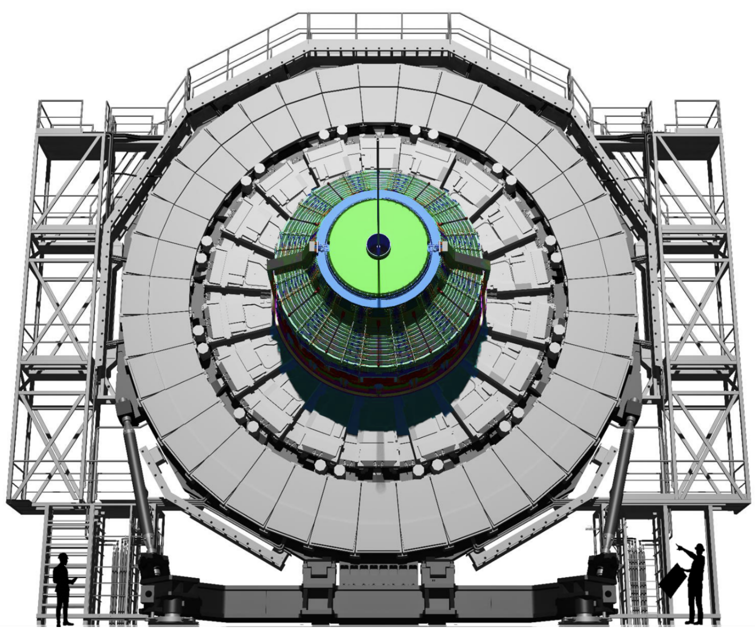
CERN Summer Student project report

CMS - HGCAL
Summer 2025



Solving the HGCAL fiber routing conundrum:
The universal harness approach

Author

Eliot Jouan

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1 Introduction and Context

1.1 The CMS Experiment and HL-LHC Upgrade

The Compact Muon Solenoid (CMS) is one of four major experiments at CERN's Large Hadron Collider (LHC), designed to study fundamental particles through high-energy proton collisions. The upcoming High-Luminosity LHC (HL-LHC) upgrade, scheduled for 2030, will increase collision rates by 5-7 times, generating ten times more data than current operations. To handle this increased data load, CMS will undergo significant upgrades, including the replacement of its endcap calorimeters with the High Granularity Calorimeter (HGCAL). This new detector will provide unprecedented precision measurements at the extreme luminosity scales of the HL-LHC.

1.2 HGCAL Architecture

HGCAL consists of 47 layers divided into two sections: the electromagnetic calorimeter (CE-E, 26 layers) using silicon sensors with tungsten absorbers, and the hadronic calorimeter (CE-H, 21 layers) using silicon sensors or scintillator tiles. The detector employs hexagonal silicon chips (hexachips) for electromagnetic detection and square scintillator tiles for hadronic detection. The detector's architecture follows a specific angular segmentation: CE-E layers are divided into 60° cassettes (6 sectors per layer), while CE-H layers use 30° cassettes (12 sectors per layer). This segmentation, combined with the detector's 120° central symmetry, creates a complex but systematic geometric structure.

2 Fiber Routing System and Initial Challenges

2.1 Current Fiber Architecture

The HGCAL readout system generates over 3,000 optical fibers carrying two types of data: raw measurement data (DAQ - Data Acquisition) and trigger data for event selection. These fibers are organized into harnesses - flat assemblies of optical fibers grouped by data type and detector module. The data transmission path follows this sequence:

- **Front-End (FE):** Detector modules with VTRX optical transmitters
- **PP0:** Initial fiber grouping into connectors of 4, 6, or 12 fibers
- **PP1:** Consolidation into standardized 24-fiber bundles
- **PP2:** Final regrouping before transmission to backend servers
- **Back-End (BE):** 16 acquisition cards (Serenity) processing the data

2.2 Identified Problems

During my initial mapping verification phase, several critical issues emerged:

1. **Connector Mismatch:** Some connectors were designed for 13 fibers on 12-fiber connectors at PP0 level

2. **Backend Capacity Overflow:** The trigger system produced 2,064 fibers at PP1 output, exceeding the 1,920-fiber capacity of the 16 available Serenity cards
3. **Complex Routing Logic:** The existing mapping prioritized technical constraints over practical assembly considerations

The overflow problem stemmed from four competing constraints:

- Maintaining DAQ/Trigger fiber pairs from each module
- Limited connector sizes (4, 6, or 12 fibers at PP0; 24 fibers at PP1)
- Balanced data flow distribution across backend cards
- Simple, redundant routing logic to prevent assembly errors

This created unavoidable "dark fibers" (unused connections) that propagated through the system, ultimately exceeding backend capacity.

3 The Universal Harness Solution

3.1 Conceptual Foundation

The universal harness concept exploits HGCAL's multiple symmetries:

- **Detector symmetry:** Two identical endcaps
- **Angular symmetry:** 3×120° identical sectors
- **Approximated symmetry:** 30° angular segments with similar characteristics
- **Layer grouping:** Sets of 4 consecutive layers with comparable throughputs and geometry

This creates $6 \times 4 \times 4 = 96$ symmetry elements, exactly matching the available Serenity cards across the entire system. The approach allows designing routing for just one 30° sector of 4 layers, then replicating this pattern throughout the detector.

3.2 Implementation Strategy

The universal harness design eliminates intermediate patch panels (PP1 and PP2), routing fibers directly from PP0 to the backend. This simplification is possible because the enhanced symmetry ensures natural load balancing across Serenity cards. For the CE-E region: 3 harnesses per 60° cassette using 12-fiber connectors For the CE-H region: 2 harnesses per 30° cassette using mixed connector sizes The routing algorithm assigns fibers to backend cards based on their geometric position and layer number, ensuring each card receives equivalent data loads due to the detector's symmetrical properties.

3.3 Technical Validation

Implementation required some code development to integrate the new routing logic into existing frameworks. This included:

- Modifying geometric databases and mapping algorithms
- Creating new pipeline processes for file generation
- Developing bandwidth analysis tools

Initial worst-case scenario analysis showed maximum data rates of 214 Gb/s per Serenity card, well within the $12 \times 25 = 300$ Gb/s limit. However, subsequent discussions revealed additional backend constraints requiring no more than 400 Gb/s across paired cards. Further study shjowed that in practice, all cards had under 200 Gb/s per card, confirming the solution's viability.

4 Optimization and Final Results

4.1 14-Serenity Configuration

Following feedback about system flexibility, a final optimization phase aimed to reduce hardware requirements from 16 to 14 Serenity cards. This involved:

- Converting some CE-E connectors from 12 to 8 fibers
- Eliminating unnecessary dark fibers
- Maintaining universal harness design principles

The optimized configuration achieved an average of 228 Gb/s per card while preserving the routing logic's simplicity and symmetry.

4.2 Advantages of the Universal Approach

The universal harness solution offers several key benefits:

1. **Simplified Assembly:** Identical harnesses across similar detector regions reduce complexity and error probability
2. **Natural Load Balancing:** Symmetry-based routing automatically distributes data loads evenly
3. **Reduced Infrastructure:** Elimination of intermediate patch panels saves space and cost
4. **Scalable Design:** The approach can accommodate different backend configurations
5. **Maintenance Efficiency:** Standardized components simplify troubleshooting and repairs

5 Additional Activities and Learning

Beyond the primary project, the internship provided extensive learning opportunities through: **Technical Lectures:** Summer student program included comprehensive courses on particle physics, quantum field theory, accelerator physics, superconductivity, and data acquisition systems. **Experimental Exposure:** Participation in hexachip testing under extreme magnetic field conditions (several Tesla) and observation of detector assembly in clean room facilities. **Collaborative**

Environment: Regular presentations at hardware team meetings and integration with software development teams provided insight into large-scale scientific collaboration.

6 Conclusions and Future Outlook

The universal harness approach successfully addresses the HGCAL fiber routing challenges by transforming complex constraints into manageable symmetries. The solution demonstrates how systematic exploitation of detector geometry can simplify engineering problems while maintaining technical performance requirements. The work produced a functional routing system that:

- Respects all technical constraints (connector sizes, bandwidth limits, load balancing)
- Simplifies assembly procedures through standardization
- Reduces infrastructure requirements
- Provides flexibility for different configuration scenarios

This approach is likely to be implemented in the final HGCAL detector construction, contributing to the successful operation of the HL-LHC physics program.apparatus.