The analysis of X-Rays dose distribution in the 350 keV/10 mA electron beam machine (EBM) acility using PHITS computer code

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Abstract. The EBM 350 keV/10mA is an electron irradiation facility located at the Centre for Accelerator Science and Technology (PSTA). The EBM generates the electrons with energy of 350 keV and the beam current of 10 mA. This generated electron beam can induce x-rays radiation when passing through materials. It is dangerous for workers if the radiation dose exceeds the dose threshold. The previous study has investigated the x-rays radiation in the EBM facility. However, it implemented an analytical approach and applied the high-Z material tabulation data for the x-rays source definition. In this work, we present a different approach using particle transport simulation. The Particle and Heavy Ion Transport code System (PHITS) was utilised to obtain the x-rays source data as well as its dose distribution in the EBM facility. Based on the PHITS simulation, the x-rays are induced by the interaction between electron beams and the EBM window through atomic fluorescence and bremsstrahlung mechanism, with the total reaction rate density of $2.6437 \times 10^{13}$ reactions/cm$^3$s. The x-rays' maximum dose rate of $1.4659 \times 10^4$ µSv/s is located around the window, and it decreases along with the position from the window. The x-rays dose rate in the preparation room (12 m away from the x-rays source, behind 45 cm concrete wall) was $7.4975 \times 10^2$ µSv/s. It exceeded the permissible dose threshold. Therefore, a radiation shield or the working-duration limits is required for the workers' safety.

1. Introduction
The electron beam has been of great concern, thanks to its various utilisation such as in the welding process [1], additive manufacturing [2–7], coating process [8–10], material treatment [11] and many more [12–15]. Along with this trend, the Centre for Accelerator Science and Technology (PSTA) has established the Electron Beam Machine (EBM) with 350 keV energy and the current of 10 mA [16]. Due to its high usage rate [17,18], PSTA plans to improve the target loading system of their EBM facility. But, it affects the layout of EBM building and makes the load preparation room became directly exposed by the induced x-rays from the EBM. This x-rays radiation can endanger the workers. Therefore, an analysis of x-rays dose distribution in the facility is required to determine which areas that exceeded the permissible dose threshold.

The previous work has examined x-rays radiation in the EBM facility. They implemented the high-Z material target data to estimate the generated x-rays, then used an analytical method to calculate the x-ray radiation dose that passed through the concrete wall of the EBM facility [19]. However, it could not figure the x-rays dose distribution.
The different investigation has predicted the x-rays dose using particle transport simulation in a different EBM facility. They utilised the Monte Carlo N-Particle 5 (MCNP5) computer code and applied the point detector tally. Still, they also implemented the high-Z material target data as an estimation of the x-rays source in their simulation, instead of directly simulated the induced x-rays from electron interaction [20]. Additionally, MCNP has a limitation in the allowed number of point detector, thus narrowing its capabilities to illustrate the x-rays dose distribution [21].

There is another computer code for particle transport simulation, namely the Particle and Heavy Ion Transport code System (PHITS) [22]. It gets rid of the limitation found on the MCNP, using a different approach [23]. There have been many studies using PHITS in various disciplines [24–27]. Furthermore, the other investigations also had validated the PHITS’ simulation result [28,29].

In this work, we performed the particle transport simulation using PHITS to find out the x-rays source data and its dose distribution in the EBM facility. Thus, we will know which areas that exceeded the permissible dose threshold. This investigation result can also be used as the database in designing the suitable radiation protection shield as well as the layout of EBM building for the workers' safety.

2. Method

![Flowchart of the PHITS’ simulation procedure.](image)

Figure 1. Flowchart of the PHITS’ simulation procedure.

In this investigation, we used the procedure as in Figure 1, with the following steps:

2.1. Installation of PHITS package

We installed the PHITS package with the official licence from the Center for Computational Science & e-Systems – Japan Atomic Energy Agency (JAEA) into the personal computer with the windows 10 operating system. The package contains the PHITS 3.20 binary execution file and the supplemental data such as Japanese Evaluated Nuclear Data Library (JENDL 4.0).
2.2. **Make the user input file**

PHITS requires the user input file to perform particle transport simulation. It consists of several data such as parameters of the simulation, the geometry of the simulated system, materials used in the simulation, and tally.

We defined the parameters of the PHITS simulation to perform the normal calculation mode based on the Electron Gamma Shower 5 (EGS5) algorithm for the electron and photon transport with one keV cut-off energy. The source particles are 350 keV mono-energetic electrons with the current of 10 mA, which is equivalent to $6.25 \times 10^{16}$ electrons/s. They are generated and equally distributed over the top surface of the EBM' scanning window made from titanium foil with an area of $108 \times 6$ cm$^2$ and thickness of 50 µm. The generated electron beams are mono-directional and moving downward perpendicularly with the surface of EBM' scanning window.

![Figure 2. Layout of the EBM’ facility building.](image)

The model of the simulated system consists of the facility building and the EBM' components such as electron source, accelerator tube, focusing system, vacuum system and scanning system. Figure 2 represents the layout of the facility building. We provide the necessary materials data in Table 1 [30].

We used [T-interact] tally to obtain the occurred interactions data such as atomic fluorescence x-rays emission, bremsstrahlung and Compton scattering. The output data can be further analysed to find out the x rays source data.

[T-track] tally can be used to obtain the particle flux. Whenever particles pass through a specific region, this tally scored the track length then divided by the region's volume and the number of source particles. [T-track] tally resulted in the particle flux because the source particle is in the unit of particles/s. PHITS provides the flux data in every mesh of the region. With this approach, it eliminates the shortcoming such as found on point detector tally of the MCNP.

The [T-track]' output data can be further processed to estimate the effective dose rate in the specific region. We applied the [multiplier] section with built-in conversion coefficient based on the ICRP 103 for isotropic photon irradiation, and the multiplier factor $1 \times 10^{-6}$ µSv/pSv [31]. It multiplies the [T-track]' output data depend on the particle energies to obtain the dose rate (in the unit of µSv/s) at the respective region.

2.3. **Run PHITS simulation**

After making the user input file, we performed the PHITS simulation based on that file and also the JENDL. We used the parallel mode with the Message Passing Interface – Chameleon (MPICH) to accelerate our simulation. After PHITS finished the simulation, it provided us with the output file that contains the x-rays source data and its dose distribution in the EBM facility. Then, we compare the
obtained dose to the dose threshold for the radiation workers [32]. We assumed that there are 250 days of work in a year and 5 hours of work per day. Thus, the dose threshold per hour is 16 µSv.

Table 1. Materials data of the EBM model.

| Material                | Density (g/cm³) | Composition                       |
|-------------------------|----------------|----------------------------------|
|                         |                | Element | Weight Fraction (%) | Element | Weight Fraction (%) |
| Air                     | 0.001205       | C       | 0.000124            | O       | 0.231781            |
|                         |                | N       | 0.755268            | Ar      | 0.012827            |
| Aluminium Oxide         | 3.970000       | O       | 0.470749            | Al      | 0.529251            |
| Concrete                | 2.350000       | H       | 0.008485            | Si      | 0.145100            |
|                         |                | C       | 0.050064            | S       | 0.002970            |
|                         |                | O       | 0.473483            | K       | 0.001697            |
|                         |                | Mg      | 0.024183            | Ca      | 0.246924            |
|                         |                | Al      | 0.036065            | Fe      | 0.011031            |
| Copper                  | 8.960000       | Cu      | 1.000000            |         |                     |
| Stainless Steel 316L    | 8.000000       | C       | 0.000300            | Mn      | 0.020000            |
|                         |                | Si      | 0.010000            | Fe      | 0.653950            |
|                         |                | P       | 0.000450            | Ni      | 0.120000            |
|                         |                | S       | 0.000300            | Mo      | 0.025000            |
|                         |                | Cr      | 0.170000            |         |                     |
| Titanium Foil           | 4.510000       | H       | 0.000060            | Ti      | 0.994965            |
|                         |                | C       | 0.000300            | Cr      | 0.000050            |
|                         |                | N       | 0.000150            | Mn      | 0.000100            |
|                         |                | O       | 0.002000            | Fe      | 0.001500            |
|                         |                | Al      | 0.000300            | Ni      | 0.000050            |
|                         |                | Si      | 0.000300            | Cu      | 0.000005            |
|                         |                | Ca      | 0.000020            | Sn      | 0.000200            |

3. Result and Discussions

Based on the PHITS simulation, the interaction between the electron beams and the window generated x-rays through bremsstrahlung and atomic fluorescence mechanism. Their reaction rate densities are $7.5590 \times 10^{12}$ and $1.8878 \times 10^{13}$ reactions/cm³s, respectively. On the journey, electrons lost their energy due to interaction with the elements of the window. PHITS terminated the electron beams that are below energy cut-off, while the rest successfully escaped into the air.

The peak of electron flux is located at the range of 5 to 8 cm bellow the EBM’ window. In that position, the flux reaches the order of $10^{13}$ electrons/cm²s. PHITS depict the path of the electron beams as well as its flux in Figure 3. The escaped electrons interacted with the air and produced additional x-rays with reaction rate density of $3.3954 \times 10^{10}$ reactions/cm³s. Some of the electrons scattered back towards the other EBM components and interacted with it. The reaction rate density between scattered electrons and the other EBM components is $4.8546 \times 10^{10}$ reactions/cm³s. The reaction rate density in the window is much higher than both combined air and other EBM components. It is because of the energy and flux of electrons in the window is larger than in the other EBM components. Also, the window is denser than the air.
The EBM facility occupies some room in the accelerator building of PSTA. In this work, we modelled the irradiation room and the preparation room with an area of $13 \times 10$ m$^2$ and $6 \times 6$ m$^2$ respectively. The concrete walls around the irradiation room have the thickness of one meter on the near EBM position and 45 cm on the other sides. The preparation room also had 45 cm thickness of the concrete walls around it. There is an access hole for the workers and conveyor, that connecting the preparation room to the irradiation room.

PHITS exhibited the x-rays dose distribution in the irradiation room, as displayed in Figure 4. The x-rays primarily generated in the window. It then spread into the entire irradiation room. The area below the window had a maximum dose rate that reaches $1.4659 \times 10^4$ µSv/s. It is because of the x-rays still had its maximum flux and energy in that area. The dose rate then declines along with the position from the window. It is because the flux is inversely proportional to the square of the distance. Also, the x-rays lost its energy while crossing the air inside of the irradiation room.
Based on the simulation, the x-rays can not pass through the concrete walls, because it bulky enough to effectively attenuate the x-rays. The irradiation room also large and sufficient to disperse the energy and flux of x-rays, albeit there is a wall that is near the EBM. However, the x-rays escaped through the access hole into the preparation room as predicted.

The x-ray dose rate in the access hole and the preparation room are high, reaching $7.6716 \times 10^{-4}$ µSv/s and $7.4975 \times 10^{-3}$ µSv/s respectively. These values exceeded the safety threshold of 16 µSv/h or $4.4444 \times 10^{-3}$ µSv/s. Therefore, a radiation shield is required to block the x-rays' direct exposure from EBM, without interrupting the conveyor system. Thus, the preparation room became safe for its usage when EBM is operating.

There is another approach to avoid the exceeding of the dose threshold by limiting the working duration in the preparation room. If the dose threshold in one working day is 80 µSv, then the time limit for the x-rays dose rate of $7.4975 \times 10^{-2}$ µSv/s is 17 minutes. But, it is less efficient than building the appropriate radiation shielding and correctly setting the layout of the irradiation room.

### 4. Conclusion

The x-rays in the EBM facility are primarily induced by the interaction between electron beams and the EBM' window through atomic fluorescence and bremsstrahlung mechanism, with the reaction rate density of $7.5590 \times 10^{22}$ and $1.8878 \times 10^{19}$ reactions/cm²s, respectively. The x-rays' maximum dose rate of $1.4659 \times 10^{2}$ µSv/s is located around the window. The dose rate decreases along with the position from the window. It can not pass the concrete walls but escaped through the access hole into the preparation room. The dose rate in that area is sixteen times higher than the threshold, reaching $7.4975 \times 10^{-2}$ µSv/s. Thus, a radiation shield or the working-duration limits is needed for the safety.

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