Engineering Challenges of the CMS High Granularity Calorimeter

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On behalf of the CMS collaboration

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Challenges at HL-LHC

- High Luminosity-LHC plans $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ instantaneous luminosity and 3000 fb$^{-1}$ integrated luminosity
  - High pile-up conditions (Up to 200 interaction per bunch crossing)
  - High radiation dose (150 Mrad, $10^{16}$ n/cm$^2$)
- The current Electromagnetic and Hadronic Endcap Calorimeter cannot stand the radiation dose and needs replacement
CMS High Granularity Calorimeter

- A sampling calorimeter
- \(~500 \text{ m}^2\) of Scintillators
- \(~600 \text{ m}^2\) of Silicon sensors
  - Expecting 6M channels
  - Expected to dissipate 220kW heat
- Will be operating at -30 °C
- To reduce radiation damage

Electromagnetic section
- Active element: Silicon
- Absorber: Lead, Copper-Tungsten, Copper

Hadronic section
- Active elements: Silicon and Scintillator
- Absorber: Stainless Steel

See Nural Akchurin’s talk
https://indico.cern.ch/event/642256/contributions/2962409/

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HGCal Modules and Cassettes

- Cassettes provide support and cooling for the modules

Hexagonal modules based on Si sensors

Printed Circuit Board

Silicon sensor

Kapton sheet

Base-plate

Scintillating tiles with SiPM readout
Addressing Thermal and Mechanical Challenges

**Challenges:**
- Silicon detector has to operate at -30°C
  - CO₂ system temperature -35°C
- 220kW heat load is expected
- To address the challenges a mock-up program is in place

**Goals of the thermal and mechanical mock-up:**
- **Study thermal performance of cassette**
  - Temperature measurements of cooling plate and silicon sensors
  - Comparisons to FEA calculations
- **Study mechanical properties of the cassette**
  - Demonstrating module mounting scheme
  - Achieving tolerances
  - Investigating ease of assembly
  - Addressing thermal contraction issues
Addressing Thermal and Mechanical Challenges

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*NOT SO EASY!!*
Geometry of the 1st Mock-up Cassette

- Designed a 30 degree all Silicon Hadronic cassette
  - ~1.5m x 1m in size

Diagram:
- Motherboards
- Copper cover
- Cooling tube embedded into Copper cooling plate
- Silicon Modules
Mock-up Module Layers

- **Base plate; 1 mm thick**
  - Provides support for the active element
  - Enables mounting

- **Silicon; 750 \(\mu\)m thick**

- **Kapton sheet; 110 \(\mu\)m thick**
  - Provides electrical insulation of the sensor back-plane from the baseplate

- **Printed Circuit Board; 1.6 mm thick**
  - Enables performing thermal studies

- **Glue; 100 \(\mu\)m thick**
  (Not shown in the picture)
Mock-up Si Sensor and Base-plates

- Mockup Si sensors cut from blank 8” Silicon wafers
  - 750 μm thick
  - 320 μm thick (design)
- 1 mm thick base-plates:
  - Material with Coefficient of Thermal Expansion close to that of Silicon:
    - Carbon Fiber (Electromagnetic design)
    - Copper/Tungsten (Hadronic design)
- Currently investigating economical choices:
  - Brass
  - Stainless Steel
  - Ceramics

- **Mock-up results are so far based on Brass base-plates**
Module Boards

- Mockup of 432 channel module board
  - Designed to apply heat loads and measure temperature of the silicon

12 heaters mocking 12 read-out chips

8 RTDs in contact with Silicon

ADS124S0x chip for heater control and temp measurements

High bandwidth connectors
  - 2mm high rigid

8” mock-up module board
Mock-up Module Assembly
• The assembly is placed for 30 minutes in vacuum to remove the air bubbles

• The assembly is placed in an oven at ~40°C for the epoxy to cure (3 hours)
Mock-up Module Assembly

7

8

9

10
Initial Gluing Challenges in Module Construction

- Coefficient of Thermal Expansion of Brass module baseplate and PCB: $12 \times 10^{-6} \text{ K}^{-1}$ and $19 \times 10^{-6} \text{ K}^{-1}$
- Coefficient of Thermal Expansion of Silicon: $2.8 \times 10^{-6} \text{ K}^{-1}$
- At $-30 \, ^\circ\text{C}$, the Brass baseplate and the PCB are pulling the silicon sensor in opposite directions
  - The glue has to resist the stress
- 3 modules with insufficient amount of glue had the PCB delaminated at $-40 \, ^\circ\text{C}$ and the sensor cracked
- After insuring sufficient glue is applied no more failure was observed
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Automated Module Assembly

• A pick-and-place gantry is used for mating the main components of Silicon modules
• Ensures consistent dispense of right amount of glue
Dynamic Mounting of Modules in Cassettes

- Lower Coefficient of Thermal Expansion of Silicon module w.r.t. Copper necessitates a dynamic mounting scheme for the modules
Thermal FEA Simulation Set-up

- The expected performance of the cooling system is calculated based on the combination of FEA simulations in two steps:
  - Full size Copper cooling plate and CO$_2$
  - Single Silicon module and Copper cooling plate
Cooling Plate Performance

**Copper cooling plate and CO\textsubscript{2}:**
- FEA calculations have been made assuming an expected uniform heat load of 200W
  - 6.8 meter long tube
  - 2.197 g/sec CO\textsubscript{2} mass flow
  - Pressure Drop = 0.8 psi

- At most the Copper cooling plate is expected to be 2.5 °C warmer than the CO\textsubscript{2} temperature.
Expected Performance at Silicon Level

Copper cooling plate and Silicon:

- On average the Si is expected to be 1.5 °C warmer than the Copper cooling plate
- As a result all Si sensors satisfy the requirement of being colder than -30 °C
Assembled the Mock-up Cassette

- The mockup cassette has been fabricated, assembled and cold tested
- 16 full modules and 6 motherboards
• 6 W heat load applied per module (12 heaters; each 0.5W)
• The Si temperature was measured ~5.2°C above CO₂ outlet on average for 6W heat load per module
Module Flatness at Cold Temperatures

- Measured the height of the center and 6 corners of the modules installed on cooling plate with the Coordinate Measurement Machine at -30 °C.
- The center of the modules is measured ~800 μm higher than the corners at -30 °C.
  - The air gap below the warped modules explains why the measured temperatures are larger than expected.
- Other base-plate material is being investigated that can prevent modules from warping.

Measured at -30 °C
Conclusions

• The CMS HGCal is addressing high pile-up and high radiation dose issues at HL-LHC
  • Radiation hard Si modules
    • Operation at -30 °C
  • 6 M channels
    • 220 kW heat dissipation
• The thermo-mechanical design must
  • Address challenges of efficient heat removal over large surfaces
  • Safely accommodate the large differences in CTE of most commonly used materials (such as PCBs, most metals, etc.) compared to that of the Silicon sensors
• A baseline design which addresses these issues has been developed for the TDR
  • An extensive set of detailed simulations and tests with full scale realistic mock-ups is currently under way to further optimize this design and arrive at a fully engineered solution
Back-up
CMS HGCal Cassette Installation

- Cassettes are built around a central copper cooling plate
  - Provides mechanical support and cooling for active elements
- Cassettes are assembled and tested at assembly sites
- Shipped to Point5 and installed into the calorimeter
  - Electromagnetic cassettes stacked
  - Hadronic cassettes inserted
HGCal Cassette Types

- 3 types of cassettes
- Single-sided Si + scintillator cassettes for CE-H layers 9 -- 24
- Single-sided Si only cassettes for CE-H layers 1 -- 8
- Double-sided Si only cassettes with Pb absorber for CE-E, 14 x 2 layers
HGCal Cooling System

- The cooling of the HGCal detector is based on bi-phase $\text{CO}_2$
- Rigid vacuum-jacketed stainless steel pipes carry the $\text{CO}_2$ from the refrigeration plants to the detector.
- The flow is fed to the detector cold volume via 24 vacuum-insulated coaxial lines on each Endcap.

Vacuum jacketed coaxial lines over the Endcap suspension system brackets

two sets of supply and return lines every 30°
Design Question Being Addressed

- **Cassette boundary shape**
  - 30 or 60 degree cassettes
  - Whole modules or half modules at the edge

- **Mounting scheme of modules**
  - One shared screw for three module corners or individual ones, special mounting on cassette edge, washer design, location of module locating pins

- **CO$_2$ cooling pipe shape and capillary design**
  - Operating pressure difference of cooling plant and heat power drives the design

- **Geometry of motherboards and connections to modules**
  - Single or double row of modules, number of modules per motherboard
  - Rigid, compression, flex cable connectors

- **Power delivery**
  - Location of DC to DC converters
  - Power bus bar or inside motherboard

- **Cassette interface patch panel design**

- **Assembly procedures, tooling and testing**
Segmentation of the Cassettes

- The interface between cassettes follows the outline of whole-size modules.
- The size of the Electromagnetic (CE-E) cassettes has been chosen to be 60 degrees.
- The size of the Hadronic (CE-H) cassettes has been chosen to be 30 degrees to ease fabrication and assembly of components.
  - Cassettes can be inserted in pairs as a 60-degree unit.
- All cassettes use common design where possible.
More Views of the Mock-up Cassette
Module Design Modifications

- Introducing new High Voltage wire-bond locations to simplify bonding and potting
Motherboard and DAQ System

- DAQ system available to read order of 50 ADC chips and 800 RTDs
- DAQ is based on Raspberry Pi that communication to ADC chips on SPI bus
- At the end of motherboard chains, a Raspberry Pi carrier board is connected which communicates to the DAQ PC via ethernet