The Phase-2 Upgrade of the CMS Outer Tracker

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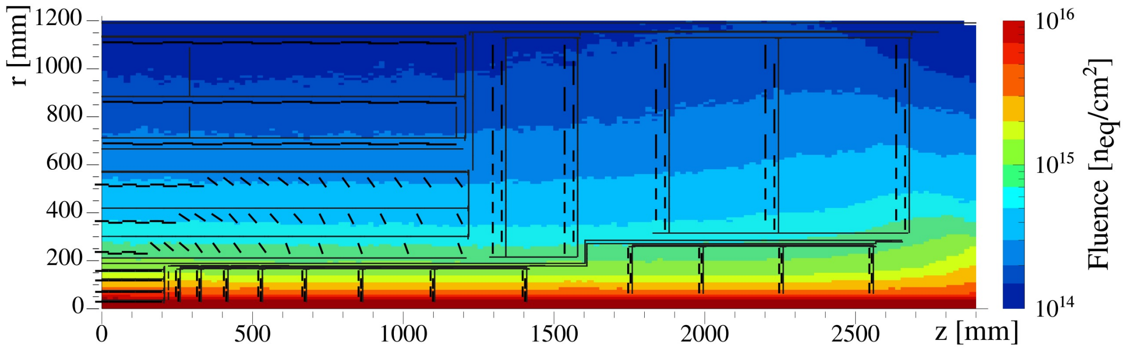
for the CMS Outer Tracker Upgrade Team

HL-LHC

- LHC upgrade to increase instantaneous luminosity
  - Currently the LHC runs at $1.5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$
    - Exceeds design luminosity by 50%
  - Upgrade (HL-LHC) to increase the luminosity by a factor of 5
- The HL-LHC offers large improvements and unique challenges
  - Large PU increase (~140-200 PU/event!)
  - Need a higher granularity due to the increased density
  - Unprecedented radiation levels
- Need to upgrade full CMS detector to be robust to these challenges

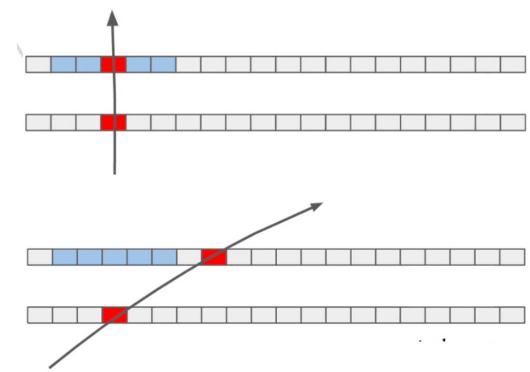
Design Constraints

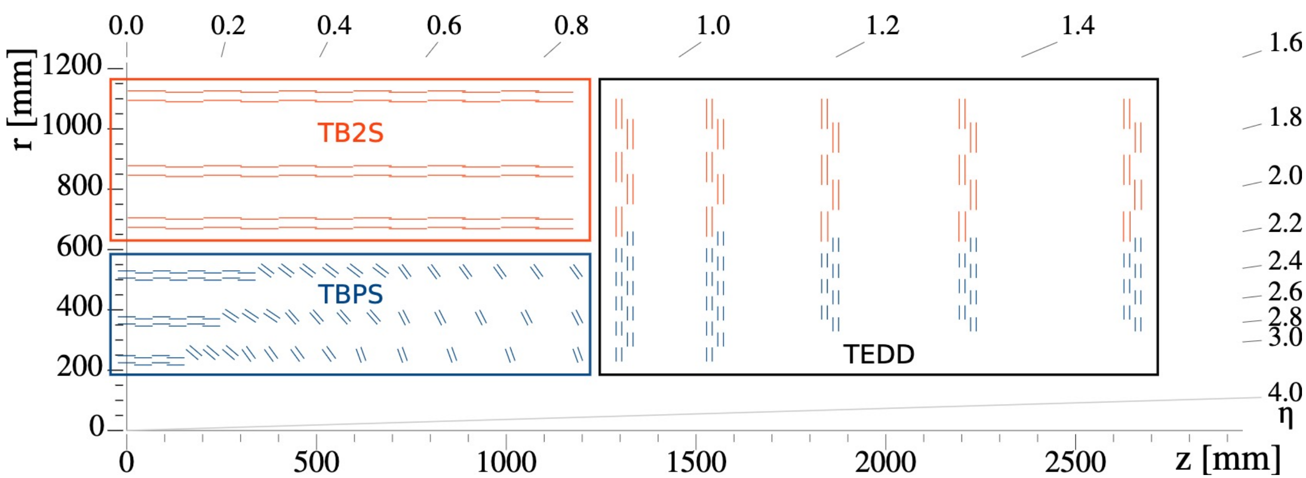
- The Phase-2 outer tracker is designed to satisfy stringent constraints
- Radiation
  - Expected Fluence of ~10^{15}neq/cm^2
  - Needs to be efficient up to the full 3000 fb^{-1}
- Power Consumption
  - Tight FE power requirements
    - 8W for the PS module
    - 5W for the 2S module
- Granularity
  - Occupancy to be kept at or below the percent level given the increased pileup



OT Upgrade Overview

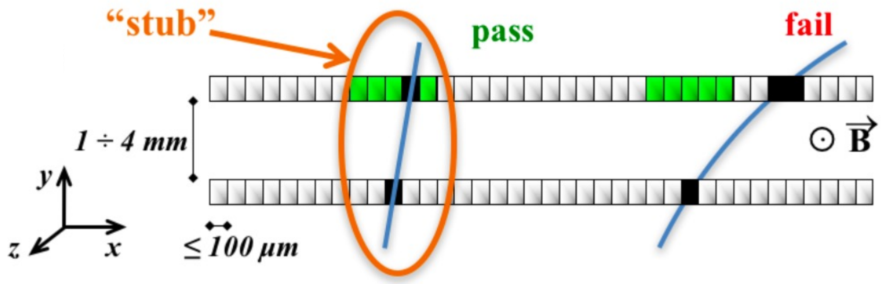
- Upgraded CMS outer tracker to be segmented into three regions and two module types
  - TBPS – PS module in the inner barrel
  - TB2S – 2S module in the outer barrel
  - TEDD – Endcap 2S and PS modules
- TBPS uses a tilted barrel design
- Modules are based on the “p_T module” concept
  - Two sensor planes can give a coarse (fast) track p_T measurement to be used for triggering

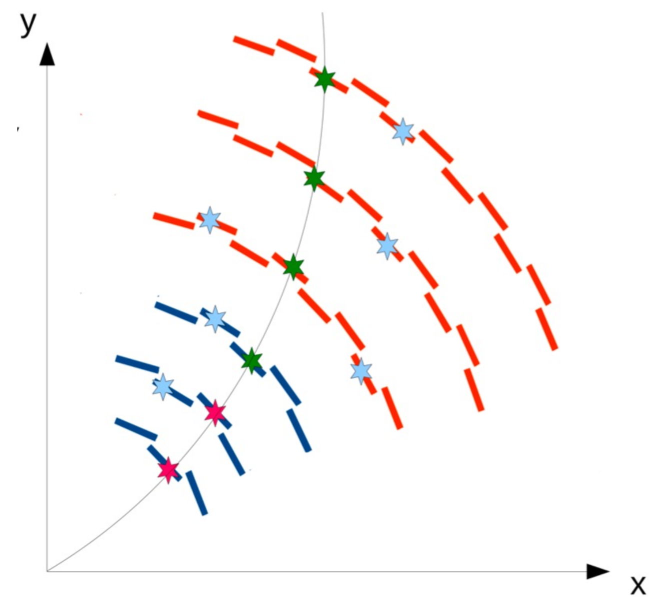




Stubs

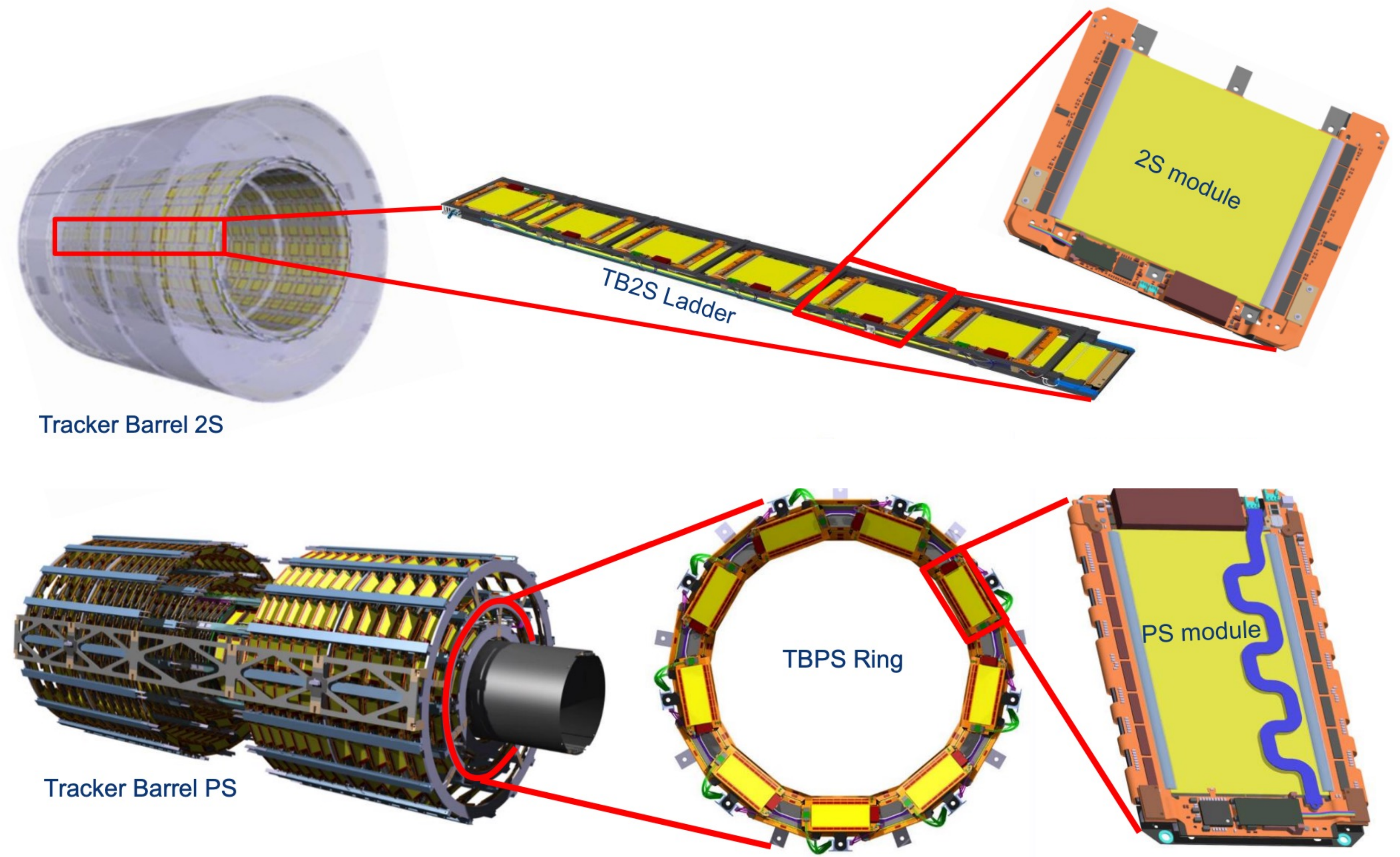
- Stubs
  - Closely spaced sensors
  - Fast p_T measurement
  - Reject stubs with high bend
- L1 Track Trigger
  - Associate track to stubs from OT layers and extract p_T measurement
  - Trigger events based on track p_T at L1





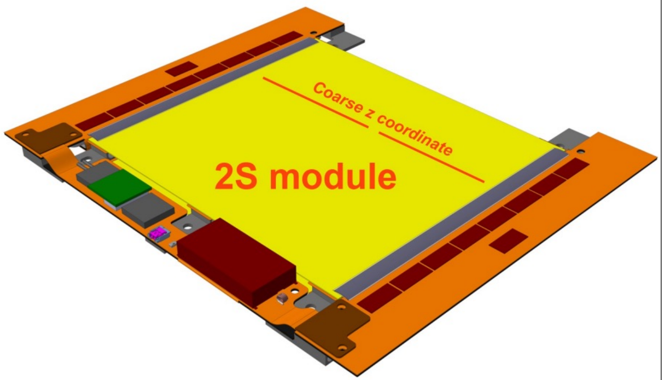
Vertex 2021

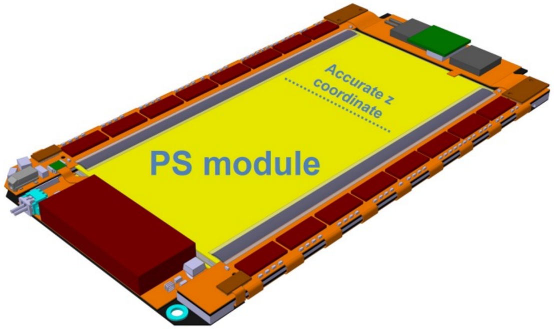
Barrel Geometry



Modules

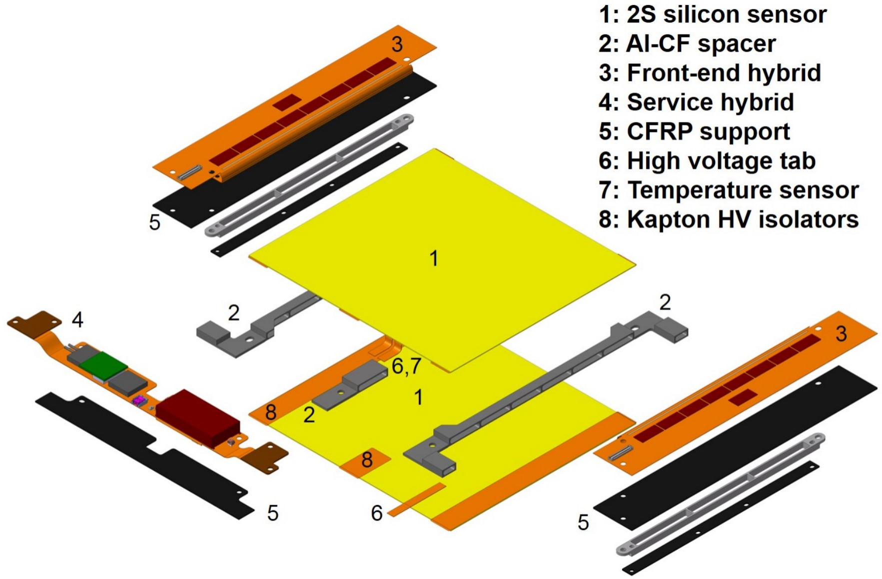
- 2S Modules
  - Strip-Strip layout
  - 2×1016 strips $5\text{cm}\times90\mu\text{m}$ per side
  - 90cm^2 active area
  - In region $60 < r < 120\text{cm}$
  - Spacing 1.8mm and 4.0mm
- PS Modules
  - Pixel-Strip layout
  - 2×960 Strips $2.5\text{cm}\times100\mu\text{m}$
  - 32×960 macro-pixels $1.5\text{mm}\times100\mu\text{m}$
  - 45cm^2 active area
  - In region $20 < r < 60\text{cm}$
  - Spacing 1.6mm, 2.6mm and 4.0mm

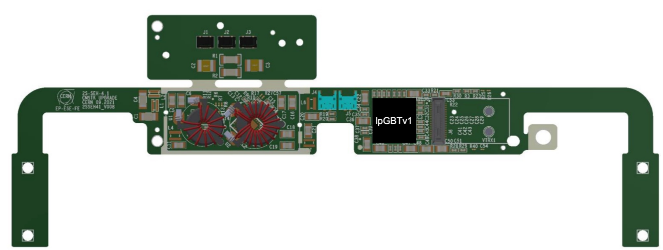


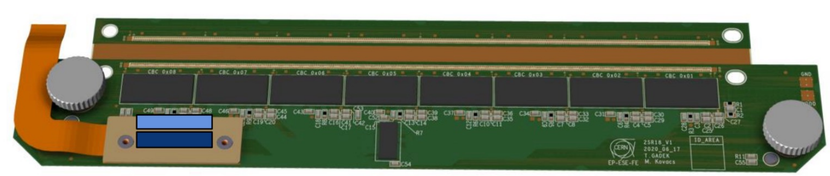


2S Hybrids

- Service Hybrid
  - Provide LV power to 2S Module (~3.2W total)
  - Provide HV bias input
  - Send data to backend through optical cable
  - 5Gb/s or 10Gb/s
- Front End Hybrid
  - CBCs bump bonded to FEH
  - Send hits from both planes to CBCs through flex cable
  - Concentrate data from all CBC output

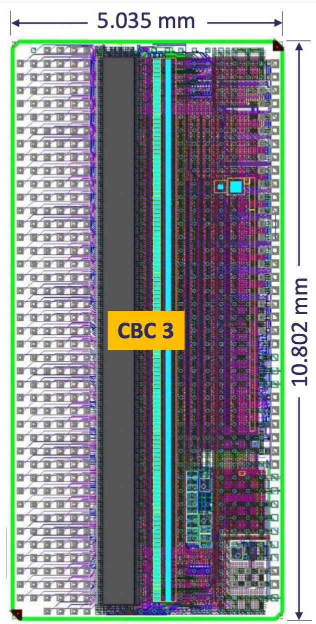






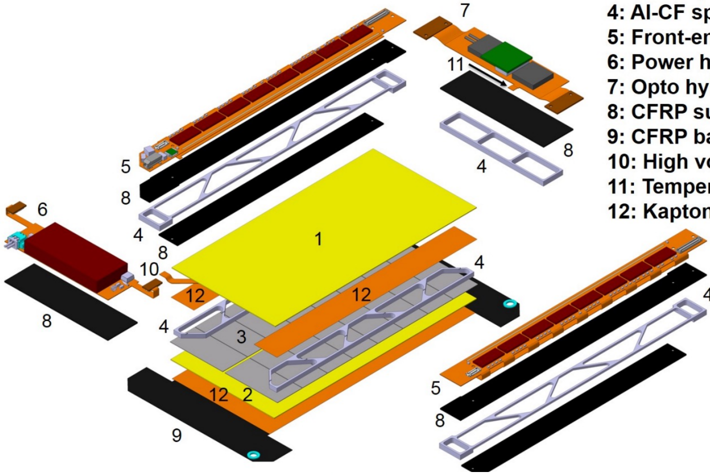
2S ROC

- CBC - 254 strips (both planes)
  - Bump bonded to hybrid, hybrid wire bonded to strip sensor
  - Input: Hit array from both sensor planes
  - Cluster and correlate to create stubs
  - Output: Two data formats passed to CIC
    - L1 hits – Send full event clusters along single SLVS line
      - Cluster = x centroid, width
    - Stubs – Send stub info along 5 SLVS lines
      - Stub = x centroid, bend

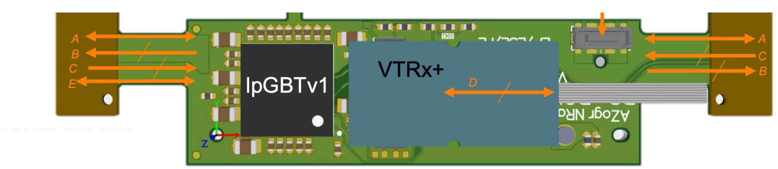


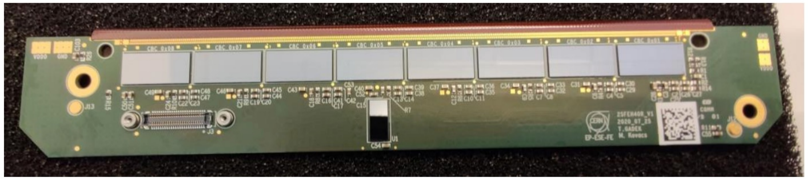
PS Hybrids

- Power Hybrid
  - Provide power to PS Module (~5.5W total)
- Readout Hybrid
  - Send data to backend through optical cable
  - 5Gb/s or 10Gb/s
- Front End Hybrid
  - SSAs bump bonded to FEH
  - Send SSA-MPA communication through flex cable
  - Concentrate data from all MPA output



1: PS-s sensor
2: PS-p sensor
3: Macro-pixel ASICs
4: Al-CF spacer
5: Front-end hybrid
6: Power hybrid
7: Opto hybrid
8: CFRP support
9: CFRP baseplate
10: High voltage tab
11: Temperature sensor
12: Kapton HV isolators

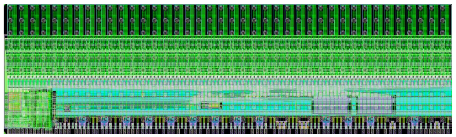




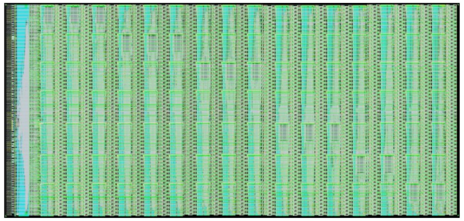
PS ROC

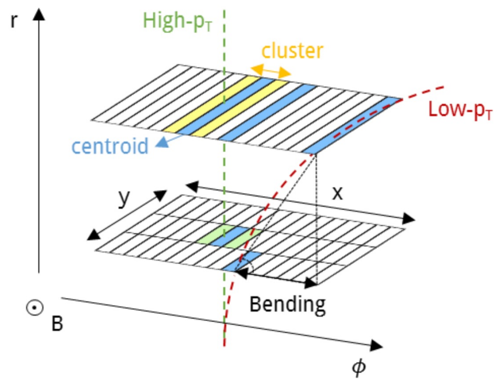
- SSA - 120 strips (100μm)
  - Bump bonded to hybrid, hybrid wire bonded to strip sensor
  - Input: Hits from PS-S
  - Output: Two data formats passed to MPA
    - L1 hits – Send full strip array along single SLVS line
    - Stub preliminary – Send strip centroids along 8 SLVS lines
- MPA ROC - 120x16 pixels (100μm x 1.5mm)
  - Bump bonded to pixel sensor, wire bonded to hybrid
  - Input: Hits from PS-P, and SSA output
  - Perform stub association
  - Output: Two data formats passed to CIC
    - L1 hits – Perform clustering and merge MPA and SSA info along single SLVS line
      - Cluster = x centroid, y position, width
    - Stubs – Send stub centroids and bend info along 5 SLVS lines
      - Stub = x centroid, y position, bend

SSA



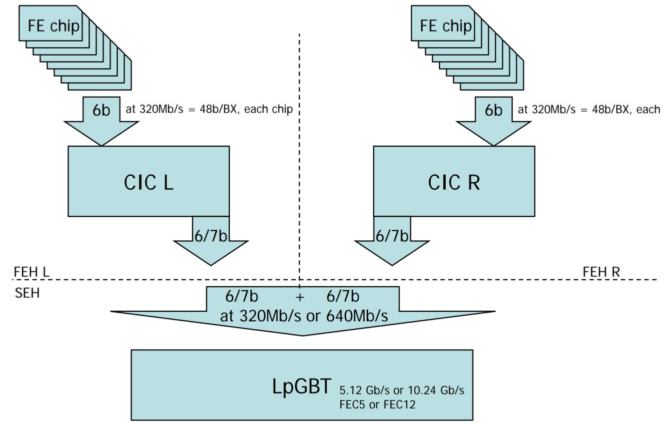
MPA

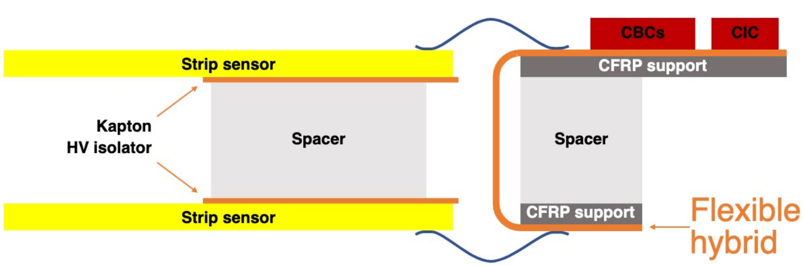


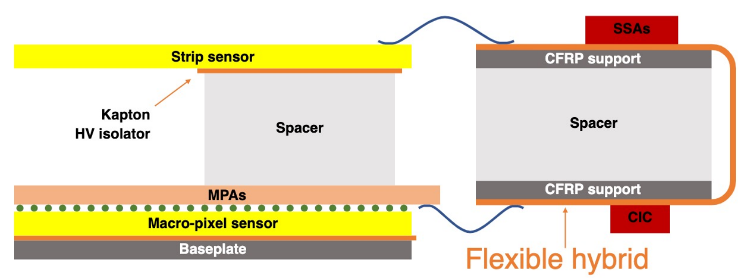


Full Modules

- Sensor sandwich
  - CBC,2x2S-S
  - SSA,PS-S + MPA,PS-P
- CIC – Concentrator chip
  - Output stub and hit data sent to CIC along SLVS lines
  - 8 FE->1 CIC, 48 SLVS in -> 6 SLVS out
- LPGBT – Optical transceiver
  - 2 CIC->1 LPGBT
  - Output sent to BE board via optical link

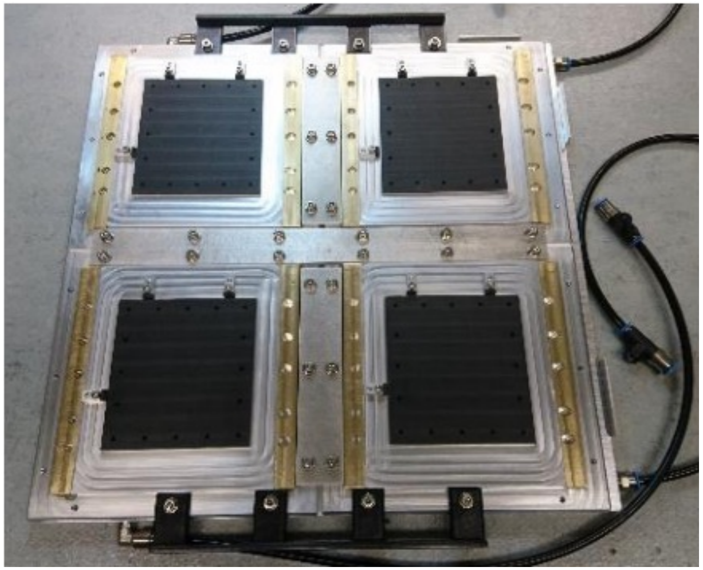


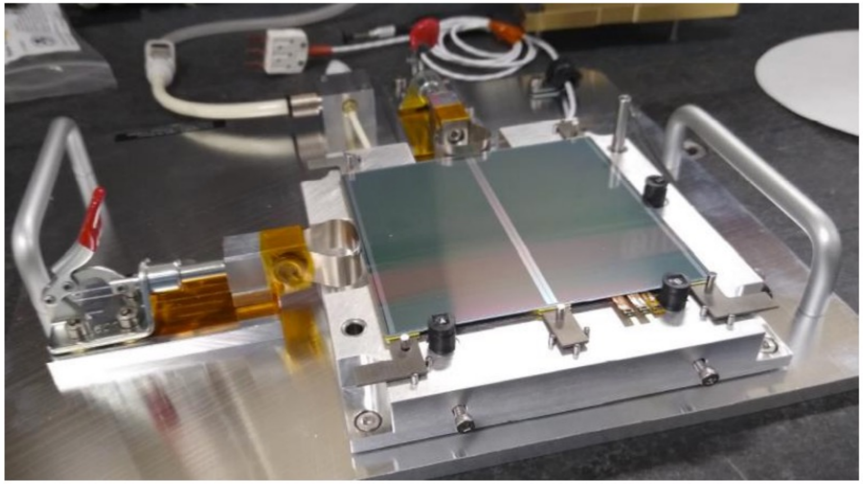


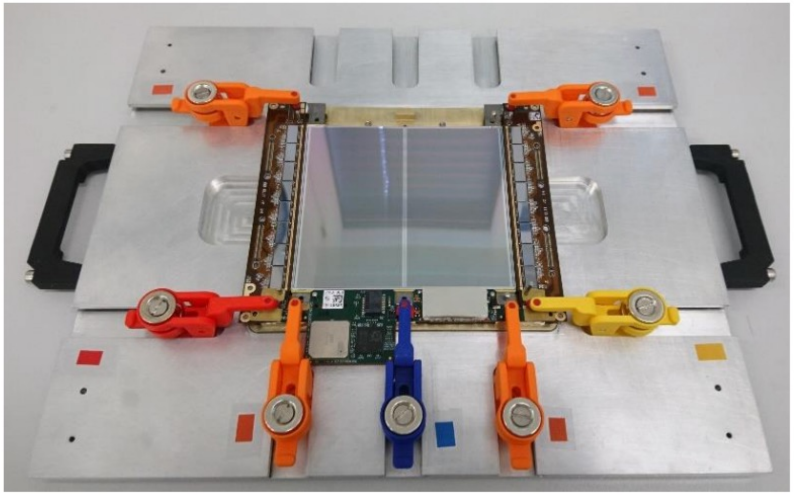


2S Assembly

- Kapton/HV tail gluing fixture
- Sensor assembly fixture
- Hybrid gluing fixture set

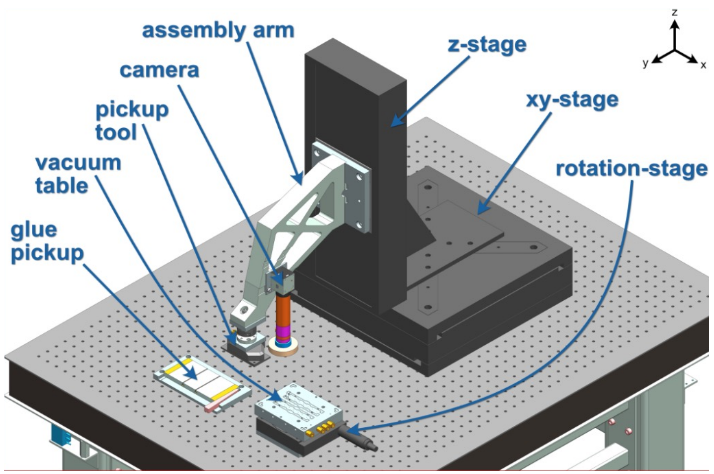


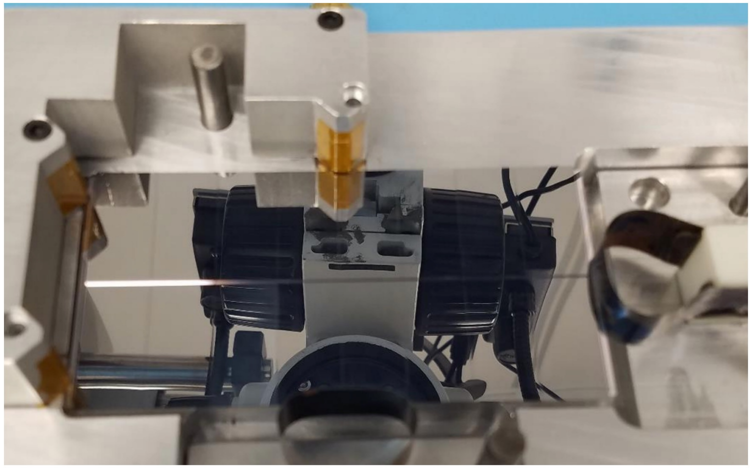




PS Assembly

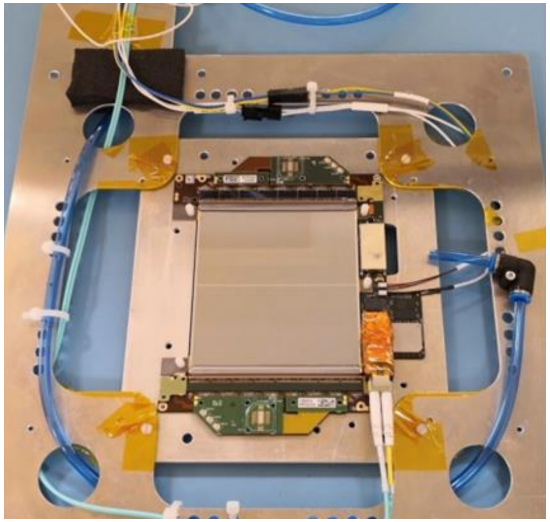
- PS Assembly has been studied with mechanical components
- Module assembly
  - Create sensor sandwich
    - Align PS-S and MaPSA
  - Assembly via fixture
    - Use sensor edge to align
  - Assembly via robotic arm
    - Use optical targets for alignment
- Hybrid assembly
  - Fixture based assembly
    - Precision pins used for alignment
  - Mate hybrid connectors

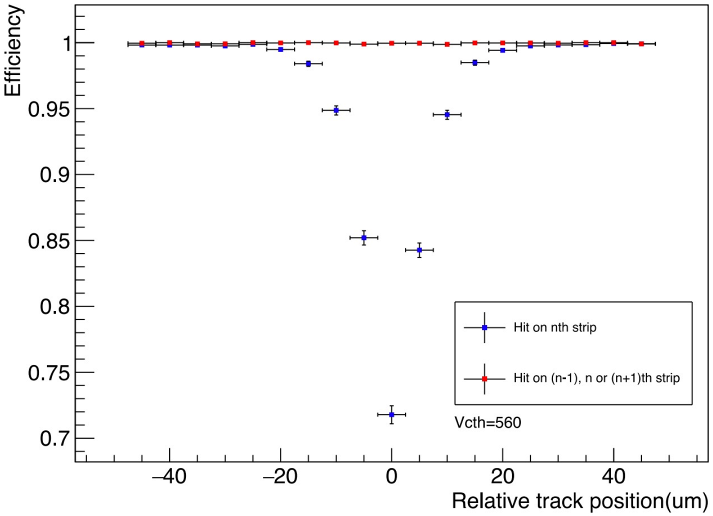




2S Test Systems

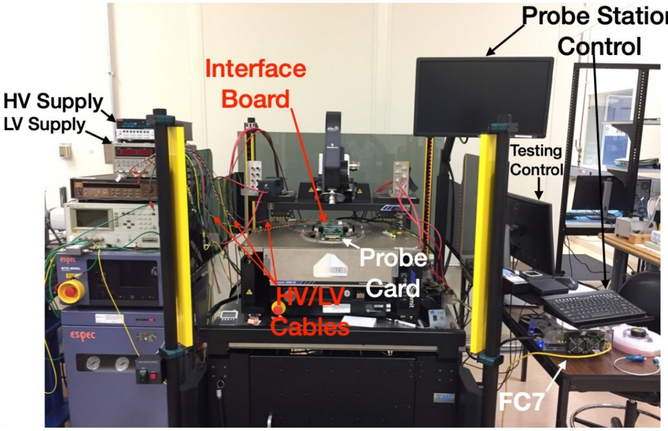
- 36 functional 2S prototypes
  - Two with irradiated sensors
  - IV curves consistent during assembly
  - Noise distribution as expected
- 2S module thermal cycling tests
  - Cycle module between $-20°C$ and $20°C$
  - Noise and IV curves seem stable
- Beam tests
  - Irradiated and un-irradiated sensors used
  - Very good performance at 600V after $4.6 \times 10^{15} \mathrm{neq/cm^2}$
    - Hit efficiency > 99.5%
    - Stub efficiency > 99%

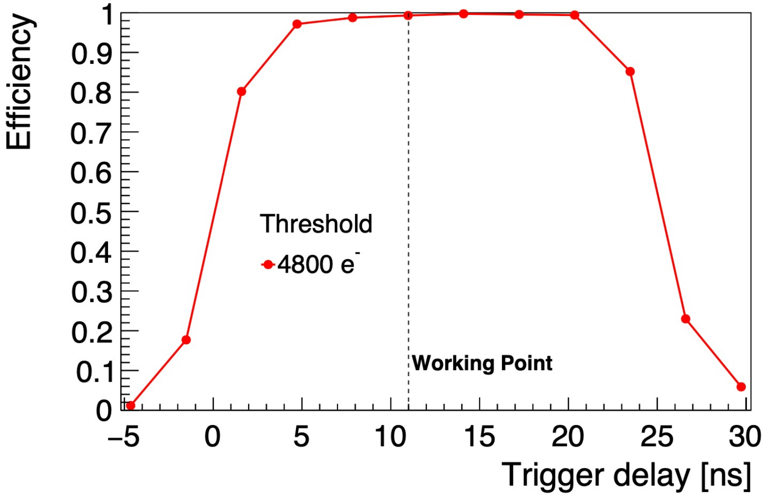




PS Test Systems

- SSA prototypes (strip plane)
- FNAL beam test
  - Position resolution
  - Timing Efficiency
- MaPSA prototypes (pixelized plane)
  - 16 MPAs with sensors
- Rigorous vendor testing program using probe station
  - Tested vendors found to be over 80% yield
- Module prototypes now available
  - Half and full PS module ready
  - Prototype testing in progress!





Summary

- The HL-LHC upgrade offers a large improvement to the instantaneous luminosity, but also unique challenges
- The CMS Outer Tracker will need to be completely redesigned
  - Withstand the high radiation environment
  - Provide sufficient granularity
- Prototyping of the ambitious upgrade hardware is ongoing and is now at the stage of full module characterization

Back Up