Monte Carlo Simulation to Test the Effectiveness of Crystal Detector Length for PHITS-Based PET Modality

Gusti Atika Urfa*, Nurma Sari, Totok Wianto, Sri C Wahyono, Arfan E Fahrudin, & Amar V Nasrulloh
Department of Physics, Universitas Lambung Mangkurat, Indonesia
*Corresponding Author: gusti.urfa@ulm.ac.id

Received: 28 February 2023; **Accepted**: 09 April 2023; **Published**: 30 May 2023
DOI: https://dx.doi.org/10.29303/jpft.v9i1.4896

Abstract *- PET (Positron-emission tomography) is used to determine physiological and metabolic functions in the body. Monte Carlo simulation is an important part of PET imaging, and the Particle Heavy Ion Transport code System (PHITS) is a simulation platform that can be used to perform Monte Carlo simulations. This study uses a Monte Carlo simulation based on PHITS to determine the range of gamma absorption with an energy of 511 keV in a scintillation detector crystal material. The gamma absorption range determines the effective crystal length in the PET modality. The simulation process is carried out by shooting Gamma at various types of materials, which are the materials used in PET scintillation crystals. The materials used in this simulation are NaI (Sodium Iodide), BaF_2 (Barium Florida), BGO (Bismuth Germanate), and GSO (Gadolinium Oxyorthosilicate), considering their atomic number and crystal density. The crystal material is capable of absorbing gamma radiation with an energy of 511 keV with detailed crystal lengths for each NaI crystal of 0.26 cm; 0.25 cm BaF_2 crystals; 0.1cm BGO crystals; and 0.18 cm GSO crystals. The crystal length from this simulation is smaller than the commercially available crystal length (range 1-3 cm). Based on the crystal length data, the most effective crystal for absorbing gamma radiation is the BGO crystal.*

Keywords: *PET; PHITS Simulation; Detector.*

INTRODUCTION

Positron Emission Tomography (PET) is a nuclear medicine modality used to assess physiological and metabolic functions within the body (Hambitzer, 2012; Saha, 2010; Vaquero & Kinahan, 2015). The main components of PET include radiopharmaceuticals injected into the body, radiation detectors to capture radiation emitted from within the body and a computer for image reconstruction. Radiopharmaceuticals are administered into the body through intravenous injection, inhalation through the respiratory system, or oral administration (Bushong, 2005). These radiopharmaceuticals distribute to the targeted tissues in the body and decay by emitting positrons. The positrons interact with surrounding electrons, resulting in annihilation and the emission of two gamma rays with an energy of 511 KeV, each in opposite directions. These gamma rays are then captured by detectors around the body (Berger, 2003; Xie et al., 2020).

The radiation detector used in PET consists of scintillation crystals and needs good resolution, sensitivity, and efficiency. The narrowness of its cross-section influences the detector's resolution, sensitivity is affected by the type and material of the crystal, and the detector's length influences efficiency. Scintillation crystals must be sufficiently long to detect all incoming radiation (Cates & Levin, 2018). Commercially available PET scintillation crystals have lengths ranging from 10 to 30 mm with cross-sectional widths of 4 to 5 mm (Cates & Levin, 2018; Van Eijk, 2003). Various studies have been conducted on the efficiency of scintillation crystal detectors using different materials, such as NaI, BaF2, BGO, and GSO (Chanho Kim et al., 2021; Tai & Piccini, 2004). From the study results, it has been observed that increasing the length of the crystal detector leads to a decrease in the signal-to-noise ratio (SNR).

Monte Carlo simulation is an essential part of PET imaging. The results of this simulation can be used to assist in the design, optimization, and evaluation of imaging systems. It can also be utilized to predict equipment performance, optimize parameter acquisition, and reconstruction algorithms to enhance image quality (Salvadori et al., 2020). PHITS (Particle Heavy Ion Transport code System) is one simulation platform that can be used for Monte Carlo simulations. PHITS, developed by the Japanese Atomic Energy Agency (JAEA), has been enhanced in version 3.2 to expand its energy range and accuracy, making it suitable for medical applications (Sato et al., 2018).

This study focuses on using Monte Carlo simulation (PHITS) to determine the range of absorption of 511 keV gamma radiation in scintillation crystal detector materials. This research aims to determine the range of gamma radiation absorption in PET detectors. The range of gamma absorption is calculated to determine the effective crystal length used in PET modality. By knowing the effective radiation absorption range, the crystal length can be reduced, resulting in a more cost-effective and efficient modality.

RESEARCH METHODS

The research stages are depicted in Figure 1. This study is based on PHITS version 3.29. The simulation code was developed using Notepad++, and the visualization was performed using Sumatra PDF and GoScript 3D applications (Iwamoto et al., 2022). The simulation process involves data collection and data analysis.

The simulation setup includes the radiation source and scintillation crystal detector material geometry. The radiation source geometry is represented by a circular shape with a radius of 1 mm. The chosen radiation source is gamma rays with an energy of 511 keV, and 1000 particles are used in the simulation. The gamma rays are directed at the crystal at a distance of 1 cm from the surface of the scintillation crystal. The scintillation crystal has a cylindrical shape with a radius of 1 cm and a length of 3 cm, as shown in Figure 2.

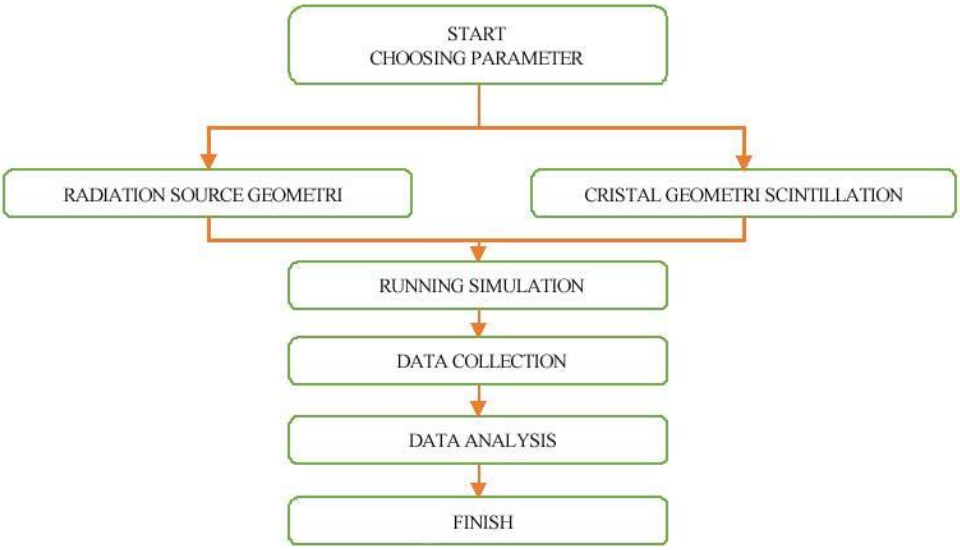


Figure 1. Research Step

The gamma rays are directed at various types of materials used in PET scintillation crystals, namely NaI (Sodium Iodide), BaF2 (Barium Fluoride), BGO

(Bismuth Germanate), and GSO (Gadolinium Oxyorthosilicate), with specific parameters as listed in Table 1. The material's radiation absorption is influenced by atomic number, material density, and radiation energy (Podgorsak, 2004).

Table 1. The parameters of the scintillation crystal detector material used in the simulation (Melcher, 2000).

	NaI	BaF_2	BGO	GSO
Number of Atom (Z)	51	54	74	59
Density	3,67 g/cm^3	4,89 g/cm^3	7,13 g/cm^3	6,70 g/cm^3

The data collection stage involves the following steps: a) setting parameters; b) creating geometry; c) running the simulation; d) collecting data; e) analyzing the data. The data in this simulation is obtained from computer calculations based on pre-determined parameters, including the density and atomic number of the scintillation crystal material, the geometry, and the energy of the incident gamma rays.

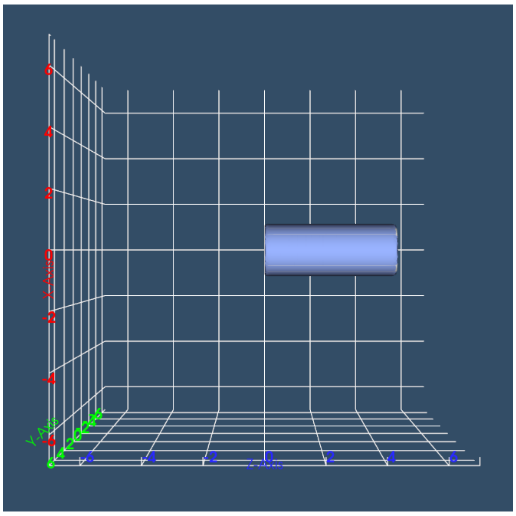


Figure 2. The result of the crystal detector simulation in PHITS

The data analysis is conducted in a semi-qualitative manner. The original data obtained from the PHITS simulation is visualized using the Sumatra PDF application. The photon energy used in the simulation is 511 keV, which is the energy of photons emitted by the body due to the process of positron formation from the decay of radioisotopes inside the body.

RESULTS AND DISCUSSION

Results

1. **The interaction of 511 keV gamma radiation in NaI (Sodium Iodide) crystal**

The gamma radiation simulation with NaI crystal, which has a density of 3.67 g/cm^3 and an effective atomic number of 51, has been conducted. The simulation results show the radiation fluence on the axial and lateral detector cross-sections, as shown in Figure 3. The distribution of absorbed radiation dose in the crystal is visible in Figure 4.

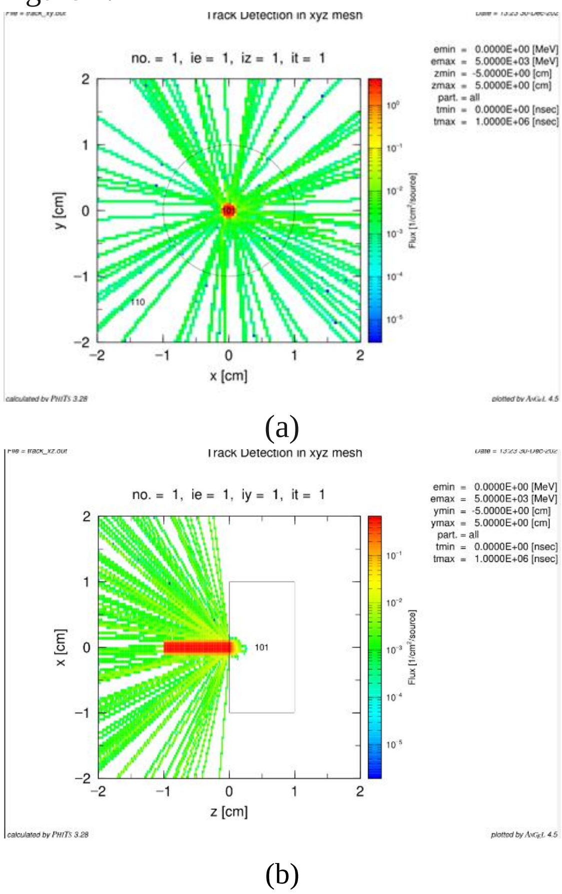


Figure 3. The absorbed radiation fluence in the NaI detector crystal. (a) Axial cross-section. (b) Lateral cross-section.

Gamma rays that approach the crystal will be partially reflected and partially absorbed by the crystal. The reflected gamma rays are isotropic or scattered in all directions. From the simulation results, it can be observed that the range of 511 keV gamma rays in NaI crystal is 0.27 cm.

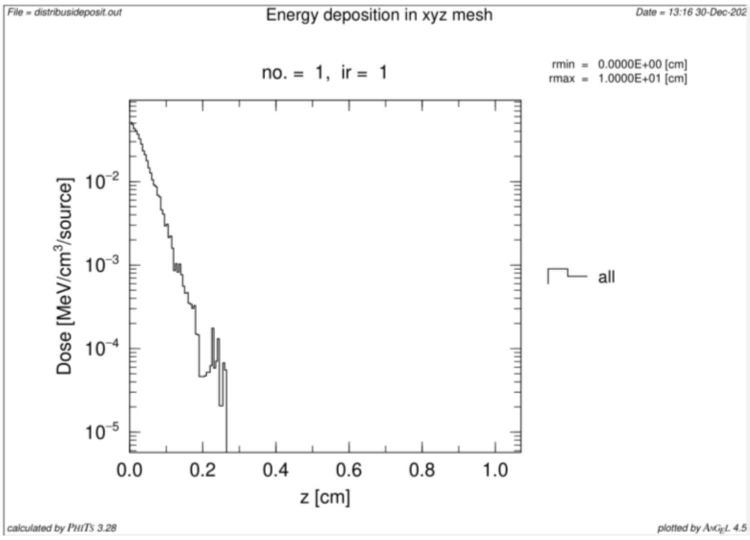


Figure 4. Radiation dose distribution in NaI detector crystal

2. **The interaction of 511 keV gamma radiation in BaF_2 crystal**

Gamma radiation simulation has been conducted with BaF_2 crystal, which has a 4.89 g/cm3 density and an effective atomic number of 54. The simulation results show the radiation fluence on the axial and lateral detector cross-sections, as shown in Figure 5. The distribution of absorbed radiation dose in the crystal is visible in Figure 6.

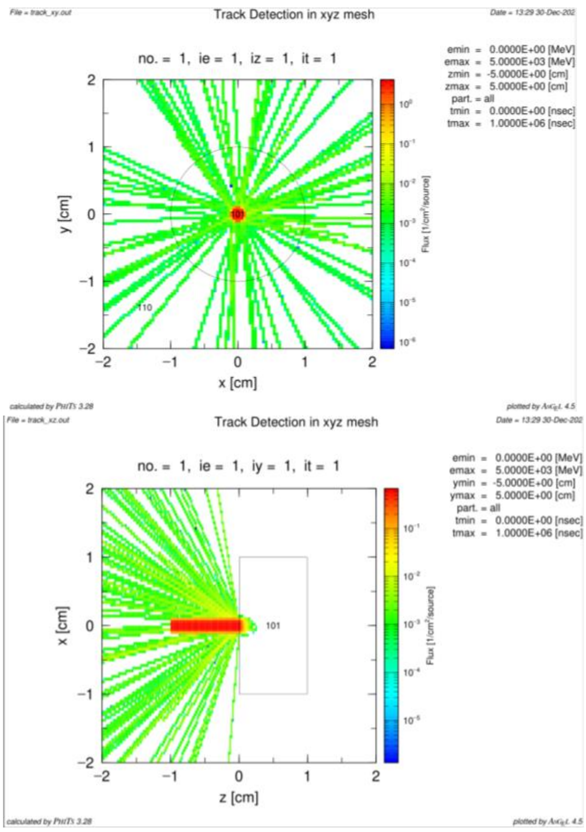


Figure 5. Radiation fluence absorbed in BaF_2 detector crystal. (Left) Axial section. (Right) Lateral section

From the obtained results, 511 keV gamma rays have a range of 0.25 cm in BaF_2 crystal. Compared to NaI crystal, BaF_2 crystal has a shorter range. It is because BaF_2 crystal has a higher atomic number and density than NaI crystal.

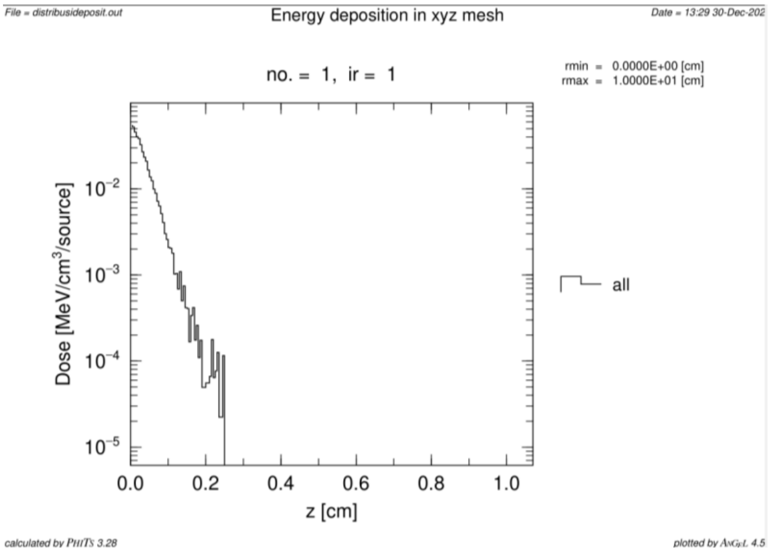
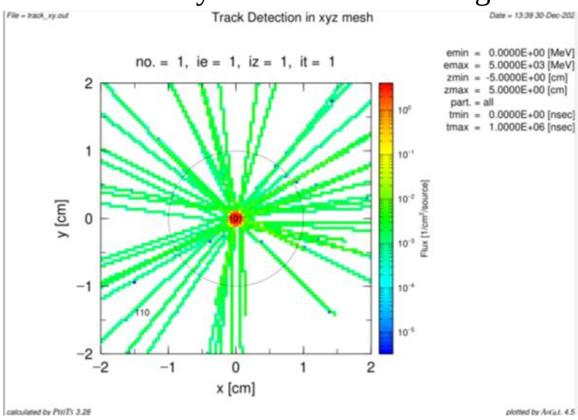


Figure 6. Distribution of radiation dose in BaF_2 detector crystal.

From the obtained results, 511 keV gamma rays have a range of 0.25 cm in BaF_2 crystal. Compared to NaI crystal, BaF_2 crystal has a shorter range. It is because BaF_2 crystal has a higher atomic number and density than NaI crystal.

3. The interaction of 511 keV gamma radiation in BGO crystal

Gamma radiation simulation has been conducted with BGO crystal, which has a 7.13 g/cm3 density and an effective atomic number of 74. The simulation results show the radiation fluence on the axial and lateral detector cross-sections, as shown in Figure 7. The distribution of absorbed radiation dose in the crystal is visible in Figure 8.



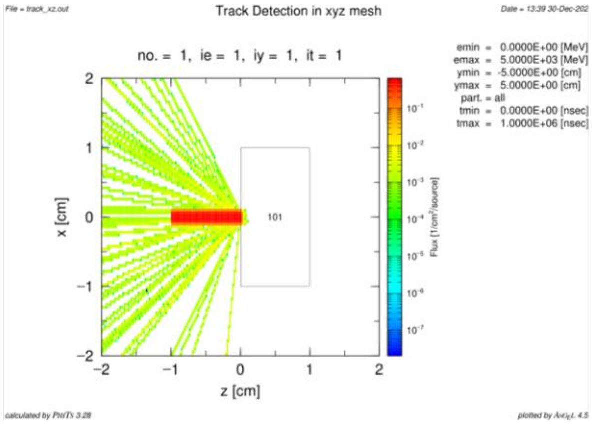


Figure 7. Absorbed radiation fluence in BGO detector crystal. (Left) Axial cross-section. (Right) Lateral cross-section.

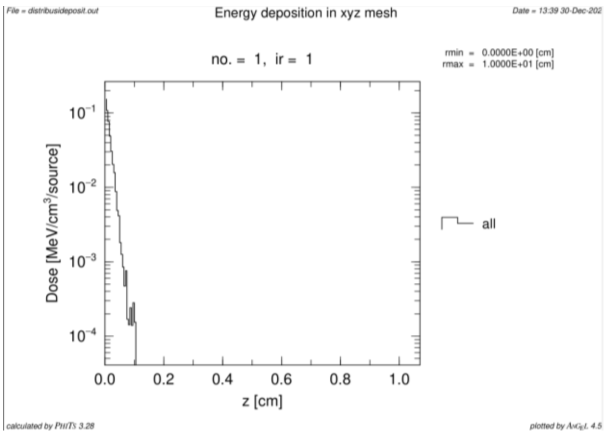


Figure 8. Radiation dose distribution in BGO detector crystal.

The simulation results show that gamma rays with an energy of 511 keV stop at a range of 0.1 cm in the GSO crystal. The obtained range is smaller than NaI and BaF2 crystals because the GSO crystal has a higher atomic number and density than NaI and BaF_2.

4. The interaction of 511 keV gamma radiation in GSO crystal

Gamma radiation simulation has been conducted with GSO crystal, which has a 6.7 g/cm3 density and an effective atomic number of 59. The simulation results show the radiation fluence on the axial and lateral detector cross-sections, as shown in Figure 9. The distribution of absorbed radiation dose in the crystal is visible in Figure 10.

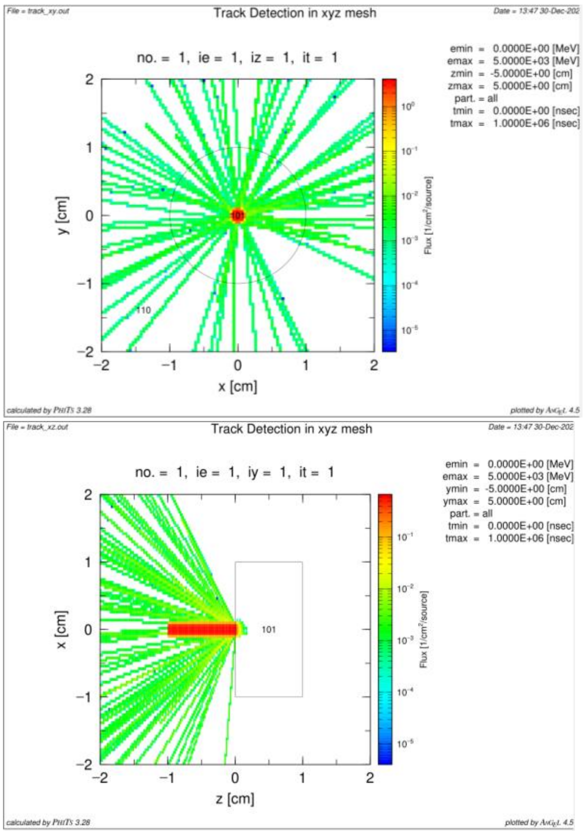


Figure 9. Absorbed radiation fluence in GSO detector crystal. (Left) Axial cross-section. (Right) Lateral cross-section.

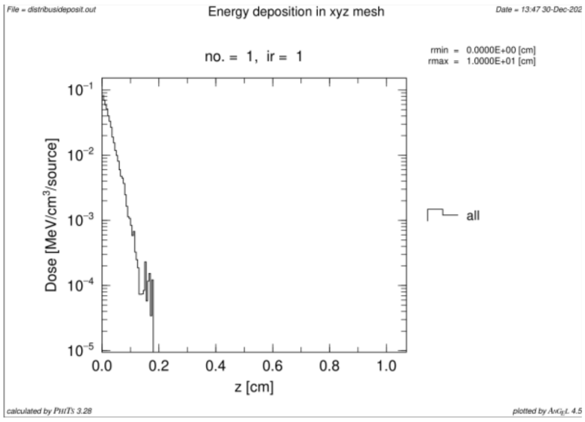


Figure 10. Distribution of radiation dose in GSO detector crystal.

The above simulation results show that the range of 511 keV gamma rays in the GSO crystal is 0.18 cm. This value is larger than the range of 511 keV in the BGO crystal and smaller than the NaI and BaF_2 crystals. It is because the GSO crystal has a lower atomic number and density than the BGO crystal and a higher atomic number and density than the NaI and BaF_2 crystals.

Discussion

Fundamentally, the interaction of gamma rays with matter occurs exponentially and is influenced by the attenuation coefficient of the material and the radiation source energy. Two important factors that affect the attenuation coefficient of a material are its density and atomic number. The higher the attenuation coefficient, the more effectively the material absorbs radiation. On the other hand, the higher the radiation energy, the greater the penetrating power and range in a material (Bushong, 2005).

The simulation of the four materials shows that the most effective material for absorbing radiation is the BGO crystal due to its higher atomic number and density. The ranges of the four scintillation crystals for absorbing 511 keV gamma rays are less than 1 cm, with the NaI crystal having a range of 0.26 cm, the BaF_2 crystal having a range of

0.25 cm, the BGO crystal having a range of 0.1 cm, and the GSO crystal having a range of 0.18 cm. The typical length of scintillation crystals used in commercially available PET detectors is 1-3 cm (Van Eijk, 2008; Vaquero & Kinahan, 2015). The simulation results show that the length of the scintillation crystal can be reduced to less than 1 cm.

CONCLUSION

From the simulation results, considering the atomic number and density of the crystals, it can be concluded that the use of 1 cm scintillation crystals in PET detectors, namely NaI, BaF_2, BGO, and GSO, is already capable of absorbing 511 keV gamma radiation. The specific lengths of the crystals for absorbing 511 keV gamma rays are as follows: NaI crystal - 0.26 cm, BaF_2 crystal - 0.25 cm, BGO crystal - 0.1 cm, and GSO crystal - 0.18 cm. Based on these crystal lengths, it can be determined that the most effective crystal for absorbing gamma radiation is the BGO crystal.

ACKNOWLEDGEMENT

The author would like to express gratitude to the software development team of PHITS at JAEA, including Yosuke Iwamoto, Shintaro Hashimoto, Tatsuhiko Sato, Norihiro Matsuda, Satoshi Kunieda, Yurdunaz Celik, Naoya Furutachi, and Koji Nota.

REFERENCES

Berger, A. (2003). Positron emission tomography. *British Medical Journal*, *326*(7404), 1449. https://doi.org/10.1136/bmj.326.7404.1449

Bushong, S. C. (2005). *Radiologic Science for Technologist*. 1–29.

Cates, J. W., & Levin, C. S. (2018). Evaluation of a TOF-PET detector design that achieves ≤ 100 ps coincidence time resolution. *2017 IEEE Nuclear Science Symposium and Medical Imaging Conference, NSS/MIC 2017 - Conference Proceedings*. https://doi.org/10.1109/NSSMIC.2017.8532998

Chanho Kim, Wonhi Lee, Alima Melis, Abdallah Elmughrabi, Kisung Lee, & Chansun Park. (2021). A Review of Inorganic Scintillation Crystals for Extreme Environments. *Crystals*, *11*(6), 669.

Hambitzer, A. (2012). *Masterarbeit in Physik. September*.

Iwamoto, Y., Hashimoto, S., Sato, T., Matsuda, N., Kunieda, S., Çelik, Y., Furutachi, N., & Niita, K. (2022). Benchmark study of particle and heavy-ion transport code system using shielding integral benchmark archive and database for accelerator-shielding experiments. *Journal of Nuclear Science and Technology*, *59*(5), 665–675. https://doi.org/10.1080/00223131.2021.1993372

Melcher, C. L. (2000). Scintillation crystals for PET. *Journal of Nuclear Medicine*, *41*(6), 1051–1055.

Podgorsak, E. . (2004). Radiation Oncology Physics: A Handbook for Teachers and Students. In *Journal of Agricultural and Food Chemistry* (Vol. 52, Issue 20). https://doi.org/10.1021/jf030837o

Saha, G. B. (2010). *Basics of PET Imaging*. 97–117. https://doi.org/10.1007/978-1-4419-0805-6

Salvadori, J., Labour, J., Odille, F., Marie, P. Y., Badel, J. N., Imbert, L., & Sarrut, D. (2020). Monte Carlo simulation of digital photon counting PET. *EJNMMI Physics*, *7*(1). https://doi.org/10.1186/s40658-020-00288-w

Sato, T., Iwamoto, Y., Hashimoto, S.,

Ogawa, T., Furuta, T., Abe, S. ichiro, Kai, T., Tsai, P. E., Matsuda, N., Iwase, H., Shigyo, N., Sihver, L., & Niita, K. (2018). Features of Particle and Heavy Ion Transport code System (PHITS) version 3.02. *Journal of Nuclear Science and Technology*, *55*(6), 684–690. https://doi.org/10.1080/00223131.2017.1419890

Tai, Y. F., & Piccini, P. (2004). Applications of positron emission tomography (PET) in neurology. *Journal of Neurology, Neurosurgery and Psychiatry*, *75*(5), 669–676. https://doi.org/10.1136/jnnp.2003.028175

Van Eijk, C. W. E. (2003). Inorganic scintillators in medical imaging detectors. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *509*(1–3), 17–25. https://doi.org/10.1016/S0168-9002(03)01542-0

Vaquero, J. J., & Kinahan, P. (2015). Positron Emission Tomography: Current Challenges and Opportunities for Technological Advances in Clinical and Preclinical Imaging Systems. *Annual Review of Biomedical Engineering*, *17*, 385–414. https://doi.org/10.1146/annurev-bioeng-071114-040723

Xie, S., Zhang, X., Zhang, Y., Ying, G., Huang, Q., Xu, J., & Peng, Q. (2020). Evaluation of various scintillator materials in radiation detector design for positron emission tomography (Pet). *Crystals*, *10*(10), 1–15. https://doi.org/10.3390/cryst10100869