Summary of the GranuLAr workshop

Nicolas Morange, on behalf of the
FCC Noble Liquid Calorimetry group

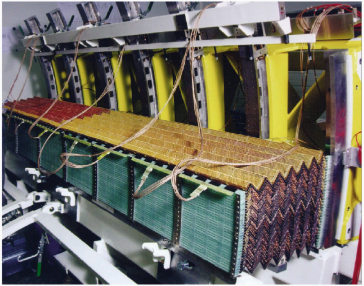
FCC Week, Paris, June 1 2022

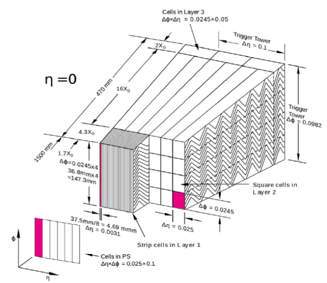
Noble Liquid Calorimeters

- Decades of success at particle physics experiments: HERA, D0, NA31, NA48, ATLAS...
- Mostly LAr, a bit of LKr
- Simple principles
- Many good properties
- Not too expensive to build

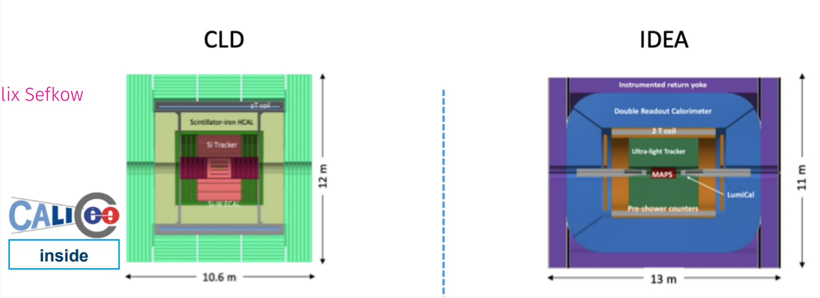
LAr calorimetry today: ATLAS experiment

- Excellent physics performance matching its specs.
  - Instrumental to Higgs boson discovery !
  - Resolution: $10\%/\sqrt{E} \oplus 0.2/E \oplus 0.7\%$
  - Linearity at per-mille level over 4 orders of magnitude
  - Stability over time at 10^{-4}
- 14 years of successful operation
- Electronics upgrades to make it cope with HL-LHC





Felix Sefkow



FCC-ee context

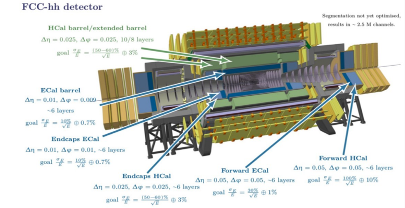
- 2-4 interaction points: several detectors / technologies needed
- Very advanced R&D on new calorimeter concepts: highly-granular (CALICE), dual-readout (DREAM)
- R&D on LAr calos stopped 25 years ago
  - Noble Liquid calos can be competitive, but R&D has to be restarted to explore new ideas

Requirements for FCC-ee

- Excellent shower shape discrimination for event classification
- Unprecedented hadronic resolution: $\sim$ 4% at 50 GeV
- $\rightarrow$ Points toward high granularity, optimised for use in Particle Flow algorithm
- High EM resolution even at low energy for b and τ physics at the Z peak

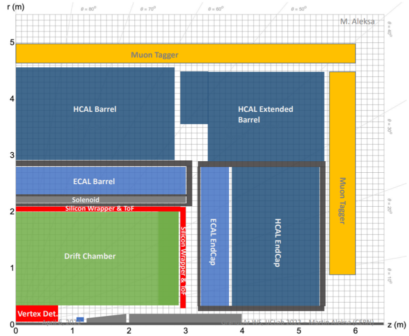
Initial studies for FCC-hh

- R&D initially started for ESPP studies for an FCC-hh calo
- Radiation levels at FCC-hh make Noble Liquid the only viable option



R&D then shifted to calo concept for FCC-ee

- ”Simpler” FCC-ee conditions ⇒ optimization towards ultimate performance
- Small but active community: CERN, IJCLab, Charles Univ. Prague, Copenhagen
  - Funding by CERN EP R&D and AIDAInnova
- Shaping a new detector concept
  - See presentation by Martin Aleksa



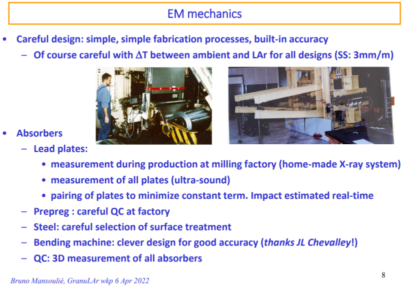
https://indico.ijclab.in2p3.fr/event/7664/

First ever workshop on noble liquid R&D for FCC

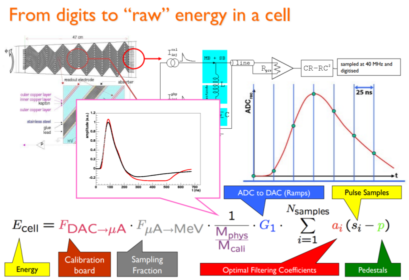
- Meet together for the first time after 2 years of Zoom meetings
- Status of the ongoing R&Ds
- Experience sharing from long-term ATLAS LAr experts
- Discussion of our mid-term goals
  - Towards a detector concept
  - Towards a prototype going to testbeam

In-depth presentations from ATLAS experts

- Covering design, construction, operation, simulation, digitization, reconstruction, calibration
- Even people with 10 years of ATLAS LAr experience (e.g me) learned a lot !



B. Mansoulié



M. Delmastro

Achieving high granularity for PFlow, π^0 identification

- High granularity electrodes
- High density feedthroughs

High EM energy resolution

- Minimize dead material (cryostat, solenoid)
- Low noise electronics

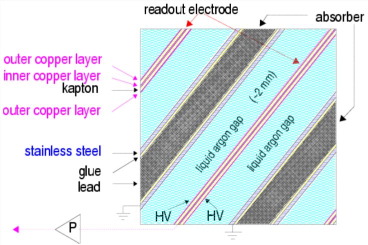
Simulations to allow performance optimization

- Choice of absorber (Pb, W) and active material (LAr, LKr)
- Optimization of granularity

FUTURE CIRCULAR COLLIDER

Reaching 10× ATLAS granularity

- 200000 cells → few million cells
- Readout in ATLAS uses simple copper/kapton electrodes
- Issue: traces to route signals to front or back of electrode take space !
- For 10× more granular: go to multilayer PCB to route signals in a deep layer

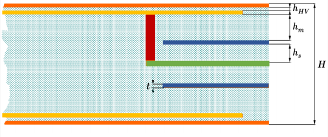


Basic design

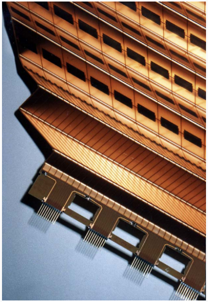
- Multi-layer PCB cannot be bent to accordion as ATLAS Kapton electrode

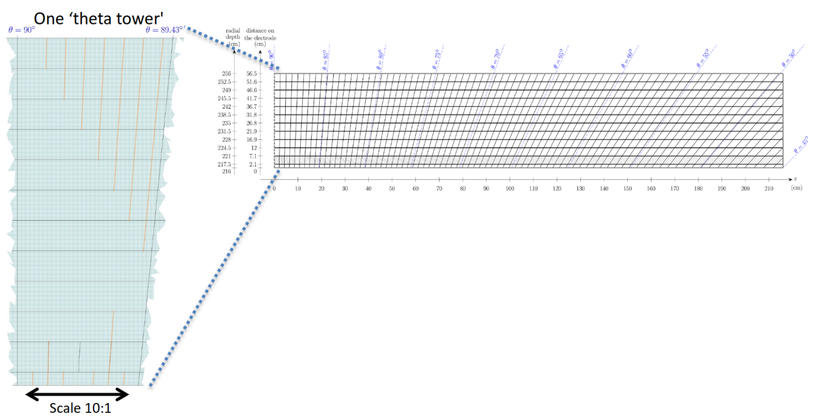
⇒ Straight planes inclined around the barrel

- Simulation in a specific IDEA-LAr setup



Side view




One 'theta tower'
$\theta = 90°$
$\theta = 89.43°$
Scale 10:1
radial depth (cm)
distance on the electrode (cm)
(cm)

General considerations

- Sampling calo: baseline with Pb absorber and LAr active material
- PCBs as readout planes: lots of possibilities
  - Projective cells along η and ϕ
  - Possibility to group electrodes into cells
  - Finer segmentation where needed, i.e 'strips' in ATLAS for π^0 rejection
  - adjust depth of each layer

Barrel

- Tilted planes around barrel: non-trivial geometry
- Gap widening at high radius

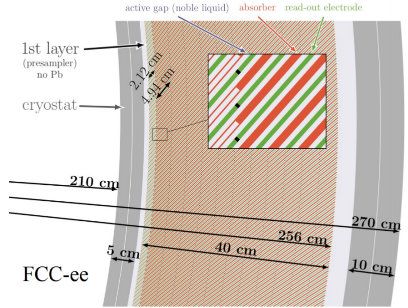
⇒ non-constant sampling fraction within a cell

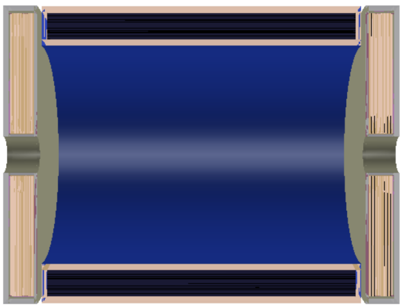
⇒ mitigated by high longitudinal segmentation

  - 12 layers in baseline design

Endcaps

- Simple design: planes perpendicular to beam axis
- May be revisited for mechanical considerations



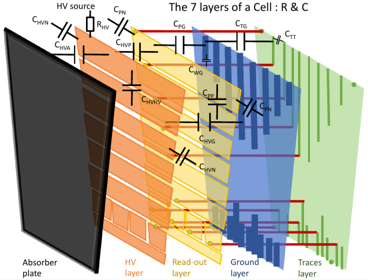


J. Faltova

FUTURE CIRCULAR COLLIDER

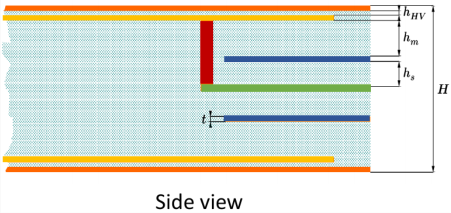
Principle

- HV layer capacitively coupled to readout layer
- Signal transferred from both sides to read-out trace through a via
- Shielding traces reduce cross-talk from other segments



Calculation of cell properties

- Multi-parameter optimisation:
  - Trade-off capacitance (noise) / cross-talk ?
  - What is the maximum density of signal traces ?
- Studies ongoing with simulations and building prototypes

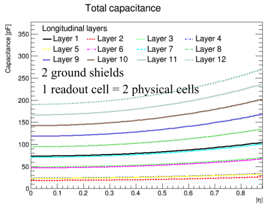


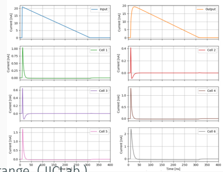
Electrodes prototypes

Simulations of capacitances and cross-talk

- Use Cadence/Sigrity and FEM tool ANSYS HFSS
- Cell capacitance driven by readout - shield capa
- Cross-talk limited $< 0.2\%$ for long shaping times

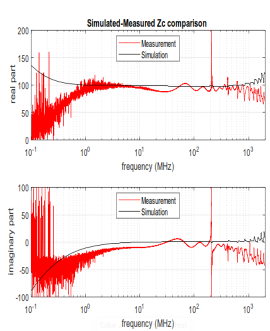
B. François



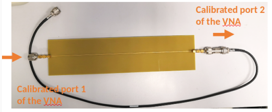


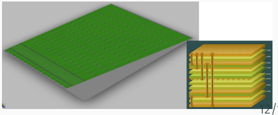
Prototypes

- First prototype "test structure" built
  - Learn subtleties of measurements
  - Validate simulation tool ⇒ good agreement for frequencies of interest
- Next prototypes designed and being fabricated
  - Varying sizes of shields, depths of layers, etc...
  - Measurements of realistic cells



R. Chiche





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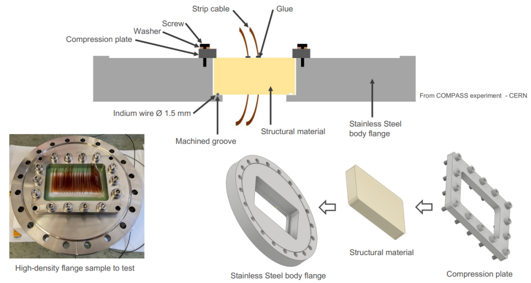
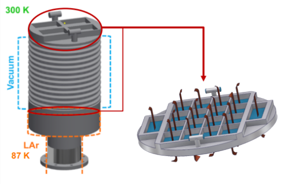




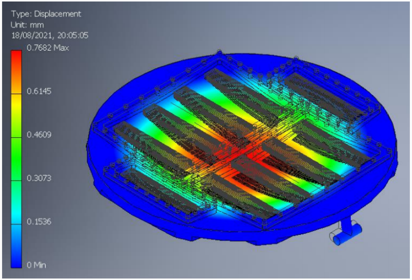
M. Barba

Signal extraction from cryostat

- High density feedthroughs needed in case readout electronics outside of cryostat
- Aim for $\sim \times 5$ density and $\sim \times 2$ area wrt ATLAS

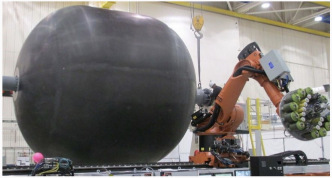
Ongoing CERN R&D

- Prototypes of 3D-printed epoxy resins structures with slits for strip cables, glued to the flange
- Leak tests and pressure tests at 300 K and 77 K
  - Suitable materials identified
- Stress / deformation simulations of complete designs at 300 K and 77 K



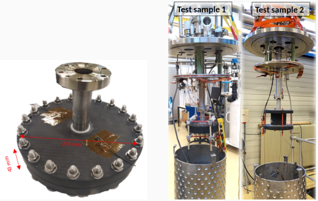
Minimizing dead material in front of calo

- Crucial for low energy measurements at FCCee
- Ongoing R&D for cryostats using new materials and sandwiches
  - Generic R&D at CERN as cryos will be used for solenoids in all experiments
  - Synergy with progress in aerospace
  - Test microcack resistance, sealing methods, leak and pressure tests
  - Address CFRP/Metal interfaces
- Promises for 'transparent' cryostats: few % of X_0 !



NASA's lineless cryotank

Criteria: Safety Factor = 2	Honeycomb Al				Solid shell			
	HM CFRP		Al		HM CFRP		Al	
	OWC	ICC	OWC	ICC	OWC	ICC	OWC	ICC
Material budget X/X0	0.03	0.043	0.094	0.17	0.092	0.12	0.34	0.44
X0 % savings	-68%	-75%	REF	REF	-2%	-29%	262%	159%
Skin Th. [mm]	3.2	4.8	3.9	7.5				
Core Th. [mm]	32	38	40	40				
Total Th. [mm]	38.4	47.6	47.8	55	24	30.4	30	39
Thickness % savings	-20%	-13%	REF	REF	-50%	-45%	-37%	-29%



Sealing with Belleville washers

S. Molina

Goals of low noise

- Good resolution even for ~ 300 MeV photons
- Measure MIPs deposits

Master formula

- Dominant noise term goes as $C\sqrt{4kT/(g_m\tau_p)}$
- Where C depends on cell capacitance and on the transmission line
- τ_p can be much larger than in ATLAS: 50 $\rightarrow$ 200 ns

Cold electronics ?

- Gain on g_m, T and C (short transmission line) !
  - Noise requirements easily achieved
- No radiation hardness issue at FCCee, could simplify feedthrough design
- Challenges are heat dissipation and difficulty of repairs

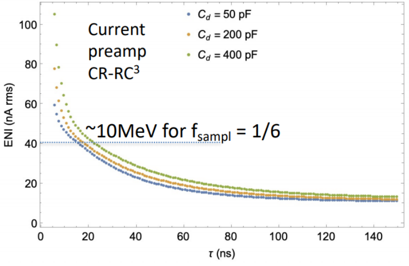
Warm electronics ?

- A la ATLAS, with longer shaping
- Low enough noise level seems achievable ($S/N > 3$ for MIPs)

$$C_{cable} = \frac{\tau_{delay}}{Z_c}$$

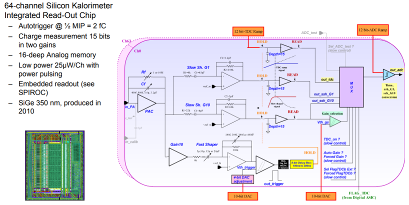
	ENC (keV)	Peaking time = 500 ns
Warm electronics, L = 5 m, C_{cable} = 500 pF / 1 nF	Cd = 100pF – 50/25 Ω	1400 / 2500
	Cd = 200pF – 50/25 Ω	1600 / 2800
	Cd = 400pF – 50/25 Ω	2100 / 3200
	Cd = 800pF – 50/25 Ω	2900 / 4100
Cold electronics, L=10 cm, C_{cable} = 10 pF / 20 pF	Cd = 100pF – 50/25 Ω	140 / 150
	Cd = 200pF – 50/25 Ω	250 / 260
	Cd = 400pF – 50/25 Ω	470 / 470
	Cd = 800pF – 50/25 Ω	910 / 910

R. Chiche



M. Aleksa

FUTURE CIRCULAR COLLIDER



Goal: $\sim 40 \times 40$cm proto in a few years

- Only testbeam will tell if the concept will work

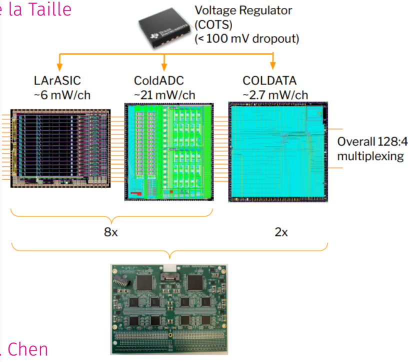
Mechanics

- Work on absorbers to start in Autumn
- Spacers: ideas for 3D-printing

Readout electronics

- Requirements not too far from other projects
- SKIROC chip for CALICE good candidate
  - Does not work at cryo temperatures
  - Energy consumption too high
  - Can be used for warm electronics
- DUNE readout electronics
  - Dynamic range not large enough
  - Sufficient for cold electronics in a first prototype

C. de la Taille



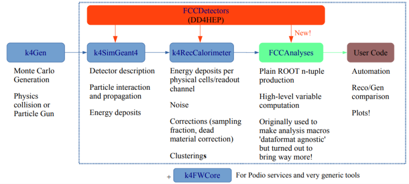
H. Chen

Cryostat

- Possible synergy with first carbon fiber prototype from CERN

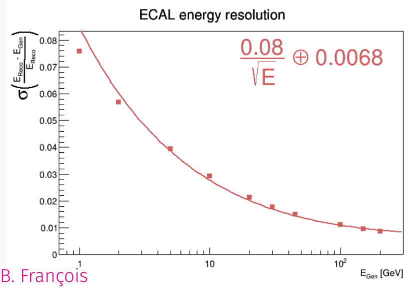
Geometry implemented in FCC SW

- 12 layers, 22 X^0
- 2x1.2 mm LAr, 2mm Pb/Steel, 1.2mm PCB, inclined by 50^o
- Typical cell size: 2x2x3 cm^3
- Reconstruction and simple cluster corrections enable first performance studies
  - See presentation from Valentin Volkl

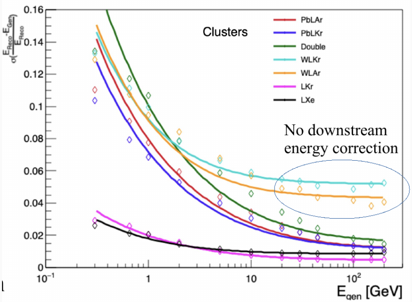


Optimizing the design

- Important design options: Pb vs W, LAr vs LKr
- Photon energy resolution: baseline design gives $8\%/\sqrt{E}$
- Preliminary comparisons performed



B. François



M. Waterlaat

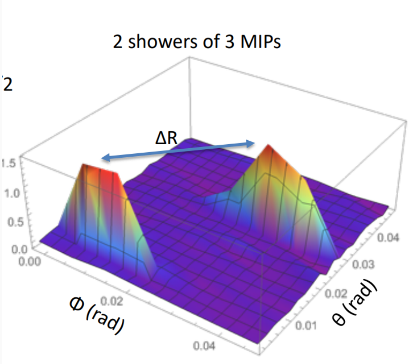
FUTURE CIRCULAR COLLIDER

Optimizing the granularity

- Use of PCB gives large flexibility
- First studies focusing on π^0 identification efficiency and classification of τ decay modes
  - Also points towards using LKr to benefit from smaller R_M (4cm with LAr)

Next step: move to jet physics

- Jet energy resolution of $\sim$ 4% at 45 GeV requirement for Higgs physics
- Pandora PFA integration in FCC SW in progress
  - J. Smiesko
- Assuming some HCAL, will allow to perform end-to-end detector optimization
- Calo concept also well suited for new clustering techniques (e.g CLUE), ML approaches



M. Aleksa

Recon → / Gen ↓	$\pi^\pm\nu$	$\pi^\pm\pi^0\nu$	$\pi^\pm 2\pi^0\nu$	$\pi^\pm 3\pi^0\nu$	$\pi^\pm 4\pi^0\nu$
$\pi^\pm\nu$	**0.9560**	0.0425	0.0010	0.0003	0.0002
$\pi^\pm\pi^0\nu$	0.0374	**0.9020**	0.0586	0.0016	0.0002
$\pi^\pm 2\pi^0\nu$	0.0090	0.1277	**0.7802**	0.0808	0.0022
$\pi^\pm 3\pi^0\nu$	0.0036	0.0372	0.2679	**0.5972**	0.0910

K. Wandall-Christensen

FUTURE CIRCULAR COLLIDER

A very productive GranuLAr workshop

- Covering all aspects of the project
- Very lively discussion after each talk
- Gaining evidence that high-granularity LAr could be a very versatile solution, fulfilling stringent FCC-ee requirements
  - Good progress on high granularity PCBs
  - Successful R&D on high-density feedthroughs
  - Clear synergy with "transparent" cryostats
  - First simulations show great performance can be achieved

Way forward

- First steps towards a detector concept
- Milestone: build a small prototype within a few years
  - Lots of technical challenges still ahead, plenty of room for new collaborators !
  - Only testbeam will prove the feasibility of the concept