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

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ABSTRACT: The CMS Tracker Phase-2 Upgrade requires the production of two co-planar strip sensor (2S) modules, and strip and macro-pixel sensor (PS) modules to cope with the requirements of the HL-LHC. Altogether 47520 hybrid circuits are required to construct 8000 2S and 5880 PS modules. The hybrids pre-production phase is now complete. A pre-series batch enabled the identification of different issues that were resolved with the completion of the pre-production. Various issues and solutions are reported.

KEYWORDS: Detector design and construction technologies and materials; Front-end electronics for detector readout; Electronic detector readout concepts (solid-state); Particle tracking detectors (Solid-state detectors)

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1 Introduction to the CMS tracker upgrade for the HL-LHC

A major upgrade of the CMS detector is required to cope with the planned luminosity of the High Luminosity LHC (HL-LHC) [1]. The development of the new front-end modules for the CMS Outer Tracker aims to provide higher granularity, lower mass and the capability for higher data rates. Rejection of low momentum tracks for the L1 track trigger is enabled in the front-end electronics by locally correlating the signals from a pair of silicon sensors [2].

The 2S modules (figure 1, left) are constructed from two co-planar strip sensors with spacings of 1.8 mm and 4.0 mm, two front-end hybrids (2SFEH) and a service hybrid (2SSEH). The PS modules (figure 1, right) consist of a strip and a macro-pixel sensor with spacings of 1.6 mm, 2.6 mm and 4.0 mm, assembled with two front-end hybrids (PSFEH), a readout hybrid (PSROH) and a power hybrid (PSPOH). The modules operate at -35°C . All hybrids are built on a flexible substrate reinforced with carbon-fiber or FR4 stiffeners in the case of the PS power hybrid. The hybrids use advanced High-Density Interconnect (HDI) flexible circuits and integrate flip-chip ASICs [3, 4].

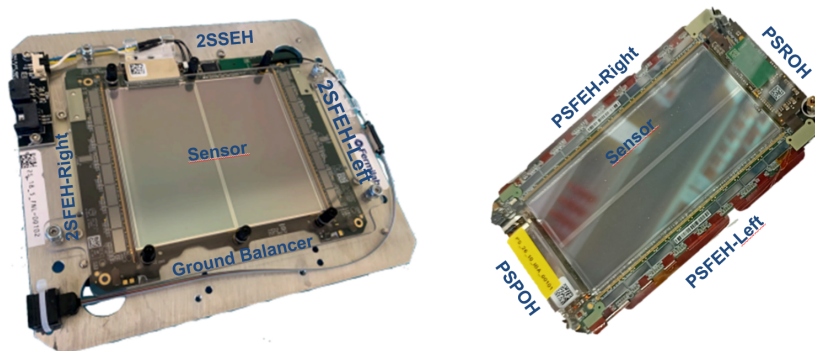


Figure 1. 2S module (left) and PS module (right).

2 Pre-series and pre-production issues

2.1 Procurement organization and volumes

A total of 24000 hybrids are required to assemble 8000 2S modules, and 23520 additional hybrids are required to assemble 5880 PS modules, covering the needs for the upgraded tracker. To address this major volume production on a timescale of two and a half years and a completion by the first quarter of 2026, the procurement plan was split into three major phases: a pre-series batch, a pre-production batch and a series production phase.

The pre-series batch consisted of subsets of hybrids enabling the assembly of thirty 1.8 mm sensor-spacing 2S modules and thirty 2.6 mm sensor-spacing PS modules. The pre-series PS power hybrids and 2S service hybrids were designed in a split-plane grounding variant, and in a common plane grounding variant [5], aiming to minimize the noise injected into the modules. Several issues were identified in this phase [6] and are described hereafter. The issues were corrected and validated with the pre-production, with the exception of contamination and delamination.

2.2 Hybrids contamination

The 2S and PS front-end hybrids contain large wire-bond pad arrays [4] whose Electroless Nickel and Immersion Gold (ENIG) surface plating must remain clean. The lamination of the carbon fiber stiffeners on hybrids exposes them to adhesive residues and stresses the bare flexible circuits. The bond arrays must present a minimal wire-bond pull force of 8g with a maximal standard deviation of 15%, and a maximum of 20% bond-lifts is allowed, all evaluated on ten pads per hybrid with 25 μm aluminum wedge bonds. The bare hybrids are also visually inspected using a coaxial light source combined with a polarized filter (figure 2) to expose the contaminated areas on a sample basis at CERN before moving forward with the assembly.

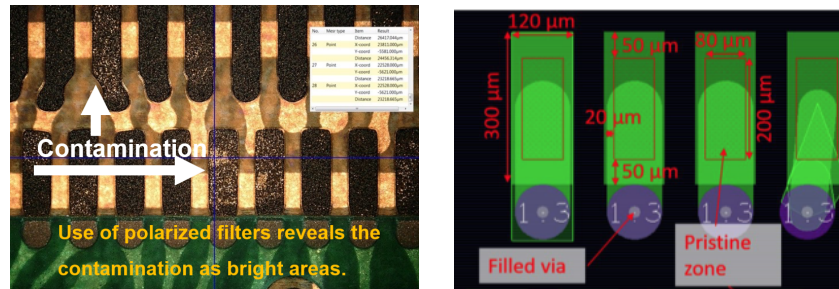


Figure 2. Identification of contaminated pads using polarized filters with a coaxial light source (left) and identification of pristine areas on bonding pads (right).

The assembly of hybrids also exposes them to further sources of contamination. The bare hybrids are cleaned in ultrasonic baths upon arrival, including regular control of the cleaning agents to avoid cross-contamination, and are screened with polarized filtered microscopes prior to assembly. The circuits undergo a fold-over gluing and curing process with custom tools, including gluing of aluminum nitride spacers when required. Next, the components are soldered on both sides of the hybrid with respective reflow processes. The bare dies are then underfilled. The assembled hybrids undergo additional cleaning phases in ultrasonic baths and are plasma cleaned. Finally, when required, a high voltage conformal coating is applied. The hybrids are again visually inspected and then delivered to CERN [2].

All the above-mentioned processes can contaminate the bond pads with adhesive and resin residues, with solder flux and with solder material, resulting in low yield. In view of the difficulties observed with the pre-series, the cleanliness requirements were reviewed for the pre-production and series batches, defining a pristine area ($80\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$, figure 2, right) in the center of the bond pads where the bond foot sit. The pads are categorized as accepted, conditionally accepted or rejected based on their contamination level. An acceptance criterion is introduced, allowing a certain number of rejected or conditionally accepted pads. This allowed increasing the acceptance yield without compromising the bondability of modules. The cleanliness of hybrids continues to be a critical aspect for volume production.

2.3 Fold-over integrity

The pre-series PSFEH hybrids were designed as four-layers circuits [3]. Their fold-over area has a folding radius as low as 0.72 mm, exposing the soldermask in this region to crack. A coverlay was used instead in the folding area, overlapped by the soldermask on the flat areas (figure 3). Delamination at this interface appeared on the pre-series hybrids. As the coverage could not be made larger or the overlap moved further inside the flat areas, the pre-production PSFEH hybrids were modified to a five-layers design. The full top layer now covered with a plain polyimide layer and the absence of soldermask to coverlay overlap eliminated the delamination (figure 3).

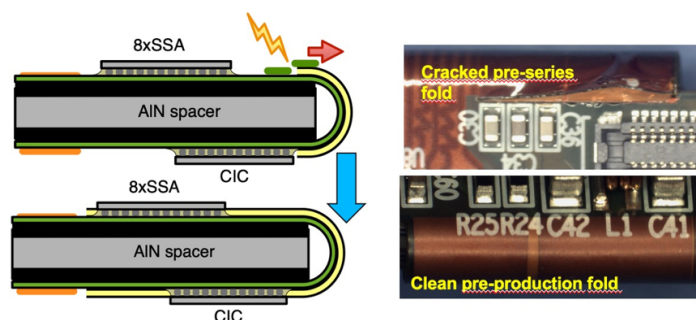


Figure 3. Development of a crack in the overlap of the soldermask with the coverlay area (top), resolved with a change to a five layers design that removed this overlap (bottom).

The PSROH hybrids have two flexible tails to be shaped to connect to the PSFEH. A soldermask was used in the tails of the pre-series hybrids. During module construction, electrical discontinuities appeared on tracks routed through the tails after a couple of folds. The PSROH circuit is more exposed to thermal stress during its fabrication (two reflows, three glue curing cycles) that weakens the soldermask causing it to crack during the shaping of the tails. The fragile bottom soldermask was then replaced with a coverlay for pre-production (figure 4): this eliminated the development of cracks and preserved the electrical continuity along the tracks.

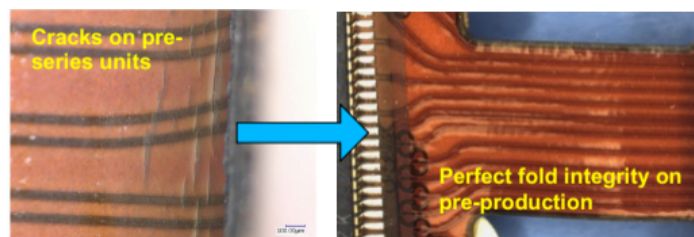


Figure 4. PSROH tails cracks suppressed using coverlay in pre-production.

2.4 Supply voltage tuning

All ASICs within the 2S and PS modules must be powered in their operating range, for all load conditions, at room temperature and at -35°C , and up to the expected lifetime radiation levels. This required voltage tunings on the front-end, service and power hybrids on basis of the output voltage distributions of the BPOL2V5 DC-DC stages [5, 7]. Those are powered by a single BPOL12-V6 DC-DC [8] stage that delivers 2.5 V and powers also the VTRx+ optical module. The maximal input voltage for the BPOL2V5 is set to 2.5 V, while the VTRx+ required a minimal supply of 2.5 V: a compromise on a narrow supply voltage that still enables the module operation over its lifetime is required. This was achieved by using 0.1% tolerance resistors to set the BPOL12 output voltage; however, the dispersion of the BPOL12 bandgap voltage ($\pm 3.2\%$ around a nominal voltage of 630 mV) turned out to be excessive to achieve the required voltage margins. To reduce the 2.5 V voltage dispersion, the 16000 production BPOL12 ASICs were then sorted on the basis of their bandgap voltages, forming one group for PS modules with a bandgap range of [615.8 mV; 628.7 mV], and a second group for 2S modules with a bandgap range of [628.7 mV; 651.6 mV] (figure 5). The dies having bandgap voltages beyond these ranges (6.25% of the full lot) were rejected. Altogether, a compromise in the supply range comprised between 2.38 V and 2.67 V compatible with the modules operation was achieved for all modules [5].

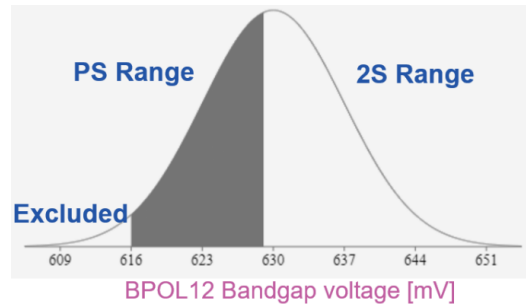


Figure 5. Sorting of BPOL12 ASICs on the basis of their bandgap voltage.

The PS module is the most power-demanding module (9.7 W per module); it requires also two low voltage outputs (1.2 V and 1.0 V). The PSPOH hybrid therefore hosts two BPOL2V5 stages (instead of one on the 2SSEH) that result in a power layout more exposed to internal voltage drops. To compensate for this, the BPOL2V5 stages in the PSPOH are designed to regulate the output voltage close to the connectors in a remote sensing scheme, instead of the usual regulation at proximity of the BPOL2V5 die used in the 2SSEH. The voltage supply range along a full PS module was successfully measured for all front-end dies.

2.5 Optimal grounding

The mitigation of noise developed in the 2S and PS modules was addressed on several fronts, with the introduction of resistive elements in the high voltage bias lines, with the addition of a grounding balancer linking the two 2SFEH grounds in a 2S module, but also evaluating two grounding schemes in the 2SSEH and PSPOH [9]: a common ground plane variant that had a unique ground layer for DC outputs and switching power currents, and a split plane variant that separated the DC ground from the switching current ground, linked at a common point.

Several 2S pre-series modules were characterized at room temperature and at cold ($-35\text{ }^{\circ}\text{C}$), and with or without the ground balancer [9]. The noise is evaluated in terms of threshold voltage DAC units (V_{CTH}). The common ground variant reached a noise level of $6.5 V_{\text{CTH}}$, like the noise obtained with prototypes at room temperature, further reduced to $5 V_{\text{CTH}}$ at cold operation and using the ground balancer. The split plane variants with the ground balancer delivered a noise of $8 V_{\text{CTH}}$. Therefore, the common ground variant was selected for the continuation of pre-production. Similarly, several PS modules were also characterized. No major difference in noise was observed when comparing the common and split ground variants, reaching noise levels of $4 V_{\text{CTH}}$ for the strip sensor and $2.5 V_{\text{CTH}}$ for the macro-pixel sensor in cold operation. These noise levels were within requirements, and, for consistency, the common ground PSPOH was selected.

2.6 BPOL2V5 oscillations

At cold operating temperatures, a ripple of 30 mV_{pp} (figure 6) was observed at the BPOL2V5 outputs in PS modules, leading to an increase of the macro-pixel noise. This excess of ripple appeared as an oscillation in the BPOL2V5 output that could induce long term reliability issues. The phase and gain margin analysis and simulations revealed the presence of an instability originating in the remote sensing scheme implemented in the PSPOH. Shorting the pi filter coil ($L2$) and increasing the filter capacitances to $40\text{ }\mu\text{F}$ ($C1$) and $47\text{ }\mu\text{F}$ ($C2$) eliminated the oscillation: the ripple was reduced to around 1 mV_{pp} .



Figure 6. BPOL2V5 cold oscillations and correction of the remote sensing scheme.

2.7 Delamination

The fold-over of the 2SFEH and PSFEH is glued with the H70E-4 epoxy adhesive. The hybrids are folded with a dedicated tool, pressed and cured at $125\text{ }^{\circ}\text{C}$ for a duration of one hour, followed by two reflow cycles that expose the fold-over joint to thermal and mechanical stress. The PSFEH26 and PSFEH40 contain an aluminum nitride spacer in the fold to obtain the correct sensor spacing. This spacer contains various cavities that reduce the gluing area of the fold. Delamination in the glue joint (figure 7), sometimes peeling away the first ply of the carbon fiber stiffener, were observed, resulting in a long-term reliability concern and compromising the hybrid bondability. The increase of the curing temperature to $150\text{ }^{\circ}\text{C}$ partially improved the gluing strength. The control of the glue bond line thickness using micro ceramic balls and the extension of the gluing area in the spacer are currently being explored.

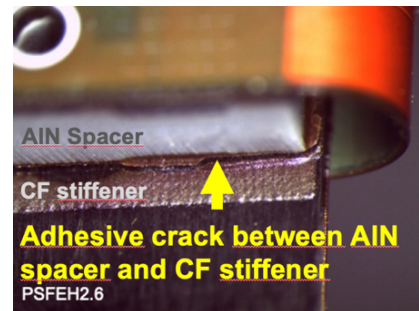


Figure 7. PSFEH delamination of adhesive joint between Aluminum Nitride spacer and Carbon Fiber stiffener.

3 Conclusion

The pre-series allowed the identification of several design and manufacturing issues that were mostly resolved for the launch of the pre-production. Major design changes were introduced in the PSFEH and PSROH with the replacement of soldermask with coverlay or polyimide layers. The noise performance was significantly improved with the choice of proper grounding schemes, and with the stabilization of the DC-DC stage in the PSPOH. Narrow powering ranges for the VTRx+ and the BPOL2V5 ASICs were set with the BPOL12 sorting. The contamination was and still is the most difficult issue to resolve, requiring significant cleanliness management and visual control at all locations. The development of delamination in the PSFEH folds is also a major concern, still under investigation today. Nevertheless, more than 1400 hybrids were finally delivered achieving satisfactory yields in terms of visual control and functional testing for the start of this complex and challenging production of more than 45000 hybrids.

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