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Integration tests with 2S module prototypes for the Phase-2 Upgrade of the CMS Outer Tracker

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The CMS experiment will be upgraded by 2028 to fully exploit the physics potential from the increased luminosity of the HL-LHC. The entire tracking system will be replaced during this Phase-2 Upgrade. The CMS Outer Tracker will be equipped with modules containing two silicon sensors that are separated by a few mm to provide an on-module transverse momentum measurement. These are placed on mechanical structures called ladders in the central barrel of the Outer Tracker or discs in the endcap regions. During the prototyping phase the modules are initially investigated individually to evaluate their performance. Next steps towards the production phase are integration tests performed with the purpose to test the module functionality on the final detector structures. Investigations focus on the cooling performance as well as on electrical performance of a group of modules on the mechanical structures. This contribution summarizes integration tests with the Outer Tracker module prototypes. The main focus is on a thermal ladder integration test performed at CERN and a full ladder integration test at Institut Pluridisciplinaire Hubert Curien (IPHC, Strasbourg). A short summary of an integration test on endcap discs at DESY (Hamburg) is also given.

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1. The Phase-2 Upgrade of the CMS Outer Tracker

The High-Luminosity LHC (HL-LHC) is designed to deliver an integrated luminosity of 4000 fb^{-1}. To allow a physics performance similar to Run 3 the detector needs to deal with much higher occupancies and withstand a much harsher radiation environment. The new tracker will have two parts: The Inner Tracker with silicon pixel modules and the Outer Tracker with double-layered silicon sensor modules. The inner part of the Outer Tracker will be equipped with PS modules, which consist of one macro-pixel and one strip sensor each. In the outermost tracker region, 2S modules with a stack of two silicon strip sensors with parallel aligned strips are used.

The spacing of the two silicon strip sensors of the 2S modules will be provided by bridges made of aluminum-carbon fiber composite. These bridges also provide the mechanical fixation of the modules on the mounting points of the detector structures and act as main cooling path to reach a sensor temperature of about $-20\,°C$ during module operation.

The outer part of the tracker barrel is called Tracker Barrel with 2S Modules (TB2S). It consists of 372 ladders with 4464 2S modules in total. The drawing of a fully equipped ladder with twelve modules is shown in figure 1. The modules are mounted on aluminum inserts enclosing the cooling pipe with an outer diameter of 2.2 mm. CO_2 in the evaporative mode is used as cooling medium [1].

The endcaps of the Outer Tracker are called Tracker Endcap Double-Discs (TEDD). Each TEDD will be built of five double-discs (DD). One DD provides the hermetic coverage of one detector plane and is made of two discs, each build from two half-discs called dees. The picture of one prototype dee can be found in figure 6 (left). The dee is a sandwich composed of two carbon fibre sheets surrounding an inner foam layer with the cooling pipes passing through the foam. The cooling contact to the backside of the PS modules is provided by carbon foam blocks while the cooling of the 2S modules is provided via six cooling inserts per module. In total, 3216 2S and 2744 PS modules will be mounted in the endcaps.

During the operation of the HL-LHC, the maximum 1 MeV neutron equivalent fluence for 2S modules mounted in the TB2S is $\Phi_{eq} = 3.68 \times 10^{14}\,cm^{-2}$ [2]. With increasing radiation the leakage current of the silicon sensors increases as well [3]. By operating the modules with a silicon sensor temperature of about $-20\,°C$, the leakage current can be significantly reduced [4]. Finite Volume Model (FVM) simulations are used to simulate the cooling performance of the modules on the

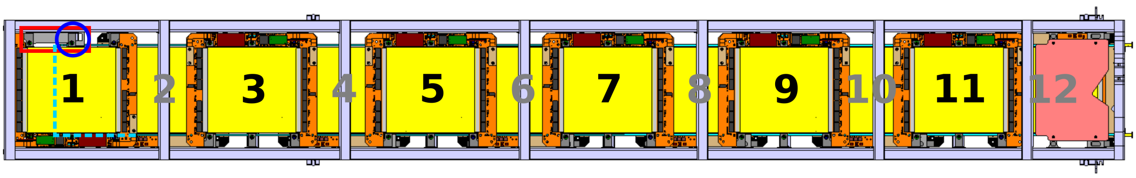

Figure 1: Drawing of a fully equipped ladder. Modules are mounted on both sides of the ladder on cooling inserts surrounding the cooling pipe (very thin light blue line). To allow overlap of the ladders from both sides of the collision point along the beam axis, the cooling pipe has its return loop below module number 1 (dashed line). Due to that the left side of module 1 has worse cooling performance than the other module positions caused by the long cooling insert (red rectangle). To compensate for that and the highest radiation level in the inner ladder layer, a sixth cooling point (blue circle) was added to the modules at position 1 and all modules of the innermost layer.

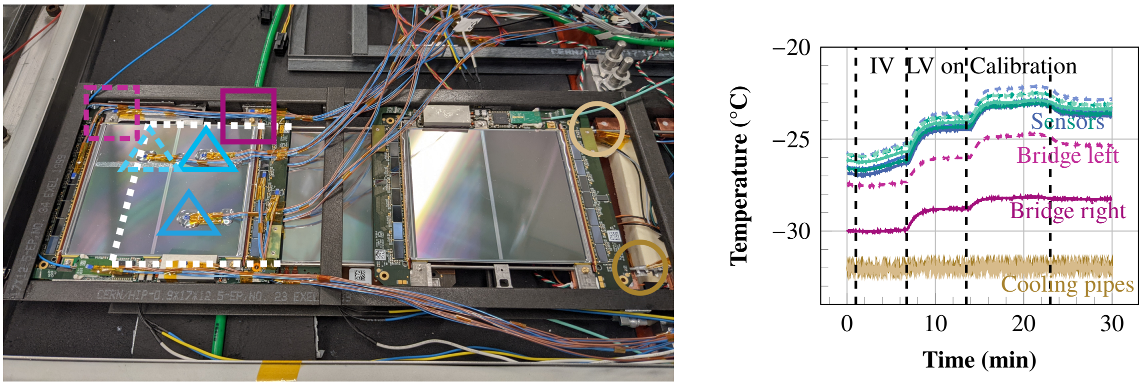

Figure 2: (left) Photograph of the modules during the thermal TB2S ladder integration test. The irradiated module is mounted at position 1 and is equipped with 16 temperature sensors. The squares indicate the location of the temperature sensors at the bridges and the triangles the ones on the top silicon sensor. The cooling pipe below the module is indicated with a white dashed line. The circles indicate the temperature sensors at the cooling pipe before and after passing the modules. (right) The plot shows the temperatures measured on the irradiated module during its operation. The color-code is the same as in the picture on the left. The temperatures measured at the left module side are marked with dashed lines whereas the ones on the right side are indicated with solid lines. For the meaning of the indicated time intervals (vertical dashed lines) see main text.

substructures after irradiation. As already indicated in the TDR [5], the FVM simulations will be verified by measurements when all the prototype components are available. The measurements presented in section 2 of this article contribute to this verification. Section 3 describes the results of a 2S module integration test on a TB2S ladder, while section 4 shows an integration test with both 2S and PS modules on a TEDD dee.

2. Thermal TB2S ladder integration test

The thermal TB2S ladder integration test aims for testing the cooling performance of a TB2S prototype ladder with an irradiated module. The test was performed in March 2022 in a cold room at CERN. This room can be cooled down to −35 °C. In the cold room an insulated dry-air flushed aluminum box is placed in which two ladder prototypes are placed next to each other. Both are connected in series to a CO_2 cooling system [1].

As shown in figure 2 (left), the ladder under test is populated with three modules. An irradiated module is mounted at position 1, which is the most challenging position with respect to the cooling performance (see figure 1). This specific module was built without a sixth cooling point. Two non-irradiated modules are mounted at positions 2 and 3. On the inserts of the other positions, heating resistors are mounted to emulate the heat load of further irradiated modules. The irradiated module is equipped with 16 temperature sensors on the silicon sensors and the readout electronics. They are read out every two seconds during the whole measurement time.

Figure 2 (right) shows the temperatures measured at the cooling pipes, bridges and silicon sensors. While increasing the bias voltage V_{bias} the leakage current of the silicon sensors increases (label "IV"). The resulting higher power consumption of the sensors P_{HV} ($P_{\text{HV}} \approx 450\,\text{mW}$ at $V_{\text{bias}} =$

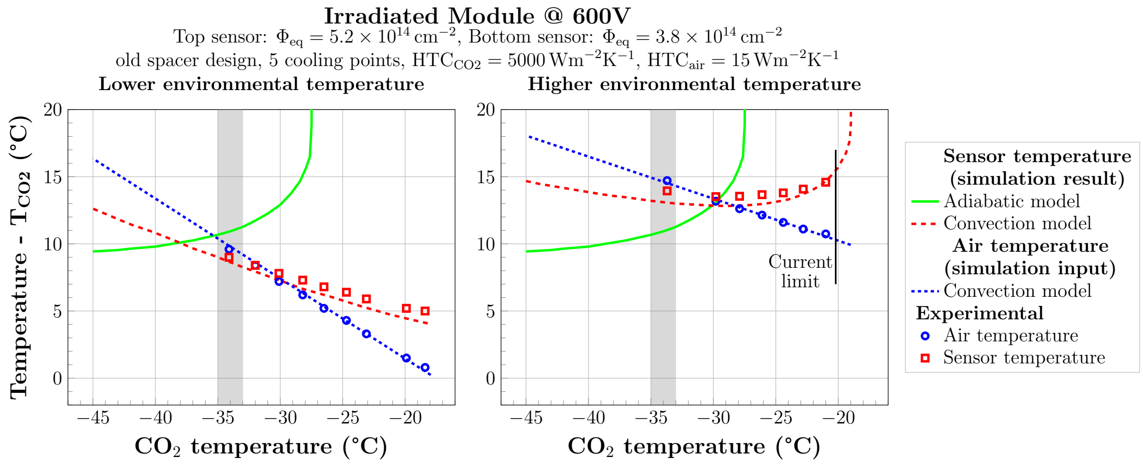

Figure 3: Comparison of data and simulation of the thermal runaway measurement. The aimed CO_2 temperature during tracker operation is indicated with the grey area between −35 °C and −33 °C. The solid green line shows the simulation result for the temperature difference between sensor and CO_2 using an adiabatic model while the dashed red curve shows simulation results taking air convection into account. The circles indicate the measured air temperature profile in the box as input for the simulation (dotted blue line). The squares show the measurement results for the sensor temperature. The vertical line in the right plot at about −20 °C indicates the temperature conditions during the measurements at which the current limit of 5 mA of the power supply was reached.

800 V and $T_{\text{sensor}} \approx -26\,°\text{C}$) leads to increasing silicon sensor temperature T_{sensor}. When the low voltage is switched on the power consumption of the module increases due to the additional power consumption ($P_{\text{HV, LV}} \approx 2.7$ W at $V_{\text{bias}} = 600$ V and $T_{\text{sensor}} \approx -24\,°\text{C}$) of the module electronics (label "LV on"). As a result, the temperature of the silicon as well as the temperatures measured at the bridges of the module increase. At the point of temperature stability, the routine of calibrating the module and measuring the electronic noise is started (label "Calibration"). The low voltage power consumption increases again ($P_{\text{HV, LV}} \approx 4.8$ W at $V_{\text{bias}} = 600$ V and $T_{\text{sensor}} \approx -22.5\,°\text{C}$), which results in another temperature increase on the module. For stable operation of the modules, the silicon sensor temperature should stay below −20 °C at a CO_2 set temperature between −35 °C and −33 °C. The measurements show that this is the case during the module operation with a cooling pipe temperature of −32 °C. Since the module power consumption during the calibration performed in this test is even higher than during the normal data taking with beam, this is also valid for the later use case of the modules in the tracker. The temperature at the left bridge is about 2.5 °C higher than at the right one. The reason for this worse cooling performance at the left side is given by the fact that the module inserts of that side are not connected directly with the cooling pipe but with a long cooling insert as described in section 1. This temperature difference results in a spread of the silicon sensor temperatures of about 1 °C. Since this is the position of the module with the worst cooling performance this is the highest expected spread of the temperature differences on the silicon sensors.

For tracker operation, it is required to operate the modules after irradiation in stable operation conditions. Stable operation means that the cooling system is able to compensate the heat load of the system completely. The situation where the system comes to an uncontrolled self-heating loop

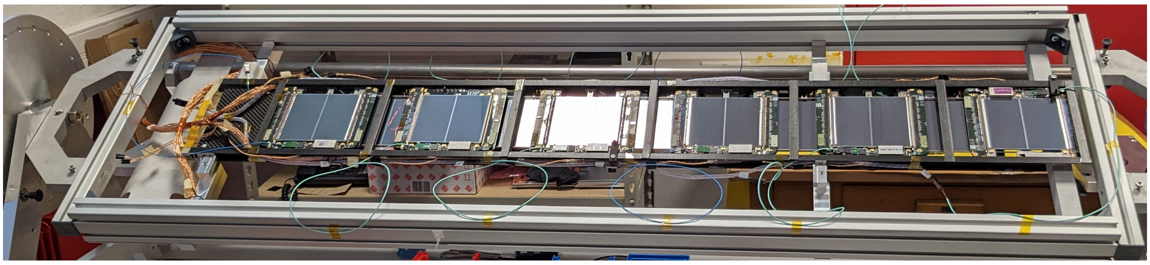

Figure 4: Photograph of a fully equipped TB2S ladder prototype. The ladder equipped with twelve modules is mounted into an aluminum frame which allows safe handling and transportation of the whole ladder.

is called thermal runaway. To measure this thermal runaway, the CO_2 temperature is changed while the silicon sensor temperature as well as the air temperature surrounding the modules is monitored. Figure 3 shows the comparison between the thermal runaway measurements and the results of the simulation performed by Cristiano Turrioni [6]. The parameters such as high voltage, irradiation levels, materials and heat transfer coefficients of the simulation are taken as written in the plot. They match the measurement conditions. The only unknown parameter is the heat transfer coefficient of the air to the silicon sensors. With a value of $\mathrm{HTC_{air}} = 15\,\mathrm{Wm^{-2}K^{-1}}$ the simulation fits the data within 1 °C for two different air temperature conditions (colder air on the left side of figure 3 and warmer air on the right side of figure 3). The operation margin from −35 °C to −33 °C, which is aimed for stable operation of the Outer Tracker, is shown as a grey band in figure 3. In figure 3 the thermal runaway temperature is the one at which the difference of the sensor temperature and the CO_2 temperature diverges. For stable operation of the future tracker it is important that there is a safety margin between the operation target temperature and the thermal runaway temperature, which is already the case for the adiabatic model. Taking air convection into account even increases this margin by almost 10 °C.

To summarize, the measurements show stable operation with a CO_2 set temperature in the aimed operation range. Additional safety margin for the extrapolation to operations comes from adding the sixth cooling point and the significantly higher fluence compared to the maximum fluence reached at an integrated luminosity of $4000\,\mathrm{fb^{-1}}$ of the measured sensors.

3. Full TB2S ladder integration test

In January 2023 a TB2S ladder integration test was performed at IPHC in Strasbourg. During that test a prototype ladder was fully equipped with twelve 2S modules. A photograph can be seen in figure 4. Prototypes of electrical and optical services were used. The low and high voltage power was distributed either from a lab power supply or from a prototype power supply for the Phase-2 tracker with its 60 m long cable.

One purpose of this test was to exercise the integration procedure itself. It turned out that the module handling and tooling works as intended. Ideas for minor changes came up and were adopted.

The electronic noise of the modules is an important measurement variable that can be used to verify the modules functionality and their electrical grounding to the supporting structure. Due to the binary readout of the module channels the noise cannot be measured directly. Instead, a

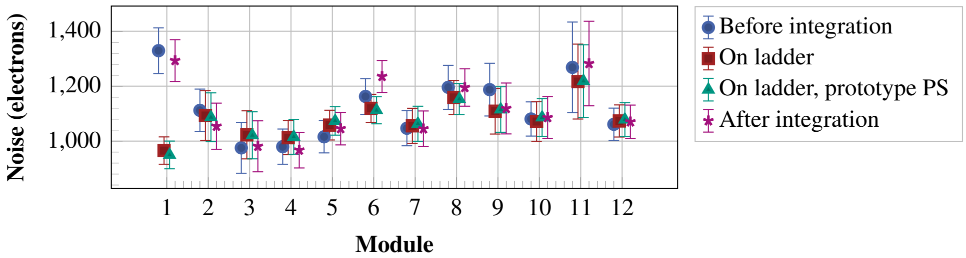

Figure 5: Module noise on the ladder. The mean strip noise of each of the twelve modules is shown with the standard deviation of the distribution as error bars before the integration, on the ladder powered with a lab power supply as well as with the Phase-2 prototype power supply and after the integration. For module 1 just the top sensor noise is shown. The noise value is significantly reduced on the ladder because the bottom sensor was not biased during the measurements on the ladder. A sensor that is not biased leads to significantly reduced noise on the other sensor [7].

threshold scan is performed during which 1000 events are recorded at each threshold step. The hit occupancy of each readout channel of that measurement has an S-curved shape. From a fit to this curve for each channel, the width can be determined and is referred to as the noise. The mean value of a histogram of all the 4064 strip noise values is called the module noise. In figure 5 this is shown for the twelve modules on the ladder. The modules were individually characterized before and after integration. The corresponding data points in figure 5 demonstrate no deterioration during the integration procedure. The noise levels even converge slightly when the modules are mounted on the same supporting structure with the same ground level (label “On ladder“). The noise level is also independent of the power supply powering the modules (label “On ladder, prototype PS“).

4. TEDD dee integration test

In June 2023 a first integration test on a TEDD was performed at DESY in Hamburg. During that test, 13 prototype modules of both types, 2S and PS modules, were placed on a TEDD dee prototype. A photograph of the integrated modules can be seen in figure 6. The modules were mounted in the center region of the dee because the transition area from the PS modules at lower radii and the 2S modules in the outer part is the most critical regarding the distances of the modules.

Measurements of the electronic noise were performed and are depicted on the right of figure 6. The noise values on the dee are as expected from the single modules measurements before the integration.

5. Summary

The Phase-2 Outer Tracker Upgrade project is now moving from the prototyping phase towards the production phase. Integration tests were and will continue to be performed to ensure the functionality of the modules on the supporting structures in the future tracker. A thermal TB2S integration test showed sufficient cooling in the barrel part of the detector despite the fact that the specific measurement configuration was the worst regarding the irradiation level of the silicon sensors and the cooling path during the measurements. A TB2S ladder was fully populated with

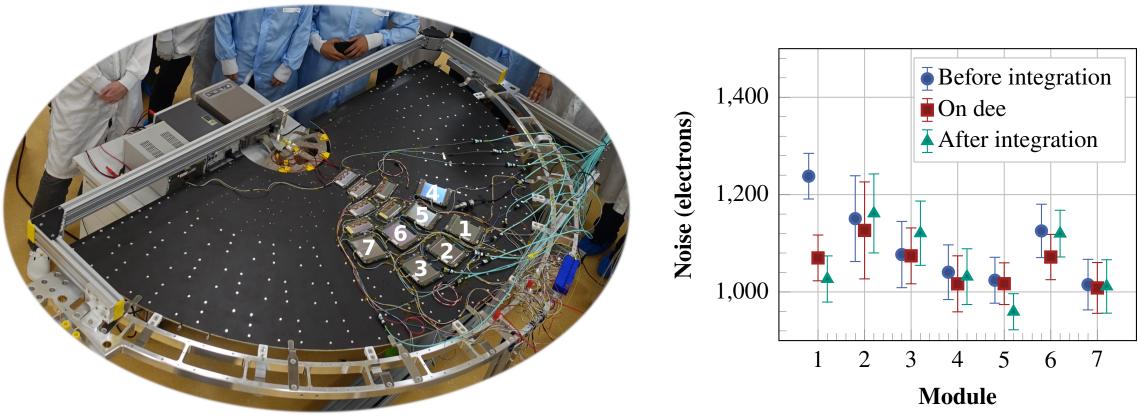

Figure 6: (left) Photograph of the 13 PS and 2S modules on the TEDD dee. The numbers on the 2S modules correspond to the numbers used in the plot on the right. (right) Noise values of the 2S modules before the integration, on the TEDD dee and after the integration. The noise of module 1 differs between the measurements due to different grounding schemes during the measurements.

twelve 2S modules, and 13 outer tracker modules were integrated on a TEDD dee. The measurements of the electronic noise during both integration tests show good performance of the modules on the subdetector structures, and the integration procedure is well understood. Further integration tests with final subdetector structures, modules and services are planned.

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