STUDY OF EXISTING SHIELDING CHARATERISTICS OF MALAYSIAN NUCLEAR AGENCY - DENSE PLASMA FOCUS (MNA-PF) USING MONTE CARLO PHITS

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ABSTRACT

This study employs modelling tools to evaluate the effectiveness of existing shielding for the Dense Plasma Focus (DPF) neutron source at the Malaysian Nuclear Agency using the Monte Carlo simulation capabilities of the Particle and Heavy Ion Transport Code System (PHITS). Simulating the current shielding configuration, we assess its ability to attenuate neutron flux and radiation doses. The simulation results provide insights into the spatial distribution of radiation within the facility. This analysis focuses on verifying the adequacy of the existing shielding to ensure personnel safety during experiments conducted inside the room while also serving as a reference for future shielding assessments.

ABSTRAK

Kajian ini menilai keberkesanan perisai sedia ada untuk sumber neutron Fokus Plasma Padat (DPF) di Agensi Nuklear Malaysia menggunakan keupayaan simulasi Monte Carlo bagi Sistem Kod Pengangkutan Zarah dan Ion Berat (PHITS). Dengan memodelkan konfigurasi perisai semasa, kami menilai prestasinya dalam mengurangkan bilangan neutron dan dos radiasi. Hasil simulasi memberikan pandangan mengenai taburan radiasi. Analisis ini bertujuan untuk mengkaji penggunaan perisai semasa untuk memastikan keselamatan kakitangan semasa menjalankan eksperimen di dalam bilik dan digunakan sebagai rujukan untuk penilaian perisai pada masa hadapan.

Keywords: PHITS, shielding, neutron, plasma focus

INTRODUCTION

The Dense Plasma Focus (DPF) as depicted in Figure 1 is a device that can produce ions, neutrons, electrons, and X-rays (Puteri Nuraliah Husna Mohd Tajuddin et al., 2023). The device produces electromagnetic pinched (Lim et al., 2016). However, in addition to gamma radiation, DPF is a rich source of neutrons that flow through plasma. Although this kind and level of radiation is helpful for research, using the device and conducting tests can expose humans to radioactive hazards (Nemati et al., 2012).

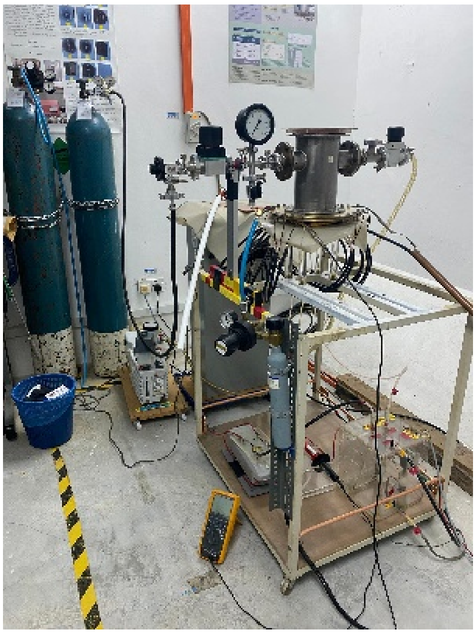

Figure 1 Malaysian Nuclear Agency-Plasma Focus (MNA-PF) that has been located at Block 43T, Malaysian Nuclear Agency

The Plasma Focus at the Malaysian Nuclear Agency (MNA) is a Mather-type device (Rokiah Mohd Sabri et al., 2013). Plasma focus devices are critical tools used for advancing research and applications in plasma physics and nuclear fusion (Troy Carter et al., 2020). It is essential to implement effective shielding to ensure the safety of personnel and the environment. Shielding effectiveness is a paramount concern, given the potential hazards of neutron radiation (Babaei et al., 2016). Shielding available in the Malaysian Nuclear Agency is the 'cave' shield designed from paraffin.

Due to its high hydrogen content, paraffin is often employed as a neutron shielding material in plasma focus devices. Paraffin can moderate neutrons due to its high macroscopic cross-section and ability to absorb them (Sardjono et al., 2022). This process, known as neutron moderation, is crucial in plasma focus devices where neutron radiation is a significant by-product of fusion reactions. The effectiveness of paraffin in neutron shielding lies in its ability to slow down fast neutrons to thermal energies, which can then be more easily absorbed or captured by other materials. Additionally, paraffin is relatively inexpensive and easy to shape and handle, making it a practical choice for constructing neutron shields in various experimental and industrial applications involving plasma focus devices (O'Brien, 2006).

Monte Carlo methods have long been used in radiation transport simulations because they can accurately model complex geometries and interactions between radiation and matter. The PHITS (Particle and Heavy Ion Transport Code System) is a general-purpose Monte Carlo particle transport simulation software developed by the Japan Atomic Energy Agency. It can simulate various types of radiation transport, including photons, electrons, and heavy ions, making it an ideal tool for studying radiation shielding (Sato et al., 2018).

This study aims to evaluate the existing shielding of the Malaysian Nuclear Agency-Plasma Focus (MNA-PF) using the Monte Carlo Particle and Heavy Ion Transport Code System (PHITS). The PHITS code, renowned for its versatility and accuracy, provides a robust framework for simulating the transport and interaction of particles within complex geometries. By leveraging PHITS, this research seeks to model the neutron emission and transport processes within the DPF facility and verify the effectiveness of the current shielding to ensure it meets safety standards and operational requirements (Iwamoto et al., 2017).

The significance of this study lies in its role in assessing radiation safety standards and validating the adequacy of shielding design for MNA-PF operations. With the growing interest in fusion research and its applications, ensuring effective shielding is essential for operational safety and compliance with international radiation protection standards (Noonbede et al., 2015). The neutron yield from the device can reach up to 1×10^8 neutrons per shot (Lim et al., 2016), underscoring the importance of evaluating the existing shielding to ensure it continues to provide sufficient protection

In conclusion, the study of existing shielding for the MNA-PF using Monte Carlo PHITS simulation software is crucial for verifying personnel safety and ensuring compliance with radiation protection standards. By accurately modelling radiation transport and dose distributions, this research confirms the adequacy of the current shielding design in protecting human health. While the device is deemed safe for personnel, this study further emphasizes the importance of continuous monitoring and evaluation to maintain high safety standards for workers and the surrounding environment.

METHODOLOGY

The Particle and Heavy Ion Transport code System (PHITS) is required to simulate to study the effect of shielding in studying radiation. It can simulate the radiation track that includes the neutron in the plasma focus device (Sato et al., 2018). The geometry of the Plasma Focus device and shielding must be be defined in the Surface and Cell section. The geometry of the MNA-PF has been defined before in the Study of Neutron Field Around Malaysian Nuclear Agency-Plasma Focus (MNA-PF) using PHITS (Puteri Nuraliah Husna Mohd Tajuddin et al., 2023)..

Figure 2 ‘Cave’ design shielding used for MNA-PF

Before running the simulation, the ‘cave’ design shielding of MNA-PF used in the Malaysian Nuclear Agency must be measured. Figure 2 shows the schematic view of the shielding of MNA-PF. The length and width of the shielding are 104 cm and 91 cm, respectively. The height of the shielding is 189 cm. The outer part of the shield is made of stainless steel, and the inner part of the shielding is poured with paraffin, with a composition of 14.86% hydrogen and 85.14% oxygen. The composition of shielding has been defined in the Material section of PHITS.

Next, we have to define the source. The collision of plasma for the D-D reaction causes the production of neutrons. In the simulation, the neutron yield is 7500 neutrons/shot. It has been defined using totfact. The value of neutron yield in the MNA-PF is being obtained from the previous study and experiment that had been done in the paper of Preliminary results of Malaysian Nuclear Agency Plasma Focus (MNA-PF) as a slow focus mode device for deuterium filling gas in correlation with Lee model code (Zin et al., 2017).

The results are obtained from the output file. Several output files have been created. The T-Track in the PHITS obtained the neutron flux, effective dose rate, and dose mapping in the plasma focus device. The T-Track has been configured to convert the unit from pSv/sec to µSv/hr to determine the effective dose rate. The results have displayed the effective dose rate spectrum. The number of batches (maxbch) and the history number per batch (maxcas) have been set high to reduce the relative inaccuracy (Sato et al., 2018). This results from the uncertainty relying on the total number of historical events. Less than 5% relative error is given in the results.

RESULTS AND DISCUSSIONS

The results will include the neutron distribution around the MNA-PF and paraffin shielding. These results are obtained after running the PHITS simulation and obtain from the output file.

Neutron Distribution

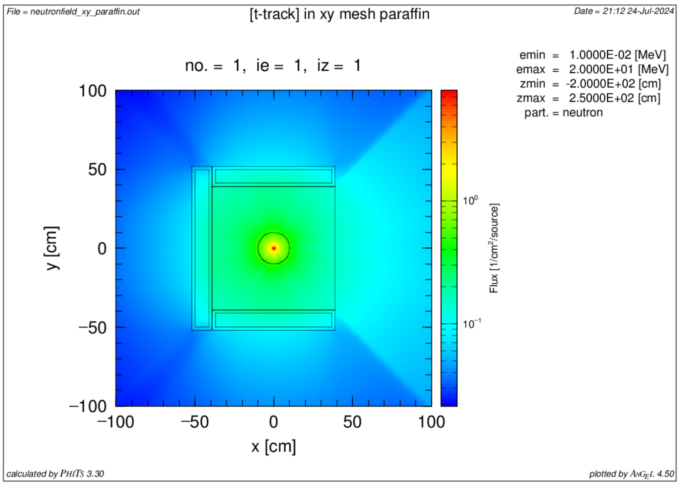

Figure 3 Neutron distribution around MNA-PF and paraffin shielding

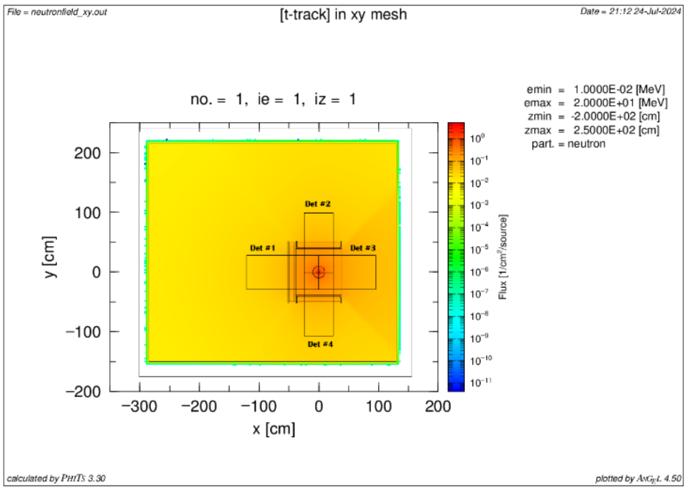

Figure 4 Neutron distribution in the MNA-PF's lab.

The neutron distribution for the Dense Plasma Focus (DPF) device at the Malaysian Nuclear Agency (MNA-PF) has been assessed using Monte Carlo PHITS simulations, as illustrated in Figure 3 and Figure 4. Figure 3 presents the neutron distribution around the MNA-PF with paraffin shielding from -100 cm to 100 cm. The blue region in Figure 3 at the plot's periphery indicates the lowest neutron flux, 10^3 neutrons/cm^2/source particle. The cave's design shielding shows that the paraffin effectively slows down the neutron as the neutron flux is higher at the opening part of the shielding.

Figure 4, shows that the centre of MNA-PF consists of the highest neutron flux indicated by the red and yellow region. The peak flux reaches values of 10^5 neutrons/cm^2/source particle. This indicates that the flux is highest near the source. As moving outward from the centre of Figure 4, the neutron flux decreases. It shows that the scattering and absorption of neutrons happen as they travel through the paraffin moderator.

Figure 4 displays the neutron flux distribution in the XY-plane, and the locations of four detectors around the central neutron source. Detector 1 is situated along the negative x-axis, detector 2 is placed along the positive y-axis, detector 3 is along the positive x-axis, and detector 4 is located along the negative y-axis. All detectors are equidistant from the central neutron source, forming a cross-like arrangement. This setup ensures comprehensive coverage of neutron flux measurements in multiple directions, enabling accurate characterization of neutron emission and shielding performance within the experimental setup.

Effective Dose Rate

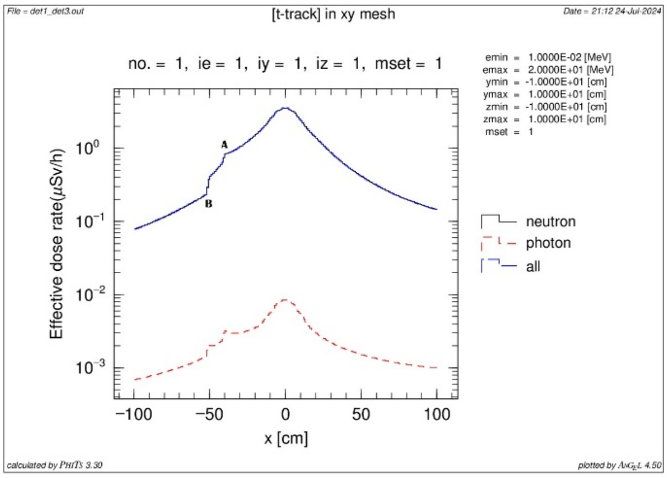

Figure 5 Effective dose rate distribution in XY-mesh for detector 1 and detector 3 that have been located along the x-axis.

Figure 5 represents the effective dose rate distribution in an XY-mesh. The effective dose rates for neutrons, photons, and all are plotted along the x-axis, ranging from -100 cm to 100 cm. The neutron effective dose rate, represented by the solid black line, shows a peak near the centre (x = 0 cm) with values approaching approximately one µSv/hr. The peak area indicates the highest radiation exposure in this region. The gradual decrease in dose rate indicates the attenuation of radiation as it travels through the medium. Points A and B highlight the attenuation of radiation through the paraffin shielding.

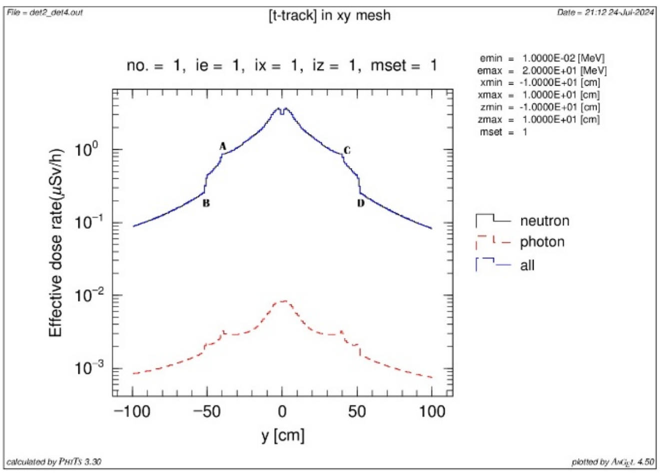

Figure 6 Effective dose rate distribution in XY-mesh for detector 2 and detector 4 that has been located along the y-axis.

Figure 6 represents the effective dose rate distribution in an XY-mesh. The effective dose rates for neutrons, photons, and all are plotted along the y-axis, ranging from -100 cm to 100 cm. The dose rate has a maximum value around the centre (y=0cm). The peak area indicates the highest radiation exposure in this region. The gradual decrease in dose rate indicates the attenuation of radiation as it travels through the medium. Points A and B highlight the attenuation of radiation through the paraffin shielding.

The photon effective dose rate, depicted by the dashed red line, is consistently lower than the neutron dose rate across the measured range. The maximum photon dose rate is observed near the centre, reaching approximately 10^{-2} µSv/hr. The photon's result shows that while photon radiation is present, it is much less intense than neutron radiation. The photon dose rate also diminishes with increasing distance from the centre, confirming the shielding's effectiveness.

The total effective dose rate, shown by the dashed blue line, combines the contributions from both neutrons and photons. The total dose rate peaks at around one µSv/hr at the centre and decreases to below 10^{-1} µSv/hr as the distance increases. This overall dose rate is critical for evaluating the facility's safety, ensuring that the combined radiation exposure remains within acceptable limits.

The data reveals that the current shielding configuration effectively reduces radiation exposure to safe levels. The highest observed dose rates are still well within the regulatory safety limits for occupational exposure, which typically allow for a maximum dose rate of 2.28 µSv/hr or 20 mSv/yr (International Atomic Energy Agency, 2018). The significant reduction in dose rates with increasing distance from the centre indicates that the shielding materials and design successfully mitigate the DPF device's radiation.

These results suggest that while the existing shielding is adequate, continuous monitoring and regular reassessment are essential to maintain compliance with radiation safety standards. Addressing areas with relatively higher dose rates ensures radiation exposure remains as low as reasonably achievable (ALARA), reinforcing personnel's safety and the surrounding environment. The MNA-PF facility ensures operational safety and adherence to international radiation safety guidelines by maintaining strict radiation protection measures.

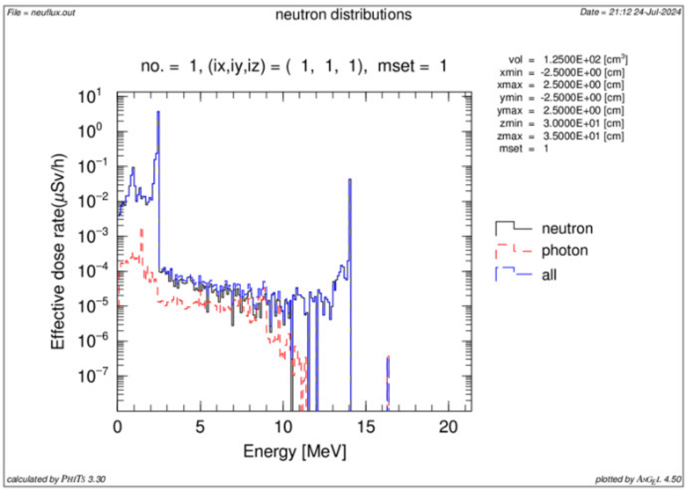

Figure 7 Effective dose rate as a function of energy

The graph in Figure 7 provides insight into the energy-dependent distribution of neutron and photon doses resulting from a neutron source. Figure 7 shows that neutrons contribute more significantly to the total effective dose rate than photons. The peaks at 2.5 MeV show the maximum effective dose, more than one µSv/hr. Below 2.5 MeV, the neutron dose rate rapidly decreases, indicating lower neutron flux at these energies. The sharp peak at 14.5 MeV is the secondary interaction that occurs. Using a logarithmic scale for the dose rate effectively highlights the wide range of dose contributions across different energies, emphasizing both high and low-dose regions.

The maximum effective dose rate from the PHITS output file for the plasma focus device is 1.03×10^{-3} µSv per shot. Approximately 6 million shots per year would be required to meet the occupational safety limit of 20 mSv/year. This calculation ensures that the cumulative exposure stays within the safety threshold for occupational radiation exposure, protecting workers from exceeding the annual dose limit. By carefully monitoring the number of shots and adhering to this limit, safety protocols can be maintained effectively in the operational environment of the plasma focus device.

CONCLUSION

The study of the existing shielding for the Malaysian Nuclear Agency's Dense Plasma Focus (MNA-PF) using Monte Carlo PHITS simulations has provided valuable insights into the effectiveness of the current shielding configuration. By simulating neutron flux and energy distribution, the study verified areas where the shielding performs adequately and identified conditions that could benefit from further analysis. The neutron yield of 7.5×10^3 served as a critical parameter, ensuring the simulations accurately represented the operational conditions of the MNA-PF. These findings could serve as a reference for future simulations, guiding the evaluation of shielding materials and geometries before implementing new designs. Additionally, controlling the number of device shots could be an alternative to modifying materials or geometries, ensuring compliance with safety standards while maintaining experimental flexibility. This research underscores the importance of simulation studies in supporting the safe and efficient operation of plasma focus devices.

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