BEAM DUMP DESIGN AND SIMULATION FOR A 280-MeV ELECTRON LINEAR ACCELERATOR

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Abstract

A 280-MeV electron linear accelerator has been designed to expand the research capabilities and applications of high-energy electron beams in Thailand. For commissioning and energy verification, two dedicated beam dumps are positioned downstream of the bending magnet. This work presents the simulation-based design and optimization of these beam dumps using the PHITS Monte Carlo radiation transport code. Different material configurations and geometries were evaluated to reduce prompt radiation and suppress secondary particle leakage. A multilayer structure combining high-Z and low-Z materials was found to provide effective energy absorption while confining photon and neutron secondaries within the shielding volume. The resulting radiation field in the tunnel meets all applicable safety criteria and regulatory limits. These results establish the validated baseline design for the beam dumps and support their transition to detailed engineering and fabrication.

INTRODUCTION

Synchrotron Light Research Institute has developed a high-energy electron beam accelerator intended to provide 280-MeV electron beam to various applications and serve as a prototype of the pre-injector for the future light source. The pre-injector primarily consists of a thermionic electron gun, two sub-harmonic bunchers, and four accelerating structures. To facilitate machine commissioning, two beam dumps will be installed: one at 0° to absorb the beam from the linac and another at 45° following the bending magnet to measure the beam energy. Since both beam dumps are intentionally used to collect the electron beam of equivalent energy, a single design is sufficient. The main purpose of the design is to develop a compact beam dump built with simple materials and structure, while ensuring the radiation leakage dose remains below the Thai regulatory limit.

COMPUTATIONAL SETUP

The beam dump design has been evaluated using PHITS, a Monte Carlo particle transport simulation code [1]. The simulation used the EGS5 library package for electromagnetic interaction; JENDL-4, JENDL-5, INCL4.6, and GEM library packages for nuclear interaction; and DCHAIN for a decay chain analysis and activation study.

Figure 1 illustrates the geometry of the pre-injector vault containing two beam dumps. The vault is shielded by the 1.2-m thick concrete wall, floor, and ceiling to prevent radiation leakage to the controlled area dedicated to a linac klystron gallery, and by the 1.5-m thick wall that separates the vault from the main tunnel. Two entrance doors were designed to allow access to the vault: the concrete door positioned opposite the beam dump and a composite door—comprising iron, lead, and polyethylene layers with a total thickness of 13 cm—located at the beginning of the maze. To monitor radiation leakage around the vault, six NaI detectors with a radius of 15 cm are placed virtually outside the shielding wall in the area of expected high radiation or where personnel exposure is most likely.

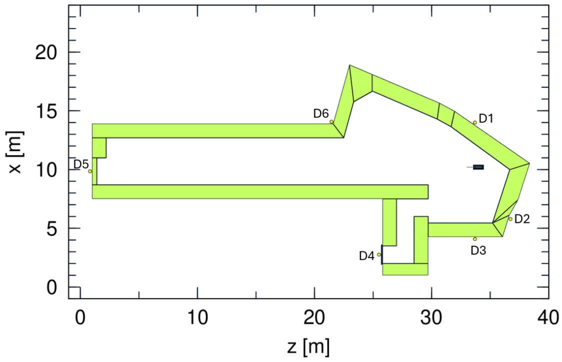

Figure 1: Pre-injector vault geometry where a beam dump is located, together with six detectors outside shielding walls.

The beam dump is designed to absorb the electron beam from a linear accelerator and attenuate the radiation field in the vault, ensuring that the external dose rate remains below the Thai regulatory limit of 3 µSv h^{-1}. Accounting for uncertainties in Monte-Carlo simulation and nuclear data, a safety factor of 10 was applied, resulting in a conservative target dose of 0.3 µSv h^{-1}. Figure 2 depicts the beam dump design, featuring a central core surrounded by three shielding layers:

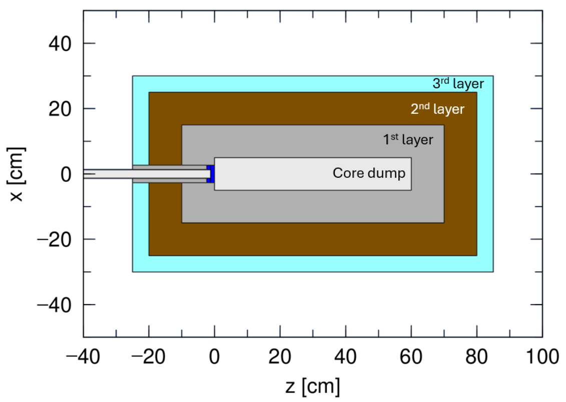

Figure 2: Design of a beam dump with an aluminum core dump and three layers of lead, steel, and borated polyethylene.

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lead, low-carbon steel, and borated polyethylene. A modular block geometry was selected to simplify installation. To evaluate efficiency, a 15 cm long tungsten core and a 60 cm long aluminum alloy core, both with 10 cm thickness, were compared. The core dump is housed with three different layer thickness configurations, detailed in Table 1. Tungsten was selected for its high density, short radiation length, and small Molière radius, allowing for a more compact footprint (see Table 2); however, its low critical energy leads to higher bremsstrahlung production. In contrast, the aluminum alloy core requires a greater length to achieve comparable absorption but benefits from higher critical energy and lower secondary particle yields.

Table 1: Configuration of Layer Thickness

Configuration	**Layer 1 [cm]**	**Layer 2 [cm]**	**Layer 3 [cm]**
5-5-5-Al/W	5	5	5
10-5-5-Al/W	10	5	5
10-10-5-Al/W	10	10	5

Table 2: Material Properties of Tungsten, Aluminum, Lead, Steel, and Borated Polyethylene (BPE)

Material	ρ **[g/cm^3]**	X_0 **[cm]**	R_M **[cm]**	**CE [MeV]**
Tungsten	19.3	0.35	0.93	7.79
Aluminum	2.70	8.90	4.42	42.7
Lead	11.4	0.56	1.6	7.43
Steel	7.85	1.76	1.72	21.68
BPE	1.04	45	8	92.0

To shield the lateral and forward radiation generated from the interaction of the primary electron beam, a multiple-layer approach combining simple high-Z and low-Z materials is employed. The first layer is made of lead intended to attenuate high-intensity bremsstrahlung photons across the energy spectrum, although it generates significant secondary neutrons due to its low critical energy. Low-carbon steel is selected as the second layer to further reduce photon transmission and moderate neutrons toward the thermal energy range. The third layer, borated polyethylene (BPE), is chosen to capture these thermal neutrons via the boron neutron capture reaction, converting them into lithium. Various combinations of layer thicknesses were studied to achieve a compact beam dump design with a minimized radiation field. Table 2 lists materials and their properties, where ρ is density, X_0 is radiation length, R_M is Molière radius, and CE is critical energy.

To simplify the simulation, a parallel electron beam with a uniform energy of 280 MeV was modeled, originating in the vacuum pipe 30 cm from the beam dump. The beam radius, based on the calculation of electron beam dynamics, is conservatively estimated at 1.6 mm, covering 99% of the actual beam profile. The pre-injector is designed to operate at 2 Hz with a 417.3-pC bunch charge, yielding a normalization factor of 1.88×10^{13} electrons per hour. Dose conversion coefficients were based on the ICRP103 definition (AP) [2]. To optimize the computational efficiency, the electron energy cutoff of 1 MeV was applied.

RESULTS AND DISCUSSIONS

The radiation dose distribution within the vault following electron beam impingement on the core dump was investigated. Figure 3 compares the dose rate distributions for the tungsten and aluminum cores using a shielding configuration of 5-cm lead, 10-cm steel, and 10-cm BPE. The results indicate that radiation leakage beyond the shielding wall is slightly higher for the aluminum core than for the tungsten core. For the tungsten core, the calculated dose at the detector nearest the beam dump is approximately 6.5×10^{-4} µSv h^{-1}, while the dose resulting from backscattering is 5.0×10^{-2} µSv h^{-1}. Conversely, the maximum dose rate calculated for the aluminum core in the vicinity of the beam dump is 2.0×10^{-2} µSv h^{-1}.

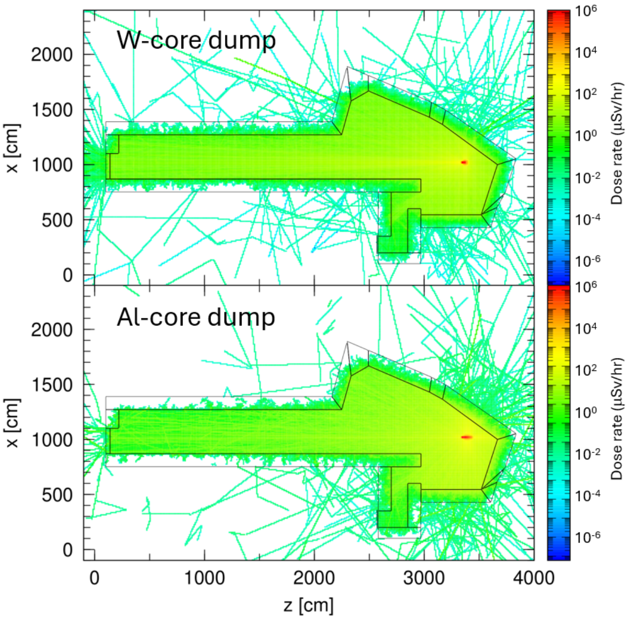

Figure 3: Comparison of dose rate distribution from a tungsten (top) and an aluminum (bottom) core dumps in the pre-injector vault.

Figure 4 provides a detailed comparison of the dose rate distributions in the immediate vicinity of the tungsten and aluminum core dumps. The data show that the dose rate for the tungsten core is slightly lower than that of the aluminum core. This is attributed to the fact that secondary particles are more effectively confined within the tungsten core, leading to reduced forward radiation leakage compared to the aluminum alternative.

To evaluate the effectiveness of the beam dump in shielding and attenuating secondary particles, particle fluxes were tracked as they crossed each interface. Figure 5 compares photon, electron, and neutron fluxes across adjacent surfaces for both aluminum and tungsten cores under various layer

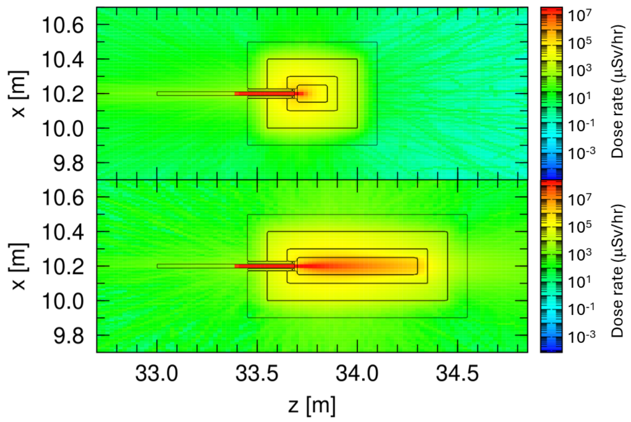

Figure 4: Comparison of dose rate distribution from a tungsten and an aluminum core dumps around the beam dump.

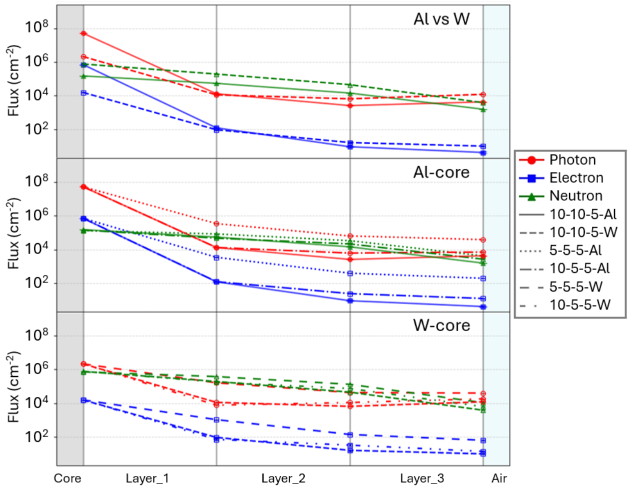

Figure 5: Photon (red), electron (blue), and neutron (green) fluxes crossing adjacent surfaces, when comparing between aluminum and tungsten core dump (top) and three different layer configurations with aluminum (middle) and tungsten core dump (bottom).

configurations. When comparing core materials, the tungsten core more efficiently absorbs the primary electron beam and transmits fewer photons to the lead layer, though it generates a higher neutron flux due to photoneutron production. However, a 10-cm lead layer effectively equalizes the photon and electron fluxes for both core types before they reach the steel layer. In contrast, the neutron flux generated by the tungsten core remains one order of magnitude higher at the beam dump surface and throughout the outer layers into the surrounding air.

Analysis of the three shielding configurations indicates that a setup consisting of 10-cm lead, 10-cm steel, and 5-cm BPE is the most effective, regardless of the core material. This configuration reduces photon and electron fluxes by up to two and four orders of magnitude for the tungsten and aluminum cores, respectively, while minimizing neutron transmission to subsequent layers. This arrangement also results in the lowest radiation leakage into the air, whereas the 5-cm lead configuration allows the highest leakage. The 5-cm BPE layer fulfills its design objective by reducing the neutron flux by approximately one order of magnitude, with a minor trade-off in photon production resulting from boron neutron capture.

Air activation within the pre-injector vault was evaluated under a scenario involving eight hours of continuous irradiation at maximum beam current followed by an eight-hour cooling period. Figure 6 compares the resulting air activity for both aluminum and tungsten core dumps. The activity levels for the tungsten core are significantly higher than those for aluminum, as the tungsten beam dump releases a greater neutron flux into the vault atmosphere. Despite the difference in magnitude, both cases follow an identical trend: activity increases rapidly at the start of irradiation, peaks at the end of the eight-hour period, and decreases during the rest period. The total activity is primarily dominated by ^{41}Ar, with secondary contributions from ^{16}N for the aluminum core and ^{13}N for the tungsten core. In all configurations, the calculated activity remains well below the ICRP DAC limit of 1.5×10^4 Bq m^{-3}.

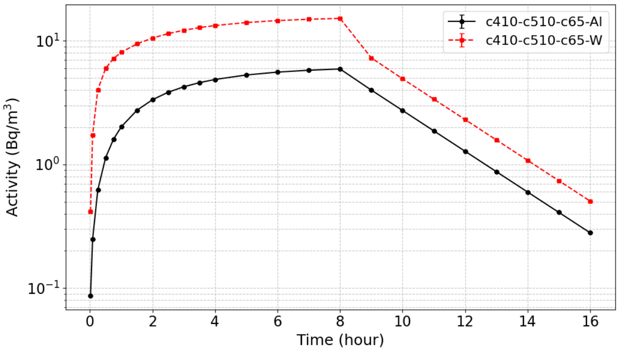

Figure 6: Air activation in the pre-injector vault compared between aluminum (black) and tungsten (red) core dump.

CONCLUSION

The beam dump design for the 280-MeV pre-injector was investigated across various shielding configurations and core materials. The comprehensive results—encompassing dose distributions, particle fluxes, and air activation levels—confirm that an aluminum alloy core housed within three layers (10-cm lead, 10-cm steel, and 5-cm BPE) is the optimal candidate for the intended application. These findings will serve as the definitive baseline for subsequent mechanical engineering, detailed design, and fabrication.

REFERENCES

[1] T. Sato *et al.*, ”Recent improvements of the Particle and Heavy Ion Transport code System - PHITS version 3.33”, *J. Nucl. Sci. Technol.* vol. 61, pp. 127–135, 2024. `doi:10.1080/00223131.2023.2275736`

[2] ICRP Publication 103 Protection Quantities and ICRU Report 39/51 Operational Quantities, *J. ICRU.*, vol. 20, pp. 20–23, 2020. `doi:10.1177/1473669120966212`