

ECal/MPD

Dubna, November 2018, Rev. 3.6

MPD NICA

Technical Design Report

of the

Electromagnetic calorimeter (ECal)

Dubna 2018

Contents

1	Introduction.....	4
1.1	The NICA/MPD experiment.....	4
1.2	Physics motivation.....	4
1.2.1	<i>Probing chiral symmetry restoration in A+A.....</i>	5
1.2.2	<i>Electromagnetic probes : study of flow signal.....</i>	7
1.2.3	<i>Electromagnetic probes : correlations.....</i>	8
1.3	General design considerations.....	9
1.3.1	<i>Basic requirements.....</i>	10
1.3.2	<i>Required time resolution of the ECal system of MPD.....</i>	18
2	ECal performances.....	21
2.1	Charged particle reconstruction.....	21
2.2	Photons reconstruction.....	24
2.3	New geometry - projective.....	34
2.4	MC detector study with clustering algorithm.....	37
3	ECal design.....	41
3.1	ECal module.....	43
3.2	FE electronics.....	48
3.3	Slow Control.....	49
3.3.1	<i>High Voltage.....</i>	50
3.3.2	<i>LED Generator.....</i>	51
3.3.3	<i>Temperature and pressure.....</i>	52
3.4	Power consumption and cooling.....	52
3.5	Power Structure of the Calorimeter.....	53
4	Test results.....	56
4.1	Calibration.....	56
4.1.1	<i>MAPD Calibration.....</i>	56

4.1.2	<i>Calorimeter calibration</i>	59
4.2	Temperature compensation.....	61
4.3	Energy resolution.....	63
4.4	Time resolution.....	66
4.5	Coordinate resolution.....	67
4.6	Heat extraction.....	68
5	Time table and cost estimation	70
.	Reference	72

1 Introduction

Investigation of hot and dense baryonic matter is a challenging task in modern physics. It provides information on the in-medium properties of hadrons and nuclear matter equation of state, allows a search for possible manifestations of the deconfinement and/or chiral symmetry restoration, phase transition, mixed phase and critical end point, and sheds light on the evolution of the Early Universe and formation of neutron stars.

1.1 The NICA/MPD experiment

An essential part of the JINR scientific program resulted from many discussions in view of the Dubna Nuclotron upgrade is dedicated to the study of hot and dense baryonic matter. Realization of this ambitious goal is related to the construction of a new JINR accelerator complex – the Nuclotron-based Ion Collider fAcility (NICA) to provide collisions of heavy-ions over a wide range of atomic masses, from Au+Au collisions at a centre-of-mass energy of $\sqrt{s_{NN}} = 11\text{GeV}$ (for Au^{79+}) and an average luminosity of $L = 10^{27}\text{cm}^{-2}\text{s}^{-1}$, to proton-proton collisions with

$$\sqrt{s_{pp}} = 20\text{GeV} \text{ and } L \approx 10^{30}\text{cm}^{-2}\text{s}^{-1}.$$

Two interaction points are foreseen at the NICA collider, which provide a possibility for two detectors to operate simultaneously. One of these detectors, the MultiPurpose Detector (MPD), is optimized for the study of properties of hot and dense matter in heavy-ion collisions and, in particular, for the search a manifestation of possible deconfinement and/or chiral symmetry restoration phase transitions, critical end-point and mixed quark-hadron phase [1].

1.2 Physics motivation

The main goal of the NICA heavy-ion program at JINR is an experimental investigation of the properties of nuclear matter in the energy region of the maximum baryonic density [2-4]. Lattice QCD calculations predict the deconfinement phase transition to be happened at high enough energy densities achieved in head-on collisions of relativistic nuclei. Recent experimental data on hadron

production at SPS [5] indicate that this transition may happen within the energy range of the NICA collider (4-11A GeV). Among the observables that give insight into the state of matter created in heavy-ion interactions electromagnetic probes are very attractive because of two reasons: 1) direct photons and lepton pairs are produced over the entire evolution of the reaction from the initial collision until the hadronization process and freeze-out, thus all stages of the fireball evolution can be probed; 2) once produced the gammas and leptons escape the interaction region unaffected by subsequent strong interactions carrying to the detectors information about the properties of the medium at the time of their creation.

All models of QGP formation require information about the rate of its thermalization, thus, of particular interest is the extent to which the measured particle yields show equilibration. The degree of equilibrium can be tested by analyzing particle abundances and ratios, while the transverse distributions probe the temperature evolution in the source from a high temperature deconfinement phase to the decoupling stage at the thermal freeze-out. Therefore, photon and dilepton rates, transverse momentum and azimuthal angle distributions, as well as correlations of $e/\gamma/\pi^0$ provide us valuable (and complement to hadron probes) information about the nature, bulk properties and sizes of the matter created in heavy-ion collisions.

1.2.1 Probing chiral symmetry restoration in A+A

The deconfinement phase transition in heavy-ion collisions can be accomplished by partial restoration of the chiral symmetry [6, 7]. A prompt signal for the chiral symmetry restoration in A+A interactions could come from domains of disoriented chiral condensate. The most likely origin of a coherent low-energy excitation of the pion field would be a collective isosinglet excitation of the Goldstone boson field (σ, π) associated with the spontaneous breaking of chiral symmetry describing as a nonlinear wave in the sigma model [8, 9]. The latter corresponds to coherent excitations of the pion field decaying into neutral and charged pions with the probability distribution with quite large deviations from isospin neutrality. Thus, a very strong signature of the chiral phase transition would be pion charge ratios N_{π^0}/N_{π^\pm} significantly different from 1/3. Such a scenario is more likely to occur

in a relativistic heavy-ion collision, because the chiral transition is accompanied by a large change in the energy density. Thus, in order to probe chiral symmetry restoration, the MPD detector will be capable to measure all three pion species.

In addition, partial restoration of the chiral symmetry manifests itself in modifications of hadronic spectral functions in dense hadronic matter. The correlated electron-positron pairs (dileptons) from decays of vector mesons (ρ , ω , ϕ) are the best candidates to study such in-medium modifications since they escape the interaction region unaffected by subsequent strong interactions. Production of low-mass dileptons in heavy-ion collisions has been studied at the CERN-SPS at center-of-mass energy of 8.8, 17 and 19 AGeV [10-14]. The CERES Collaboration has observed a strong excess in the invariant-mass spectrum of electron-positron pairs in the region dileptons invariant mass $0.2 < M_{e^+e^-} < 0.7$ [GeV/c²] above the expectations from the superposition of the known hadron decay channels based on their vacuum properties. At the Brookhaven Lab., the PHENIX [15] and STAR [16] experiments measured the dilepton production from the top RHIC energy 200 AGeV down to the top SPS energy and also reported on the excess in the dilepton spectra below the ω -meson. The dilepton spectra from the DLS [17] and HADES [18] experiments taken at much lower incident energies (1-2 AGeV) in smaller colliding systems (C+C and Ar+Ar) are well described by a superposition of elementary nucleon-nucleon collisions, in contrast to higher energies and heavier nuclei.

Until now, no dilepton measurements have been performed at center-of-mass energies of several GeV and the dilepton program at NICA is aimed to close this gap. The range of collision energies from 4 to 11 AGeV is very promising for dilepton studies since the effect of modifications is expected to be sensitive to the baryon density, while the latter happens to reach the maximum in central Au+Au collisions at NICA [19].

The experimental study of dileptons in heavy-ion collisions is a challenging task. The main difficulty is a huge combinatorial background of uncorrelated lepton pairs which mainly come from π^0 Dalitz decays and photon conversion in the detector material. A special attention should be paid to reduce this background as much as possible. The main task for MPD ECal is to reduce the false

identification of hadrons as electrons(positrons) to large extent.

1.2.2 Electromagnetic probes : study of flow signal

An important probe in heavy-ion collisions providing information about the nature of nuclear matter is flow. Azimuthal anisotropy (relative to the reaction event plane) in the particle emission have been studying as a function of collision energy, event centrality, and transverse momentum provide insight into the details of nuclear matter equation of state, its transport properties and velocity of sound. Using π^0 as a probe in the flow analysis has an advantage that neutral pions are easy to reconstruct at any Pt. Moreover, the strength of the flow signal for π^0 (or, even, for gammas from π^0 -decays) is the same as for charged pions (see Figure 1.2.2.1).

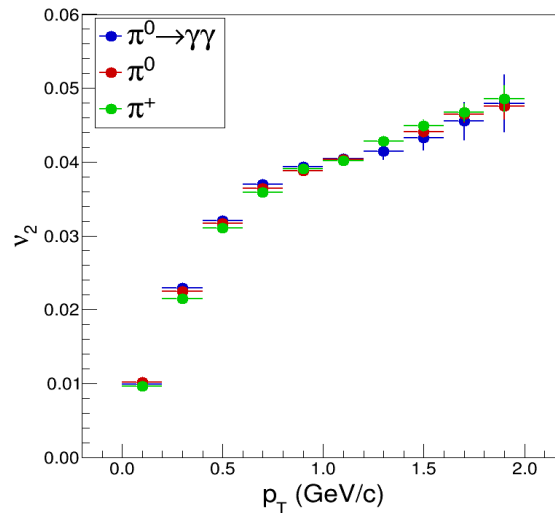


Figure 1.2.2.1: Elliptic flow v_2 as a function of p_T from mid-central Au+Au collisions (UrQMD model) for charged pions, π^0 and photons from π^0 decays.

In addition, in a non-central heavy-ion collision the charged spectators produce a strong magnetic field which interacts with the quark-gluon matter created in the reaction and might result in the phenomena of electric charge separation along the magnetic field axis - Chiral Magnetic Effect (CME) [20]. In addition, if the deconfinement phase is accompanied by a chiral symmetry restoration, the separation of chiral charges (characterizing left or right handedness) along the axis of the magnetic field is expected to be present in the case of finite density of electric charges. In this case, a propagation of chiral charge density in a long wave-length hydrodynamic mode, i.e. Chiral

Magnetic Wave (CMW), theoretically expected to modify the elliptic flow of charged hadrons leading to an increase (decrease) of the v_2 parameter of negative (positive) particles [21]. Recently, the STAR Collaboration at RHIC has measured the sizable difference in the elliptic flow parameter v_2 between π^+ and π^- on an event-by-event basis [22]. Despite of interpretation of these observations as a result of CMW, the measurements below 19GeV are suffering of low statistics and are not convincing. Moreover, the effect is measured on top of the v_2 'base line' which may be different between π^+ and π^- because of several other possible physical mechanisms [23, 24]. We suggest perform high statistics measurements of the elliptic flow coefficients for all pion species (π^+ , π^- , π^0) at NICA energies to overcome both the difficulties mentioned above. Reconstructed via the ECal information π^0 's and their azimuthal asymmetry will be used as a 'base line' in CMW-effect studies. We plan to perform a detailed study of the azimuthal distributions for charged particles as well as for neutral pions and gammas. For this, the MPD ECal must provide azimuthal symmetry and high granularity.

1.2.3 Electromagnetic probes : correlations

Interferometry of two identical particles is widely employed to get insight into the space-time structure of the interaction zone: this technique allows measure the size and lifetime of the fireball. Results on hadron correlations in A+A were obtained over the region from SIS to LHC energies (for a review see [25] and references therein). However, strongly interacting probes are mainly appear in the late stage of the fireball evolution when the dense and hot nuclear matter is getting cooler and more dilute. In contrast, photon correlations carry information about the whole story of the source evolution, since gammas are produced starting from the very early moments of the reaction and suffer practically no interactions in the interior of the medium. Thus, direct photons emitted from the early hot phase of the collision and their correlations serve as a valuable QGP signature and allow to obtain an image of the early hot and dense phase in heavy-ion collisions [26-28]. In MPD photons can be reconstructed in two ways: by using the gamma-conversion method in the material or by measuring the flux of gammas in the ECAL. Thus, in the suggested correlation analysis three

different combinations of photon pairs are possible: ECal-ECal, conversion-conversion, and ECal-conversion. The Correlation Function (CF) for the photon pairs reconstructed in ECAL can be affected by detector "non-ideality" (ECal segmentation, thresholds, etc.) and analysis cut-offs (acceptance, quality selections, etc.), while correlations of photons from the conversion process depends heavily on the tracking details in MPD (for example, on the 2-track resolution). We suppose that combining conversion photons with those from ECal the systematic errors imposed by the experimental 2-track resolution and CF Pt-cut (+other detector issues) can be eliminated (or compensated) because two different detector parts will be used in the analysis.

In summary, the particular goals of the MPD ECal are to measure of spatial positions and energy of photons and electrons in order to:

- obtain the measure of the yields, transverse momentum and azimuthal angle distributions of photons, ρ^0 (and eta-mesons) and electron-positron pairs produced in central as well as peripheral heavy-ion collisions at an energy of 4-11A GeV;
- study in detail the effects of collective flow of electromagnetic probes in heavy-ion collisions;
- search for femtoscopic correlation effects in two- (and four-) photon distributions;
- obtain new experimental data on the yields of neutral mesons in Au+Au collisions from two-, three-, and four-photon invariant mass distributions;
- search for thermal and direct photon emission in Au+Au collisions at NICA (or define its upper limit).

1.3 General design considerations

The calorimeter should satisfy many criteria of different nature and significance. Most important of requirements are coming from the of physics tasks which we are going to study with the use of calorimeter. Technological capabilities of the modern experimental physics should be estimated and taken into account in choosing type of calorimeter to be built. The price and possibility of realization should be taken into account as well to make project realistic.

1.3.1 Basic requirements

The expected high multiplicity environment (Figure 1.3.1.1) implies the high segmentation of the calorimeter, large enough distance to the vertex, and use of a dense active medium with the small Moli'ere radius. To have an adequate space resolution and to allow the separation of overlapping showers, the transverse cell size should be of the order of the Moli'ere radius. Reliable reconstruction of photons and mesons is only possible at small shower overlaps. The particle occupancy should not exceed 5% to determine the photon reconstruction efficiency with high accuracy. Above-mentioned requirements are the common ones and can be satisfied with the help of different types of calorimeters. But there are some requirements which reject out many solutions

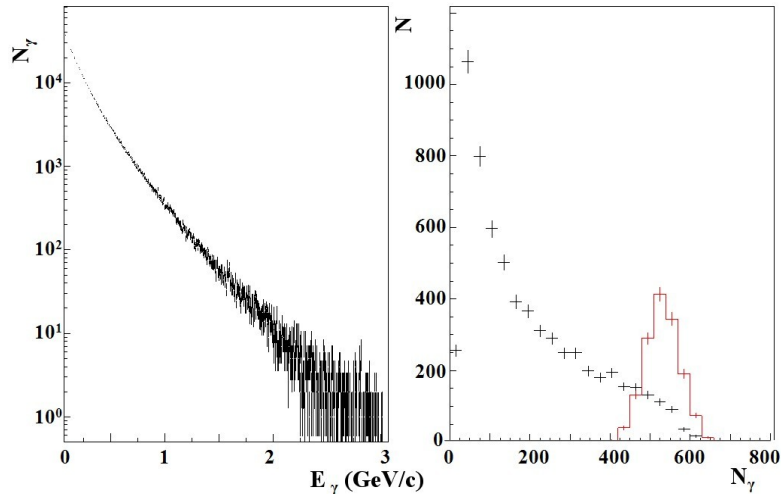


Figure 1.3.1.1: The energy spectrum of photons (left panel) and photon multiplicity distribution (right panel) in the central (red) and minimum bias (black) Au+Au collision (9 AGeV).

- Calorimeter must be able to operate in the magnetic field up to 0,5T – PM is difficult to use.
- Time resolution should be at least below 1ns to cut pile-up and noise events and close to 100 ps to participate in the time of-flight particle identification – most of crystals with reasonable price are much slow.

Due to the last requirements, already at this stage of a choice, our attention became concentrated on the "shashlyk" type calorimeter with MAPD photons detectors [29].

MC study is done on the basis of the UrQMD event generator to fix which is the energy spectrum and multiplicity of the photons is expected in the heavy ions collisions on the NICA complex (Figure 1.3.1.1).

Full MPD Monte Carlo simulation was used to estimate average occupancy of MPD barrel ECal detector. Detector sell of $4 \times 4 \text{ cm}^2$ was used. As it is clear from the plot (Figure 1.3.1.2) ECal occupancy for the most complicated for the detection-reconstruction events (Au+Au 11 AGeV) is very high (about 20%). In such condition increase of the detector sell size above $4 \times 4 \text{ cm}^2$ will complicate already difficult situation with events detection-reconstruction. MC simulation of the

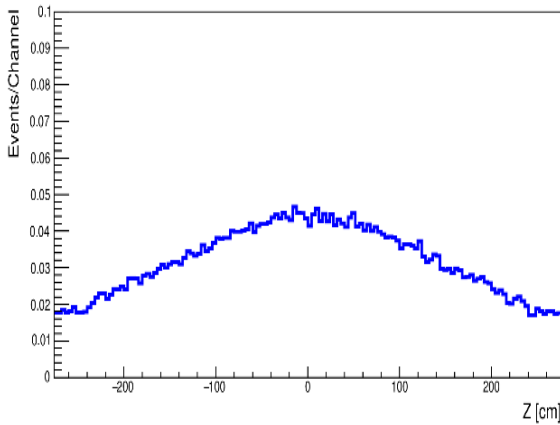


Figure 1.3.1.2: Average number of particles per channel for the barrel part of MPD ECal detector with $4 \times 4 \text{ cm}^2$ detector element. UrQMD Au+Au collision, 11 AGeV, central events .

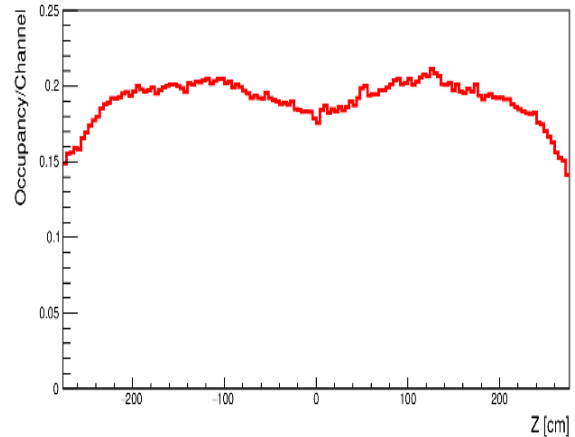


Figure 1.3.1.3: Average occupancy (charged particles + electromagnetic showers) per channel for the barrel part of MPD ECal detector with $4 \times 4 \text{ cm}^2$ detector element. UrQMD Au+Au collision, 11 AGeV, central events .

same events with the ECal when tower size is increased to the $6 \times 6 \text{ cm}^2$ shows increase of occupancy up to 45% which is totally unacceptable. Further reduction of the cell size may help in event reconstruction even in the case of Moli'ere radius of about 62 mm, but is unacceptable due to huge increase in the cost of ECal. Thus, the choice of ECal cell size of 4×4 we believe is optimal. Thus, the choice of ECal cell size of $4 \times 4 \text{ cm}^2$ we believe is optimal.

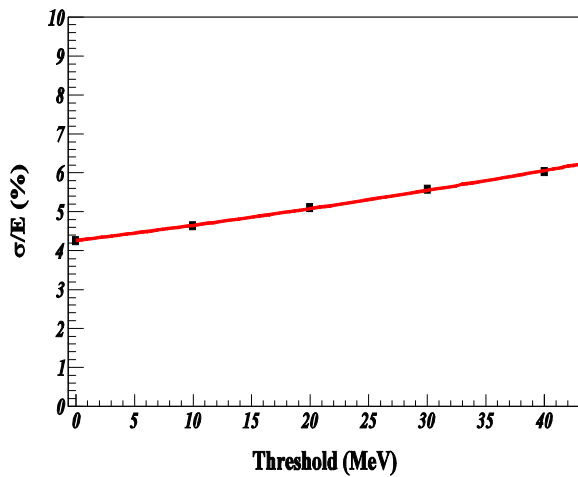


Figure 1.3.1.4: Energy resolution vs threshold (e^- 1GeV).

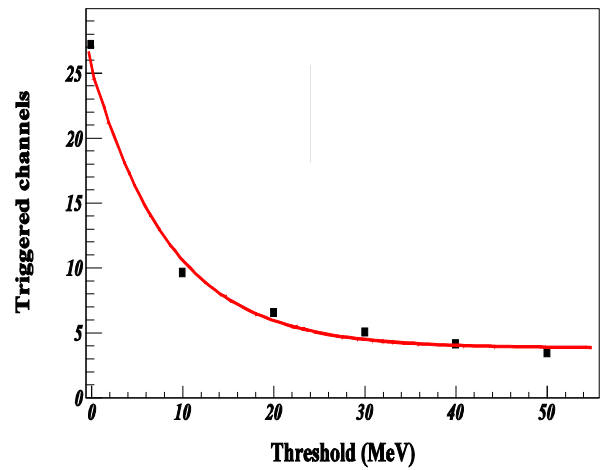


Figure 1.3.1.5: Number of cells vs threshold (e^- 1GeV).

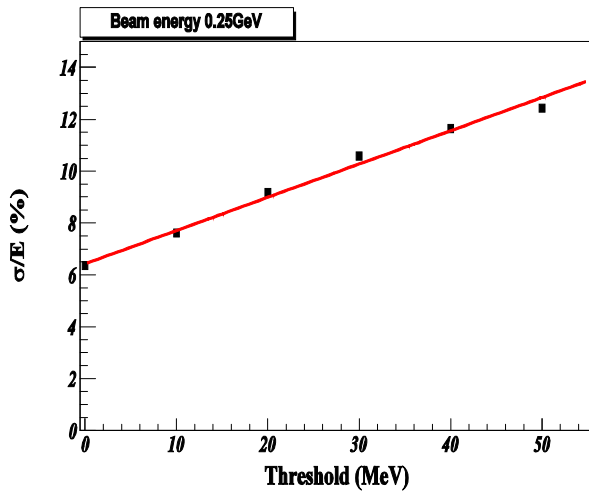


Figure 1.3.1.6: Energy resolution vs threshold (e^- 0.25GeV).

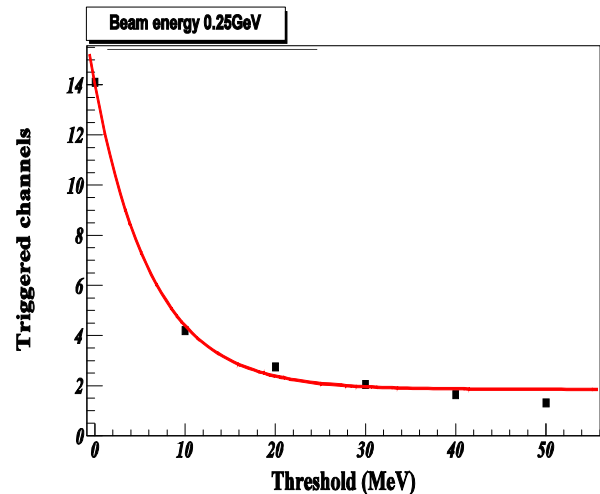


Figure 1.3.1.7: Number of cells vs threshold (e^- 0.25GeV)

The special efforts in the software together with threshold tuning should be done to reach effective and accurate registration of electromagnetic showers in this high particle multiplicity environment. The choice of registration threshold is a compromise between energy resolution and the number of active cells. Obviously (Figure 1.3.1.4) that to reach high energy resolution we have to collect all hits (even very small) that means low registration threshold. Low registration threshold, in turn, leads to the big number of cells (Figure 1.3.1.5).

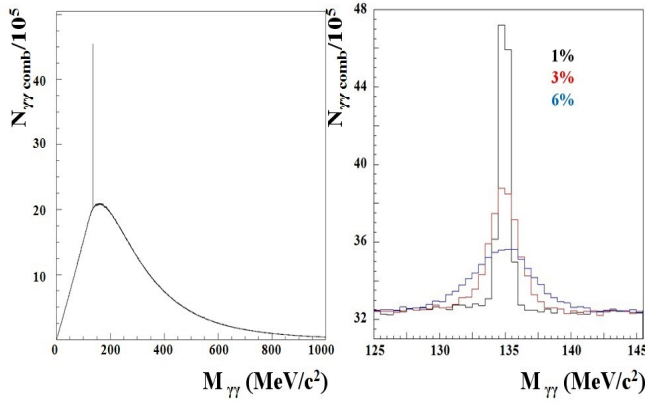


Figure 1.3.1.8: π^0 reconstruction in the intermediate π^0 transverse momentum regions for different photon detector energy resolutions. Left panel – ideal detector. Au+Au collision (at $\sqrt{s_{NN}} = 9$ AGeV).

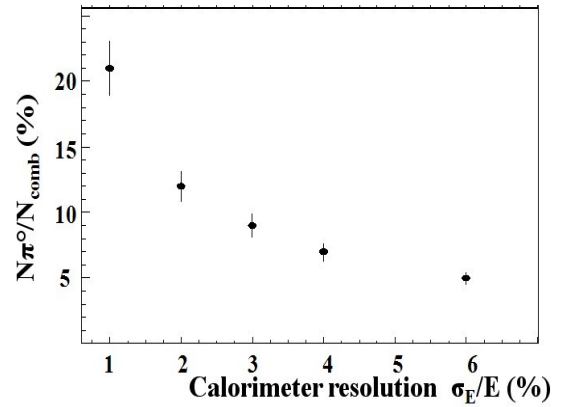


Figure 1.3.1.9: The ratio of number of reconstructed π^0 mesons to a number of events from combinatorial background vs the calorimeter energy resolution.

The energy resolution of the photon detector is a critical point in the conditions of high photon multiplicity. Achievement of the best possible energy resolution (at least of 5% for the 1GeV photons) is highly desirable. This can be illustrated on the example of π^0 reconstruction and measurements of π^0 flux (Figure 1.3.1.8 and Figure 1.3.1.9). Effect of the registration threshold is very small and it can be illustrated by the π^0 reconstruction efficiency (Figure 1.3.1.10).

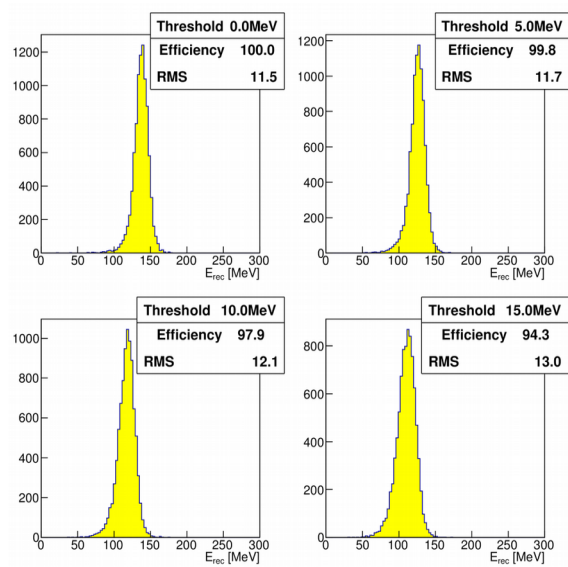


Figure 1.3.1.10: π^0 distributions at different threshold values and calculated efficiency of registration.

According to the KOPIO study [30], sampling ratio, i.e. the relation between thicknesses of lead and scintillator tiles, dominates in the energy resolution of the "shashlyk". But, its value is smaller than the cumulative effect of other contributions. So, photostatistics and nonuniformity of light collections add to the total energy resolution $2.1\%/ \sqrt{E}$ and $1.8\%/ \sqrt{E}$, respectively. And, many attention should be paid to improving the quality of scintillator, optical and mechanical, and to selecting the photo-detector with higher quantum efficiency.

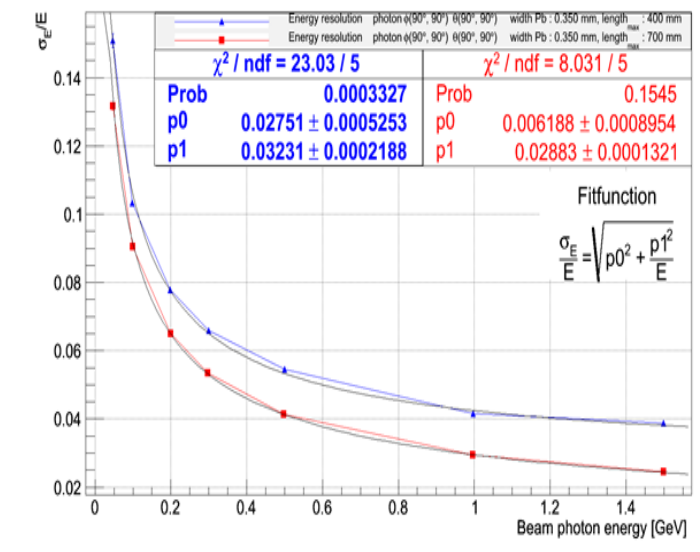


Figure 1.3.1.11: Energy resolutions of the calorimeter with two different lengths of the modules – 400mm and 700mm.

Unfortunately, space available for the ECal in the MPD is rather small (40 cm for the active part) what a priori does unattainable the maximum energy resolution. Shower leakage even for the low energy particles is rather big (Figure 1.3.1.11).

In this situation sampling study was done to choose optimal lead thickness - increase of lead thickness reduce shower leakage but increase a sampling contribution to the energy resolution and vice versa. Comparison of energy resolution for 0.5mm lead plate and 0.3mm one (Figure 1.3.1.12) is a clear illustration of this feature. Lead plate thickness have been fixed as 0.3mm because further reduction of this value will make calorimeter too transparent.

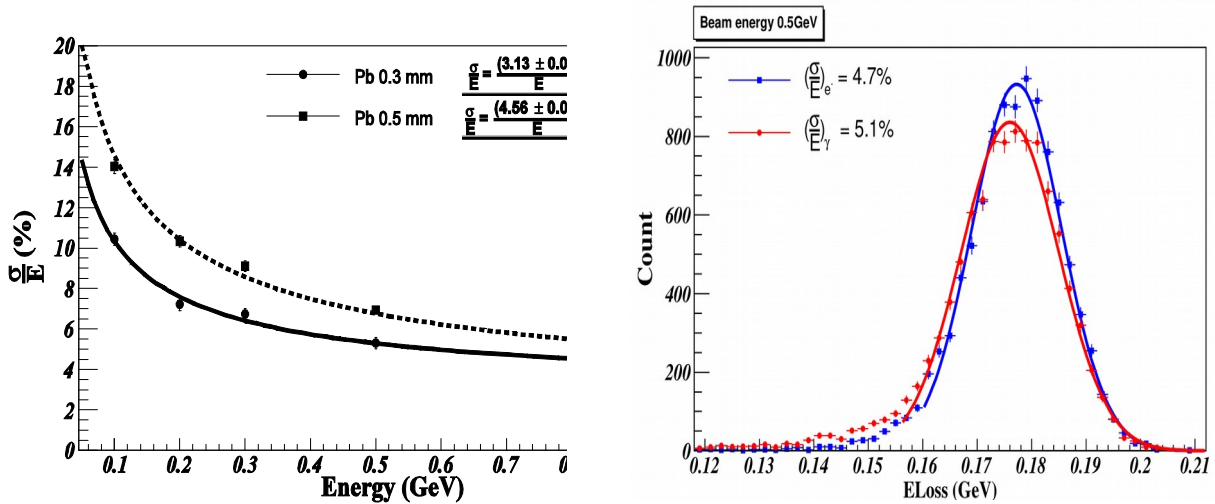


Figure 1.3.1.12: Comparison of energy resolution for modules with lead thickness 0.5mm and 0.3mm (left). The ECal response from electron and photons (right).

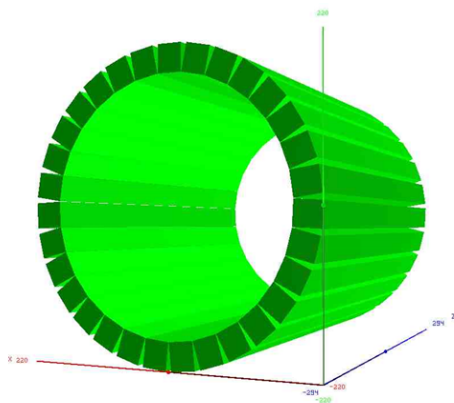


Figure 1.3.1.13: Geometry of ECal (rectangular modules).

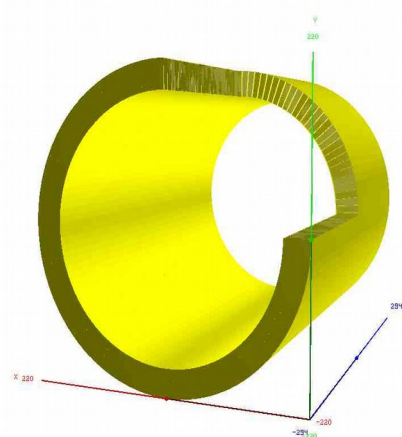


Figure 1.3.1.14: Geometry of ECal (trapezoidal modules).

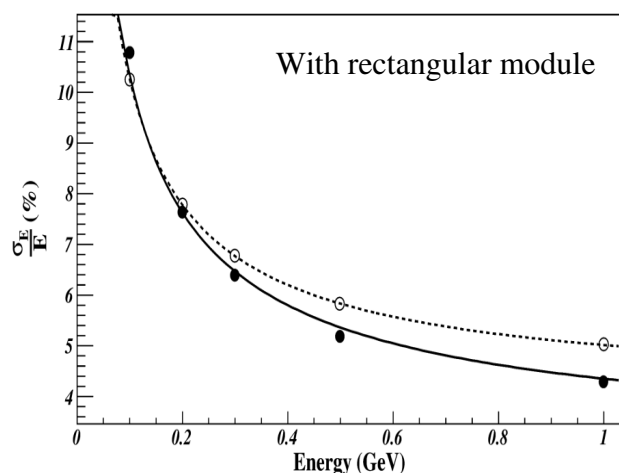


Figure 1.3.1.15: Comparison of energy resolution when photons hit in center of the rectangular module and photons flow randomly distributed in the barrel.

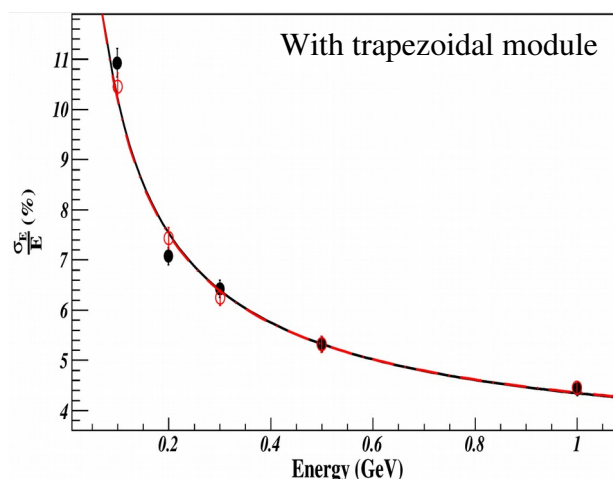


Figure 1.3.1.16: Comparison of energy resolution when photons hit in center of module and photons flow randomly distributed in the barrel.

If the barrel part of ECal will be built from the usual square shaped modules (Figure 1.3.1.13) dead spaces between modules will certainly reduce energy resolution in average.

This effect is illustrated on figure 1.3.1.15 where MC comparison is presented of energy resolution for the case when particles hit the module in their center and when particle flow randomly distributed in the barrel.

To reduce the dead zones effect all modules will be cut from two sides at an angle 1.5 degree. After such a cut modules will have a trapeze shape in the $r\phi$ plain. This modification will significantly reduce dead zones effect (Figure 1.3.1.14 and Figure 1.3.1.16). On the figure 1.3.1.17 shows the comparison of the geometry composed of the rectangular and trapezoidal modules.

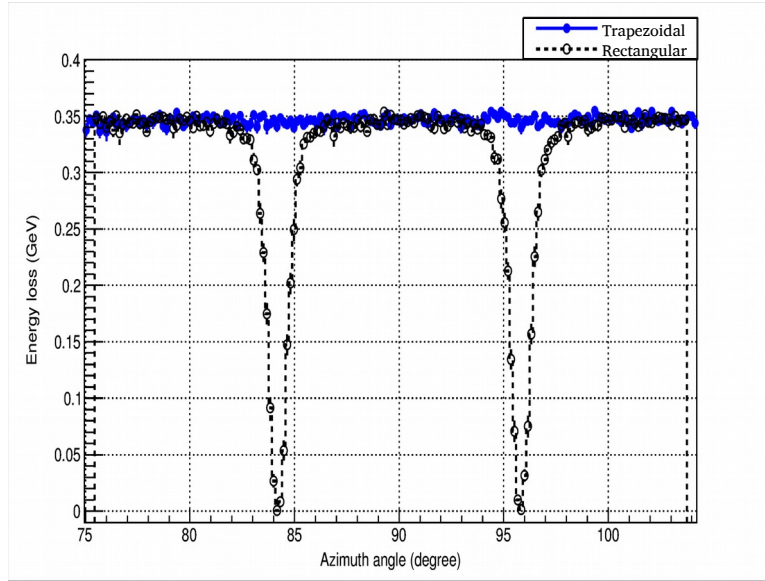


Figure 1.3.1.17: Energy resolution of the azimuth angle in the geometries composed with rectangular and trapezoidal modules.

One more important factor which gives impact on the energy resolution of calorimeter is the material budget in front of ECal. This influence was studied by the MC simulation program which is using full information about all MPD sub-detectors and the distribution of the material in these sub-detectors. Certainly, effect of material leads to the degradation of the ECal energy resolution (Figure 1.3.1.18), essentially in the low energy region. This degradation is not dramatic, but it is an indication - all efforts should be done to reduce amount of material in the MPD detector.

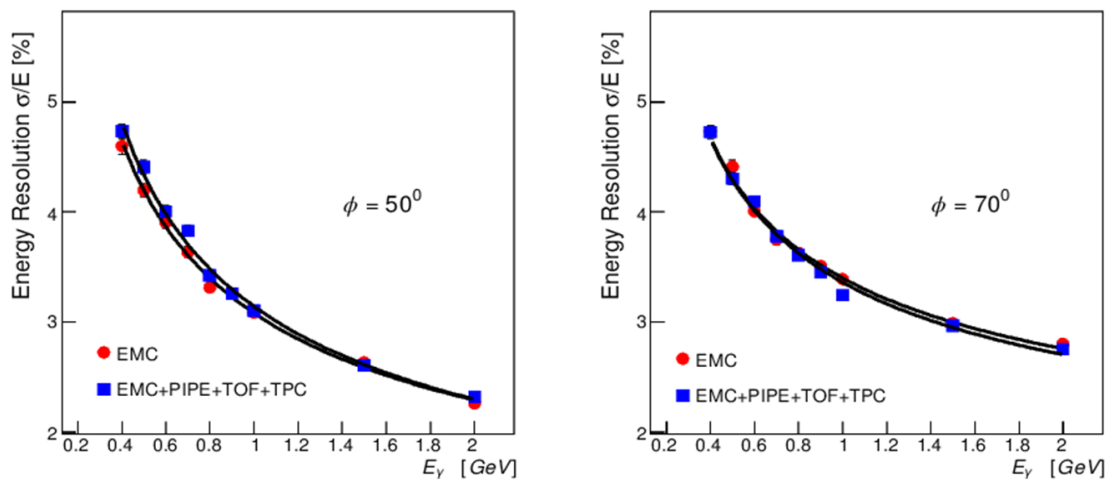


Figure 1.3.1.18: Coordinate resolution at an azimuth angle of 50 degrees and 70 degrees.

1.3.2 Required time resolution of the ECal system of MPD

Important feature of the "shashlyk" calorimeter is the possibility to make precise time measurements. There are three fields where time measurements is extremely useful.

1. First, time resolution of the order of 10ns is necessary to reduce of background and pile-up noise. Simple calculations shows (which later have been confirmed by the measurements. See section 3.4) that 10ns time resolution will reduce undesirable registrations practically to zero.
2. The order of magnitude higher time resolution required for the suppression of the secondary photons from the interaction in the material of the MPD detector (Figure 1.3.2.1). Most of such photons originate from the reaction with the neutrons and arrive in the ECal with sufficient delay. Monte Carlo study shows that time resolution of the order of 1ns will be sufficient to suppress such background down to the negligible level. This tas is complicated for the very soft photons (100MeV and even lower).

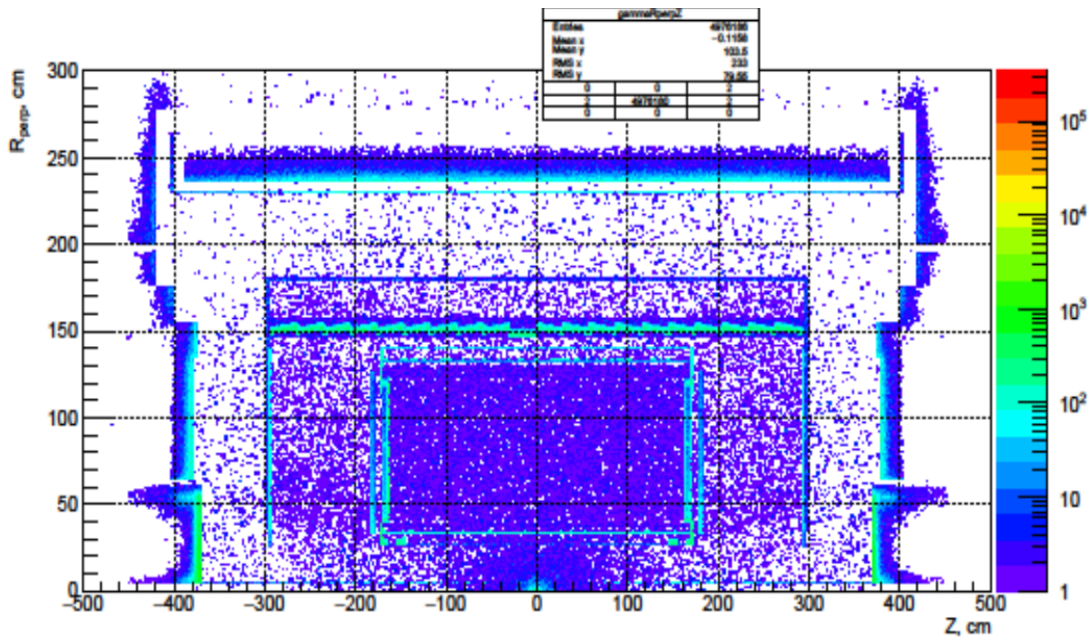


Figure 1.3.2.1: Spatial distribution of points where photons which have been registered by a calorimeter was born.

Using arrival time cut, which depends from the path of the photons in the detector (entry point in to the calorimeter), number of secondary photons can be significantly reduced (Figure 1.3.2.2).

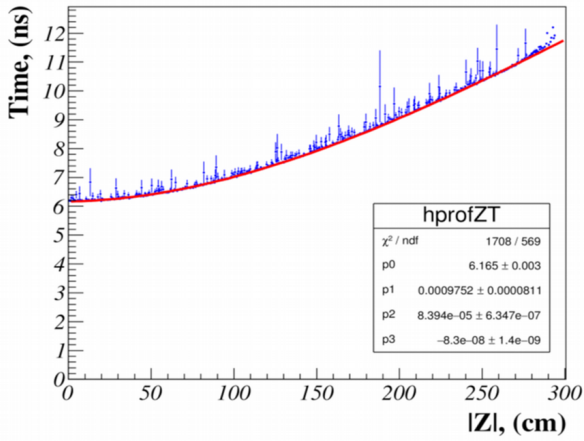


Figure 1.3.2.2: MC results – photons arrival time vs arrival Z position.

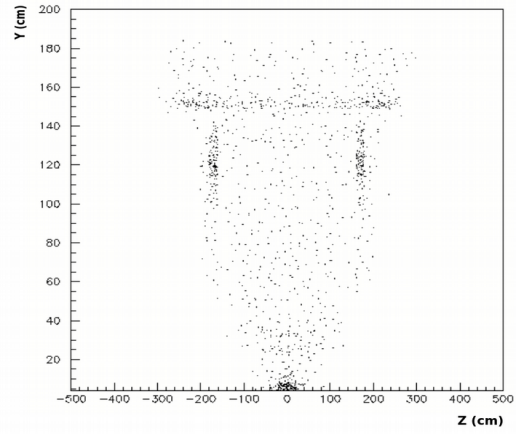


Figure 1.3.2.3: Points of birth of the photons registered in ECal, after time cut.

For the events generated by UrQMD generator for the 11GeV, Au+Au, central events, such cut reduce number of secondary photons detected by the calorimeter to the value about 3% form the total number of photons detected.

Last modification of the ECal (with 6x6mm² HAMAMATSU photo-detectors) was tested on the electron test beam at DESY and time resolution reached in those tests is batter than 1ns almost in all energy region (Figure 4.4.2).

Sub-nanosecond time measurements in the ECal will allow to use this device as a time-of-flight device in the support to the main TOF detector. According KOPIO data [30] the conservative estimation of the calorimeter time resolution is:

$$\sigma_t (ps) \approx \frac{100}{\sqrt{E (GeV)}}$$

Such a time resolution have been attributed to the calorimeter and MC study of particle identification was performed. Particle identification done with the use of time measurements from the calorimeter is illustrated by the figures 1.3.2.4 and 1.3.2.5.

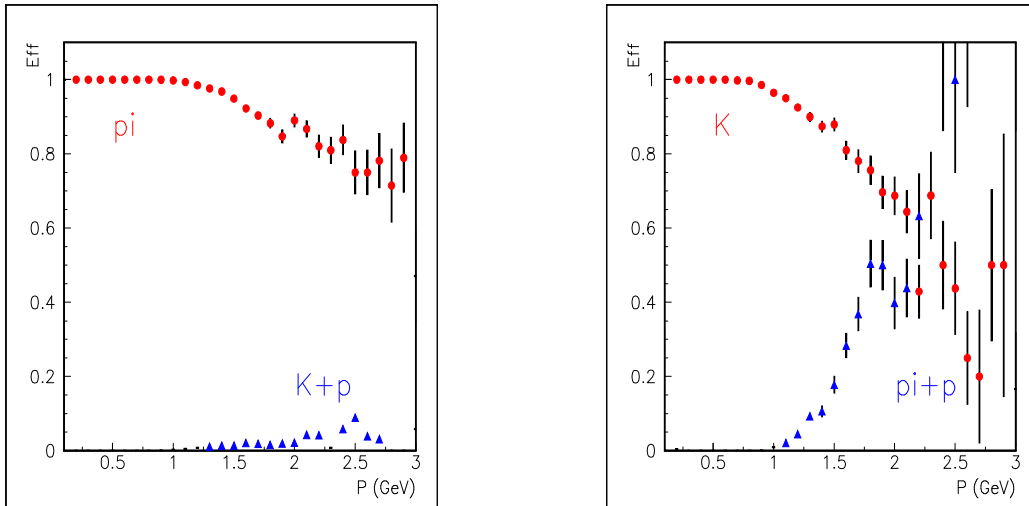


Figure 1.3.2.4: Efficiency versus momentum: left – Separation of pions from kaons and protons; right – Separation of kaons from pions and protons.

Decision was taken to concentrate efforts on the first two tasks. The ECal operation in the TOF mode is possible but require not only much higher manpower efforts, but also require new Front-End (FE) electronics. Such FE electronics will be more expensive and more power consuming.

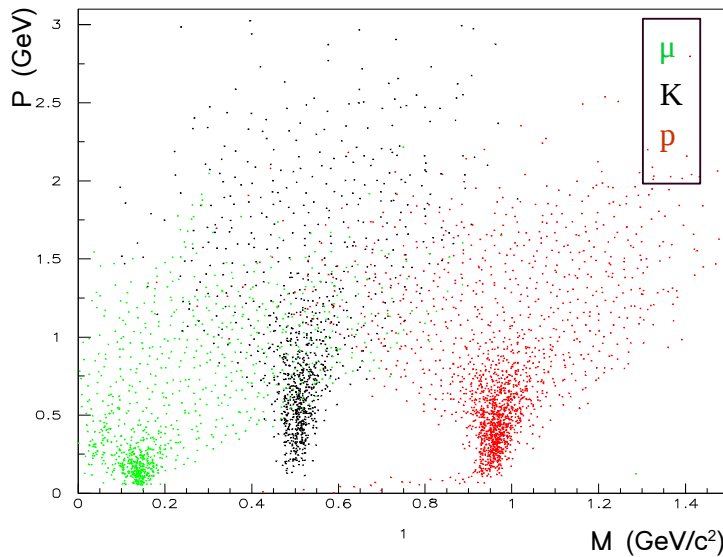


Figure 1.3.2.5: Particle identification with the use of time measurement.

2 ECal performances

The main goals of the calorimeter are the participation in particles identification (namely - final cleaning of the selected e^{+-} sample) and measurements of the photons flux as well as reconstruction of some decays with participation of the photons. In these tasks final result depends on performances of all or most of MPD detectors. Some studies of the efficiency of combined event reconstruction with the use of most important MPD detectors (TPC, TOF and ECal) will be presented below.

This study was done by the Monte Carlo simulation based on the reliable description of MPD sub-detectors. MC simulation of the ECal was tested many times during beams tests at CERN and DESY and cosmic ray tests and found as a very realistic.

2.1 Charged particle reconstruction

The trajectories of charged particles inside the MPD detector are reconstructed using dedicated tracking detector - TPC. This device gives precise trajectory of the charged particle as well as its dE/dx which is used for the particle identification. The TOF detector is the dedicated device for the charged particles identification on the basis of time of flight measurements. These detectors described in the relevant chapters. To improve charged particle identification and make measurements of the flux of neutral particles (photons) the energy deposition from the charged particles in the ECal should be matched to the reconstructed trajectories.

First, hits detected in the ECal, in the correct time interval and with energy deposition higher certain threshold (10MeV) was joined into the clusters according simple rules -

1. Hits should have common border;
2. Hits should have energy deposition above threshold (10MeV);
3. Number of such hits should be higher than N_{tr} (3 hits) to form a cluster;

Then, charged particle trajectory, reconstructed in the TPC is extended into the volume of the ECal

and if some cluster fit to this track extinction then such cluster is matched with this track. One example, when charged (pion) track reliably associated with cluster in the ECal, is presented on the figure 2.1.1. Clear elongated structure presented in most of clusters. Elongation in the z direction is due to the non projective structure of ECal. In azimuthal (ϕ) direction it is due to the rotation of charged particles trajectory in the magnetic field. The size of first type of elongation depends from the particle polar angle. The size of second type of elongation depends from the particle momentum. Second type of elongation is inherent only for the charged particles. In future these features of the cluster shape can be used for the improvement of the event reconstruction.

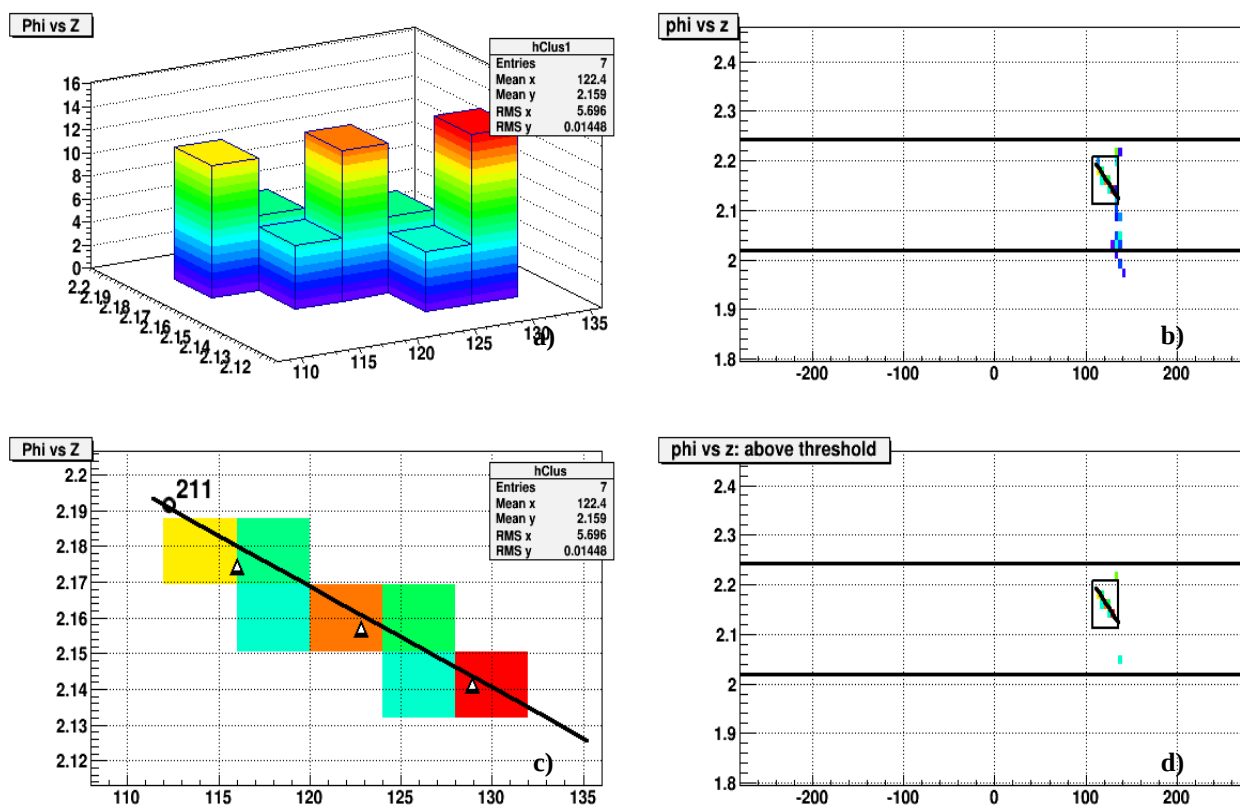


Figure 2.1.1: Cluster in ECal which formed by the charged pion with momentum of 0.5 GeV/c. a,b,c) Z- ϕ plots without threshold; d) Plot Z- ϕ with threshold of 10 MeV;

In some cases pions, crossing ECal, starts hadronic shower. In such case shape of cluster in the ECal becoming more complicated (Figure 2.1.2). This leads to the reduction of the accuracy of matching clusters to the tracks. As it is seen from the plot, some fraction of hits produced in such case do not matched to the pion track. For the electrons fraction of unmatched hits is close to zero.

Efficiency of hits matching to the charged pions tracks was calculated for the MC generated tracks created in the central AuAu interaction (7GeV). Dependencies of the efficiency of the clusters matching to the track versus the particles momentum and rapidity are shown on figures 2.1.3 and 2.1.4.

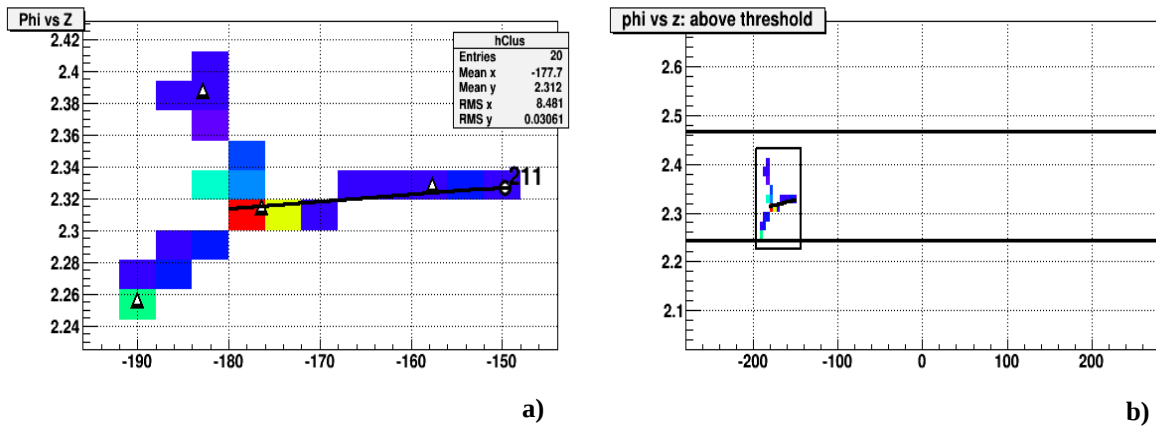


Figure 2.1.2: Clusters in ECal which are produced by charged pion, which is initiated hadronic shower. Both plots (a,b) with threshold of 10MeV.

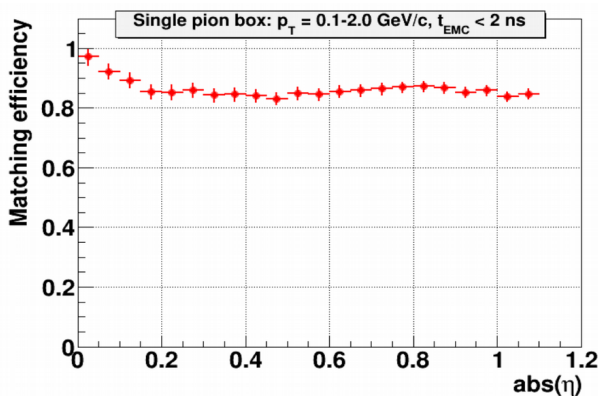


Figure 2.1.3: Dependency of the efficiency of the clusters matching to the track from the particles rapidity.

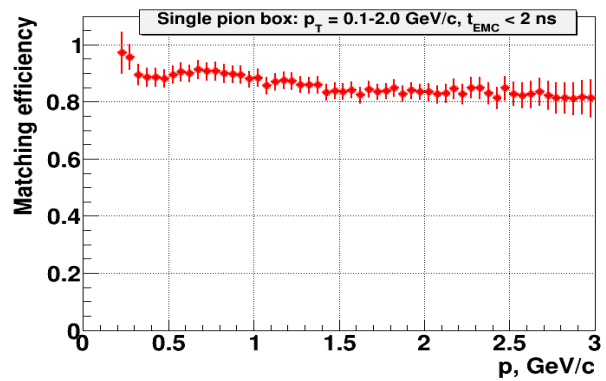


Figure 2.1.4: Dependency of the efficiency of the clusters matching to the track from the particles momentum .

Unmatched hits will give fake contribution to the neutral particles multiplicity and energy. Fortunately this effect will concern only very low energy part of spectra.

2.2 Photons reconstruction

When some hits in the ECal are associated with the trajectories of the charged particles then the rest of hits is the basis for the neutral particles reconstruction. Again, hits detected in the ECal, in the correct time interval and with energy deposition higher than certain threshold (10MeV) was joined into the clusters according simple rules -

1. Hits should have common border;
2. Hits should have energy deposition above threshold (10MeV);
3. Number of such hits should be higher than N_{tr} (3 hits) to form a cluster.

In case of neutral particles there is no elongation of the clusters in the ϕ direction (due to the rotation of particles trajectory in the magnetic field). Clear elongation in the Z direction should be presented and it should be Z dependent. First study of neutral particles reconstruction efficiency was done for the 250MeV photons and presented below on figures 2.2.1-2.2.4.

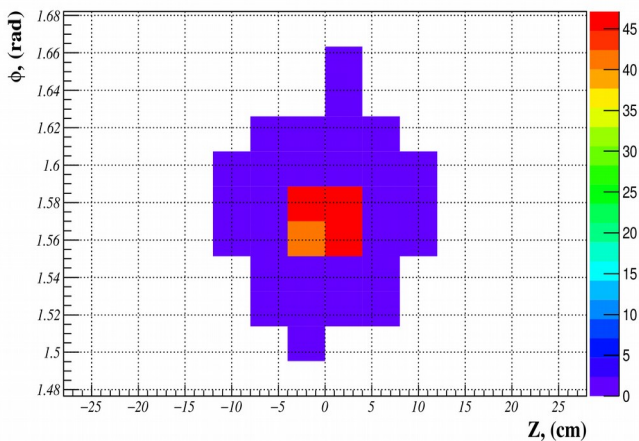


Figure 2.2.1: Distribution (Z - ϕ) of clusters produced by the 250MeV photon hitting the 90 degree of polar angle (θ).

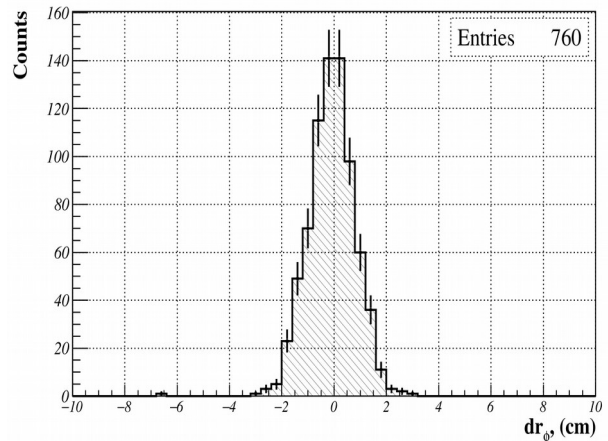


Figure 2.2.2: Distribution of residuals between photon entry position (in the ϕ direction) and centre of gravity of the reconstructed cluster, when the particles hit in the 90 degree of θ (250MeV).

In this case cluster size is the same in the Z and ϕ directions and no elongation in the Z direction can be seen (Figures 2.2.1-2.2.4). Residuals distribution between particles position in the ϕ direction (known from the MC) and centre of gravity of the reconstructed cluster is presented on figure 2.2.2. On the basis of this distribution the cut was chosen to be used in the procedure of neutral particle reconstruction. The cut $|dr\phi| < 4\text{cm}$ ($dr\phi$ – distance in ϕ direction) is used on the next steps of procedure.

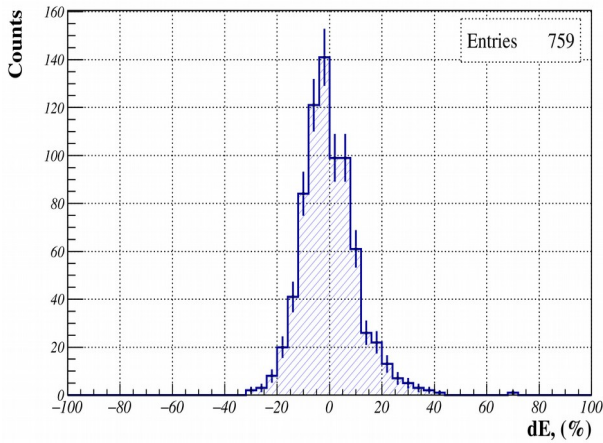


Figure 2.2.3: Distribution of the difference between photon energy and the reconstructed cluster energy (250MeV, 90 degree of θ).

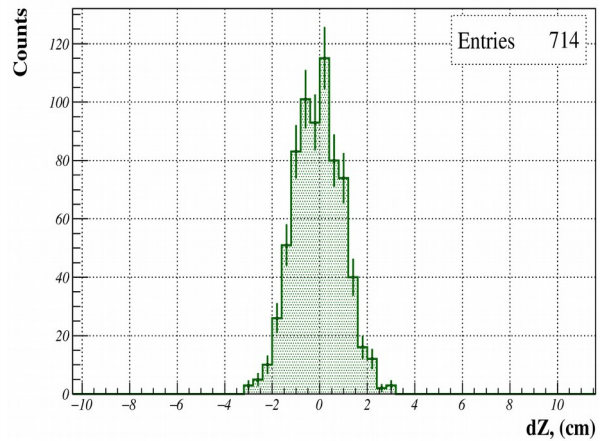


Figure 2.2.4: Distribution of the difference between photon Z position and the reconstructed cluster Z position (250MeV, 90 degree of θ).

Difference between photon energy and the reconstructed cluster energy (which satisfy $|dr\phi| < 4\text{cm}$ criteria) is plotted on the figure 2.2.3. For these low energy photons the cut of $|dE| < 20\%$ can be used to calculate cluster reconstruction efficiency.

Last distribution is just an illustration, and will be not used in the selection procedure because of the elongation of the particle spot in the Z direction (Figure 2.2.4).

On the following pictures the same distributions are presented for the incidence polar angle (θ) of 70 degree are presented.

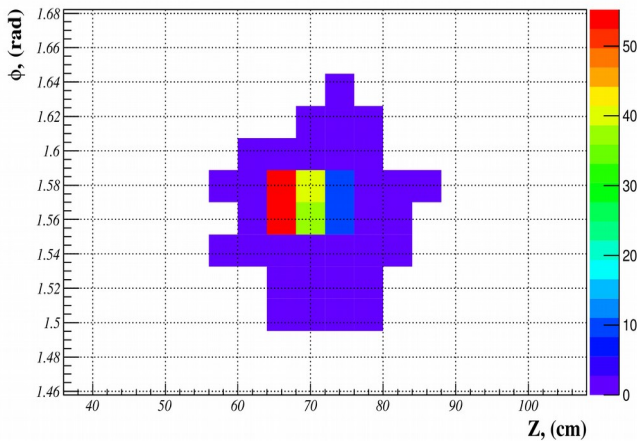


Figure 2.2.5: Distribution (Z - ϕ) of clusters produced by the 250MeV photon hitting the 70 degree of θ .

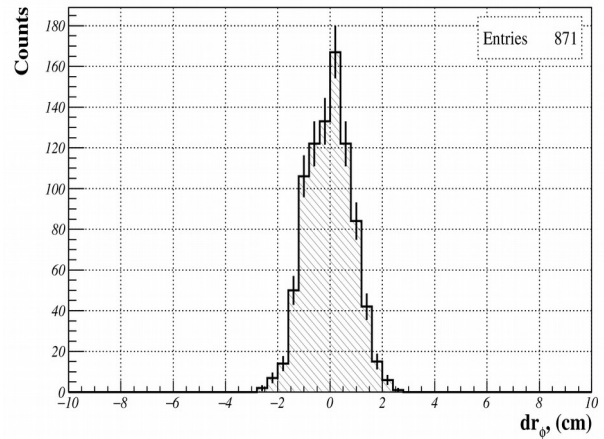


Figure 2.2.6: Distribution of residuals between photon entry position (in the ϕ direction) and centre of gravity of the reconstructed cluster, when the particles hit in the 70 degree of θ (250MeV).

All of them except the last one (Figure 2.2.8) are very similar to the previous figures. Shift from the zero in the figure 12 is reflects expected Z – elongation.

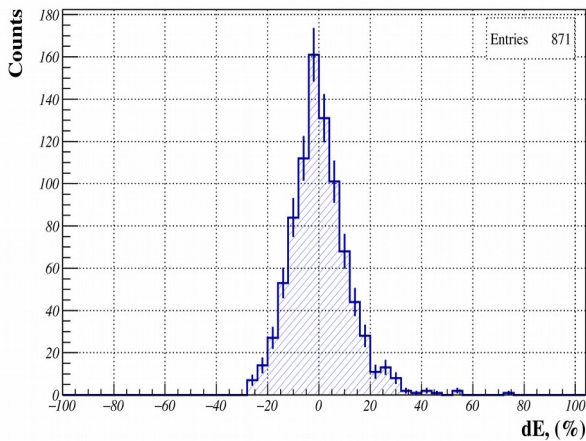


Figure 2.2.7: Distribution of the difference between photon energy and the reconstructed cluster energy (250MeV, 70 degree of θ).

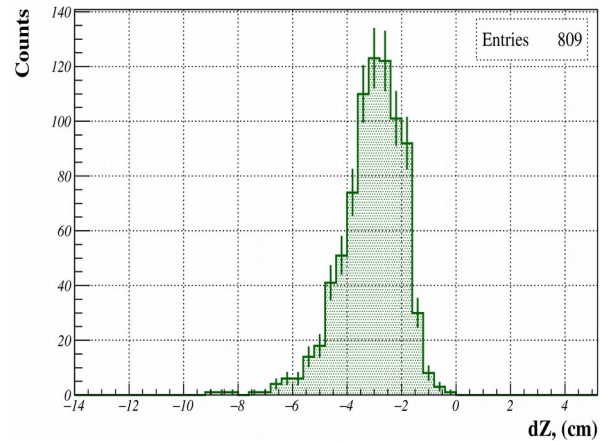


Figure 2.2.8: Distribution of the difference between photon Z position and the reconstructed cluster Z position (250MeV, 70 degree of θ).

On the next set of pictures the same distributions are presented for the incidence polar angle of 50 degree are presented.

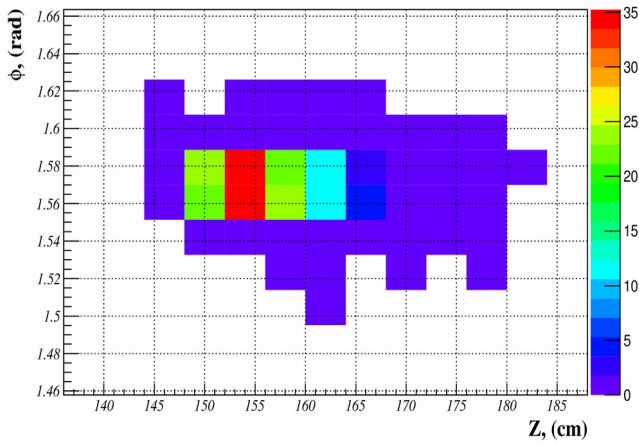


Figure 2.2.9: Distribution (Z - ϕ) of clusters produced by the 250MeV photon hitting the 50 degree of θ .

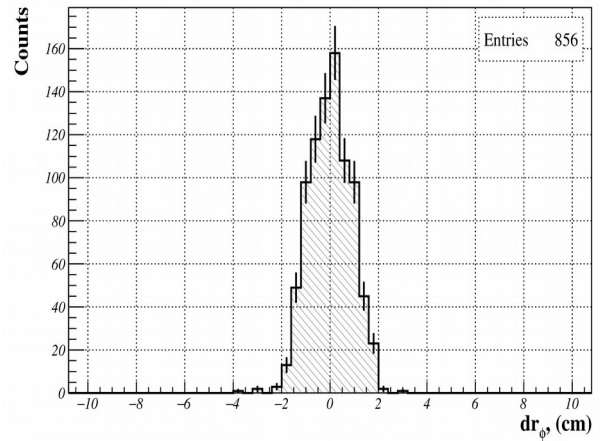


Figure 2.2.10: Distribution of residuals between photon entry position (in the ϕ direction) and centre of gravity of the reconstructed cluster, when the particles hit in the 50 degree of θ (250MeV).

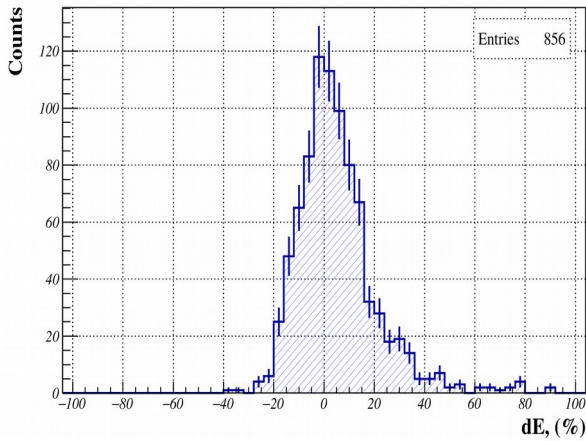


Figure 2.2.11: Distribution of the difference between photon energy and the reconstructed cluster energy (250MeV, 50 degree of θ).

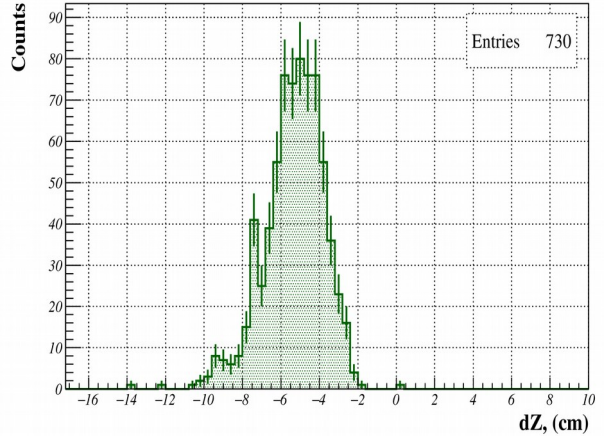


Figure 2.2.12: Distribution of the difference between photon Z position and the reconstructed cluster Z position (250MeV, 50 degree of θ).

Here elongation becoming more serious and even begins to impede for the effective detector hits association to the cluster (see figure 2.2.12). Efficiencies of the low energy photons reconstruction in the ECal are summarized in the table 1.

Theta(deg)	90	70	50
$\mathbf{dr}_\phi < 4\text{cm}$	99.9	100	100
$\mathbf{dr}_\phi < 4\text{cm} \ \&\& \ dE < 20\%$	99.3	92.9	85.3

Table 1: Efficiencies of the low energy photons reconstruction.

Next set of similar tests was done for the higher energy photons - 1 GeV.

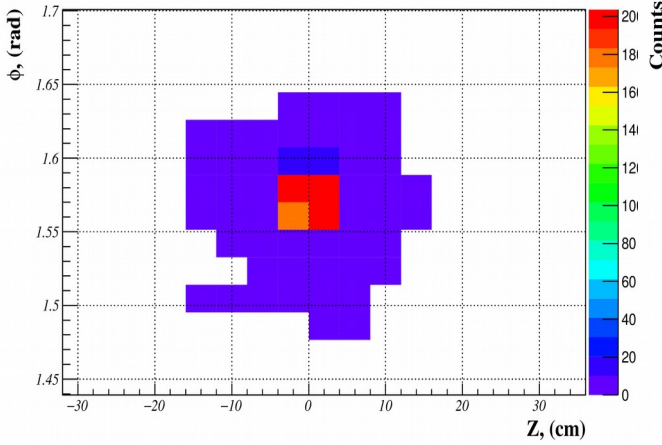


Figure 2.2.13: Distribution (Z - ϕ) of clusters produced by the 1GeV photon hitting the 90 degree of θ .

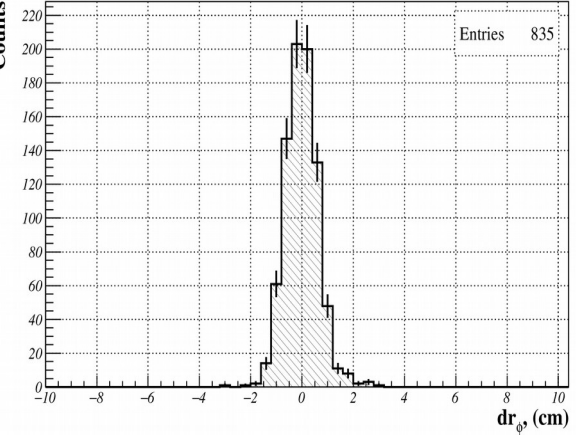


Figure 2.2.14: Distribution of residuals between photon entry position (in the ϕ direction) and centre of gravity of the reconstructed cluster, when the particles hit in the 90 degree of θ (1GeV).

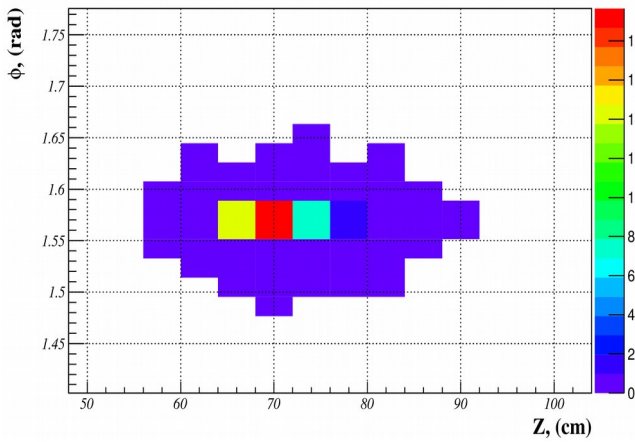


Figure 2.2.17: Distribution (Z - ϕ) of clusters produced by the 1GeV photon hitting the 70 degree of θ .

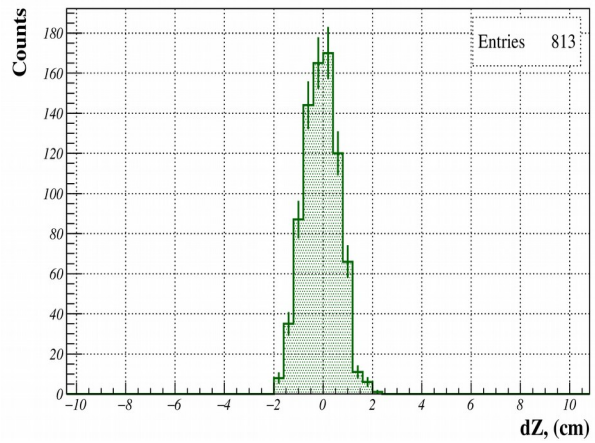


Figure 2.2.16: The distribution of the difference between photon Z position and the reconstructed cluster Z position (1GeV, 90 degree of θ) in the 70 degree of θ (1GeV).

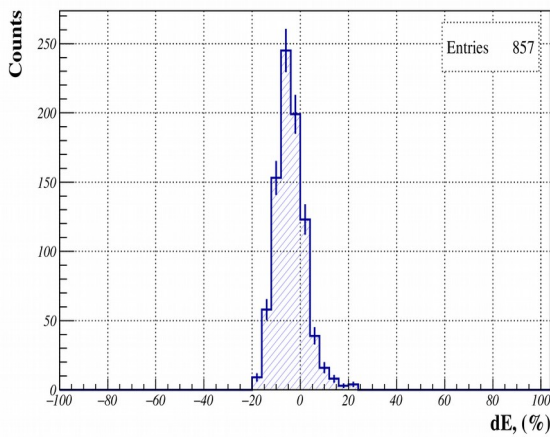


Figure 2.2.19: Distribution of the difference between photon energy and the reconstructed cluster energy (1GeV, 70 degree of θ).

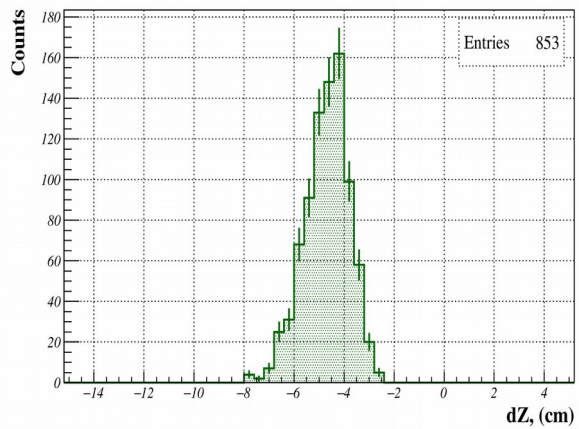


Figure 2.2.20: Distribution of the difference between photon Z position and the reconstructed cluster Z position (1GeV, 70 degree of θ).

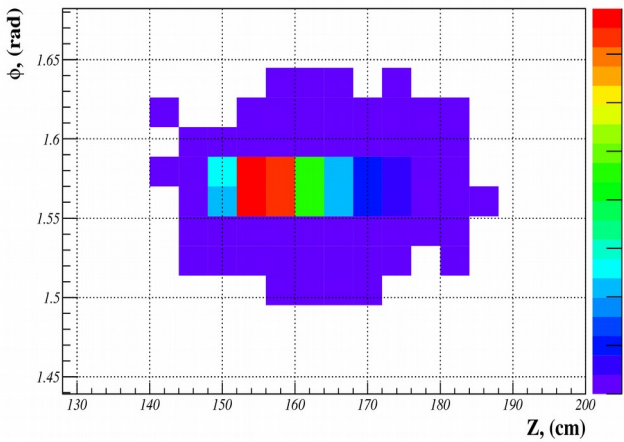


Figure 2.2.21: Distribution (Z - ϕ) of clusters produced by the 1GeV photon hitting the 50 degree of θ .

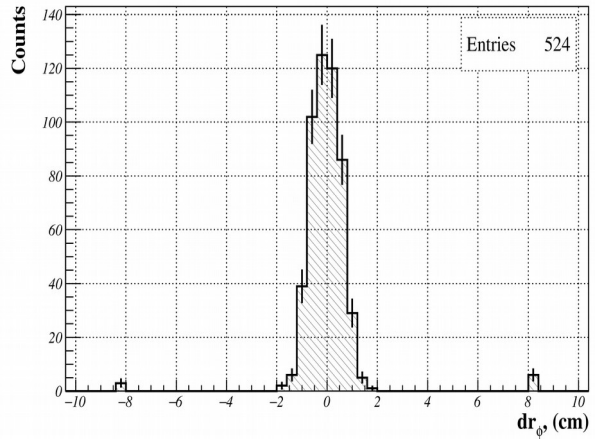


Figure 2.2.22: Distribution of residuals between photon entry position (in the ϕ direction) and centre of gravity of the reconstructed cluster, when the particles hit in the 50 degree of θ (1GeV).

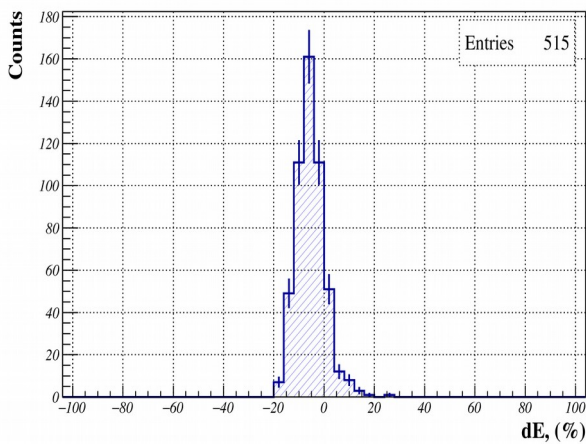


Figure 2.2.23: Distribution of the difference between photon energy and the reconstructed cluster energy (1GeV, 50 degree of θ).

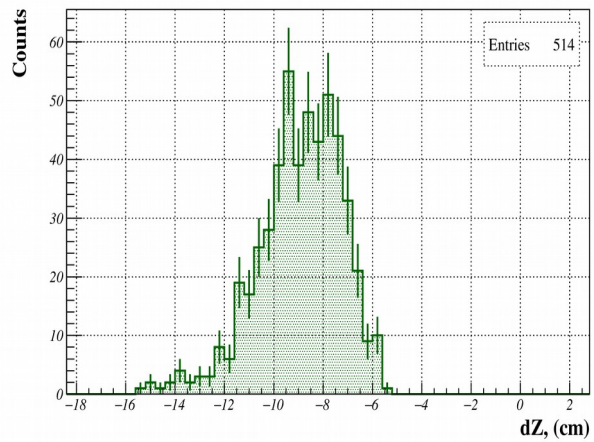


Figure 2.2.24: Distribution of the difference between photon Z position and the reconstructed cluster Z position (1GeV, 50 degree of θ).

Theta(deg)	90	70	50
$\text{dr}\phi < 4\text{cm}$	100	100	98.3
$\text{dr}\phi < 4\text{cm} \ \&\& \ dE < 20\%$	97.4	99.5	98.1

Table 2: Efficiencies of the 1GeV photons reconstruction.

All previous results was obtained for the isolated photons. Events generated by the UrQMD generator for the 7GeV/c Au-Au minimal bias interactions has been used to estimate efficiency of the photons reconstruction in the events with different particles multiplicity. Search of clusters around each entry point of the photon to the ECal have been performed. Cluster has been considered as associated with photon if it distance from the generated track below 4cm in the ϕ direction and below 50cm in the Z direction.

Number of gammas					
Range of energy		$100 \leq E_\gamma < 200$ (MeV)	$200 \leq E_\gamma < 300$ (MeV)	$300 \leq E_\gamma < 500$ (MeV)	$500 \leq E_\gamma$ (MeV)
I	Wtihout Cut	3781	2131	1936	1183
II	Cut $ r_{MC} - r_{CL} < 4\text{cm}$ && $ z_{MC} - z_{CL} < 50\text{cm}$	3093	1725	1557	904
III (%)		81.8	80.9	80.4	76.4

Table 3: Efficiencies of the cluster matching to photons.

Efficiencies of the clusters matching to the generated particles are presented in the table 3, for the different intervals of photon energy. Such studies has been performed for the events with the different impact parameters (different multiplicities of the photons) and no significant dependence of the photon reconstruction efficiency from the event multiplicity is observed.

Last test was done to study how the reconstructed neutral particles (multiplicity and total energy) correlated with the generated numbers of photons and were total energy. Results of these tests are presented on the figures 2.2.25 and 2.2.26. Strong correlation between reconstructed and generated variables clearly seen from the distributions. Unfortunately, correlations are not linear. In the high multiplicity region, it becomes weaker for both variables (N_γ and E_γ).

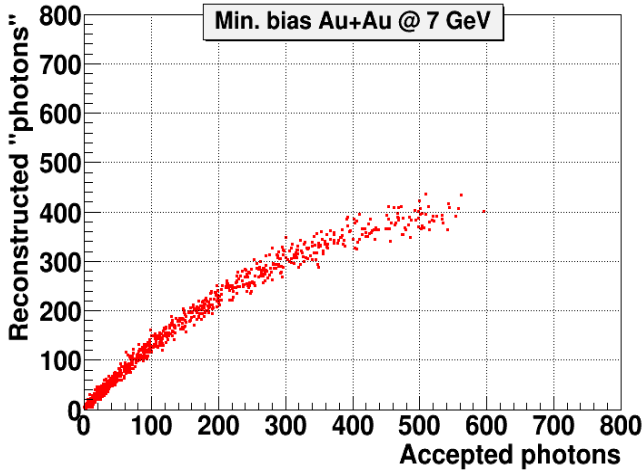


Figure 2.2.25: Distribution of reconstructed numbers of neutral particles vs generated number of photons.

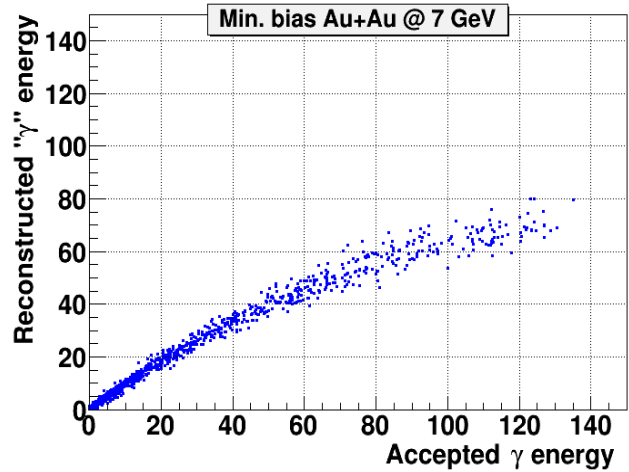


Figure 2.2.26: Distribution of reconstructed neutral particles energy vs accepted gamma energy.

Correction procedure which takes into account dependencies from the figures 2.2.25 and 2.2.26, including nonlinearities, has been developed. To estimate accuracy with which number of photons and their total energy can be reconstructed, events generated by the UrQMD generator for the 7GeV/c Au-Au minimal bias interactions have been used. Dependencies of the neutral particles flux reconstruction accuracy from the generated photon multiplicity is presented on figure 2.2.27. Similar dependence for the photon energy is presented on figure 2.2.27.

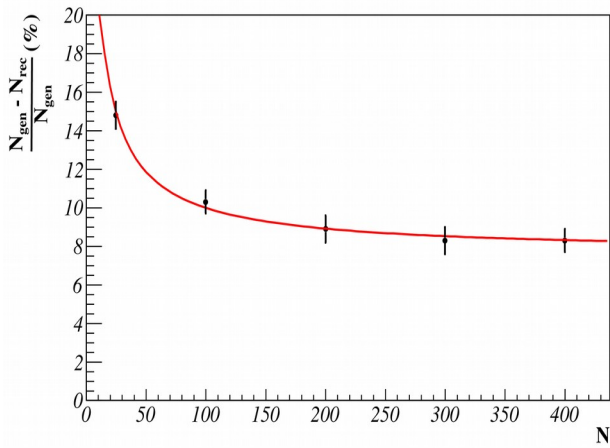


Figure 2.2.27: Dependencies of the neutral particles flux reconstruction accuracy from the generated photon multiplicity.

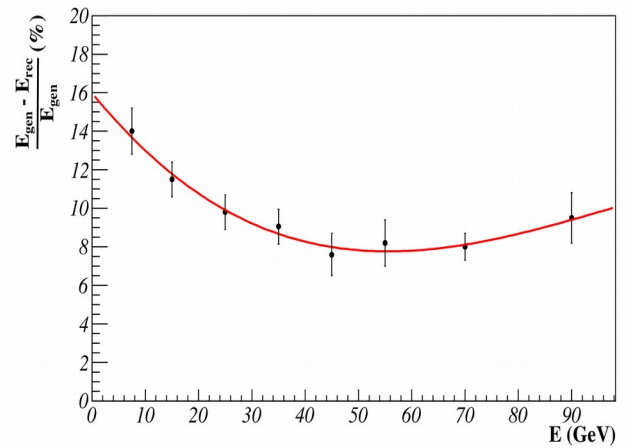


Figure 2.2.28: Dependencies of the neutral particles flux reconstruction accuracy from the photon energy.

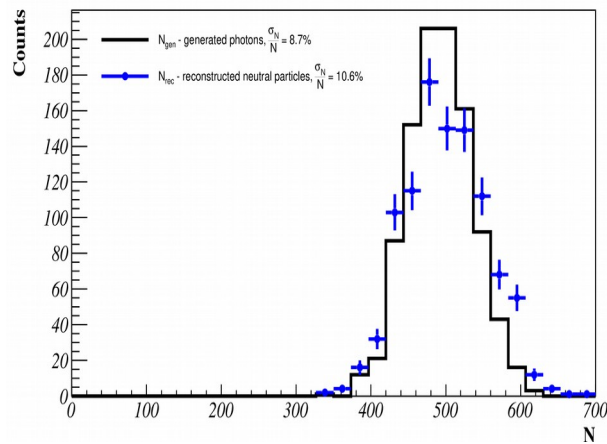


Figure 2.2.29: Distribution of generated numbers of photons and the numbers of neutral particles after full reconstruction procedure.

Events generated by the UrQMD generator for the 7GeV/c Au-Au central interactions have been used to illustrate effect of reconstruction on the measurements of the photon flux. On the figure 2.2.29 generated number of photons is shown as a solid line. Distribution with error bars is presenting the same events after full reconstruction procedure.

2.3 New geometry - projective

It was shown above that projective geometry in the polar angle direction is absolutely necessary to avoid dead space and as a result drop of particle detection efficiency and degradation of calorimeter energy resolution. Situation in azimuthal direction is very different because there are no dead space in this direction. Dependence of calorimeter energy resolution from the particle entrance angle to the detector was studied. It was shown that energy resolution is not degraded up to very high angles of particle entry with respect to calorimeter axis. In those studies energy response of the calorimeter calculated by collecting of total response of the calorimeter. But more recent studies, which was based on the new generation of the software developed for the MPD detector, demonstrated that involvement of the cluster finding algorithm (which is absolutely necessary in the conditions extremely high particle multiplicity- high occupancy of the detector) change the situation. Two different geometries – non-projective to Z plane (Figure 2.3.1) and projective (Figure 2.3.2) have been used to simulate calorimeter response taking into account full event reconstruction procedure.

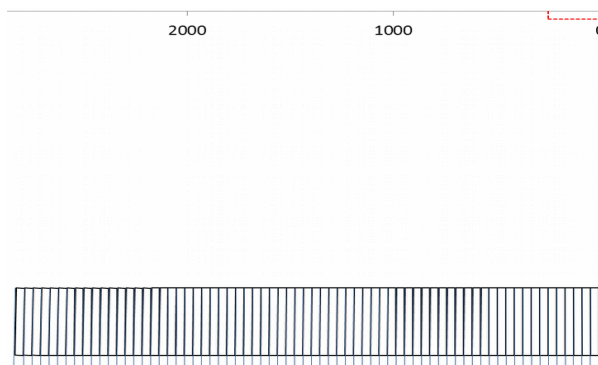


Figure 2.3.1: View of the some modules of the non-projective geometry in the Z plane.

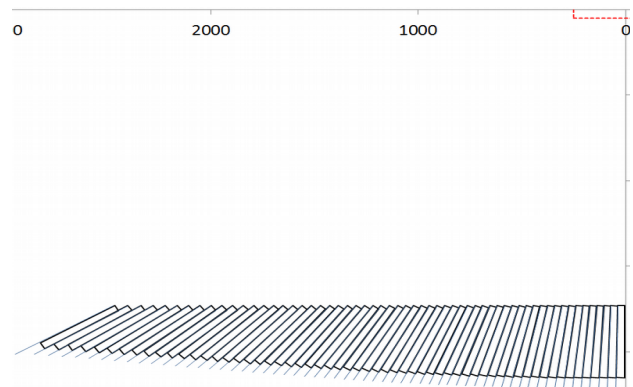


Figure 2.3.2: View of the some modules of the projective geometry in the Z plane.

Calculations have been made on the choice of the angle of inclination for the modules. The aim of the calculations is to select a single for all modules tilt angle at which the deviation of the aiming point from the center of the MPD will be minimal (Figure 2.3.3). Despite the fact that the minimum deviation is achieved when the tilt angle is 0.94 degrees, for simplicity it was decided to adopt this angle as 0.9 degrees.

All further simulations are done for the inclination angle 0.9 degree.

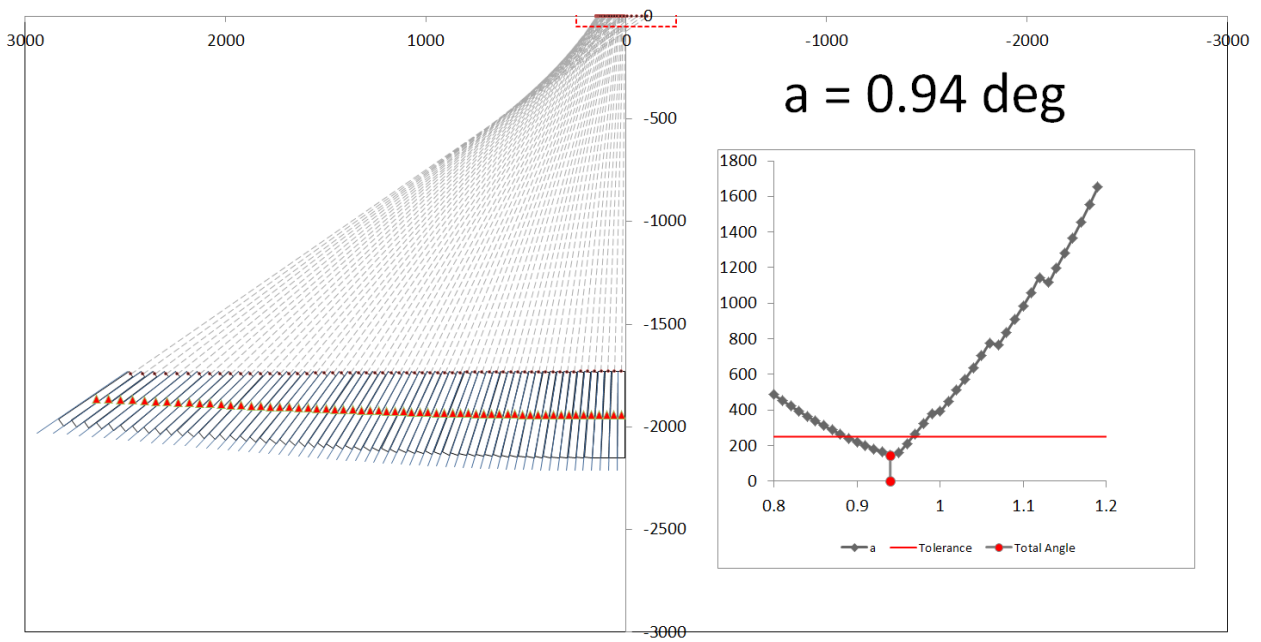


Figure 2.3.3: Optimization of the location of ECal modules in the Z plane ($a = 0.94$ deg).

It was discovered that number of clusters raising with the rise of particle incident angle (Figures 2.3.4 and 2.3.5). As a result, in spite of independence full energy deposition from the incident angle, the energy deposition per cluster is degrading with raise of incident angle (Figures 2.3.6 and 2.3.7).

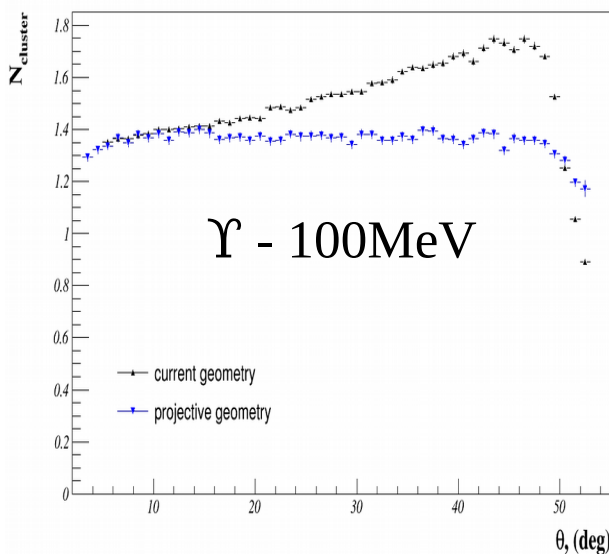


Figure 2.3.4: Distribution of the number of clusters vs angle θ (Photons with energy 100MeV).

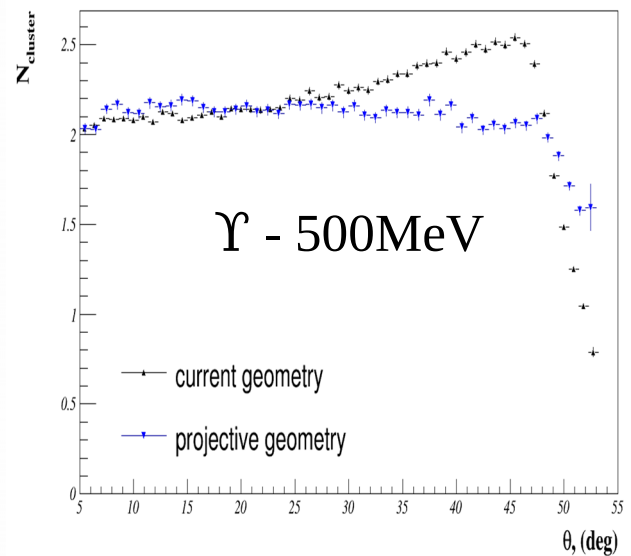


Figure 2.3.5: Distribution of the number of clusters vs angle θ (Photons with energy 500MeV).

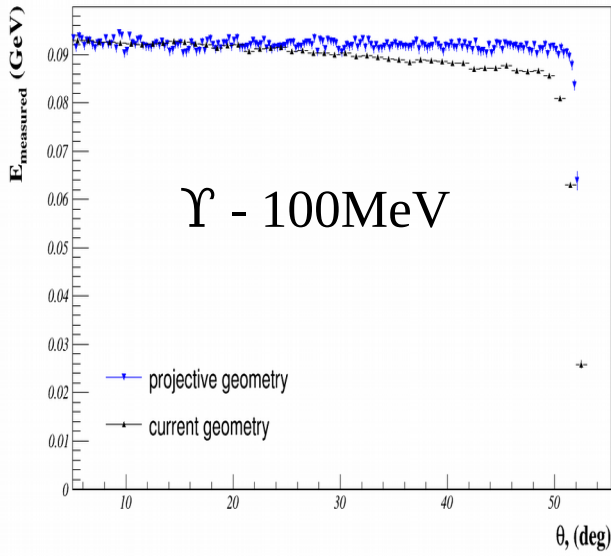


Figure 2.3.6: Distribution of the energy measured vs angle θ (Photons with energy 100MeV).

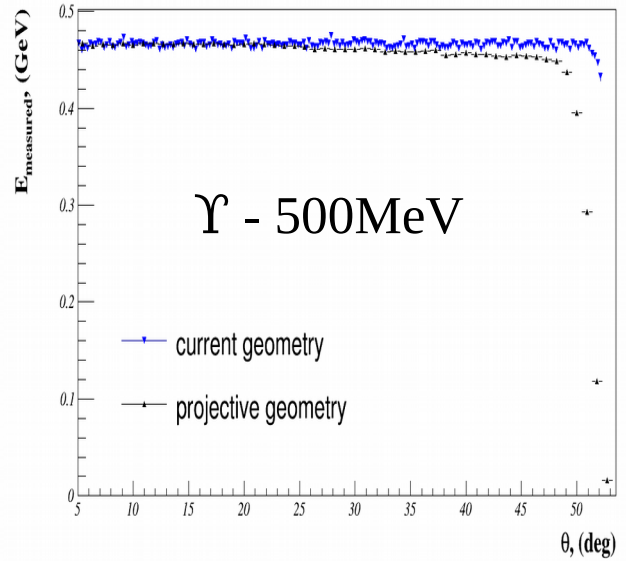


Figure 2.3.7: Distribution of the energy measured vs angle θ (Photons with energy 500MeV).

As a consequence, energy resolution and particle reconstruction efficiency becoming also dependent from the particle polar angle. In the same time it was demonstrated that making calorimeter projective in the polar angle direction, angular dependency can be completely suppressed (Figures 2.3.8 and 2.3.9).

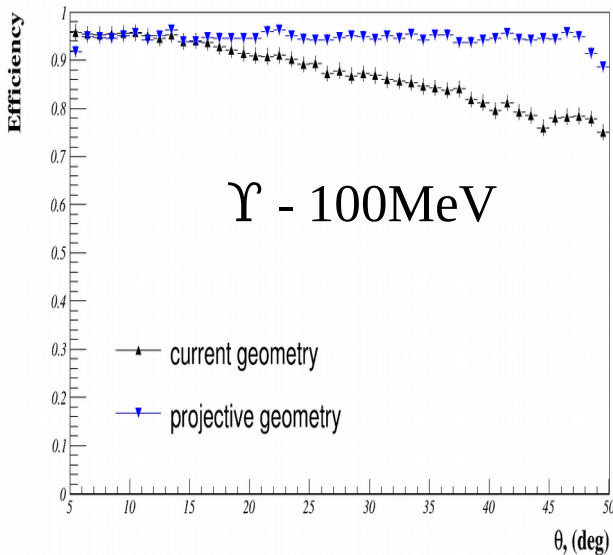


Figure 2.3.8: Distribution of the efficiency vs angle θ (Photons with energy 100MeV).

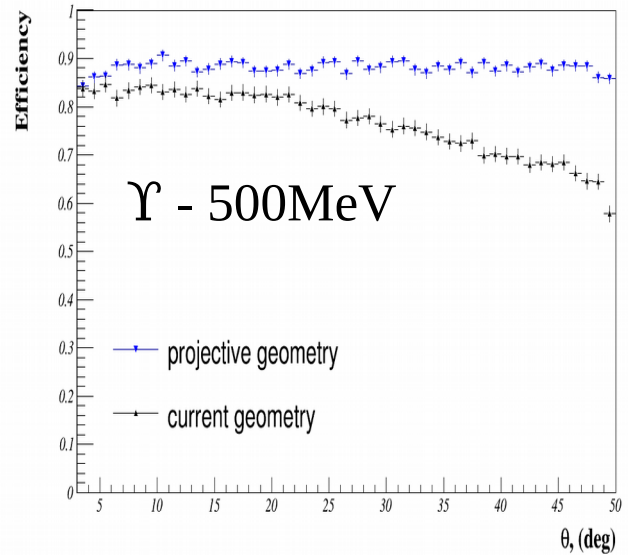


Figure 2.3.9: Distribution of the efficiency vs angle θ (Photons with energy 500MeV).

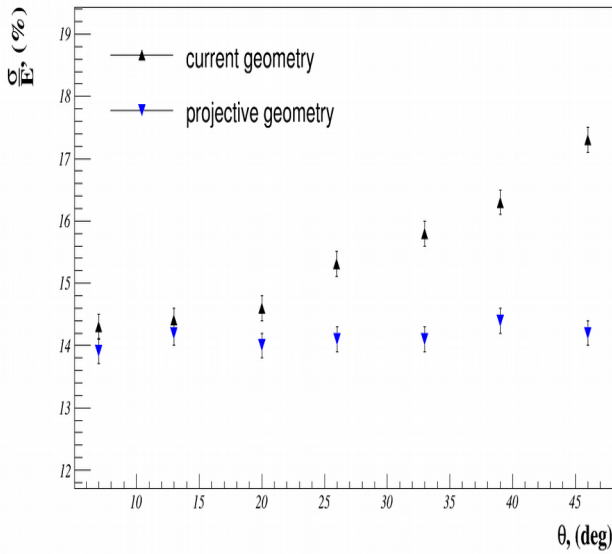


Figure 2.3.10: Distribution of the energy resolution vs angle θ (Photons with energy 100MeV).

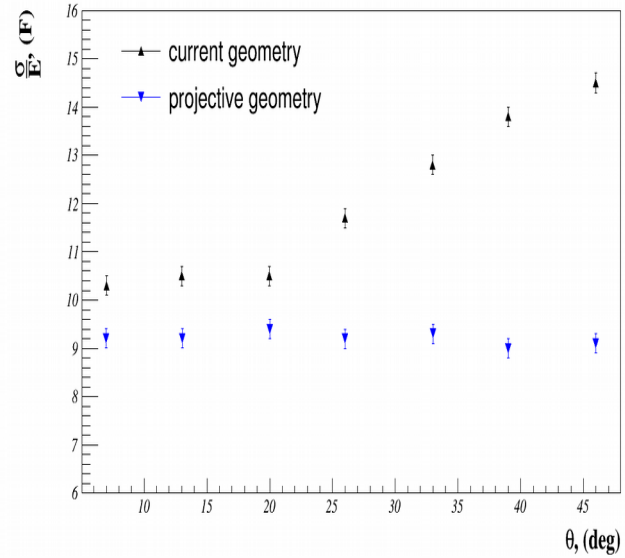


Figure 2.3.11: Distribution of the energy resolution vs angle θ (Photons with energy 500MeV).

Construction of the calorimeter which is projective in the polar direction becoming much more complicated. But the positive effect from such modification is very important for the quality of the MPD and decision was taken by the collaboration to change calorimeter design on the projective.

2.4 MC detector study with clustering algorithm

Two different classes were made to MpdRoot - Digitization and Clusterization. In the digitization, the difference between them is the amount of the collected points. In the clustering method, the difference is in the algorithm – they both are merging hits into cluster around hit with maximum energy, but the first type is based on a module frame and it uses nRow and nLine. In the second type, the cluster combines only those hits that have a common side.

Using BOX Generator were tested these two types, photons with different energy, with different polar angles, with magnetic field 0.5T, and energy threshold more than 10MeV.

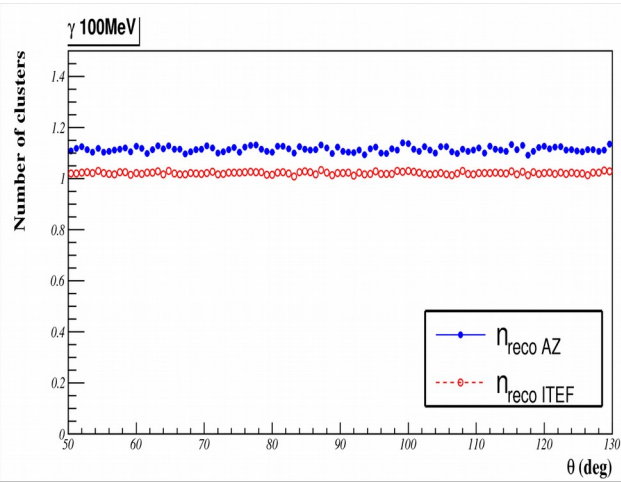


Figure 2.4.1: Distribution of number of clusters vs polar angles for second (AZ) and first type (ITEF) (Photons with energy 100MeV).

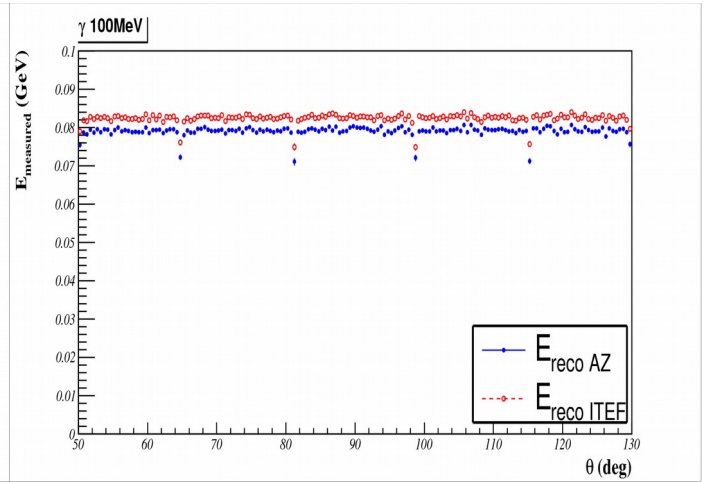


Figure 2.4.2: Distribution of energy measurement vs polar angles (Photons with energy 100MeV).

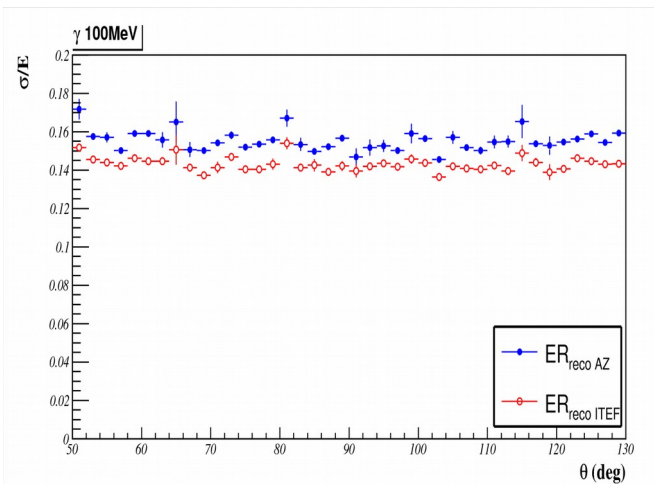


Figure 2.4.3: Distribution of energy resolution vs polar angles (Photons with energy 100MeV).

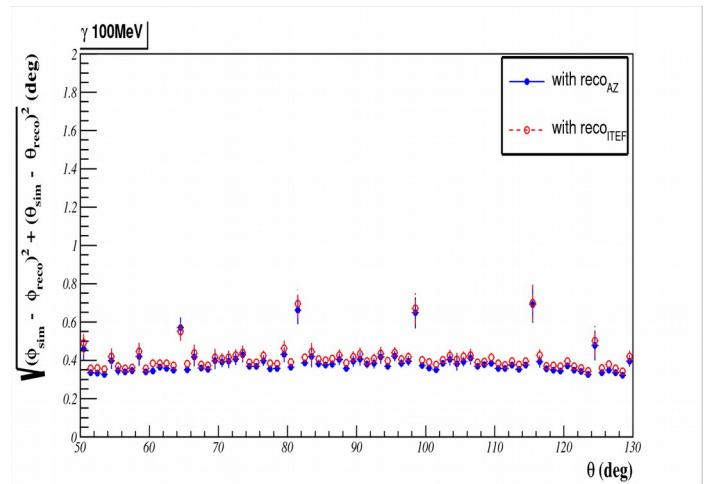


Figure 2.4.4: Distance between simulated and reconstructed points in degree vs polar angles (Photons with energy 100MeV).

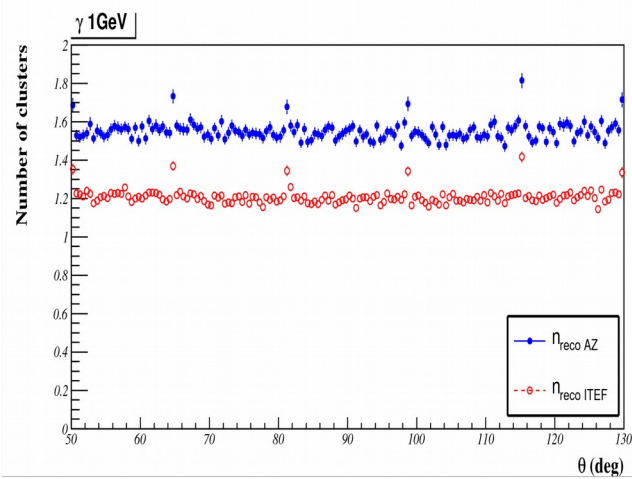


Figure 2.4.5: Distribution of number of clusters vs polar angles (Photons with energy 1GeV).

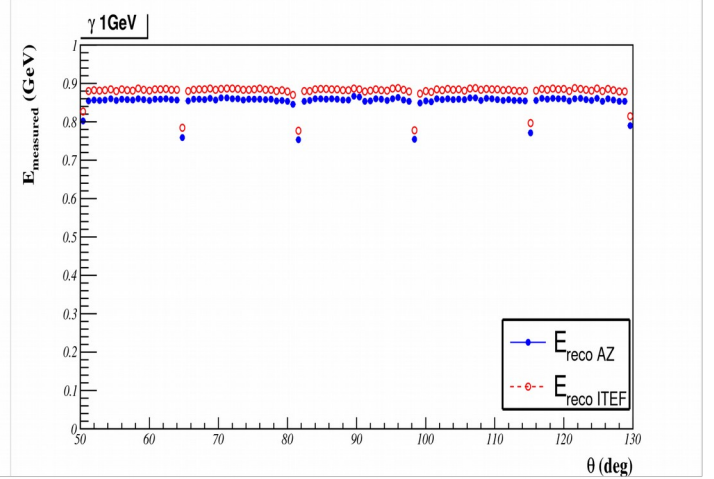


Figure 2.4.6: Distribution of energy measurement vs polar angles (Photons with energy 1GeV).

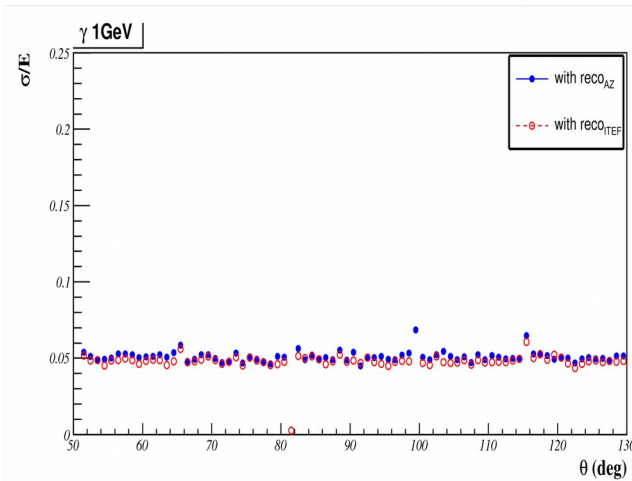


Figure 2.4.7: Distribution of energy resolution vs polar angles (Photons with energy 1GeV).

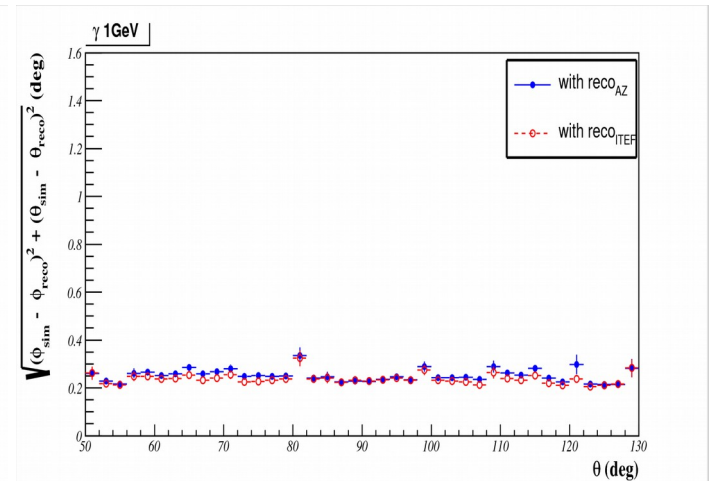


Figure 2.4.8: Distance between simulated and reconstructed points in degree vs polar angles (Photons with energy 1GeV).

First tests has been done on the application of the cluster reconstruction algorithms to the physics analysis. Attempts was done to reconstruct π^0 in the events of AuAu collision (beam energy = 11GeV). Mass spectrum of the two photon systems measured with the use of full reconstruction algorithm, including clusterization, presented on figure 2.4.9. Huge number of photons, and as a consequence big combinatorial background in such interaction, making difficult direct observation of the π^0 mass peak. But, subtracting artificially obtained mass spectrum (in which can not be π^0 by definition) from the real mass spectrum clear π^0 peak can be seen (Figure 2.4.10).

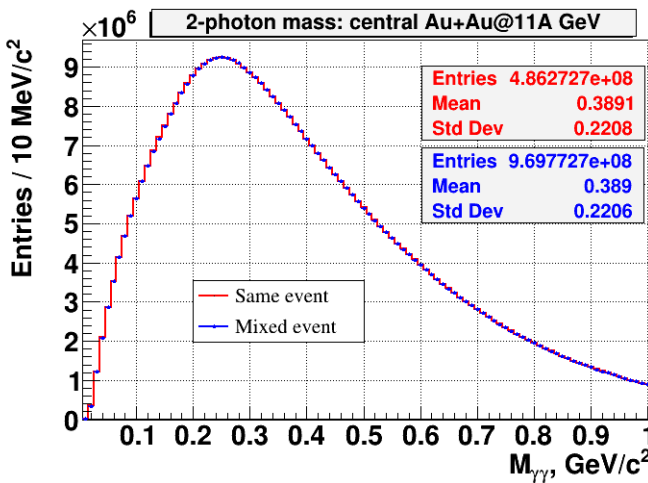


Figure 2.4.9: Mass spectra of the two photon systems.

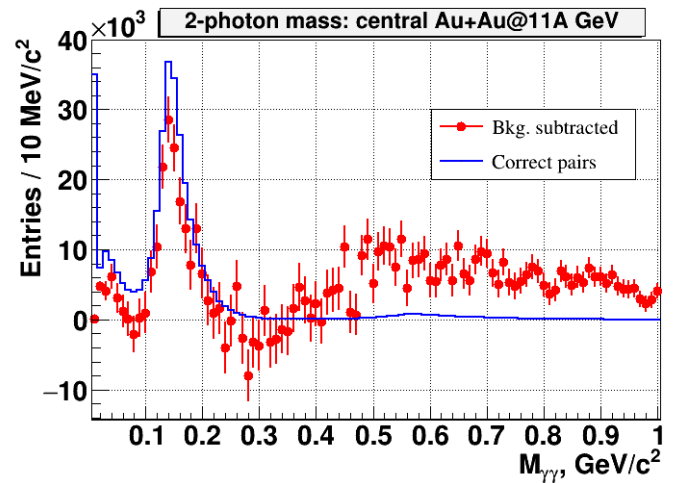


Figure 2.4.10: Difference between two mass spectra from figure 2.4.9.

3 ECal design

As it is shown above, electromagnetic calorimeter is an essential component of the MPD detector which is making contributions in the different fields of physics. In making choice of the calorimeter type and its design, we take into account features of the experiment on the NICA collider, such as particles energy, particles flow, occupancy and some others. Technological aspects, possibility of integration to the whole MPD detector and a price of calorimeter are also taken into account in the choice of calorimeter design. Only the crystal calorimeter can make the real competition to the "shashlyk" one. But much higher price and usually much worse time resolution of crystal calorimeter forced us to make a choice in favor of "shashlyk" type calorimeter.

The first Shashlyk calorimeter was designed and manufactured at Institute for Nuclear Research (Moscow) in 1991 for the experiment 865 [31] (Search for the Lepton Number Violating Decay $K^+ \rightarrow \mu^+ e^-$) at the BNL AGS. During the five-year high intensity run of the experiment, the Shashlyk calorimeter was a very stable and reliable detector. Later Pb-scintillator electromagnetic calorimeter of the "shashlyk"-type were used in the PHENIX [32], KOPIO [30], LHCb [33], T2K [34], and some other detectors. The best resolution for the "shashlyk" type calorimeter has been achieved by the KOPIO collaboration. As an example, the energy-resolution measured in the KOPIO experiment for various readouts is shown in figure 3.0.1. A quadratic fit to these experimental data gives $\sigma(E)/E = (1.96 \pm 0.1)\% \otimes (2.74 \pm 0.05)\%/p(E)(\text{GeV})$, where \otimes means quadratic summation.

Time resolution for the "shashlyk" calorimeter has been measured and estimated first by the KOPIO collaboration (Figure 3.0.2). Our design is based on the experience of existing detectors and is oriented on the industrial possibilities of JINR member states.

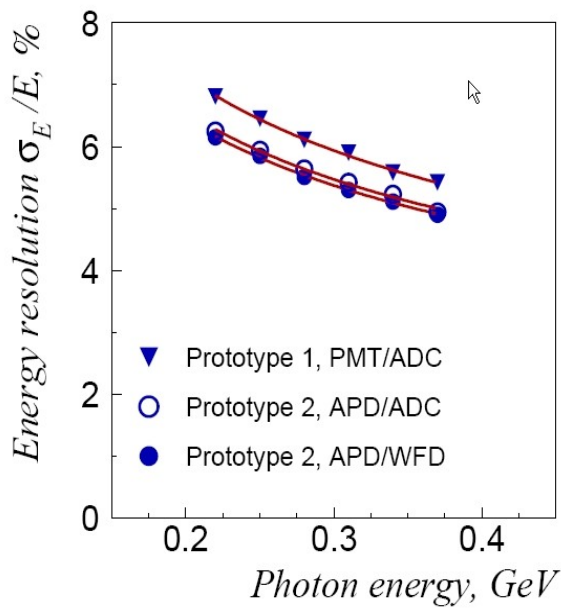


Figure 3.0.1: Energy resolution of the “Shashlyk” type calorimeter measured in the beam test.

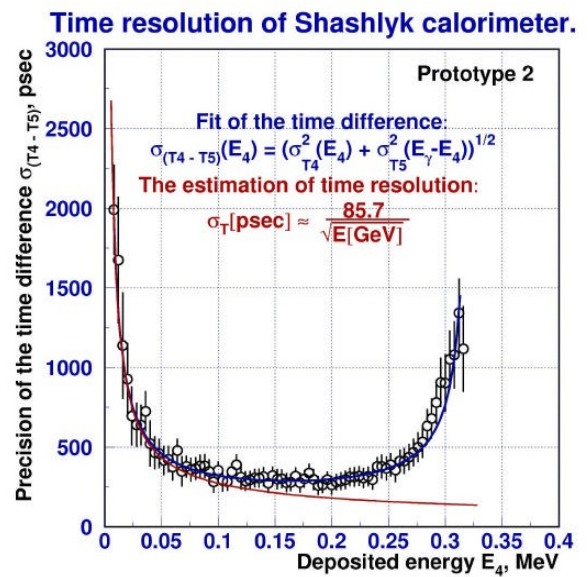


Figure 3.0.2: Time resolution of the Shashlyk type calorimeter.

Space allocated for the barrel part of ECal is shown on the figure 3.0.3 as a magenta area. More details concerning ECal place in the MPD detector can be seen on the figure 3.0.4.

The MPD electromagnetic calorimeter is proposed to be built of modules as basic building elements. Later, modules will be assembled to the sectors which will be a basic element for the ECal integration into MPD setup.

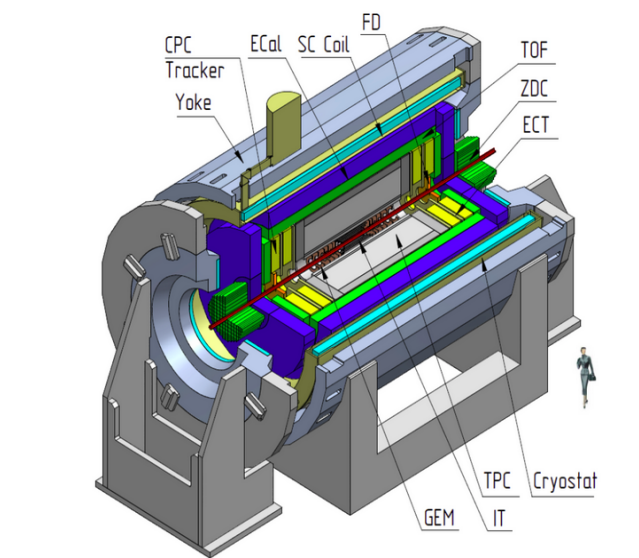


Figure 3.0.3: General view of the MPD detector.

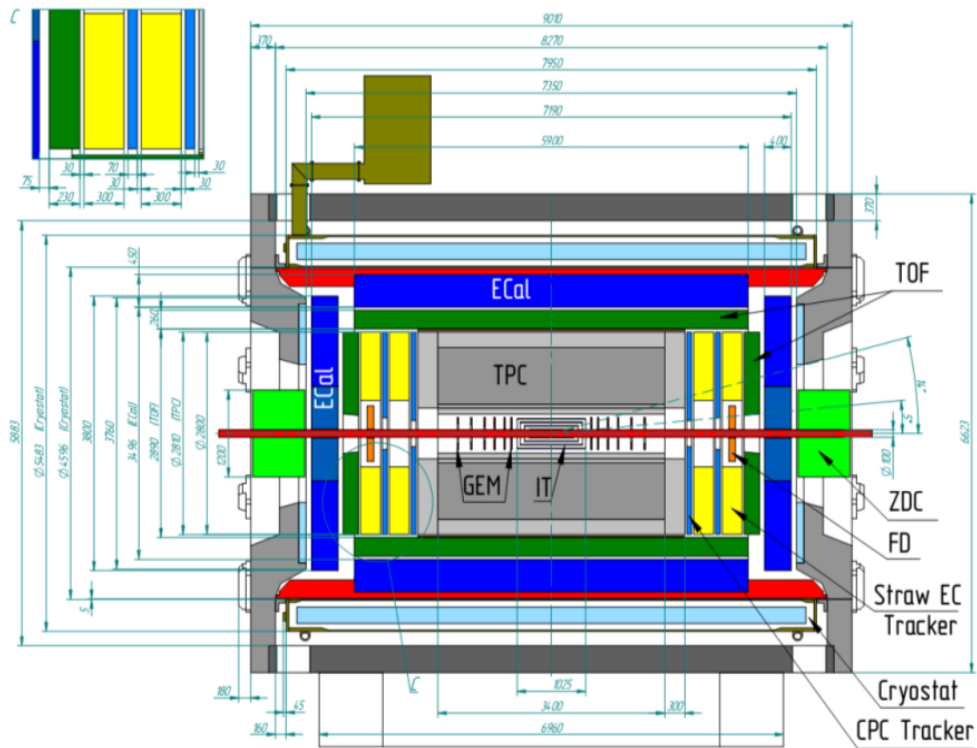


Figure 3.0.4: Cutaway side view of the Central Detector of MPD with base dimensions.

3.1 ECal module

The electromagnetic calorimeter module consists of 16 towers that are glued together. The geometry of the each module depends on the module Z-coordinate location in respect to the beams interception point. There are 8 types of the modules. The schematic views of the “shashlik” calorimeter tower and some module are shown in Figures 3.1.1 and 3.1.2. Each “shashlik” tower is a lead-scintillator sandwich that contains 220 tiles of Pb (0.3 mm thick each). The lead tiles are interleaved with 220 tiles of plastic scintillator (1.5 mm thick each). The lead and scintillation tiles are shown in the Fig. 3.1.3. The total thickness of the tower is approximately 42 cm (about 12 radiation lengths). The main parameters of ECal modules are presented in the Table 4. The photographs of the module prototypes made for the MPD in Institute for High Energy Physics (Protvino) and in Tsinghua University (Beijing, China) are shown in Figure 3.1.4.

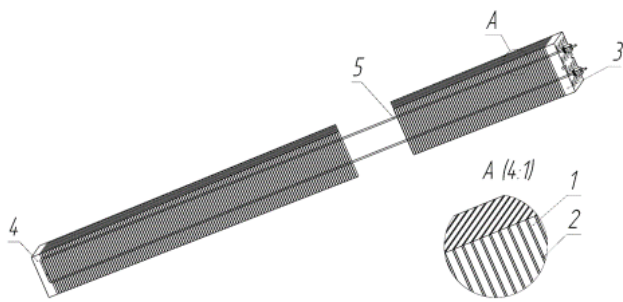


Figure 3.1.1: Construction of tower without WLS. 1 – scintillator plate, 2 - lead plate, 3 and 4 - pressure plates, 5 - pressure string.

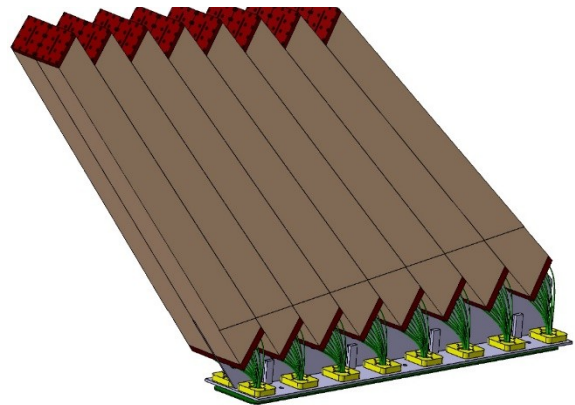


Figure 3.1.2: One of the 8 types of calorimeter module with WLS.

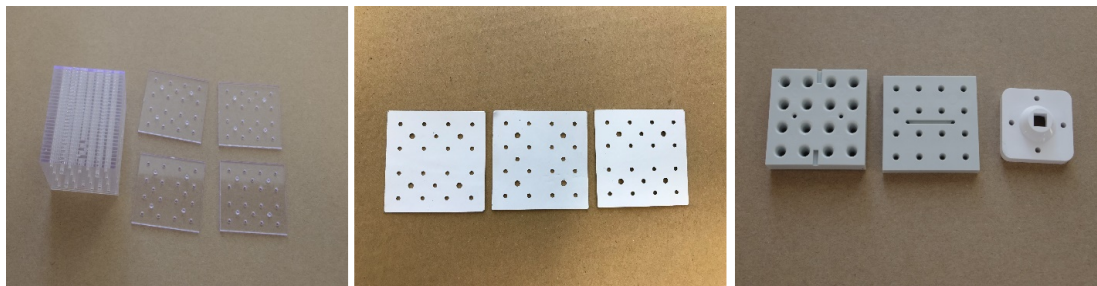


Figure 3.1.3: Plastic scintillators (left), painted lead plates (center), support plates and the collecting plate for fibers (right).

Parameters	
Maximum transverse dimensions of the tower, mm ²	40x40
Maximum transverse dimensions of the module, mm ²	80x320
Number of layers	219 ÷ 221
Paint free lead absorber thickness, mm	0.3
Paint lead absorber thickness, mm	0.4
Thickness of scintillator plate, mm	1.5
Effective radiation length, mm	32.4
Moliere radius, mm	62
Radiation length, X ₀	11.8

Table 4: Main parameters of ECal.



Figure 3.1.4: The module prototypes made for the MPD in Institute for High Energy Physics (Protvino) and in Tsinghua University (Beijing, China) are shown in the left and the right panels, correspondingly.

The scintillation light is collected via 16 Wave Length Shifting (WLS) fibers that are passing through the holes in the scintillator and lead tiles. To detect scintillation light (that is transported via the WLS fibers to the end plate of the module) special detecting heads (electronic boards) have been designed and produced. Each bundle of 16 WLS fibers of about 25 mm² cross-section area is read out with Hamamatsu S13360-6025 MAPD units (see Figure 3.1.5) of 6×6 mm² sensitive area. The properties of the MAPD units at an operating voltage are listed in Table 5.

Assembling procedure in brief can be described as a following:

	Manipulation	Comment
1	Assembly begins from the front supporting plane of assembling device. The support plate is set on the support plane.	The support plate has the groove for testing of the tower from the LED. See figure 3.1.3.
2	The first scintillator plate is set on the support plate.	Correct positioning of all lead plates and all scintillating plates are assured by the pins and corresponding holes (Lego like) on the surface of all plates of the sandwich.
3	The first lead tile is set on the scintillator plate.	As a light reflector between lead and scintillator we use a paint.

4	Consecutive repetition of the above procedure up to 220 pairs of planes.	Completion of the construction of the active module part.
5	Second support plate is set on place to cover assembled sandwich.	See figure 3.1.3.
6	A coupling procedure of the tower sandwich by means of the steel string which passed through openings in the calorimeter planes.	
7	The tower is compressed by means of the special device. The strings are fixed by the two tension device.	The compression force is controlled by the sensor. The compression time is determined experimentally.
8	Milling of two opposite faces of the each tower.	The milling angle of one side of the tower is about 0.45 degrees.
9	Consecutive repetition of the above procedure up to 8 (16) towers.	
10	Gluing the milled surfaces of 8 modules with glue paint.	Gluing places are laid reinforcing mesh.
11	Milling of two next opposite faces of the glued 8 towers.	The milling angle of the glued 8 towers is about 0.55 degrees.
12	Gluing the milled surfaces of the next 8 modules with glue paint.	The milling angle one side of the glued modules is about 0.55 degrees.
13	Gluing of the milled 16 towers with glue paint to the module.	At the same time, all other necessary parts of the module construction are glued in.
14	Sixteen WLS fibers of first tower are inserted and connected in the collecting plate on the adapter plate.	Preliminarily one of the ends of each WLS was covered by a reflector.
15	Consecutive repetition of the above procedure up to 16 towers.	
16	The collecting plates, in turn, are fixed on the adapter plate, on which the readout electronics board is installed.	
17	All fibers gluing in each of the 16 collecting plates.	Epoxy resin is used,

18	WLS fibers on the adapter plate are milled and polished.	
19	The modul is covered with glue paint from the outside.	
20	The characteristics of the module are measured and its passport is compiled.	All data fix on the module.
21	Packing of finished products.	

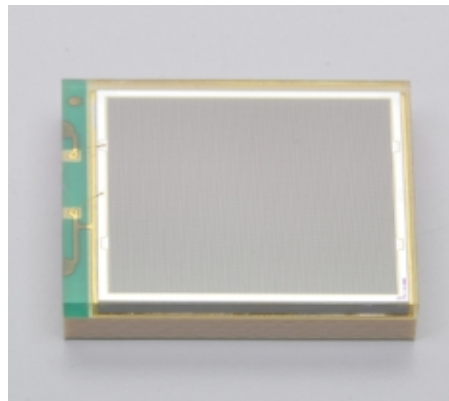


Figure 3.1.5: HAMAMATSU S13360-6025PE MAPD.

These MAPD devices have been chosen due to significant advantages compared to the others MAPDs that we tested. The advantages are:

- surface mount devices (viz., compactness);
- high photon detection efficiency;
- very low dead time;
- availability on the market;
- identity of detectors of one type;

Type no.	Measurement conditions	Spectral response range λ (nm)	Peak sensitivity wavelength λ_p (nm)	Photon detection efficiency PDE ^{*4} $\lambda = \lambda_p$ (%)	Dark count ^{*5}		Terminal capacitance C_t (pF)	Gain M	Break-down voltage V_{BR} (V)	Crosstalk probability (%)	Recommended operating voltage V_{op} (V)	Temperature coefficient at recommended operating voltage ΔTV_{op} (mV/°C)
					Typ. (kcps)	Max. (kcps)						
S13360-1325CS	V _{over} = 5 V	270 to 900		25	70	210	60	7.0×10^5		1	V _{BR} + 5	
S13360-1325PE		320 to 900										
S13360-3025CS		270 to 900										
S13360-3025PE		320 to 900										
S13360-6025CS		270 to 900										
S13360-6025PE		320 to 900										

Table 5: Parameters HAMAMATSU MAPD S13360-6025.

After production, each detector head (readout board) will be tested, and all MAPDs in it will be preliminary calibrated. Then, calibrated heads will be assembled with module, and each module will be calibrated on the cosmic muons. After calibration, the modules are ready for the assembled to the half-sectors.

3.2 FE electronics

Front-End (FE) electronics will be located directly on the calorimeter. This solution is chosen due to the evident advantages:

- Small path of analog signal to FE means less signal distortion and pickup noises.
- Much simpler transport of digital signal from the calorimeter to the event building electronics. Number of connectors between FE boards and electronics outside detector falls from 1536 (number of channels per sectors) in case of analog signal transport falls to 24 (number of channels per sector / number of channels in ADC board (64)) in case of digital signal transport. In the later case we use very thin optical cable.
- Very high event read out rate can be reached by using zero suppression and even signal processing directly on the FE board.
- One disadvantage of this solution is the need to extract the heat from the FE electronics out of MPD detector.

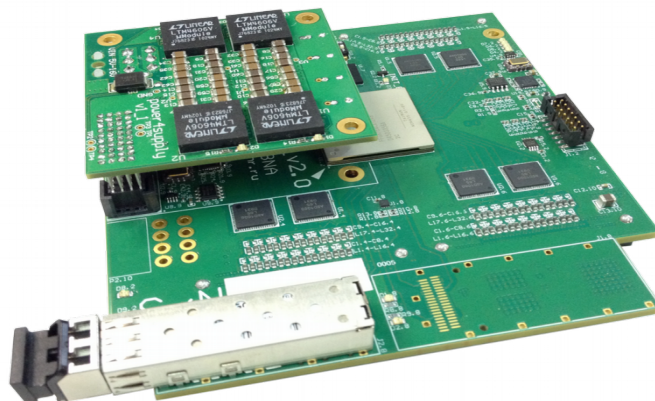


Figure 3.2.1: ADC64s2 – Front-End board with ADCs amplifiers Ethernet communicator 2411 [37].

As a FE electronics unit we have designed and constructed ADC 64 channel board

(Figure 3.2.1). ADC board is a waveform digitizer. It quantize analogue input signal and samples it at fixed time intervals. Zero suppression logic is based on baseline estimation and threshold value. Signal shaping is performed in digital form with FIR filters. It allows to reduce the number of waveform points required for digital signal representation with minimum loss of accuracy. The ring type memory allows the read back of last 30 μ s of waveforms. It sets the limit on trigger latency to this value.

ADC board allows to be integrated to the White Rabbit system. White Rabbit provides sub-nanosecond accuracy and picoseconds precision of synchronization for large distributed systems. It also allows for deterministic and reliable data delivery.

3.3 Slow Control

The main objectives of system for monitoring of slowly changing parameters and management of auxiliary electronic systems in physical experiment (slow-control system) are:

- Monitoring of parameters of work of the equipment.
- Management of work of slow-control equipment. In our case - low-voltage and high-voltage power supplies, calibration system.
- Record of slow-control commands commands and data.
- The notification about problems (Alarms).

The aspects concerning SC system general logic, software and platform will be discussed in the special section. Here we give short description of hardware designed for the ECal SC system.

High voltage system has been designed especially for the MAPD based devices. Specific points of this system are:

- Multichannel (60 000 channels);
- Very precise voltage setting for each channel;
- Need of voltage correction depending of temperature of MAPD;

3.3.1 High Voltage

All these requirements have been realised by "HVSys" company in the HCal HV system including following components:

- 9 channel board;
- system unit;
- system bus;

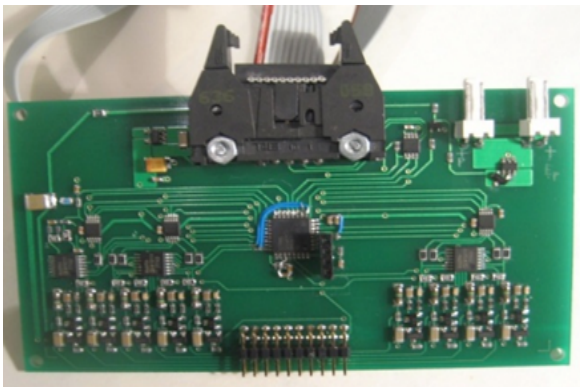


Figure 3.3.1.1: HV module.



Figure 3.3.1.2: Control Units (Communication base voltage generation).

Each ECal module will be connected with one 9-channel HV board, which will be located in the ventilated box close to the module detection part. Via system bus each HV board receives base voltage 90 V and driving commands from the system unit.

Through the short (not more than 15cm) flat cable each HV board will deliver individually tuned voltage on nine sectors of the calorimeter module.

One line of this flat cable is dedicated to the temperature measurements on the detection head of the

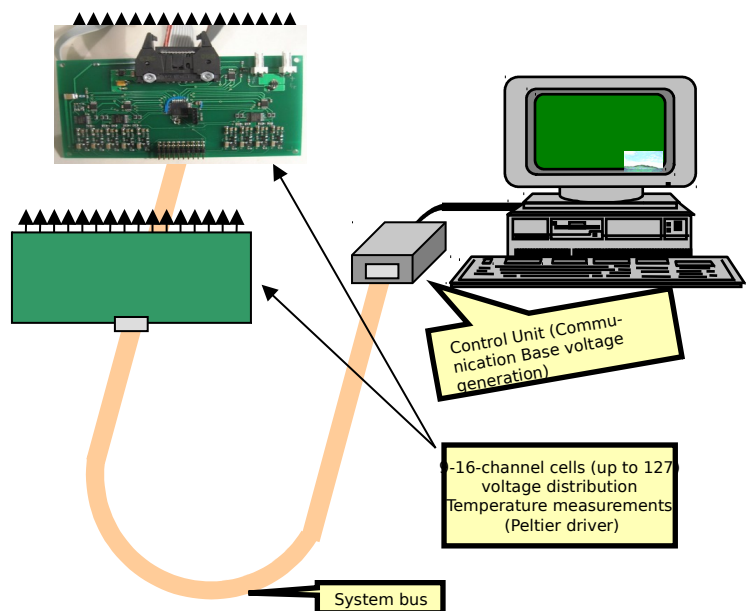


Figure 3.3.1.3: HV system block diagram.

Ecal module. On the basis of these measurements of temperature HV system will make voltage correction, to compensate temperature dependency of the MAPD amplification.

Most important HV system parameters are listed in the table 6.

1	Range of max output voltage	Up to 250V
2	Range of output voltage regulation	Umin - Umax
3	Precision of output voltage regulation	20v/10 bit
4	Output voltages spread (channel from channel)	1%
5	Stability of an output voltages	0,005 %
6	Temperature coefficient of an output voltage	200 ppm/K
7	Maximal average output current	10 mkA
8	Self-diagnosis of the BV channel	Yes
9	Current measurements	Possible
10	System bus	6 line flat cable
11	Max length of system bus	Up to 100 m
12	Number of cells per system bus	Up to 127

Table 6: HV system parameters.

2.3.2 LED Generator

To make a precise calibration of each ECal registration channel and also for the continuous monitoring of channel amplification LED generator of short bright blue light signals has been designed and built. Main requirement to this device is its stability. Light intensity variation should be below 1%. Block diagram of calibrator is shown on figure 3.3.2.1. To reach such stability two solutions have been realized in this device. First, special mode of operation for the LED driver was been found. In this high-charge mode LED operation becoming much more stable comparing with usual one. Second, to reduce residual variations of LED light intensity the feedback loop has been implemented to the device. The pin diode has been located on the LED back side. Light from the LED back side detected by this pin diode digitized by the ADC and analyzed by the comparator. Result of this analysis is used to correct

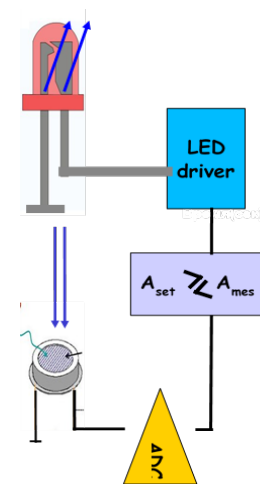


Figure 3.3.2.1: Block diagram of the calibrator.

the LED light intensity by changing the current in the driving signal. This correction allows to keep LED light constant and equal to the set value.

3.3.3 Temperature and pressure

Due to the sensitivity of MAPD detectors to the temperature its stability is the subject of our constant attention. Temperature sensors will be located along the ECal sectors. Through these sensors Slow Control system will take temperature conditions around ECal under constant attention. Pressure and temperature inside the ventilated duct with electronics is the subject not only registration but also control of these correlated parameters via the operated input/output valves .

3.4 Power consumption and cooling

The power consumption is estimated for the ECal subsystems as about 11.6 KW in total. This does not include DAQ systems outside the MPD barrel. All FE and Slow Control electronics located directly on the ECal module inside the MPD barrel. The heat from these electronics devices should be evacuated from the MPD barrel. Total power estimated as a 250mW/ch, that brings to about 207W per ECal sector. Even this small amount of heat cannot be left inside closed volume of the barrel. According our estimation (experimentally tested, see below) this amount of heat can be extracted by the air ventilation inside the closed duct with all electronic devices inside. It is duct 3 meters long with cross-section of 100x50 mm². To minimize cross-section of inlet and outlet pipes connecting duct with the outside barrel equipment the air pumped inside with some overpressure and evacuated by the intensive pumping out. To avoid over/under pressure inside duct pressure inside duct measured by the Slow Control system and controlled by this system via input/output valves. According our calculations, to have a guaranteed cooling and even some spare power in the cooling system size of inlet-outlet pipes should be about 10 cm². This size easily fit dedicated to ECal space in the cable holes in the detector body.

3.5 Power Structure of the Calorimeter

Geometrically, the ECal consists of 54 isolated half-sectors forming a 6-m-long (along the beams direction) cylindrical shell having inner and outer radii of about 1.71 m and 2.278 m, respectively. Each half-sector is a segment of that shell of about 3-m long (half-length of the calorimeter). In the transverse plane, each half-sector occupies the φ -angle range of about $360^\circ/27 = 13.3^\circ$. Such a segmentation is not fundamentally important, these numbers are selected to have the half-sector light enough for safe transportation and installation into the ECal, and for easy organization of electronics readout. The primary support structure of the half-sector is a basket, which consists of a honeycomb structure made of carbon composite material. Honeycomb have a wall thickness of about 0.8 mm, which ensures sufficient rigidity of the entire structure and has no significant impact on the characteristics of the calorimeter. The half-sector contains 48 calorimeter modules [= (8 modules of the different types in the longitudinal direction) x (6 modules of the same type in the transverse direction)] that are locked (glued) into the basket, so the modules contribute to the rigidity of the whole half-sector. The "bottom" (most close to the beams) part of the basket is made of the thicker (5-10 mm) carbon composite material with windows underneath every module. These windows are big enough to allows an access of a simple mechanism to lift the modules during the assembling of half-sectors. The basket and the modules are designed a such way that after the modules installation, the "top" bars with output windows of WLS fibers for all 8 modules in the longitudinal direction form the common plane that is tilted in respect to the beam direction by the angle $\theta \approx 1.5^\circ$. "Above" this output-windows plane in the "top" part of the half-sector (which is located far away from the beams), there is a space to be used for readout electronics installation. The size of that space varies from 60 mm in the calorimeter center to 140 mm at the ECal edge, and it's enough to place the directing rails to insert or extract a 3-m-long box that carries the ADC modules as well as the boards with photo-detectors and preamplifiers. The simple system of adjustment screws allows to position the photo-detector boards with about 0.2 mm accuracy in respect to the output windows of WLS fibers as well as to keep this accuracy after electronics re-installation. Using this method of the electronics installation, we have an ability to replace or repair the

electronics (if needed) without extracting heavy half-sectors from the ECal. There are 3 such electronics-installation systems per each half-sector. The total weight of the half-sector is about 1300kg.

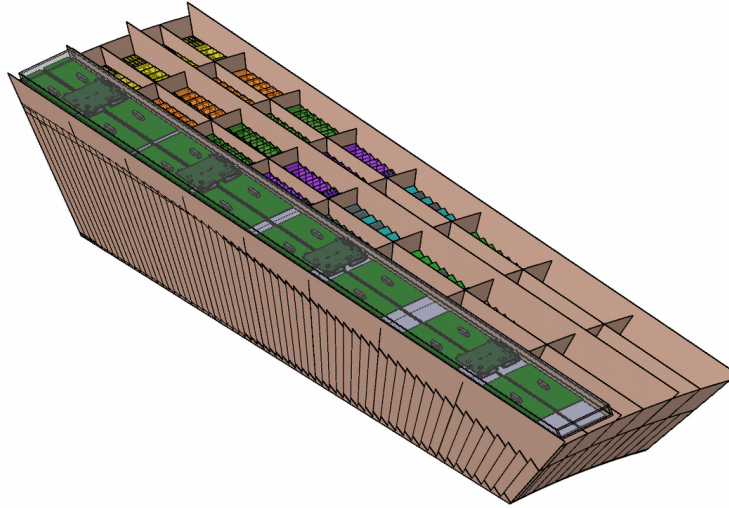


Figure 3.5.1: *The view of the half-sector with one installed system of readout electronics.*

The half-sector with one electronics-installation system is shown in Figure 3.5.1.

To install the half-sectors into MPD, the power frame made of carbon composite material is used. The frame consists of two nested in each other mesh cylinders. The bigger one has an inner radius of about 2.28 m, and the smaller one has an outside radius of 1.695 m. There are 27 mesh partitions between the cylinders that (together with mesh cylinders) form 27 cells for half-sectors installation using specially designed tools (2 half-sectors in one cell). Besides the stationing of the ECal half-sectors, the power frame is used as a structural support for the other detectors of the central part of MPD (viz., TOF, TPC, CPC and Straw EC trackers) as well as patch panels, cables, power lines etc. The total load on the power frame is estimated to be about 94 tons. The power frame is fasten with the magnet yoke via 2 support rings on both ends of the frame. The exact position of the power frame relative to the magnet yoke can be adjusted within about 2 cm that is enough to correct a possible inaccuracy of the magnet position relative to the beams. Different views of the power frame are shown in Figure 3.5.2.

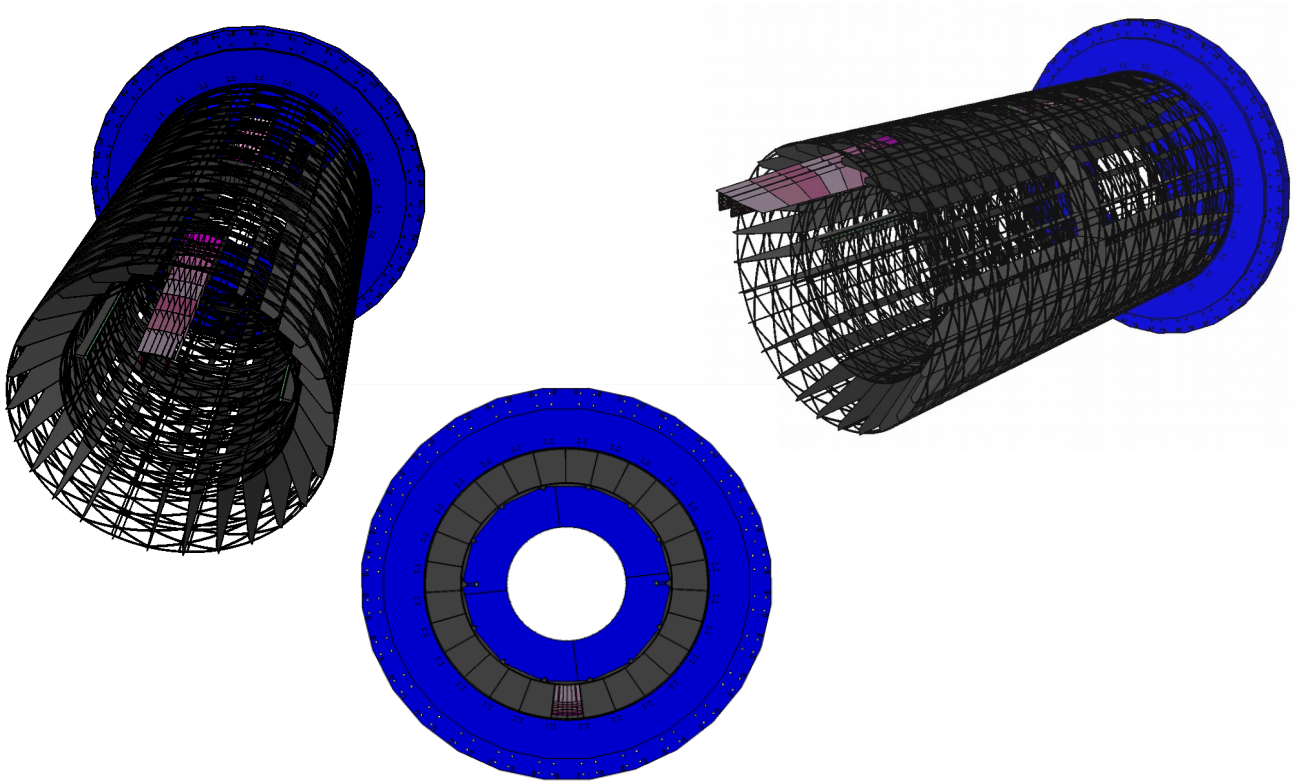


Figure 3.5.2: Different views of the power frame. One support ring is shown in blue outside the power frame. The blue object inside the power frame is a field correction magnet. Also, the installation of one half-sector (pink object) is shown.

4 Test results

All parts of ECal detector have been produced some of them in few iterations. ECal "Shashlyk" modules have been produced in Kharkov (Ukraine). The FE and Slow Control electronics was designed at JINR. Many tests with all elements of ECal detector was performed during last three years.

4.1 Calibration

4.1.1 MAPD Calibration

Despite that all MAPD detectors are calibrated and certified by the producer, the verification procedure should be developed. This procedure should be almost automatic, taking into account huge number of channels in the MPD ECal detector. The MAPD detectors was lit by the short light

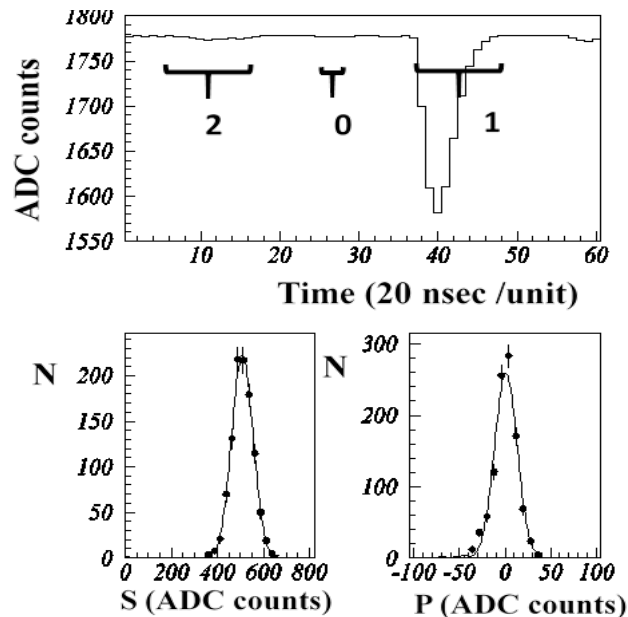


Figure 4.1.1.1: Up – measured signal from LED pulse light. Region “0” - measurements of the pedestal, “1” - measurements of the signal, “2” - background (pedestal integral). Bottom left – signal amplitude distribution (S). Bottom right – pedestal integral distribution (P).

impulses generated by the LED generator. Such impulse is registered by the FE electronics – figure 4.1.1.1.

Amplitude of the LED pulse was chosen to have number of fired MAPD pixels big enough to be well detected above noise, but not too big in order to be sensitive to the statistical fluctuations of this number. Measurements of these statistical fluctuations is the basis to calculate MAPD characteristics. In each event, we are calculating first the pedestal (formula 1), as average calculated over n ADC channels in the region far from the signal (zone “0”) (Figure 4.1.1.1). This pedestal is used then as a zero level in calculation of the signal integral (region "1" on the Figure 4.1.1.1, formula 2) and the pedestal integral (region "2" on the Figure 4.1.1.1 and formula 3), where N is ADC channels in the region "1" and "2".

$$Ped = \frac{\sum_{i=1}^n ADC_{counts}^i}{n} \quad (1)$$

$$S = \sum_N^i (ADC_{counts}^i - Ped) \quad (2)$$

$$P = \sum_N^i (ADC_{counts}^i - Ped) \quad (3)$$

As a result of many such measurements under the same conditions (HV and temperature) we are getting two distributions - signal and pedestal integral (Figure 4.1.1.1). Fit of this distributions by the Gaussian give us four numbers - average (A_s, A_p) and sigma (σ_s, σ_p) for both distributions. From these numbers we are calculating few variables, which are characterizing operation of the given MAPD in the given conditions. According statistical laws:

$$N_{pix} = \frac{A_s^2}{\sigma^2} \quad (4)$$

$$U = \frac{\sigma^2}{A_s} \quad (5)$$

$$SB = \frac{A_s}{\sigma_p} \quad (6)$$

where (4) is number of fired pixels, (5) - amplification (ADC bit per one fired pixel), (6) - signal to background ratio, σ is $\sigma = \sqrt{\sigma_s^2 - \sigma_p^2}$.

In reality only three measured variables are in the game, A_p is by definition very close to zero. To determine working point for each of MAPD the HV scan should be done starting from the HV where LED light signal is becoming visible till the HV then the MAPD passes the working limit of current. Current limit is set to $1 \mu\text{a}$ for all examined photo-detectors. In each point of the HV scan the variables listed above are calculated and plotted. Example of such plot is shown on the figure 4.1.1.2.

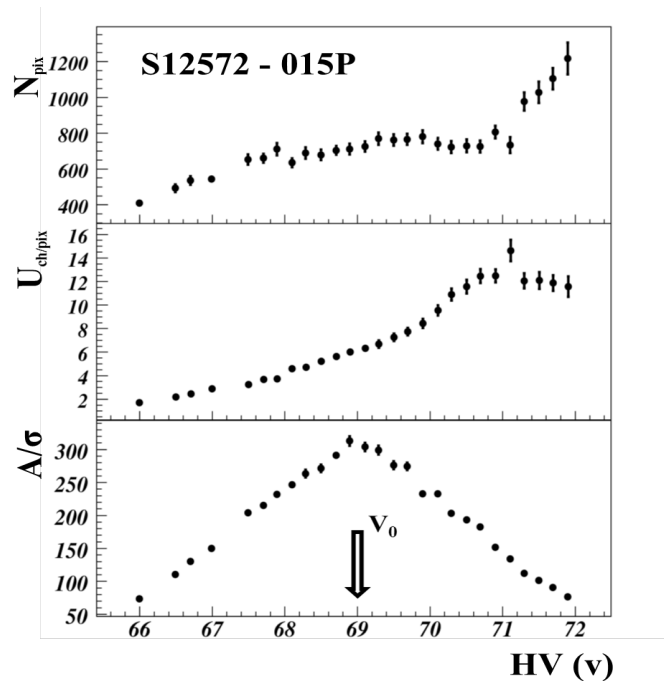


Figure 4.1.1.2: MAPD parameters versus HV (one channel)

From the behavior of the variables on the figure 4.1.1.2 the choice of the working point is quite evident - best signal to noise ratio around HV= 69V. Later, detector becomes more noisy. At lower HV the MAPD amplification is lower, what is also undesirable. The behavior of all MAPD detectors is very similar (Figure 4.1.1.3 as an example - nine MAPD detectors from one ECal module) and the search of working points can be done almost automatically. Only final control of HV working points search is expected.

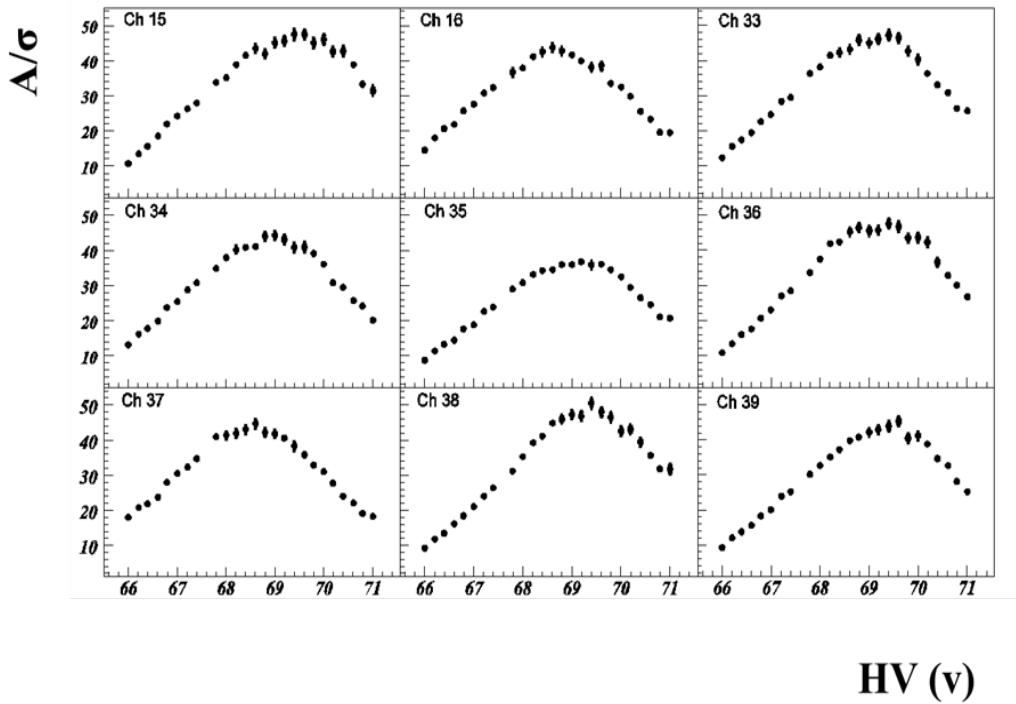


Figure 4.1.1.3: Signal to background ration versus HV for the MAPDs of ECal module.

4.1.2 Calorimeter calibration

Crucial point of calorimetric measurements is its calibration. Best way of absolute calibration is the use of physical events with well known energy. This procedure will be used during physics runs on the collider. Most evident physics for this procedure will be π^0 reconstruction and electron energy measurements for the electrons registered by the TPC. This procedure of this final calibration becoming much more simple if for all calorimeter channels relative calibrations have been made in advance. For this preliminary calibration cosmic muons can be used. To select muons crossing calorimeter tower in right direction scintillation hodoscope will be build for the test area. Another way to use cosmic muons which do not require special trigger system has been proposed and tested. Self triggering feature of our FE electronics is used in this method. Event is registered if at least in one channel signal amplitude exceeds threshold. During analysis events with candidates on the track in the calorimeter selected (see Figure 4.1.2.1) and signal amplitude in each channel is considered as

a signal from the cosmic muon. Results of such analysis presented on the fig.4.1.2.2. Data in each channel was used to calculate correction factors to equalize all amplitudes. Distribution of those factors is presented on the figure 4.1.2.3. Test was done to prove these correction factors reflects real difference in channel sensitivity and their application will improve calorimeter performance.

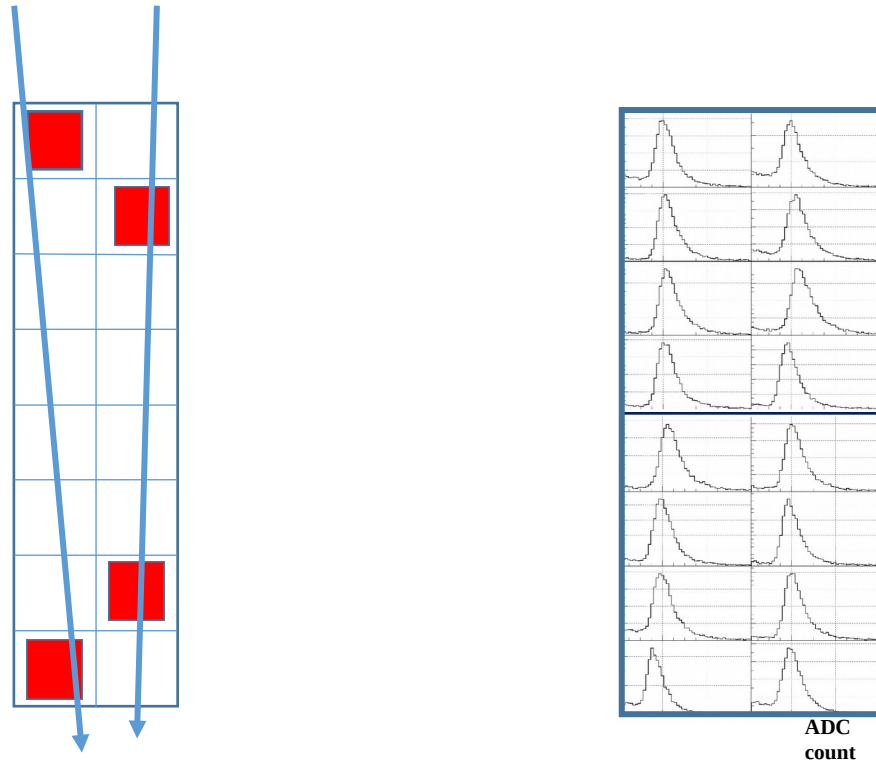


Figure 4.1.2.2: Examples of the muon signals

Figure 4.1.2.1: Cosmic muon selection algorithm. Two examples of muon track selection. Red squares - are the monitor

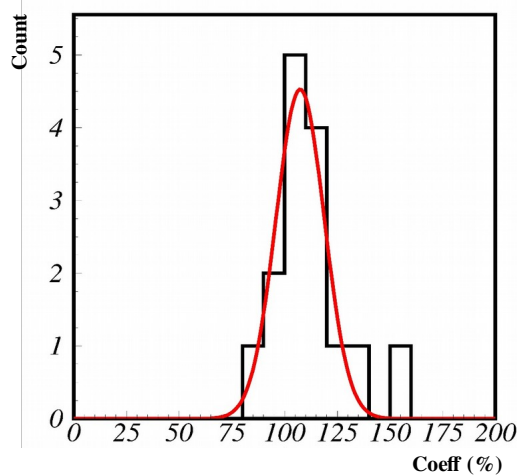


Figure 4.1.2.3: Distribution of the correction coefficients for the tested module.

Test was done to prove these correction factors reflects real difference in channel sensitivity and their application will improve calorimeter performance. On the figure 4.1.2.4 energy scan done for the different space positions is presented. Clear difference in the channels sensitivity can be seen. Next figure 4.1.2.5 presents the same data after correction coefficients applied.

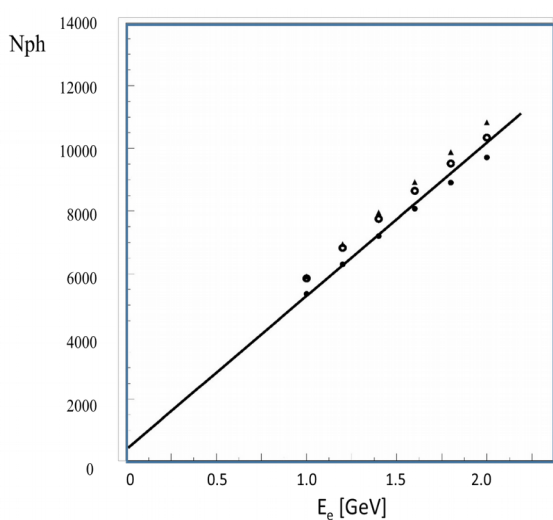


Figure 4.1.2.4: Detector response to the electrons of different energies hitting calorimeter in three different points (see sketch on left from the plot).

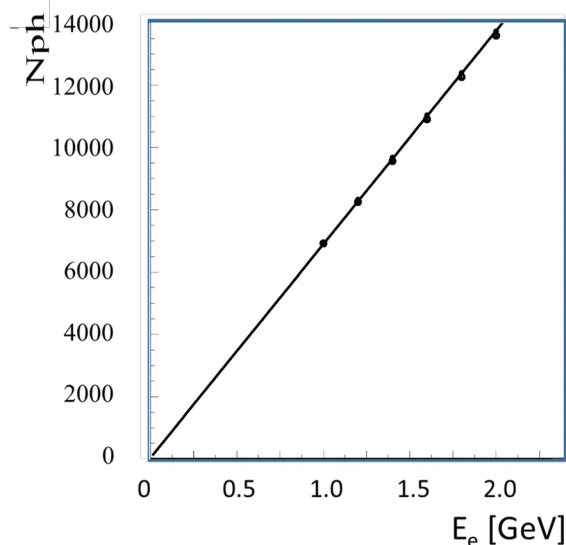


Figure 4.1.2.5: Detector response (same as on previous plot) after correction.

4.2 Temperature compensation

Amplification of all MAPD detectors depends from the temperature. To make precise measurements with the devices based on the MAPD detectors we need to stabilize temperature around MAPD or compensate temperature drift of MAPD amplification by the corresponding shift of HV. The dependency of the voltage compensation versus temperature shift is a convolution of two functions - dependency of the MAPD amplification from the temperature (Figure 4.2.1) and the dependency of the MAPD amplification from the HV (Figure 4.2.2). As a result of these measurements linear correction with slope of 0.045V/deg is implemented in the HV source. On the figure 4.2.3 the amplitude of the signal from the LED source is shown as a function of temperature

without temperature compensation. While on the figure 4.2.4 the temperature compensation is activated.

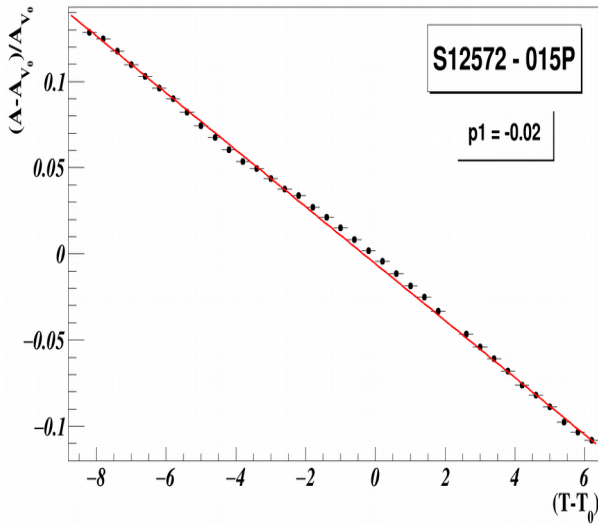


Figure 4.2.1: Dependency of the MAPD amplification from the temperature.

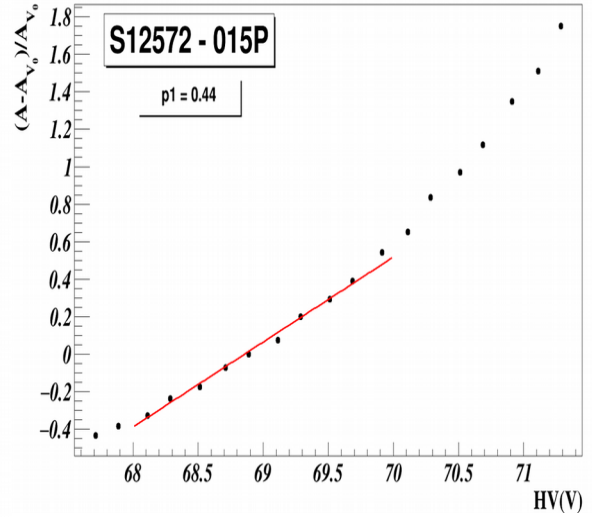


Figure 4.2.2: Dependency of the MAPD amplification from the HV.

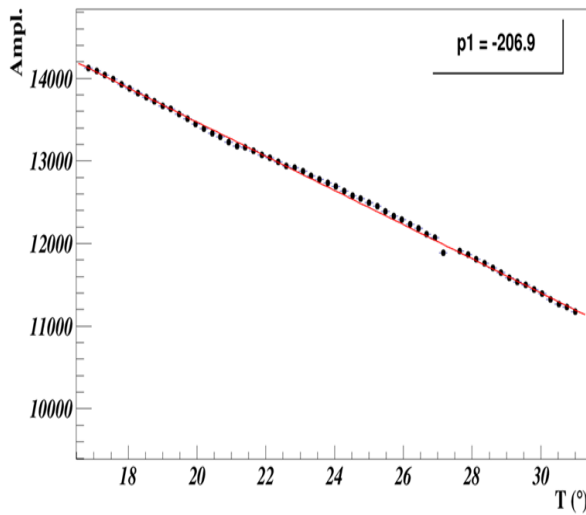


Figure 4.2.3: Signal amplitude versus temperature (without temperature correction).

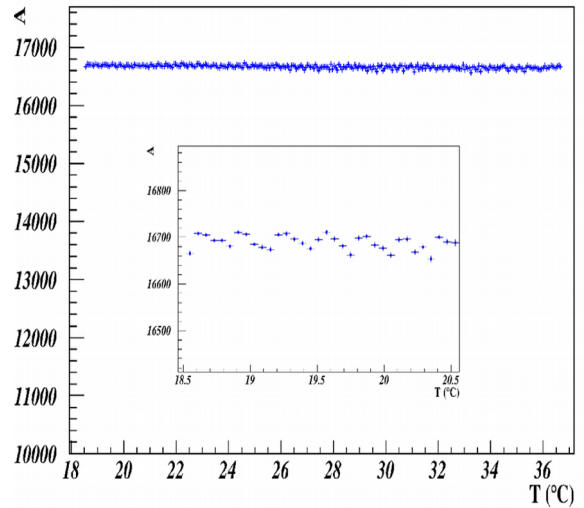


Figure 4.2.4: Signal amplitude versus temperature (with temperature correction). Zoom inside shows the change of the signal due to one bit (25mV) voltage correction.

Variation of the signal on the figure 4.2.4 is below 1%, what is quite admissible in our case. Zoom inside figure 4.2.4 illustrating small amplitude variation corresponding to the change of the HV on minimal possible value (1 DAC bit = 10 mV).

4.3 Energy resolution

Many beam tests has been performed during last years. Electron beams available now at CERN and at DESY and both these facilities was used to study MPD ECal.

Advantage of DESY test area is availability and wide electrons energy range (1-6 GeV). At CERN it is possibility to use muons and very small energy spread in the beam.

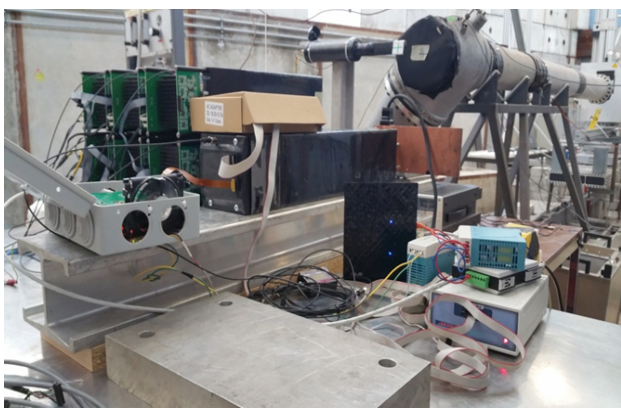


Figure 4.3.1: Stand with electromagnetic calorimeter in test area in CERN.

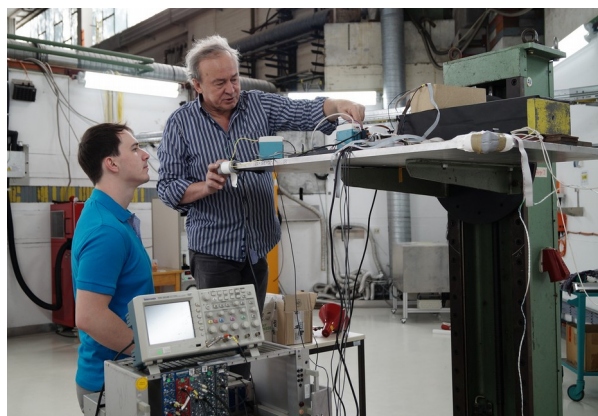


Figure 4.3.2: Stand with electromagnetic calorimeter in test area in DESY.

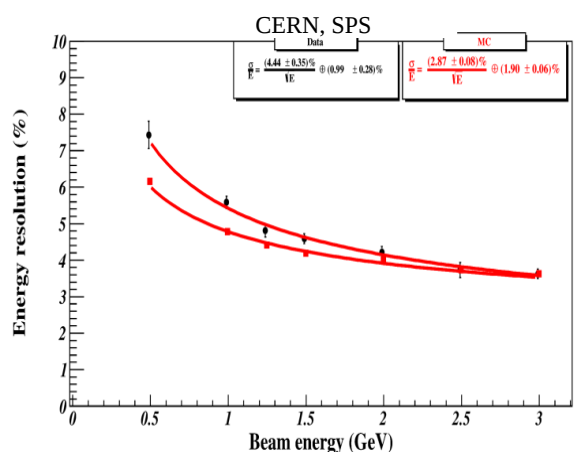


Figure 4.3.3: Energy resolution vs electron energy for data and MC.

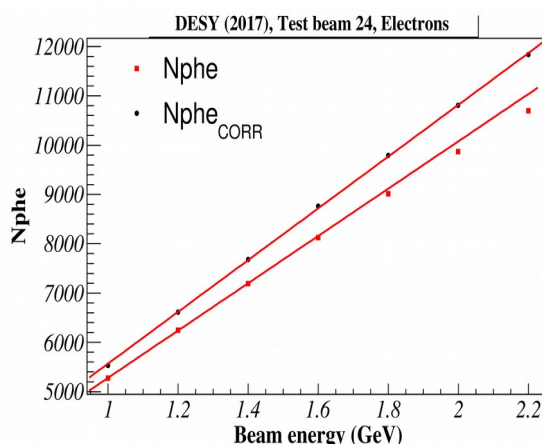


Figure 4.3.4: Detector response to the hitting electrons of different energies.

Energy resolution is the most important feature of the ECal was measured at CERN (Figure 4.3.3). Experimental results are slightly worse of the MC expectations in the energy region below 2 GeV. The reason of this disagreement is the matter for the future study.

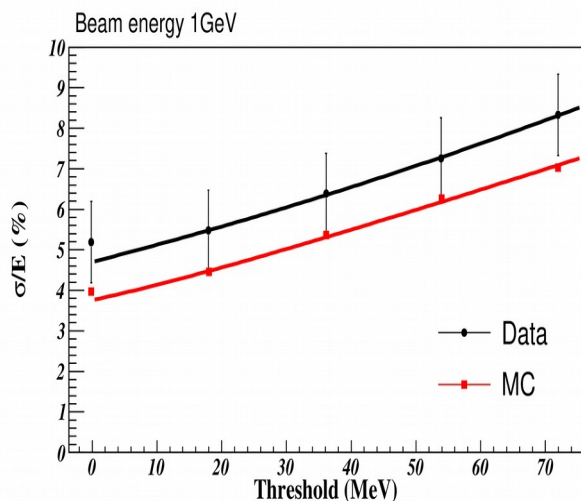


Figure 4.3.5: Energy resolution versus threshold.

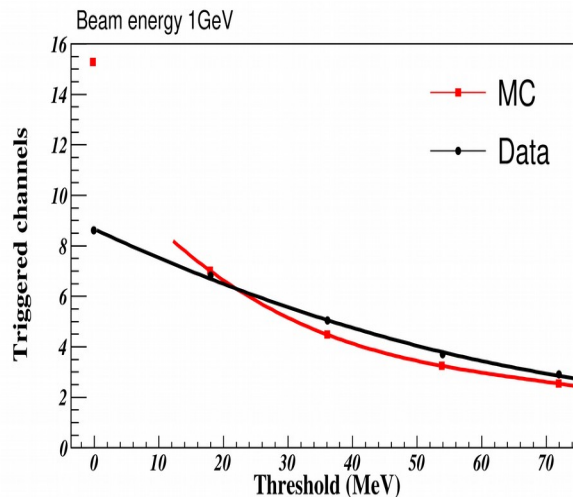


Figure 4.3.6: Triggered channels versus threshold.

The test was done to make a choice of the registration threshold for the DAQ electronics. Here the choice is a compromise between better energy resolution for the low threshold (Figure 4.3.5) and

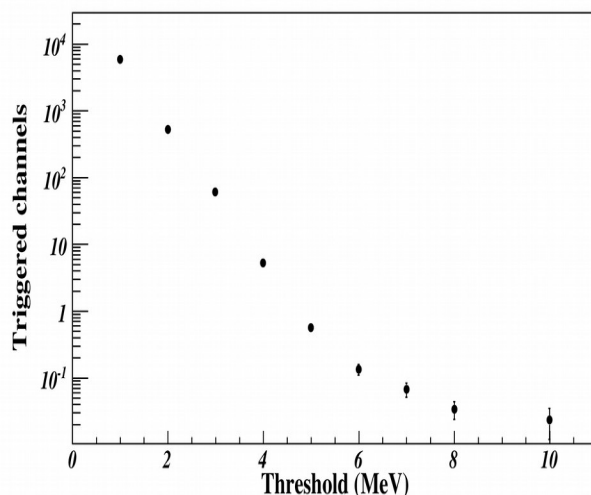


Figure 4.3.7: Number of noise channel per event for the whole ECal (40230 channels) versus threshold.

reduction of number of active channels per particle, reduction of data flow per events, reduction of

number of noise hits in the case of increase of the registration threshold (Figure 4.3.6). From the data shown in figure 4.3.7 we conclude that threshold in our case should be in the region 5-10 MeV. Further reduction of the threshold does not improve energy resolution too much, but increasing number of hits per shower a lot with all negative consequences.

Calorimeter responses to the incident muon. 0.5 GeV electron and 3 GeV electron are shown in the figure 4.3.8 and figure 4.3.9. Slightly wider spectra in the low energy region is seen here as it is follow from the figure 4.3.3.

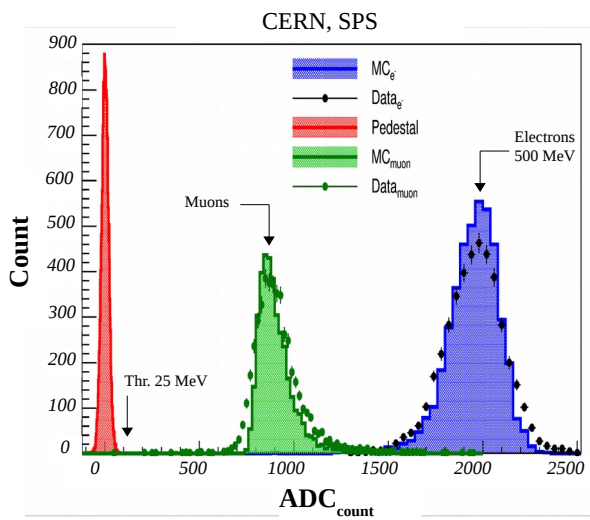


Figure 4.3.8: Signal spectrum for the pedestal, muons, electrons 0.5GeV.

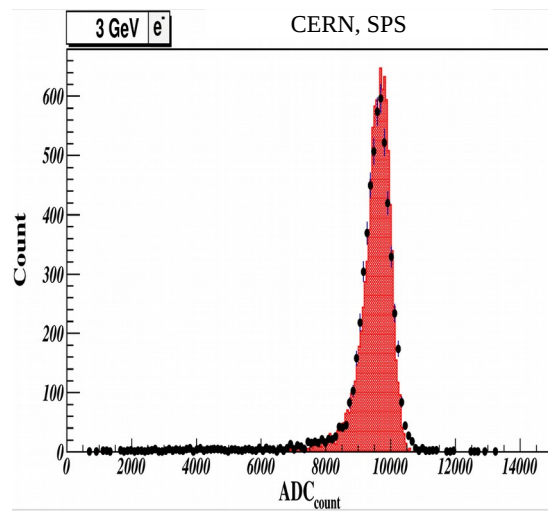


Figure 4.3.9: Signal spectrum for electrons 3GeV.

As it is clear from the figure 4.3.8 MIP energy deposition is much higher than the noise of electronics (pedestal) and such particles can be effectively restarted by the calorimeter. Electronics threshold clearly can be set below 25 MeV. To choose electronics threshold more precisely the special tests was done Figure 4.3.7. The time window in this test have been chosen quite wide - 5 time bins (100 ns). These tests is used to choose a compromise value of the threshold, low enough to obtain good energy resolution and high enough to reduce the number of triggered channels (both real and noise).

The calorimeter modules were tested on the beam of the Nuclotron in the installation of the BM@N. A scintillation counter has been used to allocate primary hadrons and their spectra are presented in figure 4.3.10 and figure 4.3.11. The background of the graphs is associated with the

inefficient allocation of primary hadrons. Despite considerable background data and MC agreement is quite good.

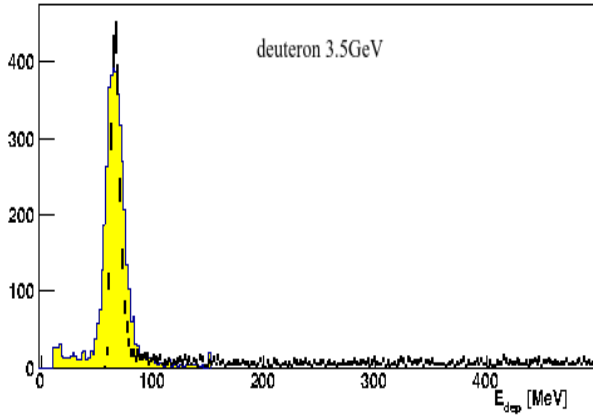


Figure 4.3.10: Detector response to deuterium.

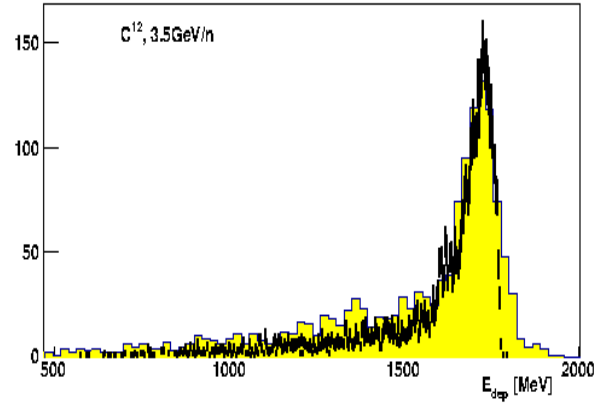


Figure 4.3.11: Detector response to C^{12} .

4.4 Time resolution

The tests of time resolution of the calorimeter using various type of electronics have been

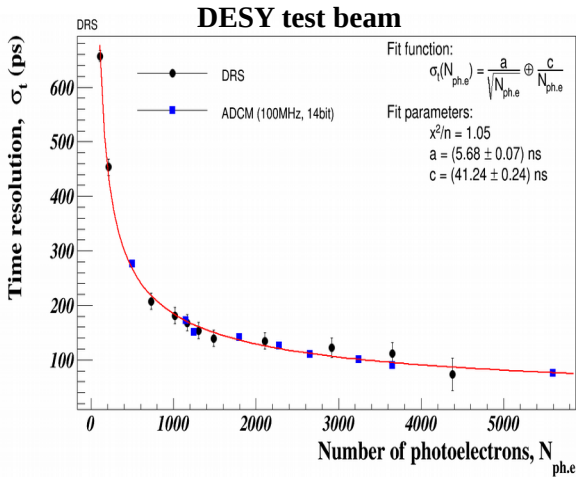


Figure 4.4.1: Time resolution vs number of detected photoelectrons measured with different methods and different electronics. Time bin: DRS -200 ps [36] and ADCM-10ns [37].

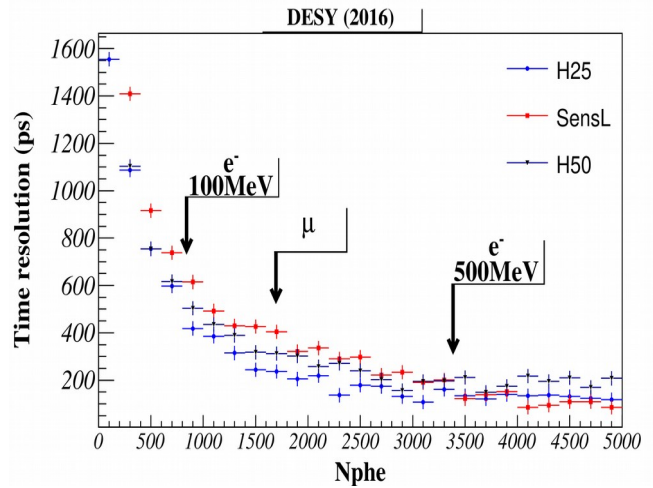


Figure 4.4.2: Time resolution vs number of detected photoelectrons of different photo-detectors.

performed. The results of previous studies (Figure 4.4.1 and Figure 4.4.2) have been confirmed . It is shown that the dependence of time resolution from the number of registered photoelectrons displays the properties of the calorimeter but not the effect of electronics channel. As a result we are expecting time resolution for the MIP on the level of 150 ps.

4.5 Coordinate resolution

Calorimeter prototypes tests done at DESY discovered another unexpected feature - sampling of proposed for MPD calorimeter allow quite accurate measure the position of electromagnetic shower. For the first time the possibility of precise measurements of coordinates of particles in the calorimeter was studied (Figure 4.5.1). It was shown that the response function of the calorimeter at coordinate is not linear. The deviation from linearity is very close to sinusoidal with zeros in the center and at the edges of the module (Figure 4.5.2). The possibility to correct this nonlinearity (Figure 4.5.3) and to achieve a coordinate resolution on level 4-1 mm (Figure 4.5.4) depending on the energy deposited in the electromagnetic shower have been demonstrated.

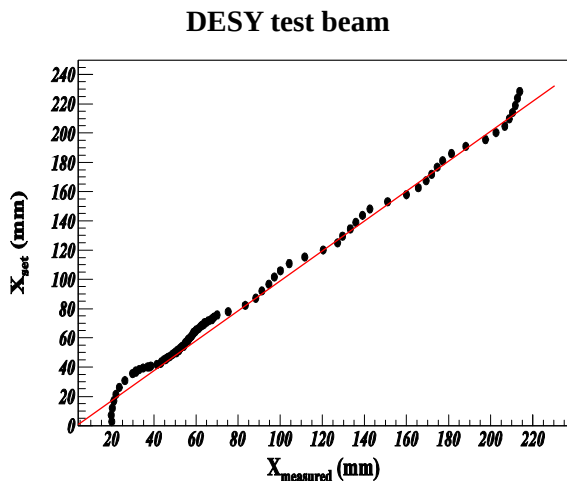


Figure 4.5.1: Correlation between set and measured coordinates.

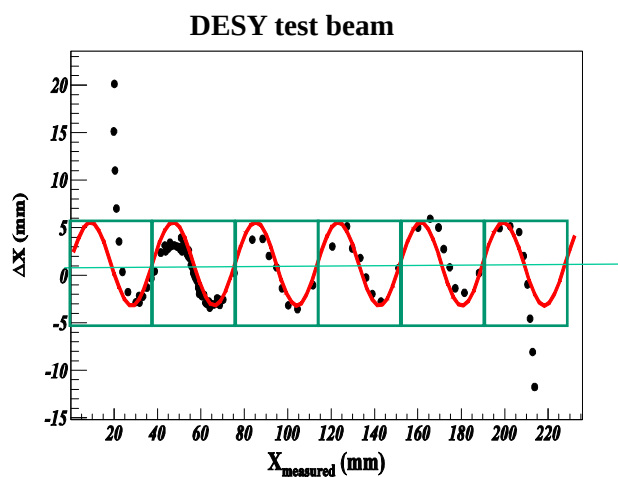


Figure 4.5.2: Deviation of the measured coordinates from the linear dependence.

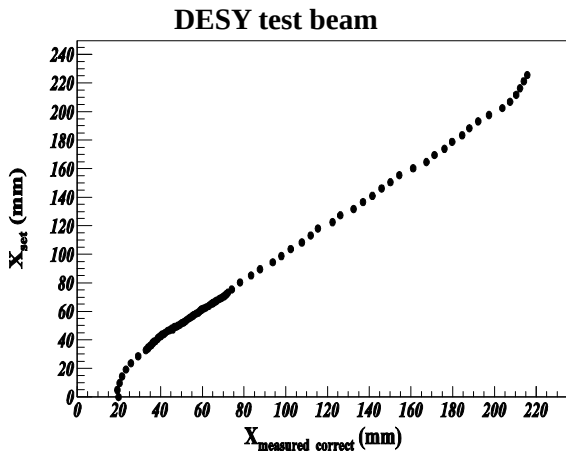


Figure 4.5.3: Correlation between set and measured coordinates – after corrections.

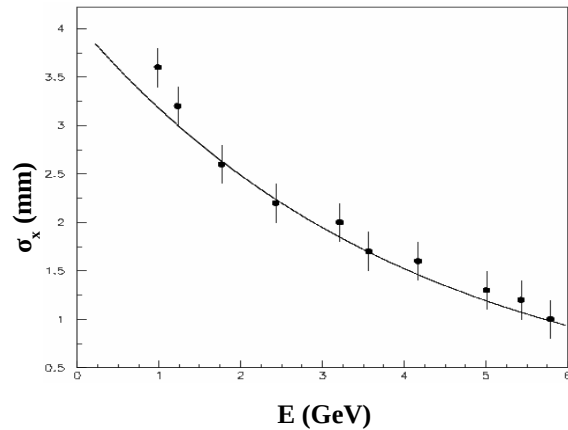


Figure 4.5.4: Space resolution versus energy of electromagnetic shower.

4.6 Heat extraction

Special attention we pay to the problem of heat extraction from the MPD barrel due to the possible influence of the mistakes in this operation on the operation not only ECal detector but also on the all detectors around. To verify the ideas which are placed in the basis of the ECal heat extraction system we have carried out tests with prototype of such system (Figure 4.6.1). Boards with resistors have been distributed along the ventilation duct to simulate the real electronics. Power supply is able to assure production of heat in the wide region, but for tests we have used current producing roughly twice more heat than it is expected in the real experiment. Temperature sensors was used to registrate with high accuracy temperature of the air on the input and output of the ventilation duct. One temperature sensor located far away from the heating part of setup was used as a reference, and one to measure the temperature of the outer wall of the ventilation duct. Air flow and pressure was steered through the electronic valves connected to the computer.

Results are shown on the figure 4.6.2 and figure 4.6.3 for two different intensities of air flow inside the ventilation duct. In both cases first 300 s the ventilation was not activated and temperature inside the ventilation duct was going up. After 300 s ventilation was activated an temperature starts to go down along all channel of ventilation. Minimal air flow through the one ECal sector which

guarantees normal conditions inside all duct is estimated 1000 l/min.

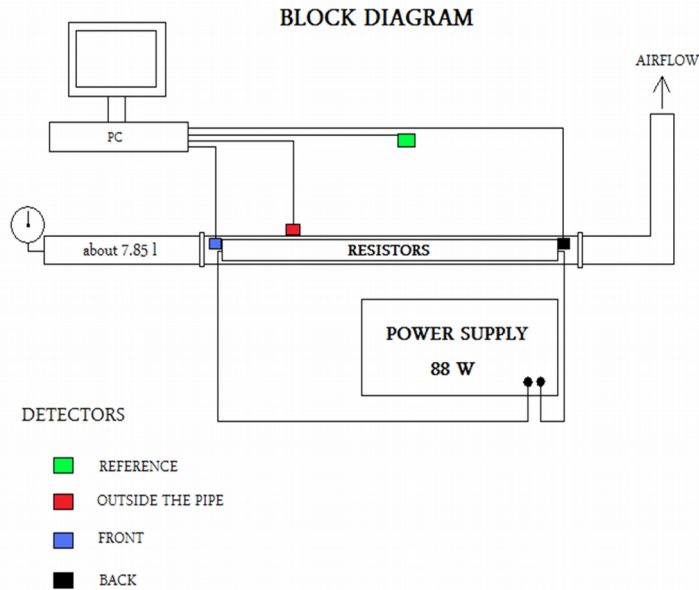


Figure 4.6.1: Prototype set up of hit extraction system.

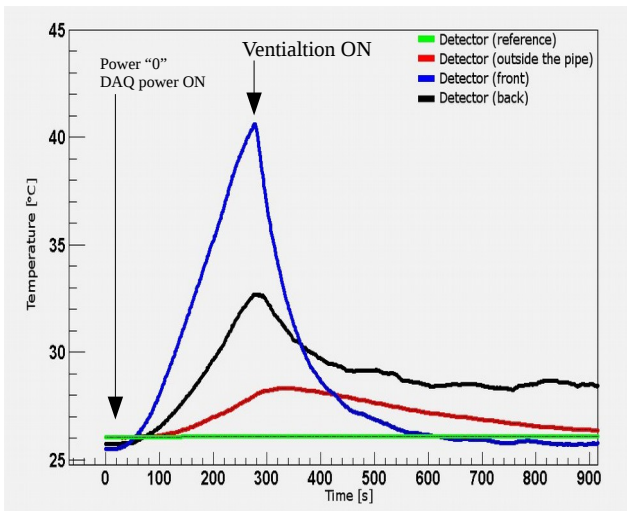


Figure 4.6.2: Temperature dependency in different points of test set up versus time. Slow ventilation (AirFlowVelocity 2 m/s = 16 l/s).

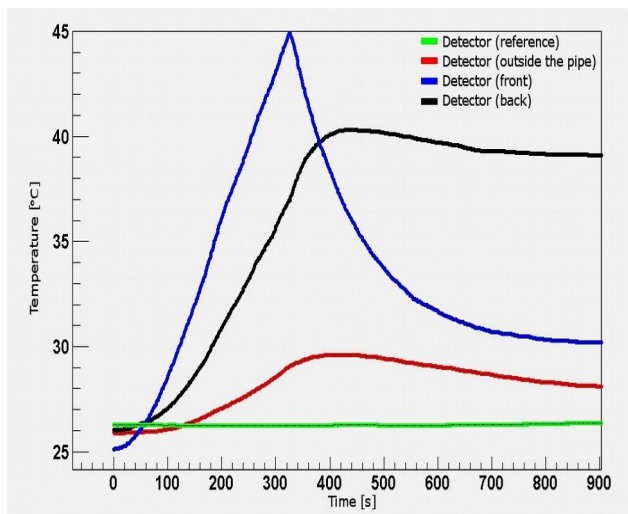


Figure 4.6.3: Temperature dependency in different points of test set up versus time. Faster ventilation (AirFlowVelocity 1.2 m/s = 9.6 l/s).

In the test set-up the size of the inlet pipe is about 4 cm². To have a guaranteed cooling and even some spare power in the cooling system size of inlet-outlet pipes can be increased up to 10 cm². This size easily fit dedicated to ECal space in the cable holes in the detector body.

R&D, Design, Prototyping	227.63	2010 - 2018
Production Cost	15 497.98	2016 - 2020
Infrastructure Cost	653.00	2016 - 2018
Total (k\$):	16 378.61	

. Reference

- [1] The MultiPurpose Detector – MPD to study Heavy Ion Collisions at NICA (Conceptual Design Report), Version1.4.
- [2] G. Trubnikov, A. Kovalenko, V. Kekelidze, I. Meshkov, R. Lednicky, A. Sissakian, A. Sorin, PoS (ICHEP 2010) 523.
- [3] G. Trubnikov, N. Agapov, V.Kekelidze, A. Kovalenko, V. Matveev, I.Meshkov, R. Lednicky, A. Sorin, PoS 36th International Conference of High Energy Physics (ICHEP2012), July 4-11, Melbourne, Australia.
- [4] V.Kekelidze, A. Kovalenko, R. Lednicky, V. Matveev, I.Meshkov, A. Sorin, G. Trubnikov, 37th International Conference on High Energy Physics, ICHEP 2014, Valencia, Spain, 2 Jul 2014 - 9 Jul 2014 Nuclear physics B Proceedings supplements (2014).
- [5] C. Alt et al, Phys. Rev. C77, 024903 (2008).
- [6] R. Rapp and J. Wambach, Adv. Nucl. Phys. 25, 1 (2000).
- [7] G.E. Brown and M. Rho, Phys. Rev. Lett. 66, 2720 (1991).
- [8] A. A. Anselm and M. G. Ryskin, Phys. Lett. B266, 482 (1989).
- [9] J.-P. Blaizot and A. Krzywicki, Phys. Rev. D46, 246 (1992).
- [10] G. Agakichiev et al. (CERES Collaboration) Phys. Lett. B 422 (1998) 405.
- [11] D. Adamova et al. (CERES Collaboration) Phys. Rev. Lett. 91 (2003) 042301.
- [12] G. Agakichiev et al. (CERES Collaboration) Eur. Phys. J. C 41 (2005) 475.
- [13] D. Adamova et al. (CERES Collaboration) Phys. Lett. 666 (2008) 425.
- [14] R. Arnaldi et al. (NA60 Collaboration) Phys. Rev. Lett. 2006. V.96. P.162302.
- [15] A. Adare et al. (PHENIX Collaboration) Phys. Rev. C. 2010. V.81. P.034911.
- [16] F. Geurts, Di-Lepton Physics Program at STAR. Quark Matter 2012 Conference.
- [17] R.J. Porter et al. (DLS Collaboration) Phys. Rev. Lett. 79 (1997). 1229.
- [18] A. Rustamov et al. (HADES Collaboration)} Int. Jour. Mod. Phys. A 26, 384.
- [19] J. Randrup and J. Cleymans, Phys. Rev. C 74 (2006) 047901.
- [20] D. Kharzeev, Phys. Lett. B633, 260 (2006).

- [21] Y. Burnier, D. E. Kharzeev, J. Liao, and H.-U. Yee, Phys. Rev. Lett. 107, 052303 (2011)
- [22] L. Adamczyk et al (STAR Collaboration), Phys. Rev. Lett. 114, 252302 (2015)
- [23] J. C. Dunlop, M. A. Lisa, and P. Sorensen, Phys. Rev. C 84, 044914 (2011).
- [24] J. Xu, L.-W. Chen, C. M. Ko, and Z.-W. Lin, Phys. Rev. C 85, 041901 (2012).
- [25]. T. Csorgo, Journal of Physics Conferences Series 50(1):259, November 2006.
- [26] D.K.Srivastava and J.I.Kapusta, Phys. Rev. C 48, 1335(1993).
- [27] A.Timmermann, M.Plumer, L.Razumov and R.M.Weiner, Phys.Rev.C 50, 3060(1994).
- [28] J.Alam, B.Mohanty, P.Roy, S.Sarkar and B.Sinha, Phys. Rev. C 67, 054902(2003).
- [29] I.Chirikov-Zorin et al, Part.Nucl., Lett 11(2014) 412-417
- [30] G. Atoian et al., Nucl.Instrum.Meth. A531, 467 (2004).
- [31] G. Atoian et al., Nucl.Instrum.Meth. A320, 144 (1992).
- [32] L. Aphecetche et al., NIM A499, 521 (2003).
- [33] S. Barsuk, in XI Int.Conf. Calorimetry in High Energy Physics, Italy, 2004.
- [34] D. Karlen et al., Nuclear Physics B 159, 91 (2006).
- [35] [http:// www.hamamatsu.com](http://www.hamamatsu.com)
- [36] <http://psi.ch/drs/>
- [37] <http://afi.jinr.ru/>