Design
of new detector for Hall A Möller Polarimeter

1 Introduction

The Möller Polarimeter of Hall A successfully operates since the middle of 1997 providing the measuring of beam polarization with accuracy up to 3-5% for resonable measuring time, near half-an-hour. At detector design the 8 lead-glass blocks are used, as elements of left and right arms godoscopes. Together with left and right aperture scintillation counters the detector device provides the measuring of Möller events in coincidence with counting rate upto 50-100 kHz, energy resolution near 12-14% and low background level and accidental coincidence rate at all energy range from 1 GeV to 4 GeV, near 1%.

However, some conclusion can be done from approximately one year exploitation period:

1) the using more high intensity beam currents is restricted not only by Möller target heating but by the effects of high counting rate - pile-up and overlooping;

2) the using standard lead-glass blocks with 8×8 cm^2 transverse dimension does not allowed to get a good spatial resolution along momentum dispersion direction and to increase the Möller event selection;

3) the lead-glass material is showing the visible radioactive damage ability, that can easy to destroy of Möller detector device in an accident with a wrong beam trip.

As result, for improvement of the Möller polarimeter detector parameters we suppose to redesign this device.

The following ways and requirements to the project were put forward:

1) to use the same shielding box and the same room space as for old detector version;

2) to use as detector blocks the spaggetti-type Pb-plastic scintillator calorimeters for electrons detection;

3) the increasing of detector counting rate upto 200 kHz by using of the fast scintillators and the fast photomultipliers (PM) in detector device;

4) at the same time the using plastic scintillator is able to increase the resistivity of detector to radioactive damage;

5) the increasing of the detector spatial resolution with using 5×9 cm^2 transverse dimension modules with short distance along dispersive direction;

6) the design of additional 5×9 cm^2 transverse dimension scintillation godoscope module with using 10 plastic scintillator with 0.5×0.5×9.0 cm^3 and position sensitive PM;

7) the design of additional device for remote positioning of single detector module with scintillation godoscope module upstream the main detector shielding box.

2 Review of prototypes

There are some types of non-glass electromagnetic calorimeters for high-energy facilities: three of them are a spaggetti- and a shashlik-calorimeters and a lead-scintillator sandwich calorimeter with wave-length shifter. Spaggetti- and shashlik-calorimeters are able to provide position resolution near 10.0 mm, angular resolution close to 100 mrad for 1 GeV electrons and energy resolution near 6-8%, but these versions of calorimeters are much more difficult in fabrication and assembling and resonable for using only in high spatial resolution devises (usually in 4π-detectors).

Sandwich-type electromagnetic calorimeters are more simple for fabrication and are using for forward endcap electromagnetic calorimeters (FEEC) [1,2] in high radiation detector areas. The FEEC is sampling electromagnetic calorimeter and consists from single modules with transverse dimensions 10×10 cm^2. The most careful investigation of single module is fulfilled at DESY for ARGUS detector at DORIS [1]. The same design was used for module of the Fermilab E760 electromagnetic calorimeter [2]. Then we will use the approachs and formulas published in [3] and [4].

The main conclusions that had be done from results simulation and testing of the electromagnetic calorimeter [3] are consist:

1) the total length of module has to be chosen near 15 radiation lengths of material that corresponds to a longitudinal shower containment in excess of 95% for 3 Gev energy electrons over this length;

2) for 1 GeV electron hitting the center of module predicted value leakage into neighboring module is equal 8-12%, predicted value for spatial resolution, averaged over the surface over module for the centroid of each shower is 3 cm in the transverse dimension;

3) the largest output for low energy electrons (near 100 Mev) was obtained with module of 6-to-1 volume ratio of scintillator to lead (1 mm thickness Pb, 6 mm - scintillator) and POPOP wavelength shifter (WLS) plate with thickness 6,4 mm;

4) the largest photoelectron (p.e.) yields at low energy 60 Mev is 23 ± 8 p.e. (or 383 p.e./GeV) and at energy 500 MeV is 255 ± 36 p.e. (or 510 p.e./GeV) with using Scintiplex III acrylic scintillator, National Diagnostic, 1013-1017 Kennedy Blvd., Manville, NJ 08835,USA;

5) the chosen scintillator and WLS are able pulse width ($\leq$50 ns) that reduces the dead time from high frequency (700 kHz) counting rate and are resistant to radiation damage from background;

6) nonlinearity in the energy range 1-3 GeV are no more a few percent.

The spaggetti-type radiator much more difficult in fabrication and demands the using complex technology approach, but fortunately the spaggetti-type material was used for calorimeter design created early at HaLL B for detector device. Two pieces of spaggetti-type Pb-plastic material are remained, one of them - the block with $121\times15.1\times9$ cm^3 dimension was borrowed for the new Möller detector device. This block was assembled with using rolled Pb-plates with semicircle channels and contained between every neighboring plates the raws of the thin 1 mm diameter plastic scintilator fibers along the detected particle trajectory. The Pb-material contains the Sb (6% in volume of Pb). All assembly is connected by glue in rectangular piece. The whole piece is cut to four equal blocks with dimension $30\times15.1\times9$ cm^3. The cut ends (front and back) are polished.

So we will represent some estimations and draft technical design for calorimeter modules of two type as elements of new Hall A the Möller polarimeter detector: sandwich-type and spaggetti-type ones.

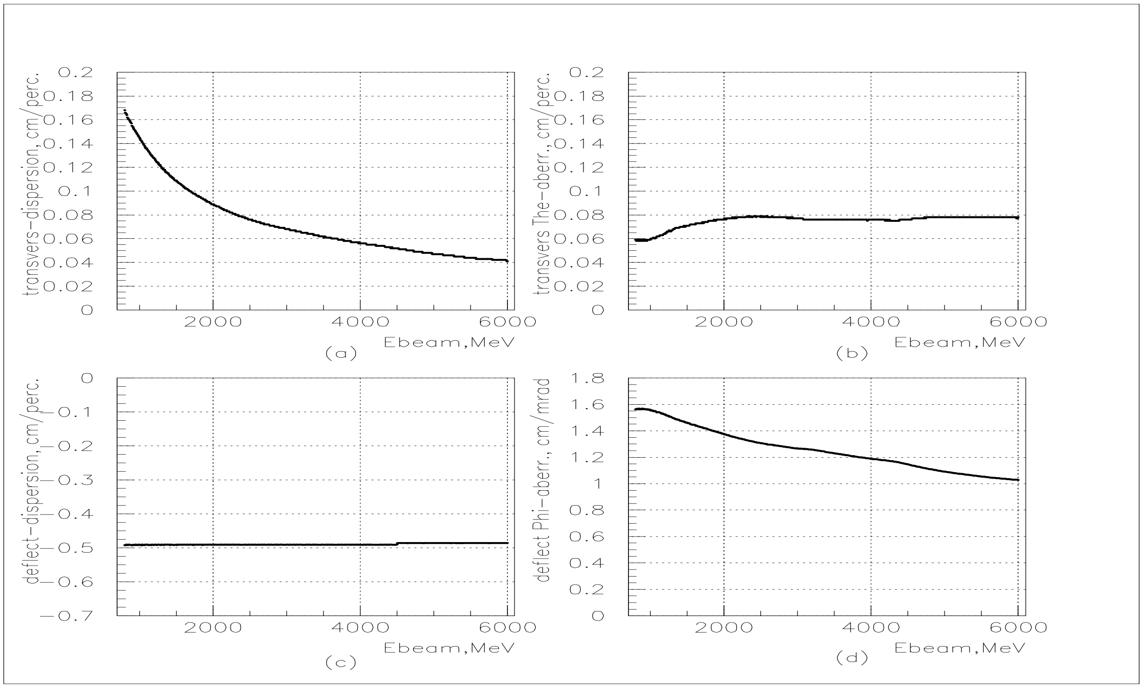

Fig.1,(a,c).The dispersion and ϕ-angle aberration in deflective direction of the detector plane for beam energy range 1.0-6.0 Gev.
(b,d).The dispersion and θ-angle aberration in transverse direction to the detector plane for beam energy range 1.0-6.0 Gev.

3 Choise of design parameterts (based on referenced sources)

The goal of design: two-arms calorimeter counters for Möller polarimeter. We need to detect pairs of Möller electrons with the energy at the range 0.5-3 GeV. Shower counters are the most optimized for this goal.

The main particularity of the Hall A Möller polarimeter design is a combination of the crossing magnetic fields of Quadrupoles and Dipole using for transport of Möller scattered electrons to the detector plane. The optical parameters of the complex magnetic system are simulated by RAYTRACE code, and the dispersion values in deflective dipole plane and in transverse direction together with θ- and ϕ-angle aberration, correspondingly, can be represented at fig.1(a-d).

From fig.1(a-b) we can see that values of the transverse energy dispersion and transverse θ-aberration are small, almost the same in values and the same in sign. On the other hand, $\mathrm{d}\theta^*/\theta^*$=-$\mathrm{d}E_e/E_e$, accordingly the Möller scattering kinematics.

As results quadrupole focusing fields in horizontal plane thank to some compensation of the transverse dispersion and θ-angle aberration in transverse direction to the detector plane almost at whole energy range we have nearly the full focus in the transverse direction to the detector plane, and the dispersion value near 5 mm/% in deflective direction. The expected typical energy resolution of designed shower counter has a value better than 8%. As a result we can choose for the module dimension along the dispersive direction in value 4-5 cm. In this case the dispersive energy resolution of a single module and the sampling resolution component of will be the same order in a value.

As usually, when we have a deal with electron (and photon) registration at high energy, it is convenient to measure the thickness of the material in units of the radiation length X_0. The values of X_0 for different materials are well known. For example, for Pb, C, H_2 and plastic scintillator (ρ for solid materials, correspondingly, 11.35, 2,27 and 1.032 g/cm^2) these values are 6.54, 42.70, 61.28 and 44.10 g/cm^2 (0.56, 18.8, 865 and 42 cm), correspondingly. The radiation length in a mixture or a compound may be approximated by

$$\frac{1}{X_0} = \sum \frac{f_i}{X_i}, \qquad (1)$$

where f_i and X_i are the fraction by weight and radiation length for ith element.

For the total radiation length of the composed structure as in sandwich- or or spaggetti-type calorimeters we can write

$$X_{tot}/X_0 = n \times \sum \frac{t_i}{X_i}, \qquad (1a)$$

where t_i and X_i are the partial thickness and and radiation length for ith element in an alloy, n - total number of the composite alloy.

The calculated values of the total radiation lengths for sandwich-type composed structures for different relations between thickness Pb (t_{Pb}) and plastic scintillator (t_{Ps}) alloys in mm are represented at Table 1.

Table 1.

t_{Pb}/t_{Sc}	X_0	t_{Pb}/X_0	t_{Sc}/X_0	N_i/X_0	$N_{tot}/12X_0$	$L_{tot}/12X_0$
mm/mm	g/cm^2	mm	mm	$alloy$	$alloy$	cm
1/6	9.3541	5.332	31.996	5.3	64	44.8
1/5	8.9138	5.399	26.992	5.4	65	38.9
1/4	8.4640	5.468	21.874	5.5	66	32.8
1/3	8.0026	5.540	16.618	5.55	66	26.6

The calculated values of the total radiation length for spaggetti-type composed material (35% of Pb and 65% plastic-scintillator fibers at volume) are listed at the Table 2. Addition Sb material is neglected in this calculation.

Table 2.

V_{Pb}/V_{Sc}	$\rho^{Sp}, g/cm^2$	${X_0}^{Sp}, g/cm^2$	${X_0}^{Sp}, cm$	$19X_0, cm$
0.35	4.643	7.269	1.565	30.0

The basic formula for calculation electromagnetic shower calorimeters are known. It is the formula for the mean longitudinal profile of the energy deposition in an electromagnetic cascade that is reasonable well described by a gamma distribution [5]:

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}. \tag{2}$$

As usually in describing shower behavior, it is convenient to use the scaling variables $t = x/X_0$ and $y = E_0/E_c$ so that distance is measured in units of radiation length and energy in units of critical energy. The maximum t_{max} occurs at $(a-1)/b$. As result the fits to shower profiles in different elements at wide energy range up to 100 GeV, the energy deposition profile are well described by high mentioned equation with

$$t_{max} = (a-1)/b = 1.0 \times (lny + C_i), \qquad i = e, \gamma, \tag{3}$$

where C_e= -0.5 for electron-induced cascades and C_γ= +0.5 for photon induced cascades and y - scaling factor is equal E/E_c with E_c - critical energy that for electron is given approximately by

$$E_c = \frac{800\ MeV}{Z + 1.2}. \tag{4}$$

Correspondingly,the E_c-values for H, C and Pb are equal to 800, 100 and 10 Mev approximately. The b value depends upon both Z and incident energy. The mean b value for carbon in interested energy range near 0.69 and near 0.4 for uranium (or Pb). For spaggetti-type composed structure (see Table 2) we can approximate Z^*=34, E_c=23 Mev, b=5. The some calculated profiles of energy deposition for the fixed construction parameters of the spaggetti-type calorimeter are shown at fig.2.

Measurements of the lateral distribution in electromagnetic cascades are shown in [6,7]. On the average only 10% of the energy lies outside the cylinder with radius R_M, where R_M is the $Moliere\ radius$, given by

$$R_M = X_0 E_S / E_C, \tag{5}$$

where E_S=21.2 MeV. The Molier radius in a material containing a weight fraction f_i of the element with critical energy E_{ci} and radiation length X_i is given

$$\frac{1}{R_M} = \frac{1}{E_s} \sum \frac{f_i E_{ci}}{X_i}. \tag{6}$$

For above mentioned spaggetti-type material we calculate for R_M-value 1.61 cm. About 99% is contained inside of $3.5R_M$ (5.64 cm), but at this radius and beyond composition effects become important and the scaling with R_M fails. For spaggetti-type calorimeter the material distrubution across the trajectory can be produce the chanalling effects, which are able to make worse the energy resolution value and decrease the $Moliere\ radius$ value. The distributions are characterized by a narrow core, and broaden as the shower develops. They are often represented as the sum of two Gaussians, and can be described with the function

$$f(r) = \frac{2rR^2}{(r^2 + R^2)^2}, \tag{7}$$

where R is a phenomenological function of x/X_0 and lnE [8].

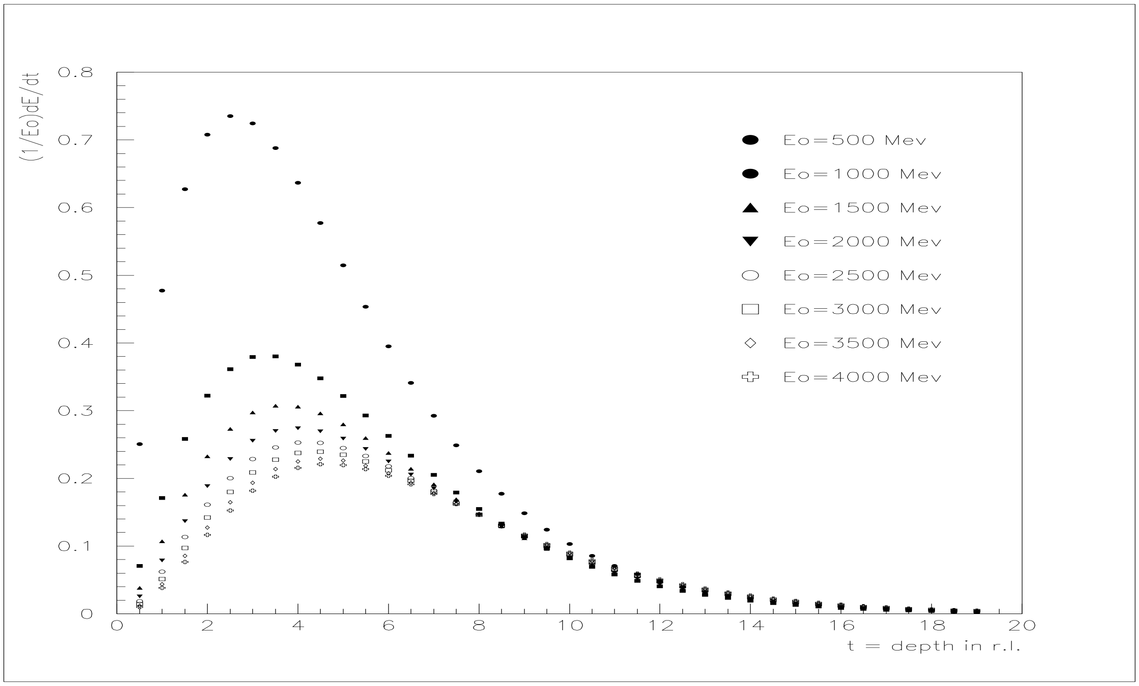

Fig.2. The energy deposition of electron induced shower for different particle energy in spaggetti-type material.

Energy resolution of sampling shower counter is determined by three components:

1) Due to leakage, mainly at the rear end, the total amount of energy deposited in the shower counter may fluctuate. An estimate of the energy spread E_L due to rear leakage is given by

$$\delta E_L \simeq \delta t (dE/dt)_{t_o}, \tag{8}$$

where $(dE/dt)_{t_o}$ is average energy deposited per radiation length at the rear end t_o of the counter, and δt is r.m.s. fluctuation of the shower center within the absorber in units of X_0. Since δt for electron (not for photon) is mainly determined by the length of calorimeter, we can take δt to be close to 0. Using a standard parametrization for (dE/dt) [3]

$$(dE/dt) = E_o A t^{\alpha} e^{-\beta t} \tag{9}$$

and ignoring the small (logarithmic) variation of α and β with the electron energy E_o, we obtain for energies near 1 GeV [3]

$$(dE/dt) = E_0 \gamma t^2 e^{\frac{-t}{2}} \tag{10}$$

with γ=0.063, or

$$\sigma_L = (\delta E_L / E_o) \simeq \gamma t_o^2 e^{-t_o/2} \tag{11}$$

For spaggetti-type calorimeter (t_o=19.0 r.l.) we calculate for σ_L-value 0.17%.

2) Fluctuation of the fraction of energy deposited in the scintillator. These sampling fluctuation depends on the size τ of one sampling step, i.e. the thickness of one lead-scintillator cell measured in unit of X_0. The ammount of these sampling fluctuations can de estimated by noting that the total track length L (in units of X_0) of particles in the shower,

$$L \simeq E_o/E_c, \tag{12}$$

where E_c is critical energy, is sampled in steps of τ, yeilding $N = (E_o/E_c\tau)$ crossings of particles through detection layers. The relative r.m.s. fluctuation of the energy seen in the scintillator is then

$$\sigma_S = \delta E_{scint}/E_{scint} \simeq N^{-1/2} = (\tau E_c/E_0)^{1/2}. \tag{13}$$

This value can be serious one for spaggetti-type calorimeter, where the mean sampling value can be estimated from relation of the *Molier radius* value equal to 1.61 cm and transverse sampling Pb-scintillator structure near 1 mm. But the complex regularity (almost continuious in radius) of this structure can be improve the situation. The correct calculation can be provided only by the careful simulation of electromagnetic cascades for real spatial distribution of spaggetti-type material.

The some corrections in this equation are small and can be neglected in the present case.

3) Noise is fluctuation of the signals from the detector layers. The most stringent limitation is due to the finite number of photoelectrons in the PM, yielding

$$\sigma_N = \delta E_N/E_0 \simeq (E_0\overline{n}^{-1/2}), \tag{14}$$

where $\overline{n}$ is the mean number of photoelectron per unit incident energy.

Combining all fluctuations, we obtain for the relative energy resolution

$$\sigma = \delta E/E_0 \simeq (\gamma^2 t_0^4 e^{-t_0} + \frac{\tau\varepsilon}{E_0} + \frac{1}{E_o\overline{n}})^{1/2}, \tag{15}$$

or, in terms of the normalized resolution

$$\sigma_0 = \sigma E_0^{1/2} \simeq (E_0\gamma^2 t_0^4 e^{t_0} + \tau\varepsilon + \frac{1}{\overline{n}})^{1/2}. \tag{16}$$

σ_0 is energy independent provided that leakage is negligible; at large energies, however, the leakage term dominates.

We can further estimate the position resolution of an array of calorimeter modules. In typical energies, the ammount of shower energy-leaking through a boundary at a distance y from the shower axis into a neighboring module can be approximated by [9]

$$E_L \simeq \frac{E}{2} e^{-y/a_o}, \tag{17}$$

with $a_0 \simeq 2$ cm. Assuming that the fluctuation of E_L is given earlier, we find

$$\delta x \simeq \frac{a_0\sigma_0}{E_0^{1/2}} e^{A/4a_0}. \tag{18}$$

In reality, δx will be somewhat larger, since due to correlation the fluctuation of E_L is increased as compared with sampling effects.

The design criteria for the counter modules are now obvious: the energy resolution at low energies is determined mainly by the thickness of the lead plates, $\tau \simeq \tau_{lead}$, provided that the scintillator thickness is chosen such that photoelectron statistics does not limit the energy resolution.

As a compromise between the size of the counters and the influence of leakage, t_0 should be chosen such that at high energy the term connected with leakage and sampling are of the same order of magnitude.

For the standard configuration of counter the varios terms contributing to total normalized resolution are of the following order of magnitude:

Sampling fluctuation $\sigma E^{1/2}=$ 5%GeV$^{1/2}$

Photoelectron statistics 3-4%GeV$^{1/2}$

(estimated using the known efficiencies for light collection, conversion,and transport to the photocathode)

Leakage fluctuations:

at $E_0 \simeq 1$ GeV 2%

at $E_0 \simeq 5$ GeV 5%

yielding $\sigma \simeq 6...7\%$ GeV$^{1/2}$ at low energies, and $\sigma \simeq 8\%$ at $E_0 \simeq 5$ CeV.

For the position resolution in transverse detector plane projection we expect that

$$\delta x \simeq b/E_0^{1/2} \tag{19}$$

with b of the order 0.5 cm. In the along detector plane projection we expect the best resolution is connected with 5 cm sample dimension in this direction.

4 Construction details

The Mӧller detector is sampling calorimeter detector. It consist of four rectangular blocks consisted from 2x6 separated detector volumes as shown in fig.3. The basic design of a single block can be seen at fig.4.

Each block consists of 90×150 alternative layers of acrilic scintillator fibers, separated by specially rolled 1 mm Pb plates which were glued in single assembly. The rolled lead plates and scintillator fibers

are spaced along the longitudinal dimension of a block. All scintillator fibers are 1.0 mm diameter, the fraction of Pb at volume 35%. Resulting active length of the block of 30 cm (20 radiation lengths).

All block-assembly is packed in two rectangular semiboxes ($9 \times 15.1 \times 60$ cm^3), that provides structural support of a spaggetti-block, three light quides and three photomultiplier to total assembly.

All four blocks, assembled as 6 single detectors modules from each sides are supported by a stainless steel plate (2.5 cm thickness) located in a median plane of the dipole magnet inside the detector shielding. The connection of stainless steel plate to support plate of the shielding gorizontal translator provides the possibility of alightment of the calorimeter assembly relatively of the median plane and of the detector collimator.

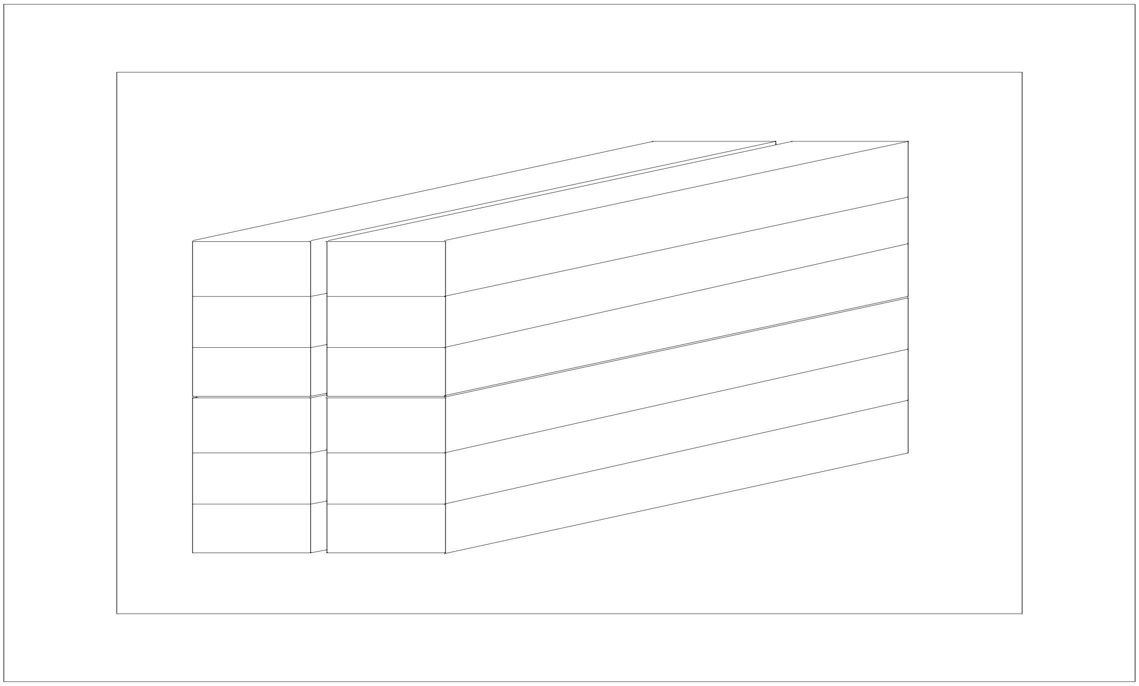

Fig.3. Schematic drawing of the construction of a spaggetti-type detector consisted from four separate modules each with three detector chanels.

5 Test Module

The Test Module Assembly (TMA) is used for investigation of the position sensitivity and energy resolution of the standard Möller detector block. The design of the TMA the same as of standard module. TMA consists from a single standard module with (15.1x9 cm^2) assembled transverse dimension. Only one middle zone with transverse dimension 5×9 cm^2 is connected through the air light guide to 3 inches diameter PMT Hamamatsu R3036.

This module was tested in cosmic run with using two apperture scintilation counters placed at top and under bottom spaggetty-type block with spatial acceptance 5×10 cm^2 each. The cosmic muon trajectories were directed vertically accross the wide side spaggetty-block at the block center. The estimated thickness material is equal 42 G/cm^2. The corresponding thickness scintillator fiber is equal 6 G/cm^2. It corresponds to 12 Mev deposited energy of a relativistic muon. The run time was equal near 60 hours. The resulting amplitude spectra is shown at fig.5. We have for σ-value approximately 17%. If suppose that for electromagnetic cascade with total energy value 1 GeV the dissipated energy at scintillator fibers will be equal 160 MeV, we can expect the 3-4 times best σ-value. The pessimistic evaluations can give the expected energy resolution near 6-8%.

At front TMA the special designed position sensitive scintillation aperture counter (PSAC) will be placed. The active elements of PSAC consist from a raw of the sixteen of rectangular scintillators $0.5\times0.5\times12$ cm^3 placed with plane in perpendicular to hitting electron direction.

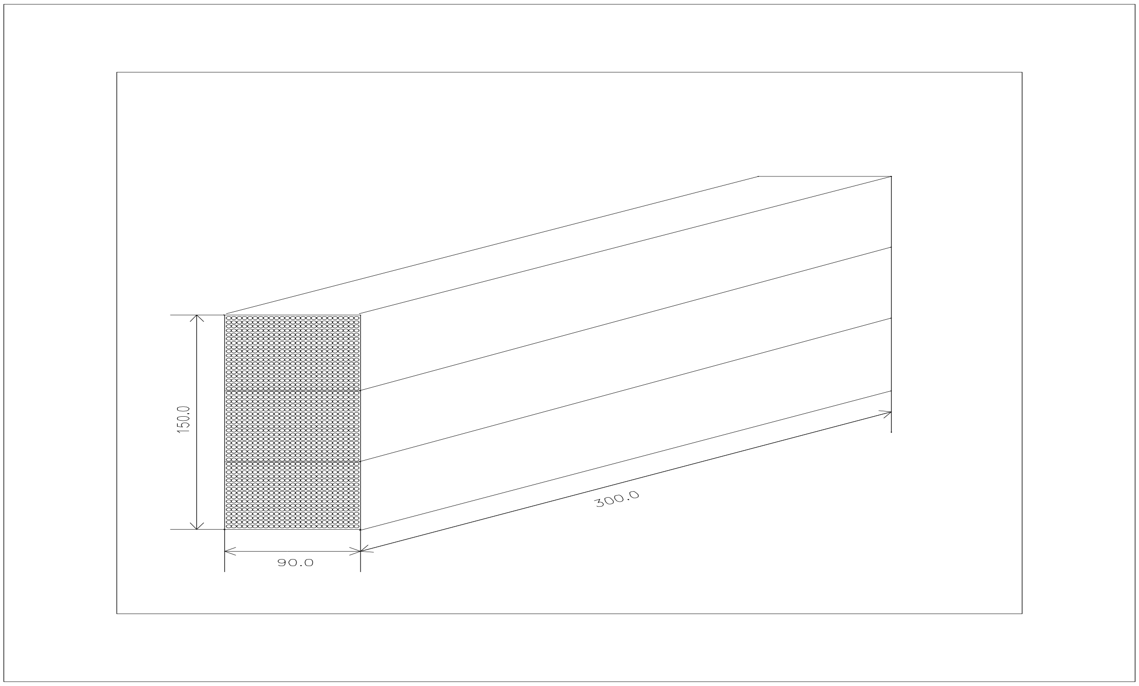

Fig.4. Schematic drawing of the construction of a single spaggetti-type module with three detector chanels.

All scintillators are glued to adiabatic lucite light guides and connected with a Position Sensitive PM Hamamatcu H6568 (3×3 cm^2). Sensitive area with 1.8×1.8 cm^2 has 4×4 Multi-anode. The PM gain 5×10^5 suplies the 100 mV pulses for relativistic electrons. Special remote translation device is able to place TMA with PSAC at front the main detector shielding box in the left arm position.

6 References

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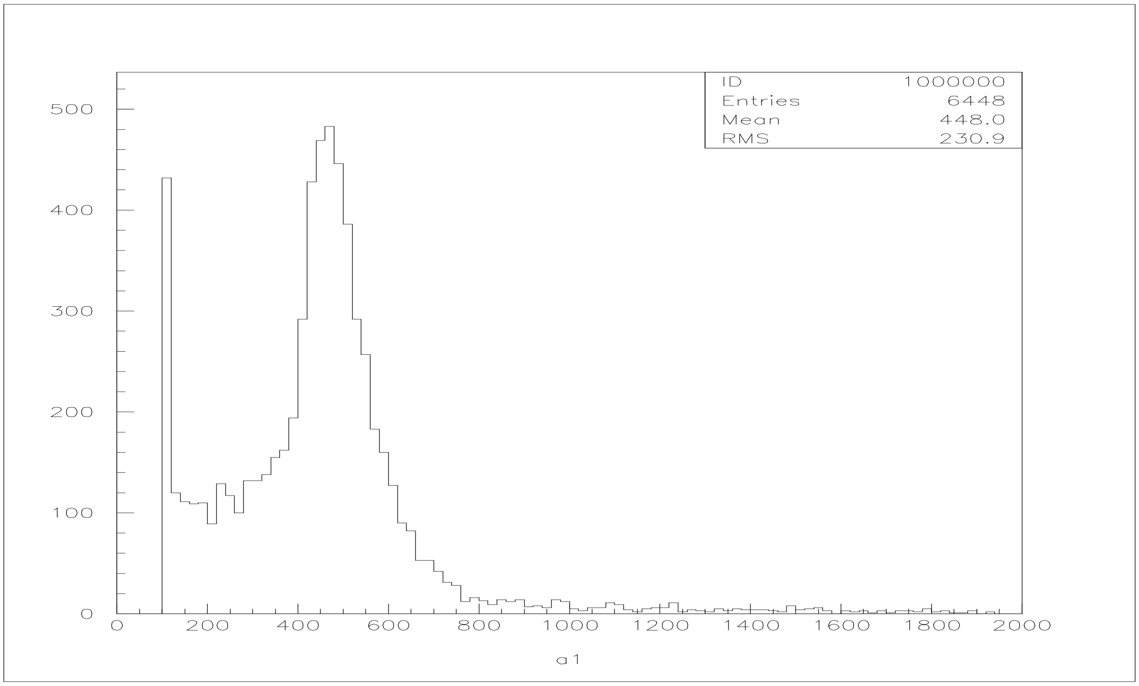

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Fig.5. Amplitude spectra from Test Module as result of Möller electron measurement in beam line position before Möller detector shielding box. E_0=2000 MeV.

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