# Design and performance of the calorimeter system for ALLEGRO FCC-ee detector concept

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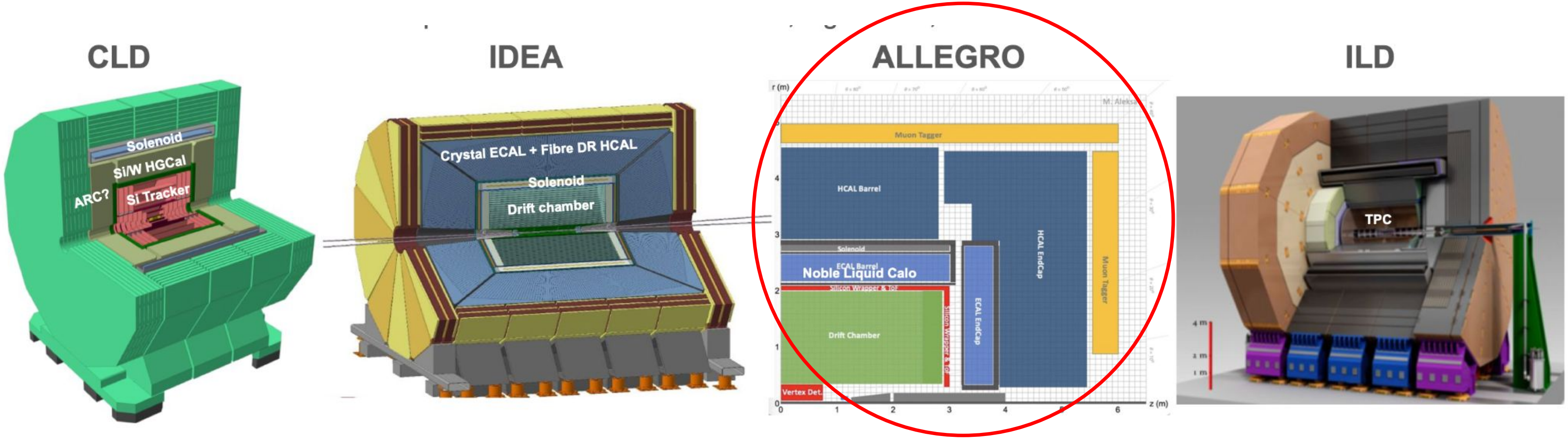
on behalf of the ALLEGRO team

ECFA workshop 2024

# FCC-ee detector concepts under study

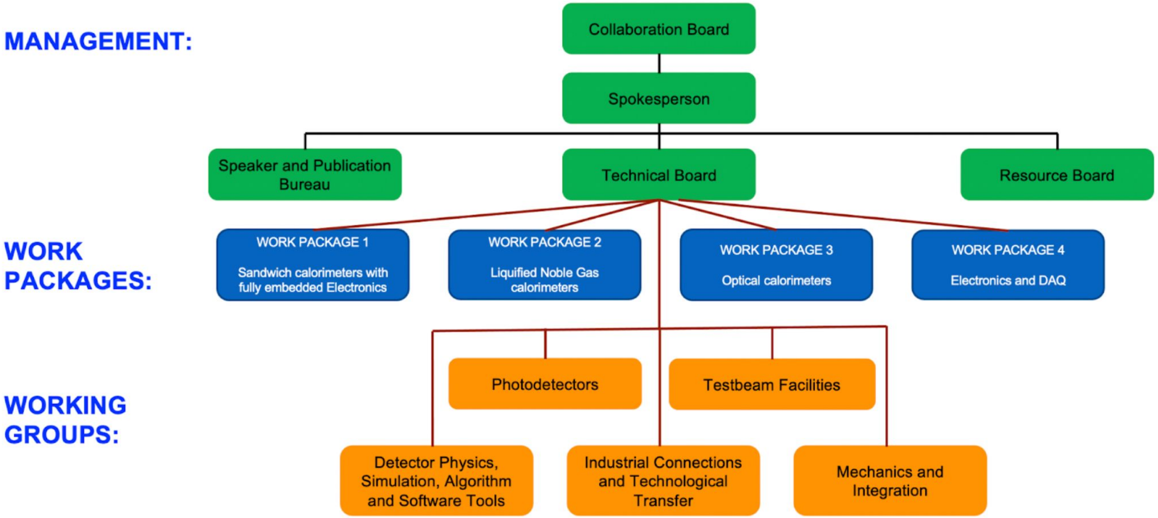



## ALLEGRO

- A design in its infancy
- Si vertex detector
- Ultra light drift chamber (or straw tracker or Si)
- High granularity Noble Liquid ECAL inside 2T solenoid
- TileCal-like or CALICE-like HCAL
- Muon system

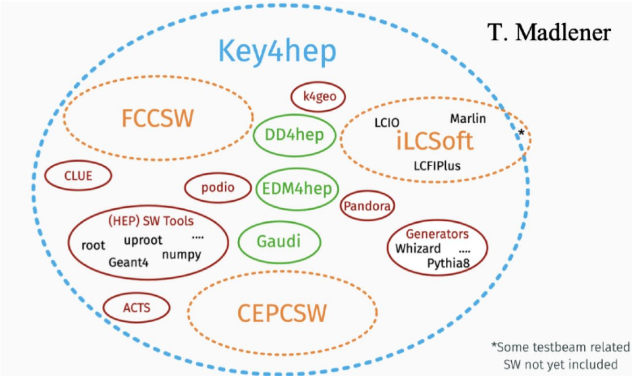
# DRD6 Collaboration

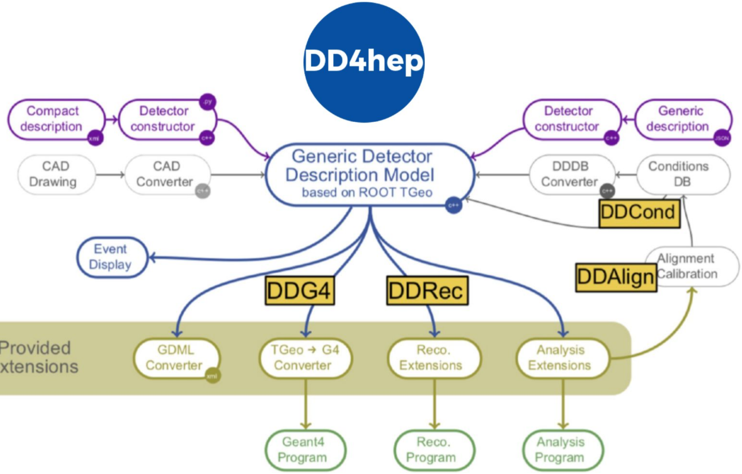
- **Detector R&D (DRD) collaborations** being set-up to implement the **ECFA detector R&D Roadmap**
- **DRD6 on calorimetry** with 4 work packages (WP) and several transversal activities
  - Noble Liquid Calorimeter R&D part of WP 2 (20 institutes from 7 countries)
  - TileCal R&D part of WP 3 (7 institutes from 6 countries)
  - CALICE-like AHCAL part of WP 1 (10 institutes from 4 countries)
- DRD Proposal has been submitted, implementation beginning of 2024



# Simulation

- Detailed (Geant4-based) simulation is required to evaluate and optimize detector designs
- For ALLEGRO, this is done with the key4hep SW ecosystem
- Geometry defined with DD4hep
- C++ code defines structure, with parameters taken from xml files
  - simple to make modifications
  - swap in/out detector systems, etc.
- More in talk by Juraj Smiesko



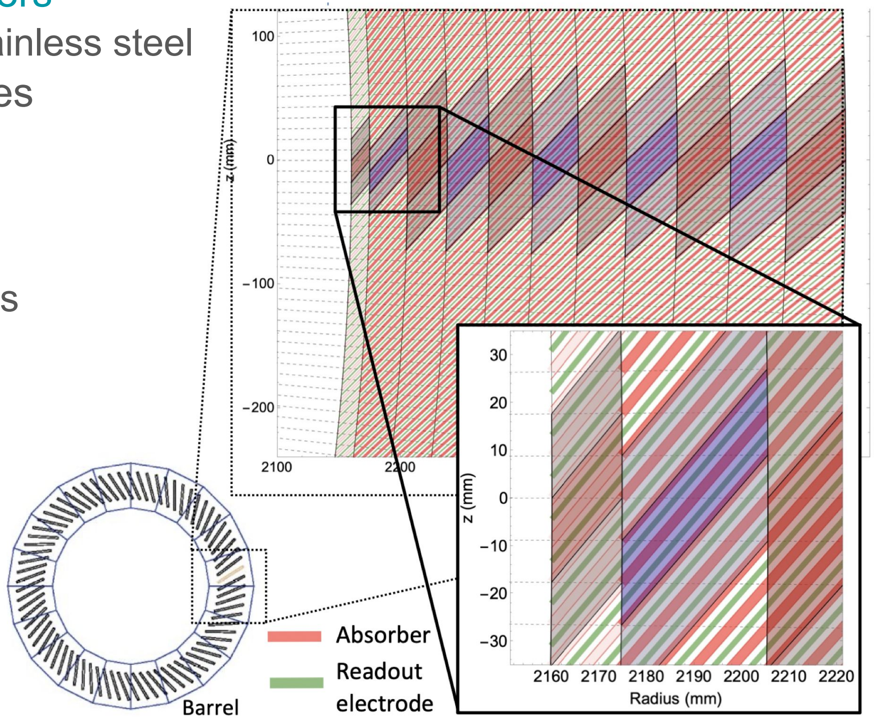



# ALLEGRO detector concept and its calorimeters

- **A L**epton co**L**lider **E**xperiment with **G**ranular **R**ead-**O**ut
- Highly-granular noble liquid ECal
  - Pb/W+LAr (or denser W+LKr)
  - Light coil (0.76 $X_0$) inside same low-material cryostat (< 0.1$X_0$) as ECal
- TileCal-like or CALICE-like HCal
  - TileCal: WS fibres+SiPMs at outer radius
  - Calice: SiPMs directly on scintillators
- Detector design optimisation not finalized
  - Current focus on implementing all calorimeters in the full simulation
  - Advanced reconstruction techniques needed (e.g. particle flow)
  - Will present preliminary results

# ECal barrel design

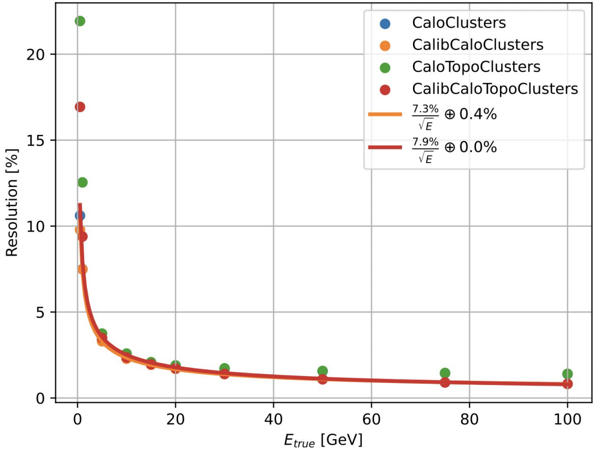
- **Baseline design** (exact parameters subject to further optimisation):
  - 1536 straight inclined (50.4°) 2 mm absorbers
    - 1.8 mm Pb, 0.1 mm glue and 0.1 mm stainless steel
  - Multi-layer PCBs used as readout electrodes
  - 1.2-2.4 mm LAr gaps
  - 40 cm deep (≈ 22 $X_0$)
  - Segmentation
    - $\Delta\theta$ ~ 10 (2.5) mrad for regular (strip) cells
    - $\Delta\phi$ ~ 8 mrad
  - 11 longitudinal compartments (in depth)

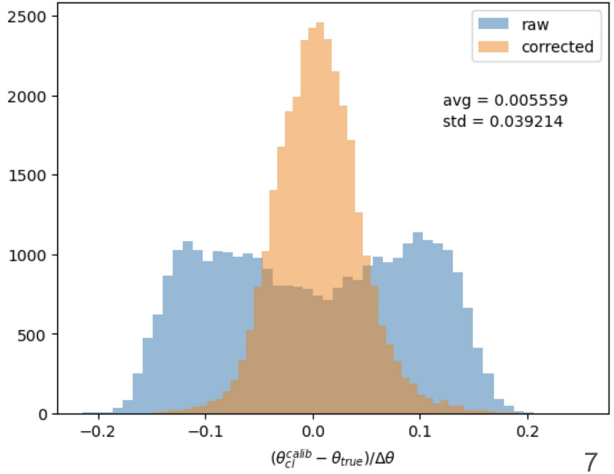



- **Possible options**
  - LKr or LAr active medium
  - W or Pb absorbers
  - Al or carbon fibre cryostat
  - Absorbers thicker at outer radius

# ECal barrel simulation

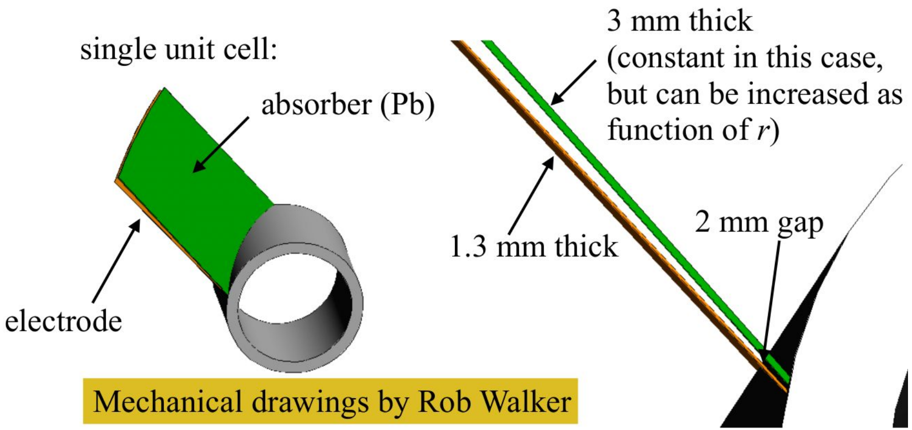
- EM resolution with a sampling term of 7-8%
- Flexible geometry implemented in FCC-SW full sim
- Benchmark for geometry optimization: photon/$\pi^0$ separation
- **Calibrations** of reconstruction
  - Simple MVA energy regression of EM clusters
  - Per layer correction for cluster barycentre position
- Implementation ongoing of Pandora **Particle Flow** (arXiv:1308.4537)
  - For technical reasons, pioneered in detector simulation with ALLEGRO ECal + CLD Tracker
- More in posters by Tong Li and Filomena Sopkova



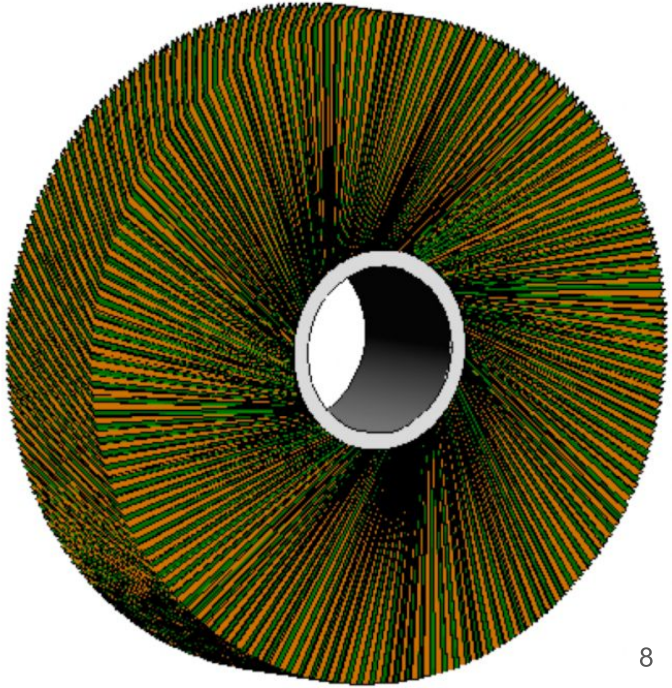



# ECal endcap design

- Endcap design more complex than barrel. A few preliminary ideas on the table
- Showing here one being implemented in the simulation ("Turbine design")
  - Similar to barrel design, with many thin absorber plates
  - Readout from high-|z| face (minimize dead material upstream of calorimeter)
  - Symmetric in $\phi$
  - Exact parameters are subject to optimization
    - width of LAr gap
    - thickness of absorbers,
    - angle of turbine blades

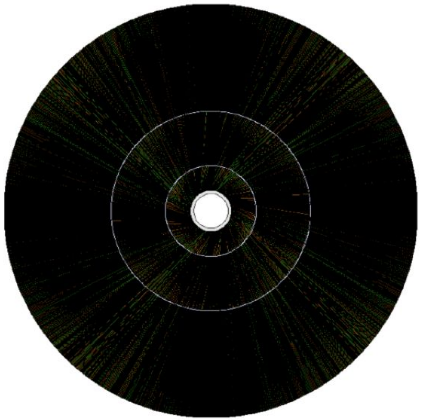



Mechanical drawings by Rob Walker

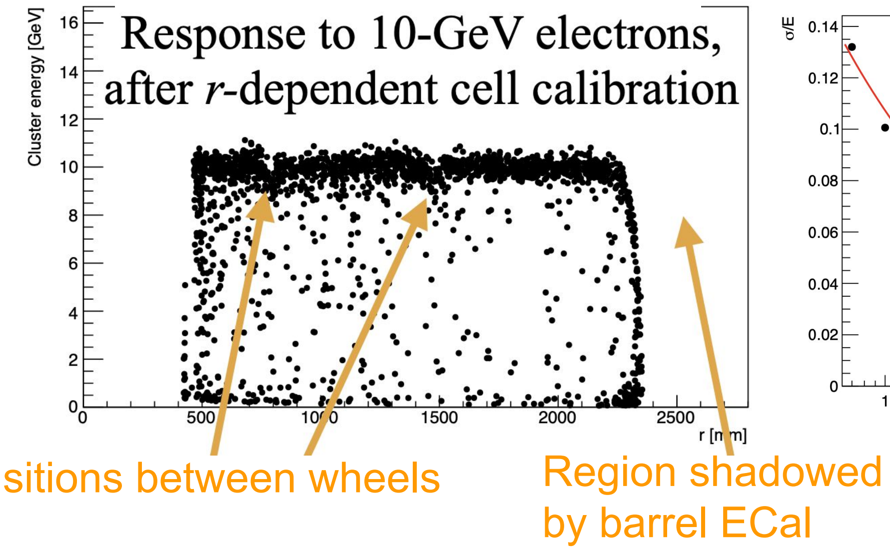


# ECal endcap simulation

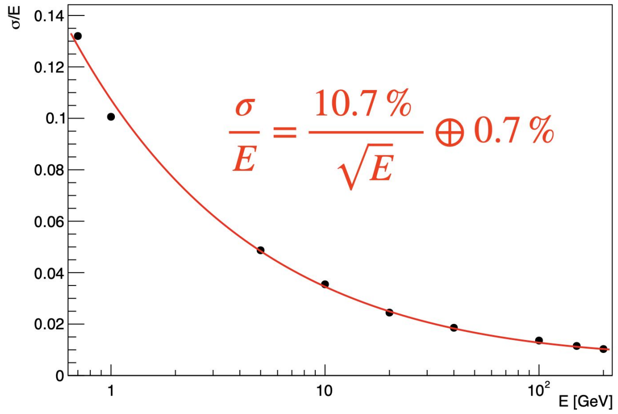
- One consideration is the variation of the gap with radius
  - It means that response is very different at the inner and outer radii (42 cm and 275 cm)
- To mitigate this, the detector can be subdivided into a set of nested wheels
- Tapering the absorbers to be thicker with increasing *r* may be necessary



LAr + tapered Pb absorbers



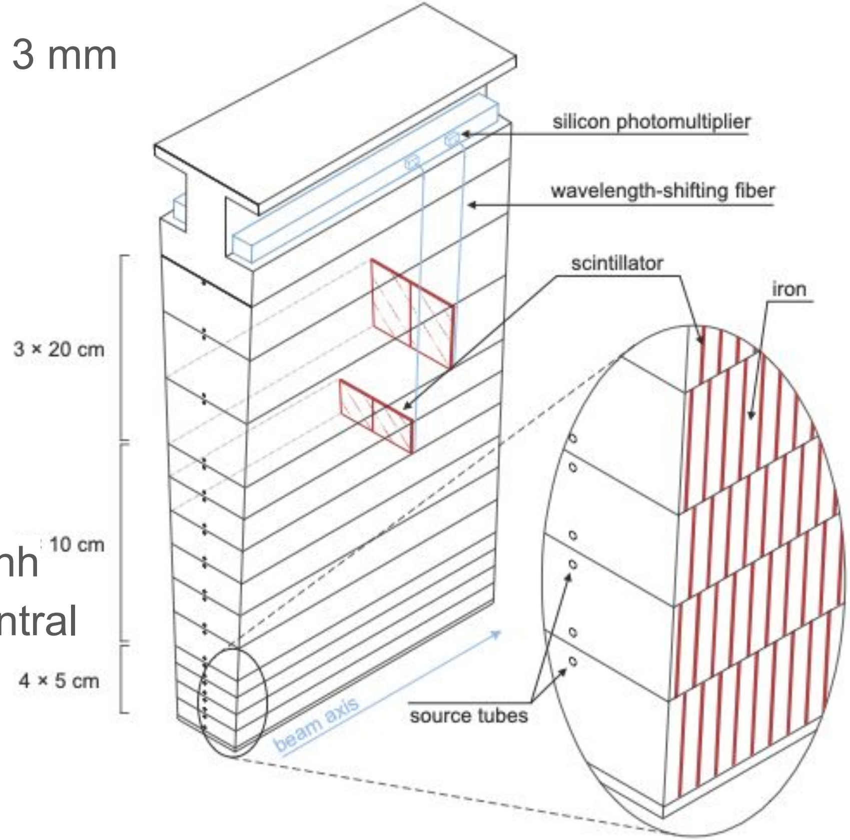

Resolution similar to barrel ECal



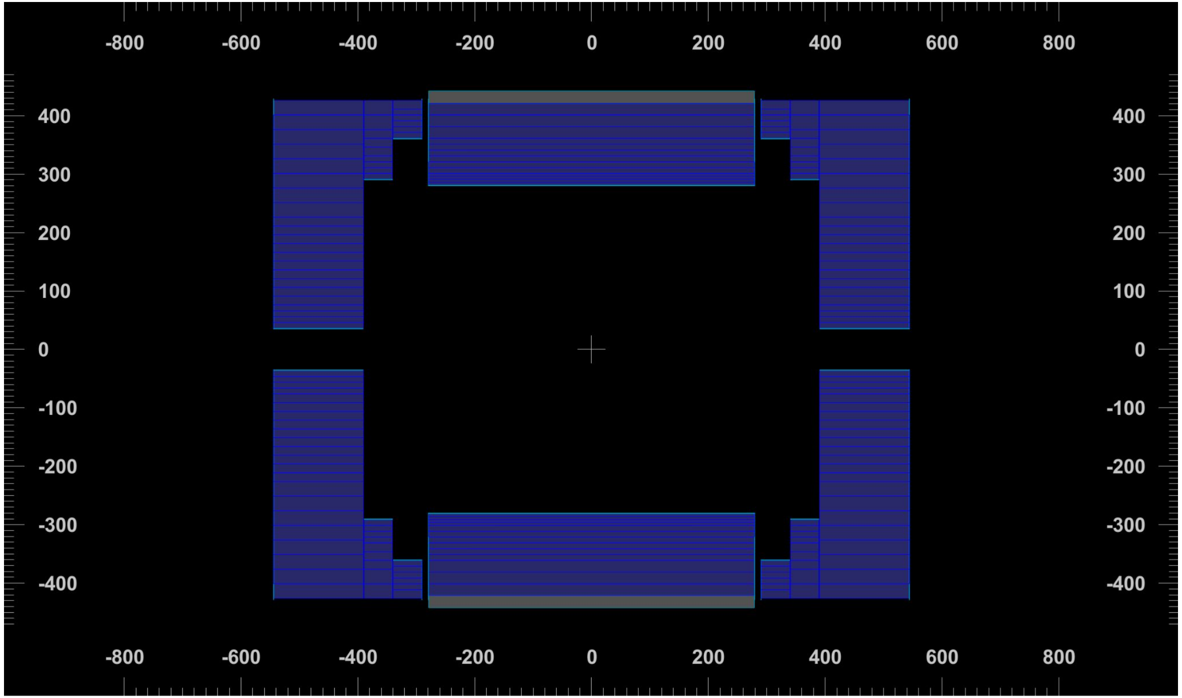
# HCal barrel and endcap design

## Currently implemented in the simulation: **TileCal-like** design

- 5 mm steel absorber plates alternating with 3 mm scintillator plates
- 140 cm deep (8-9 $\lambda$)
- Segmentation
  - $\Delta\theta$ ~ 22 mrad (grouping 3-4 tiles)
  - 128 modules in $\phi$,
    - 2 tile/module $\rightarrow$ $\Delta\phi$ = 25 mrad
- Barrel: 13 radial layers
- Endcap: 6 - 9 - 22 radial layers
- Removed the Pb plates compared to FCC-hh design (HCal acts as return yoke for the central solenoid)



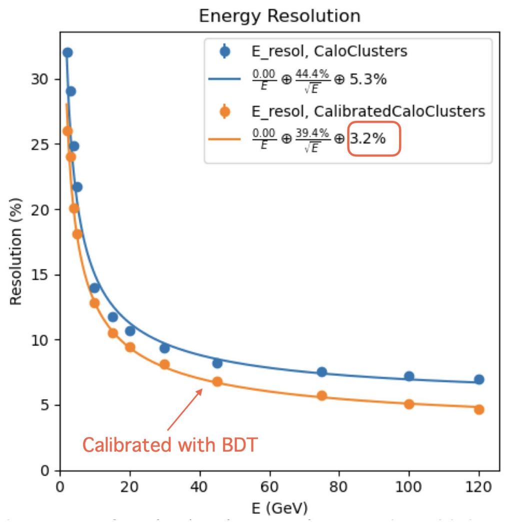
# HCal barrel and endcap visualisation



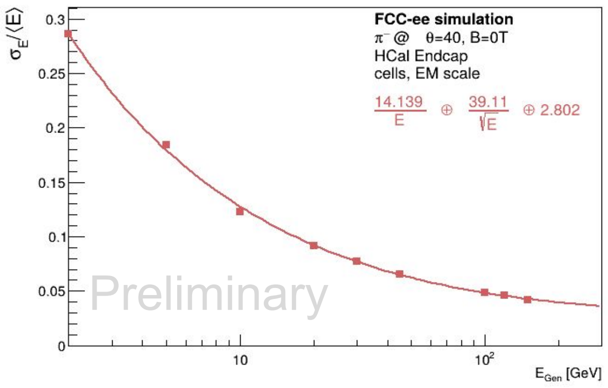

- TileCal technology is not well-suited for the endcap region near the beam pipe
- We are open to exploring other possibilities and welcome new proposals or ideas
- For now, our goal is to complete the full detector simulation to enable physics studies

# HCal barrel and endcap simulation

- Barrel: Implemented MVA calibration of cluster energy, using boosted decision tree (BDT), compared to cell-based approximate calibration using 100 GeV $\pi^-$
  - Inputs: total cluster energy $E_{cluster}$ and energy per layer → $E_i/E_{cluster}$
  - Regression target: $E_{true}/E_{cluster}$
  - Constant term decreased from 5.3% to 3.2%, energy response $(E_{cluster}-E_{true})/E_{true}$ → within 1-2%

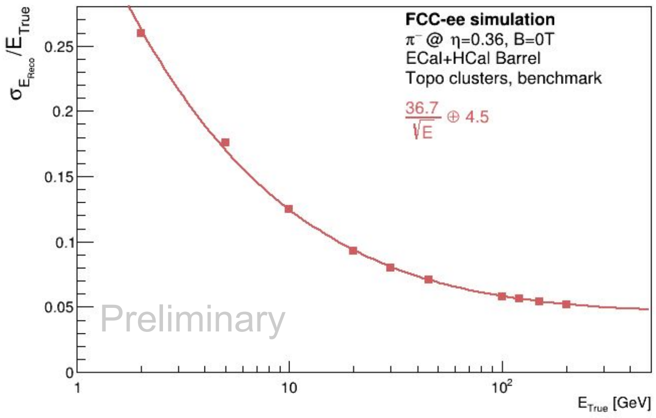


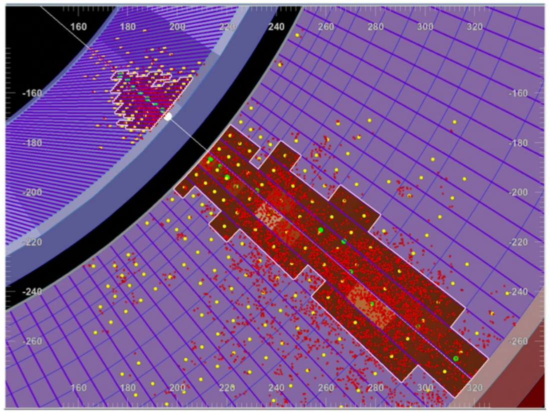

- Endcap: Implemented the detector geometry, cells readout and sliding window clustering algorithm
  - Topological clustering implementation on the way
- Next: Include HCal in the particle flow

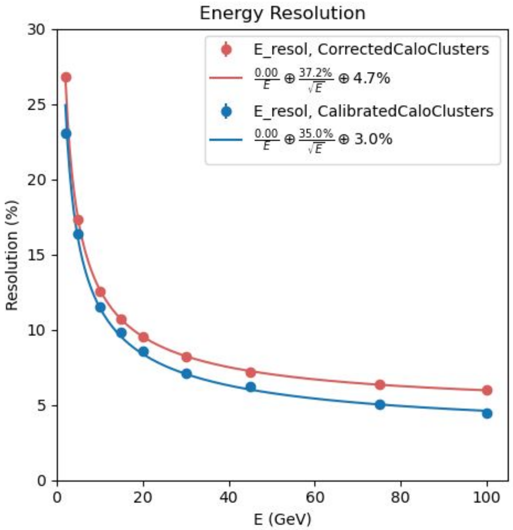


# ECal+HCal barrel combined simulation

- The goal is to combine ECal and HCal calorimeter information (and later add tracker and do particle flow)
- Topological clustering implemented in the barrel region, sliding window algorithm available as well
- Cluster energy calibration done with a BDT (similar to HCal)

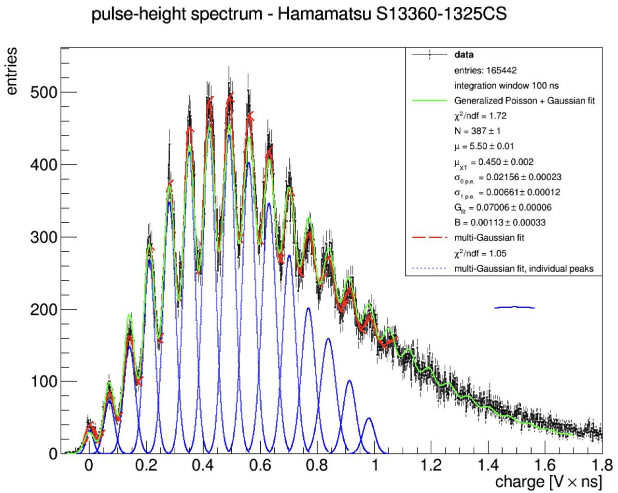




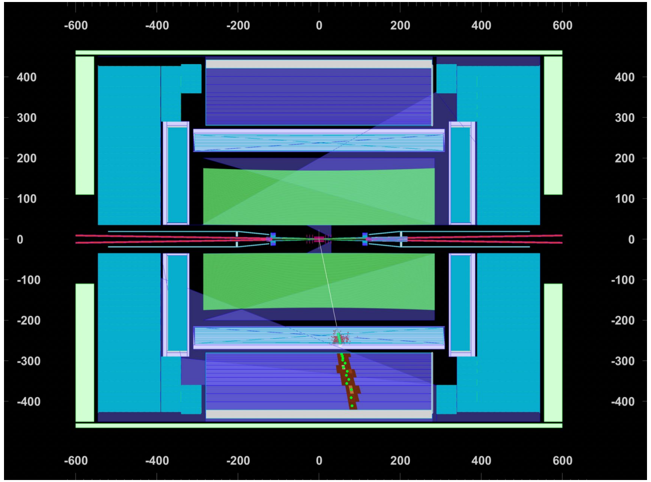
# The road towards test beam prototypes

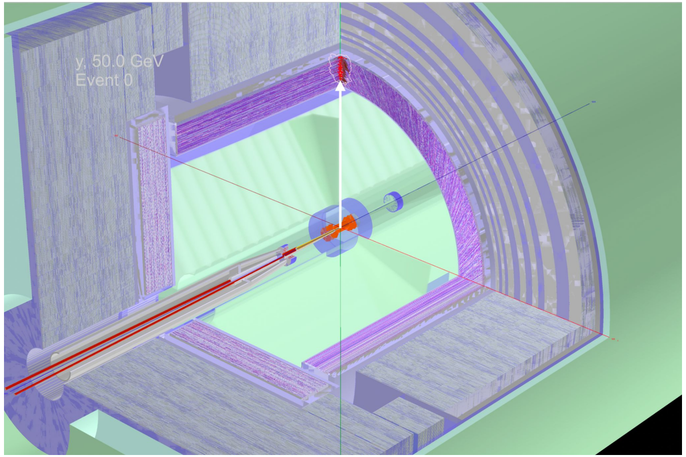
- ECal prototype discussed in Fares talk
- Similarly, HCal community plans to build several (3-5) test beam modules within the next 5 years:
  - Light response study of plastic scintillator tiles with SiPM readout
  - Research new plastic scintillating materials, PEN (Polyethylene Naphthalate) and PET (Polyethylene Terephthalate)
  - Mechanical design studies, produced first elements of the absorber stacks




# Conclusions

- Detector R&D for FCC-ee is a rich field totally orthogonal to challenges at HL-LHC!
- Strong International effort on setting up Detector R&D Collaborations (DRD6 on Calorimeters)
- Many interesting questions and research topics ahead of us!
- ALLEGRO is a new detector concept for FCC-ee
- A lot of progress towards the full detector simulation of ALLEGRO done over the past years
- Both, ECal and HCal communities plan to build a test-beam prototype(s) in coming years

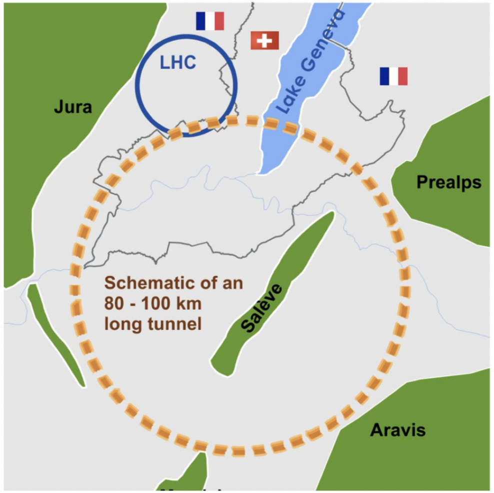


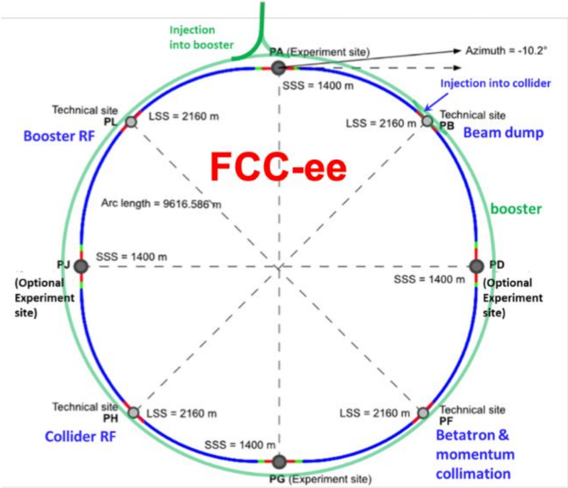



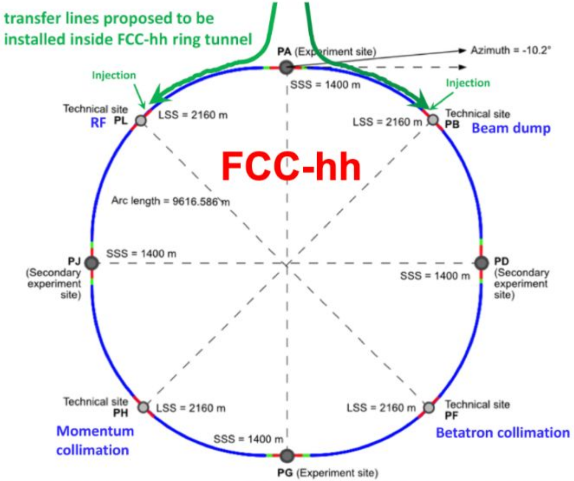
# BONUS SLIDES

# The Future Circular Collider

- International FCC collaboration (150 institutes, 34 countries)
- Stage 1: FCC-ee (Z, W, H, tt) as Higgs factory, electroweak & top factory at highest luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier
- common civil engineering and technical infrastructures, building on and reusing CERN’s existing infrastructure



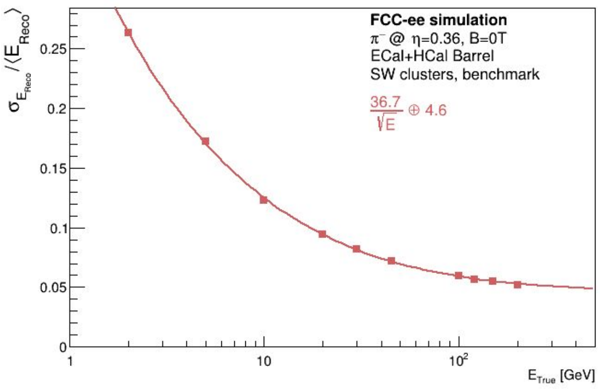

- 2040 | 2045 - 2060 | 2070 - 2095

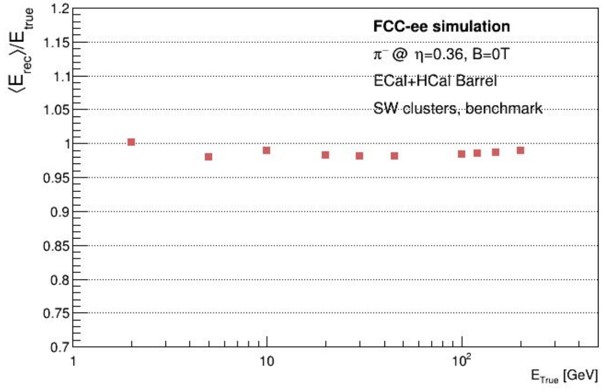
# ECal+HCal barrel combined simulation (I)

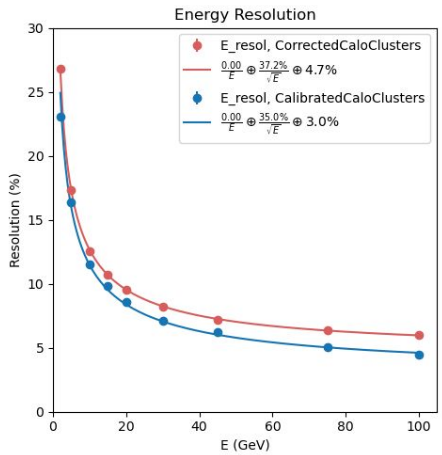
- The goal is to combine ECal and HCal calorimeter information (and later add tracker and do particle flow)
- Tested two approaches for energy calibration of sliding window clusters
  - Using cell-based calibration developed for ATLAS test-beams

$$E_{\text{rec}}^{\text{bench}} = p_0 \cdot E_{\text{EB}}^{\text{EM}} + p_1 \cdot E_{\text{HB}}^{\text{HAD}} + p_2 \sqrt{\left| p_0 \cdot E_{\text{EB}}^{\text{last layer}} \cdot E_{\text{HB}}^{\text{first layer}} \right|} + p_3 (p_0 \cdot E_{\text{EB}}^{\text{EM}})^2 + p_4 \cdot E_{\text{EB}}^{\text{first layer}}$$

  - Using MVA calibration (similar to HCal standalone)
    - Constant term decreases from 4.7% to 3.0%, response linearity within 1%



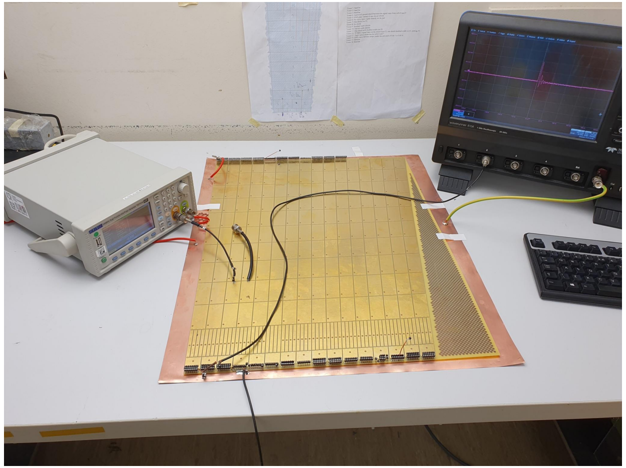



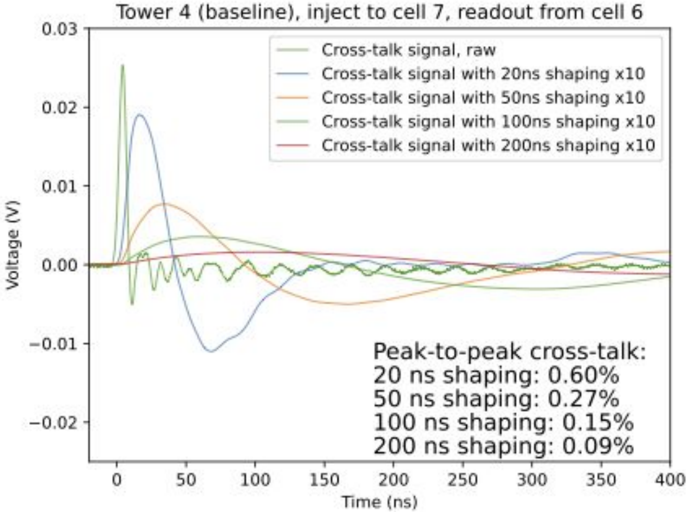
# The road towards ECal test beam prototype

- Printed circuit board (PCB) technology allows "arbitrarily" high granularity
  - Signal traces inside the electrode
- First large-scale prototype PCB 58cm×44cm was built
  - Split to 16 θ-towers & 12 depth layers
  - Narrow strips in front for $\pi^0$ detection
  - 240 cells in total in the first prototype
  - Read-out from inner and outer edge
- First prototype of two absorbers built as well
  - Tested in liquid nitrogen bath
- Test-beam prototype with 64 layers by 2027-28
  - 64 electrodes and absorbers
  - Placed in a cryostat for beam tests
  - Design to be frozen by September 2025

# ECal PCB measurements

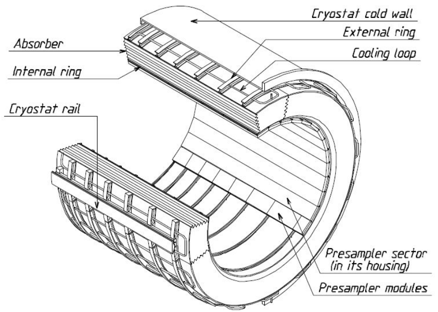
- Signal traversing under other cells induces cross-talk
  - Traces need to be shielded to minimize cross-talk
  - Grounded shields increase detector capacitance and hence noise
  - Need to find the best compromise
- Electrical properties of the PCB measured with a simple table-top setup
- Function generator used for injecting sharp-edged triangular signal
- Signal read with oscilloscope, analyzed offline
- Cross-talk down to 0.1% and less with long shaping time



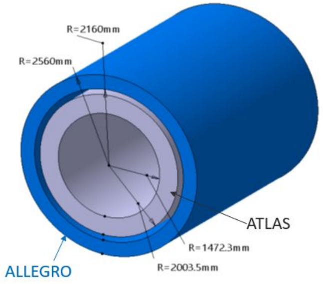


# Mechanical studies

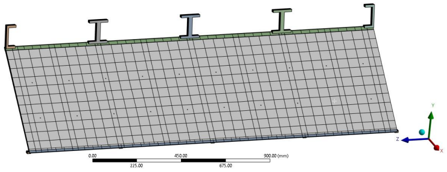
- Calorimeter in ATLAS experiment is taken as reference.
  - Bigger, heavier (≈ +40%) and different geometry of the electrodes.
- Finite element analysis are performed to size the structural elements.
- First prototype of two absorbers and one electrode was build.
- The prototype was tested by immersing it into liquid nitrogen bath.



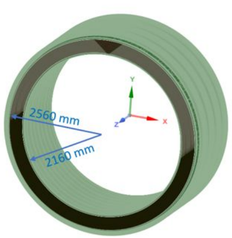

ATLAS liquid argon calorimeter general layout

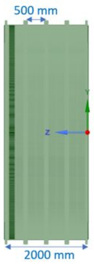



Detection zones size comparison

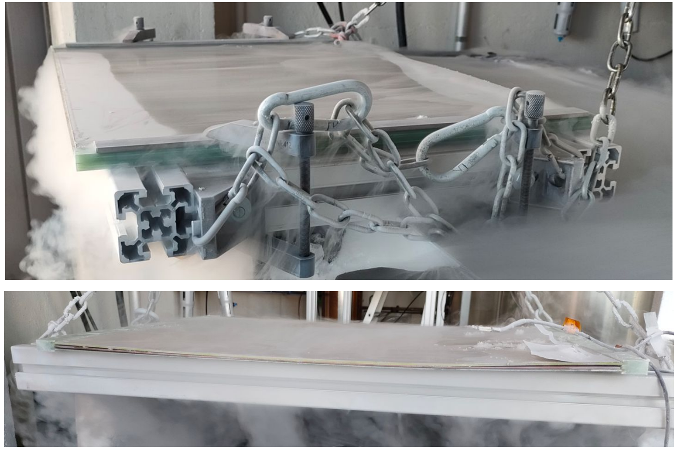


Finite elements model which is multiplied 1536 times

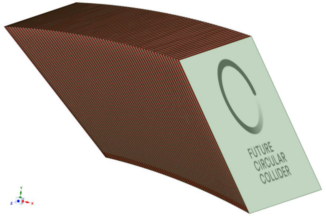


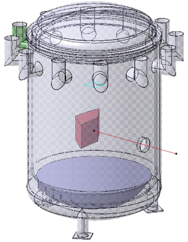

2 meters long FEM



First cold test. Liquid nitrogen bath was used.




Test beam prototype. 64 electrodes and absorbers.



Test beam in the cryostat

# Mechanical results

- Section of the external rings chosen to expect about 3 mm of radial deformation.
- Spacers between absorbers and electrodes separated 200 mm. They are needed in the edges.
- The FEM of 2 meters long returns relative deflections in the absorbers of 2.7 mm due to gravity at room temperature.
- Assuming 2.9 Mpa as yielding point of the lead, the stainless-steel plates reach 107 MPa in compression just because of the cooling down to 77 K. If the value of the yielding point of the lead is higher, the stress in the steel is also bigger (8 MPa □ 183 MPa). Adding the effect of the gravity, the stainless steel could also reach the yield point.
- In the cold tests, where the assembly was subjected to thermal shocks, some depressions were found after warming up. Some more studies will be done to understand this phenomena (local buckling, steel yielding…? Due to the thermal shock or it appears also when it´s slowly cold?).