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PERFORMANCE OF SHASHLYK CALORIMETER READ OUT BY **SiPMs** WITH HIGH PIXEL DENSITY

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Чириков-Зорин И. Е. и др. E13-2018-30
Характеристики калориметра типа шашлык со съемом света SiФЭУ
с высокой плотностью пикселей

В диапазоне энергий электронов 1–30 ГэВ исследована матрица из 3×3 модулей ЭМ-калориметра ECAL0 (COMPASS II) со съемом света SiФЭУ MPPC S12572-010P с плотностью пикселей 10^4 мм$^{-2}$ и площадью 3×3 мм. Обнаружено, что MPPC имеют дополнительную нелинейность отклика и значительно меньший динамический диапазон выходных сигналов, чем ожидалось. Предложен механизм эффекта, основанный на влиянии паразитных емкостей между пикселями на усиление пикселя. Измерено энергетическое разрешение калориметра $\frac{\sigma_E}{E} = \frac{7{,}1\,\%}{\sqrt{E}}\left(1 + \frac{0{,}06}{E}\right) \oplus 1{,}4\,\% E^{0{,}25}$.

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Chirikov-Zorin I. et al. E13-2018-30
Performance of Shashlyk Calorimeter Read Out by SiPMs
with High Pixel Density

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

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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INTRODUCTION

One of the main objectives of the COMPASS II experiment [1] is the study of generalized parton distributions in the reaction of Deep-Virtual Compton Scattering (DVCS) of muons $\mu p \to \mu p \gamma$. A new-generation electromagnetic calorimeter ECAL0 was developed at DLNP, JINR, to detect photons with large angles in the DVCS reaction.

ECAL0 is a shashlyk-type sandwich with high granularity (cell size 4×4 cm) 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 silicon photomultipliers (SiPM) (Hamamatsu) with a record high density of surface pixels 10^4 mm^{-2} and an area of 3×3 mm. The prototype calorimeter module design is described in [2, 3].

1. RESPONSE OF MPPC S12572-010P SiPM

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

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

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

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

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

The MPPC S12572-010P used in ECAL0 have $N_0 = 90\,000$ pixels, but approximation 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 with a pulse width of 40 ps. The responses of MPPC S12572-010P, S12572-015C, and S10362-11-025U with the pixel pitch of 10, 15, and 25 μm, respectively, were measured.

The theoretical response function approximates well the experimental data obtained with MPPC S10362-11-025U (Fig. 2), but absolutely does not describe the data from MPPC S12572-010P and S12572-015C.

The response of 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. 3. As can be seen in the figure, the response is much smaller than the theoretical function. Such a decrease in the dynamic range is associated with a decrease in the gain factor due to occupancy of MPPC pixels $\Sigma = N_{\rm fired}/N_0$. Dividing the measured response by the theoretical one, we obtain the dependence of the average pixel gain $\overline{G}_{\rm pix}$ on the pixel occupancy Σ (Fig. 4). At full illumination of MPPC, the average pixel gain decreases by more than 40%.

Let us consider the mechanism of the observed effect based on the effect of parasitic capacitance between the pixels $C_{\rm pp}$ on the pixel gain. A simplified

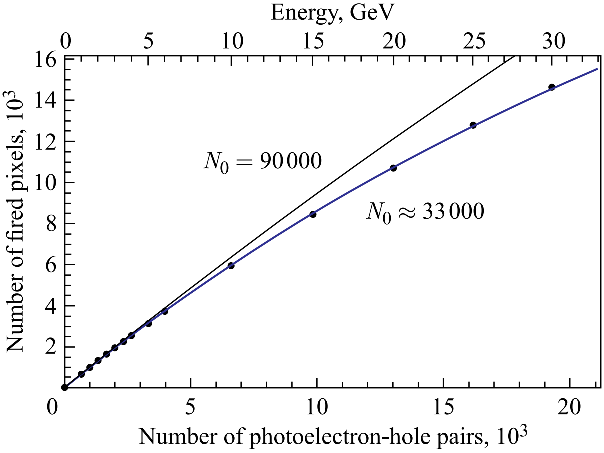

Fig. 1. The dependence of the response of the ECAL0 cell read out by MPPC S12572-010P on the electron beam energy and the average number of the photoelectron-hole pairs produced in MPPC

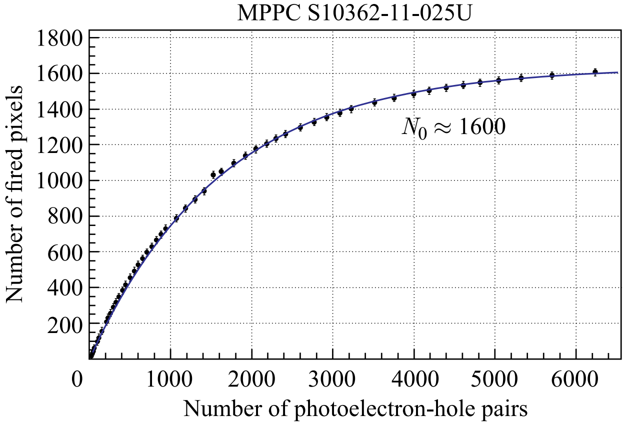

Fig. 2. The response function of MPPC S10362-11-025U with a pixel pitch of 25 μm, size of 1×1 mm, and total number of pixels $N_0 = 1600$ exposed to light from a laser with a pulse width of 40 ps

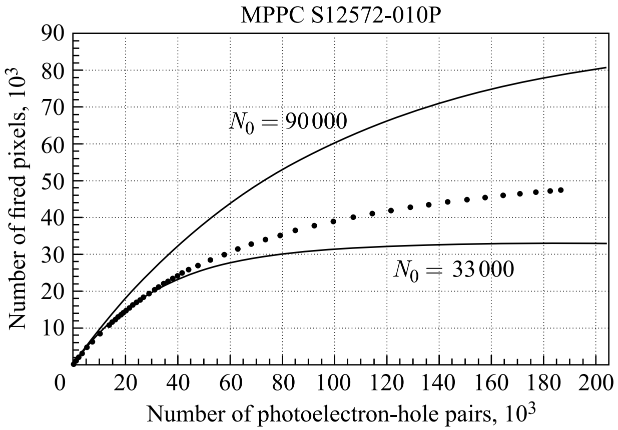

Fig. 3. The response of MPPC S12572-010P with a total number of pixels $N_0 = 90\,000$ exposed to light from a laser with a pulse width of 40 ps. For comparison, theoretical functions (1) with $N_0 = 90\,000$ and $N_0 = 33\,000$ are shown

equivalent MPPC circuit is shown in Fig. 5. 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 $C_{\rm ppi}$ with eight adjacent pixels, and the second is the charge $C_{\rm ppi}$ from the external power source. Thus, the effective capacity of the fired pixel and, consequently, the gain increase.

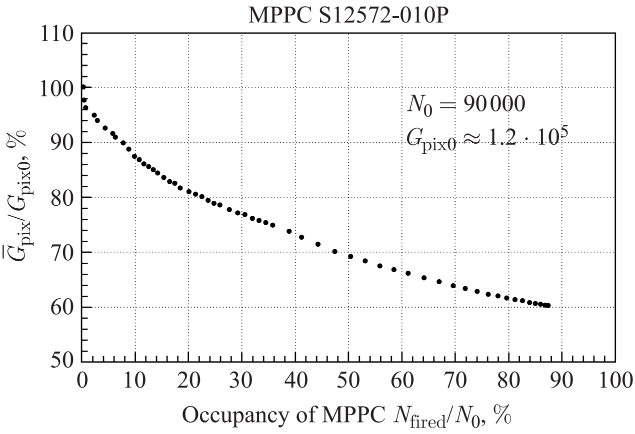

Fig. 4. The dependence of the average MPPC S12572-010P gain on the occupancy of pixels

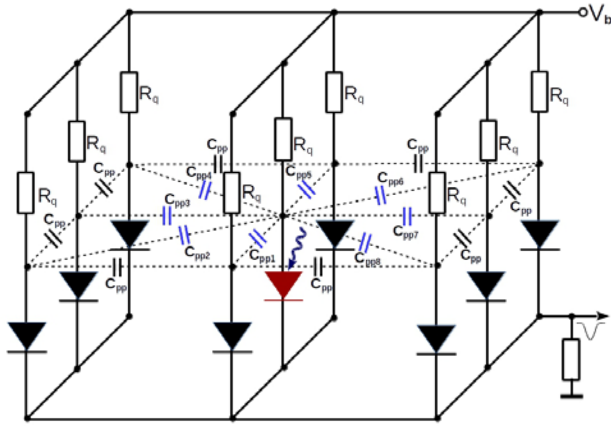

Fig. 5. A simplified equivalent circuit of MPPC S12572-010 and S12572-015 with high pixel density

The pixel gain factor at the detection of single photons by MPPC is $G_{\text{pix0}} = C_{\text{pix0}}\Delta V/e$, where C_{pix0} is the effective capacitance of the pixel, and ΔV 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 $C_{\text{pix0}} = C_{\text{pixr}} + \sum\limits_{i=1}^{8} C_{\text{ppi}}$.

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 at 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 $C_{\rm pix} = C_{\rm pixr} + \sum\limits_{i=1}^{8} C_{\rm ppi} - \sum\limits_{i=1}^{n} C_{\rm ppi}$, where $n = 1, 2, \ldots, 8$ is the number of the fired neighboring pixels. Therefore, as the pixel occupancy Σ increases, the average pixel gain of MPPC S12572-010P decreases, and at full illumination it becomes minimal $G_{\rm pixm} = C_{\rm pixr}\Delta V/e$.

Thus, the high-pixel-density SiPM MPPC S12572-010 (S12572-015) has additional response nonlinearity and a significantly smaller dynamic range of output signals than expected.

2. ENERGY RESOLUTION OF THE CALORIMETER ECAL0

The length of the calorimeter ECAL0 module is only $15.2X_0$, which is insufficient for the total absorption of the electron energy in the studied range 1–30 GeV. At energies above 10 GeV, the signal spectra 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. 6) was parameterized by the formula $\dfrac{\sigma_E}{E} = \dfrac{a}{\sqrt{E}}\left(1 + \dfrac{m}{E}\right) \oplus cE^d$, where a is a stochastic term, and m is the parameter associated with the ADC registration threshold. The ECAL0 has a high granularity, so the ADC registration threshold degrades the energy resolution, especially at low energies. The last term in the formula determines the contribution of energy leakages, etc.

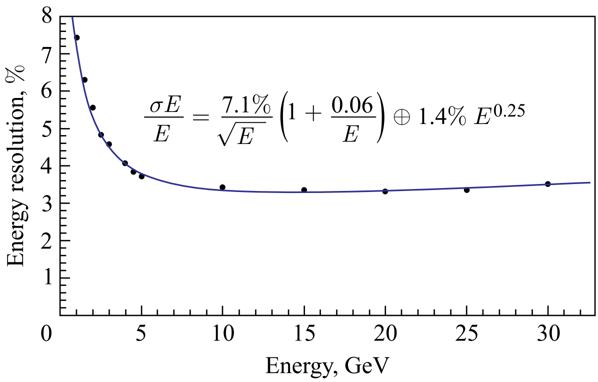

Fig. 6. The dependence of the energy resolution of the ECAL0 3×3 module matrix read out by the MPPC S12572-010P on the electron beam energy

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