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A Study on the Spatial Resolution of Gas Detectors Based on EGS4 Calculations

B. S. Moon · S. H. Han · Y. K. Kim and C. E. Chung
Korea Atomic Energy Research Institute

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Abstract – Results of EGS4 based calculations to study the spatial resolution of gas detectors are described. The calculations include radial distribution of electrons generated by photons of various energies penetrating into variable thickness of Ar and Xe gas layers. Given a desired spatial resolution, the maximum allowed thickness of gas layer for each energy level is determined. In order to obtain 0.1mm spatial resolution, the maximum thickness for the Ar gas is found to be 2mm for photon energies below 14keV while the optimum energy of photons for Xe gas with the same thickness is about 45keV. The results of calculations performed to compare the number of electrons generated by CsI coated micro-channel plate and the number of electrons generated by the Ar and Xe gas layers are described. The results show that the number of electrons generated by the gases is about 10 times higher than the one generated by CsI coated micro-channel plate. A few sample gray scale images generated by these calculations are included.

Key words : gas detectors; spatial resolution; micro-channel plate; EGS4 simulations

INTRODUCTION

During the course of developing an X-ray imaging system [1] based on a set of GEM plates [2], we performed an analysis on the spatial resolution of gas detectors. The gases like Ar and Xe produce more electrons than solid photo-converters but there are greater limitations in the spatial resolution when gases are used. We describe in this paper the results of a study based on EGS4 calculations for the spatial resolution of gas detectors. The term 'spatial resolution' is used to indicate the smallest width of a pair of lead strips that can be distinguished from each other when they are separated by a distance same as the width of the strips. The thickness of the lead strips is fixed at 5mm and the gas detector is assumed to be located directly below the lead strips when the images are to be generated.

First, we compute the radial distribution and energy spectrum of the electrons generated in Ar and Xe gas layers of various thickness ranging from 1mm to 10mm. The photons are assumed to penetrate into the gas layers perpendicularly from a point source located 1cm to 10cm away from the gas layers. To determine an optimum energy for input photons, we made computations for various energy values. The energy ranges we studied are from 15keV to 25keV for Ar gas and 40keV to 60keV for Xe gas. We generated a series of example images by using the lead strips described above with various width and some of the resulting images are included in this paper.

For a comparison purpose, we also include the results of calculations for CsI coated micro-channel plates. We chose CsI as the photo-cathode material since it is found to have better conversion efficiency than other materials. Martin et al.[3] showed that CsI is better than CsBr or any combinations of CsI and CsBr when X-ray energy is below 10keV. For higher X-ray energies ranging up to 100keV, Burginyon et al.[4] made a comparative study on the detector efficiency of micro-channel plates with gold photo-cathode against BC422 plastic scintillator material. Tremsin et al.[5] studied the gain of the micro-channel plates with gold coated against nichrome coating.

The micro-channel plate we will be using is 0.5mm thick and has holes of diameter 25μm with pitch size 37μm. The top of the plate and inner parts of holes are coated with the a photo-cathode material. The plate is assumed to be made of PbO and the photo-cathode material is CsI with 0.1-1μm thickness. Some of the experimental results of Frumkin et al.[6] had to be used for estimating the electron range of secondary electrons due to the limitation of EGS4 for not being capable of transporting electrons of energy less than 10keV. Along with the EGS4 calculations, we used the escape depth of 56nm for CsI and the universal yield curve to estimate the number of electrons generated inside an MCP hole.

RADIAL DISTRIBUTION OF ELECTRONS GENERATED BY GASES

In this section, we describe the results of calculations performed to study the radial distribution of electrons generated by photons penetrating into a thin gas layer perpendicularly. We studied Ar and Xe gas layers in the range of 1mm to 5mm thick with 0.5mm intervals. Photons of various energies ranging from 15keV to 100keV are assumed to penetrate into the gas layer starting from a fixed point.

First, we consider the case of 3mm thick Ar gas layer. Using EGS4, we transported the photons inside the Ar gas until their energy becomes below 1keV and the electrons generated by the photons until their energy becomes below 10keV. We computed the radial distribution of the number of electrons generated by the photons whose energy ranges from 15keV to 35keV. The results of calculations using 5million photons are shown in fig. 1. One can see from the figure that the photons with larger energies tend to move farther in the radial direction and that if their energy is 15keV, the maximum distance is about 0.2mm. The numbers inside parentheses in fig. 1 are the numbers of photons that made at least one interaction inside the gas layer before they get out of the layer. The figure on the right hand side is obtained by reducing the thickness of Ar gas to 2mm. From this figure, one can see that a spatial resolution of 0.1mm can be obtained if the X-ray energy is kept below 15keV.

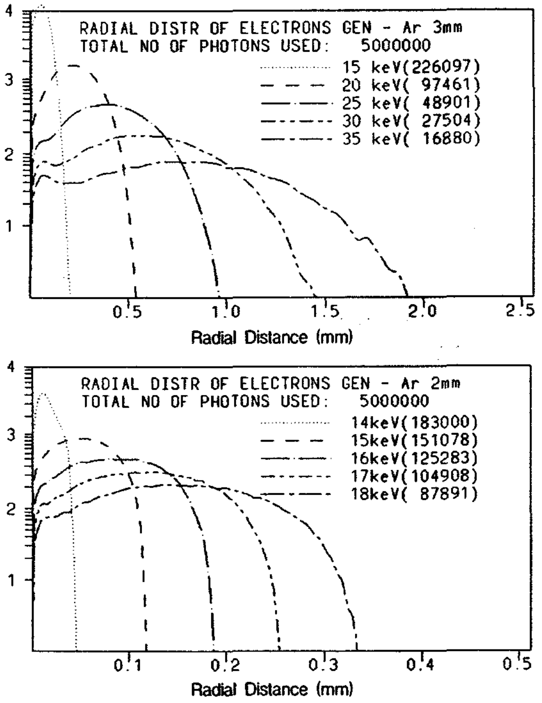


Fig. 1. Radial distribution of Electrons generated in Ar gas (Left-3mm, Right 2mm).

The left side figure in fig. 2 shows the calculated results with 5 million photons when the photon energy is kept at 30keV while the thickness is varied from 1mm to 5mm. The right hand side figure shows the results when the photon energy is kept at 15keV. The numbers inside the parentheses in the right side graph are the number of electrons generated inside the gas. One can deduce from this figure that if the energy of input photons is kept below 15keV, then the radial distribution of the generated

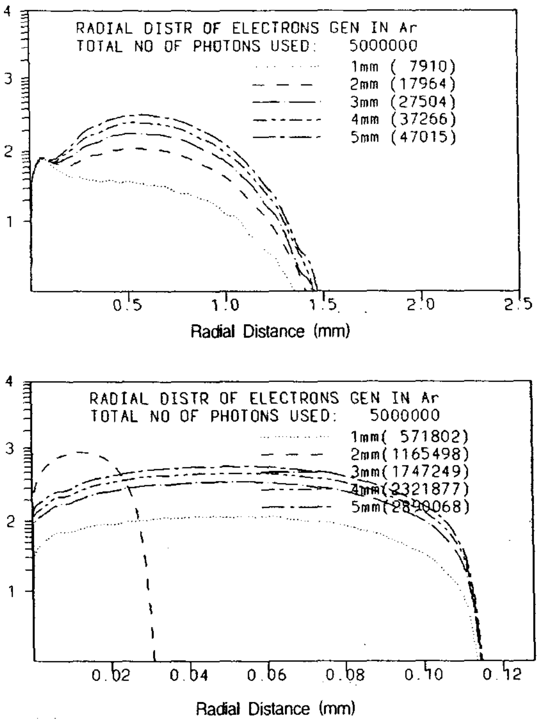


Fig. 2. Radial distribution of electrons in Ar gas layer (Left-30keV, Right-15keV).

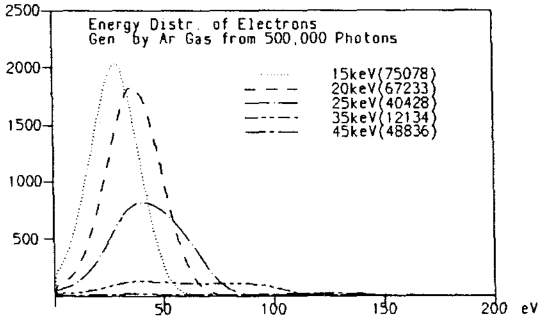


Fig. 3. Energy spectrum of electrons generated versus the input photon energy.

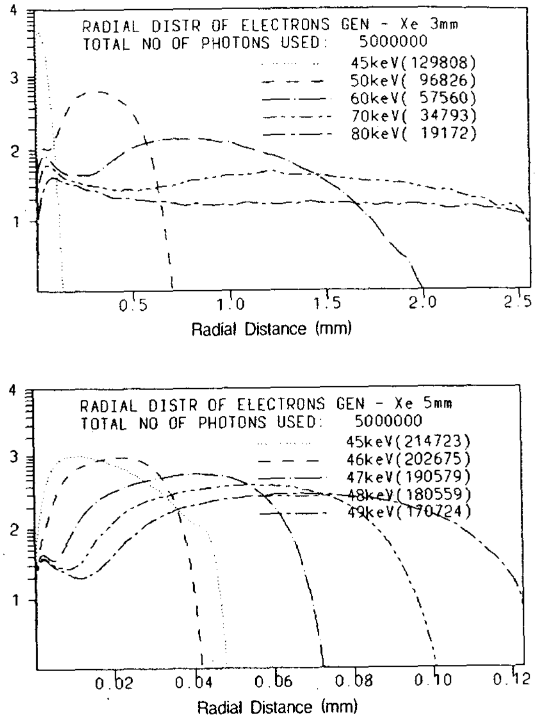


Fig. 4. Radial Distribution of Electrons Generated in Xe gas layer (Left-3mm, Right-5mm).

electrons is within 0.12mm from the penetrating location and the maximum movements of electrons do not vary much as the thickness of gas layer varies. From the figure on the left side of fig. 2, one can see that the spatial resolution of 0.1mm cannot be obtained for the Ar gas if the input energy ofphotons is 30keV. The energy spectrum of electrons generated inside the gas layer is shown in fig. 3. One can see from this figure that the generated electrons have energies mostly below 50eV and that the adequate energy of photons to be used for Ar gas is below 20keV.

Next, we performed the same set of calculations for the Xe gas. When 5 million photons have been input to a 3mm Xe gas layer, we obtained the radial distribution of generated electrons as shown in fig. 4. We found that photons of energies less than 40keV generated relatively little amount of electrons and they are not shown in thefigure. Thus, we conclude that photons of energies near 45keV must be used if Xe gas is to be used in the detector. The figure on the right shows that if the photon energy is kept below 45keV, one can obtain a spatial resolution that is much better than the case of Ar gas.

Figure 5 shows the variation of the radial distribution of electrons generated inside a Xe gas layer as the thickness of the gas layer varies when 45keV photons are used. The numbers inside the parentheses are the number of electrons generated inside the gas layer. Note that the number of electrons generated inside the gas layer is increasing almost linearly as the thickness increases. Figures 6 and 7 show the total number and the energy spectrum of electrons generated inside the Xe gas.

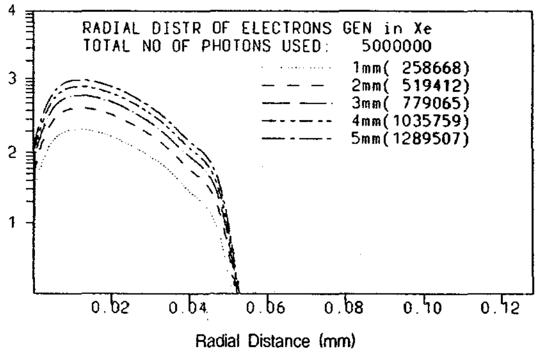


Fig. 5. Radial distribution of electrons in Xe gas layer by 45keV photons.

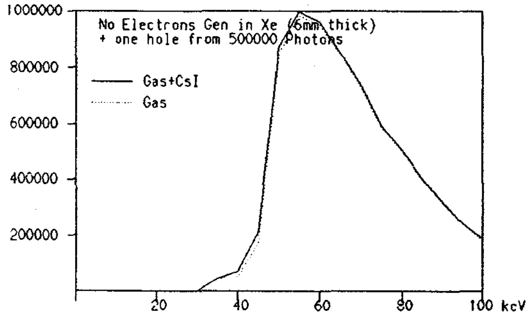


Fig. 6. No of Electrons Generated (3mm Xe).

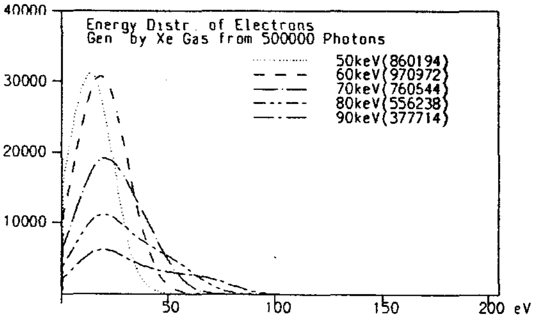


Fig. 7. Energy Spectrum of Electrons (3mm Xe).

EXAMPLE IMAGES GENERATED BY GAS DETECTORS

In this section, we describe the example images created by taking the number of electrons generated by EGS4 calculations as the gray scale of an image. The geometry used in the simulation for creating the images is shown in fig. 8, where the object located at the top is a lead plate with two strips cut out and a gas layer is located below with a vacuum layer in between. We counted the number of electrons generated inside the gas by putting artificial grids inside the gas layer.

In both figures fig. 9 and fig. 10, the dark strips indicate the gaps in between the lead(Pb) strips and the white areas are the lead strip images. From these figures, one can see that the spatial resolution for the case of Xe with 45keV

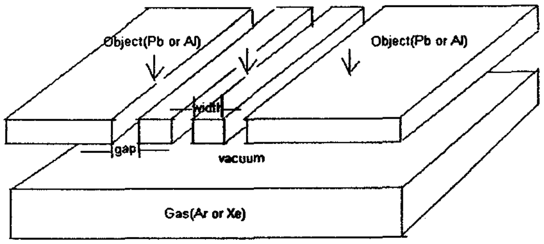
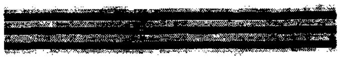
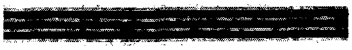


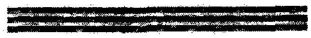
Fig. 8. Geometry to generate simulate the image generation.



Width-0.2mm, Gap-0.2mm

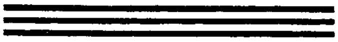


Width-0.1, Gap-0.2mm



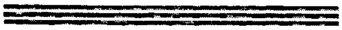
Width-0.2mm, Gap-0.1mm

Fig. 9. Sample images generated by EGS4 for Ar gas layer of 3mm thick.



Width-0.2mm, Gap-0.2mm

Width-0.1mm, Gap-0.2



Width-0.2mm, Gap-0.1mm

Fig. 10. Sample images generated by EGS4 for Xe gas layer of 3mm thick.

photons (fig. 10) is better than the case of Ar with 15keV photons (fig. 9). This is what was expected from the radial distribution of electrons shown in fig. 2 and fig. 5. The difference comes from the difference in the electron ranges in the two different gases. Comparing the middle and the right side images in both fig. 9 and fig. 10, one can see that more electrons tend to make the image clearer. This is what makes the difference between gas detectors and the detectors using micro-channel plates, i.e. the gas generates more electrons than the micro-channel plates even though electrons have larger ranges in gases.

COMPARISON WITH DETECTORS USING MICRO-CHANNEL PLATES

In this section, we describe the results of EGS4 calculations performed for a micro-channel plate to see if the spatial resolution of images generated by the micro-channel plate can be compared with the resolution of images generated by the gas detectors described in the previous section. First, we transport photons normally incident to a thin CsI plate using EGS4 until the energy becomes less than 1keV and the energy of generated electrons become less than 10keV. Next, we estimate the secondary electrons emitted from the plate in two parts. The first part is the secondary electrons generated near the plate boundary within the escape depth which is 56nm for CsI and the other part is the secondary electron yield from the electrons of energy in the range from 100eV to 10keV.

The first part is estimated by integrating the product of the number of secondary electrons generated and a probability function for electrons at different locations to get out of the plate. The second part is computed by using the 'universal yield curve'[6] along with the same probability function. Fig. 11 shows the geometry used for the calculations with only one hole. To determine an optimum energy level for the photo-converter used, we performed the calculations for various energy levels and the results are as shown in fig. 11, from which we conclude that the optimum energy level for CsI is near 40keV.

To generate an image through simulations for a micro-channel plate, we must not only program for the over 40,000 holes for an image of size 1Cm^2 but also perform the calculations for all these holes. Assuming that an average of 100 electrons are desired for each hole, the total number of electrons is about 4 million. The conversion efficiency turns out to be about 3% for the geometry that we use as described below and hence we must transport at least 120 million photons to get an image. Note that we have not included the object lying in between the source and the detector in our estimation. Thus, we decided to perform calculations for one hole only. Since the electron range in CsI is smaller than

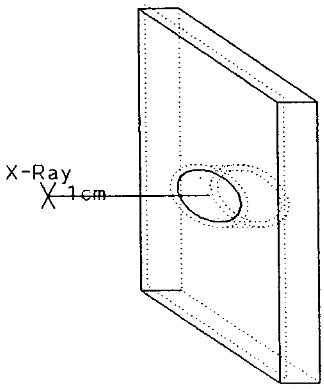


Fig. 11. Micro-channel plate.

that in Xe gas, the spatial resolution of the image generated by an MCP should be no worse than the image generated by the Xe gas. Hence, we may assume that the image looks clearer than the one generated by Xe. However, there is a difference in the total number of electrons generated by the same number of photons. To compute this difference, first we note that the electrons are generated mostly from the coating material inside the holes when we a thickness of 0.0003mm is used for CsI.

In an actual micro-channel plate, there are about 20×20holes in $1mm^2$ area and each hole is 25 micron in diameter. Thus, the fraction of the surface area occupied by the holes is $400 \times \pi \times 0.0125^2$ $mm^2 \approx 0.196$ mm^2, about 20% of the total surface area. Therefore, we decided to take a disk area whose radius is $\sqrt{5}$ times the cross section area of the hole as the area for input photons. The computed results show that the total number of electrons generated by one CsI coated micro-channel plate hole is 312,000 electrons from a 10,000,000 input photons and hence the efficiency is about 3.1%. For the case of Xe gas, one can read from fig. 5 that a total sum of 1,289,507 electrons are generated from a 5mm thick gas layer from 5,000,000 photons of 45keV, from which one can compute an efficiency of 26%. Therefore, we conclude that the spatial resolution of images generated by a micro-channel plate is better than that of images generated by gas detectors if long enough exposure time is used for the micro-channel plate. The amount of time required for the same clarity is about 10 times longer than the case of gas detectors.

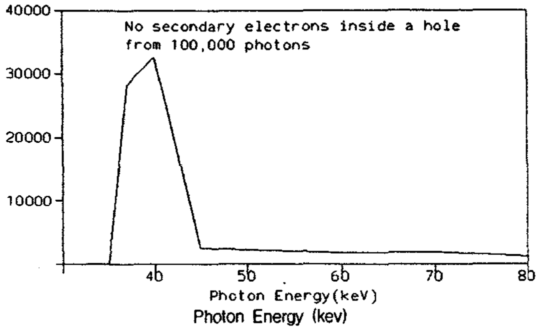


Fig. 12. Number of Electrons Generated vs Photon Energy.

CONCLUSION

Based on EGS4 calculations, we have determined that the spatial resolution of 100μm can be obtained when Ar gas is used with thickness 2mm or less and with the energy of photons kept below 14keV. For the Xe gas, however, the thickness can be up to 10mm for the 100μm resolution if the photon energy is below 45keV. When a CsI coated micro-channel plate is used, we found that the number of electrons generated is about one tenth of the number generated by 5mm thick Xe gasand hence it should take 10 times longer time for the exposure to obtain the same resolution.

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