Development of POTATO for 2S Module Grading for the CMS Phase-2 Outer Tracker Upgrade

Anna Klupshas[1] and Fabio Ravera[2]
[1)] *Purdue Unviersity*
[2)] *Fermi National Accelerator Laboratory*

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Due to the High Luminosity-Large Hadron Collider (HL-LHC) upgrade, several detectors of the Compact Muon Solenoid (CMS) will need to be upgraded, specifically the new Outer Tracker detector that will be composed of 13,200 silicon modules. The Outer Tracker features two types of modules; the PS (pixel-strip) and the 2S (strip-strip) modules. With a large influx of production of modules, extensive testing is required to ensure they fulfill the performance requirements. This research introduces POTATO (Phase-II Outer Tracker Analyzer of Test Outputs), a specialized software developed in C++ to analyze, grade, and store results in a centralized database since module data will be collected from various international production facilities. The implementation of POTATO will facilitate the selection of the best performing modules for the Outer Tracker upgrade. This paper is focused on the implementation of the analysis of 2S Module results within POTATO.

I. INTRODUCTION

The Compact Muon Solenoid (CMS) is one of the experiments at the Large Hadron Collider (LHC) located in France and Switzerland. CMS is a general purpose detector designed for studying high-energy particle collisions. In the late 2020s, the LHC is expected to undergo a High Luminosity upgrade (HL-LHC) in order to increase its instantaneous luminosity to about 10 times the nominal one. This research focuses on the upgrades to the Outer Tracker, which is one of the innermost layers of the CMS detector. There are six barrel layers in the Outer Tracker, with five endcap disks on each side. Specific sections of the Outer Tracker include the Tracker Barrel with PS modules (TBPS), the Tracker Barrel with 2S modules (TB2S)[FIG. 1], and the Tracker Endcap Double Discs (TEDD). Within the Outer Tracker there are 2S (strip-strip) and PS (pixel-strip) modules which serve the purpose of reconstructing the charged particle trajectory.

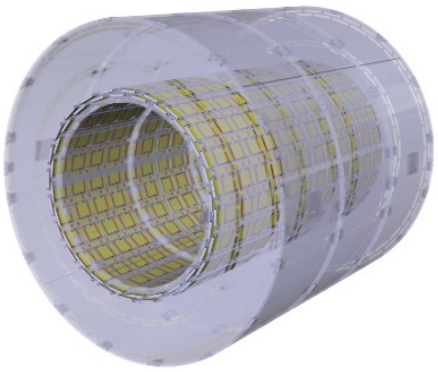

FIG. 1. Image of planned TB2S for the HL-LHC CMS Outer Tracker

The Outer Tracker will also contribute to the first CMS trigger level (L1 trigger) system thanks to the p_T-modules. This design consists of two closely spaced sensors read-out by the same electronics. Due to the 3.8 T magnetic field of CMS, it is possible to discriminate on the particle transverse momentum (p_T) based on the incident angle: particles with high p_T will have a small curvature, producing two closely separated hits on the two sensors, and generating a 'stub'. Low-p_T particles will instead arrive with a large angle, the two hits will be widely separated and no stub is generated. By selecting the size of the window in which the two hits must lie, it is possible to tune the p_T threshold used to identify the stubs as seen in Figure 2.

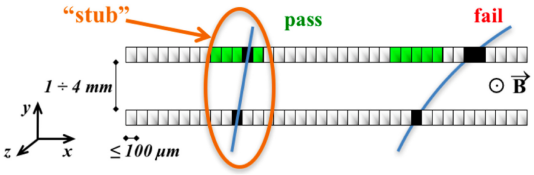

FIG. 2. Track selection algorithm

II. 2S MODULES

The 2S module is composed of two silicon strip sensors that are closely spaced one on top of the other. Each silicon detector has 2032 strips, or two columns of 1016 strips. The strip pitch is 90 μm with a length of 5 cm. Between the silicon strip sensors are spacers which are composed of aluminum-carbon fiber, with the purpose of holding the two silicon strip sensors 1.8 mm or 4.0 mm apart according to the final position in the detector. shown in Figure 4, a Front-End Hybrid (FEH) is attached on each side of the silicon sensors. Each FEH has eight CMS Binary Chips (CBC) which have the capability to read-out 254 strips, 127 strips from the top and bottom sensors. The CBC chips are able to correlate hits from the two sensors, and then send the stub data to the Concentrator Integrated Circuit (CIC) chip, shown in Figure II. Connected to the FEHs are Service End Hybrids (SEH) which contain Low Power GigaBit Transceiver (LpGBT) and High Voltage (HV) circuitry.

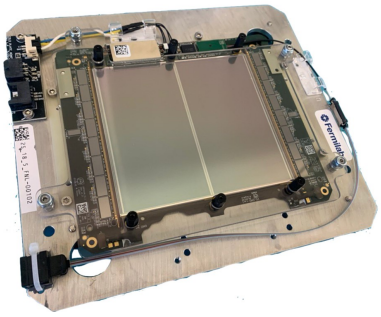

FIG. 3. Image of assembled 2S Module

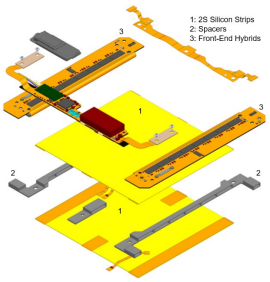

FIG. 4. Exploded view of 2S Module specifying the silicon strips, spacers, and front-end hybrids

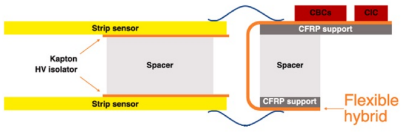

FIG. 5. Side view of 2S Module detailing the spacer and strip connection to the hybrids

III. MODULE TESTING

Fermilab plans to produce 1,000 2S and 1,250 PS Modules. In total, the Outer Tracker will require 7,608 2S and 5,592 PS Modules. To ensure they fulfill the performance requirements, assembled modules will undergo rigorous testing inside a burnin box. Calibrations will be performed to measure characteristics such as identifying broken channels and measuring noise levels. The burn-in box will then chill the modules to -33℃, repeat the calibration process, and subsequently warm the modules back to room temperature. This cycle will be repeated continuously over a 24-hour period. After testing, the results are saved in a ROOT file, with each tested module having its own dedicated file.

FIG. 6. Burnin Box

IV. POTATO

The Phase-2 Outer Tracker Analysis of Test Outputs (POTATO) software is responsible for grading the 2S and PS module test results. The software provides a graphical user interface, as seen in Figure 7, that allows for the user to search for specific modules and analyze corresponding histograms. Due to the large influx of modules being assembled and tested, a plethora of data will need to be analyzed. The purpose of POTATO is to be utilized by the international production facilities to assess the quality of modules assembled using the same grading criteria. After a module is assembled, it is placed within a burnin box. A dedicated software runs the tests on the module, and outputs a ROOT file. POTATO takes this file and first uploads it into the database, then analyzes the file to assign a grade to the module itself. This workflow is summarized in Figure 8.

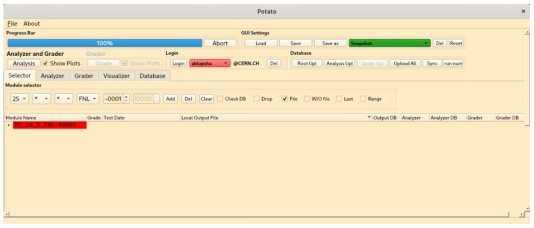

FIG. 7. POTATO's Graphical User Interface

FIG. 8. Module Assessment Flowchart

A. Analysis

The analysis function within POTATO processes data from a ROOT file allowing the user to view various histograms. The analysis extracts various metrics such as noise averages, noise average outlier counts, pedestal averages, pedestal average outlier counts, alignment efficiency, etc., from the module tests contained in the ROOT file. Metrics of the modules can be assessed on the module, hybrid, and/or chip level. The analysis summary is saved in an XML file, as shown in Figure 9, that can be uploaded to the database.


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FIG. 9. Analysis XML File


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FIG. 10. Grading XML File

B. Grading

The grading feature of POTATO assigns grades based on defined criteria decided by the Outer Tracker community. Grading of the module can be assigned on the module, hybrid, and chip level. Modules can receive an 'A', 'B', 'C', or in some cases 'F'. Based on discussed criteria, modules will receive an overall grade which determines its eligibility to be placed within the Outer Tracker for the HL-LHC. In certain cases a module will have to be completely discarded due to irreparable malfunctions. Summaries of the grader are saved within an XML file, as seen in Figure 10, that can be uploaded to the database.

V. ACCOMPLISHMENTS

During my internship, I added several grading fields into POTATO. These variables were added based on histograms produced from module testing, and then used to improve the grading criteria for a module. Depending on the test, the criteria can be assessed on the module, hybrid, and/or chip level.

A. Noise

The module noise is one of the most important parameters for assigning a grade to a module. In order to keep the signal to noise ratio suitable to keep high efficiencies during data taking, the module noise caused by the electronics and the sensor should stay within a certain value. For grading purposes, this noise average should not be too high as it may indicate underlying issues with the module. Conversely, if the value is too low, it may signify unconnected wire bonds. As seen in Figure 11, various noise histograms are analyzed to determine these grading baselines. The noise fields added to POTATO include the total number of noise outliers for the analyzer, and the number of noise outliers for both the left and right front-end hybrids for grading.

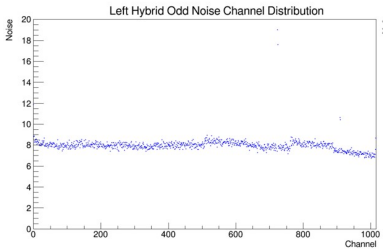

FIG. 11. Example of Noise Histogram

B. Pedestal

Pedestal refers to the baseline voltage level after the electronics amplification in absence of a signal. By construction, every channel would have a different pedestal value and a calibration step is done to equalize them and therefore having the same effective threshold for all channels. Figure 12 shows the pedestal distribution for each channel obtained by the threshold equalization procedure. In POTATO, the average value of the pedestal and the pedestal's RMS value are calculated and stored in the analyzer and grading XML files. The channels with pedestal outside of the 3 σ envelope are classified as outliers. The total number of outliers and their location are included in the XML file as well.

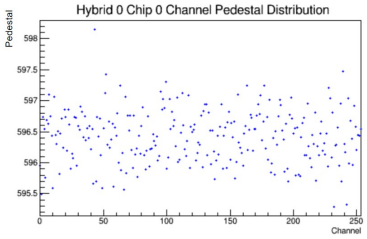

FIG. 12. Example of Pedestal Histogram

C. Inter-chip Communication Efficiency

The read-out alignment refers to how efficiently the data lines are sampled by the readout clock. As seen in Figure 13, this efficiency should be 100% to avoid any read out error that could result in fake hits or inefficient tracking. In case this efficiency is 0, it could likely signal that one of the data lines is broken and no data can be read-out from the module. This last condition means that the module needs to be reworked or else it cannot be mounted on the detector.

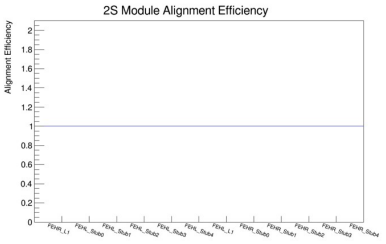

FIG. 13. Example of Alignment Efficiency Histogram

VI. FUTURE WORK

The initial version of POTATO is nearing completion with future iterations expected to evolve alongside increased statistics from module testing, during production. Continual addition of

various fields into POTATO will be implemented for further refining of module grading. Furthermore, the new fields created within POTATO will be integrated into the database to support comprehensive data analysis.

VII. CONCLUSION

The assembly of modules is set to begin within the coming year signaling the start of substantial data collection efforts for POTATO. This software will be utilized globally as production starts. In total, the Outer Tracker will require 7,608 2S modules. Each module will be assembled in production facilities around the world and graded with the POTATO software. The research presented will allow the CMS collaboration to identify the modules that will be installed in the detector.

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