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CMS CR -2022/185

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

14 October 2022 (v4, 21 October 2022)

CMS Outer Tracker Phase-2 Upgrade module noise and mitigation

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Abstract

The CMS Outer Tracker phase-2 upgrade silicon modules are required to reach noise levels close to the ones expected from the analogue front-end attached to an ideal pixel/strip. Module prototypes, featuring the latest and final prototype hybrids before the production, showed noise that was higher than the expected which could pose a problem in terms of achieving the hit efficiency target. Investigations, reveal the failure modes which are modelled in order to guide mitigation tweaks for the production designs. Knowledge acquired from the investigations along with the noise mitigation design changes implemented on the production hybrids are presented.

Presented at *TWEPP2022 Topical Workshop of Electronics for Particle Physics*

CMS Outer Tracker Phase-2 Upgrade module noise and mitigation

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ABSTRACT:

The CMS Outer Tracker phase-2 upgrade silicon modules are required to reach noise levels close to the ones expected from the analogue front-end attached to an ideal pixel/strip. Module prototypes, featuring the latest and final prototype hybrids before the production, showed noise that was higher than the expected which could pose a problem in terms of achieving the hit efficiency target. Investigations, reveal the failure modes which are modelled in order to guide mitigation tweaks for the production designs. Knowledge acquired from the investigations along with the noise mitigation design changes implemented on the production hybrids are presented.

KEYWORDS: Detector design and construction technologies and materials, Detector grounding, Analogue electronic circuits, Front-end electronics for detector readout

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1. The CMS Phase-2 Upgrade Outer Tracker modules

A major upgrade of the CMS detector is required to cope with the planned luminosity of the High Luminosity LHC [1]. The development of the new front-end (FE) silicon modules for the Compact Muon Solenoid (CMS) Outer Tracker (OT) aims to deliver almost ten times higher granularity, lower mass (by a factor of two) and provide higher data rates and local track segments at 40MHz. The rejection of low momentum tracks for the L1 track trigger is performed in the FE electronics by locally correlating the signals from a pair of silicon sensors [1].

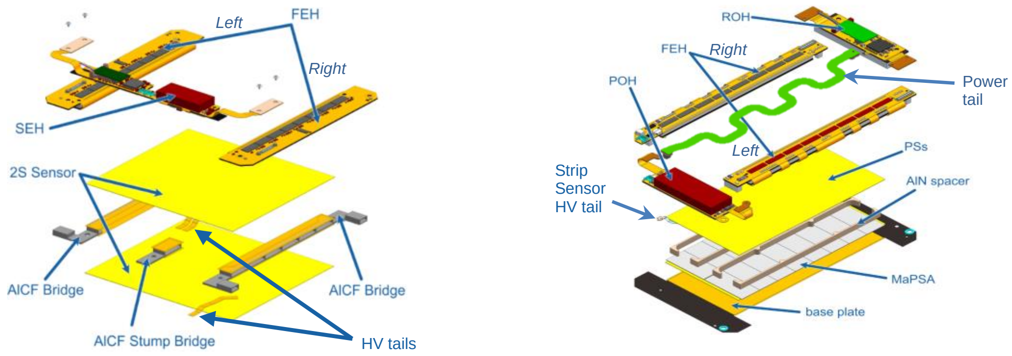

Figure 1. Modules of the CMS OT: The 2S (left) and PS (right).

Two module types (2S and PS) will be used in the CMS OT Phase-2 Upgrade. The 2S modules contain a double strip sensor configuration with an active area of (10×10) cm^2, wire-bonded to two front-end hybrids (FEH) [2] that are powered and controlled by a service hybrid (SEH) (Fig. 1) [3]. The PS modules contain a strip sensor and a macro-pixel sensor of (5×10) cm^2 wire- bonded to two FEHs interconnected with a power hybrid (POH) on one side and with an optical readout hybrid (ROH) on the opposite side (Fig. 1).

2. Noise problem description

The noise per analogue channel affects directly the hit efficiency. The FE Application Specific Integrated Circuits (ASICs) of the OT employ binary readout (Fig. 2). Higher noise

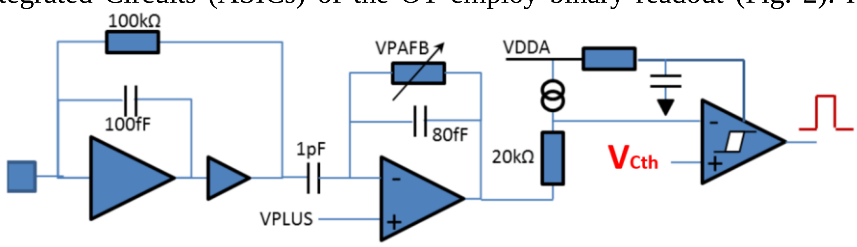

Figure 2. Simplified version of the CBC3 analogue FE.

means higher threshold is needed for the comparator to avoid false hits and consequently a higher percentile of real signals not being detectable. The CMS collaboration is targeting a hit efficiency of at least 99.5% [4] on the active sensor region which leads to a very stringent requirement for the analogue channel noise of the final system.

Noise measurements of modules built from previous hybrid prototypes showed levels acceptable for the hit efficiency targets [5] [6] but those earlier prototypes were not representative of the final modules. Modules built with more recent prototypes with all features and optimized for thermal, power and noise performance unexpectedly started showing higher than anticipated noise for the 2S and PS-strip sensors (Fig. 3). Noise is defined and presented here in threshold units called V_{Cth} [7] corresponding to a few hundred electrons (e^-) depending on the module type.

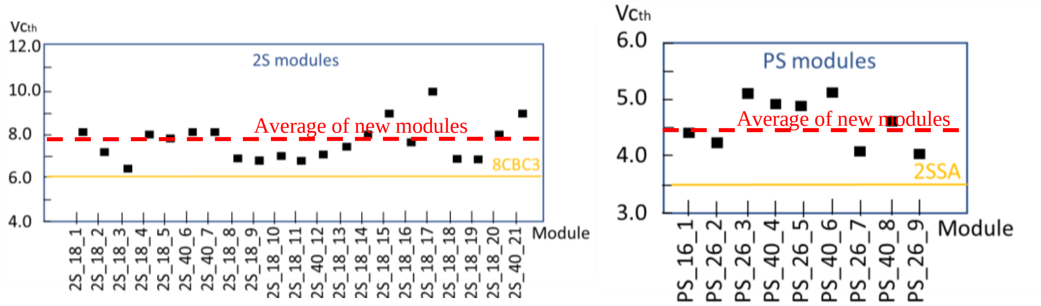

Figure 3. Noise measurements (average of all channels) from 2S (left) and PS (right) modules. Yellow lines are the baseline defined as the noise that was measured with earlier prototypes.

3. The noise investigations

The modules of the CMS Phase-2 OT are complex. Electrical diagrams are not sufficient when considering the different noise sources and paths. The geometry of the circuits and cables comprising the modules are equally important since they form different parasitic elements which do not appear in schematics. The sensitivity of these systems – required to be able to detect signals at the few thousand e^- level – mean they are also very susceptible to small noise sources. For these reasons, such systems can be difficult to debug. In general, the process of debugging such a system looks like this:

1) Explorative measurements with near field probes and oscilloscopes looking e.g. for significant emissions or rippling on powering nets. Searching for correlations between noise and usage of different grounding schemes, disconnections of certain elements like sensors, cables and sub-circuits.
2) Building models of noise injection that explain any findings from the investigation above.
3) Testing the models built, by checking their predictive power.

3.1. Investigation for the 2S module's noise

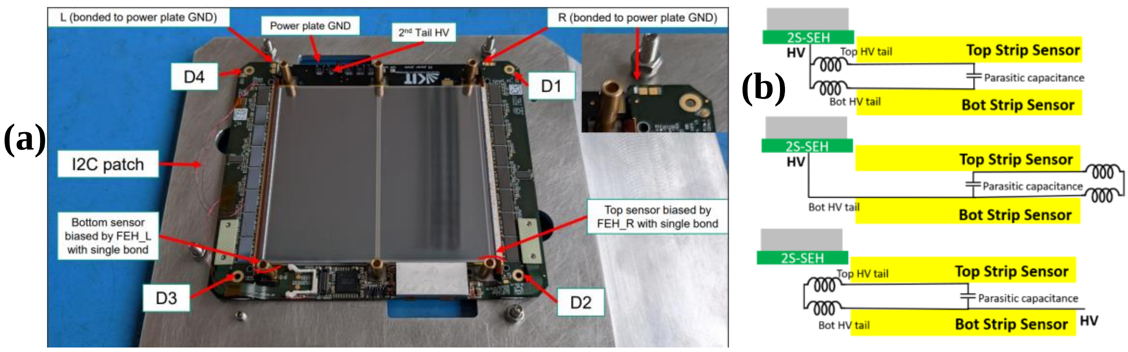

Figure 4. (a) 2S module with 2 HV circuits on opposite sides, 2S-SEH not glued, no wirebond encapsulation. **(b)** Different HV supplying schemes. Only the middle configuration showed reduced noise.

Full 2S modules were the first ones to be built with final hybrids. They were also the ones we acquired the most data from. In the beginning the new FEH design was suspected but after extensive testing it was shown that it was not the culprit. The noise investigations then focused on the DC-DC converter effects from the 2S-SEH, the high voltage (HV) tails and the effect of different grounding schemes. A 2S module was built with different features to enable extensive tests related to the noise investigations (Fig. 4 (a)). Multiple standalone measurements were taken from the latest generation of SEHs as well, to investigate the possible radiated and conducted emissions (Fig. 5).

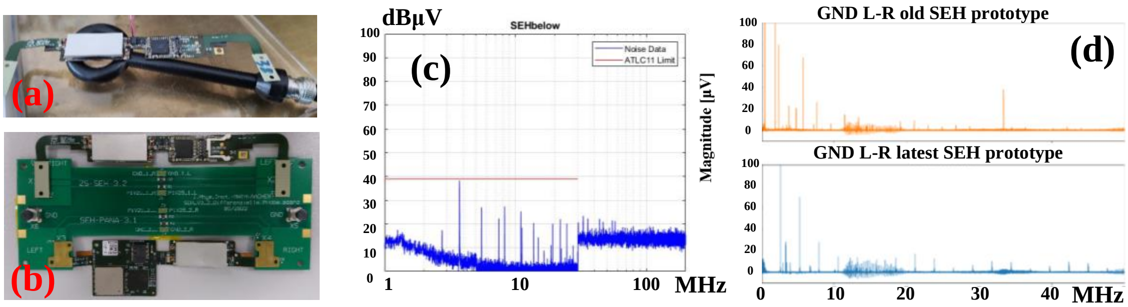

Figure 5: **(a)** H-Field emission 3-cm loop probe used to investigate emissions underneath the 2S-SEH and close to the HV circuit. **(b)** Board developed to enable GND common mode noise measurements and compare previous 2S-SEH prototype with the latest one. **(c)** Measurements from the setup of Fig. 5 (a). Many high frequency components are clearly visible. **(d)** Measurements from the setup of Fig. 5 (b) comparing the old and new hybrids. The new hybrid design seems to have smaller peaks (outside of the plot) but more harmonics are visible and are larger.

The involvement of the HV tails became apparent from the beginning. A model to explain their effect which was based on an LC resonant circuit formed with the tails and the two sensors (Fig. 4 (b)) led to investigations that helped us pin down the real issue (cf. Section 4).

3.2. Investigation for the PS module's noise

For the PS modules fewer data were available and they were less consistent, making the investigations more difficult. Some modules showed increased noise while others did not. Some showed the noise was increasing towards the DC-DC converters but only on the FEH left and some not. Proper grounding of the modules with grounding springs present on the FEHs was found to reduce the noise significantly. The investigations here focused more on the conducted effects.

Changes in the powering scheme of the module were explored and their effect on noise was investigated with one notable example being the powering of a PS module using a single PS-POH tail, which showed noise reduction. Measurements of conducted and radiated noise were also gathered from "skeletons": modules built without baseplate and sensor (Fig. 6).

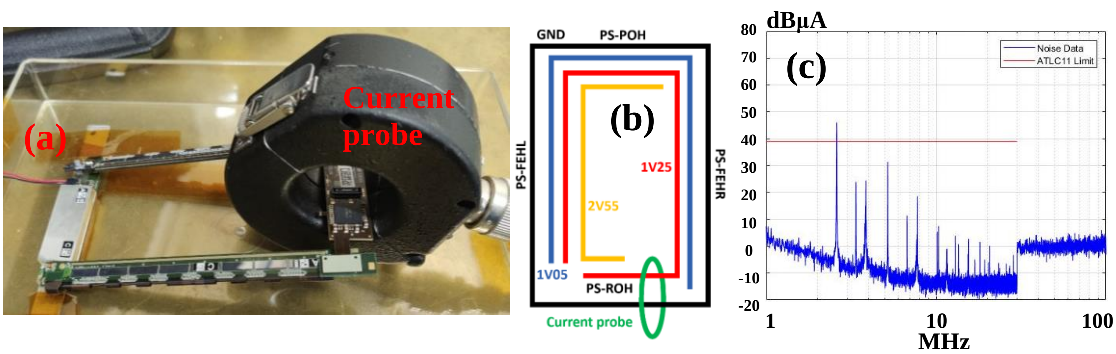

Figure 6. (a) Current probe connected to EMI receiver used on a PS skeleton. **(b)** Power nets in a PS skeleton: Only GND net is closing the loop allowing for indirect measurements on common mode GND noise. **(c)** Measurements from the setup of Fig. 6 (a).

4. Conclusions from the module noise investigations

With the investigations that took place it was proven that there are two main noise contributions, one conductive, affecting both module types, the other radiative. The latter only affects the 2S module but exposed a design vulnerability that could be addressed also on the PS module:

First, switching currents from the operation of the DC-DC converters on the hybrids (switching at 2.5 MHz and 4 MHz) generate a common mode (CM) voltage difference on the GNDs of the left and right side of the modules. This voltage generates currents that flow through the sensors which injects noise indirectly into the analogue FEs. Moreover, this CM voltage appears between the GND of the HV circuit and the analogue FE (Fig. 7 (a)).

Second, a time-varying magnetic field is escaping through the PCB of the 2S-SEH and gets picked-up by a small loop formed by the two HV tails that are connecting underneath the 2S-SEH (Fig. 7 (b), (c), (d)). This loop has small impedance (~Ω) at the frequencies relevant for the analogue FE (~ 1–30 MHz). As a result, a very small electromotive force is capable of generating large noise currents which appear as noise in the analogue FEs. In the 2S module this effect was shown to create noise. In the PS case, a similar, low impedance loop exists as well and presents a vulnerability to external noise, but is less exposed to magnetic fields generated on the module.

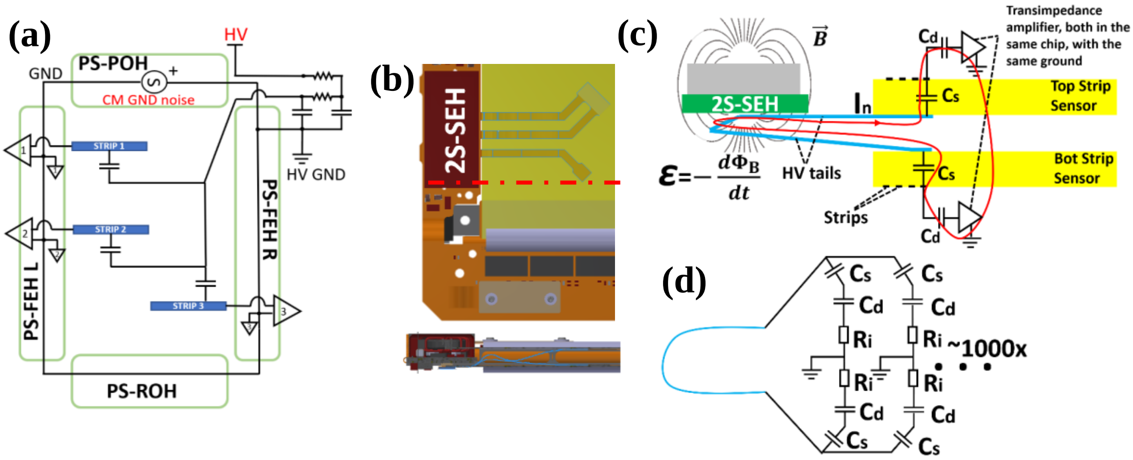

Figure 7. (a) GND diagram of a PS module. Similar to the 2S type diagram. **(b)** Top and side sliced view (slice on red dashed line) of the 2S module. Light blue marks the HV tails. Both HV tails connect to a single net underneath the 2S-SEH. In the side view the air-core coil of the 2S-SEH is also visible. **(c)** Electrical diagram of the loop formed by the HV tails with the strips and analogue FEs in the 2S module for a single top and bot strip pair which are read out by a single ASIC. Light blue marks the HV tails and in red the path of the noise current (I_n) can be seen. **(d)** Simplified electrical diagram for the full 2S module strips and HV tails. The values of the elements shown are C_s~10 pF, C_d~100 pF and R_i~ kΩ at the frequencies of interest.

5. Changes in the hybrids

Three main changes implemented for the production of the hybrids to address the two issues:

- Insertion of a small (100 Ω) resistor in series with the loop formed with the HV tails in the 2S and PS modules. This changes the impedance of the loop by orders of magnitude thus reducing the currents that can flow (Fig. 8 (a)).

- Removal of the output capacitor in the HV filter of the 2S module and study of possible repercussions of the removal also on the PS module. This restricts the capability of the HV circuit and analogue FE GND difference to generate high noise currents (Fig. 8 (a)).
- PCB design change on the PS-POH and 2S-SEH to separate the GND on which the DC-DC converters operate in and the GND that is distributed to left and right side hybrids on the PS and 2S modules (Fig. 8 (b)).

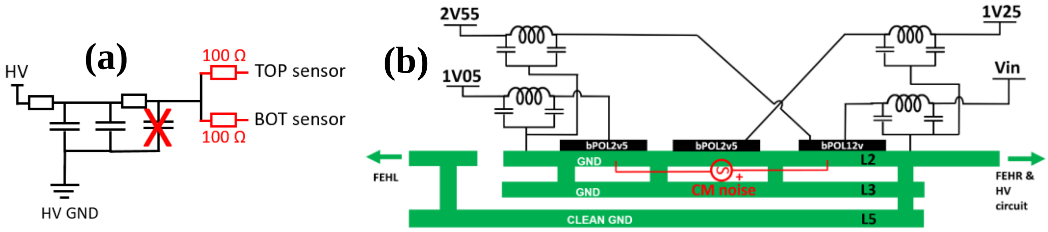

Figure 8. (a) HV circuit changes. **(b)** Side view of GND planes of the PS-POH. One input (V_{IN}) and three output (1V25, 1V05, 2V55) power nets visible.

Implementing the separated GND plane design for both PS and 2S modules is challenging:

- Unavoidable increase in the resistance of the GND in one of the two sides has to be minimized. In the PS-POH case the new design -after optimization- leads to 13 mV of GND drop (7.5 mV originally) on the left side at the nominal load and an 11% increase in PCB power losses (Fig. 9 (a)).
- Considerations have to be made for the GND of the output Pi filters of the DC-DC converters in the new scheme. In the new scheme the CM voltage is "redirected" as small ripple on the 2V55 and 1V05 rails.
- The effect of such a design was studied in advance as much as possible (Fig. 9 (b), (c)) and a risk mitigation strategy is adopted for the production: The "normal" and split plane designs will both be produced and studied for both PS-POH and 2S-SEH with the kick-off circuit production.

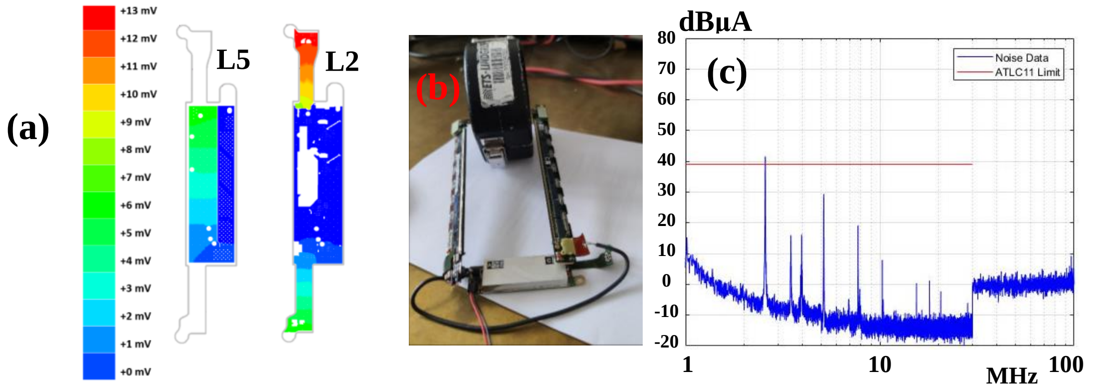

Figure 9. (a) IR drop simulations of PS-POH with the separated GND planes. **(b)** Setup similar to the one of Fig. 6 (a) but here, the GND of the PS-POH is connected in the same way to the skeleton as it will be in the separated GND design. **(c)** Measurements from the setup of Fig. 9 (b). Compared to the current design (Fig. 6 (c)) the peaks are smaller and some high frequency components disappear completely.

6. Conclusion

Module prototypes for the CMS Phase-2 Outer Tracker with the latest hybrid designs showed higher than anticipated noise figures. Investigations revealed several noise components that will be addressed with design changes for the upcoming production.

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