Prototyping of Hybrid Circuits for the CMS Phase Two Outer Tracker Upgrade at the HL-LHC

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N. Rasevic, A. La Rosa, A. Zografos

On behalf of the CMS Collaboration

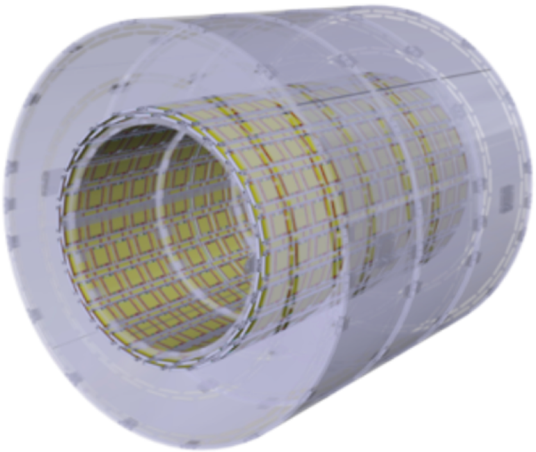
- Introduction of the Phase-2 tracker upgrade.
- Module topologies.
- Front-end hybrids variants.
- Hybrids in Modules.

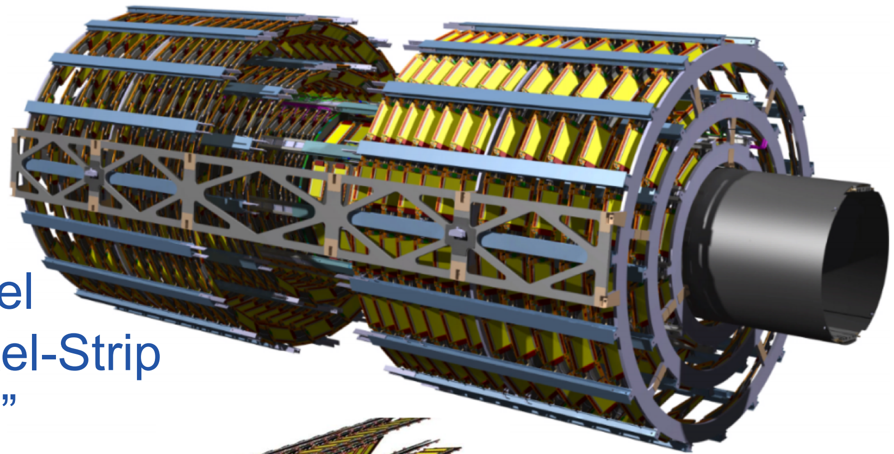
- Carbon-Fibre stiffeners: CTE and Cooling.
- Adhesive selection and gluing.
- Bow and Compensators.
- Outgassing.
- Conclusion.

The CMS Tracker requires a full upgrade to cope with the new HL-LHC constraints:

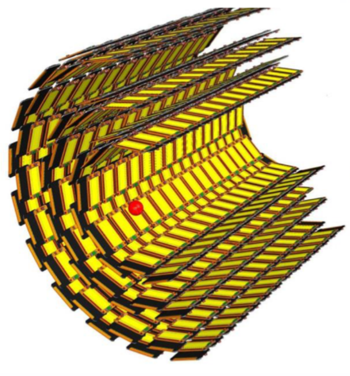
- Increased granularity: to cope with higher rate of events.
- Improved radiation hardness: to cope with increased luminosity.
- Reduction of mass: to obtain the required resolution.
- Provide L1 tracking information: to reduce the data volume.

- R&D for the future upgrade of the CMS tracker started in 2013, and is the scope of the hybrid circuits developments.

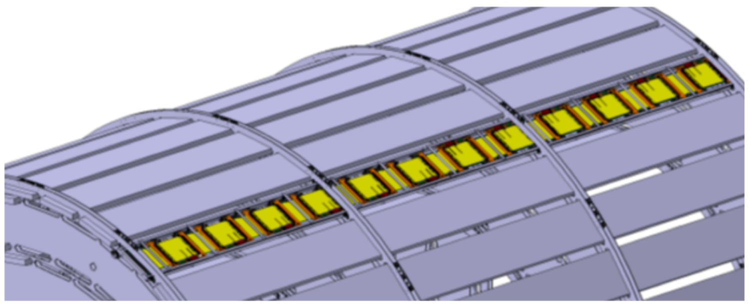




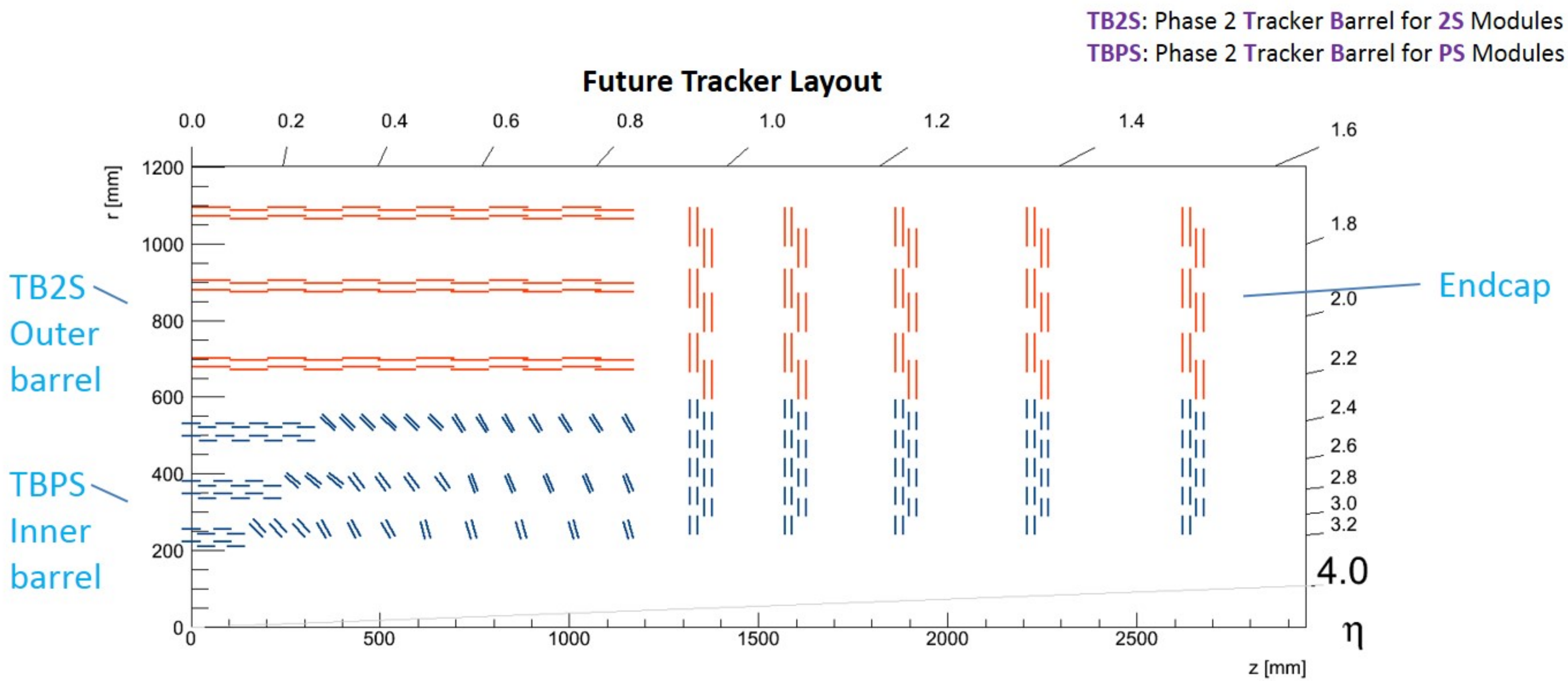
Barrel
Macro-Pixel-Strip
"PS"



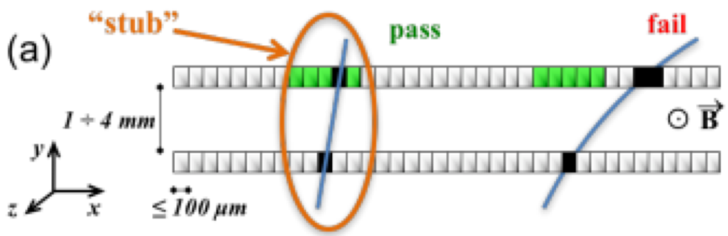
Barrel
Strip-Strip
"2S"



New Tracker Geometry and Low Momentum Rejection

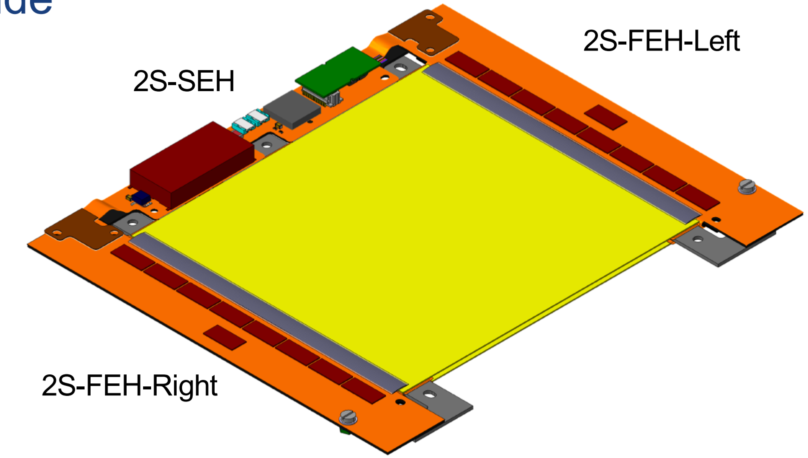


- Tracks of interest must be selected to cope with the higher rate of events.
- Focus only on high momentum tracks.
- Two parallel sensors provide the momentum information.
- The inner barrel adds also Z axis resolution.
- Stubs are formed from the high momentum tracks. They are used for L1 triggering construction at the back-end.



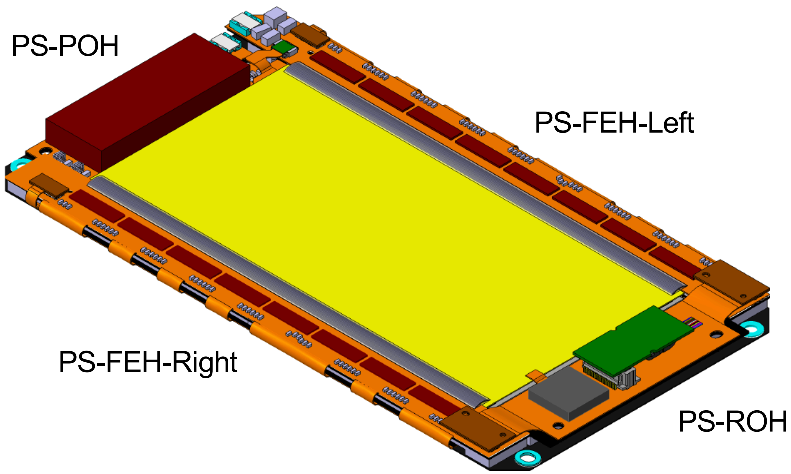
2S Modules

- 2 Strip Sensors: 2 × 1016 strips 5cm × 90 µm per side
- 90 cm^2 active area
- For R > 60 cm
- Spacing 1.8 mm and 4.0 mm
- Two front-end hybrids and one service hybrid (opto + power).



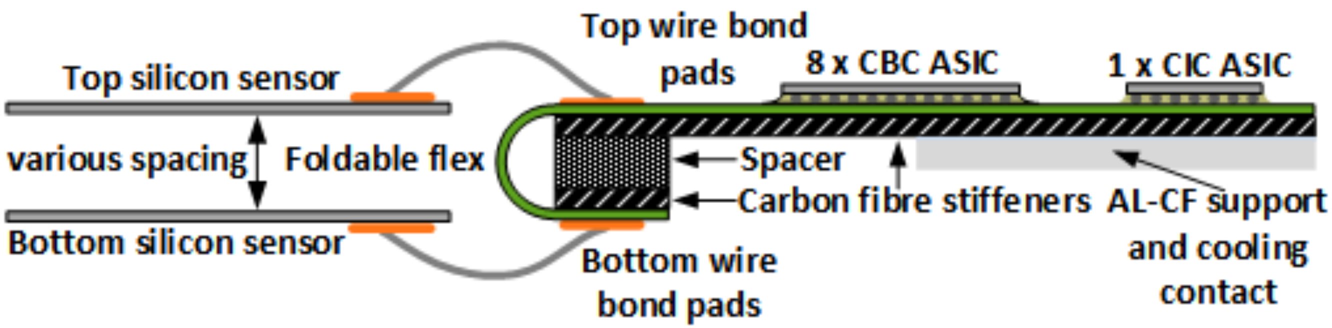
PS Modules

- Macro-Pixel + Strip Sensors
- 2 × 960 Strips 2.5 cm × 100 µm
- 32 ×960 macro-pixels 1.5 mm × 100 µm
- 45 cm^2 active area
- For R > 20 cm
- Spacing 1.6 mm, 2.6 mm and 4.0 mm

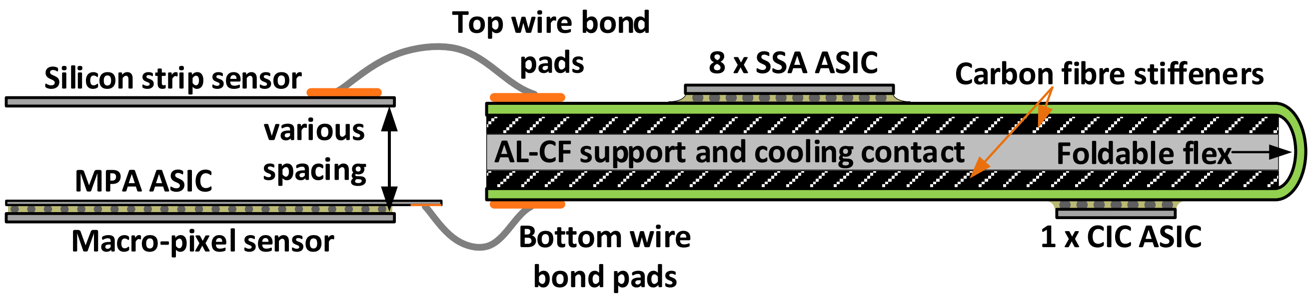


Cooling operation: -30 ºC

2S Hybrid



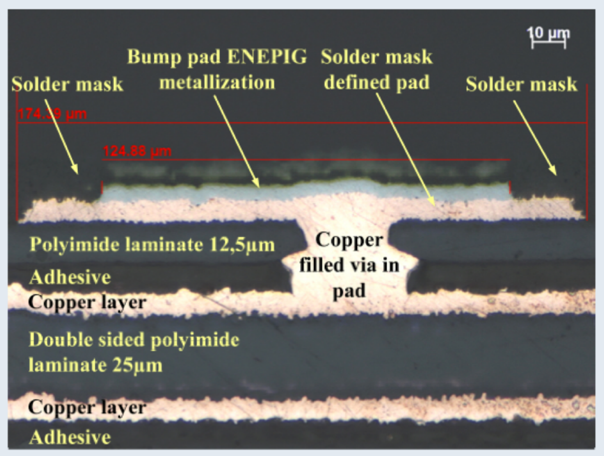
PS Hybrid

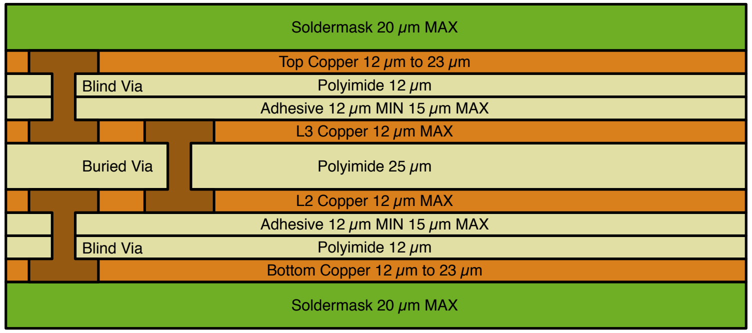


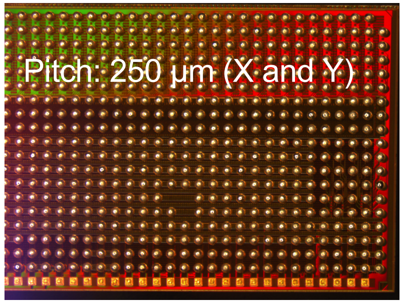
- 42.5 µm tracks width and spacing: high density interconnect
- 25 µm laser drilled copper filled microvias, 120 µm capture pads.
- 500 µm radius tight fold.
- 250 µm pitch flip chips with high pin-count: CBC3, SSA, CIC.
- 90 Ω high speed differential pairs in 150 µm, 4 layers thin flex.
- **All these constraints are on technological edge for flexible circuit manufacturers.**

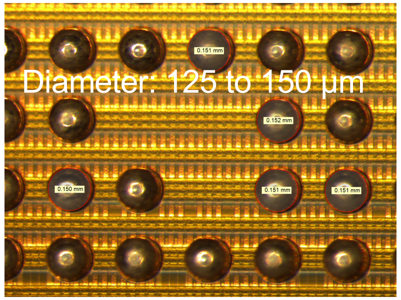
Typical 2S Hybrid Design

- Build-up: 150 µm thick HDI Kapton in 4 layers, with more than 18.000 blind and buried vias.
- The more than 6500 flip-chip pads are copper-filled via-in-pad microvias, using drill diameters of 25 to 50 µm.
- Copper tracks: 42.5 µm width and spacing are mandatory to fan out the flip-chip bump patterns and to obtain the correct impedance at differential pairs with this thin polyimide stack-up.



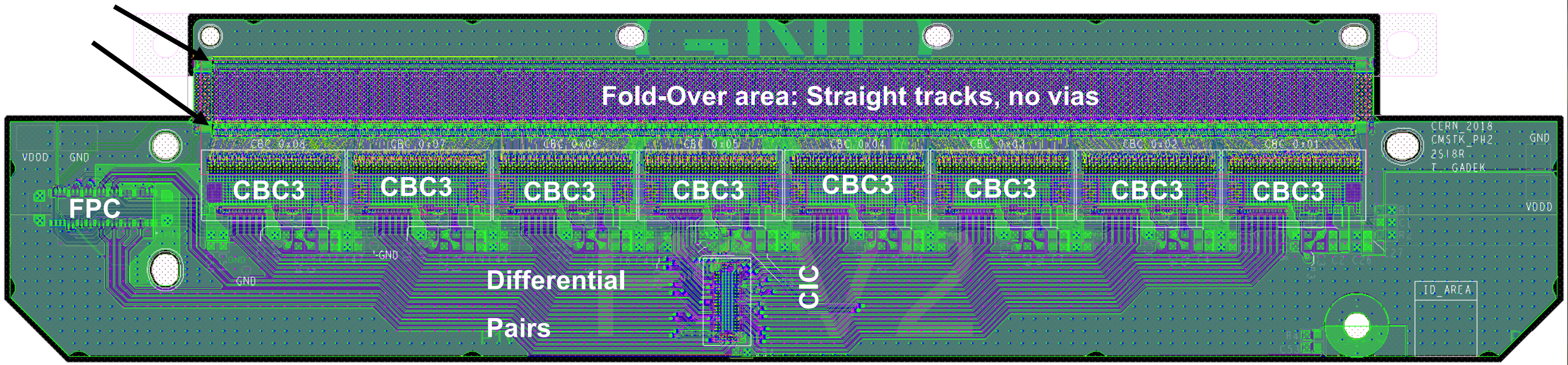


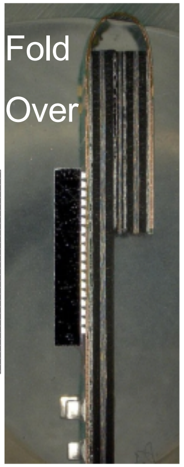


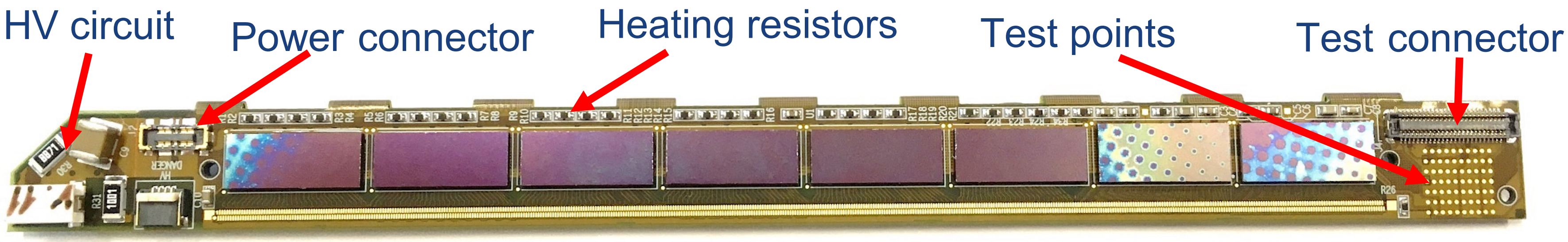


Wirebond pad arrays:

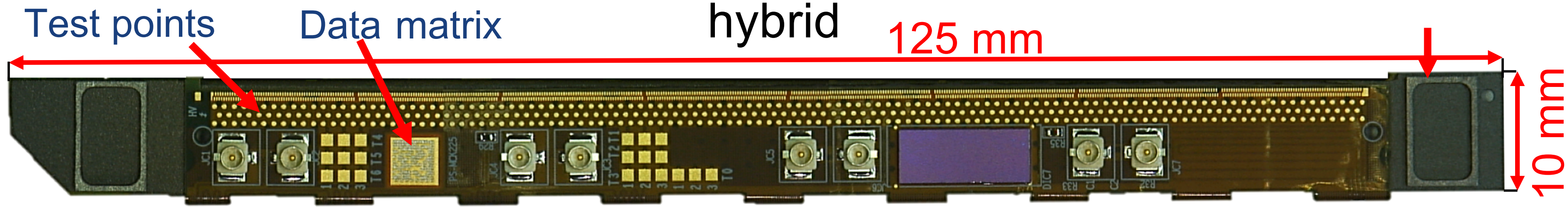
2X1016 staggered bond pads







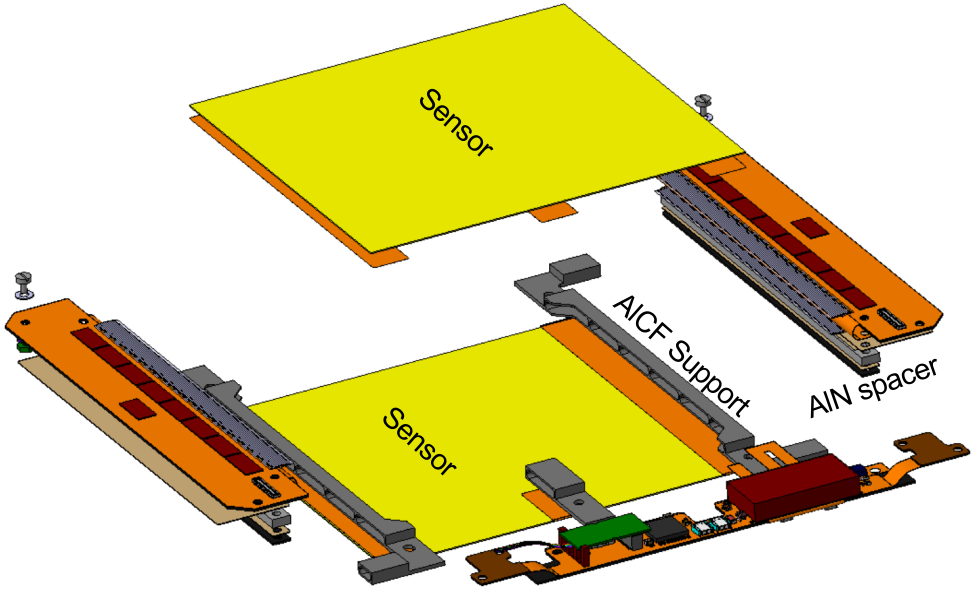
Top view of the PS-MCK hybrid



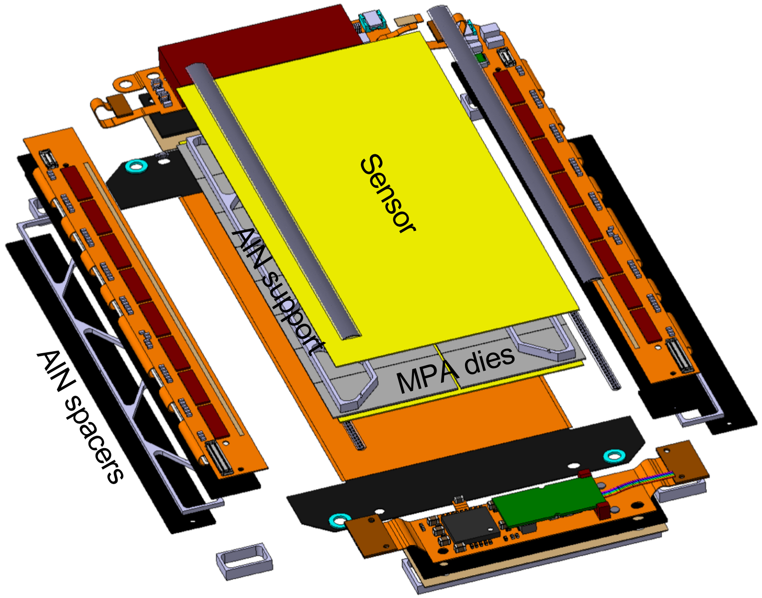
Bottom view of the PS-MCK

- PS Mockup to evaluate manufacturability, final PS-FEH is now in production.
- Major difficulty: delamination of flex from stiffeners during reflow. Problem was observed also on the second production batch of 8CBC2 hybrids.

2S Module, 4 mm sensor spacing



PS Module, 2.6 mm sensor spacing



In order to avoid mechanical stress and deformations at -35 ºC operation:

- Need to match the CTE of:
  - The Al-CF supporting structures.
  - The Al-CF or AL-N spacers.
  - The silicon dies and of the sensors.

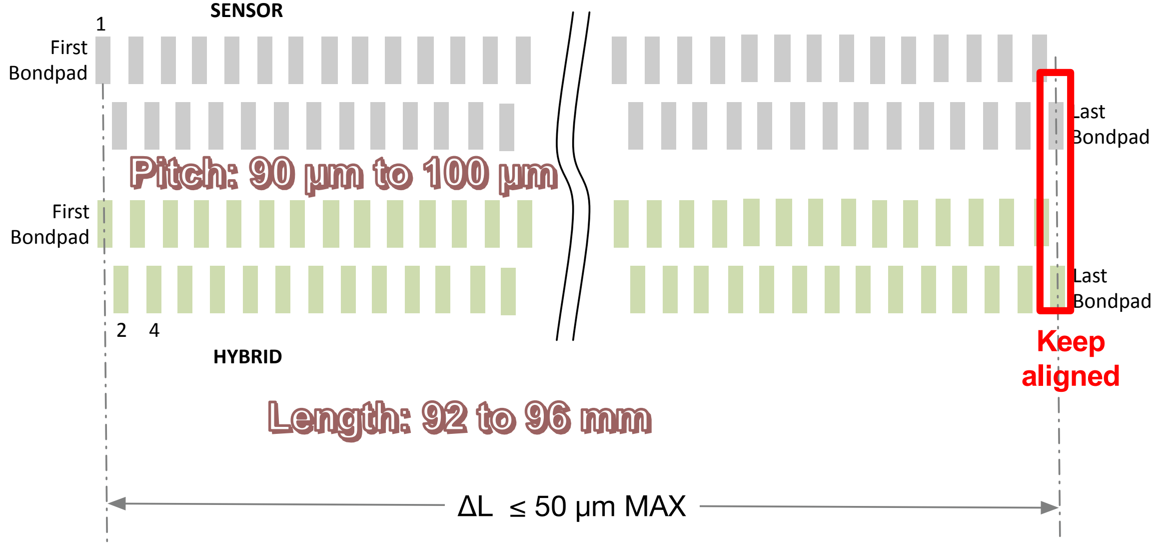
Also, the materials used to stiff the hybrids must have good thermal conductivity

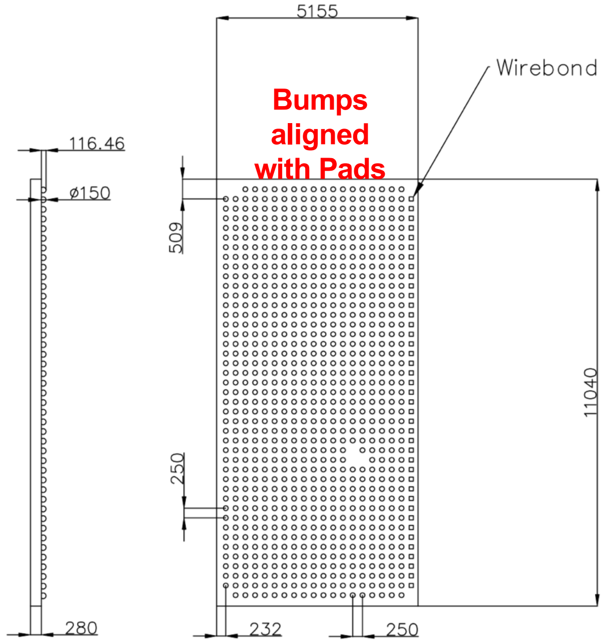
  - To transfer the heat to the Al-CF supports, that interface with the cooling circuit.

CTE controlled with Carbon Fiber stiffeners exposed to reflow (240 ºC) and cold operation (-35ºC)

- Flex Kapton CTE: 16 ppm/ºC
- Silicon dies and sensors CTE: 2.6 ppm/ºC
- Carbon fiber CTE: 0 ppm/ºC
- AlN and Al-CF spacers CTE: 4 ppm/ºC

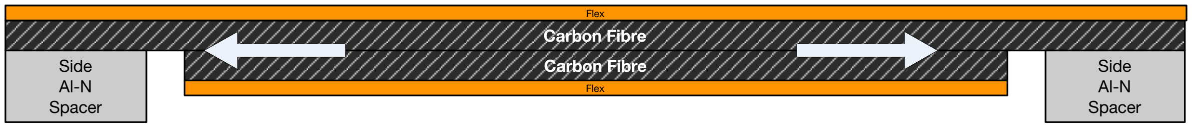
- CTE's have to match to limit mechanical stress in modules, dominated by Silicon and Al-CF supports.
- The lamination of a large CTE flexible circuit on a zero CTE carbon fiber stiffener allows bonding the flip chip and sensors without developing offsets during the reflow process and the cold operation.





Thermal management with Carbon Fiber stiffeners

- FR4 thermal conductivity vs X_0: 0.3 W/m.K – X_0/ρ_0 = 160 mm
- Al thermal conductivity vs X_0: 210 W/m.K – X_0/ρ_0 = 89 mm
- Cu thermal conductivity vs X_0: 400 W/m.K – X_0/ρ_0 = 14.4 mm
- CF thermal conductivity vs X_0: 800 W/m.K – X_0/ρ_0 = 237 mm with K13D2U



DIALEAD

K13D2U

COAL TAR PITCH-BASED CARBON FIBERS

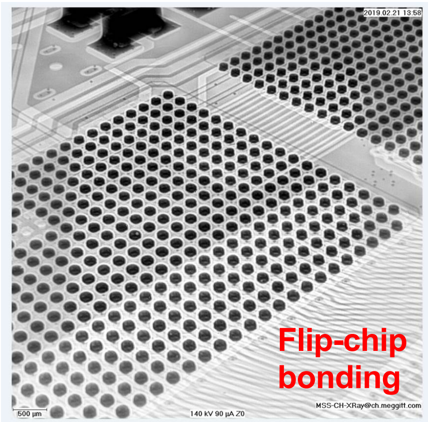
TYPICAL PROPERTIES

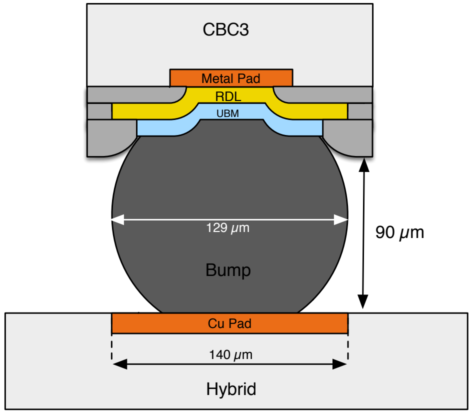
Tensile Strength	*535 Ksi*
Tensile Modulus	*135 Msi*
Ult Elongation	*.40 %*
Yield	*1360 yard/Lb*
Density	*2.2 g/cm³*
Electrical Resistivity	*1.5 x* 10^{-6} ohm·m
Thermal Conductivity	*800 W/m·K*
Sizing Amount (Epoxy Type)	*2 %*
Number of Filaments	*2 K*
Filament Diameter	*11 u*
Twist	*0 untwisted type*
Carbon Content	*over 99 %*

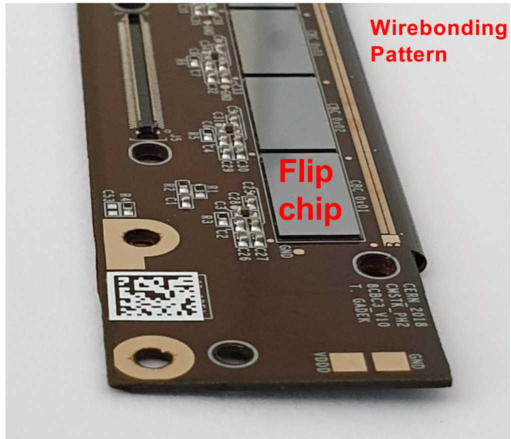
- The hybrids are cooled by a CO_2 circuit embedded in the module base plate.
- A thermal path from the dies to this network is required.
- The K13D2U high conduction carbon fibre provides the best thermal conductivity with the lowest material budget contribution.
- Its CTE is close to zero and matches the hybrids CTE requirement.

The adhesion of the carbon fibre to the flex is essential for hybrid performance

- **The stiffeners provide a flat and rigid surface for the soldering of components and wirebonding.**



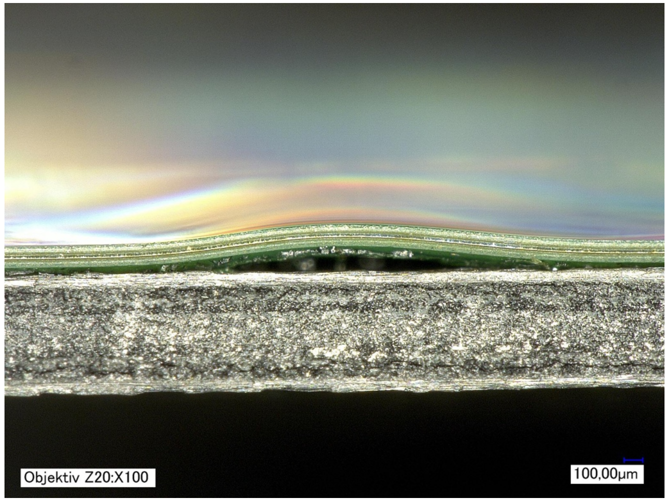


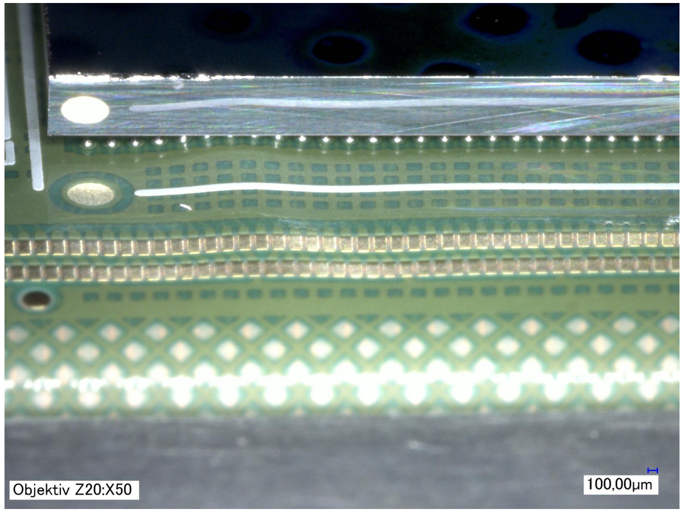


- **Soft adhesives**, usually in the form of a acrylic tape, are the most convenient gluing process:
  - Adhesive film is laser cut and integrated in the flex lamination process.
  - Helps to control the glue leaks and preserve the guiding holes.
  - Cold gluing process, but gets soft during reflow, enabling the flex to float on its stiffener during soldering, with risk of delamination.
- **Hard adhesives**, usually in the form acrylic or epoxies are applied as laser cut tapes or with dispensers.
  - Curing at high temperature originates bow
  - Adhesive leak can seal guiding holes
  - However, a hard adhesive is compatible with reflow soldering processes.

Experience with soft adhesive

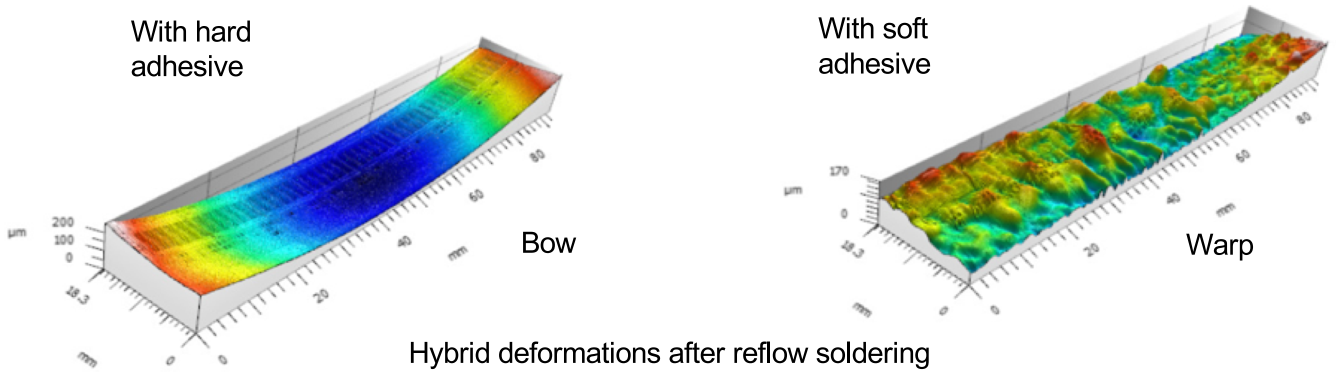
- **Several hybrid prototypes were glued with soft acrylic adhesive tapes:**
  - 3M9460, 3M9077, 3M7952.
  - Delamination appeared systematically on recent prototypes, after reflow.
  - Compromised flip chip soldering and wire bonding.





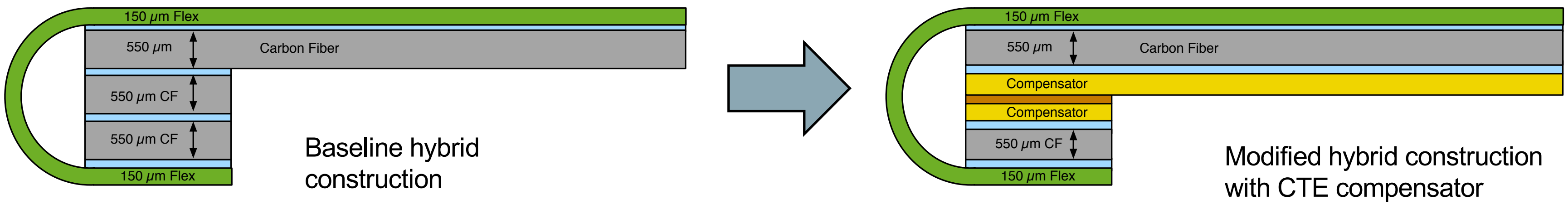
- **Detailed analysis performed**
  - Different carbon fibre laminates.
  - Different adhesive.
  - Different soldering processes.
  - No success, had to review the process from the beginning.

- **Gluing and lamination tests were performed, leading to the following conclusions:**
  - Hard adhesives result in bow during lamination and reflow.
    - Expanded flex is hard glued on zero CTE carbon fiber stiffener during curing process.
  - Soft adhesives result in warpage during reflow.



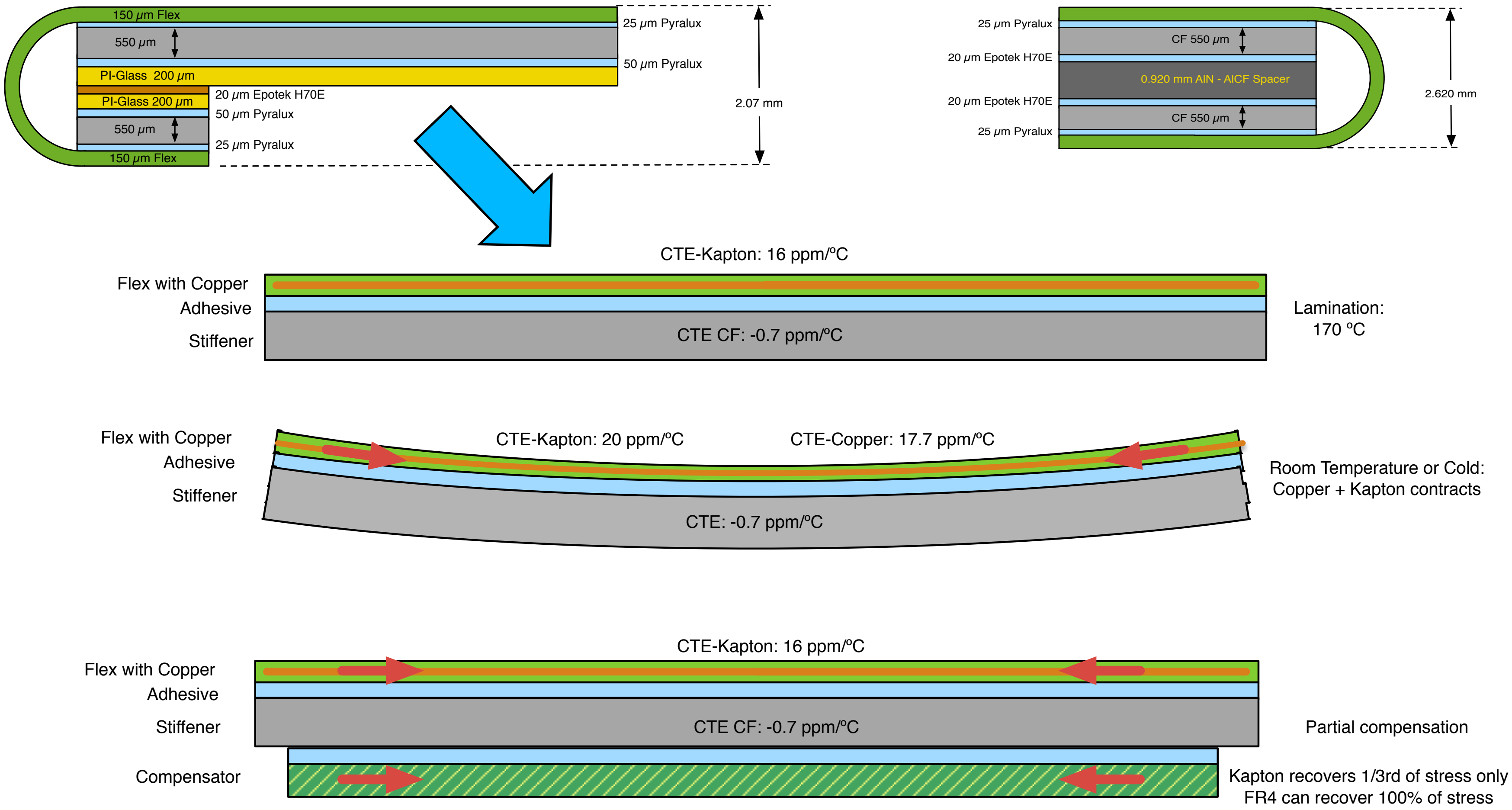
Hybrid deformations after reflow soldering

- **Opting for hard adhesives with addition of new CTE compensator to control bow**
  - Addition of flex on bottom of stiffener with CTE similar to Kapton on top will compensate the bow.
  - This requires hard adhesive, i.e. Pyralux LF well known adhesive for printed circuits manufacturing.



    - Tested ***polyimide + copper*** and ***polyimide + fibreglass successfully***.
    - Lamination with pre-preg instead of adhesive under study.

- 2S Hybrid is asymmetric: requires compensator to obtain symmetry.
- PS Hybrid is symmetric: does not require compensator.



- The optimal compensator thickness is calculated to get a symmetrical force, based on its CTE and Young’s modulus

Compensator thickness calculation

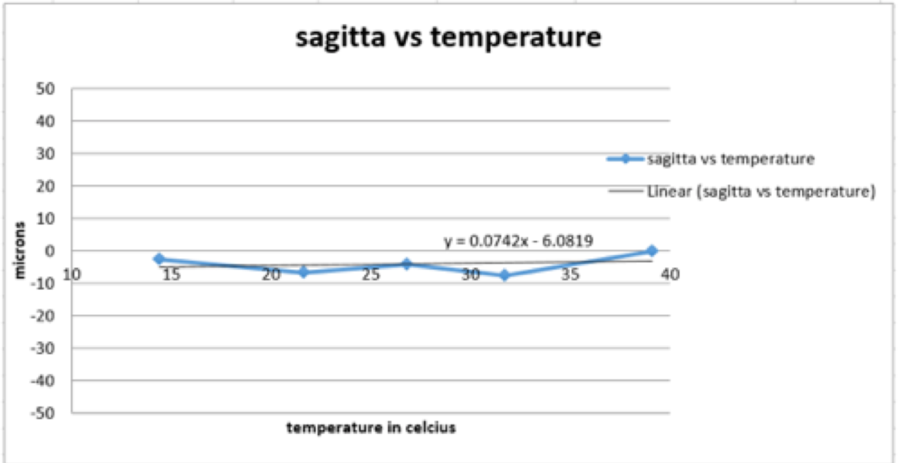
- Thermal expansion of flex, copper, adhesive layer: $\Delta L = \alpha_{CTE} \cdot L_0 \cdot \Delta T$
- CF stretching stress force set by Young's modulus: $\Delta F = Y \cdot A \cdot \Delta L / L_0$
- In absence of bow, elongation and forces must equal for all layers: $\Delta F = Y \cdot A \cdot \alpha_{CTE} \cdot \Delta T$

Hybrid flex materials:	CTE [ppm/K]	Young's modulus (Ym) [MPa]	Thickness (TH) [µm]	width (W) [mm]	Force/dT [N/K]	COMMENTS
Copper	16.6	130000	48	19.8	2.0509632	
Polyimide	18	7100	75	19.8	0.189783	
Solderrmask	7	2900	40	19.8	0.0160776	
Adhesive	67	580	24	19.8	0.018466272	
					2.275290072	Target
Glass Fibre Reinforced Polyimide						
Hitachi MCL-E-679F(J)	17	31000	200	19.8	2.08692	GOOD FIT
Hitachi MCL-I-671	13.5	38000	200	19.8	2.03148	GOOD FIT
Mitsubishi HL-832NS	10	27000	400	19.8	2.1384	GOOD FIT, too thick
Flex + 2 sides copper cladded:						
Polyimide	18	7100	100	19.8	0.253044	
copper 18 um	16.6	130000	36	19.8	1.5382224	
					1.7912664	TOO LOW
DuPont Pyralux AP	25	4800	100	19.8	0.2376	
copper 35 um	16.6	130000	70	19.8	2.990988	
					3.228588	TOO HIGH
Partially etched copper:						
DuPont Pyralux AP	25	4800	100	19.8	0.2376	
copper thinned to 24 um	16.6	130000	48	19.8	2.0509632	
					2.2885632	GOOD FIT
Isola P96						
Isola P96	13.5	42500	200	19.8	2.27205	GOOD FIT

- Hitachi MCL-I-671, partially etched copper cladded Pyralux AP and Isola P96 allowed all to obtain hybrids with a bow less than 100 µm.
- Laminar stress at operation is estimated to be of 220 K × 2.27 N/K = 500 N.

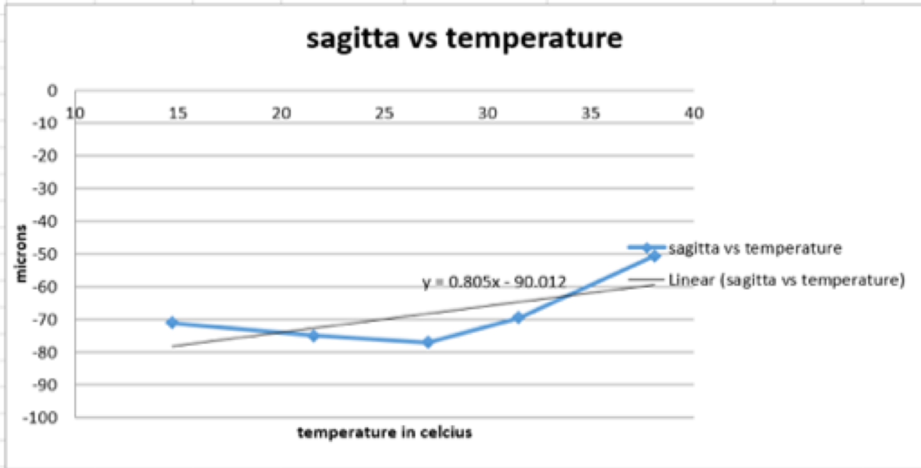
- **CTE compensated hybrids bring particular advantages**
  - **The hybrid remains flat at all temperatures**:
    - From reflow down to cold operation.
    - Good for soldering of dies.
    - Releases mechanical stress in assembled modules.

Hybrid CTE Compensated Hybrid (PI + Cu)



A compensated hybrid remains flat at all temperatures.

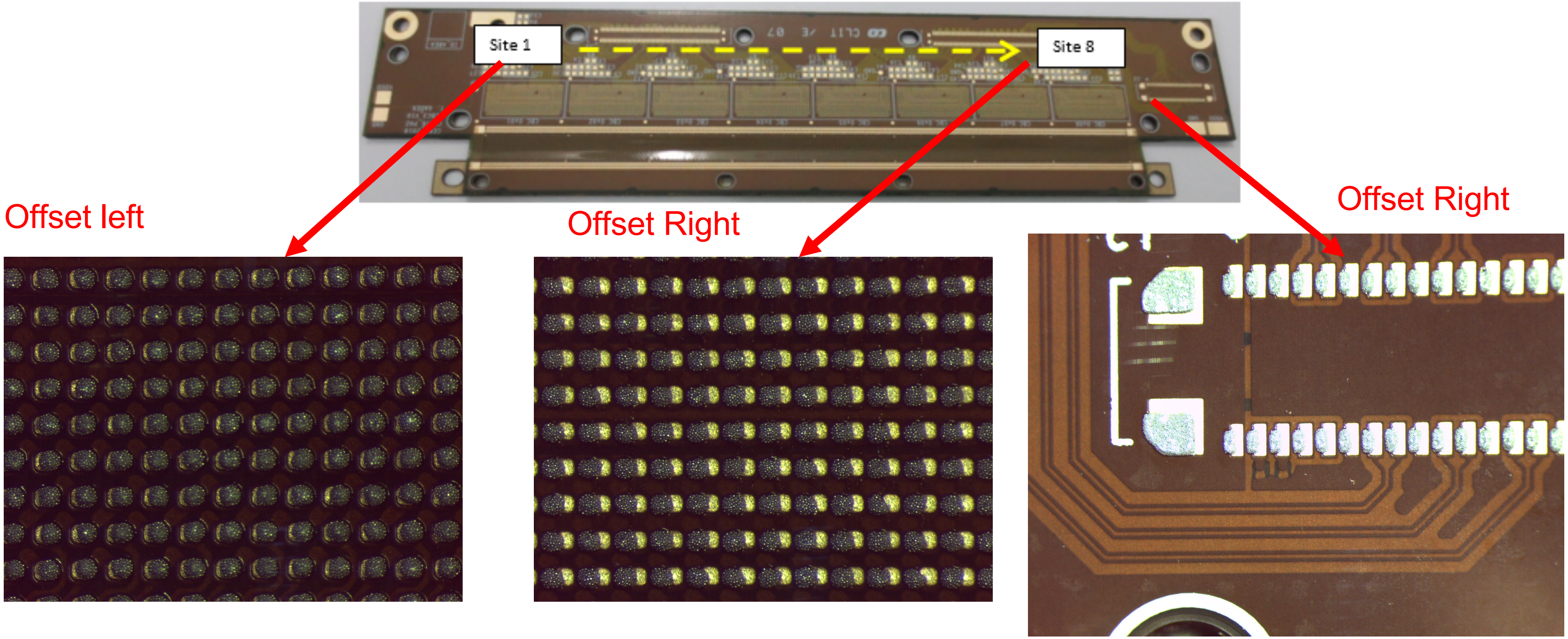
Non Compensated Hybrid



A non compensated hybrid has a bow that is function of temperature.

Stretching of compensated hybrids

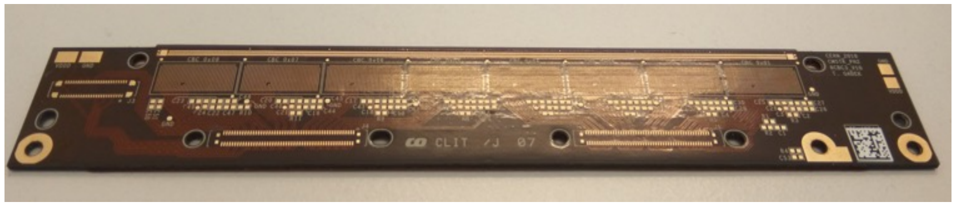
- <u>**Stretching of flex circuit: tuning is required**</u>.
    - CTE of Carbon fibre close to zero.
    - CTE of flex around 16 ppm/ºC.
    - Gluing occurs at 185 ºC: the flex expands ~250 µm and is hard glued before cool down.
    - Stress develops along the stiffener, stretch measured at 145 µm, +1.8 ‰.
    - **Solder paste must be tuned stretched away (tested successfully)-**
    - **Alternatively, the flex layers can be etched shrinked to allow for stretching during lamination.**



- **Carbon fiber cured at 120 ºC is exposed to higher temperatures during reflow:**
  - Chemical reactions develop beyond 120 ºC up to reflow soldering temperature.
  - Then outgassing continues during reflow.
  - Applying a post-cure process at 185 ºC completes the curing and prevents outgassing.

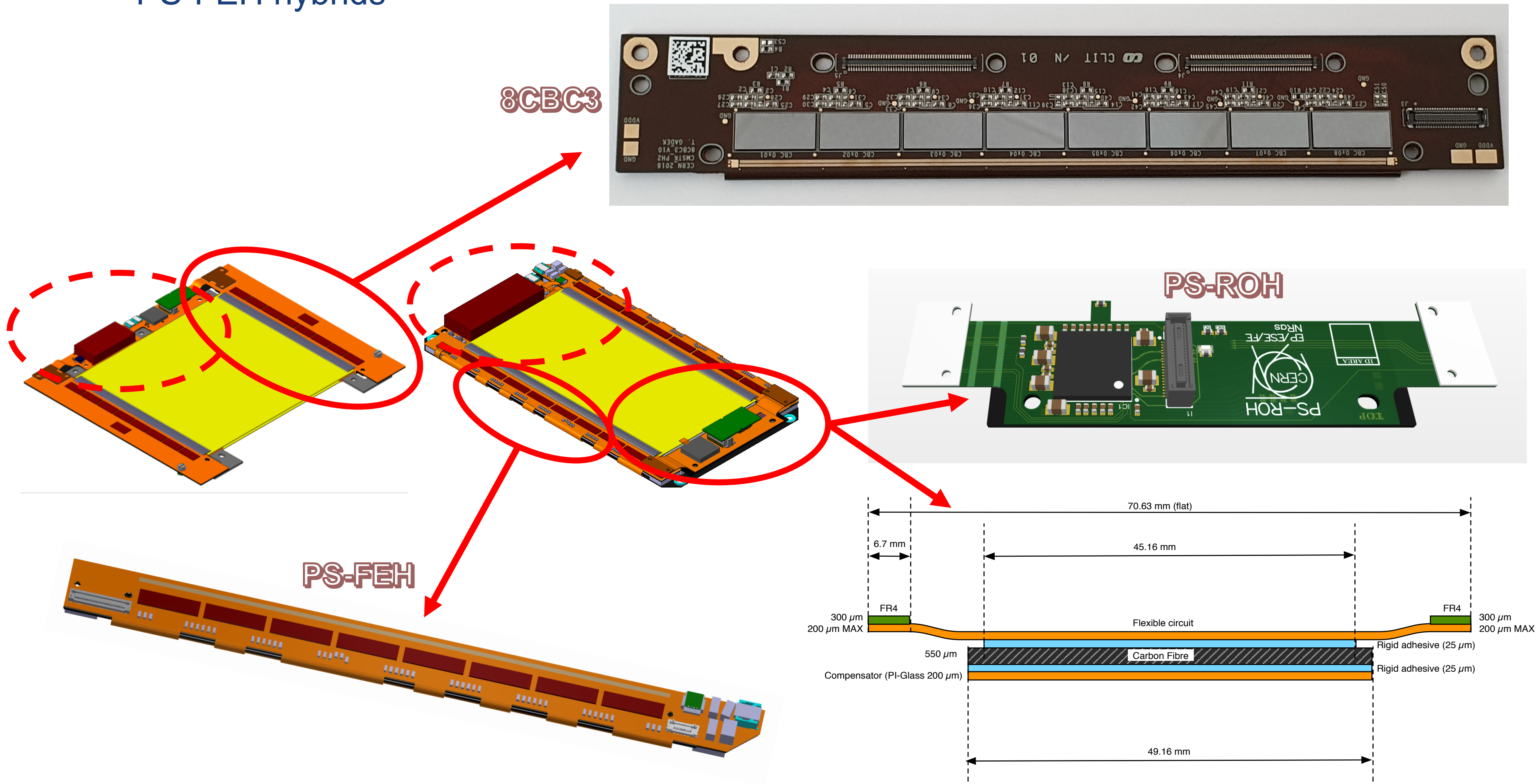
- **CF lamination mold release residues and moisture absorption degrade adhesion**
  - Sand scrubbing found to improve significantly the adhesion.
  - Drying 125 ºC 12 hours right before any gluing and lamination gets rid of moisture.
  - This eliminates delamination and outgassing to get a perfect flat hybrid surface.

Outgassing between : 120 ºC and Reflow



Post-cure and Scrubbing eliminates outgassing and improves adhesion

- **Process is now applied on:**
  - 8CBC3 hybrids
  - Service hybrids
  - PS-FEH hybrids

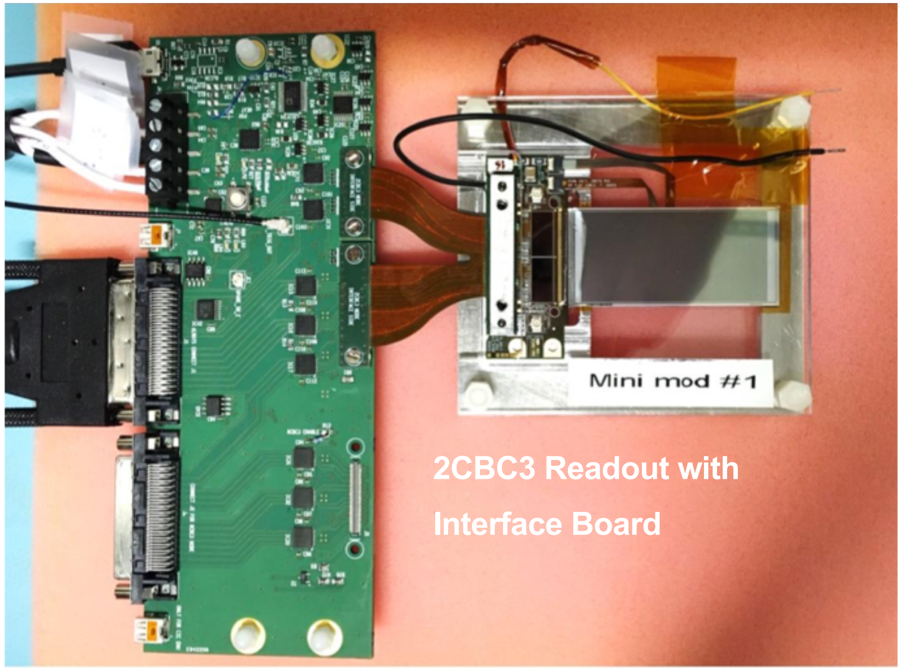


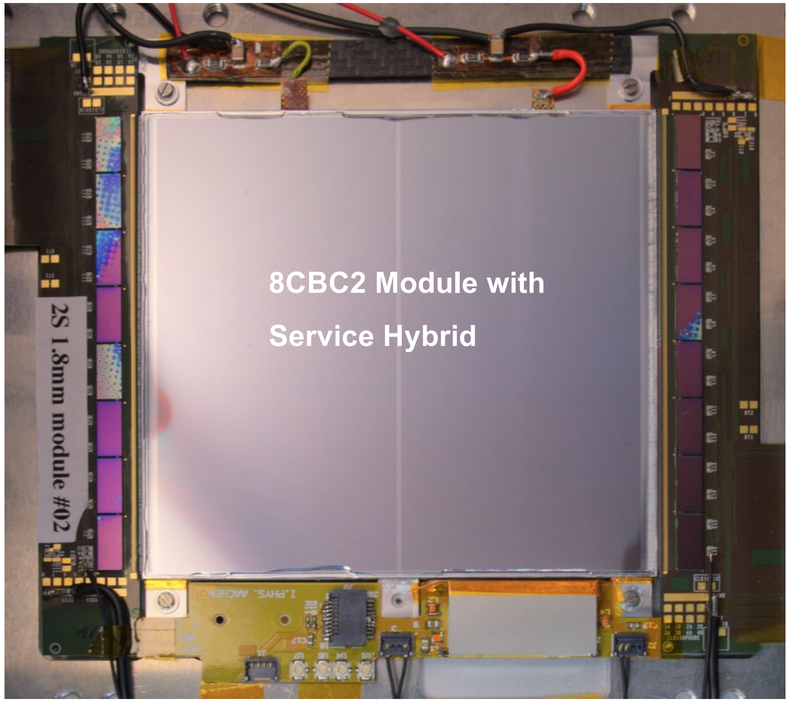
Conclusions

- Hybrids for the Tracker Upgrade are designed to match with:
  - Flip chip assembly, sensor wire bonding and module integration compatibility
  - CTE properties of silicon sensors and supporting structures.
  - Low material budget
  - Good thermal path
- The required materials need specific fabrication processes.
  - Flexible circuits: HDI
  - Adhesive materials: compatible with reflow
  - Carbon fibre stiffeners: adhesion and no outgassing
- Flex lamination to stiffener is a critical issue:
  - Post curing and sand scrubbing of carbon fibre stiffeners.
  - Moisture release through extended drying.
  - Use of hard adhesive to avoid delamination.
- Asymmetric hybrids require a CTE compensator layer to control the bow
  - Thickness tuned on selected material based on CTE and Young modulus.
- Process successfully tested on 8CBC3 hybrids and applied on new developments:
  - PS-ROH now under fabrication with compensator
  - PS-FEH with post-cured and scrubbed material, without compensator (symmetric build)
  - 2S-SEH, 2S-FEH under development, with compensators

Thanks for your attention

- Backup material

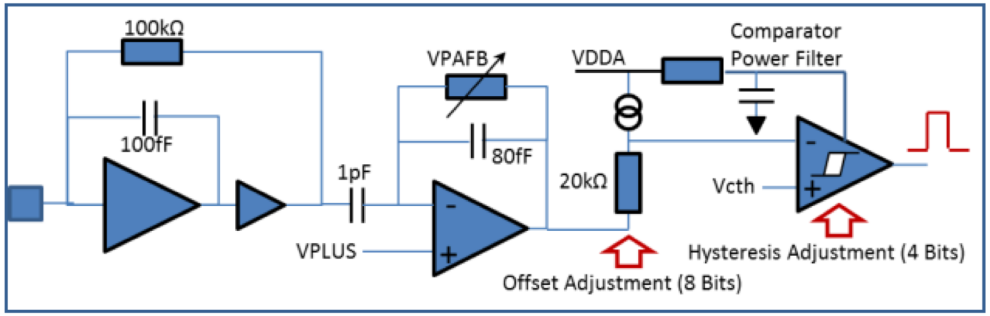

Mini mod #1
2CBC3 Readout with
Interface Board

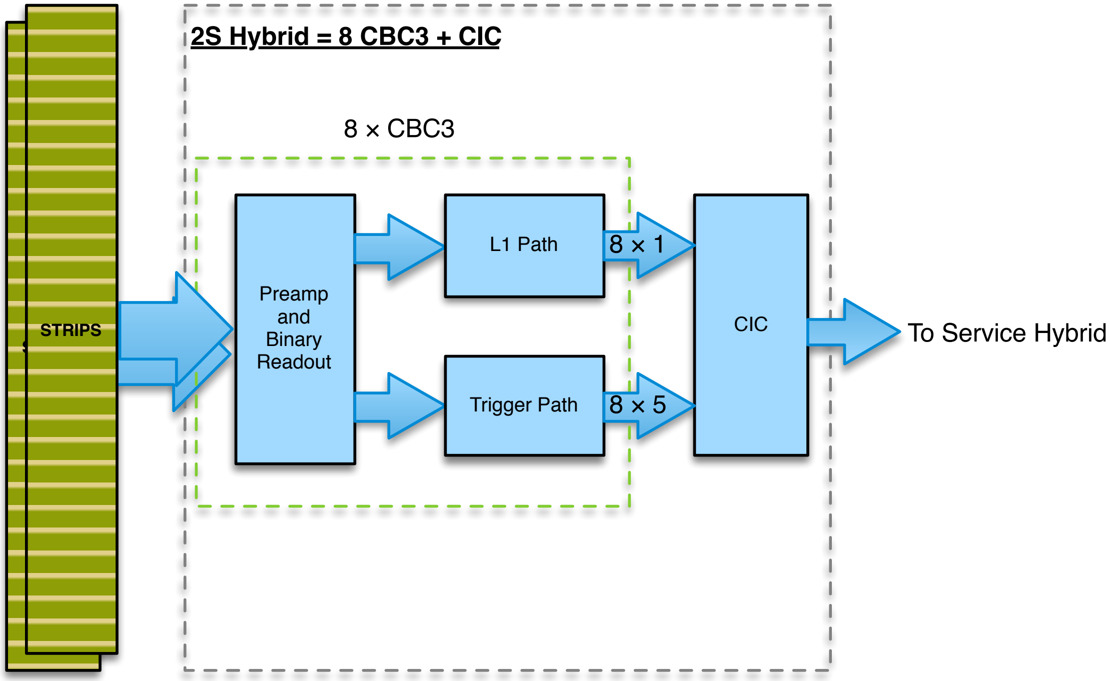

2S 1.8mm module #02
8CBC2 Module with
Service Hybrid

- Preamplifier and shaper with offset control.
- Discriminator with programmable threshold and hysteresis.
- Hit detection.

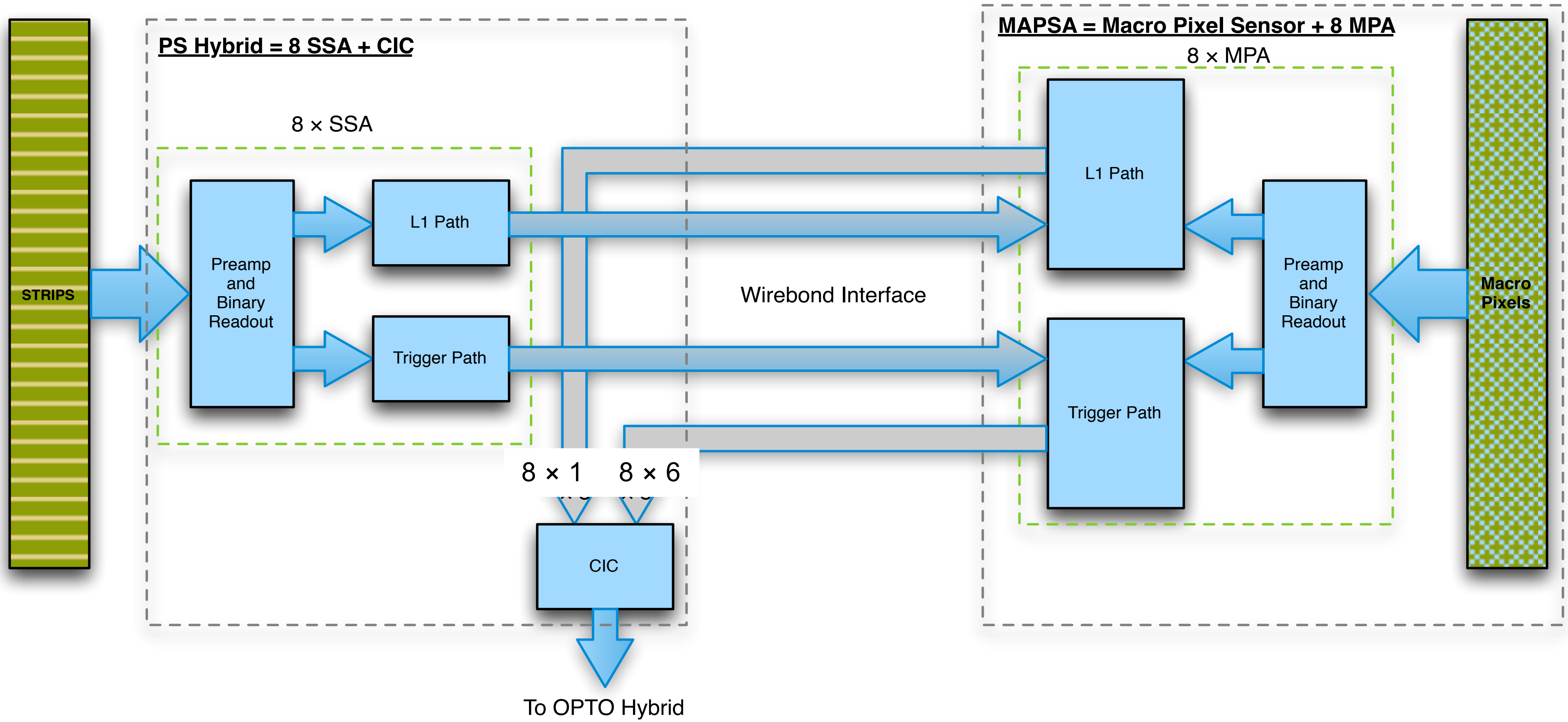
- Hits pushed into pipeline awaiting for L1 trigger.
- Hits pushed in stubs gathering logic.

- Stubs and triggered data extracted from pipeline are transmitted at LHC BC rate.





PS Block Diagram



- PS front-end hybrids contain eight SSA front-end ASICs, feeding the off-hybrid MPA front-end ASIC bonded to the macro-pixel sensor.
- The MPA chips combines its data with the SSA data to format stubs and sends it back to the hybrid.
- The formatted data is finally sent to the Concentrator (same as on 2S hybrids), forwarding serialized data towards the Opto hybrid containing the lpGBT and VL+.