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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 for the completion with the pre-production. Various issues and solutions will be reported.

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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 for the completion with the pre-production. Various issues and solutions will be reported.*

KEYWORDS: Manufacturing; Front-end electronics for detector readout; Detector design and construction; technologies and materials.

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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 of (10 × 10) cm^2 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) are more complex, consisting of a strip and a macro-pixel sensor of (5 × 10) cm^2 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 PS readout hybrid provides communication with the back-end while the PS power hybrid hosts the DC-DC power converters that power the module. In the 2S service hybrid these two functions are combined in the same circuit. The front-end hybrids host the front-end readout ASICs and concentrator ASICs on both module types. The modules operate at -35 ºC. 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].

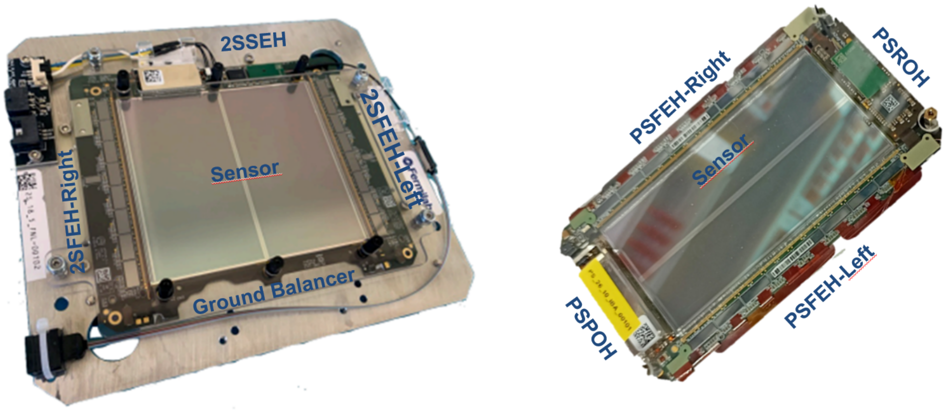


Figure 1: 2S module (left) and PS module (right).

2. Pre-production objective and issues

2.1 Pre-production 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 construction with approximately five percent spare hybrids to address eventual losses during module construction and tracker assembly. To address the major volume production of these hybrids 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 two different variants to minimize the noise injected into the modules, in a split-plane grounding version, and in a common plane grounding version [5]. Several issues were identified in this frame [6], and were corrected and approved with the pre-production, excepting the 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 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 a randomly selected subset of ten pads per hybrid with 25 µm aluminum wedge bonds. The lamination of the carbon fiber stiffeners on hybrids exposes them to adhesive residues and stresses the bare flexible circuits. The bare hybrids are evaluated for bondability and 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.

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 tested 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].

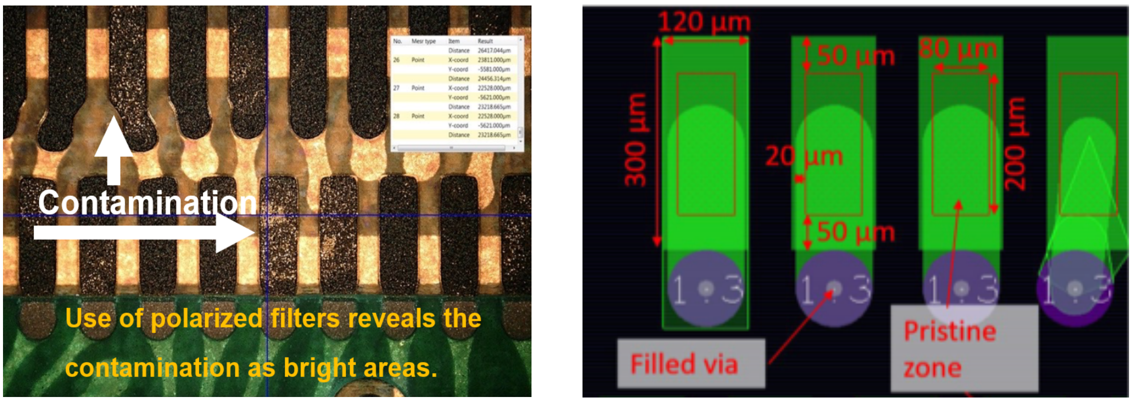


Figure 2: identification of contaminated pads using polarised filters with a coaxial light source (left) and identification of pristine areas on bonding pads (right).

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. A review of the cleanliness requirements for the pre-production and series batches allowed defining a pristine area (80 µm × 200 µm, figure 2, right) in the center of the bond pads where the bond foot sit. The pads are then 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 hybrids qualified in this way are currently being evaluated by module assembly sites. The cleanliness of hybrids continues to be a critical aspect for volume production. For instance, the effectiveness of plasma cleaning was evaluated at CERN, with significant bondability improvements when using an Ar/H_2 based plasma.

2.3 Registration and stretch

The polyimide flexible circuit has a thermal expansion coefficient (CTE) of 16 ppm/ºC while the carbon fiber where they are glued has a CTE close to zero. The gluing of the flexible circuit to the stiffener requires a curing at 180ºC which results in the thermal expansion of the flex by approximately 250 µm on its stiffener. After curing, the flexible circuit cannot recover its nominal dimensions and ends up stretched in a range of 150 µm. To compensate for this effect, bare circuits are produced with a downscaling factor of 0.1%. Measurements on pre-production units showed a final elongation between 50 µm and 100 µm at room temperature and matches the required tolerance of ± 100 µm. The stretch also compromises the location of holes and the registration of layers: the registration and clearing of holes is verified upon reception at CERN on dedicated testing jigs for pass-through tests.

2.4 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). This major change also allowed improving the power distribution along the hybrid.

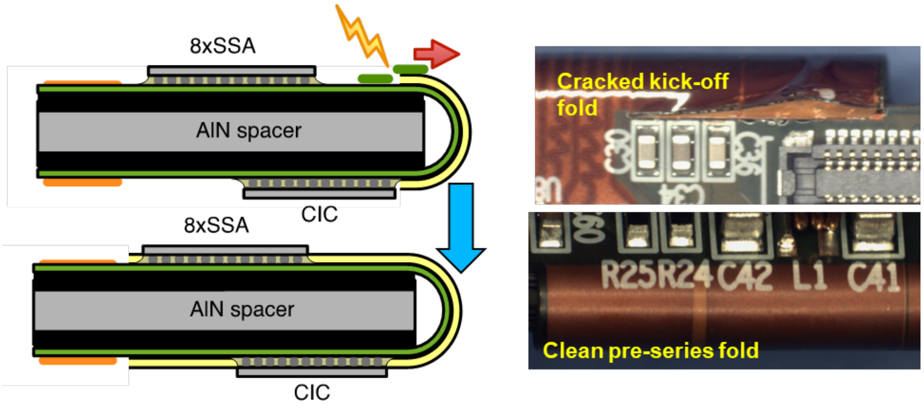


Figure 3: development of a crack in the overlap of the soldermask with the coverlay area (top), resolved with a change to a five layers design that removed this overlap (bottom).

The PSROH hybrids have two flexible tails to be shaped to connect to the PSFEH. A soldermask was used on the top and bottom layers 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.

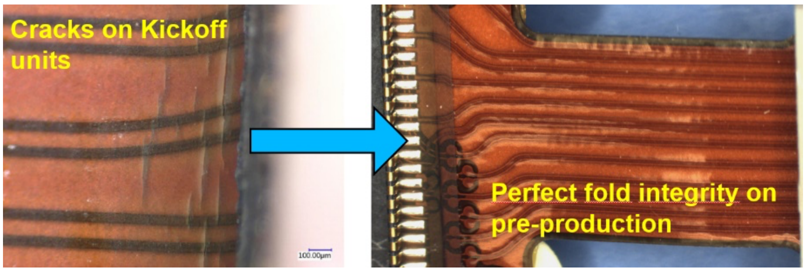


Figure 4: PSROH tails cracks suppressed using coverlay in pre-production.

2.5 Power integrity 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 ºC, and up to the expected lifetime radiation levels. This required power integrity 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 2.5V and powers also the VTRx+ optical module. The maximal input voltage for the BPOL2V5 is set to 2.5V, while the VTRx+ required a minimal supply of 2.5V: a precise supply voltage is required to minimize the deviations from these opposed minimal and maximal operating supplies. This was achieved by using 0.1% tolerance resistors to set the BPOL12 output voltage; however, the dispersion of the BPOL12 bandgap voltage (±3.2% around a nominal voltage of 630 mV) turned out to be excessive to achieve the required voltage margins for 2S and PS modules. In order to reduce the 2.5V voltage dispersion, the full production lot of the BPOL12 ASICs (around 16000 ASICs) was then sorted on the basis of their bandgap voltages, forming one group for PS modules with a bandgap range of [615.8mV; 628.7mV], and a second group for 2S modules with a bandgap range of [628.7mV; 651.6mV] (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 2.38V and 2.67V was achieved for all modules [5].

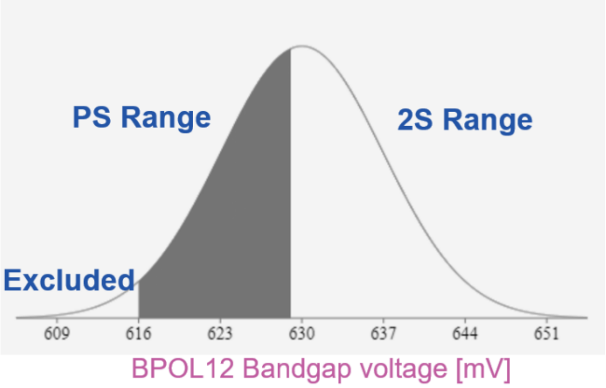


Figure 5: sorting of BPOL12 ASICs on the basis of their bandgap voltage.

The PS module is the most power-demanding module (9.7W per module); it requires also two low voltage outputs (1.2V and 1.0V). The PSPOH hybrid therefore hosts two BPOL2V5 stages (instead of one on the 2SSEH) that result in a more challenging 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 so-called remote sensing scheme, instead of the usual regulation at proximity of the BPOL2V5 die used in the 2SSEH. The power integrity along a full PS module was successfully measured for all front-end dies.

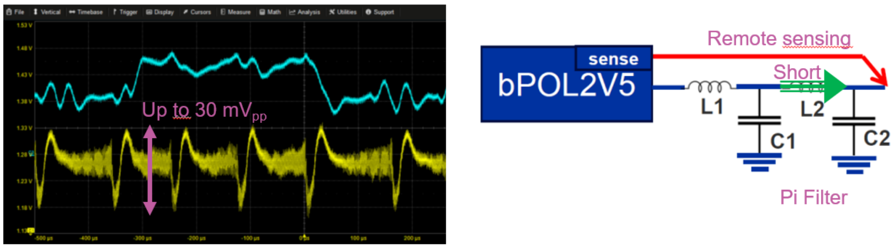
2.6 Optimal grounding

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 introduction of a grounding balancer linking the two 2SFEH grounds in a 2S module, but also employing two grounding schemes in the 2SSEH and PSPOH [9]. For these two pre-series hybrids, two grounding variants were evaluated: 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 -35 ºC, 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_{CTH}, like the noise obtained with prototypes at room temperature, further reduced to 5 V_{CTH} at cold operation (-35 ºC) and using the ground balancer. The split plane variants with the ground balancer delivered a noise of 8 V_{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_{CTH} for the strip sensor and 2.5 V_{CTH} for the macro-pixel sensor in cold operation. These noise levels were within requirements, and, for consistency, the common ground PSPOH was selected to continue with the pre-production.

2.7 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 µF (C1) and 47 µF (C2) eliminated the oscillation: the ripple was reduced to around 1 mV_{pp}.



Ripple at cold on Kickoff PS-POH

Remote sensing correction

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

2.8 Delamination

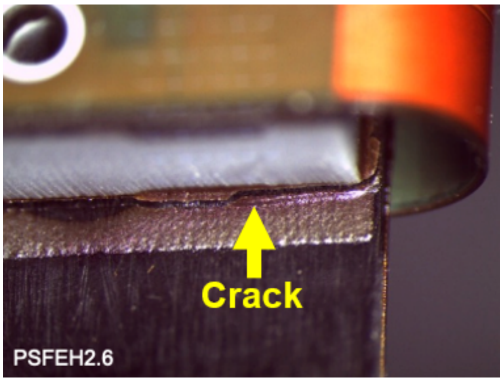


Figure 7: PSFEH delamination.

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 ºC 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 ºC 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.

3. Testing and acceptance

All the pre-series issues reported here were corrected and approved for the pre-production that aimed to produce 1800 hybrids. The losses caused by flex circuit manufacturing initial issues and contamination reduced this amount down to 1413 hybrids. All hybrids were passively thermally cycled twenty times between +50 ºC and -35 ºC and were also functionally tested at the contractor facilities [10]. The test results were stored in the CMS tracker production database. The hybrids that successfully passed the tests were delivered to CERN.

All hybrids were visually inspected at CERN and a yield of 89.5% was obtained, the losses being localized on the 2SFEH40 and PSFEH variants (contamination, delamination). The PSPOH, PSROH and 2SSEH achieved a visual control yield between 96% and 100%. The hybrids that passed the CERN visual inspection were also functionally tested and a total yield of 96.3% was achieved. The testing infrastructure required several adjustments to resolve various testing and data acquisition issues.

4. 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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