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Simulation of the electron collection efficiency of a PMT based on the MCP coated with high secondary yield material

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ABSTRACT

Owning to the serious loss of photoelectrons striking at the input electrode of traditional microchannel plate (MCP), photoelectron collection efficiency (CE) of photomultiplier tubes based on MCP (MCP-PMTs) fluctuates around the MCP open area fraction and cannot make a breakthrough. Depositing a thin film of high secondary electron yield material on the MCP is proposed as an effective approach to improve the CE. The available simulation and experimental data to validate it, however, is sparse. In our work, a three-dimensional small area MCP model is developed in CST Studio Suite to evaluate the collection efficiencies of PMTs based on the traditional MCP and the coated one, respectively. Results predict that CE of the PMT based on the coated MCP has a significant increase and a better uniformity, which is expected to reach 100%.

1. Introduction

Large area photomultiplier tubes (PMTs) with photon counting capability [1–5] are widely used in large scale neutrino and cosmic ray experiments. High gain, low transit time spread (TTS) and high photo detection efficiency (PDE) are critical parameters for such applications. Recently, the conceptual design of a novel large area photomultiplier tube based on microchannel plate (MCP-PMT) has been proposed [6]. The large area MCP-PMT incorporates MCPs in place of the conventional discrete dynodes. Compared to the dynodes, MCPs in the PMT are quite different in structure and operation and therefore offer the following outstanding features: a) High gain despite compact size. b) Fast time response. c) Stable operation even in high magnetic fields. d) Low power consumption. e) Easy assembly. However there is a fatal shortcoming: Photoelectron collection efficiency (CE) of the MCP-PMT is limited by the ratio of the open area to the total effective area of the MCP (MCP open area fraction A_{open}), which have a severe impact on the PDE.

It is well known that the front and rear surfaces of a traditional MCP are coated by a thin film of nickel–chromium (Ni–Cr) as input and output electrodes which cover the flat inter-channel areas and areas penetrating into channels. ~0.5 channel diameter penetration depth at input end is achievable. Electrons striking the Ni–Cr electrode may contribute to the overall collection efficiency if secondaries are excited, and the emitted secondaries are returned to the channel entrances by an appropriate-directed electric field. Although CE can be improved at certain incident angles and energies of photoelectrons [7], it still fluctuates around the MCP open area fraction attributing to the low secondary electron yield of nickel–chromium. Inspired by this, coating MCP input electrode including the areas penetrating into channels with a high secondary electron yield (SEY) material is proposed to make a significant breakthrough on the collection efficiency. In such case, Transit Time Spread (TTS) of electrons is negatively affected, which will be reported elsewhere in the near future.

The available simulation and experimental data to validate the feasibility and effectiveness of this method, however, is sparse. A 20-inch large area MCP-PMT as shown in Fig. 1 is employed in our calculation. Two models including a simplified model of the MCP-PMT and a small area MCP model are developed to calculate the collection efficiencies of the PMTs based on the uncoated and the coated MCPs, respectively, in CST Studio Suite by Finite Integral

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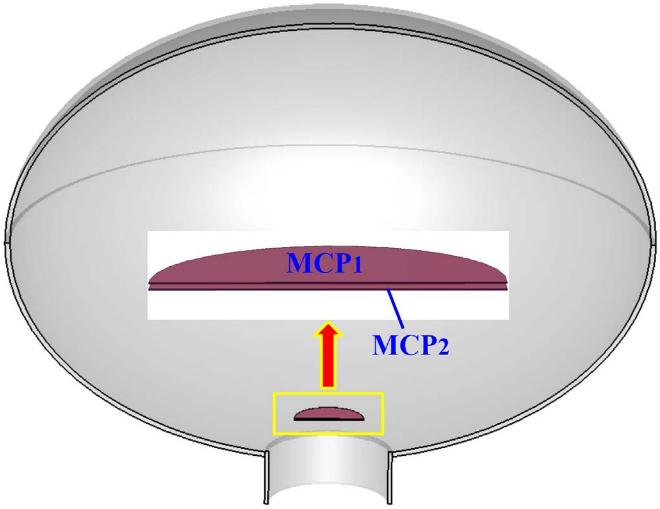

Fig. 1. The schematic diagram of the 20-inch MCP-PMT (model I).

Technique and Monte Carlo method. Results predict that depositing a high secondary yield material on the MCP is an effective approach to improve CE significantly.

2. Theory and computer simulation details

The contribution of electrons to the MCP-PMT collection efficiency can be divided into two parts, considering secondary electron emission from the MCP input electrode. One is the photoelectrons entering the channel entrances directly, which is referred to as the primary electron contribution CE_p. The other is the generations of secondaries (excited by electrons striking the MCP input electrode) entering the channel entrances by an appropriate-directed electric field, which is referred to as the secondary electron contribution CE_s. It is evident that CE_p is never greater than A_{open}. The only approach to make the CE a significant improvement is to improve the CE_s which is greatly affected by the secondary yield of the MCP input electrode. For the traditional MCP, nickel–chromium electrode has a maximum secondary yield at normal incidence

$$\left(\delta_e\right)_{max} \approx 1 \tag{1}$$

for primary energy $E \approx 500$ eV [8,9]. Most of photoelectrons striking at the Ni–Cr electrode will be absorbed without emission, which results in a low CE_s. A higher secondary yield δ_e gives rise to a larger number of excited secondaries, which increases the probability of secondaries being collected, and consequently a greater value for CE_s. Accordingly, depositing a high secondary yield material on the MCP is proposed. A material which has a maximum secondary yield at normal incidence

$$\left(\delta_e\right)_{max} = 6.4 \tag{2}$$

for primary energy $E=650$ eV is employed in our calculations.

Simulations are conducted to validate the feasibility and effectiveness. CST Studio Suit [10] is used to build the model and calculate the electric fields, electron trajectories, energies and velocities based on the Finite Integral Technique and Monte Carlo method. Inspired from previous researches [11–18], present simulations have following considerations: i. Electrostatic lens effect at the MCP channel entrances is simulated in detail, in which the electron trajectories are simulated accurately. ii. Electrons striking the MCP input electrode will excite secondaries [19–21]. iii. Furman model [22] as a relatively mature secondary electron emission model is employed in our simulation. a). Three components of the secondary electrons are well simulated. They are backscattered electrons, rediffused electrons and true-secondary electrons. b). Secondaries have a $\sim\cos\theta$ distribution in angular, which is fairly independent of the primary incident angle and incident energy. The emission angles are fully uncorrelated from each other. c). Aggregate energy of secondaries does not exceed the primary electron energy. Besides, the energy of any given secondary electron does not exceed the primary electron energy either. d). Electron yield (δ_{bs}) for the backscattered electrons is given by:

$$\delta_{bs}(E,\theta) = \delta_{bs}(E,0)\left[1+e_1\left(1-\cos^{e_2}\theta\right)\right] \tag{3}$$

where $\delta_{bs}(E,0)$ is the form for $\delta_{bs}(E,\theta)$ at normal incidence ($\theta=0$), e_1 and e_2 are two adjustable parameters. The rediffused electrons yield (δ_{rd}) is expressed as

$$\delta_{rd}(E,\theta) = \delta_{rd}(E,0)\left[1+r_1\left(1-\cos^{r_2}\theta\right)\right] \tag{4}$$

where $\delta_{rd}(E,0)$ is the form for $\delta_{rd}(E,\theta)$ at normal incidence ($\theta=0$), r_1 and r_2 are two adjustable parameters. The true secondary electron yield (δ_{ts}) is

$$\delta_{ts}(E,\theta) = \hat{\delta}(\theta)D\left(\frac{E}{\hat{E}(\theta)}\right) \tag{5}$$

the scaling function $D(x)$ is chosen to ensure that δ_{ts} reaches a peak value $\hat{\delta}$ at an energy $\hat{E}$, namely,

$$D(x) = \frac{sx}{s-1+x^s} \tag{6}$$

where s is an adjustable parameter required to be greater than 1.

It is however impossible to implement millions of MCP channels in a three-dimensional 20-inch MCP-PMT model. Two models (model I and model II) are developed in CST to evaluate the collection efficiencies of the PMTs based on the traditional MCP and the coated one. A simplified three-dimensional MCP-PMT model (model I) shown in Fig. 1 is built to simulate the electric field and the electron trajectories in it. In the model, a pair of MCPs are replaced by two perfect electric conductors (PECs). The electric field in the PMT is simulated at operating voltage applied between the photocathode and the MCP input surface $U=500$ V. The field within 720 μm of the MCP input face, which is almost uniform as shown in Fig. 2, is exported for the following simulation. Photoelectron trajectories from nine points of the PMT photocathode (as shown in Fig. 6) to the MCP input face in the electric field are simulated. 5000 photoelectrons are emitted from each point. At a distance of 20 μm away from the MCP input face, the photoelectrons' location and momentum information is also exported. Another three-dimensional small area MCP model (model II) shown in Fig. 3 is developed to simulate the electron collection process. Only a small part of the MCP with diameter of 2000 μm is built for simplification. As exhibited in Fig. 4, the information of electric field within 720 μm of the MCP input face and electrons at a distance of 20 μm away from the MCP input face exported in model I is imported in model II. Electrons are set to be emitted within the boundary of the emitting plane (as the green area shows in Fig. 3). In comparison with the MCP model, the imported electron emitting plane is small enough to prevent electrons from escaping the computational domain. Electrostatic lens effect at the MCP channel entrances is simulated in detail as shown in Fig. 5. MCP channels are hexagonally-packed as exhibited in Fig. 3. Channel pitch is 11.06 μm. A_{open} of the MCP is 74.1%. Configuration parameters of the single channel are also presented. Channel diameter is 10 μm. Photoelectron emission points and the included angle θ between the line connecting the emission point and center of the ellipsoid (origin of coordinates) and Z axis are exhibited in Fig. 6. Inclined angle of the MCP channels in the x-y plane is $-10°$. MCP bias voltage in the following