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Shielding Basis for Hall D Complex

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Introduction

This Tech Note documents the results of the facility shielding design effort conducted in conjunction with the development of the civil/architectural design for the Hall D complex associated with the CEBAF 12 GeV upgrade. The present shielding design was developed as an integral part of the evolution of the civil design – with calculations and modeling described in this report supporting the final iteration from 60% to 100% civil design.

Shielding Design Approach

The approach and design requirements used to develop the Hall D complex shielding design are essentially identical to those used by the Radiation Control Department (RadCon) for shielding considerations for both the original design of the Continuous Electron Beam Accelerator Facility (CEBAF) and the Free Electron Laser (FEL). This methodology for shielding design has been effective; resulting in very low occupational exposures, insignificant potential dose to the public, and no adverse impacts to the environment. This approach has produced a design which is optimized for ALARA considerations. The basic process involved the following aspects, described in more detail below: (1) use of conservative administrative goals for shield design criteria, (2) an iterative design process, in which conceptual plans were reviewed for radiological impact, and the resulting radiation protection recommendations fed back into subsequent conceptual/design revisions, and (3) a collaborative approach in which the RadCon Department has worked closely with the 12 GeV Project team on operational, experimental and civil design aspects of the Hall D complex.

Design Goals

In keeping with the ALARA philosophy, specific design goals, analogous to administrative dose control levels are established for the Hall D shield design. These goals are essentially identical to those used for previous shielding design work at Jefferson Lab, and are derived from several sources. First are the Safety and Operations envelopes for accelerator operations incorporated into the Jefferson Lab Final Safety Assessment Document (FSAD)[1]. Secondly, the Jefferson Lab Alert Level, establishes an ALARA design goal for all radiation workers at the lab[2][3]. These goals are associated primarily with radiation fields arising from routine operations. In addition, the Prompt Radiation Control Policy[4] establishes additional limits on possible exposures in occupied spaces resulting from a worst-case, credible accident scenario, in which an electron beam at the upper limit of the safety envelope (i.e. 1 MW) is miss-steered onto an optimum target at any location considered physically possible within the accelerator enclosure. These criteria are synopsized below.

Design criteria for the Hall D complex radiation shielding:

1. Continuous beam operations within the Operations Envelope will not:

a) produce conditions expected to result in a dose to a radiation worker greater than 250 mrem during a 2000 hour work year (i.e. within Radiologically Controlled Areas)

b) result in a non-radiological worker within the accelerator Controlled Area (outside Radiologically Controlled Areas) receiving a dose in excess of 100 mrem in a 2000 hour work year

c) result in creation of Radiation Areas in occupied spaces

d) expose a hypothetical person continually present (8760 hrs) outside the accelerator Controlled Area (i.e. accelerator fence line) to greater than 10 mrem during the year.

e) produce radioactivity in onsite groundwater above the limits specified in the applicable VPDES permit[5], and not produce any degradation of offsite surface or ground water (this translates to a working design limit of < 35 neutrons/cm^{2}sec for neutrons > 20 MeV)

2. A maximum credible accident scenario (defined above) shall not create a dose rate in excess of 15 rem/h in any potentially occupied space within the accelerator site. In addition, in keeping with prompt radiation control policy, a safety interlock system meeting the requirements of the CEBAF Personnel Safety System (PSS)[6] shall be used. The combination of physical design elements and operation of the PSS is expected to limit the total dose from any such event to less than 100 mrem. Note that the PSS is assumed in most cases to be able to terminate beam in less than two seconds from the onset of a state exceeding the applicable limits of a PSS-monitored condition.

Design Optimization

In conjunction with the design criteria described above, optimization methods were used to assure that all exposure associated with operation of Hall D is maintained ALARA. The optimization methods used at Jefferson Lab entail combining the ALARA design criteria with an iterative facility design process intended to minimize doses while observing objectives for efficient and cost-effective construction, operations and maintenance activities. This approach also has a positive impact on decommissioning activities, through optimal use of materials and thoughtful management of the project 'footprint'.

Minimization of occupational exposure often can be achieved by over-shielding of radiation sources by using unreasonably thick, heavy and expensive materials. However, our approach to the shielding design of the Hall D complex, as well as CEBAF in whole, is to use conservative calculations of realistically expected radiation fields in critical areas to set limitations on the minimum amount of shielding required to satisfy all operational exposure criteria within the projected operational parameters of the machine.

Based on the results of such calculations, we propose changes in the design layout to correct the problem, if the criteria are violated. Civil engineers and designers use our recommendations to produce the next iteration of the projected layout, we evaluate it again, and the iterations continue until all criteria are satisfied. When civil design requirements result in thickness or layout of shielding that exceeds the minimum radiological requirements, we verify that potential exposures are within the design exposure criteria. The final design of the Hall D complex is the result of several iterations during the time of the project development. The approach described results in a semi-quantitative optimization process, based on a graded approach. For numerous reasons, it is not reasonable to apply a fully quantized optimization approach employing such elements as cost-to-dose factors and multiple alternate designs. To a significant degree, the experimental program goals set the overall design layout of the Hall D complex. We then apply the conservative design exposure goals (which are all significantly more restrictive than the regulatory requirements) to the source terms to generate basic shielding configurations for each element of the facility. Then, as the design progresses, specific variations such as alternative materials or layouts for a given shielded element can be considered (within the limits of feasibility for that element). By using the iterative/collaborative methods described, we identified numerous opportunities to modify and improve building layout, access/egress pathways and construction techniques in order to optimize the final design. Radiation related requirements of the Space Program and Design Criteria Document[7] contain a descriptive record of the optimization efforts.

Significant examples of such activities include the optimization of the Hall D building structure, the optimization of the building layout for the tagger area and electron beam dump, and the use of existing materials on site for significant portions of beam dump shielding. A few details of these activities are described below.

The thickness of the walls in Hall D, sufficient for adequate personnel and environmental protection was found in the preliminary studies as dependent on the wall location along the beam: gradual increase of the wall thickness from 10 cm of concrete at the back of the Hall to 40 cm in the forward direction relative to the beam was enough. However, the construction of the walls required thicknesses between 2 and 2.5 feet depending on location, which is more than adequate for shielding around and in the vicinity of the Hall. The height of the thick portion of the walls determines the projected environmental dose accumulation at the CEBAF site boundary. The height was selected in accordance with our neutron skyshine calculations to be at least 5 m above the grade, to reliably satisfy the design basis of no more than 10 mrem yearly dose accumulation at the boundary.

Original layout of the tagger and electron beam dump buildings included a separate underground enclosure for the beam dump, which reliably prevented the radiation backscattered from the dump to penetrate the tagger enclosure. Our calculations, verified also by the experimental physicists, showed that the construction costs may be cut by combining of the two buildings into one without major consequences for the backgrounds in the tagger enclosure. Reduction in square footage also incrementally reduces the decommissioning impacts associated with the facility. Another example is the use of available steel shielding blocks already onsite in optimizing dump shielding. Using the steel blocks allows a reduction in the amount of concrete used in the dump enclosure, and makes optimum use of already mildly radioactive shield blocks. In addition, the blocks are used as muon shielding (buried in the earth berm downstream of dumps), which significantly reduces the amount of earth overburden needed and reduces issues associated with inadvertent excavation of the shield berm.

Details of the development and optimization of the Hall D facility shielding design can be reviewed by examining the several versions of the Space Program and Design Criteria Document for the Hall D complex[7], by reviewing the results of the design reviews held at the several major design milestones and of course by examination of the civil design drawings for each of the milestones. Additional details of the optimization techniques are discussed in the text below.

Scope

This Tech Note will discuss each section of the Hall D complex from the point at which the extension tunnel leaves the CEBAF North LINAC and progresses to Hall D. In each of these sections, normal operations, accident scenario situations, site boundary dose considerations, and groundwater activation concerns will be addressed. This will be done either in detail, or will based upon existing shielding designs that have been vetted in other applications at Jefferson Lab accelerators. This Tech Note will also discuss fence placement at the site boundary. We will also briefly describe the radiation monitoring systems needed for the Hall D complex, including both the Personnel Safety System (PSS) and non-PSS related systems.

In addition to radiation shielding for personnel and environmental protection, we will address an equipment-specific physics requirement for the Hall D tagger area. The shielding design objective for this area is as follows; background radiation from the electron beam dump, measured in the tagger hodoscope detectors must not exceed 1% of that from the electron beam passing through the tagger.

Methods

The methods of evaluating dose rates and optimizing shielding designs for high energy and high power electron accelerators until recently remained not ultimately well established. All pure electromagnetic processes of electron and photon interaction with materials are understood very well, and can be modeled and calculated using several approaches which in general agree with each other. However, the neutron production source terms, and generally all inelastic hadronic reactions caused by incident high energy electrons and photons, still are not thoroughly investigated as a factor contributing to the radiation backgrounds in accelerator environments.

At CEBAF, the neutron radiation source terms proved to be critically important in determining the environmental footprint of the accelerator: neutron skyshine processes are responsible for the radiation dose that can be observed at the CEBAF boundary, and energetic neutrons penetrating thick concrete shielding around the beam lines and the beam dumps are capable of producing ground water activation in the soil. The research work by G. Stapleton and P. Degtiarenko in the mid-1990s has established methods of dealing with this problem[8][9][10]. The physics model describing the nuclear fragmentation processes at high energies, developed by M. Kossov and P. Degtiarenko, was implemented in form of the computer program DINREG, and embedded in the GEANT3 detector simulation Monte Carlo software package, capable of simulating complex setups including accelerator beam lines, experimental halls, beam dumps, detectors, shielding, etc. This package has been used extensively at JLab for source term evaluations, calculations of radiation background conditions, shielding evaluation and optimization, calculations of experimental background rates. The results showed good agreement with experimental observations, such that we can be reasonably confident in the results; generally, agreements better than factor 2-3 are observed. In the following paragraphs, the results of GEANT3/DINREG calculations are used, including some parameterizations[11][12]. Use of other methods is indicated in the text.

Quantitative results (dose rates) reported in this Note are produced by running GEANT models in sufficiently long runs to achieve levels of statistical accuracy significantly better than the estimated systematics. The particle transport plots shown in the figures generally show only a small number of events, and are for visual illustration only. For some complex situations requiring solving “deep penetration” problems such as finding neutron fluxes outside of thick shielding walls, particle cascade biasing methods are used, such as artificial amplification of cross sections for the processes generating neutrons, and using methods of cascade amplification in layers of thick shielding. Biasing requires careful analysis of systematic errors introduced. The calculational strategy in such cases was chosen to keep biasing as low as it is practically possible while obtaining results with statistical errors better than about 10%. The stability of biased calculations was checked in comparing models with different degrees of biasing. The comparisons showed agreements in the numerical results within statistical errors.

Graphic illustrations of the models shown in this Note are generally plane cuts of the 3D geometrical models encoded in the GEANT software, with common color codes, such that white areas represent empty space or air, violet-hatched areas show surrounding soil, black-hatched areas correspond to concrete walls, red-hatched blocks correspond to constructions and walls made of iron. Particle tracks in the cascades are generally shown as blue dotted lines, electrons as red solid lines, and neutrons as black dash-dotted lines.

Recent Changes in Dosimetric Quantities

Estimates of the neutron dose rates derived through the Monte Carlo modeling discussed above were made by converting the energy-weighted neutron fluence rate to dose equivalent rate through the use of fluence-to-dose coefficients taken directly from 10CFR835. These coefficients were taken from NCRP-38[13]. On June 8, 2007, the DOE updated 10CFR835[14]. The update included significant changes in the requirements for quantities and units used in radiation protection work by adopting the 1990 ICRP recommendations (ICRP-60)[15] as the basis for radiation quantities in place of the 1977 recommendations (ICRP-26)[16]. The rule now mandates the use of the protection quantities *equivalent dose* and *effective dose* set out in ICRP-60, and no longer includes fluence to dose conversion coefficients. We evaluated the impact of these changes with respect to the neutron doses originally calculated, as both the definition and magnitude of the radiation weighting factors specified for neutrons have changed.

ICRP updated the conversion coefficients for external radiation fields, consistent with the ICRP-60 dosimetry regime in 1996 and published the data in ICRP-74[17]. This allows direct evaluation of the impact on the calculated neutron doses mentioned.

Figure 1 shows a comparison of the old conversion factors to the ICRP-74 recommended coefficients for use in determining the effective dose from whole-body irradiation (AP geometry) from Table A.41 of the report. AP geometry is the most conservative. It can be seen that there is generally good agreement between the data. In the region between about 0.1 and 50 keV there is significant (> 20%) underestimation of the effective dose when using the old data. However, in the energy range where the ICRP-60 radiation weighting factors (and conversion coefficients) are at a maximum, the earlier coefficients are either conservative, or are within ~ 20% of the new data. Detailed discussion of the ICRP-60 dosimetric quantities is beyond the scope of this note.[1]

Given the estimated quality of the neutron spectrum in the areas of concern, conservative assumptions made during dose modeling, and general considerations of accuracy for this type of calculation, we consider the differences in the doses calculated using the two sets of data to be acceptably small.

[1]A thorough discussion of the changes and updates to dose conversion coefficients related to the ICRP-60 recommendations can be found in ICRP-74.

Regarding the use of conversion coefficients to evaluate dose in general, in light of the removal of the conversion factors from the rule, DOE provided the following guidance in the Federal Register in its response to comments on the topic.

As long as the neutron fluence to dose conversion factors incorporate the radiation weighting factors permitted by 10 CFR part 835, DOE sites may use conversion factors appropriate to local conditions to relate neutron fluence to equivalent dose and effective dose.[18]

The use of the ICRP-74 data is consistent with the DOE requirement above. The derivation of the conversion coefficients for Table A.41 is described, in part, below.

The effective dose data were determined from evaluated organ absorbed dose data. The conversion coefficients for the organ equivalent doses, H_T/Φ*, were obtained by multiplying* D_T/Φ *by the corresponding radiation-weighting factor for neutrons of the incident neutron energy.* [1]

[1] ICRP-74, paragraph (231)

Assumptions Used for Calculations

The following set of assumptions is used throughout this Tech Note. Most of these assumptions are known to be considerably conservative. The dose-related design criteria given earlier are also part of the assumption set.

- Normal operations: Maximum current of 5 micro-amps and 12 GeV delivered to the tagger electron beam dump. Typical average operations, based on discussions with Elton Smith, involve delivery of about 10^8 photons/sec to the experimental target, corresponding conservatively to 3 micro-amps of 12 GeV electron beam current, and approximately 30 weeks of operational running time annually.
- Normal operations in CEBAF: 1 MW beam.
- Normal Operations in Hall D: 2 W beam loss in Hall D
- Normal Operations at Collimator Building: 10 W loss in collimator.
- *Physics Equipment requirement*: less than 1% background radiation for the tagger hodoscope and detector operation

The following materials are onsite and considered potentially available for use for Hall D. Several hundreds of the "non-essential" SEG blocks are assumed available, but may have to be supplemented by additional materials.

- Non-essential SEG* S4A (13"x26"x26") steel blocks (from blocks associated stored in Site Outside Storage Area and G0 shielding)
- Non-essential SEG* S2A (26"x52"x52") steel blocks (from G-0 shielding and Hall C truck ramp shielding)
- SEG S4A blocks utilized in Halls A, B, and C which may not be entirely necessary, or replaceable with different shielding
- SEG S2A blocks utilized in Hall A and C which may not be entirely necessary , or replaceable with different shielding
- Significantly greater than 100 24"x36"x48" concrete blocks outside of the Hall C truck ramp
- Many oddly shaped massive mildly activated concrete shield blocks used in the NASA SREL cyclotron, which stopped operating in the late 1970s.** These blocks are stored in a "boneyard" east of building 58 (Test Lab).

*SEG blocks are made from smelted metals from decommissioned radiological facilities, and contain low levels of residual radioactivity, primarily Co-60.

** The SREL blocks are assumed to be potentially activated. Most of these blocks show no residual activity.

Source Term and Shielding Calculations

Segment Connecting the "Racetrack" section to the Tagger Building

This segment extends from what is currently the East end of the CEBAF North LINAC to the tagger enclosure. Figure 2 – "North LINAC Tunnel Extension" shows that the area in question is similar to that of the Hall A, B, and C transport channels, and as such, has similar concerns. The thickness of the walls and ceiling remains at 1.5 feet for structural purposes. This is adequate in terms of shielding for groundwater activation, in that this is identical to the shielding throughout CEBAF. The design power in CEBAF is 1 MW, whereas the design maximum beam power in the Hall D Complex/Tagger Area is 60 kW.

There are two potential exposure "scenarios" in this region. The first is protection of individuals who may be working in the tagger building during beam operations in the North LINAC. In such a case, the condition of concern is accidental transport of high current, high energy beam down the Hall D beamline (and potentially into the tagger building). This scenario is mitigated by a beam stopper, employing essentially identical configuration as is used for the other halls. Assuming the beam stopper is located near the point of tangency at the end of the North LINAC, a 1 MW beam loss at the stopper requires a 52" iron shield wall near the entrance to the tagger area to prevent a 15 rem/h dose rate in the tagger building. This is a moveable wall constructed of SEG shield blocks. This approach follows the design requirements for the other halls and closely resembles the Hall B configuration. This shielding wall may be made thinner if the beam stop is placed closer to the Beam Switch Yard, where existing beam stoppers are located. This option has been discussed with the SSG Group Leader, Kelly Mahoney, and should be explored more fully if plans call for an operational power limit for CEBAF over 1 MW.

The second beam loss scenario occurs during normal beam delivery to the tagger area. The location of concern is outside, above the transport tunnel. In this scenario, a Hall A or Hall C beam is miss-steered into the Hall D line, and is assumed to be transported some distance down the tunnel extension. In this case, the beam would likely leave the vacuum chamber somewhat upstream of the shield wall. Maintaining the existing tunnel concrete and dirt shield thickness through this region (total of about 4 meters thick) ensures the potential dose rate above-ground is less than 15 rem/h, assuming a full, high-power beam loss event.

Tagger Area Building

The tagger area building presents a combination of shielding concerns not usually found together in one location at Jefferson Lab. The electron beam entering the area interacts with a diamond radiator and produces a bremsstrahlung photon beam for Hall D. In the same building, the electron beam terminates in an electron beam dump. In addition to personnel safety and groundwater activation, there is an experimental concern from the backscattered radiation "noise" that may adversely affect detectors that collect critical experimental data. In the following treatment of the tagger area, we address the concerns presented in the area in a roughly west to east order.

Tagger Area Truck Ramp Shielding/Labyrinth

The truck ramp is situated as shown in Figure 2 and Figure 8. This arrangement ensures the lowest possible dose rate, as indicated in Figures 3a and 3b – "Dose Rate in the Tagger Enclosure", while allowing adequate access for installation of the tagger magnet. The truck ramp itself is to be a concrete enclosure, partially covered by a dirt berm. This is similar to the truck ramp entrances for Halls A, B and C; however, the length of this truck ramp is somewhat shorter (80 feet instead of 120 feet). Additionally, the truck ramp entrance provides a direct line of sight to the tagger magnet, which is the most likely location of beam loss in the event of mis-steering. This is in contrast to Experimental Halls A, B, and C, in which there is no line of site from truck ramp exits to any point along beam lines.

After installation of the tagger magnet and other equipment, there is no expectation of a need to move large items in and out of the building. This being the case, it is reasonable to erect a "shadow shield" wall in the truck ramp opening. Placing the wall just inside the base of the truck ramp provides the best combination of shielding coverage and space for material handling passageways. This shield wall should consist of S-4A SEG blocks or 30-inch concrete blocks. This maintains the dose rate within the design requirements for both routine operations and a design-basis accidental beam loss in the tagger area, as detailed below.

Under normal operating conditions, the source term from Figure 3b indicates approximately 200 mrem/h unshielded dose rate at the base of the truck ramp. To find the dose rate at the top of the ramp, we follow methodology in NCRP 144[19] (and elsewhere) for using universal transmission curves, assuming a point source loss on axis. For purposes of calculations at the present time (final truck ramp dimensions may be somewhat revised), the width of the opening is 14 feet, and the height is 10 feet, for a labyrinth mouth area S=140 square feet. The length of the truck ramp (d), is approximately 80 feet. This results in a $d/(S)^{-1/2}$ of 80/11.8 = 6.7, giving an attenuation factor of 3E-2 for the truck tunnel. This gives an unshielded dose rate at the top of the truck ramp of approximately 6 mrem/h under normal operating conditions.

Now adding a 30 inch concrete wall, and treating the segment of the truck ramp above the wall as the second leg of a labyrinth, we determine the shielded dose rate. Using the attenuation parameters in IAEA 188[20], we estimate the approximate attenuation length for high energy photoneutrons in concrete to be 112 g/cm^2. This is based on the experimentally based formula; $\lambda = 45A^{0.3}$, where A is taken to be 21 for concrete. This yields an attenuation factor for the 30 inch wall of approximately 0.2. The dose rate at the top of the truck ramp now becomes (using the reduction from the wall, and adjusting the reduction in the tunnel to correspond to the second leg of a labyrinth with a plane source); (200mR/h)(2E-1)(3E-4) = 12 μrem/h.

Under maximum credible accident scenario situation in which 1 MW beam power impinges on the face of the tagger magnet, utilizing the same methodology as that from the 1987 CEBAF Radiation Control Review[21] results in: (1000 kW)(2.25E6 mrem h^{-1} kW^{-1} m^2)/$(4m)^2$ = 140,000 rem/h at the base of the truck ramp. Using the same attenuation values as above would yield a dose rate at the top of the ramp of approximately 4200 rem/h with no shielding blocks installed, and 8.4 rem/h in the case of the 30-inch concrete shield wall. As a note, if the maximum credible accident scenario is 60 kW, this number drops to approximately 252 rem/h without shielding, and 500 mrem/h with the shield wall. For additional information, see JLAB TN-89-0151[22].

It should be noted that there are several additional advantages to locating the shield wall within the tagger area at the base of the truck ramp. This area affords a large, flat base on which to stack and manipulate the shielding. Stacking the blocks inside the ramp itself does not allow sufficient maneuvering ability for fork trucks. As mentioned earlier, placing the wall outside the truck ramp further restricts the size of items that can be brought through the opening and precludes vehicle access. Also, it is preferable to place the shield at the base of the ramp as it adds an "enhancement" to the dirt berm and concrete walls making up the structural portion of the shielding - effectively adding to the thickness of these parts of the shielding configuration. For maximum effectiveness in this regard, the shield wall should be brought to within a foot of the ceiling in the tagger area and occlude the solid angle originating at the tagger magnet entrance and formed by the opening at the base of the truck ramp.

Tagger Area South Wall

Several shielding issues arise in the production of the photon beam and disposition of the electron beam in the tagger. The 12 GeV electron beam interacts in the radiator, producing the bremsstrahlung beam, and is then "bent" southward toward the electron dump. Some of the electrons interacting in the radiator are significantly degraded in energy and, as they traverse the tagger magnet, are scattered laterally toward the south wall as it is shown in Figure 4, and cascade in the wall. GEANT model shown in Figure 4 does not show the south wall itself; the interaction events shown just illustrate the penetrating character of the high energy electron cascade in the concrete or in the soil. The direct interactions of high energy electrons in the wall produce neutrons (not shown) in the shield. Radiation production from primary particles *in* a shield should be avoided whenever practical, and when unavoidable needs to be adequately mitigated. The calculation results indicate the need for enhanced shielding in the south wall to reduce the high energy neutron fluence rate entering the groundwater at that location. The enhancement is easily achieved by thickening this area of the wall. We have estimated a conservative value of 5 feet of concrete (or the equivalent combination of steel and concrete) for the wall, based on modeling of the beam dump area. This thickening is needed at an elevation corresponding to beam line height plus or minus 1.0 meter.

Although the solid angle of the neutron flux is confined to a relatively narrow horizontal "band", it is recommended that the wall thickness be uniform. Construction contractor error or changes to beam line height during construction could defeat the purpose of the shielding. For practical considerations in installation, the current design specifies a stack of 26" SEG blocks along the south wall to attenuate this neutron flux. For ease of construction, the thickness of the concrete is specified to remain at 3 feet along the entire length of the south wall (including the portion forming the side of the dump cave). This combination of practical considerations results in a very conservative result which may be re-evaluated to optimize cost based on additional Monte Carlo simulations.

The basis for this and other shielding intended to mitigate groundwater activation is a design limit of less than 35 neutrons/cm^{2}sec for neutrons with energies above 20 MeV. This limit on fluence rate is derived in CEBAF-TN-89-155[23]. This threshold has been used successfully throughout CEBAF and FEL shielding design efforts to prevent localized activation of groundwater in excess of permitted values imposed by the Virginia Department of Environmental Quality[5].

Tagger Area Electron Beam Dump Area

Shielding concerns in the electron beam dump area include:

- Personnel protection from prompt and residual radiation from the dump
- Protection against groundwater activation
- Attenuation of muons for personnel protection
- Experimental physics equipment background requirements
- Personnel protection against beam dump cooling water system activation

Each of these concerns is reviewed below, describing how applicable criteria were met.

For personnel protection from neutrons and photons, the shielding at the 60% design (three feet of concrete in all directions plus nominally 7 feet 7 inches of steel above, below, behind and to the sides, and 4 meters of soil and concrete roof) will ensure that above-ground nominal dose rates are less than 50 μrem/h while sending 12 GeV, 5 micro-amp electron beam to the electron beam dump. Under the maximum credible accident scenario in which 1 MW beam is delivered to the beam dump, the dose rate would still be substantially less than 15 rem/h.

Shielding for muons is currently provided by a combination of steel SEG blocks and concrete. Figure 5 shows the result of the GEANT simulation for the muon production and shielding. The primary concern with the muon shielding in this region is that, although muons are "forward peaked," they travel a great distance if not shielded by relatively dense material. Additionally, the position of the beam axis below original site grade is such that it would not be difficult to dig to a depth intersecting the muon field if it were allowed to "range out" in the soil (in fact the muon field may break the plane of the grade), unless an unreasonably thick dirt berm was applied over the entire muon range. The length of the steel block shield is 10 meters in total (including the thickness used inside the dump cave). Due to the content of low level radioactivity in the blocks (primarily Co-60), instead of direct burial, they should be encased in a thin layer of concrete. This will help mitigate any significant intrusion of the radioactivity into the surrounding soil or groundwater.

Another option for muon shielding is to provide above-ground fencing to approximately 233 feet behind the beam dump, as well as approximately 15 feet across. This approach has been discussed with other DOE accelerator labs, and is not recommended because the fence is believed to be an ineffective deterrent for those who plan on digging. Additionally, this is a large expanse of fencing, and requires some degree of attention and upkeep, compared to the existing plan, in which the shielding is built in, and by its nature of being underground, does not require any upkeep.[1]

Note that if it is desired to further reduce handling of the SEG blocks to save labor, the thickness of the concrete can be increased based essentially on the ratio of the density of the steel to the concrete, i.e., 7.8/2.35 = 3.3.

Groundwater activation shielding is the primary driver for the combination of SEG block and concrete surrounding the electron dump. As mentioned previously, the methodology for determining necessary groundwater protection is the same as that used in shielding the original CEBAF accelerator and End Stations. The design goal is to maintain the neutron fluence rate to less than 35 neutrons/cm^2sec for neutrons with energies greater than 20 MeV. This ensures that activity in the groundwater will not exceed VPDES permit limits. It should be noted that sample results from groundwater monitoring wells adjacent to the existing end-stations have never exceeded the radionuclide-specific MDCs for any accelerator-produced nuclides.

Also of note is that hydro-geological models for the CEBAF site indicate that de-watering operations at the end stations modify the groundwater flow. These models suggest that a significant portion of the potentially affected ground water may be collected in the end station dewatering system and pumped to the surface. Hall D is designed such that no dewatering is necessary or planned; there is no added margin of safety for Hall D associated with end station dewatering. Consequently, the approach used for protection of the groundwater in this area must contain due conservatism.

Within the Hall D complex, the Tagger Area Electron Beam Dump is the principal source of concern for groundwater activation. The assumption of operating continuously at 60 kW beam power would result in unnecessarily thick shielding walls. A more reasonable (yet conservative) assumption is 12 GeV, 3 micro-amps beam delivery with a duty factor of 30 weeks operation per year.

[1]For a comparison of other materials, as shown in Fig. 3.39 of NCRP 144, the result for 12 GeV yields 70 meters (233 feet) of earth required to attenuate the muons. This would necessitate fencing and posting the entire area so that no digging or excavation could occur while beam operations were conducted.

GEANT simulations were conducted using civil construction parameters taken from the 30% and 60% design plans, applying an iterative process to arrive at an acceptable solution. Figures 6 and 7 detail the neutron fluence rate at energies greater than 20 MeV exiting the beam dump enclosure into the soil. Figure 6 illustrates the 30% design model of the electron beam dump enclosure with the walls made exclusively of concrete. The calculated maximum flux of neutrons with energy above 20 MeV entering soil is about 80 n/cm2/s, above the accepted limit imposed by the allowed soil activation. The suggested increase of effective shielding material thickness around the beam dump by using extra layers of iron in the walls of the enclosure, and increasing their total thickness, as illustrated by the model in Figure 7, based on the 60% project design, allowed to reliably confine the neutrons, and significantly decrease their flux in the soil. As can be seen from the figures, the design shown in Figure 7, using a combination of SEG blocks and concrete shielding, results in sufficient protection for groundwater activation. Subsequent design changes culminating in the final civil design (Figure 8) retain these important shielding elements.

As mentioned previously, there is a concern regarding radiation streaming from the electron beam dump enclosure causing problems with Physics experimental equipment background. The layout was optimized to provide adequate distance from the dump to the tagger hodoscope and thickness of the labyrinth walls separating the dump from the tagger area. Figure 8 provides a view. This layout calls for a labyrinth of two 3-foot thick concrete block walls, and two SEG block widths, with 2 doors of at least one inch thick borated polyethylene sheets that help to absorb the thermal neutrons created from attenuation of the fast neutrons. GEANT simulation of the configuration, assuming typical run conditions of 3 micro-amps and 12 GeV is shown in Figure 9. This evaluation indicates insignificant contribution to the hodoscope detectors from the dump, compared to the radiation produced in the tagger itself. Figures 10 and 11 illustrate the advantage of using extra doors layered with borated poly to shield the tagger enclosure from thermal neutrons streaming from the dump area through the labyrinth back into the tagger area. "Open" and "closed" labyrinth configurations are shown. The final design satisfies the physics requirement of less than 1% background interference from backscattered radiation from the dump. This condition was confirmed by further Monte Carlo simulations performed by Richard Jones, as described in paper: "Simulation of Tagger Backgrounds Returning from the Electron Beam Dump".[24] A copy of this paper is attached as Appendix 1.

Another radiological consideration is the placement of the beam dump cooling water pump skids. As an ALARA measure, the beam dump cooling water pump skids were originally located in the beam dump enclosure behind two labyrinth walls. To minimize concrete costs the pump skids were relocated to the northeast corner of the tagger building while the resin tanks remain behind the beam dump labyrinth walls. These resin tanks collect the majority of the Be-7, the predominant radionuclide of concern post one hour shutdown. This decision keeps the items with the highest dose rate (resin bed tanks) in a secured, shielded area, while keeping items that may require maintenance (i.e., pumps) reasonably accessible in a lower dose area. Experience at the Hall A and C beam dump cooling water buildings indicates that dose rates near the pump skids fifteen minutes after shutdown should be well below the threshold for a High Radiation Area. The pump skids can be locally shielded for ALARA optimization (if necessary) following detailed operational measurements. Radiation levels around the pump skids will be driven primarily by very short-lived activation products such as O-15 and N-13.

Photon beam pipe from Tagger Building to Hall D collimator enclosure

Once the tagger magnet has redirected the electrons in the direction of the tagger electron beam dump, the photons continue through a large (comparative to beam size) pipe to the collimator enclosure area of Hall D proper. This section of pipe is surrounded by approximately 1 foot of concrete to provide corrosion protection and alignment stability. The combination of concrete and the associated earth berm of 4 meters are adequate to meet shielding design goals and prompt ionizing radiation protection requirements for the low power photon beam, which in operational conditions carries all of its energy down to the collimator enclosure without loss.

The primary electron beam cannot be transported beyond the tagger enclosure due to the presence of a large permanent magnet behind the tagger magnet (see Figure 8). In the event of a tagger magnet trip, the permanent magnet deflects the electron beam away from the photon beam pipe and onto the East wall of the tagger building. Thus, we do not evaluate any scenarios involving electron beam transport beyond the tagger area.

Hall D collimator enclosure

The thick concrete shielding in this area is primarily for groundwater protection based on 10 W high energy photon beam power deposited directly on the collimator. The access way is designed such that there is no direct line of sight from the collimator into the hall. The large opening from the collimator enclosure will be blocked with SEG blocks or other suitable steel shielding.

Hall D Enclosure Proper

The civil design layout of Hall D is shown in Figure 12. Photon beam power in Hall D proper is comparatively small (i.e., 2 W). From the GEANT modeling of the hall, we estimate the dose rate at the roof and inside the walls of the hall to be on the order of 1 mrem/h. For personnel exposure, points of concern are the personnel access door, the truck ramp, and the occupied spaces outside the thick concrete walls. The personnel access door lies outside a small labyrinth built into the accessway. Evaluation of the labyrinth with universal attenuation curves indicates a dose rate outside the double access doors (the closest accessible point, during operations) well below 50 μrem/h.

The truck ramp access is enclosed, and can be treated as the first leg of a labyrinth (using same method as for the tagger truck ramp). In this case, the source is off axis to the opening of the truck ramp, giving a transmission factor of no more than 1E-2. This approach gives a conservative estimate for the dose rate at the top of the truck ramp on order of 10 μrem/h. The Hall D building has a wall thickness of 2 feet that continues vertically to a level of about 16.5 feet above the local grade. A GEANT Model indicates that this should result in an average dose rate of about 7 μrem/h outside the North and South walls during typical operating conditions. For details, see Figures 13 and 14.

Photon Beam Dump

Because the power deposited is only about 2 W, the photon beam dump consists of solid iron (SEG blocks) and needs no water cooling. The photon dump shielding consists of additional SEG blocks. These SEG blocks, along with the concrete, and dirt overfill serve to minimize:

a) general outside area dose rates
b) groundwater activation
c) muon rates
d) boundary dose rates

The configuration of the photon beam dump includes a recessed 10-inch diameter "pipe thimble" cast into the East wall of the hall. The recess provided by this arrangement causes the photon beam to strike the face of the dump about one meter down-beam of the inner plane of the wall. This provides a collimating effect on the backscattered radiation, reducing the impact of this source term with respect to dose rates at the roof, North and South walls. The same requirement for muon shielding exits here as for the tagger dump – about 10 meters of steel (SEG blocks) extending East from the dump. The shielding should have a minimum radius of 1 meter, centered on the beam. To prevent groundwater activation from dumped beam, an additional one meter of SEG block is necessary for a horizontal distance of 3 meters underneath the existing 10 meters of muon shielding. Figures 15 and 16 show GEANT simulations of radiation from the dump with and without dirt berm shielding. The modeling indicates the need for approximately 3 meters of dirt shielding over the beam dump in order to keep boundary dose estimates to less than 10 mrem in a year. The SEG blocks need to be enclosed in concrete for the same activation concerns noted in the tagger area section above.

General Boundary (Fenceline) Dose Rates

The GEANT model for boundary doses is shown in Figure 17, indicating volume surfaces of interest. Of critical importance in this simulation are the doses at the North and East fence lines, shown in Figures 18 and 19, respectively. Also shown, in Figure 20, are the calculated doses for points 20 meters South of the hall (there is no property boundary in the Southern direction close enough to be relevant to these data). The data indicate that annual doses at the fence boundaries, with the shielding as specified above, will remain below 10 mrem/year at the distances larger than 50 meters east of the Hall D east wall and 45 meters north of the Hall D north wall.

Monitoring and Safety Equipment

This note provides only a cursory examination of some of the perriferral devices and equipment needed for support of the radiation safety aspects of operations in Hall D. The monitoring and safety equipment necessary for the Hall D complex will be similar to that required and in use in and around the CEBAF accelerator and experimental halls A, B, and C. Technical specifications for the civil design to support the equipment is contained in the appropriate system design documentation.

ADM-616 Radiation monitors (or technical equivalent) with a minimum of one gamma probe and one neutron probe will be located at the following areas (all units require 110V AC power and 2 twisted pairs of #12 AWG wire):

1) Accelerator tunnel extension shield wall area as part of PSS. This is similar to the function of RM 29, 30 and 31 for Halls A, B, and C.
2) At the top of the tagger building truck ramp entrance as part of PSS
3) In the tagger area service building adjacent to LCW piping run as part of PSS
4) At the Hall D personnel access door as part of PSS
5) At the top of the Hall D truck ramp entrance as part of PSS
6) In the Hall D control room by the cable access way run, as part of PSS (also covers the roof area of Hall D)

Radiation Boundary Monitor will be needed at the fence boundary in direct line with the beam dump for purposes of monitoring boundary dose. This will require a NEMA enclosure, ADM-606 (or technical equivalent), NaI gamma probe, and He-3 neutron probe.

Floor Drain Sump Accumulation area with associated Tritium Monitoring and Disposal Unit (TMDU) located in a separate room controlled by RadCon outside of the personnel entrance to Hall D. This area collects any water spills in the tagger area or Hall D, as well as the output of any air conditioning condensate systems, so that the effluent can be analyzed for radionuclides of concern to ensure that the quantities and concentrations are within the parameters established in the Hampton Roads Sanitation District (HRSD) permit[25] allowing discharge of water containing radionuclides to the HRSD sanitary sewage system.

AMS-4 air monitoring systems in the Hall D tagger area in order to monitor airborne radionuclide emissions for input into the calculations for the required annual NESHAP report.

Beam Loss Ion Chamber base unit and minimum of 4 BLICs in tagger area for locations in the electron beam dump labyrinth, near the hodoscope, and at the tagger magnet. This requires 110V AC and 20 #24 AWG wires.

Rapid Access units in Hall D and Tagger Area enclosures – up to 3 ADM-606 units in each location with three gamma probes per unit. This requires 110V AC and 20 #24 AWG wires.

Position Sensitive Ion Chamber (PSIC) at face of electron beam dump in tagger area. This requires 110V AC and 20 #24 AWG wires (this device is not yet in production).

Conclusions

The shielding design presented above is based on a cautious projection of Hall D operational parameters, sound computer modeling supported by semi-empirical calculational methodology, and CEBAF operational experience. The Hall D complex shielding design meets all requirements for radiation worker, general population, and environmental protection as discussed in the proposed operations envelope in the Project Preliminary Hazards Analysis for the 12 GeV Upgrade project.

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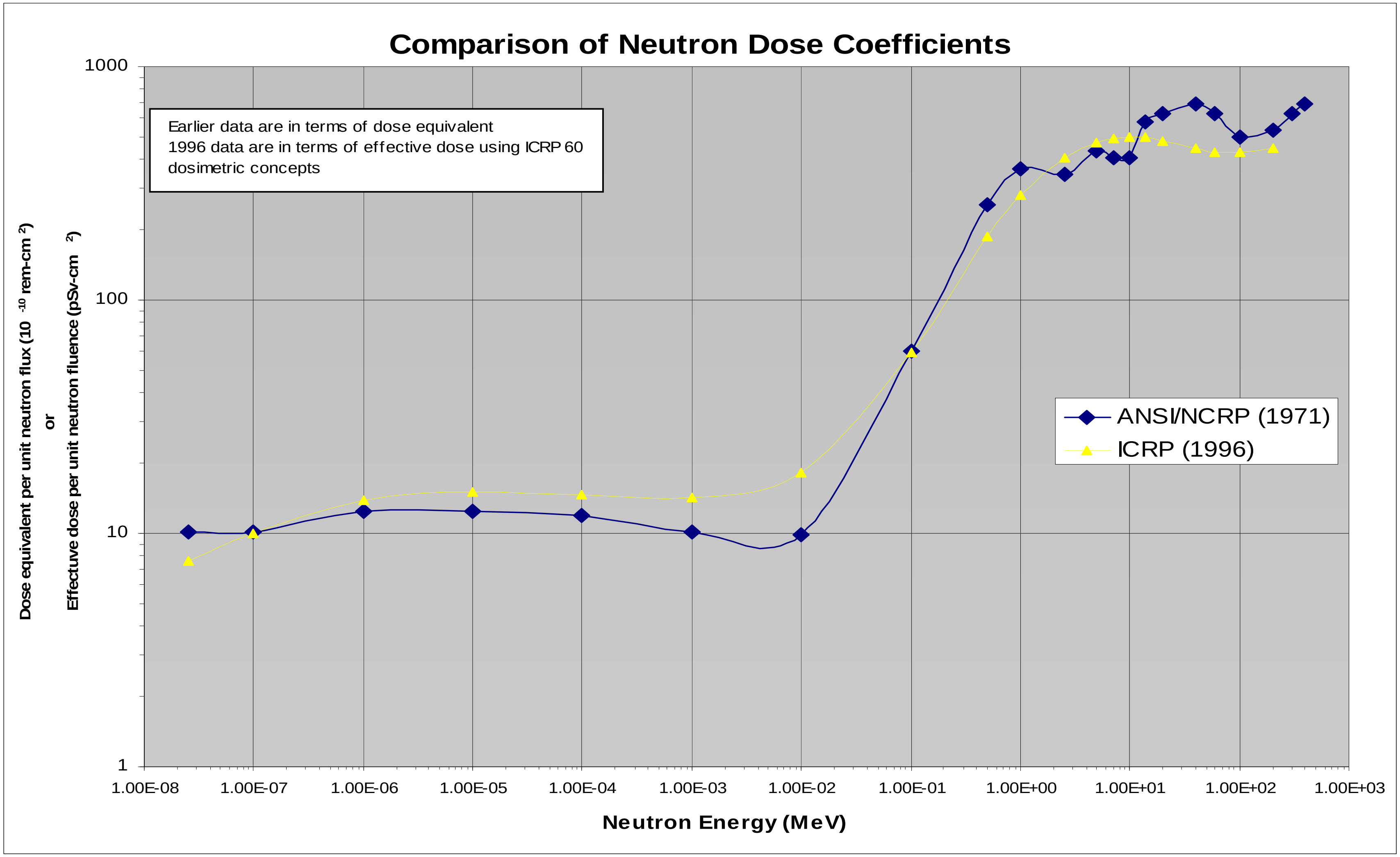

Fig. 1: Comparison of neutron fluence to dose conversion coefficients used in the Monte Carlo modeling of neutron doses from Hall D operations with updated coefficients based on ICRP-60 dosimetric quantities.[1]

[1] ANSI/NCRP data appear in previous version of 10CFR835

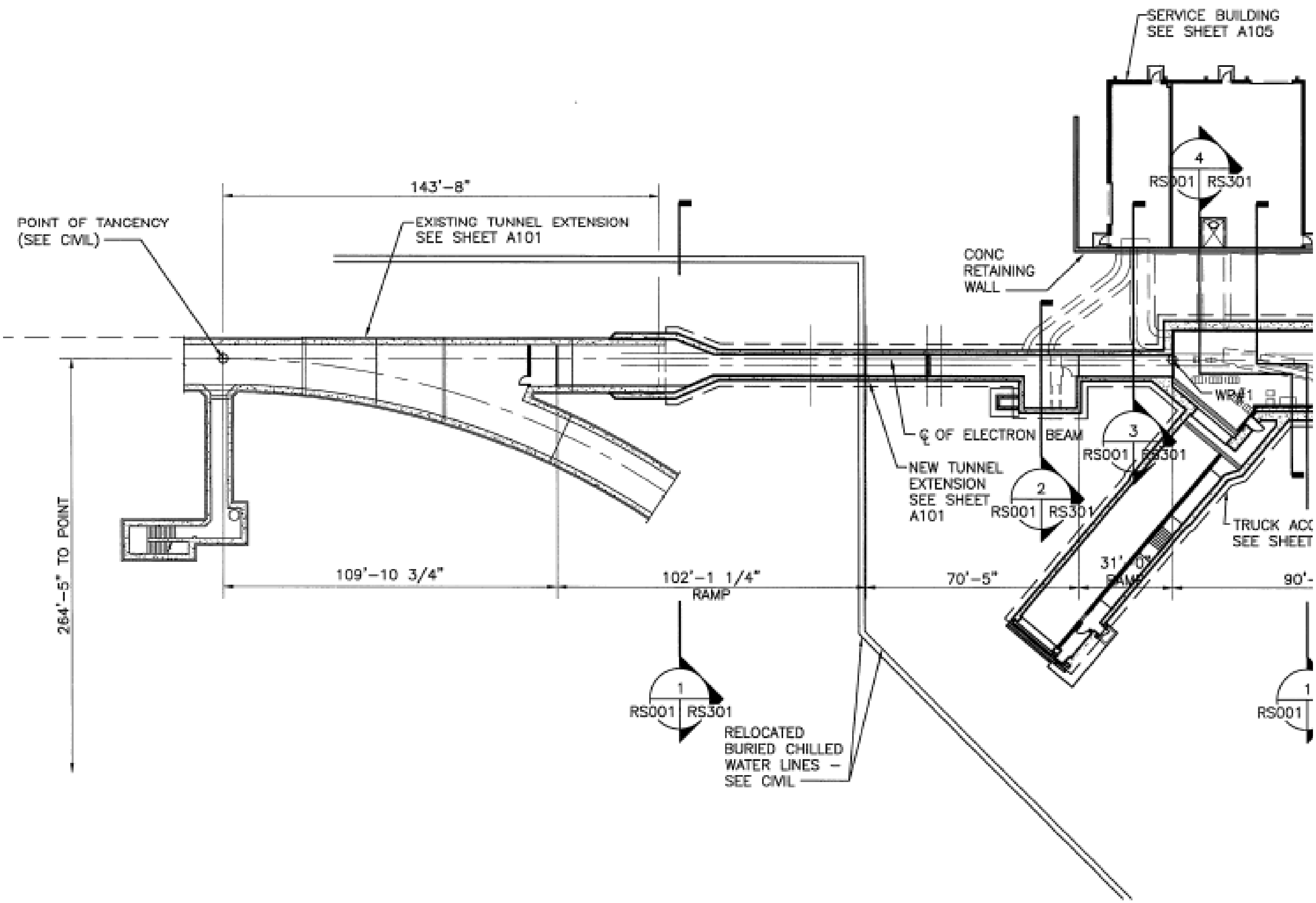

Fig. 2: North LINAC Tunnel Extension

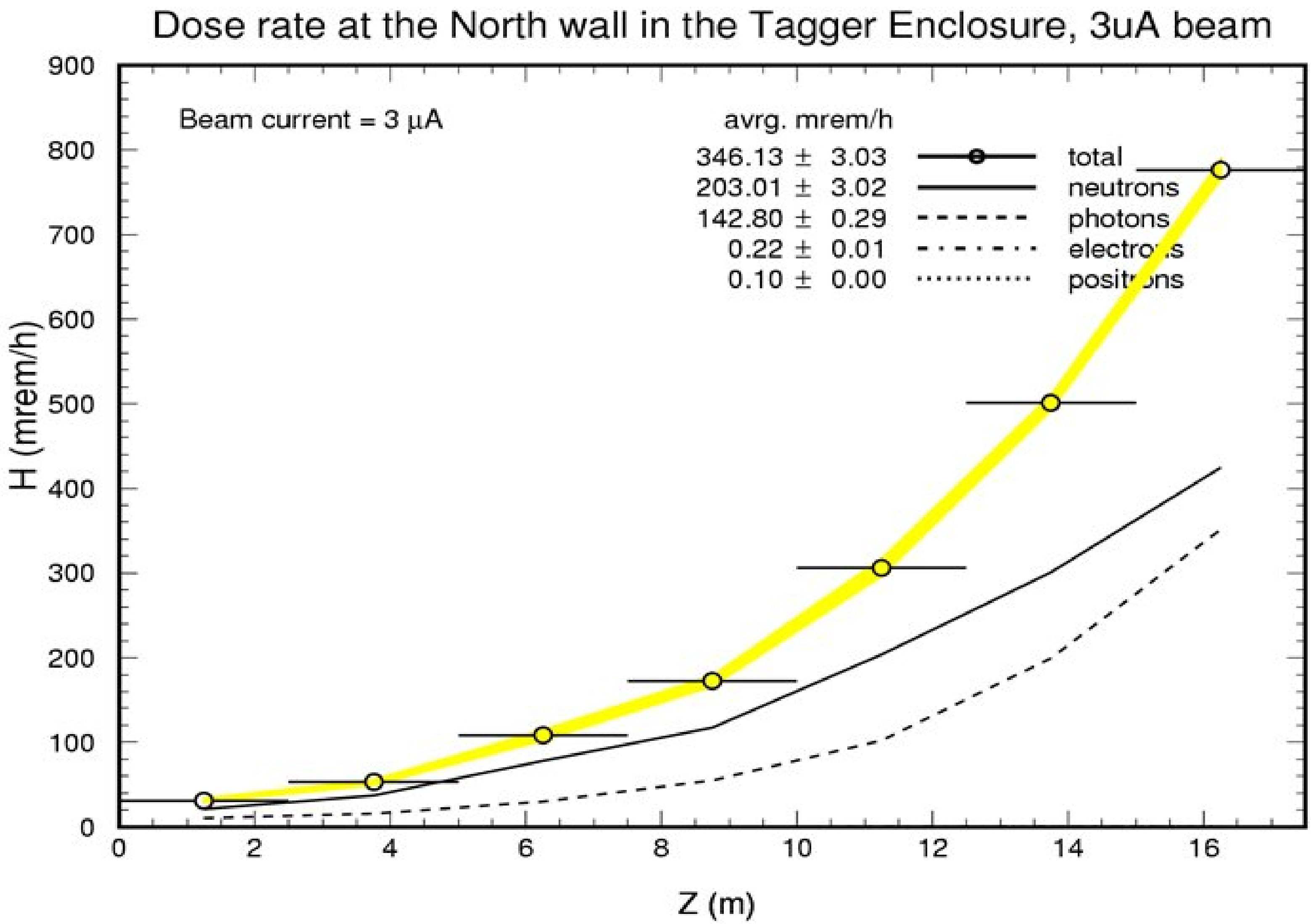

Fig. 3a: Dose Rate inside the Tagger Enclosure at the north wall. Abscissa is the coordinate along the beam in the encosure

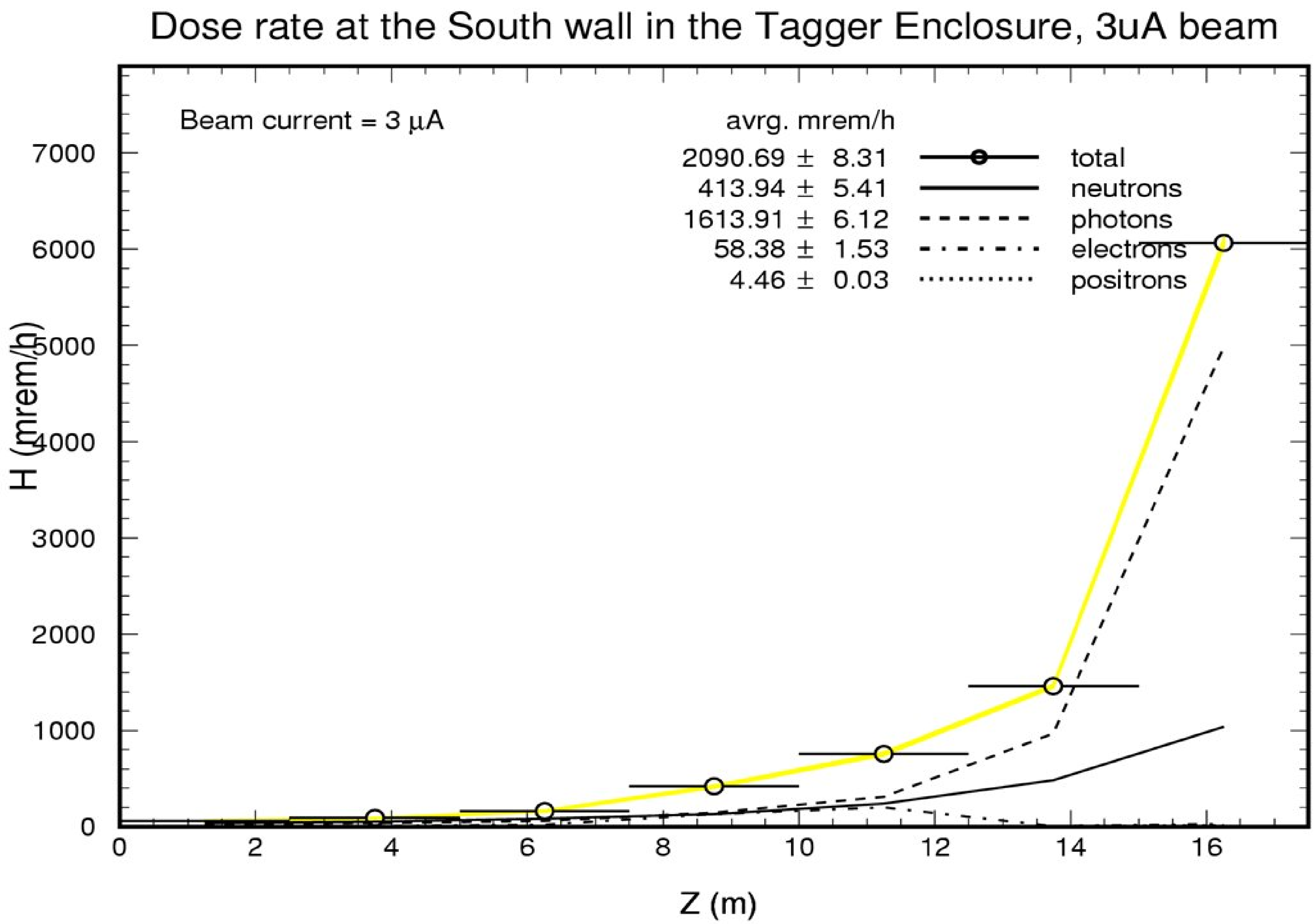

Fig. 3b: Dose Rate inside the Tagger Enclosure at the south wall. Abscissa is the coordinate along the beam in the encosure

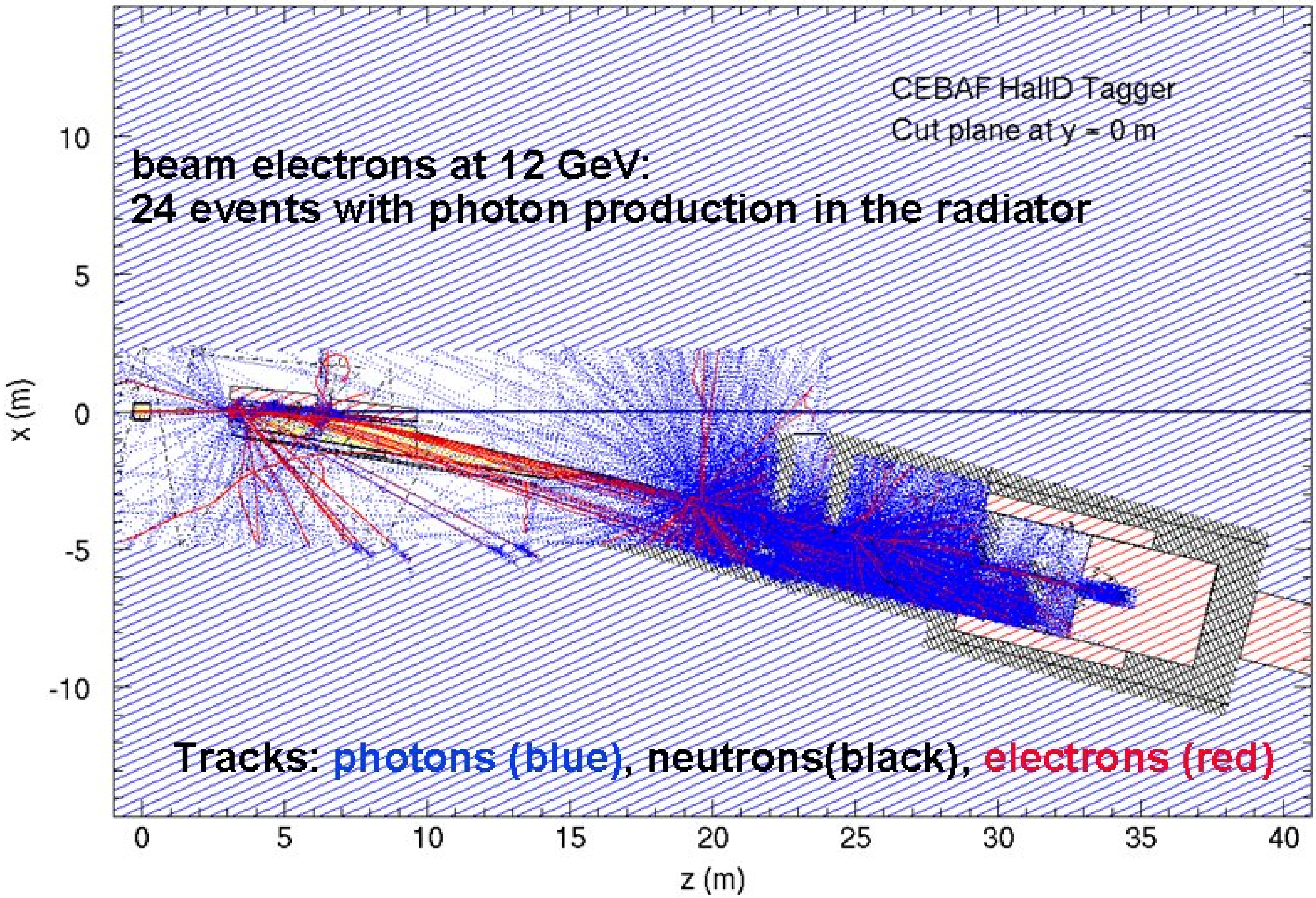

Fig. 4: Monte Carlo Simulation of Beam Interaction in Radiator. Z and X are the coordinates in the horizontal plane, Z is along the beam.

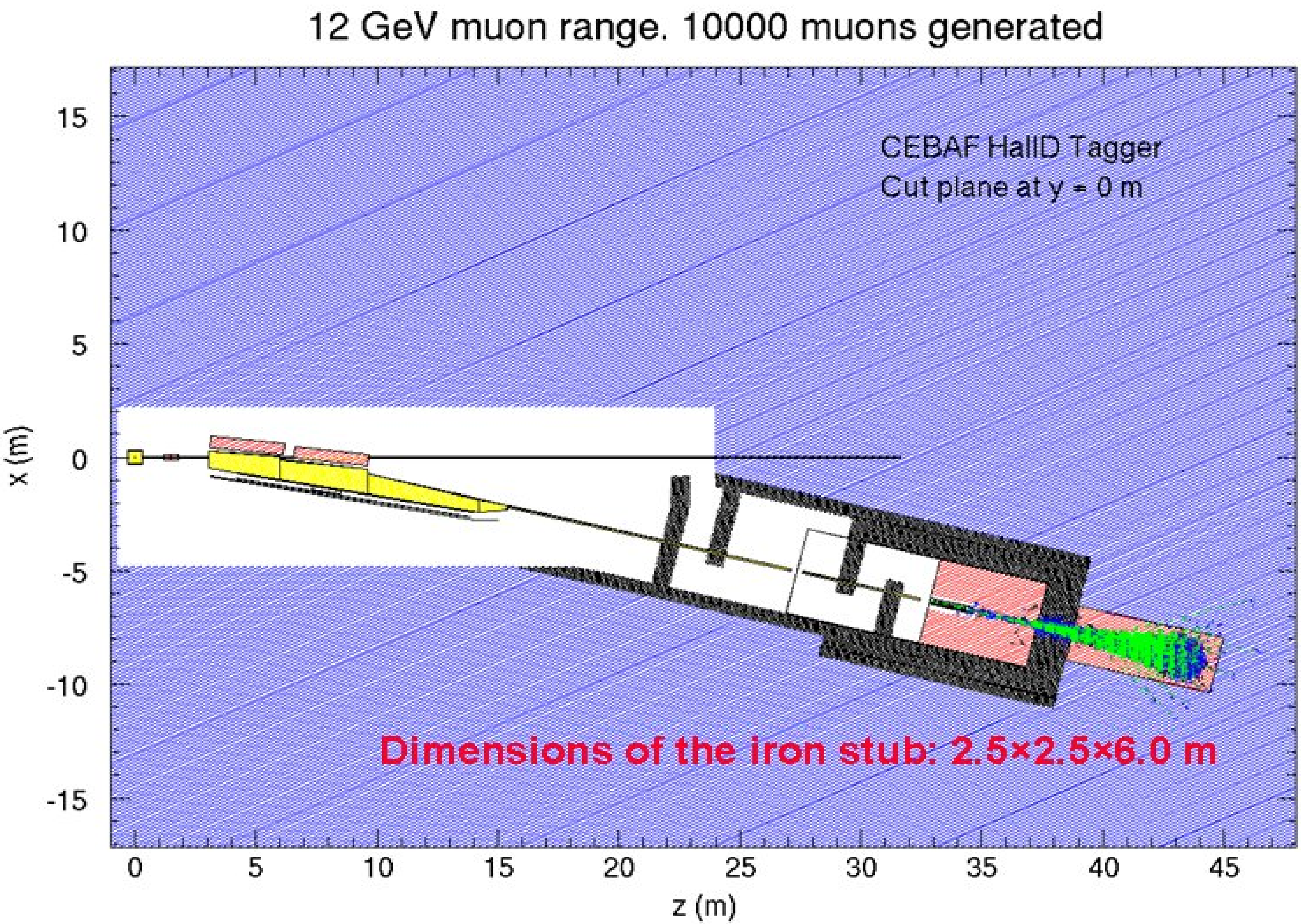

Fig. 5: Hall D Electron Beam Dump model: muons. Z and X are the coordinates in the horizontal plane, Z is along the beam.

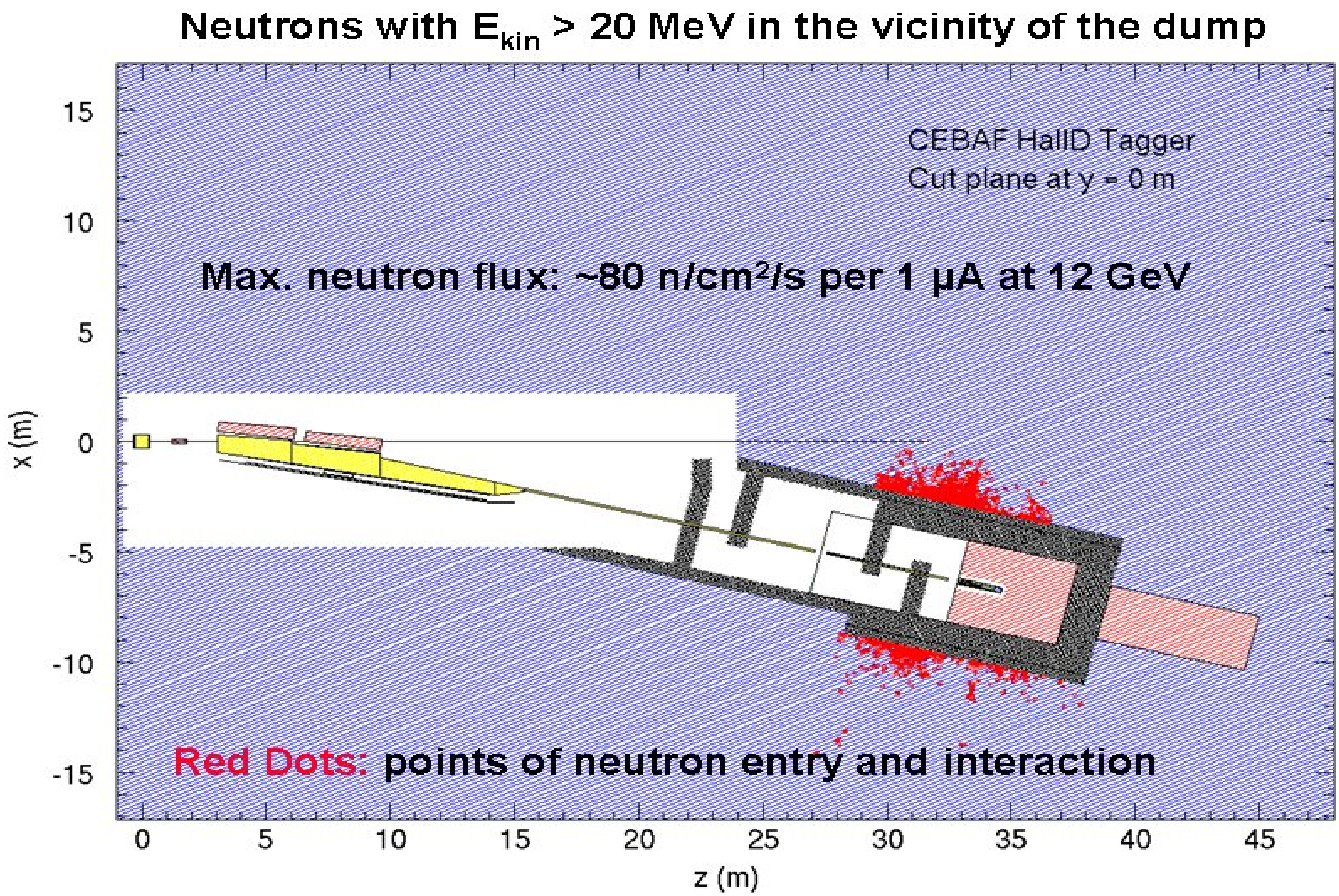

Fig. 6: Beam Dump: Neutrons in the Soil. Z and X are the coordinates in the horizontal plane, Z is along the beam.

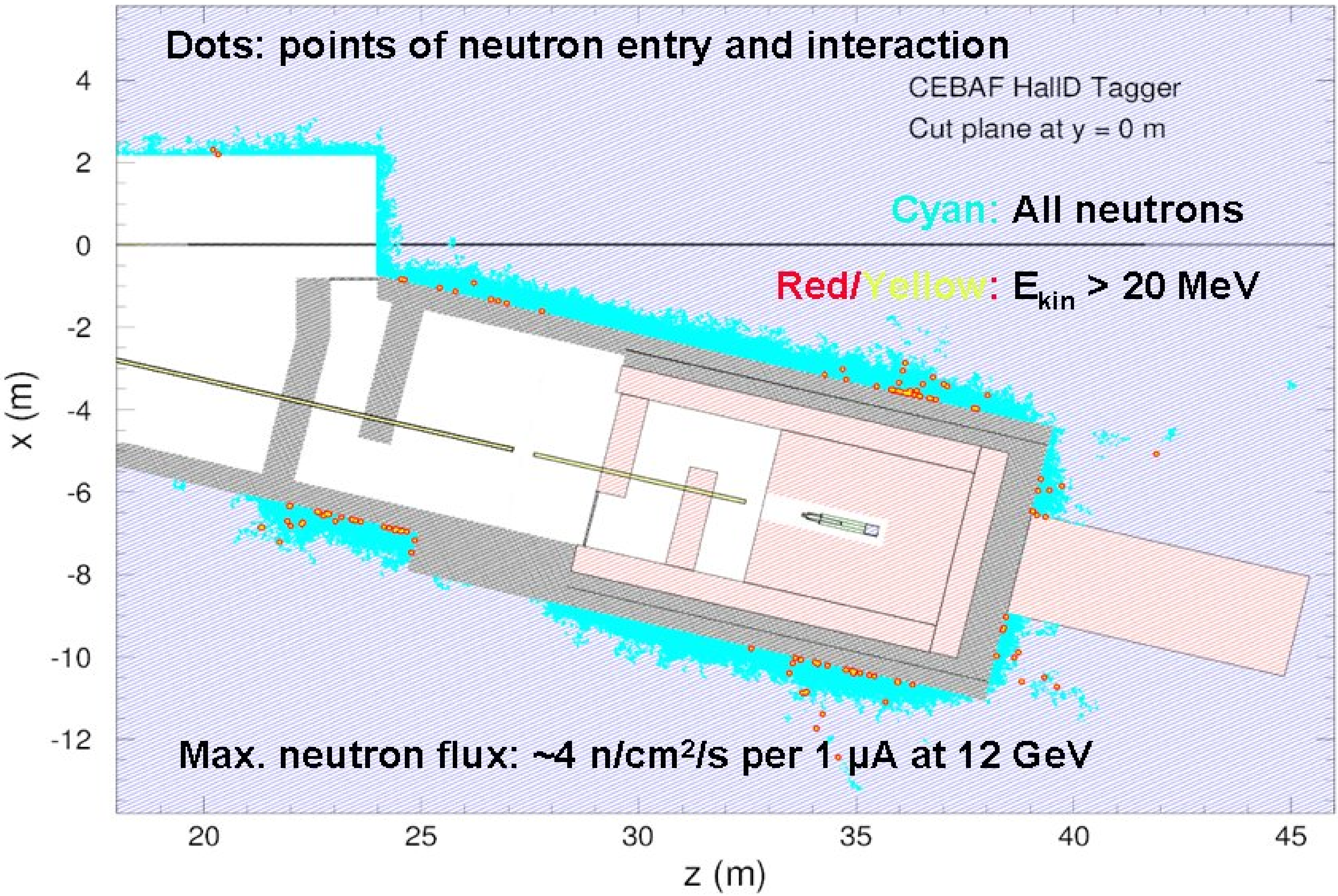

Fig. 7: Beam Dump: Neutrons in the Soil. Z and X are the coordinates in the horizontal plane, Z is along the beam.

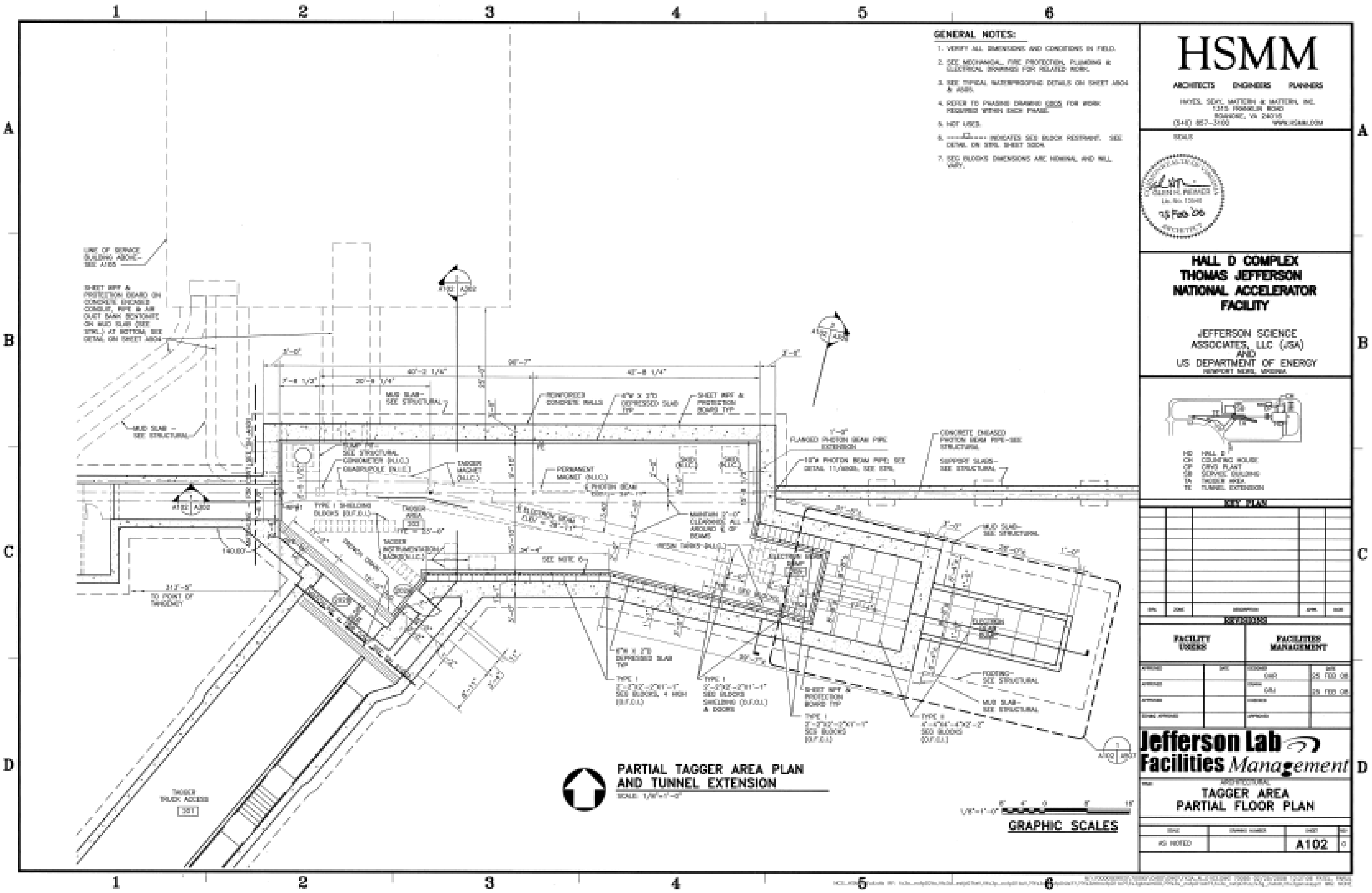

Fig. 8: Composite Hall D Complex Plan

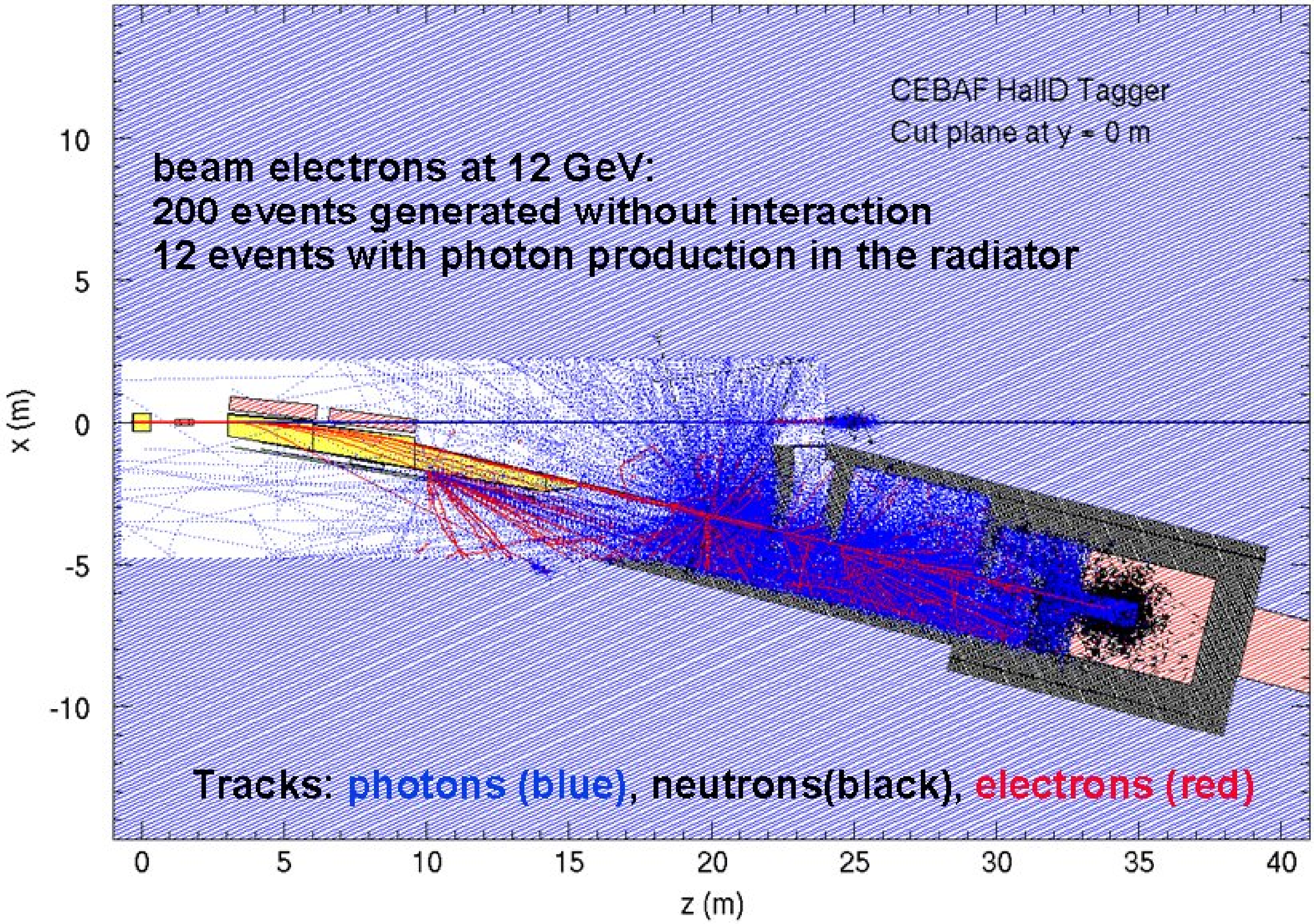

Fig. 9 : Model illustration of events with and without photon production in the radiator.
Z and X are the coordinates in the horizontal plane, Z is along the beam

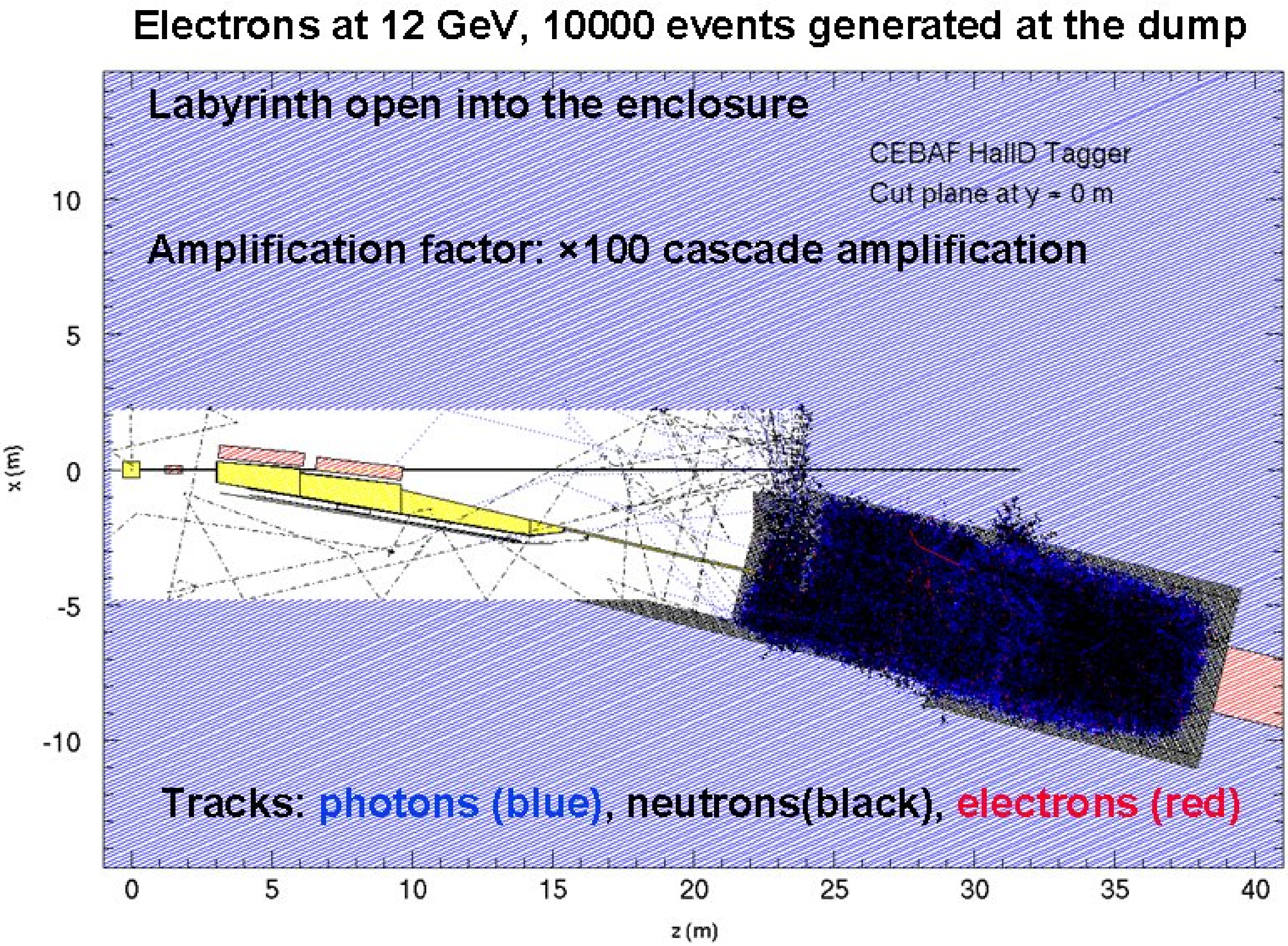

Fig. 10: Neutrons entering the tagger enclosure from the dump area. Labyrinth is open into the enclosure. Z and X are the coordinates in the horizontal plane, Z is along the beam. Neutron production biased by a factor 100

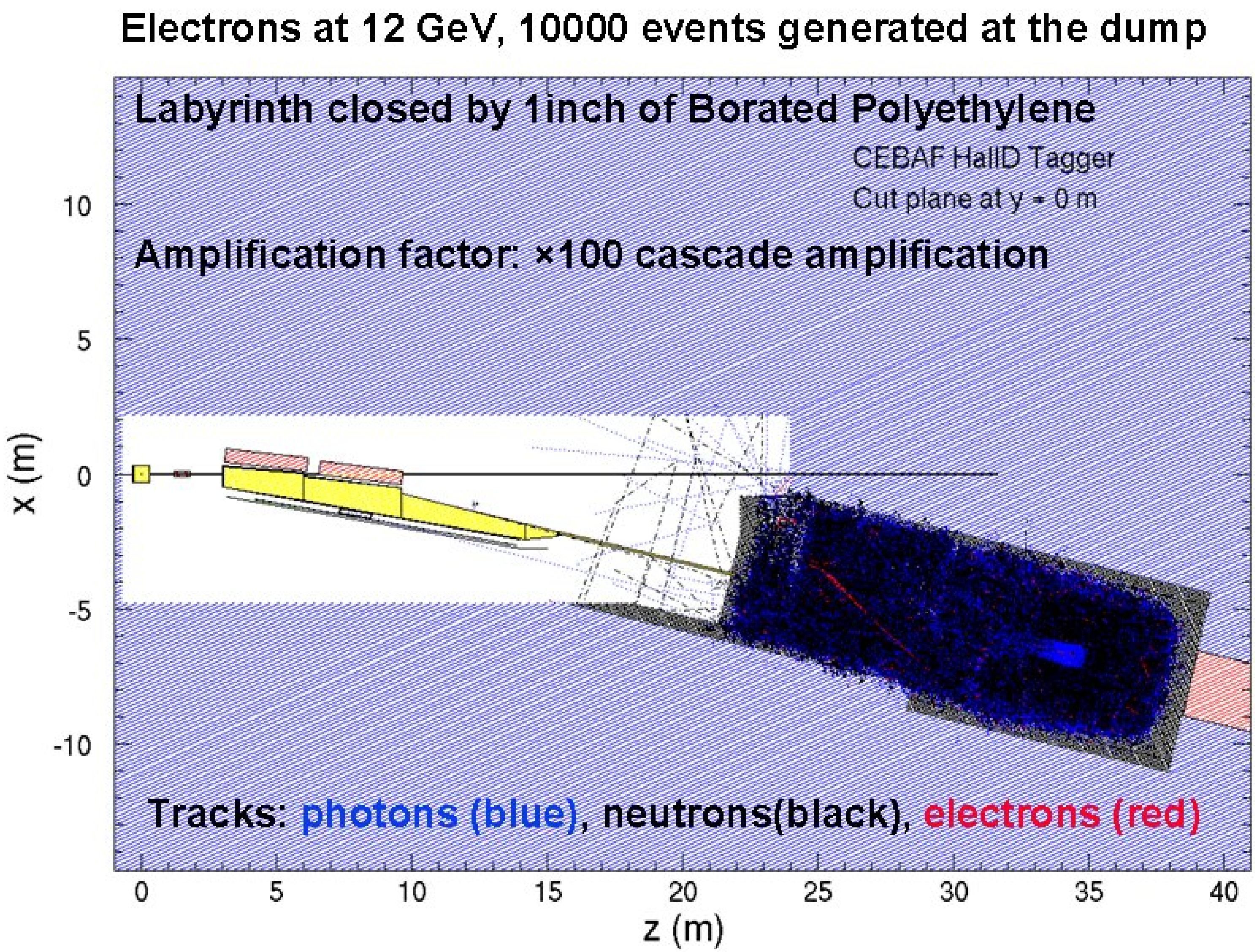

Fig. 11: Neutrons entering the tagger enclosure from the dump area. Shielding doors in the labyrinth installed.
Z and X are the coordinates in the horizontal plane, Z is along the beam . Neutron production biased by a factor 100

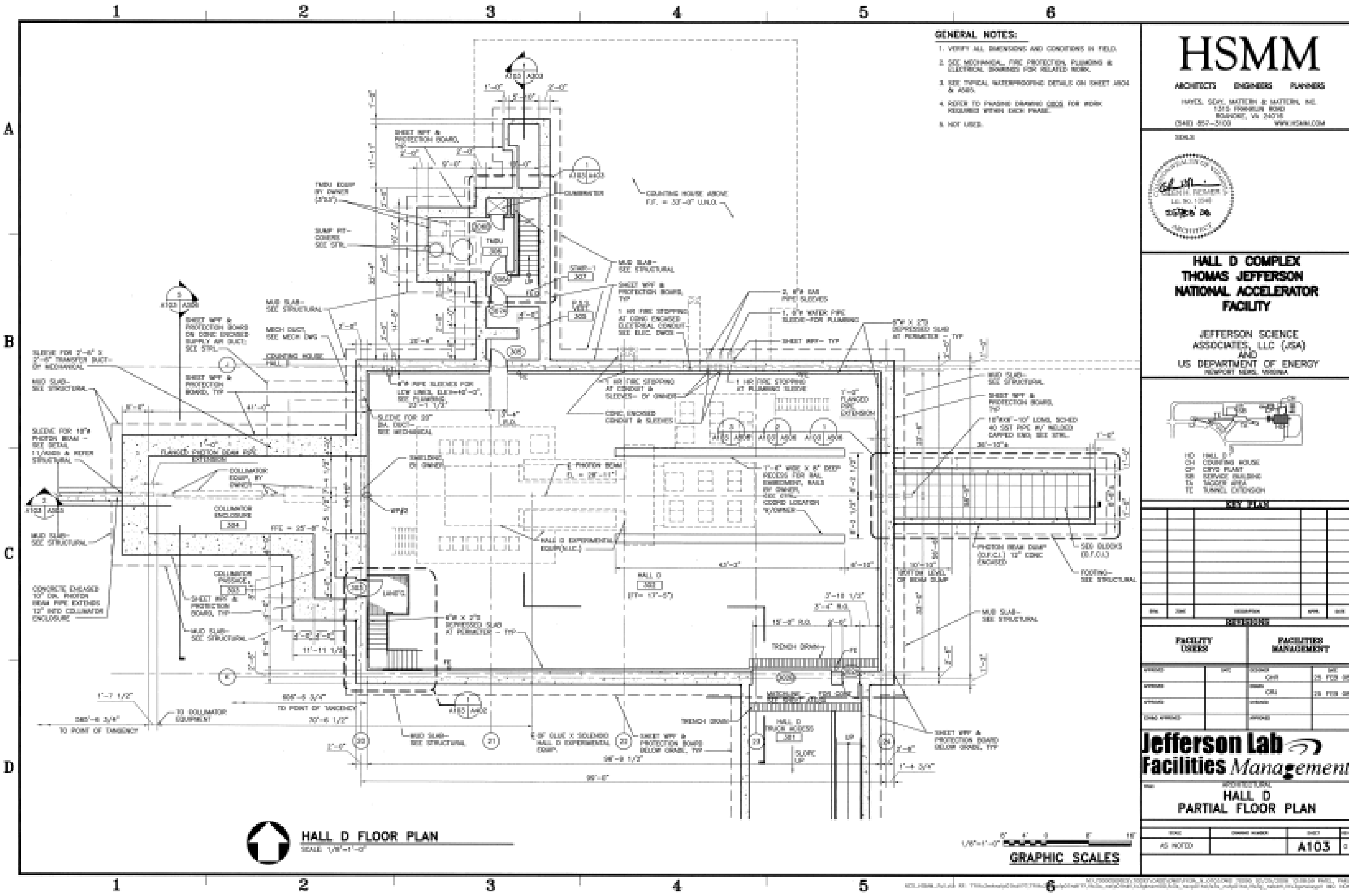

Fig. 12: Hall D Layout

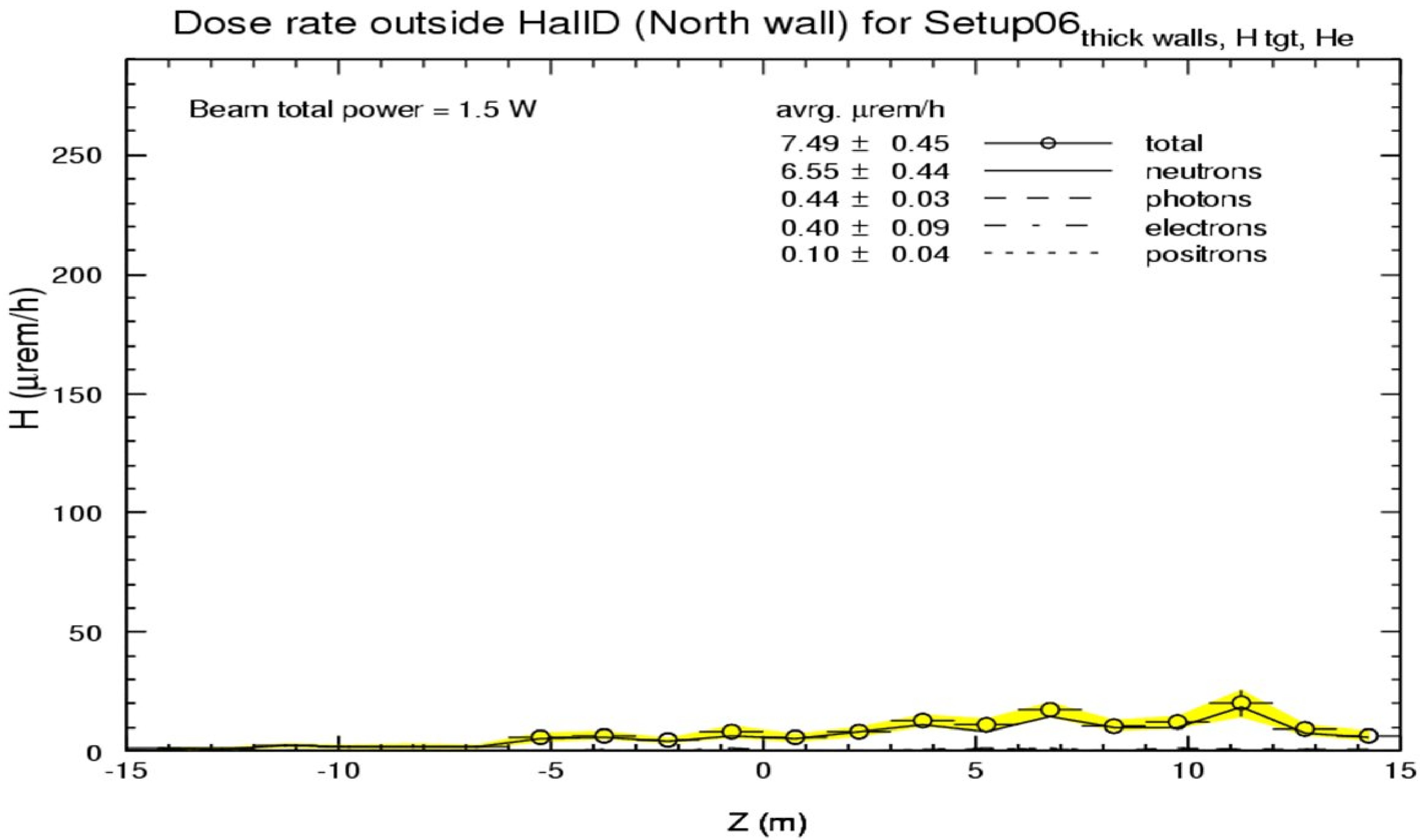

Fig. 13: Dose Rate Outside North Wall. Abscissa is the coordinate along the beam

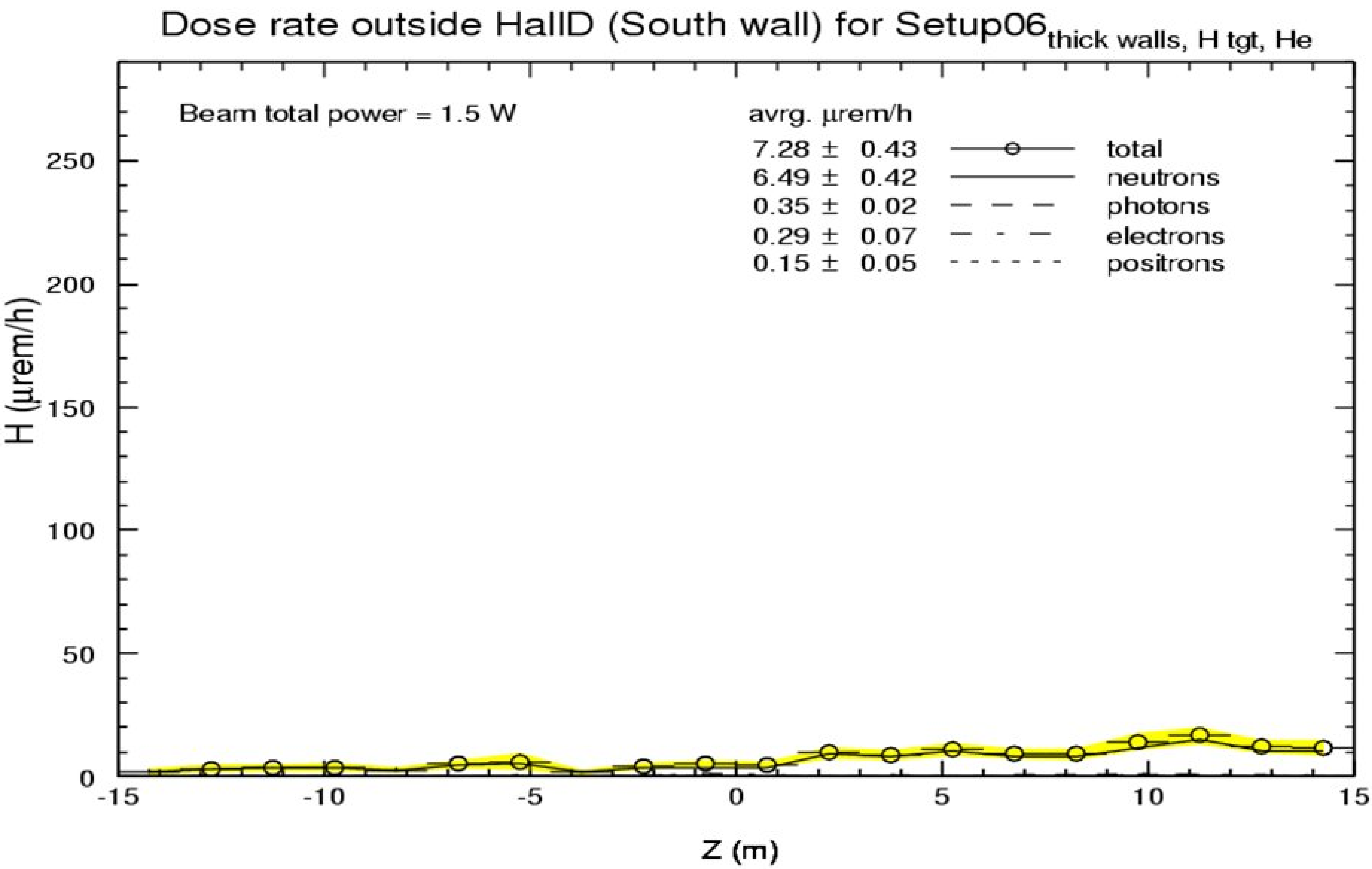

Fig. 14: Dose Rate Outside South Wall. Abscissa is the coordinate along the beam

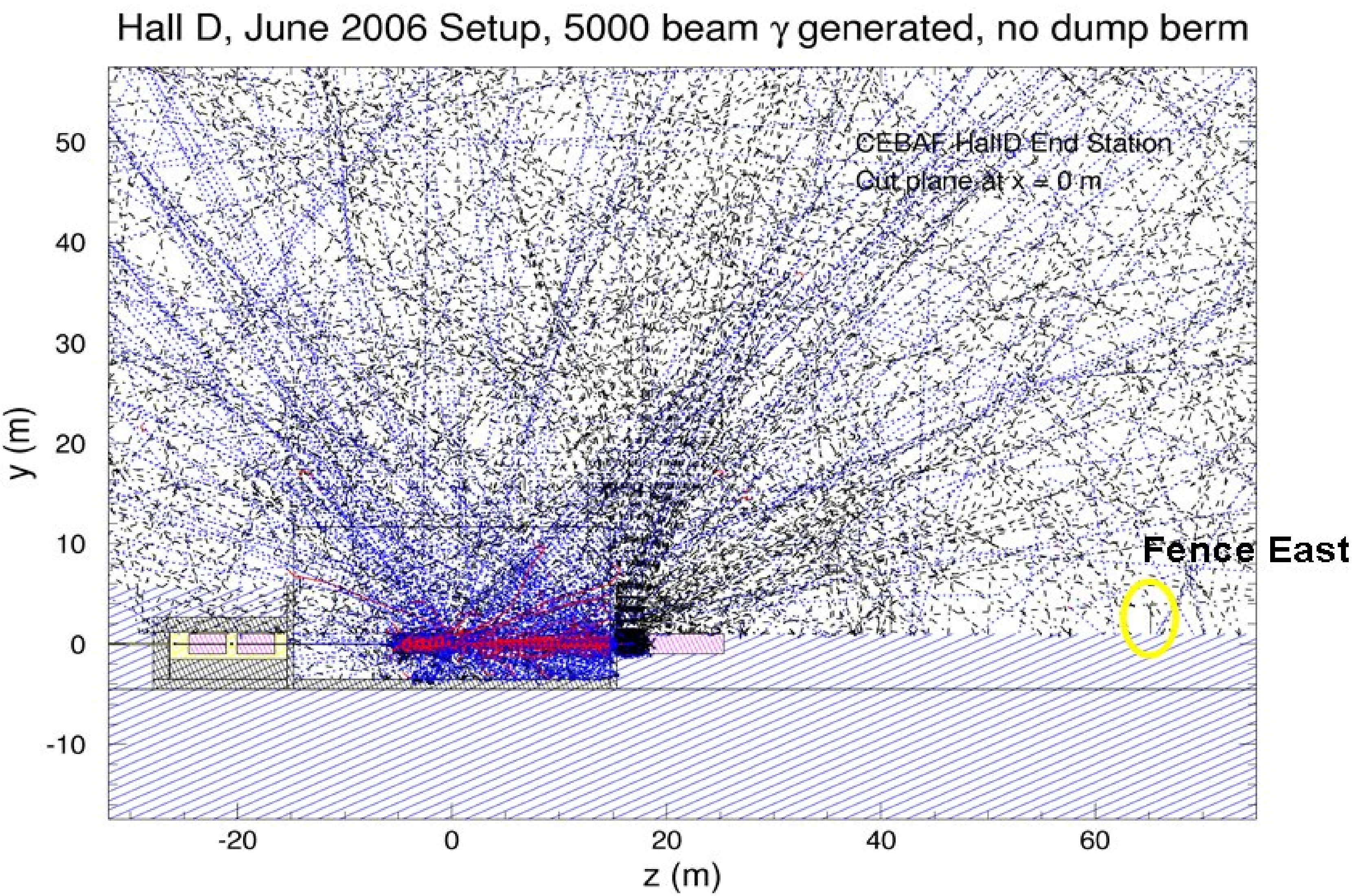

Fig. 15: Radiation Flux From Photon Dump With No Dirt Berm. Z and Y are the coordinates in the vertical plane, Z is along the beam

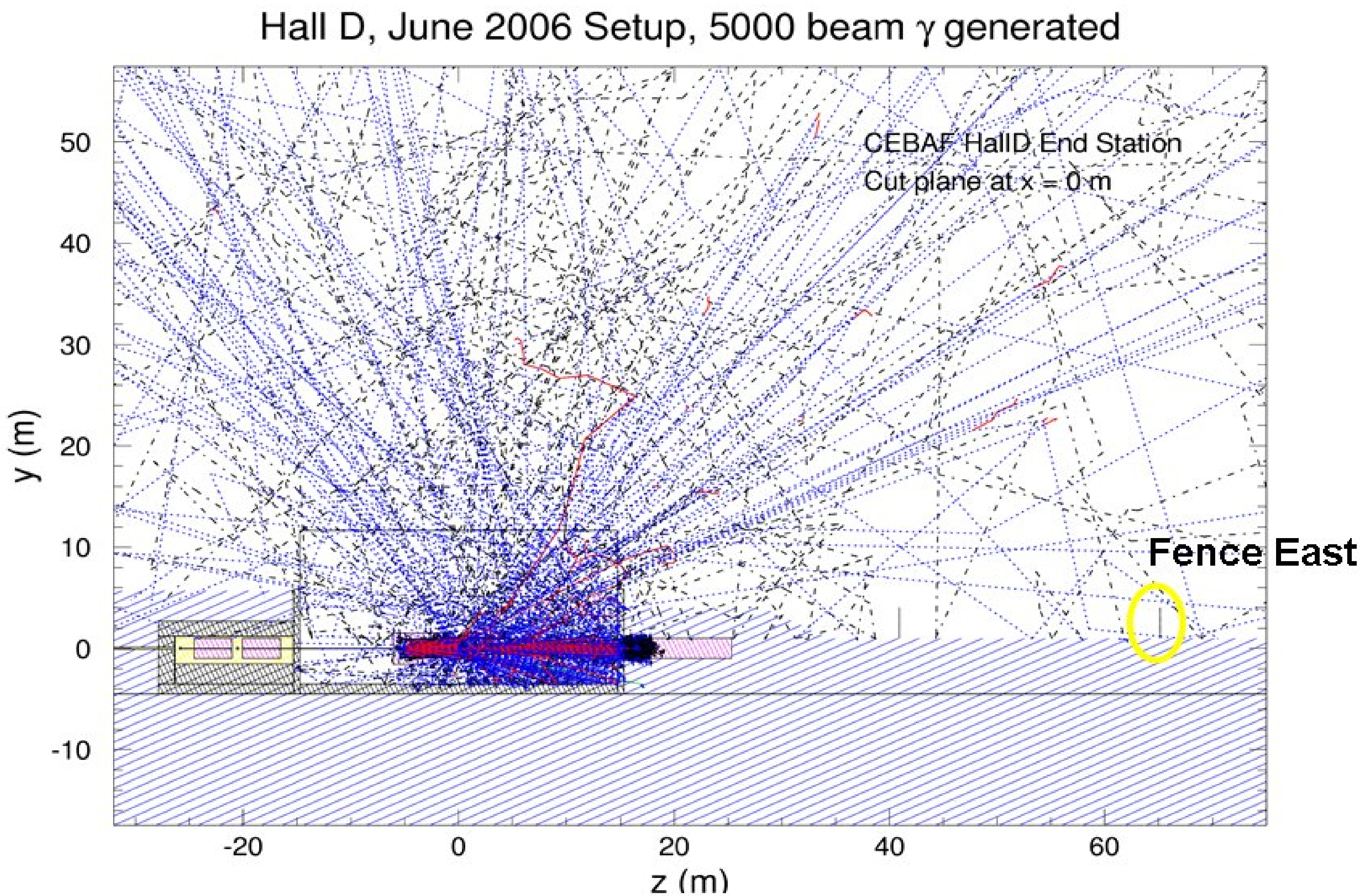

Fig. 16: Radiation Flux From Photon Dump With 3 Meters Dirt Berm. Z and Y are the coordinates in the vertical plane, Z is along the beam

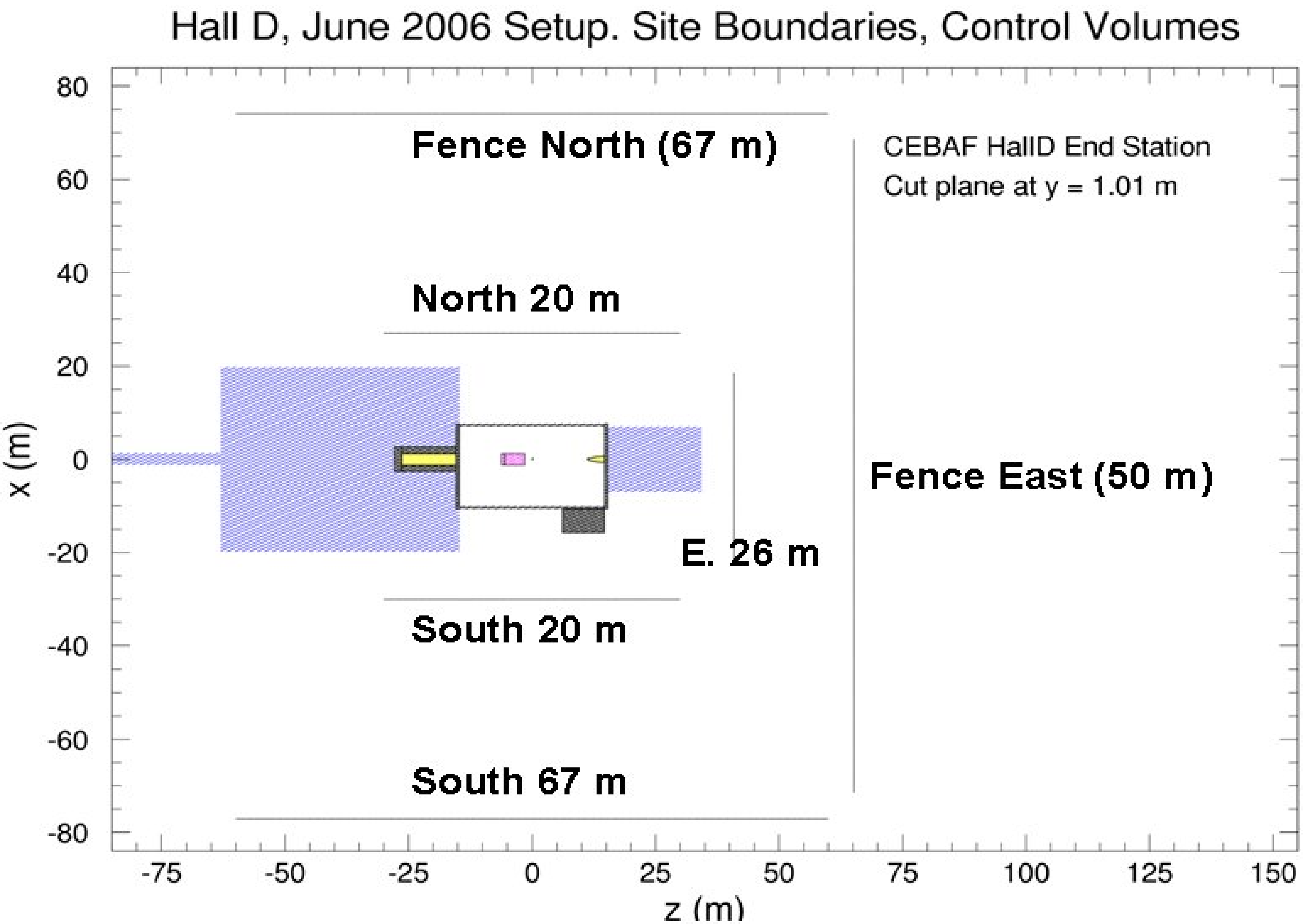

Fig. 17: GEANT Model of Site Boundaries with Control Volumes. Z and X are the coordinates in the horizontal plane, Z is along the beam

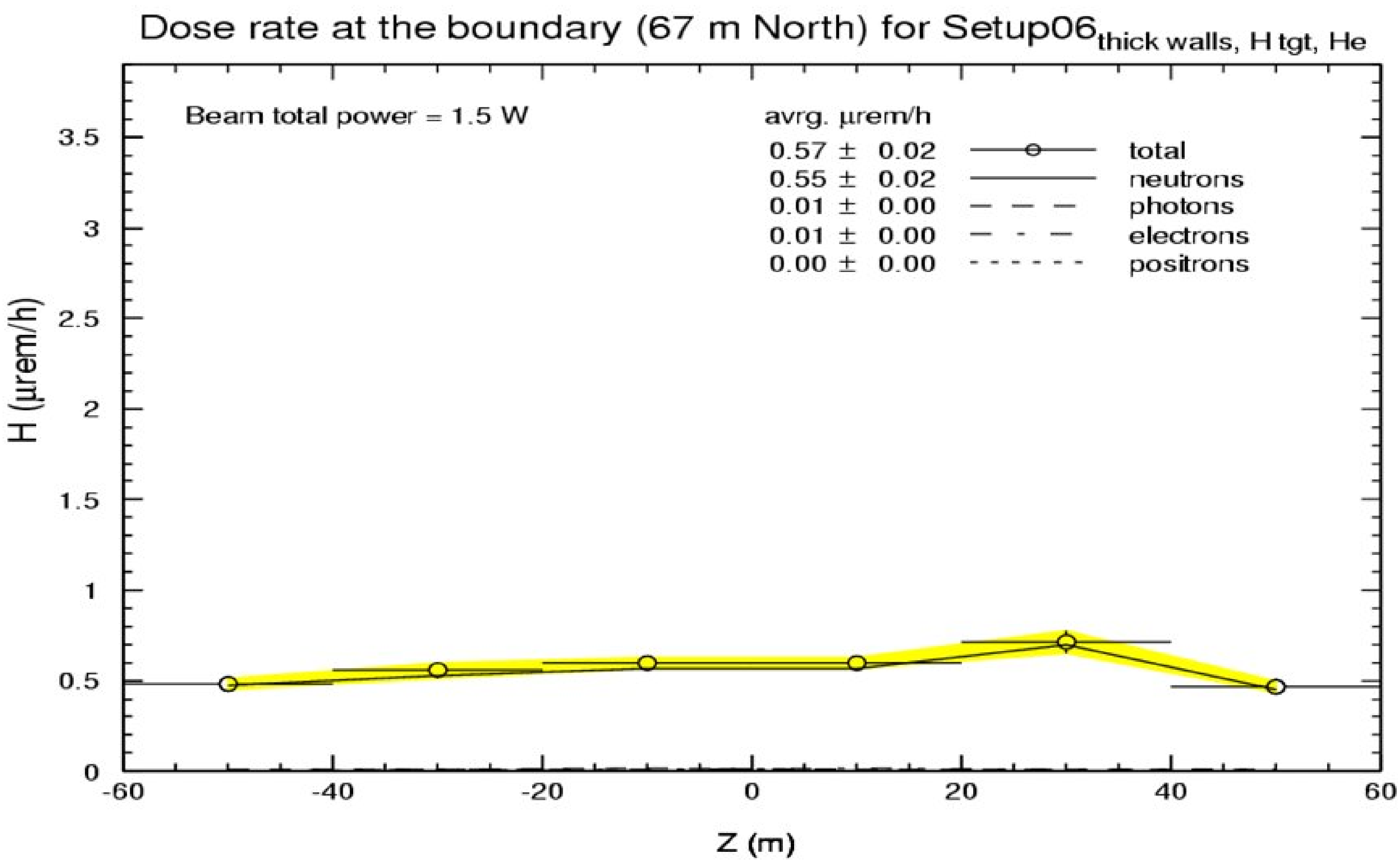

Fig. 18: Doses at North Boundary Fence. Abscissa is the coordinate along the beam

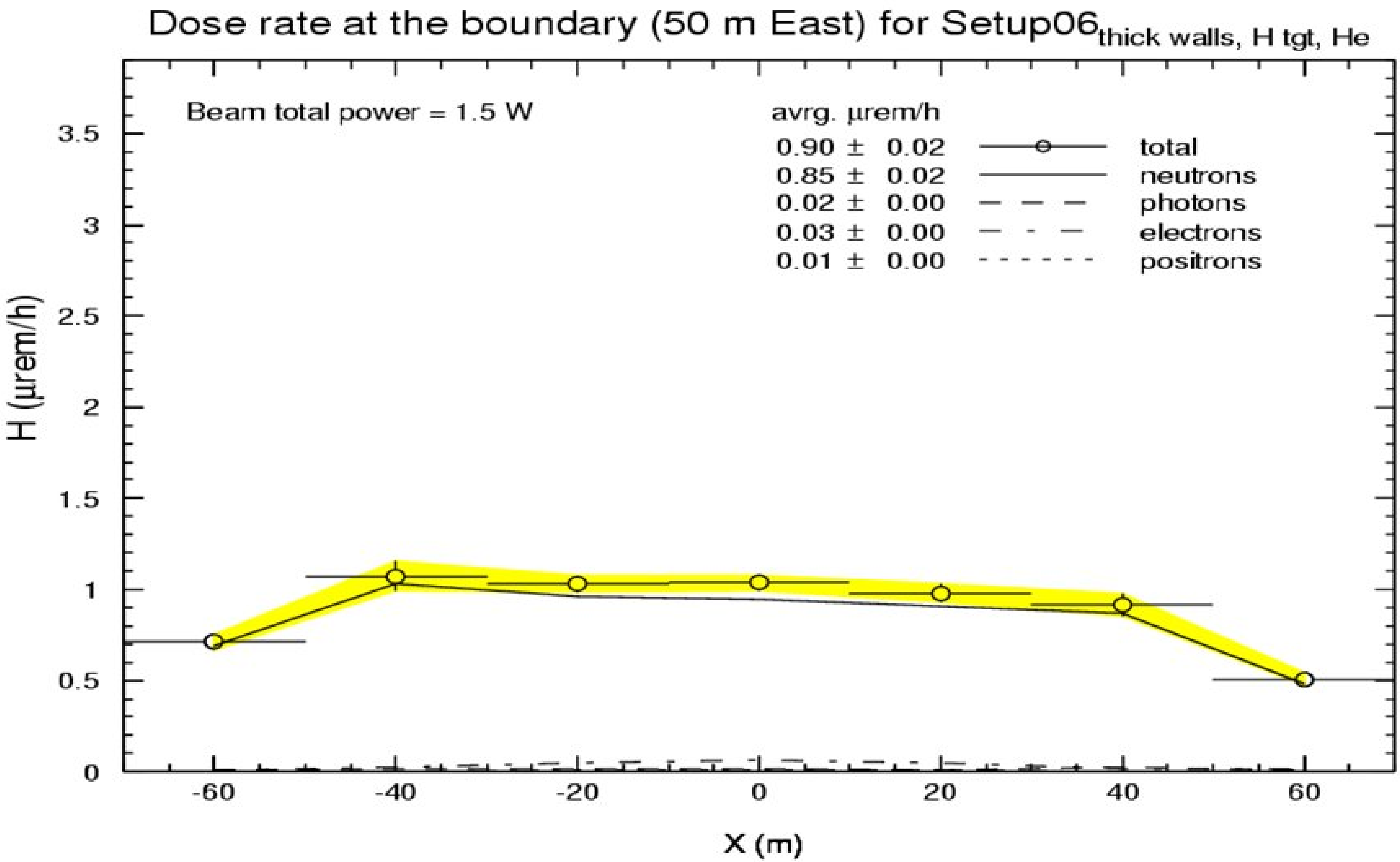

Fig. 19: Doses at East Boundary Fence. Abscissa is the coordinate in the horizontal plane perpendicular to the beam

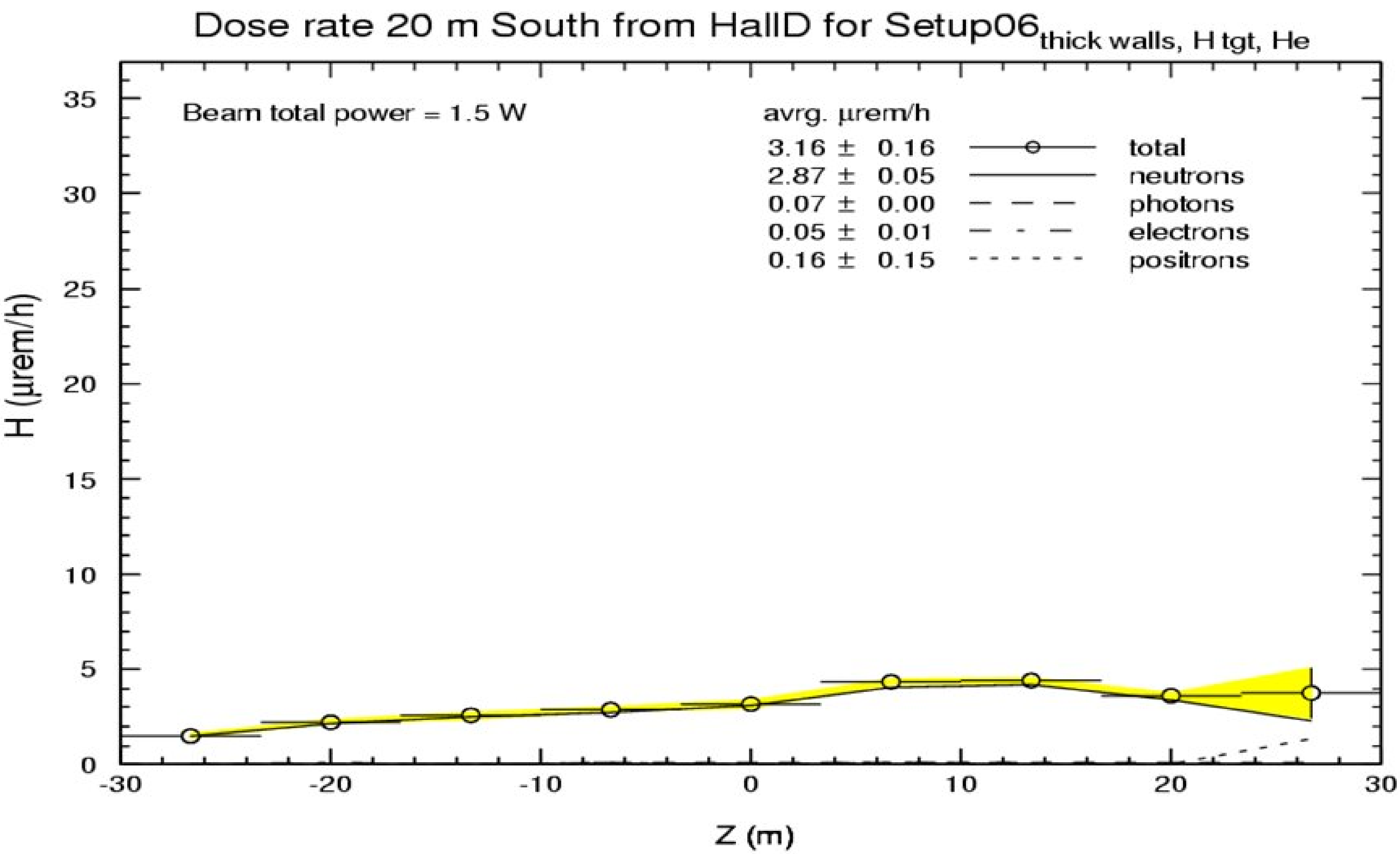

Fig. 20: Doses 20 meters South of Hall D. Abscissa is the coordinate along the beam

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Appendix 1

Simulation of Tagger Backgrounds Returning from the Electron Beam Dump

Richard Jones, University of Connecticut

May 9, 2006

Abstract

The civil engineering design team has proposed a layout of the tagger area for Hall D that has the electron beam dump located at the end of a corridor that is connected to the main tagger hall. A labyrinth composed of concrete shielding walls is proposed to shield the instrumentation in the tagger area from radiation back-streaming from the dump. The purpose of this note is to estimate residual backgrounds in the tagging counters under these conditions. Backgrounds originating within the main tagger hall, in the exit electron beam line, and in the dump itself have been investigated separately using a high-statistics Monte Carlo study. This study shows that the backgrounds coming from the electron beam downstream of the tagger vacuum chamber are negligible compared to sources located in the tagger area proper. At the level of sensitivity of this study, no backgrounds coming from the dump itself were detected in the tagging counters.

1 Simulations

A diagram of the proposed layout for the Hall D tagger area is shown in Fig. 1. The view shown is taken using a horizontal cut plane through the setup at the height of the beam. The track of a single beam electron is represented by the red trajectory superimposed on the figure. The square box at the far left is the vacuum housing containing the radiator crystal. Downstream of the radiator is a quadrupole magnet followed by the two dipoles of the tagging spectrometer. The long wedge-shaped volume surrounding the dipoles is the vacuum box of the spectrometer. The magnetic field bends electrons downward in the figure. At the lower edge of the vacuum box are located the tagging counters, the broad-band array shown in blue and the microscope shown in red. The unscattered electron beam exits the downstream end of the vacuum box and travels inside a vacuum pipe through three shielding walls down the beam dump corridor to the beam dump.

Gamma rays produced by the beam electron showering in the dump are represented by dotted blue lines. This is the dominant form of radiation that comes back from the beam dump from the showers of high energy electrons, but there are also significant numbers of neutrons, electrons and positrons. The aim of this study is to estimate the rate of this back-scattered radiation that is able to escape from the beam dump containment and generate background hits in the tagging counters.

At a nominal operating beam current of 3 μA, there are 1.9×10^{13} 12 GeV electrons per second entering the dump. Of these, only something of order 10^{10} electrons radiate a significant fraction of their energy in the radiator crystal and are detected in the tagging counters. All of them are capable, however, of producing background in the tagger area if their interactions in the electron beam line or dump produce backward-going secondaries. Fortunately most of this radiation is too low in energy to produce a hit in a scintillation detector, but it would only take a very small fraction of beam particles producing significant backward-going energy to create big problems for the tagger. For example, under nominal conditions at 3 μA the aggregate rate in the tagging microscope counters is 2.5×10^8 s^{-1}. If one out of 10^6 12 GeV electrons in the dump produced a background hit in the microscope it would degrade the signal/background ratio by 10%.

There are several sources of background in the tagging counters. A design goal for the Hall D tagger is to limit the background from any single source to less than 1%. Based on guidance from the several sources, the civil designers chose a layout that is expected to be at least this good or better. To show that this is the case using Monte Carlo simulation requires large event samples. For example, if the tagger microscope background rate from the dump is 1% of the signal rate then one would expect to have to generate 10^7 beam dump events before the first background hit would be registered in one of the microscope counters. A Monte Carlo measurement giving some information on the background spectrum requires 10^8 events at this upper bound on the background rates.

The sensitivity of the Monte Carlo to low background levels can be greatly enhanced using the so-called *cascading* simulation technique. A cascaded simulation takes advantage of the fact that the back-streaming radiation from the dump behaves like a diffuse source. Consider the green line in Fig. /ref-darea that divides the tagger area between the dump tunnel and the main hall. When cascading is enabled at that surface, any particle that crosses that boundary in the direction of entering the hall from the tunnel is amplified by a factor 1000. It is as if the particle died at the boundary and produced 1000 copies of itself, identical in energy and direction, which are all individually simulated before that event is complete. A single amplification event produces a very non-representative picture of the sources in the tunnel, but over a large number of events fluctuations smooth out and the background distribution settles approaches the true distribution, with 1000 times better statistics as regards what the effects of that radiation are in the hall.

A similar cascade can be performed at the surface represented by the green line in front of the dump in Fig. 1. Cascading from both surfaces yields a net amplification in the tagger hall of anything coming back into the hall from the dump. The goal of these cascaded simulations is to be able to measure a non-zero value for the dump backgrounds, even if they are very small.

2 Results

Three simulation runs were performed, each of 10^8 beam events. The beam particles were launched at the entrance to the radiator with an energy of exactly 12 GeV and a transverse profile consistent with the design of the GlueX photon beam line. In the place of a diamond crystal, a film of amorphous carbon was used because it was easier to set up and is equivalent for the purposes of a background simulation.

The first simulation run employed no cascading amplification. Each event released 12 GeV of energy and eventually dissipated that energy in the form of ionization. Electrons which radiated a photon of sufficient energy in the radiator were bent into the focal plane of the spectrometer and generally deposited energy in one or more of the tagging counters. Fig. 2 shows the spectrum of deposited energy in the tagger microscope (first panel) and broad-band detectors (second panel) for the complete simulation of 10^8 beam particles. The spectrum at energies below 500 keV is dominated by background coming from sources within the tagger hall, electron exit tunnel, and the dump. These sources are not differentiated in this simulation, but already it is clear that in both cases the background is less than 1% above a reasonable threshold choice for the signal amplitude.

The microscope spectrum shows a sharp minimum-ionizing peak at 4 MeV corresponding to the full 2 cm length of the individual scintillating fibers. The small peak at 8 MeV corresponds to primarily events where the electron interacted in the exit window of the vacuum box and produced a second electron or positron passing through the same counter. The broad hump under the peak in the spectrum for the broad-band array comes about because of the large variation in the effective path length inside the scintillator that takes place between the two ends of the array. These counters were modeled in the simulation as a long continuous piece of scintillator along the full length of the focal plane. A more detailed model with individual counters oriented perpendicular to the signal electron trajectories would not show this broad hump.

The second simulation was a repetition of the first, starting from a different Monte Carlo seed, with the cascade factor of 1000 set at the boundary going from the tunnel to the tagger hall. Any component of the shaded areas shown in Fig. 2 that are coming from the beam tunnel and dump should be amplified by a factor 1000 in the results from the second simulation. In the third simulation, the cascade at the tunnel-area boundary was left at a factor 1000 and a second factor 1000 cascade was turned on at the boundary going from the dump into the tunnel. In this simulation any component in the shaded areas shown in Fig. 2 coming from sources in the tunnel will be amplified by a factor 1000, and coming from the dump will be amplified by a factor 10^6. The results of both simulations two and three are shown in Fig. 3 for the tagger microscope and Fig. 4 for the broad-band array. The spectra shown in Fig. 2 have been subtracted to show only the excess coming from the tunnel and dump sources.

3 Conclusions

The simulations showed total backgrounds in the microscope tagging counters from all sources at a level of 1% of the signal rate. The corresponding level in the broad-band array counters was much higher at the 10% level, although this is not a realistic estimate for those counters because their shape and orientation in the simulation was not optimal. The point of the simulations was not to focus on background sources within the tagger hall, but those located in the electron beam exit tunnel and beam dump. The simulations produced statistically significant spectra for the background coming from the tunnel region. One likely origin for this radiation is interactions of slightly degraded electrons in the walls of the beam pipe. The energy deposition spectrum of the background from this source was very soft. For the microscope counters the count rate of these hits above a 2 MeV threshold for signal hits was statistically consistent with zero, leading to an upper bound of approximately 10^{-4} in background/signal at the 90% confidence level for background sources in the tunnel and dump. The corresponding level for background/signal in the broad-band array is $(3.0 \pm 1.3) \times 10^{-4}$.

Comparison between spectra with and without a cascade amplification factor of 1000 at the entrance to the beam dump shows that the two sets are consistent with no back-streaming from the dump. It follows that the tagger background rate coming from the dump is less than a factor 1000 smaller than those coming from sources within the exit tunnel. This leads to an upper limit of 10^-7 in the ratio background/signal in the microscope and 6×10^-7 in the broad-band counters for radiation coming from the dump.

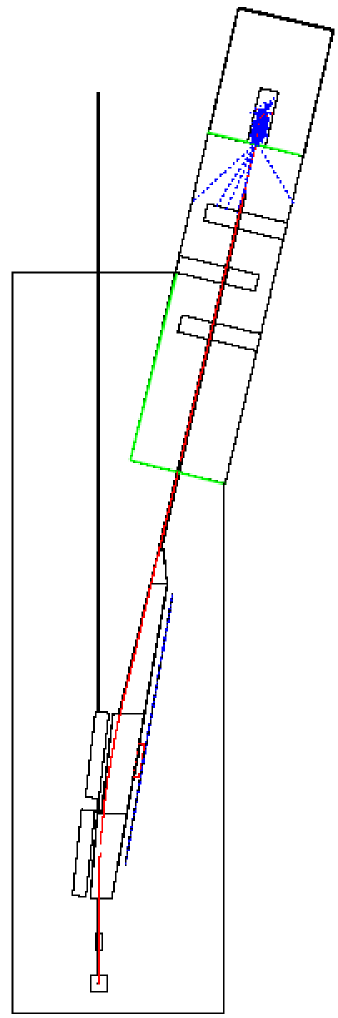

Figure 1: Cut view through the Hall D tagger area at the plane $y = 0$ in the simulation geometry. The electron beam enters the figure at the far left, passes through the radiator housing (square box), the quadrupole magnet and two dipoles of the tagging spectrometer, and continues on to the dump located in the lower right corner of the figure. The tagging counters are shown in red (microscope) and blue (broad-band array).

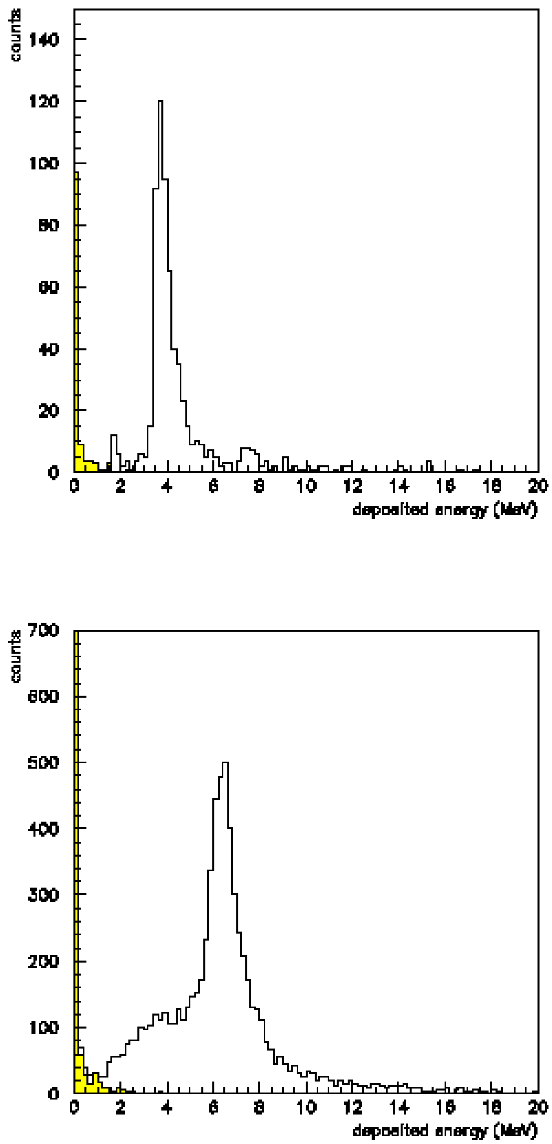

Figure 2: Spectrum of energy deposited in the microscope tagging counters (first panel) and broad-band array (second panel). The open histograms include all hits above 100 keV, both signal and background, while the shaded histograms exclude tracks that come from the direction of the radiator.

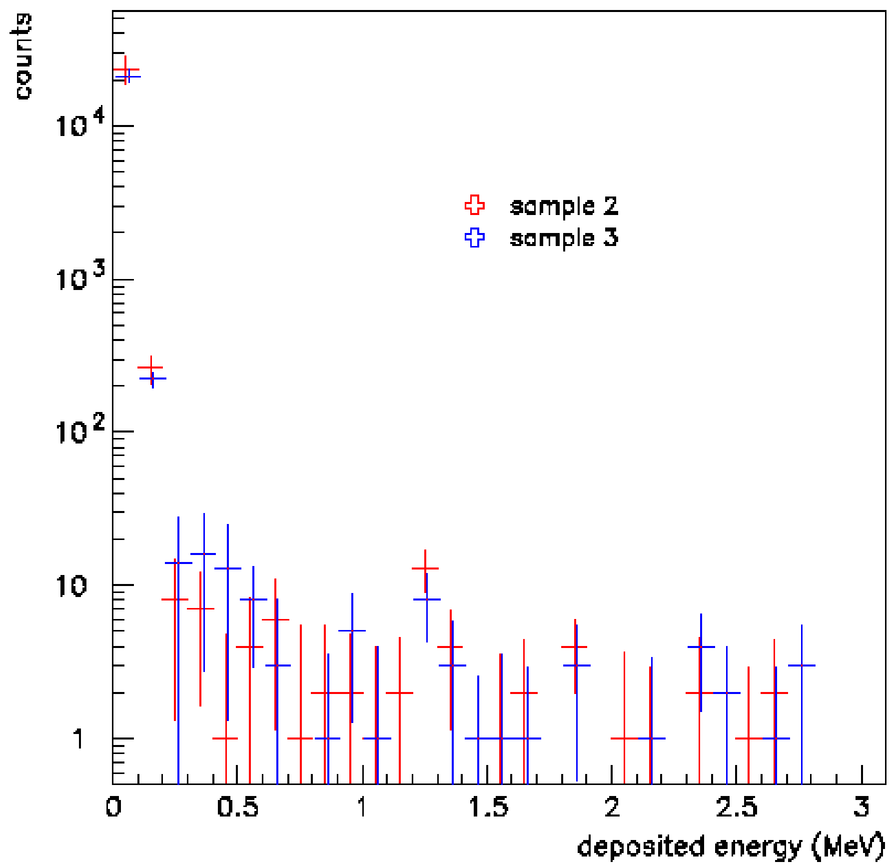

Figure 3: Spectrum of energy deposited in the microscope tagging counters after the contributions from all sources in the main tagger area have been subtracted. The red points reflect the background rates from all sources located in the electron beam dump tunnel area. The blue points are obtained under the same conditions, with any contributions coming from the dump itself amplified by a factor 1000.

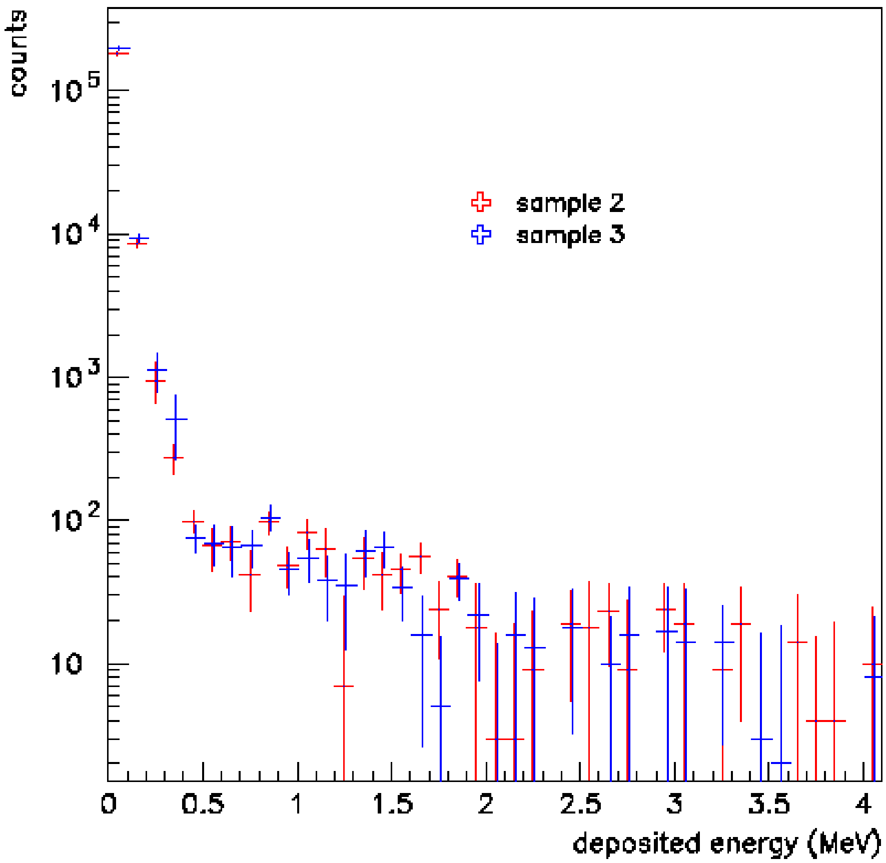

Figure 4: Spectrum of energy deposited in the broad-band tagging counters after the contributions from all sources in the main tagger area have been subtracted. The red points reflect the background rates from all sources located in the electron beam dump tunnel area. The blue points are obtained under the same conditions, with any contributions coming from the dump itself amplified by a factor 1000.