# Assembly and Testing of 2S Module Prototypes for the CMS Outer Tracker Phase-2 Upgrade

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## Abstract

The High Luminosity LHC (HL-LHC) requires the CMS detector to undergo a major Phase-2 upgrade, which involves the complete replacement of current tracker. The new tracker will be divided into two main parts: inner tracker and outer tracker. The Phase-2 outer tracker will employ two types of silicon modules, 2S and PS, based on a novel pT discrimination concept. These modules aim to reduce local data in the front-end electronics by utilizing the strong magnetic field of the CMS detector, effectively rejecting low transverse momentum (pT) particles. This presentation provides a comprehensive overview of the prototyping process for 2S modules, focusing on the precise assembly techniques and testing procedures employed during the development phase. These procedures play a crucial role in ensuring the performance, functionality, and quality of the 2S modules before their implementation in the outer tracker. In addition, several test beam performance studies have been conducted on 2S module prototypes, utilizing the electron beam with energies up to 6 GeV at DESY. A comparison between the EUTelescope and Corryvreckan offline data reconstruction frameworks will be presented for the performance study of the 2S module, using the test beam data.

## CMS Outer Tracker Phase-2 Upgrade

- CMS Phase-2 Tracker is divided into **Inner Tracker** & **Outer Tracker**
- **Outer Tracker**
  - Coverage ~ **$|\eta| = 2.4$**
  - Two types of pT modules
    - ✓ **2S (Strip-to-Strip)**
    - ✓ **PS (MacroPixel-to-Strip)**

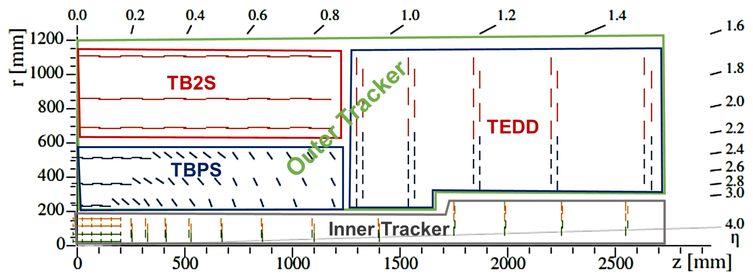



***Figure Reference:*** *"The Phase-2 Upgrade of the CMS Tracker Technical Report"*

### *pT Module Concept*

- Two silicon sensors forming **Seed and Correlation layers**, with the Seed layer oriented towards the interaction point.
- CMS magnetic field bends charged particles, hitting sensors at different position; **low pT** particles experience stronger bending
- Correlation window on **Correlation layer** enables matching hits from seed and correlation layers to create a **"Stub"**
- Contributing directly to L1 trigger

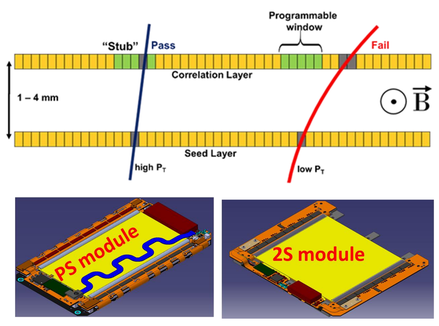
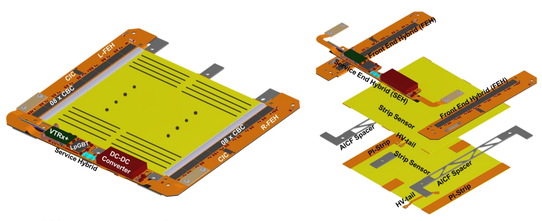



***Figure Reference:*** *"The Phase-2 Upgrade of the CMS Tracker Technical Report"*

→ Data volume reduction of ~10 **times** can be achieved with a threshold of **pT>2 GeV**

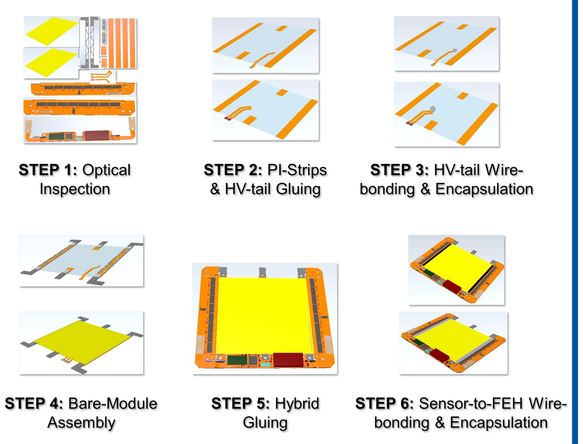
## 2S Module Assembly Procedure

### *2S Module Components*




- Silicon Strip Sensors
- Polyimide (PI) Strips
- HV-pigtails
- Aluminium Carbon Fibre (AL-CF) bridges
- Front-End Electronics (SEH, FEH)

### *Assembly Procedure*

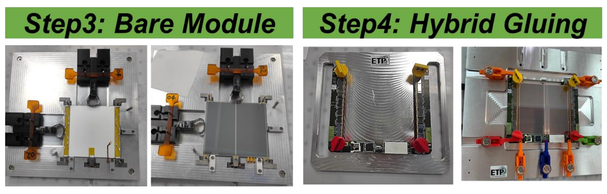


**STEP 1:** Optical Inspection
**STEP 2:** PI-Strips & HV-tail Gluing
**STEP 3:** HV-tail Wire-bonding & Encapsulation
**STEP 4:** Bare-Module Assembly
**STEP 5:** Hybrid Gluing
**STEP 6:** Sensor-to-FEH Wire-bonding & Encapsulation

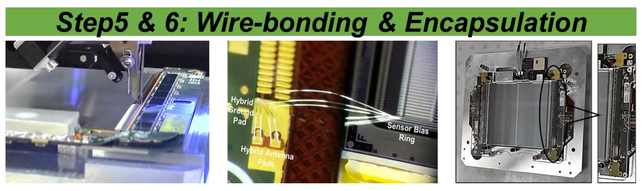
### *Customized Jigs for Assembly*

***Step2 : PI-Strips & HV-tail Gluing***

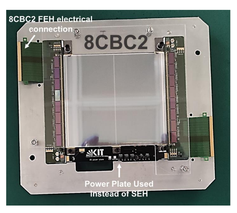

***Step3: Bare Module*** ***Step4: Hybrid Gluing***

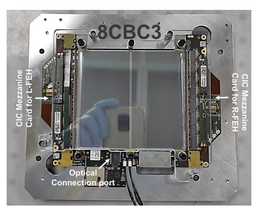


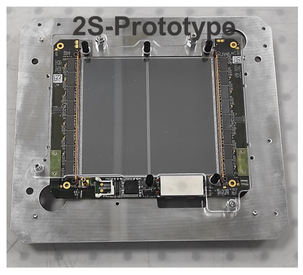
***Step5 & 6: Wire-bonding & Encapsulation***




### *2S Module Prototypes*

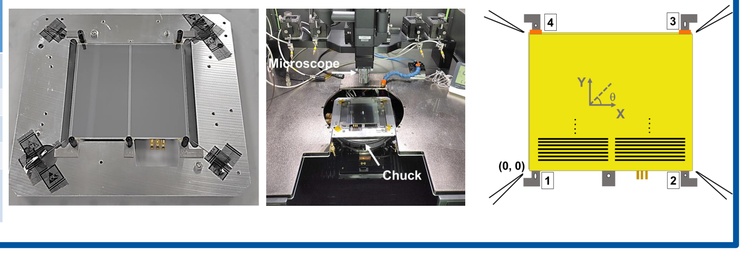



### *Bare Module Metrology (Needle Based Method)*

| Reading # | Δθ (μrad) tolerance < 400 μrad | Δx (μm) tolerance < 100 μm | Δy (μm) tolerance < 50 μm | Measurement Mark |
|---|---|---|---|---|
| 1 | -17 | -12 | -4 | Sensor Corner |
| 2 | -23 | -14 | -4 | |
| 3 | -24 | -13 | -4 | |
| 4 | -24 | -13 | -4 | |
| Avg. value | -22 | -13 | -4 | |

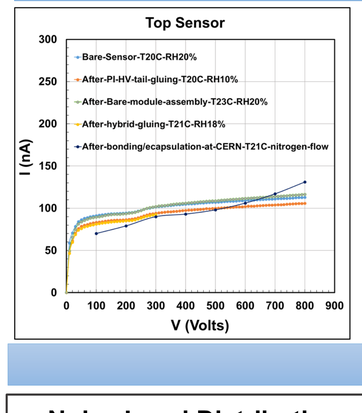


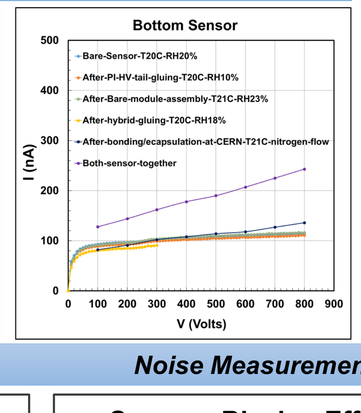




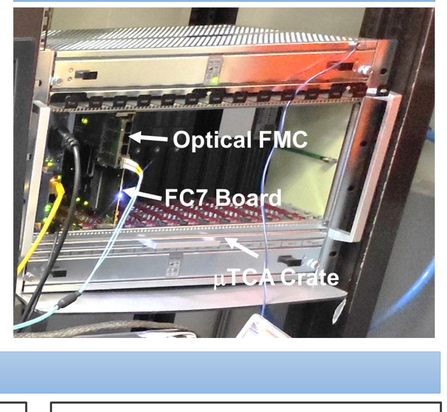
## Module Testing

### *IV Measurement During Assembly*

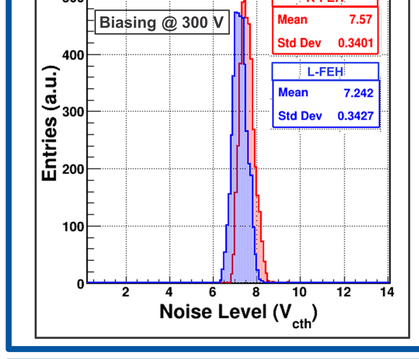


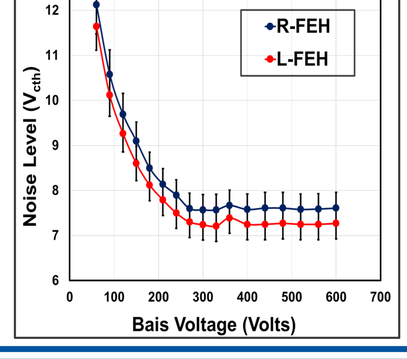



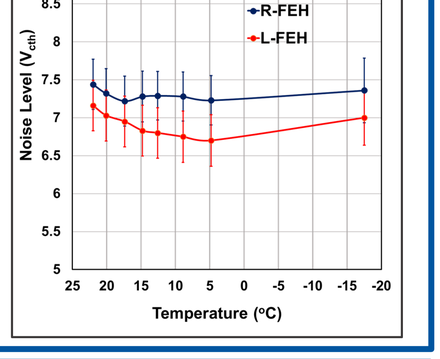

### *Noise Measurement Setup*




### *Noise Measurement*



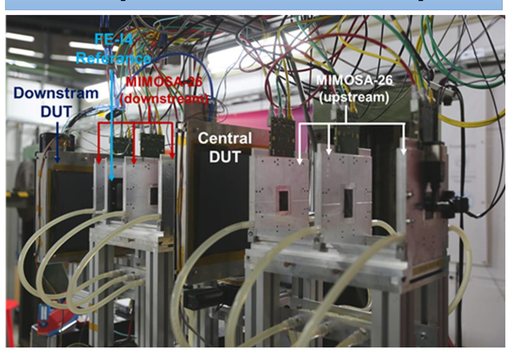

## Test Beam Data Reconstruction Framework Comparison

- Test Beam Setup at DESY: 1-6 GeV $e^-$ beam
- EUDET Data Acquisition
- Reconstruction framework Comaprison **EUTelescope & Corryvreckan**

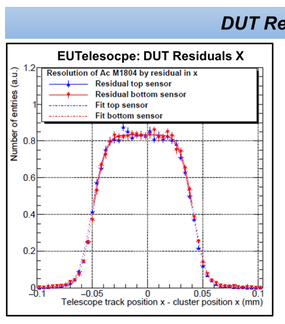
$$\epsilon_{hit-detection} = \frac{Number\ of\ DUT\ hits\ linked\ to\ telescope\ isolated\ tracks\ associated\ to\ refernce\ plane}{Number\ of\ isolated\ telescope\ tracks\ associated\ to\ refernce\ plane}$$

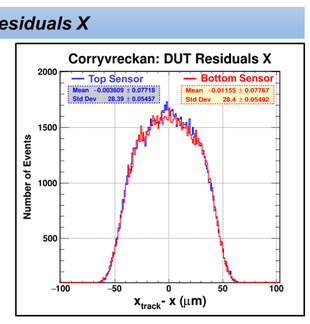
$$\epsilon_{stub} = \frac{Number\ of\ stubs\ linked\ to\ telescope\ isolated\ tracks\ associated\ to\ refernce\ plane}{Number\ of\ isolated\ telescope\ tracks\ associated\ to\ refernce\ plane}$$

### *Setup: DATURA Telescope*

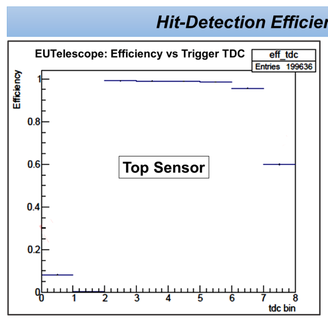


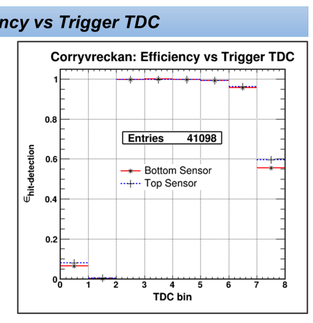

***DUT Residuals X***



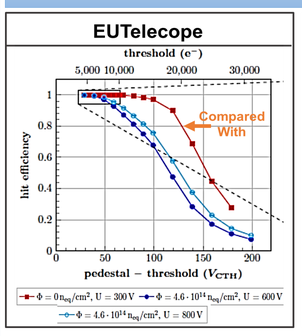



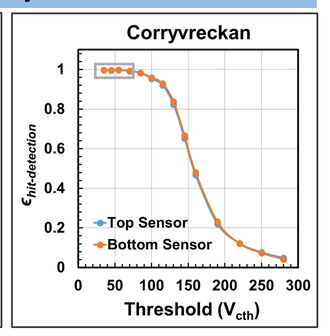

***Hit-Detection Efficiency vs Trigger TDC***



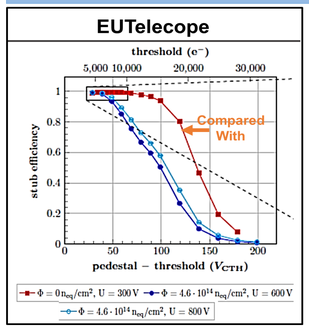



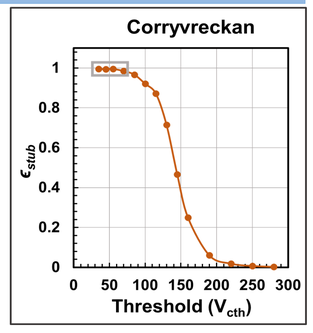

***Hit-Detection Efficiency vs Threshold Scan***




***Module Stub Efficiency vs Threshold Scan***




## Summary

The innovative pT module design will enhance the CMS Phase-2 Outer Tracker role by contributing directly to the L1 trigger. With precise assembly, the 2S module meets strict mechanical criteria, achieving angular displacement under 400 μrad between sensors, <50 μm translational displacement perpendicular, and <100 μm parallel to strips. Electrically, the module shows good IV behavior at each assembly step, alongside a noise level of ~7.5 $V_{cth}$ (equivalent to 1200 $e^-$), near the 1000 $e^-$ target. Notably, the user friendly Corryvreckan's hit detection and stub analysis closely align within 1% of the established EUTelescope framework, highlighting its promising future potential.