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U.S. DEPARTMENT of ENERGY

Calorimetry for FCC-ee

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Detector Research and Development

European Committee for Future Accelerators (ECFA) released 2021 Detector R&D Roadmap: nine (technology) focus domains

=>Task forces developed into Detector R&D (DRD) collaborations:

- Gaseous Detectors (DRD1) [ex RD51]
- Liquid Detectors (DRD2)
- Semiconductor Detectors (DRD3) [ex RD50, RD42,..]
- Photodetectors & Particle ID (DRD4)
- Quantum Sensors (DRD5)
- Calorimetry (DRD6)
- Electronics (DRD7)
- Integration (DRD8)

DRDs are **international (global)** collaborations, hosted by CERN

Proposals describing the scope are on CDS – new ideas welcome!

Focus on strategic RnD to bridge the gap between “blue sky” research and deployment in a HEP experiment – includes targeted FCC R&D

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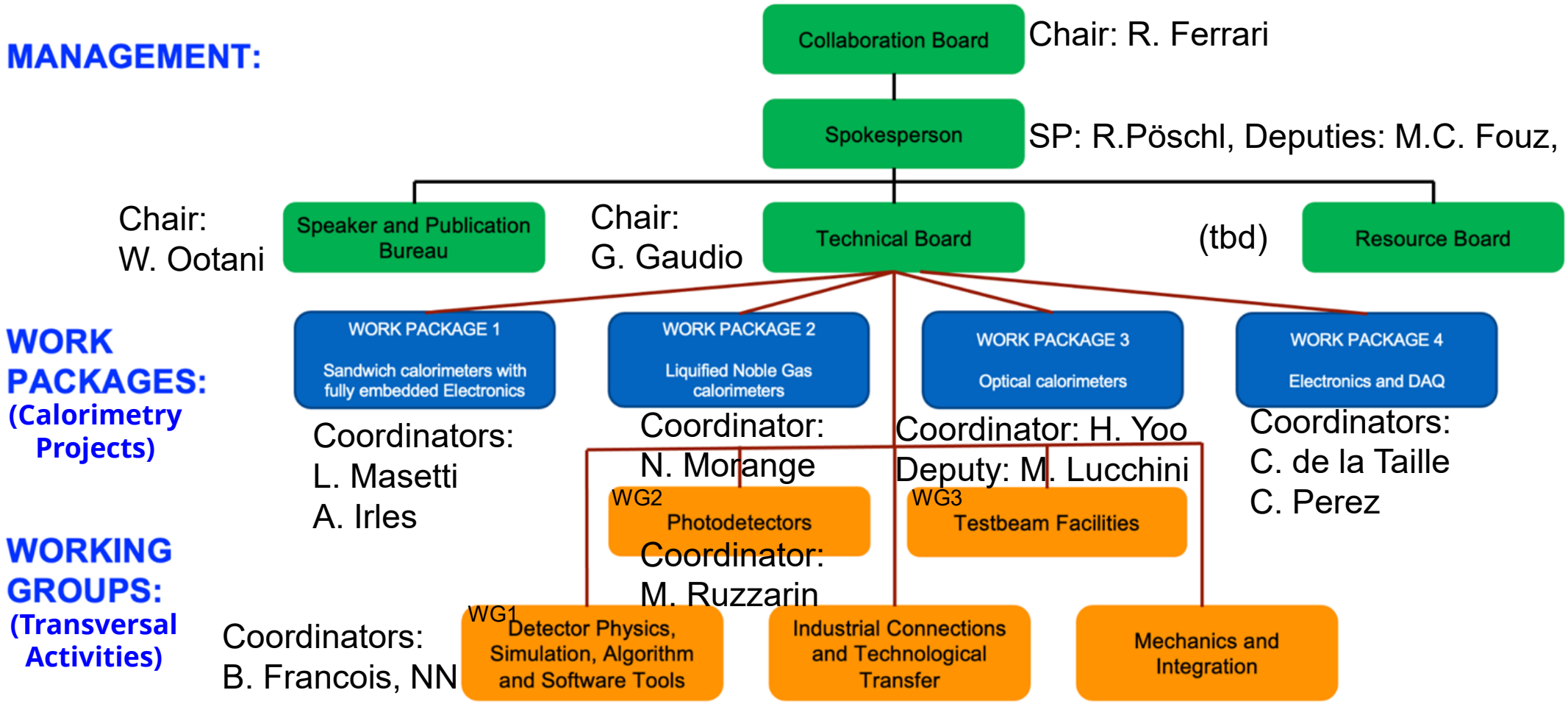
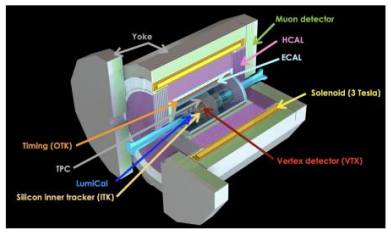
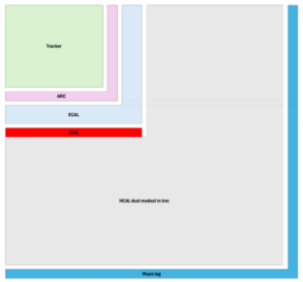
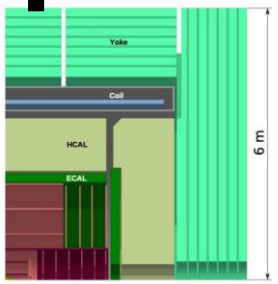
DRD Calo Organization

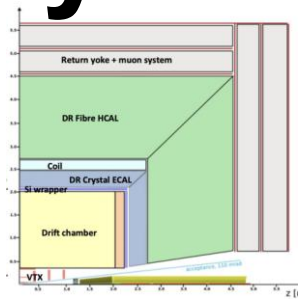


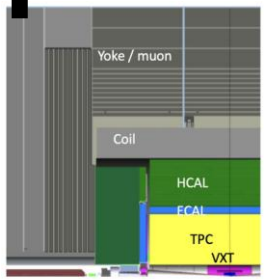
FCC-ee Detector Concept Study Groups











	AGORA	ALFA	ALLEGRO	CLD	IDEA	ILD
Vertex	MAPS	MAPS (ITS-3 like)	MAPS (ITS-3 like)	Si	MAPS (ITS-3 like)	Si
Tracker	TPC + Si strips	All MAPS	DCH / Straw / SciFi + Si	Full Si	Drift Chamber + Si strip	TPC + Si strips
ECAL	**Crystals**	**GRAiNITA (crystal grains)**	**Liquefied Noble Gas**	**Si-W highly granular**	**Crystals w. DR**	**Si-W highly granular**
HCAL	**Glass scint. + steel**	**Tile DR + steel yoke**	**TileCal (steel/scint.)**	**Scint. sampling**	**Fibre DR**	**Scint. or RPC**
Muon	Scint. in yoke	TBD	TBD	RPC in iron yoke	uRWELL	Scint. in iron yoke
PID	tracker dN/dx (+ TOF)	Cerenkov ARC	tracker dN/dx (+ TOF)	RICH (option)	tracker dN/dx (+ TOF)	tracker dN/dx (+ TOF)
Coil/B-field	Outside HCAL 3T	Inside HCAL 3T	Inside HCAL 2T	Outside HCAL 2T	Inside HCAL 2T (3T HTS R&D)	Outside HCAL 3.5 T -> 2-3 T

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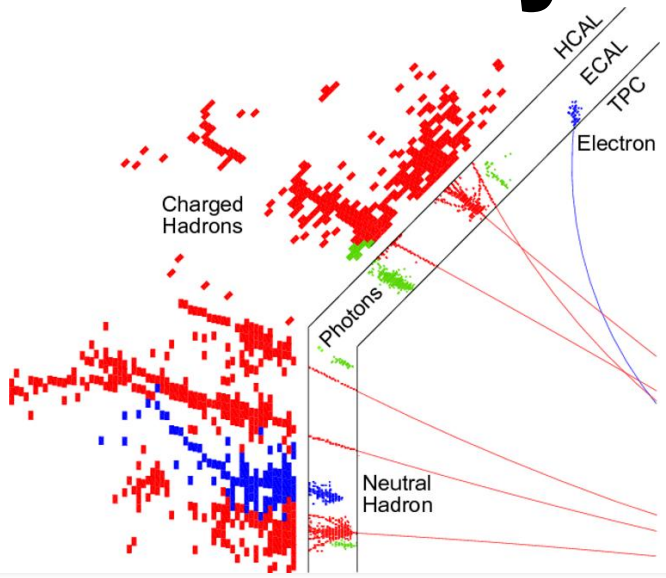
…and all of them need a lumi-cal as well…

WP 1: Sandwich calorimeters with fully embedded Electronics

- Imaging calorimeters optimized for particle flow: high-resolution in 3D plus time and energy
  - Proof of concept within the CALICE and FCAL collaborations
  - Focus originally on linear colliders
- High pixelization & 4π hermeticity challenge room for services
- Three groups of tasks:
  - highly pixelized electromagnetic section,
  - hadronic section with optical tiles,
  - hadronic section with gaseous readout
- Some technologies already adopted for HL-LHC upgrades
  - CMS HGCAL with silicon pads and scintillator tiles
  - ALICE FoCAL with MAPS
- Adaptation to FCC-ee: examples of common tasks across concepts
  - Readout to cope with continuous data taking
  - Addition of active cooling
  - Addition of timing capabilities for better particle separation
  - Layout optimization within specific detector concept (e.g. CLD and ILD@FCC-ee)



Task/Subtask	Sensitive Material/ Absorber
Task 1.1: Highly pixelised electromagnetic section	
Subtask 1.1.1: SiW-ECAL	Silicon/ Tungsten
Subtask 1.1.2: Highly compact calo	Solid state (Si or GaAs)/Tungsten
Subtask 1.1.3: DECAL	CMOS MAPS/Tungsten
Subtask 1.1.4: Sc-Ecal	Scintillating plastic strips/Tungsten
Task 1.2: Hadronic section with optical tiles	
Subtask 1.2.1: AHCAL	Scintillating plastic tiles/Steel
Subtask 1.2.2: ScintGlassHCAL	Heavy glass tiles/Steel
Task 1.3: Hadronic section with gaseous readout	
Subtask 1.3.1: T-SDHCAL	Resistive Plate Chambers/Steel
Subtask 1.3.2: MPGD-HCAL	Multipattern Gas Detectors/Steel
Subtask 1.3.3: ADRIANO3	Resistive Plate Chambers+Scintillating plastic tiles/ Heavy Glass

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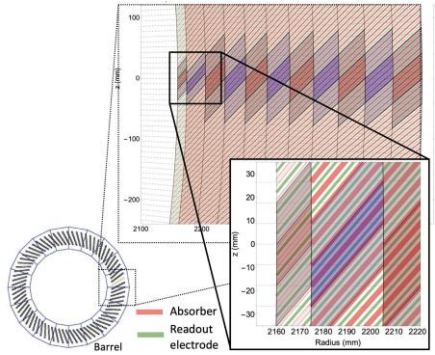
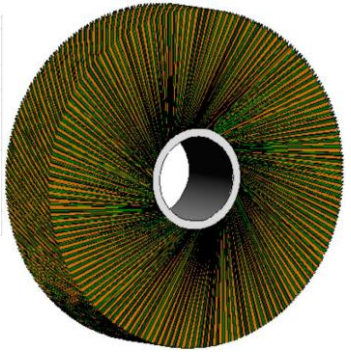
For a more detailed overview, see Lucia's slides in Helsinki

WP 2: Liquefied Noble Gas Calorimetry

- Noble-liquid calorimetry: long history of successful deployment in HEP (DZero, ATLAS, …) due to its excellent energy resolution, linearity, stability and uniformity
- WP 2 focus: sampling EM calorimeter for ALLEGRO detector concept – LAr goes PFlow!
  - Highly granular (ATLAS x 10) calo with absorbers planes inclined in r-phi (barrel) / arranged in turbine-like structure (endcap)
  - Readout by segmented PCB planes alternated to Pb (or W) absorbers, gaps in between filled with LAr (or LKr)
- Work towards large (full em shower containment) prototype
  - optimization of the detector material, geometry and segmentation
  - overall detector mechanical structure and integration
  - readout electronics (using cold elx to reduce noise & #cables - 150 kW power dissipation in barrel cryostat)
  - prototyping and testing of various detector elements
- Next intermediate step: “mini-prototype”
  - demonstrate mechanical feasibility: tolerances, ease of construction, tolerance for warm → cold transitions
  - Can also be used to connect prototypes of readout electronics and test with sources, cosmics, test-beam

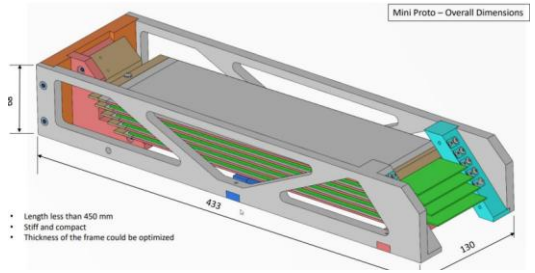


Barrel



Endcap

Absorber cold test

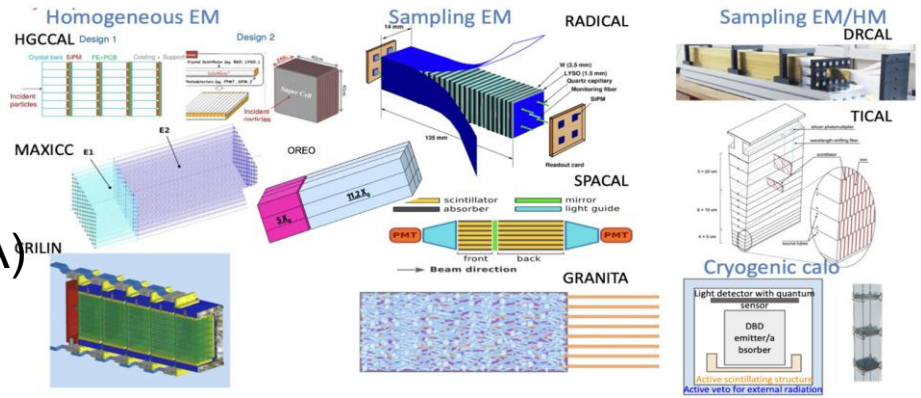


Mini-Prototype

For a more detailed overview, see Mikael’s slides in Helsinki

WP 3: Optical Calorimeters

- Very diverse work package: 12 active projects, ~70 institutes
- Goal: explore, optimize and demonstrate with full shower containment prototypes, new concepts of sampling and homogeneous calorimeters based on scintillating materials
- Some effort pivoting from radiation-hardness focus to FCC-ee (e.g. CRILIN)
- R&D on scintillators (SCINTCAL) will turn into a working group in DRD Calo, connecting WP1 and WP3
- Examples as parts of FCC-ee detector concepts include:
  - Dual-readout Crystal ECAL and Fiber HCAL (IDEA)
  - Grainita ECAL and Dual-readout HCAL in iron (ALFA)
  - TileCal HCAL (ALLEGRO)

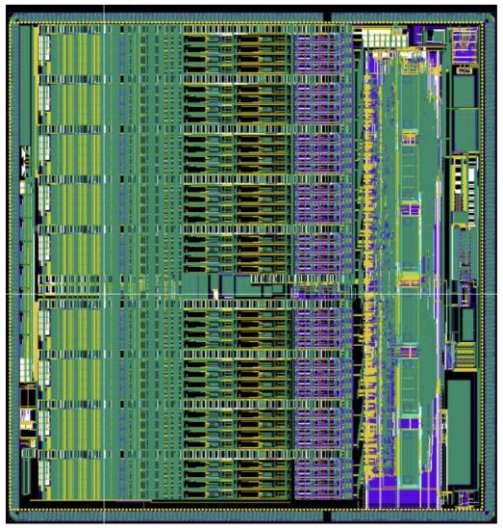


(Sub)tasks	Calorimeter type
HGCCAL	Homogeneous and quasi-homogeneous EM calorimeters
MAXICC	
CRILIN	
OREO	
GRAINITA	Sampling EM calorimeters
SPACAL	
RADICAL	
3DCaloNu	
DRCAL	Sampling HAD calorimeters
TILECAL	
SCINTCAL	R&D on scintillators
CRYODBD-CAL	Calorimeter at low energy

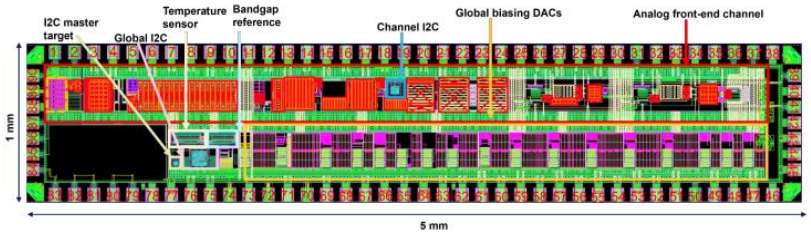
For a more detailed overview, see Hwidong's slides in Helsinki

WP 4: Electronics and DAQ

- Calorimeter electronics commonalities: large dynamic range (10-16 bits), very low noise, high accuracy (< 1%), usually large capacitance (100's of pF)
- R&D challenges for highly granular 5D calorimetry include
  - reducing power dissipation down to ~ 1mW/ch to enable increased granularity (WP1), cryogenic operation inside noble liquid (WP2)
  - Improve the timing performance to sub-ns (WP3)
  - Develop a family of ASICs, optimized for different subdetectors, sharing as much as possible common back-end and readout systems
  - Process accessibility / stability can be an issue these days (TSMC 130 nm)
- Organization of DAQ in DRD Calo
  - Aim to share HW/FW/SW + experience as much as possible
  - Allow common test-beams and maximize commonalities
- Electronics and DAQ are transversal activity across WPs - will be transformed (back) from WP to WG



CALOROC: 36 channels @ 15 mW/ch



CHARMS250: 1 channel @ < 10 mW/ch

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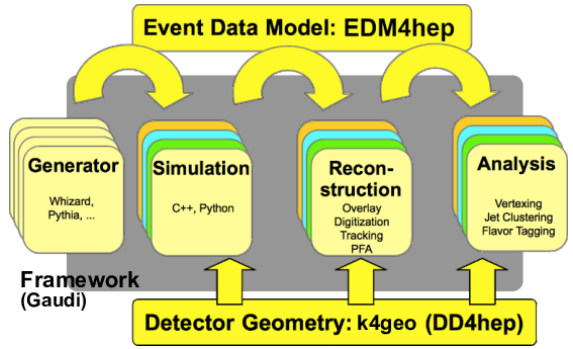
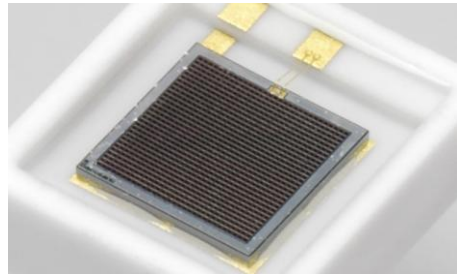
Working Groups – Tying it all together

- WG1 – Software
  - Detector R&D activities heavily rely on software tools: Simulation, Reconstruction, Analysis, …
  - Use common Key4hep software ecosystem to utilize synergies
  - WG 1 coordinates activities, provides training and resources (DRD Calo storage, VO, Grid submissions)
  - WG 1 will ensure efficient data analysis, data preservation, simulation improvement/validation with test beam data
- WG 2 – Photodetectors
  - Photon detection crucial for many calorimeters (crystals and scintillators; Cherenkov vs scintillation light for dual-readout) - consolidate requirements across WPs, work in close connection with DRD4
  - Work with vendors for upcoming prototypes: align sensor developments with detector R&D priorities, lower unit cost, foster synergies between photodetector R&D and front-end electronics developments
- WG 3 – Test-Beams
  - Central hub for DRD Calo projects test-beam (TB) needs at CERN, DESY, KEK, SLAC, FNAL
  - Promote smooth interactions with TB facilities coordination, optimal use of beam time (sharing/combining where possible), common tools (EUDAQ)
  - Pursuing dedicated test beam area at CERN to optimize resources, streamline hardware and software setup, exploit synergies



[EPJCONF]

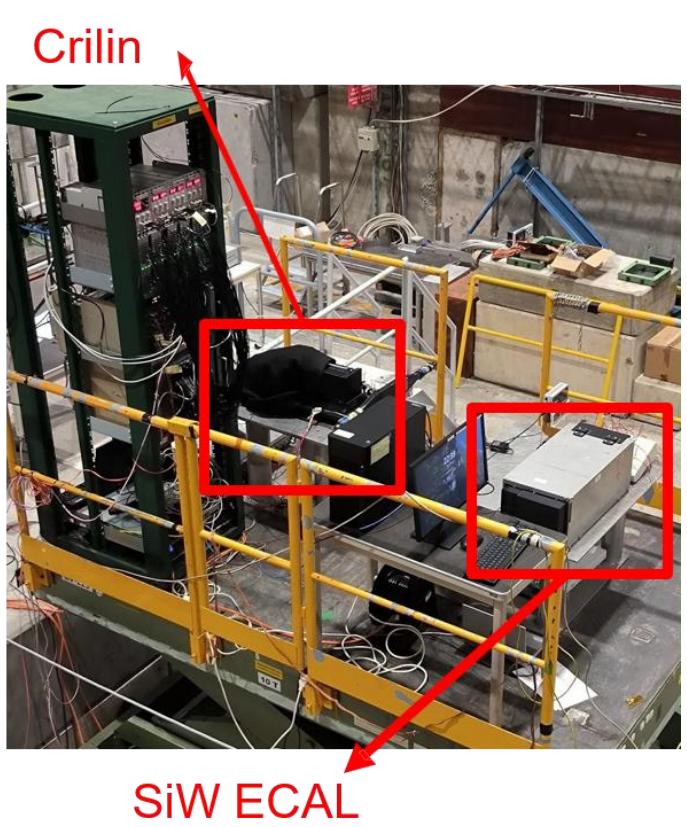


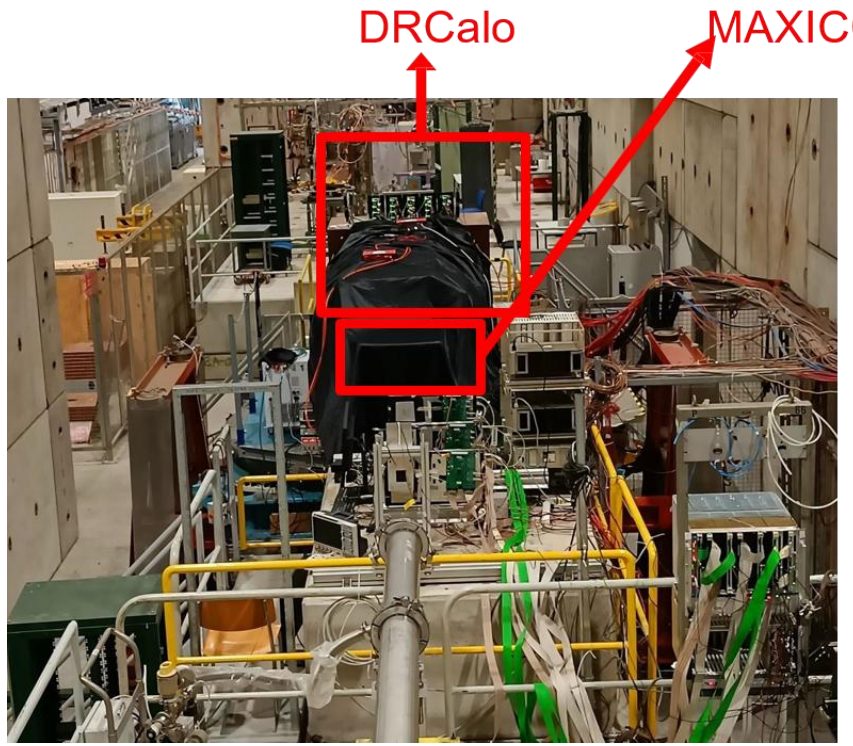
[Multi-Pixel Photon Counter]

2026 CERN Test-Beam

DRD Calo in action!

Impressions from test beams at CERN this year:





- Groups shared allocated beam time and/or organized combined ECAL/HCAL test beams
- See also presentations by Bob and Jim on Tuesday!

Conclusions

- DRD Calo pursues strategic R&D for calorimeters for future colliders, in particular FCC-ee and in close connection with the other DRDs
  - Partially new efforts, partially capitalizing on pre-existing activities
  - Large diversity of calorimeter technologies
  - No lack of challenges or areas to contribute!

134 institutes from 27 countries

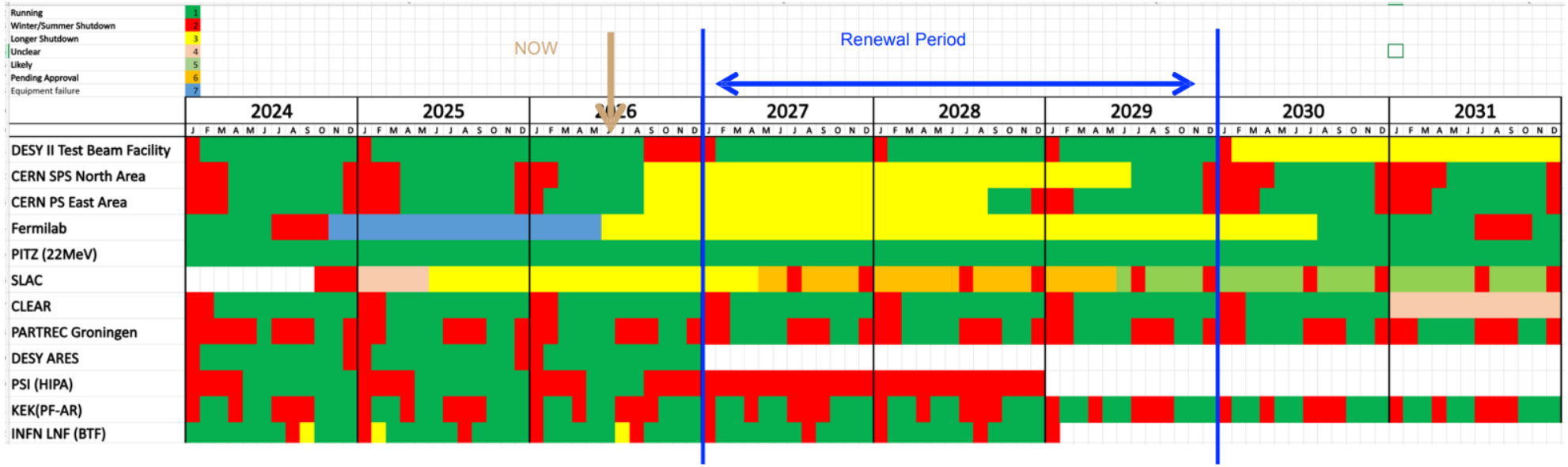
- The scientific program is bearing fruit
  - 59 talks/seminars, 10 conference proceedings, 10 papers so far
  - Lots of test-beam data to analyze!
  - Tangible benefits of the synergies for all: test-beam access, computing resources, shared software and hardware, …

2026 collaboration meeting at CERN

- Next collaboration meeting @ DESY, October 6-9
- Visit our webpage: https://drdcalo.web.cern.ch/
- We are open for new members, ideas, contributions!

Backup

Test Beam access in the next years



Electron beam (> GeV):
- KEK up to 5 GeV
- DESY up to 6 GeV
- SLAC up to 8 GeV
- FNAL up to 32 GeV

Hadron beam (> GeV):
- CERN PS up to 15 GeV
- CERN SPS up to 450 GeV
- FNAL up to 120 GeV

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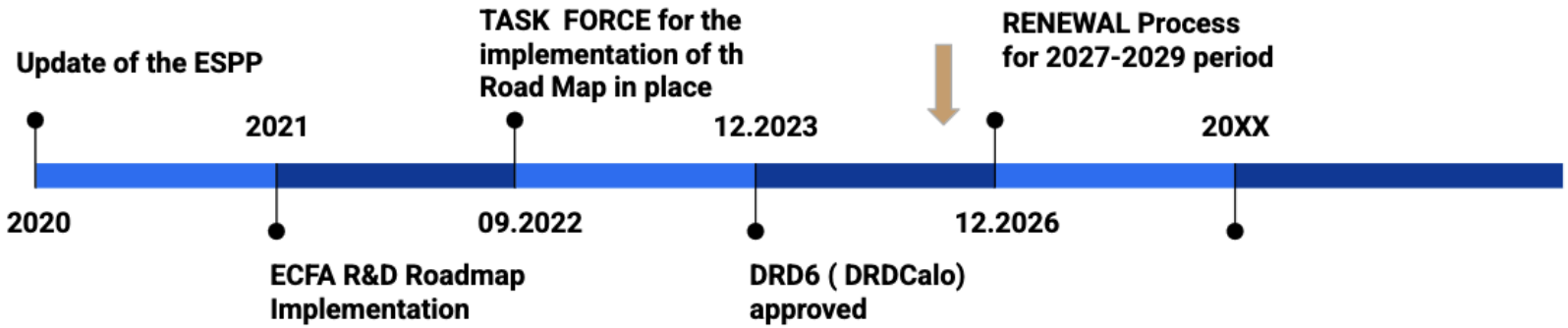
DRD Calo Renewal



- DRD Calo was approved for 3 years at the end of 2023, with the option to extend
  - We are now undergoing the "**extension" procedure** (for another 3 years)
  - Two documents will be provided (Sep. 20th 2026)
    - **Status Report**
      - When were milestones and deliverable reached/fulfilled
      - How were they reached
    - **Proposal Update**: plans for the next approval period
      - High-level technological goals, updated work plan, realistic funding estimates
      - **Prioritisation of developments** aligned with the European Strategy outcome i.e. **relevant for FCC-ee** (more throughout the talk)

Reference Design Phase (2026-2028)

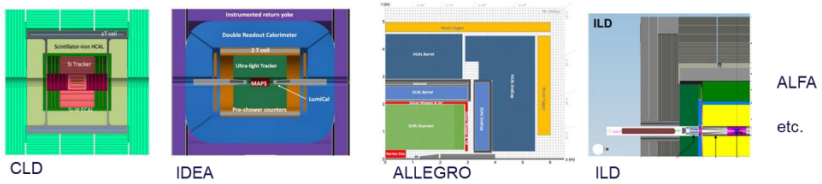
FCC has entered its Reference Design Phase to provide the CERN Council all the technical elements for an informed decision in 2028.

Reference Design Phase (RDP) objectives

- Increase maturity of technical design (incl. recommendations from feasibility study reviews)
- Overall project integration and requirements on civil engineering sufficiently detailed to enable subsequent launch of civil engineering tender design in case of project approval
- Overall project design sufficiently detailed to allow advancing with environmental impact and evaluation as core parts of project authorisation processes in Host States
- Reducing project risks via:
  - **Integrated planning across all domains and interface management**
  - **Prototyping of critical systems**
  - **Build up cost / performance contingency by design optimization**
  - **Civil engineering refinement**
  - **Close coordination with Host States on territorial implementation aspects**
  - **Reinforcing collaboration as basis for global support for the project**

Physics, Experiments, Detectors - objectives

- Continue developing the **international high-energy physics community**
- Consolidation of the **interaction region layout, detector integration,** and **beam-background** mitigation
- Optimised **procedures for √s calibration** & possible **monochromatic operation at √s = 125 GeV**
- Finalising common **software/analysis framework** and developing **common computing architecture**
- Realistic studies of **experimental systematic uncertainties** for some **EW precision** measurements and consolidation of the **pertaining requirements** on collider, detectors, and theory
- **Engagement of theory community** to address theory challenge and nurture the young generation
- Proposal for staging implementation and improvements of the **staged/descoped FCC-ee**
- **Prepare** to answer call for (at least 4) **documented EoI's for FCC-ee experiments end 2028**



[Michael Benedikt's Helsinki slides]

Get involved in Detector Concepts!

Group name	Email	Signup	Indico
Calorimetry	FCC-PED-DetectorConcepts-Calorimetry@cern.ch	click	click
Luminometry	FCC-PED-DetectorConcepts-Luminometry@cern.ch	click	click
Magnet	FCC-PED-DetectorConcepts-Magnet@cern.ch	click	click
Muon	FCC-PED-DetectorConcepts-Muon@cern.ch	click	click
TDAQ	FCC-PED-DetectorConcepts-TDAQ@cern.ch	click	click
Tracker & PID	FCC-PED-DetectorConcepts-Tracker@cern.ch	click	click
AGORA	FCC-PED-DetectorConcepts-AGORA@cern.ch	click	click
ALFA	FCC-PED-DetectorConcepts-ALFA@cern.ch	click	click
ALLEGRO	FCC-PED-DetectorConcepts-ALLEGRO@cern.ch	click	click
CLD	FCC-PED-DetectorConcepts-CLD@cern.ch	click	click
IDEA	FCC-PED-DetectorConcepts-IDEA@cern.ch	click	click
ILD	FCC-PED-DetectorConcepts-ILD@cern.ch	click	click

- Signing up to any of the above e-groups adds you to the overall "FCC-PED-DetectorConcepts@cern.ch" e-group as well
- Indico categories are available for Detector Subsystems and Concept Studies
- See indico meeting calendar for upcoming meetings

Concept Studies

- AGORA
- ALFA
- ALLEGRO
- CLD
- IDEA
- ILD

Detector Subsystems

- Calorimetry
- Luminometry
- Magnet
- Muon
- TDAQ
- Tracker & PID

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Timescale towards FCC-ee