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CALORIMETER FOR DETECTION OF HADRONS IN THE ENERGY RANGE 10–100 GEV

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Калориметр для регистрации адронов с энергиями 10–100 ГэВ

Описан калориметр, предназначенный для регистрации адронов в интервале энергий 10–100 ГэВ в эксперименте NA58 (COMPASS), ЦЕРН, цель которого — изучение структуры нуклонов и спектроскопия очарованных частиц. Калориметр состоит из 480 модулей, имеющих поперечное сечение 15×15 см и собранных в матрицу $4{,}2 \times 3$ м, с прямоугольным отверстием в центре $1{,}2 \times 0{,}6$ м. Каждый модуль содержит 40 слоев железо–сцинтиллятор, полная толщина которых 4,8 ядерных длин взаимодействий. Энергетическое разрешение калориметра для адронов (пионов) и электронов, а также пространственное разрешение были определены на тестовых пучках и составляют $(\sigma_\pi(E))/E = (59{,}4 \pm 2{,}9)/\sqrt{E} \oplus (7{,}6 \pm 0{,}4)\,\%$; $(\sigma_e(E))/E = (24{,}6 \pm 0{,}7)/\sqrt{E} \oplus (0{,}7 \pm 0{,}4)\,\%$; $\sigma_{x,y} = (14 \pm 2)$ мм соответственно, где E выражается в ГэВ. Среднее значение отношения e/π, характеризующего амплитудные отклики калориметра при регистрации электронов и пионов одинаковой энергии в указанном диапазоне энергий, равно $1{,}2 \pm 0{,}1$.

Работа выполнена в Лаборатории физики частиц ОИЯИ.

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Gavrishchuk O. P. et al. D13-2004-186
Calorimeter for Detection of Hadrons
in the Energy Range 10–100 GeV

The calorimeter for hadron detection in the energy range 10–100 GeV is described. It is used at CERN in the experiment NA58 (COMPASS) designed to study the nucleon structure and charmed particle spectroscopy. The calorimeter consists of 480 modules (15×15 cm in cross section, 4.8 interaction lengths) assembled in matrix 4.2×3 m with a central hole of 1.2×0.6 m. The energy resolutions of the calorimeter for hadrons (σ_π) and electrons (σ_e) as well as coordinate resolution ($\sigma_{x,y}$) have been determined in the test beams to be $(\sigma_\pi(E))/E = (59.4 \pm 2.9)/\sqrt{E} \oplus (7.6 \pm 0.4)$, $(\sigma_e(E))/E = (24.6 \pm 0.7)/\sqrt{E} \oplus (0.7 \pm 0.4)$, $\sigma_{x,y} = (14 \pm 2)$ mm, respectively. The average ratio, characterizing the amplitude responses of the calorimeter to electrons and pions, has been measured to be $e/\pi = 1.2 \pm 0.1$. The calorimeter is used to measure hadron energy and as element of the COMPASS trigger system. The calorimeter has been working stably during the long COMPASS runs with characteristics close to those determined in the test beams.

The investigation has been performed at the Laboratory of Particle Physics, JINR.

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INTRODUCTION

The hadron calorimeter described below is used in CERN experiment NA58 (COMPASS) [1], designed to study the nucleon structure and spectroscopy of charmed particles by using the polarized μ^+ and hadron beams in the energy range $100-300$ GeV. The muon program includes, mainly, studies of the gluon polarization in nucleons via measuring asymmetries in the production of charmed mesons $D^0 \to K^-\pi^+$ and $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$ on the longitudinally polarized deuterons or in the production of the high-p_t hadron pairs, momentum distributions of quarks in transversely and longitudinally polarized nucleons, $\Lambda(\bar{\Lambda})$ polarizations in DIS and other reactions. The hadron program includes searches for glueballs and hybrid quark–gluon states at the level above the world standards, observations of double-charmed baryons, studies of the semileptonic decays of charmed particles and other processes. Both programs require detection of the secondary hadrons.

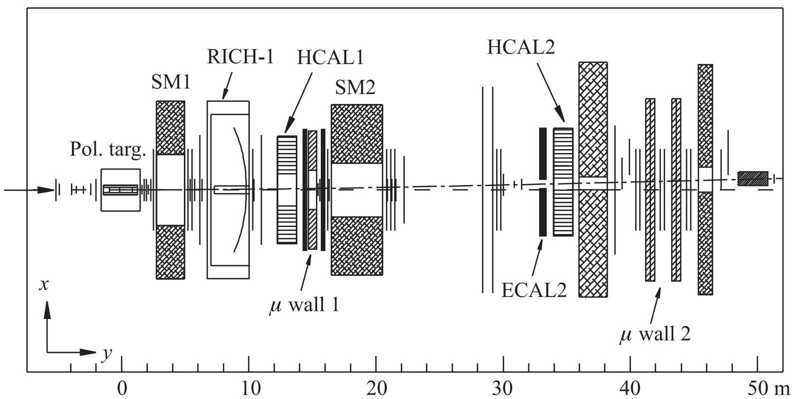

Fig. 1. The lay-out of COMPASS

The lay-out of COMPASS is shown in Fig. 1. It is a double-arm forward spectrometer. Each part of it is equipped with a magnet (SM1 and SM2), a system of tracking detectors, shown by vertical lines, and detectors identifying the secondary particles: electromagnetic (ECAL1 and 2) and hadron (HCAL1 and 2) calorimeters, muon detectors (μ walls 1 and 2) and Cherenkov counters (RICH1 and 2)*. Description of the HCAL1 is the aim of this paper.

*ECAL1 and RICH2 have not been installed yet.

The HCAL1 is placed (see Fig. 1) in front of the muon detector μ wall 1. It carries out a double task in COMPASS: measures the hadron energy and participates in COMPASS fast triggers enhancing the number of events with presence of hadrons in the final states. For both purposes a modular structure of the calorimeter is preferable. To reach the goals defined in the proposal [1], HCAL1 should have rather a good energy resolution for hadrons of the order of $\sigma_\pi(E) \approx 80\%/\sqrt{E}$ and coordinate resolutions of the order of $\sigma_{x,y} \approx 15$ mm. It should also stand a rather high counting rate $10^5 - 10^6$ s^{-1} per module.

The paper is organized as follows: Sec. 1 briefly outlines the simulations of the calorimeter; Sec. 2 describes the structure of the calorimeter and its modules; Sec. 3 presents studies of the calorimeter in the test beams; the system of the calorimeter control is described in Sec. 4; in Sec. 5 the performance of the HCAL1 in COMPASS during the runs is described; in Sec. 6 its participation in the trigger is illustrated.

1. SIMULATIONS

The HCAL1 is a sampling calorimeter with iron and scintillating plates, in which photonuclear cascades initiated by primary hadrons are developed. Part of the cascade energy transformed in the light is detected by a photomultiplier (PM). The sum of all PM amplitudes is proportional to the total energy losses in the calorimeter matter, i.e. to the energy of the primary particle if it is fully absorbed.

Simulations of the calorimeter, consisting of 40 layers of iron and scintillator 20 and 5 mm in thickness, respectively, have been performed by Monte Carlo method using GEANT [2] and GCALOR [3]. The energy resolutions for electrons and hadrons, coordinate resolutions and ratio e/π, have been calculated in the energy range 10–100 GeV and reported in the corresponding places below. Simulations have also shown that hadrons are almost fully absorbed in this calorimeter.

2. THE STRUCTURE OF THE CALORIMETER

The structure of the calorimeter and its modules have been chosen taking into account requirements of the NA58 experiment, the experience gained during construction of other calorimeters [4–7] and results of simulations. The general scheme of HCAL1 is shown in Fig. 2.

The calorimeter modules were assembled and framed in matrix 28 (horizontal) $\times$ 20 (vertical), out of which 12 modules were removed from each corner. At the center of matrix, there is a rectangular window of 8×4 modules. The outside dimensions of the calorimeter are 4.2×3 m and a useful surface, excluding window is 10.8 m^2. The window has no supporting elements which could be sources of additional background due to interactions in them of particles originated from the target. Over the window there is a bridge built of 4×10 module layers. The modules of these layers are fixed in the front and rear parts to the steel plates ($15\times145\times1490$ mm) producing single units resting on the side modules of the window (shadowed in Fig. 2). Calculations and tests have shown that under a load of 6 t the sagitta of the bridge is of the order of 3 mm. To prevent shifts of

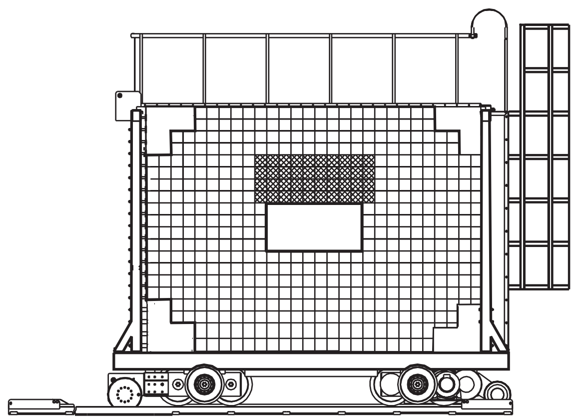

Fig. 2. The general scheme of the HCAL1 and platform

the side window modules inside the window, they have been fixed to the frame by aluminum strips 5×40 mm in cross sections. The calorimeter and its frame are mounted on the platform which can be moved on rails in and out of the beam for technical services. The movement of 80 t platform with calorimeter is performed by means of special mechanism and remotely controlled electric motor. The range of movement is ±2.5 m with respect to the beam axis, and precision of the remote stops is ±2 mm, while the speed of movement is 15 cm/min. The HCAL1 platform is placed on another platform, common for the ECAL1 and HCAL1, which can be moved along the beam axis.

The structure of the calorimeter module [6] is shown in Fig. 3 and its basic characteristics are summarized in table.

The iron and scintillator plates and a light guide are placed in a rectangular container with a cover made of the 1.4 mm steel. The scintillator plates are placed between the iron plates freely but tightly. To reinforce the structure, six of the regular iron plates are fixed to the container by screws and the first and the last plates are welded to it. The rear plate has a hole for an optical connector and a removable part with the space for the light guide, which allows one to take it out without disassembling the module. The steel cylinder with the 5-mm-thick wall containing the PM and its high-voltage divider is also fixed to this part. The

PM is additionally shielded against the magnetic field with the three permalloy cylinders, each 0.1 mm thick, isolated from the steel cylinder by dielectric rings. The steel and permalloy cylinders reduce the magnetic field by a factor of 10 (100) in the longitudinal (transverse) direction.

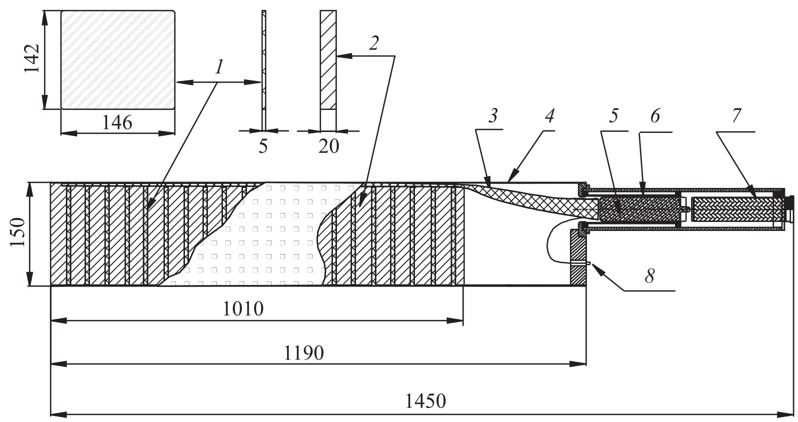

Fig. 3. Structure of the HCAL1 modules: *1* denotes scintillators; *2*, iron plates; *3*, light guide; *4*, container; *5*, PM; *6*, magnetic shielding; *7*, Cockroft–Walton divider; *8*, optical connector

The basic technical characteristics of the HCAL1

Active area	10.8 m^2
Number of modules	480
Number of iron/scintillator plates in a module	40
Thickness of iron plate	20 mm
Thickness of scintillator plates	5 mm
Plate cross section	142×146 mm
Length of light guides	1200 mm
Active length of light guides	1050 mm
Thickness of light guides	3 mm
Active length of a module	1000 mm ($4.8\lambda_{\rm int}$)
Total length of a module	1450 mm
Weight of a module	150 kg
Total weight of calorimeter with platform	80 t

The resolution of the sampling calorimeter depends on technology and quality of production of the scintillators, light guide and PM.

The scintillators should have the high light output, uniform light collection over the volume and high radiation resistance [7] during the long-time operations.

Scintillators of the HCAL1 have been produced by molding under pressure from the granulated polystirol PSM-115 mixed with P-terphenyl (1.5%) and POPOP (0.04%) [8]. They have the radiation resistance of about 1 Mrad. The attenuation length of the scintillating light in the plates, which have a maximum of wavelengths at about 420 nm, was measured to be 60 ± 10 cm [8].

In the HCAL1 modules, the scintillating light, exiting directly or after reflections through one of the side surfaces, is collected by the light guide and directed to the PM. To improve the light collection and make it uniform over the plate's surface, the part of it (1/3), which is close to the light guide, has been masked by black paper and the rest of the surface by the aluminized mylar. As a result, the measured uniformity of the light collection over the plate surface became about 5% [8].

The light from scintillators collected in the HCAL1 modules by means of a single flat light guide placed directly on the open sides of scintillators via two nylon fiber spacers $0.6-0.8$ mm thick. These spacers keep a constant gap between scintillators and light guide and prevent it from mechanical damage by iron plates. The light guides are fabricated from the organic glass CO-95 or CO-120 and painted over the surface by cumarin K-30 solved in alcohol. It reemits the scintillating light into the light with a greater wavelength and greater attenuation length in the light guide. The active part of the light guide (1050^{+50} mm) was painted only. The thickness of the paint varied between 5 and 20 μm to guarantee uniform light transmission over the light guide length. The unpainted part of it was adiabatically transformed to the PM photocathode size. The whole light guide was covered by aluminized mylar minimizing the losses of the light. As a result of all these measures, the amount of the light emitted and collected from a single scintillator, traversed by a minimum ionizing particle, was enough to produce 4–6 photoelectrons at the PM photocathode.

The 12-cascade Russian PM of the type FEU-84-3 was used in the HCAL1. It has a multisodium photocathode with a maximum of quantum efficiency 0.18–0.26 at the wavelength 460 nm, possesses a large dynamic range (100) and can operate with the average current up to 5 mA. The PM belongs to the spectrometric class with a typical pulse rise time 15–18 ns and full width of the pulse 40–50 ns at the level 0.1 of its amplitude.

Instead of high-voltage (HV) power supply and resistive divider of tensions for the PM dynodes, in the HCAL1 module a single unit (divider) is used, which generates the dynode tensions from the basic tension of 100 V using the Cockroft–Walton voltage multiplication scheme [9]. This type of the HV source for PM does not require expensive commercial HV power supply and HV cables. The principle scheme of the divider is shown in Fig. 4 [10].

Its parameters are the following:

— range of output voltage: 2–1700 V;

— low voltage: ± 6 V (20 mA, 5 mA);

— basic voltage: 100 V (0.2 mA without PM current);

— generator frequency: 15 kHz;

— variation of the output voltage: 1–2 mV.

The divider is assembled on the printed board which is connected to PM base and has connectors for anode and control signals. It is compact, requires low current and provides stable tensions ($\sim 10^{-4}$) at PM current up to 2 mA and rates up to 10^6 s^{-1}.

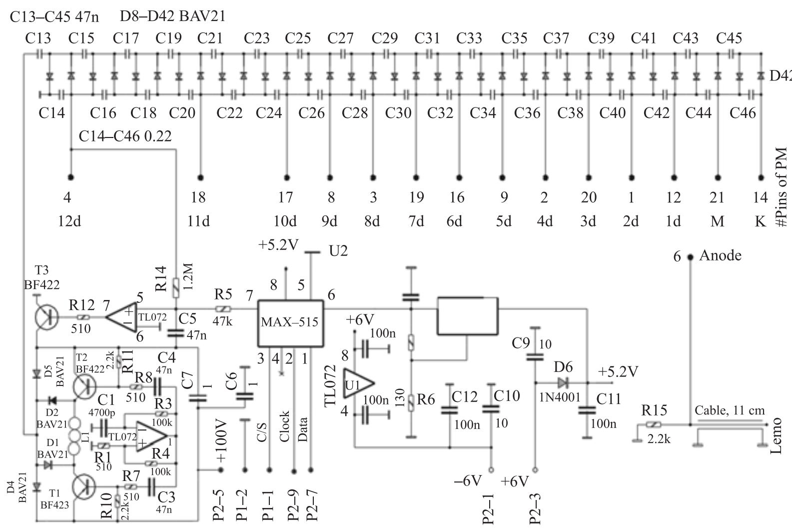

Fig. 4. The scheme of the PM HV divider

To minimize the influence of external electric and magnetic fields on the divider performance, it is placed inside two steel tubes isolated from each other by brass rings. The outer tube is fixed to the removable part of the rear wall of the module's container. By means of spring, placed between the tubes, PM with divider is pressed to the light guide.

The electronics of the calorimeter HV system consists of two parts (see diagram in Fig. 5):

— electronics providing voltage for dividers,

— electronics providing remotely controlled distribution of voltage between calorimeter modules.

The remote control block is made in the CAMAC standard and placed in the experimental hut at about 100 m from the calorimeter.

The electronics providing and distributing voltage between dividers is assembled in the CAMAC crate fixed to the HCAL1 platform. In this crate there are:

— block of Data Receiver accepting signals from the remote control,

— block of the horizontal line selection (C/S),

— seven blocks of data (D1–D7) with addresses of the vertical lines to transmit tensions to the dividers,

— block providing the basic tension 100 V.

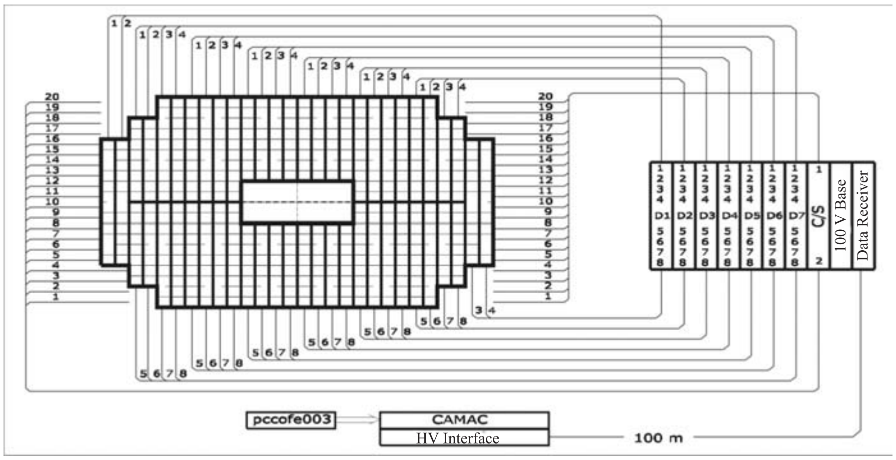

Fig. 5. The diagram of the HV supply of the calorimeter: D1–D7 denote the blocks of data; C/S, block of the horizontal line selection; 100 V Base, the source of basic tension; Data Receiver block; pccofe003, computer; HV Interface, remote control

The ±6 V for dividers is also taken from this crate. The transmission of the data is performed with a consecutive 10 bit code. Data and tensions are delivered to dividers via 5-pair flat cables to the connector P2 (see Fig. 4). One block of data contains 8 subaddresses; to each of them 6–12 dividers are connected in parallel.

Block C/S selects the horizontal line, on which a given module and its divider are placed. This block has 48 outputs addressed via CAMAC W1–W6 lines. Only 40 outputs are used because the calorimeter was divided in two parts (left and right), each consisting of 20 horizontal lines.

All HCAL1 modules with respect to HV supply of PMs are combined in 20 horizontal and 7×4 vertical groups. The control and regulation of tension are performed for the module at the cross-over of the horizontal and vertical lines. The tension codes are transmitted via vertical lines while selection codes are transmitted via horizontal lines.

The HV system of PMs is equipped with a security system using optotrons 6N138 for groups of 6–12 modules. The security system turns off the ±6 V when the corresponding current exceeds 20 mA. The security system is controlled by the computer via the program of HV supply. This program sends an alarm signal showing suspected modules at the screen of monitor as red boxes. If it happens accidentally and does not relate with major damages of dividers, the tension can be restored remotely via computer.

The block of basic tension 100 V is assembled in the CAMAC module of the 8-station width and has 10 independent outputs (7 used, 3 spare) with 120 mA maximum current in each of them. This block can work only when ± 6 V is present. The rise of tension at each divider takes about 40–50 s. If the current accidentally rises above 120 mA, the security system turns the block off. The front panel of the block contains microswitches and indicators on/off for each channel, a digital voltmeter, switches and terminals to measure tensions and currents. There is a plug at the rear panel of the block to connect it to the slow control system of COMPASS.

The HV is delivered to the PMs in 3 steps: first, after switching on the CAMAC crate, the dividers are supplied with ± 6 V, second, the source of basic tension 100 V is put on, and third, the required tensions are set remotely via computer and HV program.

3. STUDIES OF THE CALORIMETER IN THE TEST BEAMS

The main characteristics of the calorimeter — calorimeter linearity vs. energy, energy and space resolutions — have been determined at CERN using the hadron (pion) and lepton negative test beams with fixed energies in the range 10–100 GeV. To reach these goals, first of all, the calorimeter should be calibrated.

A procedure, which we call «calibration», includes determination of normalization coefficients for the module amplitudes and determination of the correspondence between the amplitude value in terms of ADC and the particle energy.

In general, the energy of the hadron detected by the calorimeter is determined as

$$E = K_E \sum_{1}^{n} a_i k_i, \tag{1}$$

where n is a number of modules detecting the part of the photonuclear cascade energy; a_i is an amplitude of i module in terms of ADC channels after pedestal subtraction; k_i is a relative coefficient of the amplitude normalizations obtained as a result of calibration; K_E is a coefficient of the absolute energy to ADC channel correspondence. This coefficient is determined by dividing the value of the test beam energy by the number of the ADC channels corresponding to the maximum of the ADC spectrum recorded at this energy.

For the test beam studies we have used a calorimeter consisting of 25 modules assembled in $5{\times}5$ matrix and placed on the remotely movable support. The support can be moved horizontally (x) and vertically (y) and x, y coordinates of the modules can be determined with precision of ± 1 mm. The read-out of the signal amplitudes from the modules was triggered by coincidence of two scintillating counters, two multiwire proportional chambers and two gas Cherenkov counters placed at the beam line upstream of the modules. The amplitudes were registered by ADCs with a linear scale up to 4096 channel. These ADCs [10] have been designed on the basis of the Lecroy MQT200 chips.

The calibration procedure consisted of two steps. At the first one, each module of the 5×5 matrix was irradiated with a beam, and coefficients k_i were determined normalizing the maxima of amplitude spectra to that of the central module. At the second step, the spectra of amplitudes from all the modules were measured during passage of leptons or hadrons through the central module of the 5×5 matrix. All the information was written on the tapes and analyzed offline to obtain the energy deposition spectra. To transform the amplitude spectra into the energy deposition spectra, we used several reference points, i.e. positions of maxima of electron and pion amplitude spectra at the known beam energy of 10, 20, 40, 60, 80 and 100 GeV. Using these reference points, the coefficients $K_E^{\pi} = (31 \pm 1)$ MeV/(ADC channel) and $K_E^{e} = (36 \pm 1)$ MeV/(ADC channel)for pions and electrons have been determined. It turned out that coefficients K_E determined at different energies were the same within errors, just as it should be for the calorimeter with the linear response.

The calibration procedure has been repeated for all 480 modules assembled in 19 matrices of 5×5. The typical dependence of the ratio of the energy recorded by the calorimeter,$E_{\rm rec}$, to the beam energy, $E_{\rm beam}$, vs. $E_{\rm beam}$ is shown in Fig. 6.

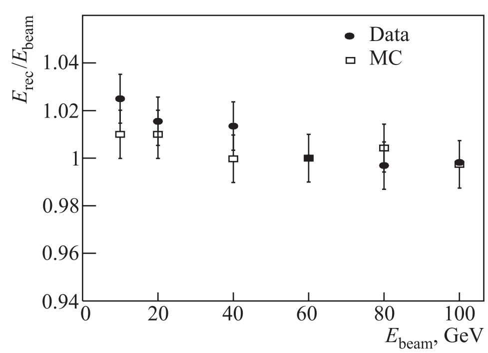

Fig. 6. The ratio $E_{\rm rec}/E_{\rm beam}$ as a function of $E_{\rm beam}$

The hadron and muon energy deposition spectra at $E = 10$ GeV obtained from the 5×5 matrix of modules are shown in Fig. 7. The solid lines represent fits of muon spectra by the Landau distribution and of hadron (pion) spectra by the Gauss distribution. For both spectra the coefficient K_E^{π} has been used. The maximum of the energy depositions by muons turns out to be at $E = 1.63$ GeV. The maximum of the pion energy deposition spectrum corresponds to the beam energy, as it should be. Due to muon contamination of the pion beam, the muons are also seen in Fig. 7, *b*.

The energy deposition spectrum of pions and electrons at energies 20 and 80 GeV and their approximations by the Gaussian distributions (thick lines) are

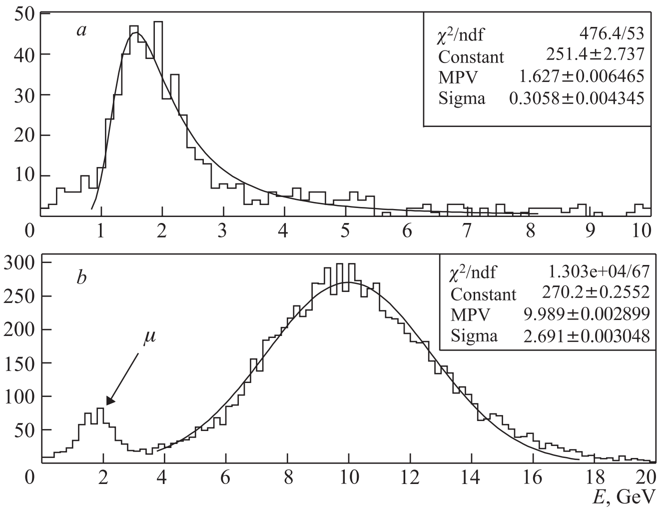

Fig. 7. The energy deposition spectra obtained from the $5{\times}5$ matrix of modules in the muon beam (*a*) and in the pion beam (*b*) at the beam energy 10 GeV

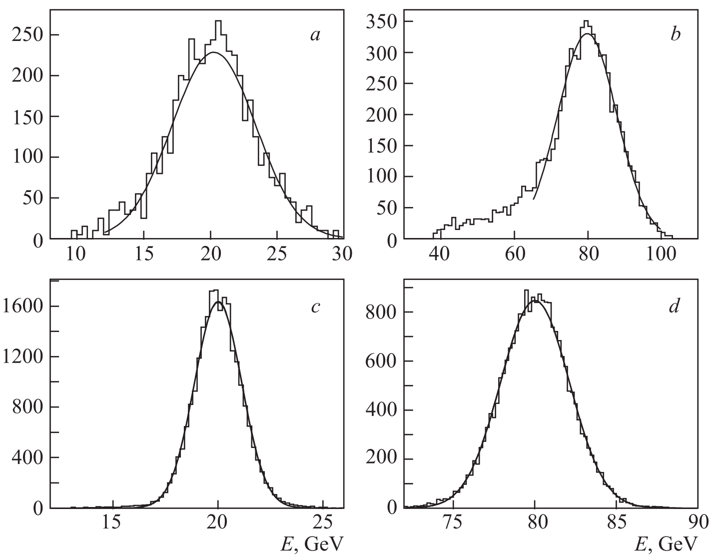

Fig. 8. The same as in Fig. 7 but for pions (*a*, *b*) and electrons (*c*, *d*) at 20 and 80 GeV

shown in Fig. 8. The coefficients K_E^π and K_E^e have been used for the corresponding spectra. Due to that the maxima of the pion and electron spectra exactly correspond to the beam energies. The values $\sigma_\pi(E)$ and $\sigma_e(E)$, found from such approximations, characterize the energy resolutions of the calorimeter for hadrons and electrons, respectively.

The energy resolutions of the calorimeter as functions of energy for pions and electrons together with Monte Carlo simulations are shown in Fig. 9. The solid lines are given by expressions:

$$\frac{\sigma_\pi(E)}{E} = \frac{59.4 \pm 2.9}{\sqrt{E}} \oplus (7.6 \pm 0.4)\%, \tag{2}$$

$$\frac{\sigma_e(E)}{E} = \frac{24.6 \pm 0.7}{\sqrt{E}} \oplus (0.7 \pm 0.4)\,\% \quad , \tag{3}$$

where energy E is in GeV.

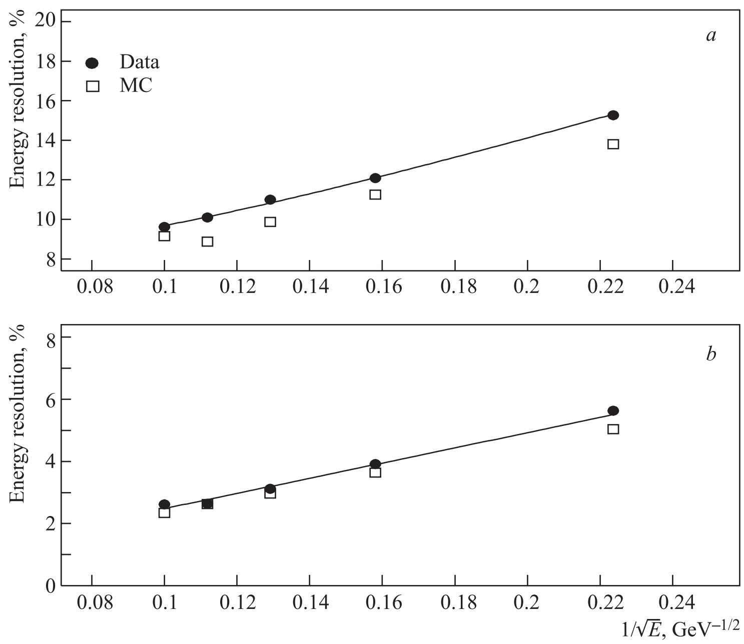

Fig. 9. The energy dependence of the HCAL1 resolutions for pions (*a*) and electrons (*b*)

The average value of the e/π ratio calculated from the positions of the electron and pion ADC spectra at the same energy appeared to be 1.2±0.1.

The coordinate resolutions were measured by beam scanning of the central module of the $5{\times}5$ matrix and offline determination of the shower centers of gravity. Differences between coordinates of the beam and coordinates of the center of gravity were determined and fitted by the Gaussian distribution. The standard deviations of these fits, σ_x, characterizing the coordinate resolutions of the calorimeter, are shown in Fig. 10 together with the results of simulations. The averaged resolutions are equal to $\sigma_{x,y} = 14 \pm 2$ mm when the beam enters the center of the module.

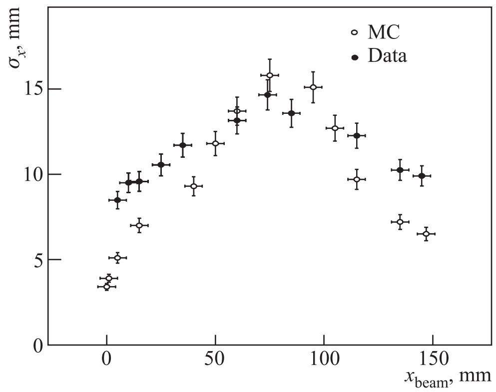

Fig. 10. The coordinate resolutions of the HCAL1 as a function of x coordinates of the beam entering the central module of the matrix $5{\times}5$ modules

4. SYSTEM OF THE CALORIMETER CONTROL

The control of the stability of the calorimeter performance is based on the usage of the single bright light emitting diode (LED) of the type MARL 110106, maximum spectrum of which corresponds to the wave length 470 nm, i.e. close to that of the PM. The control system had two tasks: first, to define a correspondence between the amplitudes of signals from LED and beam particles of known energy and, second, to control permanently the stability of the whole chain of electronics from PM to ADC.

The light of the LED is distributed and delivered to all 480-module PMs by optical fibers about 3 m long and 1 mm in diameter via optical connectors at the rear side of the module containers. The distribution of the LED light has been done in two steps, first, it is distributed between 30 groups and, then, each group is divided in 16 channels. The more stable photodiode (PIN diode, firm Hamamatsu) controls the intensity of the LED. The PIN diode is fired by the LED and its amplitude, together with amplitudes of signals from all the modules fired by LED, is recorded by the COMPASS DAQ system between the accelerator cycles. This system allows one to control the stability of the HCAL1 performance and to introduce corrections to the detected energy, if necessary. The typical time stability plot of amplitudes from all the modules fired by LED is shown in Fig. 11. The amplitude for a given time, A, is divided by the amplitude at the initial time, $A(\mathrm{ref})$, and plotted in this figure. The size of the vertical line gives the typical accidental deviation of the ratio $A/A(\mathrm{ref})$ from unity and it is observed to be about 5% during three months of operations in 2003. No systematic trend is seen from these data.

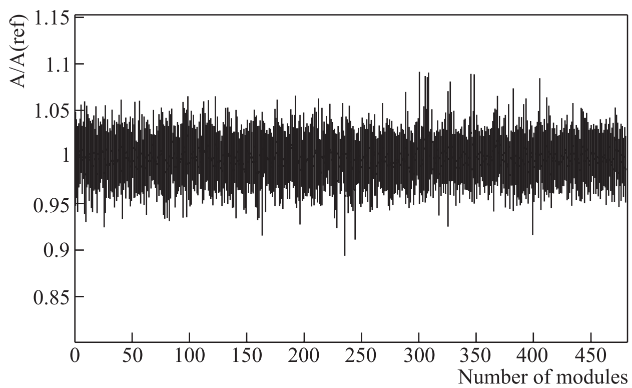

Fig. 11. Typical plot demonstrating the time variations of the relative amplitudes of all modules fired by LED

5. PERFORMANCE OF THE HCAL1 IN COMPASS

At the beginning of each run, the calibration of the calorimeter modules was checked by using the halo of the muon beam M2, which is used by the COMPASS, in a real environment with the proper length of cables and new ADC type FIADC-64 [11]. The calorimeter was triggered either by HCAL1 coincidences with two scintillating counters placed in front of the modules on the movable support or by one of COMPASS standard triggers. The amplitude spectra were measured for each of 480 modules as well as relative delays of the signals. The amplitudes were unified within 10% changing the HV settings for the trigger purposes. The halo muon calibration spectra of one of the calorimeter groups are shown in Fig. 12. The spectra were approximated by the Landau distributions and normalization coefficients were determined from positions of the amplitude spectra maxima, which correspond to the energy deposited in modules by minimum ionizing particles. The maxima, determined with the precision of about 0.1 GeV, correspond to the energy 1.8 GeV for all modules of this and other groups. It also means that the energy scales of all modules are identical. In the test beam studies it has been shown that the maximum of the amplitude spectrum deposited in the calorimeter by minimum ionizing particles with energy 10 GeV corresponds to the energy 1.63 GeV. In the M2 beam, the halo muons have a higher energy. Taking into account this feature and new ADC in read-out

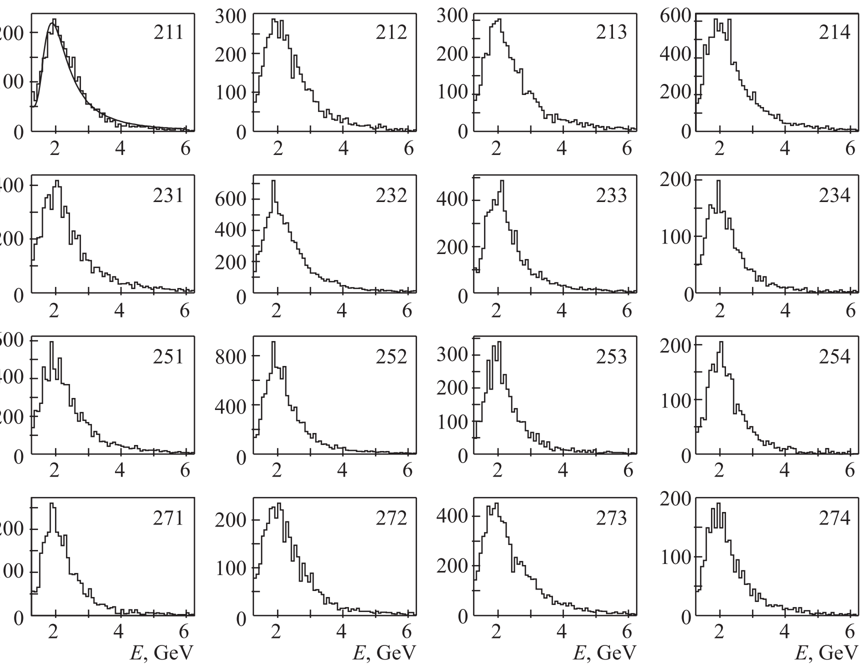

Fig. 12. An example of calibration spectra obtained with the M2 beam halo for a group of the HCAL1 modules. For the module 211 the approximation of the spectrum by Landau distribution is shown. The approximations for other modules are not shown in this figure

chain, the maxima of the amplitude spectra deposited in the modules by halo muons happened to correspond to the energy 1.8 GeV for the same calibration coefficient K_E^{π} obtained in the test beam.

The distribution of relative delays of the calorimeter signals is shown in Fig. 13 together with its approximation by the Gaussian distribution. All modules are aligned in time with $\sigma = 1.4$ ns.

The hadron energy recorded by HCAL1 has been reconstructed during the offline analysis using the following expression:

$$E = \sum_{i}^{n} a_i \cdot K_E^{\pi}(i) \cdot K_{LED}(i), \qquad (4)$$

where n is a number of adjacent modules (cluster) with amplitudes above the certain value; a_i is the same as in Eq. (1); $K_E^{\pi}(i)$ is the coefficient of absolute energy to ADC channel correspondence determined for the given module as the ratio of 1.8 GeV to the number of the ADC channels, which corresponds to the maximum of the muon amplitude spectrum (it has been corrected later by using hadrons detected in the experiment); $K_{LED}(i)$ is a coefficient of the relative correction of the amplitude obtained by means of the LED control system and accounting for the possible variation of the amplitude with time;

$$K_{LED}(i) = \frac{LED_i(t_0)}{LED_i(t)} \cdot \frac{A_{PIN}(t)}{A_{PIN}(t_0)}, \quad (5)$$

where $LED_i(t_0)\,[LED_i(t)]$ is the amplitude of the module fired by LED at the initial [given] time and $A_{PIN}(t)\,[A_{PIN}(t_0)]$ is the amplitude of the PIN diode at the given [initial] time.

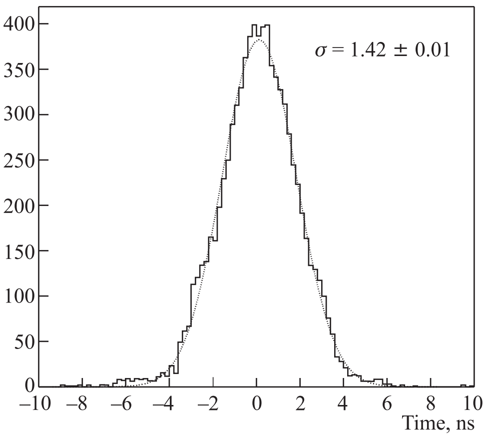

Fig. 13. The distributions of the relative delays of all HCAL1 modules and its approximation by the Gaussian distribution

During the data taking for the muon program, COMPASS uses several triggers [12, 13] among which there is an «inclusive» trigger built up from signals of scintillating hodoscopes detecting the incident muons and those scattered in the target. These muons are passing through the central window of the HCAL1 and should not be seen in it. Other particles, produced in the target in the same event within the solid angle of the first stage of COMPASS, hit the calorimeter and produce signals in the HCAL1 modules. The information, corresponding to the particular trigger, is read out from the HCAL1 modules and recorded in the Central Data Recording computers. Additionally to the signals originated in modules by particles, there are signals related with various noises of the calorimeter electronics. Looking at the spectrum of these noises without a beam, one can see that noises above 0.5 GeV appear very seldom. To remove noises completely and reduce the amount of information for further analysis, the noise threshold of 0.8 GeV is applied to the spectra.

The energy deposition spectra of associated particles, obtained during one of the COMPASS data taking periods, are shown in Fig. 14. The particle is called «associated» when it is found by the COMPASS reconstruction program CORAL [14] and extrapolated to the HCAL1 surface. For each of 1–8 spectra shown in Fig. 14, the events are selected when the energy is reconstructed from the clusters of modules (cluster size > 3 (SC > 3) and the momentum of the associated track is within ≈ 0.25 GeV/c around central values $5,\ 7, \ldots,\ 34$ GeV/c. The size of the cluster is defined as a number of adjacent modules, in which $\geqslant 90\%$ of the particle energy is deposited. This particular case SC > 3 means that four or more modules contain $\geqslant 90\%$ of the energy of the developed nuclear shower. The rest of events is excluded from this analysis. The central parts of spectra 1–8 were fitted by the Gaussian distributions and positions of the peaks as a function of the associated tracks momentum are shown in the lower right

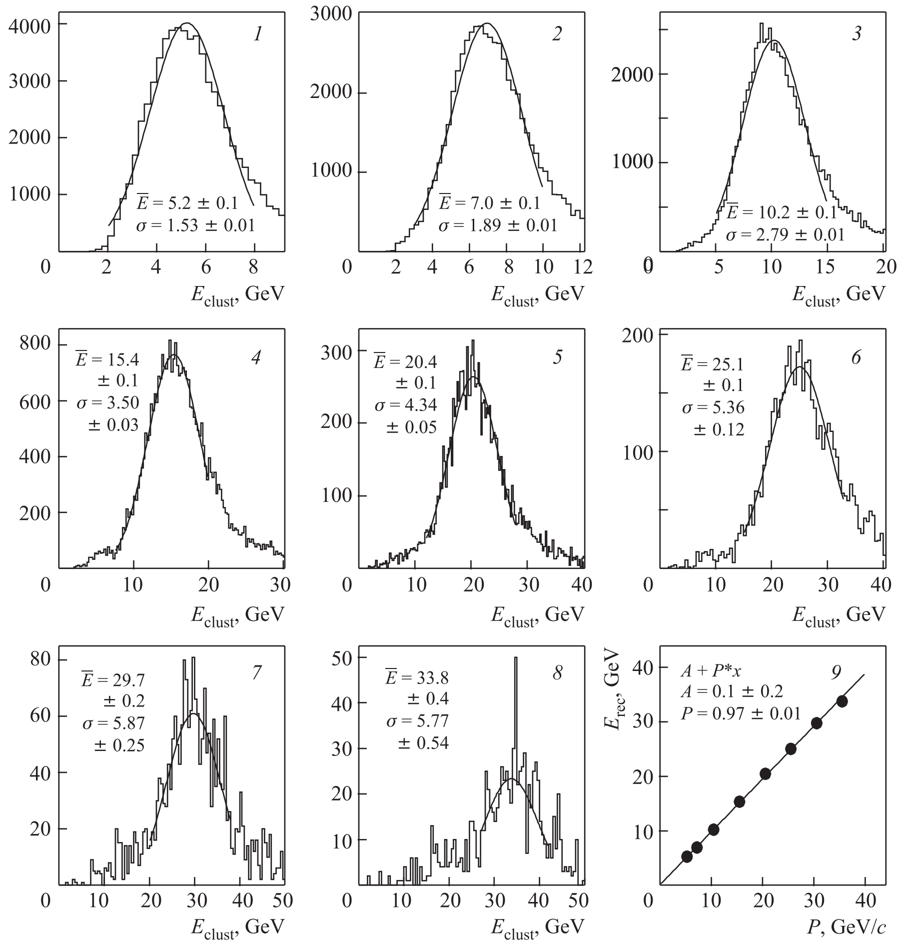

Fig. 14. The energy spectra, reconstructed in HCAL1 in different intervals of the associated track momentum from 5 to 34 GeV/*c* (plots *1*–*8*) and the reconstructed energy as a function of track momentum (plot *9*)

corner of Fig. 14 (part 9). The linear fit of this dependence gives the constant term 0.1 ± 0.2, i.e. zero within the errors, and the slope, 0.97 ± 0.01. This is a small correction factor to the coefficient $K_E^{\pi}(i)$, determined during the calibration procedure.

The calorimeter, as an electronic detector, should have almost 100% efficiency if the PM gain and thresholds are set correctly. In case of HCAL1 the definition of efficiency also includes the efficiency of the cluster search and energy reconstruction. The total HCAL1 efficiency as a function of the associated track momentum reconstructed by the CORAL is shown in Fig.15. The events selected for this plot required to have coordinates in the tracking chamber closest to HCAL1. As it is seen from Fig. 15, at $p > 5$ GeV/c the efficiency of HCAL1 is close to 100%.

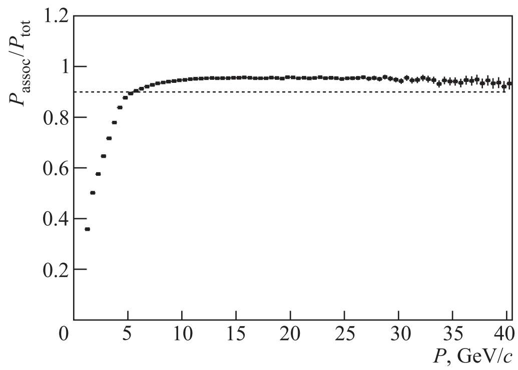

Fig. 15. The HCAL1 efficiency as a function of the associated track momentum

The energy spectra of the particles passing through the first stage of the COMPASS and HCAL1 and of those associated with tracks found by the COMPASS reconstruction program are shown in Fig. 16. The data are accumulated during the three-months-long run of COMPASS in 2002. They are subdivided in periods (P2A-P2G) and scaled for convenience by factors shown in Fig. 16. The threshold at 0.8 GeV is introduced in offline analysis to suppress the noises. As one can see from this figure, the spectra are identical demonstrating the stable operation of the HCAL1. A more detailed analysis of the calorimeter performance can be found in [15].

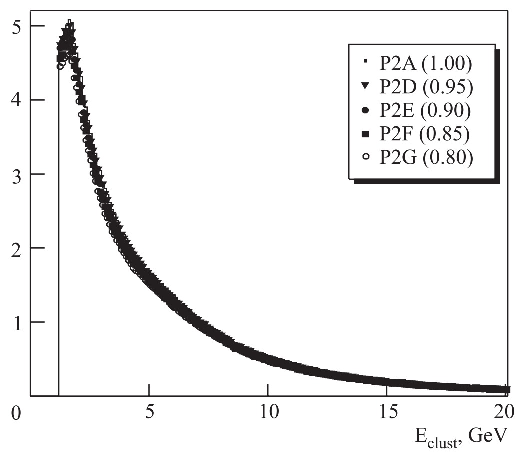

Fig. 16. The energy spectra recorded by the calorimeter during an about-three-months-long run of COMPASS

The operation of the HCAL1 during the data taking periods was monitored by two computer programs. One of them is COOOL [16] monitoring all COMPASS detectors and the second one is MONITOR HCAL1, monitoring the HCAL1 only. Both programs can be used in online and offline regimes and produce the similar graphs and plots for the whole HCAL1 or its modules. As an example, Fig. 17 demonstrates the plots which are regularly obtained in the online regime by COOOL. The size of rectangulars on the plots corresponds to the frequency of the module firing (or to the amplitude). The program MONITOR HCAL1 can produce spectra of the selected groups of 30 modules or the spectra of individual modules, spectra of LED and PIN diode, x, y two-dimensional plots, etc.

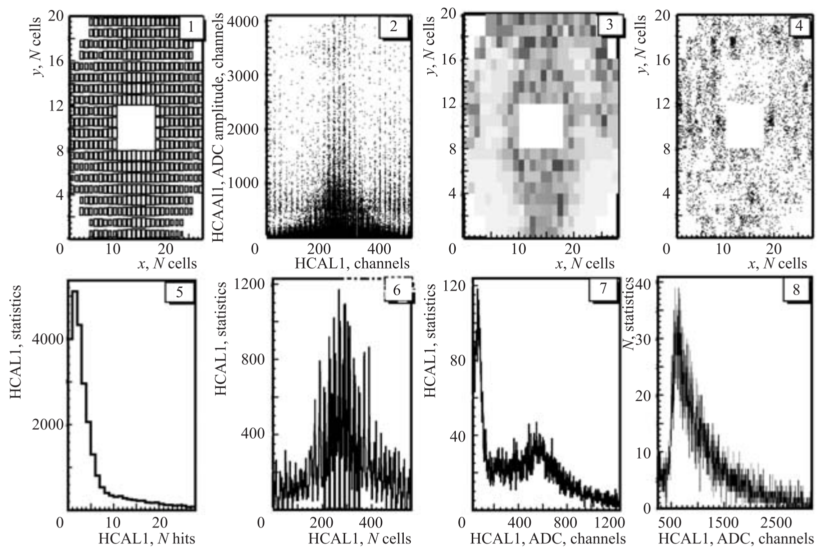

Fig. 17. Two- and one-dimensional plots produced by COOOL: *1* presents population of modules; *2*, amplitude distribution in modules; *3*, two-dimensional amplitude distribution; *4*, noise distribution in modules; *5*, multiplicity of HCAL1 hits per trigger; *6*, frequency of modules firing; *7*, amplitude in modules without threshold; *8*, amplitude in modules above the threshold

6. USE OF THE CALORIMETER IN THE COMPASS FAST TRIGGER

The modular structure of the HCAL1 allows one to use it in the calorimetric fast triggers (the first level) of COMPASS. From Monte Carlo simulations it is known that at rather a high energy of the incoming hadron more than 90% of its energy will be deposited in the cylinder radius of which is equal to one nuclear interaction length (λ_{int}), i.e. about 20 cm for HCAL1. So, the signal, corresponding to almost full energy of this hadron can be obtained summing up the energy from the surface 60×60 cm or from the group of 4×4 modules. This operation can be performed rather fast by using the analog summing. After that the resulting signal from this group is used for triggers in coincidence with scintillating hodoscopes detecting the incoming and scattered muons. The time resolution of the order 1.4 ns can be obtained in these coincidences by means of the constant fraction discriminator (CFD) [13].

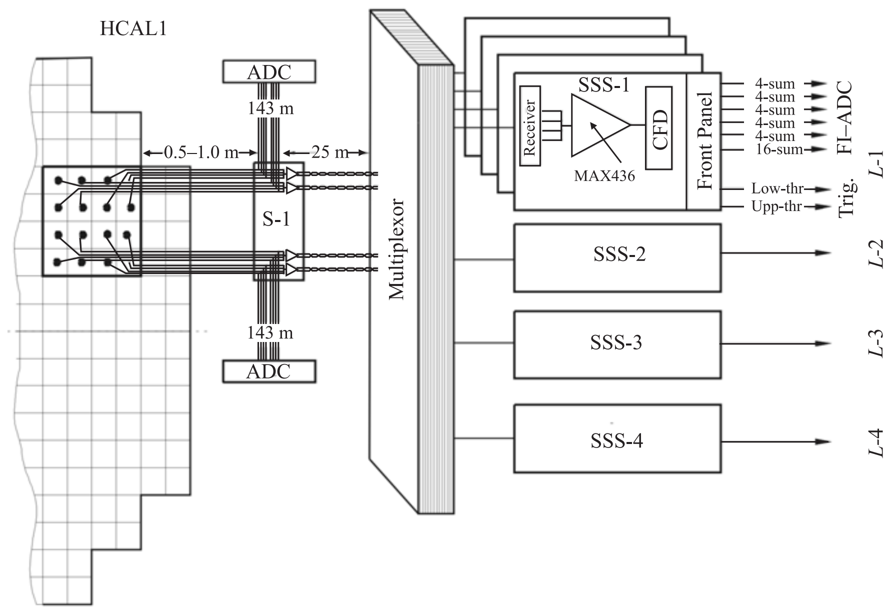

Fig. 18. The block diagram of summing up the signals of the HCAL1 modules

The summing up of the signals from the HCAL1 modules is performed in the «trigger boxes» fixed to the rear part of the calorimeter close to PMs. The signals from each group of 16 PMs (4×4 modules) are connected to the single box by 50 ohm cables of 0.6 to 2 m long compensating for the relative difference of the signal delays from corresponding PM. The compensation of delays was done after the calorimeter calibration in COMPASS setup.

At the input of the trigger boxes, the signal is split into two equal signals, one is used for summing (see Fig. 18) and the other one via 50 ohm cable of length 140 m goes to the fast ADC for further recording of the amplitude in computer together with other information about a given event.

The output signals from the trigger box (4 sums of 2×2 modules), via the 25 m twisted pairs cables, go to the experimental hut, where they are split passively into four signals used for participation in four «trigger layers» covering the whole calorimeter surface (Fig. 18) [13]. The layers are mixed via multiplexer and used in the second-level summing to remove possible holes between the groups. The signals from multiplexer via CFD with two programming outputs are sent to the trigger logic. The threshold of the first (second) CFD output usually corresponds to the deposited energy of about 5 GeV (10 GeV).

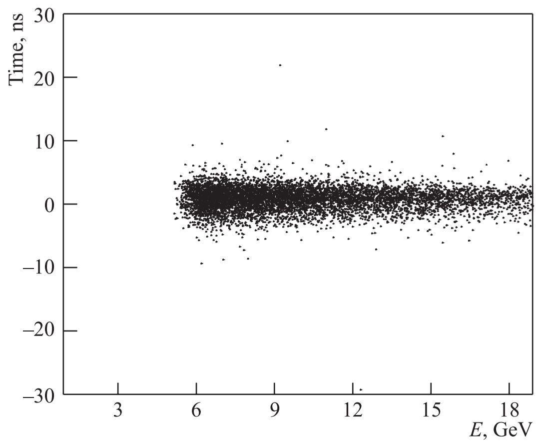

Fig. 19. The time–amplitude correlations of HCAL1 signals in the fast trigger

The analog sums of signals from the group of 16 modules (4×4) are recorded by the «trigger ADC» for control and corresponding logical signals are recorded by TDC.

The logic of the COMPASS calorimetric trigger is developed by authors of the papers [12, 13]. This trigger allows one to select events with a minimal number of tracks or/and a minimal value of the deposited energy. Figure 19 illustrates the work of the calorimeter fast trigger. The threshold was set at 5 GeV.

CONCLUSIONS

The hadron calorimeter HCAL1 has been constructed at Dubna for the experiment NA58 (COMPASS). The calorimeter can work either in autonomous or in trigger regimes. It consists of 480 modules with 15×15 cm cross section assembled in the matrix 4.2×3 m with a window 1.2×0.6 m in the center. Each module contains 40 layers of iron and scintillator plates, total interaction length of which is equal to 4.8 $\lambda_{\rm int}$. The energy resolutions of the HCAL1 for pions and electrons as well as coordinate resolutions were determined in the test beams in the energy range 10–100 GeV. They are equal to

$$\frac{\sigma_\pi(E)}{E} = \frac{59.4 \pm 2.9}{\sqrt{E}} \oplus (7.6 \pm 0.4)\%,$$

$$\frac{\sigma_e(E)}{E} = \frac{24.6 \pm 0.7}{\sqrt{E}} \oplus (0.7 \pm 0.4)\%,$$

$$\sigma_{x,y} = 14 \pm 2 \text{ mm},$$

respectively. The average value of the ratio e/π characterizing the HCAL1 response to electrons and pions (hadrons) is equal to 1.2 ± 0.1. The response is linear as a function of energy within $\pm 1\%$. The HCAL1 characteristics obtained in the offline regime are in agreement with those obtained in the test beam. The calorimeter has demonstrated the stable performance during the long COMPASS runs.

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REFERENCES

1. *The COMPASS Collab.* Common Muon and Proton Apparatus for Structure and Spectroscopy. Proposal to the CERN SPSLC, CERN/SPSLC 96-14, SPSC/P 297. March 1, 1996; Addendum. CERN/SPSLC/96-30, SPSLC/P 297 Add. 1. May 20, 1996.
2. *Brun R., Gartminati F.* GEANT 3.21. CERN, Program Library.
3. *Gabriel T. A.* // Nucl. Instr. Meth. A. 1991. V. 319. P. 106.
4. *Wigmans R.* // Nucl. Instr. Meth. A. 1987. V. 259. P. 389.
5. *Leroy C., Rancoita P. G.* // Rep. Prog. Phys. 2000. V. 63. P. 505–606.
6. *Aleev A. et al.* JINR Preprint P1-89-434. Dubna, 1989.
7. *Arefiev V. et al.* // JINR Rapid communications. 1996. No. 5[79]-96. P. 15.
8. *Kadykov M., Semenov V., Suzdalev V.* JINR Preprint 13-90-16. Dubna, 1990.
9. *Hubbeling L.* CERN/ECP 92-10. CERN, Geneva, 1992.
10. *Mikhailov Yu. V.* Private communication.
11. *Konorov I.* Private communication.

12. http://wwwcompass.cern.ch/compass/detector/trigger/muon-trigger/welcome.html

13. *Hannapel J. et al.* The COMPASS trigger system for muon scattering // Nucl. Instr. Meth. A. (submitted).

14. http://coral.web.cern.ch/coral/

15. http://wwwcompass.cern.ch/compass/note/2003-6

16. http://wwwcompass.cern.ch/compass/detector/daq/welcome.html

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