The CMS Phase-2 Tracker Upgrade: Meeting the Challenges of the HL-LHC

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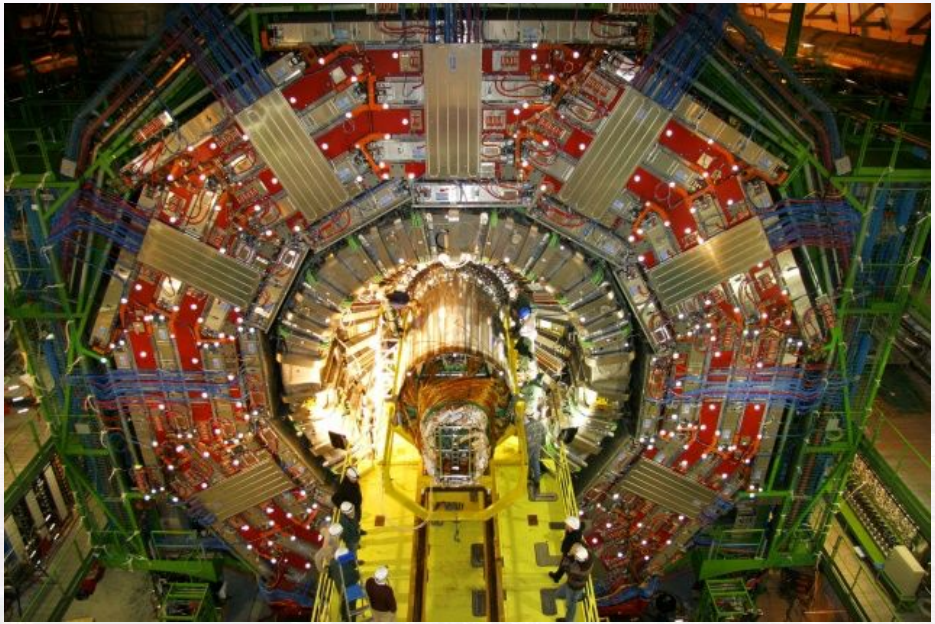
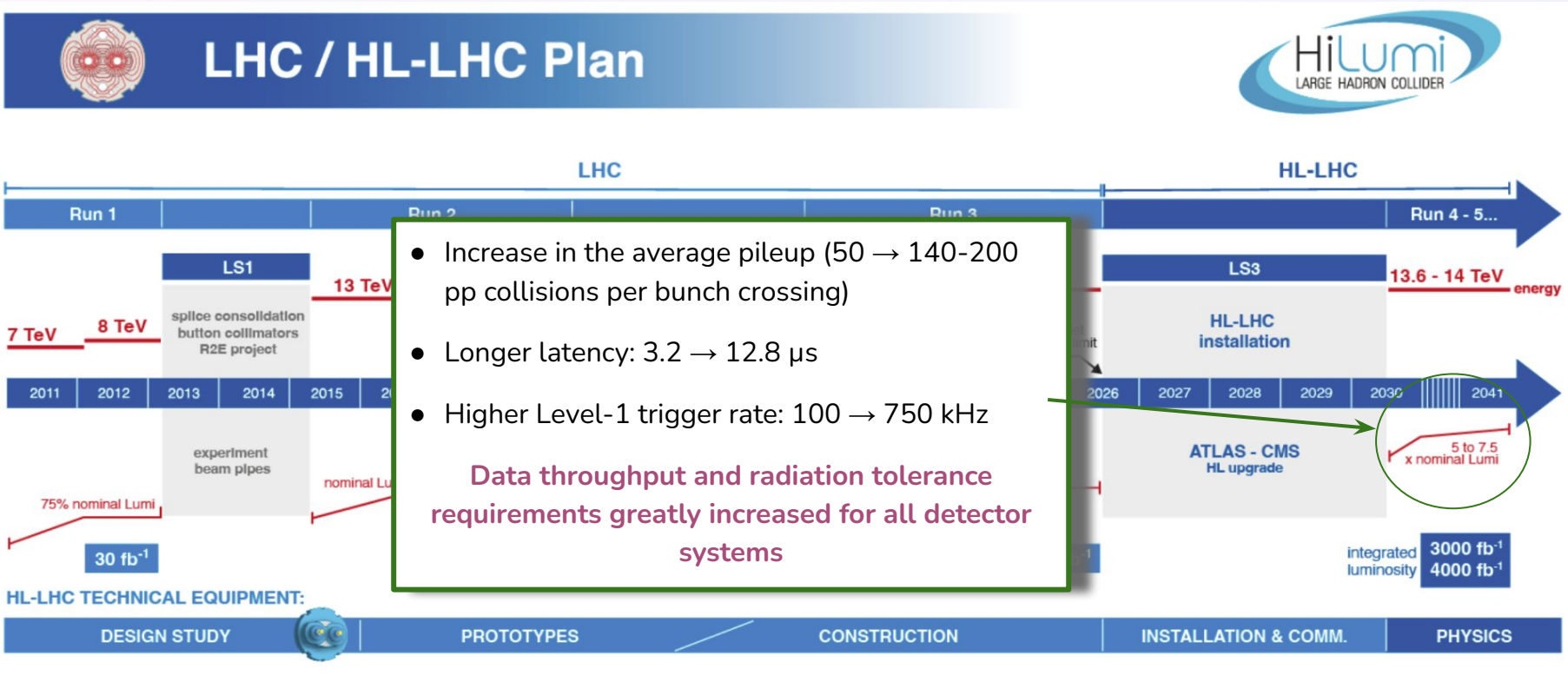
Overview

- Introduction to HL-LHC
- CMS Phase-2 Tracker Upgrade
- Outer Tracker Upgrade
  - Outer Tracker Layout and Modules
  - Module Production Status
  - Module Quality Control Tests
  - Latest Irradiation Test Results
  - Status of integration Tests
- Inner Tracker Upgrade
  - Inner Tracker Layout and Modules
  - Module Production Status
  - Module Quality Control Tests
  - Latest Irradiation Test Results
  - Status of integration Tests



Phase-1 tracker installation at CMS

Introduction

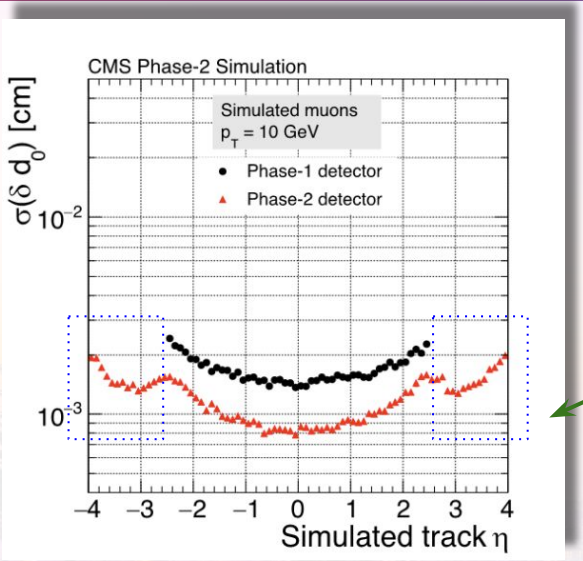


- Increase in the average pileup (50 → 140-200 pp collisions per bunch crossing)
- Longer latency: 3.2 → 12.8 μs
- Higher Level-1 trigger rate: 100 → 750 kHz

Data throughput and radiation tolerance requirements greatly increased for all detector systems

The current CMS Tracker will be replaced with an upgraded system

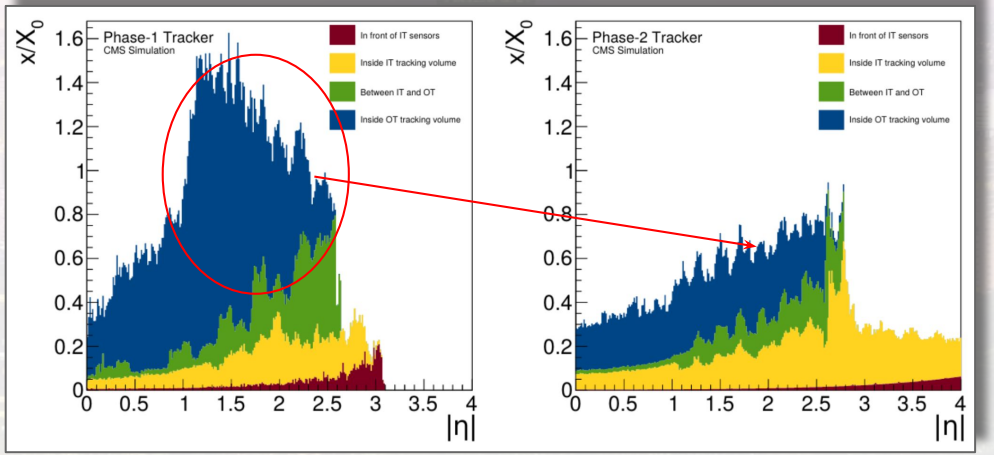
CMS Phase-2 Tracker Upgrade



Tracking performance in Phase-2 Tracker

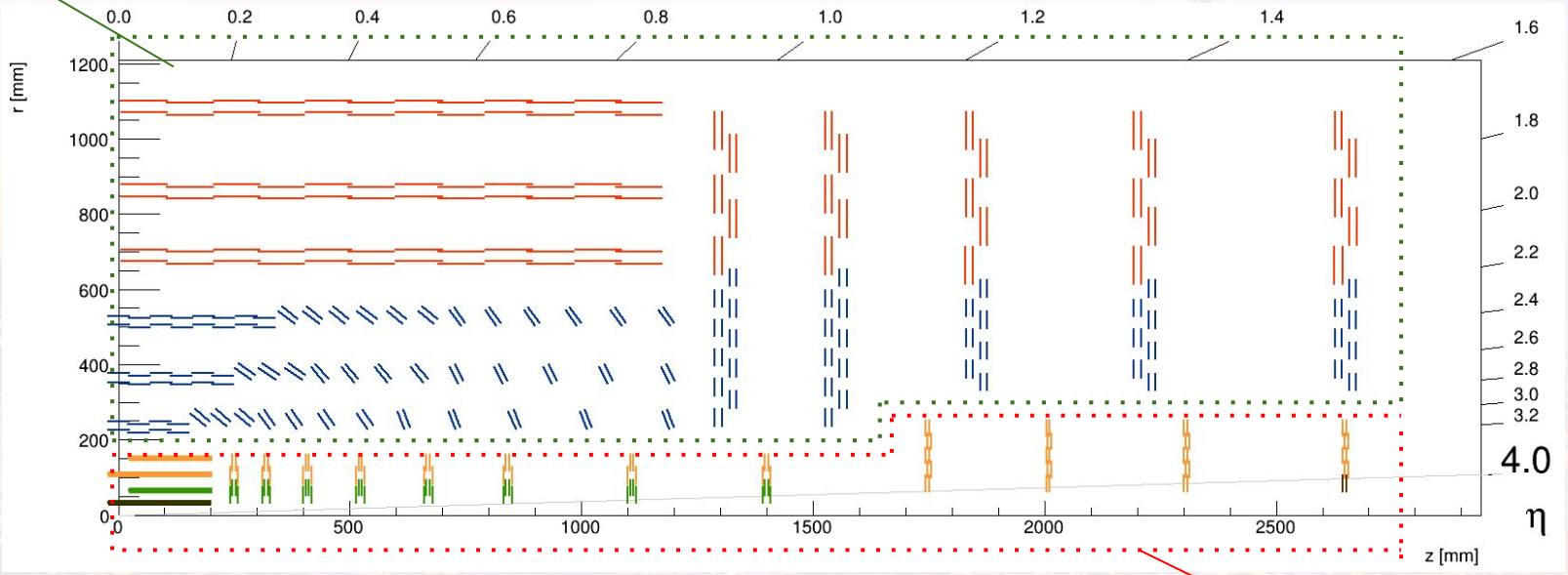
- Capable to deal with hit, track and data rates expected for **7.5 x 10^{34} $cm^{-2}s^{-1}$**
- **Increased radiation-tolerance up to 1 Grad (fluence of ~2 × 10^{16} neq/cm^2** in the innermost regions-about an order of magnitude above Phase-1*)*
- **Increased granularity** ensures efficient reconstruction under extreme pile-up conditions
- Impact parameter resolution improves by about a factor of two compared to Phase-1.
- Tracking extended from |η| ~ 2.5 to |η| ~ 4

Significant reduction in material budget in the Outer Tracker region compared to the Phase-1 Tracker



CMS Phase-2 Tracker Upgrade

Outer Tracker



Inner Tracker

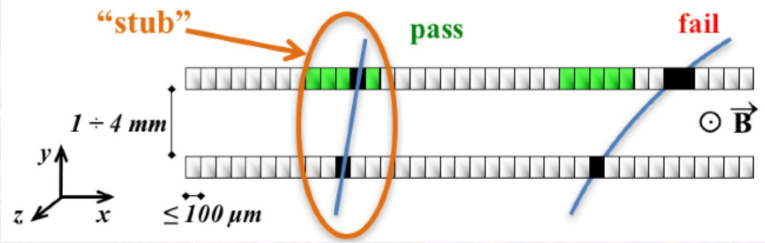
Outer Tracker Upgrade

New!

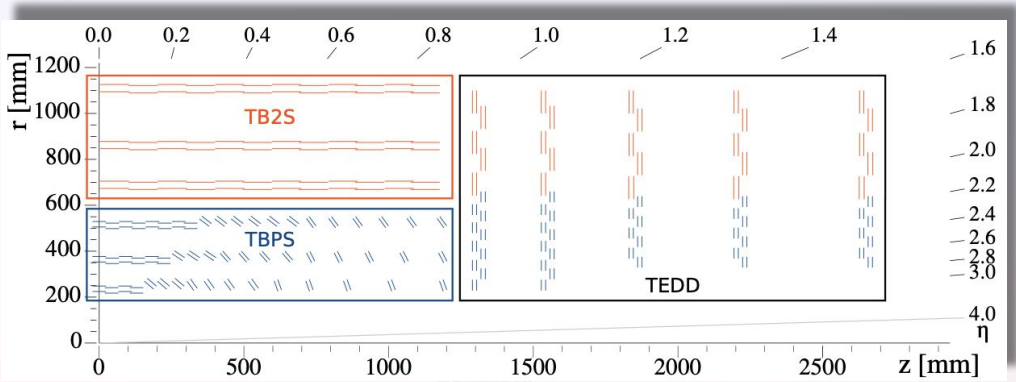
OT will send tracking information to the CMS Level 1 trigger to control the data rates

- **Two module types (pT modules):**
  Pixel-Strip (**PS**) and Strip-Strip (**2S**)
- Each module correlates hits from two closely spaced sensors to form **"stubs"**: tracks with pT > 2 GeV

pT Module Concept



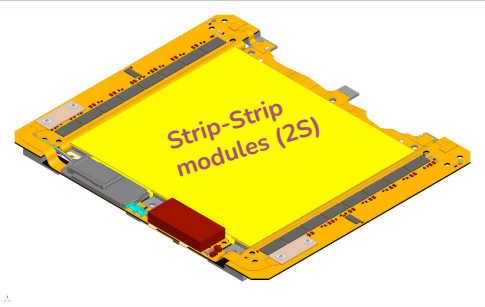
All pT-modules (TBPS, TB2S, TEDD) provide **input to the Level-1 trigger** at 40 MHz



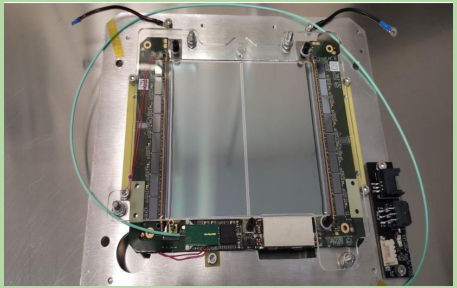
- Tracker Barrel with 2S modules (TB2S)
- Tracker Barrel with PS modules (TBPS)
- Tracker Endcap Double - Discs (TEDD)

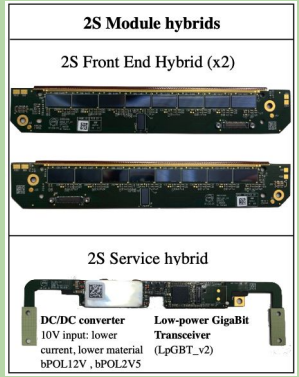
Module type and variant		TBPS	TB2S	TEDD	Total per variant	Total per type
2S	1.8 mm	0	4464	2792	7256	7680
	4.0 mm	0	0	424	424	
PS	1.6 mm	826	0	0	826	5616
	2.6 mm	1462	0	0	1462	
	4.0 mm	584	0	2744	3328	
Total		2872	4464	5960	13296	

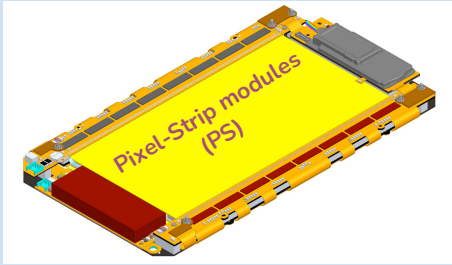
Outer Tracker Modules



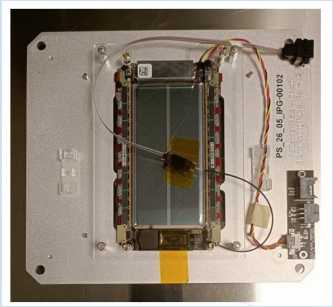
- **2 different spacings:** 1.8 & 4 mm
- **2 micro strip sensors** with 5 cm x 90 um strips
- **Sensor dimension:** 10cm x 10 cm: two columns of 1016 strips

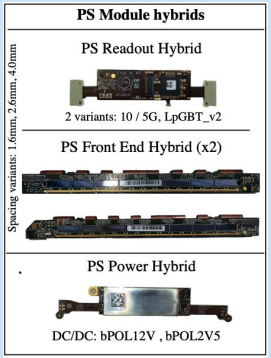






- **3 different spacing:** 1.6mm & 2.6mm & 4mm
- **Strip sensor** (2.5cm x 100µm strips) + **Macro Pixel sensor** (1.5 mm x 100 µm pixels)
- Sensor dimension 5cm x 10 cm (two column of 960 strips + 32x960 pixels)

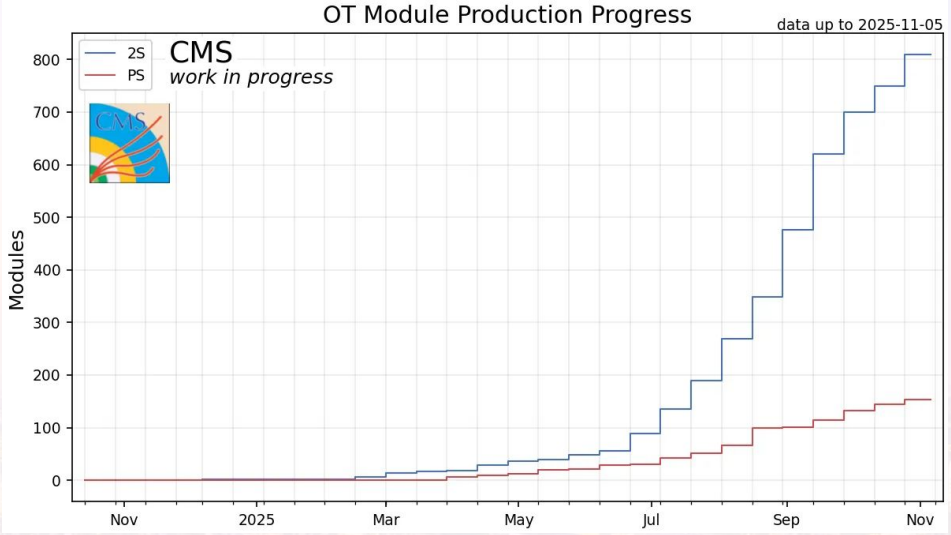




Outer Tracker Module Production

Module Production Overview

- **PS modules:** Production at 5 centers across Europe and the US
  Bari and Perugia (Italy); DESY (Germany); Brown and Purdue (USA)
- **2S modules:** Production at 7 centers across Europe, US, India, and Pakistan
  (RWTH Aachen, KIT (Germany); UCLouvain/VUB (Belgium); Brown, Purdue (USA); NISER (India); NCP (Pakistan)



Reference: https://ompo.web.cern.ch/

Production Strategy

- Transition from sequential (pipeline) assembly → to parallelized module assembly
- Production rates increasing as lines mature
- **2S production scaled up in June**; PS throughput currently limited by Front-End Hybrids (FEHs) availability

Coordinated monitoring of module production, QC results, an component flow between all assembly centres

Outer Tracker Module Quality Control

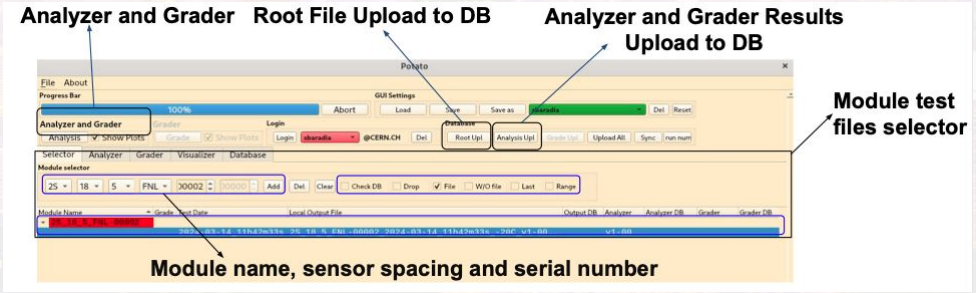
Module QC Tests

- Sensor I–V tests before and after assembly
- Sensor alignment and configuration checks
- Wire bond pull tests and visual inspection
- Noise and functionality tests

Module Burn-in & Qualification

- 48 h thermal cycling between +20 °C and −35 °C
- Electrical tests repeated at 5 points during the cycle

Results handling: automated frameworks for analysis, grading, and database uploads are fully implemented.

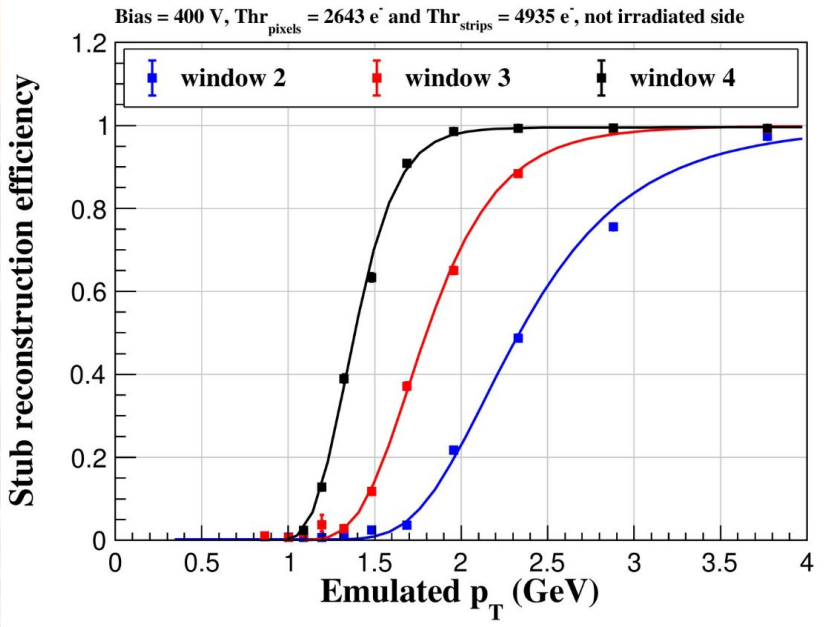


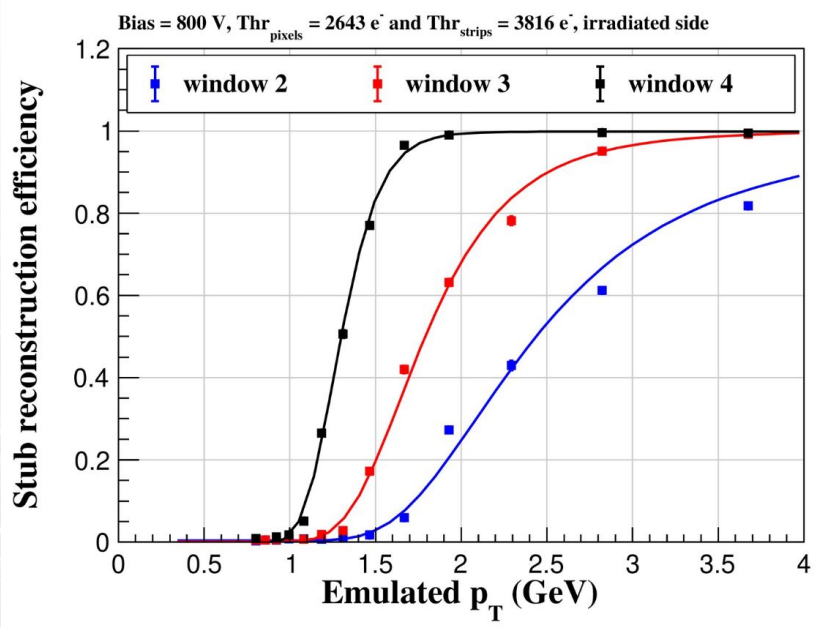
POTATO(Phase-2 Outer Tracker Analyzer of Test Outputs)

Outer Tracker Irradiation Studies

2024 Fermilab Test Beam

- PS module with 1.6 mm sensor–hybrid spacing was evaluated.
- Tested before and after irradiation to a fluence slightly above HL-LHC end-of-life levels.
- No significant performance degradation observed after irradiation.
- Indicates stable operation margin for HL-LHC conditions.





Outer Tracker Integration - System Tests

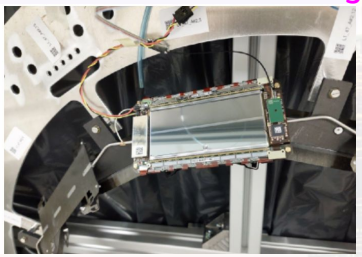
Integration Centers: Modules assembled into test ladders / planks / rings / DEEs for validation —> Results stable

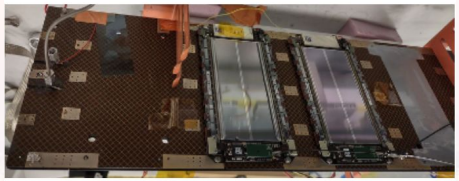
2S Ladders (TB2S, prototype):
Mechanical & thermal integrity validated on test ladders;
Electrical performance consistent with single-module results across temperatures.

PS Ring and Plank (TBPS):
Noise tested at room and cold;
Ground connection scheme under evaluation.

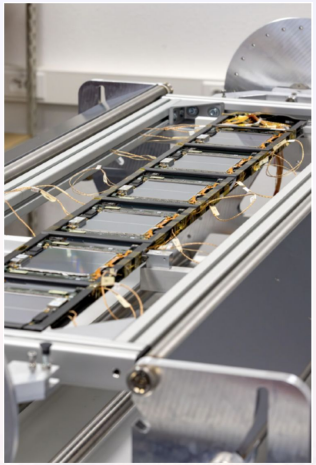
TEDD Sector Prototype:
Module mounting, service routing, and tooling successfully demonstrated;
No significant noise increase after module installation.

TBPS Ring

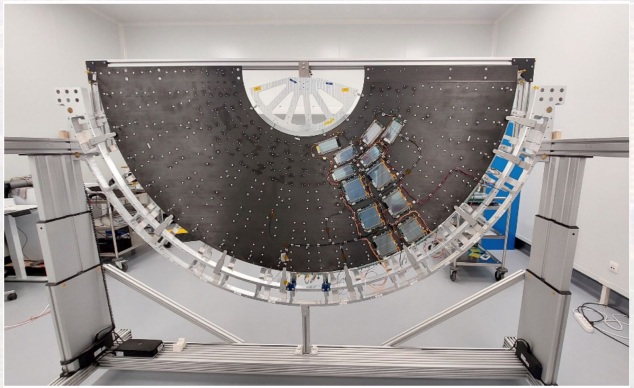




TBPS Plank



TB2S Ladder



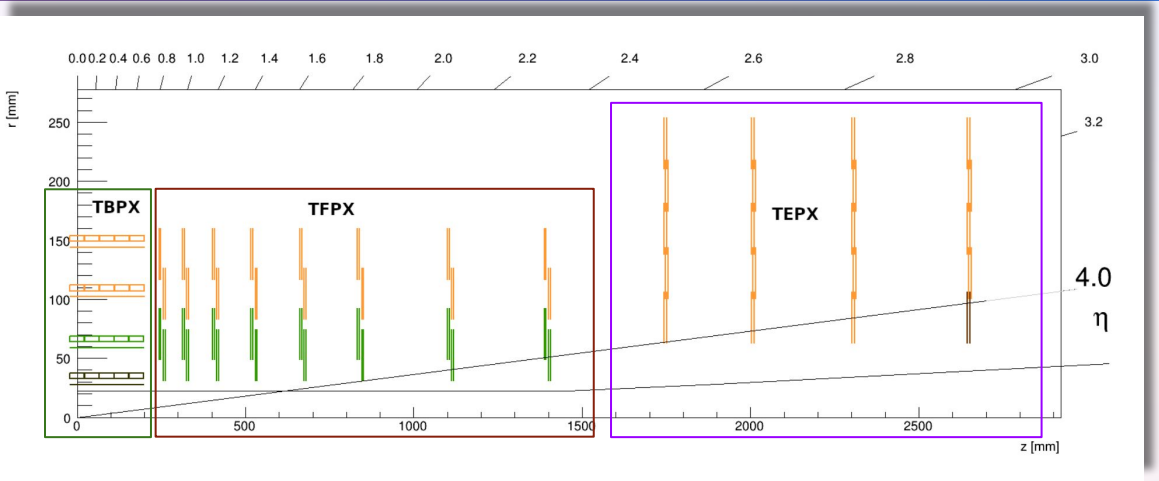
TEDD DEE

Inner Tracker Upgrade

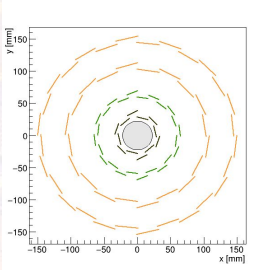
Tracker Barrel PiXel (TBPX)
- 4 layers
- 756 modules
- Innermost layer->3D modules (108 modules)

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
- Will be used for tracking and luminosity measurements
- Ring 1 of Disk 4->Fully used for luminosity measurements only

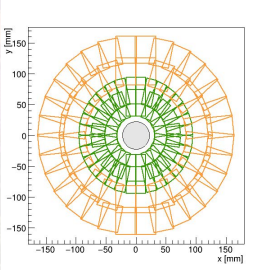


3D; Dual; Quad



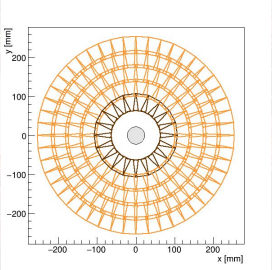
TBPX: 4 layers
4/5 modules per ladder

Dual; Quad



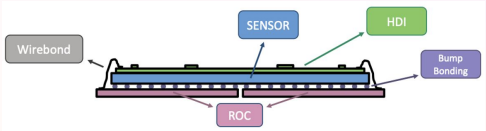
TFPX: 8 disks/end
4 rings/disk

D4R1; Quad



TEPX: 4 disks/end
5 rings/disk

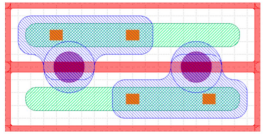
Inner Tracker Modules



Planar sensors: 25×100 μm² pixels and 150 μm thick

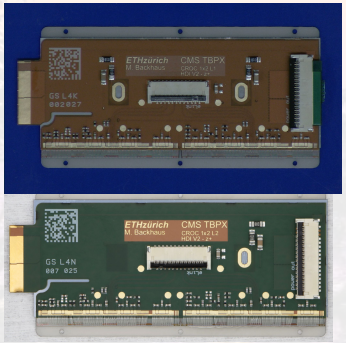
3D sensors: 25×100 μm² pixels, 150 μm thick, n⁺ readout columns (5–8 μm diameter, 115–130 μm length), enhanced radiation tolerance and lower depletion voltage

100×25 μm²

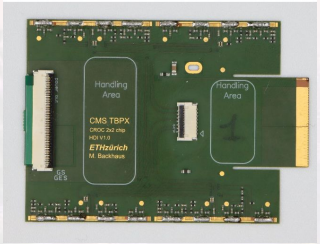


CROC readout chip (CMOS 65 nm, RD53): 50×50 μm² pixels, 3.2 GHz/cm² hit rate, radiation-hard up to 1 Grad, Shunt-LDO for serial powering

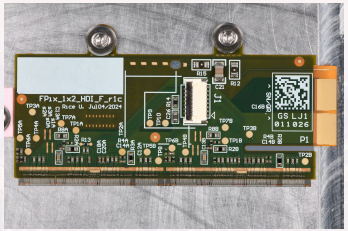
TBPX 1x2



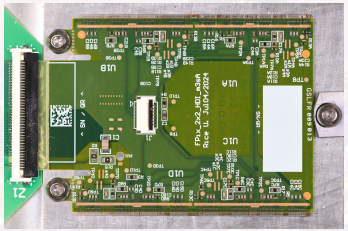
TBPX 2x2



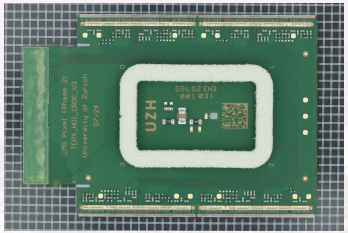
TFPX 1x2



TFPX 2x2



TEPX 2x2



TBPX Modules

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

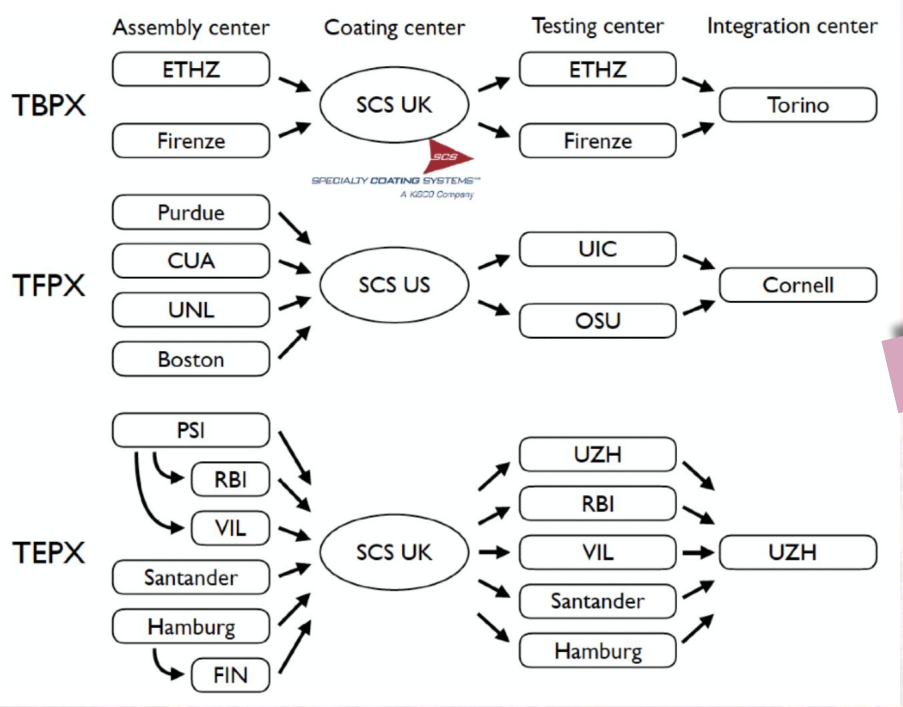
TFPX Modules

- Planar Dual
- Planar Quad

TEPX Modules

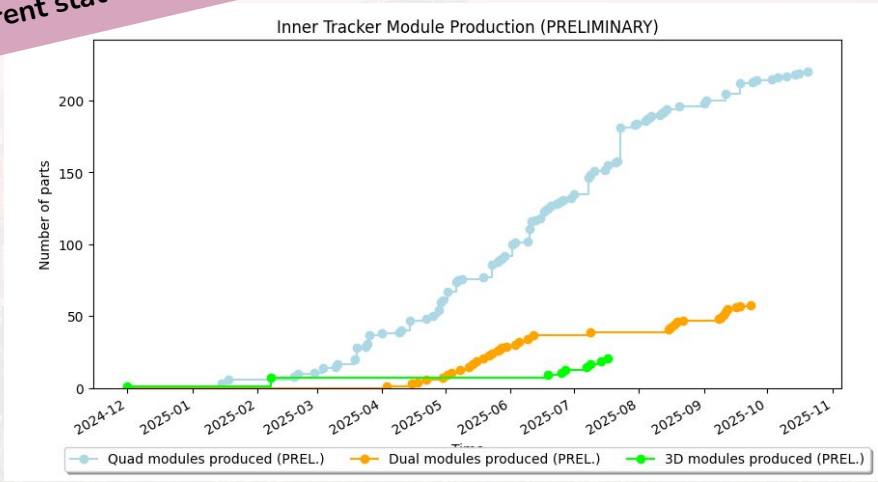
- Planar Quad

Inner Tracker Module Production 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 -> production will be launched soon

Current status of production



Poster by Chin-Chia Kuo

Details of IT module production and QC workflow:
CMS Phase-2 Inner Tracker for the HL-LHC Upgrade

Inner Tracker Module Quality Control

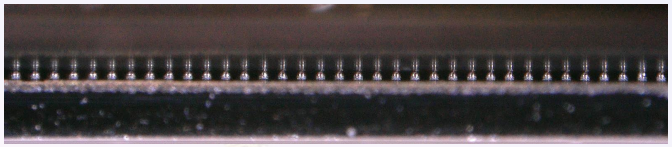
Electrical tests and Visual inspection during assembly

- **SLDO tests** (input, digital and analogue voltages of ROC)
- **Sensor I/V curves**
- **Threshold tuning and Pixel scans** (dead & inactive pixels)
- **Bump connectivity** -> Crosstalk measurements
- **Thermal cycling (BURN-IN Test)**: At least 10 thermal cycles within a temperature range of −35 °C to +40 °C.

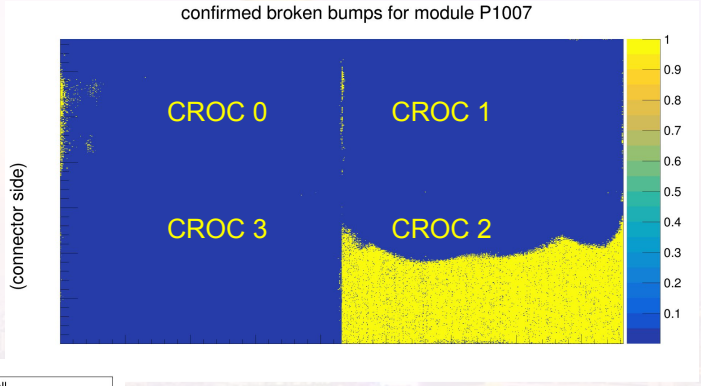
Major issues observed and under investigation:

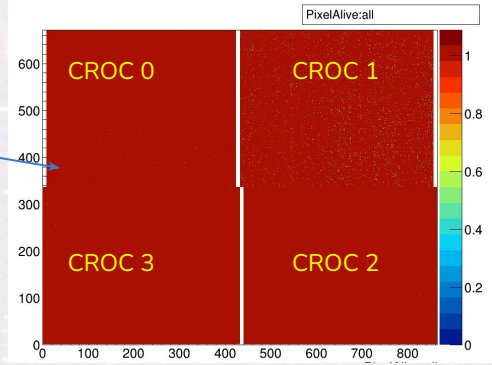
- Broken bump-bonds (non optimal bonding jigs)
- Core column issues

Coated modules are currently undergoing full performance QC to evaluate their quality



Microscope image of bump bonds



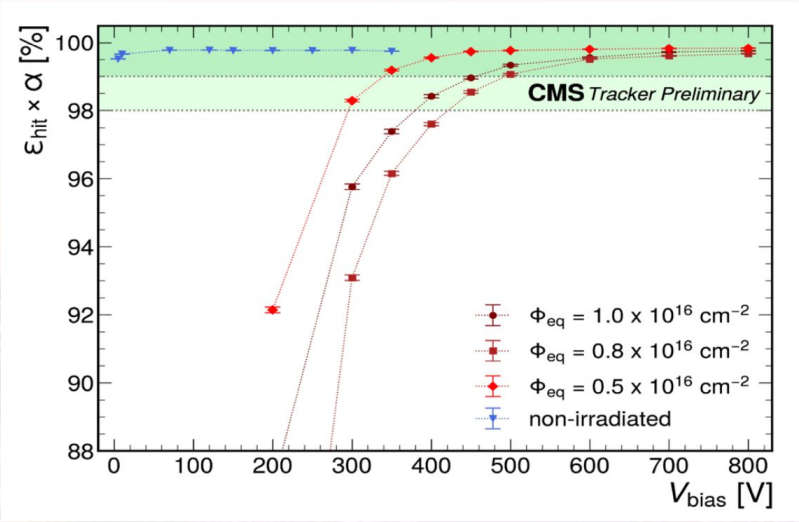


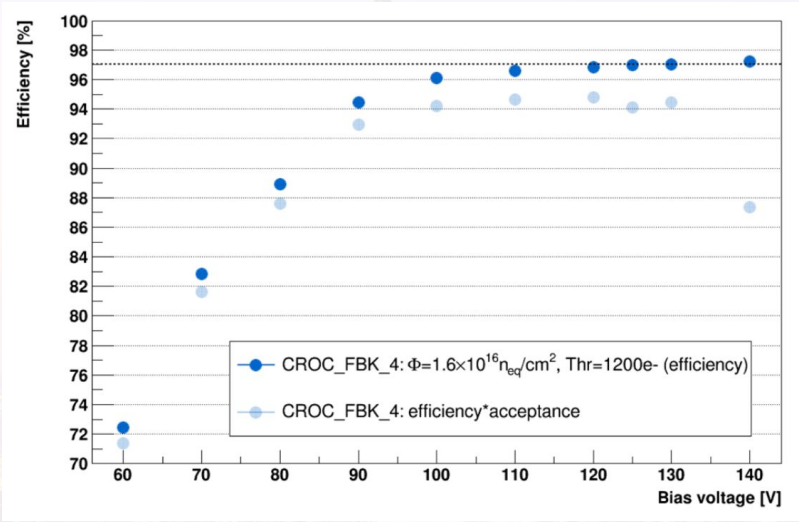
QC frameworks for automated testing, grading, and database integration are established and under further development

Inner Tracker Modules Irradiation Tests

Acceptance: $\alpha = 1 - \frac{N_{pixels}^{masked}}{N_{pixels}^{total}}$

Efficiency: $\epsilon_{hit} = \frac{N_{tracks}^{observed}}{N_{tracks}^{total}}$





Planar Sensors

- Fluence: from 0.5x10^{16} n_{eq}/cm^2 1x10^{16} n_{eq}/cm^2
- Efficiency > 99% @ 600 V (within requirements)

3D Sensors

arXiv:2510.13304

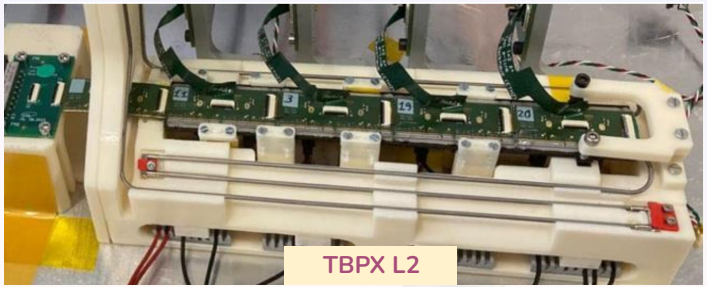
- Fluence: 1.6x10^{16} n_{eq}/cm^2 (replacement of layer-1 foreseen after 6 years of operation)
- Efficiency > 96% @ 110 V for normal incidence (within requirements*)

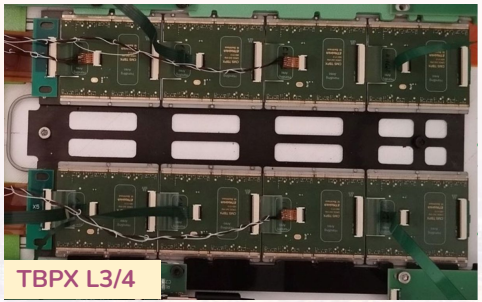
* 3Ds have geometrical inefficiency for normal incidence, because of the columns

Inner Tracker Integration - System Tests

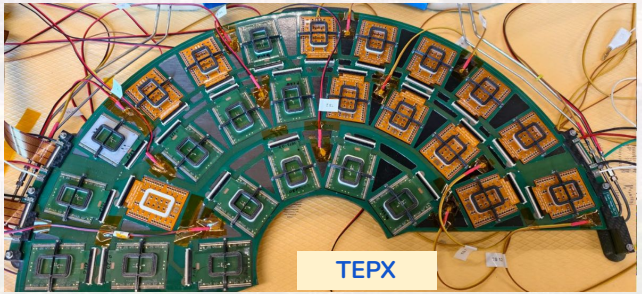
Four different setups with final integration structures:

✓ TBPX L2 and L3/4
✓ TFPX disk
✓ TEPX disk


TBPX L2


TBPX L3/4


TFPX

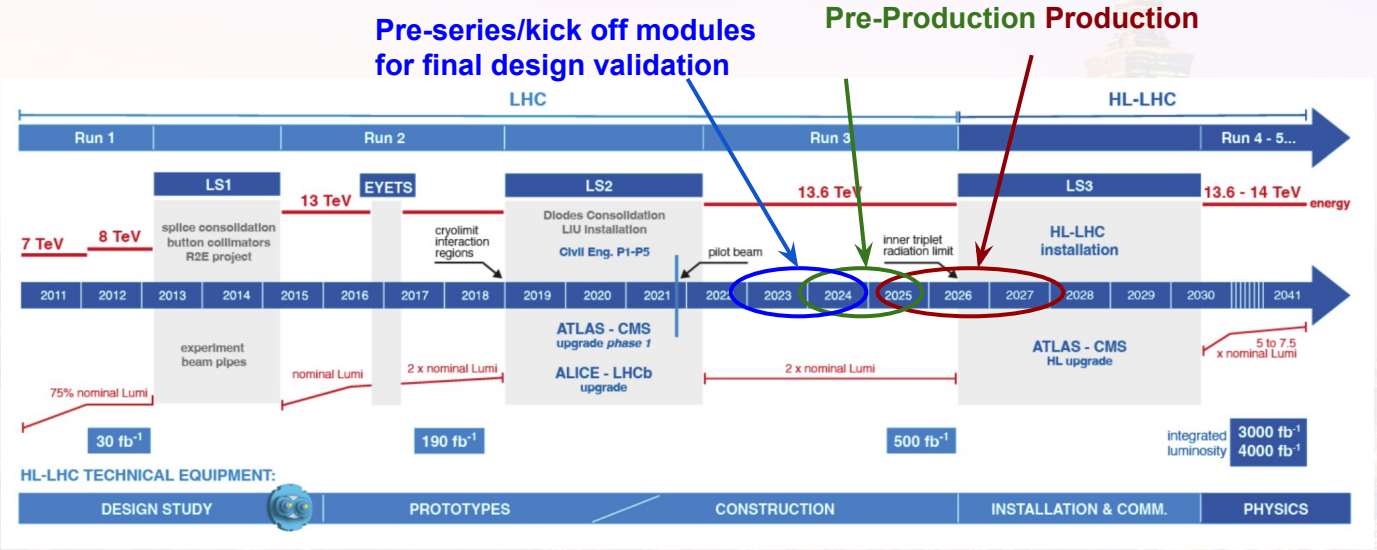

TEPX

Major studies progressing:

- Thermal studies and simulations validation
- Mechanical studies
- LV distribution tests with serial power configuration
- HV distribution and grounding studies
- Full readout chain validation

Summary and Outlook

- **The CMS Tracker will be fully replaced for the HL-LHC, featuring:**
  Extended forward acceptance (|η| < 4), higher hit-rate capability, increased radiation tolerance, reduced material budget and track information available at Level-1 trigger



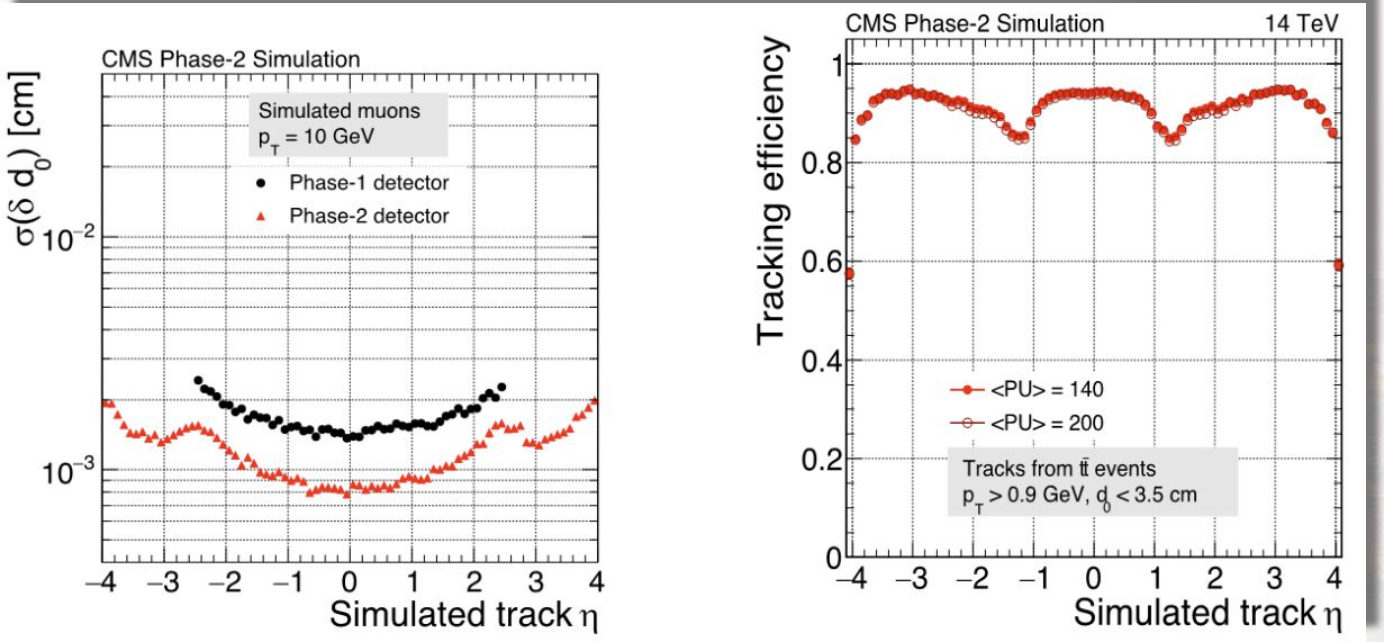
- **Module production is underway for both Inner and Outer Tracker**, with QA/QC workflows established and supporting scale-up production.
- Support systems (mechanical structures, powering, cooling) are in place and undergoing validation tests.
- **System integration tests are ongoing**, and the first assembled structural units are being built and evaluated as production ramps up.


Thank You

CMS Phase-2 Tracker Upgrade

Tracking performance in Phase-2 Tracker

- Impact parameter resolution improves by about a factor of 2 compared to Phase-1.
- Tracking extended up to $|\eta| < 4$ with resolution < 200 μm.
- High Tracking efficiency (> 85%) even at 200 pile-up

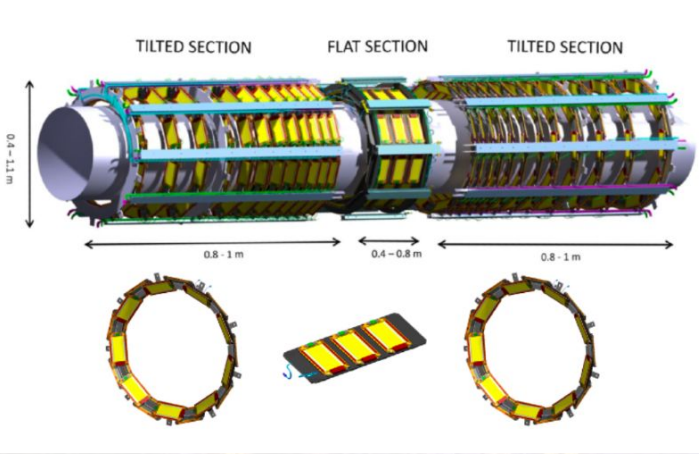


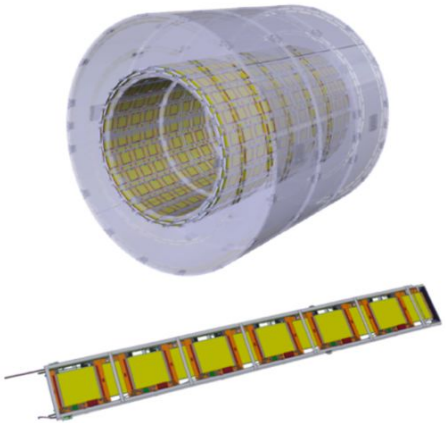
Outer Tracker: Mechanics

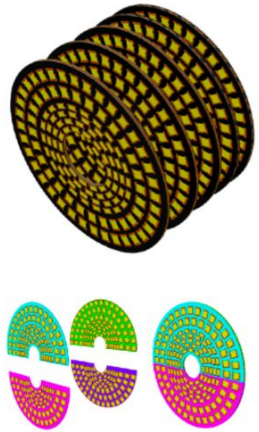
TBPS
- Planks & Rings

TB2S
- Ladders -> Cylindrical layers

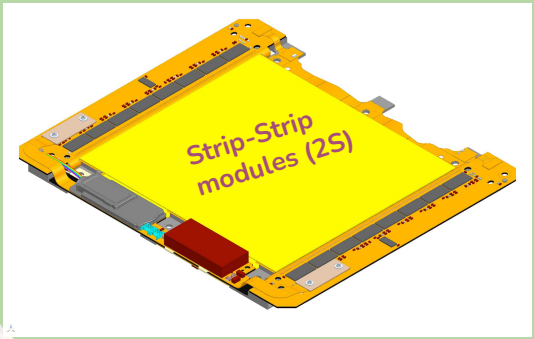
TEDD
- Double disks with dees (D shaped parts)



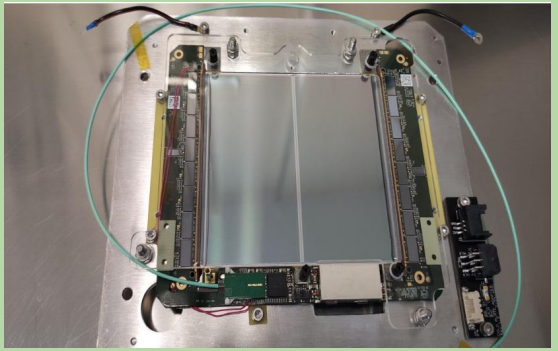




Outer Tracker Modules

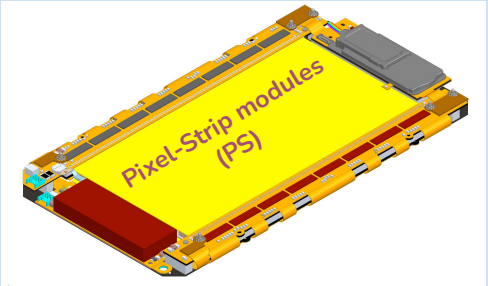


- **2 different spacings:** 1.8 & 4 mm
- **2 micro strip sensors** with 5 cm x 90 um strips
- **Sensor dimension:** 10cm x 10 cm: two columns of 1016 strips

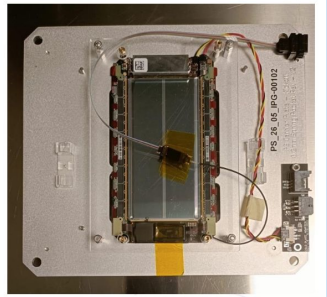


Front-end Electronics

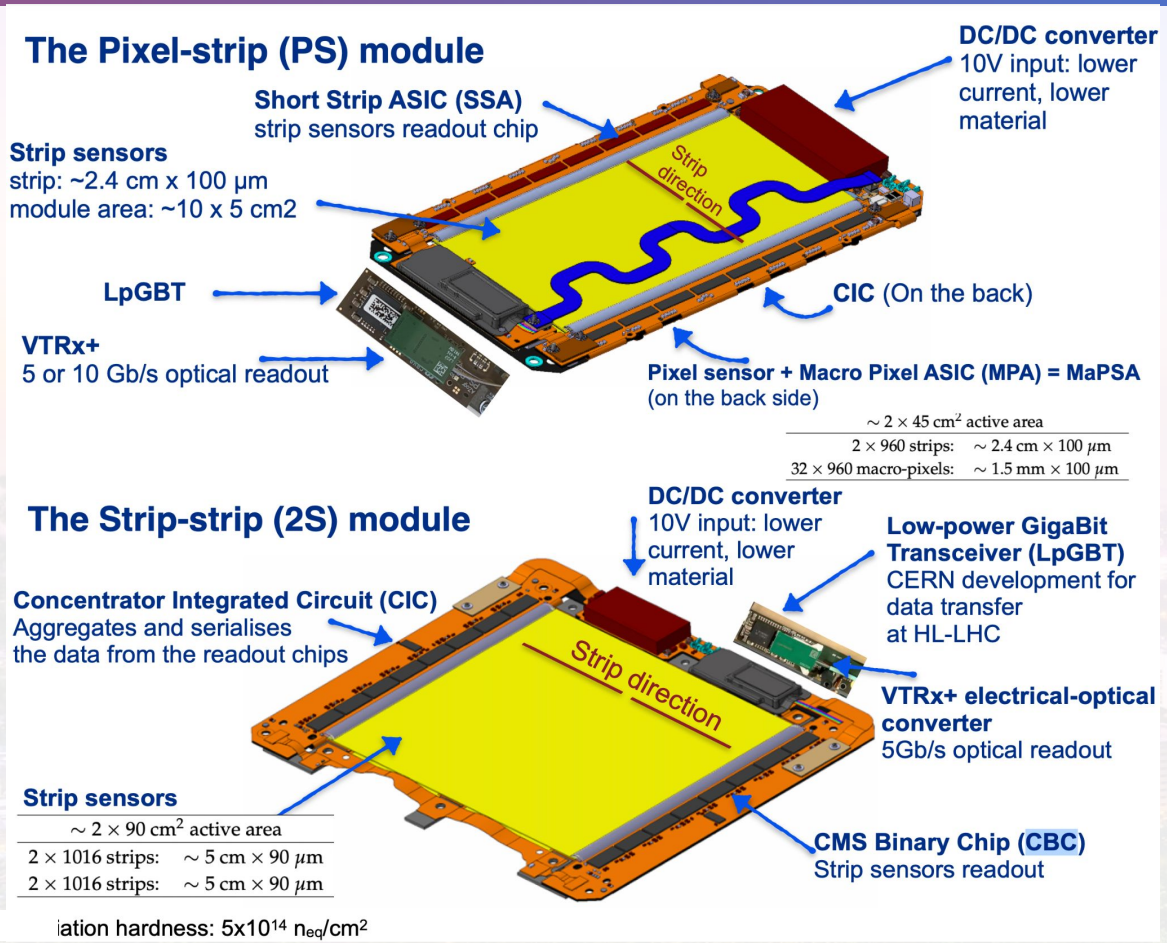
- CBC – CMS Binary Chip (130 nm): Sensor readout and stub finding in 2S modules
- SSA – Short-Strip ASIC (65 nm): Readout of the short-strip sensor in PS modules
- MPA – Macro-Pixel ASIC (65 nm): Stub finding on the macro-pixel sensor in PS modules
- CIC – Concentrator Integrated Circuit (65 nm): Aggregates and serialises data from all modules for off-detector transmission



- **3 different spacing:** 1.6mm & 2.6mm & 4mm
- **Strip sensor** (2.5cm x 100μm strips) + **Macro Pixel sensor** (1.5 mm x 100 μm pixels)
- Sensor dimension 5cm x 10 cm (two column of 960 strips + 32x960 pixels)

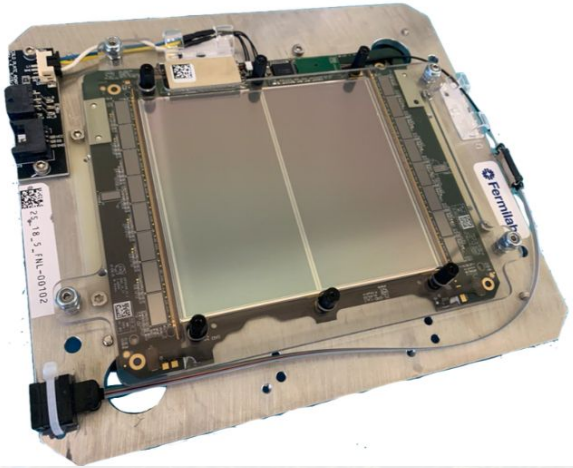


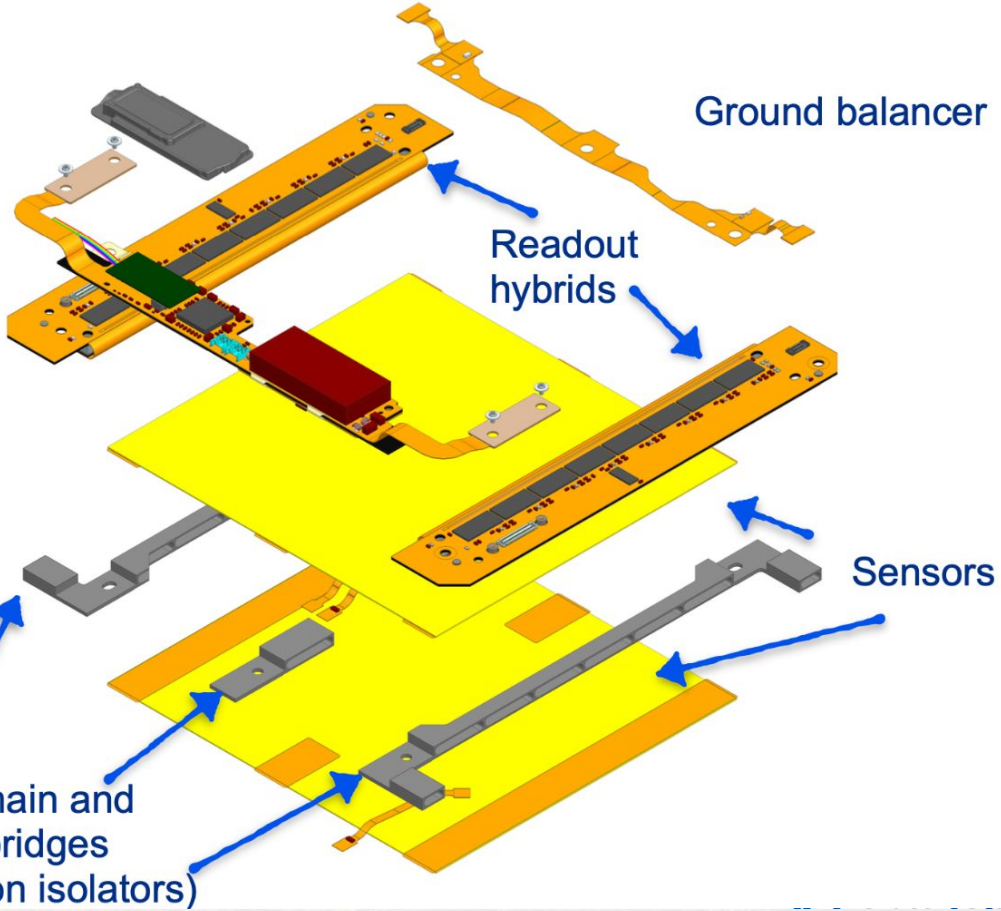
Outer Tracker Modules



2S Module Assembly

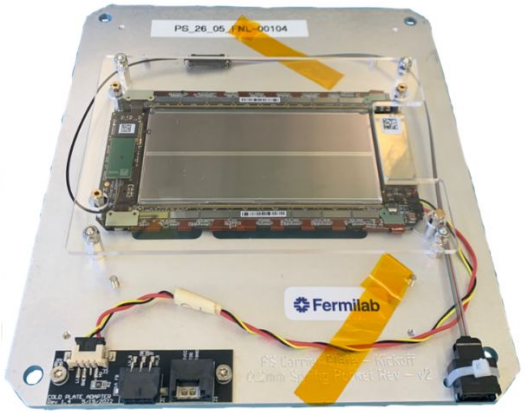
- 7608 2S + spares needed
  - 7 production centers in Europe, US, India and Pakistan

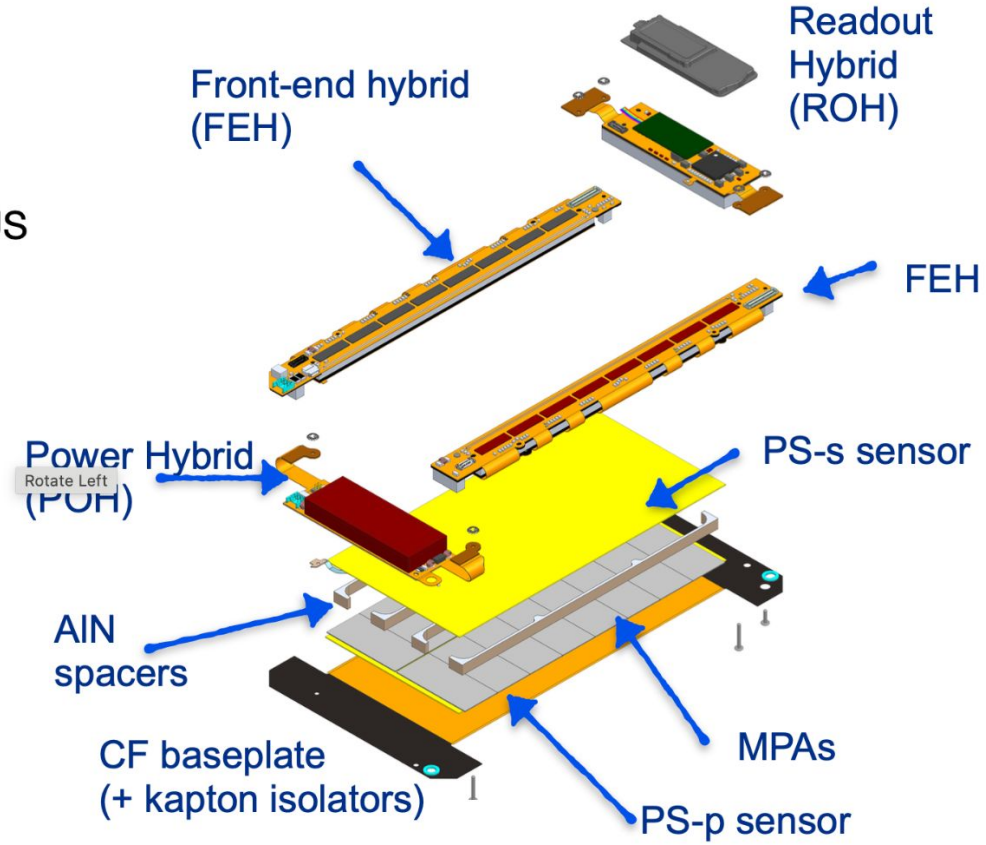




PS Module Assembly

- 5592 PS + spares needed
  - 5 production centers in Europe and US



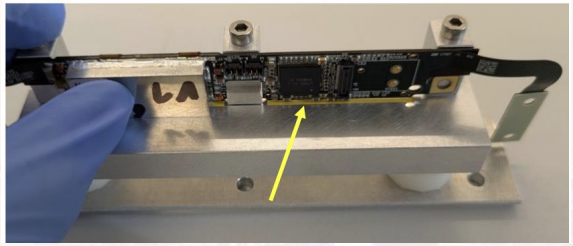


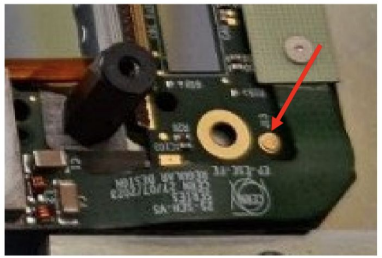
Module Production & Assembly Challenges

- **Wirebond Pad Cleanliness:** Residue contamination traced to spacer geometry → cleaning workflow improved and new spacer designs under evaluation.

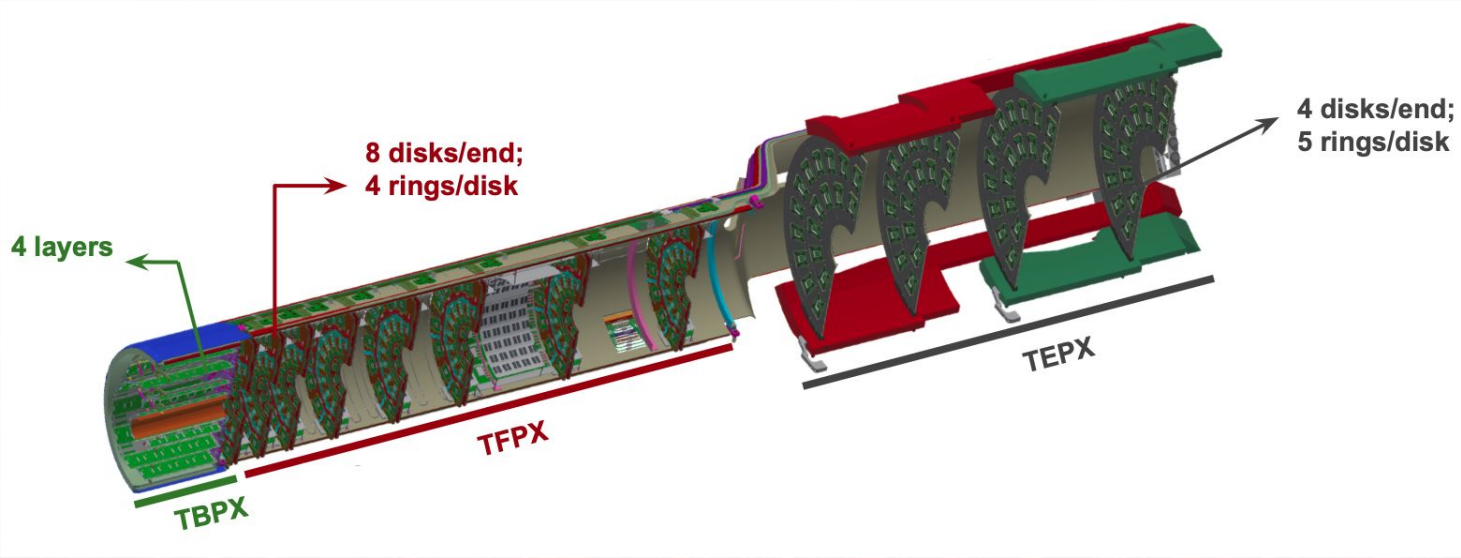
- **1.8 mm 2S High-Voltage Sensitivity:** Small sensor–stiffener spacing caused discharge and dead channels after HV tests.
  → Kapton isolation solution adopted; hybrid gluing + HV tests temporarily paused until fix applied.

- **Grounding Pin Reliability (2S & PS):**
  Inconsistent stiffener grounding and degradation after thermal cycling.
  → Standardizing on soldered grounding pins for future and existing modules.





Inner Tracker Mechanics

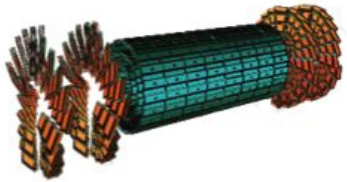


- Light Carbon Fiber structures with embedded cooling pipes
- Flat disk geometry (replaces turbine design of Phase-1)
- Can be extracted for maintenance (during extended technical stops)

- Barrel splits in half @ z~0
- Cooling based on evaporative CO2 (T=-35°C):
  - ✓ TBPX: 1.8 mm outer diameter stainless steel pipes
  - ✓ TFPX: 3.0mm outer diameter titanium pipes
  - ✓ TEPX: 2.3mm outer diameter titanium pipes

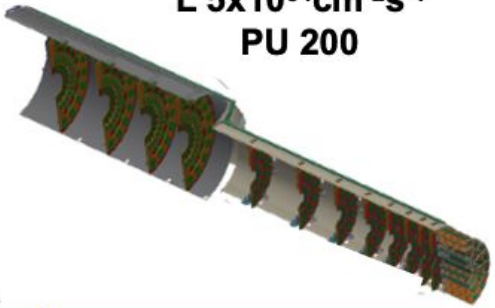
Inner Tracker Upgrades

L $1x10^{34}cm^{-2}s^{-1}$
PU 20



L $2x10^{34}cm^{-2}s^{-1}$
PU 40

L $5x10^{34}cm^{-2}s^{-1}$
PU 200



	Phase 0	Phase 1	Phase 2
Mechanics	3 layers+ 4 disks	4 layers + 6 disks	4 layers + 24 disks
Inner radius	4 cm	3 cm	3 cm
Active Si area	1 m^2	1 m^2	5m^2
Channels	66M	124M	2000M
Pixel size	100x150 μm^2	100x150 μm^2	25x100/50x50 μm^2
Radiation tolerance	100 Mrad	300 Mrad	1000 Mrad

Inner Tracker Module Assembly

TBPX:

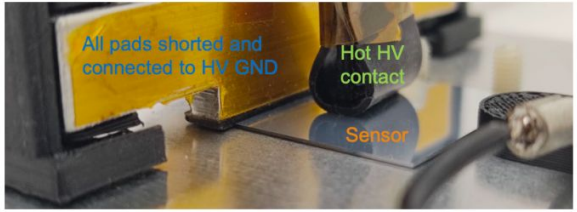
✓ Assembly with dedicated jigs

TFPX:

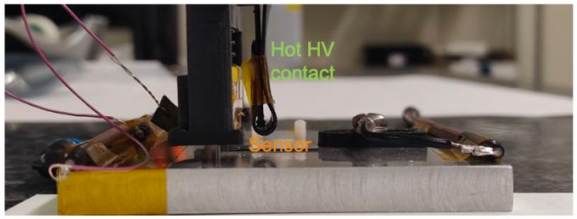
✓ Assembly with gantry

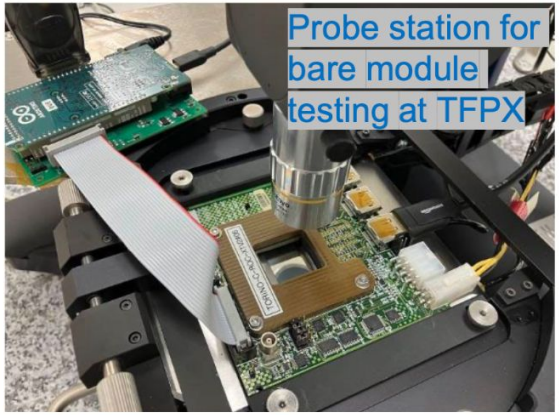
TEPX:

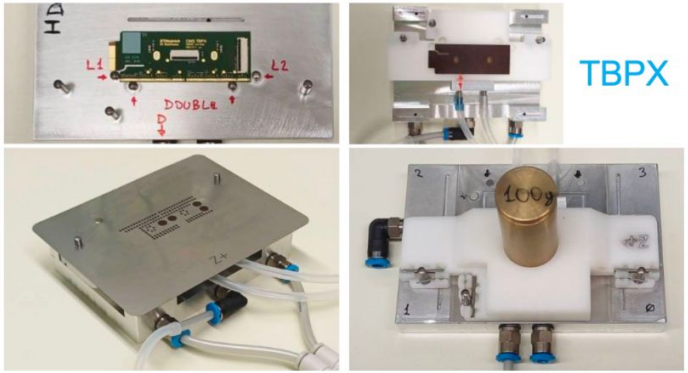
✓ Assembly with robotic arm

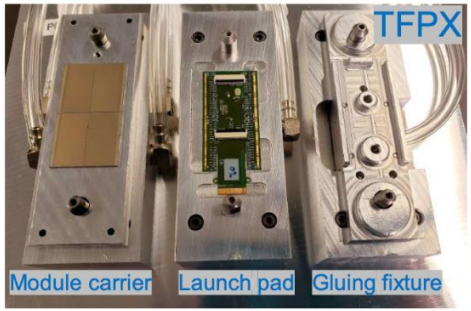


3Ds bare module HV testing tool



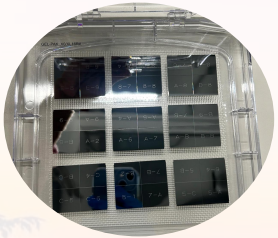






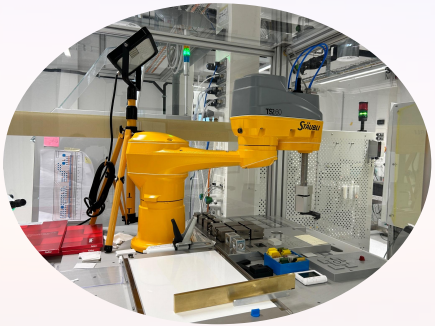
TEPX Module Assembly

Bare modules (sensor bump bonded to the chips) and HDIs arrive at PSI

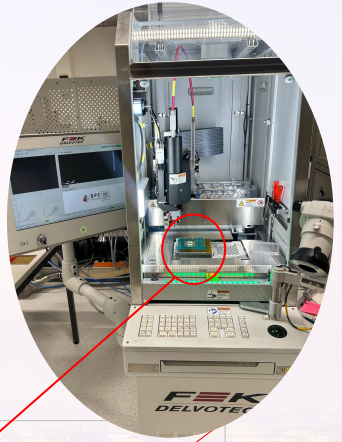


+

HDIs and Airex frames (for mechanical stability) are glued using the a robotic arm

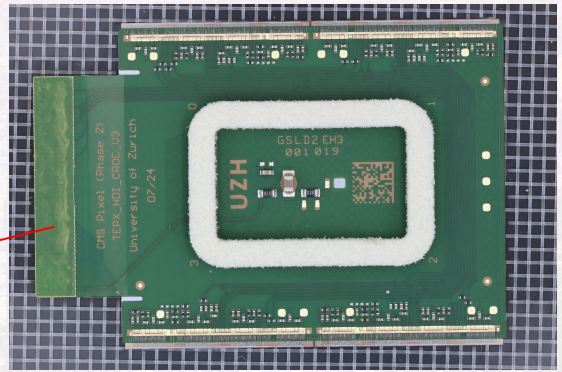


Modules are wire bonded



Module undergoes a visual inspection after assembly

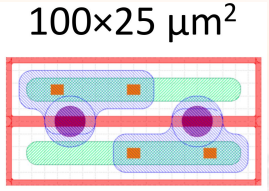
A fully assembled module

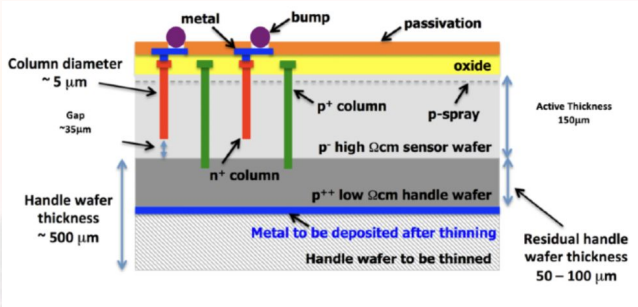


Inner Tracker Sensors and Readout Chip

Planar Sensors:

- 25 × 100 μm^2 per 150 μm active thickness
- Hit efficiency >99% after 2x10^{16} n_{eq}/cm^2



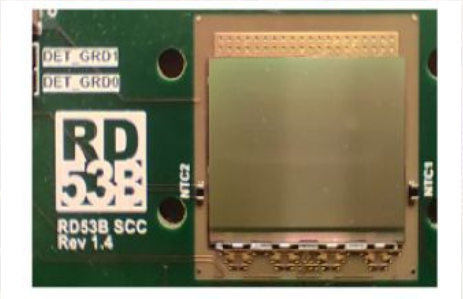


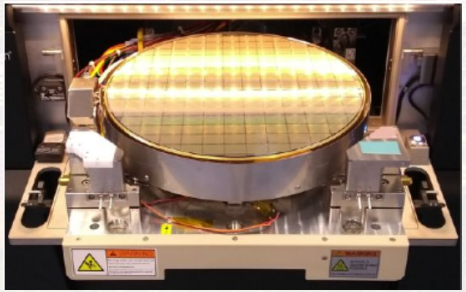
3D Sensors:

- Better performances for radiation (than planar)
- Lower depletion voltage
- Hit efficiency > 98% after 1.8×10^{16} neq/cm^2

CMS Readout Chip (CROC):

- CROC 65 nm CMOS ASIC developed by joint ATLAS-CMS RD53 Collaboration (pixels: 432 x 336; size 21.6 x 18.6 mm^2)
- 50 x 50 μm^2 cell size
- 3.2 GHz/cm² hit rate
- Radiation tolerance up to 1 Grad





Inner Tracker Powering and Readout

Powering scheme:

- Low material budget for a 60 kW detector power
- Modules are grouped in 576 serial power chains → **Serial Powering**
- Up to **11 modules/chain serially powered**
  - Within each module, chips are powered in parallel->on chip shunt-LDO regulators for serial powering
  - HV supply in parallel

Readout scheme:

- Electrical ↔ optical data conversion handled on portcards (not on modules), ~700 total.
- Portcard: 3× lpGBT + VTRx+ and DC-DC converters.
- Up-links: up to 6× E-links @ 1.28 Gb/s (module → lpGBT).
- Down-link: 1× E-link @ 160 Mb/s (clock + trigger + config).
- Optical fibers: between portcards and the Data, Trigger, and Control (DTC) boards