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Reduction of technical constraints in the hybrid circuit acceptance for the CMS Phase-2 Outer Tracker Upgrade

M. Kovacs,[a,*] **M. Abbas**,[d] **I. Ahmed**,[e] **D. Andreou**,[a] **G. Blanchot**,[a] **R. Carnesecchi**,[a] **B. Harrop**,[g] **M. Hassouna**,[f] **T. Hussain**,[h] **K. Klein**,[c] **M. Krzyzowska**,[b] **M. Mohammadi Najafabadi**,[d] **S. Musaed**,[f] **P. Szydlik**[a] and **F. Piernas Diaz**[a]

[a] *CERN,*
CH-1211 Geneva 23, Switzerland

[b] *Wroclaw University of Science and Technology,*
27 Wybrzeze Wyspianskiego st., 50-370 Wroclaw, Poland

[c] *Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen,*
Templergraben 55, 51056 Aachen, Germany

[d] *Institute for research in fundamental sciences, Tehran Province,*
Bahonar Sq, RF69+2XF Niavaran Building, Tehran, Iran

[e] *National Institute of Chemical Physics and Biophysics,*
Akadeemia tee 23, 12618 Tallinn, Estonia

[f] *Lebanese American University,*
Beirut 03797751, Lebanon

[g] *Princeton University,*
Princeton, NJ, U.S.A.

[h] *National Centre for Physics,*
Q529+233, National Centre for Physics Rd, Islamabad, Pakistan

E-mail: mark.istvan.kovacs@cern.ch

Abstract: New sensor modules are currently being produced for the Tracker in the CMS Phase-2 Upgrade. These Strip-Strip and Pixel-Strip modules are the two main building blocks of the Outer Tracker. All together 8000 Strip-Strip and 5880 Pixel-Strip modules will be constructed and their construction requires the production of 47520 hybrid circuits. Despite careful preparation of the specifications for the hybrid circuit manufacturing, actual production experience demonstrated the need to reduce and optimize some of the requirements. The proceeding will focus on two example cases where the original requirements were analysed and made less stringent while still fulfilling the project requirements.

Keywords: Manufacturing; Detector design and construction technologies and materials; Radiation-hard electronics; Data acquisition circuits

*Corresponding author.

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Contents

1 Introduction to the CMS Tracker Phase-2 upgrade

New particle detector modules are being built in the CMS Tracker Pase-2 Upgrade, to adapt to the new requirements of the HL-LHC [1]. The two main detector module types are the Strip-Strip (2S) and Pixel-Strip (PS). These modules consist of mechanical elements, electronic circuits, and silicon sensors, glued and interconnected together. In both module types a sensor sandwich is interconnected to the front-end hybrids by the means of wire-bonds. The main function of the front-end hybrids is to collect and process the hits generated by the particles passing through the silicon sensors. The front-end hybrids have high-speed digital signals routed to the Service and Readout hybrids to pass the digitized data to the serializer ASIC that transmits this data through a high-speed optical link to the back-end systems. Altogether, 8000 Strip-Strip and 5880 Pixel-Strip modules will be constructed and their construction requires the production of all-together 47520 hybrid circuits.

Once the modules are assembled, repairs are nearly impossible, therefore strict Quality Control (QC) procedures have been defined and the requirements are written in a technical specification that serves as a reference for the circuit production and QC. The modules that pass the QC made by the assembly centres are then mounted on a ladder and on structures called “rings” and “planks” with various angles [2]. The core track finding elements of CMS, the Tracker Barrel and Endcaps will be constructed from these parts. The detector modules are introducing on-module transverse momentum discrimination, which governs the module architecture with a double silicon sensor sandwich [1].

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2 The importance of a well-defined specification for the manufacturing of electronics for high-energy physics projects

With the growth in complexity and size of high-energy physics projects, the manufacturing of the electronics is becoming increasingly complex as more advanced technologies and solutions are required to satisfy the physics requirements of the project. In our example, the hybrid circuits use multiple custom-made components, such as plastic core coils, custom electromagnetic shields, Application Specific Integrated Circuits (ASIC), and special non-ferromagnetic mechanical components. The design of the flexible substrate of the circuits requires High Density Interconnect (HDI) technology, with feature sizes that are not covered by most of the current industrial standards. On top of this, the circuits are reinforced with a carbon fibre stiffener and a compensator to provide high stiffness, thermal conductivity and, excellent flatness for the assembly of flip-chip ASICs [3, 4].

The manufacturing of the circuit quantities mentioned in section 1, required a carefully drafted specification to cover all the technical and organizational aspects of the project. We carried-out a careful analysis of the applicable standards and applied several of them: IPC-2223D, IPC-2226A, IPC-JPCA-4104, IPC-6013D, IPC-4552A, IPC-A-600K and IPC-7094. However, many aspects, like the wire-bond pad cleanliness, circuit dimension and assembly tolerances, impedance, assembly procedures, etc. had to be defined in the customized part of the specification. For these custom requirements, we paid attention to not over-specify them, but at the same time keep the project protected against manufacturing issues. Despite these efforts, during the production of the circuits, it turned out that some of these criteria were too difficult to meet and could be loosened or modified to improve the manufacturing yield, while keeping the hybrid circuit quality still sufficiently good for use in the detector. In the following two paragraphs we discuss two examples where the constraints were re-evaluated.

3 Changes in the wire-bond pad cleanliness and inspection criteria

During the first production iterations of the 2S and PS Front End Hybrids, many production lots had excess contamination leading to a high rejection rate (40–50%).The circuit producer and the assembler were notified about the problem, but in the original cleanliness specification the inspection method and equipment were not specified and the suppliers could not find the same contamination patterns as we did at CERN, owing to a difference in the inspection methods and the equipment. To correct this, we added a section to the technical specification defining the visual inspection parameters and tools.

3.1 Definition of visual inspection parameters and tools

In this new part, we defined an inspection under normal lighting conditions and an inspection with polarized lighting conditions. We defined that the hybrid body and pads (except for wire-bondable pads) shall be inspected using regular light and the wire-bondable pads shall be inspected with the optimal polarization setting that is achieved by rotating a $1/4\lambda$ polarizing filter until the clean pad areas reach the darkest visible tone. For the inspection under polarized light, only the coaxial light source shall be used. For both inspections 45–60 X magnification is considered as the optimal setting. With lower magnification, some contaminants might not be visible, while with higher magnification some irrelevant contamination could appear significant.

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Additionally, we defined the recommended hardware configuration, specifying the microscope model and accessories. Based on these recommendations the suppliers procured additional equipment and were able to observe the same issues as we did at CERN.

3.2 Analysis of the correlation of wire-bonding pull-force values with optically visible contamination levels

After the suppliers implemented the inspection recommendations mentioned in section 3.1, they were able to analyse their processes and identify some of the root causes for the contamination. Corrective actions, such as duplicated automated and manual cleaning were introduced, but despite these actions, the reject rates were still high in some cases.

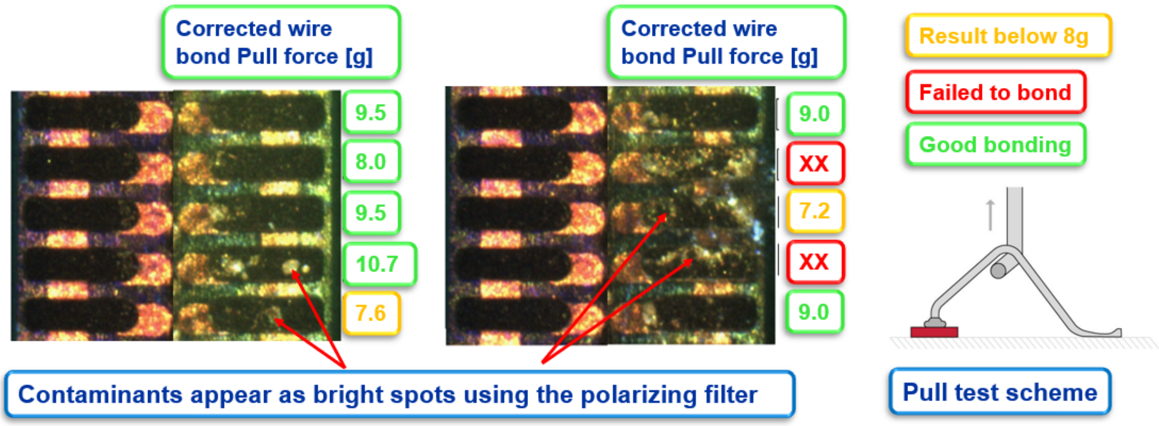

Figure 1. A correlation was found between the pull-test results and the level of contamination. While many of the heavily contaminated pads visible in the left picture were still wire-bondable and would result in a useable hybrid, some of those in the right picture were not and would cause loss of channels.

To reduce the losses in the production, we decided to analyse the impact of the different contamination levels on the weld of the wire-bonds, with the intention of easing the acceptance criteria. To test this, we wire-bonded samples with contamination and we pull tested the wires. Some of the forces measured in this test are illustrated in figure 1. Based on this result, we concluded that despite a certain level of contamination, it is possible to wire-bond the pads and in most of the cases the pull forces remain above the criteria defined by the collaboration. These criteria define a minimum of 8g corrected pull force with maximum 1g RMS and less than 20% bond lifts in the tested number of pads. These values are applicable in the case of aluminium wedge bonding with 25 µm diameter bond wires. The tested wire-bond pads and the hybrids are plated with Electroless Nickel-Gold (ENIG) with 5–6 µm nickel and 0.05–0.1 µm gold thickness. These criteria were defined to achieve a reliable wire-bond connection over the expected lifetime of the detector (10–15 years) and limit the loss of analogue channels due to the disconnection of a wire bond due to aging [5].

3.3 New approach in the wire-bond pad inspection criteria

Each 2S-FEH contains 2032 analogue wire-bond pads and 12 ground wire-bond pads. The PS-FEH contains 936 digital, 960 analogue, six ground, and one high voltage wire-bond pads. The original acceptance criteria allowed for a maximum of five contaminated pads among the analogue pads and no contamination among the digital, high voltage, and ground wire-bond pads. Because of this high

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number of wire-bond pads and very complicated assembly, many hybrids were rejected owing to even a small amount of contamination. Since the detector design could tolerate modules with fewer than ten faulty analogue channels and the results presented in section 3.2 were encouraging, we decided to apply a new, less strict criteria for a large number of circuits, to test their performance during module assembly and their reliability afterwards.

3.4 Definition of contamination levels and pristine areas

We defined four new contamination levels where wire-bond pads are categorized based on the number of bright spots in the pristine zone: No contamination; Light contamination (approx. 10 bright spots max); Medium contamination (approx. 30 bright spots max) and Heavy contamination (all pads with more contamination than in the Medium category). Examples of the different contamination levels are illustrated in figure 2.

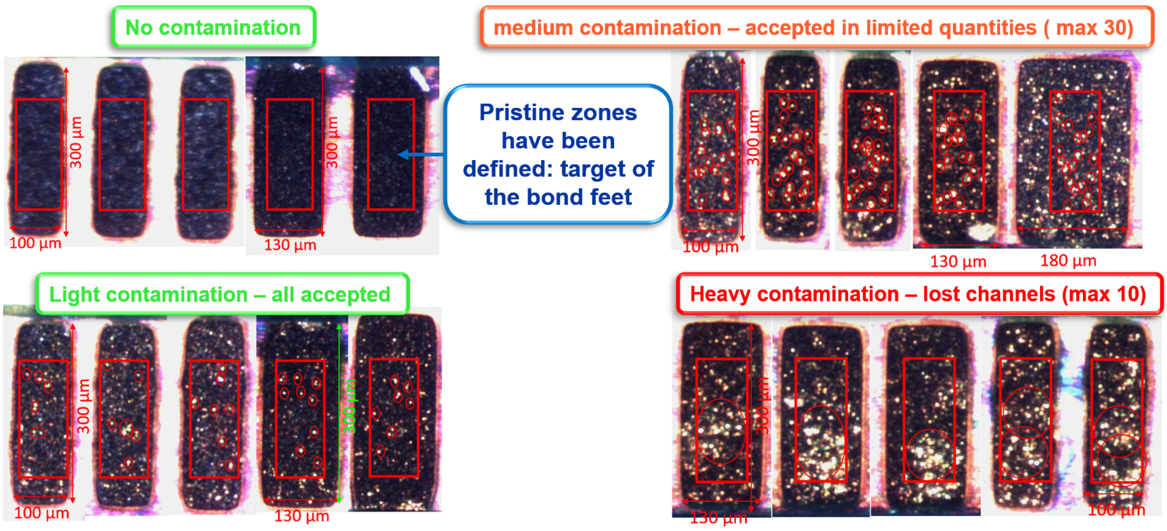

Figure 2. Pads are categorized based on the number of bright spots in the pristine zone.

Additionally, we defined pristine zones for all wire-bond pads. Since most of the pads are much larger than what is required for the wire-bond feet, in some cases the pristine zone of the pad is 30–53% smaller than the total pad area. The contamination outside of the pristine zone is not taken into account during the inspection. The pristine zones defined on the different hybrid types are illustrated in figure 3. In the case of the digital wire-bond pads on the PS-FEH, there are redundant power and ground pads among the critical signal pads.

Since many rejections were due to a single contamination on the digital wire-bond pads, we decided to accept some contamination on redundant power and ground pads. We categorized the pads in power and ground groups numbered from one to ten. These groups and the critical signal pads are illustrated in figure 4. In each group, a maximum of two pads can be contaminated. Out of these pads, two can be medium contaminated or one medium and one heavily contaminated. Up to 10 heavily contaminated or up to 30 medium contaminated pads can be tolerated on the full digital wire-bonding array of a hybrid. The number of heavily contaminated pads is deducted from the allowed number of medium contaminated pads.

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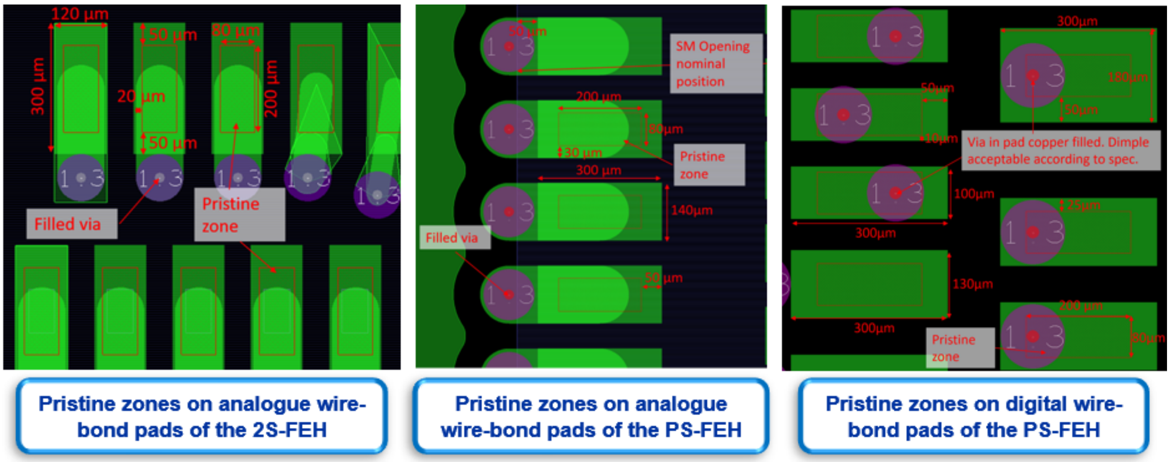

Figure 3. The pristine zone is a 200 µm × 80 µm area centred in the wire-bond pads. This size of pristine zone allows easily the placement of a wire-bond feet and an eventual repair.

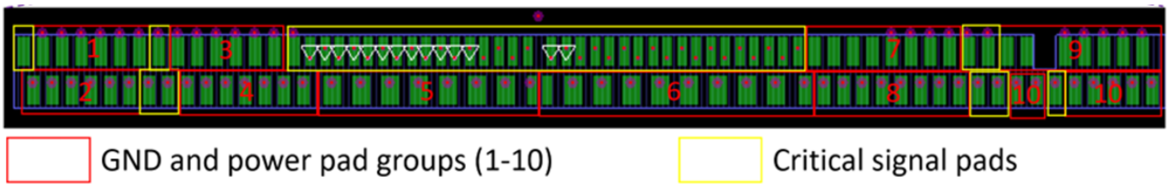

Figure 4. The eight times repeating wire-bond pad pattern of the Macro Pixel ASIC, with the definition of critical and ground and power pad groups. Pads are redundant in the ground and power pad groups.

3.5 Conclusions from the sensor module construction and tests

Since September 2024, more than 100 2S and more than 10 PS modules were built from hybrids quality controlled based on the new criteria. These modules all went through the standard assembly, qualification, and burn-in procedures [6] and no failures were reported that could be correlated with the new cleanliness criteria. Additionally, two dedicated 2S modules have been thermally cycled between -35 °C to +40 °C for 30 thermal cycles and no degradation of connectivity was observed. Based on this and dedicated wire-bonding trials on real modules, the collaboration decided to adopt the new criteria. As a result, 10–15% more hybrids were accepted during the cleanliness quality control.

4 Controlled differential impedance requirements and modifications

As a usual rule of thumb, controlled differential impedance is defined with a ±10% tolerance, which is usually a reasonable compromise between signal integrity performance and manufacturing tolerances. The technical specification of the hybrid circuits required 90 ± 9 Ω differential impedance measured on the dedicated test coupons on each production panel. However, the hybrid circuits are designed and manufactured with HDI technology, featuring line widths and spaces down to 45 µm respectively, with a 25 µm thick dielectric layer. Because of these feature sizes, a small deviation in the linewidth or dielectric thickness can cause large impedance fluctuations.

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4.1 Test coupon design and on-panel fluctuations

The flexible circuits for the hybrids are manufactured on a production panel of approximately 305 × 458 mm. The impedance test coupons are positioned close to the frame of this panel. During manufacturing, these coupons are measured to estimate the impedance of the hybrid flex circuits. In many production lots the measured differential impedance of the coupons was outside of the specified value, which would have resulted in scrapping multiple production lots. However, due to etching and plating differences within the same panel, the test coupon impedance can differ from the real circuit impedance. Additionally, it turned out that the test coupon design was slightly different from the circuit design as the plane filling was placed at 1 mm distance from the differential traces, compared to the 0.3 mm average distance in the hybrid designs. As a conclusion, we decided to review the specification and perform some estimations and simulations.

4.2 Worst-case estimations and simulations

Scrapping entire production lots due to test coupons being outside of the specification, while having possibly perfectly functional circuits on the panel, would cause significant time and financial losses to the project. Worst case calculations showed that a differential trace with 114 Ω differential impedance, paired with a termination resistor of 75 Ω would still result in a 45 mV voltage swing at the receiver with the lowest driver current setting (receiver sensitivity is 30 mV). Signal integrity simulations also confirmed that no signal integrity issues are expected at 640 Mbps data rate (max expected data rate) with 300 ps rise and fall time. Based on these results, the risk to have communication issues due to an impedance mismatch is very low.

4.3 New impedance specification

We defined the following new specification for the differential impedance: The circuit differential impedance target remains 90 Ω, but test coupon impedance measurement values in the range of 70–110 Ω are acceptable if backed-up with 3 differential pair line-width microscope measurements from the prints on the panel. Line widths of the differential pairs must be within 50 ± 10 µm on the 2S-FEHs and 45 ± 10 µm on the PS-FEHs. With these linewidths we guarantee a good operation of the hybrids as impedance is expected to be close to the 80–100 Ω range. With the application of this new specification, multiple production lots have been saved from scrapping. Since the specification was changed, hundreds of circuits were functionally tested and built into modules. No failures correlated to the differential impedance were observed.

5 Conclusions

Actual production experience demonstrated the need to reduce and optimize some parts of the technical specification for the hybrid circuit production. Two examples were discussed in the paper, the wire-bond pad cleanliness criteria and the differential impedance specification. In the new wire-bond pad cleanliness criteria, a limited level of contamination and a limited number of contaminated pads are allowed. In the new impedance specification, a larger impedance range is allowed on the test coupons if backed up with microscope linewidth measurements on the circuits. Production experience and targeted tests showed that the changes had no impact on the quality of the detector modules, however they significantly increased the production yield and therefore mitigated time and expenses in the project.

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