Status of R&D on granular Noble Liquid Calorimeters

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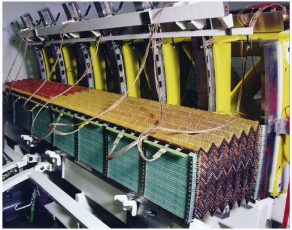
LAr Calorimeters

- LAr Calorimeters very successful at particle physics experiments: HERA, D0, NA31, ATLAS
- Sampling calorimeters, e.g Lead/LAr for ATLAS
- Excellent linearity, stability
- EM energy resolution $\frac{10\%}{\sqrt{E}} \oplus \frac{0.25}{E} \oplus 0.3\%$
- e/γ identification through 3D shower shapes

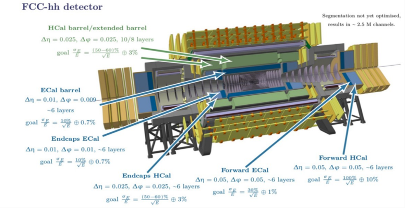


LAr Calo for FCC-hh

- First LAr study for future colliders, thanks to intrinsic radiation hardness: 1912.09962
- $\sim 10\times$ ATLAS granularity, for better use of PFlow techniques and pileup mitigation
- Reach same performance as ATLAS at much higher pileup levels

LAr Calo for *ee* machine ?

- A priori, similar concept can work very well at an e^+e^- collider too
- With *ee* conditions allowing for significant optimisations
  - On noise for low energy measurements
  - On segmentation for PID/PFlow use



Optimizing granularity for PFlow

- High granularity electrodes
- High density feedthroughs
- Add timing to the mix ?

High energy resolution

- Minimize dead material (cryostat)
- Low noise electronics

General design

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

Reaching 10× ATLAS granularity

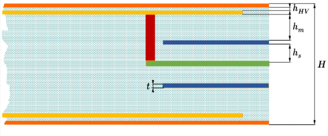
- 200000 cells → few million cells
- Readout in ATLAS uses simple copper/kapton electrodes
- Issue: traces to route signals to front or back of electrode take space !
- For 10× more granular: go to multilayer PCB to route signals in a deep layer

Basic design

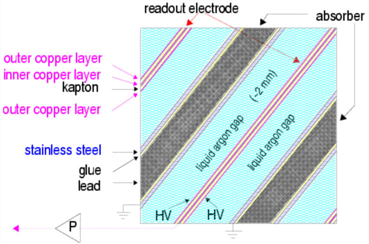
- Multi-layer PCB cannot be bent to accordion as ATLAS Kapton electrode

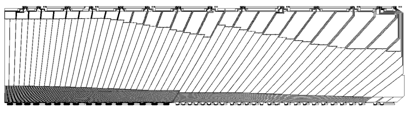
⇒ Straight planes inclined around the barrel

- Simulation in a specific IDEA-LAr setup



Side view




Design of ATLAS electrodes

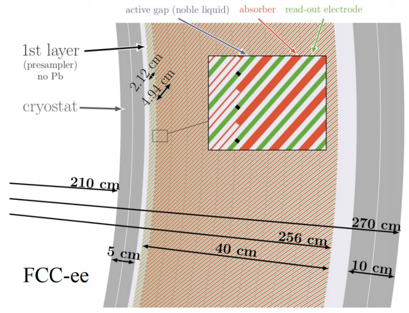
Tilted planes around cylinder: non-trivial geometry !

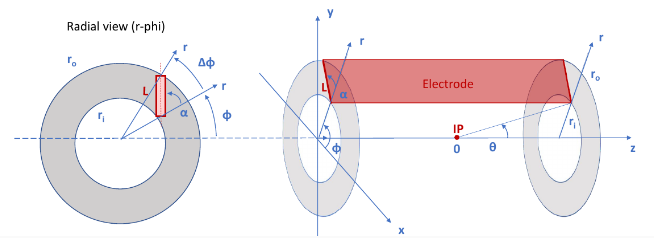
- Can be tuned to give nice properties, i.e constant number of electrodes seen across ϕ, possibility to group electrodes into cells, adjust depth of each layer...
  - Fine segmentation where needed, i.e 'strips' in ATLAS for π^0 rejection
- Projective cells along η
- Gap widening at high radius

$\Rightarrow$ non-constant sampling fraction within a cell

$\Rightarrow$ mitigated by high longitudinal segmentation

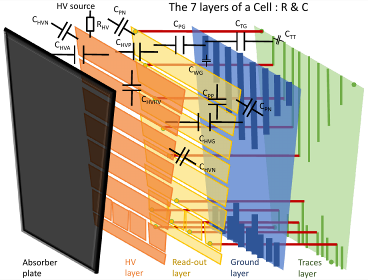
  - 12 layers in baseline design





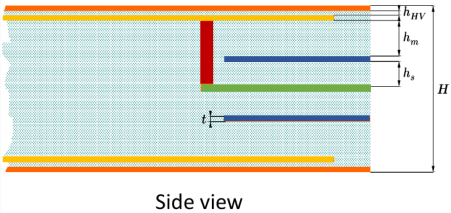
Principle

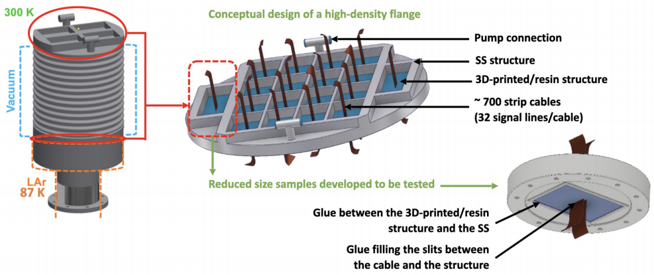
- HV layer capacitively coupled to readout layer
- Signal transferred from both sides to read-out trace through a via
- Shielding traces reduce cross-talk from other segments



Calculation of cell properties

- Cell capacitance: $C_{\text{cell}} \sim C_{HVA} + C_{PG}$
  - Estimation by analytical calculations and Finite Element Methods: 25 – 250 pF
- Transmission line capacitance adds up for noise and signal shape
- Multi-parameter optimisation:
  - Trade-off capacitance / cross-talk ?
  - What is the maximum density of signal traces ?
  - Can we readout all cells at the back, or do we have to route the first segments to the front ? (as in ATLAS)



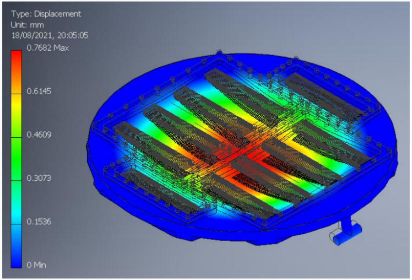


Signal extraction from cryostat

- 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

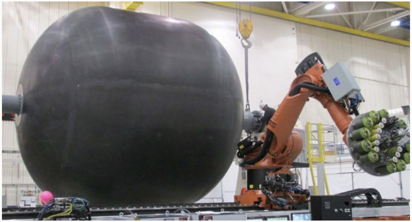
- Prototypes of 3D-printed epoxy resins structures with slits for strip cables, glued to the flange
- Leak tests and pressure tests at 300 K and 77 K
- Stress / deformation simulations of complete designs at 300 K and 77 K



Minimizing dead material in front of calo

- Crucial for low energy measurements at FCCee
- Ongoing R&D for cryostats using new materials and sandwiches
  - See talk in ECFA TF8 meeting
  - Test microcack resistance, sealing methods, leak and pressure tests
- Promises for 'transparent' cryostats: few % of X_0 !

	Sandwich			Baseline	
	UHM CFRP	HM CFRP	IM CFRP	Al	Ti
Avg. Th. [mm]	3.5	3.8	4.9	4.0	1.5
Material budget X/X_0	0.0134	0.0147	0.0189	0.045	0.034
X_0 + %	-70%	-67%	-58%	X_0	-24%
Skin Th.[mm]	1.2	1.2	1.6	1.7	
Core Th. [mm]	25	33	40	40	
Total Th. [mm]	27.4	35.4	43.2	43.4	101
Thickness + %	-37%	-18%	0%	T	+133%



NASA's lineless cryotank

Specifications

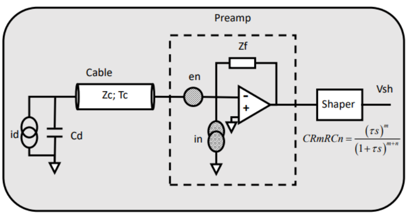
- Low noise:
  - Must "see" MIPs
  - Small noise term even for low energy photon clusters
- Cross-talk at % level
- Dynamic range ∼ 14 bit for FCCee

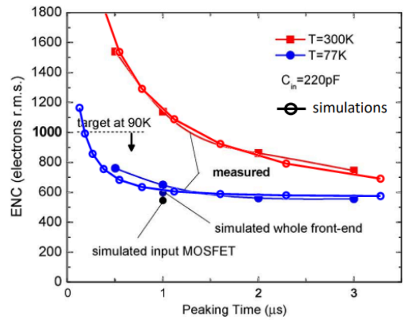
Study of the complete readout chain

- Actual performance will depend on a large number of parameters
  - Readout electrode properties
  - Transmission line
  - Type and performance of preamplifier
  - Shaping time

⇒ Produce PCB prototypes to validate simulations (AIDAInnova project)

⇒ Investigate readout electronics options on simulation, based on existing ASIC performance (ATLAS LAr, CMS HGCAL, DUNE)





Achieving very low noise

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 $\rightarrow$ 400 ns

Cold electronics ?

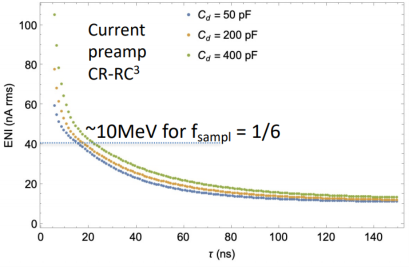
- Gain on g_m, T and C (short transmission line) !
  - Noise requirements can be achieved
- No radiation hardness issue at FCCee, could simplify feedthrough design
- Challenges are heat dissipation and difficulty of repairs

Warm electronics ?

- A la ATLAS, with longer shaping
- First calculations indicate low enough noise levels achievable ($S/N > 3$ for MIPs)

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

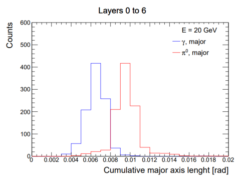
	ENC (keV)	Peaking time = 500 ns
Warm electronics, L = 5 m, C_{cable} = 500 pF / 1 nF	Cd = 100pF – 50/25 Ω	1400 / 2500
	Cd = 200pF – 50/25 Ω	1600 / 2800
	Cd = 400pF – 50/25 Ω	2100 / 3200
	Cd = 800pF – 50/25 Ω	2900 / 4100
Cold electronics, L=10 cm, C_{cable} = 10 pF / 20 pF	Cd = 100pF – 50/25 Ω	140 / 150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



Detector optimisation

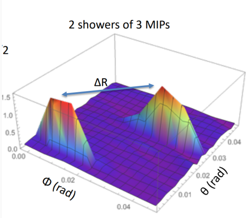
Many open design questions

- Choice of absorber (Pb, W) and active material (LAr, LKr) materials and gap sizes
  - Implications on sampling term ($\sigma \sim 8\%/\sqrt{E}$ for baseline LAr/Pb), compactness, cost
  - Also manufacturing considerations, implications on constant term
- Optimization of granularity
  - Use of PCBs gives large flexibility, with constraints on maximal density of readout cells



End-to-end detector optimisation

- Ideally perform optimization by computing figures of merits for physics analyses
- Photon energy resolution and EM shower shape discrimination can be studied with the calo design alone
  - Studies ongoing, use-case is τ physics
- But evaluation of electrons, jets, MET performance requires PFlow and full detector design
  - Integration in FCCSW key point to reach this goal
  - For now use simple cluster-level corrections for EM resolution studies



Timing capabilities

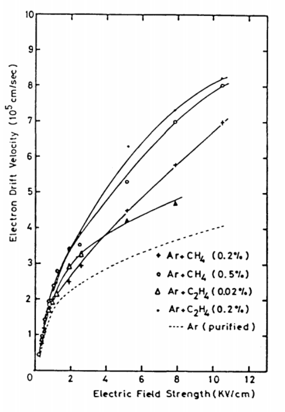
- ATLAS resolution for EM showers: $\sim$ 260 ps at 20 GeV, 130 ps at 100 GeV
- Time resolution to be evaluated on FCCee design
  - Electronics can be optimized, but limitations from stochastic ionization
- Overall detector design choices will impact usefulness of LAr timing: presence of a timing layer, dE/dx for PID...

Doping of Noble Liquid

- Increase signal yield by enhancing drift velocity
- R&D performed >25 years ago, never used in a calorimeter (fears of unsufficient radiation hardness)
- Could be studied again for FCCee use-case

Noble Liquid Scintillation

- Fast signal used in Dark Matter Noble Liquid detectors
- If measured in a calorimeter, would provide 'dual-readout'
- Huge design challenge to collect and measure this light



Project of LAr calo for FCC-ee still in early stages

- Many open questions, even basic ones
  - Absorber and active material choices
  - Design for the endcaps ?
- Liquid calorimetry has proved its merits over decades
- Physics performance evaluation for design optimisation and R&D for critical items in the design need to go in parallel

Making a LAr calo design for FCC-ee is a high-tech project !

- Some of the building blocks require exploring new technologies
  - Thin cryostat, cold integrated electronics

It has the potential to be a versatile calorimeter for FCC-ee

- Excellent EM resolution, including at low energy ($< 8\%/\sqrt{E}$ + low noise)
- (Relatively) fine granularity for PID and for PFlow
- Invariant in ϕ rotations, without any crack
- Pointing cells in both ϕ and θ

Community around the project

- Small number of institutes: CERN, Charles Univ, IJCLab, Univ of Copenhagen, Univ of Edinburgh
- Working on both technical R&D aspects and general design / performance evaluation
- New collaborators welcome !