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Insights gained from test system preparation for the hybrids production for the CMS Phase-2 Outer Tracker

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Abstract: The CMS Phase-2 Outer Tracker requires the manufacturing of 8000 Strip-Strip and 5880 Pixel-Strip silicon modules, altogether incorporating 47 520 hybrid circuits of 18 variants. To ensure complete functionality of the modules it is essential to perform production-scale testing of the hybrids before the module assembly. For that reason, a complex, scalable test system was designed, manufactured, and commissioned. However, the system deployment encountered more difficulties than anticipated which required extensive debugging and creative problem solving. The problems, solutions, and lessons learned from the system deployment are presented.

Keywords: Front-end electronics for detector readout; Modular electronics

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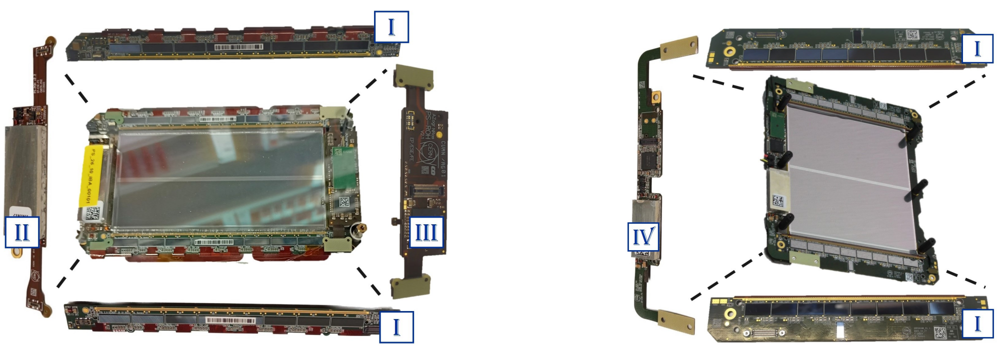
1 Objective of the test system

1.1 Quality control requirements of Outer Tracker hybrids

The Phase-2 Outer Tracker (OT) [1] of the CMS experiment [2] has rigorous requirements for the performance of its electronics. The new silicon-based detector modules, which employ a unique combination of macro-pixel and strip sensor technology, must adapt to higher total integrated luminosity and increased pileup (overlapping proton-proton collisions) at the High-Luminosity LHC (HL-LHC). The OT will be inaccessible for repairs on the detector hardware once installed, making it essential for these modules to operate reliably at -35 °C, with an expected lifetime of up to 15 years. To meet the production target of 5880 Pixel-Strip (PS) (figure 1(a)) and 8000 Strip-Strip (2S) (figure 1(b)) sensor modules, the OT hybrids project will need to produce a total of 47 520 electronic hybrid circuits in 18 variants. Therefore, to ensure the required throughput, production yield, and reliability of the electronics, a custom crate-based test system [3] was designed and manufactured as the main tool for quality control on the hybrid circuits.



(a) Pixel-Strip (PS) Module (b) Strip-Strip (2S) Module

Figure 1. The CMS Phase-2 Outer Tracker is built from 2S and PS modules, which use different hybrid types: **[I]** Front-End (PS, 2S), **[II]** Power, **[III]** Read-Out, **[IV]** Service.

1.2 Introduction to the crate-based test system

The crate-based test system can be divided into five main parts (figure 2): a computer running the testing software, FC7 FPGA cards [4] to generate and interpret signals, a test crate with multiplexing backplanes to switch the connections between 12 crate slots, test cards (TC) to operate hybrid-type specific functional tests, and various jumper interconnecting circuits (short: “jumpers” in the following) as well as adaptors to accommodate the 18 distinct hybrid variants on their dedicated test cards. The total number of components in the system, accounting for spares, is 110 backplanes, 645 test cards, and around 5000 jumpers and adaptors.

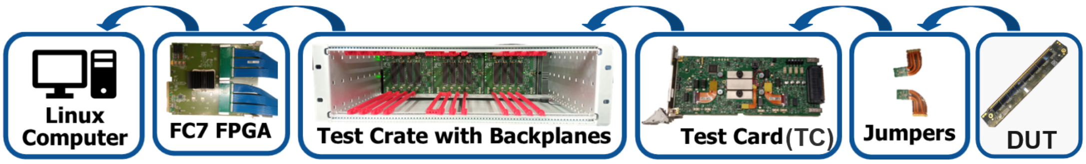
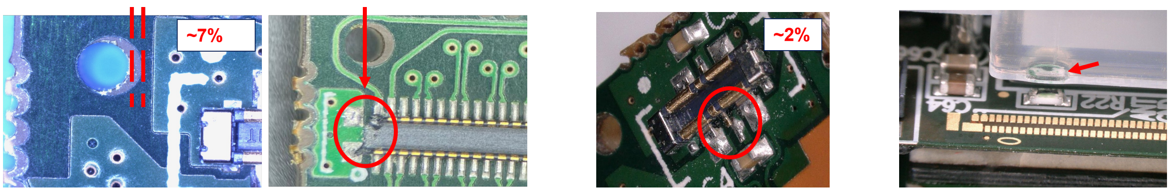


Figure 2. Simplified diagram of the crate-based test system.

2 Test system preparation

2.1 Commissioning and debugging of test system hardware

To ensure consistent performance of the test system, a comprehensive commissioning campaign was necessary, involving extensive testing to validate each component. The initial commissioning report can be found in ref. [5]. Overall, the process was time-consuming, and surprisingly, a significant amount of attention was required for the quality control of the so-called jumpers, which were initially overlooked due to their simple design. Extensive use of the system revealed that these jumpers can cause numerous interruptions and failures, some of which resulted in damage to the tested hybrid circuits. As shown in the images below, it was discovered that small tolerances and displacements of the alignment holes on the jumpers led to connector damage during its usage (figure 3(a)). Additionally, the early jumper assemblies exhibited several soldering defects (figure 3(b)) — some easily detected through visual inspection, while others, such as reversed connector orientation, were missed during inspection and only became apparent during hybrid testing. Similarly, a mid-production design change on one of the hybrid types mistakenly introduced a mechanical conflict in the test system, between plastic spacer and a passive resistor on the hybrid circuit, which caused it to be damaged (figure 3(c)).



(a) Connector damage due to misalignment (b) Soldering defects (c) Mechanical clash

Figure 3. Unexpected failures and problems with jumpers and mechanical components from early operation of the hybrid test system.

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2.2 Integration and principle of operation

The test system operation (figure 4) aims at parallelizing the work to maximize throughput, with a target of 36 hybrids pre-mounted on test cards, inserted into the system by the operator, and then managed via the test system's graphical user interface (GUI). The test software automatically controls the power supplies, climatic chamber, and FPGA boards, making the 2.5-hour testing routine fully autonomous, with tests executed at both -35 °C and +40 °C. This automation allows operators to focus on manual activities, such as dismounting previously tested hybrids from the test cards, sorting them according to their test results, and mounting the next set of hybrids on the cards for testing. This approach enables a throughput of 108 hybrids per 8-hour shift for fully occupied test crates, which translates to about 2300 hybrids tested in one month of work with one shift per day.

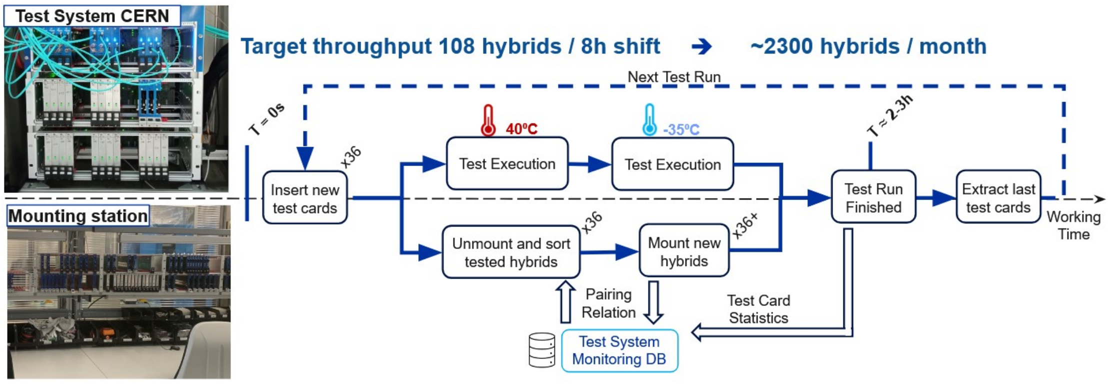


Figure 4. Diagram explaining the principle of operation of the test system.

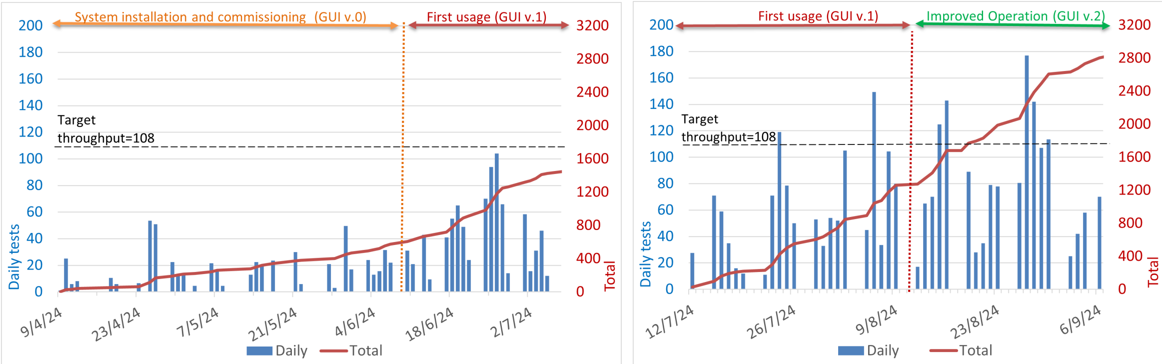
3 Installation of the test system

After completing the system commissioning and gaining more experience with its usage, a similar installation of the test system was deployed at the hybrid manufacturer, where the hybrids will undergo testing directly after assembly. The installation began in December 2023 and progressed in steps, with the final hardware being installed in mid-June 2024, just in time for the start of hybrid pre-series fabrication. A timeline of the number of tests performed at the manufacturer and at CERN is presented in the graphs below (figure 5). The horizontal axis represents the testing period for each facility. The blue bars, aligned with the primary vertical axis, represent the daily test throughput, while the red curve, corresponding to the secondary vertical axis, shows the running total of tests performed.

3.1 Testing performance at the manufacturer

During the installation, operators at the hybrid manufacturer gained experience with system operation by performing initial tests with the pre-series hybrids. In the first phase, operators were achieving very low test throughput due to the usage of an initial version of the GUI, which required more manual control, including scanning of the serial numbers of the test card-hybrid pairs and manual control of the climatic chamber temperature settings.

The final installation step which finished in mid-June 2024 included a new version of the GUI, which allowed for a more automated operation of the test cycle. The system can now automatically control the chamber temperature and execute test routines at both temperature settings. Figure 5(a)



(a) at Manufacturer between 09/04/24 and 07/07/24. (b) at CERN between 12/07/24 and 6/09/24.

Figure 5. Number of tests performed in both setups.

shows a noticeable increase in daily throughput after the installation, with one of the best weeks already near the target throughput of 108 tests per day. During this extensive usage, a new bug in the GUI was discovered, which due to incorrect management of parallel threads, caused the test software to fail and the user interface to crash. As a result of this, around 20% of test executions were invalidated and aborted, prompting the manufacturer to temporarily halt the usage of the test system. The problem in the software was thoroughly investigated during the testing activities at CERN. The bug was fixed as of mid-August 2024, and testing of hybrid production at manufacturer premises had resumed since October 2024, which confirmed that the issue had been resolved.

3.2 Testing performance at CERN

After testing at the manufacturer facility, the hybrids were shipped to CERN, where quality control and functional testing were continued. The testing performance at CERN was also affected by the bug in the initial version of the GUI reported in section 3.1. However, despite this issue, the team of technicians persistently continued the testing efforts and successfully validated around 1400 pre-series hybrids. Following significant development efforts and external software support, an improved version of the user interface was delivered. The improved GUI resolved the bug discovered by the manufacturer, and reduced machine idle time while improving the system efficiency. From figure 5(b) it can be concluded that during the best week with the updated software, CERN technicians exceeded expectations, achieving a throughput of up to 180 tests per day. This improvement was made possible thanks to the resolved software problems and the more flexible working hours of the CERN operators, allowing the test system to be used for an average of 10 hours per day. The plateau visible in the final weeks of August 2024 on the graph corresponds to the completion of pre-series hybrid testing, with only retests on few circuits as well as final debugging checks, and quality control exercises remaining.

4 Repeatability tests

The detailed statistics collected from test campaign presented on figure 5, proved that there were still some possible weaknesses in the test system operation. Recognized problems included issues with remote services, inconsistencies in software and failures of hardware. To establish trust in the test results and their repeatability an additional exercise was conducted with 36 hybrids of mixed types inserted into the test system, which were then automatically cycled through 32 full tests at -35 °C and

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+40 °C. The resulting total of 64 test results per hybrid were used to evaluate the repeatability of the system output. Figure 6 shows the repeatability score for different hybrid types with the percentage given on the vertical axis. The results are given as function of the slot in the crate.

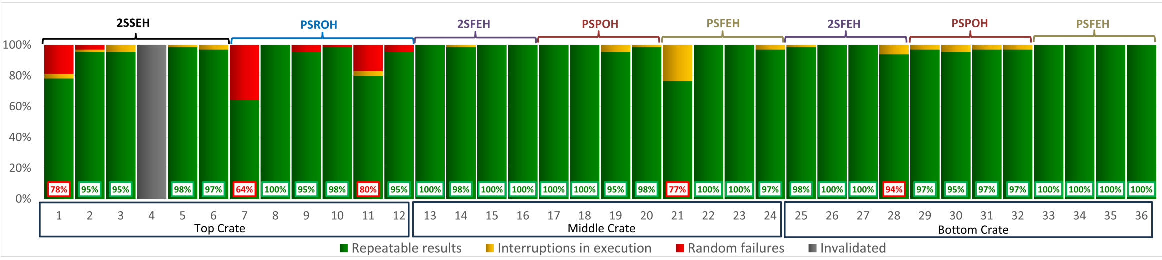

Figure 6. Repeatability of test results per position in test system.

The repeatability scores represent how consistently the test system produced the same output during subsequent test executions. Abnormal results are categorized as either interruptions in execution or random failures. Interruptions originated from failures in external test system components, such as failures of remote services or communication issues, while random failures resulted from instabilities in the test routines. The results from slot 4 had to be invalidated due to a systematic failure in the optical hardware.

As shown in the graph, the majority of tested devices, 30 out of 35 hybrids, achieved good results with a repeatability score within the defined 95% limit. Only 5 out of 35 hybrids showed unexpected fluctuations in their test results, frequently reporting failure reasons that were not entirely consistent with the physical state of the hybrid. This indicates that further debugging and investigation will be needed to improve reliability of the system. Nonetheless, the performance for certain hybrid types appeared to already meet the objectives required for the testing process.

Among the interruptions in test execution, a few were not directly related to the low-level test routine but were caused by other critical services, such as power supply communication failures, unrecognized devices on the USB bus, or loss of communication with the FPGA. Most of these issues occur very rarely, and thus require close monitoring to develop mitigation strategies that minimize interruptions during the production test campaign. It would thus be beneficial to conduct more such exercises in the future to monitor the reproducibility of the test results and the reliability of the test software.

5 Conclusions and future work

The commissioning of the crate-based test system for the production testing of the hybrids for the CMS Phase-2 Outer Tracker provided valuable insights, demonstrating both the usability and limitations of the test system during the hybrid pre-series production. Key lessons emerged, such as the importance of parallelization of work to maximize throughput. The automation of most aspects of the testing allowed the team to focus on critical areas, especially on unforeseen issues such as communication failures or temporary hardware problems that interrupted test execution.

The experience also emphasized the importance of foreseeing sufficient hybrid prototypes for system validation. These were crucial for debugging and refining the system performance. Furthermore, careful attention to every component, such as the jumper interconnecting circuits, proved essential, as even simple parts can lead to system failures if overlooked. Consequently, hardware and software

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maintenance will be necessary for the stable long-term operation of the system. Additionally, further debugging and testing exercises might still be required to increase the system reliability.

Hybrid production at the manufacturer has recently resumed, and the quantities are scaling up, with a projected peak output of 3000 hybrids per month. Lessons learned from testing and repeatability exercises on pre-series hybrids have to be applied such that the quality control process, including functional tests, can keep up with the produced number of circuits. This increase in throughput highlights both the improvements made and the need for ongoing attention to ensure reliable and efficient usage of the test system.

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