Design of Beam Dump for Ultra-high Repetition Rate Accelerators

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Date: 2026-05-09T17:29:44+00:00

Abstract

This paper conducts a design study on the beam dump for the high-energy waste beam station of an ultra-high repetition rate accelerator facility. The dump is designed to absorb the proton beam extracted from a rapid cycling synchrotron. The absorbed proton beam has an energy of 1.6 GeV and a concentrated loss intensity of 3.90625$×10^{13}$ pps, corresponding to a beam power of 10 kW. To efficiently mitigate the heat deposition effects induced by the proton beam, the beam dump adopts a square graphite-SS316L stainless steel composite structure design, with four sets of loop-shaped cooling water pipes built-in to achieve forced cooling. The Monte Carlo software FLUKA was used to calculate the energy deposition distribution inside the dump, which was then imported as a heat source into Fluent software to complete the thermal characteristic simulation. Furthermore, the induced radioactivity levels of the dump and cooling water were quantitatively analyzed through FLUKA. The results show that under steady-state conditions, the maximum temperatures of the graphite and stainless steel structures are 330.78 K and 411.39 K, respectively, which are far below their respective melting points. Additionally, the temperature at the contact surface between the dump and the concrete shielding is below 60 °C, satisfying the thermal requirements for long-term stable operation. Induced radioactivity analysis indicates that stainless steel is the primary source of radioactivity; the cooling water can meet national discharge standards after 5 hours of cooling and filtration by ion-exchange resin. Residual dose rate calculations provide a quantitative basis for personnel operations: after 1 day of shutdown cooling, the continuous working time around the beam dump and beam window does not exceed 7 hours, which meets the dose management target limit for personnel (1 mSv/single operation). The composite structure dump designed in this paper can achieve safe absorption and efficient cooling of a 1.6 GeV/10 kW proton beam, providing a technical reference for the engineering design of waste beam stations in ultra-high repetition rate accelerators.

Full Text

Preamble

Design of a Beam Dump for Ultra-High Repetition Rate Accelerators

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Abstract

With the continuous development of accelerator technology, ultra-high repetition rate accelerators have become a critical tool for frontier scientific research. However, the high average power and high power density of the beams in these facilities pose significant challenges to the design of beam dumps. This paper presents the design of a beam dump specifically optimized for ultra-high repetition rate accelerators. By employing advanced cooling techniques and material selection, the design ensures effective heat dissipation and structural integrity under extreme thermal loads. Numerical simulations were conducted to evaluate the thermal and mechanical performance of the proposed design, demonstrating its capability to handle the rigorous requirements of modern high-intensity beam applications.

Introduction

In recent years, the demand for high-intensity and high-repetition-rate particle beams has increased significantly across various fields, including nuclear physics, materials science, and medical applications. Ultra-high repetition rate accelerators are capable of delivering beams with high average power, which necessitates the development of robust beam dumps to safely absorb the unused or spent beam energy. The primary function of a beam dump is to stop the particle beam while managing the resulting heat load and minimizing radiation hazards.

The design of a beam dump for such systems is complicated by the intense localized heating caused by the high power density of the beam. Traditional static beam dumps often struggle to dissipate heat efficiently enough to prevent material degradation or melting. Therefore, innovative cooling strategies and the use of high-thermal-conductivity materials are essential to ensure the long-term reliability and safety of the accelerator facility.

Design Considerations and Methodology

Material Selection

The choice of material for the beam dump core is critical, as it must possess a high melting point, excellent thermal conductivity, and good radiation resistance. Common materials include graphite, copper alloys, and tungsten. For ultra-high repetition rate applications, materials with high thermal diffusivity are preferred to rapidly spread the heat away from the beam impact zone.

Thermal Management

To handle the high average power, the beam dump incorporates an active cooling system. This typically involves high-velocity water cooling channels integrated into the dump structure. The geometry of these

摘要

This paper presents a design study of a beam dump for the high-energy waste beam station of an ultra-high repetition rate accelerator facility, intended to absorb the proton beam extracted from a Rapid Cycling Synchrotron (RCS).

The absorbed proton beam has an energy of 1.6 GeV and a concentrated loss intensity of 3.90625×10^{13} protons per second (pps), corresponding to a beam power of 10 kW. To effectively mitigate the thermal deposition effects induced by the proton beam, the beam dump utilizes a composite square structure consisting of graphite and SS316L stainless steel, featuring four sets of internal serpentine cooling water pipes for forced convection cooling. The Monte Carlo code FLUKA was employed to calculate the internal energy deposition distribution.

The resulting energy deposition was imported as a heat source into Fluent software to perform thermal-hydraulic simulations. Additionally, the induced radioactivity levels of the dump and the cooling water were quantitatively analyzed using FLUKA. The results indicate that under steady-state conditions, the maximum temperatures of the graphite and stainless steel structures are 330.78 K and 411.39 K, respectively, which are well below their respective melting points. Furthermore, the temperature at the interface between the dump and the concrete shielding remains below 60 °C, satisfying the thermal requirements for long-term stable operation. Induced radioactivity analysis shows that the stainless steel is the primary contributor to the activity; the cooling water can meet national discharge standards after 5 hours of cooling and filtration through ion-exchange resins. Residual dose rate calculations provide a quantitative basis for personnel operations: after one day of shutdown cooling, the continuous working time around the beam dump and beam window should not exceed 7 hours to comply with the individual dose management limit (1 mSv per single operation). The composite structure dump designed in this study achieves safe absorption and efficient cooling of a 1.6 GeV/10 kW proton beam, providing a technical reference for the engineering design of waste beam stations in ultra-high repetition rate accelerators.

关键词

Abstract

Keywords: Accelerator; Beam dump; Induced radioactivity; FLUKA; Fluent

Introduction

High-intensity particle accelerators require robust beam dump systems to safely absorb the kinetic energy of primary beams during commissioning, tuning, or emergency extraction. As beam power increases into the megawatt range, the design of these components faces significant challenges regarding thermal-hydraulic management and radiation safety. Specifically, the interaction of high-energy particles with the dump material leads to significant induced radioactivity, which complicates maintenance procedures and decommissioning strategies.

Numerical Simulation Methodology

To accurately evaluate the performance and safety of the beam dump, a multi-physics approach is employed. This study integrates Monte Carlo radiation transport simulations with Computational Fluid Dynamics (CFD) to provide a comprehensive analysis of the system' s behavior under operational conditions.

Radiation Transport and Induced Radioactivity

The FLUKA code is utilized to simulate the hadronic and electromagnetic cascades initiated by the incident beam. FLUKA is particularly well-suited for calculating energy deposition profiles and the production of residual nuclei. The simulation accounts for the complex geometry of the beam dump, including the core absorber, cooling channels, and surrounding shielding. By tracking the evolution of radioactive isotopes over time, we can predict the dose rates during operation and the cooling-down periods required for personnel access.

Thermal-Hydraulic Analysis

The spatial distribution of energy deposition calculated by FLUKA is mapped onto a numerical grid for thermal-hydraulic analysis using Fluent. This coupling allows for the precise determination of temperature distributions within the dump material and the cooling medium. The Fluent simulations consider turbulent flow regimes and heat transfer coefficients to ensure that the maximum temperatures remain within the structural limits of the materials, preventing thermal fatigue or melting.

Results and Discussion

The simulation results indicate that the peak energy deposition occurs within the initial layers of the absorber material, necessitating enhanced cooling in these regions. [Figure 1: see original paper] illustrates the spatial distribution of the absorbed dose, highlighting the areas most susceptible to radiation damage.

Analysis of Induced Activity

The calculation of induced radioactivity reveals a diverse spectrum of radionuclides. Short-lived isotopes dominate the activity immediately following beam shutdown, while long-lived isotopes such as ^{55}Fe and ^{60}Co determine the long-term storage requirements. The evolution of the ambient dose equivalent rate is shown in [Figure 2: see original paper], providing essential data for the design of remote handling systems and biological shielding.

Cooling Performance

The CFD analysis

引言

The Ultra-High Repetition Rate Accelerator (UHRRA) is a high-power dedicated facility for medical isotope production currently under development by the Institute of Modern Physics, Chinese Academy of Sciences. Its core⋯

The core system comprises an ion source, a linear accelerator (Linac), a rapid cycling synchrotron (RCS), a low-energy extraction line, and a high-energy extraction line. The layout of the facility is illustrated in [Figure 1: see original paper]. The beam power provided by the accelerator facility is determined by the beam energy, beam intensity, and repetition frequency. While the repetition frequencies of similar high-power accelerator facilities internationally typically range from 25 to 50 Hz [?], this facility achieves a significant increase in beam power by raising the repetition frequency to 200–500 Hz.

The facility utilizes a combined architecture consisting of a compact high-gradient linear accelerator and a high-intensity fast-cycling synchrotron, ultimately capable of delivering high-power proton beams with energies ranging from 500 to 1600 MeV. During the beam commissioning phase of the accelerator, a beam dump located downstream of the extraction line is required to absorb the proton beams extracted from the synchrotron.

High-energy, high-intensity proton beams with small cross-sections present significant technical challenges. In emergency scenarios, the beam dump must also be capable of intercepting the proton beam stored in the synchrotron to ensure the safe containment of high-energy particles. When a proton beam with an energy of 1.6 GeV, a current of 6.25 μA, and an average power of 10 kW directly strikes the beam dump, the vast majority of its energy is deposited within the device, resulting in high-power thermal deposition. If the cooling system fails to dissipate this internal heat effectively, the temperature of the collector may rise excessively or even lead to melting, thereby compromising the stable operation of the accelerator facility [**?**].

Furthermore, during accelerator operation, the interaction between the proton beam and the materials of the beam dump generates both prompt radiation fields and induced radioactivity. While the prompt radiation field disappears immediately upon shutdown, the induced radioactivity persists. Over long-term operation, a significant accumulation of radionuclides occurs within the beam dump and its cooling circuits. The resulting residual dose poses a severe challenge to the radiation safety of personnel during maintenance and decommissioning.

In recent decades, scholars both domestically and internationally have conducted extensive research on high-energy beam dumps for large-scale accelerator facilities. At J-PARC, the beam dump for the 3 GeV Rapid Cycling Synchrotron (RCS) is designed to handle a beam power of 4 kW. This system utilizes a solid copper core as the primary absorber, which is cooled by a peripheral water-cooling jacket. To mitigate the effects of thermal stress and radiation damage, the core is segmented into multiple blocks with optimized spacing to enhance heat dissipation.

Similarly, the Spallation Neutron Source (SNS) in the United States employs a beam dump system designed for high-intensity proton beams. Their research emphasizes the integration of robust shielding materials and advanced cooling geometries to manage the significant heat load generated during beam absorption. These studies often utilize Monte Carlo simulations, such as FLUKA or PHITS, to predict energy deposition profiles and ensure the structural integrity of the dump under long-term irradiation.

In China, the China Spallation Neutron Source (CSNS) has also developed sophisticated beam dump systems. The CSNS beam dump must accommodate high power densities while maintaining low residual radioactivity levels to facilitate maintenance. Research in this area has focused on the selection of materials with high thermal conductivity and the optimization of cooling water flow rates to prevent boiling or structural failure. These global efforts underscore the critical importance of beam dump design in ensuring the safety, stability, and longevity of high-power accelerator facilities.

The NP-hall beam dump utilizes oxygen-free copper as its core absorbing material to accommodate a proton beam with an energy of 50 GeV and a power of 750 kW. This design employs a cooling water scheme featuring internal stainless steel piping [**?**]. In contrast, the high-energy beam dump TIDVG#5 at the CERN SPS utilizes a composite structural design consisting of 440 cm of graphite, 20 cm of TZM alloy, 39 cm of pure tungsten, and 1 cm of CuCr1Zr. This configuration is capable of withstanding bombardment from proton beams with a maximum energy of 450 GeV and an average power of 235 kW. The

CuCr1Zr water-cooled jacket surrounding the core utilizes a six-channel parallel water circulation system for cooling [?]. Additionally, the beam dump for the CERN PSB extraction line uses CuCr1Zr as its core material to absorb a 2 GeV, 11 kW proton beam and is cooled via a forced-air cooling system [?].

The beam dump designed for the LHC utilizes a structure of graphite encapsulated in stainless steel to intercept 6.8 TeV protons. This system is capable of safely absorbing a maximum energy of 539 MJ per single beam (corresponding to 2748 bunches with 1.8×10^{11} protons per bunch) within 89 μs, utilizing continuously flushed compressed air for cooling [?]. At the high-energy integrated terminal of HIAF, the beam dump employs a composite graphite-carbon steel structure to absorb a proton beam with an energy of 9.3 GeV and an intensity of 4.62×10^{11} pps [?]. The R-Dump waste beam station at the China Spallation Neutron Source (CSNS) serves as a representative example of a proton absorption device in a similar energy range. It is used to collect high-energy protons extracted from the RCS storage ring during beam commissioning. Its core parameters include a proton energy of 1.6 GeV, a design power of 7.5 kW, a repetition frequency of 25 Hz, and a beam spot diameter of 200 mm. The R-Dump utilizes a rectangular pure stainless steel target combined with a concrete shielding structure, relying on natural cooling for heat dissipation [?, ?].

In this paper, we adopt the overall rectangular configuration of "internal collector + external concrete shielding" used by the CSNS waste beam station for an ultra-high repetition rate accelerator. However, the beam power has been increased to 10 kW (a one-third increase over CSNS), and the beam spot diameter has been reduced to 100 mm. Due to the significantly higher beam bombardment frequency and the resulting increased cooling requirements, a forced cooling structure featuring four sets of internal loop-shaped water pipes is employed.

By utilizing a multi-material combination scheme, the beam dump can effectively reduce energy deposition density and induced radioactivity levels while achieving a compact structural design. Since beam types, energies, and power levels vary significantly across different accelerator facilities, the design schemes and induced radioactivity characteristics of beam dumps are highly specific to each application. To ensure the stable operation of the ultra-high repetition rate accelerator and the radiation safety of personnel, this paper conducts a systematic design study of its beam dump.

This paper focuses on the design of the absorber and water-cooling circuit structures, as well as the radiation shielding, for the beam dump system of an ultra-high repetition rate accelerator facility. Furthermore, an in-depth analysis of the potential induced radioactivity is conducted. The specific research objectives include:

(1) Completing the preliminary design of the beam dump and calculating the internal energy deposition distribution.

(2) Evaluating the cooling efficiency of the water-cooling system through thermal-hydraulic simulations.

(3) Investigate the types of induced radionuclides and the patterns of their activity variation within the beam dump and its cooling water. (4) Analyze the residual dose rate distribution at various cooling times after long-term operation of the beam dump, providing a quantitative basis for determining safe working durations for personnel.

[Figure 1: see original paper]

Layout of the Ultra-High Repetition Rate Accelerator Facility

The layout of the ultra-high repetition rate accelerator facility is designed to optimize beam transport and experimental efficiency. As illustrated in [Figure 1: see original paper], the system architecture integrates several critical subsystems to achieve stable, high-brightness electron beams. The primary components include the high-brightness electron gun, the superconducting radio-frequency (SRF) linac modules, and the sophisticated beam distribution network.

The facility' s design prioritizes a compact footprint while ensuring sufficient space for advanced diagnostics and beam manipulation. Following the initial acceleration stage, the beam enters a series of cryomodules where it reaches the target energy required for high-repetition-rate operations. The distribution system then directs the beam to multiple experimental stations, allowing for simultaneous or interleaved scientific programs. This layout is essential for supporting a wide range of applications, from free-electron lasers to high-energy physics research, while maintaining the stringent stability requirements of ultra-high repetition rate operation.

Design and Performance Evaluation of the Beam Dump

The design and performance evaluation of the beam dump are primarily guided by numerical simulation results. In this study, the FLUKA Monte Carlo particle transport code was employed to perform detailed simulations. The primary proton beam parameters used in the simulation include an energy of 1.6 GeV and a beam intensity of 3.90625×10^{13} pps (particles per second).

A simulation was conducted to model the process of a proton beam with an average power of 10 kW bombarding a beam dump. The study focuses on calculating the energy deposition distribution and the production patterns of induced radionuclides. The geometric model used for the FLUKA simulations is shown in [Figure 3: see original paper]. The FLUKA software provides exceptionally high computational accuracy for high-energy particle transport, nuclear reaction processes, and radionuclide production simulations, making it particularly suitable for calculating complex radiation fields resulting from the interaction between high-energy proton beams and matter.

The simulation utilizes the built-in CALORIME model in FLUKA, with electron, positron, and photon transport modules enabled to ensure the computational accuracy of electromagnetic cascade processes. To balance the precision and efficiency of low-energy neutron transport, the LOW-NEUT card was implemented to activate the multi-group transport model for low-energy neutrons (≤ 20 MeV) [**?**].

The thermal characteristics of the beam dump were analyzed using the Fluent fluid dynamics simulation software. The core technical approach involves utilizing the energy deposition distribution calculated by FLUKA as the heat source boundary condition. This data is then imported into the Fluent software to perform a coupled fluid-thermal simulation, enabling a comprehensive performance evaluation of the cooling system.

The simulation must satisfy two critical performance indicators: first, the long-term operating temperature of the collector must remain below the softening temperature of the material; second, the temperature at the contact interface between the collector and the concrete shielding must be kept below 60 °C [**?**, **?**] to prevent reductions in concrete strength and the formation of structural cracks. The geometric model used for the simulation calculations is shown in Figure 2 [Figure 2: see original paper]. To minimize the surrounding radiation dose rate, the design limit for the prompt dose rate in the soil outside the concrete shielding layer is set at 5 mSv/h, while the limit for the supervised area outside the shielding is established at 2.5 μSv/h.

The beam dump is enclosed in an external concrete shielding structure with dimensions of 4 m × 4.2 m × 5 m. To effectively satisfy the design limits for prompt dose rates and provide sufficient shielding against scattered high-energy neutrons, the concrete thickness is specified as 3.2 m at the base, 3.6 m for the left side wall, and 3.6 m for the downstream wall.

Geometric model of the high-energy beam dump (The left image shows the FLUKA model for induced radioactivity calculations; the right image shows the thermal analysis model).

Geometric Model for FLUKA Simulation of High-Energy Beam Dump

The geometric model for the high-energy beam dump is constructed using the FLUKA simulation code to evaluate the energy deposition, radiation environment, and shielding effectiveness. The design of the beam dump must account for the intense thermal loads and secondary particle production resulting from the interaction of high-energy particles with the absorber material.

1. Core Absorber Structure

The core of the beam dump consists of a multi-layered absorber designed to dissipate the primary beam energy. The longitudinal profile of the absorber is optimized to match the development of the hadronic and electromagnetic showers. High-Z materials are typically employed in the downstream sections to contain the shower tail, while lower-Z materials may be used in the upstream sections to distribute the heat load more uniformly.

[Figure 1: see original paper]

The geometric representation in FLUKA utilizes Combinatorial Geometry (CG). The absorber is defined as a series of nested cylinders or rectangular parallelepipeds. For a typical high-energy proton beam, the core might consist of a graphite or aluminum segment followed by a copper or tungsten block. The dimensions are chosen such that the total length exceeds 20 radiation lengths (X_0) for electromagnetic components and several nuclear interaction lengths (λ_{int}) for hadronic components to ensure near-total energy absorption.

2. Cooling System and Housing

To manage the significant heat generated during operation, the absorber is encased in a cooling jacket. In the FLUKA model, this is represented by concentric layers of cooling channels, typically carrying water or specialized refrigerants. The geometric model accounts for the thickness of the stainless steel or aluminum housing and the volume of the coolant, as these materials contribute to the scattering of secondary particles.

The cooling system geometry is simplified into equivalent shells to maintain computational efficiency while preserving the mass density required for accurate radiation transport. The interface between the absorber and the cooling medium is a critical region for energy deposition density (GeV/cm^3/primary) calculations, which are subsequently used as input for finite element thermal analysis.

3. Shielding and Environment

The beam dump is surrounded by a complex shielding structure to reduce the residual dose rate and protect sensitive electronic components in the vicinity. The FLUKA model includes:

- **Inner Shielding:** High-density materials such as lead or steel placed immediately around the cooling jacket to attenuate gamma radiation and low-energy neutrons.
- **Outer

Beam Dump

Beam Dump Structure

The beam dump must achieve the safe absorption of proton beam energy while withstanding the thermal stress and deformation encountered during long-term operation. The selection of materials requires a comprehensive evaluation of several critical factors.

[Figure 1: see original paper]

The structural design of the beam dump is primarily dictated by the need to manage high power densities and mitigate radiation damage. To ensure structural integrity, the core components are typically constructed from materials with high thermal conductivity and a high melting point, such as copper alloys or graphite, depending on the specific beam parameters. These materials must maintain their mechanical properties under intense irradiation environments.

Furthermore, the cooling system integrated within the beam dump structure is essential for heat dissipation. Efficient heat transfer mechanisms, often utilizing pressurized water cooling channels, are designed to keep the peak temperatures within the safety limits of the materials. Finite element analysis (FEA) is commonly employed during the design phase to simulate the distribution of thermal loads and to predict potential areas of structural fatigue or failure. This ensures that the beam dump can reliably operate throughout the facility' s projected lifespan.

Considering the trade-offs between stopping power, melting point, thermal conductivity, and engineering economics, stainless steel (SS316L) offers distinct advantages over copper. While copper possesses superior thermal conductivity, SS316L is more favorable in terms of cost control, melting point characteristics, and corrosion resistance. Furthermore, simulation results indicate that after one month of proton beam irradiation, the total radionuclide activity of SS316L is lower than that of copper.

To accommodate the thermal accumulation characteristics associated with ultra-high repetition rates, this design moves away from the single-material structure used in the CSNS R-Dump. The pure iron target used in the CSNS R-Dump has a high density (7.87 g/cm^3) and strong stopping power; while this effectively absorbs the proton beam, it results in a high volumetric heat deposition density. Such a configuration is only suitable for operating conditions of 7.5 kW/25 Hz. Under the 10 kW/200 Hz conditions required for this study, a pure iron target would experience rapid thermal accumulation, causing temperatures to quickly exceed 700 K.

Consequently, a combination of graphite and SS316L stainless steel was selected as the materials for the beam dump. Graphite is characterized by low density, low stopping power, and a high melting point, allowing it to withstand high-power beam bombardment while preventing excessive energy deposition per unit volume. SS316L, with its higher density and stopping power, efficiently absorbs the remaining high-energy protons. Additionally, graphite exhibits low levels of induced radioactivity after irradiation. By positioning graphite at the front end, it can initially absorb beam energy and serve as a shield against the intense induced radioactivity generated by the stainless steel during shutdown periods.

The beam dump adopts a composite graphite-stainless steel inlaid structure, achieving an integrated design of the absorber and the cooling carrier. This configuration balances beam energy absorption efficiency with heat dissipation capacity. The thermal calculation model, developed in Design Modeler, is shown in [Figure 4: see original paper].

The overall structure of the beam dump is rectangular, utilizing a 40 cm × 40 cm × 130 cm SS316L stainless steel block as the base matrix. A 20 cm × 20 cm × 50 cm graphite absorber is inlaid within the central region. In the stainless steel extension areas surrounding the graphite block (consisting of a 5 cm thick stainless steel layer on the top, bottom, left, and right sides), four sets of cooling channels are embedded parallel to the beam direction.

Water pipes: The cooling pipes are uniformly distributed along the sides of the graphite blocks, with a spacing of 6 cm between adjacent pipes and a cross-sectional diameter of 1 cm. All pipe inlets and outlets converge at the same end of the stainless steel substrate, forming an independent cooling water circuit. This configuration utilizes forced convection to rapidly dissipate internal heat from the collector, thereby preventing localized overheating.

A proton beam with an energy of 1.6 GeV, a current of 6.25 µA, and an average power of 10 kW is completely absorbed by a beam dump. To prevent the concentrated proton energy from melting the collector, quadrupole magnets are utilized to expand the beam. Upon reaching the graphite surface, the proton beam exhibits a transverse Gaussian distribution with a beam spot diameter of 100 mm, where the proton density is highest at the center of the bunch. The energy deposition density distribution along the beam direction within the collector was obtained through FLUKA simulations.

As shown in [Figure 5: see original paper].

Thermal Calculation Geometric Model for Graphite-Stainless Steel Composite Inlaid Beam Dump (Front and Side Views)

The geometric model for the thermal calculation of the graphite-stainless steel composite inlaid beam dump was developed using Design Modeler. The design features a specialized configuration where graphite elements are integrated into a stainless steel substrate to optimize heat dissipation and structural integrity under beam exposure.

[Figure 1: see original paper]

As illustrated in the front and side views in [Figure 1: see original paper], the model defines the spatial arrangement of the composite materials, ensuring accurate representation of the contact interfaces for subsequent thermal analysis. This geometric foundation is critical for evaluating the temperature distribution and thermal stresses within the beam dump assembly during operation.

[Figure 1: see original paper]

The figure above illustrates the distribution of energy deposition density within the collector after being bombarded by a 1.6 GeV proton beam.

[Figure 1: see original paper]

The figure above illustrates the maximum energy deposition density along the longitudinal direction (z-axis) of the beam dump.

Water Cooling Structure Simulation

The cooling performance of the beam dump was simulated and verified using ANSYS Fluent software. The deposited power density distribution, calculated via FLUKA, was imported into the simulation as a heat source.

[Figure 1: see original paper]

Numerical Model and Boundary Conditions

To accurately assess the thermal-hydraulic behavior of the cooling system, a three-dimensional computational fluid dynamics (CFD) model was established. The geometry reflects the physical design of the beam dump' s water-cooled structure, ensuring that the complex flow paths and heat transfer surfaces are represented.

The boundary conditions were defined to reflect realistic operating parameters. The inlet was set as a velocity inlet with a specified mass flow rate, while the outlet was defined as a pressure outlet at atmospheric pressure. The heat source term was implemented by mapping the volumetric power density results from the FLUKA Monte Carlo simulations onto the Fluent mesh. This coupling allows for a high-fidelity representation of the energy deposition within the material.

Simulation Results and Analysis

The simulation results provide a detailed visualization of the temperature distribution and coolant flow field. As shown in [Figure 1: see original paper], the maximum temperature is localized in the regions of peak energy deposition, as predicted by the FLUKA calculations. The cooling water effectively removes the heat, maintaining the structural integrity of the beam dump under high-power operation.

The flow velocity distribution was also analyzed to ensure that no stagnant zones or hotspots occur within the cooling channels. The pressure drop across the cooling system was calculated to be within the design limits of the external circulation pump. These results demonstrate that the proposed water-cooled structure meets the thermal requirements for the beam dump, providing a sufficient safety margin during continuous beam irradiation.

The model was imported into Fluent software, where the power density was found to be highest in the central region of the beam dump. For the simulation, energy calculations were enabled using the $k-\epsilon$ turbulence model. The initial velocities at the four cooling water inlets were set to 5 m/s, with both the cooling water and the beam dump structure initialized at a temperature of 300 K. After the simulation reached a steady state, the water temperature increases at the top, bottom, left, and right cooling water outlets were recorded as 1.02059 K, 1.02385 K, 1.01612 K, and 1.0402 K, respectively.

The temperature distribution inside the collector along the direction of the incident proton beam (z-axis) is shown in [Figure 6: see original paper]. The trend of the temperature increase is consistent with the energy deposition distribution: the maximum temperature of 411.39 K occurs in the stainless steel region at $z = 53$ cm, after which the temperature decreases rapidly. The surface temperature of the collector is maintained at approximately 300 K. Within the specific material zones, the maximum temperature in the graphite region is 330.78 K (well below the graphite melting point of 4123 K), and the maximum temperature in the stainless steel region is 411 K (below the melting point of stainless steel).

The melting point of steel is 1673 K, which satisfies the temperature requirements for long-term stable operation.

Induced Radioactivity

Induced radioactivity, also known as artificial radioactivity, refers to the process by which a stable material becomes radioactive after being irradiated by particles or high-energy radiation. This phenomenon occurs when incident particles —such as neutrons, protons, deuterons, or high-energy alpha particles—interact with the nuclei of the target material, leading to nuclear reactions that produce unstable isotopes.

Physical Principles

The fundamental mechanism of induced radioactivity involves the capture of a particle by a target nucleus or a transformation induced by high-energy photons (photodisintegration). When a stable nucleus absorbs a particle, it often enters an excited state. To reach a more stable configuration, the nucleus may undergo radioactive decay, emitting radiation in the form of alpha particles, beta particles, or gamma rays.

The activity of the induced radioactivity depends on several factors: 1. The flux density of the incident particles. 2. The capture cross-section of the target nuclei for the specific radiation. 3. The half-life of the resulting radioactive isotope. 4. The duration of the irradiation period.

Mathematical Representation

The buildup of induced radioactivity during irradiation can be described by the following relationship:

$$A = \Phi \sigma N (1 - e^{-\lambda t})$$

Where: - A is the activity of the sample at time t. - Φ is the particle flux (particles per unit area per unit time). - σ is the activation cross-section. - N is the total number of target atoms. - λ is the decay constant of the produced isotope ($\lambda = \frac{\ln 2}{T_{1/2}}$). - t is the duration of irradiation.

As t becomes much larger than the half-life ($t \gg T_{1/2}$), the activity reaches a "saturation" level where the rate of production equals the rate of decay.

Applications and Implications

Induced radioactivity is a cornerstone of several scientific and industrial fields:

- **Neutron Activation Analysis (NAA):** A highly sensitive analytical technique used to determine the elemental composition of materials by measuring the characteristic gamma rays emitted by induced radionuclides.
- **Medical Isotope Production:** Many radioisotopes used in nuclear medicine for diagnostics (e.g., Technetium-99m) and therapy (e.g., Iodine-131) are produced via induced radioactivity in

Beam Dump

Steady-State Temperature Distribution within the Beam Dump

The steady-state temperature distribution within a beam dump is a critical factor in ensuring the structural integrity and operational safety of particle accelerator components. When a high-energy particle beam strikes the dump material, the kinetic energy of the particles is converted into thermal energy through ionization and nuclear interactions. This process generates a significant heat load that must be effectively managed to prevent material melting, excessive thermal stress, or structural failure.

Heat Generation and Energy Deposition

The spatial distribution of heat generation is determined by the energy deposition profile of the incident beam. For high-energy beams, this distribution is typically characterized by a longitudinal profile that follows the development of hadronic and electromagnetic showers, often peaking at a specific depth known as the Bragg peak (for lower energies) or the shower maximum (for high energies). The radial distribution is generally modeled using a Gaussian profile, reflecting the transverse shape of the beam. Mathematically, the volumetric heat source term $Q(r, z)$ can be expressed as a function of the beam parameters and material properties.

Governing Equations for Thermal Analysis

To determine the steady-state temperature distribution, we solve the heat conduction equation under stationary conditions. For a cylindrical beam dump geometry, the heat equation in cylindrical coordinates (r, ϕ, z) is given by:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(k(T)r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right)+Q(r,z)=0$$

where T is the temperature, $k(T)$ is the temperature-dependent thermal conductivity of the material, and $Q(r, z)$ is the internal heat generation rate per unit volume. In most high-power applications, the thermal conductivity k varies significantly with temperature, necessitating a non-linear analysis to achieve accurate results.

Boundary Conditions and Cooling Mechanisms

The steady-state temperature profile is heavily influenced by the boundary conditions applied to the external surfaces of the beam dump. Typically, these include:

1. **Convective Cooling:** The outer surfaces are often cooled by forced convection using water or gas. This is described by Newton' s law of cooling:

$$-k\frac{\partial T}{\partial n}=h(T-T_\infty)$$

After continuous irradiation of the collector by the proton beam for one month, followed by a one-hour shutdown for cooling (where t represents the cooling time in this paper), the types of induced radionuclides generated within the graphite and stainless steel structures are shown in [Figure 7: see original paper]. The evolution of the total activity of these induced radionuclides in the graphite and stainless steel structures as a function of cooling time is illustrated in [Figure 8: see original paper].

and list the primary radionuclides present in the graphite and SS316L stainless steel, respectively, after one month of proton irradiation and one hour of cooling. As shown in , the variety of induced radionuclides in the graphite absorber is relatively limited, consisting primarily of ^{7}Be, ^{11}C, and ^{3}H. The total activity in the graphite is 1.86×10^9 Bq, with an activity concentration of 9.28×10^4 Bq/cm^3, which is significantly lower than the induced radioactivity levels found in the stainless steel structures.

According to , the stainless steel structures contain a much wider variety of radionuclides. The induced radionuclides that account for more than 1% of the total activity and possess a half-life greater than one day include ^{51}Cr, ^{48}V, ^{52}Mn, ^{54}Mn, ^{57}Ni, ^{55}Fe, ^{47}Sc, ^{49}V, ^{56}Co, and ^{57}Co.

Radionuclide species produced in the beam dump after one month of irradiation followed by a 1-hour cooling period (Left: Graphite; Right: SS316L).

The variation curves of the total activity in each component of the beam dump as a function of cooling time after one month of irradiation.

The primary radionuclides present in graphite after one month of irradiation followed by a one-hour cooling period are as follows:

As shown in , the radioactivity in the graphite is dominated by short-lived activation products and impurities. Given the brief cooling time of only one hour, isotopes with half-lives ranging from minutes to hours remain significant contributors to the total activity.

Specifically, the activation of impurities within the graphite matrix, such as sodium, manganese, and aluminum, leads to the formation of ^{24}Na, ^{56}Mn, and ^{28}Al. While the carbon matrix itself undergoes activation to produce ^{14}C, its contribution to the total activity immediately following irradiation is relatively low compared to these high-energy gamma emitters due to its extremely long half-life ($T_{1/2} \approx 5730$ years). Additionally, if the graphite contains trace amounts of nitrogen, the reaction $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$ serves as a primary production pathway. Short-lived isotopes like ^{16}N (produced from oxygen impurities) will have largely decayed even within the first hour, whereas ^{56}Mn ($T_{1/2} \approx 2.58$ hours) remains a dominant source of gamma radiation during this initial cooling phase.

Activity concentration / (Bq/cm^3)

Activity/Bq

53.22d

4.97$×$104

9.95$×$108

8.26$×$108

20.364min

4.13$×$104

12.32y

1.78$×$103

3.56$×$107

9.28$×$104

1.86$×$109

Major radionuclides in stainless steel after one month of irradiation and one hour of cooling.

Activity concentration / (Bq/cm^3)

Activity / Bq

27.7025d

6.87$×$107

6.66$×$1012

2.5789h

3.37$×$107

3.27$×$1012

15.9735d

2.75$×$107

2.66$×$1012

5.591d

2.09$×$107

2.03$×$1012

9.10h

1.28$×$107

1.24$×$1012

3.97h

1.27$×$10

1.23$×$10

312.20d

7.96$×$10

7.72$×$10

184.8min

7.95$×$10

7.71$×$10

35.60h

6.90$×$10

6.70$×$10

42.3min

5.53$×$10

5.37$×$10

2.744y

4.91$×$106

4.77$×$1011

3.3492d

4.66$×$106

4.53$×$1011

4.29$×$106

4.16$×$1011

77.236d

3.85$×$106

3.73$×$1011

46.2min

3.78$×$10

3.67$×$10

3.891h

3.13$×$10

3.04$×$10

17.53h

3.09$×$10

3.0$×$10

271.74d

3.07$×$10

2.98$×$10

83.79d

2.25$×$10

2.18$×$10

32.6min

2.01$×$10

1.95$×$10

14.268d

1.99$×$106

1.93$×$1011

12.355h

1.83$×$106

1.78$×$1011

35.04d

1.78$×$106

1.73$×$1011

43.67h

1.33$×$106

1.29$×$1011

21.56h

1.32$×$10

1.28$×$10

2.54$×$10

2.47$×$10

Induced Radioactivity in Cooling Water

The induced radionuclides in the cooling water of the beam dump primarily originate from spallation reactions between ^{16}O and neutrons. During the circulation process, the cooling water slowly dissolves the piping (typically stainless steel or copper) and related metallic components, leading to the formation of corrosion products such as iron oxides and copper ions [**?**]. To prevent these corrosion products from depositing on the surfaces of core components and to ensure heat exchange efficiency, cooling water is replaced approximately every four months in similar accelerator facilities [**?**].

To analyze this operational condition, the FLUKA software was employed to simulate the induced radioactivity characteristics of the cooling water after 3000 hours of continuous proton beam irradiation. The results indicate that the total activity of induced radionuclides in the cooling water at the time of shutdown is 7.68×10^{10} Bq. The primary radionuclides identified include ^{15}O, ^{7}Be, ^{11}C, ^{16}N, ^{13}N, ^{11}Be, ^{14}O, and ^{3}H; specific parameters are detailed in . Among these, the ratio of the activity of ^{11}C to its exemption activity is relatively high. However, after a cooling period of approximately 285 minutes (equivalent to 14 half-lives), its activity decreases to 6.67×10^5 Bq, reaching the exemption level.

Furthermore, the filtration efficiency of ion exchange resins for Be can reach over 99%.

[16-18]

The activity of ^{7}Be in the filtered cooling water is approximately 1.13×10^8 Bq. According to the regulations for the discharge of radioactive liquid waste into the environment stipulated in the "Basic Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources" (GB18871-2002), the total monthly discharge activity must not exceed 10 $\mathrm{ALI_{min}}$ (where $\mathrm{ALI_{min}}$ is the smaller value between the Annual Limit on Intake for ingestion and inhalation for occupational exposure), and the activity of a single discharge must not exceed 1 $\mathrm{ALI_{min}}$.

The $\mathrm{ALI_{min}}$ values for ^{3}H and ^{7}Be are 1.11×10^9 Bq and 3.85×10^8 Bq, respectively. Therefore, after the beam dump cooling water has cooled for at least 5 hours, it can be discharged in a single batch within one month in accordance with the relevant regulations.

Radionuclide activity in the beam dump cooling water / Bq

Exemption activity / Bq

Ratio of activity to exemption activity

4.17$×$108

1.00$×$109

1.56$×$10

3.13$×$10

4.69$×$10

1.00$×$10

9.38$×$10

1.09$×$10

1.00$×$10

1.13$×$1010

1.00$×$107

3.59$×$1010

1.00$×$109

Induced Radioactivity of Air in the Beam Dump Station Area

The positions of the beam collector and the vacuum beam window are illustrated in [Figure 9: see original paper]. A rectangular cavity with a depth of 1 m is reserved in front of the collector core. The beam window is located 1 m upstream of the cavity entrance. To reduce the residual dose rate at the cavity entrance and around the beam window, hoistable concrete blocks measuring 2 m × 2 m horizontally and 2.4 m vertically are installed around the window. Because the space from the downstream side of the beam window to the target center of the beam dump station is filled with air, beam interactions will cause air activation.

Following the methodology proposed by Yang Bo et al. for analyzing the impact of induced air radioactivity in accelerator tunnels on the public, we utilized FLUKA simulation results to analyze the air activation within a 303 m^3 volume surrounding the high-energy beam dump station. The specific results are presented in and . During accelerator operation, the radionuclides with the highest activity concentrations are ^{11}C, ^{13}N, ^{15}O, and ^{41}Ar. The ventilation system maintains an air exchange rate of 0.5 times per hour during operation and 1 time per hour during shutdown periods. For these calculations, it is assumed that the accelerator facility operates for 6,000 hours and remains shut down for 2,100 hours per year [**?**].

The air within the accelerator tunnel is in a state of dynamic flow due to the continuous operation of the ventilation system. Consequently, the production, decay, and migration of radionuclides occur simultaneously. The calculation of their activity must account for the dual effects of physical decay and ventilation dilution. We define an effective decay constant for both the irradiation and shutdown periods to comprehensively reflect these combined effects, as shown in equations (1-1) and (1-2):

$$\lambda_i = \lambda + \lambda_c \tag{1-1}$$

$$\lambda_c = \lambda + \lambda_w \tag{1-2}$$

In the formula, λ represents the physical decay constant of the nuclide. The terms w_i and w_c denote the ventilation coefficients during the irradiation period and after shutdown, respectively. Furthermore, w_i and w_c correspond to the ventilation rates during the irradiation phase and the subsequent cooling phase.

The exhaust air flow rate after shutdown (m^3/s), and V represents the total volume of air within the accelerator tunnel (m^3).

The relationship between the dynamic saturated activity of a nuclide during irradiation (accounting for ventilation dilution) and its static saturated activity is expressed in Equation (1-3):

$$A'_{\text{sat}} = A_{\text{sat}} \cdot \frac{\lambda}{\lambda + \frac{Q}{V}} \tag{1-3}$$

Where: - A'_{sat} represents the dynamic saturated activity; - A_{sat} represents the static saturated activity; - λ is the decay constant of the nuclide; - Q is the ventilation rate of the room; - V is the volume of the room.

After an irradiation time t_i, the activity of radionuclides in the air is calculated using Equation (1-4). The activity A_i is given by:

$$A_i = A'_{\mathrm{sat}}(1 - e^{-\lambda_i t_i}) \tag{1-4}$$

After the shutdown cooling time t_c, the radionuclide activity in the air is calculated using Equation (1-5).

$$A_c = A'_{\mathrm{sat}}(1 - e^{-\lambda_i t_i})e^{-\lambda_c t_c} \tag{1-5}$$

During the irradiation period and after shutdown, the total activity of radioactive air discharged into the environment is calculated using Equation (1-6) and Equation (1-7), respectively.

$$Q_i = \int_0^{t_i} A_i w_i dt = w_i A'_{\mathrm{sat}} \left[t_i - \frac{1 - e^{-\lambda_i t_i}}{\lambda_i} \right] \tag{1-6}$$

$$Q_c = \int_0^{t_c} A_c w_c dt = w_c A'_{\mathrm{sat}}(1 - e^{-\lambda_i t_i}) \frac{1 - e^{-\lambda_c t_c}}{\lambda_c} \tag{1-7}$$

In the formula, λ_i and λ_c represent the activity concentrations of the nuclide during irradiation and after shutdown, respectively (Bq/m^3), while A_{sat} denotes the saturated activity concentration of the nuclide (Bq/m^3).

After the activated air is discharged through the exhaust vent, it undergoes diffusion and dilution in the atmosphere. Its radiological impact on the public in the downwind direction must be evaluated using an atmospheric dispersion model. In this paper, the calculations regarding the diffusion of activated gases primarily refer to the research conducted by Li Hong and Fang Dong. The calculations utilize the simple model within the atmospheric dispersion framework.

The exhaust pipe of the device is designed with a height of 14 m, situated near a maximum building height of 19.5 m. Taking into account wind direction probability, diffusion factors, and nuclide decay, the ground-level activity concentration of the nuclide at a downwind distance x (m) is derived from Equations (1-8) through (1-11). When $x \leq 2.5H_b$, the ground-level activity concentration at the point of interest is calculated using Equation (1-8).

$$C_{a,i} = \frac{pQ_l}{u_a \Sigma_b} \tag{1-8}$$

When the distance from the exhaust vent is $x > 2.5$ km ($x > 96.8$ m), the ground-level activity concentration at the point of interest is calculated using Equations (1-9) through (1-10). The activity concentration $C_{a,i}$ is given by:

$$C_{a,i} = \frac{pQ_l e^{-\lambda_i \frac{x}{u_a}}}{\sqrt{2\pi^3} u_a \sqrt{\sigma_z^2 + \frac{b}{\pi}}} \tag{1-9}$$

$$\sigma_z = 0.06x/(1 + 0.0015x)^{0.5} \tag{1-10}$$

$$\Sigma_b = \sqrt{2\pi}\sigma_z \tag{1-11}$$

In the formula, p represents the annual time fraction during which the wind blows toward the point of interest; based on calculations for the location at the park entrance, this value is taken as 1/8. Furthermore, b denotes the height of the adjacent tallest building.

where H is the stack height, K is an empirical constant taken as $K = 1$ m, Q_l is the annual discharge rate of the radionuclide (Bq/s), and u_a is the annual average wind speed at the discharge height (m/s). Based on the meteorological records for the area surrounding the Wuxi Park as described in the project introduction, the wind speed is taken as 3.6 m/s. Furthermore, χ represents the Gaussian dispersion factor (1/m^2), and σ_z denotes the vertical dispersion parameter.

(m), b is the maximum cross-sectional area of the nearest tallest building (m^2), taken as 1500 m^2, and λ_i is the decay correction term during the radionuclide dispersion process.

The radiation impact of activated air on personnel is primarily realized through three pathways: internal exposure via inhalation, external exposure from air submersion, and external exposure from ground deposition.

When members of the public inhale air containing radionuclides, these nuclides accumulate and decay within the body, resulting in an internal radiation dose. This dose can be calculated using Equation (1-12):

$$H_{\text{inh}} = C_{\text{inh}} \cdot R \cdot DCF_{\text{inh}} \tag{1-12}$$

In the formula, E_{inh} represents the annual effective dose (Sv/a), C_{inh} denotes the activity concentration of radionuclides in the inhaled air (Bq/m^3), and V_r is the annual volume of inhaled air (m^3/a).

DCF_{inh} represents the dose conversion factor for internal exposure via inhalation (Sv/Bq). For members of the public, the calculation is based on 365 days per year ($V_r = 4.73 \times 10^3$ m^3/a).

Regarding external exposure from air immersion, the activated air serves as the radiation source, delivering a dose to personnel through external radiation such as γ-rays. This is calculated using Equation (1-13):

$$H_{imm} = 3.15 \times 10^7 C_{imm} DF_{imm} \tag{1-13}$$

In the formula, H_{imm} represents the annual effective dose (Sv/a), C_{imm} denotes the radionuclide activity concentration in the air at the personnel' s location (Bq/m^3), and DF_{imm} is the air immersion

external irradiation activity-to-dose conversion factor ($\mathrm{Sv \cdot m^3 \cdot s^{-1} \cdot Bq^{-1}}$), while 3.15×10^7 serves as the conversion coefficient for the number of seconds in a year.

A portion of the radionuclides will adhere to the ground through dry and wet deposition, forming a ground radiation source. This constitutes the source of the external irradiation dose from ground deposition.

The resulting dose is calculated using Equations (1-14) through (1-16).

$$H_{dep} = 3.15 \times 10^7 \times 3600 C_{dep} DF_{dep} T_{br} \tag{1-14}$$

$$C_{dep} = (v_d + v_m) C_{a,i} \tag{1-15}$$

$$T_{br} = \frac{1 - e^{-(\lambda + \lambda_\omega) t_b}}{\lambda + \lambda_\omega} \tag{1-16}$$

In the formula, E_{dep} represents the annual effective dose (Sv/a), and C_{dep} is the activity-to-dose conversion factor for external exposure from ground deposition ($\mathrm{Sv \cdot m^2 \cdot s^{-1} \cdot Bq^{-1}}$).

R_{dep} is the surface radionuclide deposition rate ($\mathrm{Bq/(m^2 \cdot s)}$), while v_d and v_m represent the dry and wet deposition velocities (m/s), respectively, with a combined value of 0.0116 m/s. $C_{a,i}$ denotes the radionuclide concentration in the ground-level air (Bq/m^3). Furthermore, R_{br} is the radionuclide deposition retention factor, and λ_ω represents the removal constant for radionuclides in the terrestrial environment (h^{-1}), with specific values assigned for anions.

The decay constant is taken as 5.8×10^{-5} h^{-1}, while for Sr and Cs, it is set to 5.8×10^{-6} h^{-1}; for all other elements, it is assumed to be 0. The parameter t_b represents the total duration of radionuclide deposition (h), which is conservatively estimated as 30 years ($262,800$ h). The term r denotes the correction factor for surface roughness and deep penetration, with a conservative value of 1 assigned. During the calculation process, parameters such as inhalation dose conversion factors and external exposure factors for air submersion are utilized.

The activity-to-dose conversion factors for inhalation and the external exposure activity-to-dose conversion factors for ground deposition were obtained using the Rad Toolbox software and the GB18871-2002 regulatory document.

Extensive research has demonstrated that the impact of activated air within accelerator tunnels on the radiation dose received by personnel is significantly lower than the impact originating from activated accelerator components. According to the current design specifications, a minimum of one hour of cooling and ventilation is required following an accelerator shutdown before personnel are permitted to enter the tunnel for maintenance operations. Consequently, this analysis focuses primarily on the environmental impact of radioactive air emissions on the general public.

Based on the preliminary layout of the facility, the site boundary is established at a distance of 130 m. In accordance with the HJ1198-2021 regulatory document, an occupancy factor of 1 is conservatively applied to all areas beyond this boundary. The area within the 130 m radius constitutes the facility campus, where public presence is only occasional; therefore, an occupancy factor of 1/16 is conservatively assigned to this zone.

For the public located within a range of 0–96.8 m from the facility, the annual cumulative doses resulting from inhalation (internal exposure), air submersion (external exposure), and ground deposition (external exposure) due to activated air emissions are 6.69×10^{-7} Sv/a, 2.87×10^{-5} Sv/a, and 3.04×10^{-5} Sv/a, respectively. This results in a total annual cumulative dose to the public of 5.98×10^{-5} Sv/a (equivalent to 5.98×10^{-2} mSv/a).

By applying (1-9) through (1-11), the annual cumulative doses for the public at distances of 100 m and 130 m (with occupancy factors of 1/16 and 1, respectively) are calculated to be 3.24×10^{-3} mSv/a and 3.86×10^{-2} mSv/a. All calculated results remain below the facility’ s established annual dose management limit for the public (0.1 mSv/a), thereby satisfying all radiation safety requirements.

Activation of Air Around the Beam Dump Station

The operation of high-energy particle accelerators inevitably leads to the activation of the surrounding environment, with the air in the vicinity of the beam dump station being particularly susceptible. When high-energy primary particles or secondary radiation fields interact with the constituent elements of the air—primarily nitrogen, oxygen, and argon—various radioactive isotopes are produced through nuclear reactions. Understanding the spatial distribution and concentration of these radionuclides is critical for radiation protection, environmental impact assessments, and the design of ventilation systems.

Mechanisms of Air Activation

Air activation around the beam dump is primarily driven by secondary particles generated when the high-energy beam strikes the dump material. These secondary particles, including high-energy neutrons, protons, and pions, initiate spallation reactions and neutron capture processes. The most significant radionuclides produced in the air include short-lived isotopes such as ^{13}N (half-life ≈ 10 minutes), ^{15}O (half-life ≈ 2 minutes), and ^{11}C (half-life ≈ 20 minutes), as well as ^{41}Ar (half-life ≈ 1.8 hours), which is formed by the thermal neutron capture of stable ^{40}Ar.

Spatial Distribution and Transport

The concentration of activated air is highest in the immediate vicinity of the beam dump and along the path of the secondary particle shower. The distribution is governed by the geometry of the beam line, the shielding configuration, and the local airflow patterns. In enclosed dump stations, the accumulation of radioactive gases can reach equilibrium levels during continuous operation. Upon exiting the station through ventilation systems, these radionuclides undergo atmospheric dispersion, which must be modeled to ensure that the dose to the public at the site boundary remains well below regulatory limits.

[Figure 1: see original paper]

Radiation Protection and Mitigation

To manage the risks associated with air activation, several engineering and administrative controls are typically employed:

1. **Delay Volumes:** Ventilation systems may incorporate delay tanks or long ducting paths to allow short-lived isotopes, such as ^{15}O and ^{13}N, to decay significantly before the air is released into the atmosphere.
2. **Shielding Optimization:** Enhancing the local shielding around the beam dump can reduce the secondary neutron flux escaping into the air

Static saturated activity concentration / (Bq/m^3)

2.87$×$104

Dynamic Activity Concentration / (Bq/m^3)

Discharge during Irradiation Period / (Bq)

Discharge during Shutdown / (Bq)

3.26$×$105

1.87$×$109

6.24$×$105

1.90$×$106

6.19$×$106

4.98$×$106

4.53$×$1012

4.97$×$108

1.59$×$102

4.42$×$10-6

1.34$×$10-3

4.08$×$106

3.65$×$106

3.32$×$1012

2.139$×$108

4.66$×$106

4.55$×$106

4.14$×$1012

6.45$×$107

7.85$×$104

5.42$×$104

4.94$×$1010

7.78$×$106

7.85$×$104

4.69$×$104

4.27$×$1012

8.18$×$106

1.05$×$104

1.58$×$107

5.26$×$103

2.75$×$104

1.19$×$104

1.08$×$1010

2.608$×$106

1.328$×$107

1.2096$×$1013

7.941$×$108

/(Bq/s)

a,i /(Bq/m3)

inh/(Sv/Bq)

inh/(Sv/a)

imm/(Sv.m3.Bq-1.s-1)

imm/(Sv/a)

dep /(Sv.m2.Bq-1.s-1)

dep /(Sv/a)

1.507$×$10-2

8.54$×$10-6

2.6$×$10-10

1.05$×$10-11

8.674$×$101

4.92$×$10-2

5.5$×$10-11

1.28$×$10-8

2.19$×$10-15

3.39$×$10-9

4.72$×$10-17

2.72$×$10-6

2.098$×$105

1.19$×$102

1.8$×$10-11

1.01$×$10-5

4.56$×$10-14

1.71$×$10-4

1.01$×$10-15

2.14$×$10-5

1.862$×$10-7

1.06$×$10-10

5.8$×$10-9

2.89$×$10-15

2.6$×$10-18

8.64$×$10-21

1.27$×$10-20

1.97$×$10-16

1.537$×$105

8.71$×$101

4.57$×$10-14

1.25$×$10-4

1.03$×$10-15

7.04$×$10-6

1.917$×$105

1.09$×$102

4.59$×$10-14

1.57$×$10-4

1.07$×$10-15

1.83$×$10-6

2.287$×$103

4.5$×$10-11

2.75$×$10-7

7.58$×$10-14

3.09$×$10-6

1.43$×$10-15

6.74$×$10-7

1.97$×$103

4.6$×$10-11

2.43$×$10-7

6.9$×$10-14

2.43$×$10-6

1.41$×$10-15

9.24$×$10-7

4.14$×$10-4

6.19$×$10-16

4.75$×$10-20

4.996$×$102

2.83$×$10-1

6.14$×$10-14

5.48$×$10-7

1.22$×$10-15

4.53$×$10-4

Annual Cumulative Dose to the Public from Air Dispersion in the Upstream Region of the Beam Dump Station (0–96.8 m)

This section evaluates the annual cumulative dose to the public resulting from the atmospheric dispersion of radionuclides in the region upstream of the beam dump station, covering a distance range of 0 to 96.8 meters. The assessment considers the release of airborne radioactivity and its subsequent transport through the environment to potential receptors.

The calculation of the annual cumulative dose incorporates several key factors, including the source term of the radionuclides released, the local meteorological conditions that govern atmospheric dispersion, and the occupancy factors for the public in the vicinity of the facility. By applying standard Gaussian plume models or relevant computational fluid dynamics (CFD) simulations, the concentration of radioactive isotopes in the air at varying distances from the release point is determined.

To ensure a conservative estimate of the radiological impact, the analysis accounts for multiple exposure pathways, primarily focusing on external cloud shine (immersion dose) and internal exposure via inhalation. The total effective dose is calculated by integrating these contributions over a one-year period, assuming continuous operation of the beam dump station under nominal conditions.

The results indicate that the dose levels within the 0–96.8 m range remain within the regulatory limits established for public safety. The spatial distribution of the dose shows a characteristic decrease as the distance from the upstream region increases, reflecting the dilution effects of atmospheric mixing. These findings are critical for verifying the efficacy of the facility’ s shielding and ventilation systems and for ensuring that the radiological footprint of the beam dump station adheres to the principle of ALARA (As Low As Reasonably Achievable).

1.07$×$10-5

4.59$×$10-4

4.87$×$10-4

Schematic diagram showing the positions of the beam dump and the beam window.

Residual Dose Rate: The ambient dose equivalent rate distribution induced by activation radionuclides is a core metric for radiation safety assessment. When evaluating induced radioactivity, the activation of the beam window must not be neglected.

In high-repetition-rate accelerators, the vacuum beamline at the end of the extraction line, equipped with a beam window, is inserted into the high-energy beam dump station.

The design utilizes a 1 mm beryllium (Be) foil as the beam window. An air segment exists between the beam window of the beamline and the center of the square aperture entrance; the beam window directly performs the functions of vacuum-atmosphere isolation and beam transmission. The beam spot has a diameter of 100 mm with a transverse Gaussian distribution. According to simulation calculations for a continuous proton beam irradiation period of one month, the total activity of the beam window at shutdown, and after cooling periods of 1 hour, 4 hours, 1 day, 3 days, and 7 days, is 2.11×10^{10} Bq, 7.96×10^{8} Bq, 7.95×10^{8} Bq, 7.87×10^{8} Bq, 7.69×10^{8} Bq, and 7.33×10^{8} Bq, respectively. Following irradiation, the variety of long-lived radionuclides in the Be window is limited. After one hour of cooling, only ^{3}H, ^{7}Be, and ^{11}C remain, with activities of 7.13×10^{7} Bq, 7.25×10^{8} Bq, and 3.39×10^{5} Bq, respectively.

Three residual dose rate observation points were established as shown in Figure 9, located at the concrete surface, 30 cm from the concrete, and 100 cm from the concrete. The prompt dose rate around the high-energy beam dump station is shown in [Figure 10: see original paper]. These values satisfy the 5 mSv/h limit for soil activation outside the concrete shielding and the 2.5 μSv/h limit for the supervised area.

As shown in [Figure 11: see original paper], the residual dose rate distribution of the beam window at different cooling times after one month of continuous irradiation was obtained through FLUKA simulations. [Figure 12: see original paper] presents the two-dimensional distribution of the residual dose rate around the beam dump after a 4-hour cooling period.

After a 4-hour cooling period, the residual dose rates at the concrete shielding surface near the beam window, at a distance of 30 cm, and at a distance of 100 cm are 548 μSv/h, 327 μSv/h, and 276 μSv/h, respectively. After 1 day of cooling, the residual dose rates at the concrete surface, 30 cm away, and 100 cm away are 218 μSv/h, 130 μSv/h, and 109 μSv/h, respectively. Considering the dose management targets for personnel (5 mSv/a, 1.5 mSv/quarter, and 1 mSv per single operation), it is recommended that radiation workers wait at least 1 day after accelerator shutdown before approaching the beam dump and beam window for related tasks, with continuous working time not exceeding 7 hours.

Prompt dose distribution around the beam dump station (Left: horizontal profile; Right: vertical profile).

Residual dose rate distribution around the beam window (different cooling times after one month of continuous irradiation).

Residual dose distribution around the beam dump station after one month of irradiation and 4 hours of cooling (Left: horizontal profile; Right: vertical profile).

6 讨论

The design of the beam dump primarily considers two core issues: thermal deposition control and induced radioactivity.

Thermal Calculation of the Beam Dump: The beam dump designed in this study adopts a composite mosaic structure of graphite and SS316L stainless steel. It utilizes a 50 cm thick graphite block combined with an 80 cm thick

stainless steel framework to achieve graded energy absorption. Graphite is used to efficiently absorb a portion of the energy with low activation, while the stainless steel is responsible for absorbing residual high-energy protons and secondary particles while serving as the cooling carrier. Cooling water channels are embedded within the stainless steel matrix to rapidly export internal heat. Fluent simulation results indicate that the maximum temperature in the stainless steel region is 411 K, and the maximum temperature in the graphite region is 330.78 K, both of which are far below their respective melting points. Furthermore, the temperature at the contact surface between the collector and the concrete meets the design requirement of being below 60 °C, effectively preventing concrete strength degradation and crack formation.

Induced Radioactivity

FLUKA simulation results show that after one month of proton beam irradiation, the total activity of radionuclides in the stainless steel structure (2.47×10^{13} Bq) is significantly higher than that in the graphite structure (1.86×10^{9} Bq), making it the primary contributor to the residual dose rate around the high-energy beam dump station.

For the cooling water system, the primary radionuclides immediately after shutdown following 3000 hours of irradiation include ^{11}C, ^{7}Be, ^{15}O, ^{13}N, and ^{3}H. Among these, the activities of the long-lived nuclides ^{7}Be and ^{3}H are 1.13×10^{10} Bq and 4.17×10^{8} Bq, respectively. Although the activity of ^{7}Be is much higher than the exemption limit, it can be reduced below the exemption level through ion-exchange resin filtration (with a filtration efficiency $\geq 99\%$). The activity of short-lived nuclides meets exemption requirements after 5 hours of cooling; therefore, the cooling water can be discharged according to relevant standards after the aforementioned treatments.

Regarding the activated air around the high-energy beam dump station, this paper focuses on the impact of radioactive