Phase-2 upgrade of the CMS Outer Tracker:

challenges and lessons from silicon strip module production

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PSD14: The 14th International Conference on Position Sensitive Detectors, 1-4 Sep 2026, London (United Kingdom)

High Luminosity LHC: From Physics Goals to Detector Requirements

HL-LHC upgrade:

- >5x increase in integrated luminosity
- >3x increase in instantaneous luminosity
- From ~60-70 to up to 200 simultaneous pp collisions

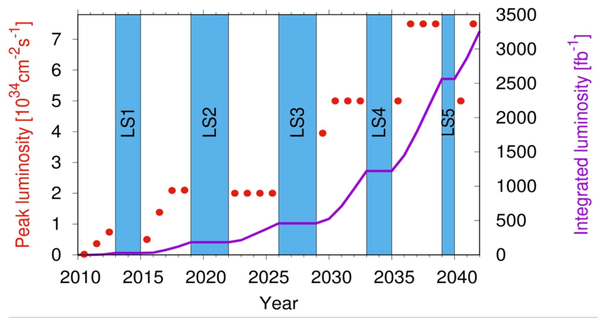
BUT WHY?

- More luminosity → smaller uncertainties
  → **Increased sensitivity to rare processes and deviations from Standard Model predictions**

CMS Phase-2 Upgrade

- Much harsher environment
  → Improved muon system
  → High granularity endcap calorimeters
  → New Timing layer
  → New silicon tracker

[1]



Potential HL-LHC schedule and proton performance for ATLAS and CMS.

New Silicon Tracker: Requirements & Design Solutions

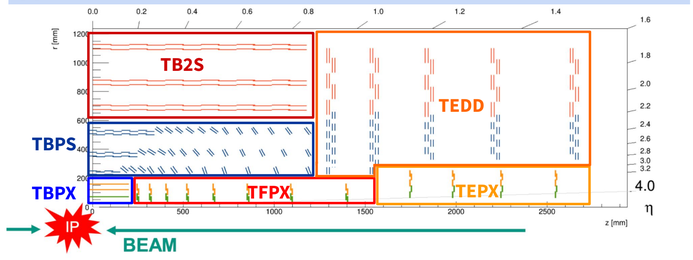
Precise tracking is crucial for CMS:

- Particle momentum, secondary vertices, c and b-jet tagging, τ-lepton tagging,...
- Necessary for Top & Higgs physics among many other

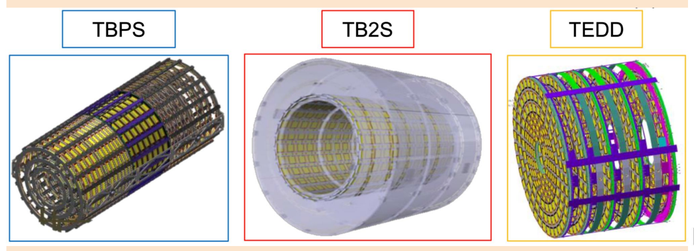
The upgraded tracker needs:

- **10 years of operation · up to 4000 fb^{-1}**
  → **High radiation tolerance**
  → Radiation-hard materials
  → Sensors operated at ~**−20°C**
- **Expanded tracking acceptance: |η| < 4**
  → **Extended forward coverage**
- **Reduce multiple scattering & γ conversions**
  → **Low-mass design**
  → Lightweight materials
  → Tilted barrel geometry
- **Fit within the existing tracker envelope**
  → **Optimized geometry**
  → Fewer module types → simplified logistics
- **Up to ×7 higher track density**
  → **Higher granularity**
  → **25 × 100 µm² pixels** in the Inner Tracker
  → **90-100 µm strip pitch** in the Outer Tracker
- **Tracking information available at L1 trigger**
  → **On-detector pT discrimination**
  → Outer Tracker uses **pT-modules**

[2]



Sketch of a quarter of the CMS Phase-2 tracker.



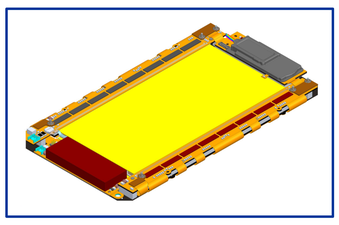
CMS Phase-2 Outer Tracker.

Outer Tracker Modules

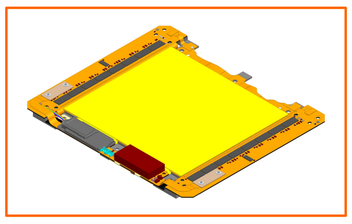
OT module design is driven by the need to select tracks at 40 MHz above a programmable threshold for triggering
→Aiming for high-pT/high energy/interesting tracks

<u>The entire Outer Tracker uses only two module types!</u>

- 5592 **PS** modules: 1.6, 2.6 and 4.0 mm versions
  →5 cm x 10 cm
  →Combination of macro-**P**ixel and **S**trip sensors
- 7608 **2S** modules: 1.8 and 4.0 mm versions
  →10 cm x 10 cm
  →**Two S**trip sensors
- Each module acts as an independent detector unit



PS Module



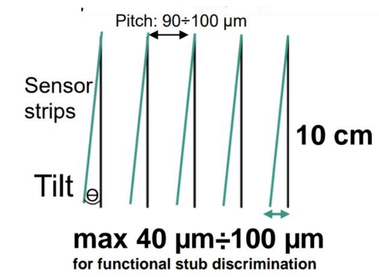
2S Module

pT Modules Concept

CMS generates hundreds of TB/s of raw data at 40 MHz bunch-crossing rate

- Level-1 trigger must reduce this to **~750 kHz** for readout

- **Two precisely aligned, stacked silicon strip sensors**
- **On-module pT discrimination**
  - **2 GeV/c threshold** → stub/data-volume reduction at module level of **~97%**
- **High-pT "stubs"** are sent to the **Level-1 Track Finder**
- **~80% of module bandwidth** is used as trigger input



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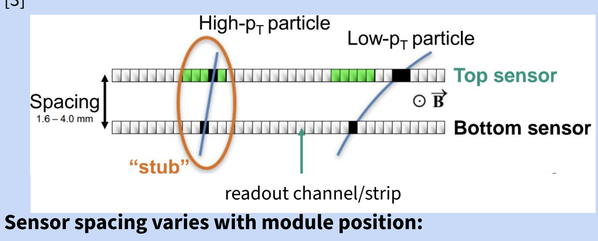


Sensor spacing varies with module position:

- **1.8 / 4.0 mm** for 2S modules
- **1.6 / 2.6 / 4.0 mm** for PS modules

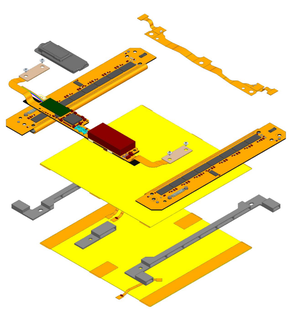
→ **pT sensitivity depends on module position and orientation:**

- **Programmable stub acceptance window** compensates for geometrical differences
- **Consistent pT selection across the tracker**

Outer Tracker Modules production

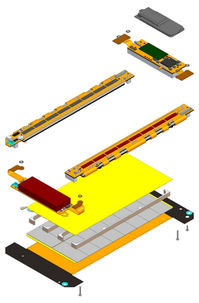
2S Module:

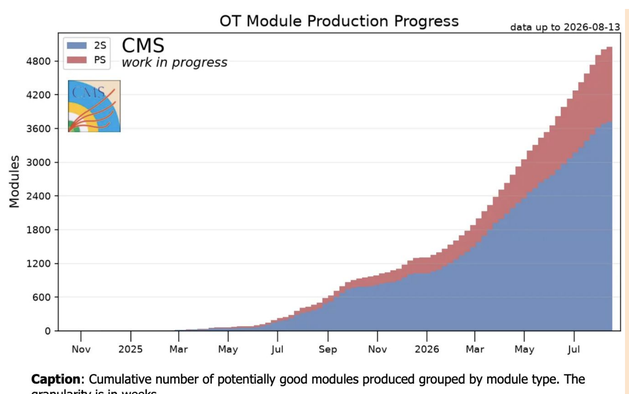
1. Two Strip Sensors
2. Two Front-End Hybrids (FEHs)
3. Service Hybrid (SEH)
4. Ground Balancer
5. Two Al-CF Main Spacers
6. One/Two Al-CF Stump Spacers
7. Two Kapton Main Isolators
8. One/Two Kapton Stump Isolators
9. HV Temperature Tail
10. HV Tail
11. VTRx+ Shield
12. Four FEH Connector Fixation Screws



PS Module:

1. PS-s — Strip Sensor
2. Pixel sensor subassembly (MaPSA)
3. Two Front-End Hybrids (FEHs)
4. Readout Hybrid (ROH)
5. Power Hybrid (POH)
6. Four AlN Sensor Spacers
7. Kapton HV Isolator
8. CF Baseplate
9. HV tail
10. VTRx+ shield
11. Aluminum inserts (2 round, 1 oval)





Caption: Cumulative number of potentially good modules produced grouped by module type. The granularity is in weeks.

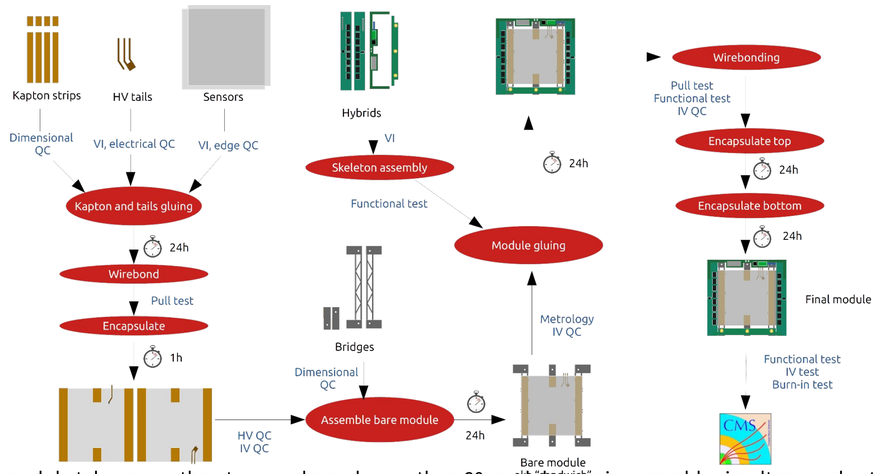
- 11 modules assembly centres across India, Pakistan, the USA, Italy, Germany, Belgium are involved in the production of ~7,600 2S modules and ~5600 PS modules, with an additional ~10% planned as spares.

  →**Belgium** has committed to one of the largest contributions to the 2S module production (**~1500**).
- Assembly centres are approaching their maximum production capacity, with almost half of the 2S modules already produced and tested.

References:
[1] Editors: I. Béjar Alonso, O. Brüning, P. Fessia, M. Lamont, L. Rossi, L. Tavian, M. Zerlauth,"High-LuminosityLargeHadronCollider(HL–LHC):Technicaldesignreportˮ,CERN Yellow Reports: Monographs,Vol.10 (2020).
[2] The CMS Collaboration, "The Phase-2 Upgrade of the CMS Tracker", CMS-TDR-014
[3] The CMS Collaboration, "The Phase-2 Upgrade of the CMS Level-1 Trigger", CMS-TDR-021

2S Modules Production Line

The module assembly process involves **assembly steps**, and also **multiple testing and quality-control** procedures.



Completing one module takes more than two weeks and more than 60 modules are in assembly simultaneously at the Belgian site, with each module costing around CHF 4,000.

bPOL12V: Power Board Failure after TID Irradiation

Details will be discussed at TWEPP26 in the dedicated session: cern.ch/twepp26-bpol

Function: Provides the required voltage conversion and power regulation for the module electronics.

Used in: In the Tracker: 2S module Service Hybrids and PS module Power Hybrids. Chip to be used in multiple CERN experiments.

Problem: After module production had already started and component production had reached full scale, bPOL12V failure after some TID irradiation was observed. This raised concerns that the SEH and POH may not withstand the HL-LHC radiation environment, potentially leading to data loss.

<u>**Impact on OT Module Production:**</u>

The bPOL12V issue has a **significant impact on the OT module production schedule and workflow**

<u>**Mitigation at assembly centers:**</u>

→ **2S production:** SEHs are detached from the modules and transferred to **temporary storage plates**. Once new SEHs equipped with the qualified replacement converter become available, they will be re-attached to the modules, followed by **final testing**.

Fully assembled 2S modules produced before the issue was identified can potentially be repaired by detaching the glued SEH using dental floss or a heat gun and replacing it with a qualified SEH.

→ **PS production:** Assembly is halted at the **bare-module stage**. Modules are transferred to temporary storage and will be completed and fully tested once new POHs become available.

→ **Production responsibilities may be redistributed:** 2S assembly centres may also contribute to **PS module completion**, requiring significant adaptations to their workflows.

→ **Temporary storage is a critical requirement:** modules cannot yet be transferred to the integration centres for installation on the structures, so **storage solutions must be established until the new bPOL12V becomes available.**

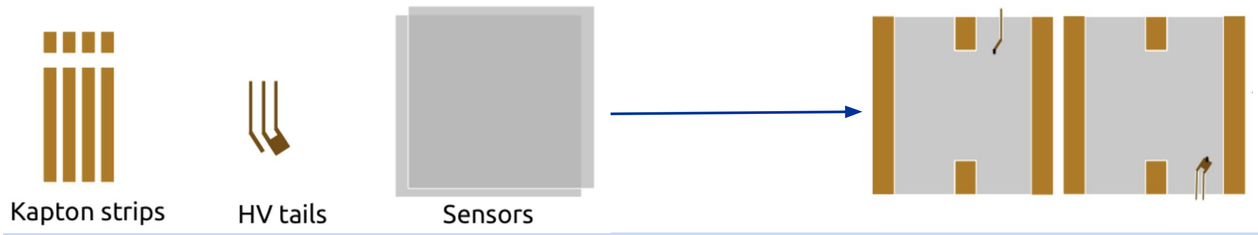
2S module storage on KIT and Brussels temporary storage plates at the Belgian assembly centre.

Tracker statement: *"The Tracker will use bPOL_FX for all on-detector PS modules. The default choice for all on-detector 2S modules is also bPOL_FX, however the Tracker has the ability to defer a final decision while continuing to benefit from partial module building until hybrid vendors are production-ready. The backup choice for 2S modules in case significant delays with bPOL_FX is to use bPOL_v6 in a configuration that minimizes time in the stress zone, which will help mitigate the original HCI issue."*

Kapton Isolators & HV Tails Gluing Fixtures for 2S assembly centers

Purpose:

Isolate the sensor backside from the Al-CF spacers and attach the HV tails to the sensor backside.



<u>**Requirements:**</u>

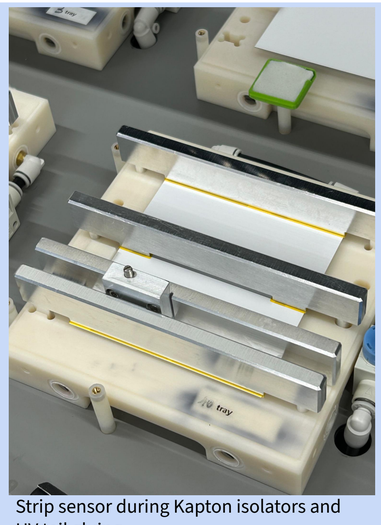
→ **ESD-safe, non-scratching material** with sufficient mechanical durability to maintain fixture precision
→ **Kapton positioning accuracy:** within **±200 µm** of the nominal position
→ **Precise HV tail positioning** to ensure alignment with the SEH connectors

<u>**Solution:**</u>

→ **ESD-safe polymer base plate** with aluminium pick-up tools
→ **Alignment station** for precise positioning of Kapton isolators
→ **Dedicated pick-up tools with cut-outs** for accurate HV tail placement

<u>**Development & deployment:**</u>

→ Design finalisation, production and distribution **led by the Belgian assembly centre**
→ Designed in collaboration **with KIT**
→ Machined in collaboration **with UCLouvain**
→ **Deployed at multiple 2S assembly centres**



Strip sensor during Kapton isolators and HV tail gluing.

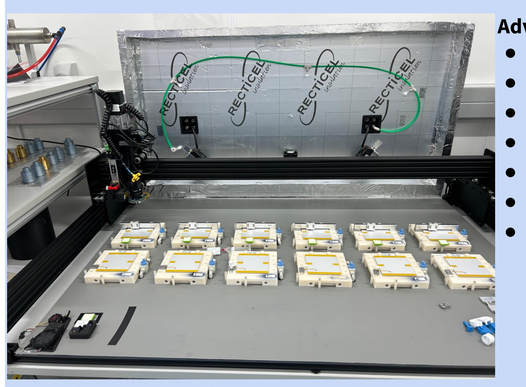
Kapton Isolators & HV Tails Gluing and Encapsulation gluing robots:

Belgian assembly center

Custom CNC robots were developed to automate and standardize:

- Kapton Isolators & HV Tails Gluing
- Encapsulation of wirebonds

Built with open-source and in-house solutions, giving full control for continuous improvement, rapid repairs and bug fixing.



Kapton isolators & HV tails gluing in Brussels

Advanced Capabilities:

- Production-scale dimensions
- Precise positioning of objects on the working area using a laser sensor
- Laser measurement of the distance to the glue-application surface
- Optical sensors for cross-calibration of the laser sensor and dispensing needle tip
- Compensation for the tilt of the glue-application surface
- Glue curing setup enabling complete curing by the next working day
- **Camera-based pattern recognition for in-process Kapton alignment**