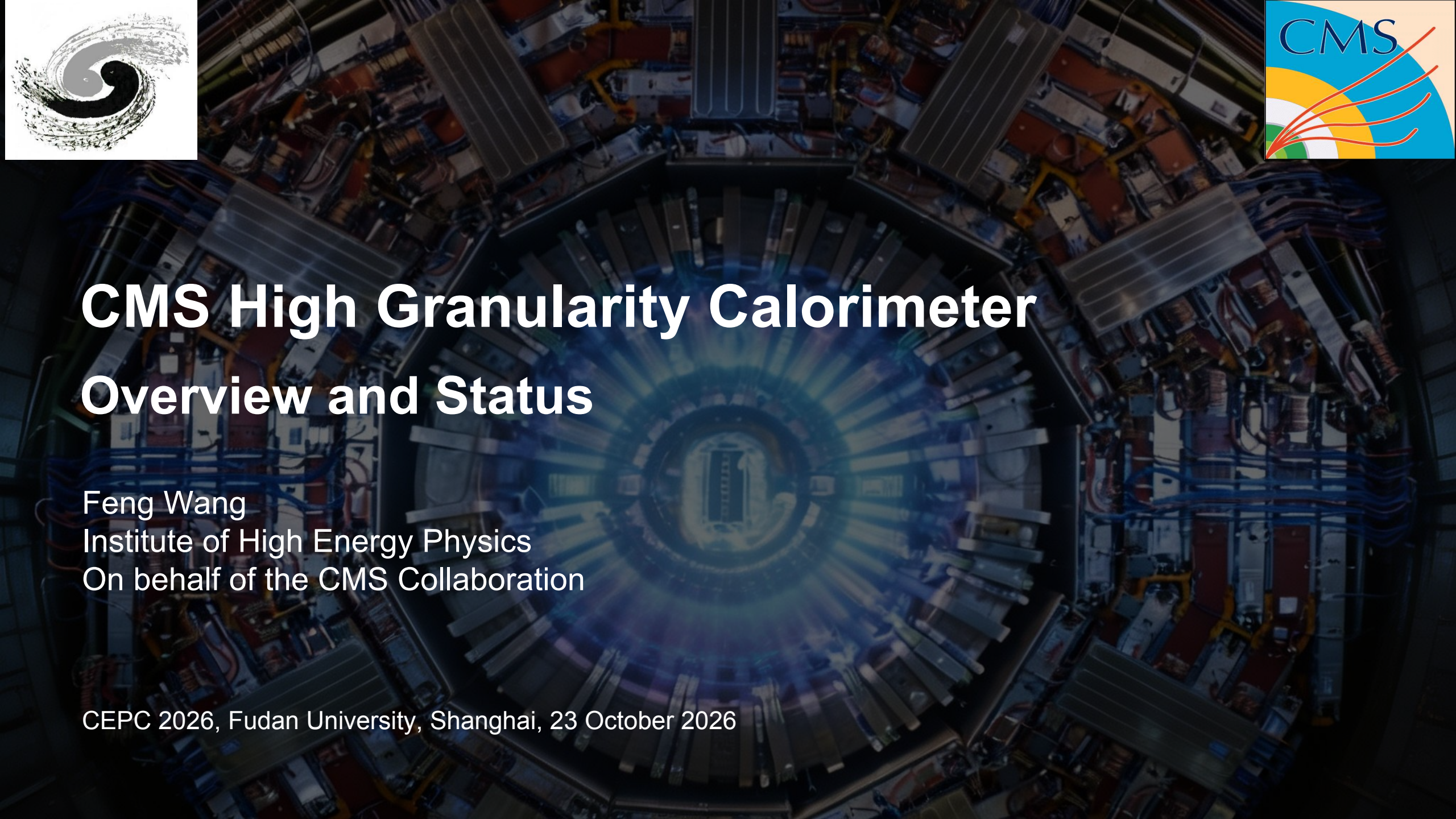


CMS High Granularity Calorimeter

Overview and Status

Feng Wang
Institute of High Energy Physics
On behalf of the CMS Collaboration

CEPC 2026, Fudan University, Shanghai, 23 October 2026

Outline

01 **Physics motivation and upgrade requirements**

The HL-LHC environment and the CMS Phase-2 upgrade

02 **Detector design and readout**

Silicon modules, scintillator tilemodules and front-end electronics

03 **Performance validation**

Radiation tolerance and beam-test measurements

04 **Construction and integration status**

Module production, cassette assembly and mechanical structures

05 **Summary and outlook**

Production ramp-up and the remaining integration milestones

The LHC and the CMS experiment



Collider and detector

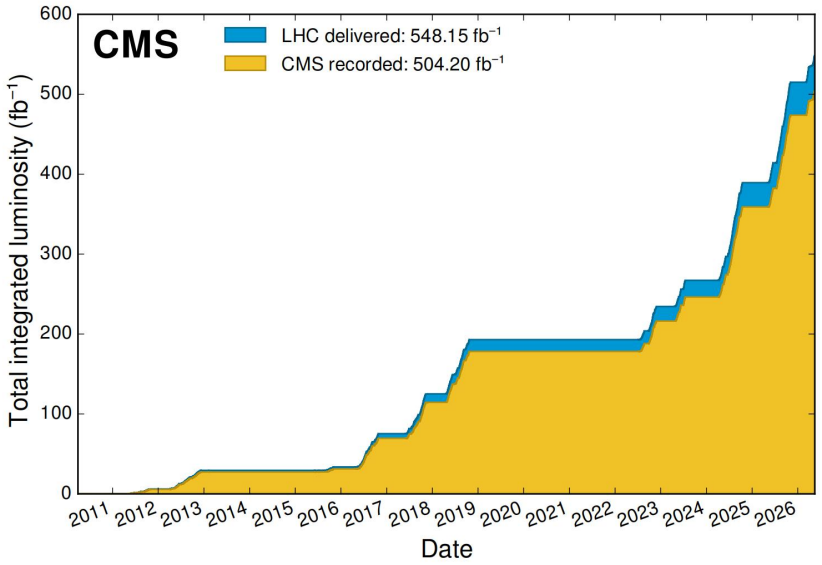
27 km ring at CERN, approximately 100 m underground

Four major experiments: ATLAS, CMS, ALICE and LHCb

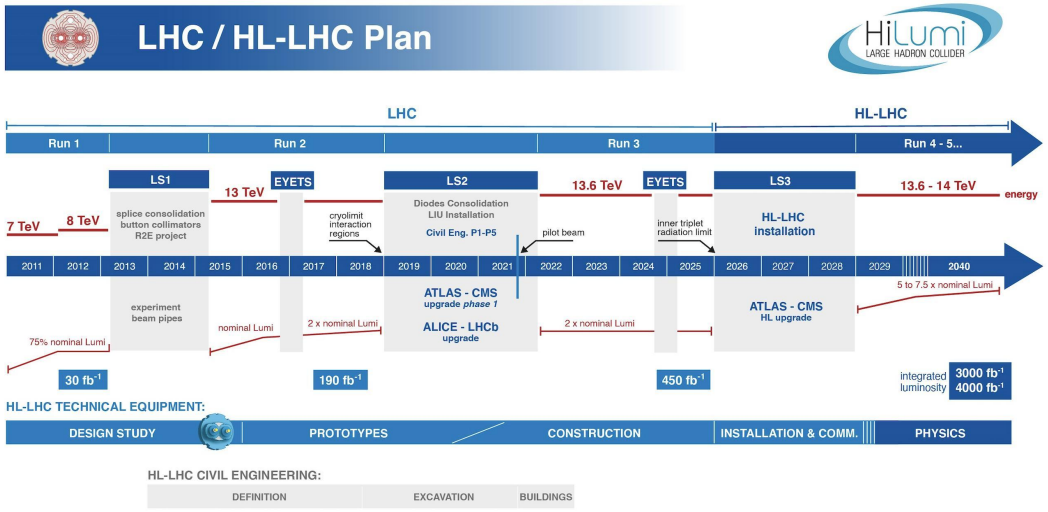
Proton collisions at centre-of-mass energies up to the 14 TeV design energy

CMS: approximately 14,000 tonnes, 21 m long and 15 m in diameter

The High-Luminosity LHC upgrade



Integrated luminosity in the supplied deck



Legacy schedule graphic. Current Run 4 start: 2030.

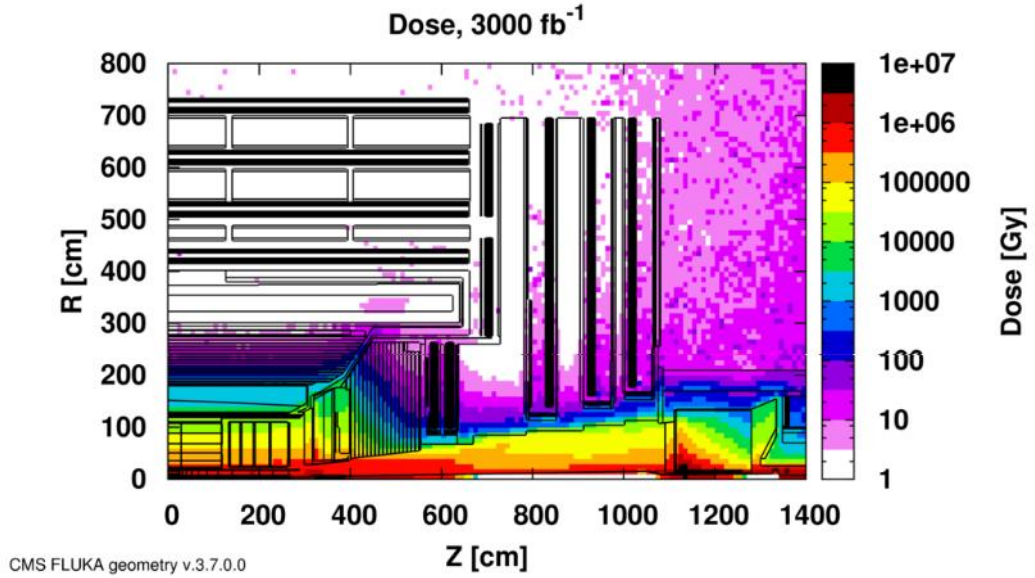
Physics goals: precision Higgs measurements, tests of the Standard Model and searches for new physics

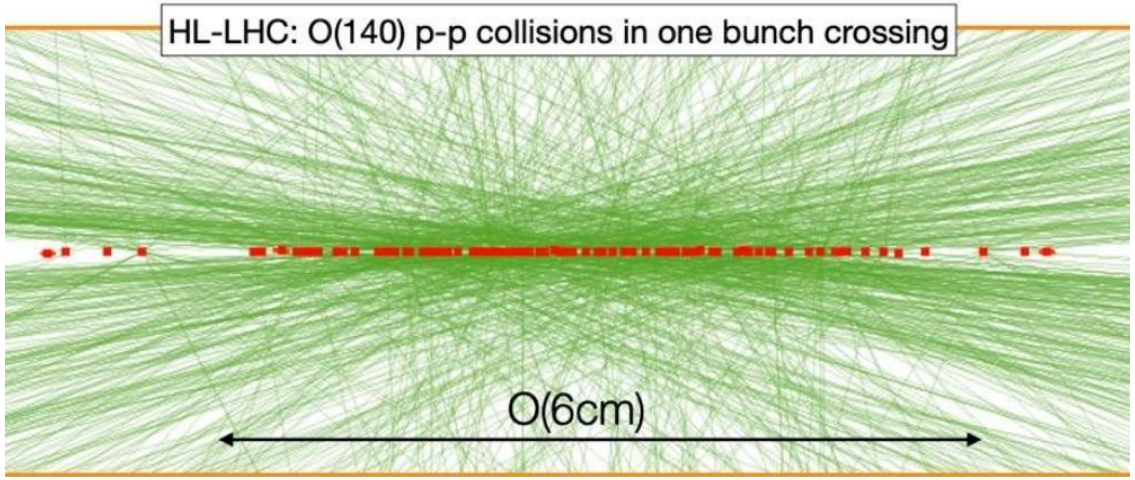
Run 3 ended on 29 June 2026. LHC delivered: 548.15 fb^{-1}. CMS recorded: 504.20 fb^{-1}.

LS3 supports accelerator and detector upgrades. HGCAL installation targets 2028, ahead of Run 4 in 2030.

HL-LHC target: ~3,000 fb^{-1}, with instantaneous luminosity of 5×10^{34} cm^{-2} s^{-1} or higher.

The HL-LHC environment





Radiation exposure

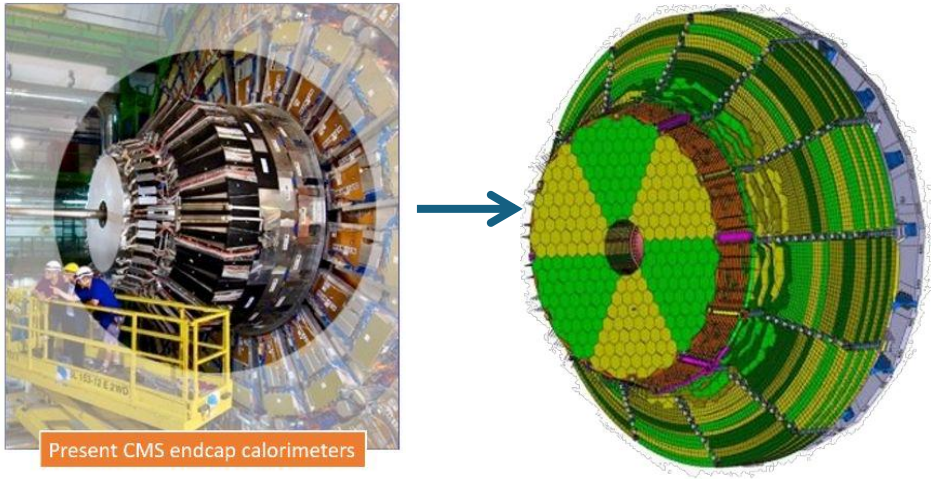
Fluence up to 10^{16} n_{eq}/cm^2 near $|\eta| \approx 3$
Total ionising dose up to 2 MGy

Pileup

140–200 interactions per bunch crossing
~3–5 times the earlier operating conditions

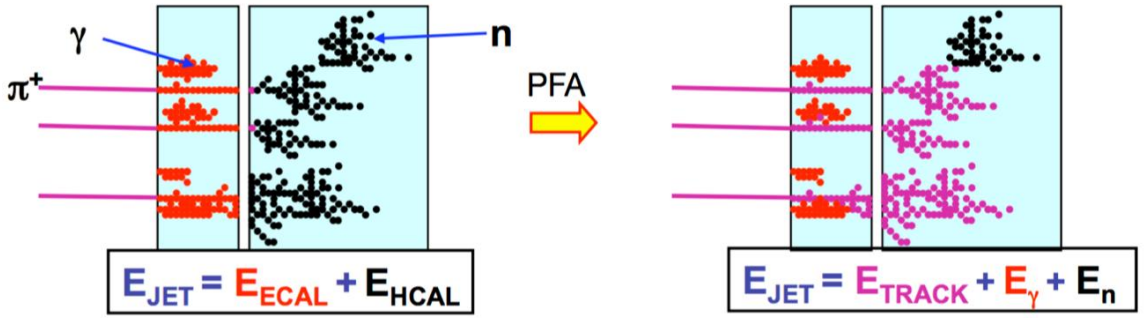
The existing endcap calorimeters were designed for ~500 fb^{-1} and cannot retain their performance throughout the HL-LHC programme.

HGCAL: imaging calorimetry with precision timing



Existing endcaps

HGCAL

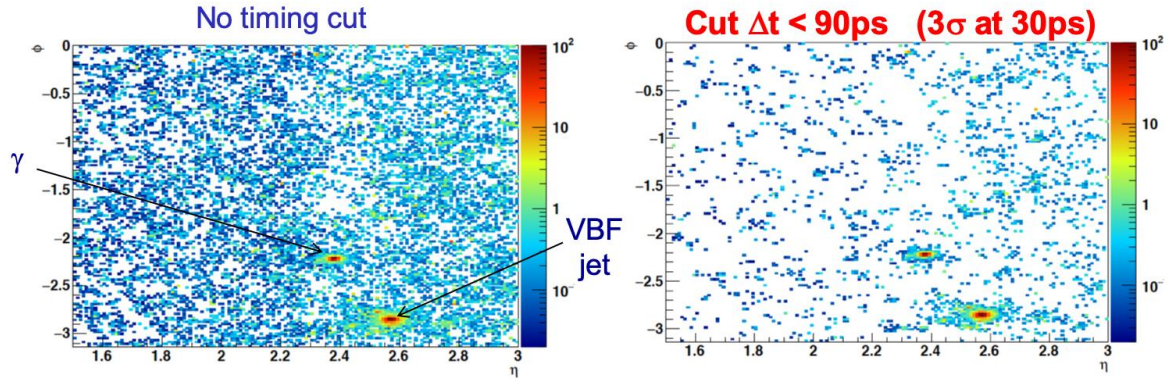


Hybrid detector technology

Silicon in the high-radiation regions
Scintillator tiles in the lower-radiation regions

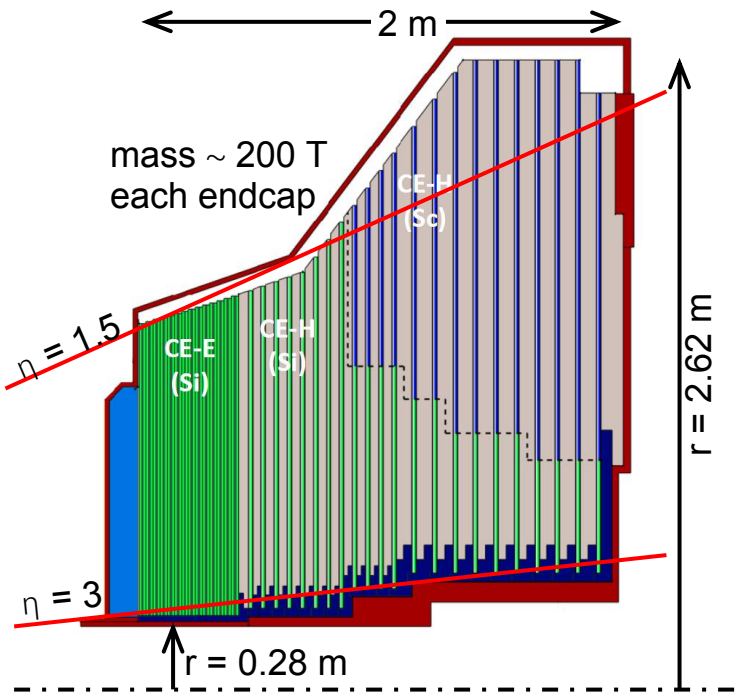
Five-dimensional shower information

Fine 3D segmentation measures (x, y, z) and energy.
Fast silicon signals and time-of-arrival readout.



Particle-flow reconstruction and timing improve shower separation and pileup rejection. CMS-TDR-019

HGCAL design parameters



1.5 < |η| < 3.0 • about 200 t per endcap

2 m deep • radii 0.28–2.62 m

Silicon system

~620 m² active area
~6 million channels
~26,000 modules
Cell areas ≈ 0.5 or 1.1 cm²

Scintillator system

~370 m² active area
~340,000 channels
~3,700 tilemodules
Tile areas: 4–30 cm²

Operating targets

Operation near −30 °C
~110 kW per endcap
Radiation tolerance:
10^{16} n_{eq}/cm² (1 MeV equivalent)

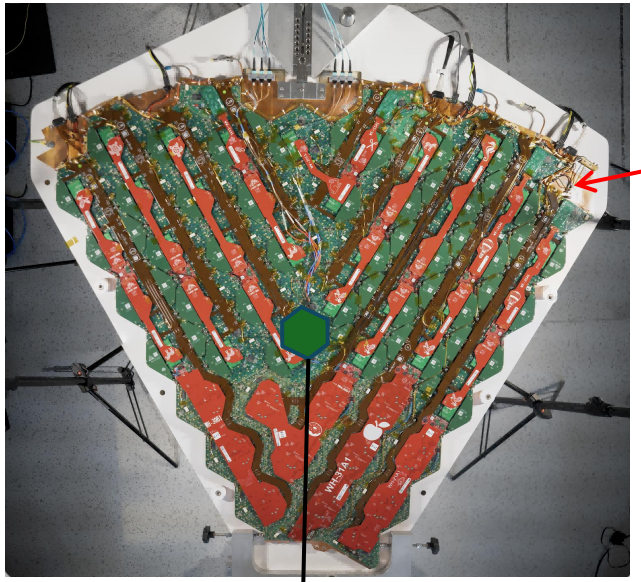
Energy and timing resolution target

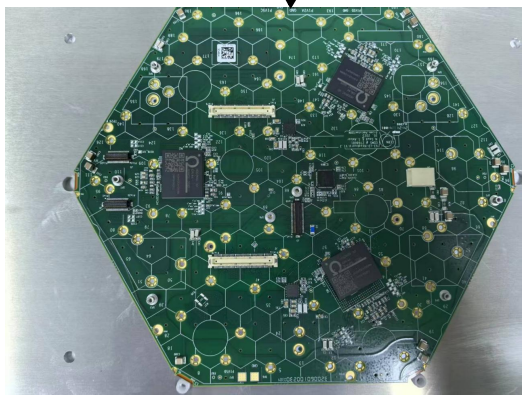
$\sigma(E)/E \approx 25\%/\sqrt{E} \oplus 1\%$
Timing resolution ≈ 50 ps

CE-E: 26 layers, Si with Cu / CuW / Pb absorbers, 25.5 X_0 and ~1.3 λ
CE-H: 21 layers, Si and scintillator with steel absorbers, ~8.5 λ

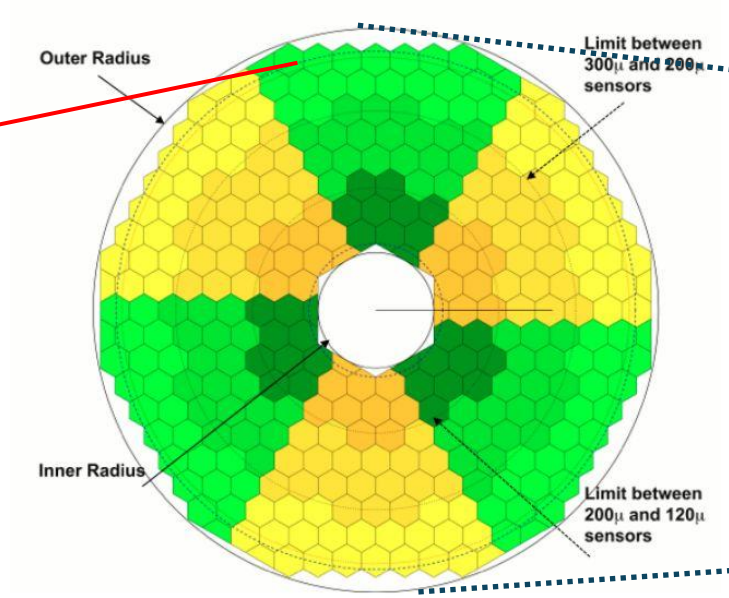
CMS-TDR-019. Cell areas are approximate and depend on module geometry.

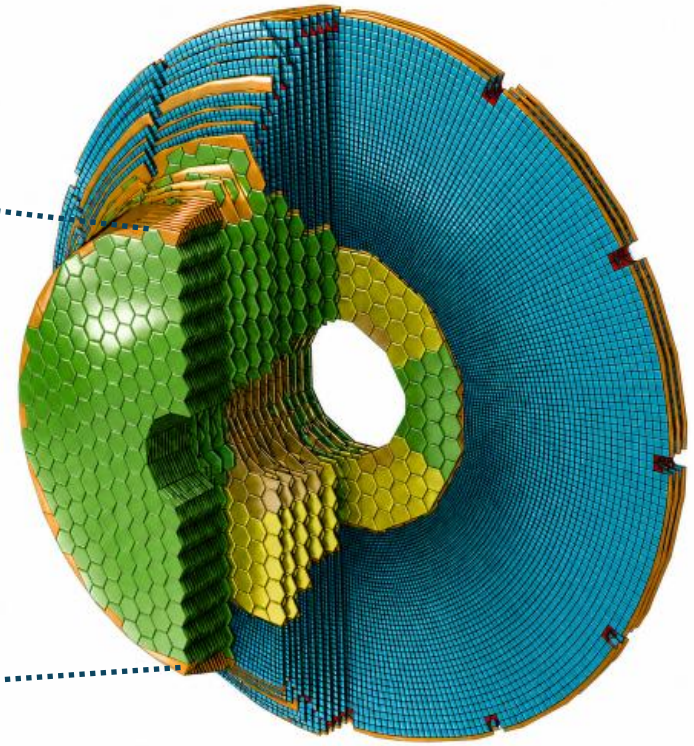
Silicon detectors in the high-radiation regions





8-inch Low density full silicon module





Coverage and scale

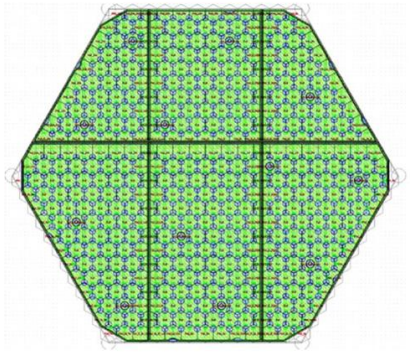
All of CE-E and the inner, higher-radiation part of CE-H
~26,000 modules and 620 m² of silicon
Si module assembly centers: IHEP, NTU, UCSB, CMU, TTU, TIFR

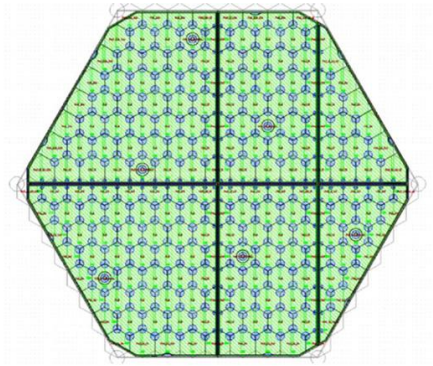
Active thickness depends on the radiation exposure:
120 μm in the innermost region, 200 μm in the intermediate region and 300 μm in the outermost silicon region.

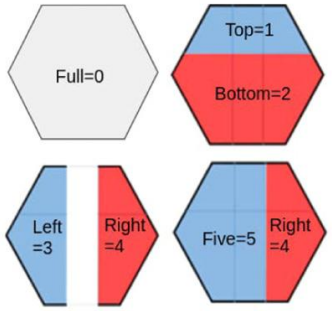
Silicon module design

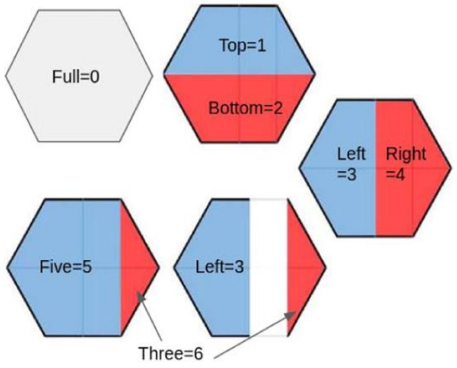
Cell geometry

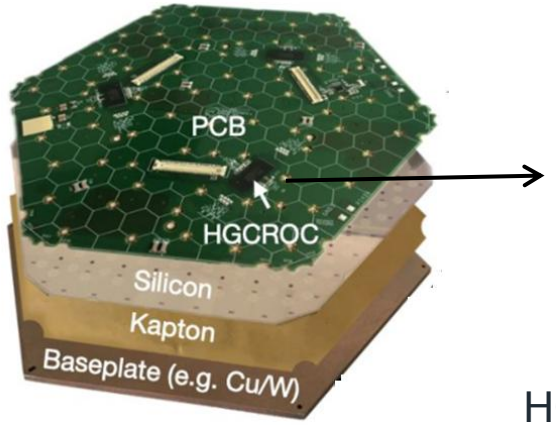
High density: ~0.5 cm² per cell
Low density: ~1.1 cm² per cell













HGCROC readout ASIC

Module stack

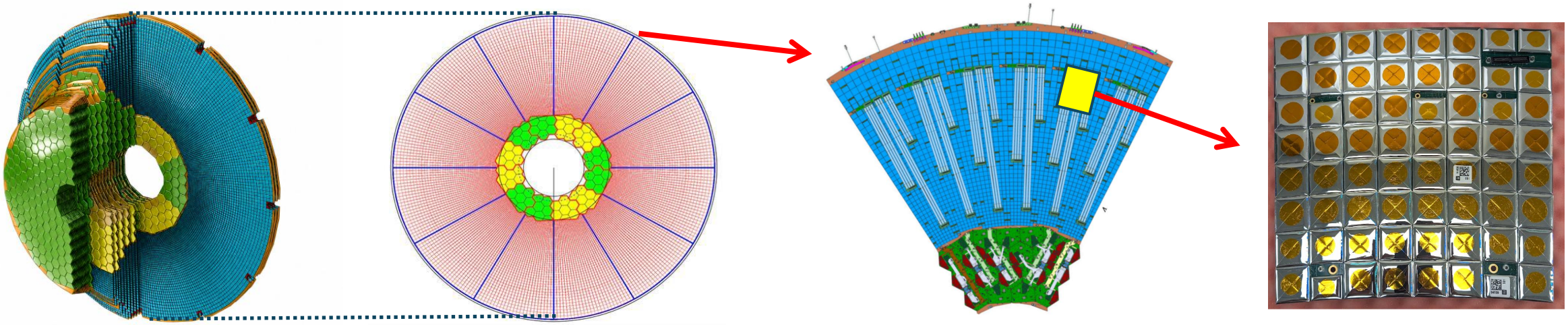
Hexaboard: HGCROC readout and data transfer

Silicon sensor: active material, 120 / 200 / 300 µm

Kapton: electrical insulation from the baseplate

Baseplate: mechanical support, rigidity and absorber material

Scintillators in the lower-radiation regions



HGCAL | Scintillator coverage | CE-H cassette | Tilemodule

- The HGCAL hadronic section (CE-H) consists of 3744 tilemodules, produced approximately equally at Fermilab and DESY
- Active element: Scintillator tiles ~370 m^2
  - 35 Tile variants： Sizes 4 -- 30 cm^2
  - Shapes： trapezoidal and rectangular
- Small cast-scintillator tiles (207 m^2) in higher radiation zone, larger moulded scintillators (163 m^2) in the rest.

Scintillator tilemodule design

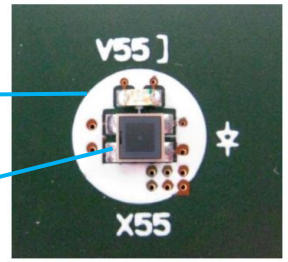
Tileboard： 32 sub-types



Tilemodule

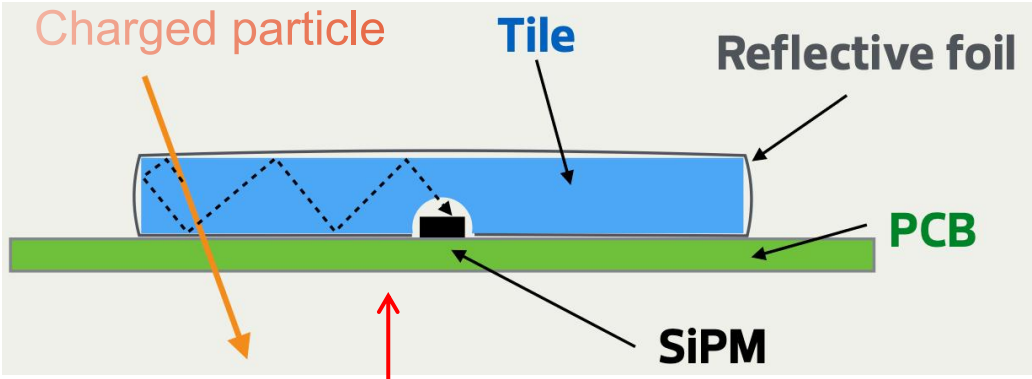
Tile and reflective wrapping

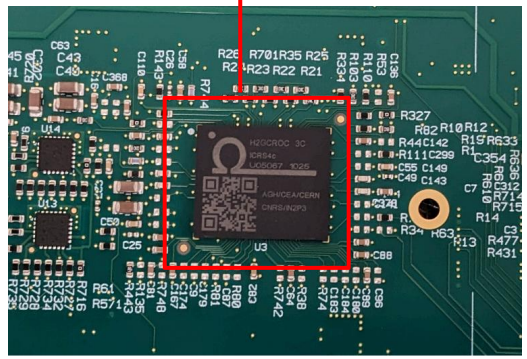




SiPM and calibration LED

Tile-on-SiPM light collection



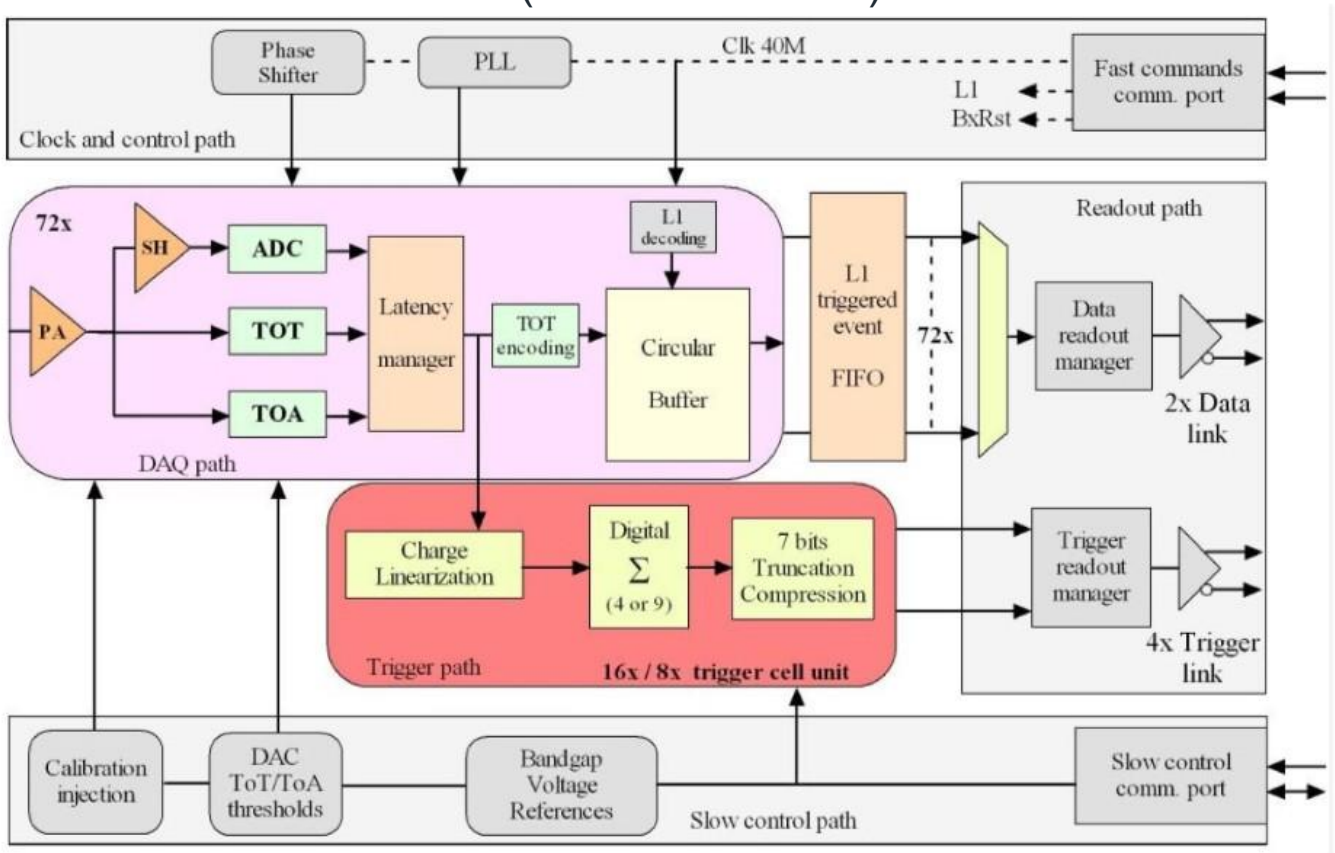


HGCROC on the tileboard reverse side

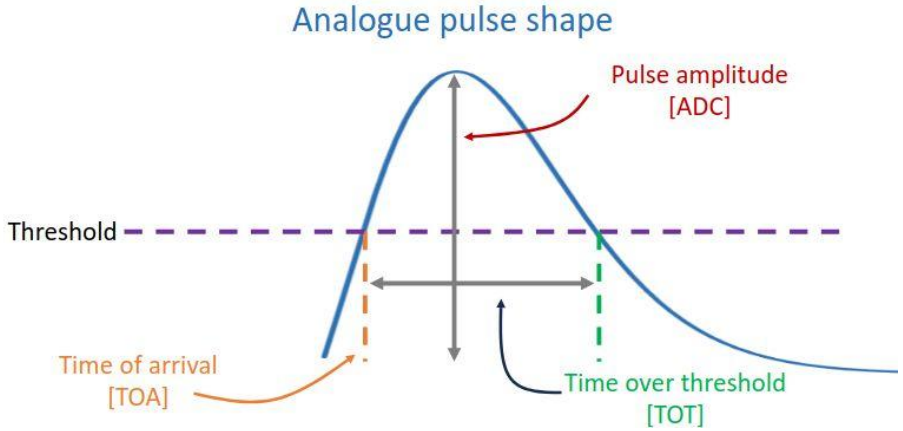
- Scintillator tile module: Scintillator tile-on-SiPMs + readout chip
- Plastic scintillator tiles coupled to SiPMs (Hamamatsu, 9 mm^2)
- ESR reflective foil maximizes light detection onto the SiPM
- Tileboard PCB hosts SiPMs, LEDs, and readout chips

HGCROC front-end readout ASIC

Fast control: 320 Mb/s (8 bits at 40 MHz)



Slow control: I²C



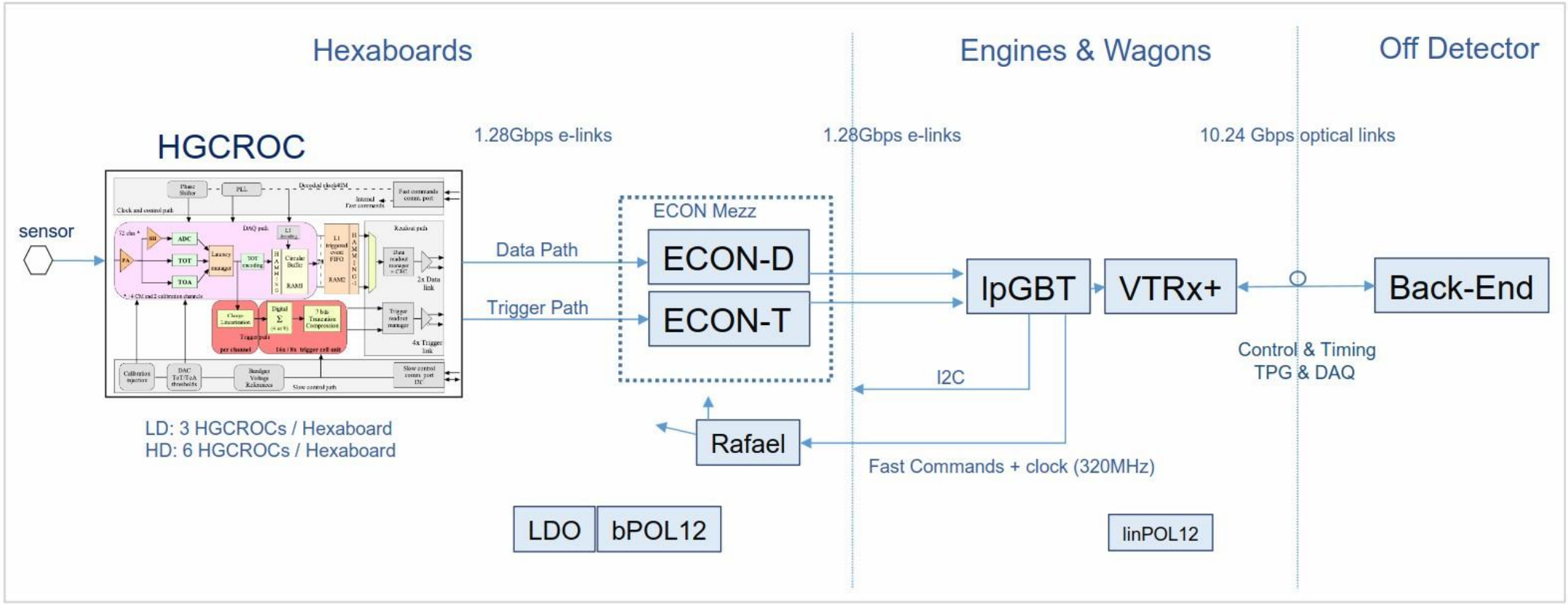
Charge and timing

10-bit ADC at 40 MHz for MIPs
12-bit time-over-threshold for showers
10-bit time-of-arrival, 25 ps LSB

F. Bouyjou et al., JINST 17 (2022) C03015; A. Grummer, EPJ Web Conf. 320 (2025) 00067.

78 channels in two halves: 72 signal + 4 common-mode + 2 calibration channels.
A 0.2 fC–10 pC range covers MIP calibration and shower signals.
Adapted for silicon and scintillator.

The HGCAL Si readout chain



C. Amendola, JINST 20 (2025) C01031, Sec. 3, Fig. 2; A. Grummer, EPJ Web Conf. 320 (2025) 00067； M. Lupi et al., arXiv:2411.03476 (2024).

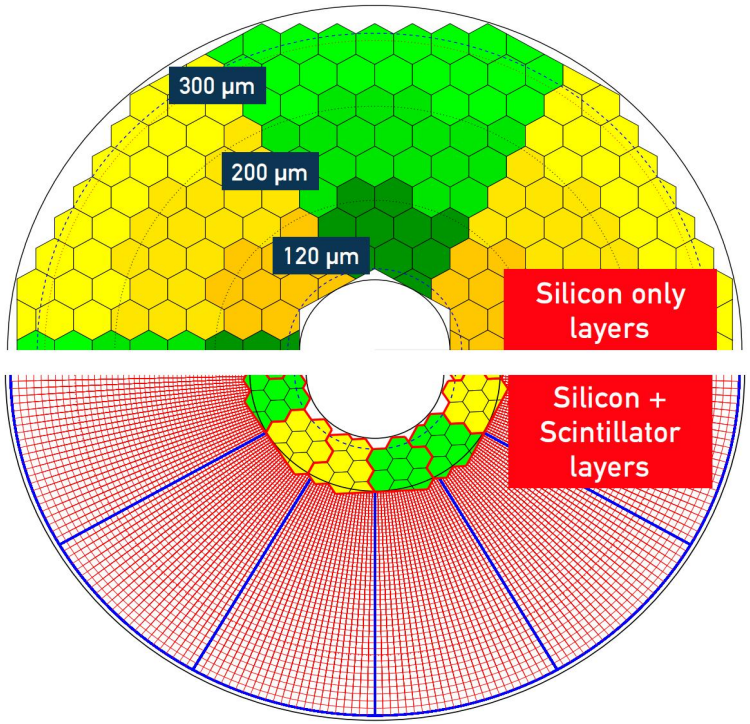
ECON concentrators

ECON-T selects and compresses trigger data at 40 MHz.
ECON-D processes triggered full-resolution data and applies zero suppression at 750 kHz.

Control and optical links

Rafael distributes clocks and fast-control signals.
lpGBT and VTRx+ provide radiation-tolerant data links and distribute clock and control signals.

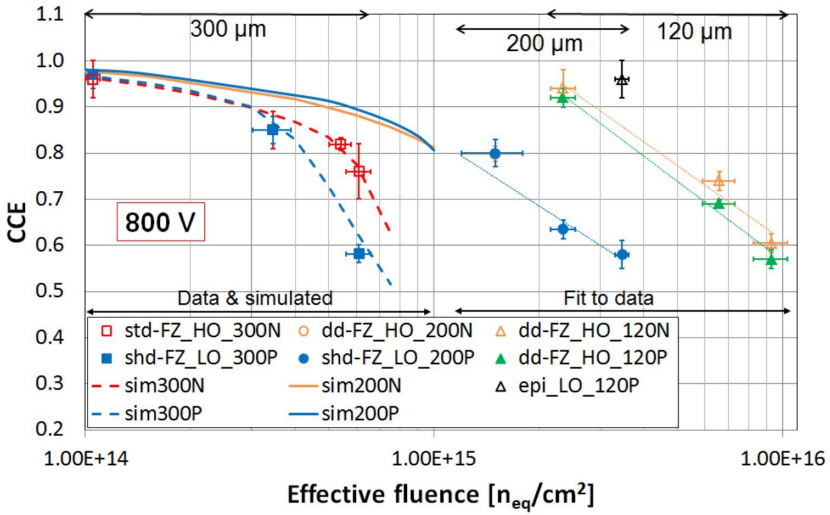
Radiation-tolerance validation

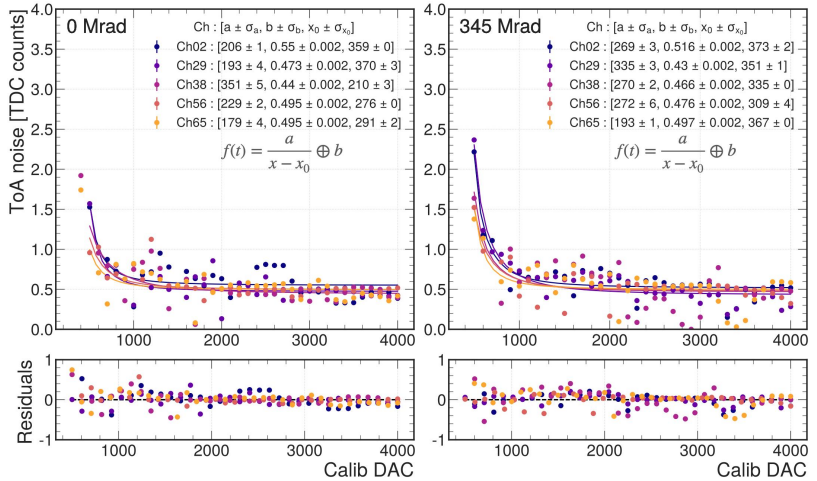


Sensors and module materials

- 120 µm sensors tested up to 10^{16} n_{eq}/cm^2. 200 and 300 µm sensors tested at their target fluences
- HGCROC V3: 345 Mrad irradiation test

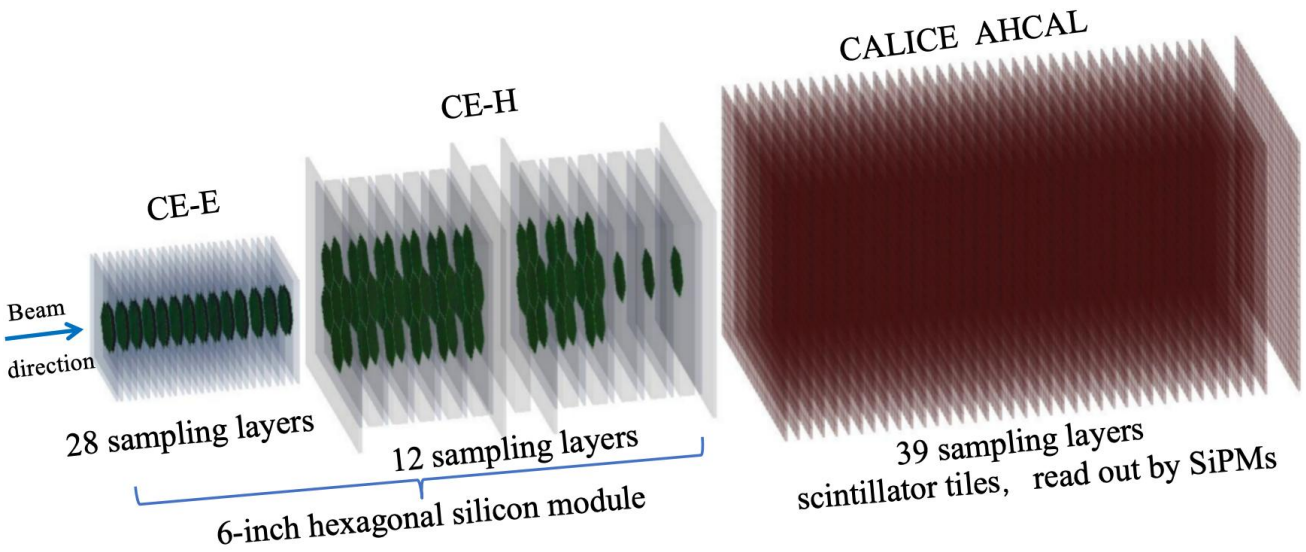
Sensors: JINST 15 (2020) P09031



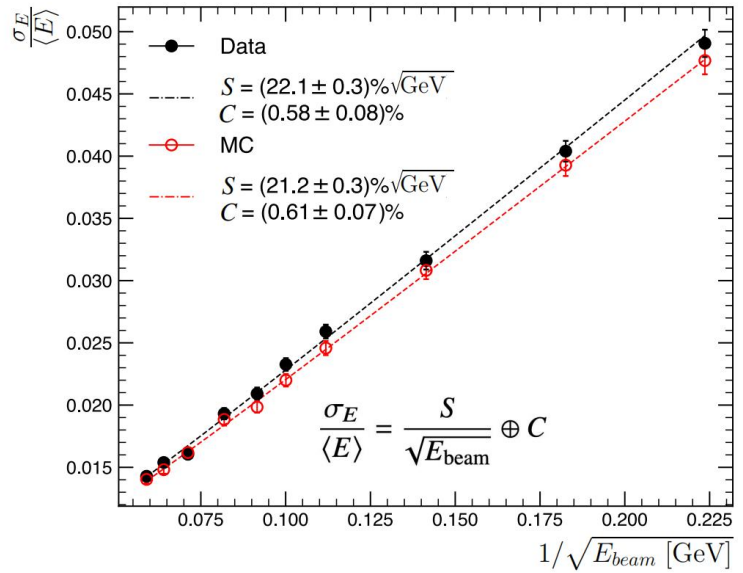


ASIC: DOI 10.1109/NSS/MIC44845.2022.10399091

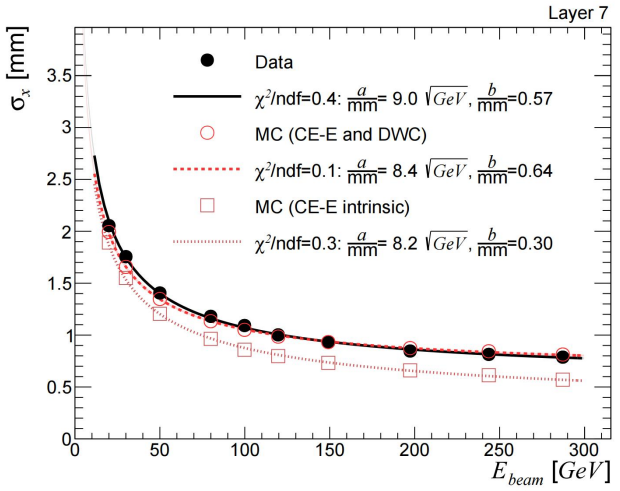
Beam-test performance validation



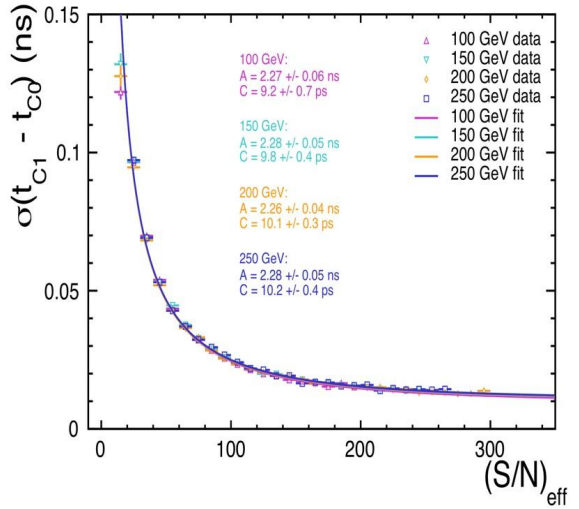
JINST 17 (2022) P05022



- 2016–2018 beam tests
  - 6-inch silicon modules with SKIROC readout and the CALICE scintillator AHCAL
  - Validated electromagnetic energy response: (CE-E) $22.1\%/\sqrt{E}\oplus 0.58\%$ (e-)
  - Position resolution below 1 mm at high energy
  - Cell-to-cell timing resolution below 50 ps



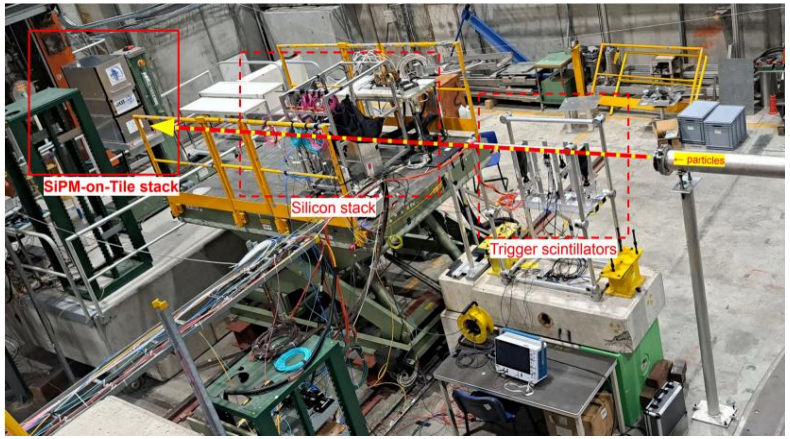
JINST 18 (2023) P08014



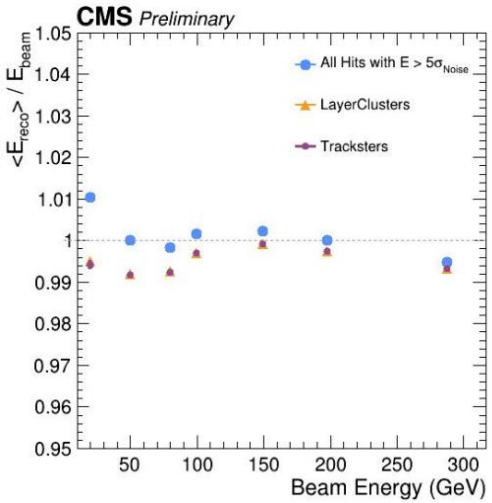
JINST 19 (2024) P04015

2025 HGCAL beam tests: preliminary performance

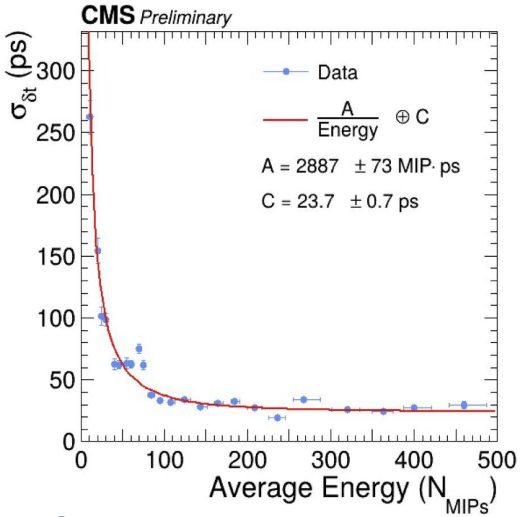
CERN SPS H2: compact silicon and SiPM-on-tile stacks with near-final modules and FE/BE readout chains [1,2]



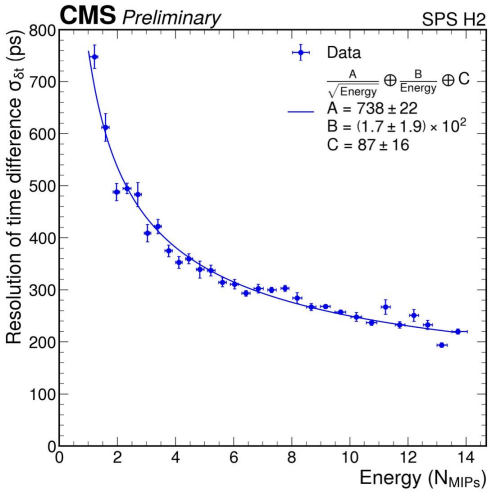
Two separately measured stacks



Silicon energy response [1]



Silicon channel-pair timing [1]



Tile channel-pair timing [2]

Setup and silicon energy response

10 silicon sampling layers (~21 X_0) and 15 scintillator layers (~15 X_0), tested separately. [1,2]

Silicon: electron response linear to within ~1% over 20–300 GeV after calibration. [1]

Coarser sampling and longitudinal leakage limit the prototype energy resolution.

Timing performance after timewalk correction

Silicon: ~20 ps (paired silicon channels);

SiPM-on-tile: ~180 ps at 10 MIPs for the example pair. [2]

Single-channel estimate assumes equal contributions: $\sigma_t = \sigma(\Delta t)/\sqrt{2}$. These are not shower timing resolutions.

[1] CMS-DP-2026-054 https://cds.cern.ch/record/2962591
[2] CMS-DP-2026-055. https://cds.cern.ch/record/2962592

Construction and integration status

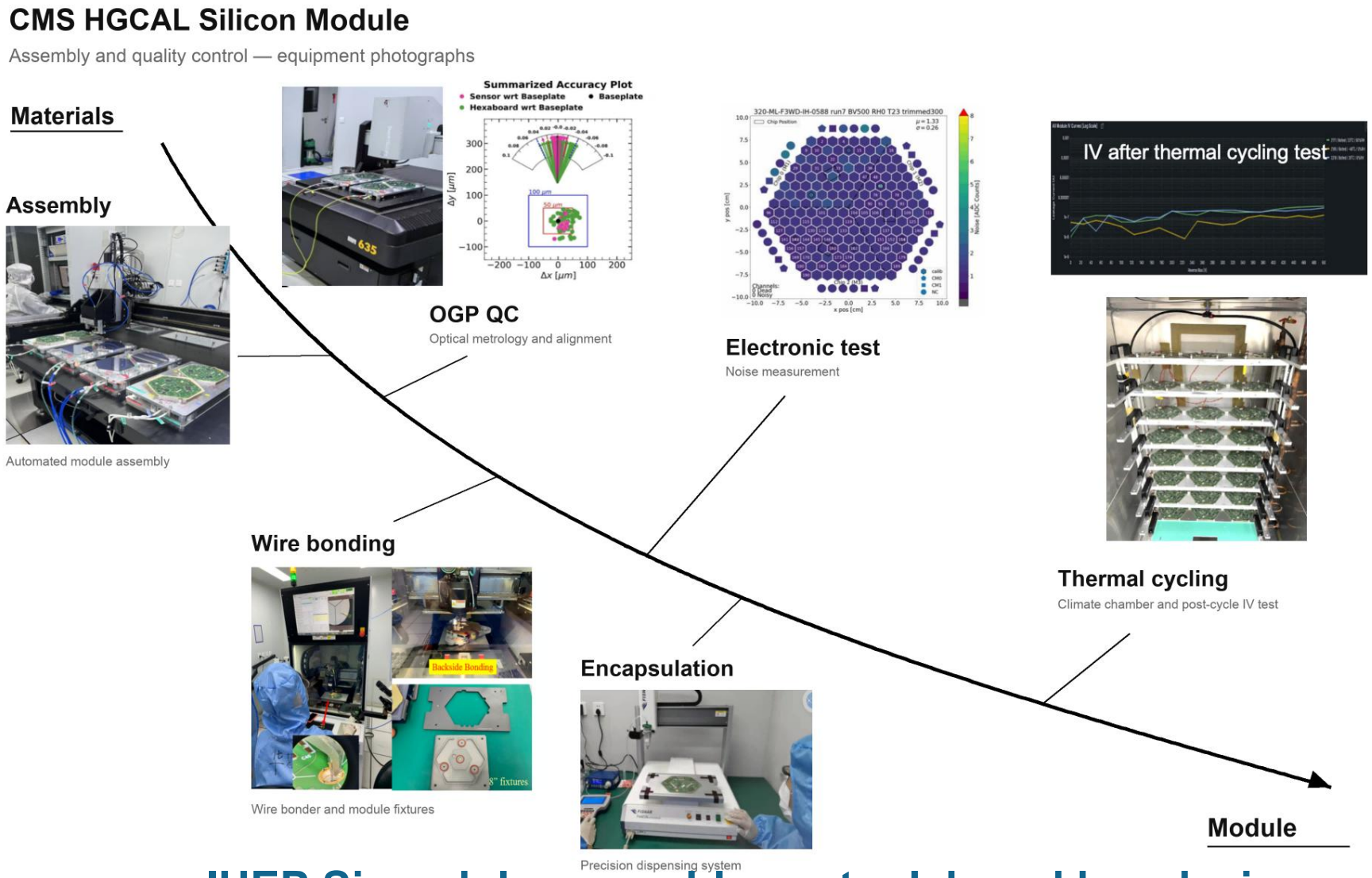
Module production

Cassette assembly

Mechanical structures and integration

Production snapshots and the 2026–2028 project schedule

Silicon module production and quality control



IHEP Si module assembly center lab and key devices

Production status

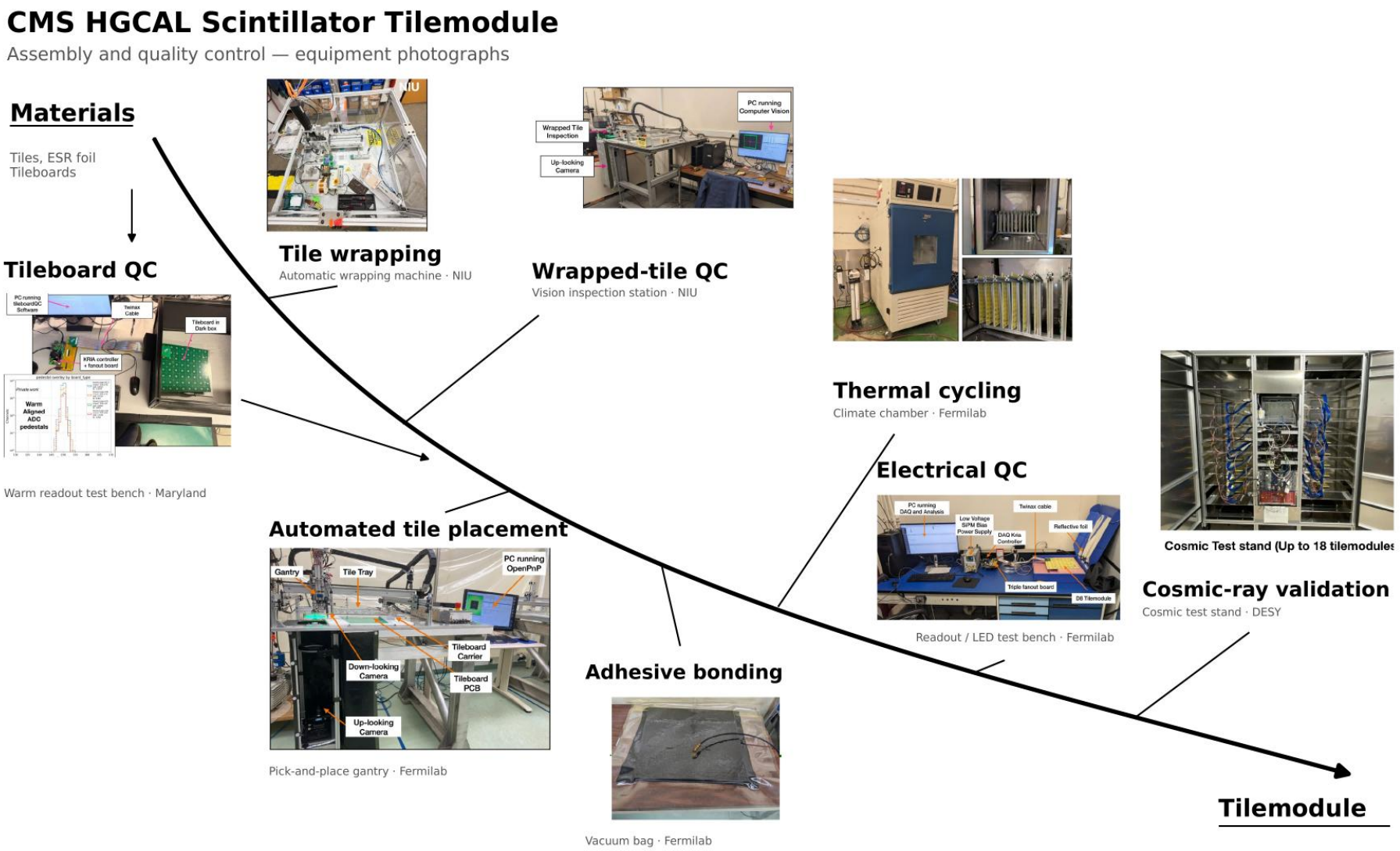
≈10%

~60 m² of silicon modules completed

Throughput

16 modules per day per assembly station has been demonstrated.

Scintillator tilemodule production and QC



Representative equipment from NIU, Maryland, Fermilab and DESY. Adhesive-transfer tape / vacuum bonding shown for Fermilab.

Production status

380

Tilemodules assembled
~10% of the total

Production is underway at Fermilab and DESY.

Both assembly centres are ramping up to full capacity.

CE-E cassette assembly at CERN

CERN Cassette Assembly Facility

Start and production scope

Preseries CEE cassette integration: May 2025; first powering: June 2025.
The first pre-production CEE cassette assembly started in July 2026.
Total scope: 156 double-sided cassettes for both endcaps.

Assembly completed: 3 of 156 cassettes

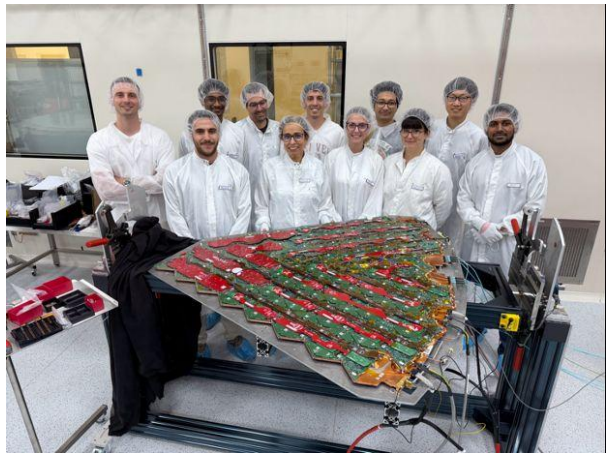
C13-001, -002 and -003 completed both sides by 9 September.
C13-004 was under assembly.
C13-003 passed post-insertion QC on 11 September.

Thermal-cycle qualification

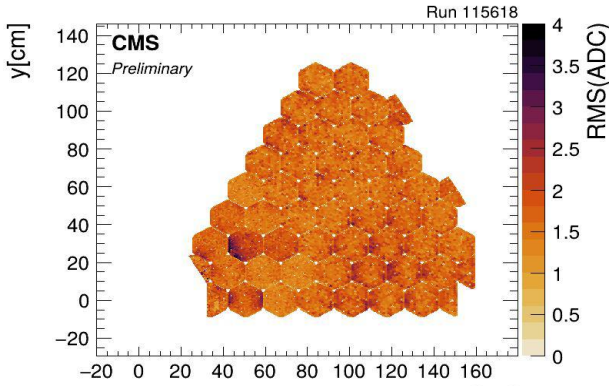
The first −35 °C test, using the preseries cassette, was still pending thermal-cycle test system commissioning.
Completed assembly does not yet imply cold qualification.

Next steps

Finish six C13 pre-production cassettes by early November; commission test system then start thermal-cycle tests.



First CE-E pre-production cassette



noise studies on pre−series double−sided cassette, layer 25

Rate target: 12 → 16 cassettes/month, subject to parts and staffing.

Sources: A. Zghiche, HGCAL Annual Review, 15 Sep 2026; R. Chudasama, CALOR 2026,.

CE-H cassette assembly at Fermilab

Fermilab Cassette Assembly Facility

Start and production scope

Preseries integration began with all-silicon 7B in August 2025.
Layer 21 pre-production started in early September 2026.
Total scope: 504 single-sided cassettes across 66 geometries.

Assembly status: 2 preseries cassettes validated

7B (all-silicon) and 18C (silicon + scintillator) assembled and used for system validation.

Cold testing: 2 preseries cassettes tested

7B and 18C tested with CO_2 at −35 °C.
Good cooling performance has been observed.

Next steps

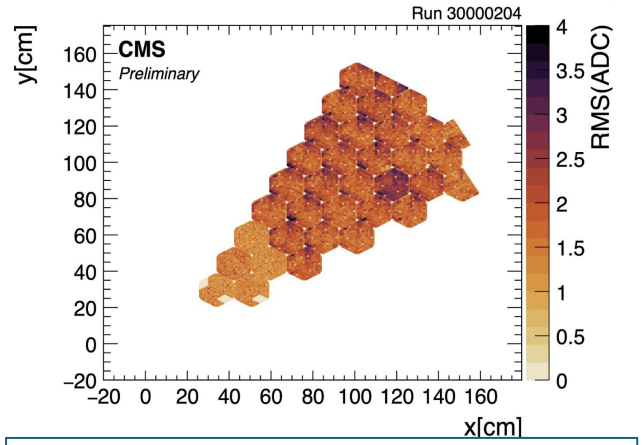
Pre-production assembly of first 24 (/504 total) cassettes started target full-rate production in November.

Mixed 18C cassette used in cold tests





7B CE-H cassette assembly at Fermilab



Noise measurements (−25C, 300V bias)

Target: 2 cassettes/day
Ship tested cassettes to CERN in stacks of 21.

Sources: Z. Gecse, HGCAL Annual Review, 15 Sep 2026; R. Chudasama, CALOR 2026.

CE-E and CE-H mechanics

Status at 15 September 2026

CE-E: heavy components delivered

Both backplates and support cylinders are at CERN.
Backplate trial fitting on CE-H succeeded.
All 312 lead sheets + 26 spares delivered.
Layer 13 lead-sheet trial assembly completed.



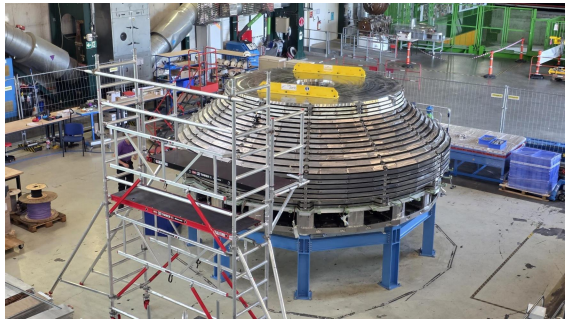
Layer 13 lead-sheet trial assembly

Next steps

Fit the first support cylinder. Measure lead-sheet thickness. Particle-moderator procurement enquiry launched.

CE-H: first structure assembled and cold-tested

CE-H1: 21 absorber plates, 170 tonnes.
Cold test reached −25 to −36 °C, with no unexpected condensation or overheating.
Wedge contraction ≈2 mm, fully reversible.



Fully assembled CE-H1 absorber

CE-H2 and integration

Machining at HMC-3. Completion planned for Dec 2026, arrival at CERN by end-Mar 2027.

Cassette insertion trials and cable mockup in preparation.

Cooling delivery plans: CE-H1 manifolds Nov 2026, flexible lines Mar 2027, capillaries Apr 2027.

Source: D. Primc, Engineering and Mechanics, HGCAL Annual Review, 15 Sep 2026.

Summary and outlook

Summary

HGCAL is 3D imaging, timing and energy reconstruction. Irradiation and beam tests validate the design under the tested conditions.

Module production is at ~10% to date: ~60 m² of silicon and 380 scintillator tilemodules.

Cassette integration is under way: 3 CE-E cassettes assembled on both sides; 2 CE-H preseries cassettes cold-tested.

CE-E supports and lead sheets have been delivered. CE-H1 is assembled and cold-tested; CE-H2 machining is in progress.

Outlook

Ramp up module and cassette production while securing cooling plates, electronics, services and trained staff.

Complete CE-E cold-test commissioning and cassette qualification; expand CE-H DAQ, power and cold-room capacity.

Complete CE-H2 mechanics and cooling services, followed by cassette insertion, cabling and detector integration.

Follow the 2026–2028 plan for stacking, integration and full-detector cold tests, ahead of Run 4 in 2030.

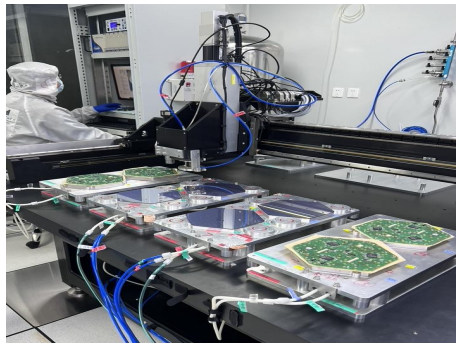
Production figures retain their source dates. Cassette/mechanics status: 15 Sep 2026. Future milestones are targets.

Thank you for your attention

With thanks to every team contributing to CMS HGCAL



Sensor inspection



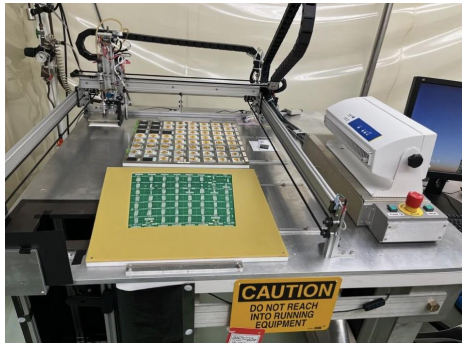
Silicon assembly



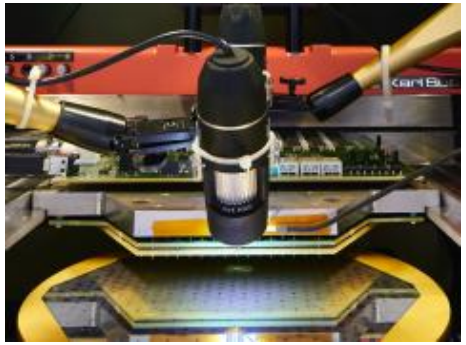
Wire bonding



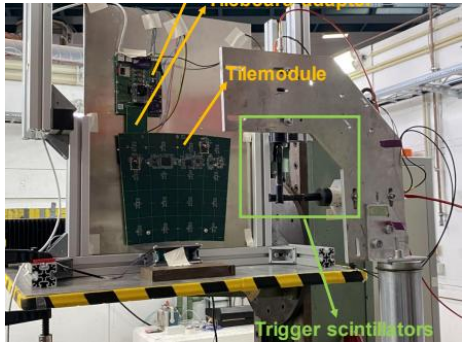
Tile wrapping



Tile placement



Sensor probing



Beam validation



Cassette assembly



Structure reception



Cold testing

To the scientists, engineers and technicians behind the detector

CMS HGCAL CE-E cassette production workflow

Cooling plate preparation → double-sided assembly → qualification → stacking

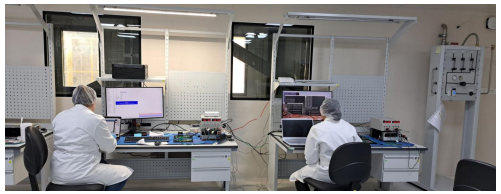
1 Cooling plate preparation



Finished CE-E cooling plates at LLR [1, p. 23]

Machine copper; integrate and solder cooling pipes; complete drilling and metrology.

2 Module reception & QC



Module test stations in CERN CR2 [2, p. 6]

Receive, test and track silicon modules; prepare the components for each cassette side.

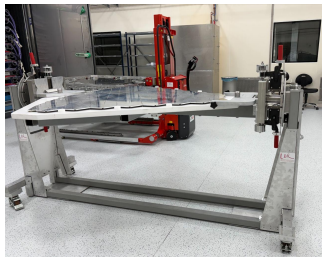
3 Side 1 assembly & QC



Hands-on assembly workshop at CERN [2, p. 15]

Mount modules, front-end electronics and services; perform single-cassette tests.

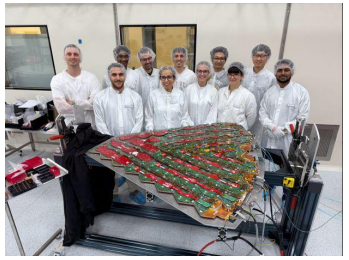
4 Protect & flip cassette



Rotating assembly table and forklift [2, p. 6]

Fit cover #2, rotate the assembly table and remove cover #1 to access side 2.

5 Side 2 assembly & QC



Pre-production cassette on its test stand [2, p. 17]

Populate side 2; check I–V, optical connections and ASIC alignment before transfer.

6 Frame & cold-box insertion



Crane and cassette handling frame [2, p. 6]

Mount the frame; transfer by forklift, slide into the cold box and repeat QC.

7 Warm / cold qualification



Cabled CE-E cold box at CERN [2, p. 6]

Planned cold test with cosmic rays (~2 weeks), with readout and environment monitoring.

8 Extraction & stacking



CE-E stacking table at CERN [2, p. 6]

Extract the cassette; perform QC, transfer to the stacking station and repeat QC.

Workflow: [2], p. 16. Photos show actual equipment and assembly activities; workshop images illustrate assembly tasks.

Status note: at 15 Sep 2026, first −35 °C qualification awaited safety-interlock commissioning. Cold testing is a planned stage.

[1] CE-E Cooling Plate MPR, 25 Aug 2026. [2] A. Zghiche, CE-E Cassette Production, HGCAL Annual Review, 15 Sep 2026.

CMS HGCAL CE-H cassette production workflow

Fermilab assembly → electrical and thermal qualification → shipment to CERN → insertion

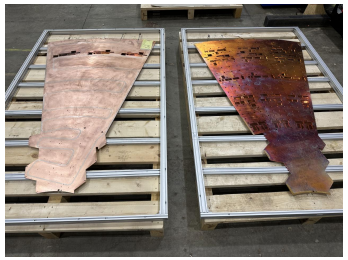
1 Cooling plate fabrication



Layer 21 plate after soldering [1, p. 14]

Machine copper; integrate cooling tubes; solder, clean and complete dimensional and leak checks.

2 Frame mounting & tracking



Cooling plates secured to frames [2, p. 25]

Secure the plate to its handling frame; register its barcode and prepare the required components.

3 Detector module installation



Module installation at Fermilab [2, p. 15]

Mount silicon modules and, for mixed cassettes, scintillator tilemodules using guided assembly.

4 Electronics & services



Mixed-cassette assembly team [2, p. 15]

Install DC–DC converters, wagons and engines; connect power, bias, optical and signal cables.

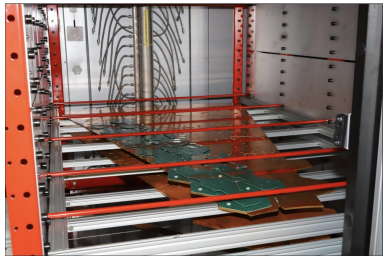
5 Warm electrical checks



Assembled cassette at Fermilab [3, p. 33]

Use the single-cassette tester for quick checks without cooling; identify and correct assembly faults.

6 Cold testing & readout QC



Cassette rack inside a cold room [2, p. 5]

Perform thermal cycling and monitor readout, noise and temperatures; collect cosmic-ray data.

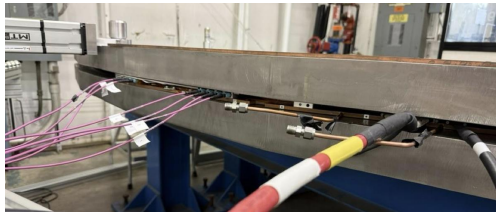
7 Qualified cassette shipment



Framed components on a handling rack [2, p. 15]

Planned: ship tested cassettes to CERN in stacks of 21, with a controlled dry environment.

8 Insertion into absorber



Prototype insertion test at Fermilab [2, p. 13]

Align and insert the cassette into the absorber; verify readout after mechanical integration.

Single-sided cassettes: all-silicon or mixed silicon / scintillator. Photographs show actual Fermilab equipment and activities. Workflow includes planned production and shipment steps. Cold-test and insertion photographs include preseries validation.

[1] CE-H Cooling Plate MPR, 28 Aug 2026. [2] Z. Gecse, Annual Review, 15 Sep 2026. [3] R. Chudasama, CALOR 2026.