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Study of a 3x3 module array of the ECAL0 calorimeter with an electron beam at the ELSA

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Abstract. ECAL0 is a new electromagnetic calorimeter designed for studying generalized parton distributions at the COMPASS II experiment at CERN. It will be located next to the target and will cover larger photon angles (up to 30 degrees). It is a modular high-granularity Shashlyk device with total number of individual channels of approx. 1700 and readout based on wavelength shifting fibers and micropixel avalanche photodiodes. Characterization of the calorimeter includes tests of particular sub-components, tests of complete modules and module arrays, as well as a pilot run of a fully-functional, quarter-size prototype in the COMPASS experiment. The main goals of the tests on low-intensity electron beam at the ELSA accelerator in Bonn were: to provide energy calibration using electrons, to measure angular response of the calorimeter and to perform an energy scan to cross-check previously collected data. A dedicated measurement setup was prepared for the tests, including a 3x3 array of the ECAL0 modules, a scintillating-fibre hodoscope and a remotely-controlled motorized movable platform. The measurements were performed using three electron energies: 3.2 GeV, 1.6 GeV and 0.8 GeV. They include a calibration of the whole detector array with a straight beam and multiple angular scans.

1. The detector

1.1. ECAL0 at COMPASS II

ECAL0 is a new electromagnetic calorimeter to be built for COMPASS II experiment at CERN for Generalized Parton Distribution (*GPD*) study. It's going to be mounted as one of the most upstream detectors, right next to the fixed target and before SM1 magnet (see figure 1). It will cover particle angles from 5 to 30 degrees and energy range from 0.2 up to 30 GeV.

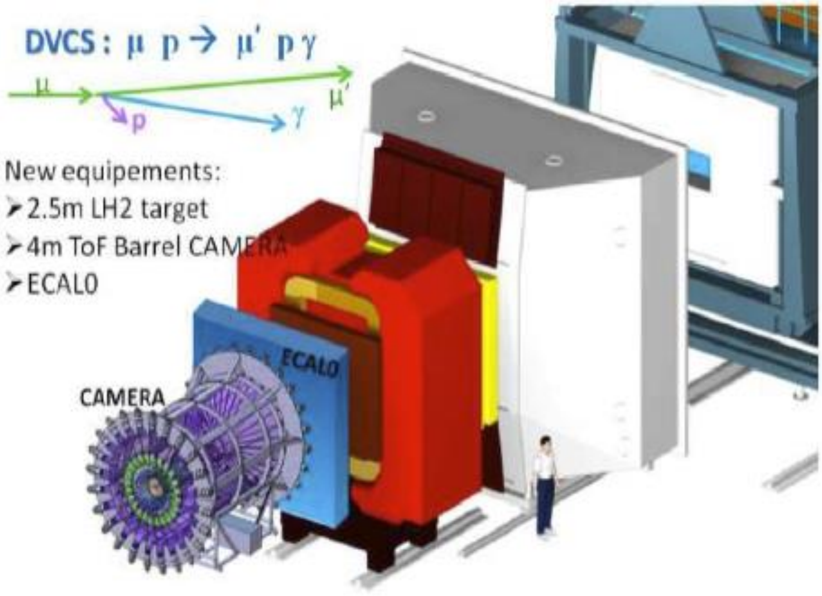

Figure 1. Upstream detectors of COMPASS II experiment. The target is installed inside the CAMERA detector.

1.2. Detector design

ECAL0 is a modular, multi-channel, sampling electromagnetic calorimeter with external dimensions of approximately 2x2m. It consists of 194 9-channel modules, giving a total of 1746 channels. The modules are aligned in an almost round pattern with rectangular beam window (see figure 2).

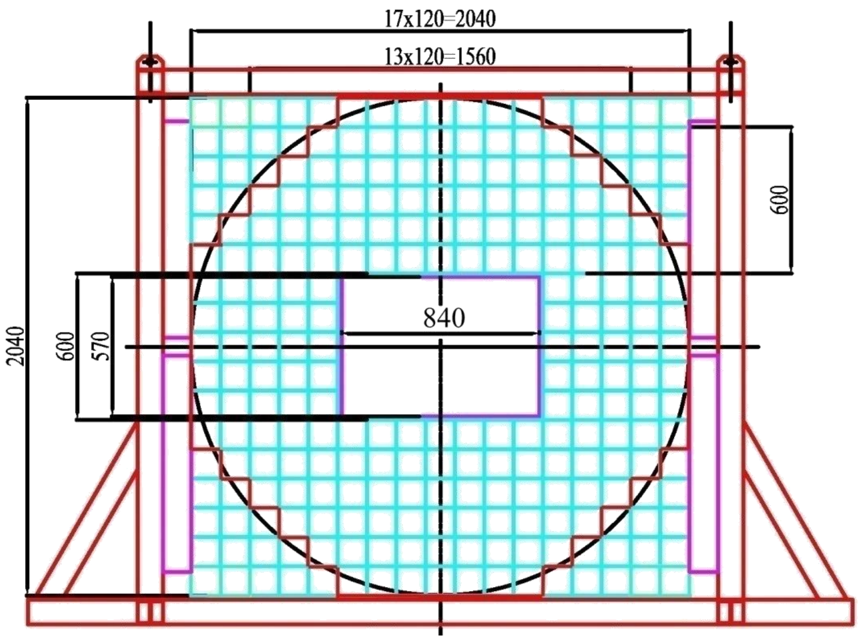

Figure 2. Front view of the detector.

The position of the detector in the experiment gave some constraints on its construction:

- due to proximity to SM1 magnet, the detector must be insensitive to magnetic field;
- the depth of the device is limited to 50 cm;
- the power consumption should be as low as possible due to limited cooling capabilities.

1.3. Colorimeter module

A single detector module consists of two main parts: calorimeter part and readout assembly (figures 3, 4, 5). They are detachable for service and for transportation.

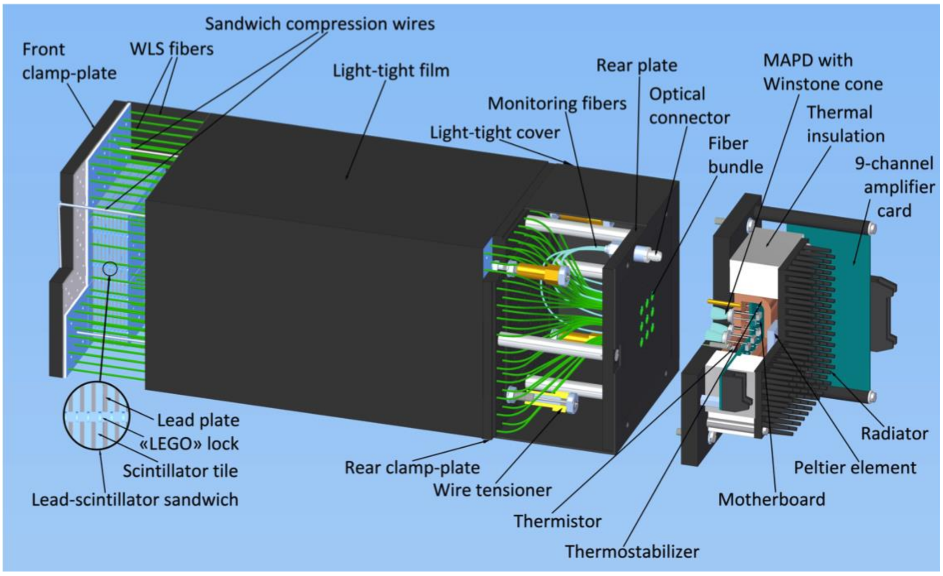

Figure 3. Overview of the detector module.

The calorimeter part (figure 4) has nine independent channels having a form of a shashlyk with 1.5 mm thick polystyrene scintillators and 0.8 mm thick lead plates, giving a total thickness of 25.2 cm with 109 layers. The Moliere radius of the detector is 3.5 cm while a single channel has a cross-section of 3 x 3 cm. The light from the scintillator plates of each channel is collected by 16 Bicron BCF91AMC WLS fibres (1.2 mm), forming a 6.5 mm bundle at the output, along with 1 clear fibre for LED monitoring.

The readout part (figure 5) incorporates photodetector and accompanying electronics as well as Peltier-based temperature stabilization system. All electronics is divided into three PCBs:

- the motherboard with photodetectors and some passive components for power supply
- slow control board with bias voltage generator (approx. 80 V), power monitoring and temperature control circuits;
- analog front-end for signal shaping and transmission over twisted pairs.

The temperature of the photodetector is kept at a constant level set around 16-18^{o}C to keep the noise on a sufficiently low level and maintain a constant, well defined electron gain.

Figure 4. Calorimeter part of the module (unsealed).

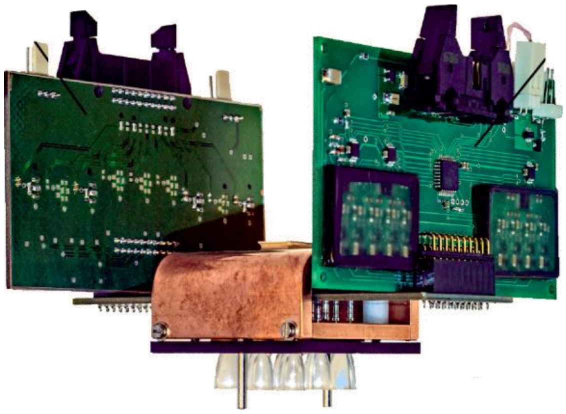

Figure 5. Readout part of the module with Winston cones, photodetectors, electronics and Peltier cooler.

1.4. Photosensors

The scintillation light is detected by multipixel avalanche photodiodes. Generally, Zecotek MAPD-3A and MAPD-3N were used for various tests of the detector, with MAPD-3N intended to be used in the final design. However, Hamamatsu MPPC S12572-10P is also considered to be used in the detector due to its low noise and reasonable price. Table 1 presents the comparison of these two products.

Table 1. Basic parameters of MAPD-3N and S12572-10P MPPC.

	Zecotek MAPD-3N	Hamamatsu S12572-10P
Size, mm^2	3 x 3	3 x 3
Pitch, μm	8 (size: 5)	10
Number of pixels	135 000	90 000
Bias voltage, V	90	70
Gain · 10^5	3-5	14
PDE, % (λ=520 nm)	30	10

Generally, MPPC has slightly lower pixel density and much lower photon detection efficiency (PDE), but it's still competitive to MAPD-3N due its high gain, low noise and short recovery time.

1.5. Signal read-out

The readout path of the detector consists of two main parts: front-end amplifiers and ADC converters (figure 6). The amplifiers are located directly on the readout modules. They provide 4th order signal shaping and transmission over a 110Ω twisted pair. This is done by two op-amps (the second one is symmetric and acts as the line driver) powered by a single +5V supply. The peaking time of the output pulses is 40 ns and is selected to be optimal for 80MHz sampling.

The analog-to-digital conversion is performed by external Mezzanine Sampling ADC (MSADC) boards installed in a 9U VME crate. Each board has 4 16-channel modules with 12-bit resolution and 80 MHz sampling rate. One MSADC board covers 7 calorimeter modules which occupy 63 channels. The remaining channel is used for debug purposes – either as analog sum of 7 modules or as LED monitor.

A patch board is designed between amplifiers and MSADC for the final design. Its main aim is to interface round, 10-pair cables from modules to 17-pair ribbons to be connected to MSADCs. It will also allow easier detector disconnecting and provide analog sum of all detector channels for trigger generation. For the prototype, slightly different patch boards were used, which were installed directly on MSADC connectors, without ribbon cables.

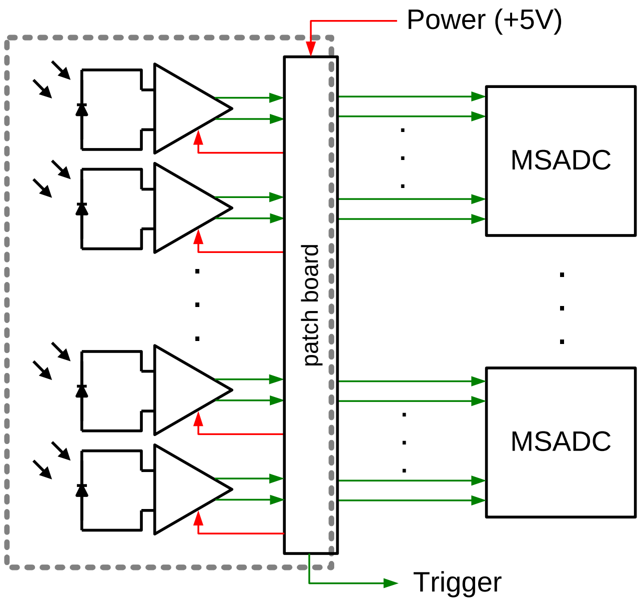

Figure 6. Block diagram of the readout electronics.

2. Previous detector tests

2.1. Prototypes and test setups

Two types of detector setup were used for various tests of ECAL0 modules. The first one is a 81-channel, 9-module (3 by 3 modules) matrix used for measuring various parameters of the modules, including the tests performed in Bonn (figure 7). The second one is a fully functional, quarter-size detector which was installed in 2012 on Compass beam to check overall detector capabilities.

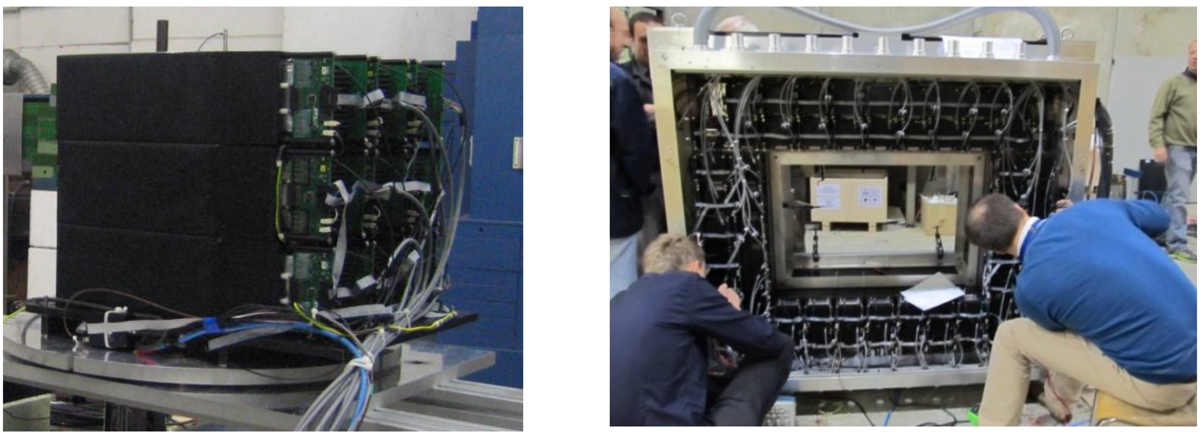

Figure 7. 3 x 3 (81-channel) setup used for various tests, including the tests in Bonn (left) and quarter-size detector for tests on Compass beam in 2012 (right).

2.2. Calibration at CERN
Before starting the experiment in Bonn, some experiments in CERN were already completed to test the detector. They included:

- tests on cosmics and muons (9-module matrix) to get energy calibration, noise performance and energy resolution;
- a pilot run of a quarter-size detector prototype within COMPASS experiment in 2012 with π^0 calibration;

Also, extensive tests of photodetectors, readout electronics, slow-control as well as tests of single modules were performed.
Some data used for energy calibration are shown in figures 8 and 9.

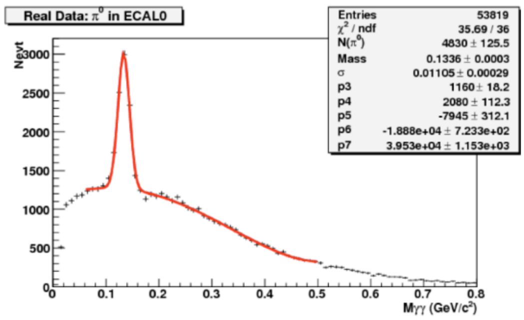

Figure 8. π^0 peak in ECAL0.

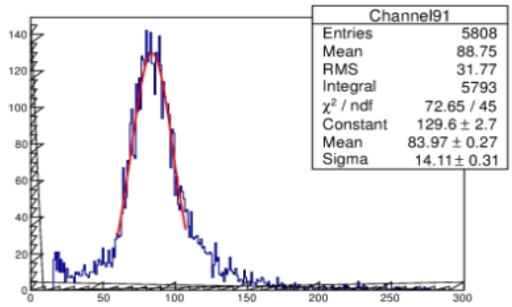

Figure 9. The muon peak.

3. Detector tests on electron beam in Bonn

3.1. Reasons and goals
The main goals for the tests to be done in Bonn at the ELSA were:

- to calibrate the energy response of the detector for electrons;
- to check the angular response of the detector over a range of 0 to 36 degrees with 6-degree step;
- to perform an energy scan over three points (3.2, 1.6 and 0.8 GeV) to cross-check previously collected data.

3.2. Measurement setup
The measurement setup for tests in Bonn (figure 10) consisted of three main parts:

- a low-intensity electron beam source, the ELSA accelerator;
- a Sci-Fi hodoscope for system triggering, high-resolution electron position readout and beam monitoring;
- a 9-module ECAL0 matrix installed on an automated moving platform for spatial and angular scanning.

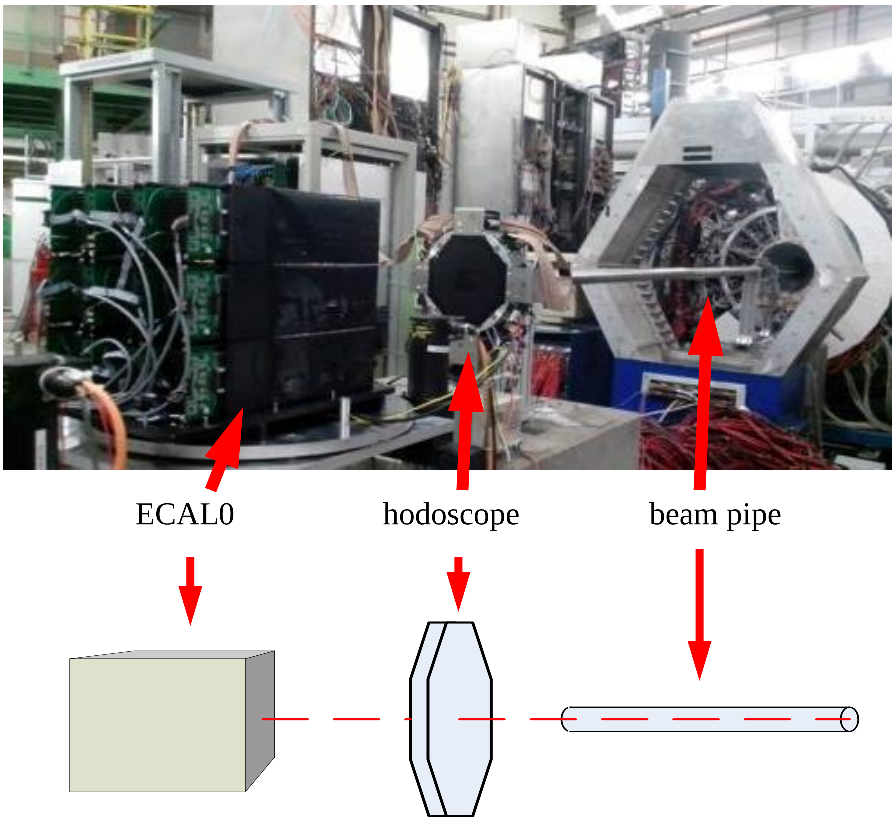

Figure 10. The measurement setup.

The first element, namely the ELSA accelerator, is capable of supplying an electron beam with energy of up to 3.5 GeV for various aims. For ECAL0 tests, the accelerator was prepared to provide a low intensity beam (approx. $2{\cdot}10^3$ particles per second, which gives as little as one electron per 1000 beam rotations). The experimantal setup was installed on a position normally occupied by the Crystal Barrel (CB) experiment. In order to make space and provide beam, some parts of the Crystal Barrel experiment were removed. Also, some parts of the beamline were removed or re-ordered. The main changes were:

- removing parts of CB experiment: TAPS, target system, photon flux detector;
- removing parts of beamline (cleaning magnet, collimator system);
- adding an evacuated beam pipe between the tagging system and the hodoscope.

The main problem was that normal beam monitoring was not possible during run due to low beam intensity and the fact that ECAL0 was installed between the beam output and the beam monitor. Thus, a special beam positioning scheme was applied:

- first, the accelerator was tuned on high intensity beam and with ECAL0 removed from the setup; after getting right beam shape, appropriate settings of the accelerator control were frozen;
- after tuning, the accelerator was switched off and re-programmed for lower intensity, wile ECAL0 was inserted into its working position;
- for the normal run, the accelerator was running on frozen settings, the beam intensity was cotrolled on-line by means of the hodoscope's trigger output, and the beam size and position was only manually checked by observing beam profiles collected by the hodoscope.

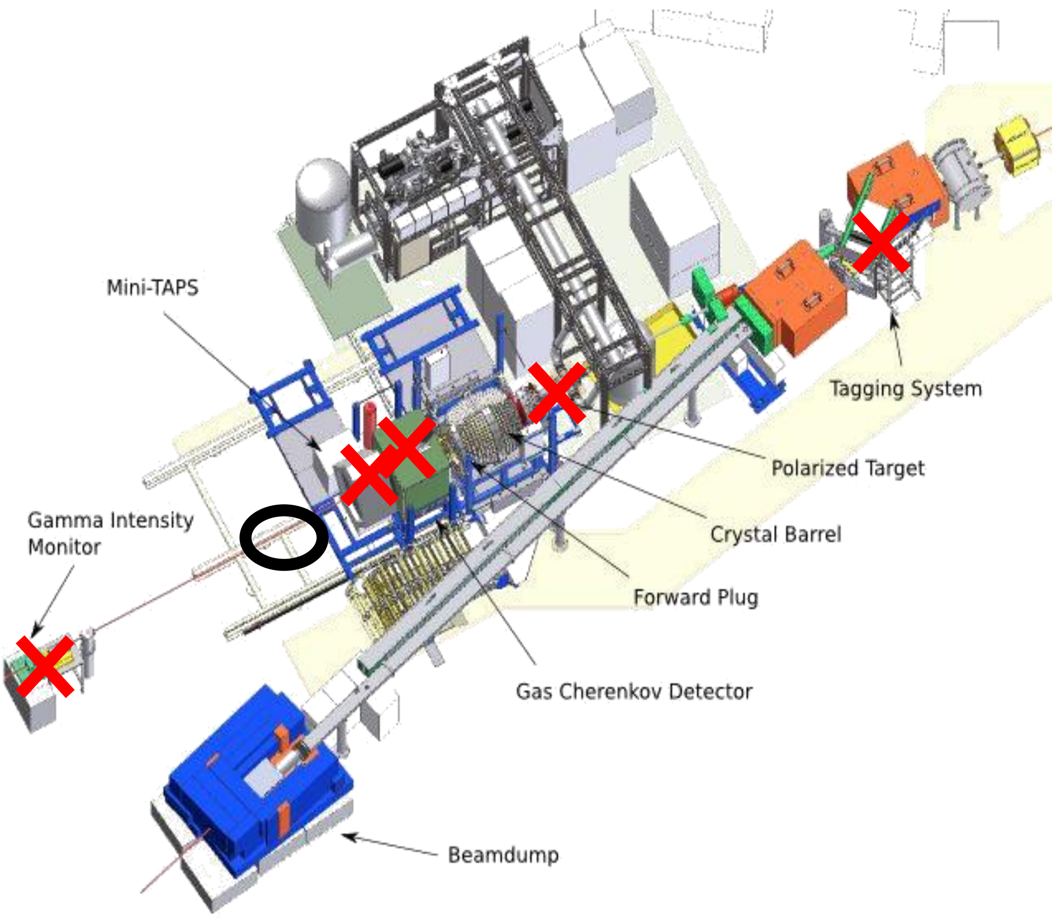

Figure 11. CB-part of the ELSA system; removed components are shown with crosses; the ECAL0 position is marked with black circle.

The Sci-Fi hodoscope was designed specially for the tests and will be described in more detail in the following paragraph.

The moving platform (kindly supplied by Giessen University) allowed high-precision positioning over two axes. It was remotely controlled via a Windows PC with Lab-View software and remote desktop. For detector rotation, a manual rotating stage was designed in Bonn and mounted on the top of the moving platform. The rotating stage allowed to fix the detector at an angle of -36 to +36 degrees with 6-degree step, as well as at +/-90^o and 180^o. Thanks to mechanical locking system, the positioning error was negligible.

3.3. Program of the tests

The program of the tests contained two parts. The first part was to scan the whole matrix (81 channels) with 3.2 GeV beam. Generally, one measurement point per one channel was collected (40 mm step), although few channels were scanned with 10 mm step to check the spatial uniformity of the response.
The second part was the angular scan, which was performed for three different energies: 3.2, 1.6 and 0.8 GeV. Seven angle settings (0-36 degrees with 6^o step) and 15 various beam positions were scanned for each energy. There were about 400 runs performed in total, which gave approx. 250 GB of raw data.

4. The Sci-Fi hodoscope

4.1. Design

The main aims to use the hodoscope were accurate read-out of the position of incident electrons and system triggering. It was used also for accelerator control, as beam intensity and shape monitor.

It was designed as two-plane Sci-Fi detector with approx. 23 x 23 mm active area and 32 channels in each plane, giving position resolution of 0.7 mm with fibre diameter of 1.2 mm. Each detector channel consists of one fibre only, so aluminium mirrors were made at the blind ends of the fibres to increase light output (the actual light output is 16 photons/MIP). Four 16-channel photomultipliers (Hamamatsu H-8711) were used as photodetectors. PMT power is supplied by an external HV power supply.

All heavier detector parts (PMTs, electronics) were mounted to a rigid aluminium frame (figure 13), while the fibre array has a support made of extruded polystyrene. Plastic covers with thin beam windows made of kapton were used to get light tightness of the whole frame. Additional covers were made to protect electronic circuits (see figure 12).

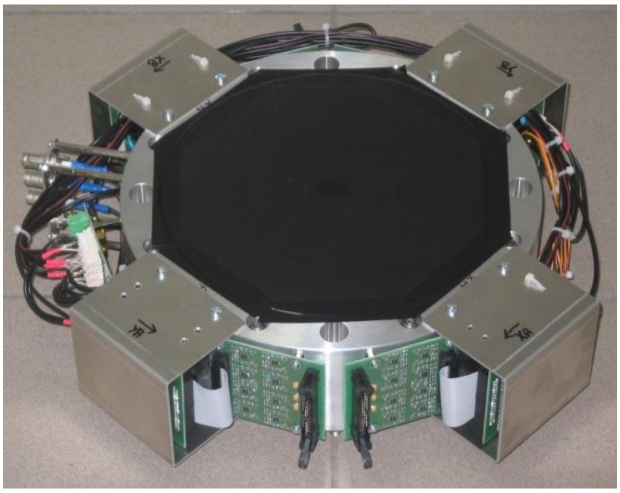

Figure 12. Complete Sci-Fi detector.

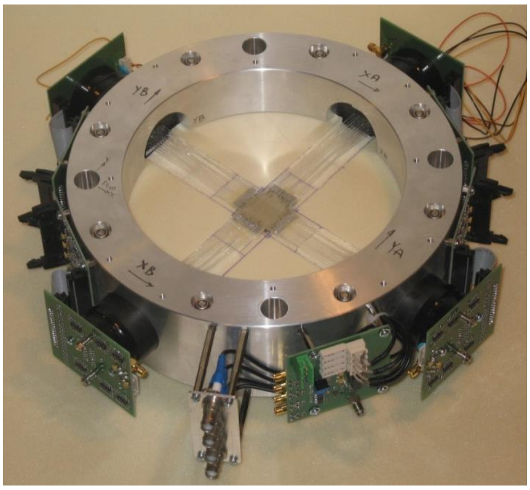

Figure 13. The detector without covers and cables. Fibres are visible inside.

4.2. Detector read-out

Two kinds of output signals are provided at the output of the Sci-Fi detector:

- channel signals for position recognition (analog);
- output trigger signal (digital).

The channel output is designed to be compatible with MSADC in terms of amplitude and signal shape, which corresponds to approx. 1 V amplitude, 40 ns pulse peaking time and differential output with 34-pin ribbon cables. It was decided to use MSADC for Sci-Fi readout to simplify the DAQ system, as the same boards were used for ECAL0.

The trigger signal is provided via LEMO connector in NIM standard to be directly connected to NIM-based trigger system of the experiment.

All the electronics for both outputs is located directly on the detector's frame to make it possibly compact. All circuits are powered from a single +5 V line consuming approx. 0.5 A.

5. Measurement Results

5.1. Beam Profiles

The first measurements concerned not the ECAL0 detector itself, but the beam spot. It turned out that the beam is very narrow for lower energies (figures 16 and 17) while a tail on X-axis is visible at 3.2 GeV, giving an increase of beam size to approx. 3 mm (σ). This is due to accelerator's intensity controlling method, which includes moving the beam relative to its nominal position in the synchrotron ring. Nevertheless, the beam size was still within desired range. The effect of the beam tail takes place also at lower energies, but is relatively smaller.
Table 2 presents beam sizes for all used energies.

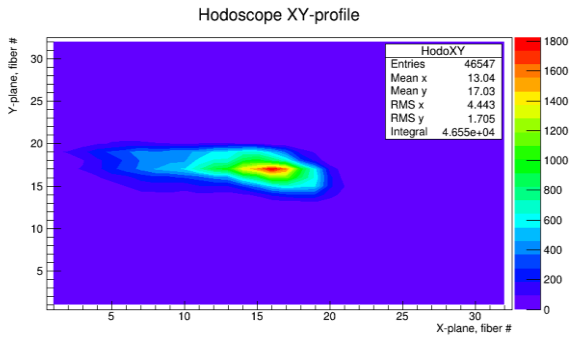

Figure 14. Beam shape at 3.2 GeV.

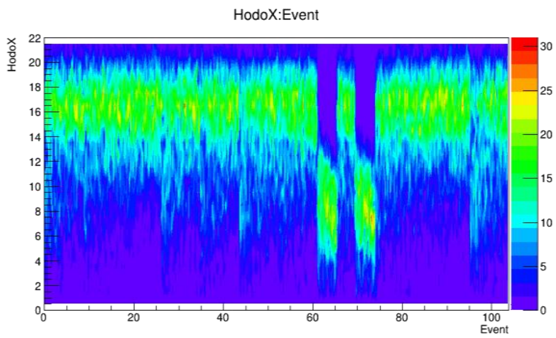

Figure 15. Beam position changes over time.

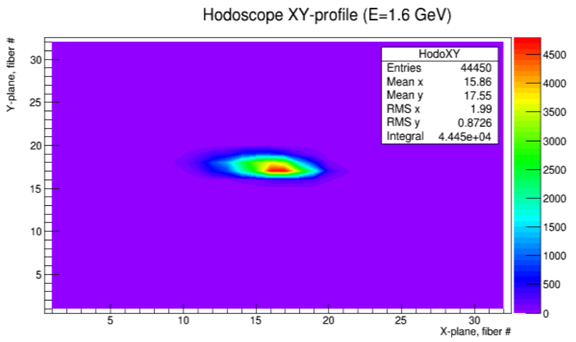

Figure 16. Beam shape at 1.6 GeV.

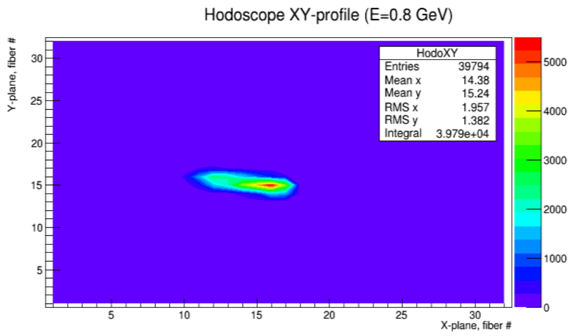

Figure 17. Beam shape at 0.8 GeV

Table 2. Beam size for different energies.

	3.2 GeV	1.6 GeV	0.8 GeV
X profile σ [mm]	3.1	1.4	1.3
Y profile σ [mm]	1.3	0.5	0.5

5.2. Energy calibration and linearity

Figure 18 presents the energy response of the detector on electrons. Three measurement points (0.8, 1.6 and 3.2 GeV) are consistent with Monte-Carlo simulations. The energy resolution (figure 19) is bigger than the expectations by approx. 20%, but it's still within desired limit of $10\% / \sqrt{E}$ [GeV].

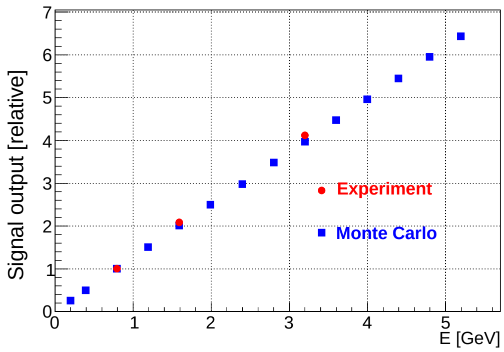

Figure 18. Energy response of the detector.

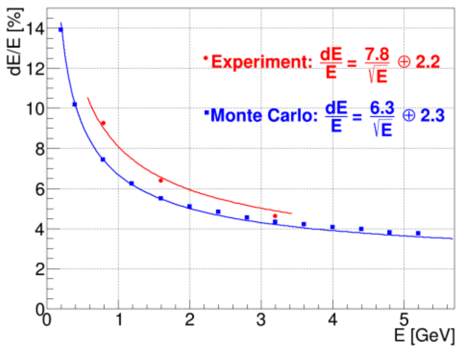

Figure 19. Measured energy resolution

5.3. Angular response

The results of the angular scan are sumarized in figure 20. The main conclusions are that:

- the energy deposit is almost independent of the incident angle;
- the energy resolution remains virtually constant over the angle.

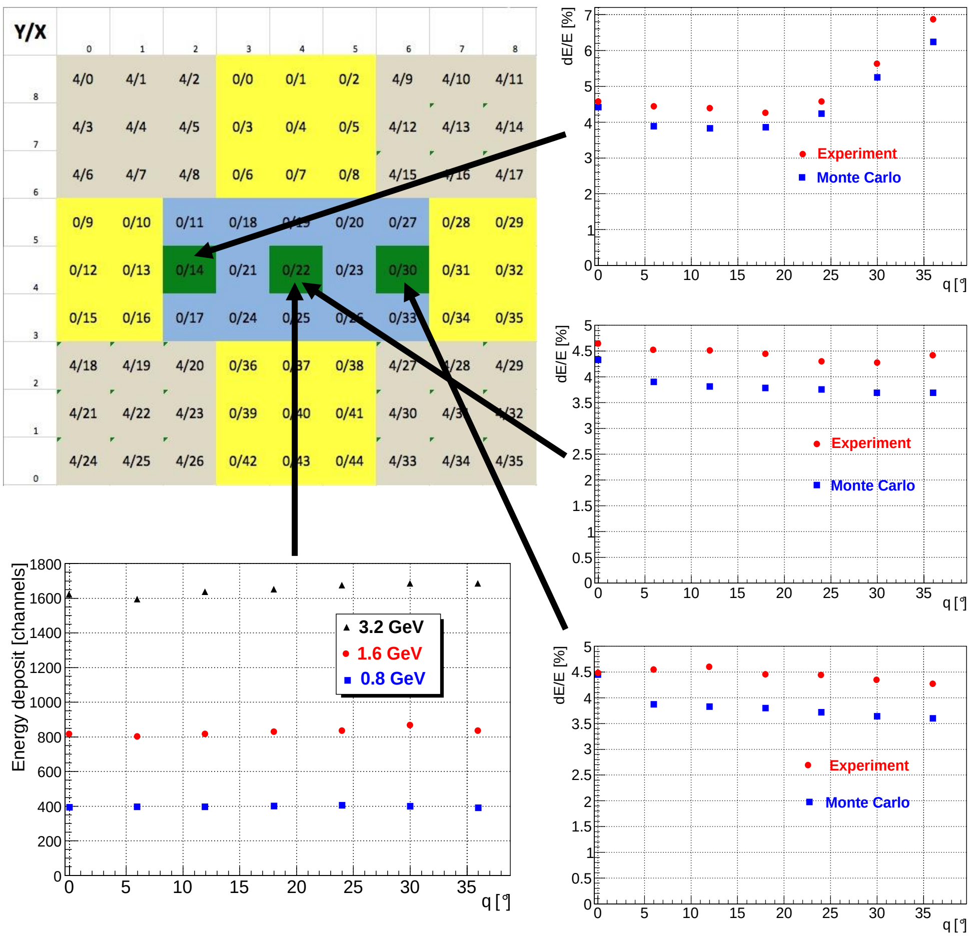

Figure 20. Energy response and resolution of the detector for different angles.

The increase of the noise in the upper right figure is an apparatus effect. The data presented comes from a cell which is close to the edge of the detector and there's a leakage of the particle shower for higher energies. The resolution decrease is due to fluctuations in the leakage from event to event.

6. Conclusions and further actions

The main outcome from the tests in Bonn is that:

- the calibration results from previous tests from 2011 were confirmed;
- measured energy resolution is within desired level and close to expectations based on Monte-Carlo simulations;
- the angle dependence of energy response and resolution is small and also consistent with Monte-Carlo.

Also, it was confirmed that a low-intensity electron beam for detector testing can be smoothly provided by ELSA. A special experimental area is considered to be developed for various detector tests not to interfere with ELSA's everyday research program.
A very good performance of built Sci-Fi tracker was confirmed. It will be used for further ECAL0 tests and probably also as a part of low-intensity beam monitoring system at the ELSA.

The next ECAL0 test to be done is planned for October 2014 at CERN T10 test beam. For these tests, installing MPPC photosensors instead of MAPD-3N is being considered, which needs minor hardware changes in the detector modules. The tests of new photodetectors are in final phase.

7. References

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