Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2013 August 25; 8853: . doi:10.1117/12.2030076.

The effect of gain variation in micro-channel plates on gamma-ray energy resolution

Ling Han^a, Harrison H. Barrett^{a,b}, H. Bradford Barber^{a,b}, and Lars R. Furenlid^{a,b}

^aCollege of Optical Sciences, University of Arizona, Tucson, AZ 85721

^bCGRI, Department of Radiology, University of Arizona, Tucson, AZ 85721

Abstract

A Monte Carlo simulation of micro-channel plate (MCP) with particular interest in its effect on energy resolution performance is presented. Important physical processes occurring in MCP channels are described and modeled, including secondary electron (SE) yield, SE emission, and primary electron reflection. The effects causing channel saturation are also introduced. A two dimensional Monte Carlo simulation is implemented under the assumption of unsaturated channel. Simulation results about basic MCP performances and especially gain and energy resolution performances are presented and analyzed. It's found that energy resolution as an intrinsic property of MCP cannot be improved simply by adjusting system parameters; however it can be improved by increasing input signal or number of photoelectrons (PEs) in the context of image intensifier. An initial experiment with BazookaSPECT detector and CsI(Tl) scintillator is performed to validate and correlate with the simulation results and good agreement is achieved.

Keywords

Micro-channel plate (MCP); Monte Carlo simulation; secondary electron emission; energy resolution; gain variation; BazookaSPECT detector; image intensifier; electron multiplier

1. INTRODUCTION

Recently a new generation of high resolution gamma ray detector operating in photon counting mode has been developed at CGRI (Center for Gamma-ray Imaging), University of Arizona by Miller BW et al.^{1,2}, called BazookaSPECT. It makes use of MCP based image intensifier coupled to scintillator (usually CsI columnar scintillator is used but others are also applicable) for detection of gamma ray photons and up-front amplification of scintillation light. After the image intensifier, through lens coupling, integrating detectors such as CCD (charge-coupled device) or CMOS (complementary metal-oxide semiconductor) is used for acquiring amplified scintillation light which appears to be a cluster of pixels corresponding to a single photon interaction. An exploded view of original BazookaSPECT detector is shown in figure 1.

BazookaSPECT has many advantageous properties which make this detector valuable in many applications such as small animal single photon emission computed tomography (SPECT), Gamma-ray microscope, photon-counting digital radiography, computed tomography (CT), and photon-counting mammography³. Ultra-high sub-100 um intrinsic

spatial resolution is achievable in certain configuration. About 56mm diameter and as short as 13cm length make the detector compact for multi-detector systems, such as stationary SPECT imaging system. Recent development of CCD and CMOS techniques makes large number of low-cost high-frame-rate CMOS and CCD currently available. Utilizing these CCD/CMOS sensors and another recent technique known as general-purpose computing on graphics processing units (GPGPU) which makes convenient real-time processing and storage feasible, BazookaSPECT is capable of acquiring 20,000 events per second at 200 fps, sufficient even rate for most small-animal SPECT imaging tasks. Also to be noted is the broad range of detector configurations and performances offered by different choices of CCD/CMOS.

However, the energy resolution performance of BazookaSPECT detector is not satisfactory and can be as large as 65% shown in an experiment performed by us which will be described later in this paper. The reason for that may include the depth of interaction (DOI) effect and attenuation (scattering and absorption) inside the scintillator, the Poisson statistics of photo-electric interactions, MCP gain variations and errors in photon energy estimation algorithm. The DOI effect and attenuation effect can be improved by using very thin scintillator. The effect of Poisson statistics can be improved by high efficiency materials. The errors in estimation algorithm can be reduced by implementing the efficient maximum-likelihood estimator although current likelihood model for BazookaSPECT is not yet available. The MCP gain variation, however, still remains a problem as an intrinsic property of MCP physics. Also, Dr. Barrett² has analyzed the statistics of CCD/CMOS-based scintillation cameras including BazookaSPECT camera and mathematically proved that energy resolution of MCP will dominate the whole system energy resolution.

So, this paper is motivated by the need to understand and further improve the energy resolution performance of BazookaSPECT detector as described above. In section 2, we look into the physics of MCP, including SE yield, SE emission, primary electron reflection and other important physical effects causing saturation. In section 3, a 2D Monte Carlo simulation is described and implemented. In section 4, we show and analyze important simulation results. In section 5, an initial experiment is performed aimed to validate the simulation results and good correlation between simulation and experiment is found. Finally conclusions of this work are given.

2. MICROCHANNEL PLATE DETECTOR PHYSICS AND MODEL

A micro-channel plate is composed of many miniature electron multipliers parallel to each other as shown in figure 2. It's made by etching away fiber cores from a fiber-optic faceplate of which the rod is made from lead glass. There are about one million separate channels in one square centimeter. Each channel works as a continuous dynode and has diameter about 5–15 μm and length to diameter ratios between 40 and 80. Typical channel center-to-center spacing is 15 μm . Channels orientation is typically 8 degree (bias angle) relative to the input surface of MCP to facilitate interactions between incident PEs and channel wall. A potential difference also called bias voltage with several hundred to one thousand volts is placed across the channels which have total resistance about 100–1000 $\text{M}\Omega$. When a single photoelectron gets into the channel and penetrates into the channel wall, it deposits its

energy along the way and produces several secondary electrons. These SEs get accelerated by the electric field produced by bias voltage and again hit the wall to produce more SEs. This process repeats leading to a cascade of SE emissions. Finally a SE cloud exits the channel with a gain of $10^4 - 10^7$. Except for high gain, micro-channel plate also has ultra-high time resolution ($<100\text{ps}$) and the spatial resolution only depends on channel diameter and center-to-center spacing.

2.1 Secondary electron yield

SE yield directly depends on the primary PE energy and incident angle. When primary PE strikes the channel wall in the wall surface normal direction, initially as the primary energy increases, the yield also increases because more energy is deposited in the wall material, producing more SEs and since the primary electron doesn't penetrate too deep inside, most of SEs are within the escape depth and can come out of the wall into the channel. However, as the primary energy keeps increasing, the yield decreases because primary electron penetrates too deep inside the wall that most SEs lose all of their energy in diffusing to the surface and less SEs come out into the channel. If the primary energy is kept fixed, as the primary angle increases relative to the wall surface normal, the distance between the location where SEs are produced and the wall surface is decreased so that more SEs have enough energy to come out and the yield increases. Also to be noticed is that as primary angle increases, more energy can be used to produce SEs for a larger energy PE than a smaller energy PE, so the yield will increase faster for larger energy PE. G.E. Hill⁴ ever performed an experiment and the results proved the dependency of SE yield on primary energy and angle.

G.E. Hill⁴ also gave a semi-empirical model of SE yield based on the elementary theory of secondary electron emission developed by Salow⁵, Bruining⁶ and others. G.J. Price and G.W. Fraser⁷ has applied this model for his study on MCP. This model describes SE yield physics which is good, but it requires many parameters to be experimentally determined which is not convenient for a simulation. So in this paper, a model given by M.A. Furman and M.T.F. Pivi⁸ and applied by Ming Wu et al.⁹ is used which also predicts the SE yield performance and doesn't require many parameters to be determined. According to the model, SE yield as a function of primary energy and angle is given by (1).

$$\delta(E, \theta) = \delta_{\max}(\theta) \frac{s \frac{E}{E_{\max}(\theta)}}{s - 1 + \left(\frac{E}{E_{\max}(\theta)}\right)^s} \quad (1)$$

Where δ is the mean SE yield, E is the primary energy, θ is the primary incident angle, s is an adjustable material-dependent parameter (1.3 is used here), $\delta_{\max}$ is the maximum possible yield for a given angle θ and is given by (2), $E_{\max}$ is the corresponding primary energy that gives the maximum yield for angle θ and is given by (3).

$$\delta_{\max}(\theta) = \delta_{\max}(0) \exp[\alpha(1 - \cos\theta)] \quad (2)$$

Where $\delta_{\max}(0)$ is the maximum yield for normal incident primary PE which basically ranges from ~3.0 to 4.0 and a value of 4.0 is used in this simulation. α is a material-dependent parameter whose value ranges from 0.4 to 0.6¹⁰ and a value of 0.5 is used.

$$E_{\max}(\theta) = \frac{E_{\max}(0)}{\sqrt{\cos\theta}} \quad (3)$$

Where $E_{\max}(0)$ is the primary energy that gives maximum yield at normal incidence whose typical value varies between 200 to 300eV¹⁰ and 260eV is chosen for this simulation.

After we calculate the mean number of SE yield, real number of SE yield is randomly sampled from a Poisson distribution with the calculated mean.

2.2 Secondary electron emission energy

Since most SEs lose lots of energy in the process diffusing to the channel wall surface and overcoming surface potential, they usually carry low energies when they are emitted into the channel. G.E. Hill⁴ gave the energy distribution of SEs and the most probable energy is about 3.0 eV. G.J. Price and G.W. Fraser⁷ used an empirical formula given by I.R. Petrovna and Yu. A. Flegontov¹¹ which expresses the SE energy distribution. Ming Wu et al.⁹ utilized the Maxwell-Boltzmann probability distribution for modeling the SE energy distribution which is a similar and simplified version of the empirical formula and is used in this paper as shown in equation (4).

$$p(E_{SE}) = C \frac{E_{SE}}{E_0} \exp\left(-\frac{E_{SE}}{E_0}\right) \quad (4)$$

Where $p(E_{SE})$ is the probability for a SE to have energy E_{SE} , C is a normalization constant, E_0 is the most probable energy for SEs whose value is taken to be 3.0eV as shown by G.E. Hill⁴.

The real value for SE energy is randomly chosen from the above distribution. Conservation of energy principle is also applied here as a constraint, that is, if total energy assigned to all SEs generated by one primary electron is greater than the primary energy, then the energies for all SEs will be sampled again until the total energy is smaller than primary energy. Also to be noticed is that SEs will be accelerated by electric field in the channel and E_{SE} will increase and work as primary energy E for next collision.

2.3 Secondary electron emission angle

The angle of SE emission relative to the channel wall surface normal is following a normalized cosine probability density distribution as shown in equation (5) which is widely used by many other people in their simulation of SE emission and is supported by Monte Carlo simulations of SE emission process performed by J. Kawata et al.^{12,13}.

$$p(\theta) = 0.5 \cos(\theta) \quad (5)$$

Physically this distribution also makes sense because to emit in a large angle, SE needs to undergo a longer distance from its generation site to the surface, leading to less probability of occurrence.

2.4 Primary electron reflection

When primary energy is very large, primary electron probably always penetrates into the wall material and incurs secondary electron emissions. These SEs will be accelerated by the potential difference across the channel and work as primary electrons for next collisions. However, since these primary electrons have different emission angles and energies, some of them may not get enough energy from the electric field before next collision and will be elastically reflected by the channel wall instead of producing SEs. This process is called the SE reflection or elastic scattering. Probability for this process to happen only depends on primary energy and is expressed by Scholtz et al.¹⁴ as shown in equation (6).

$$p_{ref}(E) = \exp[1.59 + 3.75 \ln E - 1.37 (\ln E)^2 + 0.12 (\ln E)^3] / 100 \quad (6)$$

When reflection happens, the kinetic energy of SE will not change but the direction of velocity will according to principle of reflection.

2.5 Other physical effects

The physical effects described and modeled above are dominant when the gain is small and important for our main purpose which is to study the gain variation under unsaturated channel condition. However other physical effects are dominant when gain becomes very large and are important causes for channel saturation.

In the case of straight channel, when the gain increases, the probability that electron collisions with residual gas molecules and gas molecules desorbed from channel wall due to electron strikes produce positive ions is increased. These ions usually are produced in high space-charge-density region close to the output of the channel and can drift back to the channel input to produce SEs, resulting in regenerative feedback effect and gain saturation. This effect is called ion feedback. Bending or twisting the channels and vacuum environment can be used to avoid this effect.

As mentioned earlier, channels have resistance about 100–1000 MΩ and is relative uniform down the channel so the current available to be transformed to SE space current is limited. When the gain is very high, space charge will deplete the wall current, thus reducing the electric field in the channel which in turn reduces SE yield. As a result, gain is saturated. L.A. Harris¹⁵ calculated this steady state gain.

Finally another possible cause of saturation is called space charge effect. According to Joseph Ladislav Wiza's words¹⁶ (and I'm quoting here), "at high enough gains, the space charge density at the rear of the channel reduces the 'kinetic energy' of electrons as they interact with the channel walls until the secondary electron yield is reduced to unity." Other people have also discussed this effect in the past^{17,18,19}.

3. MONTE CARLO SIMULATION

The MCP is used in image intensifier for our case which is composed of a photocathode (S25) coupled to a fiber-optic face plate, a phosphor screen (P43) coupled to fiber-optic faceplate and a MCP or two MCPs in between as shown in figure 1 (middle one). The photocathode will produce randomly sampled number of PEs from a Poisson distribution of which the mean corresponds to incident light signal. These PEs will initially have very low energy and then be accelerated by a potential difference 200–300V placed between photocathode and the MCP. With 200–300eV energy, these PEs enter MCP channels, strike the channel wall and incur electron cascade process.

This Monte Carlo simulation is based on 2D model of MCP channel, assumes nonrelativistic electron motion, and neglects correlation between electrons and any cross-talk effects between adjacent channels. Only the effects in 2.1–2.4 are considered, in other words, this simulation only works in unsaturated mode and saturation effects as described in 2.5 are not included. Also only a single channel is simulated because as long as the channels are working in unsaturated mode and correlation between electrons neglected, the difference between PEs entering multiple channels and a single channel is just a problem of spreading which is not an intrinsic property of MCP but dependent on the input light signal.

The default simulation parameters are listed below in table 1 unless future analysis requires certain parameters to be changed which will be clearly stated.

Simulation starts with one PE, calculates how many SEs will be generated upon the first collision, assigns energies and emission angles to each SE, traces their paths until next collisions and finally collects SEs coming out of the channel including information they carry. The number of incident PEs will determine how many iterations of the above simulation to be performed. Two kinds of simulation-based studies are performed in this paper. One study is to analyze time resolution, output electron cloud angular and energy distribution, and number of collisions distribution all of which are basic MCP properties, based on a fixed number of incident PEs. To study MCP gain variation and its effect on energy resolution of image intensifier, more simulations are performed based on both fixed number of PEs but varying system parameters and random number of PEs but fixed system parameters. This is also the main focus of this paper.

4. SIMULATION RESULTS AND ANALYSIS

4.1 MCP basic properties study

A total of 10 PEs are incident into one MCP channel. After electron cascade process, about 60,000 SEs are produced at the exit face of the channel. All information including number of collisions undergone, transition time used, energy and emission angle of each SE at the exit face is collected and corresponding histograms are generated from statistical perspective as shown in figure 3.

From these histograms, we see most SEs may undergo between 15 to 28 collisions with the channel wall. Broad distribution for the collision number will contribute to large gain variation, affecting energy resolution; however this is not the only factor influencing gain

variation as discussed later. Average transition time is about 128ps which is ultra-fast. Also FWHM for transition time distribution is about 40ps, leading to temporal resolution less than 100ps which is consistent with commonly known value. This also validates the simulation in some sense. From output SE energy distribution, we see the peak energy is about 15–20eV and the trend of this distribution is similar with that of SE emission energy distribution as described in section 2.2 because output SEs are simply accelerated version of newly generated SEs. Finally the angle distribution is generated only for output SEs generated on one side of the channel wall and the output SEs generated on the other side of wall will have similar distribution but with negative emission angles. Also the angle is relative to the wall surface instead of wall normal as in section 2.3. Here a peak angle of about 5 degree is observed and the percentage relative to the peak is small for output angle greater than 30 degrees. That means most output SEs are emitted along the channel surface. In the context of image intensifier, there will be another potential difference placed between exit face of MCP channel and a phosphor screen used to collect these SEs. As a result, a strong electric field is generated and will further collimate these SEs so that the angle distribution is greatly compressed, thus greatly reducing effect of angular spread of output SEs on spatial resolution.

These distributions specify different MCP properties and are sensitive to system parameters like channel diameter and length and bias voltage. These are useful results supported by this simulation, can be used to verify the effectiveness of this simulation and can be further explored if interested, but these are not the main focuses of this paper so I will not discuss in depth.

4.2 Gain performance study

To find out how the gain spectrum varies with system parameters, a fixed number of 10 PEs is used and 1000 iterations are performed. By varying MCP channel diameter (D), channel length (L) and bias voltage (U), several histograms are generated in comparison with a reference histogram (a) as shown in figure 4. Also mean gain and energy resolution are calculated for each spectrum.

A simple mathematical model used to calculate the gain of MCP is proposed by Edward H. Eberhardt²⁰ under a series of assumptions and approximations. This model simulates the gain mechanism as the product of primary PE effective gain and a number of gains corresponding to each following collision as shown in equation (7).

$$G = \delta_{PE} \delta^{n-1} \quad (7)$$

Where G is the total gain, δ_{PE} is the effective gain of primary PE, δ is the effective gain of following collisions, n is the total number of collisions or amplification stages.

With the help of this equation, we can understand the results shown in figure 4 and reach following conclusions. Both too large and too small channel diameter will lead to decreased gain because either amplification stages n is too small due to large diameter or effective yield for each stage is too small due to short acceleration distance, by comparing (a) with (b)

(c). So optimal channel diameter exists to maximize gain. Decreased channel length directly decreases number of amplification stage which results in less gain, comparing (a) and (d). Gain is very sensitive to bias voltage which mainly affects yield of each stage. A small decrease in voltage leads to a large drop of gain comparing (a) and (e).

Energy resolution which describes the gain variation is almost insensitive to these system parameters as shown in figure 4. Factors contributing to gain variation include δ and n both of which are random and have a large range of possible values around some mean value as shown in section 2.1 and figure 3. Unfortunately, the mean and range of δ and n always go together. When system parameters are adjusted to increase δ and n , their ranges also increase; when system parameters are adjusted to decrease δ and n , their ranges also decrease. That's why we don't see too much ER change when we change different system parameters.

4.3 Energy resolution study

Now we have analyzed gain performance of MCP alone, we can put MCP in the context of image intensifier and study the effect of gain variation on the energy resolution of image intensifier, which is the key component of BazookaSPECT. In image intensifier, PEs are generated by the photocathode and the number of PEs follows Poisson distribution with mean corresponding to incident light intensity. Because of Poisson statistics added into MCP gain statistics, the energy resolution of image intensifier will be larger than a single MCP as shown in figure 5.

To be noticed, the ER of (a) in figure 4 is smaller than that of left spectrum in figure 5 both of which are under exactly the same system parameters, only with different number of PEs. The reason is because MCP gain statistics can be viewed as the sum of N independent identical distributions each corresponding to a single PE where N is the number of PEs. As N increases, MCP gain statistics approximate Gaussian distribution according to central limit theorem, the ER of which also will decrease as N increases. Similarly analysis can be made for the Poisson distribution of PEs in the context of image intensifier which approximates Gaussian distribution as mean number of PEs M increases. So the energy resolution performance should be better for more PEs (larger N or M). A simulation is performed to find out the relation between ER and the mean number of PEs (N and M) as shown in figure 6.

From figure 6 we see energy resolution of image intensifier can be improved by increasing incident light signal or number of PEs. For any given energy resolution, we can estimate the mean number of PEs generated in the photocathode using this curve. Due to large gain variation of MCP plus Poisson statistics of PEs, about 800 mean number of PEs are required to improve ER to below 20%.

5. EXPERIMENTAL RESULTS AND ANALYSIS

A preliminary experiment aimed to validate and correlate with the simulation results is performed using Co57 122keV gamma-ray source, and BazookaSPECT detector with 400 μm CsI(Tl) transparent columnar scintillator and 1 MCP image intensifier made by

Proxitronic corporation. Opaque entrance is applied to the scintillator. MCP bias voltage is adjustable in the range of 400–900V by an external DC power supply made by B&K Precision Corporation. BazookaSPECT works in photon counting mode. By adjusting distance between radiation source and the photocathode input surface, no or very few events overlaps appear in each frame which facilitates event extraction in post processing. After raw images with events recorded are acquired, a series of post processing are performed including smoothing, connected components labeling, amplitude and area thresholding to extract real event clusters in the image. Then by simply summing up pixel values of each event cluster as its energy, an energy spectrum can be generated and energy resolution of the whole system can be calculated.

Since the simulation is under unsaturated channel assumption, bias voltage in the experiment is adjusted to reduce gain to avoid saturation effect and at the same time keep event clusters still visible from CCD noise. Amplitude and area thresholds are adjusted to avoid noise events and keep real events as many as possible. Energy spectrums for three bias voltages are generated and shown in figure 7.

Because this experiment is performed in low gain configurations with 1 MCP image intensifier and low voltage setup, signal noise ratio becomes very small. To separate limited number of real events from overwhelming noise clusters, thresholding will introduce truncation effect to resultant energy spectrum as shown in figure 8 and the less gain, the more severe truncation effect there will be. For example the green line will suffer from truncation effect the most among the three fitted spectrums and only a small portion of real events are collected. Another effect is channel saturation effect which is obvious in the red line from its expanded shape. The reason for saturation effect to occur is because BazookaSPECT has very good spatial resolution which means incident photons stay together closely, increasing the number of PEs entering each channel and finally causing channel saturation in some channels. The larger bias voltage, the more gain there will be and more saturation effects there will be. In sum, it's hard to satisfy unsaturation and no truncation at the same time based on the BazookaSPECT configurations. So the blue curve in the middle of the three is found to have a good balance between saturation and truncation and will best represent the system energy resolution performance.

Although scintillator, opaque entrance and energy spectrum generation algorithm all will contribute to energy resolution, their effects are small compared with that of image intensifier which has great signal amplifying power and will dominate total energy resolution of the system as mathematically described by Dr. Barrett². So take 65.1% as the ER of the image intensifier and refer to figure 6, we will know approximately 50 PEs are generated by the photocathode. Considering that the photocathode (S25) has a QE of about 9% at 550nm (peak emission wavelength of CsI:Tl scintillator), the fiber optics faceplate coupled with photocathode has a NA of 0.58 and opaque entrance absorbs half of total photons, we can calculate there are about 6000 photons generated in the scintillator. According to the literatures, CsI(Tl) scintillator has light yield of about 54 photons/keV, which means there will be 6588 photons generated for each 122keV gamma-ray photon iteration. The two results match very well which means the simulation results are reliable as

long as we work in unsaturated mode and figure 6 can be used to calculate approximately how many PEs are generated in the image intensifier for different experiments.

Since this is just an initial experiment trying to back up the simulation, more careful designs of experiment setups can be developed including accurate photon countable source, much low noise CCD/CMOS and more accurate event extraction algorithm like ML estimator, to get more reliable energy spectrum in unsaturated low gain MCP configurations and thus more accurate correlation between simulation and experiments.

CONCLUSIONS AND FUTURE WORK

In this work, we have introduced the micro-channel plate and modeled key physical effects inside the channels. Based on these effects, a 2D Monte Carlo simulation has been implemented under unsaturation assumption with respect to channel properties, gain and energy resolution performance. Simulation results have shown that MCP gain will be affected by system parameters; however the large gain variation or poor energy resolution is almost insensitive to these parameters, because of large range of amplifying stages and yield per stage. As a comparison, PMT usually has fixed amplifying stages and smaller range of yield per stage. Further exploration of gain statistics has shown that energy resolution can be improved by increasing number of incident PEs. A curve is generated relating MCP or image intensifier energy resolution to mean number of incident PEs. From this curve, we see it's possible to improve energy resolution to less than 20% when you have more than 800 PEs generated. Large QE photocathode, high light output scintillators, large NA fiber optic faceplate will all help increase number of PEs. However, you need to be cautious that the MCP may be saturated when the number of PEs is large.

To achieve more reliable experimental results to accurately correlate with this simulation, more careful designs of the experiment setup are needed, including the use of photon countable source and low noise CCD/CMOS camera. Also channel saturation effects can be further studied if necessary to get a complete picture of MCP. Finally based on the knowledge of this paper, new design of MCP structure is needed to achieve better intrinsic energy resolution as well as high gain, excellent spatial and temporal resolution, thus facilitating next generation of BazookaSPECT camera. This may be in future publications.

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Figure 1.

Exploded view of BazookaSPECT detector. A scintillator needs to be coupled to the image intensifier which has 25mm input/output diameter and 1 MCP inside. CCD camera is DragonFly Express from Point Grey Research, Inc and has 1/3" format Kodak KAI-0340 sensor with 640×480 pixels and 7.4μm pixel pitch.

Figure 2.

Left: Micro-channel plate structure. Middle: Image intensifier structure with 1 MCP inside.

Right: Amplified view of electron cascade process inside a single channel.

Figure 3.

Simulation results based on 10 incident PEs. Number of collisions distribution (top left); transition time distribution (top right); output SEs energy distribution at the exit face of MCP channel (lower left); output SEs emission angle (relative to wall surface) distribution also at the exit face (lower right).

Figure 4.

Gain spectrum under different system parameters. (a) Reference gain spectrum with channel diameter $D=6\mu\text{m}$, channel length $L=300\mu\text{m}$, bias voltage $U=1000\text{V}$, mean=40507, energy resolution (ER)=94.1%; (b) Larger diameter $D=12\mu\text{m}$ channel with other parameters same as the reference ones, mean=20543, ER=79.0%; (c) Smaller diameter $D=4\mu\text{m}$ channel, mean=14249, ER=97.8%; (d) Shorter channel length $L=200\mu\text{m}$, mean=31548, ER=108.5%; (e) Decreased bias voltage $U=900\text{V}$, mean=16785, ER=90.6%.

Figure 5.

Two histograms showing ER difference for a single MCP with 5 PEs (Left, ER=135.8%) and the same MCP in the context of image intensifier with mean number of 5 PEs (Right, ER=181.7%). System parameters are the same as in chart 1 which is also a similar configuration as a real image intensifier used in later experiment.

Figure 6.

Relation between ER and mean number of PEs. Both MCP case with fixed number of PEs and image intensifier case with Poisson distributed number of PEs are simulated. ER of ~10% can be achieved for a single MCP with 1000 fixed number of PEs and ~15% can be achieved for image intensifier with mean number of 1000 PEs equivalent light signal.

Figure 7.

Energy spectrums of BazookaSPECT detector for three different bias voltages. Black lines are experimental results; red, blue and green lines are fitted curves used to calculate energy resolution. ER=115.9%, 65.1%, 50.1% for red, blue and green curves.

Table 1

Default parameters used in this simulation

PE energy	Bias angle	Channel diameter (D)	Channel length (L)	Bias voltage (U)
200 eV	8°	6 μm	300 μm	1000 V