First Results of the Performance of CMS HGCAL Modules with Neutron Irradiated Silicon Sensors

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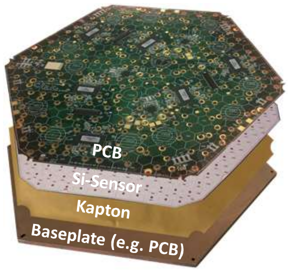
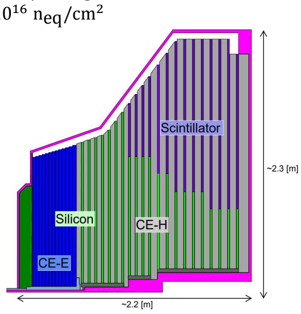
1) Introduction

- CMS upgrades endcap calorimeters to handle increased radiation and event yields at the HL-LHC
- The High-Granularity Calorimeter (HGCAL)
  - ~620 m^2 of silicon sensors + ~487 m^2 of scintillator
- Tests of the end-of-life conditions of the Si-Sensors to understand expected loss in charge collection efficiency and increases in leakage current and noise
  - Cold operation and annealing periods to partially mitigate the leakage current
  - HGCROC chips include a leakage current (I) DAC that can mitigate up to 40 μA per cell of leakage current
  - High Density (HD) thin sensors used where radiation is harsher
    - 8-inch 120μm thick sensor with ~450 channels of cell size ~0.5 cm^2
    - Tested Modules built with irradiated sensors corresponding to 3−4 ab^{-1} scenarios
      - Fluences of $1.0 * 10^{16}$ n_{eq}/cm^2 and $1.4 * 10^{16}$ n_{eq}/cm^2



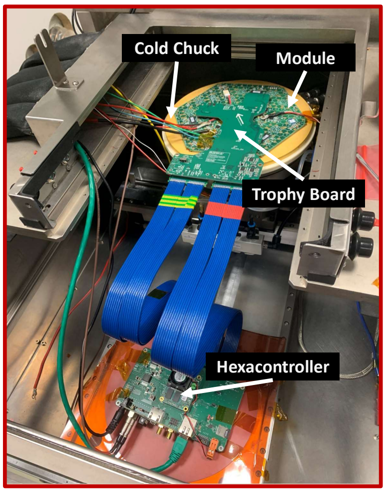
A HD module has several layers built on top of one another. PCB backplate followed by Kapton foil and the Si-Sensor. The top layer contains the electronics associated with data acquisition from the HGCROCs.



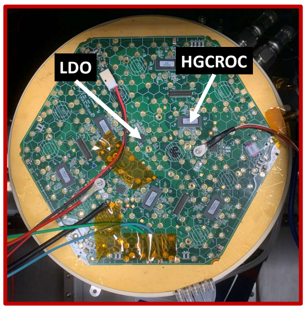
Endcap HGCAL Layout

2) Experimental Setup

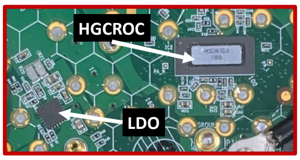
- Module tested on temperature-controlled chuck, held in place by vacuum
- Measured leakage current vs bias voltage (IV)
  - Compared to bare IV sensor at a temperature of −40℃
  - Expect temperature offset between cold chuck and the silicon sensor inside the module
    - PCB baseplate and kapton foil in-between sensor and temperature chuck
- "IDAC"- Channel-wise parameter controlling the current compensation level to prevent ADC saturation due to leakage current
  - Mitigates electronic noise
- IDAC level per channel calibrated to give target pedestal level (~150 ADC) for all measurements as recommended by the chip developers
- Reoptimized IDAC for all measurement configurations



The experimental setup for testing irradiated modules

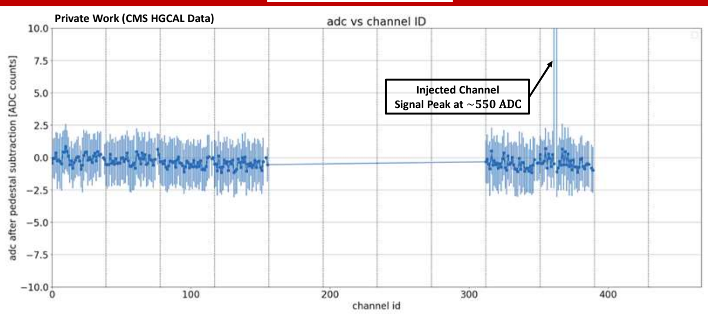


High Density (HD) HGCAL module on cold chuck



Zoomed in view of the LDO and HGCROC

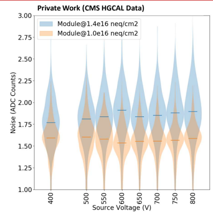
3) Light Injection



ADC Level after light injected into one cell of the module @$1.0e16\ n_{eq}/cm^2$. Three HGCROCs left unpowered due to powering issue on module during light injection measurement.

- Light injected into a single cell from laser through holes in the PCB hexaboard
- Check for cross-talk between nearby cells
- Synchronized triggers to laser driver and DAQ at 1 kHz rate
- Missing channels due to powering issue of 3 HGCROCs during data taking period
- Injected channel signal peak at ~550 ADC (non-saturated)
- No evidence of cross-talk between nearby channels

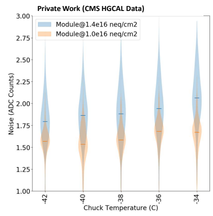
4) Noise Dependency on Bias Voltage



Noise versus bias voltage for modules @$1.4e16\ n_{eq}/cm^2$ and @$1.0e16\ n_{eq}/cm^2$

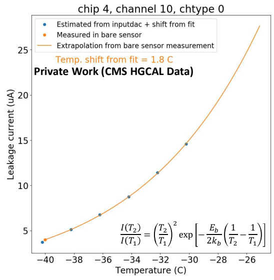
- Expect sub-leading contribution to noise from leakage current with respect to other sources
- Optimal operation and power considerations may require tuning bias voltage (V_{bias})
  - Increase of the radiation damage constant with V_{bias}
    - Very small increase in the noise level is observed
  - Noise level constant throughout changes in operational V_{bias}
  - Difference in noise level observed between the two modules

5) Profiling the Sensor Temperature

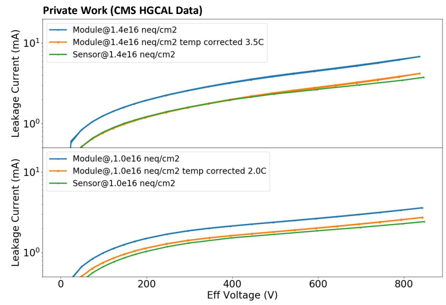


Noise versus temperature for the HD modules @$1.4e16\ n_{eq}/cm^2$ and @$1.0e16\ n_{eq}/cm^2$

- Measurements of I_{leak} at a temperature of −40℃ and applied bias of 600 V are used as a reference
  - After module mounted, expect temperature difference with respect to the chuck
  - Noise observed to increase slightly with temperature displaying the IDAC mitigation provided by the HGCROCs
  - Observe $I_{leak} = I_{leak}(T)$ scaling when temperature difference is taken into account

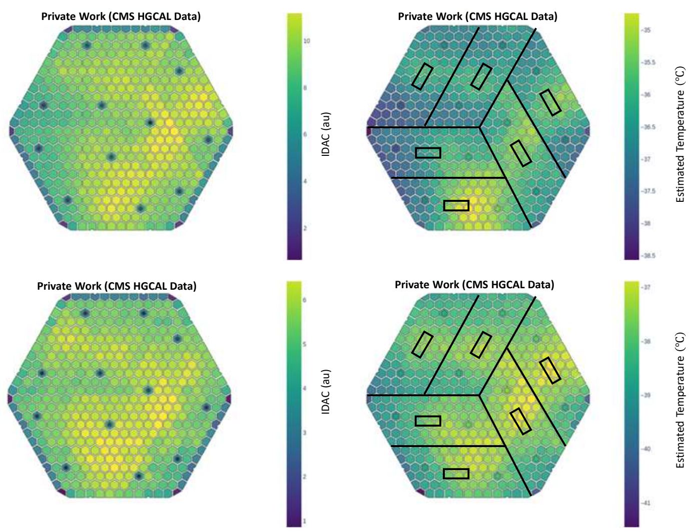


Temperature shift extrapolation for an example cell of the module @$1.0e16\ n_{eq}/cm^2$. The IDAC values from different temperatures are used to fit an Arrhenius curve with respect to the given cells bare sensor measurement.



The orange curves display the module leakage currents rescaled assuming an average temperature difference of 3.5℃ (TOP) for the module @$1.4e16\ n_{eq}/cm^2$ and 2.0℃ (BOTTOM) for the module @$1.0e16\ n_{eq}/cm^2$.

- At each temperature, the IDAC is optimized to mitigate the noise
  - Convert the measurement of the I_{leak} current
  - Perform a combined fit to extract the individual temperature of each cell
  - Temperature profile identifies hot spots in a module coinciding with the HGCROCs and LDOs positions
    - HGCROCs and LDOs generate heat on surface of module
  - Average temperature shift of all cells found to be 2.0℃ and 3.5℃
    - Different temperature shifts between sensors under investigation
  - Used as input for more detailed FEA analyses and final modeling and implementation of cassette cooling



The IDAC value (LEFT) and the extracted temperature (RIGHT) maps for modules @$1.4e16\ n_{eq}/cm^2$ (TOP) and @$1.0e16\ n_{eq}/cm^2$ (BOTTOM). The chuck temperature is assumed to be set to −40℃ and bias voltage set to 600 V. The cell temperature is then calculated from the temperature shift calculated per cell.

6) Summary

- First measurements with heavily irradiated HD modules built with close to final electronics layout
- No evidence of cross-talk with data taken from light injection
- Noise level under control in both temperature and voltage measurements
- Current compensation by HGCROC in HD modules tested and validated, used to estimate temperature map

7) References

- The CMS Collaboration. (2017). *The Phase-2 Upgrade of the CMS Endcap Calorimeter*. doi:10.17181/CERN.IV8M.1JY2