Shielding Design and Residual Dose Assessment of the XiPAF Beam Dump

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Abstract

To ensure radiation safety following the upgrade of the Xi' an 200 MeV Proton Application Facility (XiPAF), this paper presents the research and design of a beam dump. First, based on the characteristics of the secondary radiation field of medium-energy proton accelerators, a composite structure for the beam dump and a low-neutron-yield target core material—polyethylene—were determined. The beam dump was designed using FLUKA, and calculation results indicate that the maximum dose equivalent rates at the tail side and lateral side of the beam dump are 4.2 mSv/h and 3.2 mSv/h, respectively, meeting the dose limit requirement of 5.5 mSv/h. The selection of polyethylene as the target core material reduces the dose in the upstream direction by approximately 75% compared to conventional graphite targets. Finally, residual dose analysis was performed for three typical operating conditions of continuous beam extraction for 1 hour, 1 day, and 1 week, with the time required for the dose at the dump entrance to decay to 2.5 Sv/h being approximately 2–3 hours in each case. This paper provides an important reference for beam dump design in medium-energy proton accelerators, helps ensure the radiation safety of XiPAF personnel, and possesses good engineering application value.

Full Text

Preamble

Radiation Shielding Design and Residual Radioactivity Assessment for the Beam Dump at XiPAF

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Abstract

[**Background**] The Xi' an 200 MeV Proton Application Facility (XiPAF) was constructed as an accelerator facility for studying single-event effects in aerospace devices. Recently, XiPAF has been planned for upgrade and transformation into a versatile experimental facility for both proton and heavy-ion applications. [**Purpose**] To ensure radiation safety after upgrading, this paper presents the radiation shielding design and residual radioactivity assessment of the beam dump. [**Methods**] Based on Monte Carlo simulations using FLUKA, a composite-structure beam dump was designed with polyethylene as the target core material, which yields low neutron production. [**Results**] Computational results show that the ambient dose equivalent rate at the rear and transverse sides of the beam dump is 4.2 mSv/h and 3.2 mSv/h respectively (below the 5.5 mSv/h limit). Compared to traditional graphite cores, polyethylene demonstrated approximately 75% lower upstream dose while maintaining equivalent shielding performance. Analysis of residual dose under three typical operating conditions (1-hour, 1-day, and 1-week continuous irradiation) showed consistent decay patterns, reaching the dose constraint of 2.5 Sv/h after 2-3 hours cooling time. [**Conclusions**] These results provide practical reference for radiation protection design of beam dumps at similar intermediate-energy proton accelerator facilities.

Keywords: Beam dump, Radiation shielding, Radioactivity, Monte-Carlo simulation

Introduction

The Xi' an 200 MeV Proton Application Facility was built as an accelerator for studying space single-event effects in aerospace devices. During the 14th Five-Year Plan period, XiPAF is scheduled for upgrade into a proton/heavy-ion universal experimental facility [1, 2]. To ensure personnel, equipment, and environmental safety, radiation protection issues for such accelerator facilities cannot be neglected, with the beam dump playing a crucial role. The beam dump absorbs wasted beam, creating a superimposed shielding structure on top of existing shielding walls to enhance overall shielding effectiveness while preventing activation of wall and surrounding equipment materials from direct beam exposure. As shown in [Figure 1: see original paper], the beam dump is located at the end of the high-energy transport line and irradiation terminal at XiPAF, making it the most frequently accessed area by test personnel after accelerator shutdown. Therefore, research and design of the XiPAF beam dump and assessment of its residual radioactivity level are essential for facility radiation safety.

This study compares and analyzes the shielding performance of commonly used shielding materials, proposes materials and structure for the beam dump, performs shielding calculations and verification through Monte Carlo simulation, and evaluates the types and activities of radionuclides produced in the target core under different operating durations. The research results can provide reference for beam dump design and personnel radiation protection at intermediate-energy proton accelerators.

1 Design Requirements

According to the design specifications for the XiPAF heavy-ion upgrade project [2], the facility can extract protons with maximum energy of 200 MeV and heavy ions with maximum energy not exceeding 10 MeV/u. From a radiation protection perspective, proton shielding requirements dominate because protons have stronger penetration capability and their beam intensity is three orders of magnitude higher than that of heavy ions. The maximum proton beam intensity on target is 1.3×10^{10} pps, corresponding to a beam power of less than 1 W, far below the maximum power limit for natural cooling, thus heat deposition is not a concern. Currently, no specific regulations exist in China regarding the shielding effectiveness of beam dumps themselves. The China Spallation Neutron Source (CSNS) beam dump design referenced the Japanese JAERI 3 GeV storage ring proton beam dump design criteria, requiring the dose rate in soil at 1 m outside the shielding body to be below 5.5 mSv/h [3]. Considering that XiPAF' s beam energy and intensity are both lower than the above facility, and the beam dump size and construction costs are relatively controllable, this paper adopts a more conservative dose limit based on the ALARA principle, setting the dose rate limit at the outer edge of the beam dump to 5.5 mSv/h.

2.1 Design Approach

As charged particles, protons have relatively fixed ranges in materials. Proton bombardment of target materials produces various secondary particles, particularly secondary neutrons and gamma photons from nuclear reactions with target nuclei. These neutral particles have strong penetration capability and constitute the primary object of prompt radiation field shielding. For proton accelerators with energies above approximately 10 MeV, secondary neutrons make the dominant contribution to the prompt radiation field [4]. Review of available literature shows that shielding design for beam dumps at domestic and international accelerator facilities is primarily based on experience without fixed paradigms [3, 5-8]. Based on XiPAF beam parameters and radiation field characteristics, this design follows four principles: (1) The beam dump adopts a composite structure consisting of target core material, main shielding material, and peripheral shielding material, with radial symmetry about the beam axis; (2) The target core material, which directly absorbs the proton beam, should have low secondary neutron yield; (3) The main shielding material should be a high-density metal for rapid energy degradation of high-energy secondary neutrons within limited volume while providing good shielding against secondary gamma photons; (4) The peripheral shielding material should have good shielding performance against moderated neutrons.

Although empirical formulas for shielding calculations have been proposed [4], they are inconvenient for complex geometries and multiple material combinations, where Monte Carlo simulation methods offer greater advantages. The Monte Carlo simulation software FLUKA, based on simulation of particle-matter interactions, is widely used in high-energy physics, space radiation, radiotherapy, radiation shielding calculations, induced radioactivity analysis, and other fields [9]. The Monte Carlo simulation work in this paper is primarily based on FLUKA.

2.2 Material Selection

The target core absorbs the vast majority of beam energy, and its material selection must balance low secondary neutron yield with low activation characteristics. Neutron yield is defined as the average number of neutrons produced per incident proton in the target material. FLUKA was used to calculate neutron yield, defined as the number of neutrons exiting the target material' s outer surface. The target shape is a cylinder with height equal to the proton range and radius equal to the proton' s lateral straggling, designed to minimize further reactions of secondary neutrons with target material. First, the SRIM [10] program was used to quickly obtain the range (Table 1) and lateral straggling (Table 2) of 10-200 MeV protons in several common shielding materials (polyethylene, graphite, aluminum, iron, copper, lead) as geometric model parameters for FLUKA simulations. In FLUKA calculations, protons were set to vertically incident on the center of the cylinder's bottom face, and the USRBDX scoring card was used to obtain the neutron yield exiting the cylinder (Figure 2 [Figure 2: see original paper]) and neutron energy spectrum distribution (Figure 3 [Figure 3: see original paper]).

The calculated neutron yields for 30 MeV protons incident on several materials were compared with reference data from literature [11], as shown in Table 3 . The simulation results show good agreement with previous reference data, with maximum deviation less than 20% when the neutron energy threshold is 1 MeV. Since the target dimensions differ between the simulation and literature [11], and the experimental measurement in [11] counted neutrons with energy greater than 2-3 MeV, while simulation values were used for neutrons below this energy, the FLUKA results are considered basically consistent with the experimental results in [11].

Figure 2 shows that neutron yield is positively correlated with proton energy. Overall, polyethylene produces the fewest secondary neutrons when bombarded by protons, followed by graphite, while metallic target materials produce higher yields. In Figure 3, metallic materials produce fewer high-energy secondary neutrons than graphite and polyethylene, which contributes somewhat to high-energy radiation shielding. However, considering that metallic target cores would result in greater residual dose than lower atomic number materials like graphite and polyethylene, the target core material should be selected from between graphite and polyethylene. Since the secondary neutron energy spectra for 200 MeV protons incident on polyethylene and graphite are almost identical, and the former has lower neutron yield, polyethylene is selected as the target core material.

For secondary high-energy neutrons produced by proton interactions with the target core, energy loss is dominated by inelastic scattering, requiring heavy-element materials to rapidly deplete fast neutron energy. Considering cost and manufacturability, iron is selected as the main shielding material. Outside the iron, peripheral shielding material with good low-energy neutron shielding performance is installed, generally choosing hydrogen-rich materials. This paper uses boron-containing polyethylene with 5% B_4C mass fraction and density of 1.01 g/cm^3. Since ^{10}B has a high thermal neutron capture cross-section, adding B_4C to polyethylene enhances low-energy neutron absorption.

2.3 Shielding Calculation

Literature [12] lists the angular distribution of secondary neutrons after proton bombardment. For 200 MeV protons, secondary neutrons are most abundant in the forward direction and symmetrically distributed in the radial direction perpendicular to the beam axis. Therefore, a cylindrical shielding geometry is adopted overall, with the front half of the main shielding material open to ensure the target core is located in the front half, as shown in Figure 4 [Figure 4: see original paper]. Based on beam pipe dimensions and the 200 MeV proton range, the opening diameter and target core diameter are selected as 20 cm, with target core thickness of 30 cm.

The ambient dose equivalent around the beam dump was calculated using FLUKA' s USRBIN and AUXSCORE scoring cards. By adjusting shielding material dimensions in the calculation model and observing whether dose distributions meet limit requirements, the final beam dump dimensions were determined. Through shielding calculations, the main shielding iron core diameter was determined to be 70 cm with thickness of 90 cm, covered on front/rear sides and radial sides with 30 cm and 25 cm thick boron-containing polyethylene respectively. The total weight of all shielding is approximately 4.5 t. Figure 5 [Figure 5: see original paper] shows the dose distribution color map, where the contour line corresponds to a dose value of 5.5 mSv/h. The dose distribution exhibits gradual attenuation from center to periphery. At the beam dump' s rear side (Z=110 cm) and transverse side (R=60 cm), the maximum instantaneous dose rates from beam loss are 4.2 mSv/h and 3.2 mSv/h respectively, meeting design requirements. However, dose significantly exceeds the limit in the backward direction of beam incidence, which is unavoidable due to the open structure.

Figure 6 [Figure 6: see original paper] compares one-dimensional dose distributions from protons, secondary neutrons, and secondary photons, where the horizontal coordinate is position along the beam direction with target core incident surface at Z=0 cm, and the vertical coordinate is the average dose within

R=10 cm. At the target core, the total dose shows a Bragg peak, indicating that dose here is primarily contributed by proton energy deposition, while upstream and downstream of the target core, the total dose is mainly contributed by neutrons.

To verify the target core material selection, the target core material was replaced with graphite in the simulation while keeping geometry unchanged. Figure 7 [Figure 7: see original paper] compares one-dimensional dose distributions for the two target core materials. The Bragg peaks for 200 MeV protons in both materials are clearly visible at equivalent ranges. Beyond the Bragg peak, primary proton energy deposition rapidly attenuates to zero, with downstream dose contributed by secondary particles. The rear dose of beam dumps with both target core materials is comparable. Meanwhile, radial shielding with polyethylene target core is slightly better than graphite. Notably, upstream of the beam dump, the dose with polyethylene target core is only about one-quarter that with graphite target core, due to enhanced neutron backscattering with increasing target atomic mass [13]. Therefore, for 200 MeV proton accelerator beam dumps, selecting polyethylene as the target core material can significantly reduce backscattered dose compared to graphite, which is advantageous for reducing instantaneous secondary radiation at single-event-effect irradiation terminals.

3 Residual Dose Assessment

During operation of intermediate-energy proton accelerators, beam loss produces instantaneous radiation. Interaction of these beam particles with various component materials causes material activation, resulting in residual radiation after accelerator shutdown, which is an important protection concern for personnel conducting maintenance and sample exchange [6]. The beam dump is the component with the most concentrated beam loss and is located downstream of the XiPAF irradiation terminal, making assessment of its residual radiation level essential, particularly at the beam dump entrance.

Using FLUKA' s IRRPROFI, DCYTIMES, DCYSCORE input cards, key parameters such as beam loss rate, irradiation time, and cooling time can be conveniently set. With proton beam energy of 200 MeV and beam loss rate of 1.3×10^{10} pps, Figure 8 [Figure 8: see original paper] shows the residual dose rate distribution around the beam dump after continuous irradiation for 1 day and different cooling times, where the contour line corresponds to a dose value of 2.5 Sv/h. As cooling time increases, residual dose decreases, with residual radiation primarily present at the beam dump entrance.

This study further selected the area within R=10 cm on the beam dump entrance plane (Z=-40 cm) as the dose assessment point, calculating residual dose decay after continuous irradiation for 1 hour, 1 day, and 1 week, as shown in Figure 9 [Figure 9: see original paper]. The calculations show that for all three scenarios, the cooling time required for dose to decay to XiPAF' s dose management constraint value (2.5 Sv/h) is approximately 2-3 hours. Within two hours after beam shutdown, dose decay trends are essentially consistent across the three scenarios. With longer cooling times, scenarios with longer irradiation times retain higher residual doses, a characteristic attributed to the relative relationship between irradiation time, cooling time, and radionuclide half-lives.

According to radionuclide production patterns in nuclear reactions [14], the activity can be expressed as:

$$A = N_s \sigma I (1 - e^{-\lambda t_{\mathrm{irr}}}) e^{-\lambda t_{\mathrm{cool}}}$$

where A is radioactivity, N_s is the number of target nuclei per unit area, σ is the average cross-section for proton-induced production of a specific radionuclide, I is beam intensity, t_{irr} and t_{cool} are irradiation and cooling times respectively, and $T_{1/2}$ is the radionuclide half-life. When beam type, energy, and target material are constant, the factors in the equation are constants, with the bracketed term representing the saturation degree after irradiation time t_{irr}. After irradiating for 5 half-lives, the saturation degree reaches approximately 97%. Using FLUKA' s RESNUCLE scoring card, the main radionuclides produced in the polyethylene target core after 30 minutes cooling under the three scenarios are obtained, as shown in Table 4 . The results are consistent with equation (1). Since polyethylene consists of C and H elements, the variety of produced radionuclides is limited.

As residual radioactivity is contributed by various radionuclides collectively, those with relatively large activity contributions include ^{7}Be and ^{11}C. In Figure 9, dose decay within the first two hours of cooling is primarily contributed by the decay of ^{11}C, which has the largest proportion, and the production quantity of ^{11}C approaches saturation under all three scenarios, resulting in consistent early decay trends. In later, longer cooling periods, the decay trend is dominated by long-lived nuclides, whose production quantities increase with irradiation time. Therefore, longer irradiation times result in higher residual doses later on, with slower decay.

Conclusion

Based on XiPAF beam parameters (maximum energy 200 MeV, maximum extracted beam intensity 1.3×10^{10} pps), this paper conducted in-depth research on beam dump shielding design and residual radioactivity. A composite structure convenient for manufacturing was adopted, with polyethylene selected as the target core material, offering advantages of low neutron yield and low activation level compared to traditionally used graphite. Through FLUKA simulation calculations, the instantaneous dose rate around the beam dump was found to be less than 5.5 mSv/h, meeting design requirements. Comparative calculations of the two target core materials showed that the primary difference is a approximately 75% reduction in neutron dose in the forward direction with polyethylene compared to graphite, offering unique advantages for single-event-effect irradiation terminals.

Finally, residual dose from the beam dump was evaluated, with calculations of residual dose decay and major radionuclide production under three different irradiation durations. The results agree well with theoretical formulas. These three scenarios cover the vast majority of XiPAF application cases and can provide data reference for radiation safety of personnel entering terminal areas after shutdown.

Author Contributions

WANG Di was responsible for model establishment, program operation, result analysis, and manuscript writing; CHEN Wei provided scheme guidance and manuscript review; LYU Wei was responsible for mechanical design and drawing, and project supervision; YAN Yi-hua and YU Jun-ying participated in result analysis and engineering guidance; WANG Min-wen participated in manuscript review and project management; WANG Zhong-ming provided overall technical guidance, acquired research funding, and provided administrative and technical support.

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Note: Figure translations are in progress. See original paper for figures.