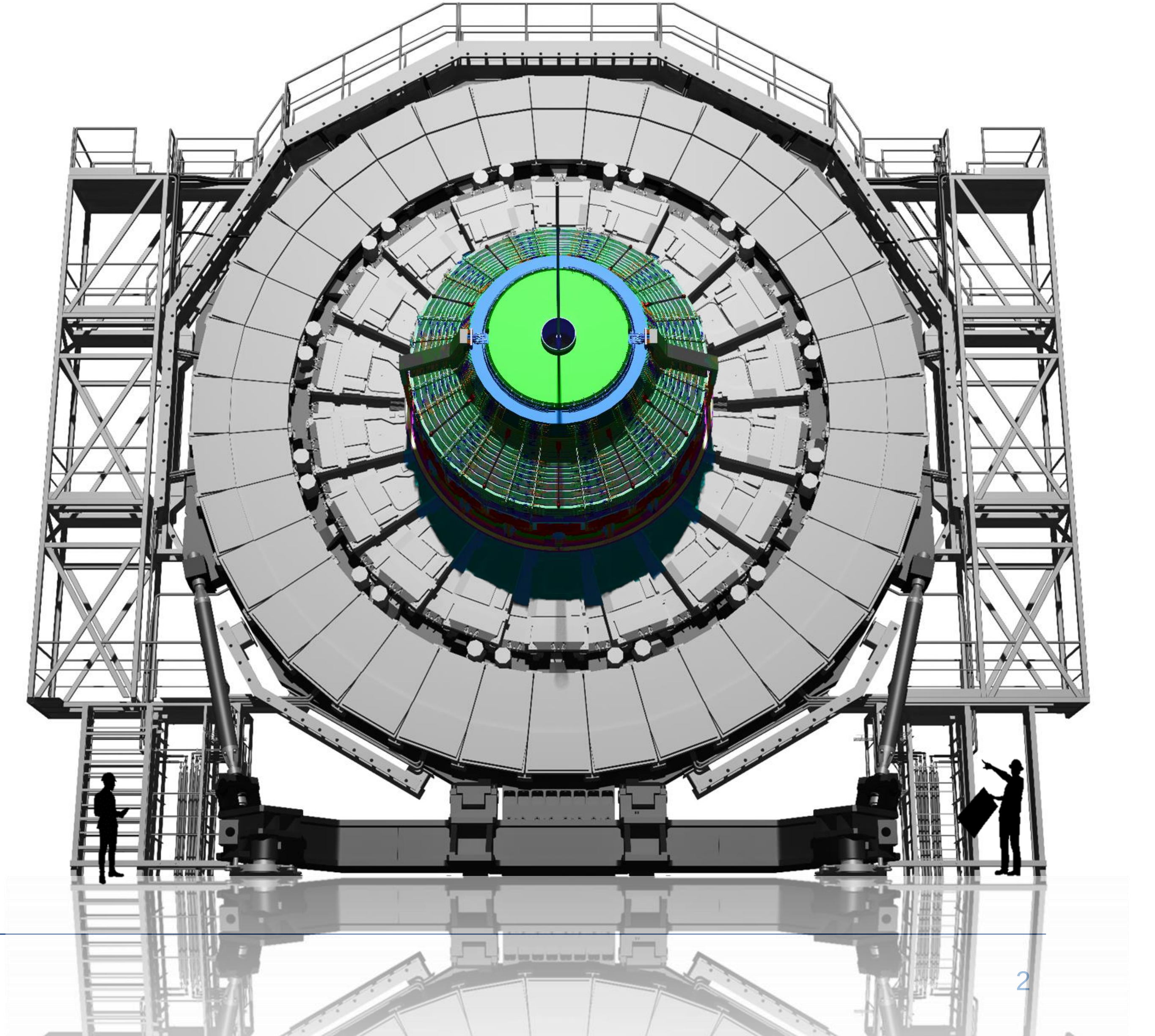
An overview of the CMS High Granularity Calorimeter, and the engineering challenges in its construction

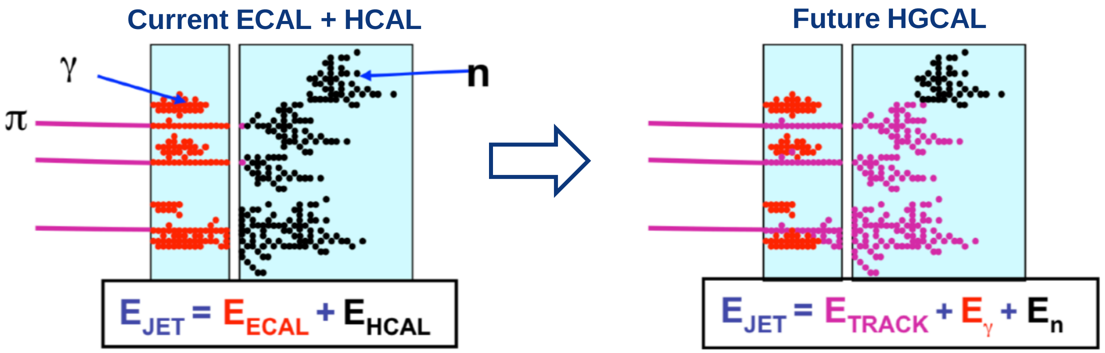
T. French (CERN) on behalf of the CMS HGCAL collaboration

CALOR 2024, 24th May 2024, Tsukuba

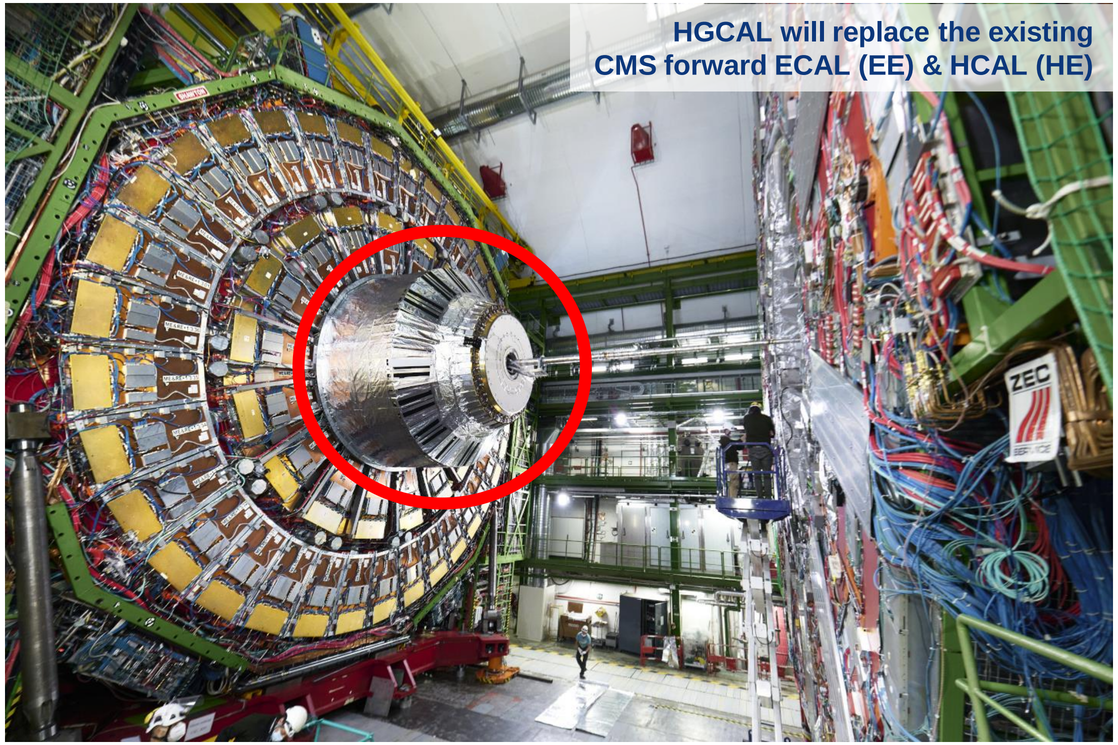
An overview of HGCAL



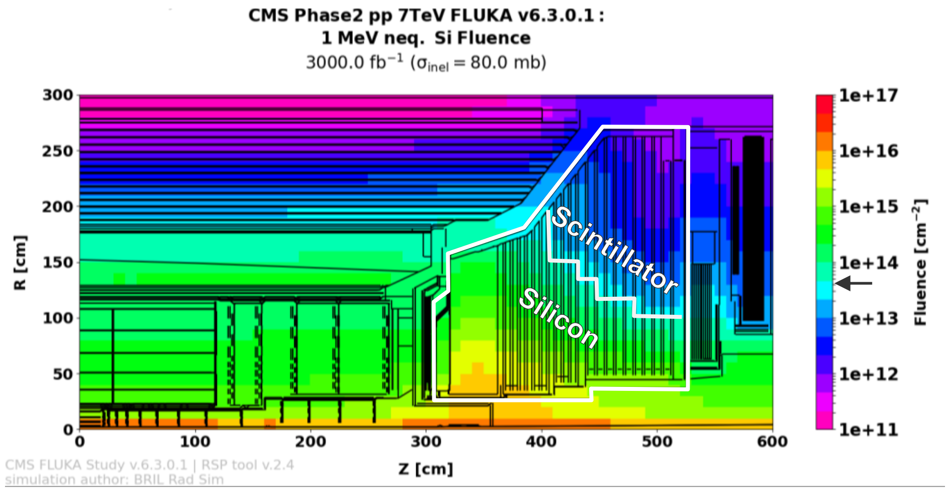
Physics Case



- **High luminosity LHC (HL-LHC) physics programme:**
  - Detailed studies of the Higgs boson and SM processes.
  - Trigger cleanly on and reconstruct the narrow vector boson fusion (VBF) jets, as well as merged jets for physics beyond the SM.
- Integrating **10x more luminosity (3000 fb^{-1})** than the LHC.
  - Challenges for **radiation tolerance and event pileup**, especially for calorimetry in the forward region.
- Performance degradation of the existing $PbWO_4$-based electromagnetic calorimeter (EE) and the plastic scintillator-based hadron calorimeter (HE), 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 Long Shutdown 3 (LS3, nominally 2026-2028).



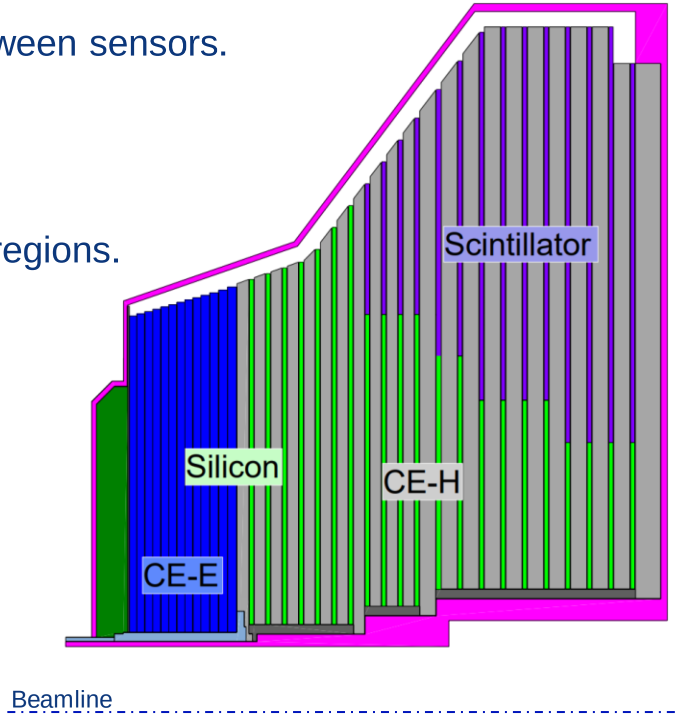
Proposed Detector – HGCAL



- HGCAL needs to fit in the envelope of the previous calorimeters (EE and HE) and provide **high granularity, radiation-tolerance (2 MGy), and efficient readout.**
- 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**, read out by SiPMs, in lower radiation regions.
- **Challenges:**
  - **Engineering (electronics, mechanical, and thermal).**
  - **Data transmission,** and level-1 (L1) trigger formation.

This presentation

See presentations by Aidan Grummer (front-end electronics and readout) and Stavros Mallios (back-end electronics).
Andre Stahl will be presenting reconstruction and performance.



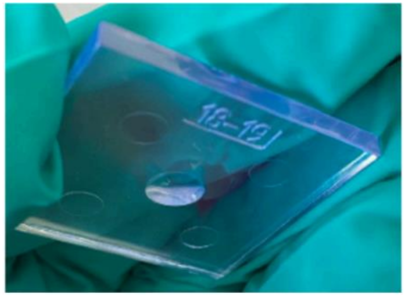
HGCAL cross-section (~axisymmetric)

Both Endcaps	Silicon	Scintillator
Area	~620 m^2	~370 m^2
Channel Size	0.5 – 1.2 cm^2	4 – 30 cm^2
# Channels	~6M	~280k
# Modules	~26k	~4k
Op. Temp.	-35 °C	-35 °C

Per Endcap	CE-E	CE-H Si	CE-H Si+Scint.
Absorber	Pb, CuW, Cu	SS, Cu	
Depth	27.7 X_0	10 λ	
Layers	26	7	14
Weight	23 t	205 t	

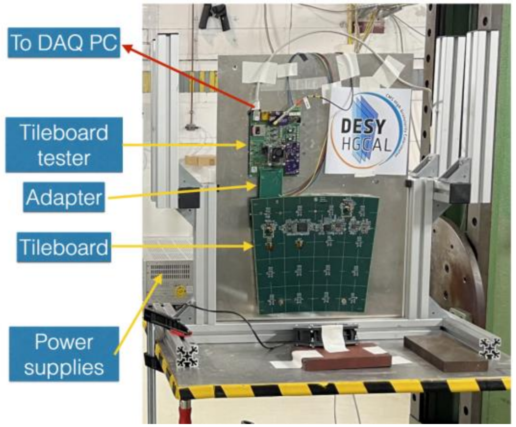
Modules, Tileboards

- **26,000 hexagonal silicon modules:**
  - Glued stack of baseplate, silicon sensor and readout hexaboard. Electrical connections to sensors are made via wire-bonding. A **zoo of partial modules** is created to fill gaps.
  - High density modules (**HD**, with 444 x 0.5 cm^2 hexagonal cells) are used in high fluence regions, low density modules (**LD**, 198 x 1.2 cm^2 cells) elsewhere.
  - Baseplates are **CuW in CE-E, contributing to the absorber material**, and **carbon fibre in CE-H.**
- **280,000 scintillator tiles:**
  - Cast (70%) and injection-moulded (30%) plastic tiles (4-30 cm^2), wrapped in reflective foil.
  - Read-out by silicon photomultipliers (SiPM) which form a **tileboard.**



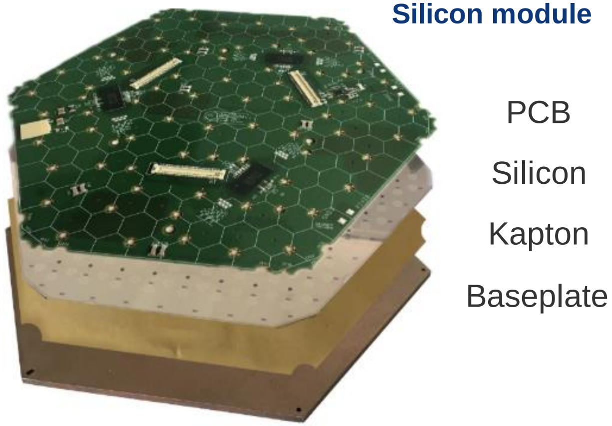
Injection moulded tile

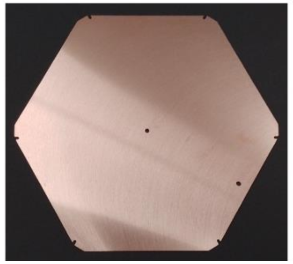
Tileboard with wrapped tiles on top of SiPMs



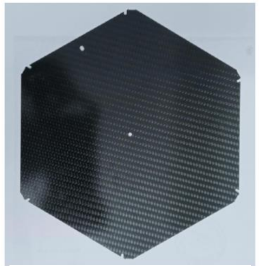
Scintillator tileboard under test (DESY)

See SiPM-on-tile poster by A. Laudrain

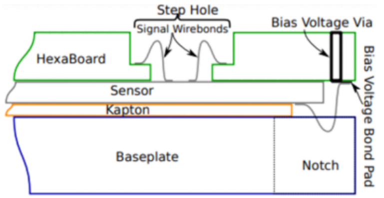




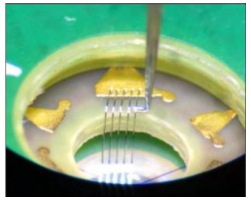
Copper Tungsten Baseplate



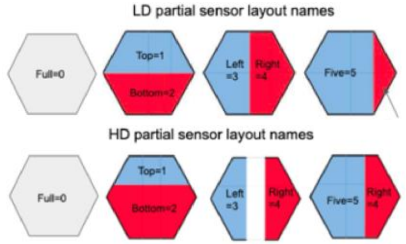
Carbon Fibre Baseplate



Silicon module cross-section

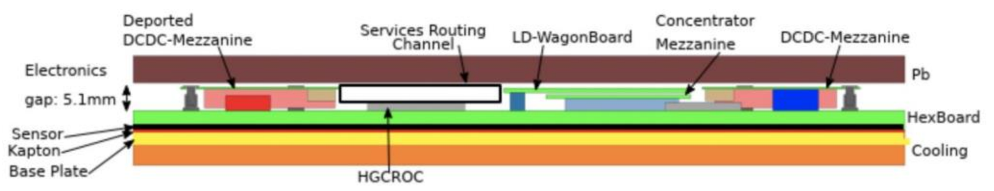


Wirebonds



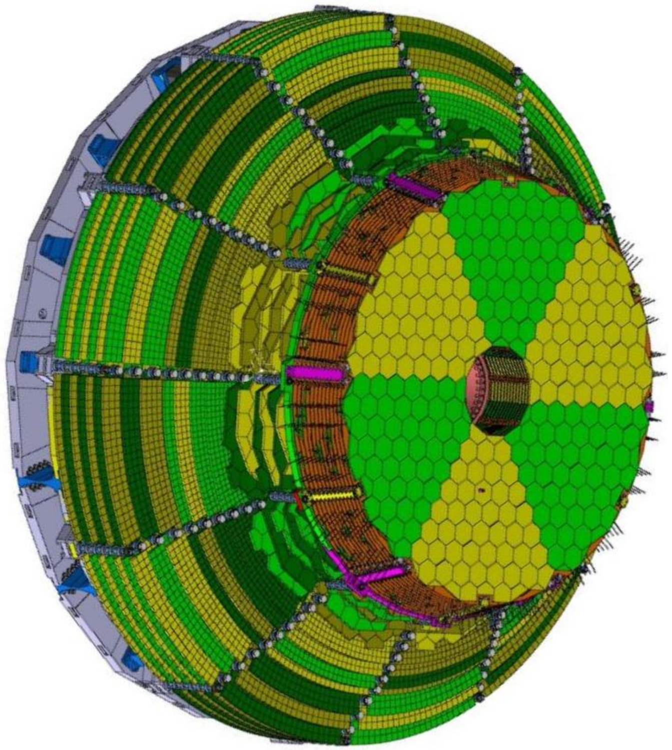
Partial sensor types

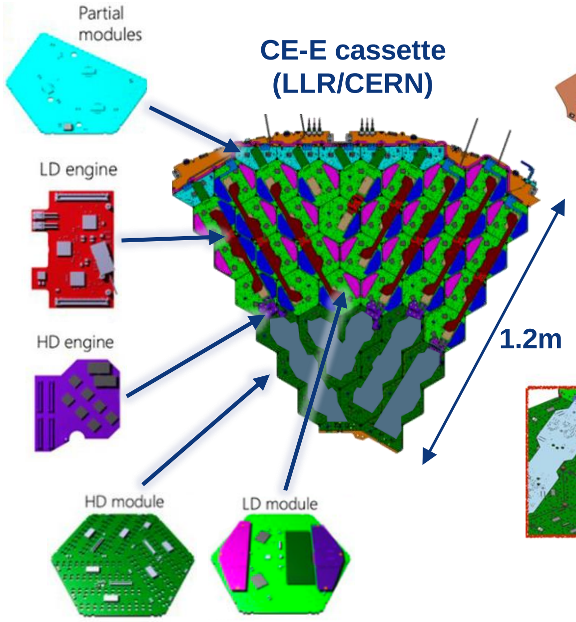
Cassettes

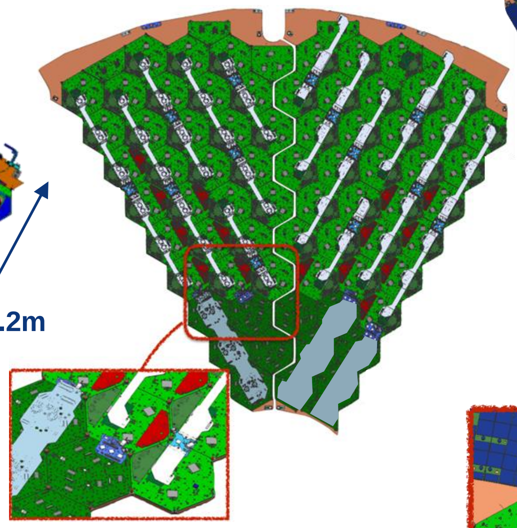


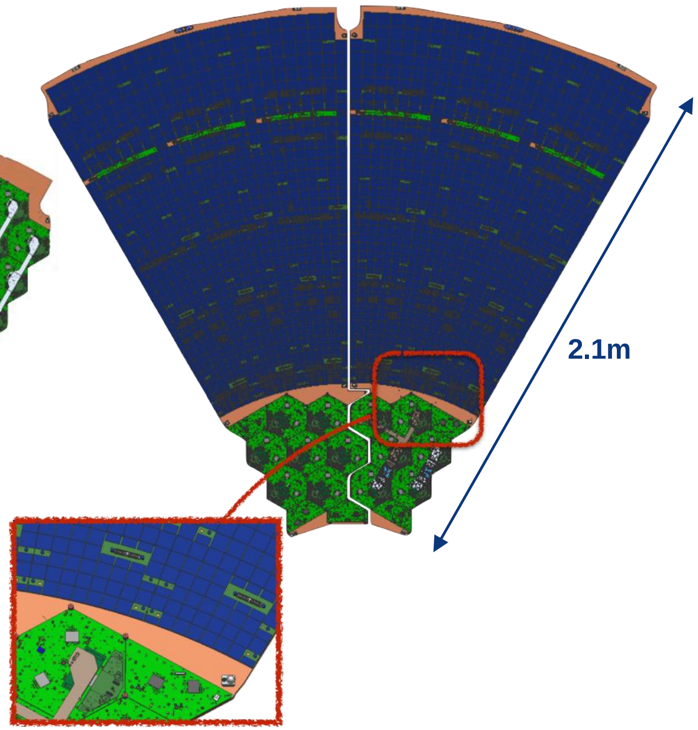
Cassette cross-section

- Modules and tileboards are mounted onto copper cooling plates = **"cassettes".**
- Cassettes are instrumented with electronics including motherboards, concentrators, and DCDC converters, in addition to services and connectors. These all must fit in a 5.1 mm gap above the modules.
- **60° CE-E cassettes have modules on both sides of the cooling plate**, and the **30° CE-H cassettes are single-sided** and exist in both all-silicon and mixed (scintillator and silicon sensor) types.

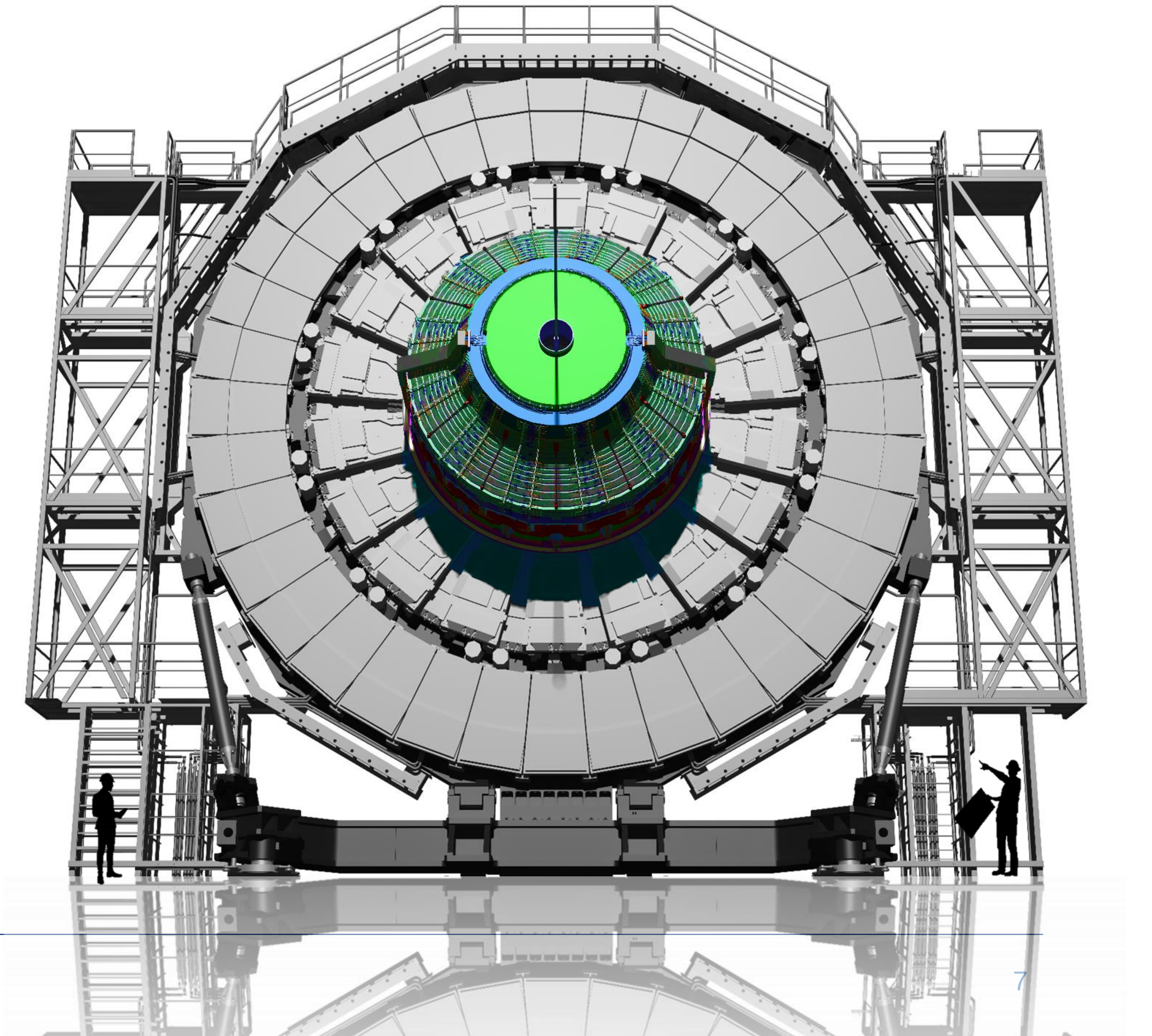

HGCAL tiling and cassette divisions







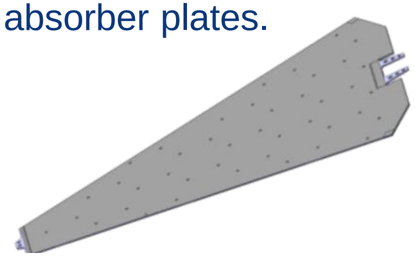
HGCAL Engineering Challenges



Detector Support Structure

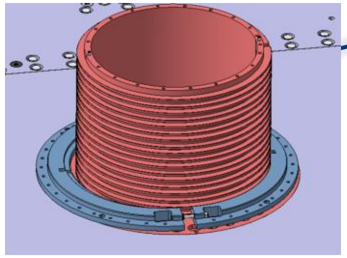
- To hold the **230 tonne, 5.4 m diameter** detector onto the CMS endcap:
  - **18 supports**, bridging gap where muon chambers (ME0) are installed, and leaving access to them.
  - Most of weight taken on 3 and 9 o'clock positions.
  - Wedges above and below these are **articulated** to avoid shear load.
  - Remaining wedges support the moment load, while **allowing 2.5 mm radial thermal contraction.**
- Supporting detector self-weight (absorbers, cassettes and CE-E) through stainless-steel inner cylindrical supports, and tie rods + super-bolts.
- The **machined Al-alloy CE-E support cylinder** holds the CE-E cassettes and lead absorber plates.

CE-E support cylinder

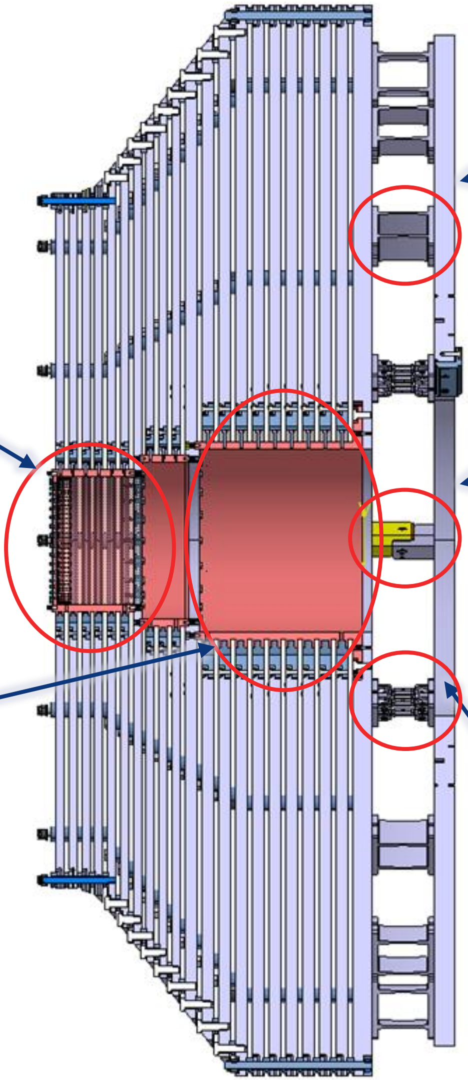


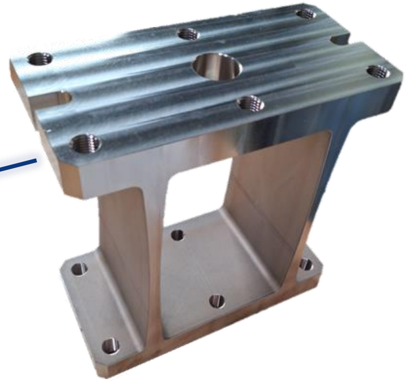
Lead absorber

CE-E support cylinder under test

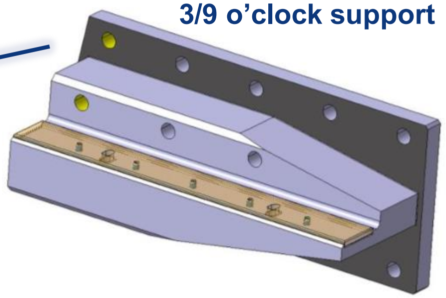


CE-H support cylinder & split rings prototype





Intermediate Ti support



3/9 o'clock support

Articulated support

M36 tie rod with super-bolt tensioner and nut

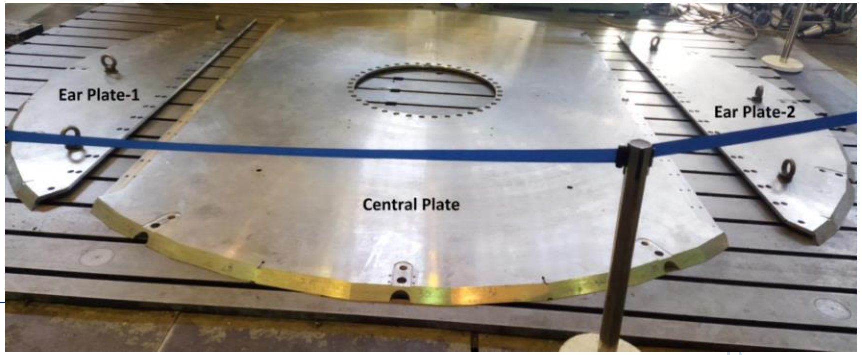
Stainless-Steel Absorbers

16m vertical boring and turn mill (3-axis CNC) at PAEC in Pakistan

12m milling machine (4-axis CNC)

- **40 thick absorber plates (42-95 mm), each weighing up to 10 tonnes.**
- <u>Key challenges:</u>
  - Tight 0.5 mm tolerance on thickness (for physics).
  - Tight 1.0 mm tolerance on flatness and 0.1-0.2 mm on positions (for alignment).
  - Milling releases stress with each cutting operation, which can result in significant bending. **Each plate is flipped multiple times** on a large vertical lathe.
    - Full machining (3 steps) takes about 3-4 weeks per disc (2 shifts, 7/7 days).
  - Sourcing SS304L material with **low magnetic permeability** which required an alloy with tight tolerance on chemical composition.
    - Calculations allowed μ_{max} = 1.05, up to 100 tonnes additional axial force from CMS 4T magnetic field.
    - Actual plates measured with a mean μ of 1.017 → 31.5 tonnes.
  - Shipping of the bulky objects via road and sea transport is quite a feat!
    - Raw material from France to Pakistan, and finished products returning.
    - 6-8 weeks shipping in each direction.

Disc facing on vertical lathe

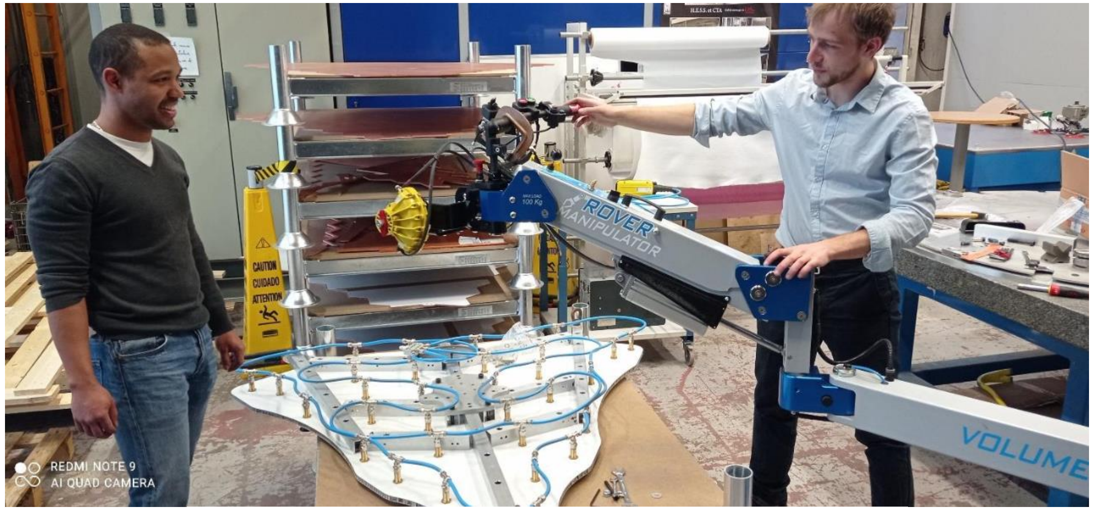


CE-H absorber disc in 3 parts

Cassette cooling plates

- **≈6 mm thick copper plates support, align and cool the modules.**
  - Each bare plate weighs about **60 kg** in the CE-E.
- Key challenges:
  - Avoiding over-constraining a system which will **shrink thermally and undergo multidirectional loading** during assembly and after rotation.
    - Adding stainless-steel mounting hardware is needed to locally strengthen the copper plates.
  - **Machining** of thousands of plain and threaded holes, outer profiles, cooling pipe groove and overall plate surface with high precision (0.1-0.2 mm).
  - **Cooling pipe insertion** (coating, bending, soldering).
    - Pipe plated with nickel then copper to improve wettability.
    - Ensuring good thermal contact and avoiding bowing of plates requires a heated table and careful manipulation.
  - Vacuum handling tooling developed to move plates.

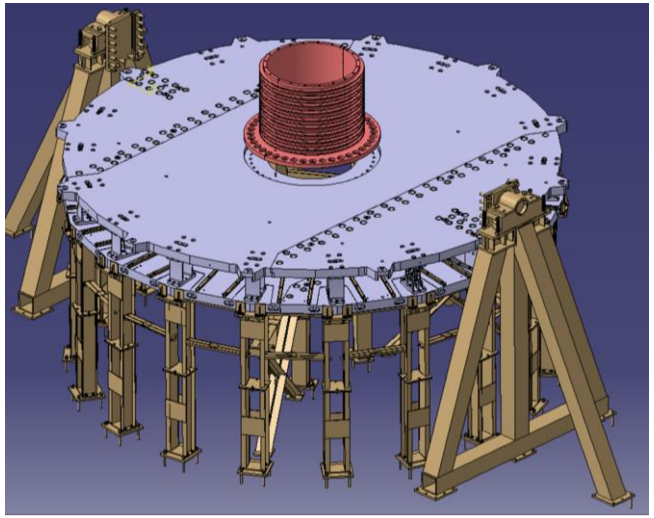
CE-E copper plate prototype with embedded cooling pipe



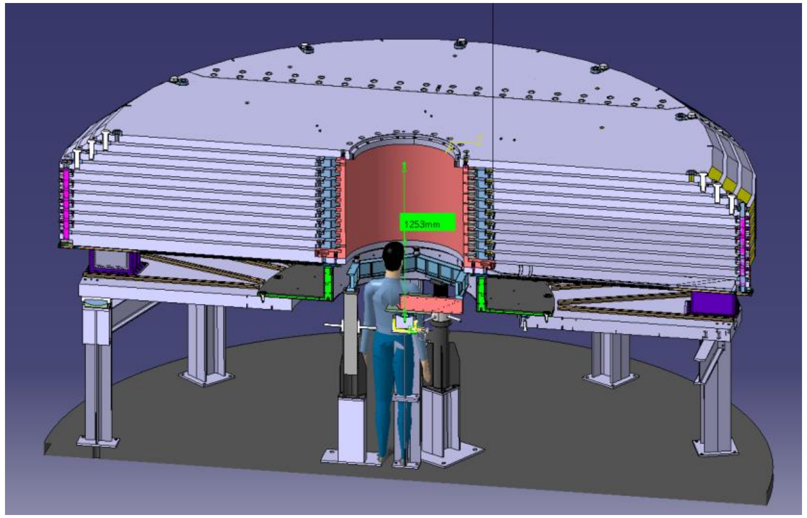
Copper plate vacuum manipulation tool at LLR

Detector Handling

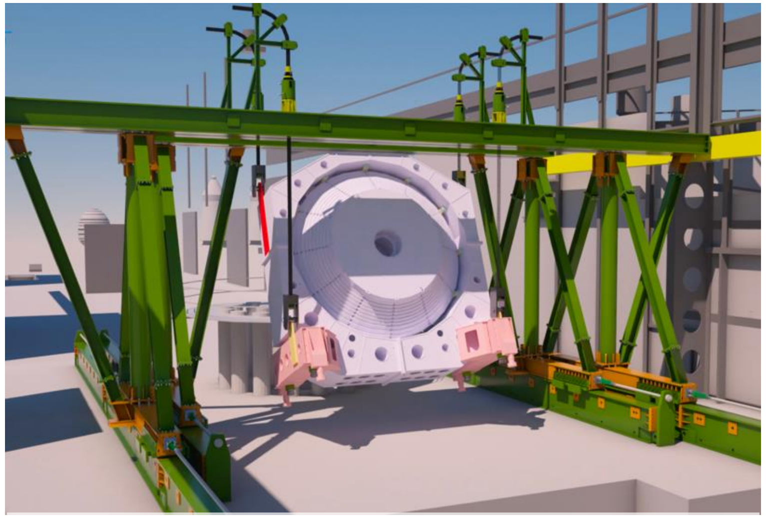
- The CE-H mechanical structure will be **machined and assembled first in Pakistan for testing, disassembled, shipped, then reassembled at CERN** for the final detector construction.
- Key challenges:
  - **Large weight with limited area for supports** – detector will be fastened by screws and held using hydraulic pistons.
  - Tooling to be used to remove the existing forward calorimeters from the cavern and reused for handling/rotating/installing HGCAL.
  - **Lowering the detector down CMS shafts, 100 m deep**, will require specialist cranes (hired by the day).



CE-H mechanics assembly in Pakistan – high rotating table



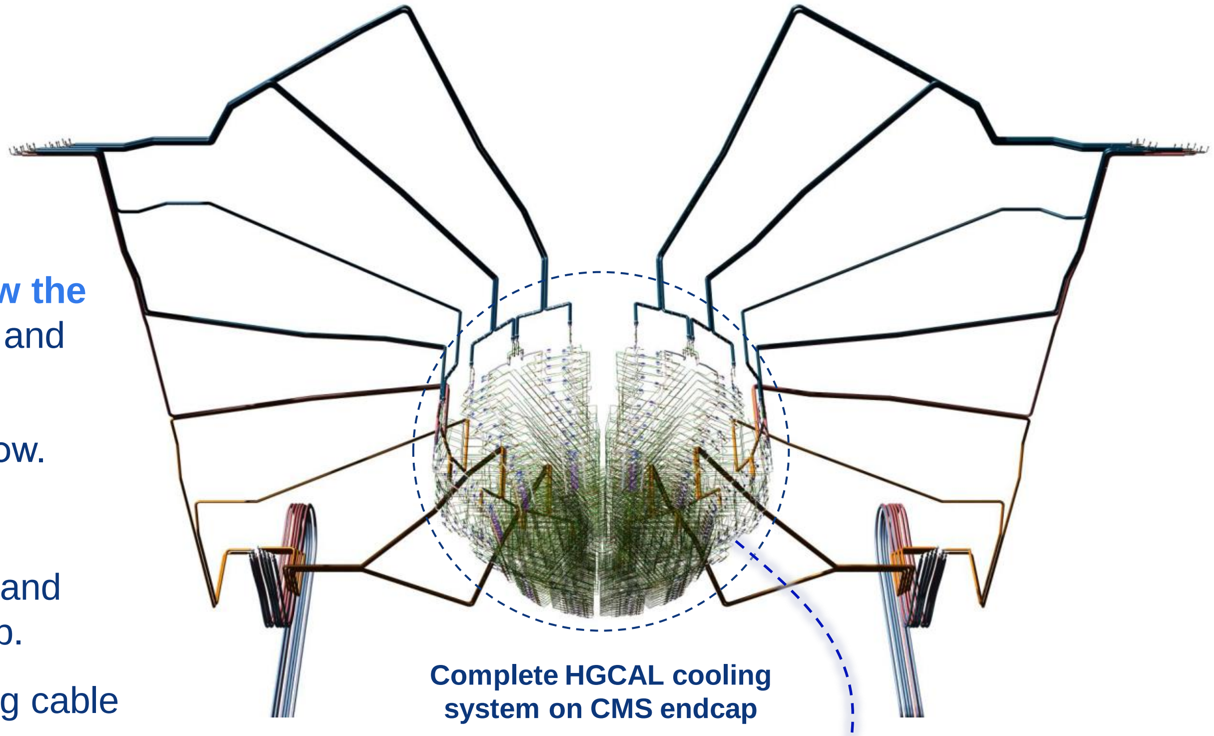
CE-H mechanics assembly at CERN – lower assembly table



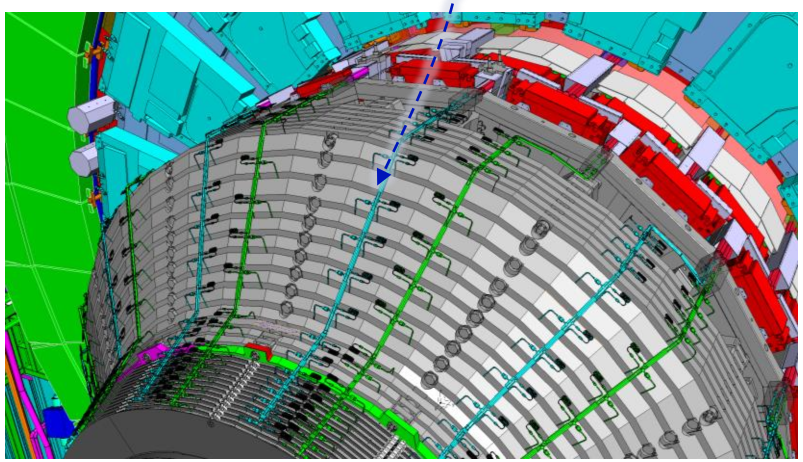
Full detector rotation using support cradle prior to lowering via strandjacking

Cooling

- **Operation at −35 °C using two-phase CO_2.**
  - To reliably operate silicon sensors after irradiation, and to **keep low the electronics noise** that results from the increased leakage current and decreased charge collection efficiency after irradiation.
  - To keep the radiation-induced SiPM electronics noise sufficiently low.
- Key challenges:
  - Ensuring system functions correctly (temperature, pressure drops and vapour quality) with a **total power estimate of 130 kW** per endcap.
  - **Flexible coaxial, vacuum-jacketed transfer lines** through moving cable chains (~100 lifetime open/close cycles), optimising pressure drops.
  - Reducing the number of welds via **custom manifolds and fittings** – saving ~2500 welds per endcap compared to the original design (5000+).

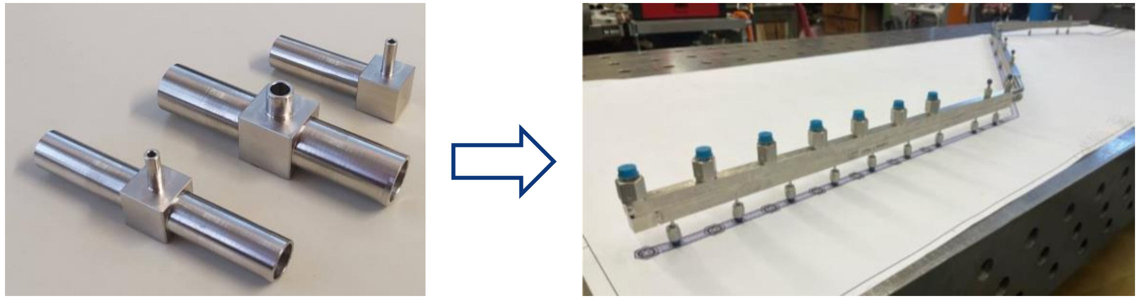


Complete HGCAL cooling system on CMS endcap



On-detector manifolds in CAD

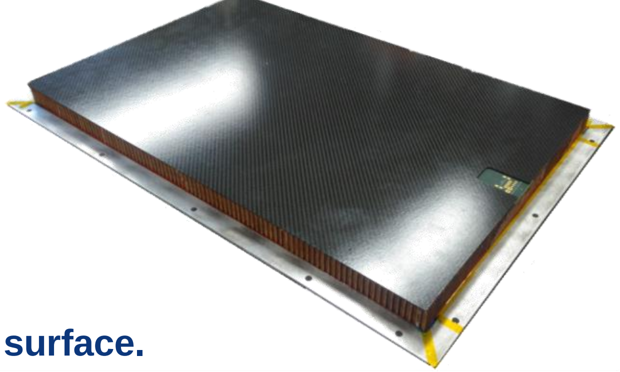
50 mm OD, 17 m long coaxial hose



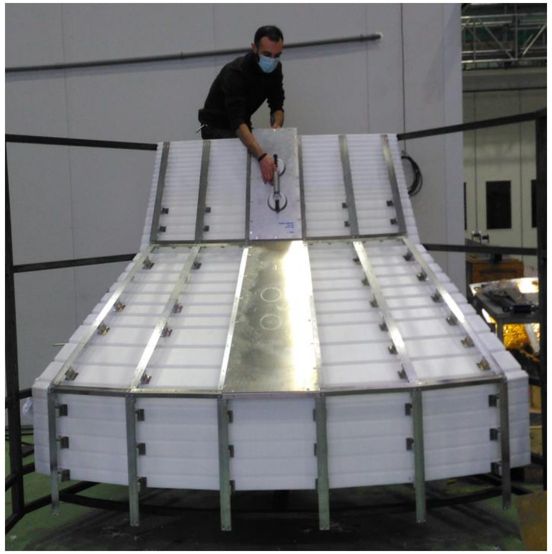
On-detector manifold optimisation: reduced number of welds (KIT proposal)

Thermal Insulation

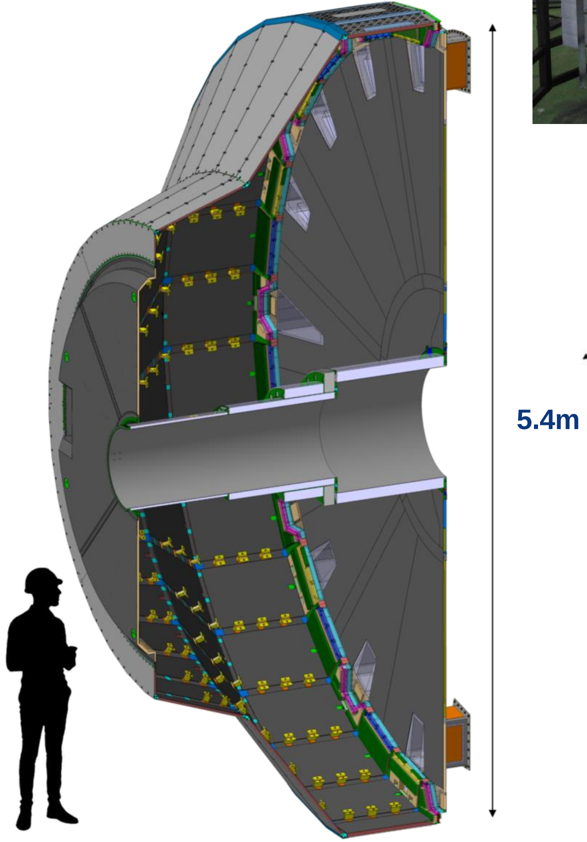
- **The “thermal screen” prevents condensation and ice formation inside the HGCAL detector, and condensation on its own outer surface.**
- Key challenges:
  - Complex shape driven by detector geometry and envelope.
  - **Sealed** (for dry gas flushing) while still allowing services access.
  - **Robust** – people can stand on it, and it protects the detector from minor impacts.
  - Low mass (to minimise particle interactions).
  - Radiation and magnetic-field tolerant.
  - Thickness: **20 to 30 mm in most places means passive insulation is not enough.**
- General design:
  - Strong, insulating layer wrapping around whole detector.
  - **Bonded composite sandwich construction (CFRP, aramid honeycomb, aluminium alloy).**
  - **Polyimide heating foils** control the external surface temperature near to ambient.



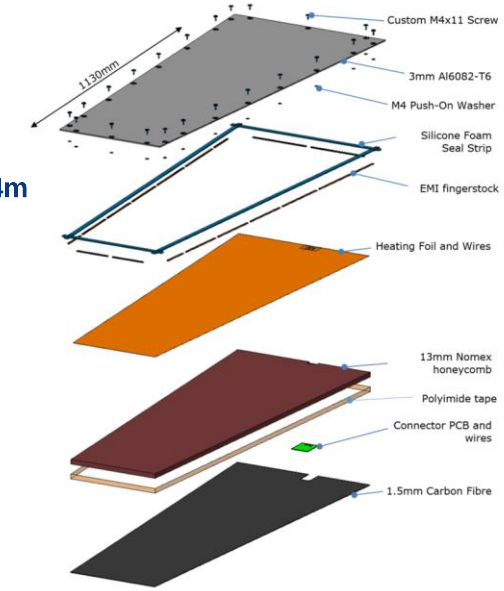
Prototype outer panel



Thermal screen prototype



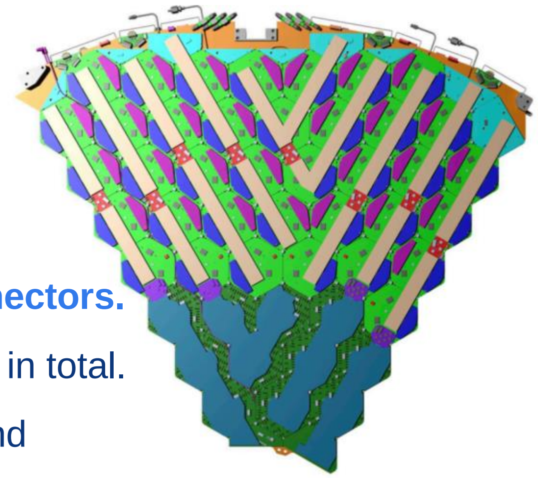
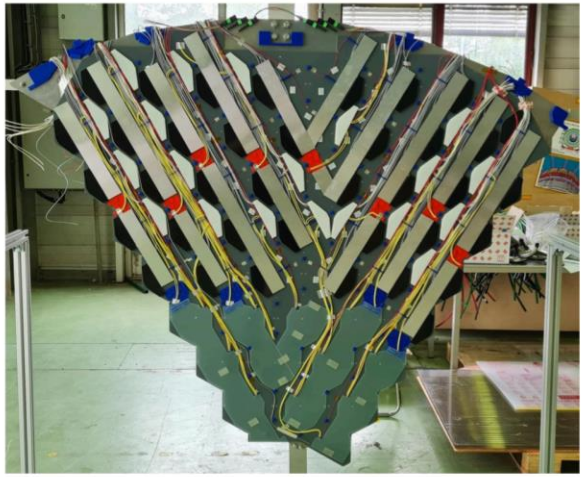
Thermal screen overview



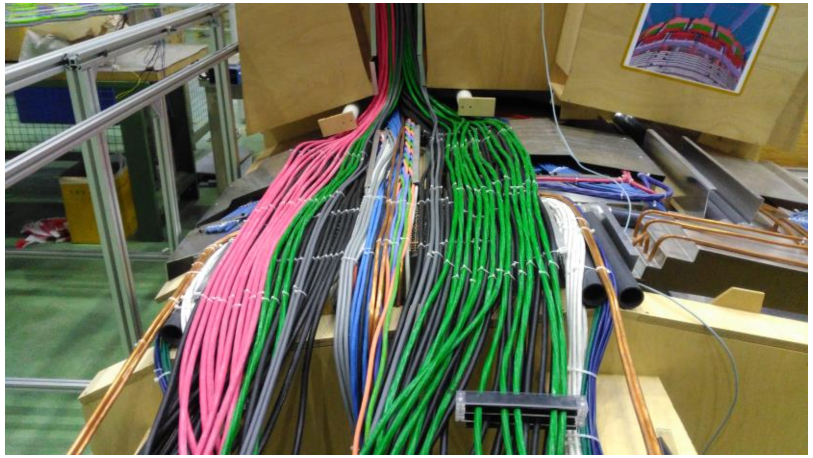
Outer panel exploded view

Services

- Huge number of services to integrate across 2 detectors:
  - **50,000+ individual wires inside the cassettes, 5,500 optical connectors.**
  - **10,800+ cables inside** the 2 detectors (excluding cassettes), **20 km** in total.
  - **4,600+ cables outside** the detector connecting to power supplies and readout racks, totalling **150 km.**
  - Dozens of pipes for cooling, dry gas, fire detection, tray water-cooling.
- Key challenges:
  - The services volume inside the envelope fixed the outer limits of the absorber.
  - All outside services need to fit in the space left by removing HE and EE services.
  - Inventive cable routing solutions required, **finding space** outside of the existing service trays.
- **Mockups and prototyping are vital!**

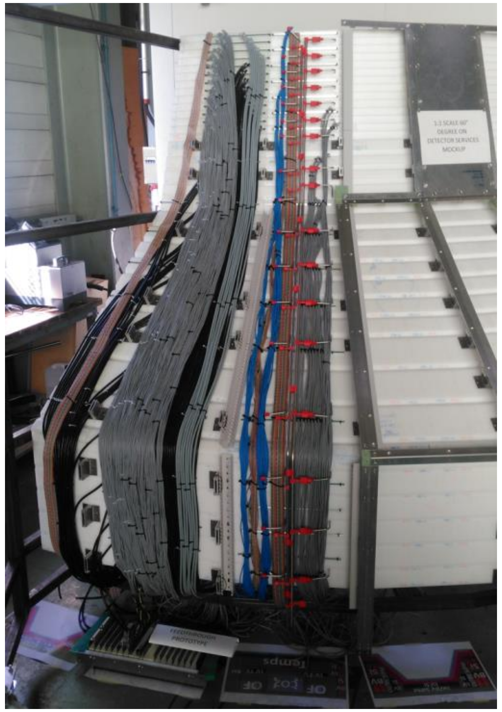



CE-E cassette 3D model and mechanical mockup with wires



External services mockup on CMS endcap

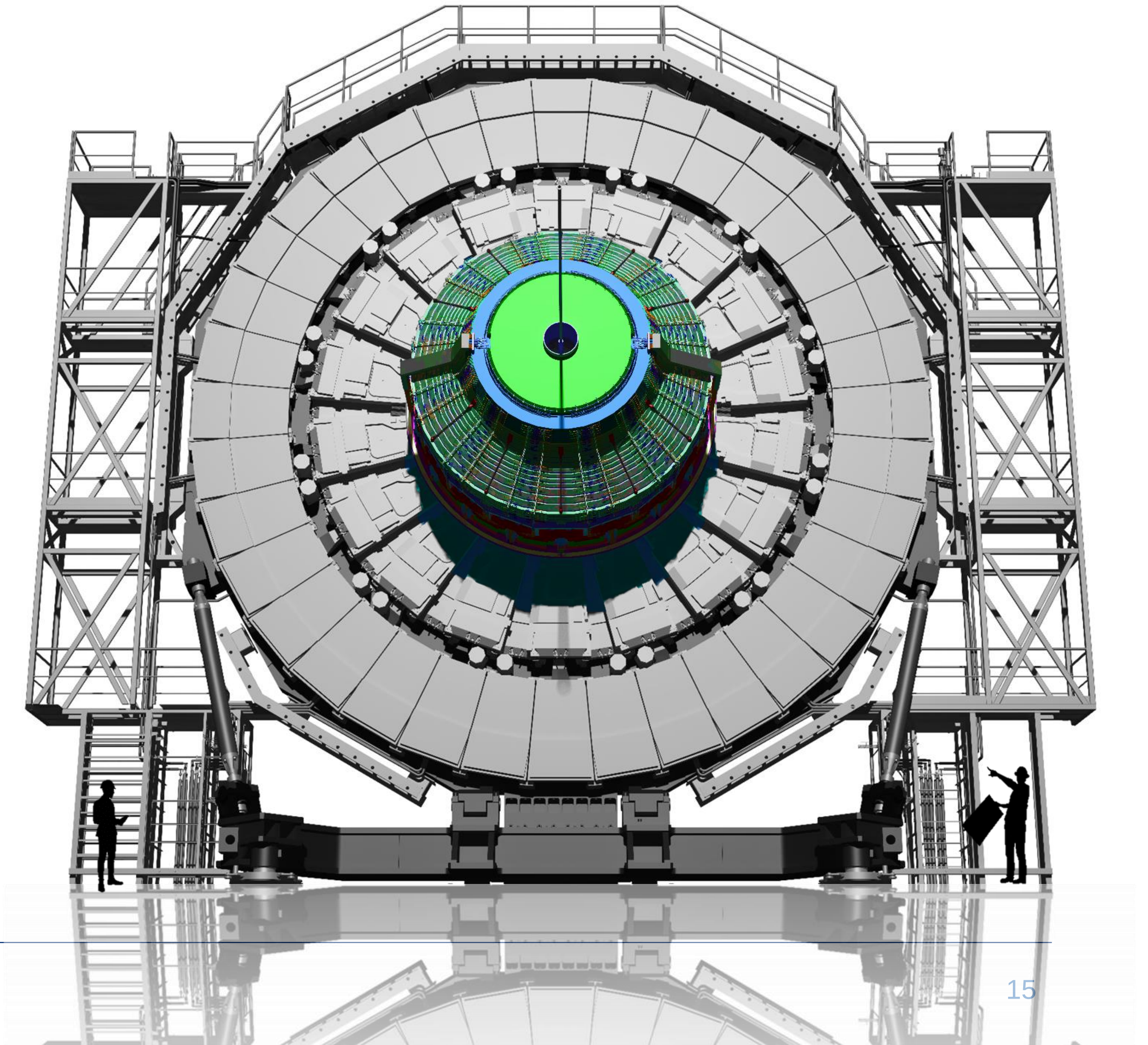
20° mixed cassette mechanical mockup



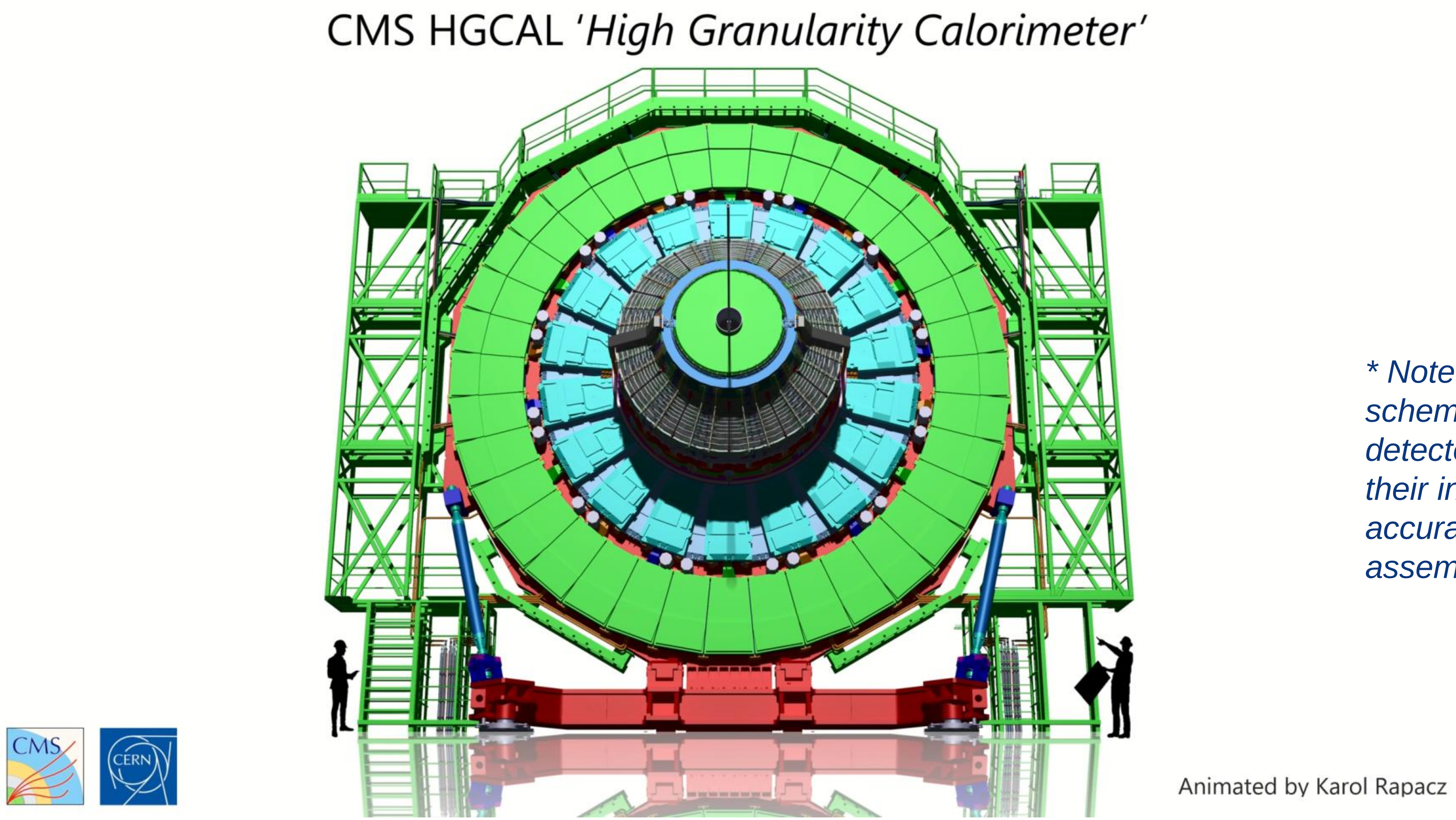
Internal services mockup

Summary

- HGCAL will be the first large scale calorimeter with Si and SiPM-on-tile technologies providing unprecedented granularity and time resolution.
- Designs are now becoming reality – **production is in full swing** on almost all components from modules to mechanics.
- A huge amount of work has enabled us to address **numerous engineering challenges.**
- Assembly of detector structures (cassettes and mechanics) is starting this year.
- Installation of the first endcap is planned for **LS3.**



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

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