GEFÖRDERT VOM
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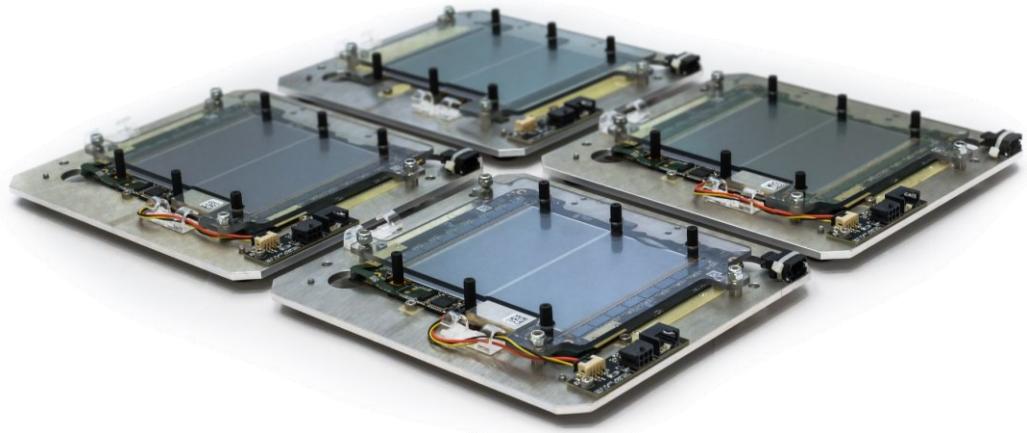


Design and construction of the CMS Outer Tracker for the HL-LHC Upgrade

13th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors, Vancouver, Canada

Nicolas Roewert on behalf of the CMS Tracker Group
I. Physikalisches Institut B, RWTH Aachen University, Germany

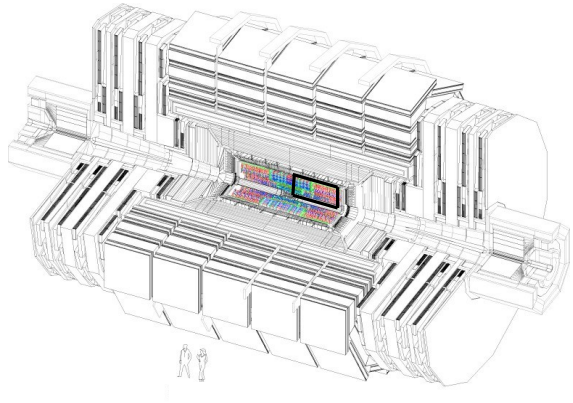
December 4, 2023

The CMS Phase-2 Outer Tracker Upgrade

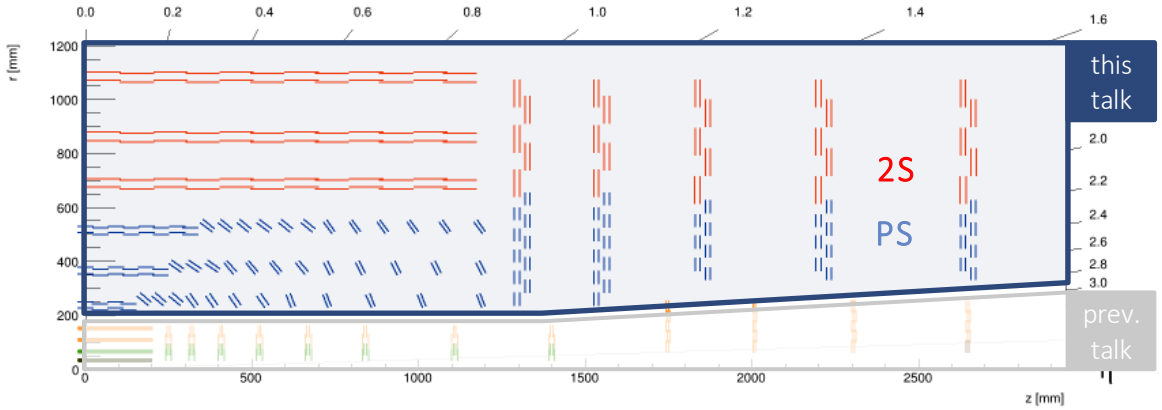
- Upgrade of LHC to **High Luminosity LHC** to achieve inst. luminosity of $5 - 7.5 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$
- Integrated luminosity and radiation dose increases from 300 $\mathrm{fb^{-1}}$ to 3000 $\mathrm{fb^{-1}}$

- Entire **replacement of CMS Outer Tracker** in the course of the Phase-2 Upgrade
  - Increased granularity for up to 200 simultaneous collisions
  - Enhanced radiation hardness
  - Reduced material in tracking volume
- Contribution of tracker data to **Level-1 trigger at 40 MHz**

- Development of **new modules for Outer Tracker:**
  - **2S** modules with **2 s**trip sensors
  - **PS** modules with one macro-**p**ixel and one **s**trip sensor
  - 192m² of active silicon and 214m channels
  - Hits in at least six layers for tracks in $|\eta| < 2.4$



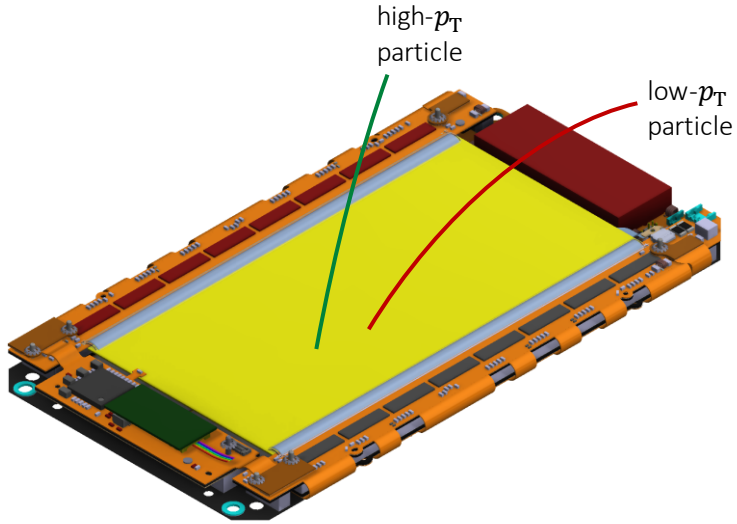
Compact Muon Solenoid



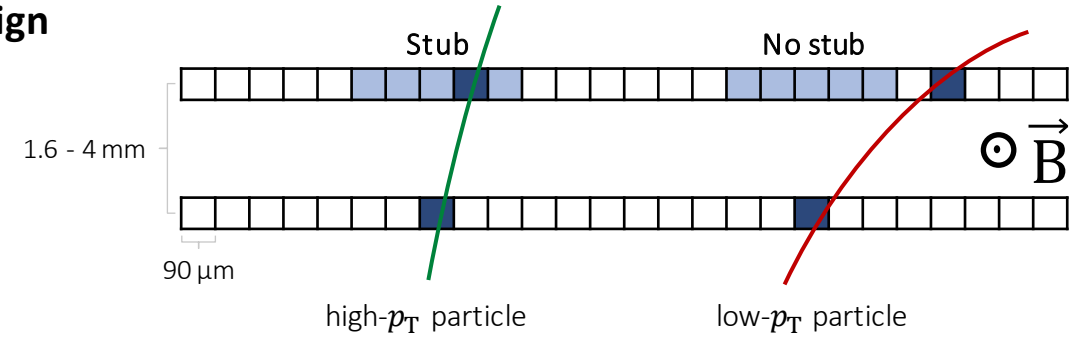
Quarter of the new CMS Tracker

Stub mechanism for identifying high-p_T particles on module level

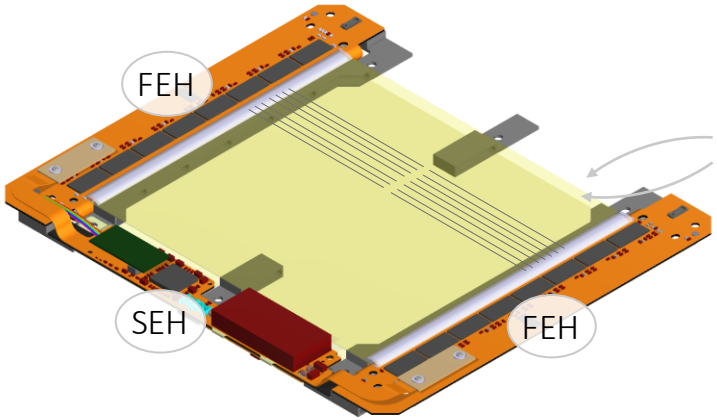
- Module based filter mechanism to **reduce data for trigger**
  - Charged particles have **curved trajectory** in the 3.8 T magnetic field of CMS
  - Comparison of hit position in strips both sensors on each module
  - Generation of 'stub' signal if trajectory complies with $\boldsymbol{p_T \geq 2}$ **GeV**
  - Five stubs per module per BX expected for pileup of 200
- Stubs sent from module to back-end **at 40 MHz**
- Level-1 trigger accept signals for full readout returned at < 750 kHz



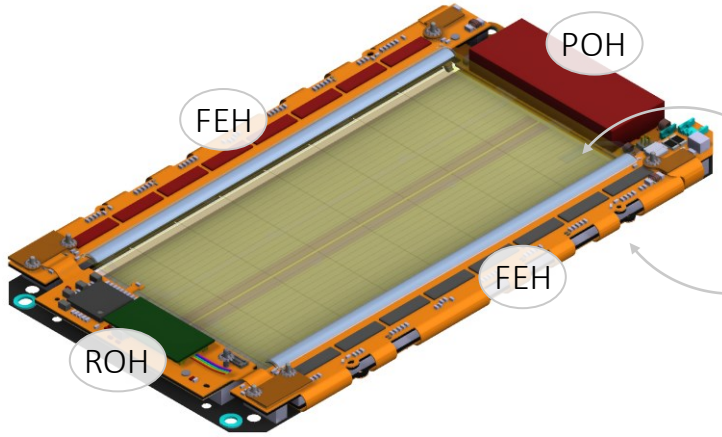
- Integration of tracker data into trigger is **main driver of module design**
- Strict **precision requirements** for assembly of stacked sensors



2S and PS module for the CMS Outer Tracker



2S sensor
n-in-p doping
320µm thickness
90µm x 5cm strips
V_{bias} = 600V (800V)



PS strip sensor
Same material as 2S
100µm x 2.4cm strips

PS pixel sensor
Same material as 2S
100µm x 1.5mm pixels

2S modules for outer layers of Outer Tracker

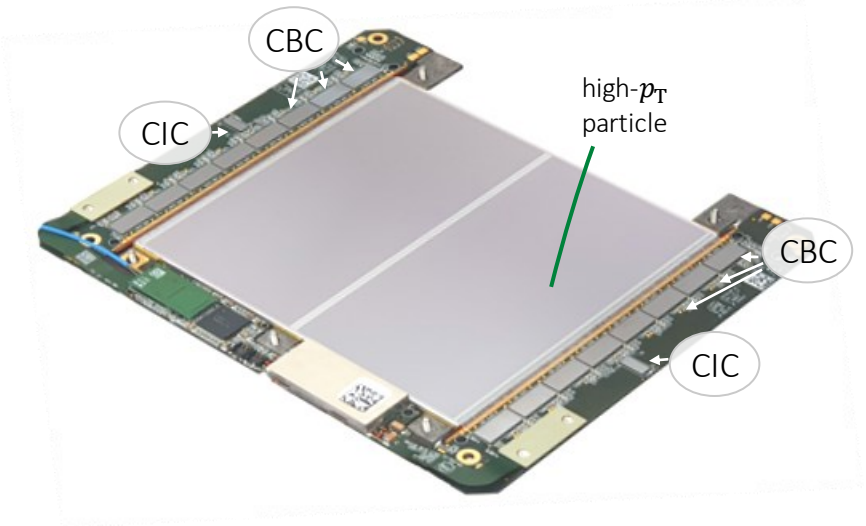
- Two 10x10cm² stacked **strip sensors** with 2032 strips each
- **Front-End Hybrids** (FEH) for signal readout
- **Service Hybrid** (SEH) for power supply, data-serialization and optical communication with tracker back-end
- Two module flavors with 1.8mm and 4mm sensor spacing

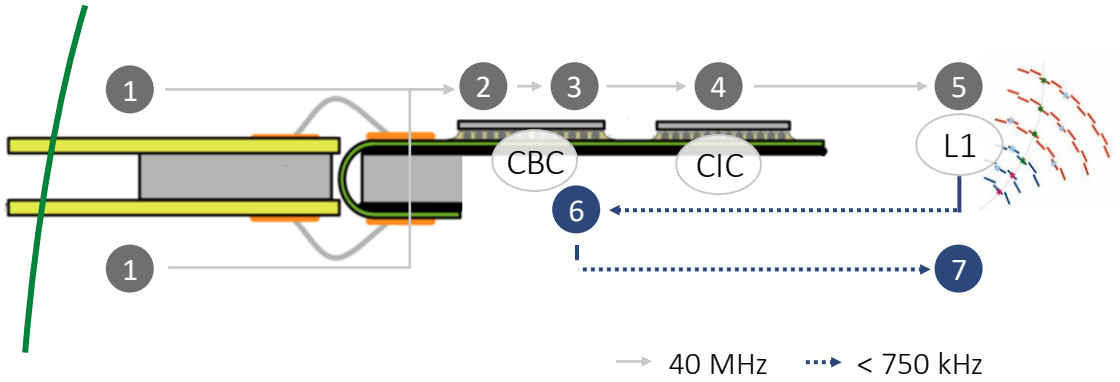
PS modules for inner layers of Outer Tracker

- One 5x10cm² **strip sensor** with 1920 strips on top of one **macro-pixel sensor** with 30720 pixels bump-bonded to ASICs
- Hybrid architecture comparable to 2S module with two FEHs, one **Power-** and one **Readout Hybrid** (POH, ROH)
- Three flavors with 1.6mm, 2.6mm and 4mm sensor spacing

Each module is **a fully functional unit** with individual power connection and communication

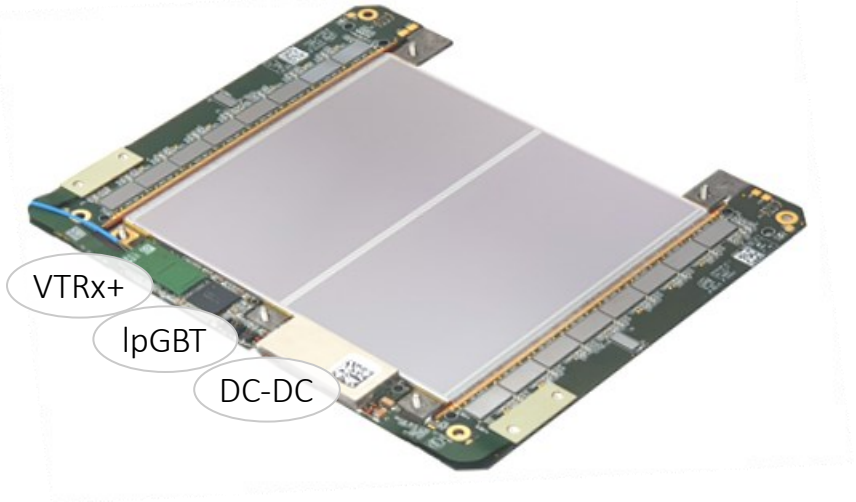
Hit readout and data transmission of the 2S module

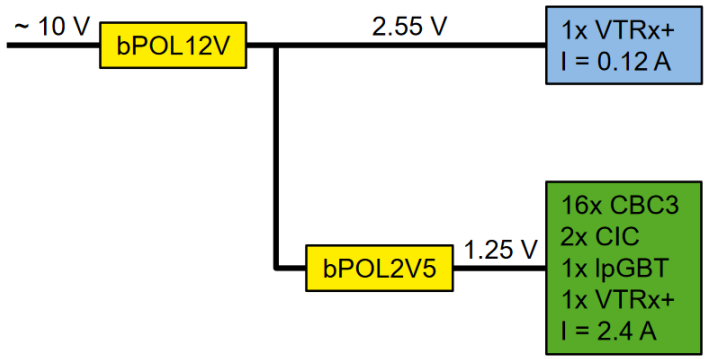




1. Particle passes through sensors and generates signals
2. By **shaping and comparing** the signal with threshold the CMS binary chip (**CBC**, 130nm) registers hits
3. CBC **correlates hits** in sensors and generates **stub data**
4. **Bundling** of stubs by Concentrator IC (**CIC,** 65nm) and transmission to Level-1 trigger via SEH
5. Analysis of event by **Level-1 trigger**
6. Request for full event data sent back to module
7. Transmission of all hits from CBCs via CIC to **back-end** for processing in **High Level Trigger**

Communication, powering and cooling of the 2S module





Two-stage DC-DC conversion scheme

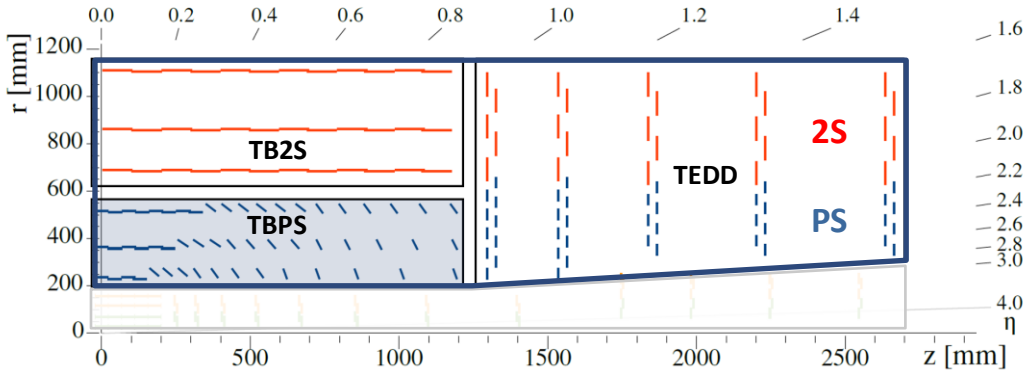
- Optical communication via Versatile Transceiver plus (**VTRx+**)
- Data serialization with Low-power Gigabit Transceiver (**lpGBT**)

- Upgraded Outer Tracker requires **3x more front-end power** of 85kW at a lower supply voltage
- Parallel powering of all modules via **DC-DC conversion** scheme
  - Use of radiation hard bPOL12V and bPOL2V5 chips
  - Module input voltage of about 10V and input power of 5W
  - First conversion stage to 2.55V for laser diode
  - Second conversion stage to 1.25V for other components

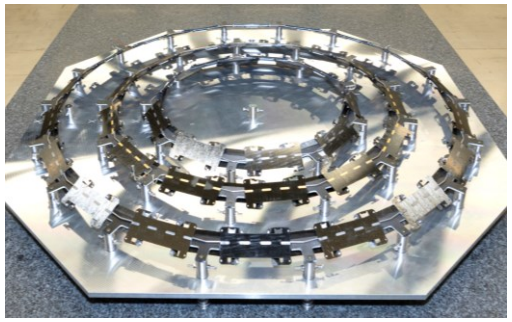
- Powerful **two-phase CO2 cooling** system to dissipate heat load
  - Coolant temperature of T= -33°C
  - Stainless steel pipes with an outer diameter of 2.3 to 3mm

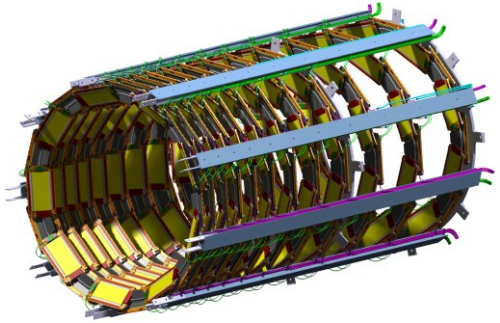
Integration of modules in the Outer Tracker

- New tracker is composed of **7680 2S** and **5616 PS modules**, which are assembled in three substructures:
  - Tracker Barrel with PS modules (**TBPS**)
    - Inner part of barrel with PS modules
    - Horizontally arranged PS modules in central part
    - **Tilted modules** in outer part for sufficient stub efficiency at large $|\eta|$ and less material
  - Tracker Barrel with 2S modules (**TB2S**)
    - Outer part of barrel with 2S modules mounted on ladders
  - Tracker Endcap Double-Disc (**TEDD**):
    - PS and 2S modules mounted on discs
    - Two discs forming one double disc, a hermetic detector plane
    - Each TEDD consisting of five double discs



Quarter of the new CMS Outer Tracker





TBPS prototype rings and a model of the inner tilted section

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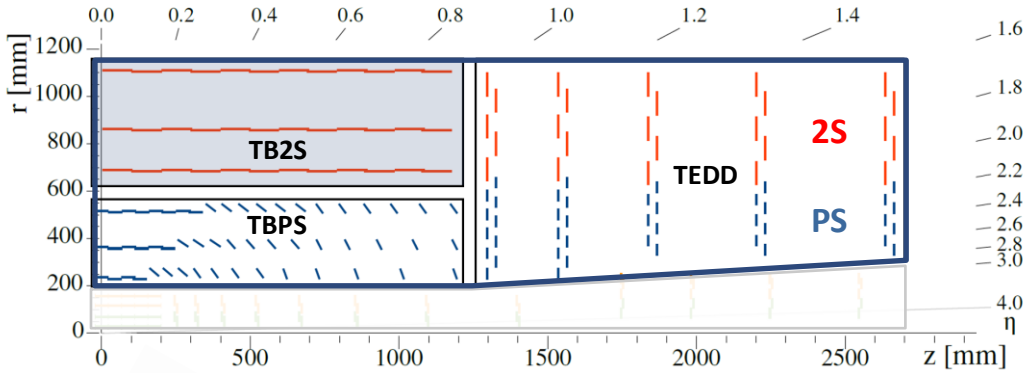

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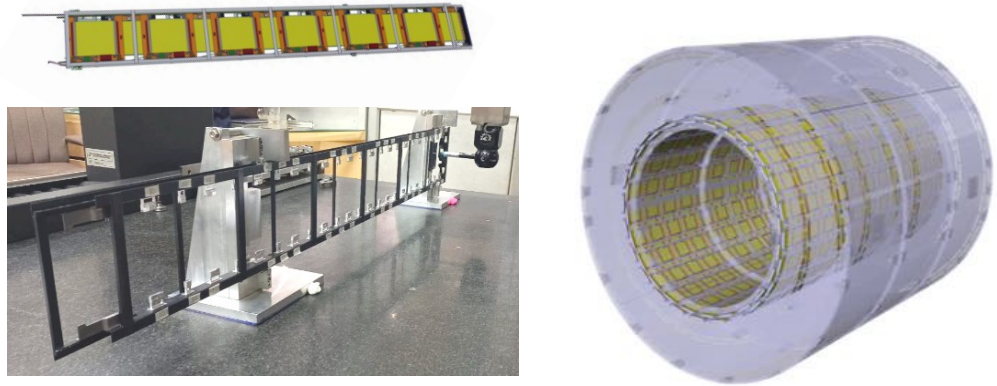

TB2S prototype ladder for 12 modules and a model of the innermost layer

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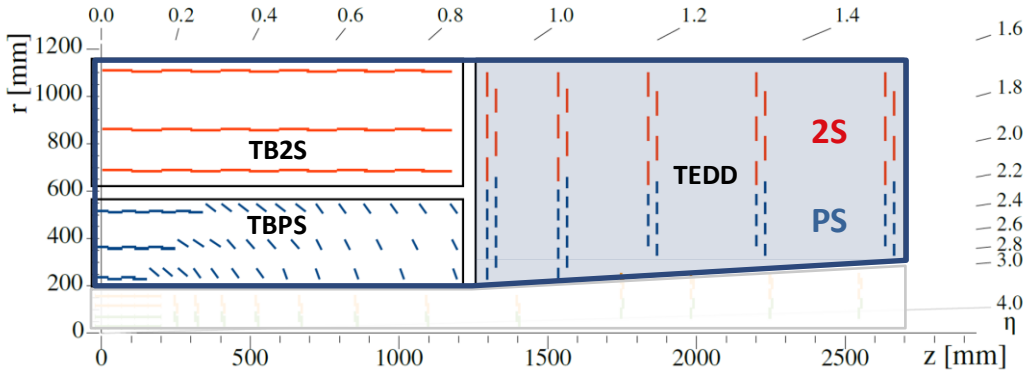

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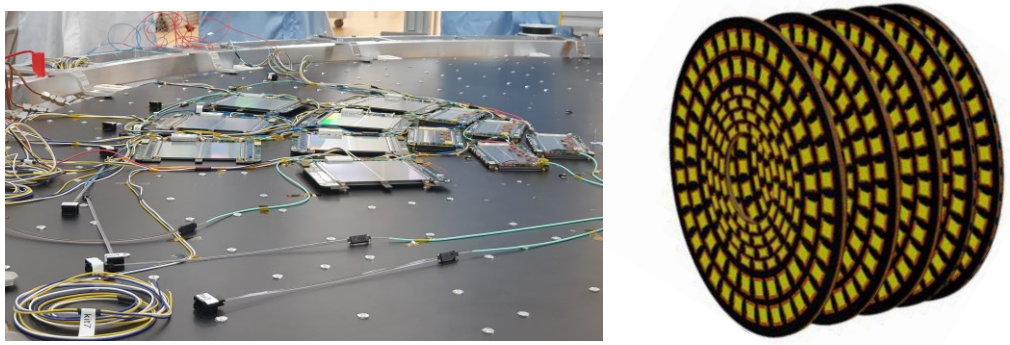
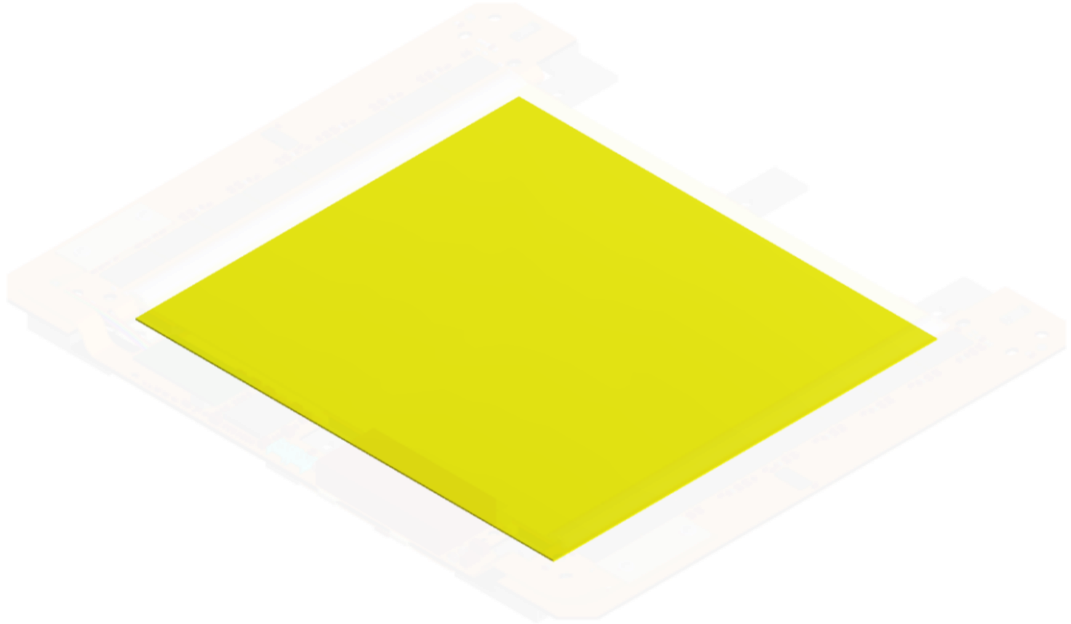


Prototype dee with modules and a model of five double discs of one TEDD

Schematic assembly of a 2S module

- Manual assembly of 2S modules at **seven assembly centers** in Germany, Belgium, US, Pakistan and India
- **Series production** of modules starting **in 2024** with a target throughput of four modules per day and site
- Special jigs and procedures for a **precise and reliable assembly**



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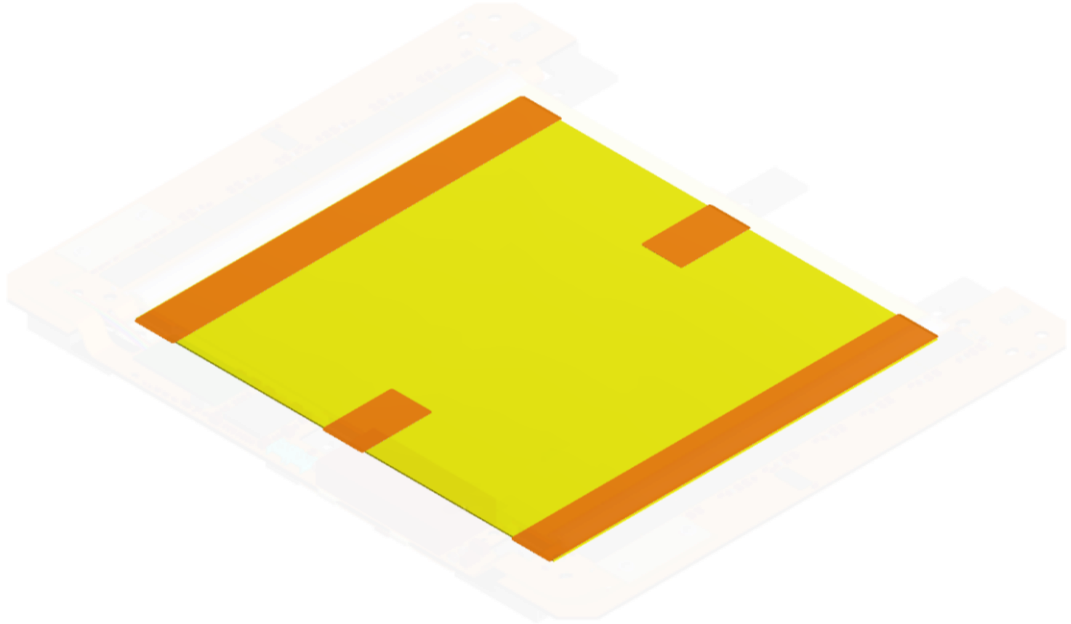

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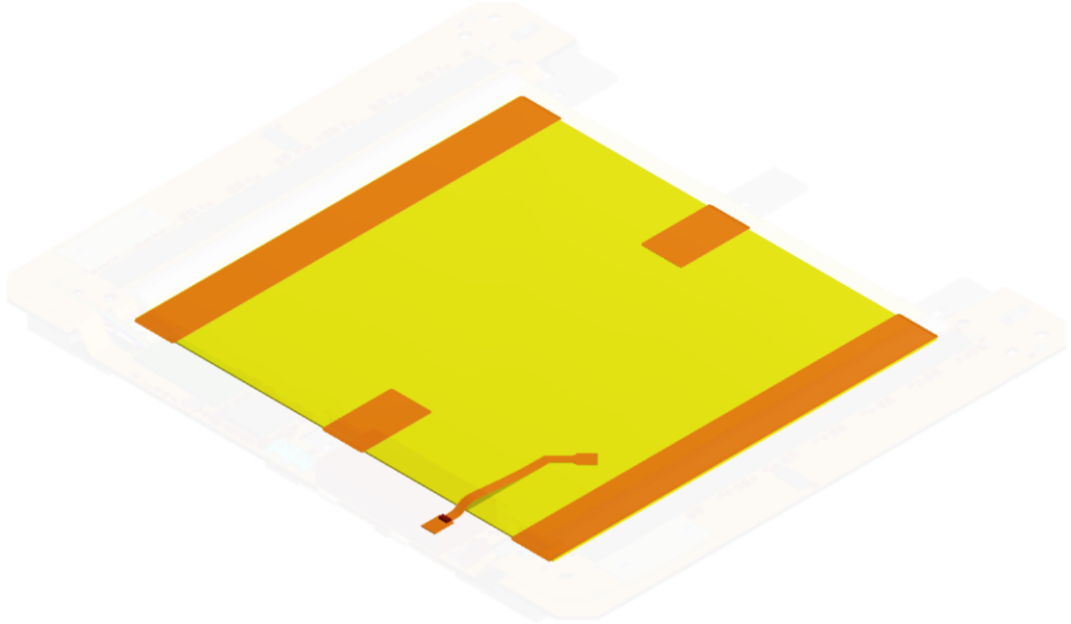

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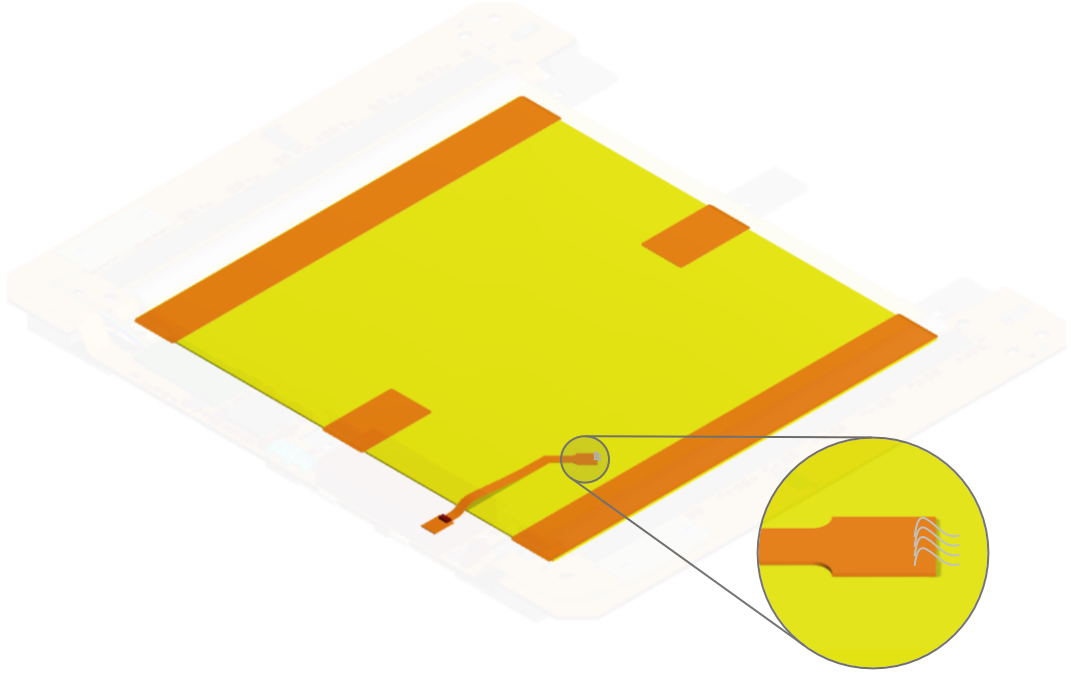

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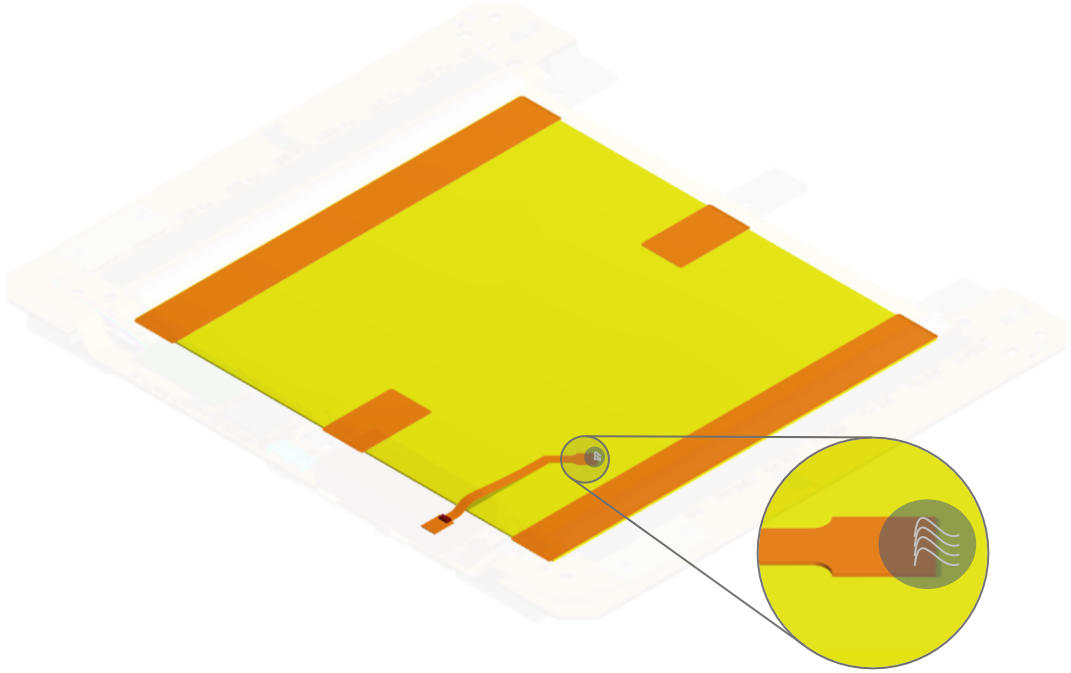

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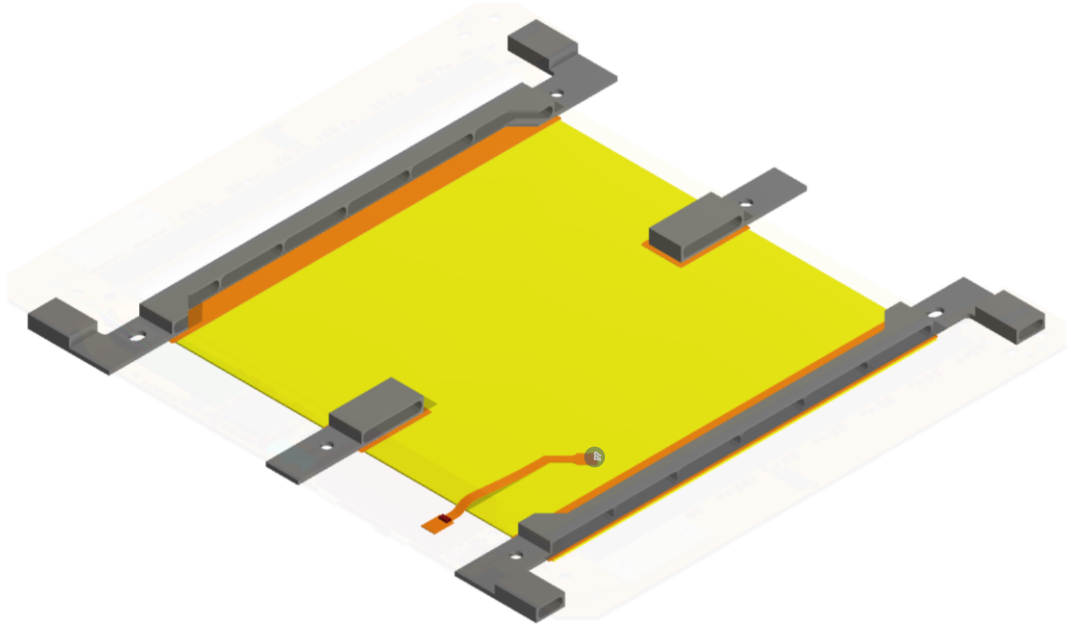

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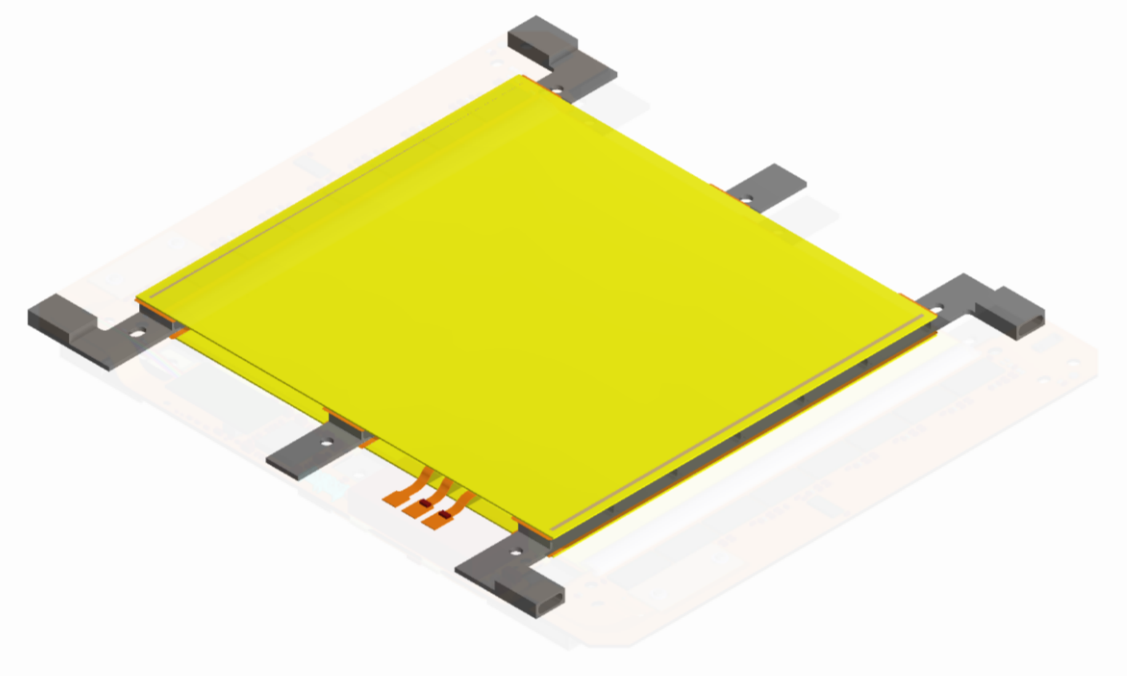

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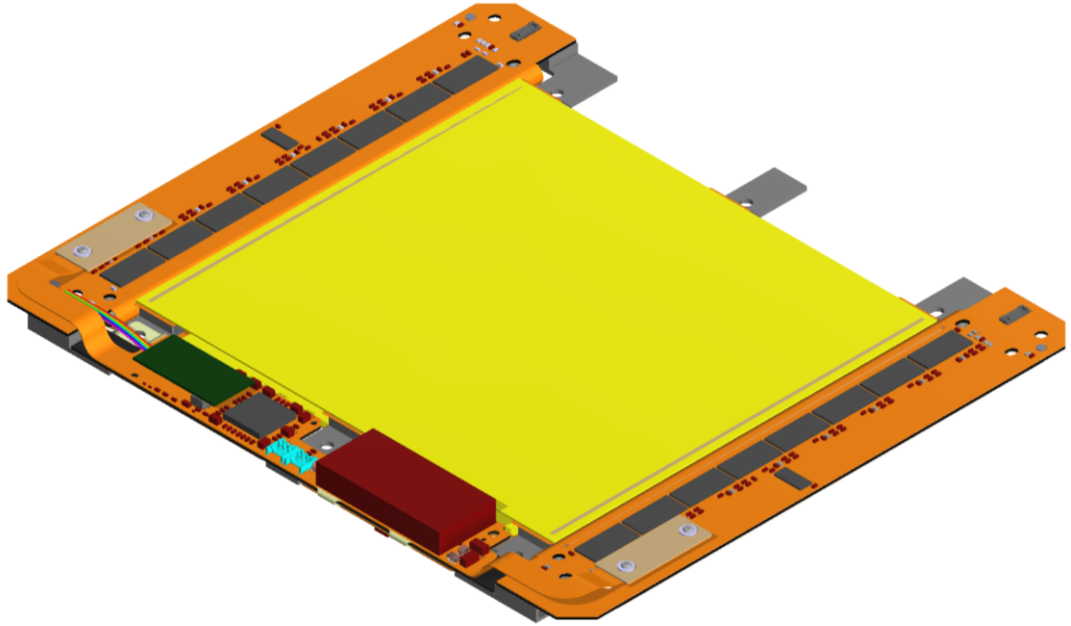

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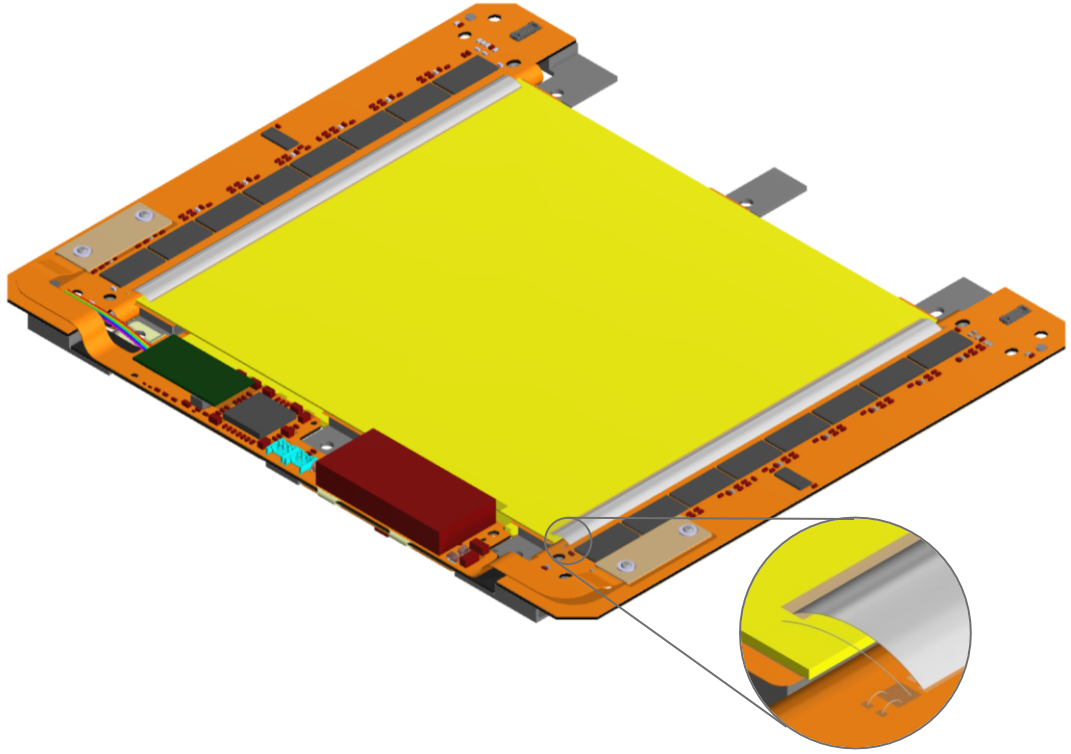

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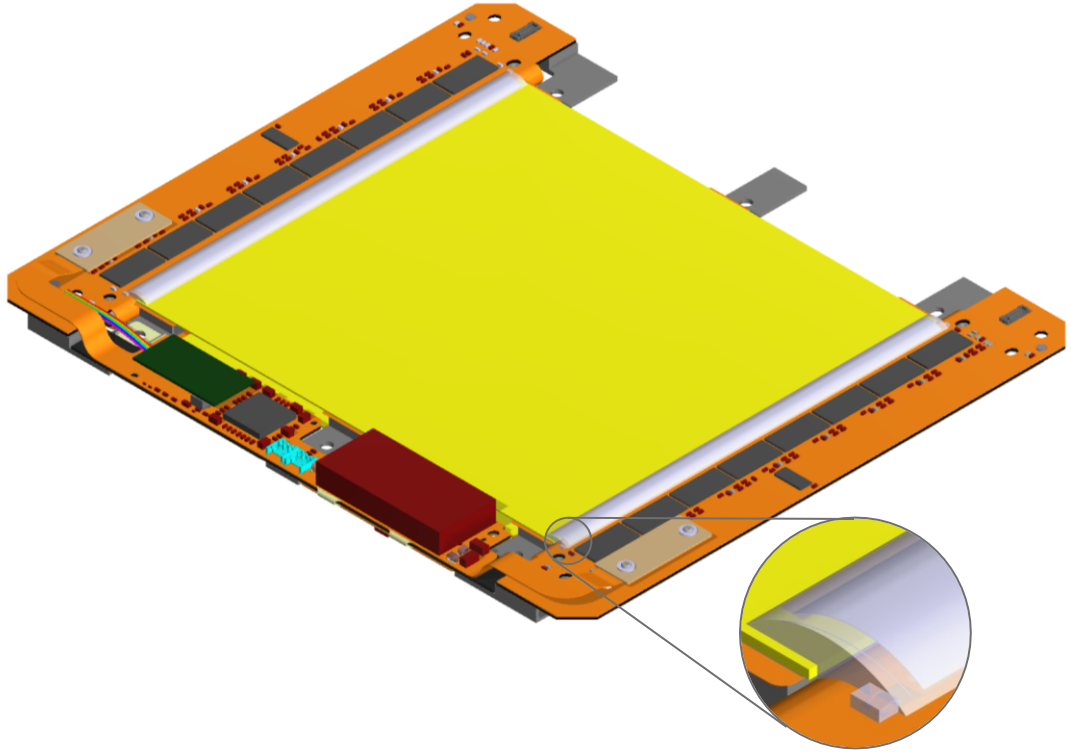

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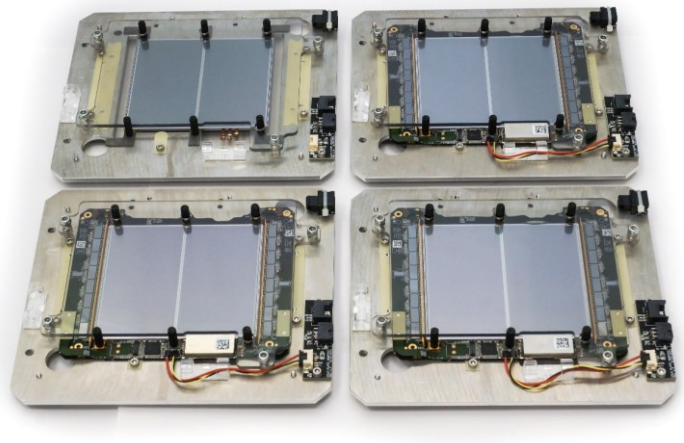
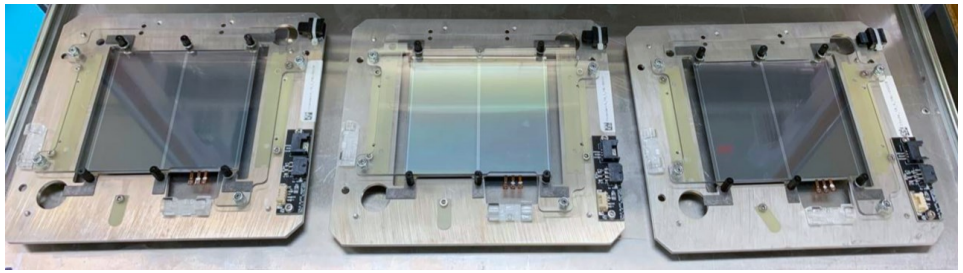
Currently: **validation of final module design** and assembly process with **'kick-off' pre-series modules**

The growing 2S kick-off module family

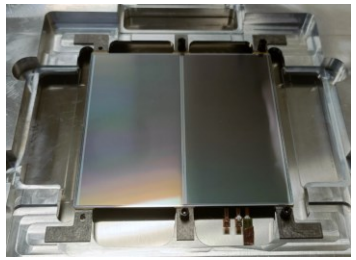


Aachen

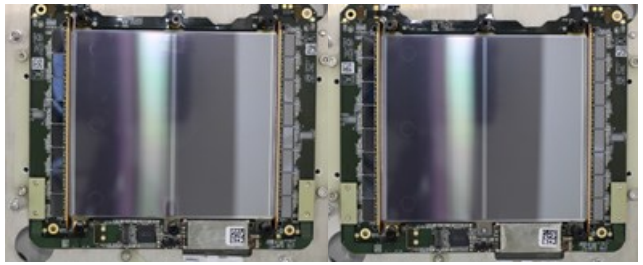
US East



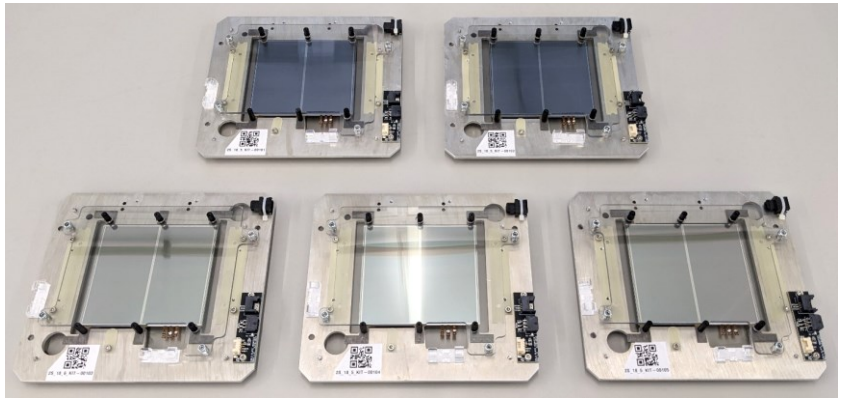
Fermilab



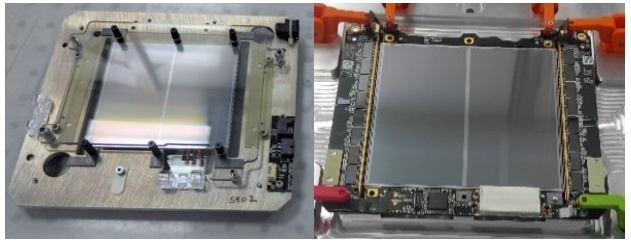
Perugia



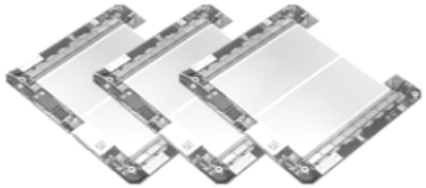
Belgium



Karlsruhe



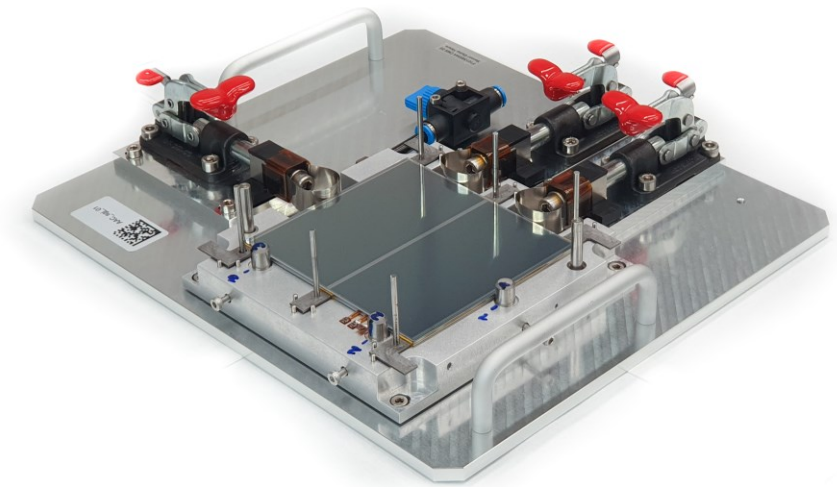
Islamabad



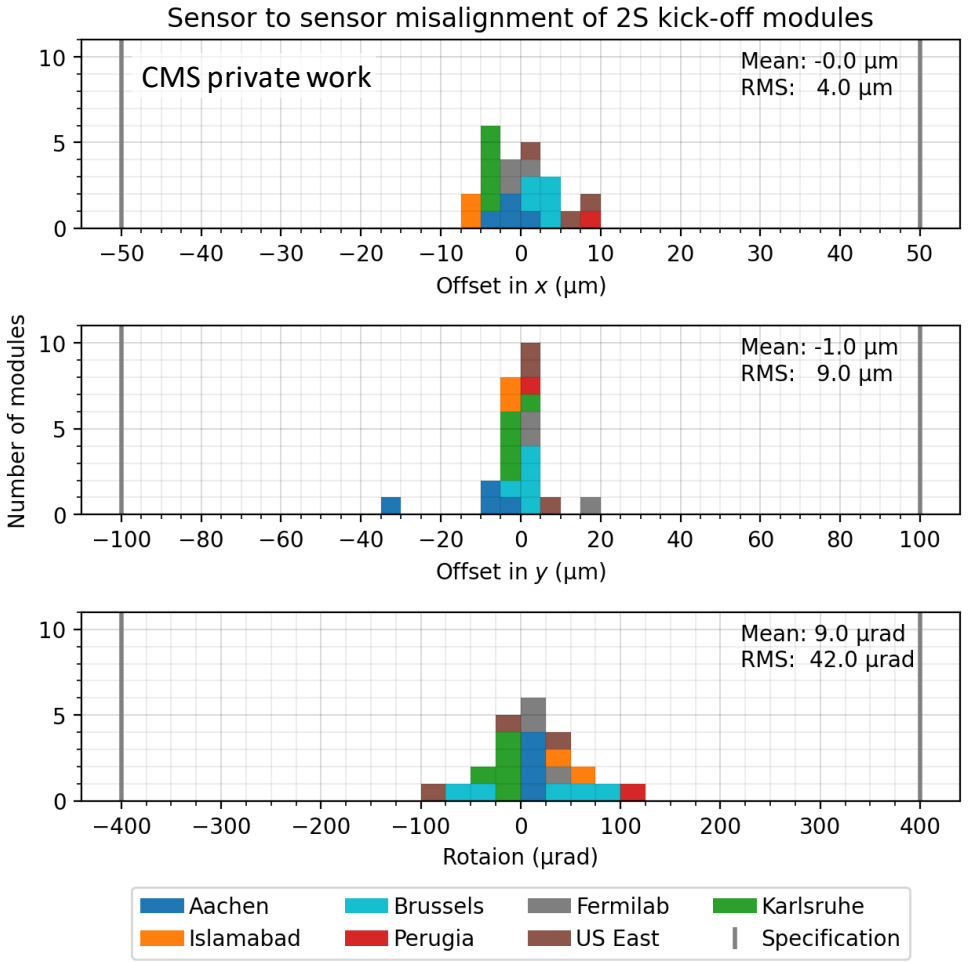
…and more modules in the assembly pipeline

Alignment of the sensor pair on 2S modules

- **Precise alignment of sensor** pair is required for working stub logic
  - Rotational misalignment: < 400 µrad
  - Offset parallel to strips: < 100 µm
  - Offset perpendicular to strips: < 50 µm
- Production of **special jigs** featuring precision bolts and spring pushers
- All kick-off modules assembled with jigs well **within specifications**



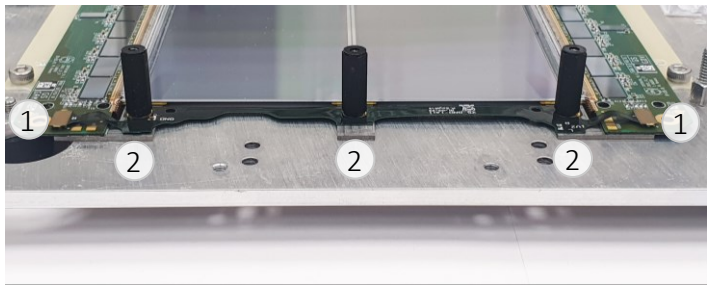
Kick-off module with assembled sensors in a jig produced by Fermilab



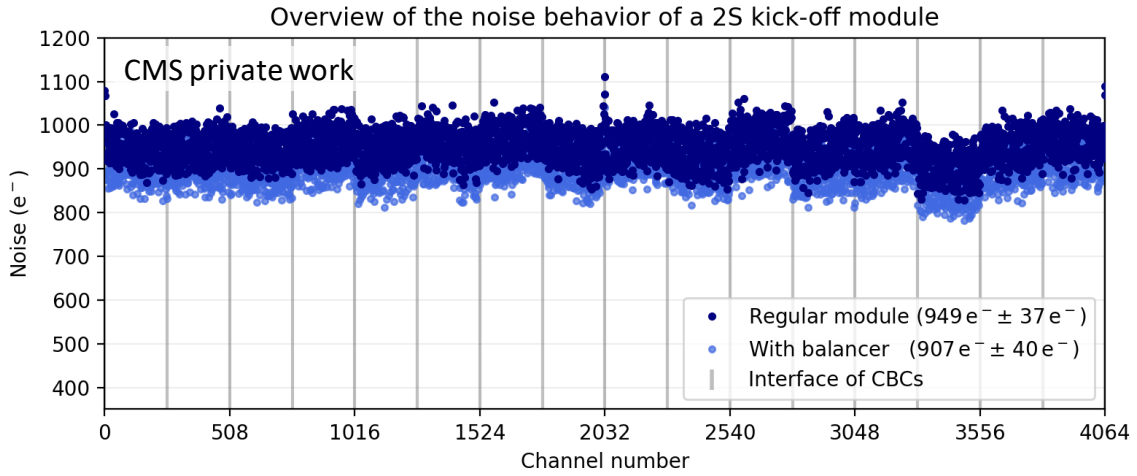
Noise performance of a 2S kick-off module

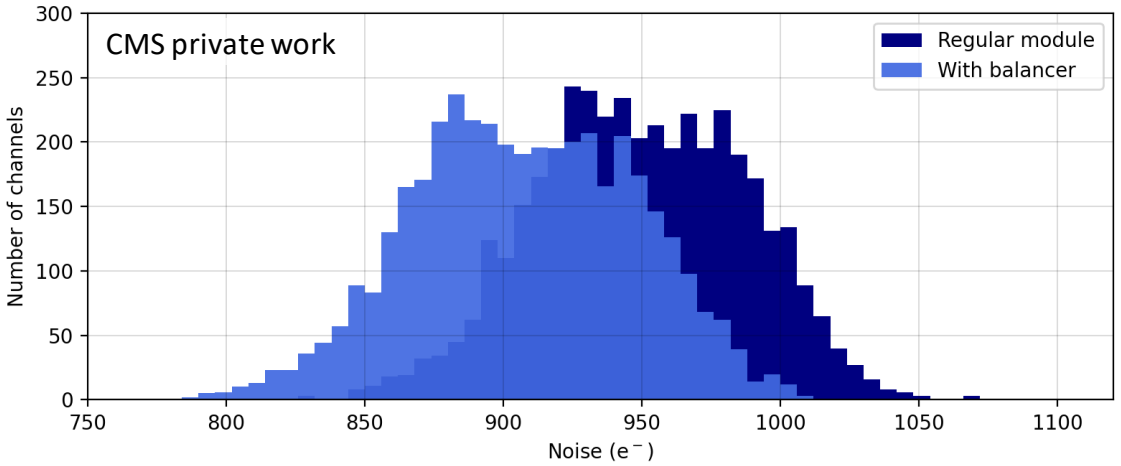
- Noise scans with binary readout by threshold sweeping
- **Noise evenly distributed** across channels of kick-off modules
- Overall level well compatible with **expected level of 1000e^-**

- Further reduction of noise using **'ground balancer' PCB**
  - Equalization of FEH ground potentials on non-SEH side of module (1)
  - Additional grounding contacts to spacers (2)
  - Implementation currently under discussion



2S kick-off module with an assembled ground balancer PCB

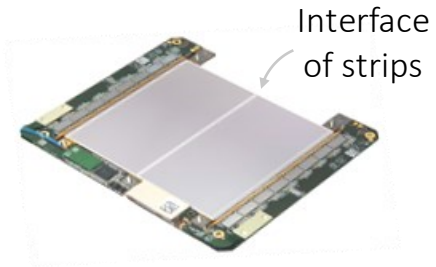


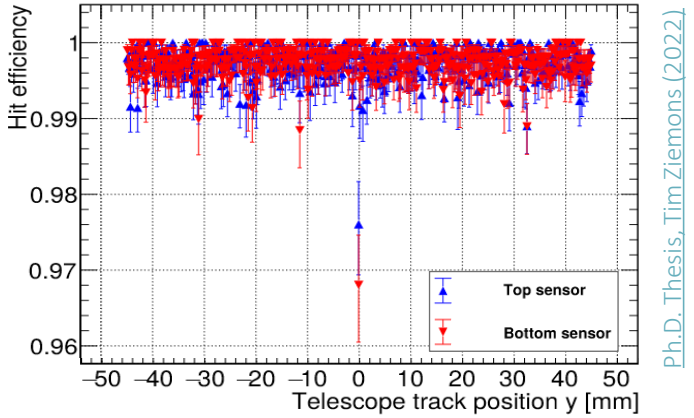


Tests and performance of module prototypes

- Prototype modules have been extensively tested at beam test facilities

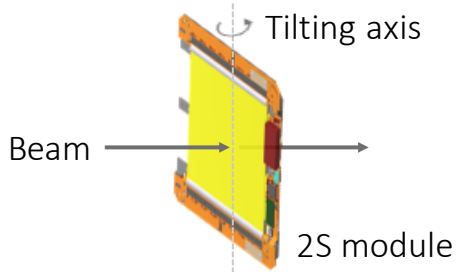
- **Measurement of hit efficiency**
  - Results well above 99% within the uncertainties
  - Drop in hit efficiency at middle of module
  - Expected behavior due to **arrangement of strips**

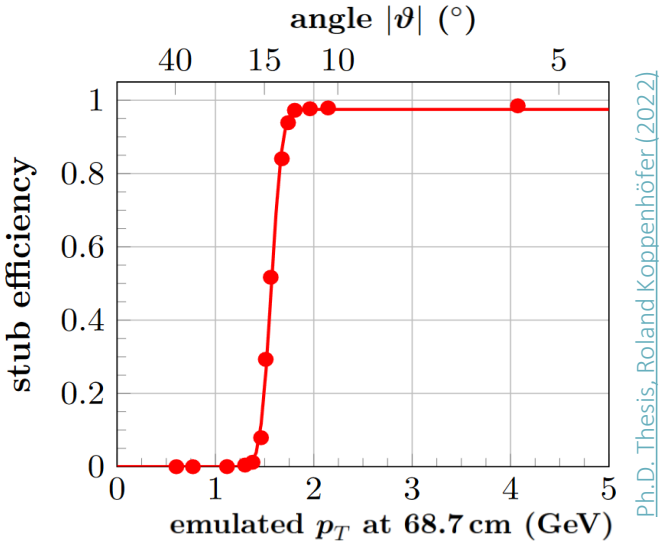




Ph.D. Thesis, Tim Ziemons (2022)

- **Measurement of stub efficiency**
  - Tested by rotating module relative to beam axis
  - Angle emulating curved trajectory of low-p_{T} particles
  - Stub window of ± 4.5 strips corresponding to momentum cut-off at $p_{\mathrm{T}} \sim 1.5$ GeV (R=68.7cm)
  - Turn-on curve showing expected behavior

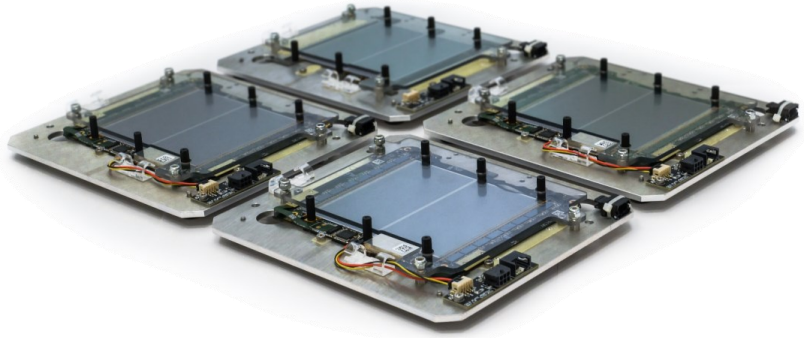




Ph.D. Thesis, Roland Koppenhöfer (2022)

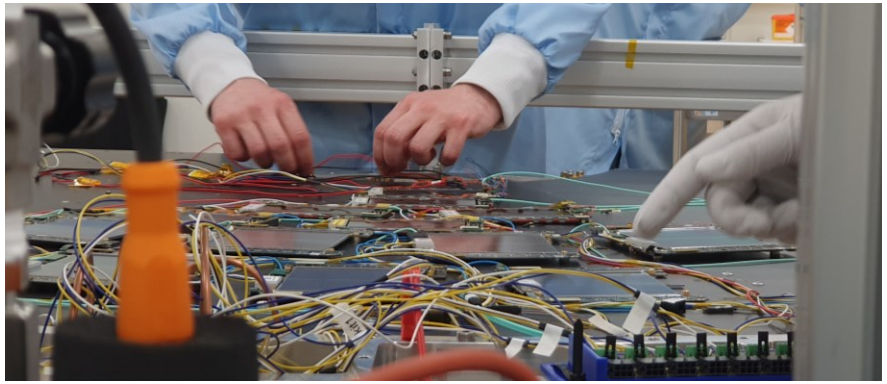
Summary and outlook

- Development of **2S and PS modules** for the Phase-2 Tracker Upgrade of CMS
  - Each module is a functional unit
  - Binary readout of hits in sensors
  - Power supply via DC-DC conversion
- **Stub mechanism** contributing tracker data to L1 trigger at 40 MHz
- Precise **assembly procedures** necessary to ensure functionality of module
- **Satisfying results** with prototypes from tests in the lab and at test beams



Four fully assembled 2S kick-off modules

- Outlook
  - Continue **extensive testing** of recent prototypes
  - Launch of **pre-series production of parts** at manufacturers
  - **Manufacturing of jigs** at institutes for coming module production



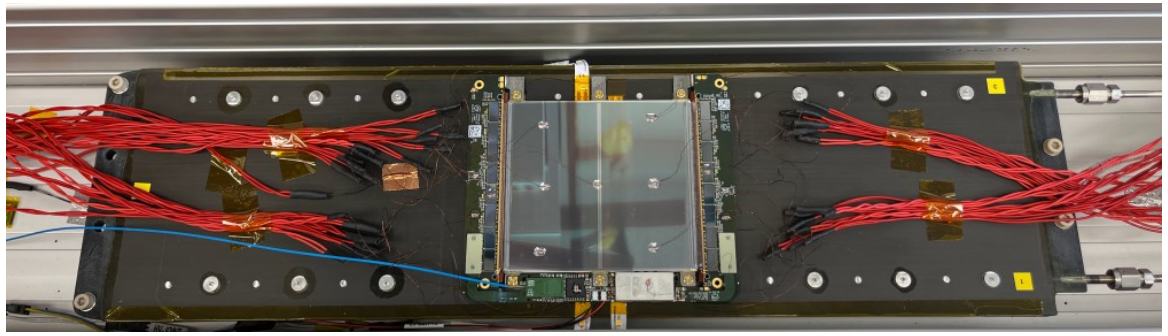
Assembly of 2S and PS modules on prototype dee structure

Backup

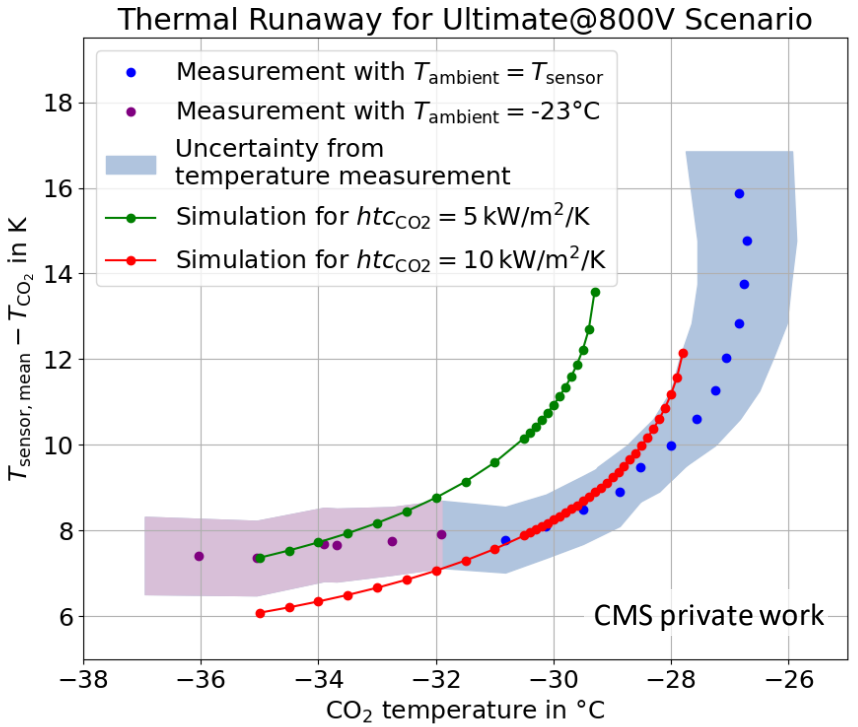
Thermal performance of a 2S module

- 2S module was equipped with temperature sensors and mounted on TEDD like structure cooled by two-phase CO2 system
- Illumination of sensors with LEDs to emulate leakage current after 3000 fb^{-1}
- Adjusting ambient temperature to sensor temperature to limit heat exchange with ambient

- Measurement of thermal runaway curve by varying CO2 temperature
- Thermal runaway recorded at -29°C well above CMS target T_{CO_2} of -33°C
- Results compatible with thermal simulation

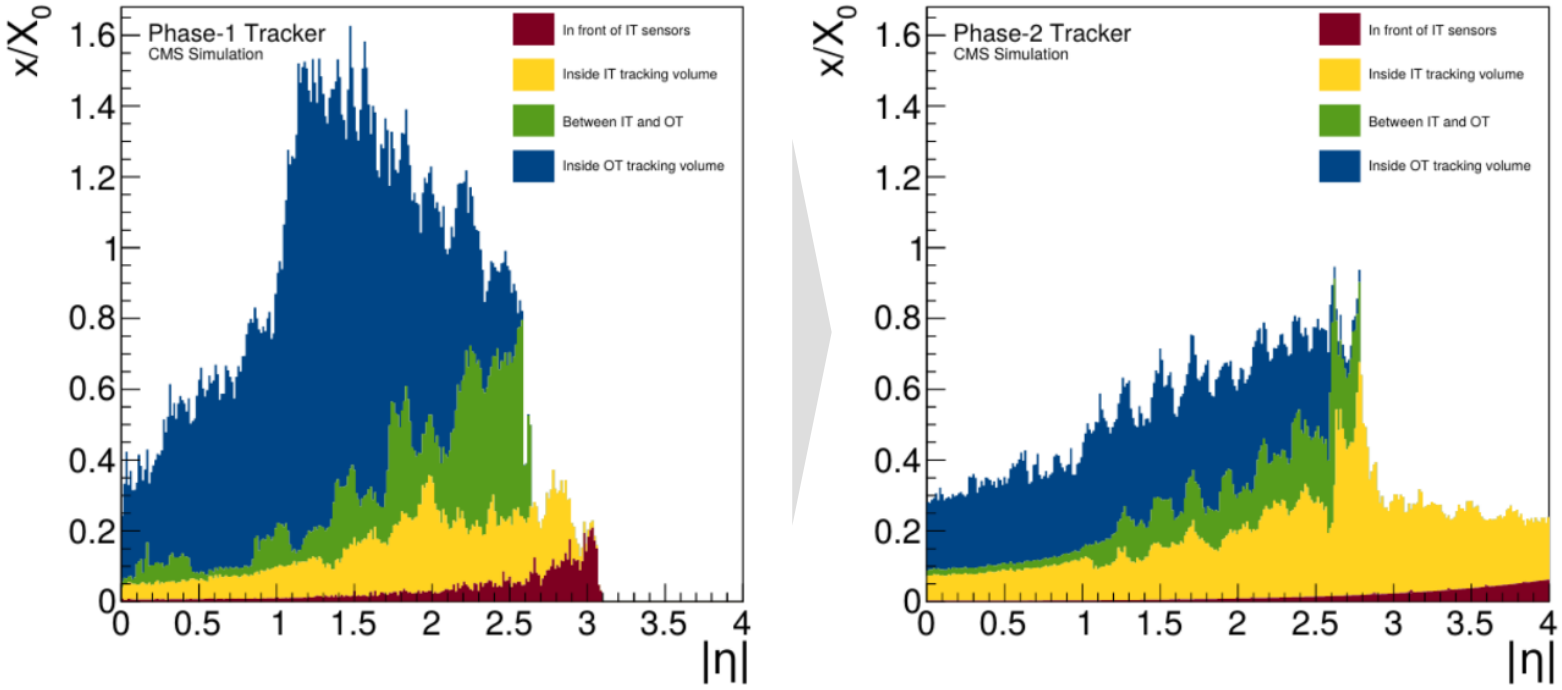


2S module mounted on TEDD like structure with temperature sensors



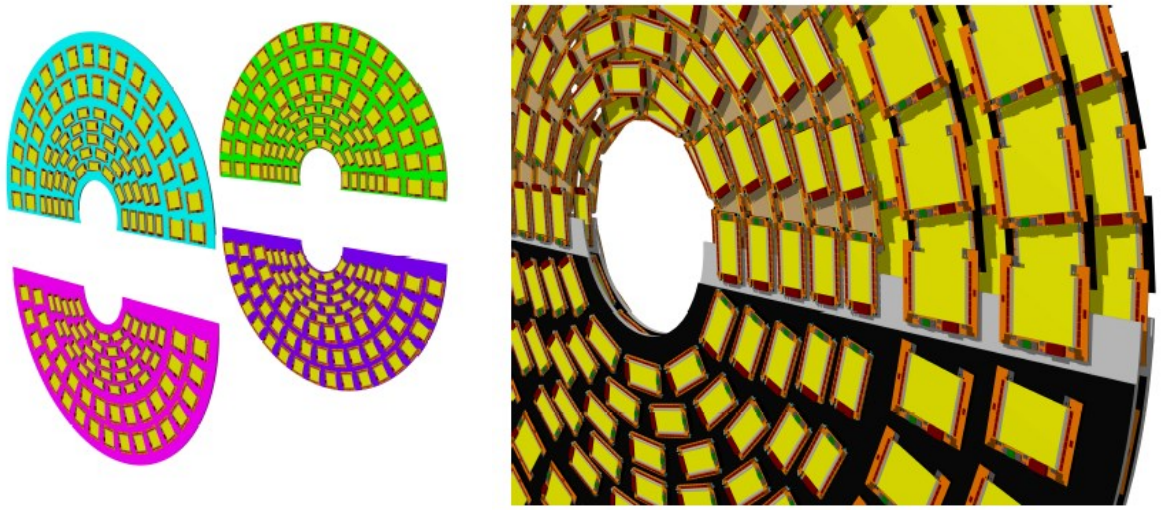
Material budget

- Material budget of Phase-2 Outer Tracker significantly lower compared to current Tracker
  - More lightweight support structures
  - More efficient routing of services
  - Implementation of CO2 cooling
  - DC-DC conversion based powering
  - Lighter module design

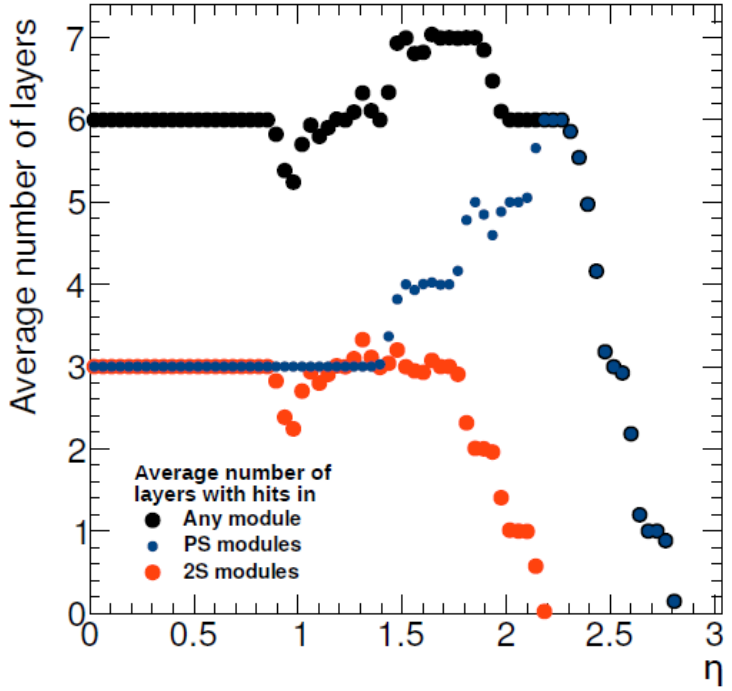


Hermetic detection

- New Outer Tracker geometry facilitates detection in six layers up $|\eta| = 2.4$



Assembly of four dee's into one double disc for a hermetic detection plane



Average number of layers with hits in 2S and PS modules