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A Monte Carlo study of the impact of phosphor optical properties on EPID imaging performance

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Abstract

We have developed a Monte Carlo computational model of a clinically employed electronic portal imaging device (EPID), and demonstrated the impact of phosphor optical properties on the imaging performance. The EPID model was built with Geant4 Application for Tomographic Emission (GATE). Both radiative and optical transport were included in the model. Modulation transfer function (MTF), normalized noise-power spectrum times the incident x-ray fluence (qNNPS), and detective quantum efficiency (DQE) were calculated for simulated and measured data, and their agreement was quantified by the normalized root-mean-square error (NRMSE). MTF was computed using a 100 μm wide slit tilted by 1.5° and qNNPS was estimated using the Fujita-Lubberts-Swank (FLS) method. DQE was calculated from MTF and qNNPS data. The NRMSE value was 0.0467 for MTF, 0.217 for qNNPS, and 0.0885 for DQE, showing good agreement between measurement and simulation. Five major optical properties, phosphor grain size, phosphor thickness, phosphor refractive index, binder refractive index, and packing ratio were tested for their influence on the qNNPS, MTF, and DQE(0) of the model. Generally, the effect on the qNNPS is greater than MTF, and no impact on DQE(0), except from phosphor thickness, was observed. Multiple applications, such as imager design optimization and investigations of the dosimetric performance, are expected to benefit from the validated model.

Keywords

EPID; Monte Carlo simulation; NPS; MTF; optical properties

1. Introduction

Dose delivery during radiation treatment can be compromised due to setup error as well as organ and patient motion (Svensson, 1984; Kutcher *et al.*, 1995). Portal imaging with radiotherapy film cassettes using the primary treatment beam has been previously applied to verify patient position before or during radiation treatment (Antonuk, 2002; Munro and Bouius, 1998). The disadvantages of film use, such as the relatively long time required for image processing and display, and limited dynamic range, were partially addressed with the development of electronic portal imaging devices (EPIDs) (Antonuk, 2002).

Most current clinical EPIDs utilize a structure consisting of a metal layer, phosphor screen e.g. gadolinium oxysulfide (GOS), and an amorphous silicon (a-Si) flat panel detector array for indirect photon detection. X-ray energy is deposited in the phosphor screen and optical photons are generated through scintillation processes. The final image is formed from the detection of optical photons that reach the underlying amorphous silicon flat panel detector. The phosphor screen consists of phosphor grains packed within a binder material. This EPID design is capable of fast digital image acquisition with high spatial resolution (El-Mohri *et al.*, 1999; Antonuk, 2002; van Elmpt *et al.*, 2008), and can withstand high radiation exposure (Antonuk, 2002; Blake *et al.*, 2013). EPIDs can be employed for several clinical applications including megavoltage (MV) cone-beam computed tomography (CBCT), high-z material artifact suppression, pre-treatment patient positioning, treatment plan quality assurance, and real-time tumor localization (Mijnheer *et al.*, 2013; Grzadziel A, 2007; Celi *et al.*, 2016; Rottmann *et al.*, 2013; Berbeco *et al.*, 2007).

Several Monte Carlo (MC) simulation studies have previously explored the impact of phosphor properties on detector imaging performance. Radcliffe *et al.* (Radcliffe *et al.*, 1993) described the effects of the thickness of phosphor and metal on phosphor screen performance metrics, such as x-ray detection efficiency, energy deposition, and signal-to-noise ratio, without considering modulation transfer function (MTF) or noise-power spectrum (NPS). Kausch *et al.* (Kausch *et al.*, 1999) evaluated the dependence of MTF, NPS, and detective quantum efficiency (DQE) on the thickness and material of metal/phosphor screen with 2 and 6 MeV mono-energetic photon beams; showing that high atomic number metal may give better DQE performance. The optical transport was simulated by a convolution of energy deposition and optical line spread function, and no other optical properties were evaluated other than phosphor thickness. Liaparinis *et al.* (Liaparinis *et al.*, 2006) evaluated the dependence of MTF on phosphor grain size and packing ratio. They found that improved resolution may be acquired with a high packing ratio and small grain size. This study was conducted with a kV energy source, and no evaluation of detector NPS was performed. The impact of the optical emission spectrum and grain size distribution on the scattering transport parameters has been investigated by Poludniowski and Evans with 2 different geometrical optic models (Poludniowski and Evans, 2013b). High sensitivity of the transport parameters on grain size and emission spectrum were observed. MTF and photon absorption efficiency were calculated with each property value, but no evaluation of detector NPS was performed. Blake *et al.* (Blake *et al.*, 2013) investigated the impact of multiple optical transport parameters on the EPID dosimetric response, showing how the full width at half maximum (FWHM) and full width at tenth maximum (FWTM) of the point spread function (PSF) varied slightly with each parameter.

It has been clearly shown that optical properties can influence the phosphor screen performance. However, for MV imaging, MTF and x-ray absorption are not the only factors to consider. Noise performance, normally evaluated by NPS, is equally important and should be estimated simultaneously as imaging dose can be a significant factor in MV EPID imaging.

In this study, a Monte Carlo computational model of a clinically employed EPID (Varian AS1200) was developed and validated. This is the first detailed Geant4-based MC

simulation of the AS1200 imager of which we are aware. The impact of five major optical properties, phosphor grain size, phosphor thickness, phosphor and binder refractive index (RI), and packing ratio, on EPID qNNPS and MTF was estimated. Further, a comparison of DQE at zero spatial frequency (DQE(0)) was evaluated as well.

2. Materials and methods

2.1. AS1200 EPID

There are three major components of the AS1200 EPID: a copper layer, which shields low energy scattered radiation and converts high energy x-rays into secondary electrons (Antonuk, 2002), a phosphor screen for conversion of x-ray energy into optical photons, and an amorphous silicon (a-Si) panel detector with glass-based substrate for optical photon detection. The phosphor screen is a Lanex Fast-Back screen (Carestream Health, Rochester, NY), consisting of a reflective support layer made of polyethylene terephthalate (PET), a phosphor layer, and a PET protection foil layer. An aluminum alloy and a lead alloy layer were attached to the back of the EPID structure for backscatter shielding. The thickness and density of each layer is listed in table 1, and the geometry is shown in figure 1 (not to scale).

The phosphor layer surface density was $133 \text{ mg/cm}^2 \text{ Gd}_2\text{O}_2\text{S:Tb}$ (GOS) and the mass density was calculated as 4.59 g/cm^3 . The packing ratio, defined as the ratio of phosphor grain volume to the screen volume, was 62%. The a-Si panel detector was simulated as a silicon dioxide (SiO_2) slab. It has a pitch of 0.336 mm and the readout array size was 1280×1280 pixels.

2.2. Monte Carlo software, beam model and AS1200 model

2.2.1. Monte Carlo software—GATE (Geant4 application for tomographic emission), a MC simulation platform (Jan *et al.*, 2011; Sarrut *et al.*, 2014), was employed for EPID simulation in this study. GATE is based on Geant4 kernel (Jan *et al.*, 2011) and is capable of simulating photons, charged particles, and optical photon transport (Agostinelli *et al.*, 2003; Allison *et al.*, 2006). It has been widely employed as a MC simulation tool for imaging and dosimetric studies (Maigne *et al.*, 2011; Grevillot *et al.*, 2011). In GATE, descriptive scripts are used to implement the simulation model and provide the information of geometric configuration, radiative and optical properties, etc. All simulations were performed on a Linux workstation equipped with 16 GB of RAM and twelve 3.8 GHz cores. GATE version 8.0 and Geant4 version 10.03.p01 were used in this study.

2.2.2. Beam model—A 6MV x-ray photon spectrum was used as the radiation source for measurements and beam modeling. This spectrum was extracted from the phase space at source-surface distance (SSD) of 100 cm of the Varian TrueBeam linac accelerator. The phase space file is available on International Atomic Energy Agency (IAEA) website, which was obtained following the method described previously (Constantin *et al.*, 2011). In the simulation, the energies of the x-ray photons were sampled from this photon spectrum.

2.2.3. AS1200 imager model—AS1200 imager model consists of a series of uniform slabs representing individual imager components that listed in Sec. 2.1. Thickness, volume

density, and material composition of each layer were set in the model. The EPID model has a detection area $15 \times 15 \text{ cm}^2$, with a pitch of 0.336 mm and the readout array size 446×446 pixels.

2.2.4. Radiative physics model—In Geant4, the physics list is a full collection of models that can be used given an appropriate situation (Allison *et al.*, 2006). Multiple electromagnetic physics lists are available for simulation. Penelope was chosen for this study due to its satisfactory accuracy and acceptable simulation speed (Star-Lack *et al.*, 2014). Simulated electromagnetic processes included photoelectric absorption, Compton scattering, Rayleigh scattering, pair production, ionization, bremsstrahlung, multiple scattering, annihilation, etc. The range cut values for x-rays, electrons and positrons were set equal to 5 μm .

2.2.5. Optical physics model—Simulated optical processes included scintillation, absorption, scattering, reflection and refraction at boundaries. The actual scintillation yield (SY) of the GOS phosphor is approximately 60,000 optical photons per MeV (opticals/MeV). A lower value was used to reduce the computation time without compromising the optical response (Star-Lack *et al.*, 2014). The SY was determined as 600 optical/MeV in accordance with Star-Lack *et al.*

The optical photon wavelength was set to 545 nm, the dominant wavelength in the GOS emission spectrum. Phosphor grains were assumed to be spherical in shape with a 7 μm diameter in the AS1200 (Poludniowski and Evans, 2013a). The RI was set equal to 2.3 for GOS phosphor and 1.0 for phosphor binder (Myronakis *et al.*, 2017). The absorption length of the GOS phosphor was 43 mm, which was derived from the GOS RI (Poludniowski and Evans, 2013a).

Both Mie scattering and Rayleigh scattering are available for simulation. In this study, Mie scattering was the main optical interaction due to the large GOS grain size with respect to the optical photon wavelength (Myronakis *et al.*, 2017). The reflector on top of the GOS phosphor was explicitly simulated as a white PET layer with 88% reflectivity at 545nm. A summary of the optical process properties is shown in table 2.

2.3. Measurement of qNNPS, MTF, and DQE

Three image quality performance values were used for the validation and investigation of EPID performance: modulation transfer function (MTF), the product of the normalized noise power spectrum (NNPS) and incident x-ray fluence (qNNPS), and the DQE. MTF describes the EPID signal performance, and NPS describes the EPID noise transfer property. The signal-to-noise performance is characterized by DQE (Siewerdsen *et al.*, 1998).

The AS1200 MTF was measured using the slit image method (Fujita *et al.*, 1992). The experiment has been described in greater detail previously (Rottmann *et al.*, 2016). Briefly, a slit image was obtained by illuminating the EPID with a narrow slit tilted by 1.5 degrees. The slit was created by a pair of tungsten alloy blocks placed on top of the detector with a separation of 100 μm . The image was acquired with $10 \times 10 \text{ cm}^2$ field size, at a 153 cm source-to-imager distance (SID), and with a 400 MU/min dose rate. Following the procedure

introduced by Fujita *et al.* (Fujita *et al.*, 1992), an finely sampled line spread function (LSF) was obtained from the slit image, the Fourier transform of which yields the MTF.

The qNNPS is the product of the average incident x-ray fluence (q) at the EPID surface and the normalized NPS (NNPS). The reference fluence at 100 cm SID was derived in a previous study (Star-Lack *et al.*, 2014) and the incident fluence q at the EPID surface (SID=153 cm) was adjusted by inverse square corrections. For NNPS measurements, 250 flood field images adjusted to 70% of a saturating dose level were obtained with $10 \times 10 \text{ cm}^2$ field size at an SID of 180 cm. A 120×120 pixel area at the central region was acquired to compute the 2D NNPS, which was converted into a 1D NNPS. Detailed description can be found in Rottmann *et al.* (Rottmann *et al.*, 2016).

DQE was calculated from MTF and qNNPS according to:

$$DQE = \frac{[MTF]^2}{qNNPS} \quad (1)$$

2.4. Simulation of qNNPS, MTF, and DQE

The simulated qNNPS, MTF, and DQE of AS1200 were calculated. For the MTF simulation, a $0.1 \times 70 \text{ mm}^2$ rectangular plane x-ray photon source tilted by 1.5° was placed right above the EPID top surface. 10^7 x-ray photons were uniformly launched onto the EPID and the optical photons were scored in each pixel of the panel detector to form the slit image. X-ray photon energies were sampled from the photon spectrum described in Sec. 2.2.2. Following the Fujita method (Fujita *et al.*, 1992), a finely sampled LSF was formed from the slit image then converted into MTF. The statistical uncertainty calculated from the number of absorbed optical photons in the slit area was less than 0.3%.

For the simulation of qNNPS the Fujita-Lubberts-Swank (FLS) method (Star-Lack *et al.*, 2014) was employed. The same slit image as the MTF simulation was used. The 2D point spread function (PSF) produced by each detected x-ray photon was collected and summed along one axis to form a 1D PSF. The corresponding NPS was calculated as:

$$NPS_i(f) = |DFT(PSF_i)|^2 \quad (2)$$

where i is the detected x-ray photon and DFT is discrete Fourier transform. The final $NPS(f)$ of the imager was obtained by averaging $NPS_i(f)$ over all detected x-ray photons. Then, qNNPS(f) was calculated as:

$$qNNPS(f) = \frac{NPS(f)}{NPS(f)_{\max}} \times \frac{1}{QE \times Swank \text{ factor}} \quad (3)$$

where $NPS(f)_{\max}$ is the maximum value in $NPS(f)$, QE is the estimated x-ray photon detection efficiency, and $Swank \text{ factor}$ is obtained from the scintillation pulse height

spectrum indicating the decrease in SNR (Swank, 1973). A detailed description can be found in Star-Lack *et al.* (Star-Lack *et al.*, 2014).

2.5. AS1200 model validation

For MTF, qNNPS, and DQE, the model and measurement are compared using with the normalized root-mean-squared-error (NRMSE) according to:

$$\text{NRMSE} = \sqrt{\frac{\sum_{i=1}^{\text{NF}} (\text{simulated}_i - \text{measured}_i)^2}{\text{NF}}} / (\text{measured}_{\text{max}} - \text{measured}_{\text{min}}) \quad (4)$$

where NF is the number of sample bins in the spatial frequency domain, ‘simulated’ and ‘measured’ refer to the simulated value and the measured value, respectively, and subscript ‘max’ and ‘min’ refer to the maximum and minimum simulated values, respectively. A NRMSE value close to zero is indicative of good agreement between measurement and simulation.

2.6. Impact of major optical properties on AS1200 qNNPS and MTF

Separate models with various grain size, phosphor thickness, phosphor RI, binder RI, and packing ratio values were simulated to determine their impact on EPID imaging performance. This test was conducted utilizing the validated AS1200 model. First, models with phosphor grain sizes of 5 μm , 6 μm , 7 μm , 8 μm , and 9 μm were implemented. The impact of phosphor grain size was quantified using the NRMSE

$$\text{NRMSE}(n) = \sqrt{\frac{\sum_{i=1}^{\text{NF}} (X_i(n) - X_i(\text{ref}))^2}{\text{NF}}} / (X_{\text{max}}(\text{ref}) - X_{\text{min}}(\text{ref})) \quad (5)$$

where n labels the values tested, NF is the number of sample bins on spatial frequency domain, X is the simulated value (qNNPS or MTF), ‘ref’ refers to the reference, subscript ‘max’ and ‘min’ refer to the maximum and minimum simulated values, respectively. Grain size of 7 μm was used as the reference value (Poludniowski and Evans, 2013a). Each trial was compared to the reference, and the corresponding NRMSE value was calculated for qNNPS and MTF. A large NRMSE indicates a large deviation from the reference.

Tests of other optical properties were conducted similarly, with the impact quantified by NRMSE. A summary of tested properties values is shown in table 3. For each property, the remaining optical parameters were assigned the corresponding reference value (marked by “*” in table 3).

Along with the qNNPS and MTF curves, DQE(0) was also calculated for each property value according to:

$$DQE(0) = \frac{1}{qNNPS(0)} \quad (6)$$

3. Results

3.1. AS1200 model validation

Comparison of the measured versus the simulated qNNPS, MTF, and DQE of AS1200 EPID is shown in figure 2. The NRMSE value is 0.0217 for qNNPS, 0.0467 for MTF, and 0.0885 for DQE. Good agreement is observed from both visual inspection of the curves and the low NRMSE.

3.2. Impact of phosphor grain size

The qNNPS and MTF are compared across different phosphor grain sizes in figure 3. A closer view may be found in the inset of each graph. The qNNPS curves and the MTF curves decrease with increasing grain size.

The impact of phosphor grain size was quantified using NRMSE, which is tabulated in table 4. Generally, larger NRMSE values were observed in qNNPS than that in MTF, indicating a greater impact of grain size on qNNPS than on MTF.

3.3. Impact of phosphor thickness

As shown in figure 4, both qNNPS and MTF curves decrease with increasing phosphor thickness. The impact of phosphor thickness is much greater on qNNPS than on MTF, as indicated by the larger NRMSE values in table 5.

3.4. Impact of phosphor RI

The qNNPS and MTF curves with different phosphor RI are shown in figure 5. Increasing the phosphor RI increases the qNNPS and MTF. The NRMSE values are listed in table 6. Phosphor RI has greater impact on qNNPS than on MTF.

3.5. Impact of binder RI

The qNNPS and MTF curves with different binder RI are shown in figure 6. Increasing the binder RI degrades the qNNPS and MTF. The NRMSE values are listed in table 7. The impact of the binder RI on the qNNPS is greater than on MTF.

3.6. Impact of packing ratio

The qNNPS and MTF curves with different packing ratio are shown in figure 7. Increasing the packing ratio increases the qNNPS and MTF. The NRMSE values are listed in table 8. The impact of the packing ratio on qNNPS is much greater than on MTF.

3.7. DQE(0) with various optical properties

DQE(0) values for tests in Sec. 3.2 ~ 3.6 are listed in table 9. By changing optical properties values, only phosphor thickness has a significant impact on DQE(0), while other properties only show a slight difference.

4. Discussion

In the present study, a MC model of AS1200 EPID was developed and validated against physical measurements. The NRMSE between measured and simulated qNNPS, MTF, and DQE were 0.0217, 0.0467, and 0.0885, respectively. DQE had a slightly higher NRMSE value, because it is calculated from MTF and qNNPS, and deviation from both parameters was propagated to DQE. Slight deviations of the simulated DQE in the low frequency regions are attributable to a corresponding decrease in qNNPS, while the deviation at frequencies of 0.5 to 1 mm^{-1} is caused by the increase in MTF.

The qNNPS curve decreases with an increase in grain size, phosphor thickness, and binder RI, as well as with a decrease in phosphor RI and packing ratio. In terms of phosphor grain size, the optical photons tend to scatter at small angles along the incident direction as a result of large grain size, which leads to less noise and degrading qNNPS. For phosphor thickness, a thicker phosphor results in greater x-ray photon absorption and optical photon emission, leading to better noise performance. Also, optical photons scatter at a smaller angle as binder RI increases. This can be explained with the relative RI of grain to binder. The relative RI is defined as the ratio of grain RI to binder RI. With lower relative RI, photons scatter at smaller angles (Poludniowski and Evans, 2013a). With equivalent grain RI, a large binder RI reduces relative RI, producing a smaller scatter angle and less noise. This also helps explain the impact of phosphor RI. With equivalent binder RI, a small phosphor RI reduces relative RI, producing a smaller scatter angle and less noise. Regarding packing ratio, a lower packing ratio results in fewer grains in phosphor. The optical photons tend to scatter fewer times before exiting phosphor, which leads to less noise.

The major optical properties affect EPID MTF in a similar manner as qNNPS. The MTF curve degrades with increasing grain size, phosphor thickness, and binder RI, and with decreasing phosphor RI and packing ratio. The impact of grain size and packing ratio agrees well with previous work (Liaparinis *et al.*, 2006; Poludniowski and Evans, 2013b). It has been shown that, a decrease in grain fraction within the phosphor layer, equivalent to larger grain size and lower packing ratio, will cause a decrease in the number of optical photon scattering events. This further leads to a worse overall directivity of photon flux propagation within the detector, resulting in a degraded MTF. A low relative RI, equivalent to low phosphor RI and high binder RI, will result in a smaller scatter angle, so that optical photons propagate with worse directivity, leading to a degraded MTF as well. Similar results can be found in previous work (Poludniowski and Evans, 2013a). The negative impact of phosphor thickness on MTF is due to increased scatter of the optical photons, resulting in a lateral spread and a degraded MTF (Kausch *et al.*, 1999).

DQE(0) increases significantly with the phosphor thickness, while other properties do not substantially influence DQE(0). This is to be expected because quantum detection efficiency

of x-rays depends mainly on phosphor thickness (Kausch *et al.*, 1999), but for other properties, they only influence the optical photon propagation and interaction in the phosphor.

It is challenging to offer an optimal configuration of the phosphor optical properties for EPID design optimization because it depends on the imaging task and user's expectation. In this case, understanding the influence of optical properties can help determine the proper values for optimization. For MTF-weighted optimization, a thin phosphor with small grain size, high relative RI, and large packing ratio would be a better option. Alternatively, a qNNPS-weighted optimization requires a thick phosphor consisting of large grains, under low relative RI and small packing ratio. Since qNNPS shows stronger response to optical property variation, an intensive degrading in the noise performance is expected during MTF-weighted optimization. For DQE-weighted optimization, phosphor thickness is the major issue to consider, and an EPID imager with the thickest phosphor (up to 1 mm) would be preferred (Kausch *et al.*, 1999).

Compared to previous detectors, the Varian AS1200 has a larger detector area and smaller pixel pitch (Antonuk, 2002; Star-Lack *et al.*, 2014; Rottmann *et al.*, 2016). Siebers *et al.* (Siebers *et al.*, 2004) developed an EGS4-based MC model for AS500, with one layer of water material attached to the back to compensate for the measured backscatter. A similar study was done by Ko *et al.* (Ko *et al.*, 2004). A MC model of AS500 was built and the impact of different backscattering materials was studied for the optimization of the backscatter effects. Star-Lack *et al.* (Star-Lack *et al.*, 2014) developed a Geant4-based MC model for AS1000, with both radiative and optical transport included. Excellent agreement was shown between the measured and calculated EPID performance.

Other techniques have been explored to improve EPID image quality. Conventional GOS-based EPID performance is hindered by low DQE, approximately 1.5% for AS1200 imager with 6MV beam, which has limited its clinical application (Star-Lack *et al.*, 2015). Multiple attempts have been previously made to increase the DQE. Segmented crystalline scintillators were studied as an alternative to phosphor films and gave very high DQE (Sawant *et al.*, 2005; Wang *et al.*, 2008; Star-Lack *et al.*, 2015; Mosleh-Shirazi *et al.*, 1998). Sawant *et al.* reported DQE(0) approximately 22 times higher than that of the conventional active matrix flat panel imager (AMFPI). Star-Lack *et al.* reported more than 20 times higher DQE(0) than that of a conventional copper plate/phosphor screen design (Star-Lack *et al.*, 2015). A stacked four-layer EPID was reported to provide roughly five times higher DQE(0) compared to a reference EPID (Rottmann *et al.*, 2016; Myronakis *et al.*, 2017).

5. Conclusion

A Monte Carlo model for AS1200 EPID was developed with GATE, a Geant4-based MC platform. Both radiative and optical photon transport were simulated, and the model was validated with experimental data. The effect of five major phosphor optical properties (grain size, phosphor thickness, phosphor RI, binder RI, and packing ratio) on qNNPS, MTF, and DQE(0), was fully investigated. It was shown how these parameters affect x-ray absorption, optical photon scattering, and therefore overall EPID performance. With a complete

understanding of the optical performance within the imager, future simulations of EPID imagers can be performed to optimize performance for specific clinical applications.

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Figure 1.
Cross-sectional view of AS1200 model geometry

Figure 2.
Simulated (solid line) and measured (dash line)
(a) qNNPS,
(b) MTF, and
(c) DQE curves for AS1200 EPID.

Figure 3.

Simulated curves of

(a) qNNPS, and

(b) MTF with different phosphor grain size. In graph (a), the qNNPS curves from 1 mm^{-1} to 1.3 mm^{-1} are plotted in a smaller window on the top right. In graph (b), the MTF curves from 1 mm^{-1} to 1.2 mm^{-1} are plotted in a smaller window on the top right.

Figure 4.
Simulated curves of
(a) $qNNPS$, and
(b) MTF with different phosphor thickness.

Figure 5.

Simulated curves of

(a) qNNPS, and

(b) MTF with different phosphor RI. In graph (b), the MTF curves from 1 mm⁻¹ to 1.2 mm⁻¹ are plotted in a smaller window on the top right.

Figure 6.
Simulated curves of
(a) qNNPS, and
(b) MTF with different binder RI.

Figure 7.
 Simulated curves of
 (a) qNNPS, and
 (b) MTF with different packing ratio. In graph (b), the MTF curves from 1 mm^{-1} to 1.2 mm^{-1} are plotted in a smaller window on the top right.

Table 1.

Thickness and density of AS1200 structures

Structure	Thickness (mm)	Density (g/cm ³)
Copper layer	1	8.9
Reflective layer	0.18	1.38
GOS phosphor	0.29	4.59
Protection foil	0.075	1.38
a-Si panel detector	0.7	2.6
Al alloy	1	2.8
Pb alloy	3	10.95

Table 2.

Optical parameters of AS1200

Structure	Parameter	AS1200
Reflective layer	Absorption length	10 mm
	Refractive index	1.58
	PET reflectivity	88%
GOS phosphor	Scintillation yield	600 optical/MeV
	Photon emission wavelength	545 nm
	Absorption length	43 mm
	Phosphor refractive index	2.3
	Binder refractive index	1.0
	Grain size (diameter)	7 μm
	Mie scattering length	0.00346mm
Protection foil	Absorption length	10 mm
	Refractive index	1.58
Panel detector	Absorption length	0.0001 mm
	Refractive index	1.52

Table 3.

The impact of optical properties on EPID performance

Property	Values tested
Grain size (μm)	5, 6, 7 [*] , 8, 9
Phosphor thickness (mm)	0.15, 0.29 [*] , 0.5, 0.75, 1
Phosphor RI	1.1, 1.3, 1.5, 2, 2.3 [*] , 3
Binder RI	1 [*] , 1.35, 1.5
Packing ratio	0.1, 0.2, 0.3, 0.4, 0.5, 0.62 [*]

^{*}
Reference value

Table 4.NRMSE of each grain size relative to the reference (7 μm) for qNNPS and MTF

Parameters	5 μm	6 μm	7 μm	8 μm	9 μm
qNNPS	3.29%	1.71%	0	2.06%	3.79%
MTF	1.24%	0.69%	0	0.72%	1.46%

Table 5.

NRMSE of each phosphor thickness relative to the reference (0.29 mm) for qNNPS and MTF

Parameters	0.15 mm	0.29 mm	0.5 mm	0.75 mm	1 mm
qNNPS	32.32%	0	19.05%	28.96%	33.57%
MTF	2.69%	0	4.86%	8.94%	11.76%

Table 6.

NRMSE of each phosphor RI relative to the reference (2.3) for qNNPS and MTF

Parameters	1.1	1.3	1.5	2.0	2.3	3.0
qNNPS	17.42%	7.64%	4.8%	1.15%	0	0.73%
MTF	8.96%	3.69%	1.92%	0.69%	0	0.27%

Table 7.

NRMSE of each binder RI relative to the reference (1.0) for qNNPS and MTF

Parameters	1.0	1.35	1.5
qNNPS	0	4.7%	6.6%
MTF	0	2.0%	2.9%

Table 8.

NRMSE of each packing ratio relative to the reference (0.62) for qNNPS and MTF

Parameters	0.1	0.2	0.3	0.4	0.5	0.62
qNNPS	16.86%	9.56%	5.63%	3.55%	1.31%	0
MTF	8.69%	4.55%	2.78%	1.45%	0.77%	0

Table 9.

DQE(0) of each optical properties values

Grain size (μm)	5	6	7	8	9	
DQE(0)	0.0147	0.0148	0.015	0.0152	0.0153	
Phosphor Thickness (mm)	0.15	0.29	0.5	0.75	1	
DQE(0)	0.0112	0.015	0.0196	0.0234	0.026	
Phosphor RI	1.1	1.3	1.5	2	2.3	3
DQE(0)	0.0164	0.0159	0.0156	0.0153	0.015	0.0153
Binder RI	1.0	1.35	1.5			
DQE(0)	0.015	0.0152	0.0155			
Packing ratio	0.1	0.2	0.3	0.4	0.5	0.62
DQE(0)	0.0163	0.016	0.0156	0.0156	0.0153	0.015