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# Performance of the COMPASS II shashlyk calorimeter ECAL0 read out by SiPMs

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ABSTRACT

The matrix of 3 × 3 modules of the EM calorimeter ECAL0 (COMPASS II) read out by MPPC S12572-010P SiPMs with the pixel density of $10^4$ mm$^{-2}$ and an area of 3 × 3 mm$^2$ is studied in the range of electron energies 1–30 GeV. It is observed that the MPPC has additional response nonlinearity and a significantly smaller dynamic range of output signals than expected. The influence of parasitic capacitance between pixels on the pixel gain is discussed and proposed as explanation. The energy resolution of the calorimeter is measured to be $\sigma_E/E = 7.1\%(1+0.06/E)/\sqrt{E} \bigoplus 1.4\% E^{0.25}$, where electron energy $E$ is given in GeV.

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## 1. Introduction

A new-generation EM calorimeter ECAL0 was developed at the DLNP, JINR, for the COMPASS II experiment [1]. ECAL0 is a shashlyk-type sandwich with high granularity (cell size 4 × 4 cm$^2$) consisting of 194 modules. A calorimeter module (3 × 3 cells) consists of 109 alternating layers of lead (0.8 mm) and a polystyrene scintillator (1.5 mm) and a nine-channel photodetector unit with MPPC S12572-010P SiPMs (Hamamatsu) with high density of pixels $10^4$ mm$^{-2}$ and an area of 3 × 3 mm$^2$. The prototype calorimeter module design is described in [2,3].

## 2. Response of MPPC S12572-010P SiPM

The matrix of 3 × 3 modules (81 cells) was studies with test beams at CERN in the range of electron energies 1–30 GeV.

The SiPM response function is actually nonlinear due to the finite number of pixels, which leads to saturation of the response at high light levels. Under the assumption that the pixels are independent microcounters of photons at the homogeneous illumination of the SiPM surface, the number of fired pixels is determined by the expression

$$N_{\text{fired}} = N_0 \left(1 - e^{-\mu/N_0}\right), \quad (1)$$

where $N_0$ is the total number of pixels, $\mu$ is the number of photoelectron–hole pairs produced in the SiPM; $\mu = N_{\text{ph}} PDE$, where $N_{\text{ph}}$ is the number of incident photons, and $PDE$ is the photon detection efficiency.

Fig. 1 shows the dependence of the calorimeter cell response on the electron beam energy and the energy absorbed in the cell, expressed in term of the average number of electron–hole pairs produced in the MPPC. The response is represented by the number of fired pixels of the MPPC $N_{\text{fired}} = \bar{Q}/Q_1$, where $\bar{Q}$ is the average output charge of the MPPC; $Q_1 = e\,G_{\text{pix0}}$, where $e$ is the electron charge, and $G_{\text{pix0}}$ is the pixel gain measured when one detects single photons.

The MPPC S12572-010P used in ECAL0 have $N_0 = 90\,000$ pixels, but interpolation of the data by theoretical response function (1) shows that the total number of pixels is $N_0 \approx 33\,000$. For comparison, Fig. 1 shows the theoretical response function with $N_0 = 90\,000$. A detailed study of the observed effect was carried out using a laser.

The response of the MPPC S12572-010P measured in a large range of light signals and the theoretical functions with $N_0 = 90\,000$ and $N_0 = 33\,000$ are shown in Fig. 2. As can be seen in the figure, the response is much smaller than the theoretical function corresponding to $N_0 = 90\,000$.

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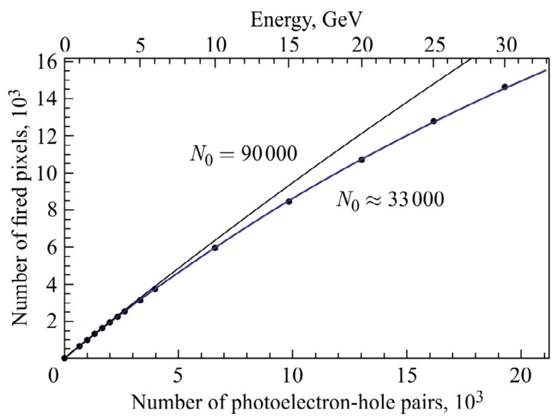


**Fig. 1.** The dependence of the response of the ECAL0 cell read out by the MPPC S12572-010P on the electron beam energy, and the average number of the photoelectron–hole pairs produced in the MPPC.

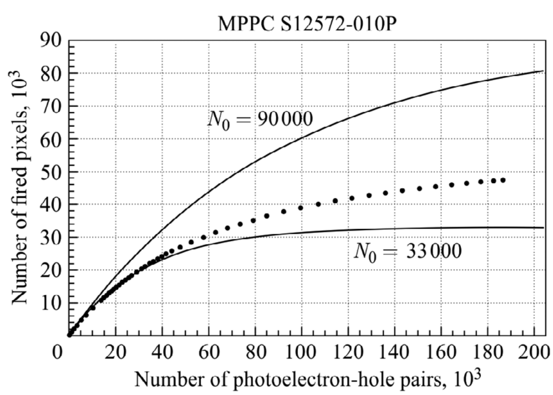


**Fig. 2.** The response of the MPPC S12572-010P with a total number of pixels $N_0 = 90\,000$ exposed to light from a laser with a pulse width of 40 ps. For comparison, theoretical functions (1) with $N_0 = 90\,000$ and $N_0 = 33\,000$ are shown.

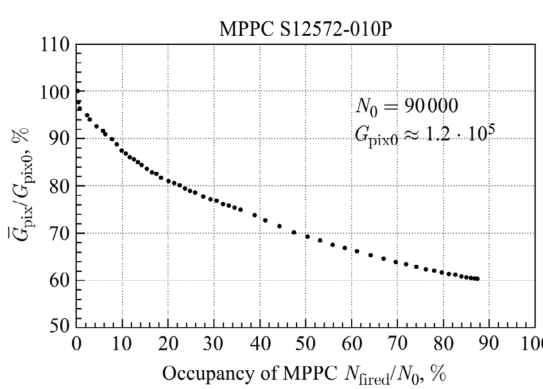


**Fig. 3.** The dependence of the average MPPC S12572-010P gain on the occupancy of pixels.

Such a decrease in the dynamic range is associated with a decrease in the gain factor due to occupancy of MPPC pixels $\Sigma = N_{fired}/N_0$. Dividing the measured response by the theoretical one, we obtain the dependence of the average pixel gain $\bar{G}_{pix}$ on the pixel occupancy $\Sigma$ (Fig. 3). At full illumination of the MPPC, the average pixel gain decreases by more than 40%.

Let us consider as explanation of the observed effect the influence of parasitic capacitance between the pixels $C_{pp}$ on the pixel gain. A simplified equivalent MPPC circuit is shown in Fig. 4. When MPPC detects a single photon and one pixel fires, two processes occur. The first is the capacity discharge of the fired pixel, which creates a potential difference on the parasitic capacitances $C_{ppi}$ with eight adjacent pixels, and the second is the charge $C_{ppi}$ from the external power source. Thus, the effective capacity of the fired pixel and consequently the gain increase.

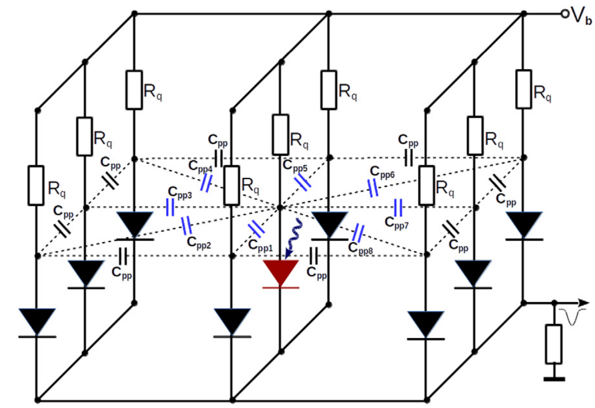


**Fig. 4.** A simplified equivalent circuit of the MPPC S12572-010 with high pixel density.

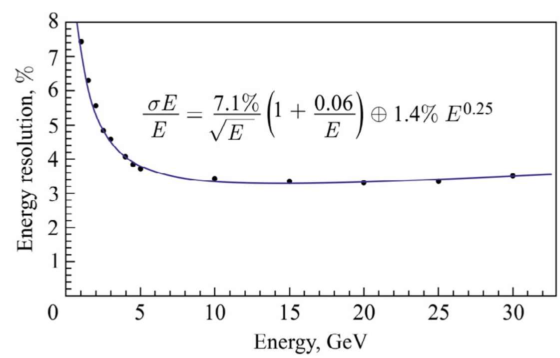


**Fig. 5.** The dependence of the energy resolution of the ECAL0 3 × 3 module matrix read out by the MPPC S12572-010P on the electron beam energy.

The pixel gain factor at the detection of single photons by the MPPC is $G_{pix0} = C_{pix0}\,\Delta V/e$, where $C_{pix0}$ is the effective capacitance of the pixel, and $\Delta V$ is the overvoltage. The effective capacitance of a pixel is the sum of the real capacitance of a pixel $C_{pixr}$ and eight effective parasitic capacitances $C_{pix0} = C_{pixr} + \sum_{i=1}^{8} C_{ppi}$.

With increasing light intensity, when two adjacent pixels are fired, their parasitic capacitance is not charged because, when the adjacent pixels are simultaneously discharged, no potential difference is created on their parasitic capacitance. Therefore, the effective capacities and the gain of these two pixels are reduced.

The effective capacity of a pixel when one or more adjacent pixels are fired can be expressed as $C_{pix} = C_{pixr} + \sum_{i=1}^{8} C_{ppi} - \sum_{i=1}^{n} C_{ppi}$, where n = 1, 2, …, 8 is the number of the fired neighboring pixels. Therefore, as the pixel occupancy $\Sigma$ increases, the average pixel gain of the MPPC S12572-010P decreases, and at full illumination it becomes minimal $G_{pixm} = C_{pixr}\,\Delta V/e$.

## 3. Energy resolution of the calorimeter ECAL0

The length of the calorimeter ECAL0 module is only 15.2 $X_0$, which is insufficient for the total absorption of the electron energy in the studied range 1–30 GeV. At energies above 10 GeV, the lineshapes observed for monoenergetic electron beams become asymmetric due to leakages of shower energy, and therefore they were approximated by the logarithmic Gaussian distribution [4].

The energy resolution of the calorimeter (Fig. 5) was parameterized by the formula $\sigma_E/E = a(1+m/E)/\sqrt{E} \bigoplus cE^d$, where $a$ is a stochastic term, and $m$ is the parameter associated with the ADC threshold. The ECAL0 has a high granularity, so the ADC threshold degrades the energy resolution, especially at low energies. The last term in the formula takes into account the contribution of energy leakages, etc.

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