# Completing the CMS HCAL Endcap Phase 1 Upgrade

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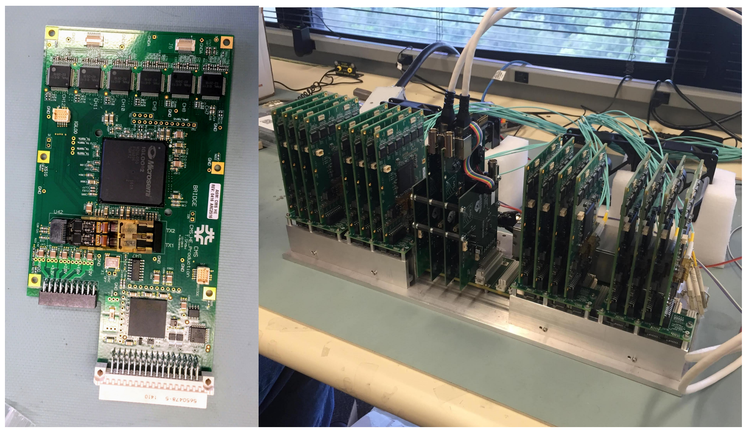
## New HCAL Readout Electronics

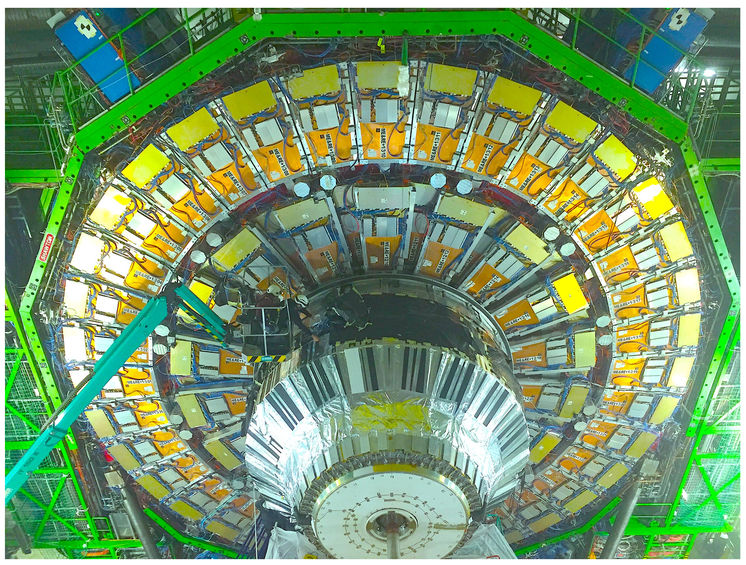
The CMS HCAL Endcap (HE) Phase 1 upgrade was completed to mitigate the effects of radiation damage. The hybrid photodiodes (HPD) were replaced by silicon photomultipliers (SiPM). New on-detector readout electronics (QIE cards) were installed to integrate and encode the SiPM output signals.

All QIE cards were first tested at Fermilab in 2016. After visual inspection and basic electrical connectivity tests, firmware was uploaded to the QIE card FPGAs and the functionality of important QIE card registers was verified. Additionally various QIE chip settings were scanned, and each QIE chip was calibrated based on response to input charge.

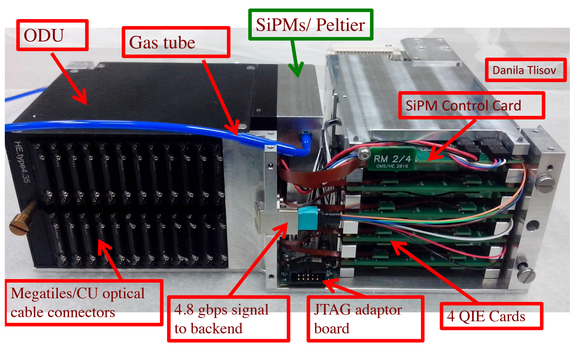
The QIE cards were sent to CERN and assembled into readout modules (RM). Following an extended burn-in period, the RMs were installed into readout boxes (RBX) in CMS in 2018. The HE detector was first calibrated using a radioactive Cobalt-60 source. Then the HE detector was fully integrated into CMS in preparation for proton-proton collision data. The timing was tuned for every channel, and HE was included in the CMS Level 1 trigger.



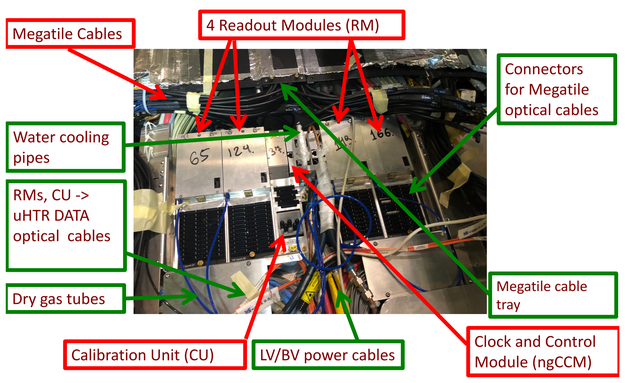
Charge integrator and encoder (QIE) cards undergoing quality control testing at Fermilab.



Two installation team members in a cherry-picker working on installing new readout electronics for the HCAL Endcap (HE). Various commissioning tests were conducted to check control and data links. Then pedestal, laser, and LED runs were taken. Afterwards megatile cables were connected and radiation Cobalt-60 sourcing data was recorded.

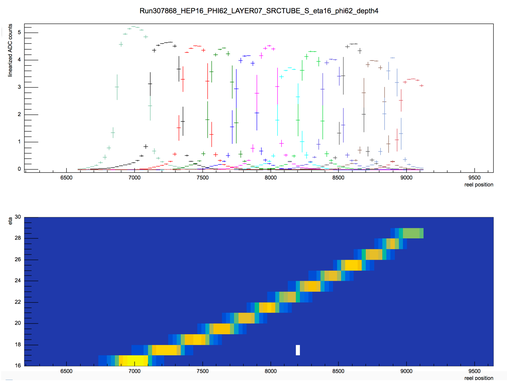



HE readout module (RM) containing 4 QIE cards, 1 SiPM control card, 48 QIE chips, 48 SiPMs and 1 optical decoder unit (ODU). The ODU accepts light input from megatile cables and outputs light onto the SiPMs. The SiPMs output current to the QIE chips. Data from QIE chips is sent through FPGAs to the off-detector electronics.

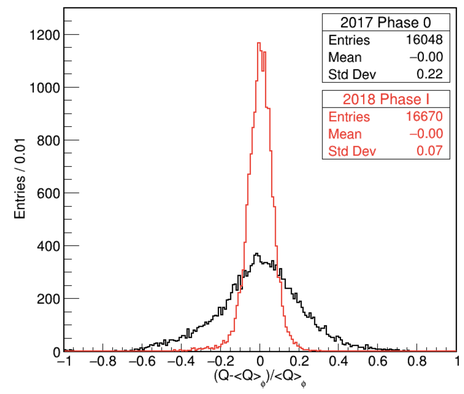



HE readout box (RBX) containing 4 RMs, 1 clock and control module (ngCCM) and 1 calibration unit (CU). Megatile cables transmit light from HCAL scintillators to the RBX. The ngCCM has a bidirectional optical fiber "control link" to an off-detector ngFEC (front-end controller). Each RM has a unidirectional optical fiber "data link" to an off-detector $\mu$HTR ($\mu$TCA HCAL Trigger and Readout).

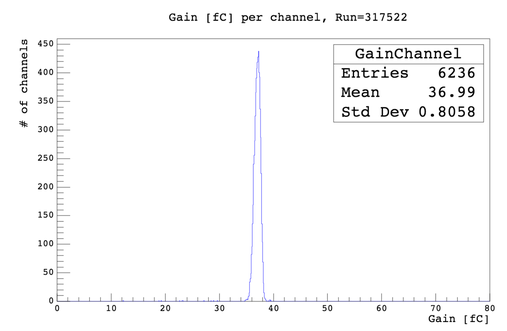
Sourcing: Cobalt-60 source pushed through tubes that run through HE.



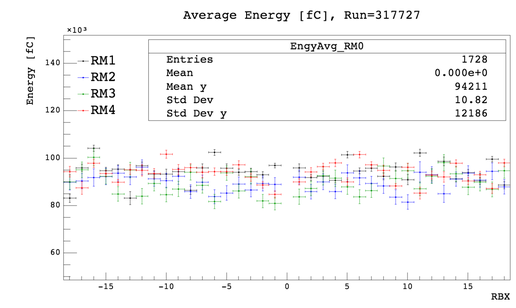

HE Cobalt-60 sourcing data for one sourcing tube. The x-axis is the position of the source in the tube (mm) and the y-axis is iη (integer eta). Sourcing verifies proper channel mapping.




Comparison of Cobalt-60 sourcing data from HPDs in 2017 (black) with data from SiPMs in 2018 (red). HE has a more uniform response with SiPMs.




SiPM "gain" for HE channels from a low intensity LED run. The gain distribution is centered at 37 with a 2% spread.




SiPM charge in fC per readout module (RM) measured for a high intensity LED run. The average charge measured is approximately 94.2 pC with a 13% spread.

## New HCAL Online Software

New software was developed to interface with the new HCAL readout electronics. A server provides communication with the on-detector electronics. Various applications query the server for important hardware register values. Specific hardware settings (QIE shunts, SiPM bias voltages, etc.) are set during HCAL configurations before data taking. Live monitoring records relevant values and sends notifications when there are anomalous values or communication problems.

PerHEQIE

| ID | QIE | QIE-Er61Count | QIE-Gsel | QIE-IllegalTDC_count | QIE-NoLockCount | RBX | RM |
|---|---|---|---|---|---|---|---|
| 1010022 | 1 | 0 | 18 | 9 | 0 | HEM01 | 1 |
| 2010022 | 2 | 0 | 18 | 9 | 0 | HEM01 | 1 |
| 3010022 | 3 | 0 | 18 | 9 | 0 | HEM01 | 1 |
| 4010022 | 4 | 0 | 18 | 9 | 0 | HEM01 | 1 |
| 5010022 | 5 | 0 | 18 | 9 | 0 | HEM01 | 1 |
| 6010022 | 6 | 0 | 18 | 9 | 0 | HEM01 | 1 |
| 7010022 | 7 | 0 | 18 | 9 | 0 | HEM01 | 1 |
| 8010022 | 8 | 0 | 18 | 9 | 0 | HEM01 | 1 |
| 9010022 | 9 | 0 | 18 | 9 | 0 | HEM01 | 1 |
| 10010022 | 10 | 0 | 18 | 9 | 0 | HEM01 | 1 |
| 11010022 | 11 | 0 | 18 | 9 | 0 | HEM01 | 1 |
| 12010022 | 12 | 0 | 18 | 9 | 0 | HEM01 | 1 |

Table storing live register values read from every HE QIE chip. There are also tables for QIE cards, ngCCMs, and ngFECs. The values in these tables are checked against alarm conditions. Alarm notifications are sent to on-call experts when anomalous values or communication errors arise.

Many people from many institutions contributed to the testing, installation, and operation of the HE Phase 1 upgrade. I am glad that I had the opportunity to work with and learn from many people both at FNAL and CERN. A special thanks goes to Joe Pastika for teaching me about HCAL readout electronics, Seth Cooper for teaching me about HCAL Online Software, and Jay Dittmann for enabling me contribute to CMS HCAL.