

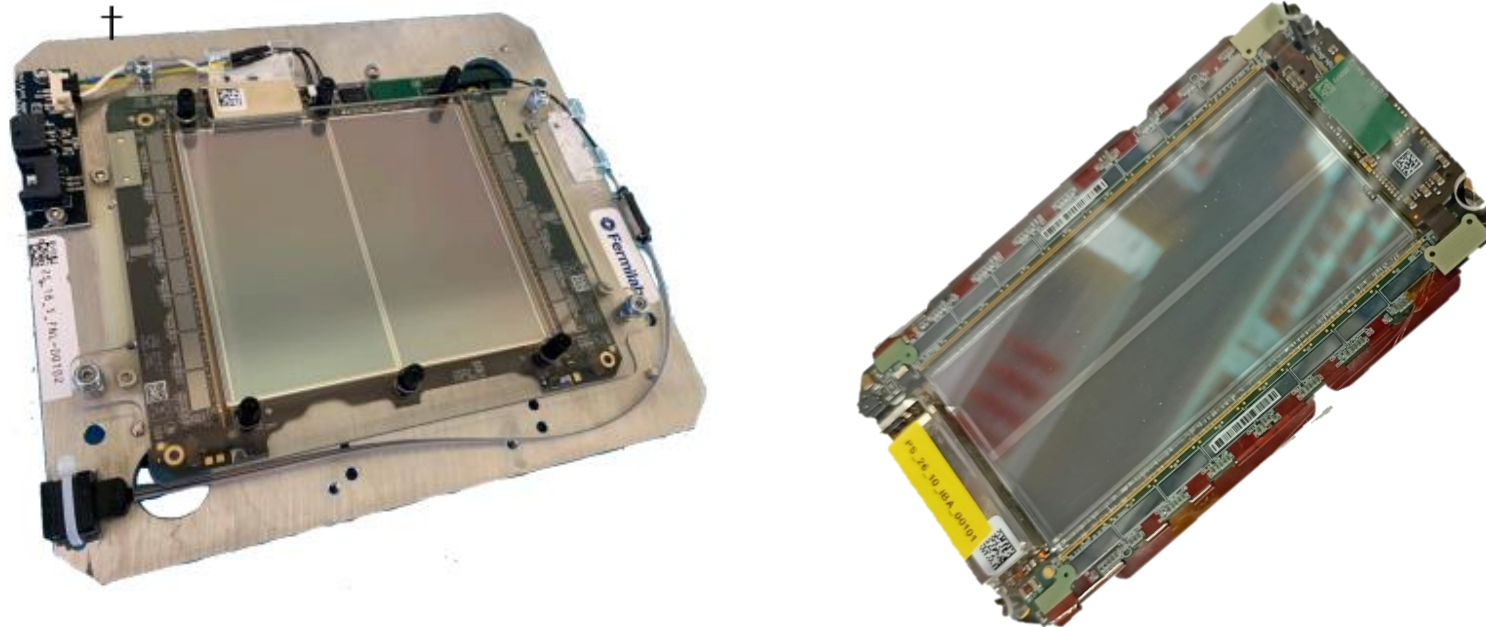
# Hybrids pre-production results for the CMS Outer Tracker Phase-2 Upgrade

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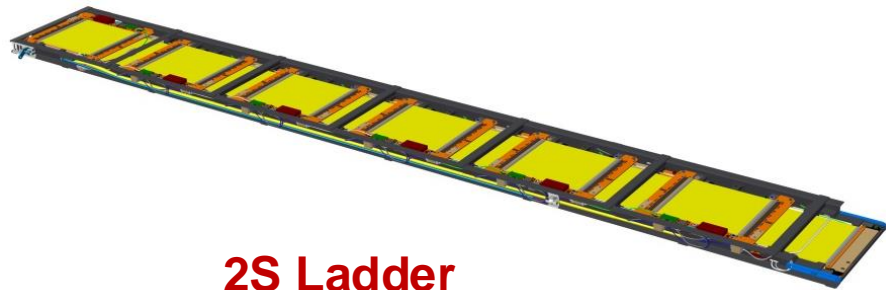
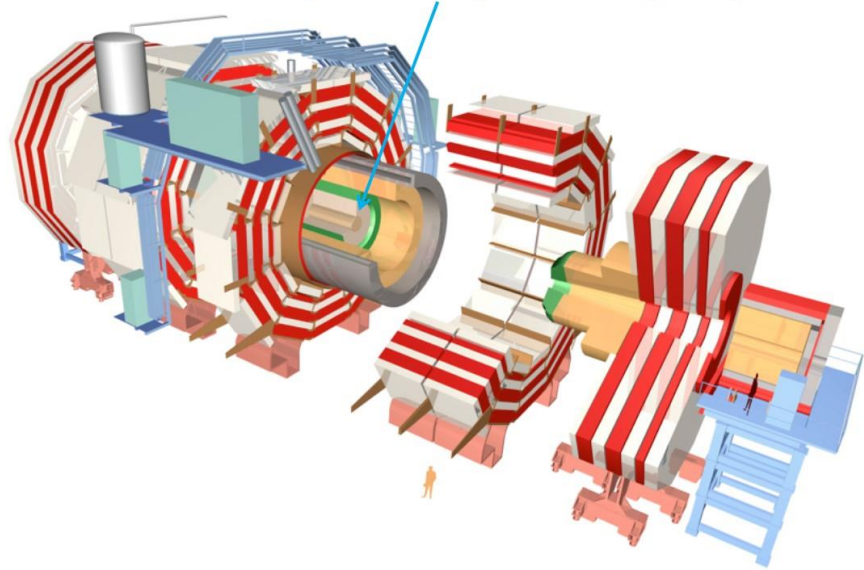
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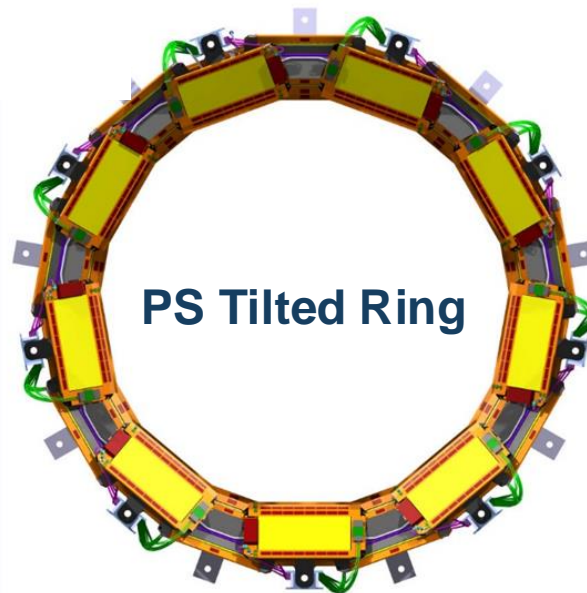
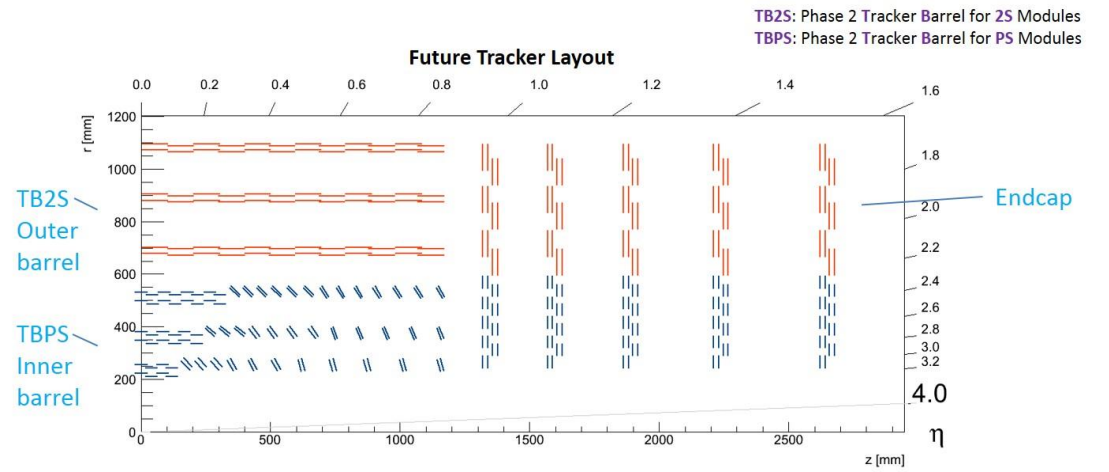


<sup>†</sup>For the CMS Collaboration

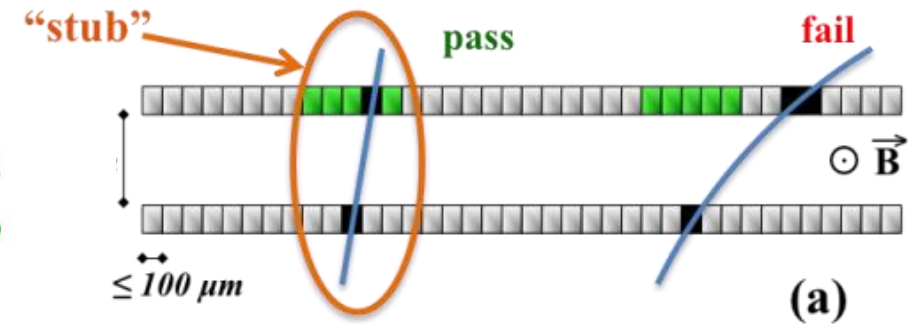
Replacement of the Silicon Tracker during the LHC Long Shutdown 3



**2S Ladder**

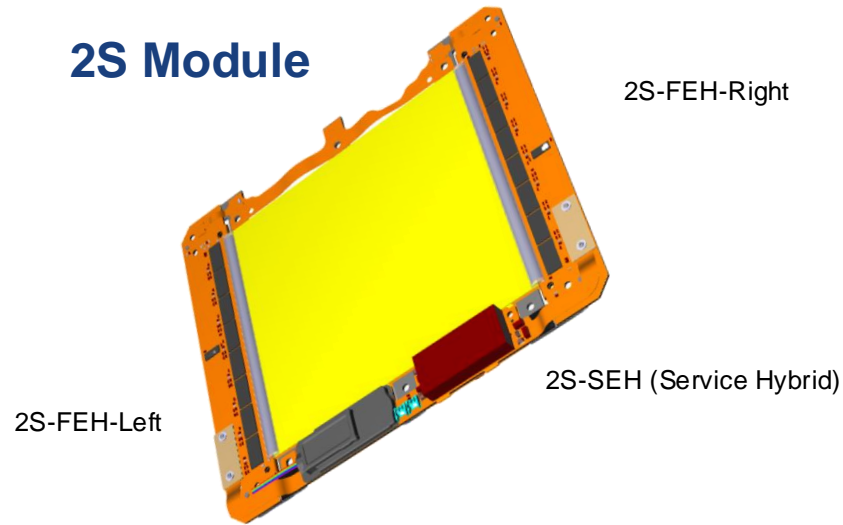


**PS Tilted Ring**

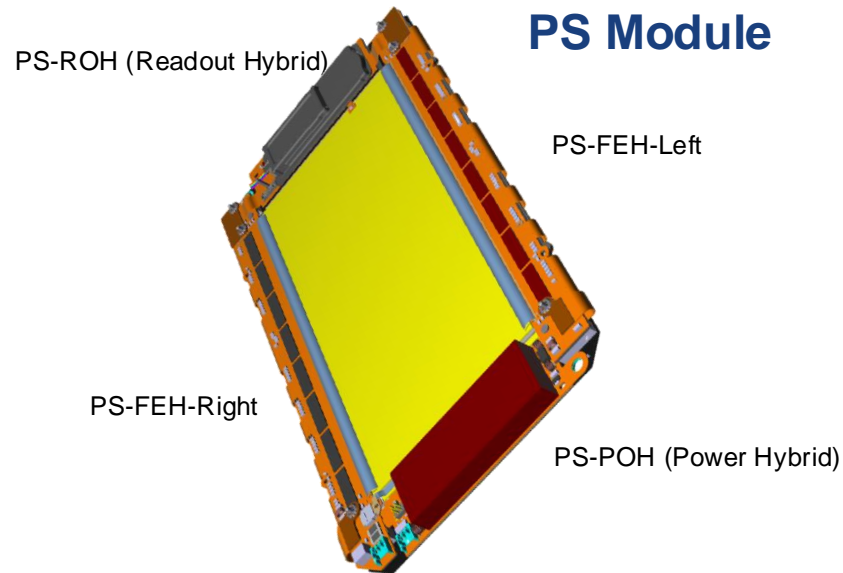


**Low  $p_T$  rejection using parallel sensors**

## 2S Module



- **Two parallel silicon strip sensors.**
  - 2 × 1016 strips, 90 μm pitch.
  - 90 cm<sup>2</sup> active area.
- **Left and Right side 2S-FEH front-end hybrids.**
  - Each based on eight CBC3.1 chips and one CIC2.1 chip.
- **One 2S-SEH service hybrid containing:**
  - DCDC converters based on one BPOL12.V6 and one BPOL2V5-V3.3 chip.
  - Optical readout based on the IpGBT-V1 and the VTRx+.

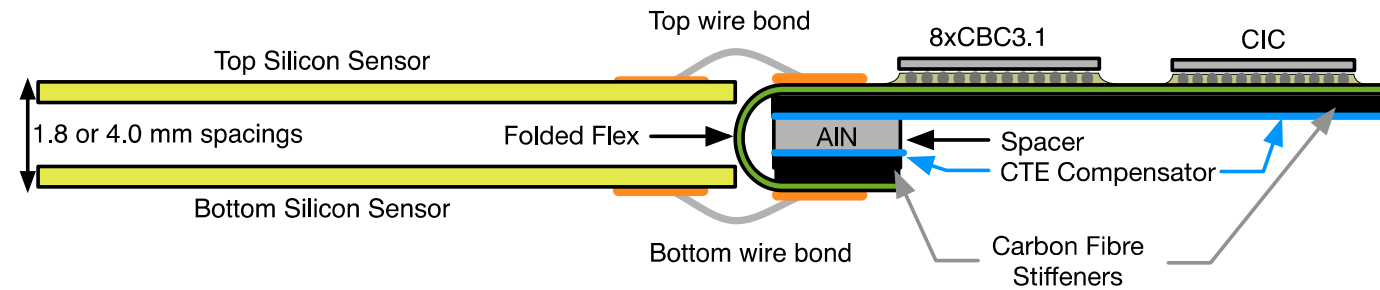


## PS Module

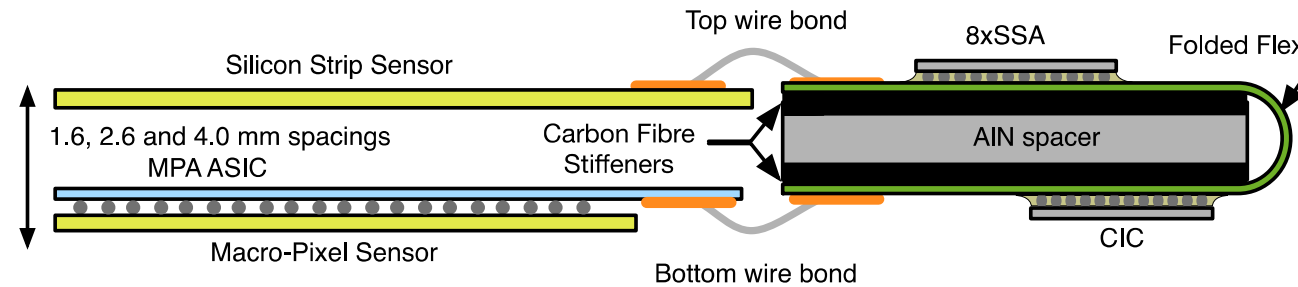
- **Silicon strip and macro-pixel sensors.**
  - 2 × 960 strips, 100 μm pitch.
  - 32 × 960 macro-pixels, 1.5 mm × 100 μm.
  - 45 cm<sup>2</sup> active area.
- **Left and Right-side PS-FEH front-end hybrids.**
  - Each based on eight SSA2.1 chips and one CIC2.1 chip, wire bonded to MaPSA array.
- **Two service hybrids:**
  - PS-POH Power Hybrid based on one BPOL12-V6 and two BPOL2V5-V3.3 chips.
  - PS-ROH Readout Hybrid based on one IpGBT-V1 chip and the VTRx+.

A total of 5 hybrid types in 18 different variants (sensor spacings, left or right sides, optical link speeds 5G or 10G).

## 2S Front-End Hybrid



## PS Front-End Hybrid



- High density interconnect: 42.5  $\mu\text{m}$  tracks width and spacing.
- Copper filled microvias on all layers: 25  $\mu\text{m}$  to 50  $\mu\text{m}$  laser drills, 110  $\mu\text{m}$  smallest capture pads.
- Tight fold.
- Carbon fibre stiffener lamination.
- High pin-count 250  $\mu\text{m}$  pitch flip chips: CBC3.1, SSA2, CIC2.1.
- High speed 90  $\Omega$  differential pairs in 150  $\mu\text{m}$  thick flex.
- All these constraints are on the technological edge for flexible circuit manufacturers.

- **Kickoff batch to start production: 210 hybrids**
  - 2S-FEH and 2S-SEH for 1.8 mm modules.
  - PS-FEH, PS-ROH and PS-POH for 2.6 mm modules..
  - Test two grounding variants for 2SSEH and PSPOH.
  - Completed in September 2023.
  - Objective: construction of 30 2S modules and 30 PS modules.
  
- **Pre-series batch: 1800 hybrids.**
  - All variants, all spacings, larger quantities.
  - Improved designs and processes.
  - Selected grounding variants for 2SSEH and PSPOH.
  - Completed in September 2024.
  - Objective: construction of 200 2S modules and 300 PS modules.
  
- **Series: 45510 hybrids**
  - All variants, all spacings, full volume.
  - Production started in September 2024, completion expected Q1 2026.

Hybrid Variant	Pre-Series		Series Production
	Kick-off batch	Rest of the batch	
2S-FEH-18-L	30	170	7350
2S-FEH-18-R	30	170	7350
2S-FEH-40-L		30	420
2S-FEH-40-R		30	420
PS-FEH-16-L		50	820
PS-FEH-16-R		50	820
PS-FEH-26-L	30	60	1450
PS-FEH-26-R	30	60	1450
PS-FEH-40-L		190	3280
PS-FEH-40-R		190	3280
2S-SEH	15 + 15	200	7770
PS-ROH 16 5G		30	540
PS-ROH 16 10G		20	280
PS-ROH 26 5G	20	30	860
PS-ROH 26 10G	10	30	590
PS-ROH 40 5G		80	1400
PS-ROH 40 10G		110	1880
PS-POH	15 + 15	300	5550

Completed

Completed

## ➤ Contamination of 2S-FEH and PS-FEH bond pads appeared as major difficulty.

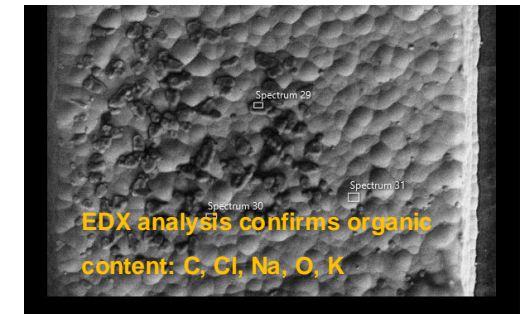
- Contamination is identified using polarized filters with coaxial light sources.
- Compromises the bondability of hybrids that must be automated.
- Cleanliness requirements were tuned with the assembly contractor,
  - Reach a production compromise
  - Stay acceptable for module assembly sites.

## ➤ Prevention actions.

- Bare hybrids:
  - Reinforced cleaning and control at flex manufacturer.
- Assembly contractor:
  - Ultrasonic cleaning upon reception, controls to avoid cross-contamination.
  - Plasma cleaning of hybrids before gluing and after reflow.
  - Visual control, manual cleaning if needed.



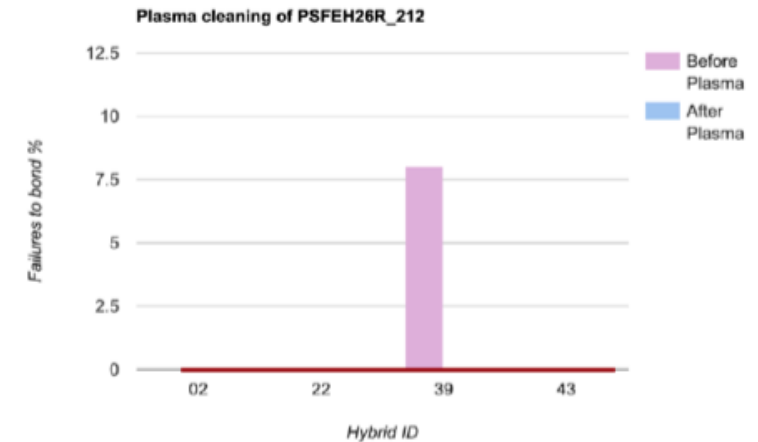
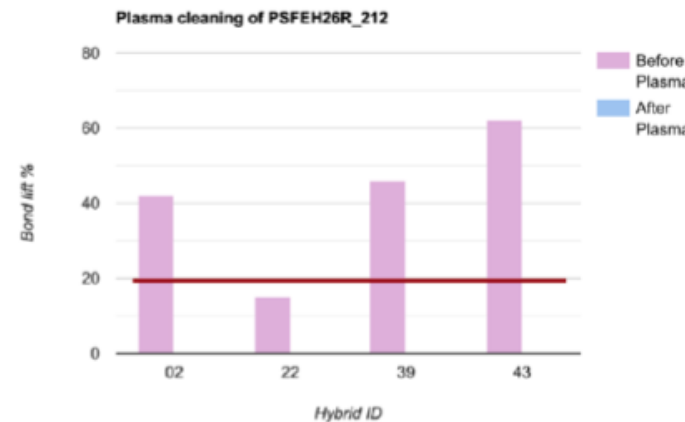
Use of polarized filters for inspection.



EDX analysis confirms organic content: C, Cl, Na, O, K

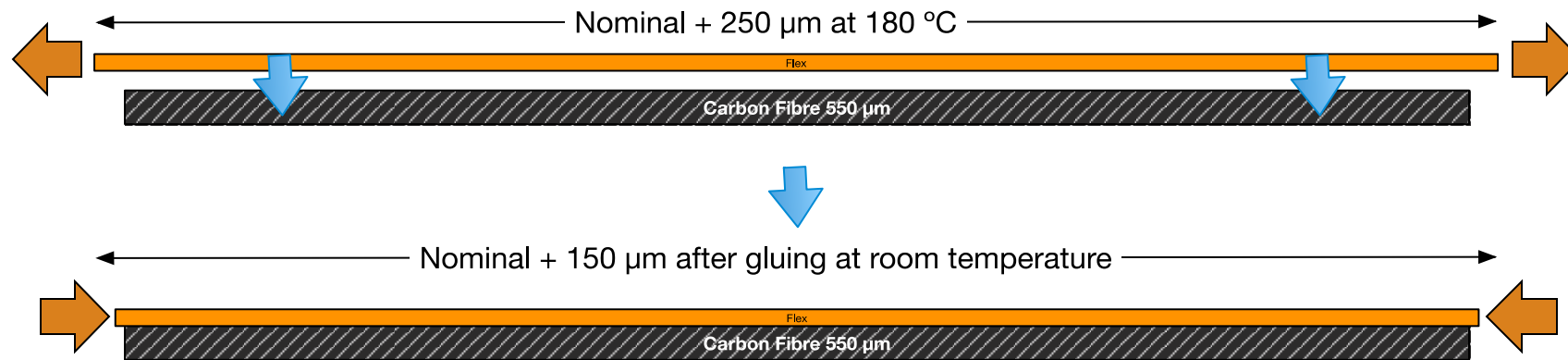
## ➤ Control at CERN.

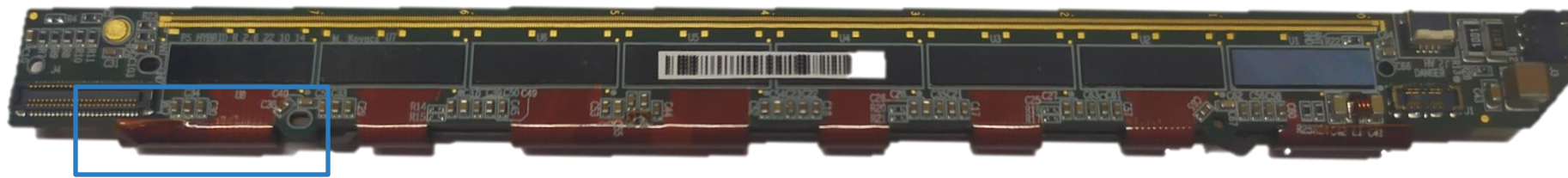
- Exhaustive visual inspection., manual cleaning if needed.
- Wire bonding tests on sample basis.
- Ar/H<sub>2</sub> plasma cleaning improves bondability.



## ➤ Elongation of hybrids caused by CTE mismatch.

- CF CTE is close to zero: no elongation at gluing.
- PI CTE close to 16 ppm/°C: hybrids elongates 250 μm during lamination made at 180 °C.
- The flex cannot recover its nominal dimension after gluing: +150 μm is normally observed at room temperature.
  - Compromises the bonding arrays: pitch errors
  - Compromises the tooling holes: misalignments.
- Compensation: 0.1% downscaling of designs for flex fabrication.
- **Measurements on pre-series units showed a resulting elongation between 50 μm and 100 μm at room temperature.**
  - Matches the required specification ± 100 μm of nominal dimension to preserve automated bonding.
  - Tooling holes cleared.

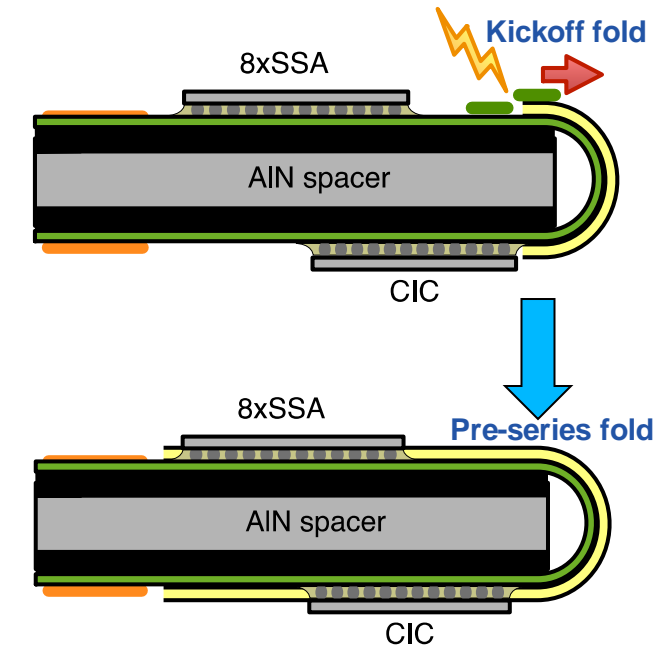
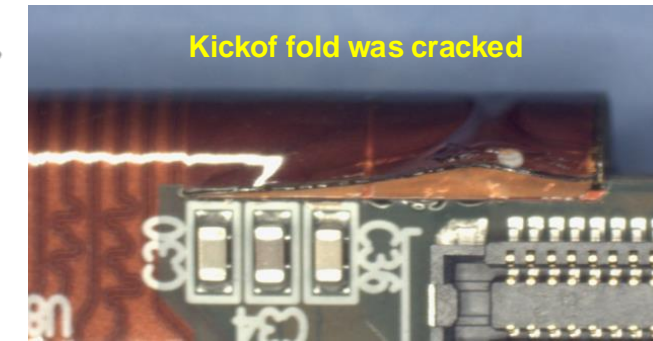




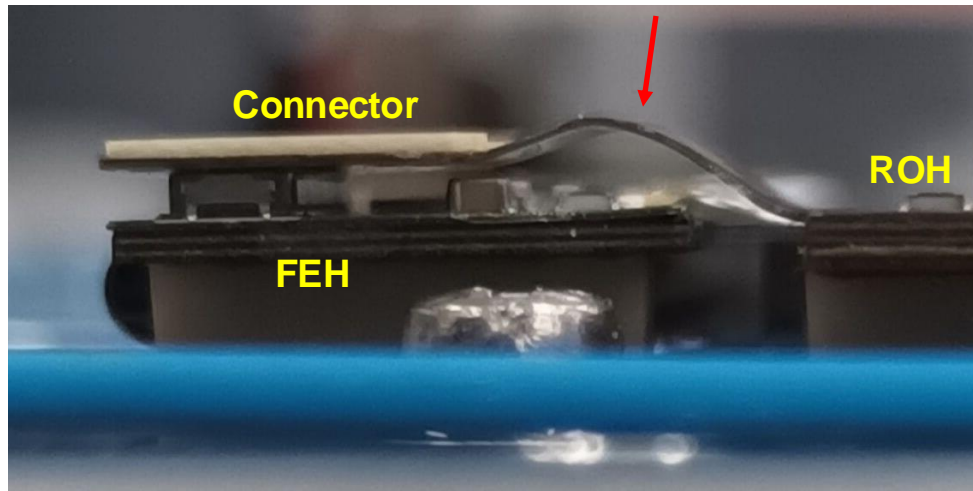
- **The PS-FEH was initially designed as a four layers flex.**
  - Coverlay in the fold-over region to prevent cracks in the fold.
  - Soldermask on the flat areas overlapping the coverlay.
  - Overlap still too close of the fold on kickoff hybrids: coverlay chipping.
  - Overlap could not be moved further: a more radical change was required for pre-series.

- **PS-FEH moved to a five layers flex for pre-series**
  - **Eliminates the overlap.**
    - Robust solution, considered low risk.
    - Required a major re-design of the six PS-FEH variants for pre-series.

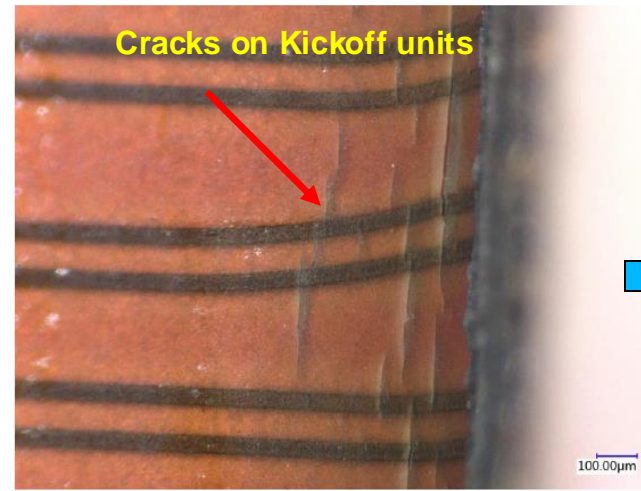
- **No more delaminations observed on pre-series.**
  - Design change definitively validated.



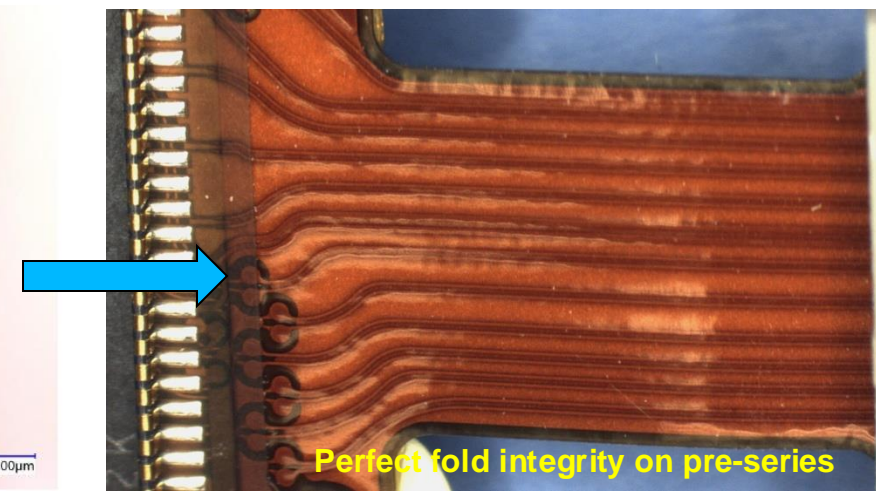
- **Cracks observed on Kickoff PS-ROH tails during module integration.**
  - Electrical discontinuities observed.
  
- **Exposition to high temperature cycles during fabrication process fragilizes the soldermask.**
  - This circuit is more exposed to high temperature cycles than the other variants.
  
- **Action for pre-series: replaced soldermask with coverlay in bottom tail area.**
  - No damages observed anymore.
  - Fully validated in pre-series units.



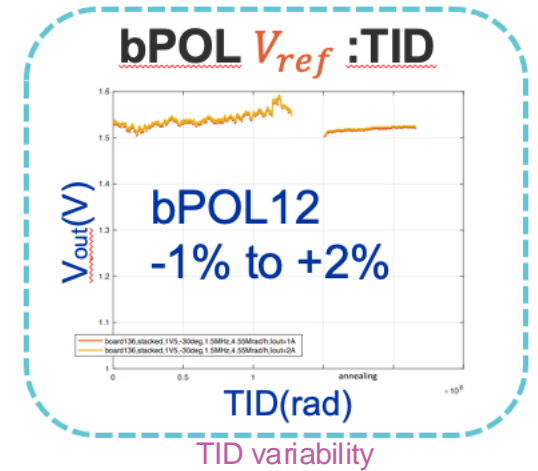
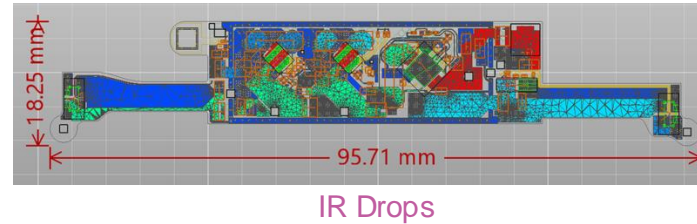
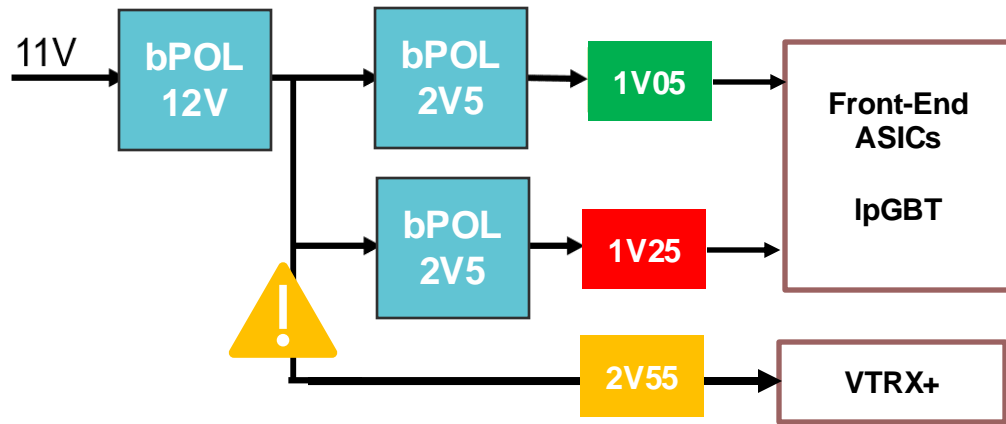
Typical tail bending



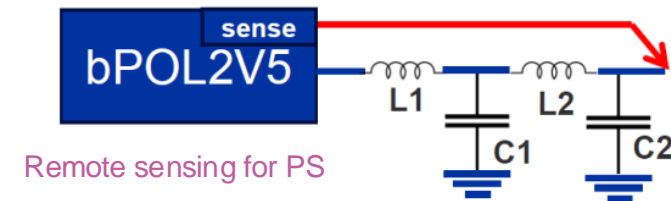
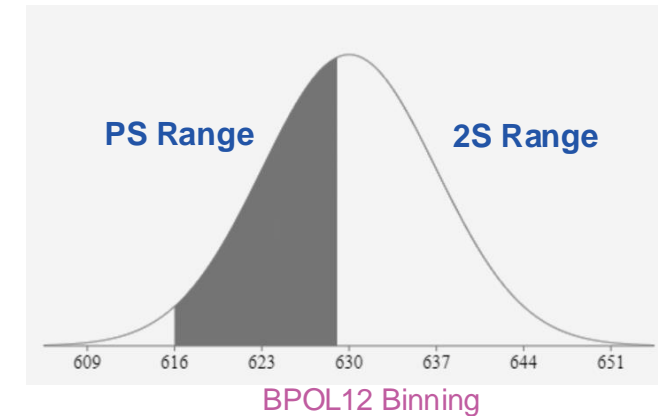
Bending tests on Kickoff PS-ROH



New tail with coverlay

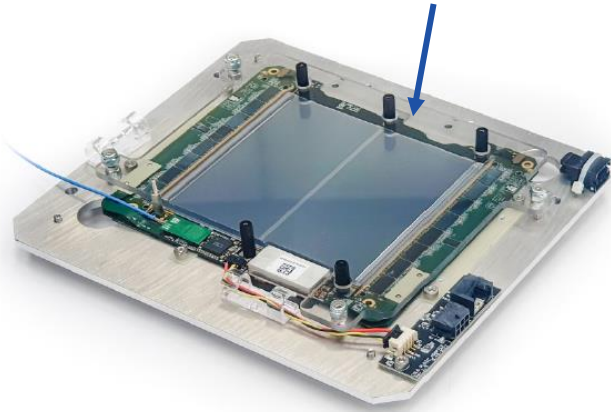


- **Tight supply voltage range required for ASICs and IpGBT.**
  - Limited by tolerances on bandgap voltage and resistors.
  - For all temperatures, radiation, voltage drops within hybrids and all operation margins.
  - 2.5V is the minimum voltage for VTRx+ and maximal voltage for BPOL2V5: colliding requirements
- **Implementation of accurate voltage setting on the 2.55V rail.**
  - Binning of the BPOL12 in two groups for 2S and PS variants, on basis of their bandgap voltages.
  - Use of 0.1% tolerance resistors for accurate output voltage setting.
  - Voltage dispersion reduced and measured to  $175 \text{ mV} \pm 20 \text{ mV}$  in a range from 2.38V min. to 2.67V max..
- **Remote sensing on PS hybrids.**
  - To compensate voltage drops on PS-POH hybrids.

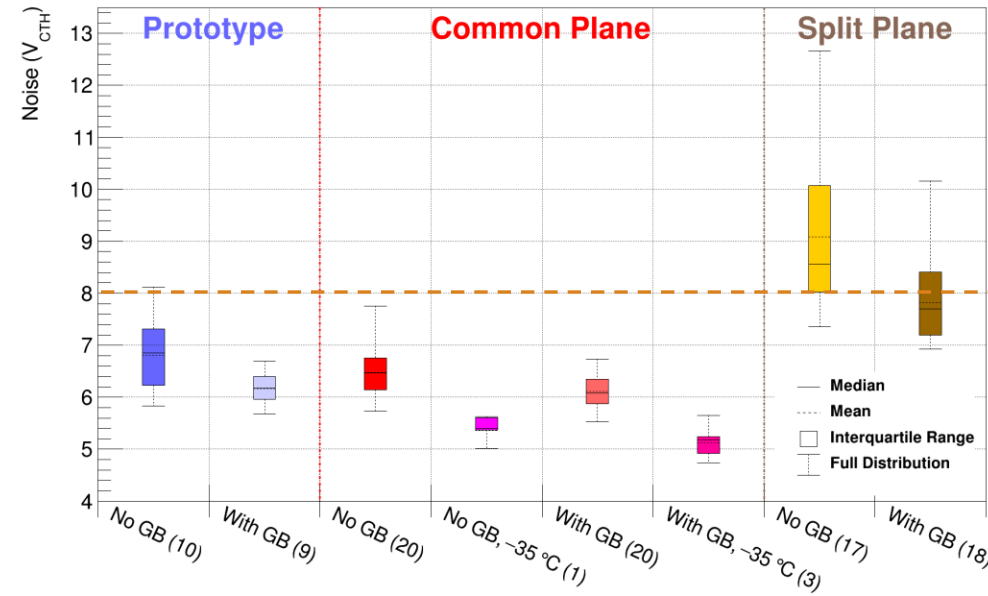


Remote sensing for PS

GB: Ground Balancer



2S Module Noise Comparison

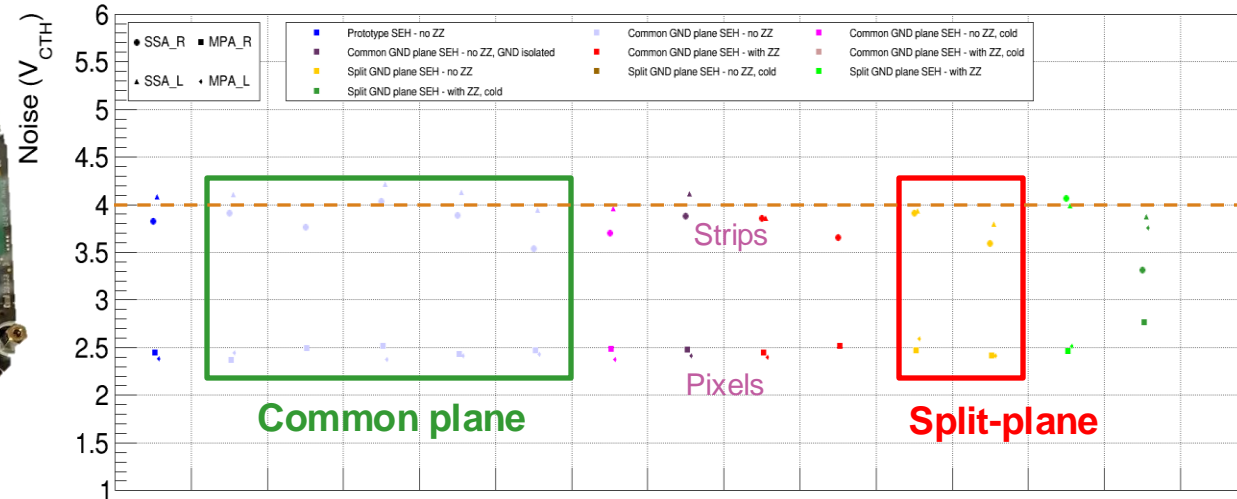


➤ **Two grounding configurations tested on Kickoff.**

- Unique ground plane for switching nodes and DC output nodes.
- Split planes (switching versus DC) interconnected at one location.

➤ **2S: lower noise with common plane.**

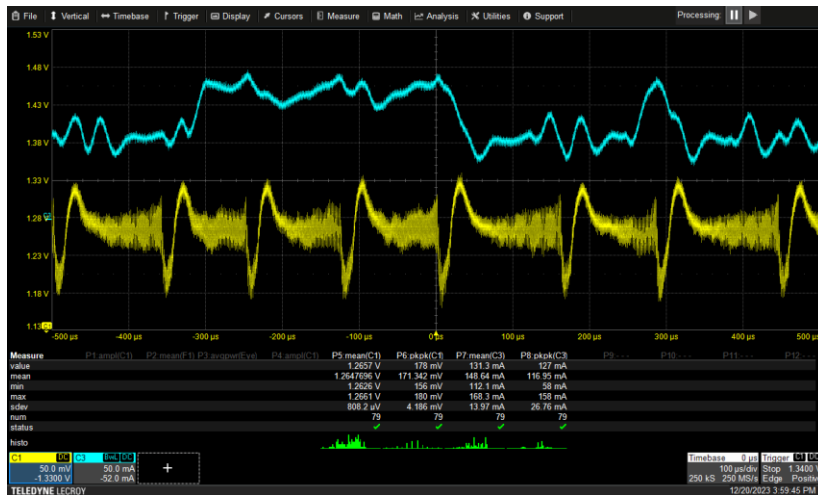
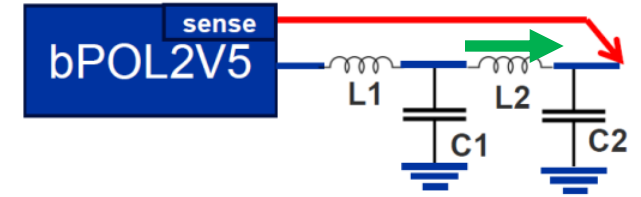
- Common plane design adopted for pre-series and series.
- A ground balancer that interconnects the grounds on left and right sides of the 2S module, helps reducing the noise.



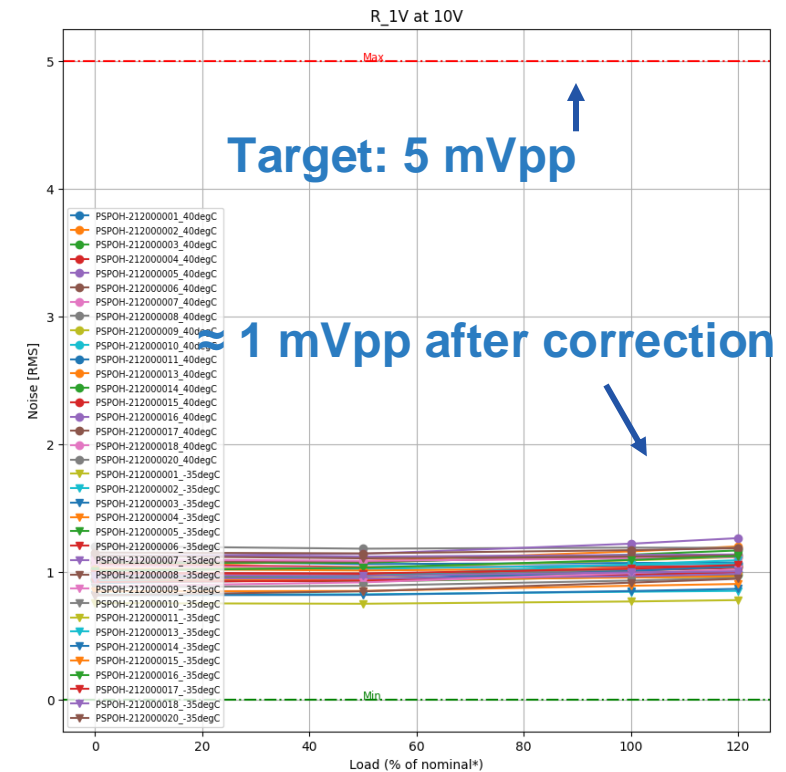
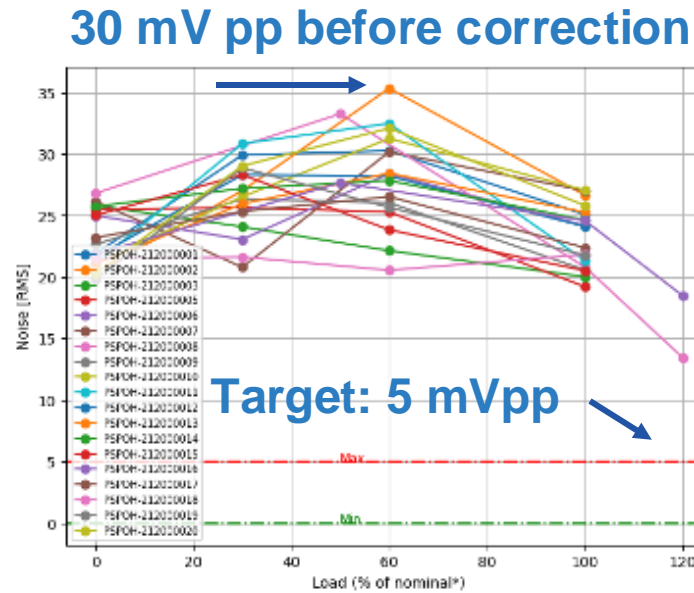
➤ **PS: no major difference.**

- Common plane design adopted for pre-series and series.

- **Excess of ripple observed on BPOL2V5 outputs on Kickoff PS-POH hybrids.**
  - Increased noise at cold operation.
  - Concern for long term operation.
  - **PS-POH implements remote sensing on BPOL2V5 after its output filter to reduce voltage drops.**
    - This scheme turned out to induce oscillations in the BPOL2V5 regulation loop.
  - **Correction: increase filter capacitors (C1, C2) and short the filter coil (L2).**
    - Ripple reduced to 1 mVpp (instead of 30 mVpp).
    - Noise performance at cold for macro-pixels fully recovered.
    - Correction applied for pre-series and series.



**Ripple at cold on Kickoff PS-POH**





➤ Visual control and functional test at contractor facilities and then at CERN.

➤ [Refer to dedicated presentation from Patryk Szydlik on this topic.](#)

*“Insights gained from test system preparation for the hybrids production for the CMS Outer Tracker Phase-2 Upgrade”.*

➤ Only hybrids that passed the visual control are functionally tested.

➤ Rejects: contamination, delamination or assembly issues on 2SFEH40 and PSFEH, caused a significant reduction of deliverables.

➤ Visual control yield: 89%.

➤ Functional testing yield: 96.

	Target	Received	Visual Control Good	Visual Control Yield [%]	Functionally Tested Hybrids	Functionally Tested Good	Functional Test Yield [%]
2S-FEH-18-L	170	119	107	91.45	100	95	95.00
2S-FEH-18-R	170	112	109	97.32	99	96	96.97
2S-FEH-40-L	30	15	10	66.67	10	10	100.00
2S-FEH-40-R	30	9	3	33.33	3	3	100.00
PS-FEH-16-L	50	40	28	70.00	16	16	100.00
PS-FEH-16-R	50	46	35	76.09	18	18	100.00
PS-FEH-26-L	60	37	27	72.97	25	25	100.00
PS-FEH-26-R	60	40	21	52.50	21	21	100.00
PS-FEH-40-L	190	172	155	90.12	153	149	97.39
PS-FEH-40-R	190	76	39	51.32	36	34	94.44
2S-SEH	200	161	161	100.00	161	160	99.38
PS-ROH-16_5G	30	30	30	100.00	14	14	100.00
PS-ROH-26_5G	30	29	29	100.00	20	18	90.00
PS-ROH-40_5G	80	70	69	98.57	41	41	100.00
PS-ROH-16_10G	20	21	21	100.00	15	14	93.33
PS-ROH-26_10G	30	30	30	100.00	30	28	93.33
PS-ROH-40_10G	110	100	96	96.00	89	82	92.13
PS-POH	300	306	288	96.00	278	263	94.60
<b>Total</b>	<b>1800</b>	<b>1413</b>	<b>1258</b>	<b>89.54%</b>	<b>1258</b>	<b>1087</b>	<b>96.28%</b>

- **The kickoff and pre-series batches for outer tracker hybrids were completed by summer 2024 on a duration of 18 months.**
  
- **The Kickoff batch on reduced set of hybrids helped resolving several issues, to achieve stable designs for pre-series:**
  - Better specification of cleanliness requirements.
  - PSFEH change to five layers to prevent soldermask to coverlay delamination.
  - PSROH replacement of soldermask with coverlay to prevent cracks in fold area.
  - Improved supply voltage accuracy through BPOL12 binning and tight tolerance setpoint resistors.
  - Selection of optimal grounding schemes on 2SSEH and PSPOH to achieve the target noise performance on modules.
  - Elimination of BPOL2V5 oscillations.
  
- **The pre-series batch was validated with all these changes, but new issues were identified that are now being resolved:**
  - Need for improvements on cleanliness, and visual control is very time consuming.
  - Delamination on PSFEH gluing joints imposing design and fabrication process reviews.
  
- **The series production is now started.**
  - Bare hybrids in production and assembly ongoing for 2S hybrids.



➤ **Hybrids are tested 100% at contractor facilities, and as much as possible at CERN.**

- The test system uses multiplexed test cards and is a major project on its own.
- Tests performed warm (+40 °C) and cold (-35 °C) in a climatic chamber.
- Results archived in production database.
- Only good hybrids are delivered to CERN.
- [Refer to dedicated presentation from Patryk Szydlak on this topic.](#)

***“Insights gained from test system preparation for the hybrids production for the CMS Outer Tracker Phase-2 Upgrade”.***

➤ **The test system was commissioned at contractor facilities.**

- Pre-series hybrids could be tested at contractor facilities and at CERN.
- **Hardware and software issues were identified and were or are still being resolved.**
  - Hardware issues: connectivity problems, optical links stability.
  - Software issues: DAQ procedures, uncertain results, repeatability of tests.

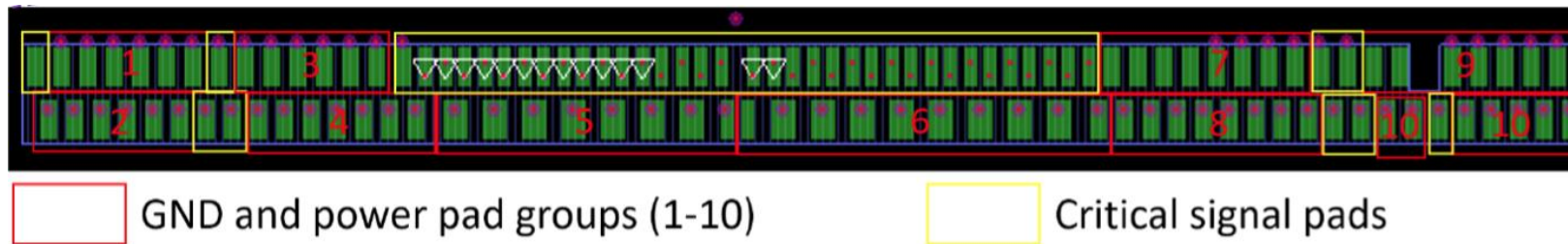
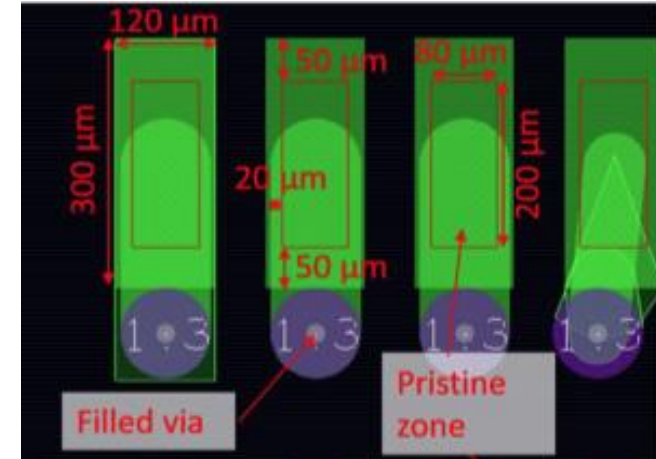
➤ **Sustained support from CERN to the contractor is required.**

- Improvements and optimization of test procedures (all ongoing).
- On-site resolution of issue discovered while using the test system.
- The test system reached readiness for volume testing.



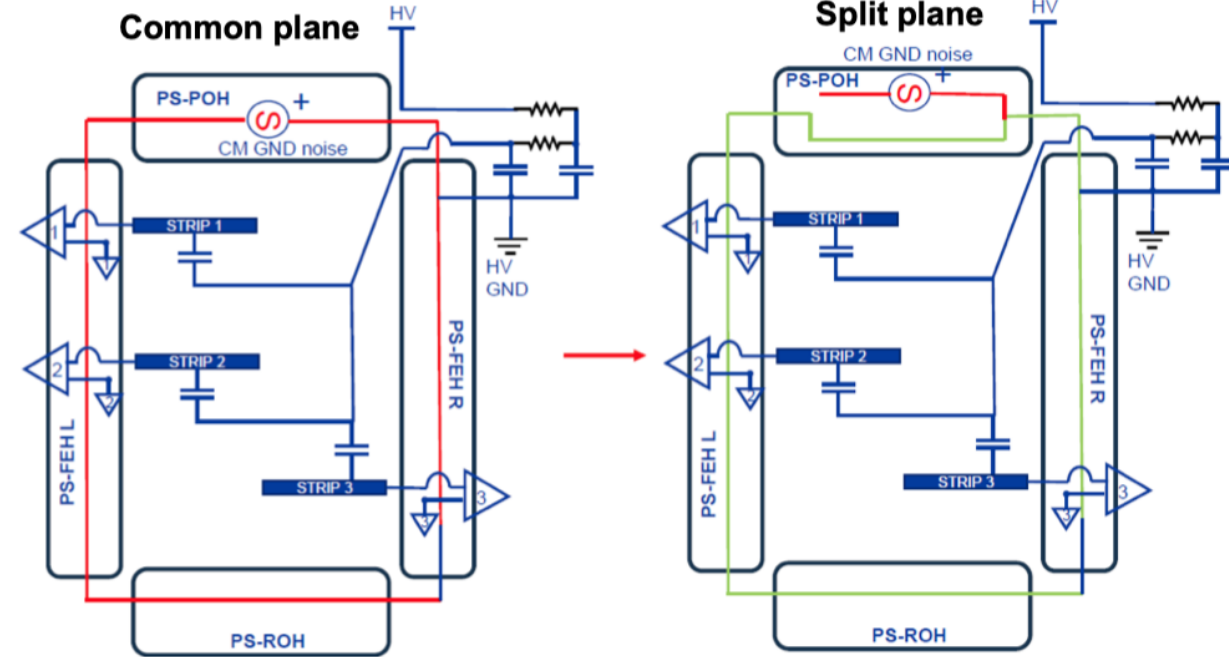
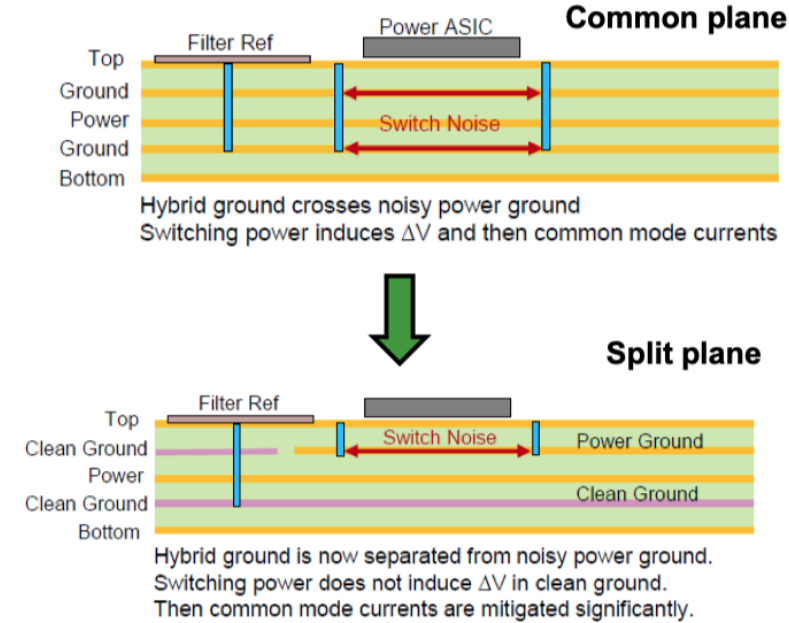
## ➤ Definitions and acceptance criteria.

- Definition of a pristine zone in the center of the bond pads.
  - Categorization of the cleanliness levels: clean, light, medium or heavy.
  - Categorization of pads cleanliness: acceptable, conditionally acceptable, rejected.
- Accept up to 10 refused bond pads on 2SFEH and PSFEH strip sensor bondpad arrays.
- Accept up to 1 refused pad on each power group (redundant pads), 10 per hybrid in total.
- No refused pads on digital signals.
- Do not exceed a combination of up to 30 conditionally accepted pads and refused pads as defined above.

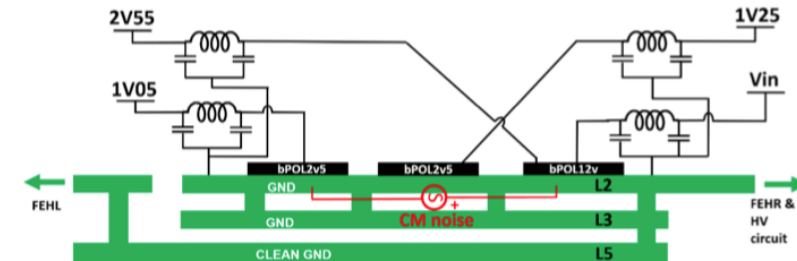


## ➤ These requirements were used by the assembly contractor for pre-series.

- Time consuming inspections at their location but also at CERN.
- Additional cleaning was sometimes still required at CERN.
- Yield reached 91% for 2SFEH (including cleaning at CERN).
- Good yield also on PSFEH, but still impacted from other problems.



- Basic idea was: in prototype designs the switching noise of the DC-DC converters propagates through the ground layer of the module
- Regular or common-plane design is similar to prototypes
- Split-plane design attempts to introduce a clean ground through which no large currents flow, and left and right module sides are referenced at a common point



**Split Plane**