NOBLE LIQUID CALORIMETRY FOR FCC-EE

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FCC Noble Liquid Calorimetry group

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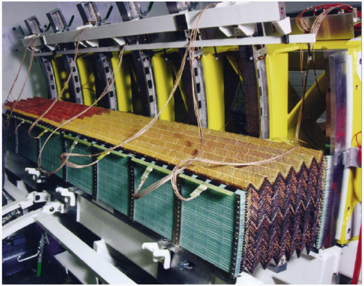
INTRODUCTION

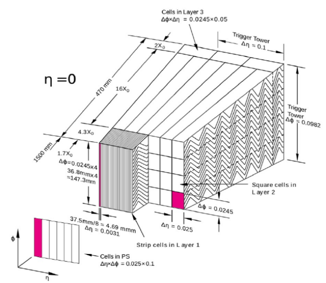
Noble Liquid Calorimeters

- 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

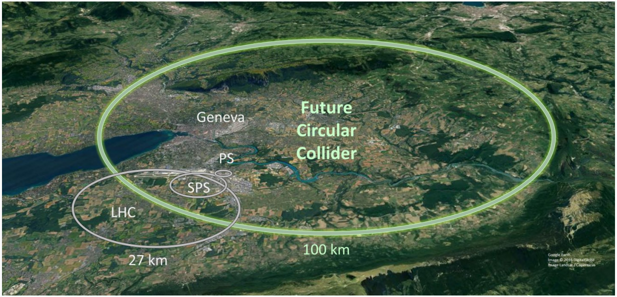
- Excellent physics performance matching its specs.
    - Instrumental to Higgs boson discovery !
    - Resolution: $10\%/\sqrt{E} \oplus 0.2/E \oplus 0.7\%$
    - Linearity at per-mille level over 4 orders of magnitude
    - Stability over time at 10^{-4}
- 14 years of successful operation
    - See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





CONTEXT: CALORIMETERS FOR FCC-EE

ESPP 2020: An e^+e^- Higgs factory is the highest-priority next collider



The possible next machine at CERN

- 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

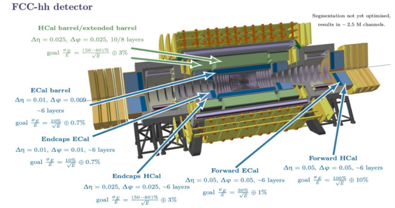
Requirements for FCC-ee

- Excellent shower shape discrimination for event classification
- Unprecedented hadronic resolution: $\sim 4\%$ at 50 GeV
- → 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

NOBLE LIQUID CALORIMETRY FOR FCC

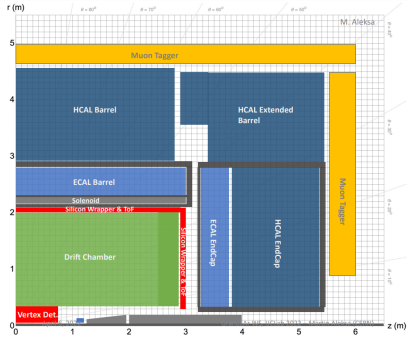
Initial studies for FCC-hh

- 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
- First ever workhop organised at IJCLab in April 2022



GRANULAR NOBLE LIQUID CALO FOR *ee* MACHINES: HOW ?

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

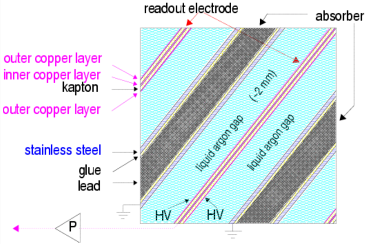
Simulations to allow performance optimization

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

Concept of High granularity electrodes

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

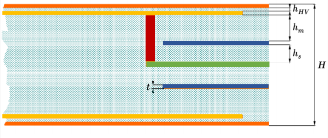


Basic design

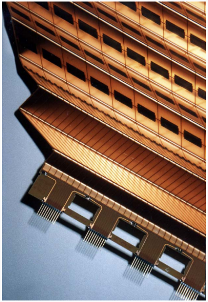
- Multi-layer PCB cannot be bent to accordion as ATLAS Kapton electrode

⇒ Straight planes inclined around the barrel

- Simulation in a specific IDEA-LAr setup



Side view



DETECTOR GENERAL DESIGN

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

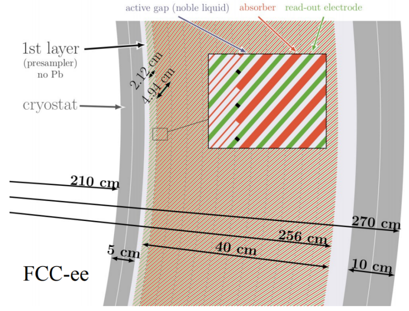
$\Rightarrow$ non-constant sampling fraction within a cell

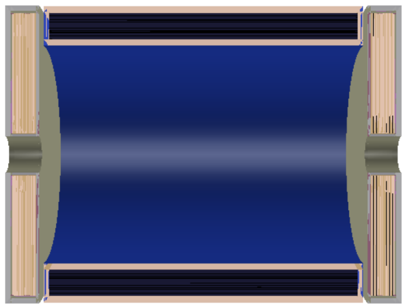
$\Rightarrow$ mitigated by high longitudinal segmentation

  - 12 layers in baseline design

Endcaps

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

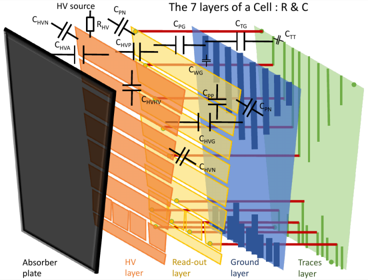




ELECTRODES DESIGN AND PROPERTIES

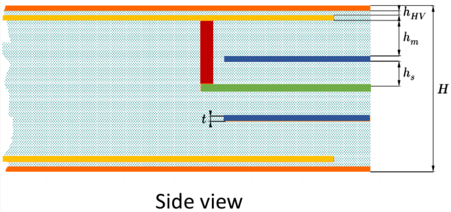
Principle

- 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



Side view

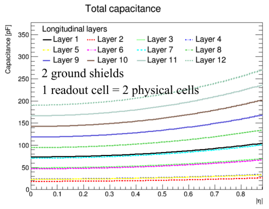
ELECTRODES PROTOTYPES

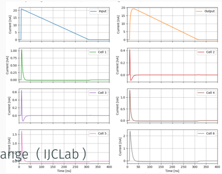
Simulations of capacitances and cross-talk

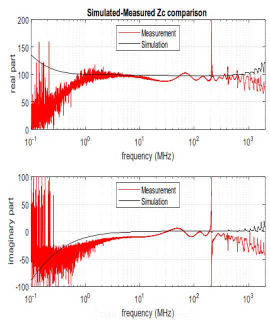
- Use Cadence/Sigrity and FEM tool ANSYS HFSS
- Cell capacitance driven by readout - shield capa
- Cross-talk limited $< 0.2\%$ for long shaping times

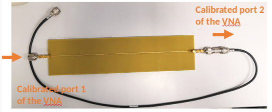
Prototypes

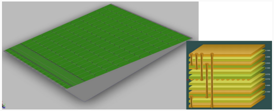
- First prototype "test structure" built
  - Learn subtleties of measurements
  - Validate simulation tool ⇒ good agreement for frequencies of interest
- Next prototypes designed and being fabricated
  - Varying sizes of shields, depths of layers, etc...
  - Measurements of realistic cells



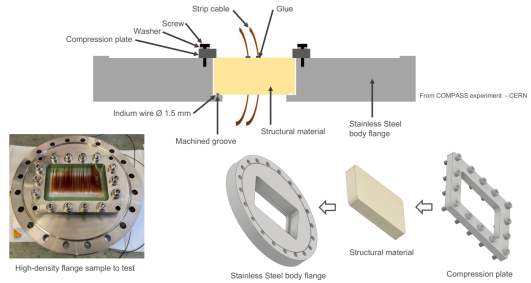


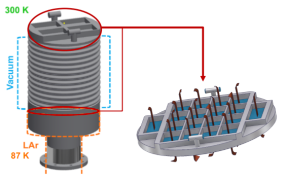






HIGH DENSITY FEEDTHROUGHS



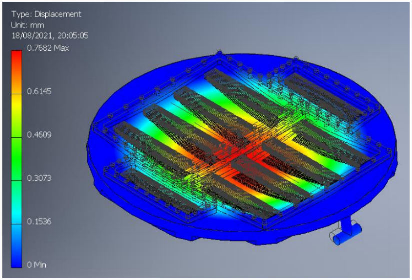


Signal extraction from cryostat

- High density feedthroughs needed in case readout electronics outside of cryostat
- Aim for ∼ ×5 density and ∼ ×2 area wrt ATLAS

Ongoing CERN R&D

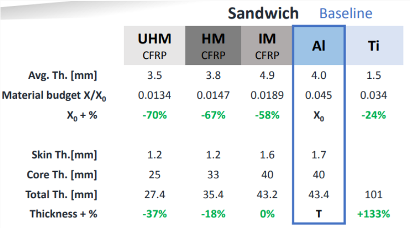
- Prototypes of 3D-printed epoxy resins structures with slits for strip cables, glued to the flange
- Leak tests and pressure tests at 300 K and 77 K
  - Suitable materials identified
- Stress / deformation simulations of complete designs at 300 K and 77 K



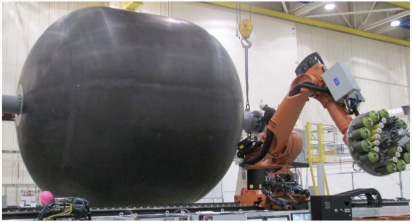
THIN CRYOSTAT

Minimizing dead material in front of calo

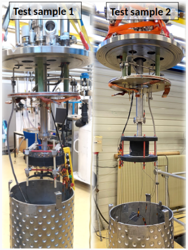
- Crucial for low energy measurements at FCCee
- Ongoing R&D for cryostats using new materials and sandwiches
  - Generic R&D at CERN as cryos will be used for solenoids in all experiments
  - Synergy with progress in aerospace
  - Test microcack resistance, sealing methods, leak and pressure tests
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



	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



READOUT ELECTRONICS: ACHIEVING VERY LOW NOISE

Goals of low noise

- Good resolution even for $\sim$ 300 MeV photons
- Measure MIPs deposits

Master formula

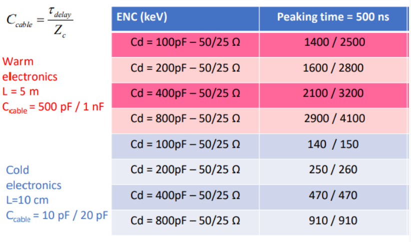
- Dominant noise term goes as $C\sqrt{4kT/(g_m \tau_p)}$
- Where C depends on cell capacitance and on the transmission line
- τ_p can be much larger than in ATLAS: 50 $\rightarrow$ 200 ns

Cold electronics ?

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

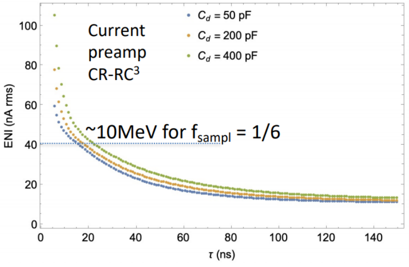
Warm electronics ?

- 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



TOWARDS A FIRST CALORIMETER PROTOTYPE

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

- Only testbeam will tell if the concept will work

Mechanics

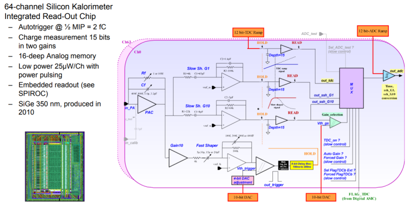
- Work on absorbers to start in Autumn
- Spacers: ideas for 3D-print

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

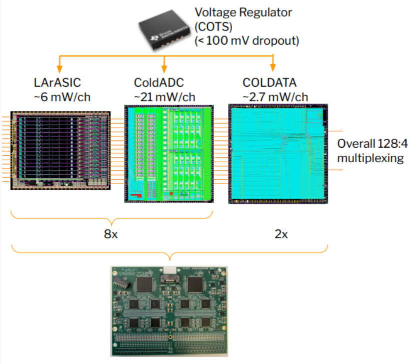
Cryostat

- Possible synergy with first carbon fiber prototype from CERN



64-channel Silicon Kalorimeter Integrated Read-Out Chip

- Autotrigger @ ½ MIP = 2 fC
- Charge measurement 15 bits in two gains
- 16-deep Analog memory
- Low power 25μW/Ch with power pulsing
- Embedded readout (see SPIROC)
- SiGe 350 nm, produced in 2010



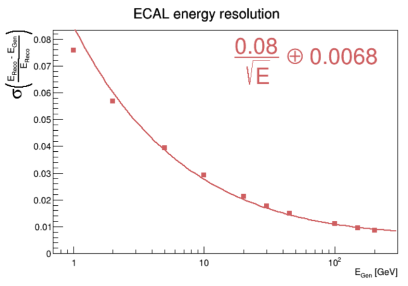
SIMULATION AND PERFORMANCE I

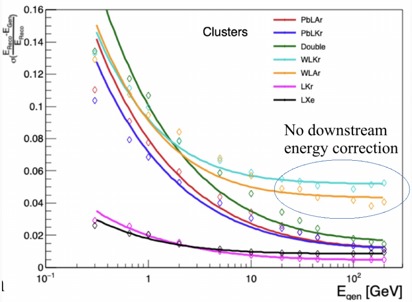
Geometry implemented in FCC SW

- 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

Optimizing the design

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





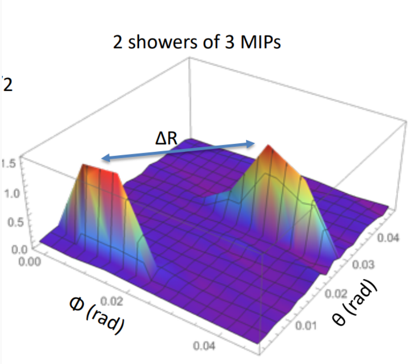
SIMULATION AND PERFORMANCE II

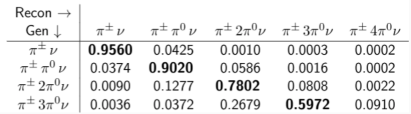
Optimizing the granularity

- 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
- Assuming some HCAL, will allow to perform end-to-end detector optimization
- Calo concept also well suited for new clustering techniques, ML approaches





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

OPENING UP OTHER R&D OPPORTUNITIES

Timing capabilities

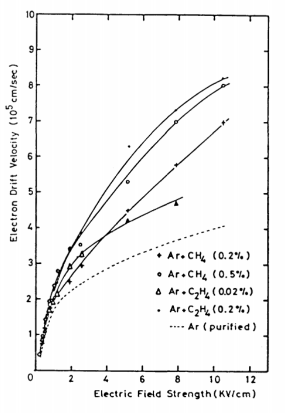
- ATLAS resolution for EM showers: $\sim$ 260 ps at 20 GeV, 130 ps at 100 GeV
- Time resolution to be evaluated on FCCee design
    - Electronics can be optimized, but limitations from stochastic ionization
- Overall detector design choices will impact usefulness of LAr timing: presence of a timing layer,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



CONCLUSIONS

Noble Liquid Gas is an excellent technology for calorimeters

- Resolution, granularity, linearity, uniformity, stability

An appealing candidate for a FCC-ee detector

- Small but active R&D starting again to shape future detectors
- Gaining evidence that high-granularity LAr could be a very versatile solution, fulfilling stringent FCC-ee requirements
  - Capacitance and cross-talk of high-granular readout PCBs good
  - Successful R&D on high-density feedthroughs
  - Synergy with ”transparent” cryostats
  - First simulations show great performance can be achieved
- Starting the design of a full detector concept around such a calorimeter