ECFA
European Committee for Future Accelerators

CERN

Integration Challenges for Calorimetry

Martin Aleksa

Based on Material from the ECFA Detector R&D Roadmap Input Sessions (https://indico.cern.ch/category/13180/)
I am grateful for interesting discussions and input provided by E. Auffray-Hillemanns, D. Barney, J. Bremer, M. Chalifour, R. Ferrari, S. Moccia, R. Pöschl, F. Sefkow, F. Simon

Introduction

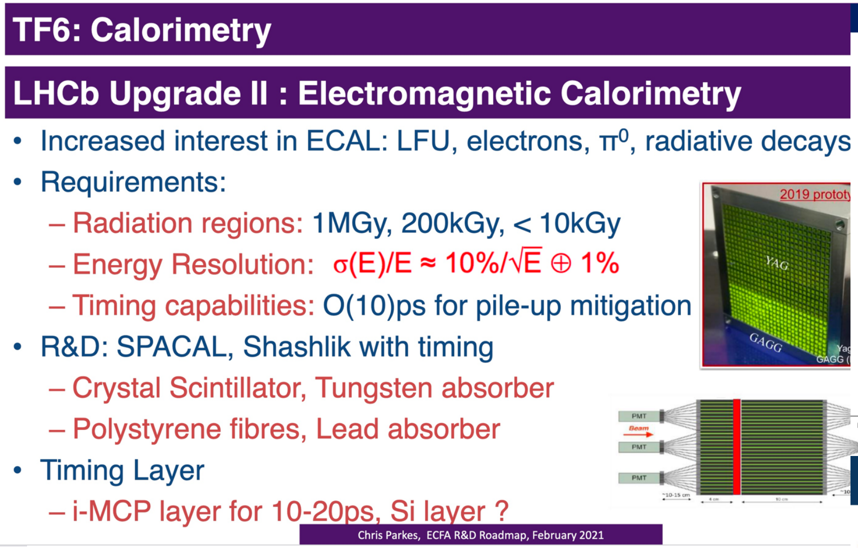
Introduction

- **Calorimeters** are large systems, based on **various types of active sensors**. Integration challenges very often are closely **linked to the calorimeter type chosen and its implementation inside a specific experiment**.
  - **R&D needs for calorimetry** will be discussed in the symposium of TF6 (May 7)
  - In this talk I will try to cover **mechanical challenges, integration challenges, infrastructure challenges**

- **R&D and Engineering:**
  - In the following I will concentrate on integration challenges that different types of calorimeters are facing.
  - Many of these challenges can be solved by a dedicated engineering effort, not all will need R&D effort
  - The development and integration of calorimeters involves strong engineering contributions and needs close collaboration between physicists and engineers (electronics and mechanical): Calorimeter projects are usually driven by labs with strong engineering resources, rather than small university groups
  - → Calorimeters need – more than other detectors – a strong collaboration of engineers and physicists, relying on large labs and their infrastructure, must make sure that this is supported by our funding agencies

- **Outline:**
  - Brief summary of calorimeters under study for future collider experiments
    - from ECFA Roadmap Input Sessions, https://indico.cern.ch/category/13180/
  - Input from different detector communities on their view of engineering challenges for their calorimeter types
  - Thoughts on Engineering Challenges and R&D Needs

Input Session – Calorimeters

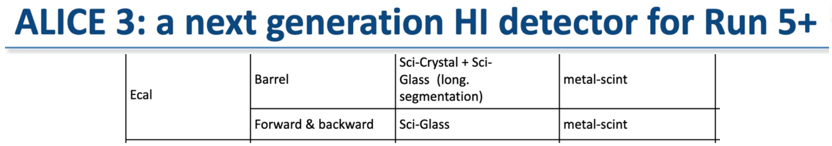


TF6: Calorimetry

LHCb Upgrade II : Electromagnetic Calorimetry

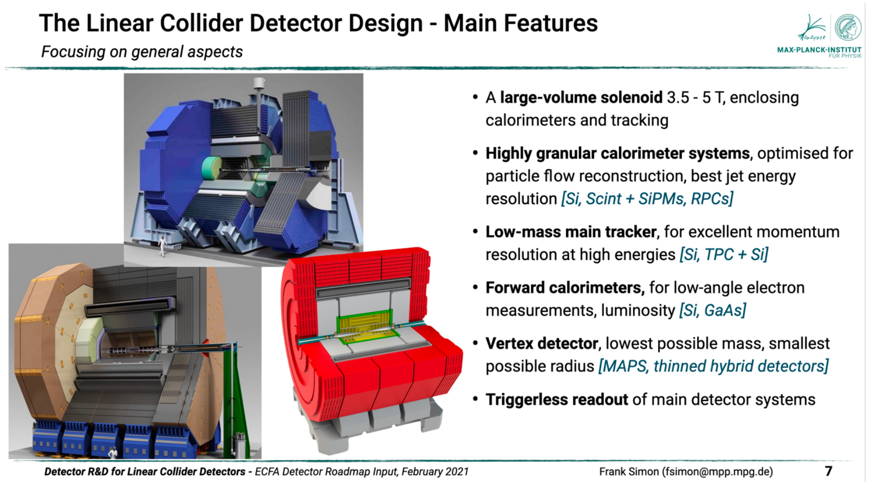
- Increased interest in ECAL: LFU, electrons, π^0, radiative decays
- Requirements:
  - Radiation regions: 1MGy, 200kGy, < 10kGy
  - Energy Resolution: $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
  - Timing capabilities: O(10)ps for pile-up mitigation
- R&D: SPACAL, Shashlik with timing
  - Crystal Scintillator, Tungsten absorber
  - Polystyrene fibres, Lead absorber
- Timing Layer
  - i-MCP layer for 10-20ps, Si layer ?

Chris Parkes, ECFA R&D Roadmap, February 2021



ALICE 3: a next generation HI detector for Run 5+

Ecal	Barrel	Sci-Crystal + Sci-Glass (long. segmentation)	metal-scint
	Forward & backward	Sci-Glass	metal-scint



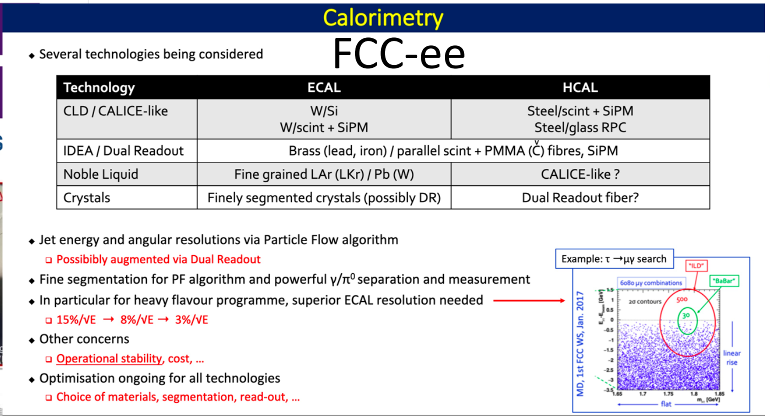
The Linear Collider Detector Design - Main Features

Focusing on general aspects

MAX-PLANCK-INSTITUT FÜR PHYSIK

- A **large-volume solenoid** 3.5 - 5 T, enclosing calorimeters and tracking
- **Highly granular calorimeter systems**, optimised for particle flow reconstruction, best jet energy resolution *[Si, Scint + SiPMs, RPCs]*
- **Low-mass main tracker**, for excellent momentum resolution at high energies *[Si, TPC + Si]*
- **Forward calorimeters**, for low-angle electron measurements, luminosity *[Si, GaAs]*
- **Vertex detector**, lowest possible mass, smallest possible radius *[MAPS, thinned hybrid detectors]*
- **Triggerless readout** of main detector systems

***Detector R&D for Linear Collider Detectors** - ECFA Detector Roadmap Input, February 2021* Frank Simon (fsimon@mpp.mpg.de) 7



Calorimetry

FCC-ee

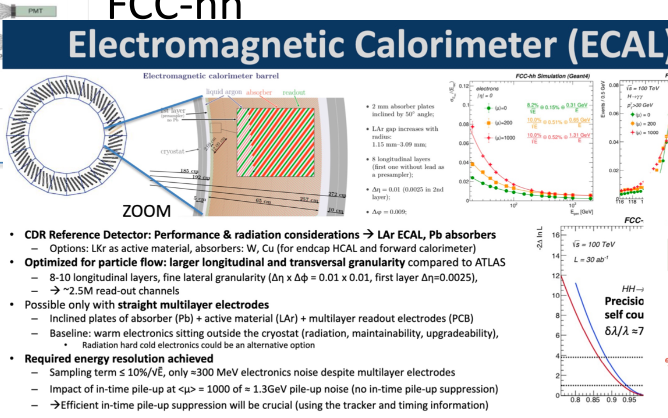
- Several technologies being considered

Technology	ECAL	HCAL
CLD / CALICE-like	W/Si W/scint + SiPM	Steel/scint + SiPM Steel/glass RPC
IDEA / Dual Readout	Brass (lead, iron) / parallel scint + PMMA (Č) fibres, SiPM	
Noble Liquid	Fine grained LAr (LKr) / Pb (W)	CALICE-like ?
Crystals	Finely segmented crystals (possibly DR)	Dual Readout fiber?

- Jet energy and angular resolutions via Particle Flow algorithm
  - Possibly augmented via Dual Readout
- Fine segmentation for PF algorithm and powerful γ/π^0 separation and measurement
- In particular for heavy flavour programme, superior ECAL resolution needed
  - $15\%/\sqrt{E} \rightarrow 8\%/\sqrt{E} \rightarrow 3\%/\sqrt{E}$
- Other concerns
  - Operational stability, cost, …
- Optimisation ongoing for all technologies
  - Choice of materials, segmentation, read-out, …

Example: $\tau \rightarrow \mu\gamma$ search

Mogens Dam / NBI Copenhagen ECFA Detector R&D Roadmap Input Session 19 Feb, 2021 18



FCC-hh

Electromagnetic Calorimeter (ECAL)

- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;

$\frac{8.2\%}{\sqrt{E}} \oplus 0.15\% \oplus \frac{0.31\ \text{GeV}}{E}$

$\frac{10.0\%}{\sqrt{E}} \oplus 0.51\% \oplus \frac{0.65\ \text{GeV}}{E}$

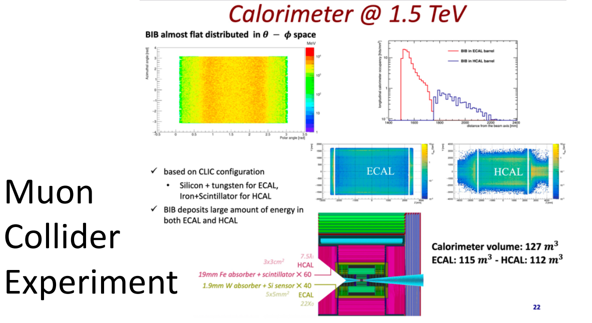
$\frac{10.0\%}{\sqrt{E}} \oplus 0.52\% \oplus \frac{1.31\ \text{GeV}}{E}$

$\frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = 1.32\% \pm 0.01\%$

$\frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = 1.9\% \pm 0.03\%$

$\frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = 2.29\% \pm 0.06\%$

- **CDR Reference Detector: Performance & radiation considerations → LAr ECAL, Pb absorbers**
  - Options: LKr as active material, absorbers: W, Cu (for endcap HCAL and forward calorimeter)
- **Optimized for particle flow: larger longitudinal and transversal granularity** compared to ATLAS
  - 8-10 longitudinal layers, fine lateral granularity ($\Delta\eta \times \Delta\phi = 0.01 \times 0.01$, first layer $\Delta\eta=0.0025$),
  - → ~2.5M read-out channels
- Possible only with **straight multilayer electrodes**
  - Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
  - Baseline: warm electronics sitting outside the cryostat (radiation, maintainability, upgradeability),
    - Radiation hard cold electronics could be an alternative option
- **Required energy resolution achieved**
  - Sampling term ≤ $10\%/\sqrt{E}$, only ≈300 MeV electronics noise despite multilayer electrodes
  - Impact of in-time pile-up at <μ> = 1000 of ≈ 1.3GeV pile-up noise (no in-time pile-up suppression)
  - →Efficient in-time pile-up suppression will be crucial (using the tracker and timing information)



Muon Collider Experiment

Calorimeter @ 1.5 TeV

BIB almost flat distributed in $\theta - \phi$ space

- ✓ based on CLIC configuration
  - Silicon + tungsten for ECAL, Iron+Scintillator for HCAL
- ✓ BIB deposits large amount of energy in both ECAL and HCAL

Calorimeter volume: 127 m^3
ECAL: 115 m^3 - HCAL: 112 m^3

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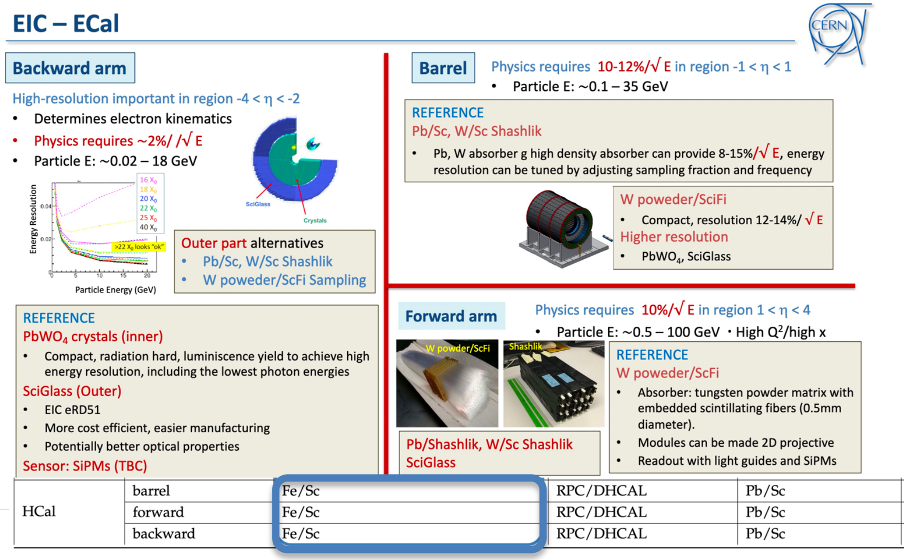


EIC – ECal

Backward arm

High-resolution important in region $-4 < \eta < -2$

- Determines electron kinematics
- Physics requires ~2%/ /√ E
- Particle E: ~0.02 – 18 GeV

Outer part alternatives
- Pb/Sc, W/Sc Shashlik
- W poweder/ScFi Sampling

REFERENCE
PbWO$_4$ crystals (inner)
- Compact, radiation hard, luminiscence yield to achieve high energy resolution, including the lowest photon energies

SciGlass (Outer)
- EIC eRD51
- More cost efficient, easier manufacturing
- Potentially better optical properties

Sensor: SiPMs (TBC)

Barrel Physics requires 10-12%/√ E in region $-1 < \eta < 1$
- Particle E: ~0.1 – 35 GeV

REFERENCE
Pb/Sc, W/Sc Shashlik
- Pb, W absorber g high density absorber can provide 8-15%/√ E, energy resolution can be tuned by adjusting sampling fraction and frequency

W poweder/SciFi
- Compact, resolution 12-14%/ √ E

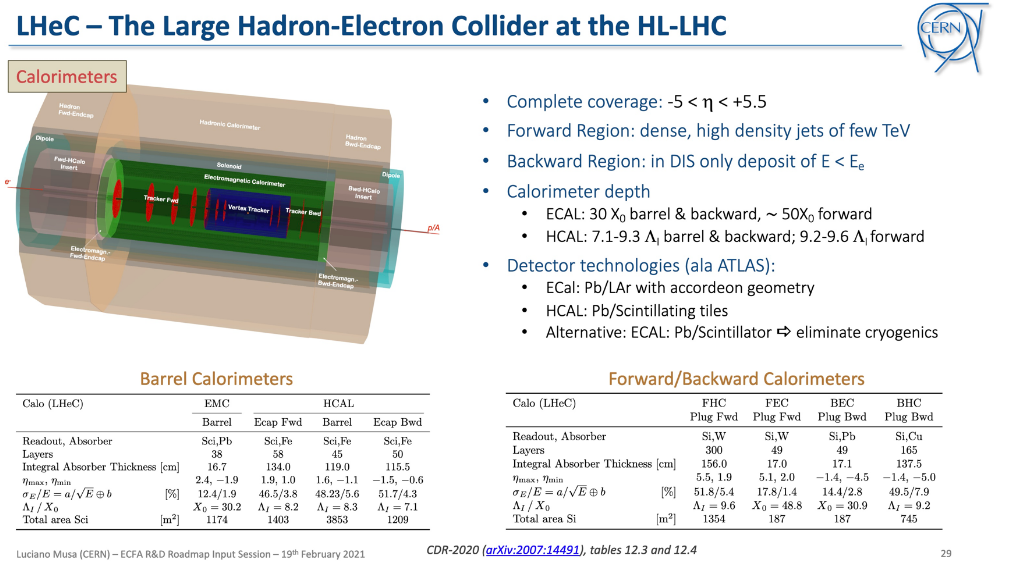
Higher resolution
- PbWO$_4$, SciGlass

Forward arm Physics requires 10%/√ E in region $1 < \eta < 4$
- Particle E: ~0.5 – 100 GeV • High Q^2/high x

Pb/Shashlik, W/Sc Shashlik
SciGlass

REFERENCE
W poweder/ScFi
- Absorber: tungsten powder matrix with embedded scintillating fibers (0.5mm diameter).
- Modules can be made 2D projective
- Readout with light guides and SiPMs

HCal	barrel	Fe/Sc	RPC/DHCAL	Pb/Sc
	forward	Fe/Sc	RPC/DHCAL	Pb/Sc
	backward	Fe/Sc	RPC/DHCAL	Pb/Sc



LHeC – The Large Hadron-Electron Collider at the HL-LHC

Calorimeters

- Complete coverage: $-5 < \eta < +5.5$
- Forward Region: dense, high density jets of few TeV
- Backward Region: in DIS only deposit of E < E$_e$
- Calorimeter depth
  - ECAL: 30 X$_0$ barrel & backward, ~ 50X$_0$ forward
  - HCAL: 7.1-9.3 Λ$_I$ barrel & backward; 9.2-9.6 Λ$_I$ forward
- Detector technologies (ala ATLAS):
  - ECAL: Pb/LAr with accordeon geometry
  - HCAL: Pb/Scintillating tiles
  - Alternative: ECAL: Pb/Scintillator ⇨ eliminate cryogenics

Barrel Calorimeters

Calo (LHeC)	EMC	HCAL		
	Barrel	Ecap Fwd	Barrel	Ecap Bwd
Readout, Absorber	Sci,Pb	Sci,Fe	Sci,Fe	Sci,Fe
Layers	38	58	45	50
Integral Absorber Thickness [cm]	16.7	134.0	119.0	115.5
$\eta_{\max}, \eta_{\min}$	2.4, −1.9	1.9, 1.0	1.6, −1.1	−1.5, −0.6
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	12.4/1.9	46.5/3.8	48.23/5.6	51.7/4.3
Λ_I / X_0	$X_0 = 30.2$	$\Lambda_I = 8.2$	$\Lambda_I = 8.3$	$\Lambda_I = 7.1$
Total area Sci [m^2]	1174	1403	3853	1209

Forward/Backward Calorimeters

Calo (LHeC)	FHC Plug Fwd	FEC Plug Fwd	BEC Plug Bwd	BHC Plug Bwd
Readout, Absorber	Si,W	Si,W	Si,Pb	Si,Cu
Layers	300	49	49	165
Integral Absorber Thickness [cm]	156.0	17.0	17.1	137.5
$\eta_{\max}, \eta_{\min}$	5.5, 1.9	5.1, 2.0	−1.4, −4.5	−1.4, −5.0
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	51.8/5.4	17.8/1.4	14.4/2.8	49.5/7.9
Λ_I / X_0	$\Lambda_I = 9.6$	$X_0 = 48.8$	$X_0 = 30.9$	$\Lambda_I = 9.2$
Total area Si [m^2]	1354	187	187	745

Luciano Musa (CERN) – ECFA R&D Roadmap Input Session – 19th February 2021

CDR-2020 (arXiv:2007:14491), tables 12.3 and 12.4

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Input Sessions – Calorimeter Summary

- **During the input session future accelerator projects were introduced, the below calorimeter types were mentioned as possible candidates (non-exhaustive):**

- **Scintillator/Crystal/Fibre based**
  - CMS HGCal: scintillator/steel
  - LHCb Upgrade II ECAL: Shashlik or fibre SpaCal,
  - ALICE 3 ECAL: scintillator crystal, scintillator glass
  - Linear collider experiments HCAL and ECAL: scintillator + SiPMs
  - EIC ECAL: $PbWO_4$, scintillator/glass + SiPMs,
  - Muon Collider Experiment HCAL
  - LHeC HCAL
  - FCC-hh HCAL: scintillator/steel
  - FCC-ee ECAL & HCAL
  - FCC-ee: dual read-out calorimeter

- **Si Based**
  - CMS HGCal: Si/W
  - Linear Collider Experiments ECAL: Si/W
  - Muon Collider Experiment ECAL: Si/W
  - FCC-ee ECAL: Si/W
  - FCC-hh DECAL: Si/W
- **Noble-Liquid Based**
  - FCC-hh ECAL
  - FCC-ee ECAL
  - LHeC ECAL
- **Gas Detector Based** (RPC) – see gas detector session
  - Linear collider experiments HCAL

Engineering Challenges and Ongoing R&D

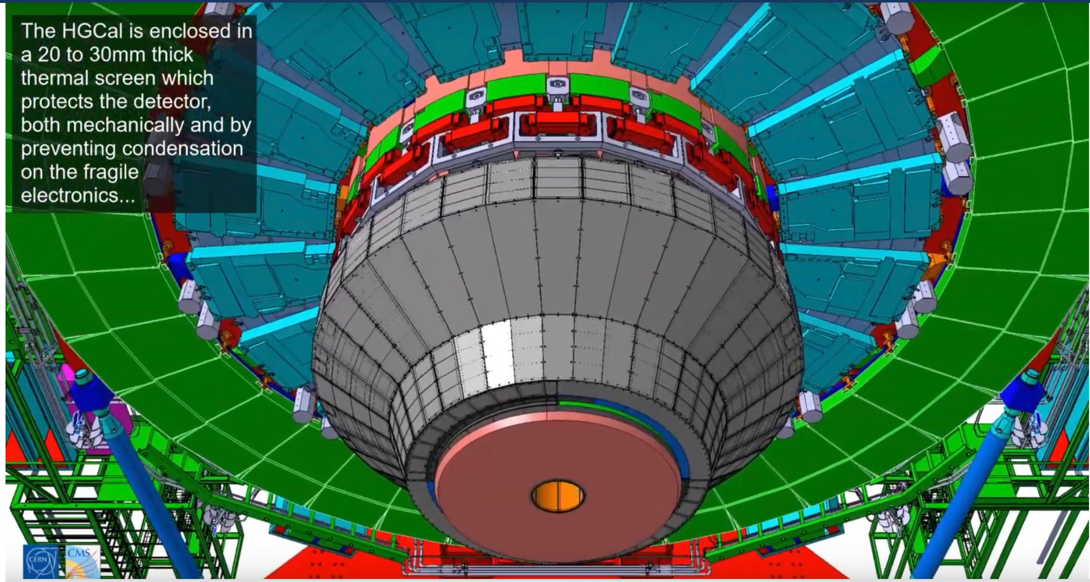
Challenges for Si/W and Scintillator/Fe Calos (HGCal, CALICE)

- **Active components** of this type of calorimeters (Si sensors and also the SiPMs to read out scintillators) need to be operated at *low temperatures* for those applications in a **significant radiation environment**
  - e.g. -35 degrees for CMS
- **Thermal enclosures, heat shields, thermal screen:**
  - Strength, radiation resistance, thermal capacity
  - Thermal shield in pieces as the shape to cover is large and complex.
  - *Avoid condensation* on the surface (large temperature gradient of 55^{o}C through thin thermal screen)
  - Need to be thin to maximize the room taken by sensitive components (not to cut into fiducial volume) → *standard insulation thicknesses take too much space*, so *heating foils* on the outside surface are needed to compensate for the lack of extra insulation and guarantee temperatures above due point → *additional power for heaters*, additional power for the cooling as well
  - → R&D on building light thermal screens based on vacuum insulation technology (a bit like a cryostat) to make them almost passive elements
- **Feedthroughs:**
  - PCBs embedded in metallic structures (e.g. CMS pre-shower, HGCal, …)
  - Huge space constraints!
- **Dry gas:**
  - Difficult to *ensure good flow* around the very compact insides of a calorimeter.
  - *Engineering solution for HGCal:* thin pipes into each cassette to carry dry gas to the heart of the system.

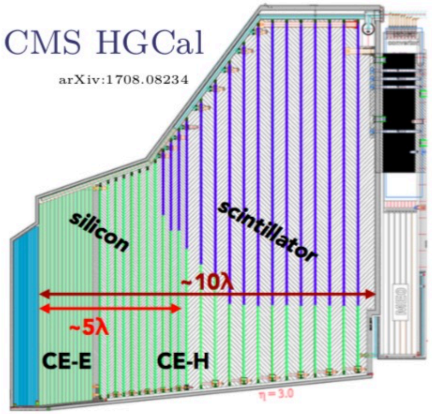
Further literature:
HGCal TDR: https://cds.cern.ch/record/2293646?ln=en
ILD IDR: https://arxiv.org/abs/2003.01116

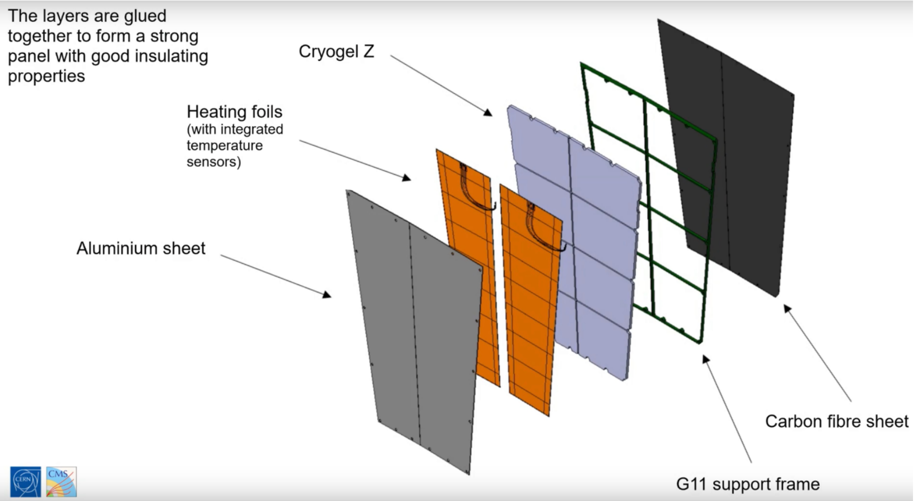
Example: CMS HGCal Thermal Screen

- 120+ thermal screen panels per endcap
- 55°C temperature difference across panels
- High radiation dose: up to 200Mrad
- 10kW of power delivered to heating foils to keep outer surface at 20°C
- Internally pressurized to prevent moisture ingress
- 2500+ cables passing through the thermal screen at the feedthroughs



The HGCal is enclosed in a 20 to 30mm thick thermal screen which protects the detector, both mechanically and by preventing condensation on the fragile electronics...





The layers are glued together to form a strong panel with good insulating properties

To route services out of the cold volume, feedthroughs will be integrated into the back thermal screen panels

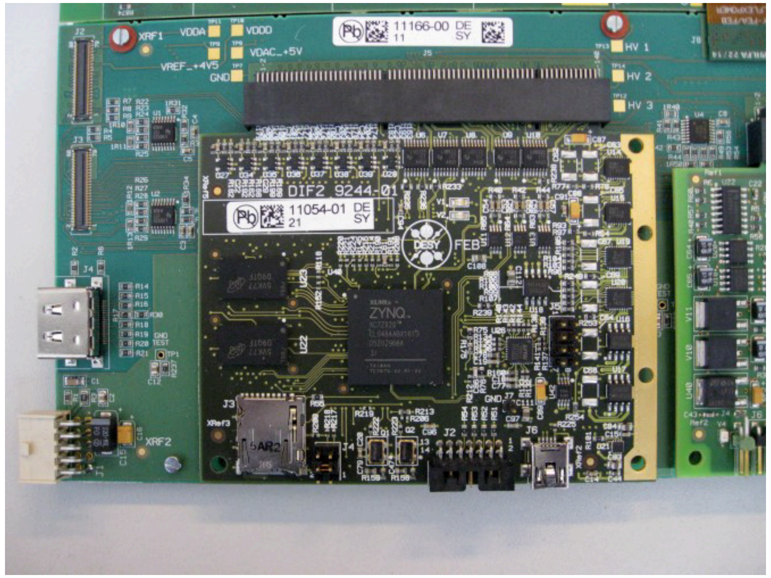
Challenges for Si/W and Scintillator/Fe Calos (HGCal, CALICE)

- **Cooling:** (see talks this morning by B. Verlaat, M. Vos and P. Petagna)
  - *HGCal: CO_2 cooling:* Cooling plant requires a lot of space (→ development of more compact systems would be better), and the lowest temperature to be reached is about -40.
  - *Like for trackers:* high-granularity Si-based calorimeters for future hadron colliders will need to go colder (if silicon remains viable)
- **Electro-mechanical integration**
  - Minimize un-instrumented regions
  - Getting *power and clock in*
  - Getting *heat out*
    - pulsing or active cooling
  - Getting data out
  - *Manufacturability and achievable tolerances* enter as much as the *potential for miniaturisation* of the *electronics* or cost considerations for sensors.
  - Compactness is a particular challenge for the ECAL even more in the barrel where everything has to fit into the solenoid.
  - *Grounding and shielding scheme:* avoiding ground loops leading to noise that removes the possibility of calibrating on single mips

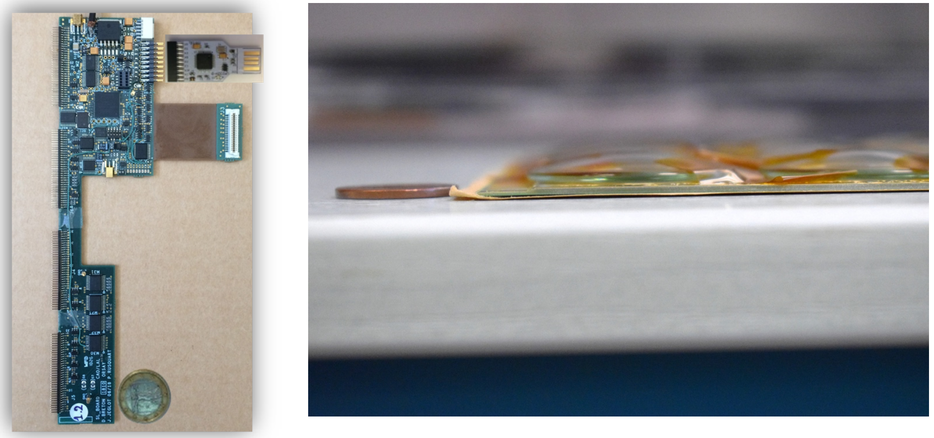
Further literature:
HGCal TDR: https://cds.cern.ch/record/2293646?ln=en
ILD IDR: https://arxiv.org/abs/2003.01116

Example: CALICE – Miniaturisation of Components

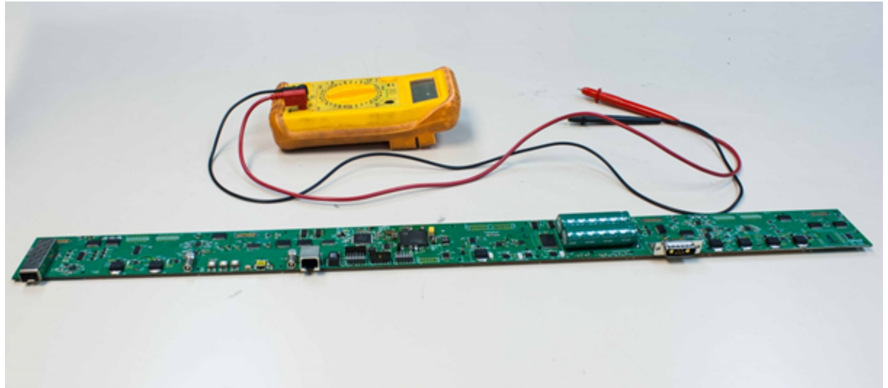
Current detector interface card - AHCAL



Current detector interface card and thin detection unit – SiW Ecal



Current detector interface card - SDHCAL



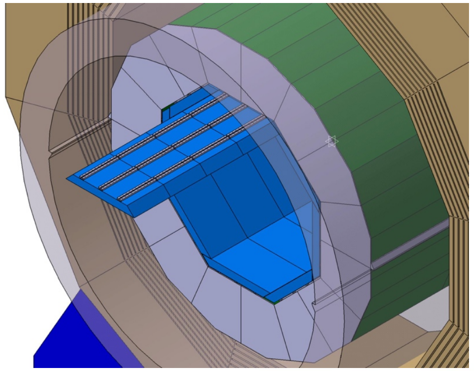
Cooling:

- Total average power consumption 20 kW for a calorimeter system with10^8 cells*
  - Only possible through power pulsing
- The art is to store the power very locally
- Issue for upcoming R&D
- Main challenge is to avoid that hubs and concentrator cards will become local hotspots (expect consumption < 5 W)

* Compare with 2x140 kW for CMS HGCAL 6×10^6 cells

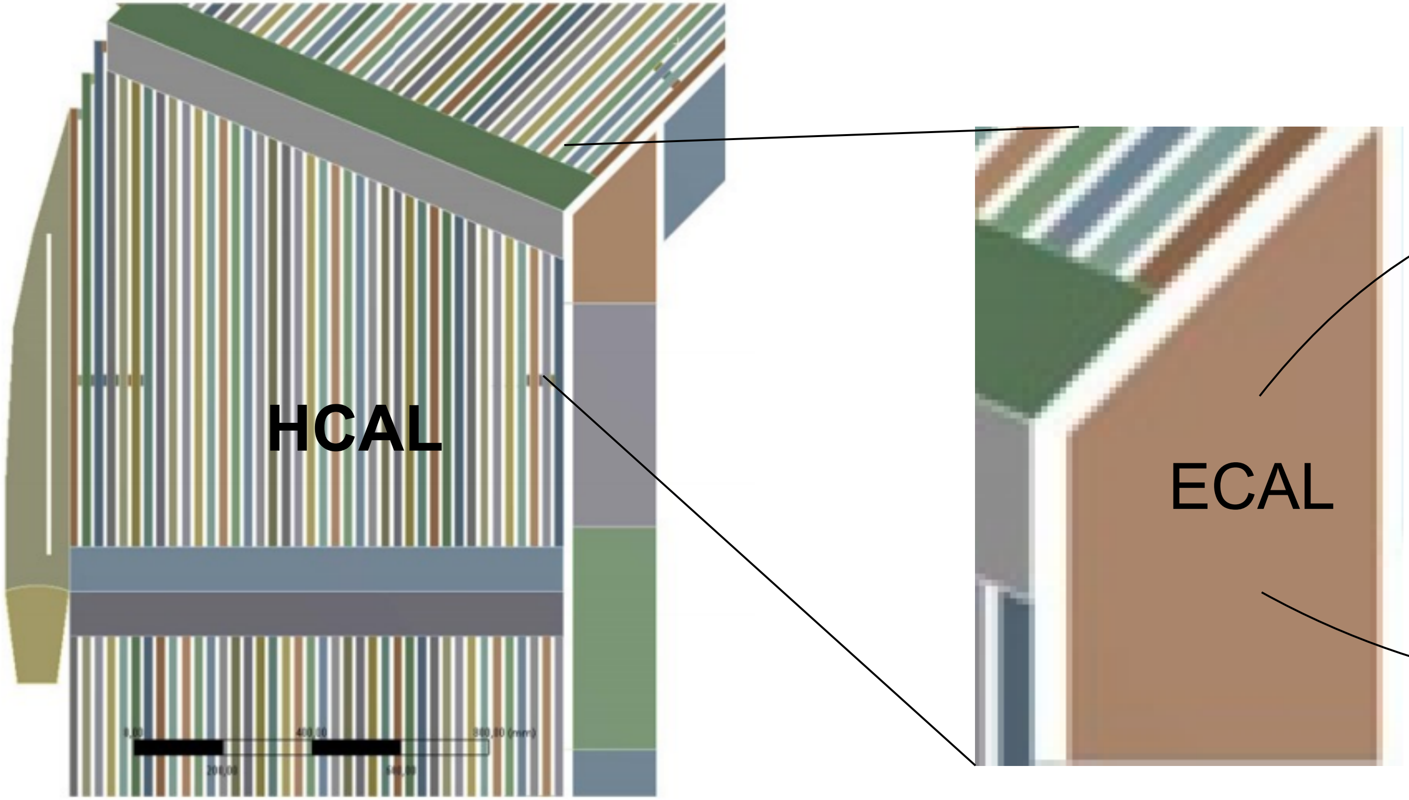
- “Dead space free” granular calorimeters put tight demands on compactness
- Current developments within CALICE meet these requirements
- Can be applied/adapted wherever compactness is mandatory
- Components will/did already go through scrutiny phase in beam tests

Example: CALICE – Integration Issues



- Successful application of PFA requires calorimeters to be inside the magnetic coil

=> Tight lateral and longitudinal space constraints



40-70mm
for services,
readout,
cooling and
power

~200mm for up to 30 layers
with 10-20 kcells each

Challenges for Scintillator-Based Calorimeters

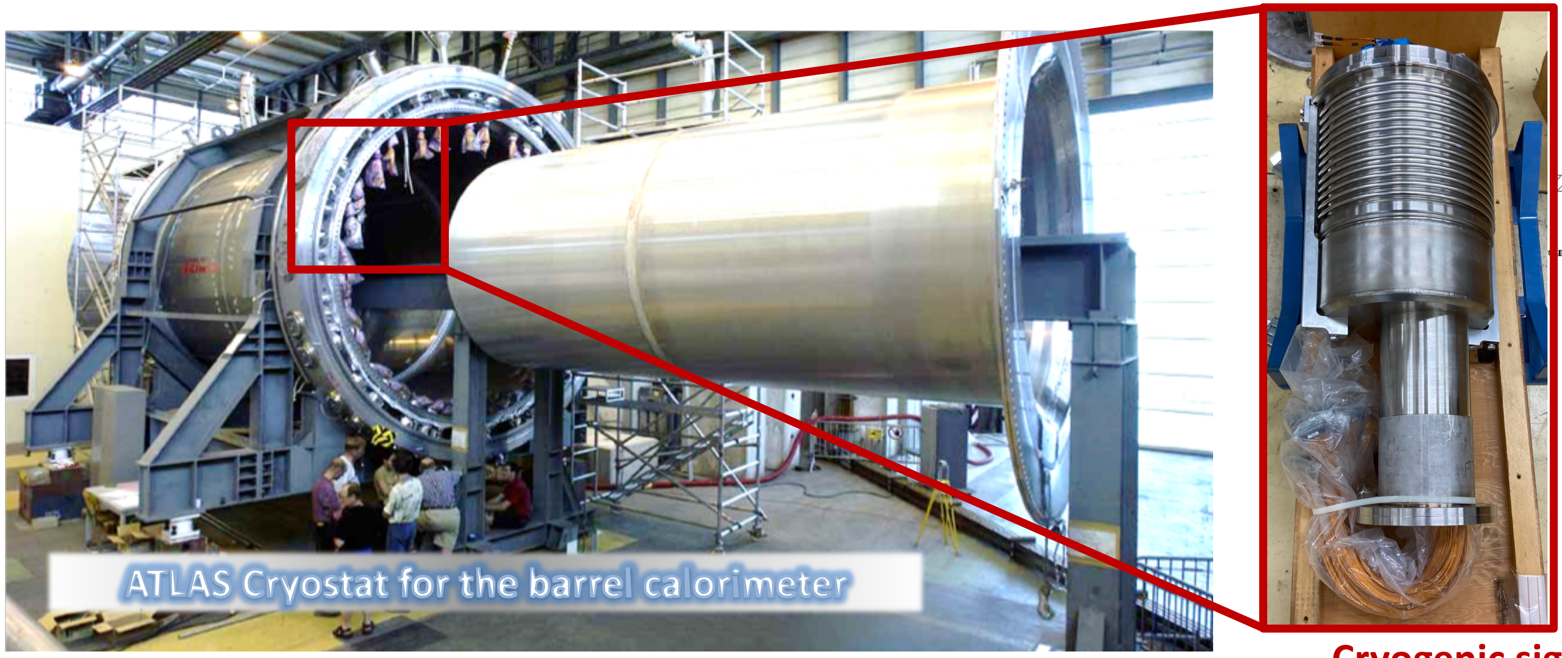
- **Temperature stability and monitoring**
  - As light *yield* of scintillating crystals can *vary with temperature* and also the *gain of photodetector* is temperature dependent (case of APDs or SiPMs) it is important to have a well *controlled stabilised temperature* and to be sure that the heat dissipated by electronics is removed. E.g. in CMS ECAL stability at ±0.05°C working at 18°C.
- **Cooling of Photodetectors**
  - Cooling advantageous for *noise behaviour of photodetectors* in particular silicon photodetectors in *presence of high radiation* (noise also increases with irradiation)
    - For Instance in CMS ECAL for HL-LHC the operating temperature will be reduced from 18°C to 9°C to mitigate the increase of dark current in the APDs.
    - In case of barrel timing layer of CMS where SiPM will be used, the temperature will be around -35°C. Similarly for the SiPM in the back of the HGCAL
  - → Thermal enclosures, dry air / N_2 system to avoid condensation
- **Mechanics of fibre dual-readout calorimeters:**
  - Challenging *stability, reproducibility and uniformity*
- **Monitoring of light yield and transmission of scintillators** → Calibration systems

Challenges for Noble-Liquid Based Calorimeters

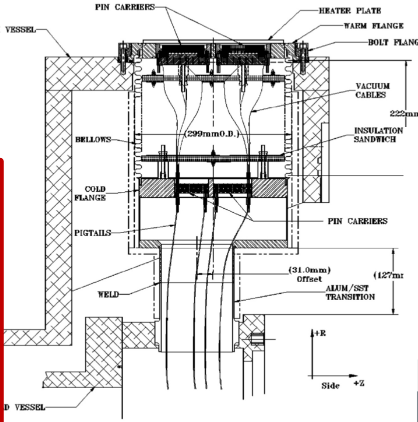
- **Engineering Challenges:**
  - *Large cryostats, low material budget* → aluminum (ATLAS), Al honeycomb structures, carbon fibre (see presentations earlier today by C. Gargiulo and H. Ten Kate)
  - *Heavy calorimeters* (100s of tons) need to be *supported by cryostat*
- **Cryogenic feedthroughs:**
  - The *large granularity* of future calorimeters will require an *increased signal density* at the feedthroughs (FT) of up to 20-50 signals/cm^2 which is a factor ~5-10 more than in ATLAS (ATLAS used gold pin carriers sealed in glass).
    - Novel technologies have to be developed in collaboration with industry (e.g. CERN cyo lab R&D).
- **Large size cryogenic systems:** purity of the noble liquid O(0.2ppm), less stringent requirement than for neutrino- or dark matter detectors
- **Large-size read-out electrodes** O(1m x 3m), might be realised in several smaller pieces
    - PCBs or copper/kapton/glue with resistors made of resistive ink (ATLAS)).
    - Optimisation of capacitance to ground (noise) while keeping cross-talk at a reasonable level O(1%).
- **Preamplification and optical transmission of signals:**
  - *Warm electronics:* no active elements inside the cryostat (upgradeability!), very small signals, long transmission lines → Noise!
  - *Cold electronics:* active elements inside the cryostat, potentially lower noise
    - Cryogenic feedthroughs for optical fibres – one fibre carries signal of many channels → advantage for cryogenic feedthroughs
    - Cold electronics heat dissipation inside the noble-liquid bath → needs to be taken into account for the cooling of the noble liquid

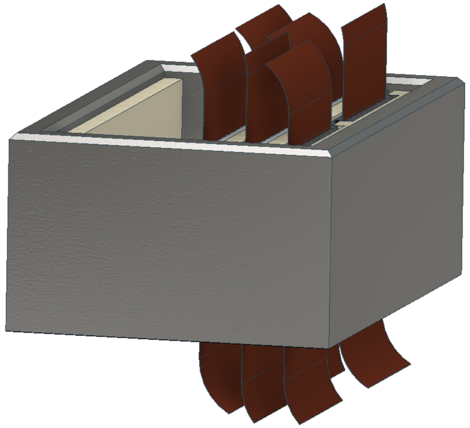
Example: Cryogenic High-Density Signal Feedthroughs

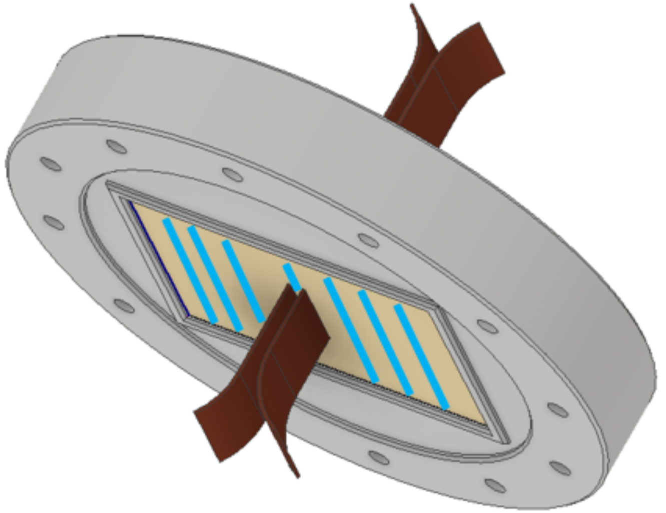
Goal: 10 times more signal wires than ATLAS feedthroughs (density x5 area x2) → 20 to 50 wires/cm^2



Cryogenic signal feedthrough







- Future calorimeter: higher granularity → higher number of read-out channels → high-density signal feedthroughs

Development of high-density flanges:

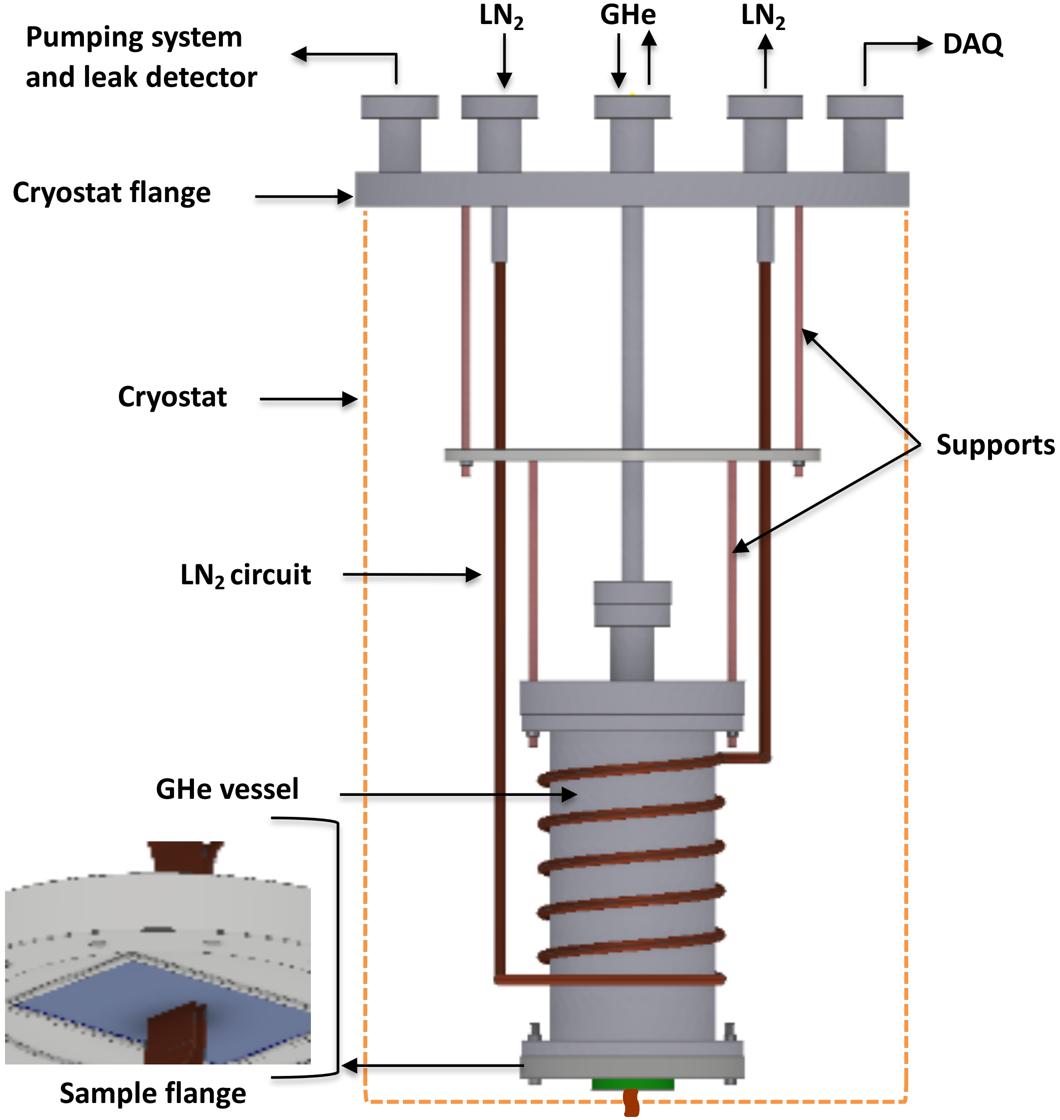
- 3D printed epoxy pieces / fiberglass pieces (G10) and epoxy glues → avoiding connectors

Curtesy: Presentation by M.B. Higueras at 4th FCC Physics and Experiments WS

Example: Cryogenic High-Density Signal Feedthroughs

Experimental setup (CERN cryo lab)

- Leak and pressure tests at room (300 K) and low temperature (77 K)
- Tests flanges with 4 different 3D-printed or fiberglass materials (Accura25, Accura48, MY750 and G10) have been designed, fabricated in collaboration with the Polymer Laboratory at CERN, and thermally shocked in liquid nitrogen.

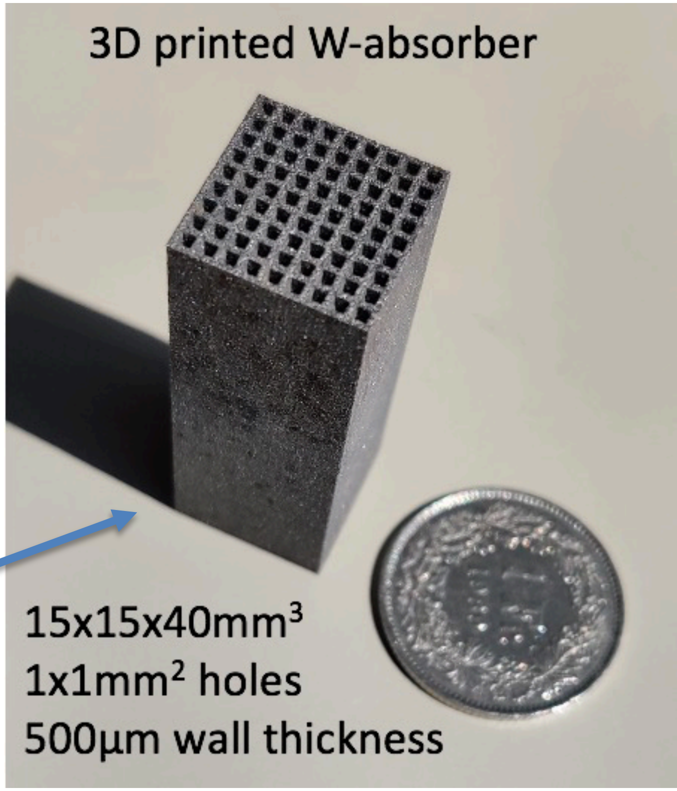


Curtesy: Presentation by M.B. Higueras at 4th FCC Physics and Experiments WS

Challenges for Integration and Mechanics

- **Integration:** Fitting everything in without loosing fiducial volume!
  - Calorimeters often inside the solenoid coil → every centimetre in radius counts → *compactness*!
  - Very little space for cooling, services, electronics, low-profile connectors
- **Absorbers** (mainly covered in talks in TF6 symposium):
  - Utmost *precision of absorbers* is the ingredient for a *small constant term and high uniformity* → direct impact on energy measurement
    - Machining of absorber materials, R&D on better machinable alloys (W alloys) → see symposium of TF6 (Calorimetry)
    - Flatness is a challenge (e.g. HGCal needs 0.5mm for 5.3m stainless steel disks)
    - Constant thickness of absorbers difficult to achieve (e.g. ATLAS LAr achieved 0.31% (5µm) rms in lead-thichness → 0.2% contribution to constant term)
  - Absorber structures *cannot be built in house* in a little workshop or lab, therefore, during the design phase, time needs to be spent exploring the current technology available in the outside industry → close collaboration with industry to reach a good compromise between quality, cost and manufacturing time.
  - *R&D on absorber materials for better machinability* (e.g. LHCb Upgrade II, 3D printing of W under study)
  - *Specs for the raw material:* e.g. CMS needs very low permeability steel to avoid magnetic-induced forces of hundreds of tonnes

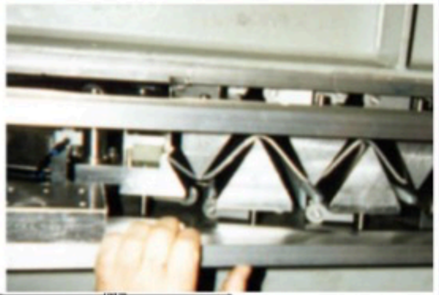
3D printed W-absorber

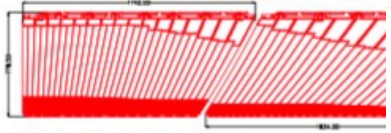


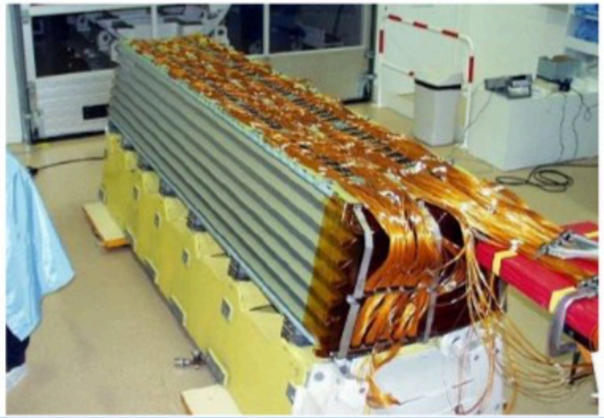
15x15x40mm^3
1x1mm^2 holes
500µm wall thickness

Example: ATLAS LAr Calorimeter

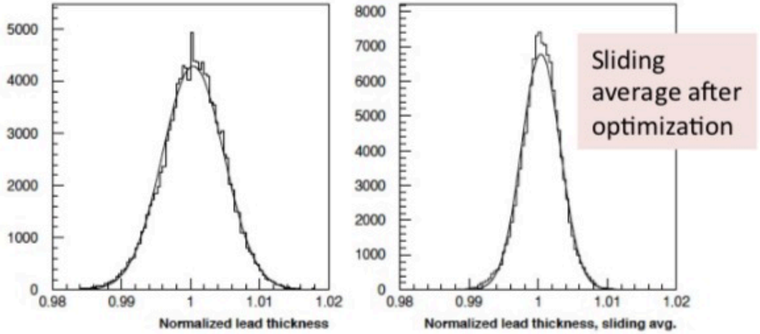
- **High precision requirements** (constant term!) – accordion geometry challenging
- **Absorbers** (lead + glue + stainless steel)
  - Lead thickness precisely monitored at rolling factory
  - after gluing: accordion shape: bent, then cured in heating press (rotating jaws for endcap!)
- **Electrodes** (4 types, ≈ 2m x 1m)
  - 3 layers (2 ext. HV, int. for signal collection) with patterns etched: cells, electrical paths
  - Substrate (kapton) flexible and same thermal expansion Cu
  - HV resistors applied on surface (R-ink)
  - Bending, testing
- Fiberglass-epoxy (G10) **precision bars** holding absorbers with precisely engineered thermal contraction (5µm precision)
- Spacers (honeycomb)
- **Stacking** of gaps
  - Monitoring of bulging, measure capacitances and test HV.
- **Cabling** of modules
- **Cold tests** (check cabling, HV, LAr purity), **wheel assembly**, **integr. into cryostats**,...







- **Lead thickness and absorber thickness was precisely measured during construction**
  - Since 1 cell is the sum of 4 electrodes between 4 absorbers **optimizing the arrangement** of consecutive **absorbers** can minimize impact on phi-uniformity
- The effect of optimizing the arrangement of consecutive absorbers can be seen in the **reduction of the rms** of the sliding average from **0.44% to 0.31%**
  - No systematic trends in phi
  - Residual contribution to **constant term is 0.19%**.
- The absorber thickness has an impact because thicker absorbers would reduce the LAr gap: Additional contribution to the **constant term of 0.07%**.



https://indico.cern.ch/event/186337/contributions/1457895/attachments/258183/360740/VCI-ATLAS-EM-Calorimeter.pdf

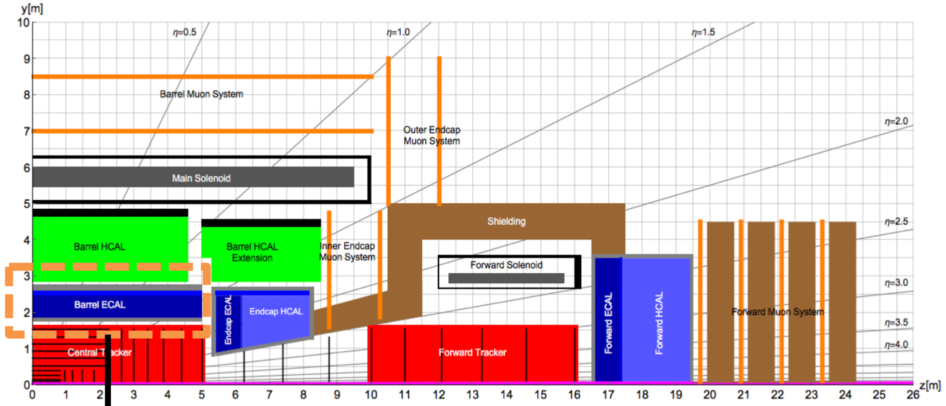
Challenges for Integration and Mechanics

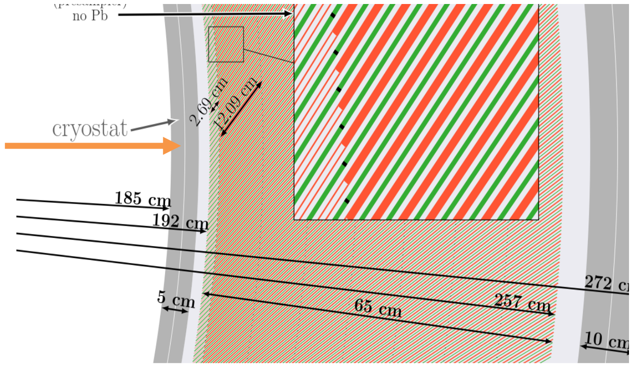
- **Mechanical Challenge:**
  - Calorimeters are *heavy objects* (100s of tons).
  - *High-precision large-scale structures* capable of supporting such masses:
    - Little space
    - Small budget in radiation lengths or interaction lengths
    - Support structures and services routing ideally should create no cracks in phi, no gaps in theta (eta)
  - → Carpenter-like (roof-top) scales and cabinet-maker type tolerances
  - *Gluing connections:*
    - Very common in trackers, getting more important for calorimeters, need to avoid delamination despite heavy thermal cycling
    - Design, glue materials, radiation hardness, gluing technology, QA/QC.
- **Upgradeability:**
  - Lifetime of future accelerator experiments might span several decades (see LHC experiments)
  - Adaptation to *changing environment of experiment* (e.g. instantaneous luminosity increase, pile-up increase)
  - *Modular construction and accessibility*

Example: R&D on Low-Mass Cryostats

Goal: decrease thickness and material budget of the next generation of cryostats for HEP → using Carbon Fibre Reinforced Plastic or Al honeycomb structures (see talk by C. Gargiulo)

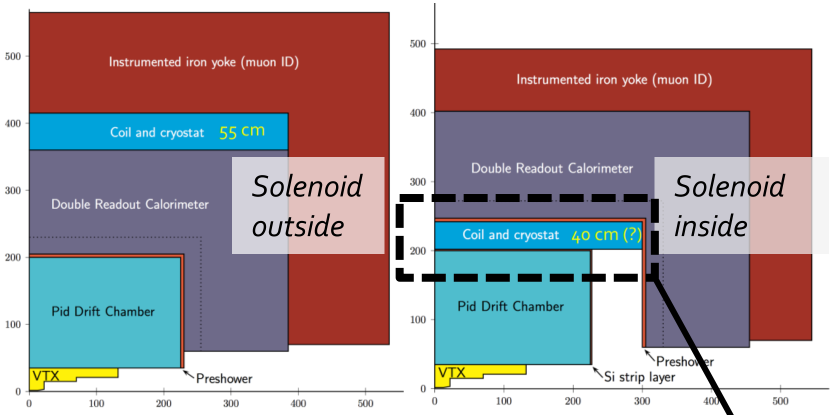
Baseline geometry, **FCC-hh** LAr barrel ECAL :
Cryostat calorimeter (double vessel)

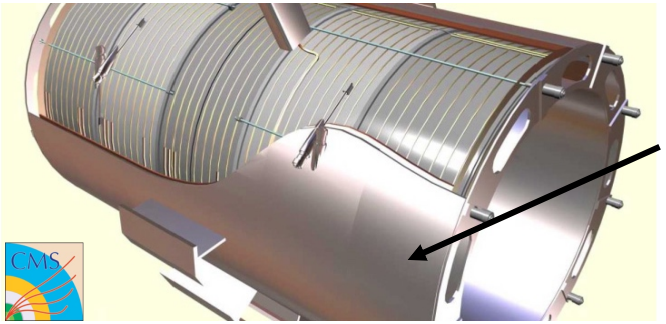




minimum material

Baseline geometry, **FCC-ee** :
Cryostat magnet



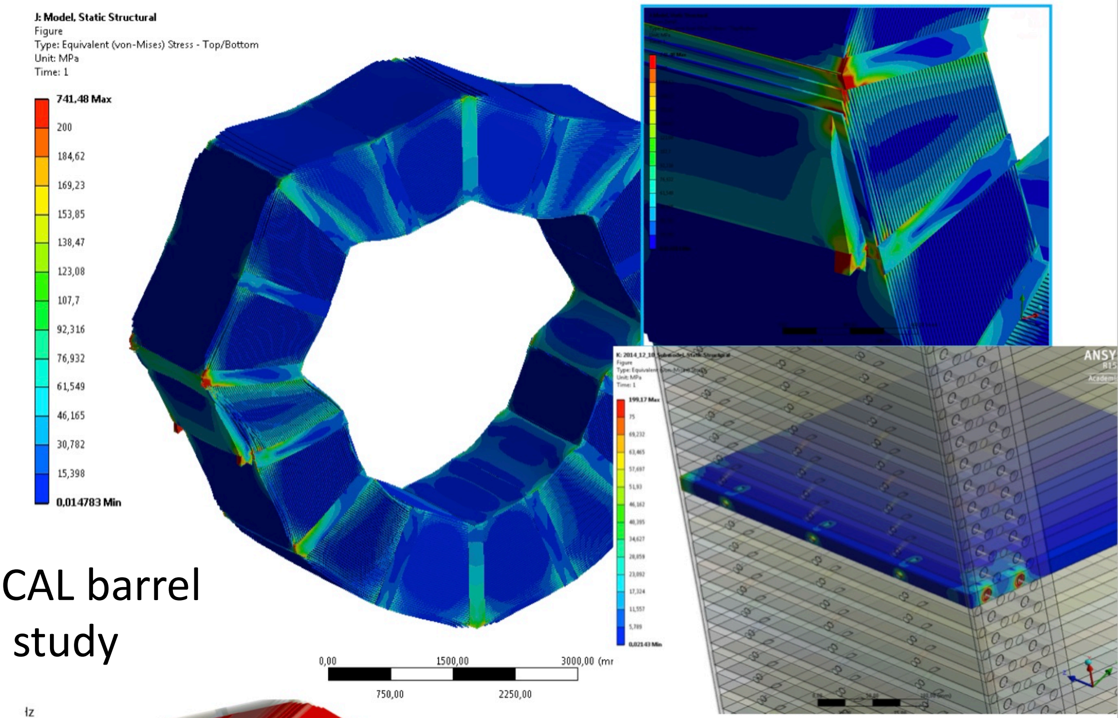


minimum material / buckling resistance

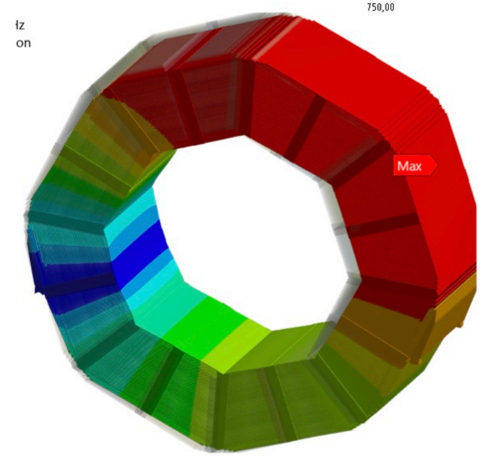
Curtesy: Presentation by M.B. Higueras and M.S. Molina at 4th FCC Physics and Experiments WS

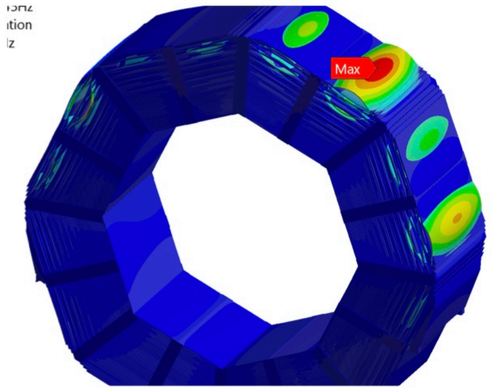
Example: CALICE ECAL & HCAL – FEA Studies

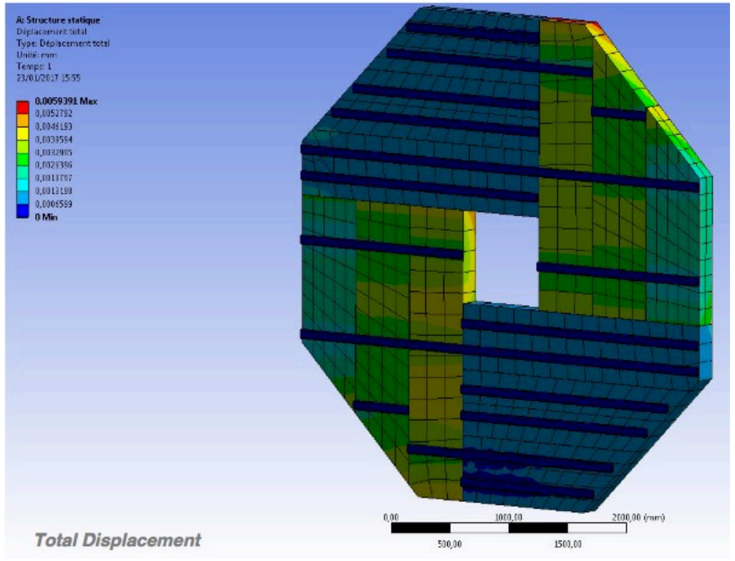
- **HCAL structures for particle flow:**
  - Carpenter-like (roof-top) scales and cabinet-maker type tolerances.
  - → Challenge for FEA calculations
  - Large but fine-spaced mesh needed to model the impact of macroscopic excitations on individual joints → less standard than one may think, and the DESY central mechanical engineering team had several interactions with the ANSYS developers - and access to powerful computing resources
  - Mixed team of engineers and physicists on analysing the earthquake stability
- **Validation of static stability done**
- Dynamic simulation of **earthquake scenarios** being done
- Worst case w.r.t. smaller or coarser structure



ILD HCAL barrel static study





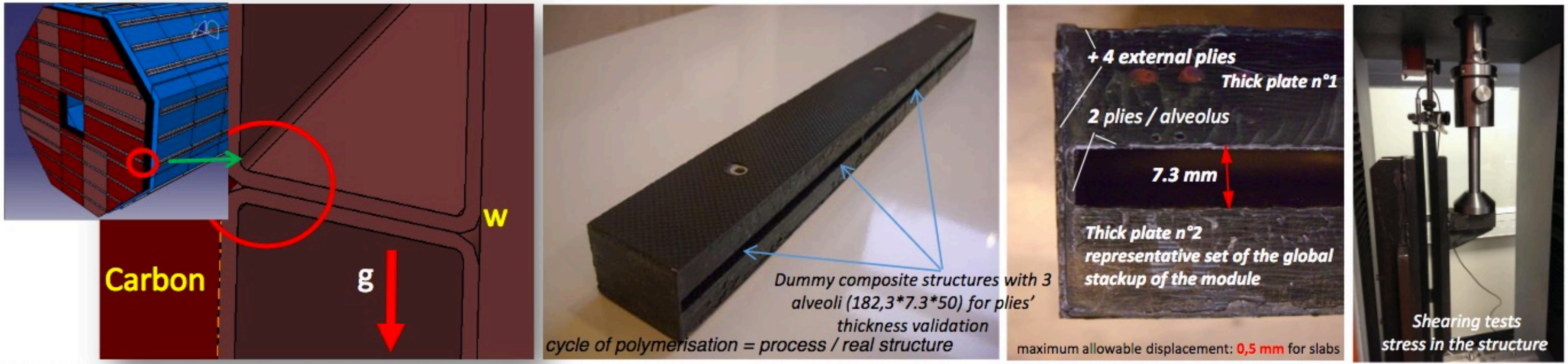


ILD ECAL endcap static study

Example: CALICE ECAL Endcaps – Mechanical Stability

Shearing tests of composite structure

Goal: Adapt FEA parameters to simulate the whole structure



*Dummy composite structures with 3 alveoli (182,3*7.3*50) for plies' thickness validation*

cycle of polymerisation = process / real structure

maximum allowable displacement: 0,5 mm for slabs

Shearing tests stress in the structure

Charge & discharge cycles: hysteresis in specimens' behaviour which evolves towards a progressive decrease in the force / displacement with the gradual breakdown of the resin before destruction of the composite

- Correlation of tests with FEA simulations
- Optimization of composite wrapping / long structure
- Shearing tests on demonstrators
- Ensure repeatability of process & characteristics

https://agenda.linearcollider.org/event/9076/contributions/47680/attachments/36528/57052/ECAL_EC-Cooling-2021-03-24.pdf

R&D Needs

Thoughts on R&D Needs

- Very difficult to distinguish between **engineering needs and R&D needs**!
- Many of the mentioned challenges can be solved by **dedicated engineering effort, some will need additional R&D**
- In most cases **HEP** will be able to profit from **progress in industry**
  - **Exceptions** are often linked to **one or a combination** of the following **challenges**:
    - radiation hardness, cryogenic temperatures, extremely tight space requirements, low dead material requirement and the combination of high precision and large-heavy structures
  - Many **engineering challenges** can be met by having sufficient funding for **outsourcing to industry experts**
- There are **generic R&D opportunities**, however, some of the **R&D needs** are **closely linked to the specific design**
- **Biggest calorimeter project** under construction: **CMS HGCal** → learning a lot from this experience

Thoughts on R&D Needs

- As discussed, some topics mentioned in this talk will **profit from current calorimeter projects** and/or **profit from fast progress in industry**
- Some topics, however, are **more specific to HEP**, and will probably not progress enough without strong participation by the HEP community. They will need to be **further developed by the HEP community** in strong collaboration with industry
  - **Low-mass cryostats** (Carbon fibre, Al honeycomb structures)
    - Mechanical strength (support of several 100s of tons), precision
    - Junctions between stainless steel / Aluminum / carbon fibre / epoxy
  - **High-precision large-scale support structures** capable of supporting large calorimeter masses (carbon fibre structures)
  - **Cryogenic high-density signal feedthroughs**
  - **Light thermal screens based on vacuum insulation technology** (a bit like a cryostat) to make them almost passive elements
  - **Radiation hard materials for calorimeters**
    - Hadron colliders with extreme radiation environment (1 MeV neutron eq. fluence up to $10^{16}/cm^2$, TID 1MGy)
    - Electrodes, spacers, mechanical structures, isolators,…
  - **Radiation hard reliable gluing connections**
    - 1 MeV neutron eq. fluence up to $10^{16}/cm^2$, TID 1MGy
  - **Cooling systems** for temperatures below -40^{o}C

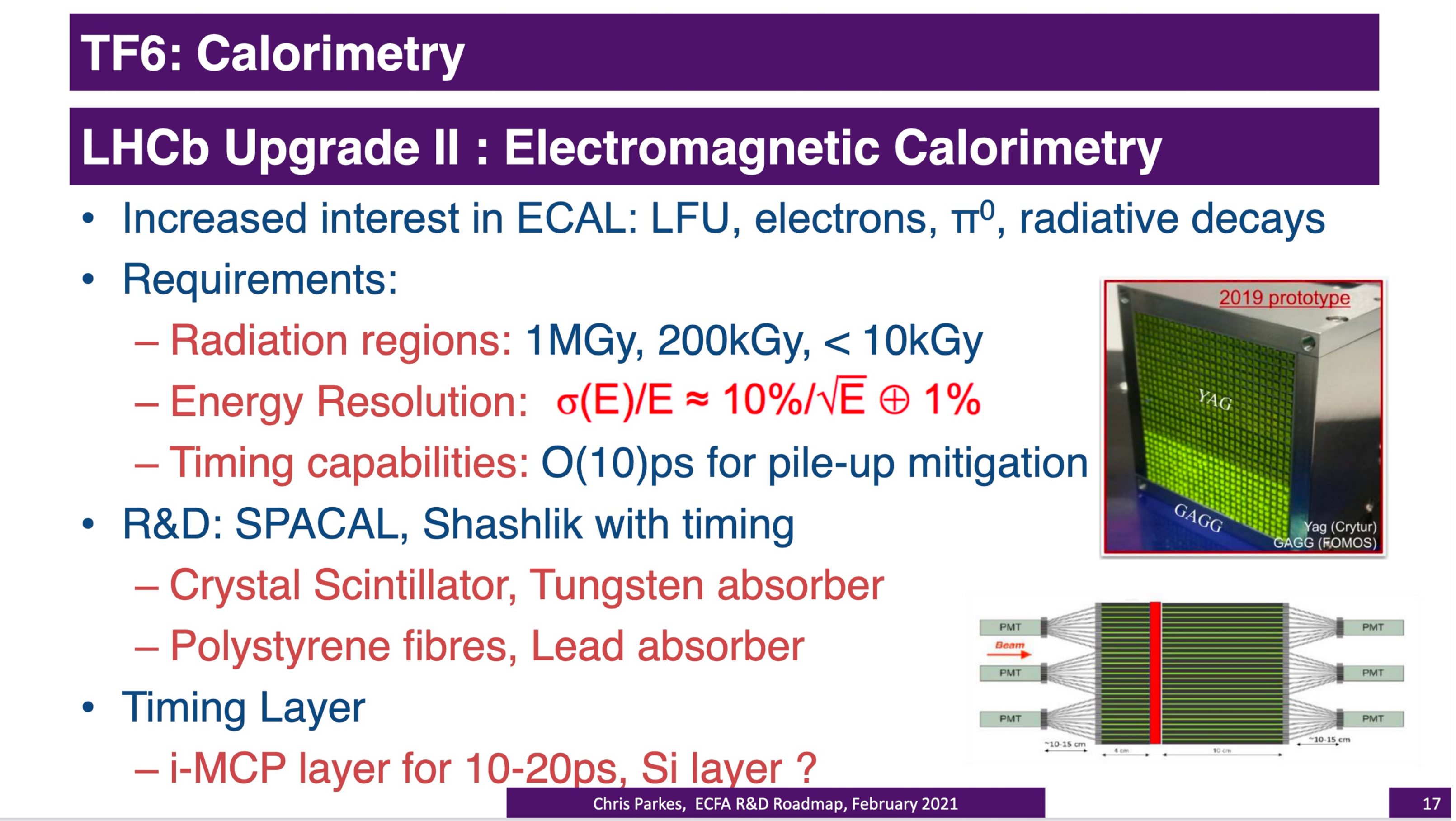
Conclusions

- Broad overview of engineering challenges of different types of calorimeters
- Needs of generic R&D identified, in some cases R&D needs closely linked to the specific design and the chosen implementation in an experiment
- HEP will profit from fast progress in industry, however, some areas are more specific to HEP, and will probably not progress enough without strong participation by the HEP community
- Calorimeters need – more than other detectors – a strong collaboration of engineers and physicists, often relying on large labs with necessary infrastructure:
  - We must make sure that these labs and infrastructures are maintained and supported by our funding agencies

Thank You for Your Attention!

Backup

LHCb Upgrade II and ALICE 3



TF6: Calorimetry

LHCb Upgrade II : Electromagnetic Calorimetry

- Increased interest in ECAL: LFU, electrons, π^0, radiative decays
- Requirements:
  - – Radiation regions: 1MGy, 200kGy, < 10kGy
  - – Energy Resolution: $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
  - – Timing capabilities: O(10)ps for pile-up mitigation
- R&D: SPACAL, Shashlik with timing
  - – Crystal Scintillator, Tungsten absorber
  - – Polystyrene fibres, Lead absorber
- Timing Layer
  - – i-MCP layer for 10-20ps, Si layer ?

Chris Parkes, ECFA R&D Roadmap, February 2021

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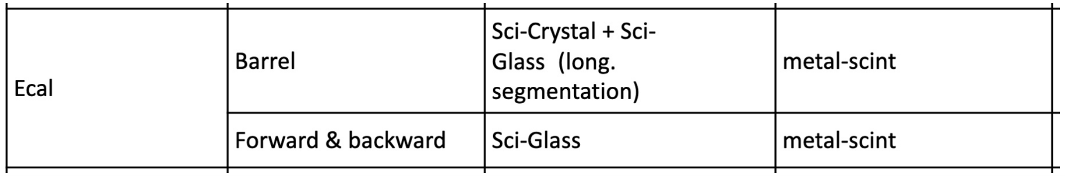
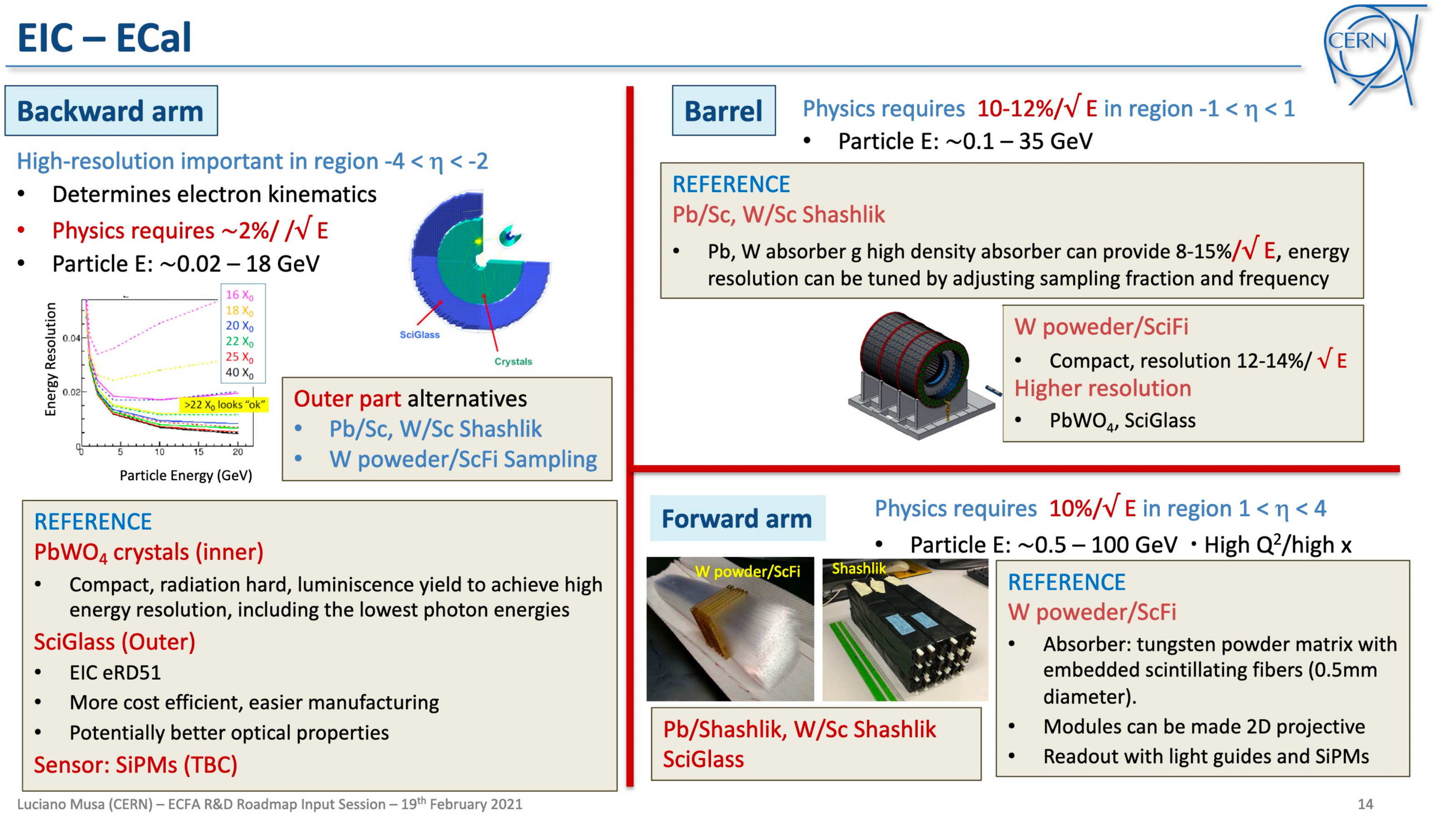
ALICE 3: a next generation HI detector for Run 5+



Ecal	Barrel	Sci-Crystal + Sci-Glass (long. segmentation)	metal-scint
	Forward & backward	Sci-Glass	metal-scint

EIC – ECAL and HCAL



EIC – ECal

Backward arm

High-resolution important in region $-4 < \eta < -2$

- Determines electron kinematics
- Physics requires ~2%/ /√ E
- Particle E: ~0.02 – 18 GeV

Outer part alternatives

- Pb/Sc, W/Sc Shashlik
- W poweder/ScFi Sampling

REFERENCE

$PbWO_4$ crystals (inner)

- Compact, radiation hard, luminiscence yield to achieve high energy resolution, including the lowest photon energies

SciGlass (Outer)

- EIC eRD51
- More cost efficient, easier manufacturing
- Potentially better optical properties

Sensor: SiPMs (TBC)

Barrel

Physics requires 10-12%/√ E in region $-1 < \eta < 1$

- Particle E: ~0.1 – 35 GeV

REFERENCE

Pb/Sc, W/Sc Shashlik

- Pb, W absorber g high density absorber can provide 8-15%/√ E, energy resolution can be tuned by adjusting sampling fraction and frequency

W poweder/SciFi

- Compact, resolution 12-14%/ √ E

Higher resolution

- $PbWO_4$, SciGlass

Forward arm

Physics requires 10%/√ E in region $1 < \eta < 4$

- Particle E: ~0.5 – 100 GeV • High Q^2/high x

Pb/Shashlik, W/Sc Shashlik
SciGlass

REFERENCE

W poweder/ScFi

- Absorber: tungsten powder matrix with embedded scintillating fibers (0.5mm diameter).
- Modules can be made 2D projective
- Readout with light guides and SiPMs

Luciano Musa (CERN) – ECFA R&D Roadmap Input Session – 19th February 2021

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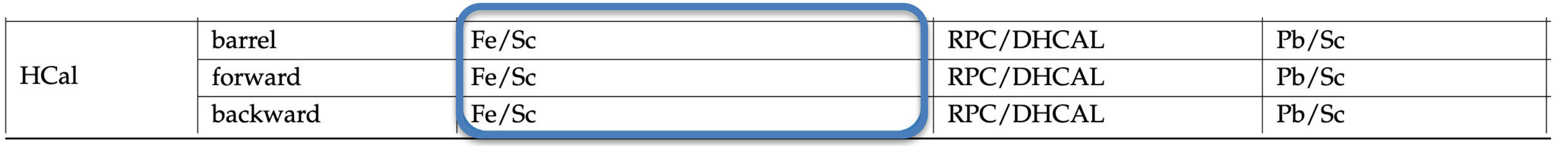
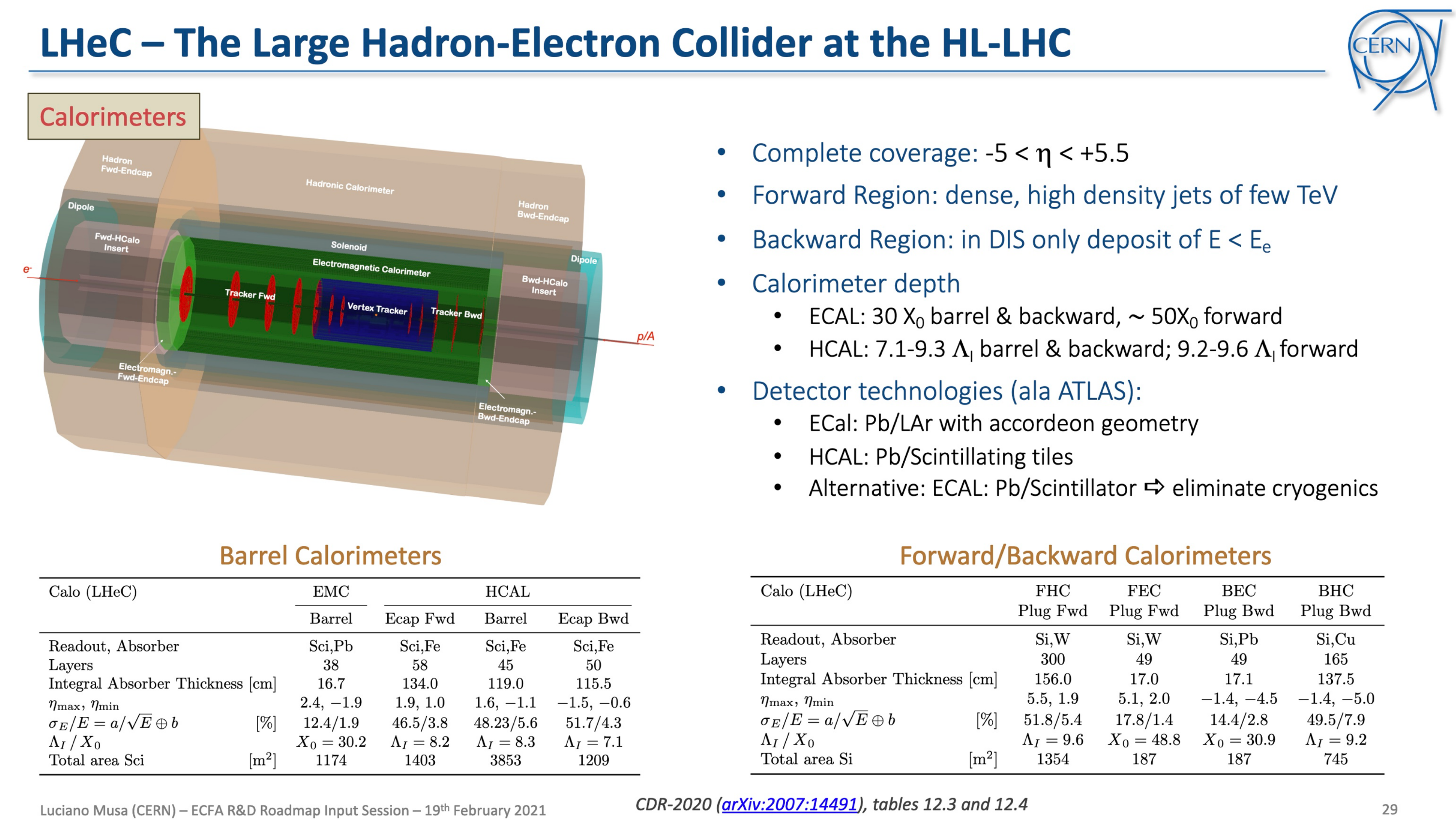


HCal	barrel	Fe/Sc	RPC/DHCAL	Pb/Sc
	forward	Fe/Sc	RPC/DHCAL	Pb/Sc
	backward	Fe/Sc	RPC/DHCAL	Pb/Sc

LHeC



LHeC – The Large Hadron-Electron Collider at the HL-LHC

Calorimeters

- Complete coverage: $-5 < \eta < +5.5$
- Forward Region: dense, high density jets of few TeV
- Backward Region: in DIS only deposit of $E < E_e$
- Calorimeter depth
  - ECAL: 30 X_0 barrel & backward, ~ 50X_0 forward
  - HCAL: 7.1-9.3 Λ_I barrel & backward; 9.2-9.6 Λ_I forward
- Detector technologies (ala ATLAS):
  - ECal: Pb/LAr with accordeon geometry
  - HCAL: Pb/Scintillating tiles
  - Alternative: ECAL: Pb/Scintillator ⇨ eliminate cryogenics

Barrel Calorimeters

Calo (LHeC)	EMC	HCAL		
	Barrel	Ecap Fwd	Barrel	Ecap Bwd
Readout, Absorber	Sci,Pb	Sci,Fe	Sci,Fe	Sci,Fe
Layers	38	58	45	50
Integral Absorber Thickness [cm]	16.7	134.0	119.0	115.5
$\eta_{\max}, \eta_{\min}$	2.4, −1.9	1.9, 1.0	1.6, −1.1	−1.5, −0.6
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	12.4/1.9	46.5/3.8	48.23/5.6	51.7/4.3
Λ_I / X_0	$X_0 = 30.2$	$\Lambda_I = 8.2$	$\Lambda_I = 8.3$	$\Lambda_I = 7.1$
Total area Sci [m^2]	1174	1403	3853	1209

Forward/Backward Calorimeters

Calo (LHeC)	FHC Plug Fwd	FEC Plug Fwd	BEC Plug Bwd	BHC Plug Bwd
Readout, Absorber	Si,W	Si,W	Si,Pb	Si,Cu
Layers	300	49	49	165
Integral Absorber Thickness [cm]	156.0	17.0	17.1	137.5
$\eta_{\max}, \eta_{\min}$	5.5, 1.9	5.1, 2.0	−1.4, −4.5	−1.4, −5.0
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	51.8/5.4	17.8/1.4	14.4/2.8	49.5/7.9
Λ_I / X_0	$\Lambda_I = 9.6$	$X_0 = 48.8$	$X_0 = 30.9$	$\Lambda_I = 9.2$
Total area Si [m^2]	1354	187	187	745

Luciano Musa (CERN) – ECFA R&D Roadmap Input Session – 19th February 2021

CDR-2020 (arXiv:2007:14491), tables 12.3 and 12.4

Linear Collider Experiments

TF6 Calorimetry

A Focus on PFA

- Calorimetry is central to the “philosophy” of Linear Collider detectors optimised for Particle Flow reconstruction - The original motivation for highly granular (“imaging”) calorimeter. Key performance demonstrated in test beams.
- Key topics for further development:
  - ***Scalability*** and ***cost-effective*** mass production
    - Silicon, Scintillator / SiPM, Gas detectors
  - ***Performance improvements*** (in particular in areas of clustering and hadronic resolution) with integration of new technical capabilities, such as ***ps-level timing***, ***novel optical materials, dual readout techniques* in high granularity**; improved ***electromagnetic resolution*** in highly granular calorimeters
  - Development of CMOS-based ***digital E***
  - Central for all: ***highest possible integra*** minimum volume for interfaces, small possible, …

➩ Calorimetry drives dev

TF8 Integration

- ***Precision*** and ***stability*** on all components and overall detector crucial to acl of e$^+$e$^-$ colliders
- High ***compactness*** central for Linear Collider concepts:
  - Extreme demands on ***overall integration***: mechanics, electronics, services
  - Minimal tolerances, for example highly ***precise, earthquake-stable*** calorimeter absorber structures
- ***System-level power-pulsing*** concepts with low-mass cables, compatible with magnetic field environment
- ***Reproducible alignment*** after push-pull operations
- Extreme mechanical precision for machine-detector interface, combined with ***fast feedback*** and precise beam steering (nm precision) to maximise luminosity during bunch trains
  - Beam size (σ_x x σ_y) 500 x 8 nm^2 (ILC 250 GeV) - 40 x 1 nm^2 (CLIC 3 TeV), bunch trains at CLIC ~ 160 ns, at ILC ~ 700 µs
- ***Low-mass support structures*** for trackers; tracker supports with integrated cooling - building on significant R&D already performed
  - ***Mechanical stability*** in the presence ***forced air cooling*** - in particular for vertex detectors

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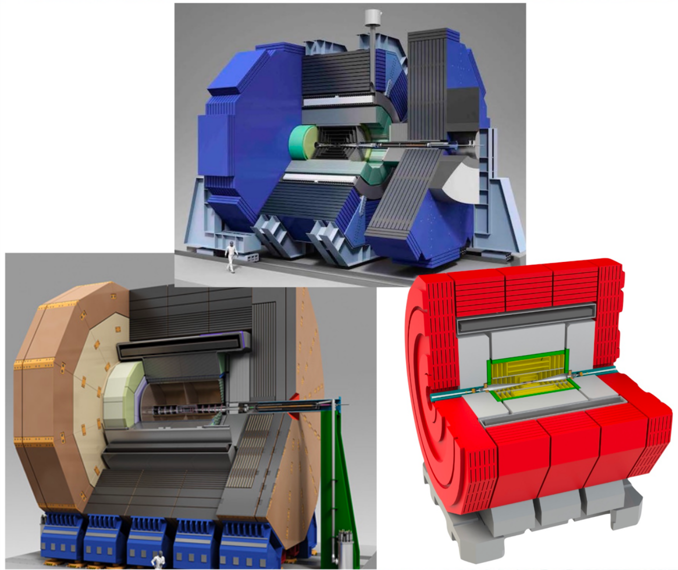
The Linear Collider Detector Design - Main Features

Focusing on general aspects



- A **large-volume solenoid** 3.5 - 5 T, enclosing calorimeters and tracking
- **Highly granular calorimeter systems**, optimised for particle flow reconstruction, best jet energy resolution *[Si, Scint + SiPMs, RPCs]*
- **Low-mass main tracker**, for excellent momentum resolution at high energies *[Si, TPC + Si]*
- **Forward calorimeters,** for low-angle electron measurements, luminosity *[Si, GaAs]*
- **Vertex detector**, lowest possible mass, smallest possible radius *[MAPS, thinned hybrid detectors]*
- **Triggerless readout** of main detector systems

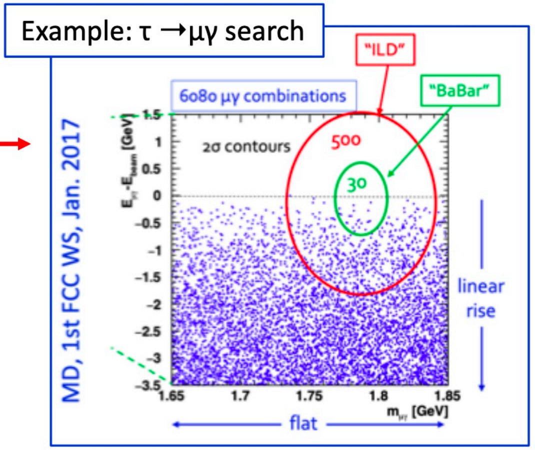
FCC-ee

Calorimetry

- Several technologies being considered

Technology	ECAL	HCAL
CLD / CALICE-like	W/Si W/scint + SiPM	Steel/scint + SiPM Steel/glass RPC
IDEA / Dual Readout	Brass (lead, iron) / parallel scint + PMMA (Č) fibres, SiPM	
Noble Liquid	Fine grained LAr (LKr) / Pb (W)	CALICE-like ?
Crystals	Finely segmented crystals (possibly DR)	Dual Readout fiber?

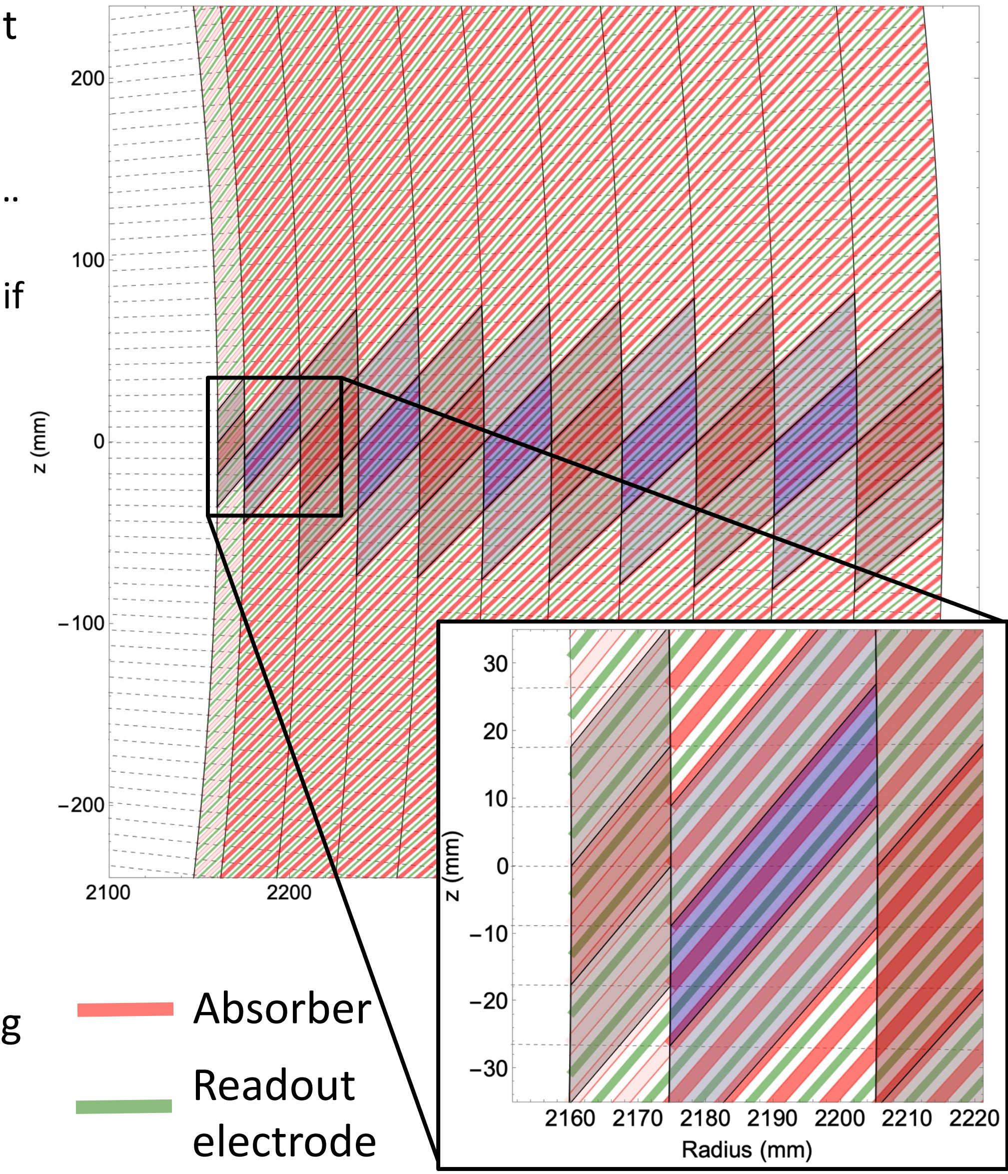
- Jet energy and angular resolutions via Particle Flow algorithm
  - Possibibly augmented via Dual Readout
- Fine segmentation for PF algorithm and powerful γ/π^0 separation and measurement
- In particular for heavy flavour programme, superior ECAL resolution needed →
  - 15%/√E → 8%/√E → 3%/√E
- Other concerns
  - Operational stability, cost, …
- Optimisation ongoing for all technologies
  - Choice of materials, segmentation, read-out, …


Example: τ →μγ search

MD, 1st FCC WS, Jan. 2017

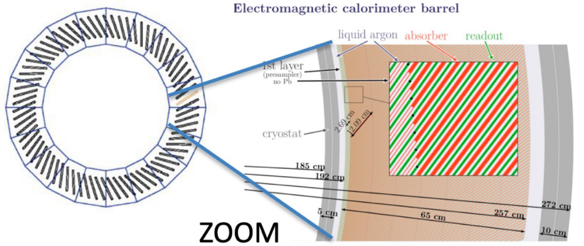
Example: FCC-ee Design for Noble-Liquid Barrel ECAL

- **Low-material cryostat (inner radius = 210cm)**, assuming 5cm thick Al cryostat (R&D ongoing on thin Al and composite cryostats)
- **1536 absorbers in 2π, inclined by ~50.4°, |z| ≤ 2 m along the beam axis**
  - Sandwich of 2 mm Pb absorber – active gap – 1.2 mm readout PCB – active gap – …
  - → ~1.24 mm active gap x 2 at the inner radius per absorber
  - With LAr as active material 19 - 22 X_0 reached after 40 cm (22 X_0 for 2mm Pb, less if between steel sheets)
  - Also investigated: Absorbers with increasing thickness in depth (in steps)
- **→ ~42 absorbers crossed in depth by a straight projective trajectory**
- **Granularity:**
  - 11 or 12 longitudinal compartments in r, rhomboid like shape
    - first compartment without Pb absorbers → pre-sampler to correct for energy losses in upstream material
    - Second compartment with fine granularity in θ and Φ → "strips", only two double-gaps and 2 absorbers per cell → optimized for π^0 rejection.
  - **Δθ ~ 2.5 mrad in the strips (5.4 mm), 10 mrad in other compartments** → optimization ongoing to maximize particle ID and
  - **ΔΦ:** Strips: adding 2 absorbers (and their 2 double-gaps) into one read-out cell leads **to ΔΦ ~ 8.2 mrad (17.7mm),** other compartments probably adding 4 absorbers and their double gaps → optimization needed
- **Optimization with FCC-SW** Full Sim: granularity, sampling frequency, sampling fraction, active material (LAr, LKrypton, ...), absorber material (Pb/W)
  - E.g. using W instead of Pb → radial depth decreases by ~15 cm

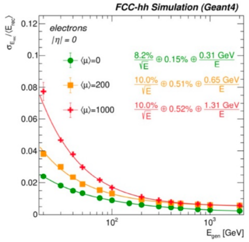


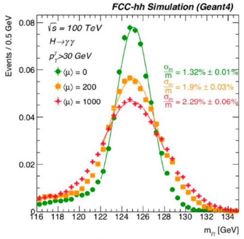
FCC-hh

Electromagnetic Calorimeter (ECAL)

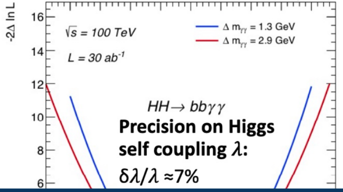


- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;





- **CDR Reference Detector: Performance & radiation considerations → LAr ECAL, Pb absorbers**
  - Options: LKr as active material, absorbers: W, Cu (for endcap HCAL and forward calorimeter)
- **Optimized for particle flow: larger longitudinal and transversal granularity** compared to ATLAS
  - 8-10 longitudinal layers, fine lateral granularity ($\Delta\eta \times \Delta\phi = 0.01 \times 0.01$, first layer $\Delta\eta=0.0025$),
  - → ~2.5M read-out channels
- Possible only with **straight multilayer electrodes**
  - Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
  - Baseline: warm electronics sitting outside the cryostat (radiation, maintainability, upgradeability),
    - Radiation hard cold electronics could be an alternative option
- **Required energy resolution achieved**
  - Sampling term ≤ 10%/√Ē, only ≈300 MeV electronics noise despite multilay
  - Impact of in-time pile-up at <μ> = 1000 of ≈ 1.3GeV pile-up noise (no in-tim
  - →Efficient in-time pile-up suppression will be crucial (using the tracker and



Precision on Higgs self coupling λ:

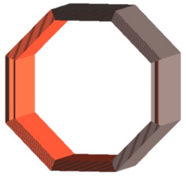
$\delta\lambda/\lambda \approx 7\%$

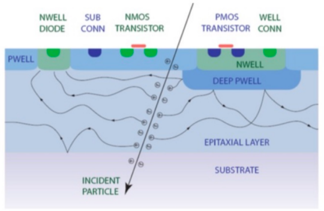
Barrel ECAL – Other Options

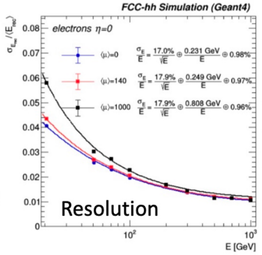
Other options considered for ECAL Barrel:

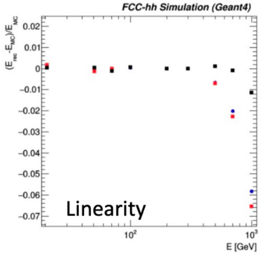
- **Digital Si/W DECal (MAPS):**
  - 18µm epitaxial thickness, on a substrate of 300µm.
  - 50×50 µm² pitch pixels are summed into 5×5 mm²
  - 2.1 mm thick tungsten absorber is located directly after the two silicon layers, followed by a 3 mm air gap (space foreseen for services, cooling,…)
  - Threshold at $6\sigma_{noise}$ = 480e⁻
  - MIP signal in 18µm Si: 1400e⁻
  - **Non-linearity for E > 300GeV due to multiple particles traversing single pixel → corrections necessary**

fit from experience









Hadronic Calorimeter (HCAL)

Barrel HCAL:

- **ATLAS type TileCal optimized for particle flow**
  - Scintillator tiles – steel,
  - Read-out via wavelength shifting fibres and SiPMs
- **Higher granularity** than ATLAS
  - $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$
  - 10 instead of 3 longitudinal layers
  - Steel –> stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout → faster, less noise, less space
- Total of 0.3M channels

Combined pion resolution (w/o tracker!):

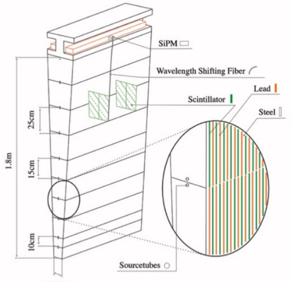
- Simple calibration: 44%/√Ē to 48%/√Ē
- Calibration using neural network (calo only):
  - Sampling term of 37%/√Ē

Jet resolution:

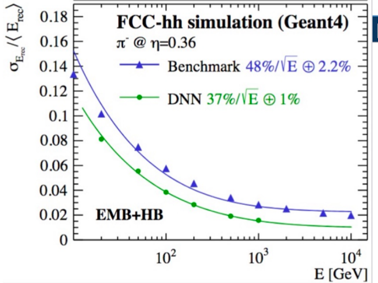
- Jet reconstruction impossible without the tracker @ 4T → particle flow.

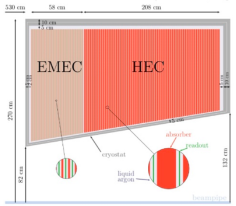
Endcap HCAL and forward calorimeter:

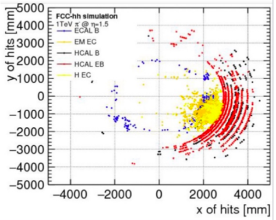
- Radiation hardness!
- LAr/Cu, LAr/W



TileCal: e/h ratio very close to 1 → achieved using steel absorbers and lead spacers (high Z material)



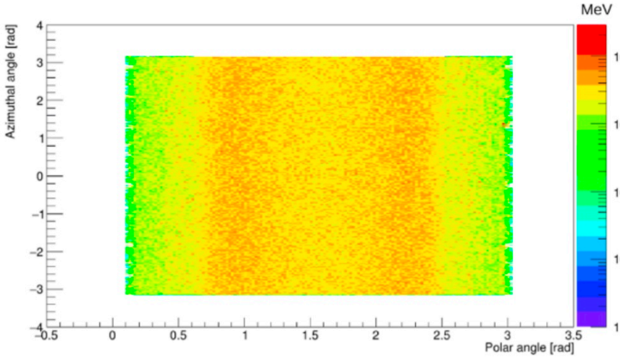


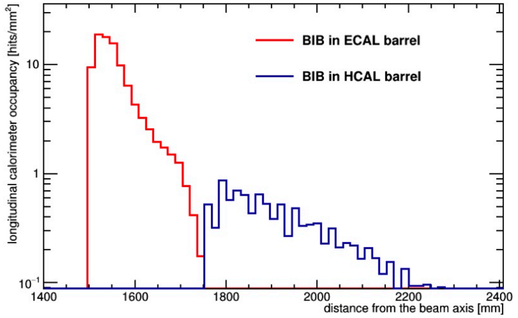


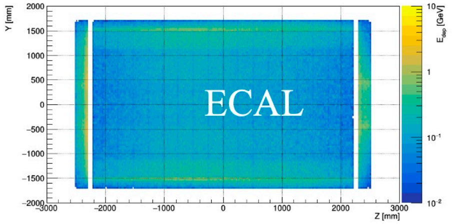
Muon Collider

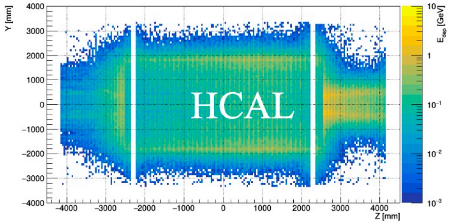
Calorimeter @ 1.5 TeV

BIB almost flat distributed in $\theta - \phi$ space

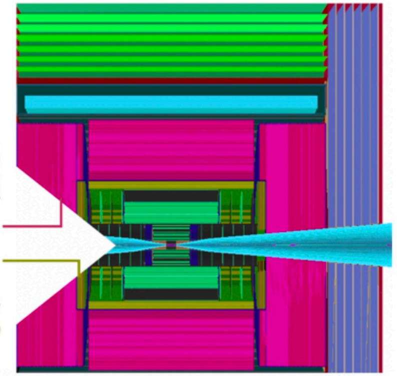








- ✓ based on CLIC configuration
  - Silicon + tungsten for ECAL, Iron+Scintillator for HCAL
- ✓ BIB deposits large amount of energy in both ECAL and HCAL



7.5λ_I

3x3cm^2

HCAL

19mm Fe absorber + scintillator × 60

1.9mm W absorber + Si sensor × 40

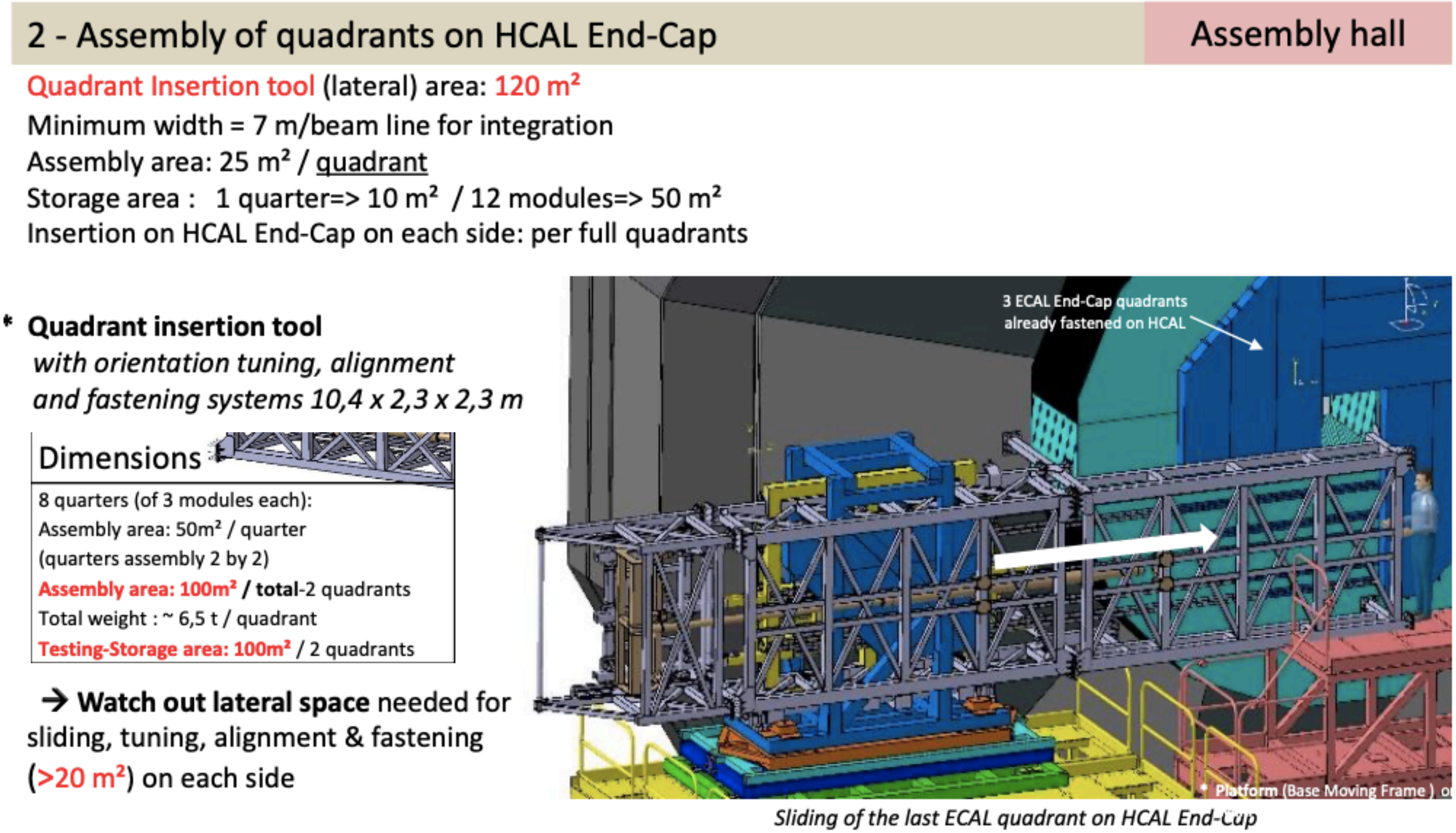
5x5mm^2

ECAL

22X_0

Calorimeter volume: 127 m^3
ECAL: 115 m^3 - HCAL: 112 m^3

Example: CALICE ECAL Endcaps



2 - Assembly of quadrants on HCAL End-Cap

Assembly hall

Quadrant Insertion tool (lateral) area: 120 m²
Minimum width = 7 m/beam line for integration
Assembly area: 25 m² / quadrant
Storage area : 1 quarter=> 10 m² / 12 modules=> 50 m²
Insertion on HCAL End-Cap on each side: per full quadrants

- **Quadrant insertion tool**
  with orientation tuning, alignment and fastening systems 10,4 x 2,3 x 2,3 m

Dimensions

8 quarters (of 3 modules each):
Assembly area: 50m² / quarter
(quarters assembly 2 by 2)
Assembly area: 100m² / total-2 quadrants
Total weight : ~ 6,5 t / quadrant
Testing-Storage area: 100m² / 2 quadrants

→ **Watch out lateral space** needed for sliding, tuning, alignment & fastening (>20 m²) on each side

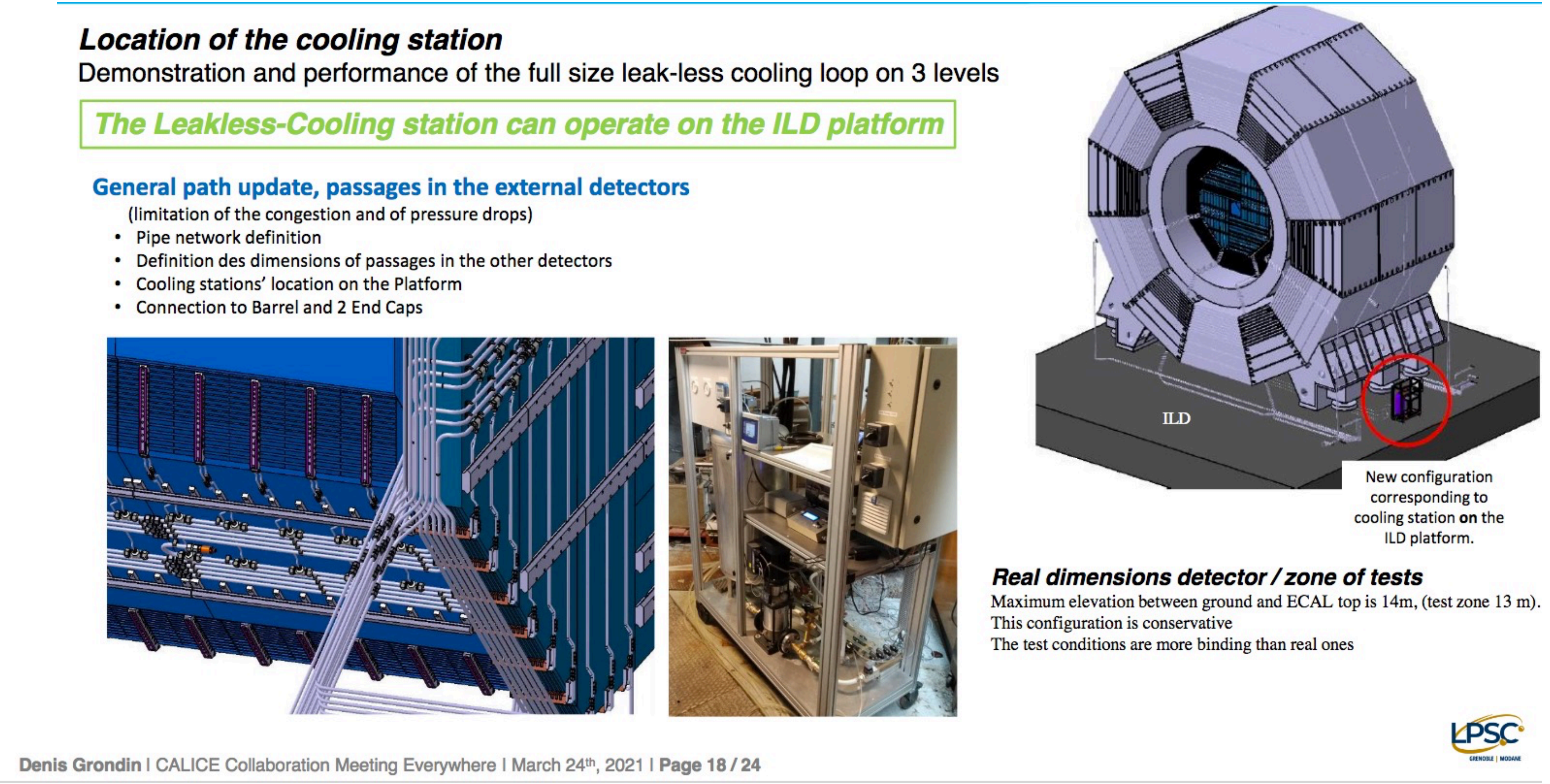
3 ECAL End-Cap quadrants already fastened on HCAL

Platform (Base Moving Frame) o

Sliding of the last ECAL quadrant on HCAL End-Cap

Example: ILD ECAL Cooling

Leakless cooling system for low-power calorimeter read-out electronics



Location of the cooling station

Demonstration and performance of the full size leak-less cooling loop on 3 levels

The Leakless-Cooling station can operate on the ILD platform

General path update, passages in the external detectors

(limitation of the congestion and of pressure drops)

- Pipe network definition
- Definition des dimensions of passages in the other detectors
- Cooling stations' location on the Platform
- Connection to Barrel and 2 End Caps

New configuration corresponding to cooling station **on** the ILD platform.

Real dimensions detector / zone of tests

Maximum elevation between ground and ECAL top is 14m, (test zone 13 m).
This configuration is conservative
The test conditions are more binding than real ones

Denis Grondin I CALICE Collaboration Meeting Everywhere I March 24th, 2021 I **Page 18 / 24**