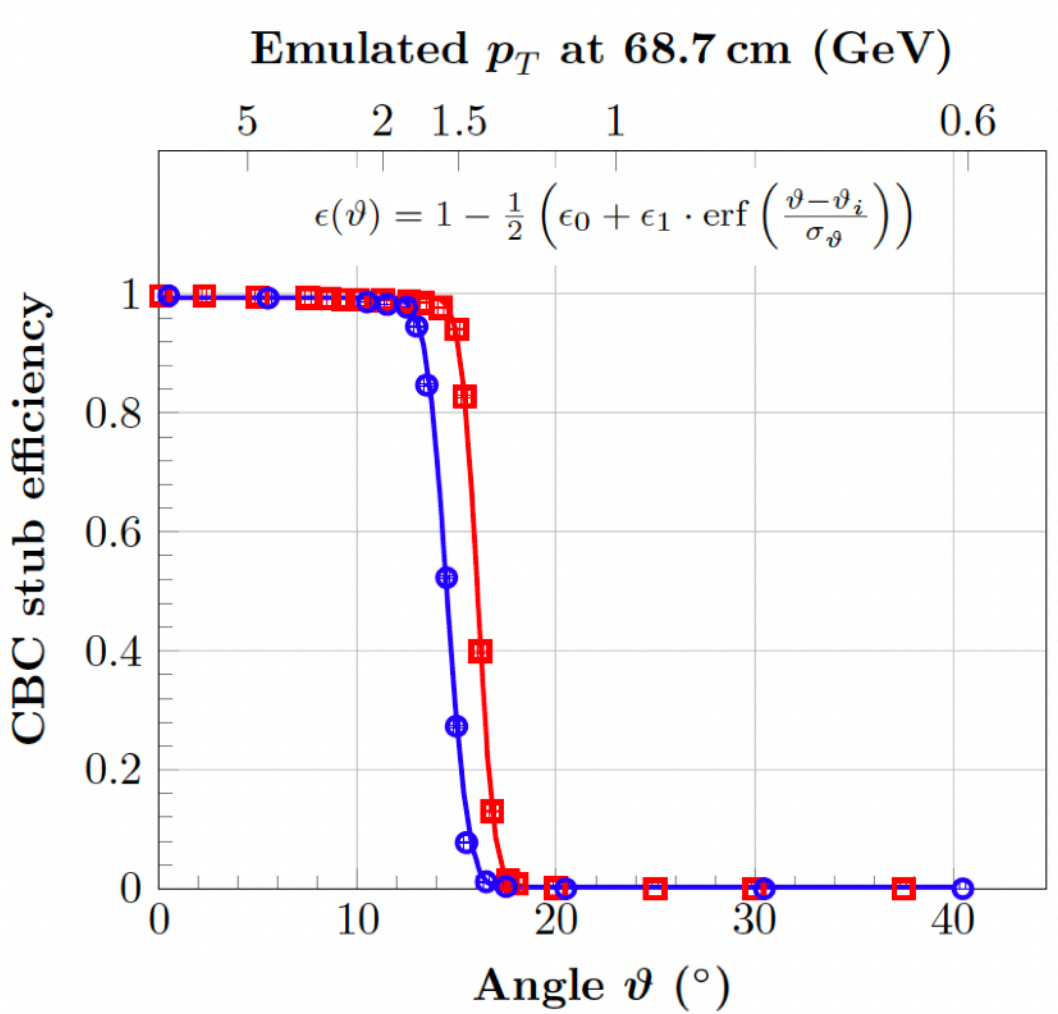


PS Module Noise Comparison CMS-CR-2025-081



Outer Tracker: Irradiation studies

- Conditions:
  - 2S prototype irradiated module (blue) at 4.6 x10^{14} n_{eq}/cm^2, Stub window size: ±4.5 strips, V = 600V
  - 2S prototype non irradiated module (red), Stub window size: ±5 strips, V = 300V
  - 68.7cm -> closest distance of 2S modules to the interaction point
- Stub efficiency:
  - Drop at ~ 16° and 14.5°
  - Meeting the geometrical expectations

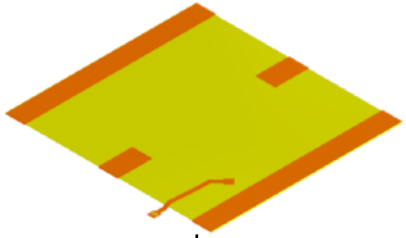


W. Adam et al 2024 JINST 19 P10032

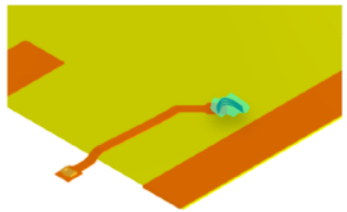
Outer Tracker: 2S Module assembly

Metrology of sensors

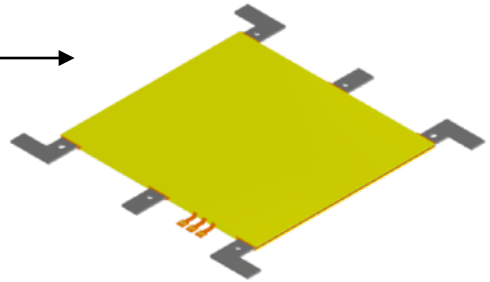
HV isolation. HV tails attachment. Visual inspection



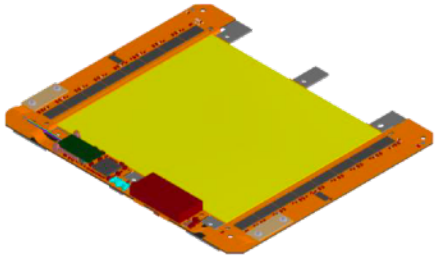
HV tail wire bonding & encapsulation. I/V testing



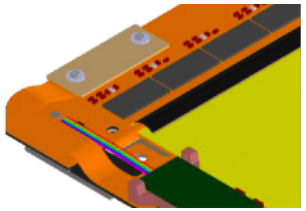
Gluing of bridges



Hybrid gluing



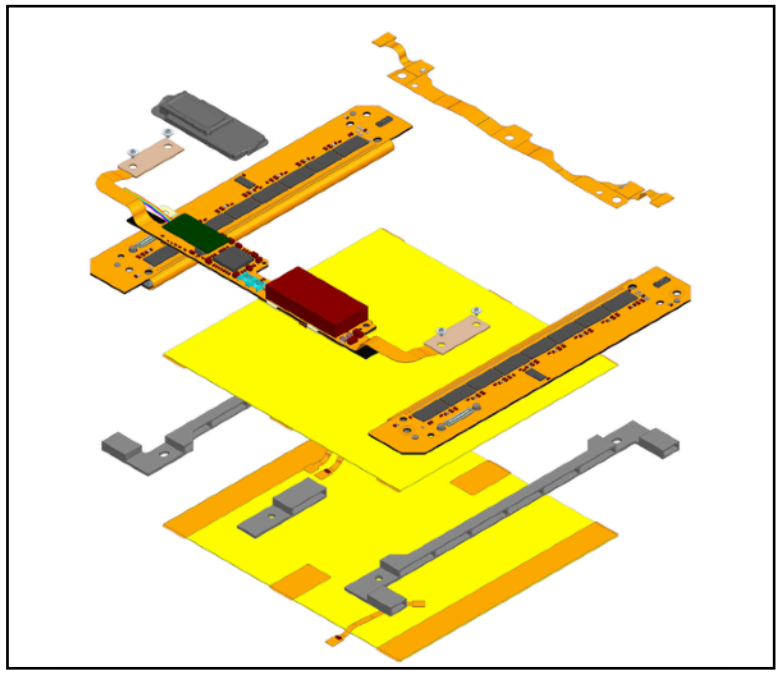
Wirebonding & Encapsulation

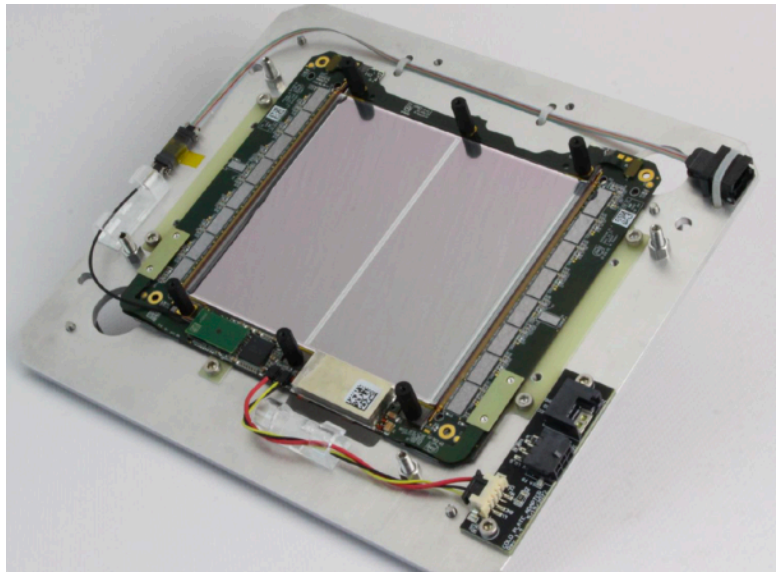


VTRx+ → & Light shield

- Skeleton test on hybrids, before hybrid gluing

- Electrical tests & Metrology at different production stages





Outer Tracker: PS Module assembly

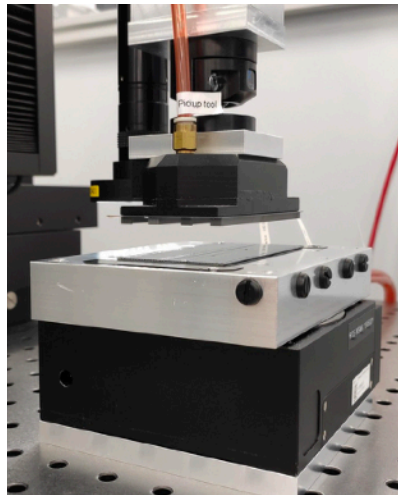
Quality control of individual components

↓

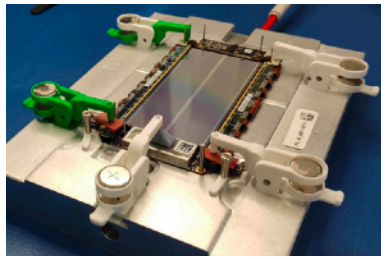
HV tail gluing, wire bonding and encapsulation

↓

Assembly sensor stack on baseplate



Hybrids gluing



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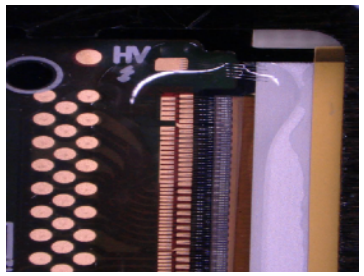
Wirebonding & Encapsulation



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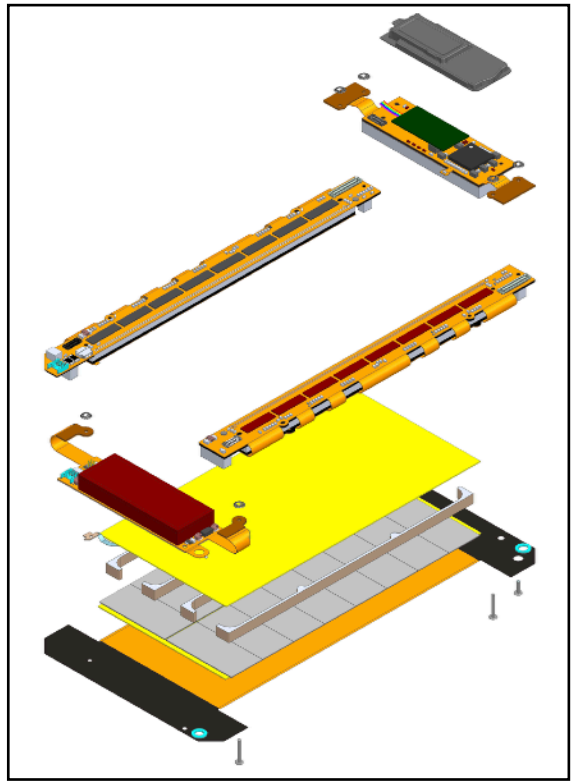
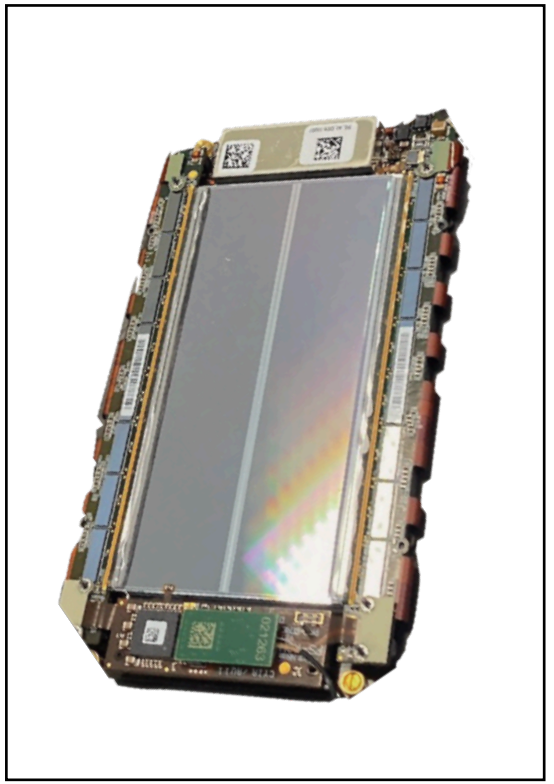
VTRx+ & Light shield

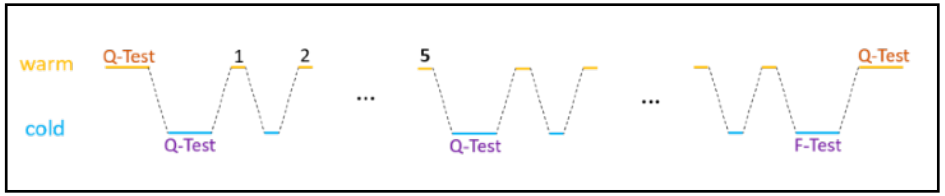




- Electrical tests & Metrology at different production stages
- Automated procedures to comply with the high precisions

Outer Tracker: Module Quality Control

- Module electrical tests
  - I/V characteristic of the sensors before and after assembly
  - Configuration of the module, chip alignment and verification
  - Noise measurements
- Module Burn-in
  - 48h thermal cycles between 20 °C to -35 °C
  - Electrical tests at 5 different cycles



Analysis, Grading & Database storage of module results

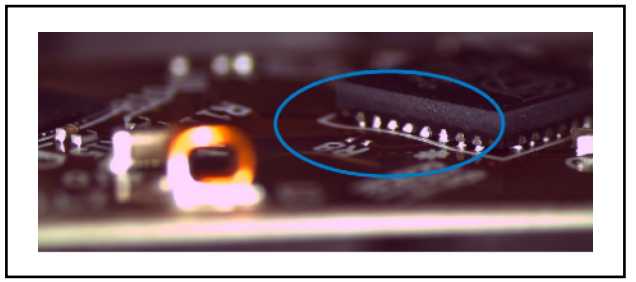
Phase 2 Outer Tracker Analyzer of Test Outputs

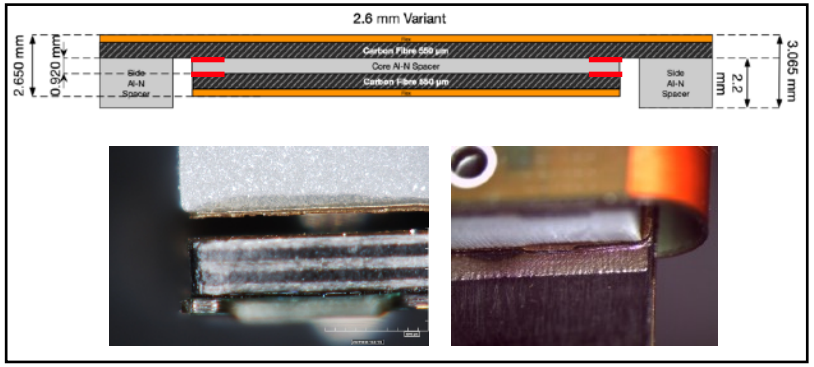
POTATO!

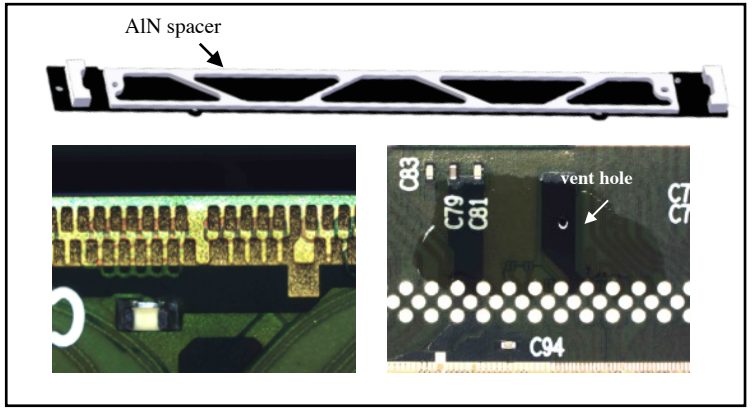
Posters: Grading and assembly of modules for the CMS Phase-II Outer Tracker upgrade by Allie Dabney
Coordinating the CMS Outer Tracker Upgrade with POTATO by Olivia Clark
Quality-control tools for CMS Phase-2 Outer Tracker module production by Micah Hilman

Outer Tracker: Assembly insights (hybrids)

- Flex delamination in hybrids of PS family
  - Delamination - induced bulges on the surface of the flex. Confirmed with cross sections.
  - Improvements in the drying process of bare flexes
- Cracks in the glue joints in PS-FEHs between CF stiffener and AlN spacer (2.6 & 4.0mm versions) after reflow
  - Improvements in the gluing process
- Contamination on wire bonding pads (FEH)
  - Main source: Trapping of cleaning agent in the cavities of the spacers, entering through the vent holes
  - Wire bonding pads cleaning -> in place. Different spacer designs available - under investigation.





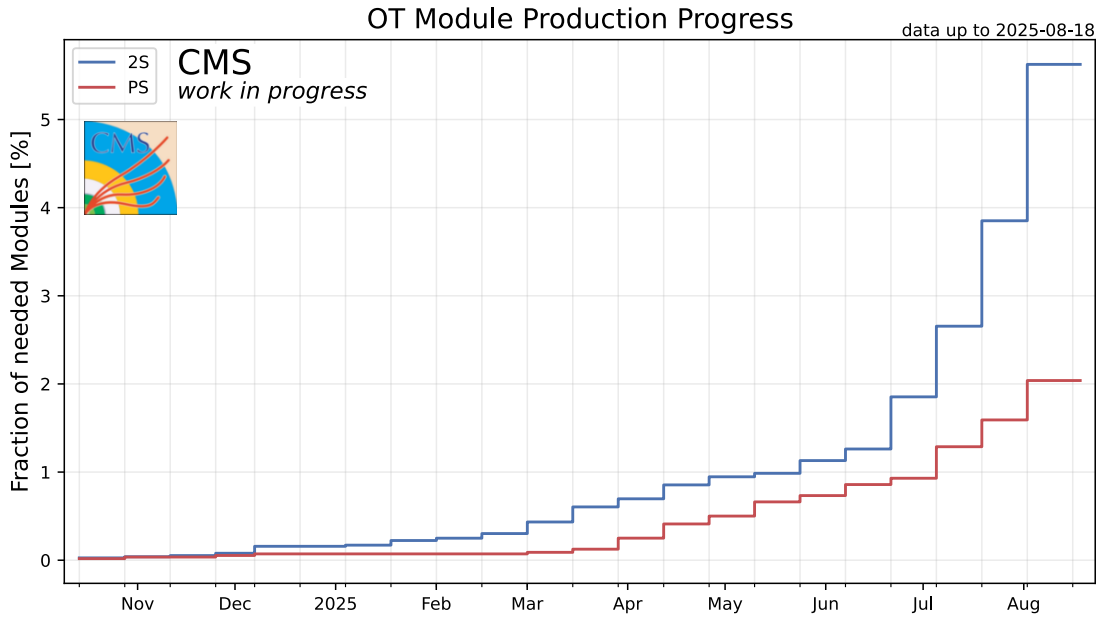


Outer Tracker: Assembly insights (modules)

- MaPSA HV isolation initially with kapton strips. Difficulties in application and in long term reliability. Sylgard -> sensor to MPA isolation.
- Alignment issues of MaPSA and FEH hybrid.
  - Differences in actual MPA/MaPSA dimensions and CAD model.
  - Resolved with alignment pin adjustments.
- Tooling adjustments to facilitate the assembly of different module thicknesses.
- Mitigation of lpGBT issue
  - lpGBT v1 hybrids were intentionally not glued to the modules, to facilitate replacement
  - lpGBT v2 hybrids -> distributed. To be glued to modules & complete QC

Outer Tracker: Assembly status

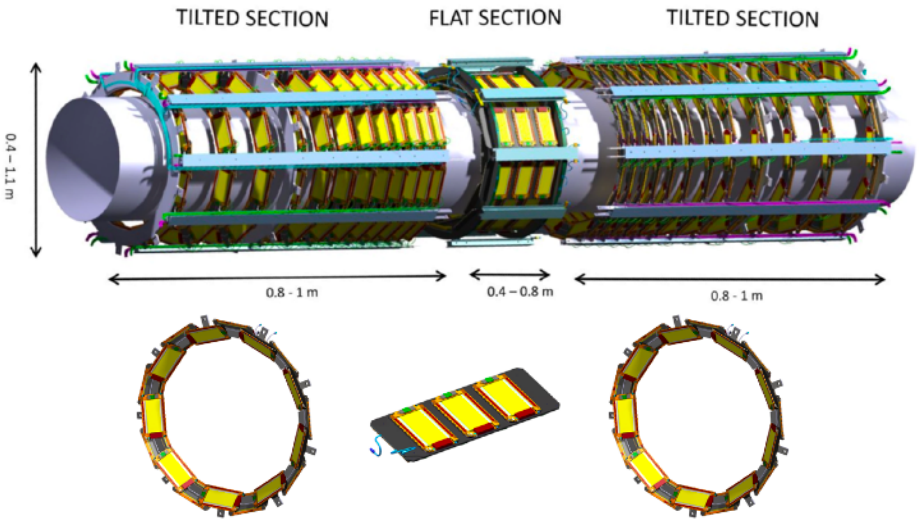
- PS modules: 5 production centers in Europe and US
- 2S modules: 7 production centers in Europe, US, India and Pakistan
- Pipeline assembly (one by one) -> Parallelised assembly of modules
- Module production rates -> Increasing
  - 2S scaled up in June. PS limited by FEH availability
- Module production monitoring
  - Latest assembly status & quality
  - Production plan
  - Logistics: module components / site
  - Tracking of shipments



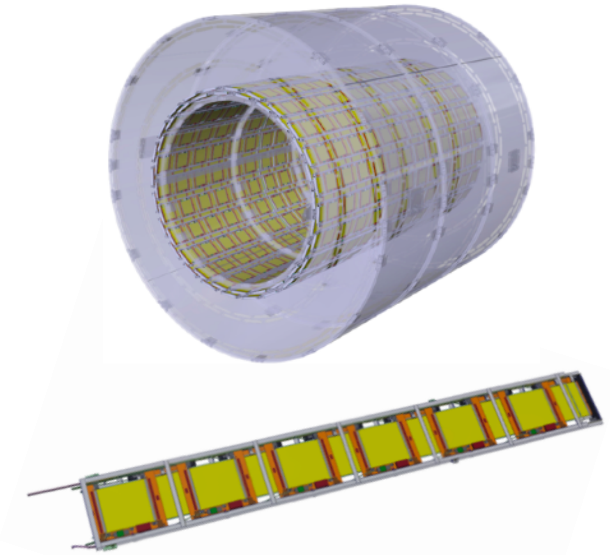
Fraction of needed modules produced excluding spares grouped by module type. The granularity is in production periods of two weeks.

Outer Tracker: Mechanics

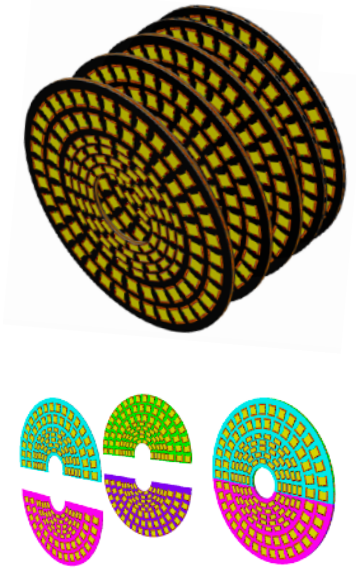
- TBPS
  - Planks & Rings



- TB2S
  - Ladders -> Cylindrical layers



- TEDD
  - Double disks with dees (D shaped parts)

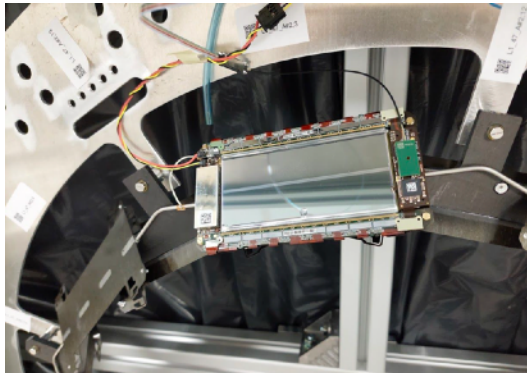


Bi-phase CO_2 cooling -> Operating temperature -35 °C

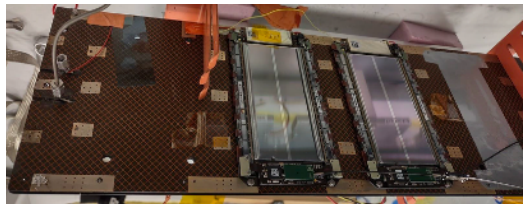
Talk: Mechanical Design and Integration of the CMS Phase-2 Tracker by Pierre Rose

Outer Tracker: Integration

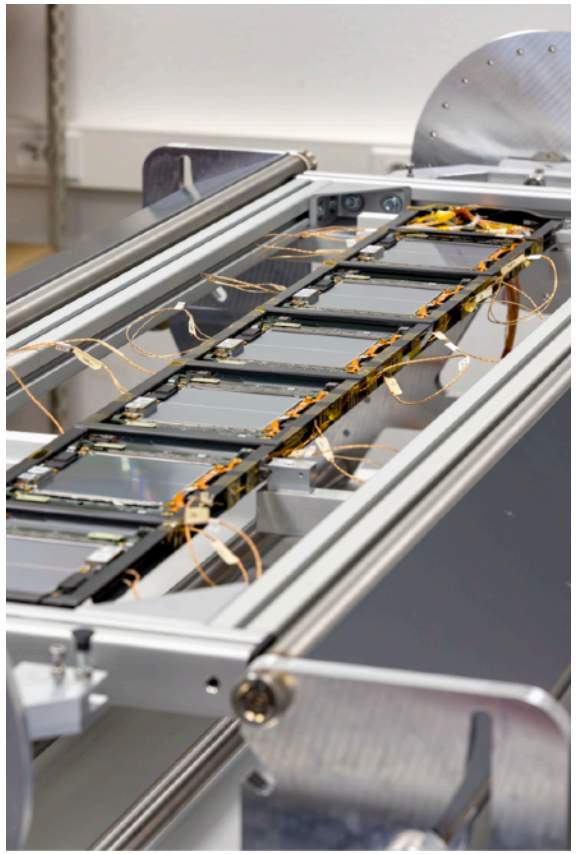
- TB2S
  - Fully integrated ladders -> Mechanical & thermal integrity validated
  - Electrical testing at different temperatures and comparison with single module results
- TBPS
  - Electrical tests (noise) at room temperature and at cold
  - Evaluation of the ground connection
- TEDD
  - Module integration process, routing of services & tooling -> Validated for a sector
  - Evaluation: Electrical testing & Thermal tests



TBPS ring



TBPS plank



TB2S ladder

Outer Tracker: Integration

- TB2S
  - Fully integrated ladders -> Mechanical & thermal integrity validated
  - Electrical testing at different temperatures and comparison with single module results
- TBPS
  - Electrical tests (noise) at room temperature and at cold
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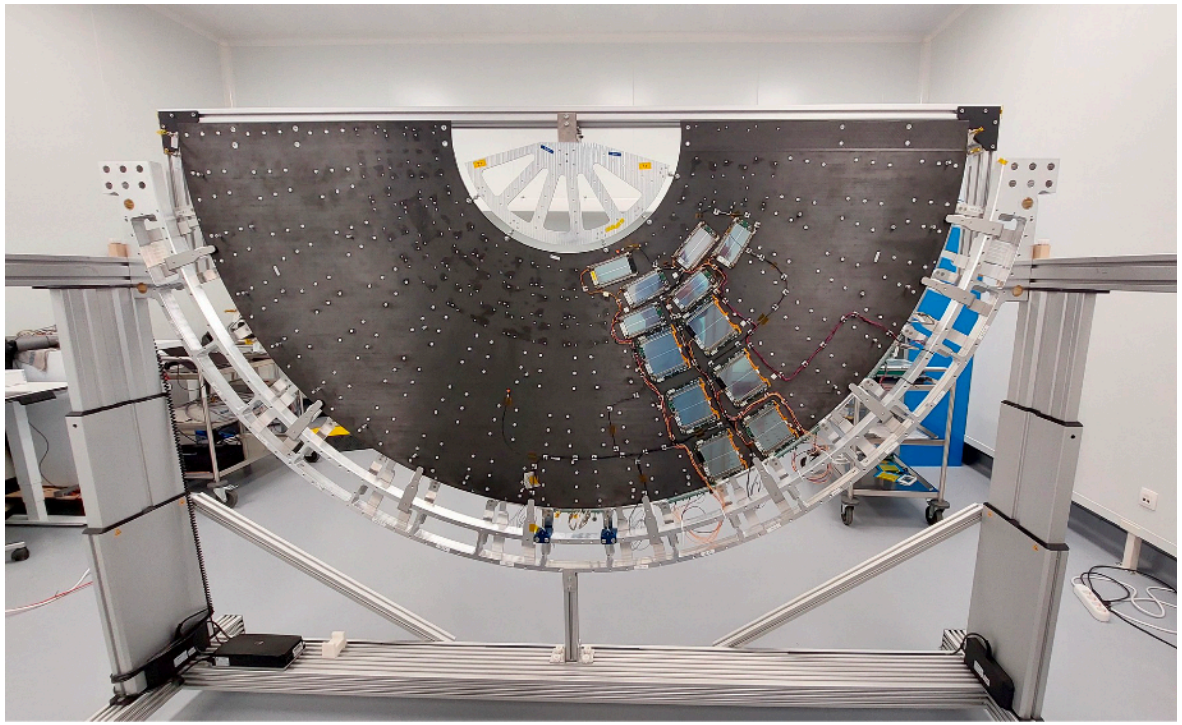

TEDD dee

Conclusions

- Inner Tracker
  - Key design choices: smaller pixels for low occupancy, extended acceptance, serial powering
  - Pre-production phase -> several modules were assembled and tested
  - Automated assembly & QC procedures -> high throughput production
  - Production is starting for ~ 4000 required in 3 years
- Outer Tracker
  - Key design choices: p_T module concept -> input to L1 trigger, reduced material budget
  - Module assembly & QC -> well established processes. Limitations on the PS -> hybrid issues being addressed
  - Integration of final modules (LpGBTv2) on larger structures is imminent
  - Production phase 2025 - 2027 ~ 13k modules

Thank you!