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Engineering challenges in mechanics and electronics in the world's first particle-flow calorimeter at a hadron collider: The CMS High-Granularity Calorimeter

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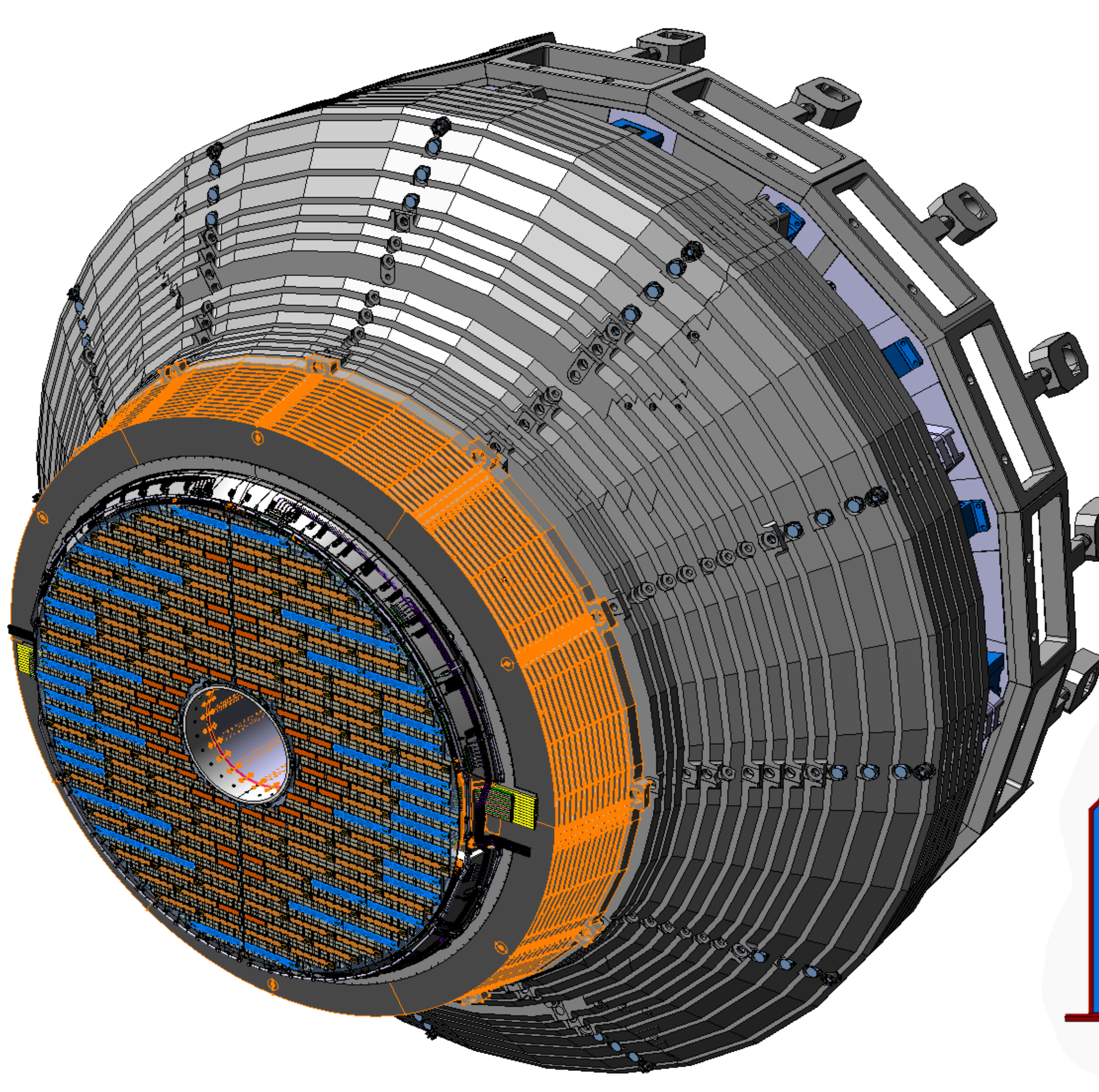
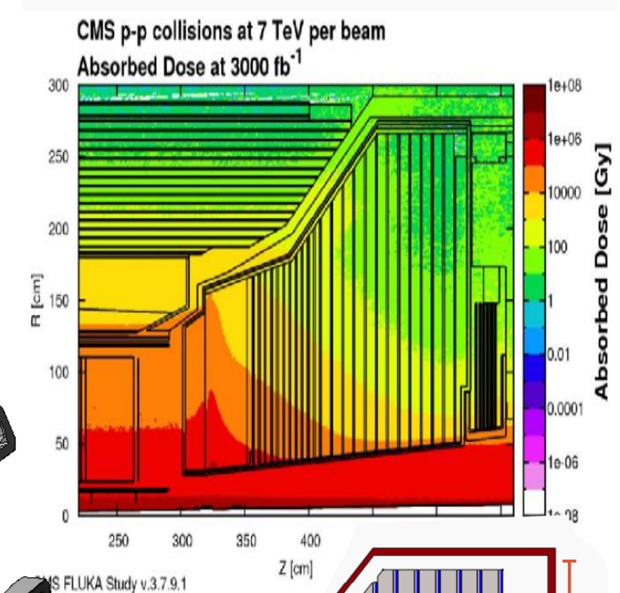
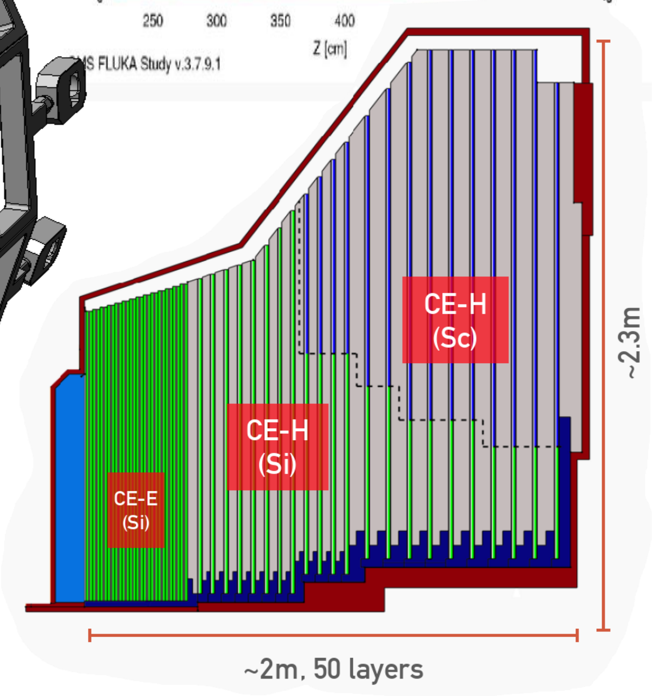
1. Introduction

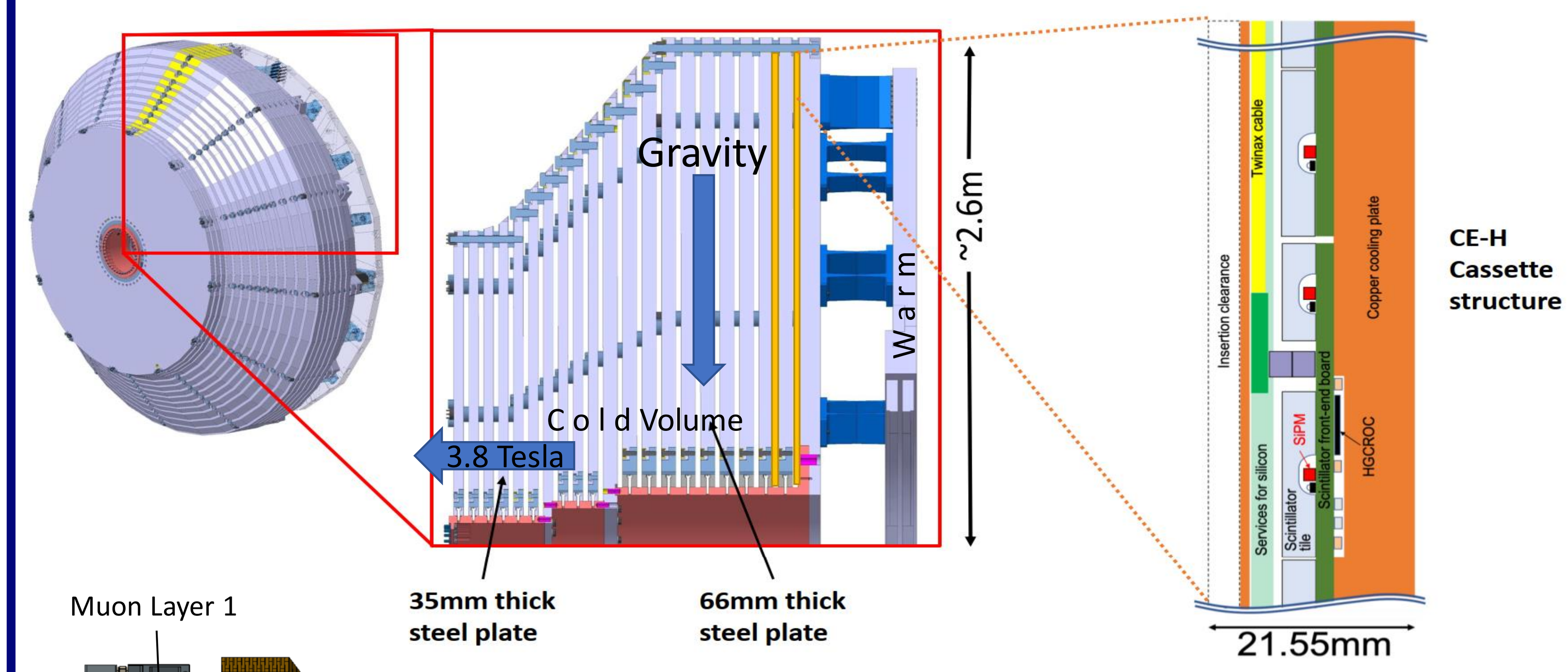
The present CMS endcap calorimeter comprises a hadronic part (brass absorbers interspersed with plastic scintillators, HE) and an electromagnetic part (homogeneous lead-tungstate crystals, EE and a silicon preshower, ES). This complete calorimeter system must be replaced during the LHC long shut down 3 as it cannot cope with the conditions of the High Luminosity LHC: radiation environment (FLUKA simulations predict neutron fluences up to 10^{16} neq/cm^2 and doses up to 1.5 MGy) and event pileup (3-5 times higher than LHC). CMS will install a new highly-granular sampling calorimeter "HGCAL" with 47 layers per endcap covering the region $1.5 < \eta < 3$. HGCAL is based on silicon sensors in the highest-radiation regions, complemented by scintillating tiles with direct SiPM readout in the regions of lower radiation. Lead and CuW alloy are the main absorbers in the electromagnetic section (CE-E) whilst stainless-steel is used in the hadronic section (CE-H). The entire HGCAL will be cooled to -30 degrees to mitigate radiation-induced effects on the silicon and SiPMs.

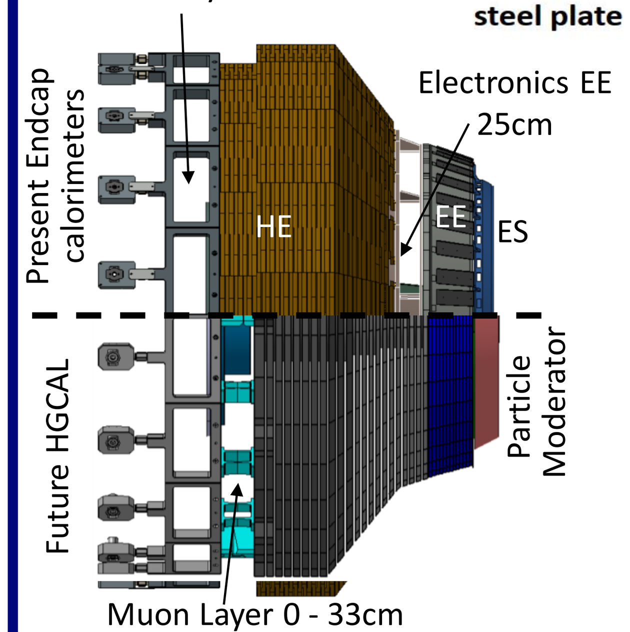


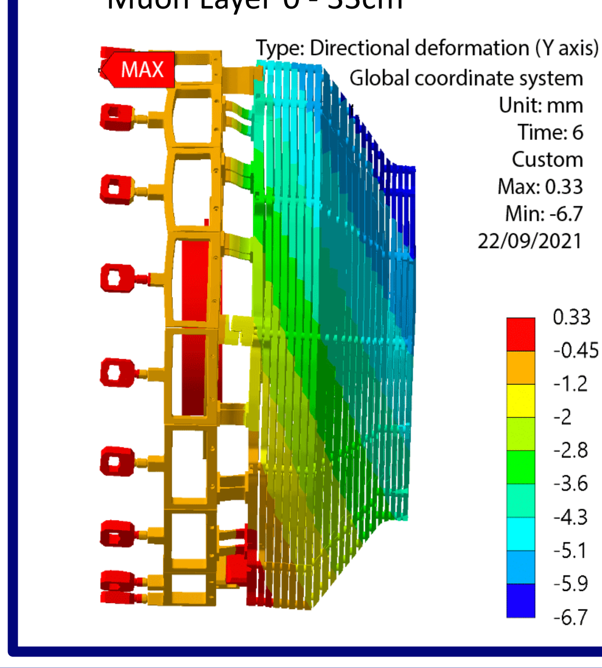




2. Endcap calorimeter architecture and challenges





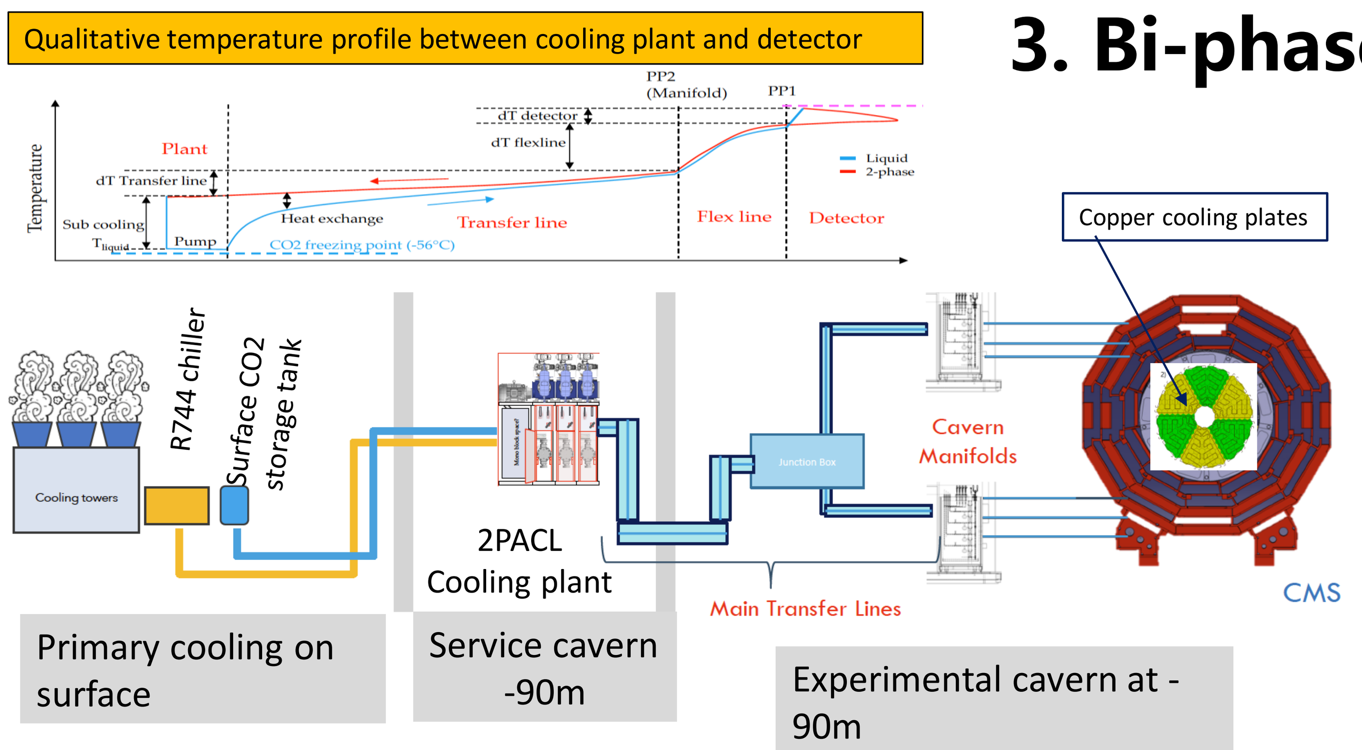


In HGCAL there is no physical separation between electromagnetic and hadronic sections. The electronics (ASICs, boards, services etc.) are integrated into each layer and must therefore be of extreme compactness. The dissipated power inside the HGCAL volume is dominated by the electronics, with some contribution from sensor leakage current. It is expected to be of the order of 125 kW per endcap.

The radiation and interaction lengths of HGCAL are the same as the present endcaps (27.7 X_0 / 8.5 λ) resulting in a total weight around 240 tonnes per endcap. But freeing-up a 33cm gap to lodge an additional layer of muon detectors, the mechanical lever arm of the calorimeter is increased w.r.t its fixing points to the endcap yoke. Fortunately, the concentration of the HGCAL towards the conical part of the endcap reduces somewhat the HGCAL mass as the diameters become smaller. Both effects compensate one another. Thus the high-strength brackets at the rear, already at their mechanical limit today, can be reused. Interleaved between the absorber plates are the silicon and scintillator modules.

3. Bi-phase CO_2, from surface to the cassettes – 100m underground

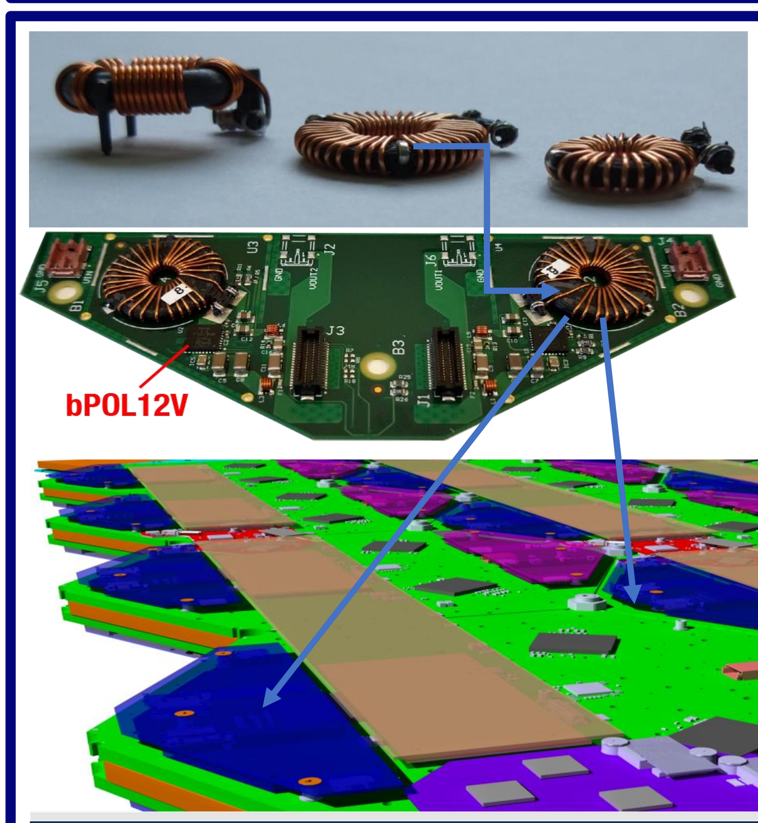
Qualitative temperature profile between cooling plant and detector



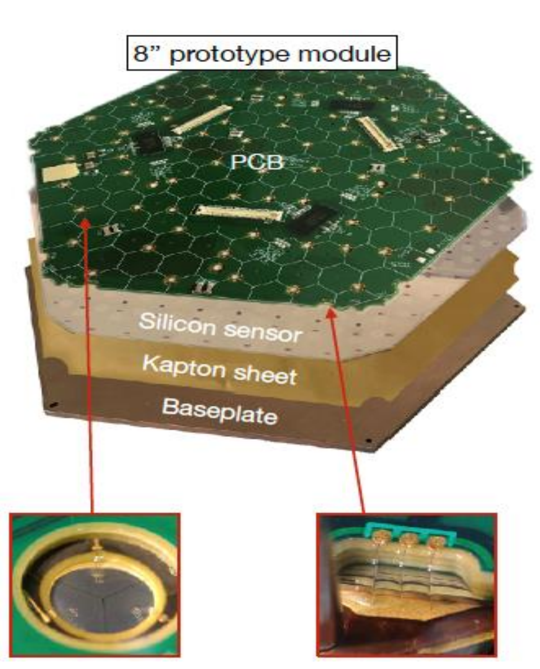
The CO_2 circuit from primary chiller to the detector at -90 m underground

The cooling system underground is based on a 2-phase accumulator-controlled loop concept (2PACL) that pumps CO_2 as a liquid in vacuum-jacketed stainless steel pipes from the service cavern to the experimental cavern. Flexible coaxial lines in the cable chains connecting to the endcap disk structure allow for opening CMS. A 15-32mm thick active thermal screen will surround the HGCAL cold volume; exterior heating foils will avoid condensation and icing. The CO_2 is channelled through thin stainless steel pipes embedded by soldering into copper cooling plates that also act as mechanical supports for the modules and electronics. On the right such a 60° sector is shown during the QA session on a marble. Last not least an impressive infrastructure with compressors & water cooling towers at the surface is necessary for the primary cooling and storage of the CO_2.

4. FE-electronics, motherboards and system integration

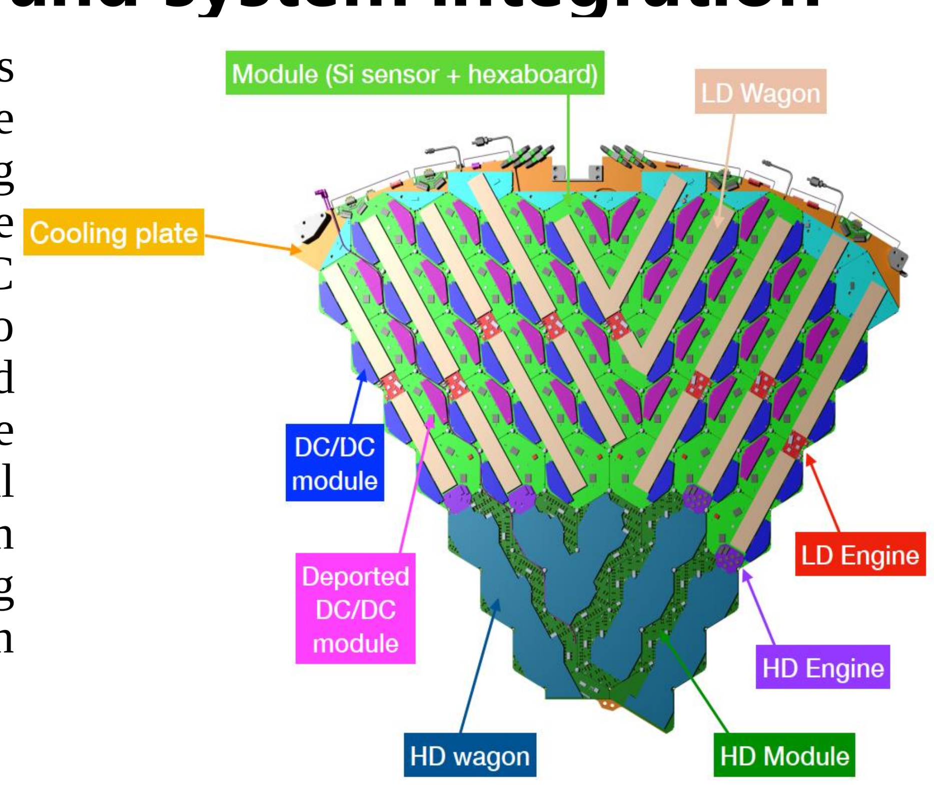


Dual-bPOL12V mezzanine fixed onto hexaboard

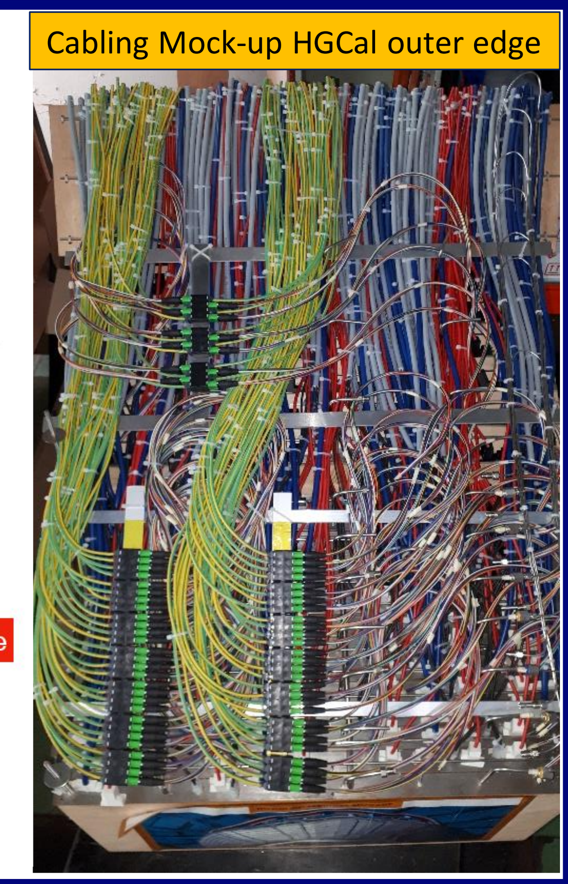


Typical lay-up of a silicon modul

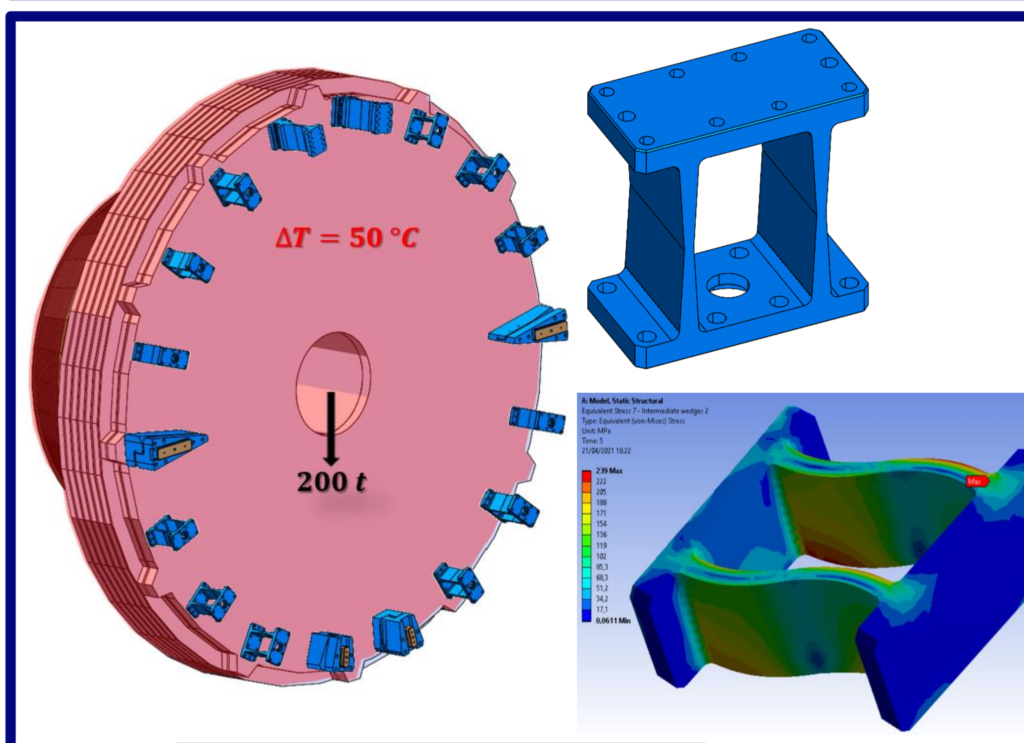
All on-detector electronics components must be as compact as possible, from the stackup of the silicon modules (featuring wire bonding through holes in PCBs to the Si sensors) to custom toroids for DCDC converters placed on mezzanine boards, to all of the passive components and connectors used. Limited vertical space also means that services (cables, optical fibres, dry-gas pipes) must weave between the electronic components without crossing each other. Service routing is studied on CAD and validated via mock-ups.



Cabling Mock-up HGCal outer edge

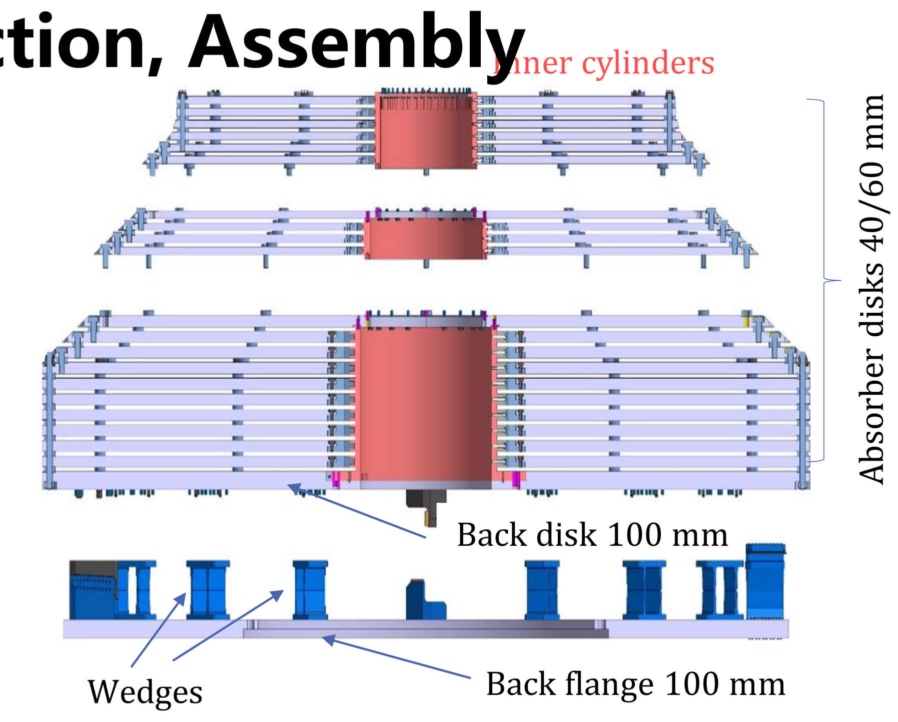


5. Material choices, Construction, Assembly

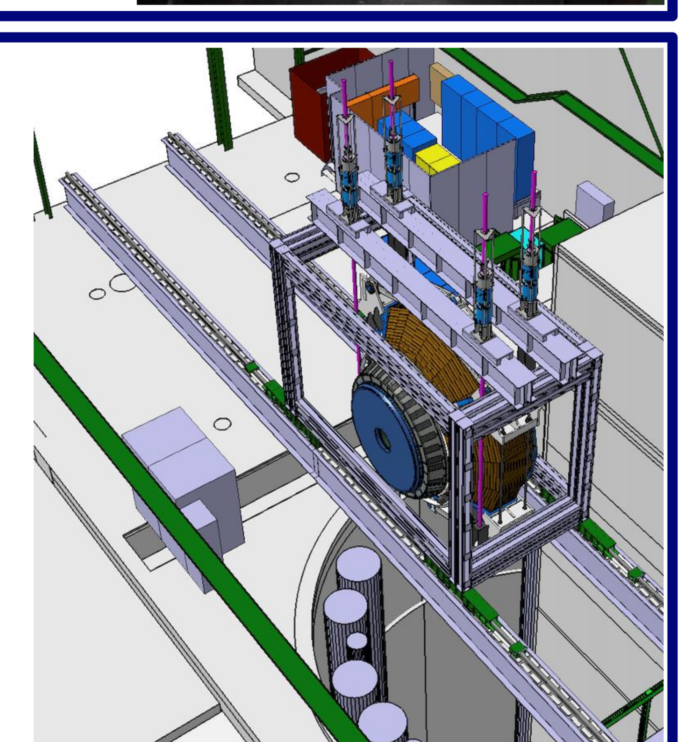


Strong but flexible titanium wedge

The hadronic section is the structural backbone of HGCAL and consists of SS304L (1.4306) austenitic steel. The assembly and service routing will be done horizontally, before rotating to the vertical, lowering and attaching the HGCAL to the endcap disks. A layer of titanium grade-4 wedges guarantees the load transfer between cold and warm regions and limit the heat conduction. Due to the ΔT of 50°C the box-shaped wedges will deform 2.6 mm radially but maintain parallelism between back disk and back flange. Only 12 high M36 tie-bars at the outer edge disturb the tiling.



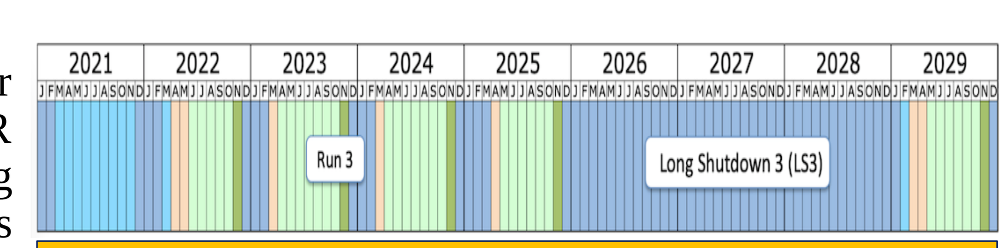
Main main packages of absorber plates in hadronic part



Custom made gantry for final lowering

6. HGCAL status and timeline

The large mechanical pieces for HGCAL have been designed. 600 tonnes of steel absorber plates are in fabrication, with the first batch due for machining at HMC-3 in Pakistan in summer 2022. Tenders for titanium wedges and lead-sandwich absorbers are foreseen for the end of 2022. LLR in Paris has equipped its workshop with a new milling centre to precision machine the CE-E Cu cooling plates (cassettes) and solder in the cooling pipes. Silicon and scintillator modules have been prototyped and tested successfully, including in beams, with some of the final electronics components. Full-scale module production is due to start next year, with cassette production following. Installation of HGCAL will be in 2027.



Actual LHC schedule with LS3 starting at the end of 2025