Radiation Shielding Design for C-ADS Injector I Postprint

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Abstract

The radiation shielding structure for C-ADS Inject-I was designed and optimized using FLUKA code. As this equipment was planned to be established in an existing tunnel hall with limited space, several shielding hot spots are re-designed and analyzed respectively as they may cause radiation dose leakage and weakening of the total shielding effect. In addition, some new shielding structures are applied in the simulation process. All designed shielding structures are discussed in this paper and the results will meet the governmental criteria for radiation protection.

Full Text

Preamble

Radiation Shielding Design for C-ADS Inject I

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The radiation shielding structure for C-ADS Inject-I was designed and optimized using the FLUKA code. Since this equipment was planned for installation in an existing tunnel hall with limited space, several shielding hot spots were re-designed and analyzed individually as they could cause radiation dose leakage and weaken the overall shielding effectiveness. Additionally, some new shielding structures were applied during the simulation process. All designed shielding structures are discussed in this paper, and the results meet governmental criteria for radiation protection.

Keywords: Monte Carlo Simulation, Radiation Shielding, FLUKA
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Introduction

A linear proton accelerator (Linac), designated Inject I, operating in continuous wave (CW) mode with designed beam parameters of 10 MeV–10 mA, will be constructed at the Institute of High Energy Physics, Chinese Academy of Sciences. This advanced research facility may serve as one of two injectors for a future high-energy accelerator and represents an important component of the China Accelerator Driven Sub-critical System (C-ADS).

Since the equipment will be installed in an existing tunnel, detailed radiation shielding simulations were performed to evaluate and re-design the existing shielding structure. The optimization focused on shielding hot spots, including the thickness of concrete shielding walls, beam dump construction, local additional concrete shielding, re-designed cable holes, and a composite material shielding door. This work emphasizes different shielding schemes tailored to radiation levels and spatial constraints, with all design techniques and various shielding structures presented herein to provide a valuable reference for similar projects.

II. Design Methods

The structure of the existing tunnel hall and the layout of accelerator devices are shown in [Figure 1: see original paper]. The tunnel contains more than ten cable holes at the bottom of the south and north shielding walls (indicated by dashed lines). A new shielding door was designed in the east wall of the tunnel for equipment transportation, with shielding effectiveness intended to be nearly equivalent to that of the adjacent concrete wall.

The beam loss is less than 1 W/m in the linear section, with beam energy ranging from 35 keV at the ECR section to 10 MeV at the end of the CM section. For conservative simulation purposes, a 10 MeV–1 W/m beam loss parameter was adopted (referred to as the linear loss situation). It is important to note that the beam dump, designed to absorb a 10 MeV–10 mA proton beam, is also located within the tunnel; therefore, a 10 MeV–10 mA beam loss parameter was used for simulations in this region. In the low-energy region, hydrogenous materials are effective for neutron shielding, while common concrete was selected as the primary shielding material for most locations due to its cost-effectiveness and adequate gamma shielding properties.

All simulations were completed using the FLUKA code [1]. Variance reduction techniques and the linear sampling method [2] were employed, with the number of primary particles set to more than 107 and the running cycle repeated more than forty times to reduce statistical errors. The tunnel structure and added shielding blocks were modeled as accurately as possible in the geometry construction.

According to the national standard GB 18871-2002, the occupational exposure limit is 20 mSv per year. However, following the ALARA (as low as reasonably achievable) philosophy, the radiation dose management goal for this project was set at 5 mSv per year. For convenience, the design target requires that the dose rate outside the tunnel remain below 2.5 µSv/h.

III. Results and Discussion

A. Thickness of Shielding Concrete Wall

As noted above, this Linac will be constructed in an existing tunnel hall, and two different beam loss parameters were adopted for the radiation shielding design. The first task was to verify whether the existing concrete shielding structure was sufficiently thick to prevent radiation penetration. As is well known, neutron radiation is the primary consideration for proton accelerator shielding, which is clearly demonstrated in [Figure 3: see original paper] and [Figure 7: see original paper]. The curves in [Figure 2: see original paper], [Figure 5: see original paper], and [Figure 10: see original paper] represent only the total radiation dose rate, which is the sum of neutron and gamma dose rates.

[Figure 2: see original paper] shows the total prompt dose rate attenuation curve during the linear loss situation. The Y-axis is perpendicular to the beam pipe, with Y = 0 cm at the beam pipe and Y = 250 cm at the inner tunnel wall; values of Y greater than 250 cm represent the concrete wall. The maximum dose rate occurs at the center of the beam pipe at approximately 400 mSv/h, decreasing rapidly with distance from the beam pipe. Analysis indicates that an 80 cm thick concrete wall is required to ensure the radiation dose rate meets the design goal.

B. Beam Dump and Additional Local Cylindrical Shielding

The beam dump for this project must absorb a 10 MeV–10 mA proton beam in CW operation, making heat dissipation and radiation shielding two critical concerns [3, 4]. For improved heat dissipation, the beam cross-section is expanded by a special magnet located upstream of the dump, and a ‘V’-structure beam dump was designed as shown in [Figure 4: see original paper]. The dump is constructed from copper with a thin nickel plating on its inner surface and is cooled by circulating water. The heat distribution in the two plates was calculated by the physics design staff using the ANSYS program, while this paper focuses primarily on radiation shielding design.

When 10 MeV–10 mA proton beams are collected by the beam dump, the maximum dose rate is approximately 107 mSv/h at the dump center. To reduce this to the design value, nearly 220 cm of concrete thickness is required. Since the adjacent concrete wall provides 120 cm of shielding, an additional 100 cm thick local cubic concrete shielding structure is needed, as shown in [Figure 4: see original paper].

However, the expanded beam cross-section creates severe back-streaming radiation to devices upstream of the dump. Therefore, an additional local cylindrical shielding scheme was proposed, as illustrated in [Figure 4: see original paper]. Two cylindrical concrete shielding sections with different radii were added in front of the dump, with final optimized dimensions determined through multiple simulations. [Figure 5: see original paper] compares the total radiation levels in the tunnel with different shielding configurations, demonstrating that the additional local cylindrical shielding sharply reduces radiation levels throughout the tunnel.

C. Re-design of Cable Pipe Hole

Cable holes are necessary for routing massive control and power cables into the tunnel. Traditional methodology often employs ‘U’ structures or multi-leg configurations to prevent radiation leakage [5]. However, the actual situation involves several straight holes connecting the tunnel floor and power supply hall floor. To address this, an additional shielding block was designed to convert the straight holes into a simple ‘T’ maze structure, as shown in [Figure 6: see original paper].

The mixed radiation field outside the cable holes, represented by the third cable hole at the bottom of [Figure 1: see original paper], is dominated by neutrons according to calculations shown in [Figure 7: see original paper], and corresponds to the maximum dose rate among all cable holes. Concrete was selected as the shielding block material due to its effective neutron and gamma shielding properties, with the constructed concrete shielding block shown in [Figure 8: see original paper]. In practice, the remaining space in the cable holes will be packed with polythene particles after cable installation to minimize neutron radiation.

D. Design for the Shielding Door

A passageway is required for equipment maintenance access and device transportation, as shown in [Figure 1: see original paper], where a new east door is located. To ensure sufficient shielding effectiveness nearly equivalent to the adjacent wall while minimizing thickness, a composite material shielding door was proposed (5 cm lead + 20 cm polyethylene + 5 cm lead, surrounded by 1 cm steel on both sides).

[Figure 9: see original paper] shows the radiation attenuation curve as radiation passes through the door. The gamma dose rate drops sharply in the outer lead layer while the neutron dose rate remains nearly stable; the opposite occurs in the inner polyethylene layer. This is consistent with theoretical analysis, and the gamma attenuation curve in lead agrees with the attenuation coefficient listed in [6]. Using this approach, a thinner 32 cm shielding door was designed that provides shielding effectiveness equivalent to 90 cm of concrete, as shown in [Figure 10: see original paper].

IV. Conclusions

This paper discussed the primary considerations for radiation shielding when constructing a new accelerator in an existing tunnel. A detailed shielding design process was presented for verifying and reinforcing the tunnel's shielding structure. Based on beam loss parameters and the existing tunnel conditions, various radiation shielding structures were designed, including local shielding configurations, additional 'T' structure shielding, and composite material applications. Furthermore, additional local shielding space was reserved for areas with inherently weak shielding structure.

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