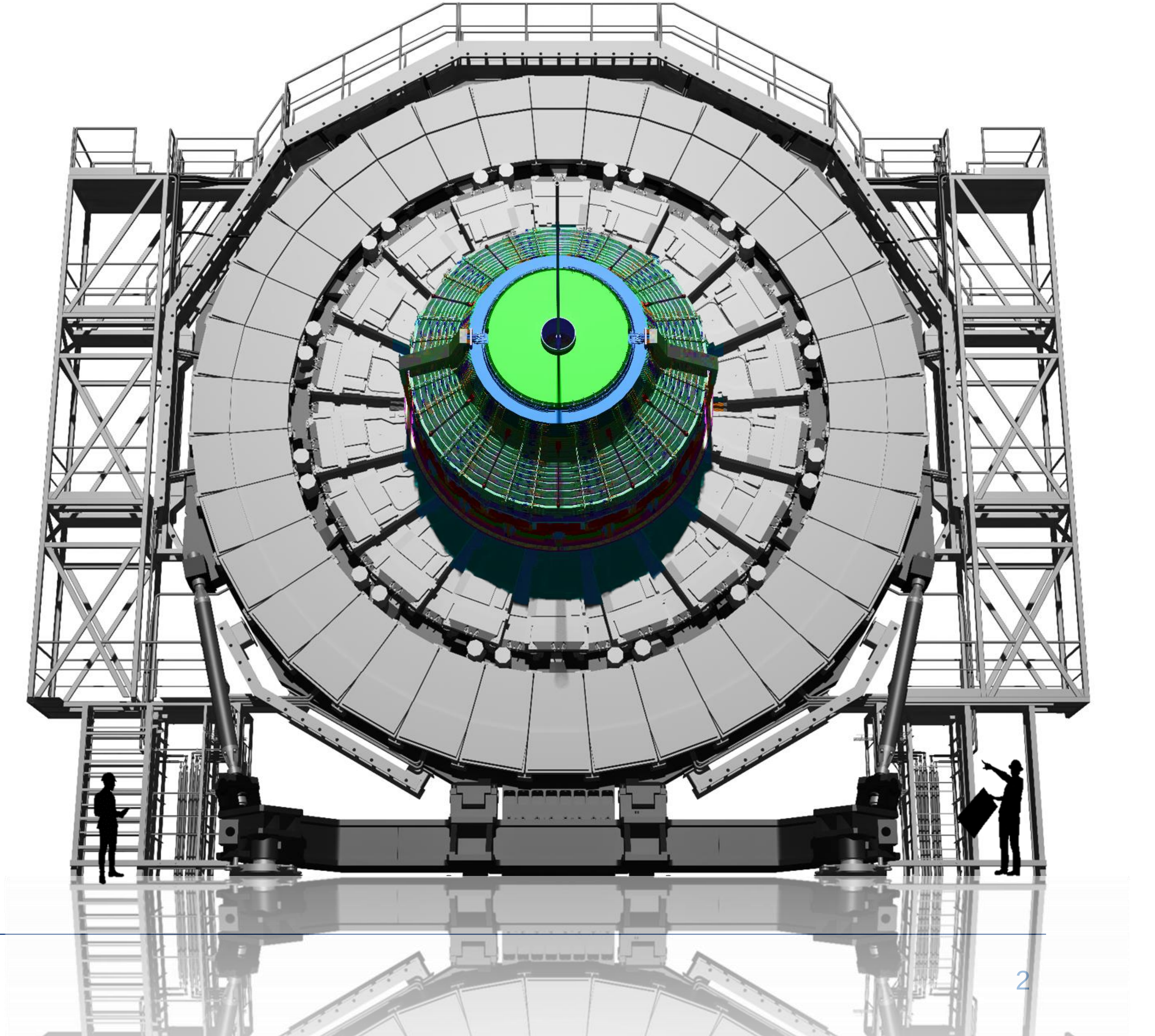
CERN - CMS HGCAL Detector - Integration

T. French (CERN) on behalf of the CMS HGCAL collaboration

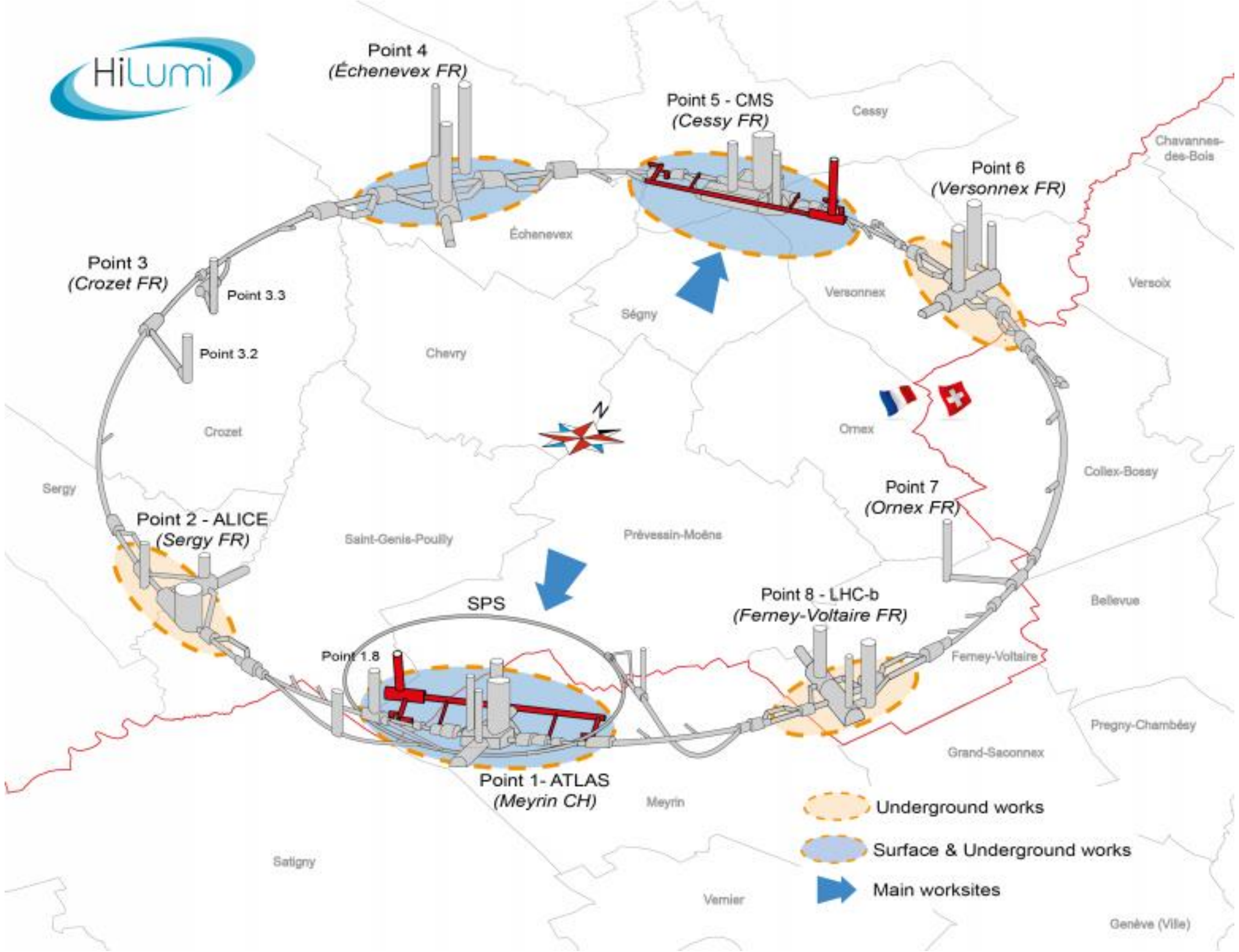
EIROforum, 6th February 2024

An overview of CMS HGCAL



CERN High Luminosity Upgrade

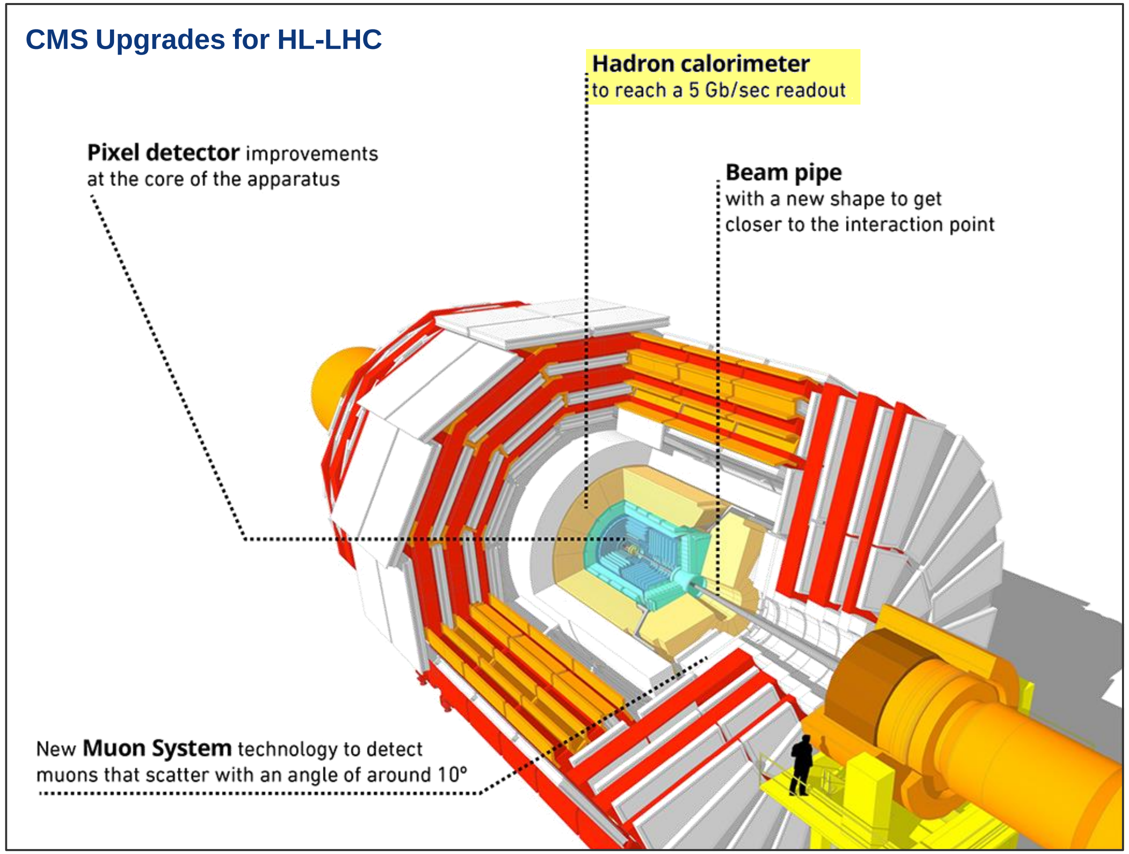
- **High luminosity LHC (HL-LHC) physics programme:**
  - Detailed studies of the Higgs boson and standard model processes.
  - Trigger cleanly on and reconstruct particle jets for physics beyond the standard model.
- Integrating **10x more luminosity (3000 fb^{-1})** than the LHC.
  - Luminosity is the number of detected events over time, divided by the cross section.
  - Challenges for **radiation tolerance and event pileup**, especially for calorimetry in the forward region.
- **Major upgrades** being made to the LHC and its experiments including ALICE, ATLAS, CMS, and LHCb.

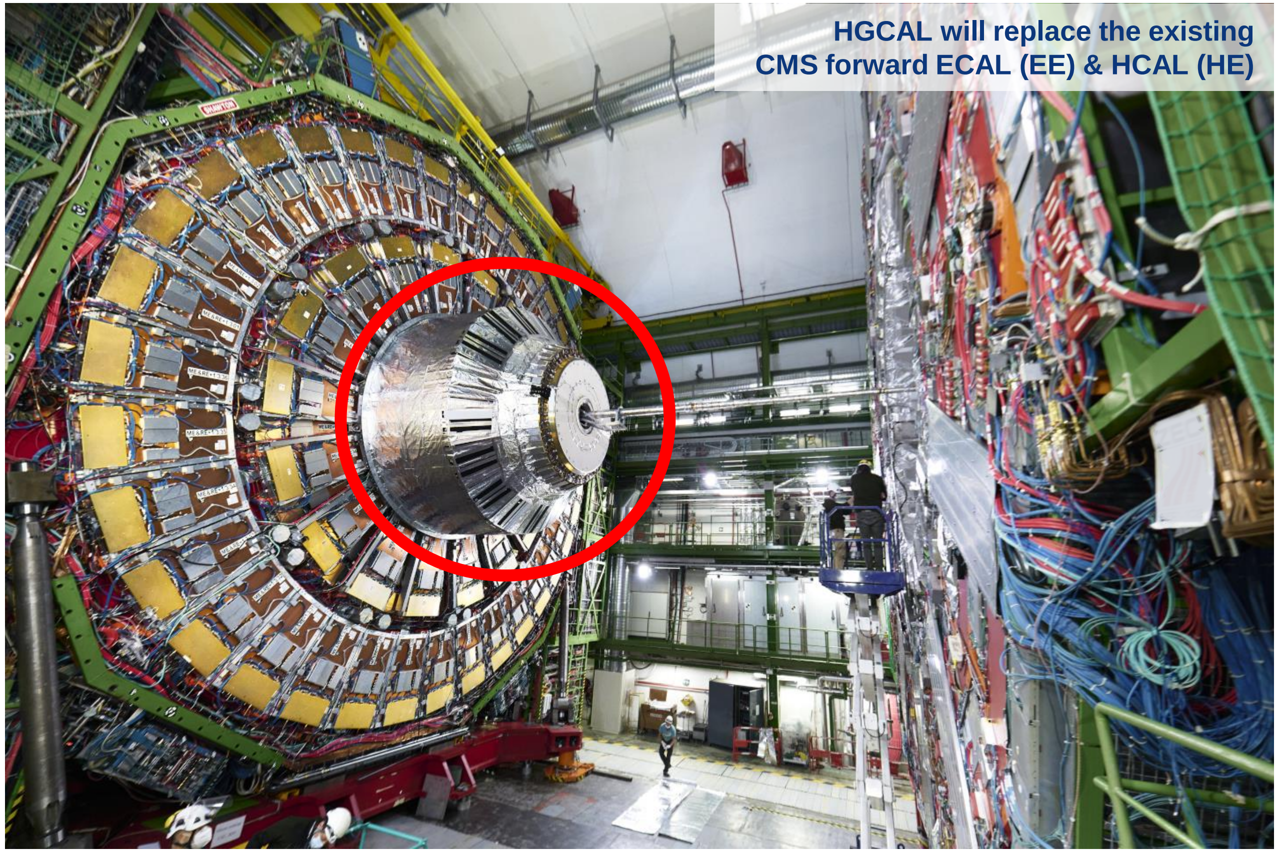


CERN LHC Upgrades for HL-LHC

CMS HGCAL Project

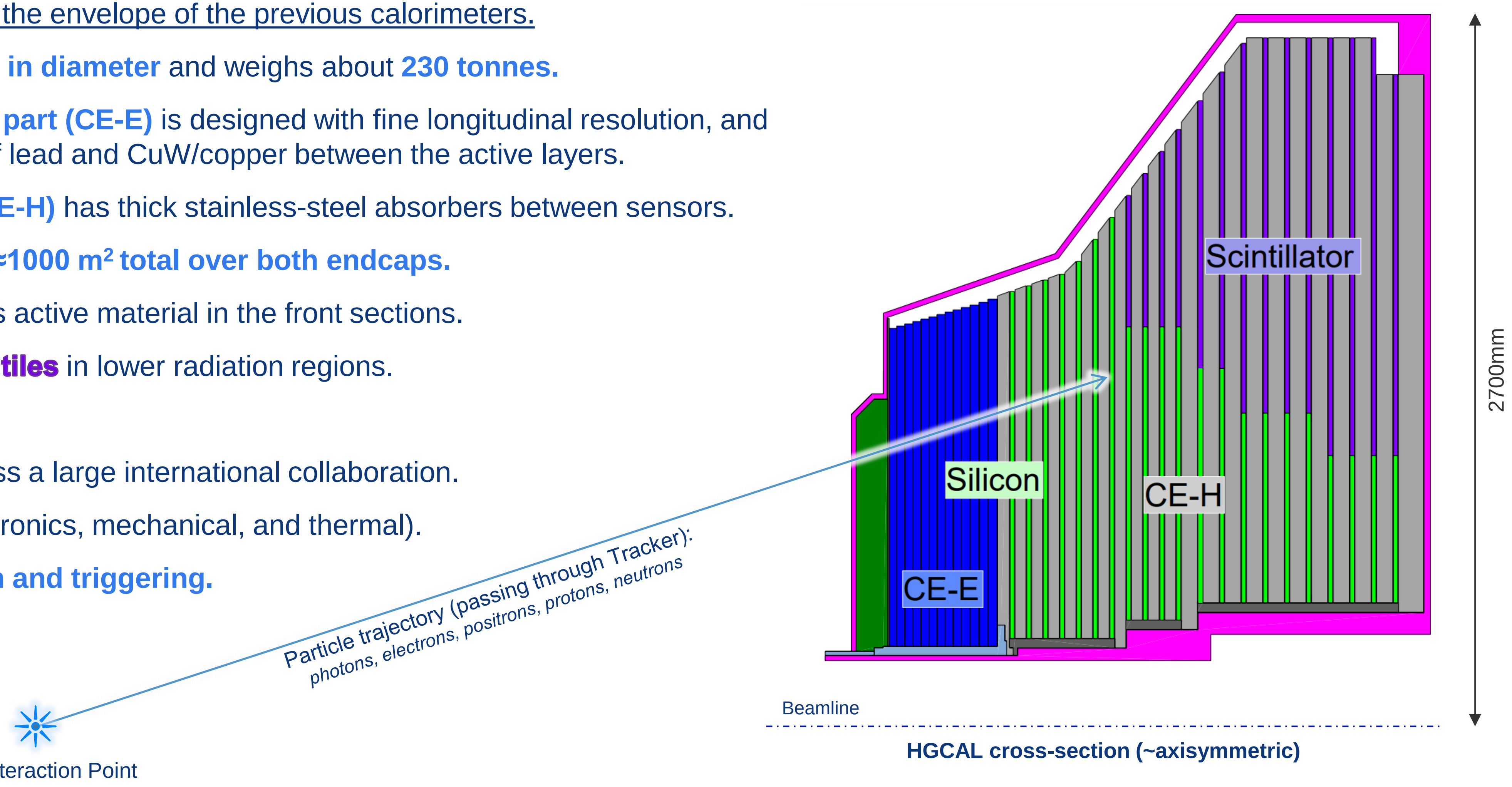
- Performance degradation of the existing calorimeters, which **were designed for an integrated luminosity of 500 fb^{-1}.**
- Two **high granularity calorimeters (HGCAL)** will replace the existing endcap calorimeters, for installation in 2026-2028 during one of CERN's "long shutdowns".





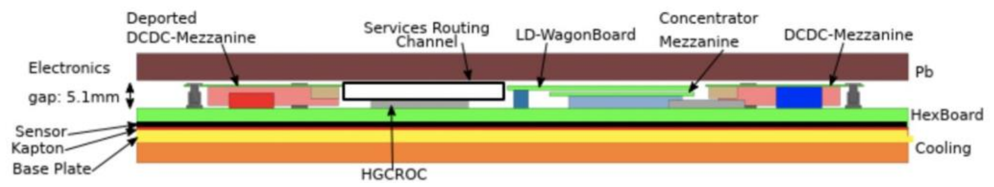
Proposed Detector – HGCAL

- HGCAL needs to fit in the envelope of the previous calorimeters.
- Each HGCAL is **5.4 m in diameter** and weighs about **230 tonnes.**
- The **electromagnetic part (CE-E)** is designed with fine longitudinal resolution, and thin absorber layers of lead and CuW/copper between the active layers.
- The **hadronic part (CE-H)** has thick stainless-steel absorbers between sensors.
- Active sensors cover **≈1000 m^2 total over both endcaps.**
  - **Silicon sensors** as active material in the front sections.
  - Plastic **scintillator tiles** in lower radiation regions.
- **Challenges:**
  - **Project work** across a large international collaboration.
  - **Engineering** (electronics, mechanical, and thermal).
  - **Data transmission and triggering.**



HGCAL cross-section (~axisymmetric)

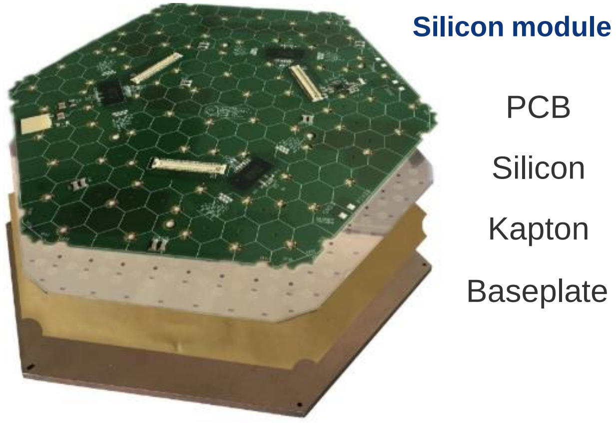
Building the HGCAL Detector



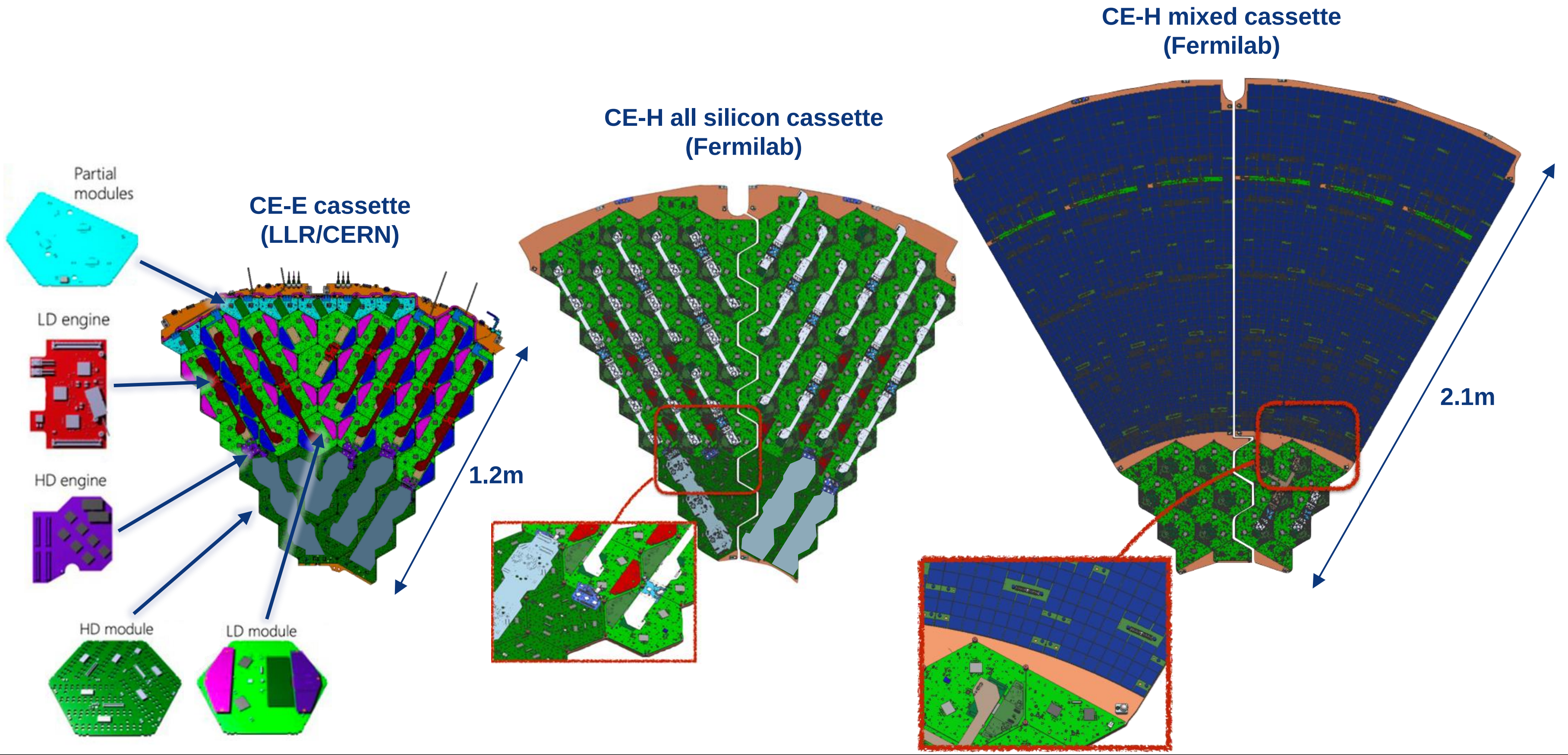
Cassette cross-section

- **26,000 hexagonal silicon modules and 280,000 scintillator tiles.**
- Assembled into "cassettes": cooled copper plates which carry the modules, tileboards, electronics, services, connectors.

Silicon module

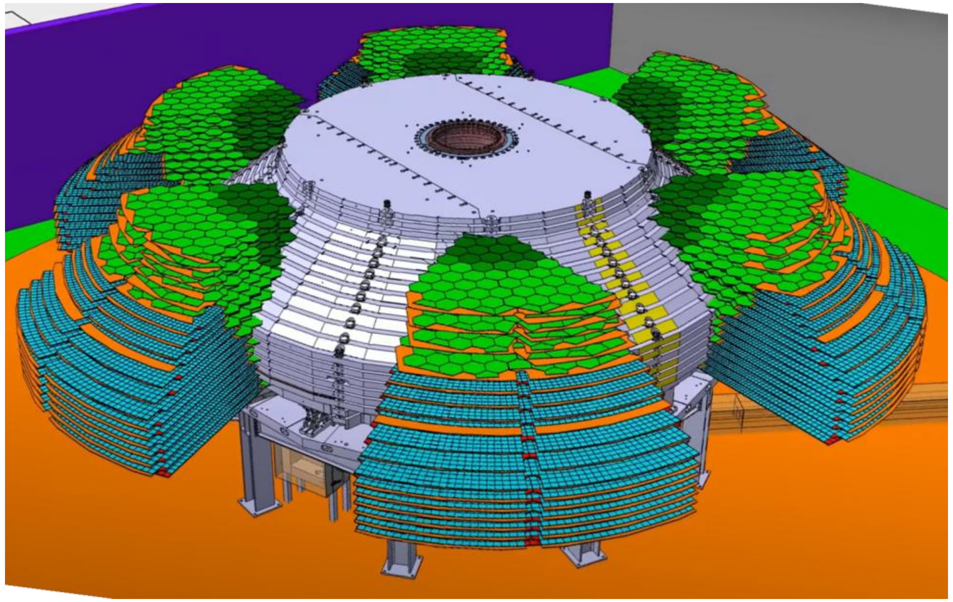


Tileboard with wrapped tiles & SiPMs

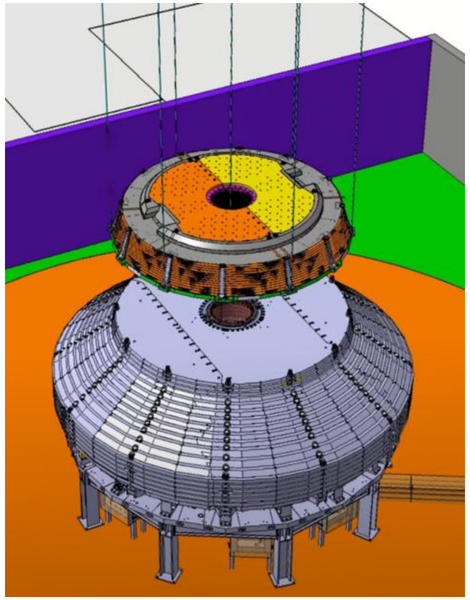


Building the HGCAL Detector

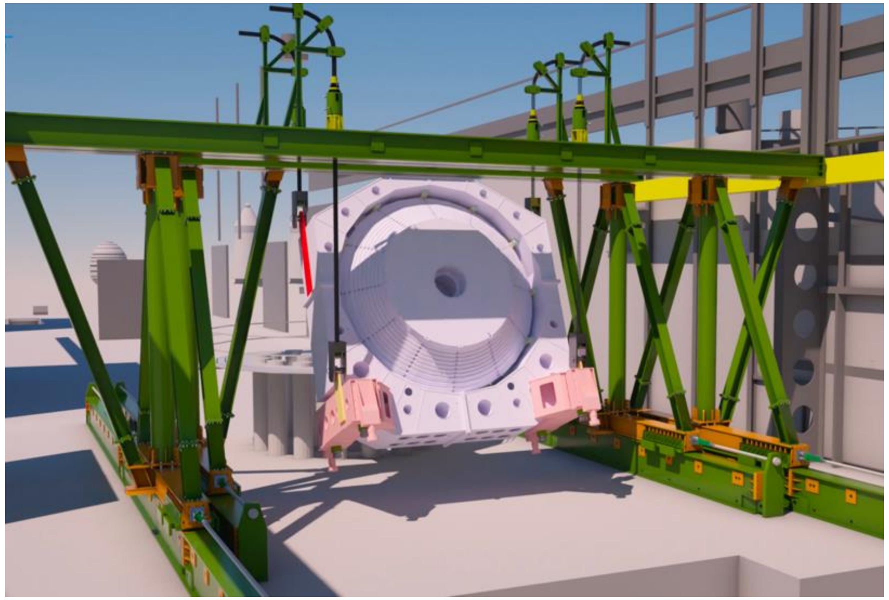
- **CE-H cassettes will be slid into gaps between the stainless steel absorbers, weighing 205 tonnes.**
- **CE-E cassettes will be stacked into a 23-tonne assembly**, and lowered on top.
- The detector will then be dressed with services and sealed with an insulating thermal screen.
- **Rotating and lowering the detector down CMS shafts, 100 m deep**, will require specialist cranes.



CE-H cassettes inserted between absorbers

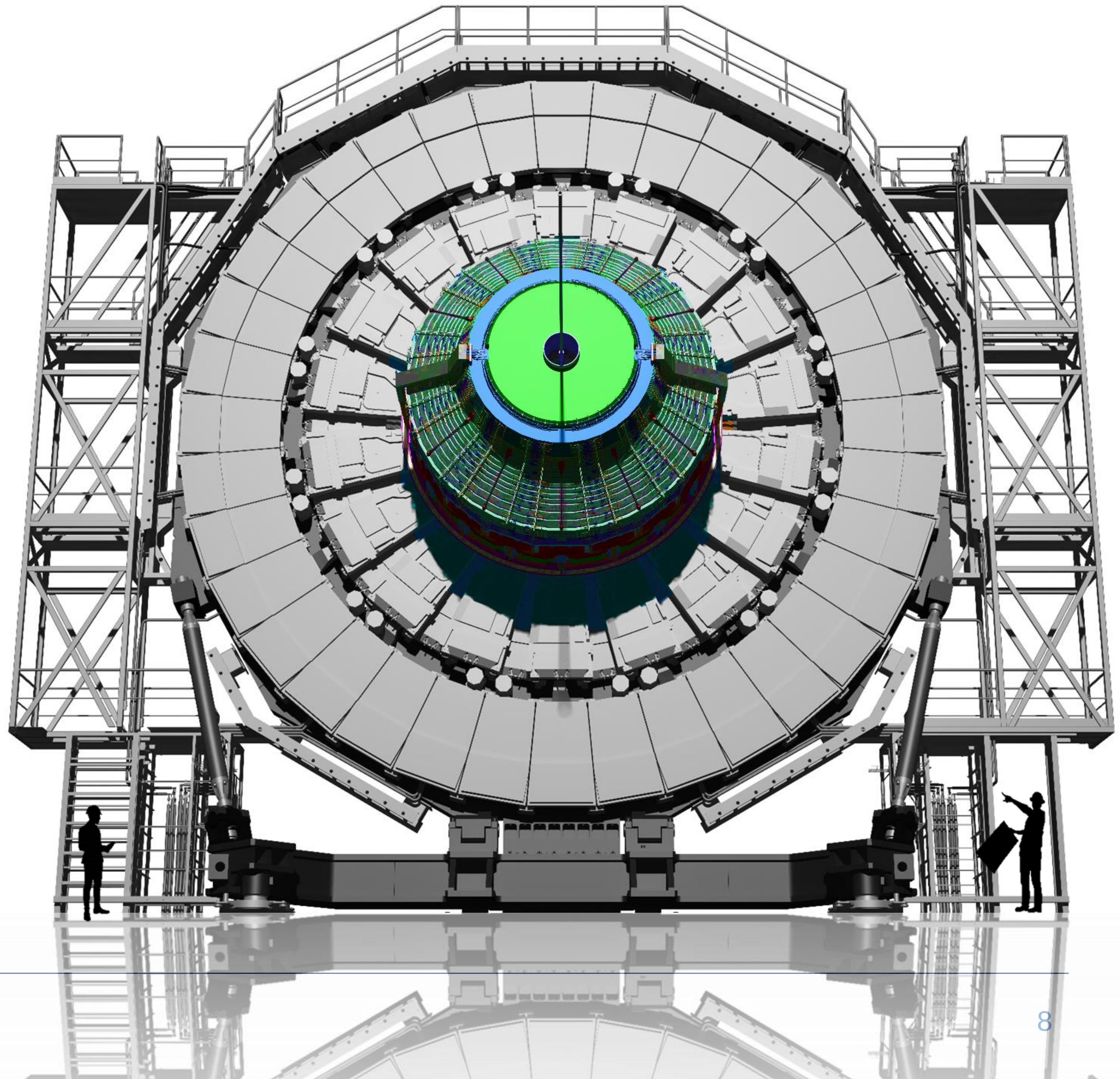


CE-E lowered onto CE-H



Full detector rotation using support cradle prior to lowering via strandjacking

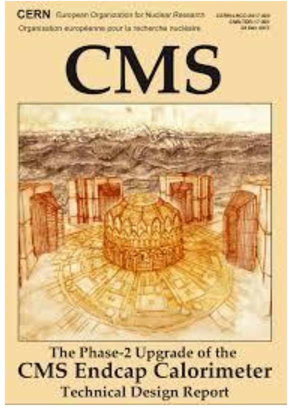
Systems Engineering



Requirements

- The project is conceived many years in advance, with feasibility studies and a technical proposal (TP) report.
- The whole system is then defined through a **technical design report** (HGCAL TDR, 2018), which defines the **top-level system requirements** (and a preliminary system design in the same document).
  - **PHYSICS**
- The system is split into broad subsystems:
  - **Electronics**
  - **Data acquisition**
  - **Trigger**
  - **Engineering**
- **Each subsystem has its own requirements** to meet the system requirements.
  - Passed down to the **sub-subsystems.**
    - How this is done and documented varies across the project.

SYSTEM
HGCAL

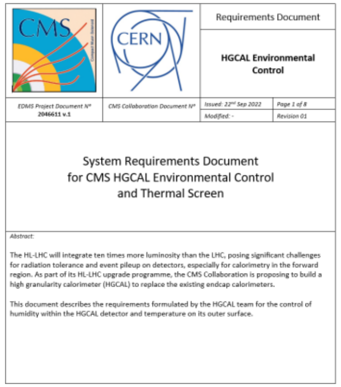


1.2 Requirements for the HGCAL upgrade

Preserving good performance over the full lifetime will require good (at the level of a few percent) inter-cell calibration. Adequate calibration accuracy can best be achieved if minimum-ionizing particles (MIPs) can be cleanly detected in each cell. This requires a good signal-to-noise ratio (S/N) for MIPs after 3000 fb^{-1}, necessitating the use of low-capacitance silicon cells, of a small size (≈0.5–1 cm^2), and scintillator cells of a small enough size for high light collection efficiency and S/N, resulting in a high lateral granularity. Fine longitudinal sampling is needed to provide good energy resolution, especially when using thin active layers (100–300 μm thick Si sensors). The fine lateral and longitudinal granularity leads to a high cell count. The main requirements for the HGCAL upgrade can be summarized as follows:

- *radiation tolerance:* fully preserve the energy resolution after 3000 fb^{-1}, requiring good inter-cell calibration (≈3%) using minimum-ionizing particles,
- *dense calorimeter:* to preserve lateral compactness of showers,
- *fine lateral granularity:* for low energy equivalent of electronics noise so as to give a high enough S/N to allow MIP calibration, to help with two shower separation and the observation of narrow jets, as well as limiting the region used for energy measurement to minimize the inclusion of energy from particles originating in pileup interactions,
- *fine longitudinal granularity:* enabling fine sampling of the longitudinal development of showers, providing good electromagnetic energy resolution (e.g. for $H \to \gamma\gamma$), pattern recognition, and discrimination against pileup,
- *precision measurement of the time of high energy showers:* to obtain precise timing from each cell with a significant amount of deposited energy, aiding rejection of energy from pileup, and the identification of the vertex of the triggering interaction,
- *ability to contribute to the level-1 trigger decision.*

SUB-SUBSYSTEM
e.g. Thermal Screen


Requirements Document

HGCAL Environmental Control

EDMS Project Document Nº 2046611 v.1 | CMS Collaboration Document Nº | Issued: 22nd Sep 2022 | Page 1 of 8 | Modified: - | Revision 01

System Requirements Document
for CMS HGCAL Environmental Control
and Thermal Screen

Abstract:

The HL-LHC will integrate ten times more luminosity than the LHC, posing significant challenges for radiation tolerance and event pileup on detectors, especially for calorimetry in the forward region. As part of its HL-LHC upgrade programme, the CMS Collaboration is proposing to build a high granularity calorimeter (HGCAL) to replace the existing endcap calorimeters.

This document describes the requirements formulated by the HGCAL team for the control of humidity within the HGCAL detector and temperature on its outer surface.

6.6 General Design & Safety

CMS_HGC_EC220: The system shall adhere to CERN electrical standards, in particular with the use of non-halogen cables.

CMS_HGC_EC230: The system shall use materials approved by CERN for fire safety.

CMS_HGC_EC240: The materials used shall be (or shall be shown to be) radiation hard for the expected fluences and absorbed dose which will range from ≈10^{14} n_{eq}/cm^2 and 0.1M MGy at the outer radius to ≈10^{16} n_{eq}/cm^2 and 2 MGy at the inner radius (corresponding to an integrated luminosity of 3000fb^{-1}).

CMS_HGC_EC250: The system shall use materials which conform with CERN IS41 (https://edms.cern.ch/document/335806/1.02).

CMS_HGC_EC255: The system shall be designed to withstand the eddy forces generated due to the changing magnetic field from a fast discharge.

Interfaces

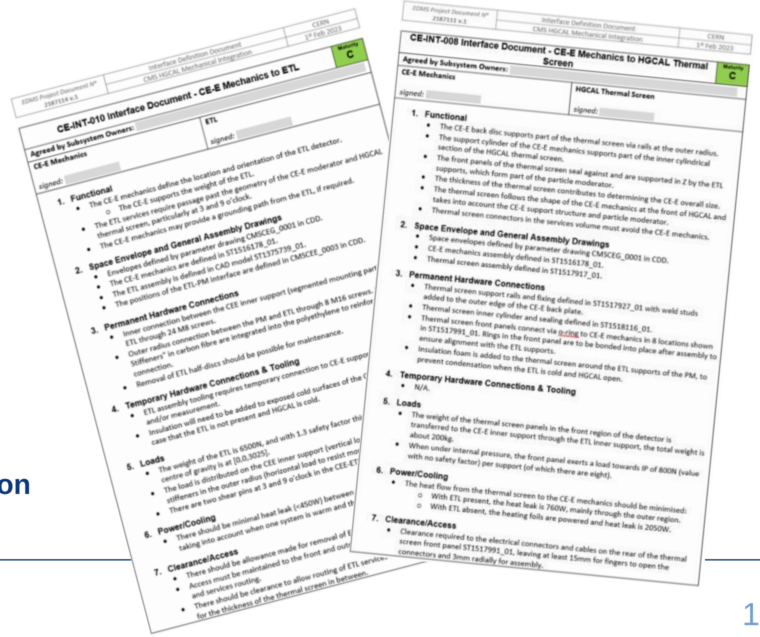
- **Define subsystems** and owners.
- Identify interfaces between subsystems.
  - Map in a **subsystem dependency structure matrix.**
- Create **interface definition documents (IDDs)**, recording:
  - **Functions.**
  - **Space envelopes, clearance/access.**
  - **Drawing references.**
  - **Hardware connections.**
  - **Key parameters (loads, power/cooling, services).**
- IDDs are signed off by subsystem owners and ranked with a maturity level.

"Engineering" Subsystem Dependency Matrix

Subsystem	CE-E Mechanics	CE-H Mechanics	CE-E Cassettes	CE-H Cassettes	CE-H Cassette Insertion Tooling	HGCAL Support System	HGCAL Cooling	HGCAL Services	HGCAL Thermal Screen	HGCAL Heavy Tooling	ETL	HGCAL Services on YE1	ME0	External Systems
CE-E Mechanics		Y	Y	Y	3D	N	3D	Y	Y	N	Y	N	N	N
CE-H Mechanics	Y		N	Y	Y	Y	3D	Y	Y	Y	N	N	3D	N
CE-E Cassettes	Y	N		N	3D	N	Y	Y	3D	3D	N	I	N	N
CE-H Cassettes	Y	Y	N		Y	N	Y	Y	3D	3D	N	I	I	N
CE-H Cassette Insertion Tooling	3D	Y	3D	Y		N	3D	3D	N	Y	N	N	N	Y
HGCAL Support System	N	Y	N	N	N		3D	3D	Y	Y	N	N	3D	Y
HGCAL Cooling	3D	3D	Y	Y	3D	3D		Y	Y	3D	Y	3D	I	Y
HGCAL Services	Y	Y	Y	Y	3D	3D	Y		Y	3D	3D	Y	3D	Y
HGCAL Thermal Screen	Y	Y	3D	3D	N	Y	Y	Y		Y	Y	N	3D	Y
HGCAL Heavy Tooling	N	Y	3D	3D	Y	Y	3D	3D	Y		I	N	N	Y
ETL	Y	N	N	N	N	N	Y	3D	Y	I		I	N	I
HGCAL Services on YE1	N	N	I	I	N	N	3D	Y	N	N	I		I	3D
ME0	N	3D	N	I	N	3D	I	3D	3D	N	N	I		Y
External Systems	N	N	N	N	Y	Y	Y	Y	Y	Y	I	3D	Y	
Master Integration Model	3D	3D	3D	3D	3D	3D	3D	3D	3D	3D	3D	3D	3D	3D

Key

Y	**Interface: requires full drawings/docs**	34
3D	**Clash-checking: captured in 3D model**	35
I	Indirect interface	8
N	No interface	28
?	Unsure of interface	0

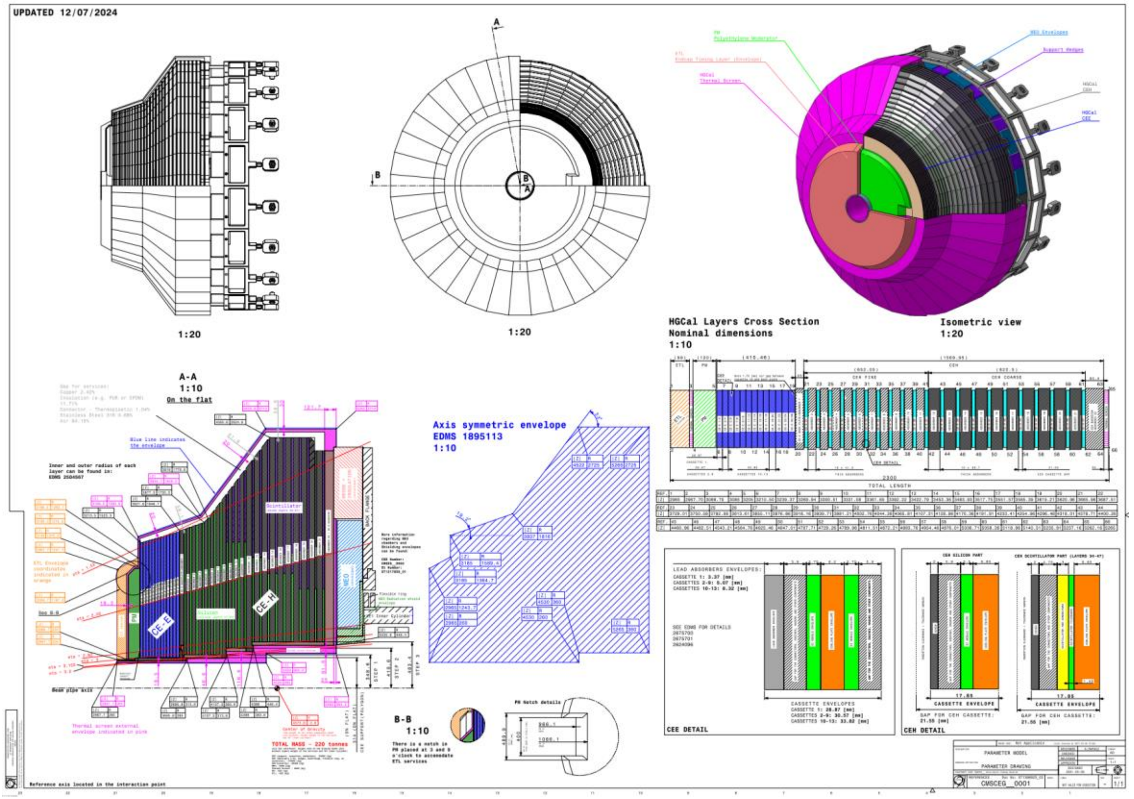

CE-INT-010 Interface Document - CE-E Mechanics to ETL
1. Functional
2. Space Envelope and General Assembly Drawings
3. Permanent Hardware Connections
4. Temporary Hardware Connections & Tooling
5. Loads
6. Power/Cooling
7. Clearance/Access

CE-INT-008 Interface Document - CE-E Mechanics to HGCAL Thermal Screen
1. Functional
2. Space Envelope and General Assembly Drawings
3. Permanent Hardware Connections
4. Temporary Hardware Connections & Tooling
5. Loads
6. Power/Cooling
7. Clearance/Access

Interface Definition Documents

CAD & Integration

- We have **many collaborating institutes each with different CAD systems** (e.g. NX at Fermilab, CATIA v6 at LLR).
  - Models shared centrally as STPs.
  - PLM used at CERN for CATIA v5 models, but most models from external institutes are stored in EDMS.
- Overall geometry controlled by a **parameter drawing** based on a parameter CAD model in CATIA v5.
- The **parameter model** is used to define **subsystem envelopes.**
  - **All subsystems must stay inside their envelopes!**
- Large number of design iterations can (in theory) be isolated to within a subsystem envelope.
  - Integration meetings held to highlight/request changes to interfaces.
  - **Changes documented and approved** at project level.



HGCAL parameter drawing based on parameter model

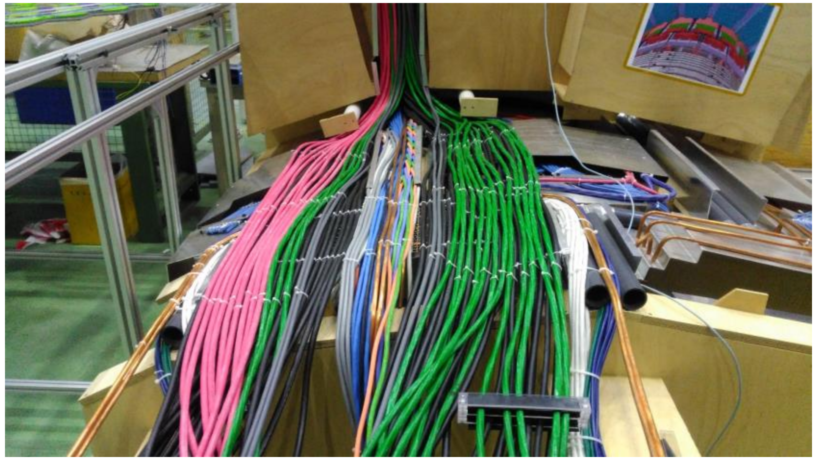
Prototyping and Infrastructure

- For a complex system, **prototyping and mock-ups are <u>essential</u>:**
  - To **verify** that the design meets the requirements (and modify if not).
  - To **validate** that the requirements are suitable (and revisit them if not).
- **Key infrastructure** is being set up:
  - Clean rooms, assembly facilities, cooling systems, powering and control racks. Still part of the "system".
  - A full set of **tooling** is needed, designed in parallel with the detector itself.
    - Handling, alignment, transport, etc.

Internal services mockup and thermal screen prototype

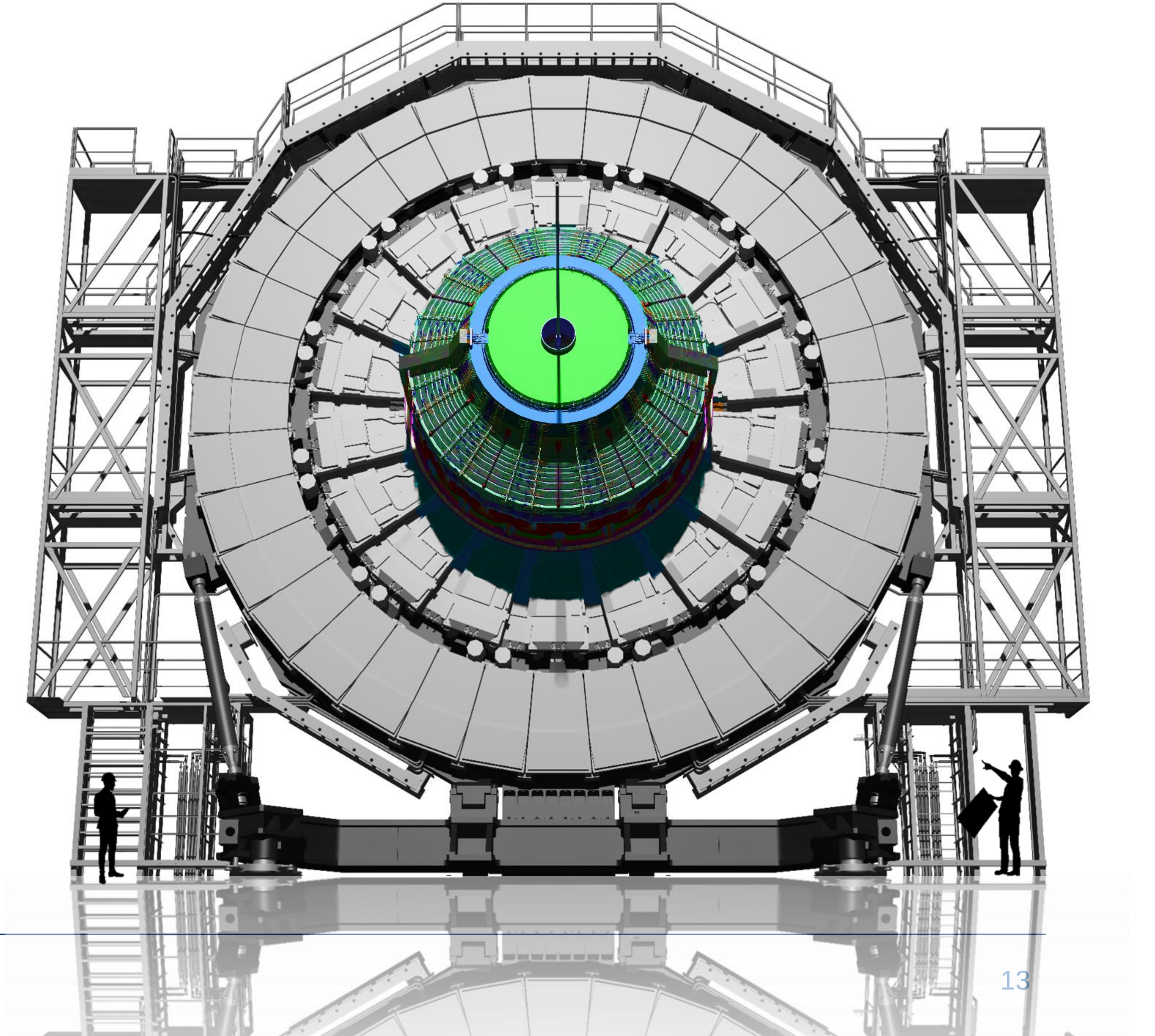
Clean room with assembly stations and test boxes at Fermilab

20° mixed cassette mechanical mockup



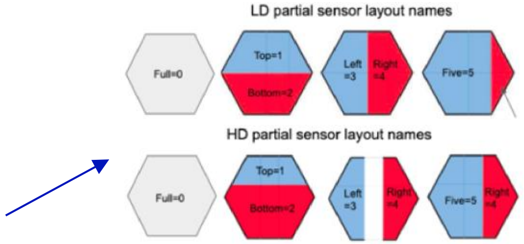
External services mockup on CMS endcap

Project Challenges and Construction Progress



Project Challenges

- **Limited resources** in central CERN team managing a project with **hundreds of contributors from collaborating institutes with no hierarchical control.**
  - Large collaborations and long projects bring **communication issues, funding delays, shifting priorities, staff turnover…**
- In our HGCAL team (CERN EP) we often have **generalist engineers responsible for all aspects of their system** (design, simulation, drafting, manufacturing, procurement, cost, schedule, testing, commissioning).
  - To effectively maintain a useful systems engineering approach, we would need a **sustained effort** by experienced staff – difficult when design and manufacture has a high priority for those same staff.
  - Not the case everywhere at CERN, the central engineering and technology departments usually have more specialised staff.
- Compromise is necessary to **achieve a working system, rather than the "ideal" system. Revising requirements to meet reality.**
  - E.g. ideally we would have 100% coverage of the sensor planes with active sensors.
    - Supports required to hold the 220-tonne detector **= reduce active area**.
    - We need to route cables, cooling pipes, gas systems, optical fibres **= reduce active area**.
    - The simplest solution would be to standardise on one size of hexagonal module, however to maximise the active area we create a number of "partial" sensors **= increased complexity**.

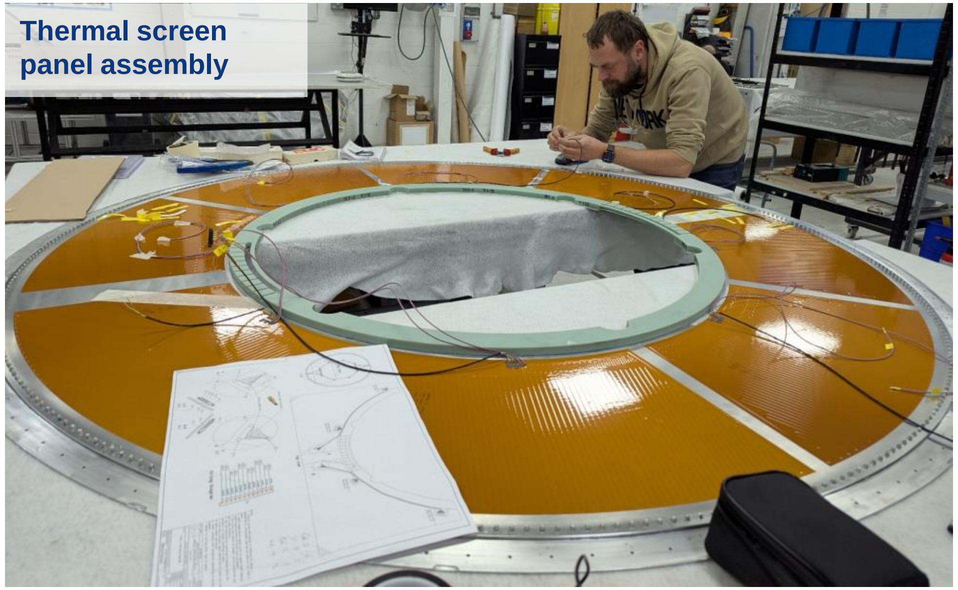


Partial sensor types

- We often have to take a risk and launch production of some components before interfacing systems are fully designed (e.g. tooling) – **we must lock the interfaces early in the process and try to build in flexibility.**
  - We pragmatically accept that some rework/modifications may be required on production components.

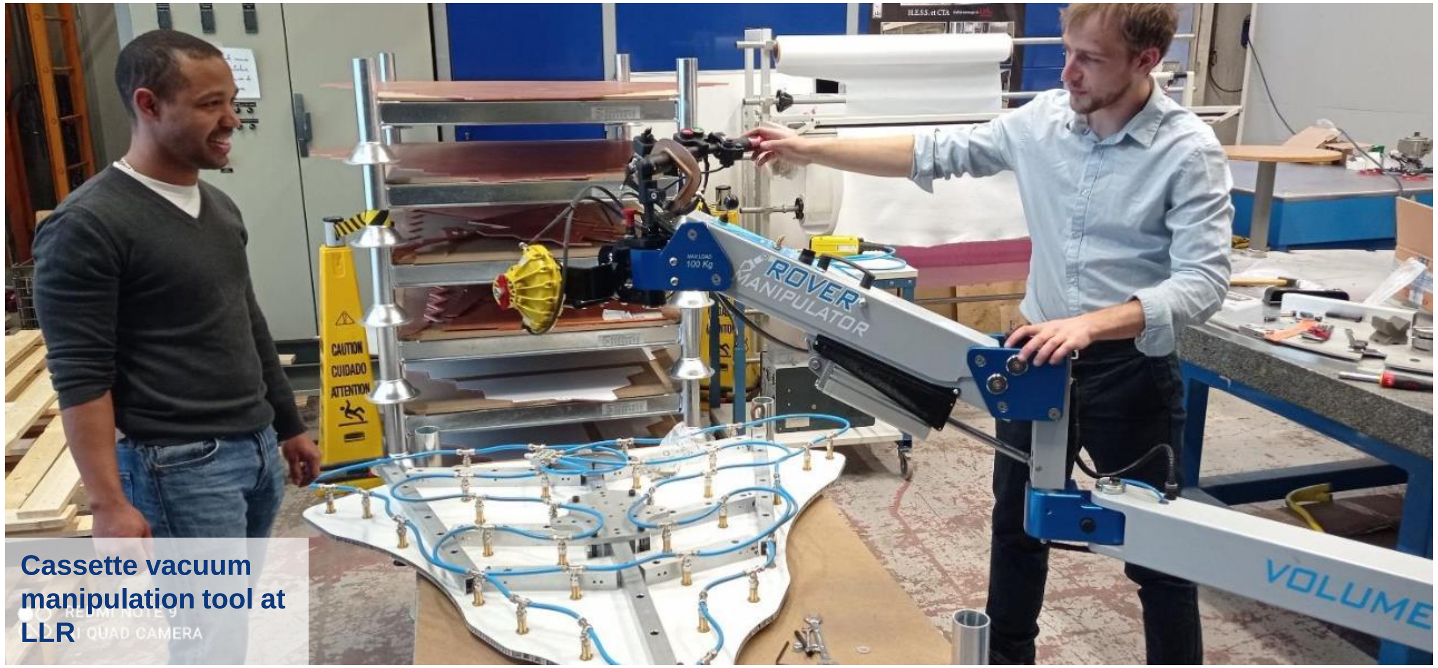
Silicon modules assembly

Detector supports machined



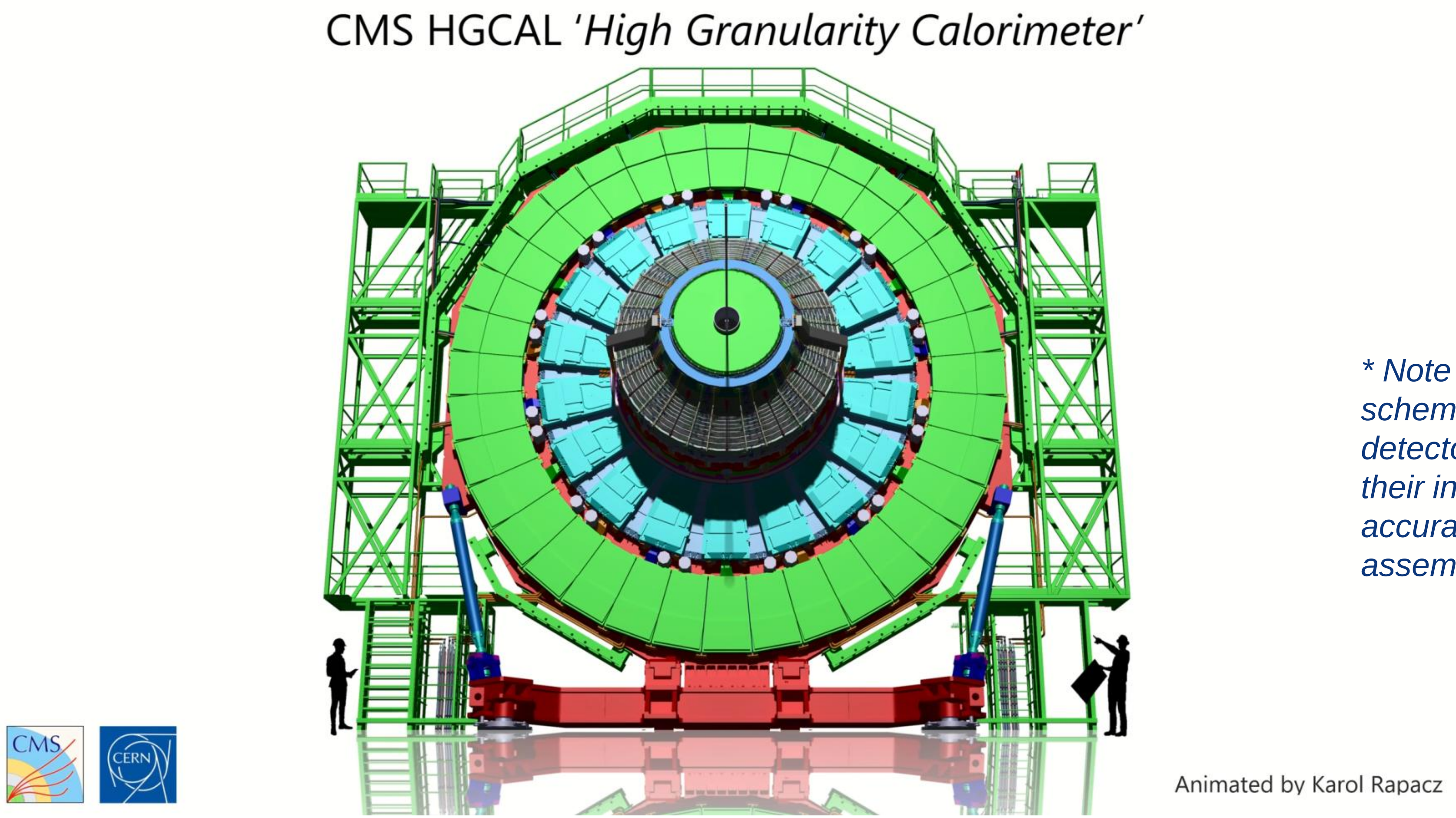
Thermal screen panel assembly

Absorbers machining and assembly at PAEC



Cassette vacuum manipulation tool at LLR

Animation



** Note – the video is a schematic illustration of the detector ingredients and their integration, not an accurate depiction of the assembly processes*

https://youtu.be/5EKumUsYinM

(8:15)