AGH University of Science and Technology

FCAL R&D on forward calorimeters

Marek Idzik AGH-UST

On behalf of the FCAL Collaboration

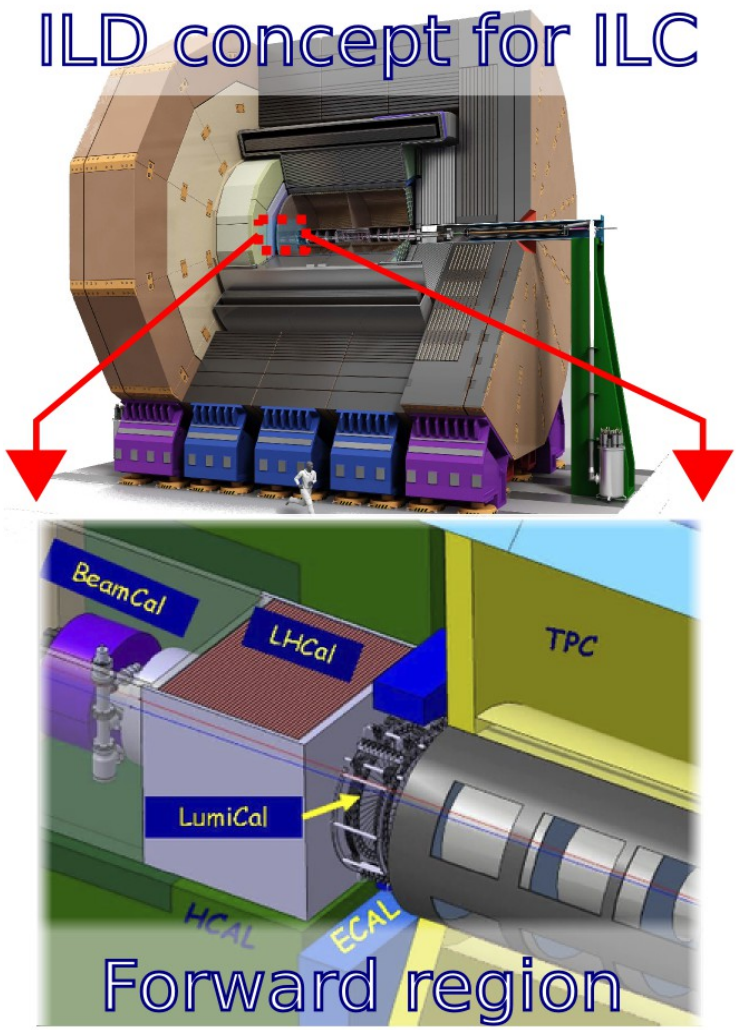
AGH-UST Cracow, CERN Geneva, DESY Zeuthen, IFJPAN Cracow, ISS Bukharest, JINR Dubna, LAL Orsay, NCPHEP Minsk, PUC Santiago de Chile, SLAC Stanford, TAU Tel Aviv, Tohoku University Sendai, University of Colorado Boulder, UC California Santa Cruz, Vinca Belgrad

XXI Cracow EPIPHANY Conference on Future High Energy Colliders, Cracow 8-10 January 2015

Outline

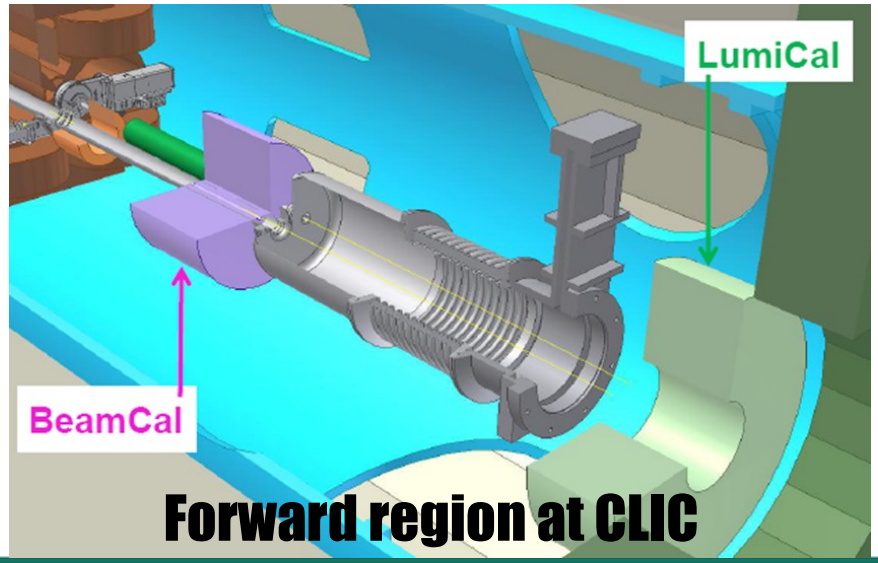
- FCAL overview
- FCAL R&D
  - performed to build the first BeamCal/LumiCal detector prototypes and to verify them in test-beams
- New&Ongoing FCAL R&D
  - for highly COMPACT calorimeter prototype
- Summary

FCAL overview
The Goal

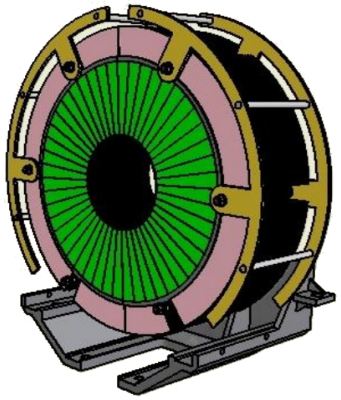


Design and optimisation of the very forward region of future Linear Collider detector

- Precision luminosity measurement
- Fast feedback and beam tuning
- Detector hermeticity



FCAL overview
Luminosity measurement by LumiCal detector

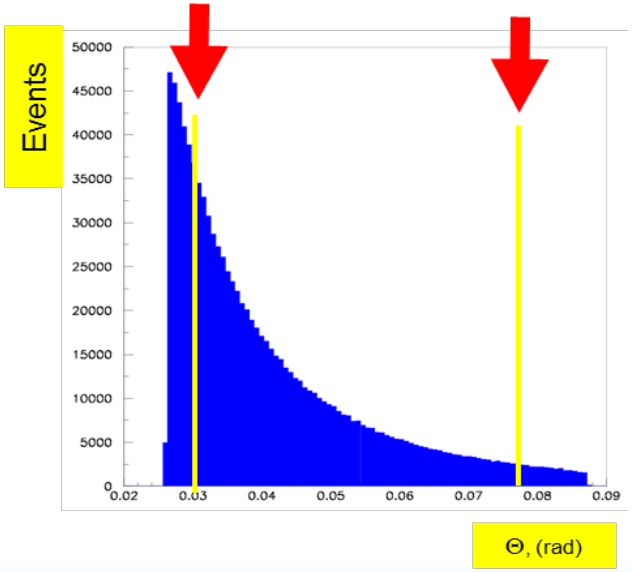


- Precise measurement of luminosity (10^{-3} at ILC, 10^{-2} at CLIC)
- Low angle physics

Gauge process for the luminosity measurement: Bhabha scattering

e+e- ⟶ e+e- (γ)

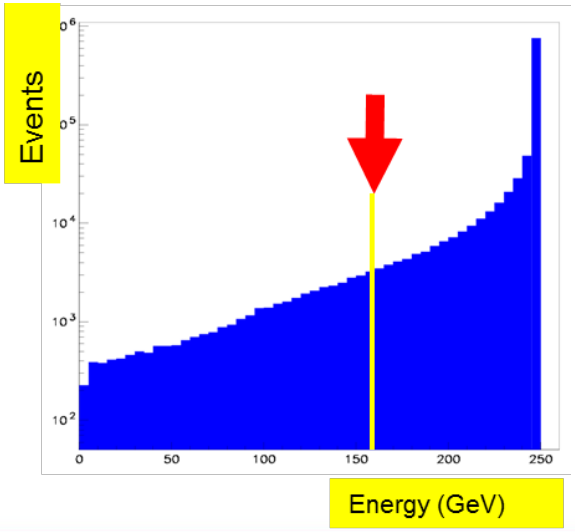
$$\frac{d\sigma_B}{d\theta} = \frac{2\pi\alpha_{em}^2}{s}\frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha_{em}^2}{s}\frac{1}{\theta^3}$$



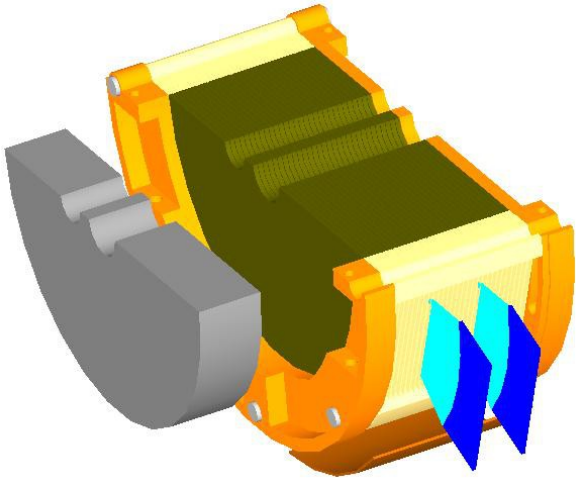
$L = N / \sigma$

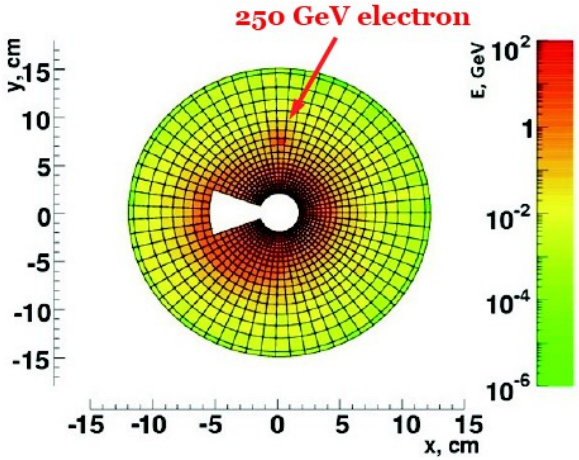
Bhabha events count

From theory



FCAL overview
BeamCal - beam tuning and electron tagging

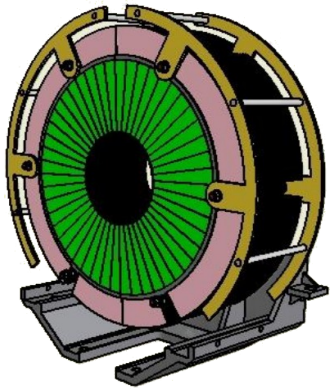




Energy deposited by beamstrahlung pairs after one bunch crossing in the sensors of BeamCal + 250 GeV electron

- Fast luminosity estimate using beamstrahlung (bunch-by-bunch at ILC)
- Beam parameter estimation
- Fast feedback to the machine
- Low angle electron tagging

FCAL overview
Forward calorimeters: LumiCal, BeamCal



LumiCal detector

FCAL MC simulation and optimization studies (DESY, IFJPAN, TAU, Vinca) led to the concept and specifications of forward calorimeters:

- Sandwich type sampling calorimeters
  - LumiCal Si-W, BeamCal GaAs(?)-W
- Both comprise 30 layers at ILC, 40 layers at CLIC. One W layer – 1 X0
- Very compact calorimeters (Moliere radius ~1cm)
- Low polar angle acceptance
  - LumiCal 42-67 mrad at ILC, 38-110 mrad at CLIC
  - BeamCal 5-45 mrad at ILC, 15-38 mrad at CLIC

Main challenges:

- rad-hard sensors for BeamCal (~1 MGy/year radiation dose)
- readout ASICs (fast readout, high occupancy, low power)
- compactness (to achieve small Moliere radius)

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  - **performed to build the first BeamCal/LumiCal detector prototypes and to verify them in test-beams**
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  - for highly COMPACT calorimeter prototype
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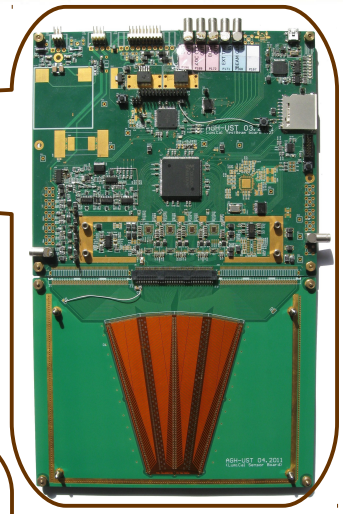
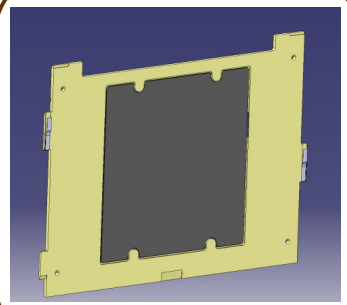
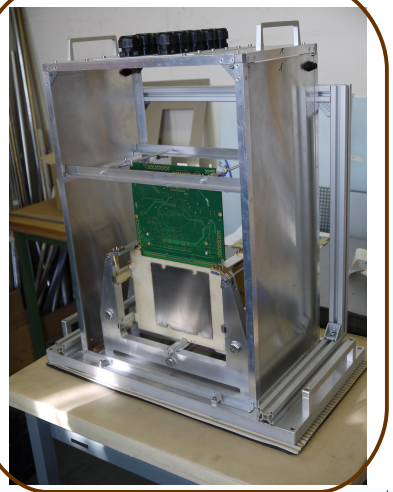
Performed FCAL R&D
Design of BeamCal/LumiCal detector prototype

LumiCal/BeamCal calorimeter prototype requires:

- Detector modules:
  - Sensors for BeamCal/LumiCal
  - Readout ASICs
  - Back-end electronics
- Absorber layers
- Precise mechanical frame
- Data acquisition system
  (EUDAQ software is used)







Performed FCAL R&D Sensors for BeamCal

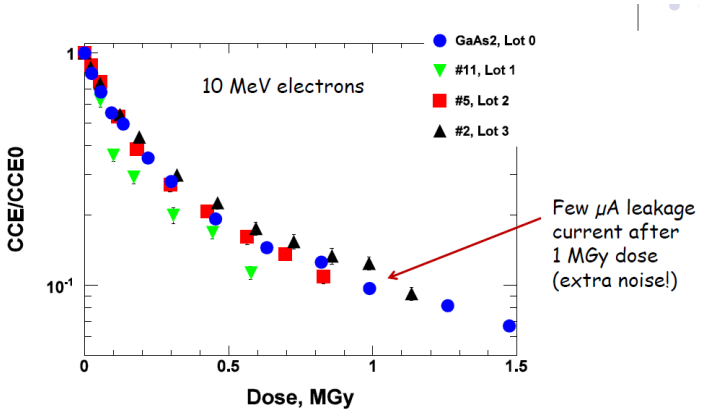
Sensor materials studied at DESY, JINR:

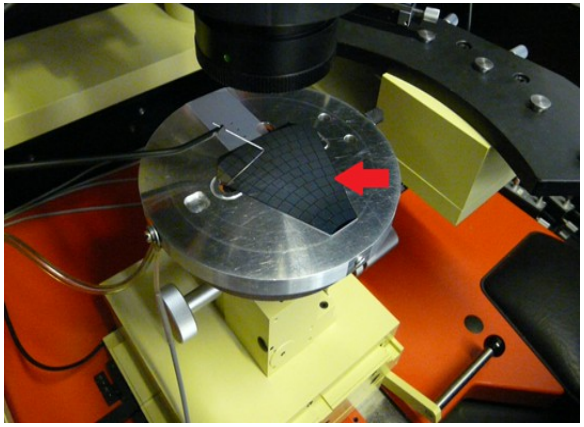
- **GaAs – baseline option**
  - Operational up to ~MGy (CCE ~ 5%)
  - Available in 3 inch wafer (at Tomsk)

- Sapphire
  - Charge collection efficiency a few %
  - Extremely high radiation hardness: after 12 MGy dose it has 30% of initial efficiency
  - Drawback: low signals

- Poly-Crystalline Diamond
  - High radiation hardness: tests up to 7 MGy
  - Availability on wafer scale
  - Drawback: high price

Irradiation of GaAs sensors

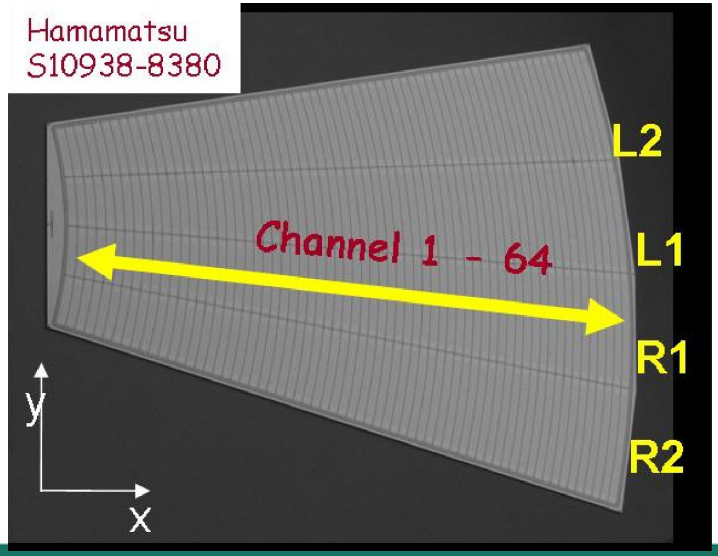




Performed FCAL R&D
Baseline solutions for FCAL sensors

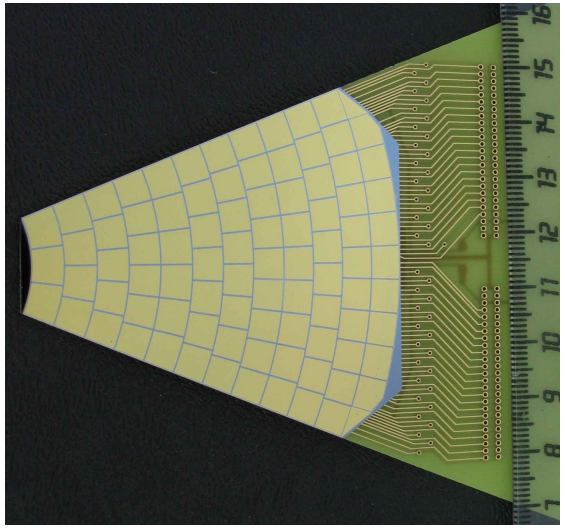
LumiCal

- standard *p* in *n* Si sensors
- 300 um thick
- pad pitch 1.8 mm
- Azimuthal/radial segmentation 48 sectors / 64 pads
- 40 tiles available (each 4 sectors)
- dedicated kapton fanout
- joint effort (IFJPAN, DESY, TAU)

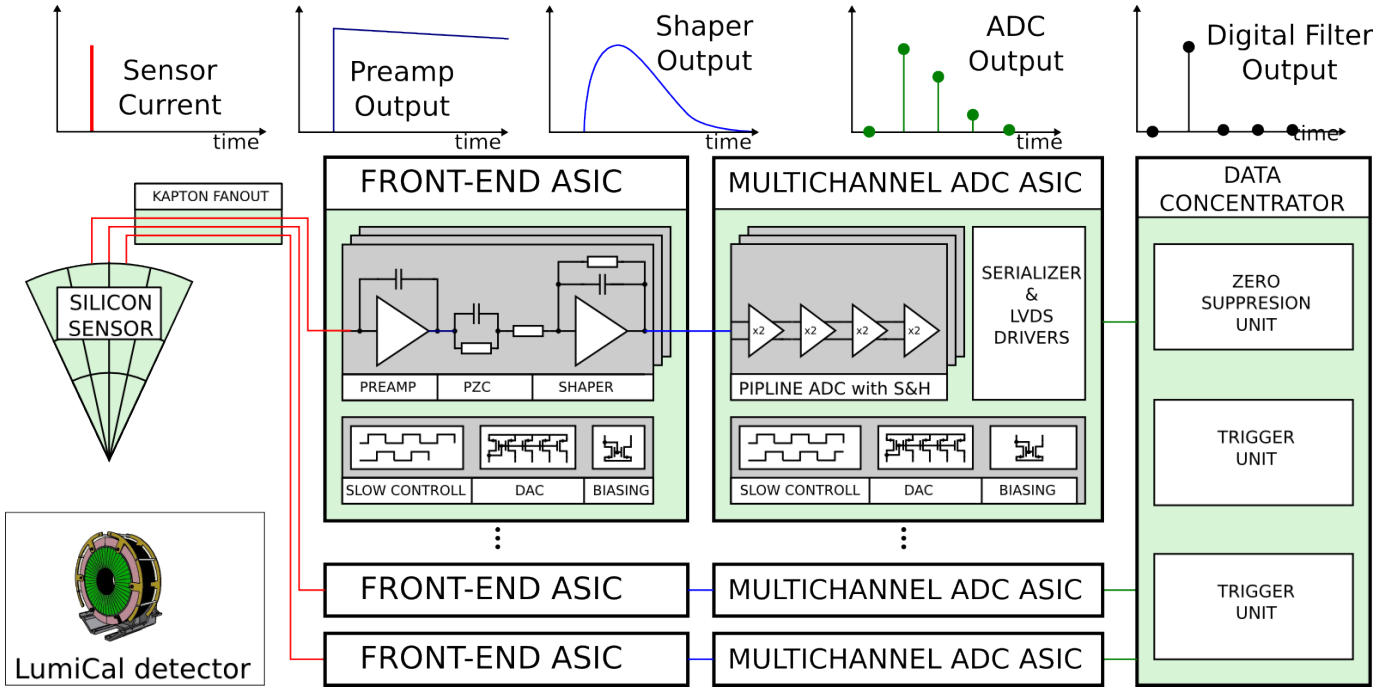


BeamCal

- compensated GaAs sensors
- 500 um thick
- uniform segmentation (equal pad size)
- 30 sensors available
- dedicated kapton fanout
- DESY, JINR collaboration



Performed FCAL R&D
Innovative Readout Electronics for LumiCal detector



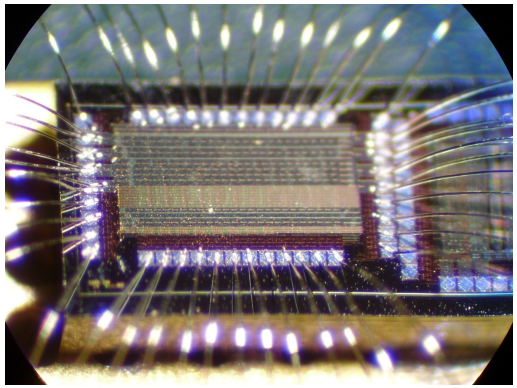
In the past ADC consumed too much power to be placed in each channel

We have proposed and developed a multichannel, low power, readout electronics ASICs comprising analog front-end and ADC in each channel. The further back-end electronics is based on FPGA technology. One of the first implementation of such architecture.

Performed FCAL R&D
Readout ASICs for LumiCal detector

Front-end ASIC features:

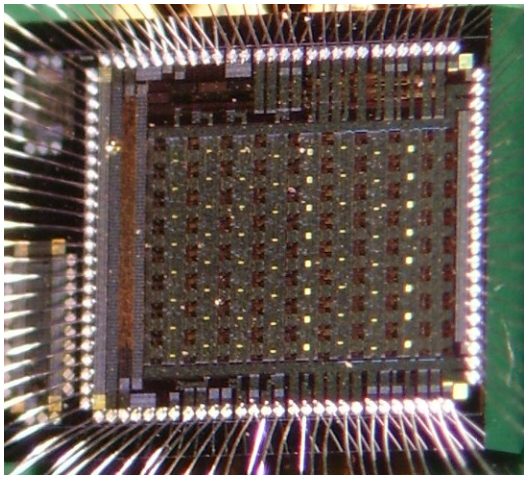
- 8-channel ASIC in CMOS AMS 0.35 um
- Cdet ≈ 0 ÷ 100pF
- 1st order shaper (Tpeak ≈ 60 ns)
- Dual gain:
  - calibration mode - MIP sensitivity (~4fC)
  - physics mode - input charge up to 10 pC
- Power consumption 8.9 mW/channel
- Developed at AGH-UST



M. Idzik, Sz. Kulis, D. Przyborowski, "Development of front-end electronics for the luminosity detector at ILC", NIM A 608 p.169-174, 2009

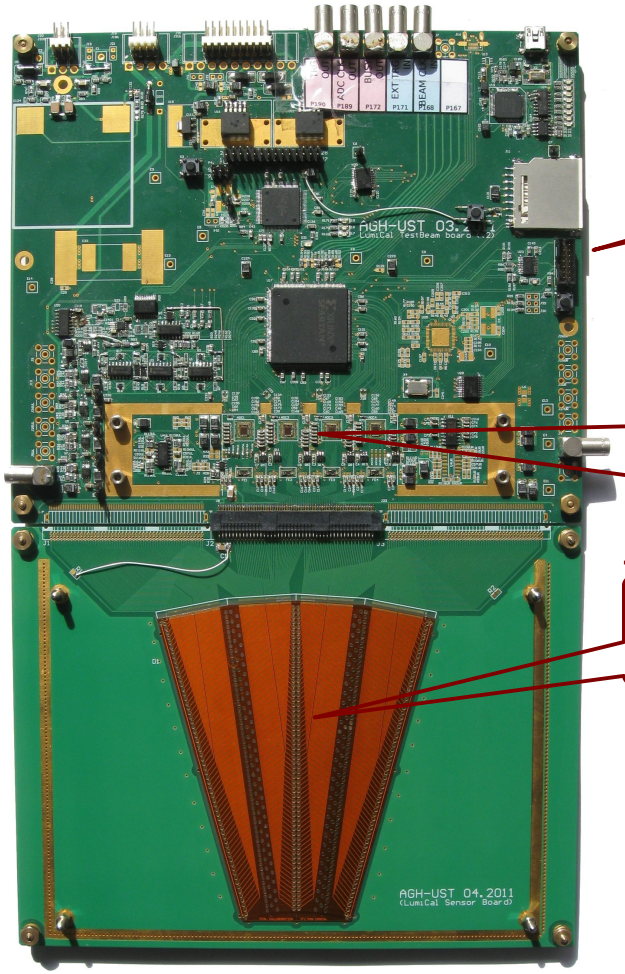
Multichannel ADC ASIC features:

- 8 channels of 10-bit ADC, AMS 0.35um technology
- Max sampling rate >20MSps
- ENOB = 9.7 bits
- Power consumption ~24mW/chn at 20MSps
- Power pulsing
- Developed at AGH-UST



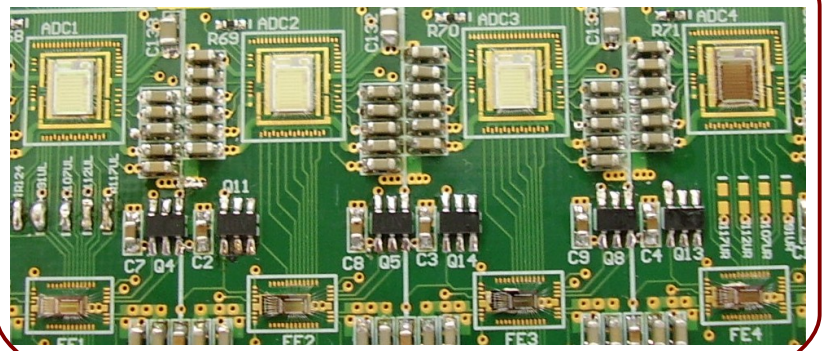
M. Idzik, K. Swientek, T. Fiutowski, Sz. Kulis, D. Przyborowski "A 10-bit multichannel digitizer ASIC for detectors in particle physics experiments", IEEE Trans. Nucl. Sci. v.59 p.294-302 2012

Performed FCAL R&D
Complete detector module



FPGA based
back-end electronics

4 pairs of front-end + ADC



Sensor covered
by kapton fanout

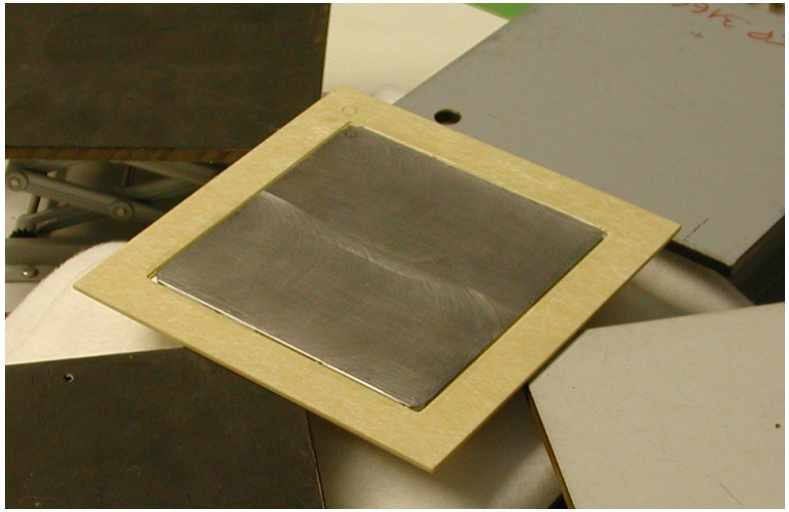
A 32-channel detector module contains:

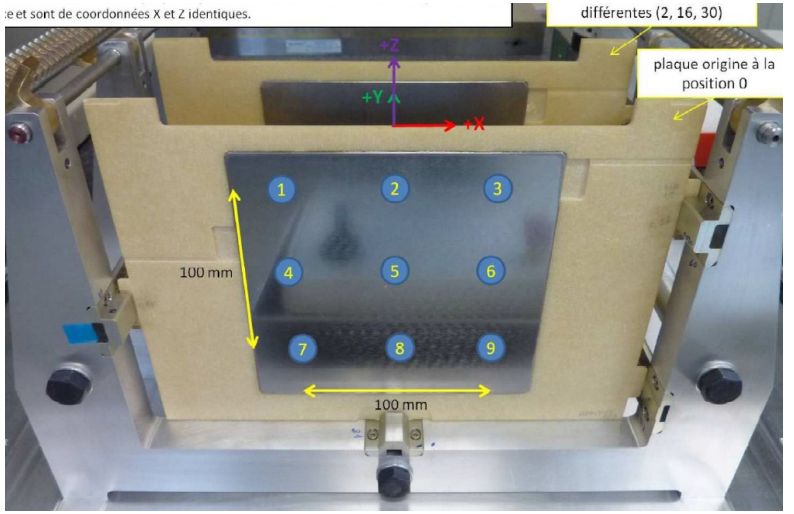
- Four 8 channel front-end ASICs (CMOS AMS 0.35um technology)
- Four 8 channel ADC ASICs (CMOS AMS 0.35um technology)
- FPGA based back-end electronics (developed at AGH-UST)
- Sensor board with kapton fanout (developed at IFJPAN for LumiCal, at DESY for BeamCal)

Performed FCAL R&D
Absorber layers

Prototype tungsten plates

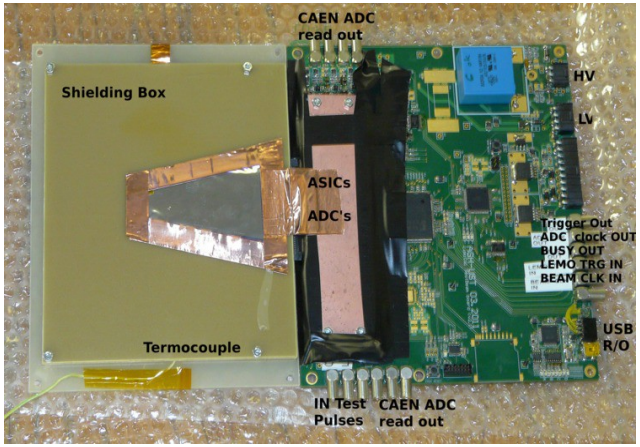
- 3.5 mm thick (one radiation length)
- Tungsten plates flatness required on front/back side - 10/50um
- 11 prototype plates produced in two companies. Four of them fulfill flatness specifications
- Joint effort CERN, AGH-UST, IFJPAN



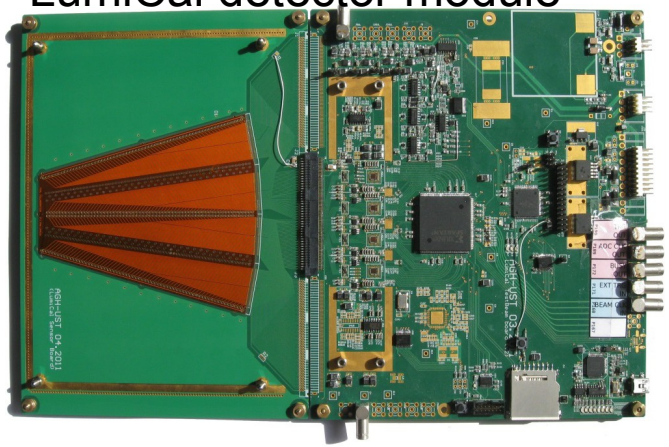


Performed FCAL R&D
Complete detector modules on test-beam

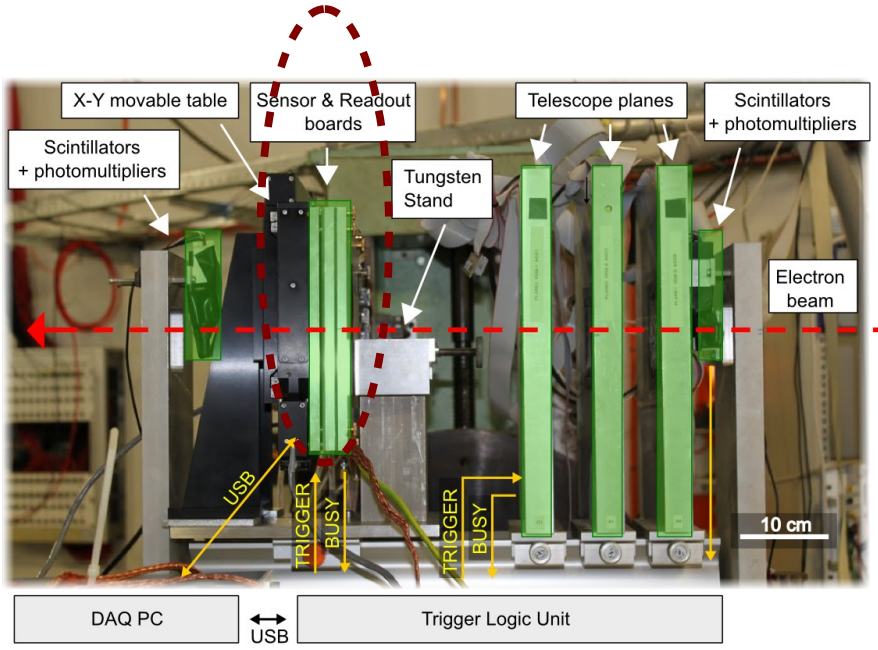
BeamCal detector module



LumiCal detector module

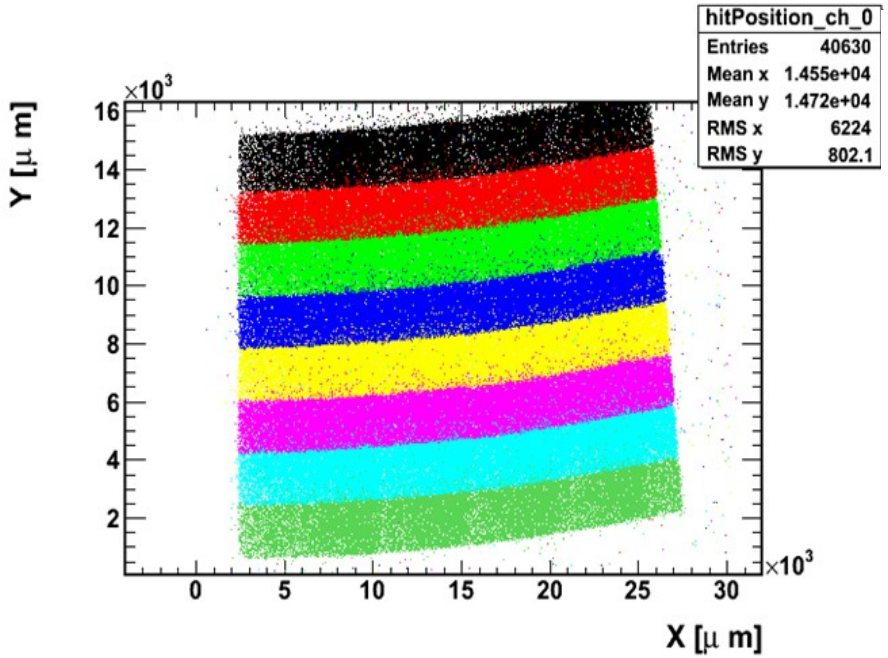


- **Performance studies of BeamCal and LumiCal detector prototypes were done in test-beams at DESY in 2010-2012**
- **More than $50*10^6$ events were taken in an electron beam 2-4.5 GeV at DESY**

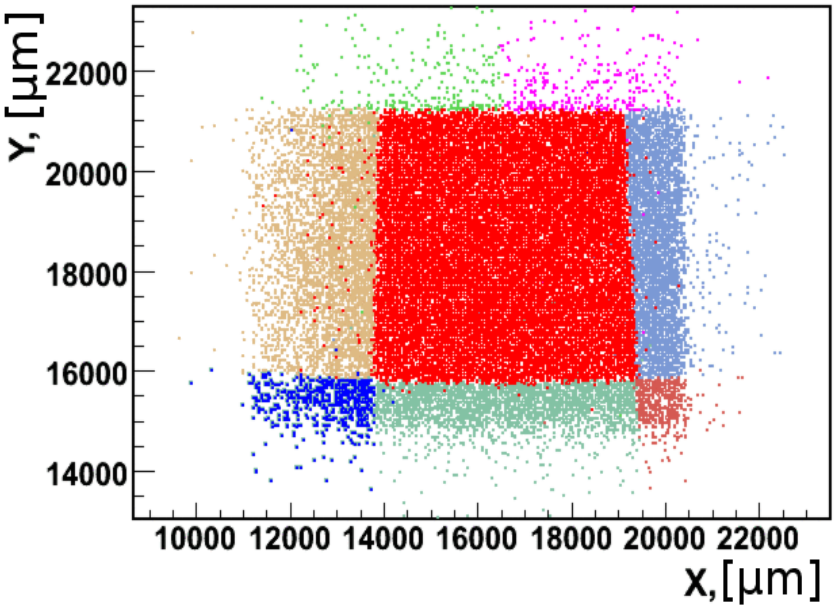


Example test-beam setup at DESY

Performed FCAL R&D
Glimps of beam-test results



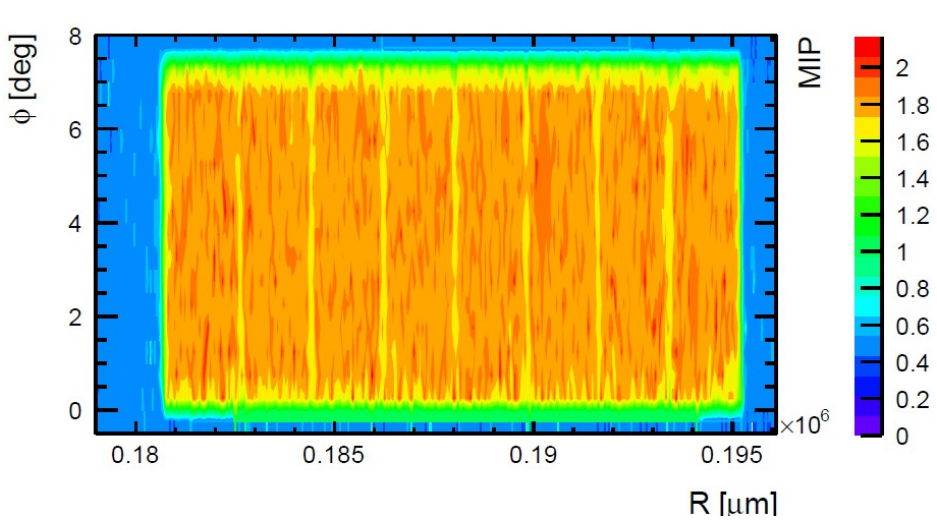
Impact point reconstruction with beam telescope and LumiCal sensor



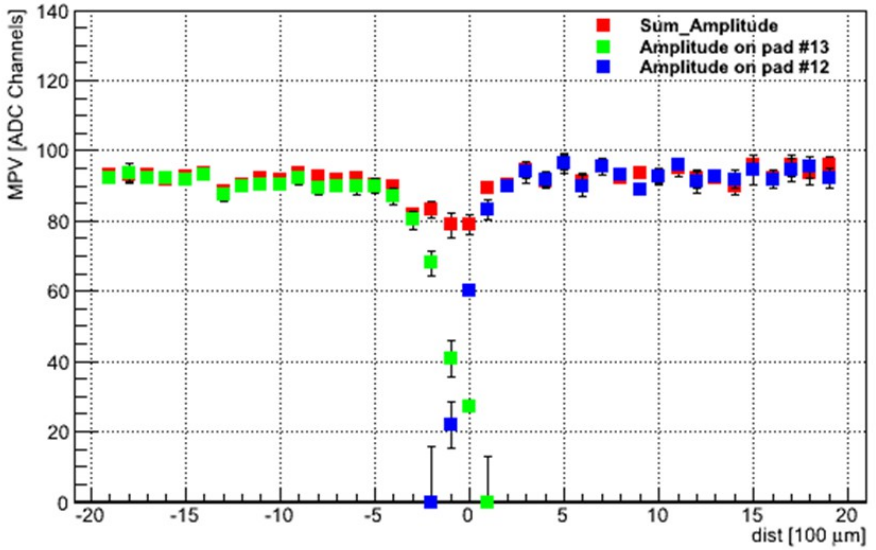
Impact point reconstruction with beam telescope and BeamCal sensor

Performed FCAL R&D
Glimps of beam-test results

Study of edge effects between sensor pads



LumiCal sensor

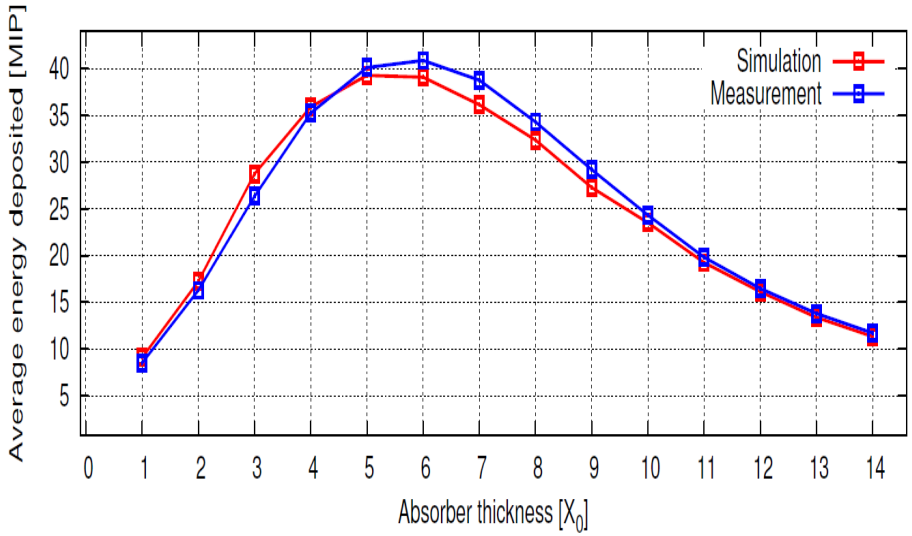


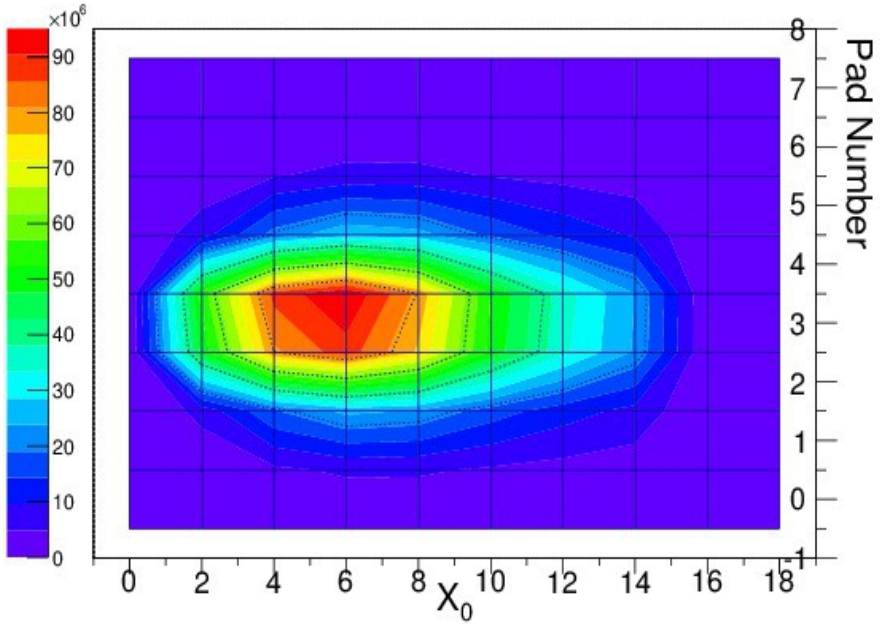
BeamCal sensor

About 10% of signal is lost for events beetwen two pads

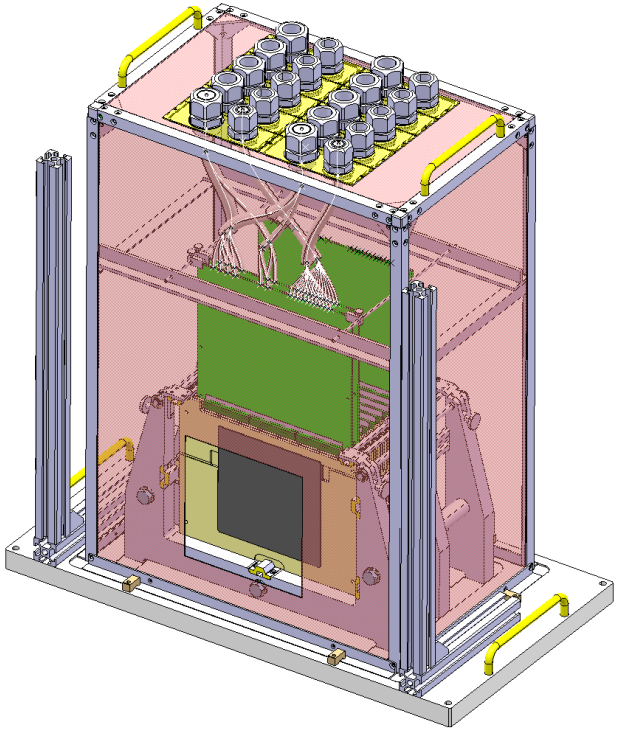
Performed FCAL R&D
Glimps of beam-test results

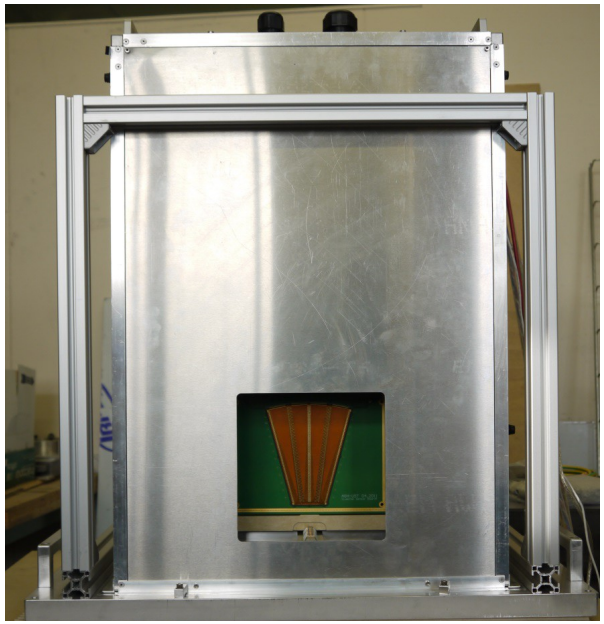
Shower profile measurements with n * X0 tungsten blocks in front of the sensors

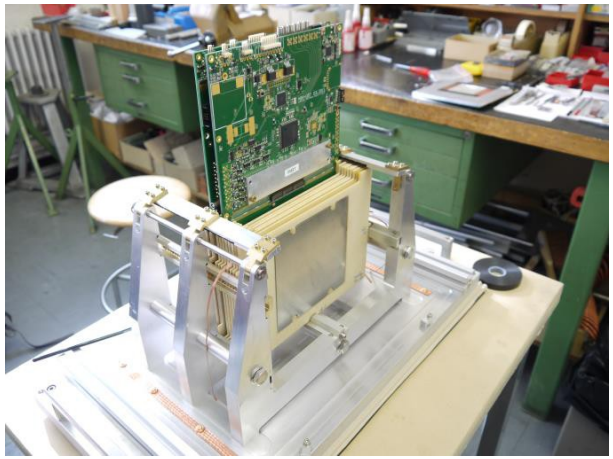




Performed FCAL R&D
Precise mechanical frame for calorimeter

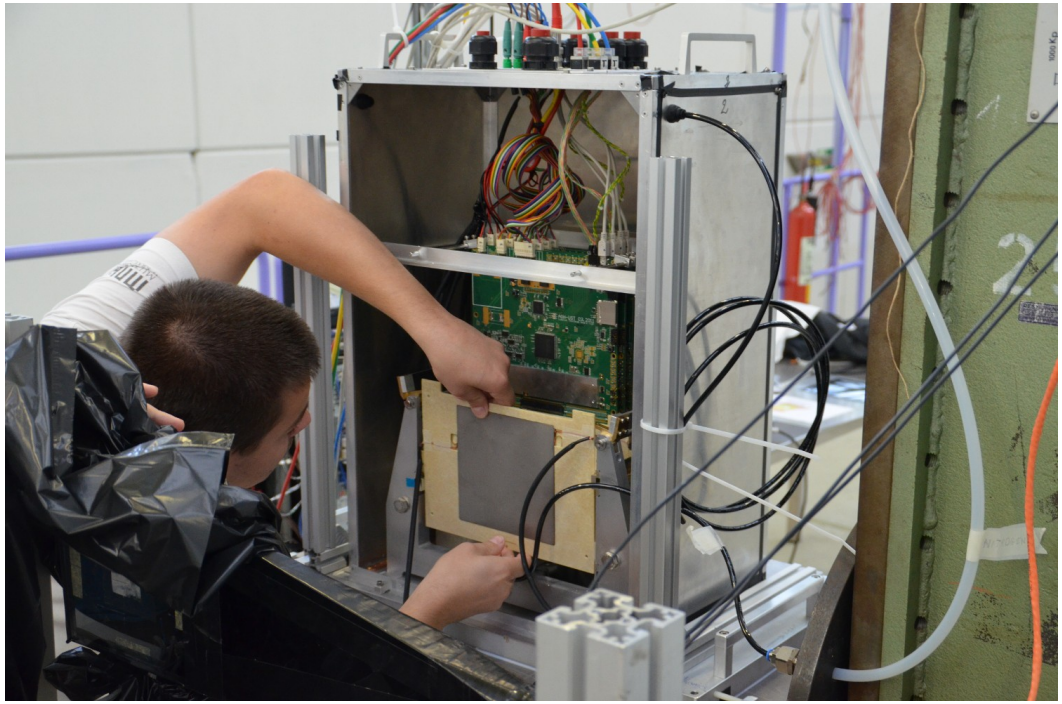






- Precise mechanical frame can hold up to 30 sensor-absorber layers
- Various configurations of detector modules and absorber plates are possible
- The frame was developed at CERN

Performed FCAL R&D
Beam-test with four detector planes



At the end of 2014 a first test-beam with multilayer detector.

Four LumiCal detector planes and several configurations of absorber plates were tested at CERN PS beam.

Data analyses are in progress and we expect results validating the design...

but

with the existing detector modules we will not build a highly compact (~1cm Moliere radius), ultra-low power (<100uW/channel) calorimeter, because of rather old technologies used

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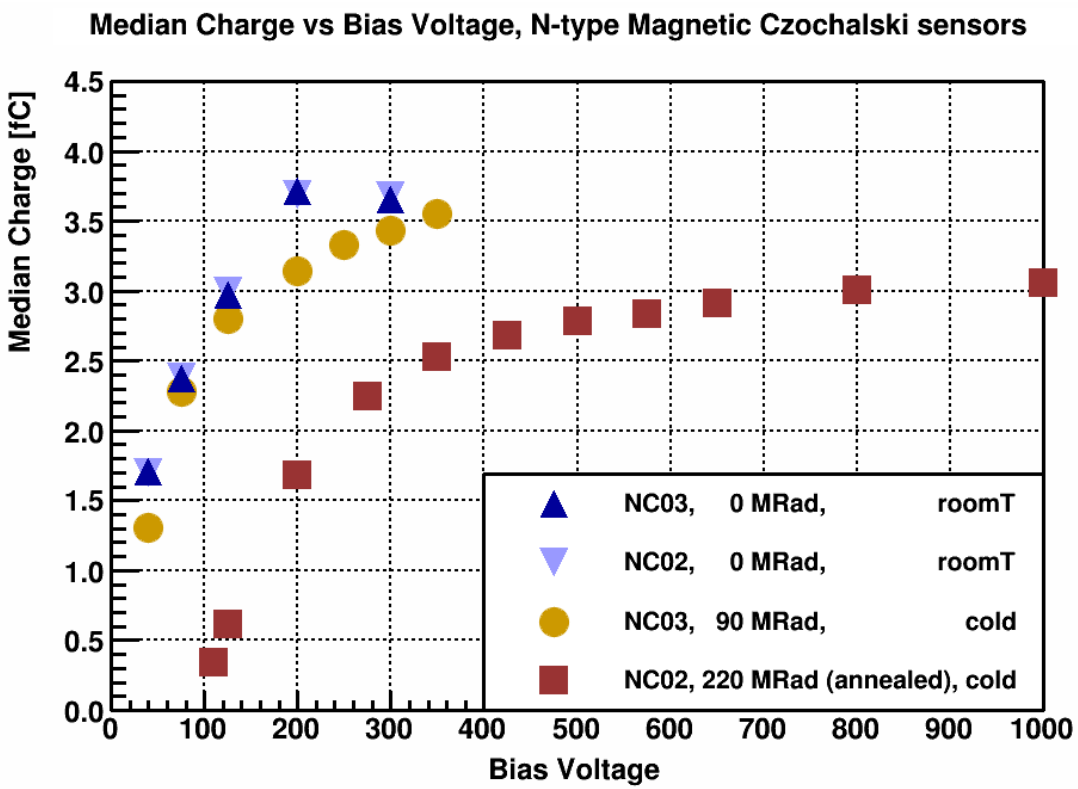
New FCAL R&D on sensors

Rad-hard Si sensors for BeamCal



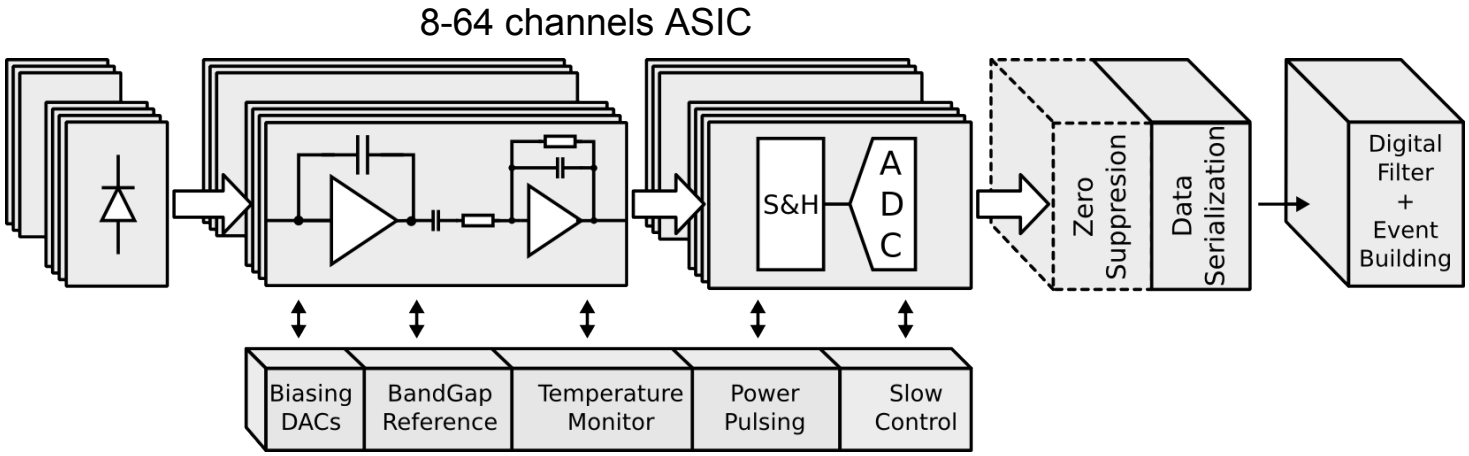
Promising first results on irradiated Si sensors

- After 2.2 MGy (220MRad) dose only ~15% charge loss
- Studies carried out at University of California

Other new sensor R&Ds:

- New concept of BeamCal detector with Sapphire senors (DESY)
- New edgeless sensors for LumiCal detector (TAU)

New FCAL R&D on ASICs
New generation of readout electronics



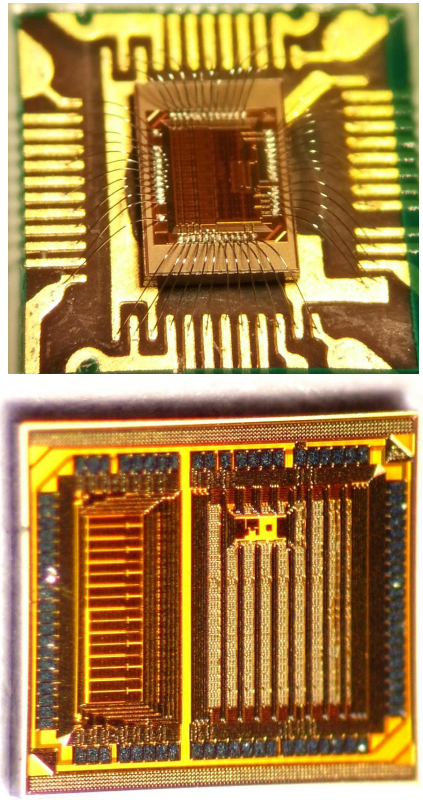
Main features/goals:

- System on Chip (SoC) type readout ASICs
  - New multichannel ASICs will comprise (almost) all readout functionalities to minimize number of external components – to enable construction of highly COMPACT calorimeter. The readout module should be small and 4.5mm thick (presently ~1 cm)
- Advanced CMOS technologies
  - CMOS 130 nm for LumiCal (AGH-UST), CMOS 180 nm for BeamCal (PUC Chile)
  - Decrease of power consumption by factor of ~10
  - Improved radiation hardness

New FCAL R&D on ASICs
Readout ASICs in CMOS 130nm for LumiCal

Front-end ASIC features:

- 8 channels
- Cdet ≈ 5 ÷ 50pF
- 1st order shaper (Tpeak ≈ 50 ns)
- Variable gain, two modes:
  - calibration - MIP sensitivity (~4fC)
  - physics - input charge up to ~5 pC
- Power pulsing
- Power consumption
  - peak ~1.5 mW/channel
  - average < 15 uW/channel
- Developed at AGH-UST



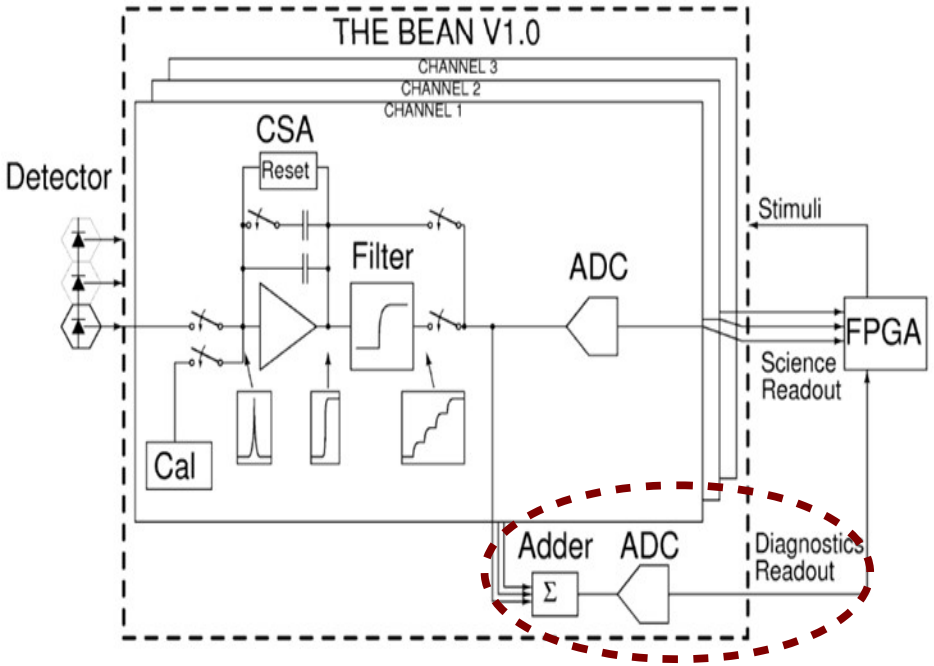
ADC ASIC features:

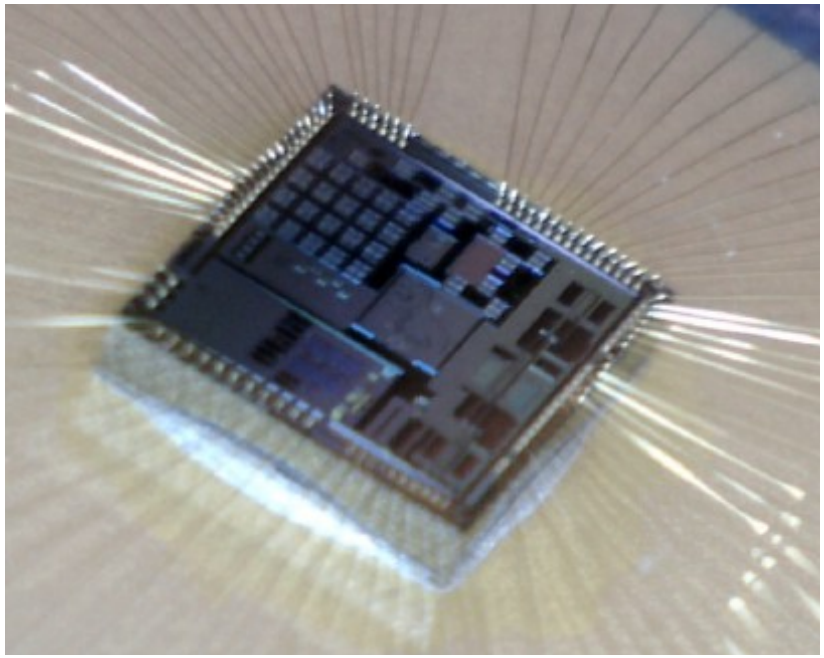
- 8-channel 10-bit SAR ADC
- Max. sampling freq. ~40MSps
- Power pulsing
- Power consumption
  - peak ~1mW/channel
  - average ~10 uW/channel
- ENOB ~ 9.3 bits
- FOM ~50 fJ/conv.
- Developed at AGH-UST

First prototypes of 8-channel front-end and 10-bit ADC ASICs have been designed, fabricated, and succesfully tested

Power consumption is about an order of magnitude less than for previous ASICs in AMS 0.35um

Ongoing FCAL R&D on ASICs
Readout ASICs for BeamCal in CMOS 180 nm



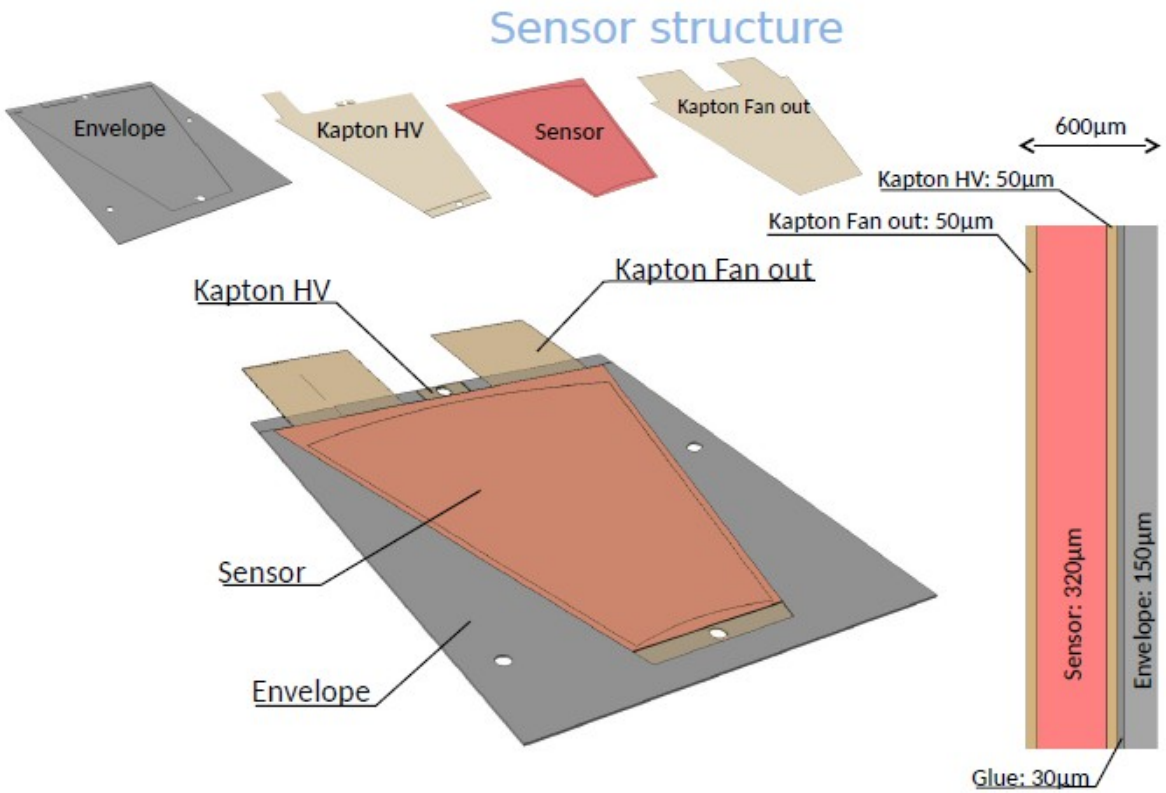


- Novel front-end architecture based on switched-capacitor filter
- Front-end and 10-bit ADC in each channel (as in LumiCal readout)
- Adder circuit for fast beam diagnostics
- First single channel prototypes fabricated and tested
- Development of next ASIC version in progress at PUC Chile

A. Abusleme, A. Dragone, G. Haller, B. Wooley "BeamCal Instrumentation IC: Design, Implementation and Test Results", IEEE Transactions on Nuclear Science, 59(3) 2012

New FCAL R&D on highly compact sensor "board"

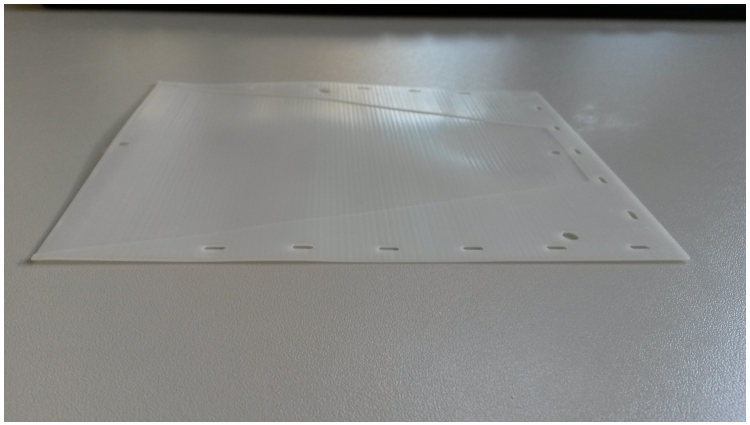
To build a compact (4.5 mm thick) sensor-absorber module the sensor "board" thickness should be < 1 mm since the absorber is 3.5 mm thick

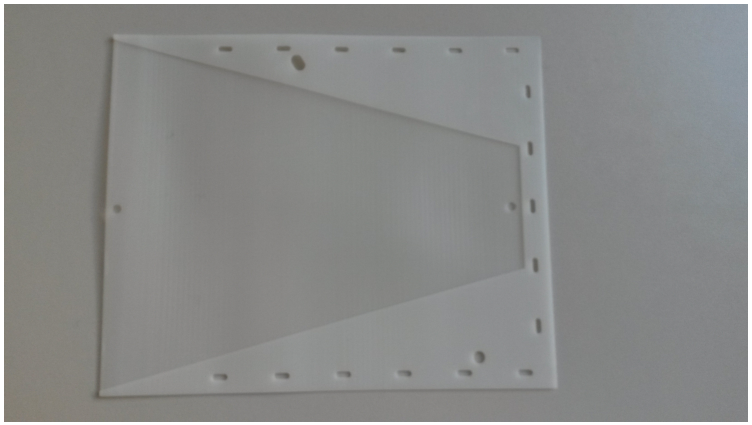


Prototype of sensor "board" is just being developed by TAU group.
Also IFJPAN works on similar concepts.

New FCAL R&D on highly compact sensor “board”…

Prototypes of first components for highly compact sensor “board” have been already designed and fabricated by TAU group



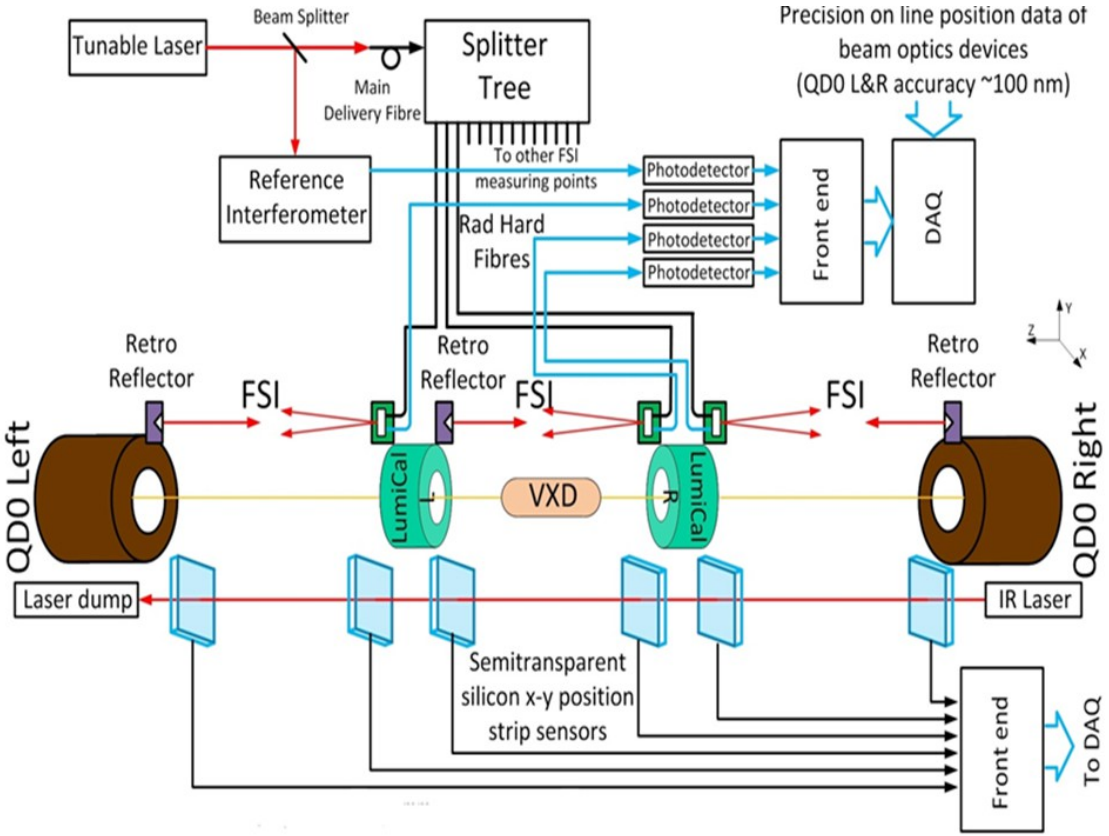


Prototype of thin envelope obtained with 3D printing with plastic risen (Accura 25)

Example of new kapton fanout

New FCAL R&D on alignment
Design of alignment system for the LumiCal

Laser alignment system (LAS) under development at IFJPAN using **FSI** and **PSD**



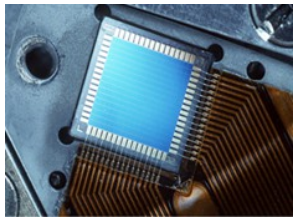
FSI (Frequency Scanning Interferometry) – measurement of absolute distance between two barrels of LumiCal detector. Measurement precision on the level of few um.

PSD – measurements of relative distances and displacements of the internal LumiCal Si layers. Measurement precision below 100 um.

PSD components: infra-red laser beam and semi-transparent position sensitive detectors
FSI componentes: tunable laser(s), beam splitters, Fabry-Perot interferometer, retroreflectors, fibers, collimators, photodetectors, mirrors, lenses

New FCAL R&D on alignment
Laboratory demonstration of LAS system

PSD

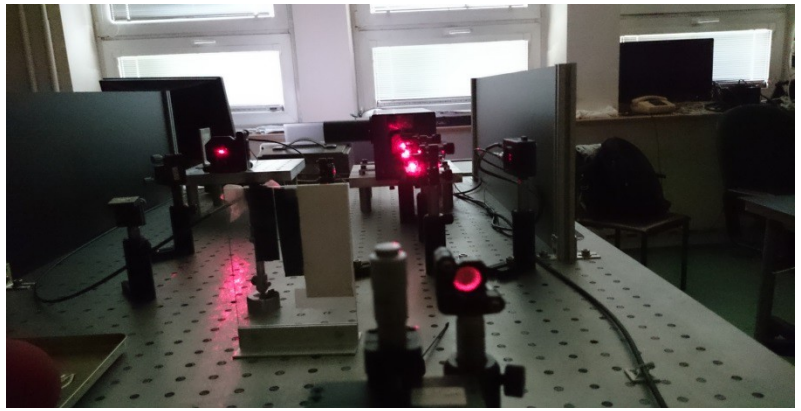


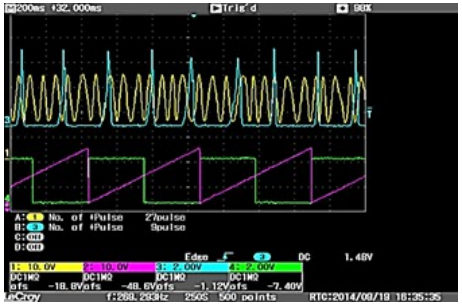
Semi-transparent sensor: 16 strips in the X and Y directions

Prototype setup with 6 sensors

Preliminary results: displacement of the tested elements was measured with precision of about 20 μm

FSI





Typical signal view (interference fringes) displayed by scope

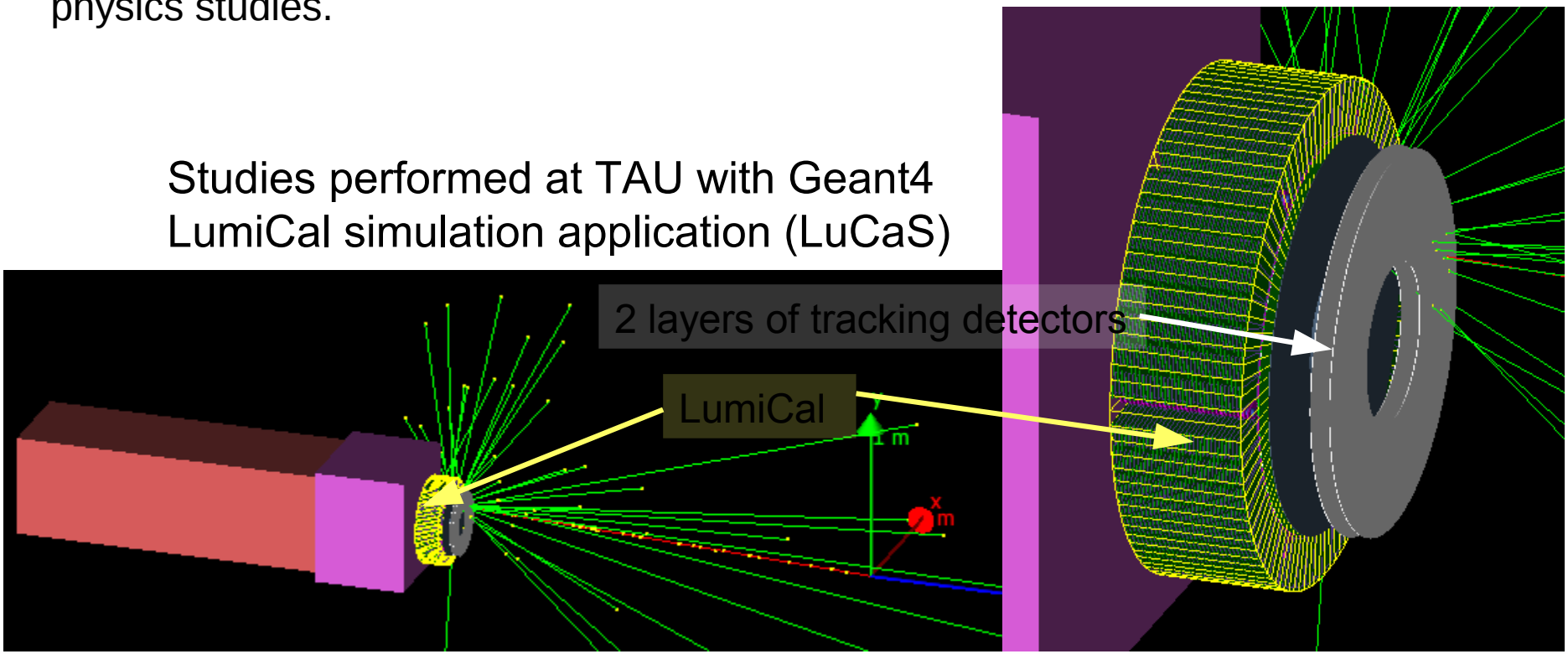
Preliminary results: accuracy of about 5, 6 and 15 μm was obtained for distance measurements on the distances 30, 50 and 90 cm respectively

The obtained results show that both systems can be used to monitor the LumiCal displacements

New FCAL R&D on Tracking Detector in front of LumiCal

- Improve polar angle measurement accuracy – important for precise luminosity evaluation;
- Provide information for better LumiCal sensors alignment;
- Provide more information to enable e/γ identification - important for various physics studies.

Studies performed at TAU with Geant4 LumiCal simulation application (LuCaS)



Summary

- FCAL Collaboration conducts R&D on forward calorimeters for future Linear Collider
- First prototypes of LumiCal and BeamCal detector modules were built and used succesfully in several test-beams. Recenty a test-beam with four sensing planes and several absorber configurations was done. Data analyses are in progress...
- New R&D activities have been started to build a prototype of a new highly COMPACT calorimeter fulfilling stringent BeamCal/LumiCal requirements. First results on readout ASICs, thin sensor boards, alignment, are very promising.

Thank you for attention