Recent Progress with Very Forward Calorimeters for Linear Colliders

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On behalf of the FCAL collaboration

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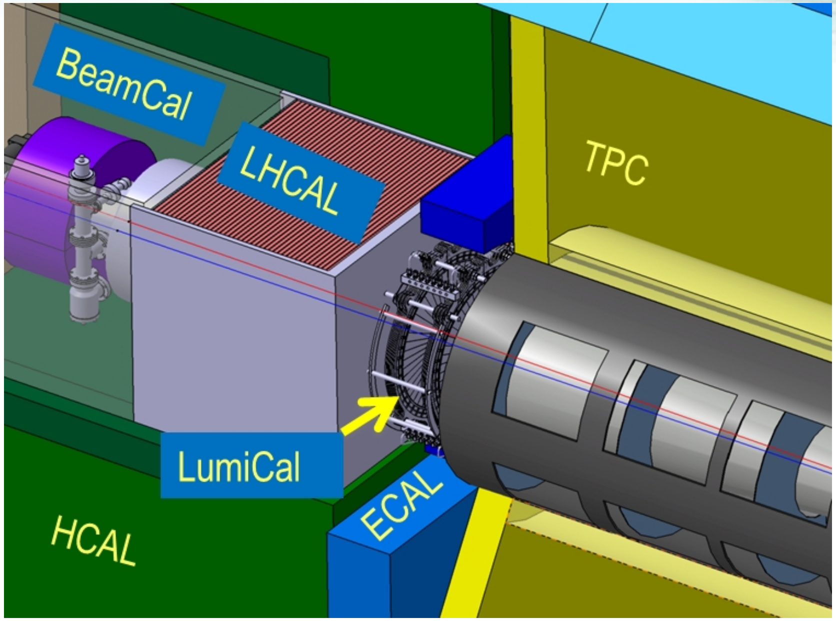
Overview

- Instrumentation of the forward regions in linear collider experiments
- FCAL multi-plane detector prototypes:
  - LumiCal module and beam test infrastructure;
  - Thin LumiCal module design;
- BeamCal and LHCal R&D
- Summary

Instrumentation of the Forward Region

Goals:

- Instant luminosity measurements;
- Provide information for beam tuning;
- Precise integrated luminosity measurements;
- Extend a calorimetric coverage to small polar angles. Important for physics analysis.



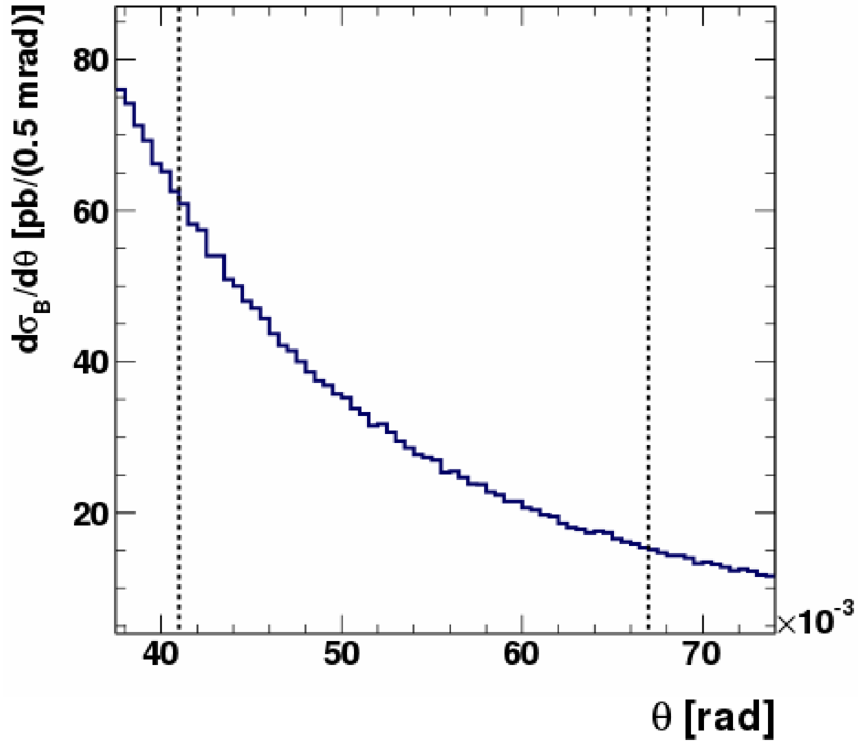
LumiCal:
- Electromagnetic calorimiter;
- 30 layers of 3.5 mm thick tungsten plates with 1 mm gap for silicon sensors;
- symmetrically on both sides at ~2.5m from the interaction point.

BeamCal: similar construction, with tungsten absorber but radiation hard sensors (GaAs, CVD diamond).

LHCal: extends the coverage of HCAL;
Design is being optimized in simulation studies.

Luminosity Measurement with LumiCal

The luminosity can be measured by counting number N_B of Bhabha events in a certain polar angle (θ) range of the scattered electron.



$$L = \frac{N_B}{\sigma_B}$$

σ_B – integral of the differential cross section over the same θ range.

The cross section of the Bhabha process can be precisely calculated.

In leading order:

$$\frac{d\sigma_B}{d\theta} = \frac{2\pi\alpha_{em}^2}{s}\frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha_{em}^2}{s}\frac{1}{\theta^3},$$

the approximation holds at small θ.

α is the fine-structure constant,

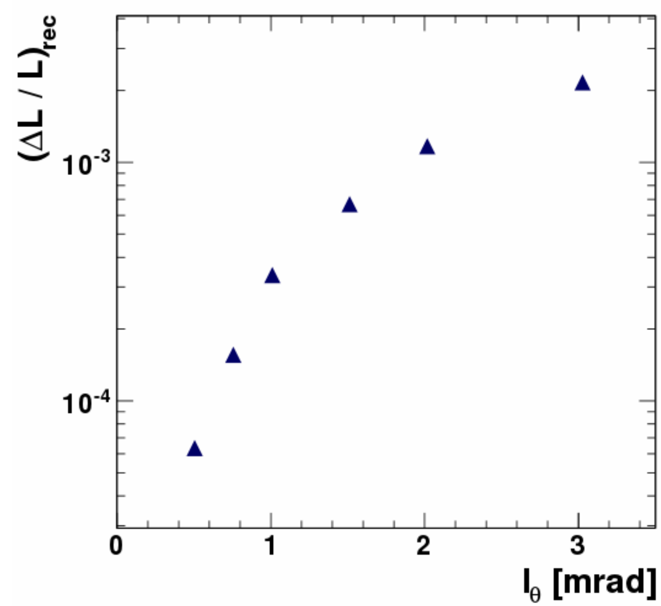
s - center-of-mass energy squared.

LumiCal Geometry

Uncertainty in luminosity measurement depends on the polar angle bias $\Delta\theta$ and minimum polar angle θ_{min} as:

$$\left(\frac{\Delta L}{L}\right)_{rec} \approx 2\frac{\Delta\theta}{\theta_{min}}$$

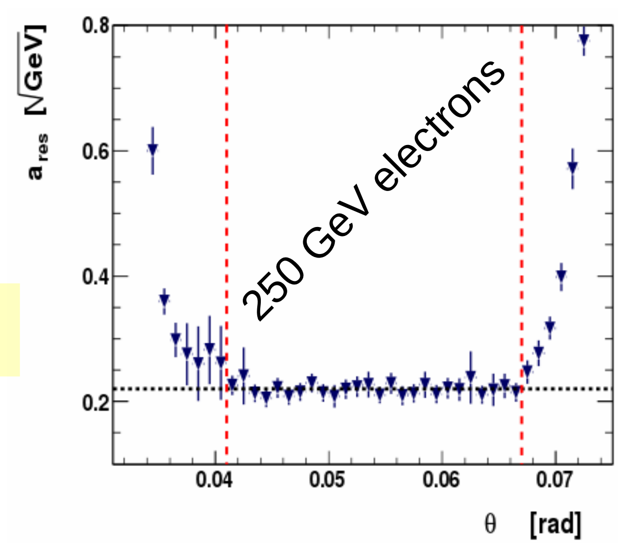
$\Delta\theta$ depends on polar angular pad size l_θ.



For l_θ=0.8 mrad, $\Delta L/L = 1.6\cdot10^{-4}$.

Energy resolution:

$$\frac{\sigma_E}{E} = \frac{a_{res}}{\sqrt{E_{beam}\,(GeV)}},$$

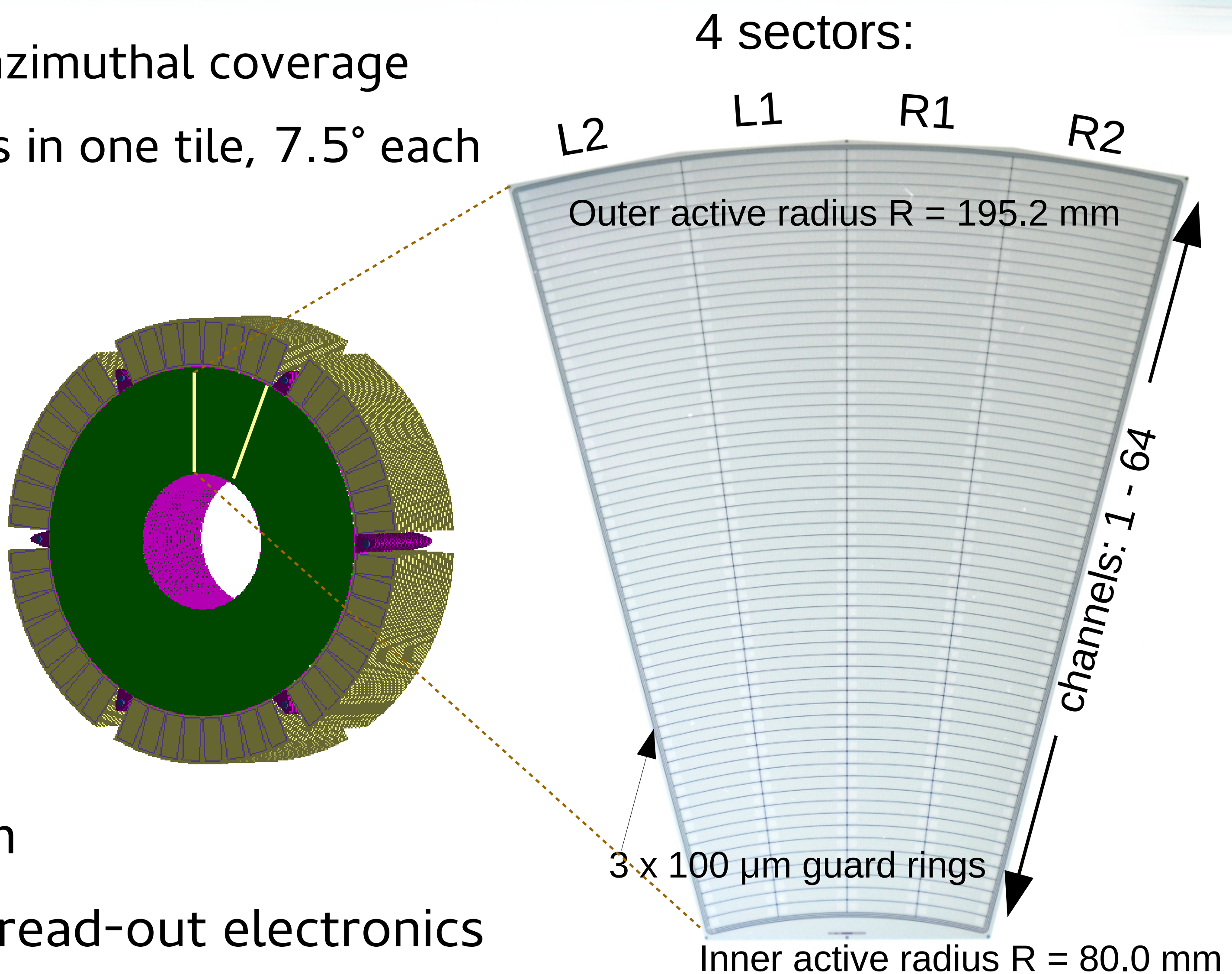


LumiCal fiducial volume: 41 < θ < 67 mrad

$a_{res} = (0.21\pm0.02)\sqrt{GeV}$.

LumiCal Design

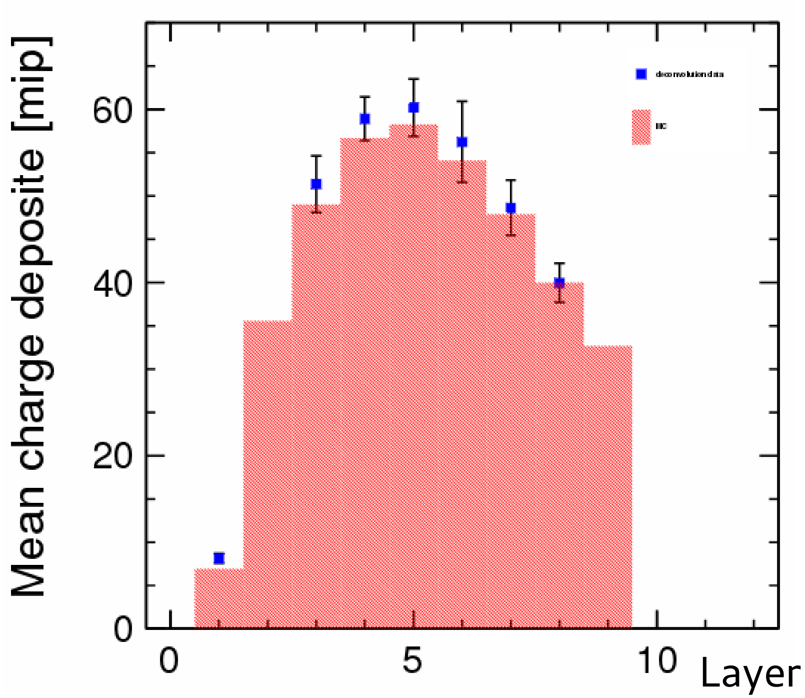
- 12 tiles make full azimuthal coverage
- 4 azimuthal sectors in one tile, 7.5° each



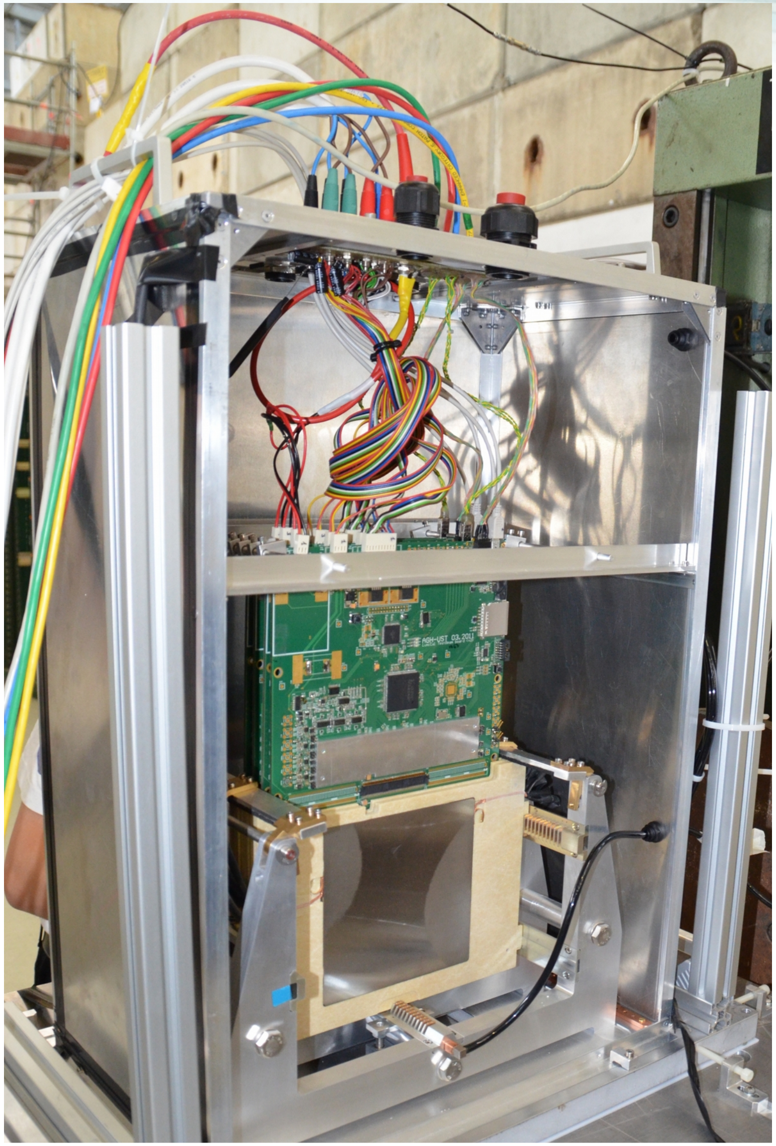
- Silicon sensor
- thickness 320 µm
- DC coupled with read-out electronics
- p+ implants in n-type bulk
- 64 radial pads, pitch 1.8 mm

Beam Test of LumiCal Multilayer Prototype

- CERN PS 5 GeV/c e- (muons, used for calibration);
- 4 LumiCal detector modules;
- 10 tungsten absorber plates in permaglas frames;
- Mechanical frame for precise (±50μm) positioning of detector and absorber layers;
- 3 configurations for longitudinal scan of the electromagnetic shower.



Longitudinal shower development



Four LumiCal modules in stack

Shower Study in Transverse Plane

Transverse shower profile is approximated as

$$F_{E(r)} = (A_C)e^{-(\frac{r}{R_C})^2} + (A_T)\frac{2rR_T^2}{(r^2+R_T^2)^2}$$

r – the distance from the shower center;
A_C, A_T, R_C, R_T – fit parameters.

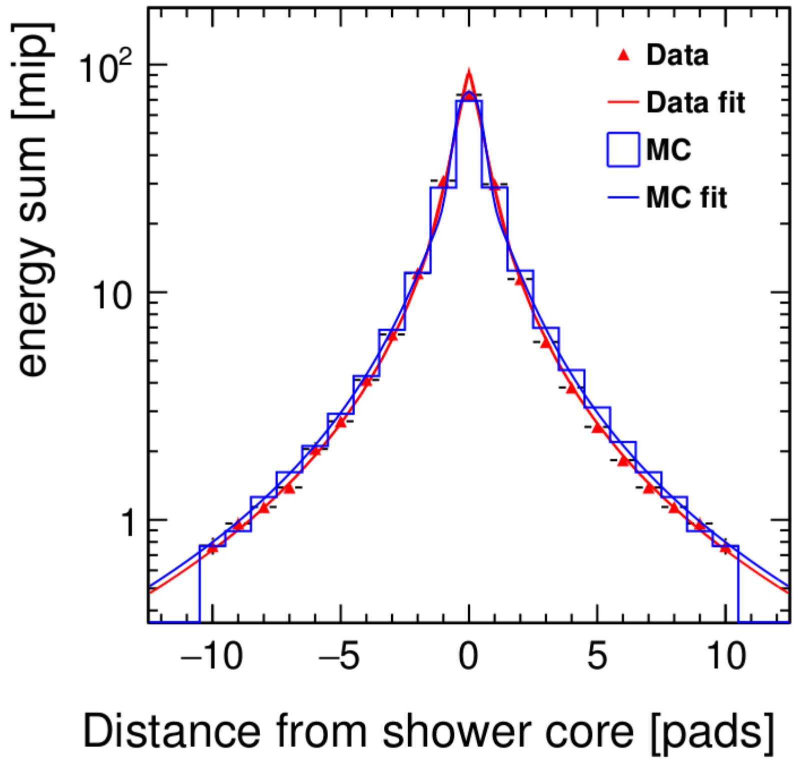
Moliere radius R_M can be found from the equation:

$$0.9 = \int_0^{2\pi} d\varphi \int_0^{R_{\mathcal{M}}} F_E(r)rdr$$

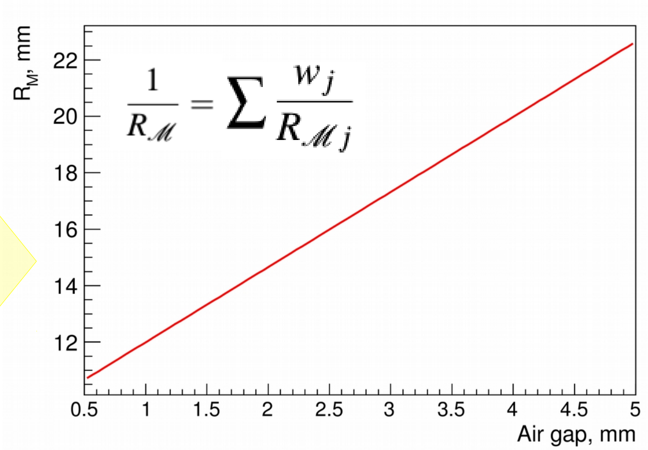
For the configuration with four detectors at $3X_0$, $5X_0$, $7X_0$ and $9X_0$,

- R_M = 15.13 mm for the data;
- R_M = 18.27 mm for MC simulation;

MC simulation does not include digitization.

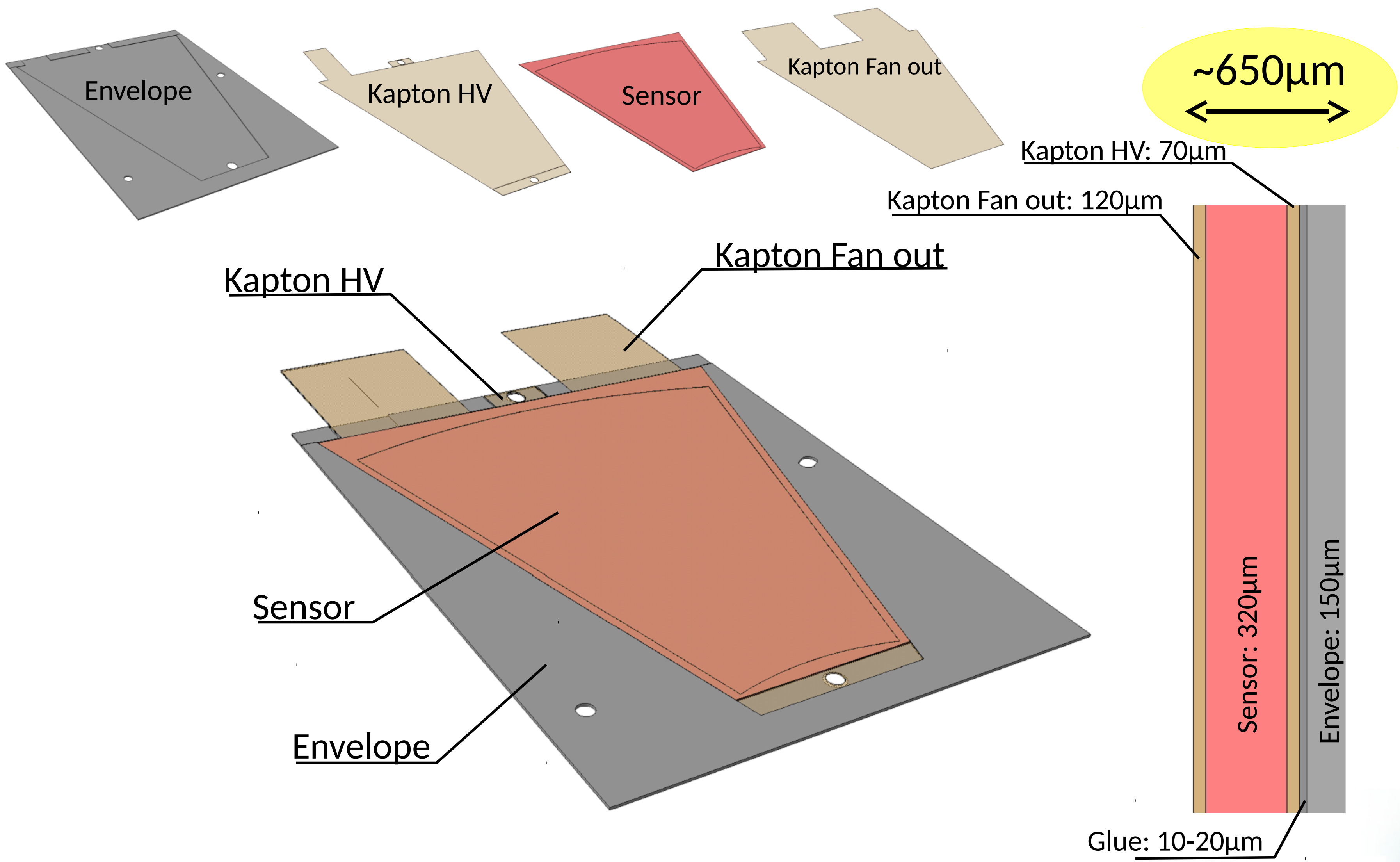


R_M as function of the air gap between 3.5 mm thick tungsten plates



Reducing air gap from 4.5 mm to 1 mm gives
RM: 21 mm -> 12 mm.

Design of the Thin LumiCal Module

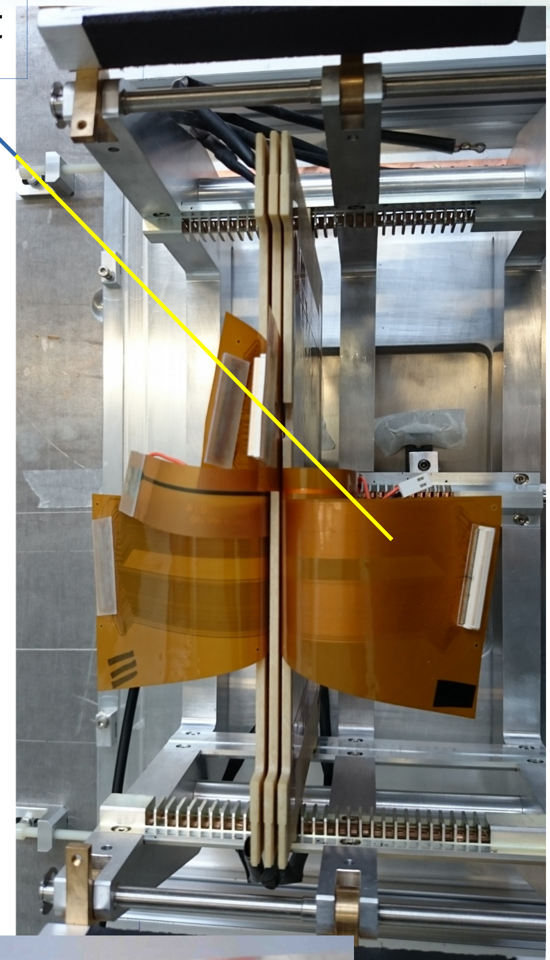


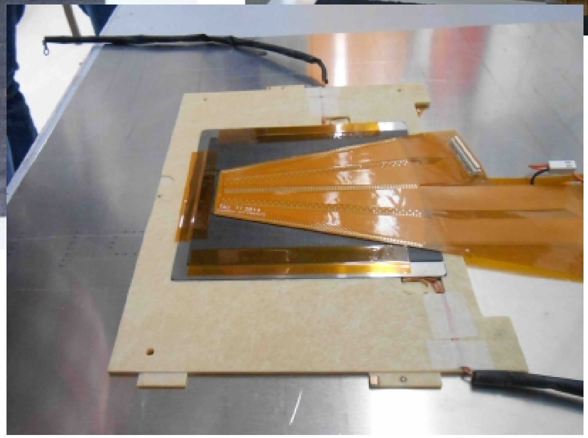
Thin LumiCal Module in Mechanical Frame

Kapton fanout

130 pin Panasonic connectors provides interface to APV-25 hybride and SRS DAQ system.

Carbon fiber supporting structure (“envelope”) provides mechanical stability and easy stack assembly.

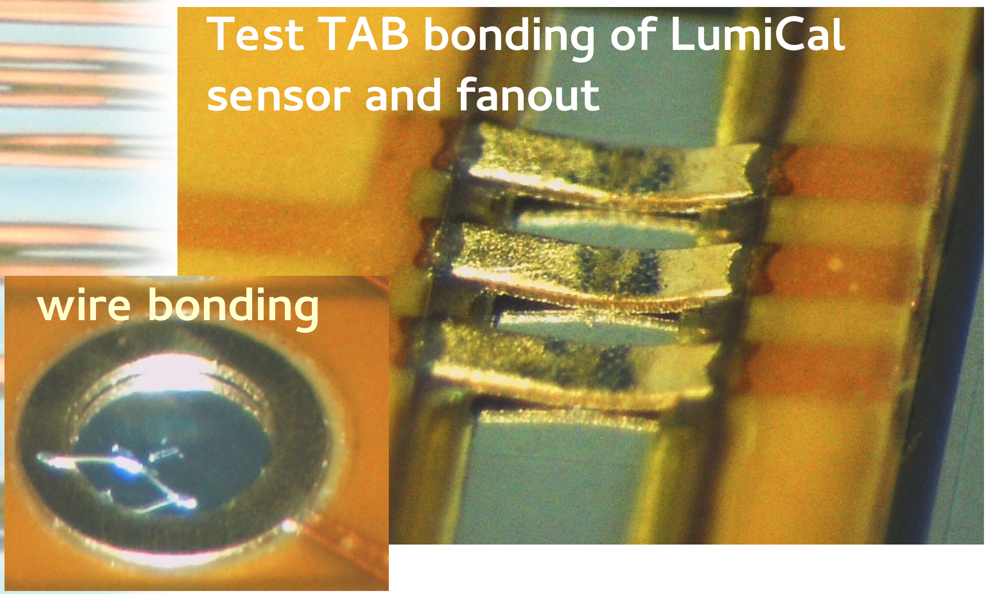




- 4 modules were successfully tested with e- beam at DESY in October 2015. Data analysis is in progress.
- 4 additional modules are in preparation for beam test in August 2016 including one assembled with TAB bonding technology.

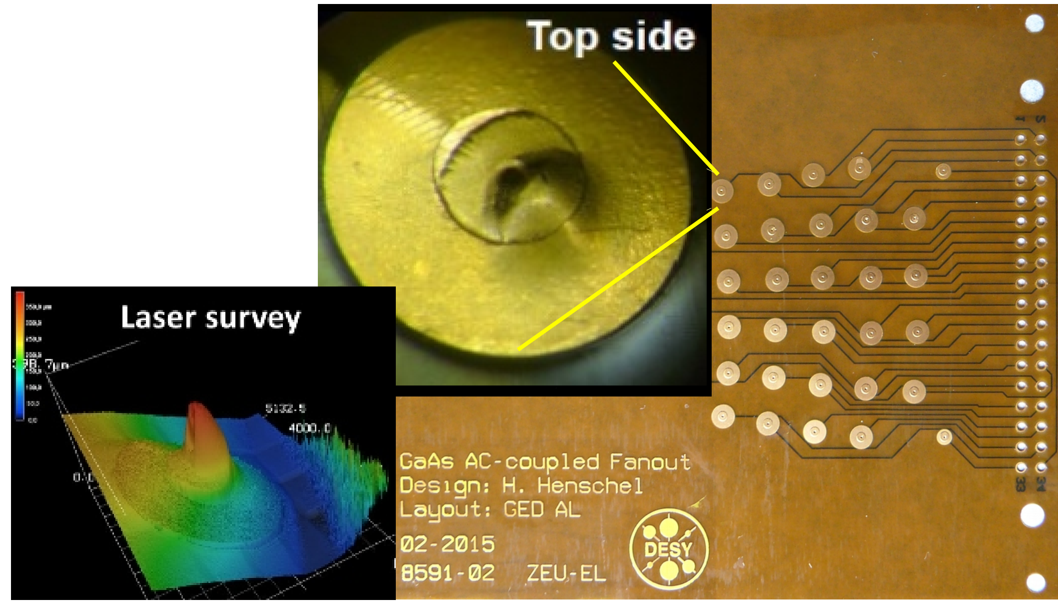
Frontend Contact Technologies

Search for long-term stable contact between sensor and readout electronics which meets LumiCal and BeamCal geometrical (compactness) requirement



Single point Tape Automated Bonding (TAB):

- No wire loop, the bond can be covered by the glue for better protection;
- One LumiCal module is being assembled and tested using TAB technology.



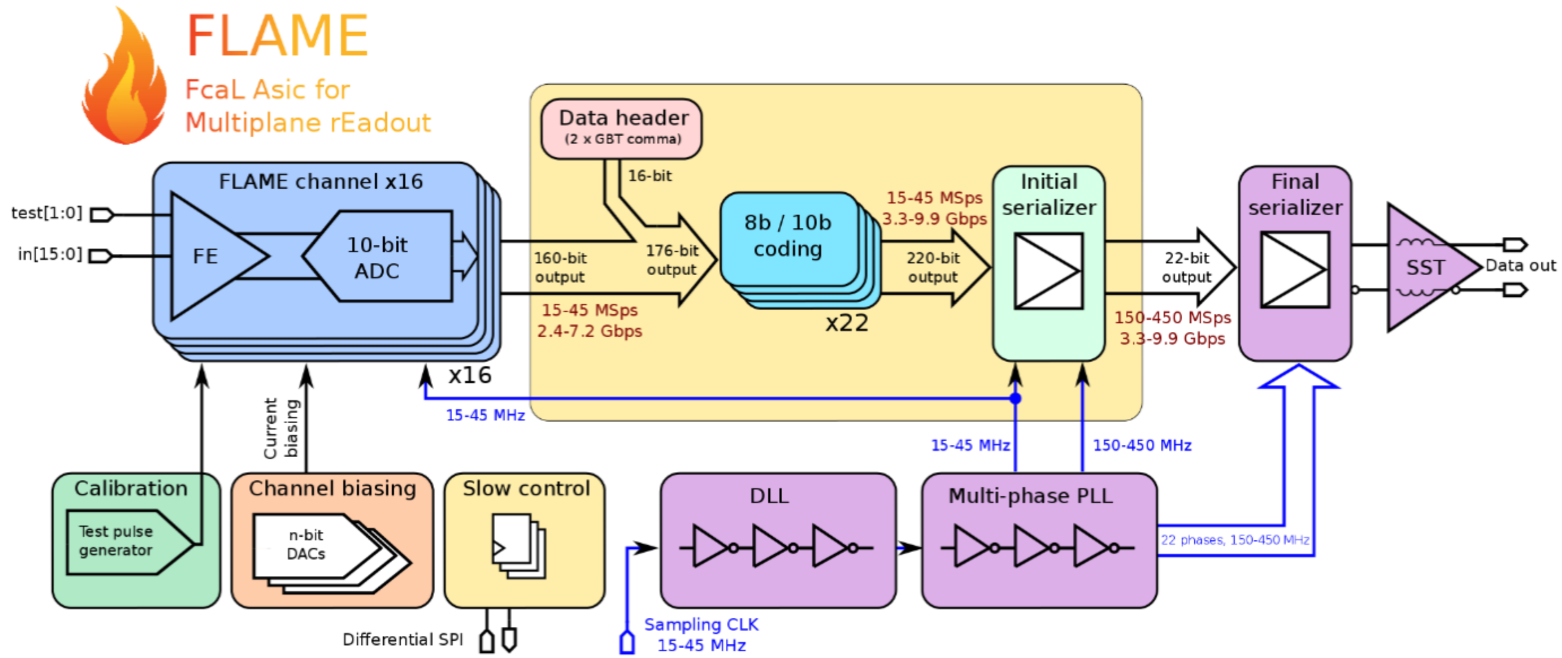
Spring Loaded Contact:

- Bumped fanout has been produced;
- It demonstrates good contact at certain pressure (~7.2kPa);
- Ongoing tests with GaAs sensor.

New LumiCal Readout ASIC

FLAME – FcaL Asic for Multiplane rEadout

16-channel ultra-low power readout ASIC in CMOS 130 nm, FE&ADC in each channel, fast serialization and data transmission, all functionalities in single ASIC.



Two components of the FLAME were designed and produced:

Prototype ASIC comprising 8 almost fully functional FLAME channels:

- Front-end with variable gain, differential CR-RC shaper, Tpeak = 50ns, ENC~900el@20pF
- 10-bit multichannel SAR ADC
- Power (FE+ADC) <2mW/channel

22b → 1b serializer with fast SST driver (3.3 – 9.9 Gbps)

- Power consumption 15 mW at 9.9 Gbps

Beam Parameters Reconstruction in BeamCal

Energy depositions in BeamCal from $e^+ e^-$ pairs, produced by beamstrahlung photons, can be used for fast beam parameter reconstruction and instant luminosity measurements.

- Use GuneaPig to simulate the beam with modified parameters:
  - Increase beam envelope at origin;
  - Move waist of electron and positron beam;
  - Change targeting angle of electron and positron beam.
- Study parameters (observables) of 3D energy deposition distribution in BeamCal:
  - Deposited energy,
  - mean depth of shower,
  - L/R and up/down asymmetries,
  - thrust (relative to barycenter) value.
- find the dependence between BeamCal observables and beam parameters.

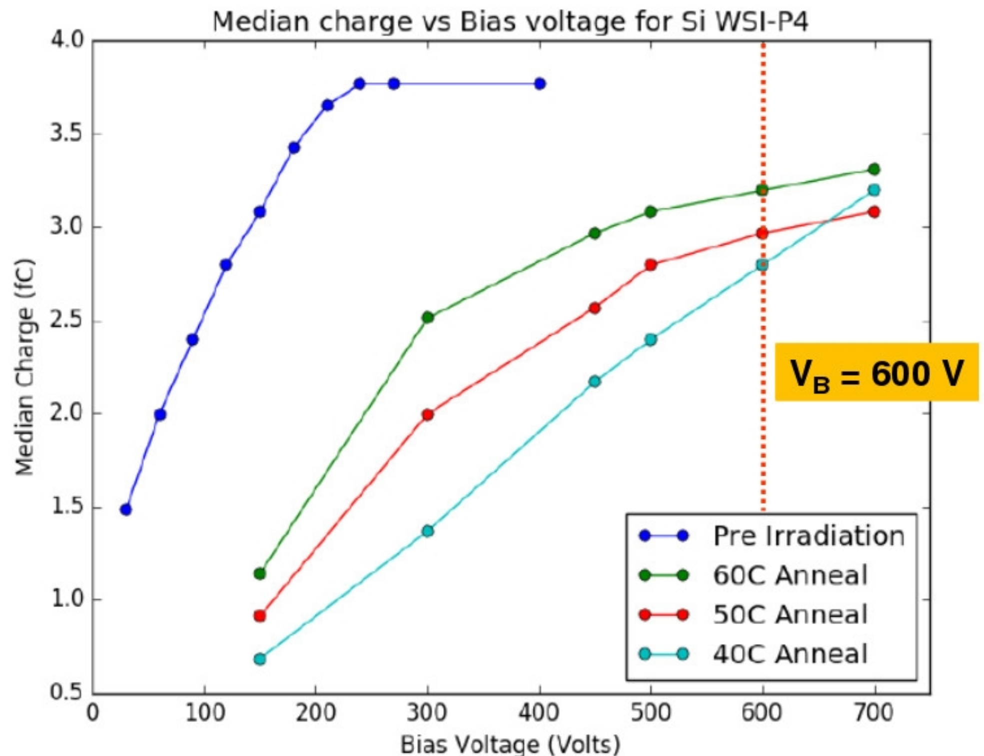
Previous study assumed linear dependence between BeamCal observables and beam parameters and used Moore-Penrose inverse of the Taylor matrix to calculate the parameters of the beam.

BeamCal Sensors Radiation Studies

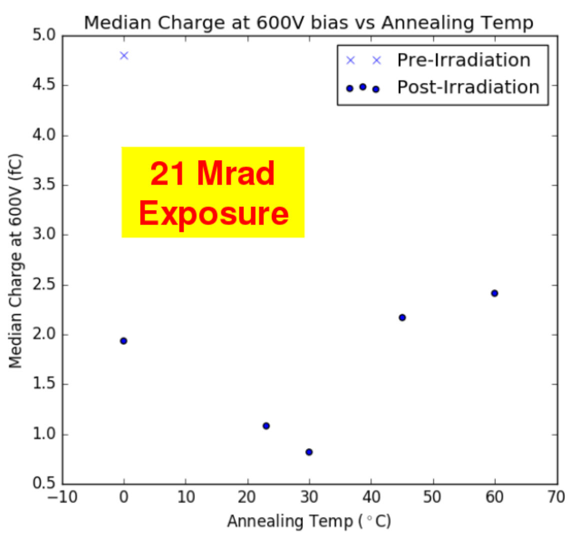
Electromagnetically-induced showers irradiation at 3°C

Sensor Type	Notable Exposures (Mrad)
GaAs	20
SiC	80
Si PF	270, 570
Si NF	300
Si PC	300
Si NC	290

P – p-type bulk; F – float zone;
N – n-type bulk; C – Czochralski



~20% loss at 600V and 60°C anneal for silicon detectors.



Mean collected charge in GaAs sensor after 21 Mrad for different annealing temperature

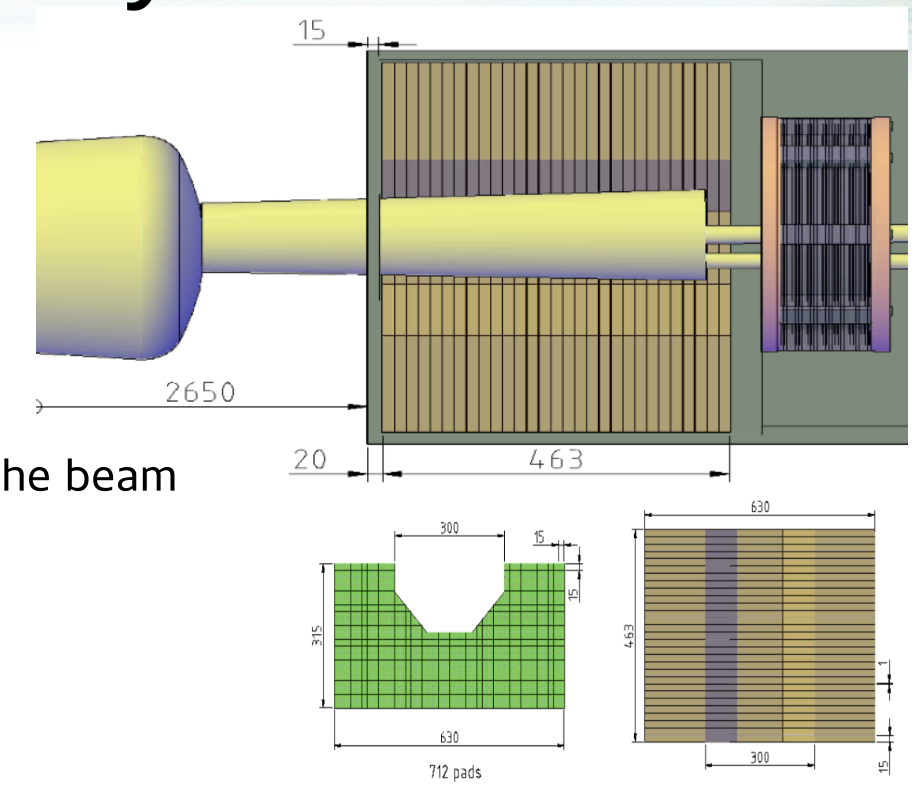
GaAs sensor shows better performance compared to the e- irradiation w/o e-m shower.

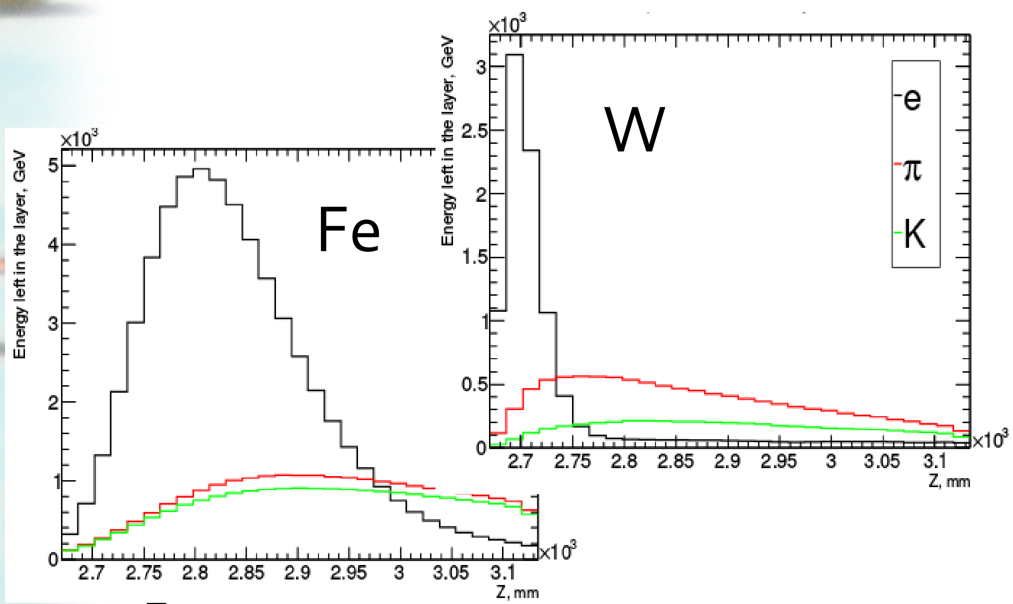
LHCal Study

- LHCal is a sampling hadronic callorimeter;
- Covers the gap between LumiCal and BeamCal;
- Provides lepton – hadron identification;

Optimized geometry and performance is studied in simulation:

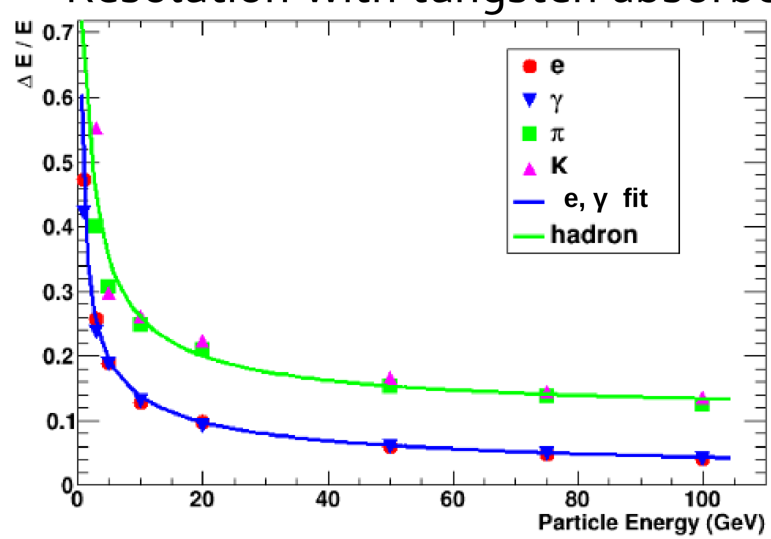
- External dimensions are constrained by the beam pipe, LumiCal and BeamCal positions;
- Fe vs. W absorbers;
- Implemented in DD4Hep.





Energy deposition per layer

Resolution with tungsten absorber



Summary

- Electromagnetic shower development in LumiCal 4-module prototype was studied using the beam test data. The paper is in final stage of preparation.
- Thin LumiCal modules with submillimeter thickness were developed and successfully produced. The LumiCal prototype with the thin modules and existing mechanical structure was assembled tested with beam. Data analysis is in progress.
- Spring Loaded Contact and TAB technologies are investigated as a possible solution to connect fanout to LumiCal and BeamCal sensors.
- Prototypes of new fast, ultra-low power SoC type readout ASIC were produced and will be tested soon.
- Studies of the LC beam parameter reconstruction using BeamCal observables and possible BeamCal sensor materials Si, GaAs, SiC continue.
- LHCal design optimization study in simulation is underway.

Thank you for your attention!