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Hybrid designs and kick-off batch production experience for the CMS Phase-2 Upgrade

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Abstract: The CMS Tracker Phase-2 Upgrade requires the production of new sensor modules to cope with the requirements of the HL-LHC. The two main building blocks of the Outer Tracker are the Strip-Strip and Pixel-Strip modules. All-together 47'520 hybrid circuits will be produced to construct 8'000 Strip-Strip and 5'880 Pixel-Strip modules. The circuit designs for the mass production were fine-tuned and kick-off batches were manufactured to verify the latest changes in the designs before the series production. This contribution focuses on lessons learned from the prototyping stage, design optimization details for the mass production as well as test results and production yield from the kick-off batches.

Keywords: Data acquisition circuits; Front-end electronics for detector readout; Manufacturing; Radiation-hard electronics

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1 Introduction of the CMS Phase-2 upgrade

In the framework of the CMS Tracker Phase-2 upgrade, a new Outer Tracker detector will be constructed from brand new silicon sensor modules to cope with the new requirements of the HL-LHC [1]. There are two main types of these modules: Strip-Strip (2S) and Pixel-Strip (PS).

In the central part, the 2S modules are mounted on structural elements to form a ladder (figure 1 top), while the PS modules are mounted on structures called "planks" and "rings". On the rings, the modules are inclined at different angles to point towards the interaction point (figure 1 bottom). In the forward region, at small angles to the beam direction, both 2S and PS modules are mounted on "Dee"-shaped structures orthogonal to the beamline with the PS modules mounted close to the beamline and the 2S modules in the outer regions. The detector modules introduce on-module transverse momentum discrimination, which governs the module architecture with a double-silicon sensor sandwich [1]. To enable this and fulfil the low mass and high thermal conductivity requirements

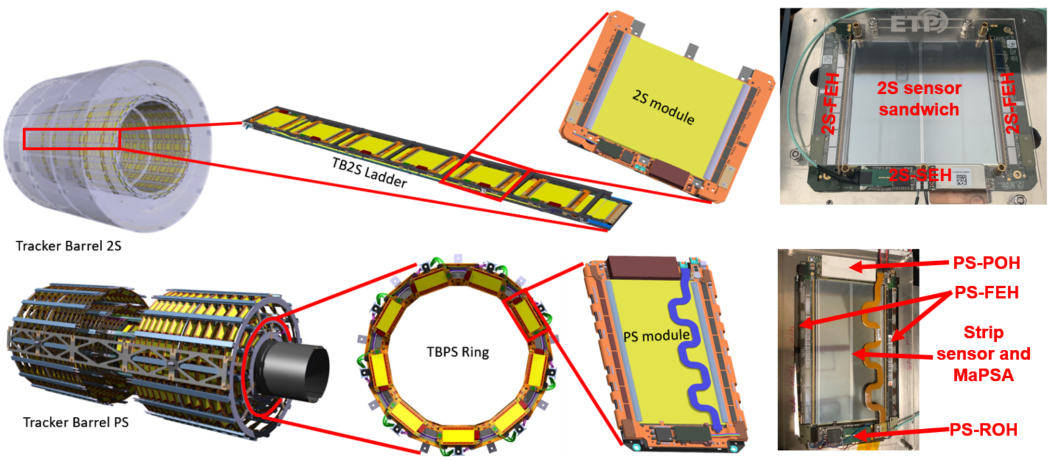

Figure 1. Different types of modules in the Outer Tracker (left) and the 2S and PS module prototypes (right).

of the detector, flexible circuits are used with carbon-fibre stiffeners. This configuration allows for a module where the wire-bond pads of the silicon sensors and the front-end hybrids are in the same plane for both sensors, enabling an optimal configuration for wire-bonding.

The 2S module is using three hybrid circuits (figure 4 right). The strip sensor sandwich is wire bonded to two 2S front-end hybrid circuits (2S-FEH). These circuits are then interconnected through high density connectors to the service hybrid (2S-SEH) which provides powering and the data communication between the FEHs and the back-end systems [2]. The different elements of the 2S module are illustrated in figure 2 in a cross-section of a half module.

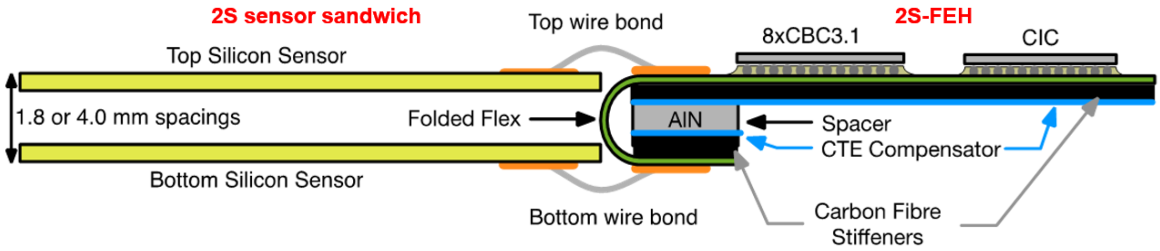

Figure 2. Cross-section of a half 2S module.

The PS modules are constructed from four hybrids (figure 4 left) and a sensor sandwich. The sensor sandwich is made from a macro-pixel sub-assembly, which consists of the macro-pixel silicon sensor bump-bonded to eight Macro Pixel ASICs (MPA), and a silicon-strip sensor. Two front-end hybrids (PS-FEH) are wire-bonded to the sandwich on the top and bottom sides. In the case of the PS module, power and data communication are provided by two separate circuits: PS-POH and PS-ROH respectively [3].

2 History of the hybrid development

The hybrid development for the Phase-2 Tracker Upgrade goes back to 2013 when the first prototype hybrid (figure 3a)) was manufactured [4]. At that time a market survey was prepared to find companies on the market that were able to manufacture High Density Interconnect (HDI) circuits. These HDI circuits require linewidth and spacing of 45 µm/45 µm, respectively and copper-filled microvias with capture pad size of 110 µm and 25–50 µm drill. The next stage of the development focused on prototype hybrids and modules. The 8CBC2 hybrid (figure 3b)) was designed and manufactured to test the module concept with flexible circuits. This prototype was glued with double-sided tape to a carbon-fibre stiffener. It was read out through a zero-insertion-force connector and used the CMS Binary Chip V2 (CBC2) ASIC [5].

As the ASIC development advanced, it allowed for new prototypes, such as the 8CBC3 (with CBC V3) hybrid with data concentrator (CIC) mezzanine (figure 3c)). These hybrids enabled the community to build realistic module prototypes and carry out beam test studies [6].

During these prototyping steps, some serious issues, such as delamination from the carbon-fibre stiffeners, had to be resolved to establish the recipe for the final build-up of the hybrids [7]. Once all hybrid types were successfully prototyped at least once, the project stepped into the invitation to tender phase, where the companies for the mass production were selected. In this phase, kick-off hybrid batches were produced to verify the last changes that were made on the prototype designs. These hybrids are illustrated in figure 4.

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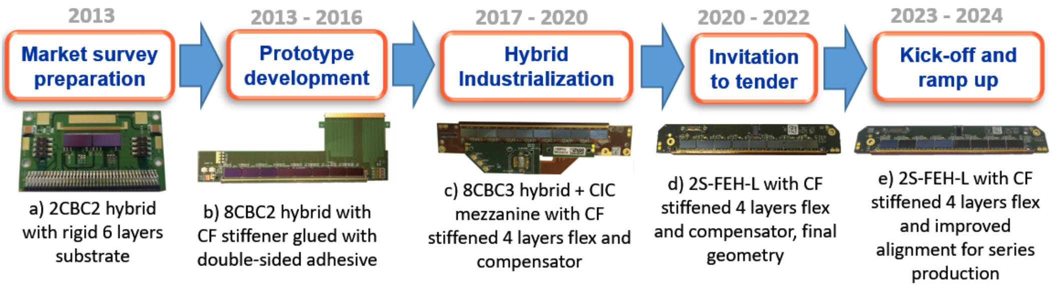

Figure 3. History of the hybrid development project and the prototypes of the 2S hybrid family related to it.

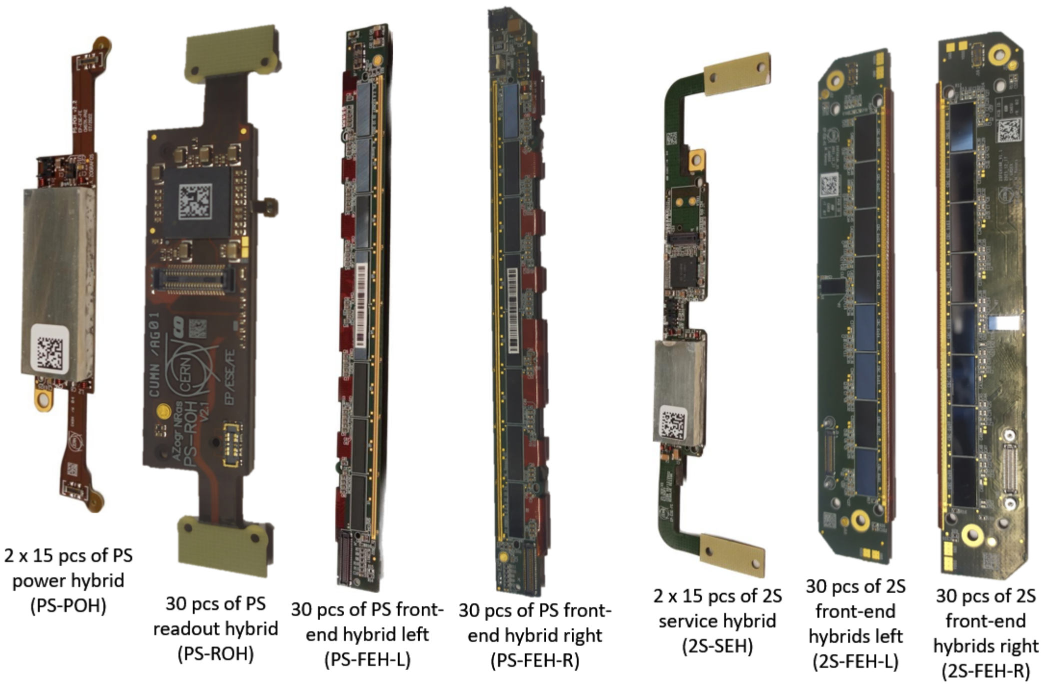

Figure 4. Hybrids from the kick-off batch production, PS family to the left and 2S family to the right.

3 Design changes and evaluation of the kick-off hybrids

The first step of the evaluation is the visual inspection which looks for damage, missing or incorrectly assembled components, and contamination on the wire-bond pads. Functional tests check the correctness of the assembly and the interconnections in the hybrids. After this, prototype modules are built where the mechanical and functional compatibility with other module components is tested. In case issues are found, corrective actions are taken.

3.1 PS-POH, PS-ROH and 2S-SEH circuit design changes

The PS-POH and ROH as well as the 2S-SEH have similar functionalities and therefore the changes in their designs were similar. The PS-ROH circuit needed only minor changes compared to the last prototype versions, mainly to improve the flexibility of the connector tails. These changes proved satisfactory and this design is now finalised for series production.

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The DCDC converter blocks of the PS-POH and 2S-SEH circuits were re-designed as their noise performance was slightly worse than the detector requirements.

A detailed noise study was carried out [8] to understand what was causing the noise and how it could be reduced. Due to the findings and recommendations of the study, the new kick-off PS-POH and 2S-SEH designs were made in two versions. A regular version with improvements in the GND connectivity (figure 5 left) and a split-plane version which had the GND plane under the DCDC converters connected in only one point to the other GND planes of the circuit.

In addition to this change, the 2S-SEH was redesigned for the kick-off production with staggered vias instead of stacked vias (figure 5 right). This was required as cracked vias were found during the prototype testing. According to supplier studies, the staggered vias should have a 20-fold higher reliability compared to stacked vias.

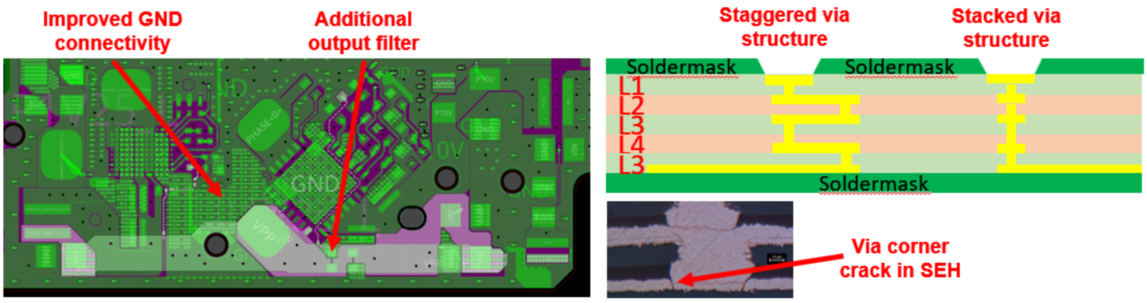

Figure 5. Improved top layer metal of the 2S-SEH (left), stacked vs staggered vias (top right) and a cracked stacked via in previous 2S-SEH prototypes (bottom right).

3.2 Evaluation of the PS-POH, 2S-SEH and PS-ROH kick-off circuits

Extensive noise tests of the 2S-SEH and PS-POH (illustrated in figure 6) showed that the noise performance of the split-plane hybrids was worse than expected, while the regular, but improved version of the 2S-SEH had slightly better noise performance compared to the prototype 2S-SEH. The regular PS-POH had a noise performance similar to that of the prototype version. The redesign from stacked vias to staggered vias in the 2S-SEH was transparent and no performance issues were discovered. Further testing is foreseen to demonstrate that the circuit reliability is sufficient for correct detector operation over its lifetime. For both the 2S-SEH and PS-POH, the regular versions with improved GND connectivity were selected for the mass production.

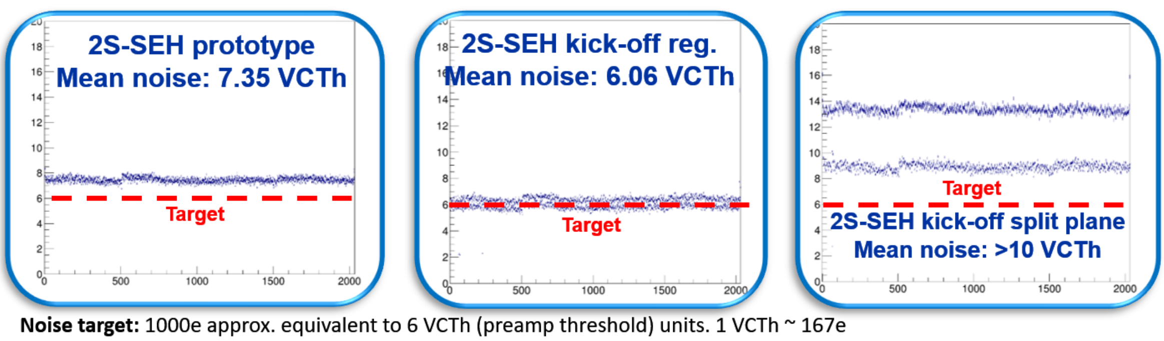

Figure 6. Noise measurement results of the 2S-SEH kick-off hybrids.

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3.3 Design changes of 2S-FEH and PS-FEH circuits

The kick-off designs of the 2S-FEH and PS-FEH had less significant changes compared to the hybrids described in section 3.1. Both circuits were equipped with new alignment holes, reserved for the alignment of the carbon-fibre stiffener and compensator during the lamination process. This was expected to improve the alignment of the stiffeners and keep the assembly tooling holes clear of adhesive. Additionally, the 2S-FEHs were equipped with a new power connector. The connector allows for a GND interconnection between the right and left sides of the 2S module and proper grounding of the aluminium carbon-fibre bridges. The PS-FEH coverlay was modified to cover a larger area in the stiffened part of the circuit to reduce the risk of delamination and cracking at the overlapping parts of the solder mask and the coverlay.

3.4 Evaluation of 2S-FEH and PS-FEH kick-off circuits

The evaluation of the 2S and PS FEHs showed that the newly introduced alignment holes were effective to improve the stiffener alignment and the cleanliness of the assembly tooling holes. No damage was observed on the PS-FEHs related to the newly introduced ears hosting the new alignment holes. The additional power connector on the 2S-FEHs was proven to be effective to decrease the noise of the modules, by interconnecting the GND between the left and right-side hybrids with a dedicated flexible circuit designed and produced for this purpose. Due the success of these changes, no further adaptation of the 2S-FEH kick-off design was deemed necessary.

For the PS-FEH the improvement of the coverlay was, however, insufficient to prevent delamination in all locations as in certain cases space constraints did not allow for a larger area coverage. An example of this delamination next to the data connector on the hybrid is shown in figure 7a). Due to this problem, all the PS-FEH variants were re-designed to a five-layer build-up in order to eliminate the need for a coverlay in the bend zone (figure 7c) and d)). In this arrangement the fine traces are routed in the L1 inner layer and are protected by the polyimide core of the L1-L2 layers (figure 7b)). Due to the staggered via structures, a significant change to the routing of the hybrid was required to adapt it to the five-layer build-up. The pre-series production of the PS-FEH is based on this new design and is currently in progress.

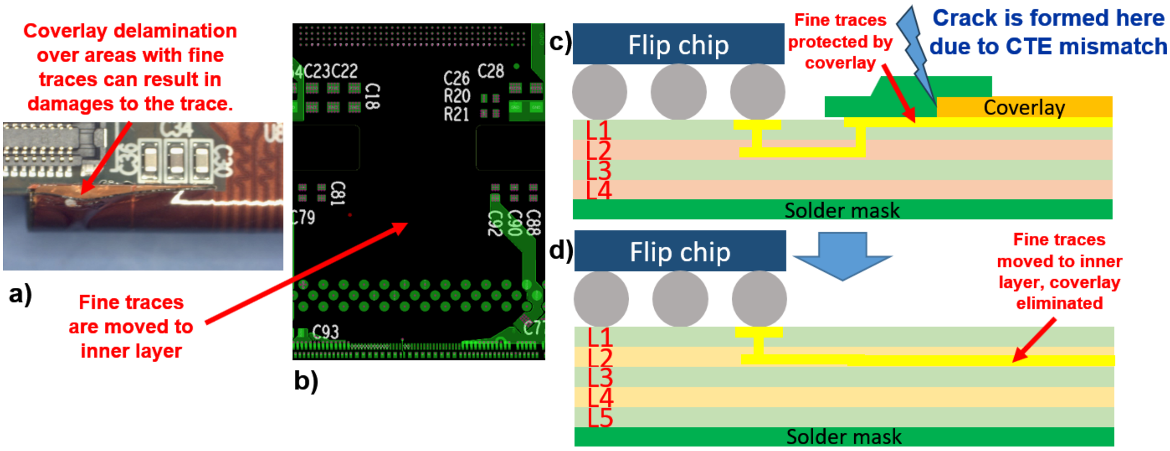

Figure 7. a) Coverlay delamination; b) sensitive area after moving to a five-layer design; c) cross section of four-layer design; d) cross section of five-layer design.

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4 Yield of the kick-off batch hybrids and assembly related issues

The yield values for the kick-off production are indicated in table 1. These are calculated based on the combination of visual inspection (VI) and functional testing results. The columns named "yield for prototyping" and "yield for production" are based on different criteria applied to the cleanliness of the wire-bond pads and the assembly tooling holes. The yield was mainly affected by three issues related to the circuit assembly. One required the rework of the 2S-SEH and PS-POH due to incorrect resistor divider values mounted during the assembly. Some hybrids were damaged beyond repair during this rework. The second issue was the wrong alignment of the fold-over part of the 2S-FEH. This misalignment reduced the assembly tooling hole size in the circuits to an unacceptable level, resulting in a 0% acceptance for these hybrids. Although, the yield must be improved for some variants, the source of the problems has been identified and the necessary corrective actions are being implemented in the pre-series production.

Table 1. Yield of the kick-off hybrids (VI: Visual inspection).

	No. of hybrids received	**VI accepted for proto.**	**VI accepted for prod.**	**Passed functional testing**	**Yield for proto.**	**Yield for prod.**
2S-FEH-18-L	26	23	0	24	85%	0%
2S-FEH-18-R	29	24	0	29	83%	0%
2S-SEH regular	17	17	16	9	60%	60%
2S-SEH split-plane	23	23	6	19	96%	26%
PS-FEH-26-L	33	33	0	*	*	*
PS-FEH-26-R	29	25	0	*	*	*
PS-POH regular	20	20	20	19	95%	95%
PS-POH split-plane	18	18	17	18	100%	94%
PS-ROH-26 5G,10G	34	34	31	32	94%	94%

*Full quantity is not yet tested.

5 Summary

All hybrid types for the CMS Phase-2 Outer Tracker Upgrade were manufactured and tested during the kick-off campaign. These designs incorporated changes required to correct previously identified issues related to via reliability and alignment hole blockage. The kick-off batches allowed these designs to be successfully validated in all cases. Two variants of the 2S-SEH and PS-POH were tested and compared in terms of noise performance. The regular design variant was selected for the pre-series for both hybrid types. In the case of the PS-FEH, a redesign to a five-layer build-up was needed to address coverlay delamination issues. All hybrid designs for the pre-series production are now validated and submitted for production.

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