

BDX on-beam background assess and MC validation

M. Battaglieri, A. Celentano, R. De Vita, L. Marsicano
Istituto Nazionale di Fisica Nucleare, Sezione di Genova, 16146 Genova, Italy

M. Bondi, M. De Napoli, N. Randazzo
Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Catania, Italy

G. Kharashvili, E.S. Smith
Jefferson Lab, Newport News, VA 23606, USA

E. Izaguirre
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada, N2L 2Y5

G. Krnjaic
Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510

D. Snowden-Ifft
Occidental College, Los Angeles, California 90041, USA

M. Carpinelli, V. Sipala
Università di Sassari e Istituto Nazionale di Fisica Nucleare, 07100 Sassari, Italy

and The BDX Collaboration

Abstract

We address the issues raised by JLAB-PAC44 regarding the experiment proposal *PR-16-001 Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab* [1]. Significant work has been completed in the area of simulation and preparation for a background measurement behind Hall A. We have worked with the JLab Radiation Control group to develop the detailed geometry of the Hall A beam dump and incorporated it into a FLUKA simulation of backgrounds. Detailed comparisons of GEANT4 and FLUKA have been made and show very good agreement for muon fluxes under identical geometries, which are expected to be reliable in both simulations. We are now using FLUKA to simulate neutron backgrounds for the experiment using importance sampling to improve significance of small background signals at the sensitivity of the experiment. These simulations have also been used to estimate muon rates that can be measured in test pipes located behind Hall A at beam level. Measuring the muon rates at this location will provide an absolute normalization of our Monte Carlo simulations as well as confirm expected background rates for the present Hall A beam dump geometry. We provide a proposal and cost estimate for this measurement.

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1 Introduction

In response to the issue raised by JLAB-PAC44 about the experiment proposal *PR-16-001 Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab* [1] we propose to measure the muon flux and the prompt background produced by the interaction of the high intensity 11 GeV electron beam with the Hall-A beam-dump. The muon flux will be sampled at different height (with-respect-to the beam axes), positions and angles downstream of the beam-dump to map-out the radiation field in the location of the future BDX hall. In order to realistically assess the beam-on background experienced by the BDX detector, we will use a detector package (BDX-Hodo) containing a CsI(Tl) crystal from the BDX electromagnetic calorimeter surrounded by plastic scintillator paddles to trigger on horizontal muons and veto cosmic rays. The BDX-Hodo is specifically designed for this measurement and will use a loose trigger to provide further information on beam-related low energy background (dominated by neutrons). Although it will not be possible to directly compare results of this test with the experimental set-up proposed in PR-16-001, that will make use of a different and optimized shielding, the measurement will be extremely useful to validate the Monte Carlo simulation tools (GEANT4 and FLUKA) used to design the new underground facility and optimize the BDX detector.

This report is organized as follow: results of the simulation of the radiation field produced by the interaction of the beam with the dump are reported in Sec. 2; the experimental set-up and the detector is described in Sec.3; the expected results of the measurement are reported in Sec. 4. Details about cost estimate, work- and time-planes are reported in the Appendix.

2 MC simulations

2.1 The Hall-A high-power beam-dump

The Hall A and C use identical high-power absorbing (up to 1 MW) beam-dumps to stop the 11 GeV beam, remnant of beam/target interaction. The dump is composed of a set of about 80 aluminium disks, each approximately 40 cm in diameter of increasing thickness (from 1 to 2 cm), for a total length of approximately 200 cm, followed by a solid Al cylinder 50 cm in diameter and approximately 100 cm long. The dump is cooled by circulating water. The full drawing of the beam-dump is shown in Fig. 1. To increase the radiation shielding, the thickness of the concrete tunnel surrounding the Al dump is about 4-5 m thick.

2.2 The beam-dump model in FLUKA

The beam-dump geometry and materials have been implemented in FLUKA-2011.2c.5 by the Jefferson Lab Radiation Control Department. Details are reported in Ref. [2]. The input card used to run the program includes all physics processes and a tuned set of weight biasing to speed up the running time while preserving the results accuracy. The μ , n, and γ fluence (differential in angle and energy) per electrons-on-target (EOT) were calculated at 411.2 cm downstream of the beam window, through a circular area of 105 cm². Figure 2 shows the FLUKA graphic representation of the beam-dump and the location of the flux detector. In our model we extended the original beam-dump description, by including the proper geometry and material composition around and downstream of the beam-dump. Figure 3 shows the geometry of the concrete bunker surrounding the beam-dump and the downstream area filled by soil as implemented in our FLUKA model.

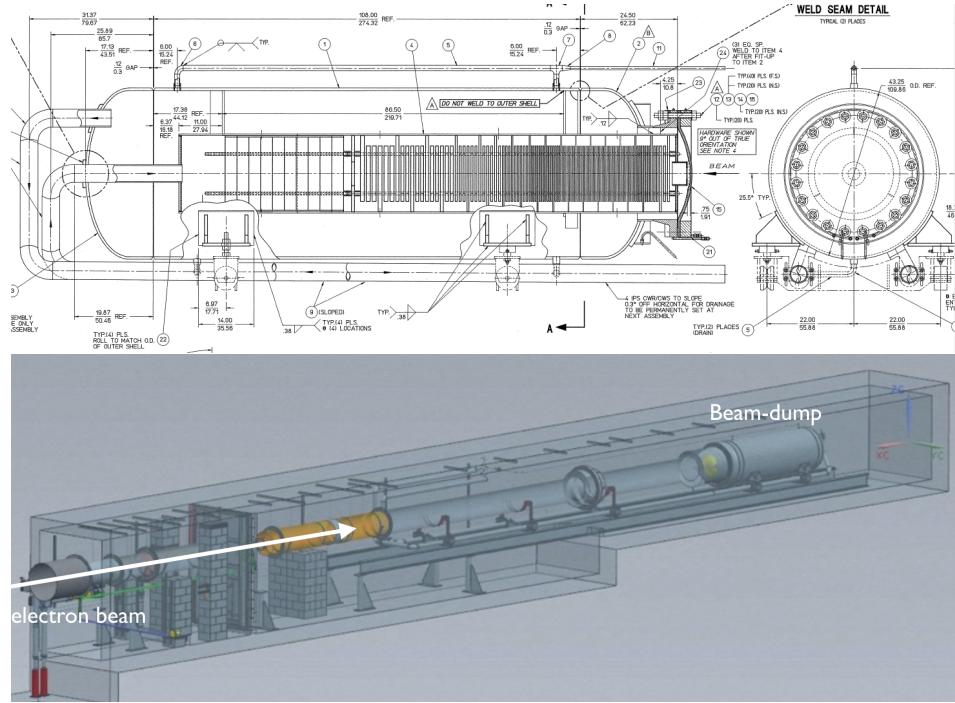


Figure 1: Hall-A beam dump and beam dump enclosure.

2.3 The beam-dump model in GEANT4 (GEMC)

The beam-dump, as well as the geometry and composition of surrounding environment, has been implemented in GEANT4 using the GEMC tool [3]. This model is a refined version with respect to the one used in PR-16-001 [1] that better describes the beam-dump geometry, matching the level of details implemented in the FLUKA model. For a better description of muon transportation, the `G4GammaConversionToMuons` has been added to the standard physics list used in simulations of PR-16-001(`FTFP_BERT_HP + STD + HP`). Particles fluence has been sampled by mean of a flux detector positioned in the same location as in the FLUKA model. Figure 4 shows the beam-dump and vicinity implemented in GEMC.

2.4 Muons from beam-dump interaction

A comparison of muon fluence downstream of the beam-dump (see above for details about the location) obtained by FLUKA and GEMC are reported in Fig. 5. Considering that low energy muons are absorbed by the bunker-head shielding, to keep the GEMC running time reasonable, only particles with energy greater than 100 MeV (`ENERGY_CUT=100*MeV`) have been tracked and sampled. A total of 4×10^9 (9×10^6) EOT have been simulated with GEMC (FLUKA). The comparison of the two simulations shows a perfect agreement in the full energy range where data were generated. In spite of a factor of $\times 100$ less statistics, FLUKA shows, as expected, smaller error bars. This reflects the optimised weight biasing used by the simulation to generate high statistics for the low probability processes keeping the total number of events limited. To penetrate the concrete shielding and the soil, a minimum energy of $E_\mu > 4$ GeV is required. With this energy cut, the integrated number of

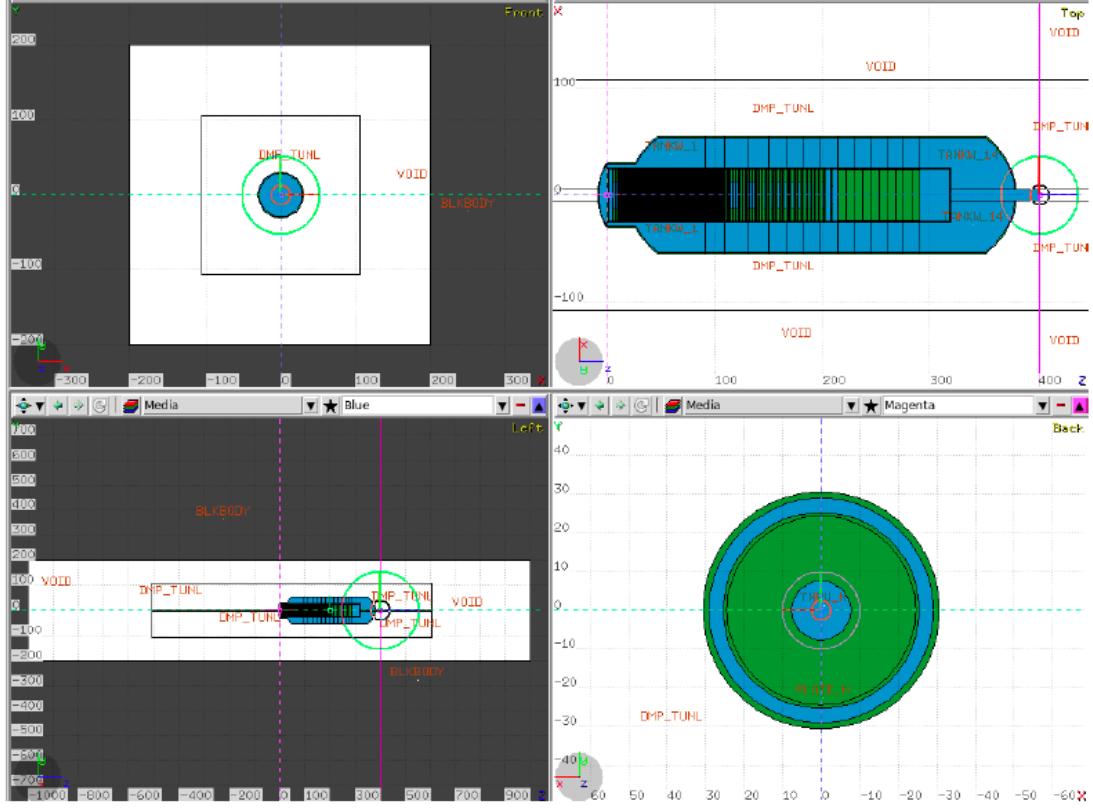


Figure 2: Hall-A beam-dump implementation in FLUKA.

muon per EOT results in $4.8 \pm 0.1 \times 10^{-7}$ ($5.5 \pm 0.2 \times 10^{-7}$) for GEMC and FLUKA respectively. Figure 6 shows the correlation between the muon energy and the azimuthal angle (with-respect-to the beam axes): the regions populated in both simulations show a similar shape.

2.5 Sampling and particle transport

The good agreement between two independent simulation tools (FLUKA and GEMC) gives us confidence about reliability of the obtained results. Both methods have pros and cons. FLUKA shows a superior speed in running but a complicated implementation of variables of interest (e.g. the final output is given via *scores* such as fluence or distribution in specific locations need to be pre-defined). GEMC (GEANT4) tracks particles in all volumes providing a straightforward output (particle four-momenta) in the desired flux detector but requires unrealistic running times to collect a reasonable statistics (in particular when an em shower is involved). In the following we describe how we overtook these difficulties.

2.5.1 Muons - GEMC

We used GEMC to simulate muons. To make the process more efficient, we followed the procedure described below:

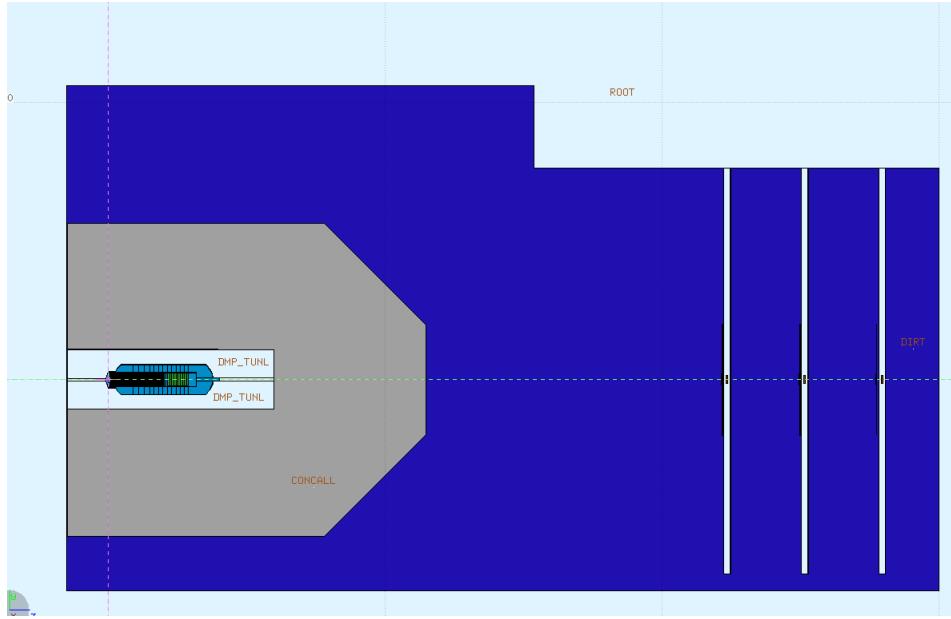


Figure 3: The geometry/composition of the concrete bunker surrounding the beam-dump and the downstream soil as implemented in FLUKA.

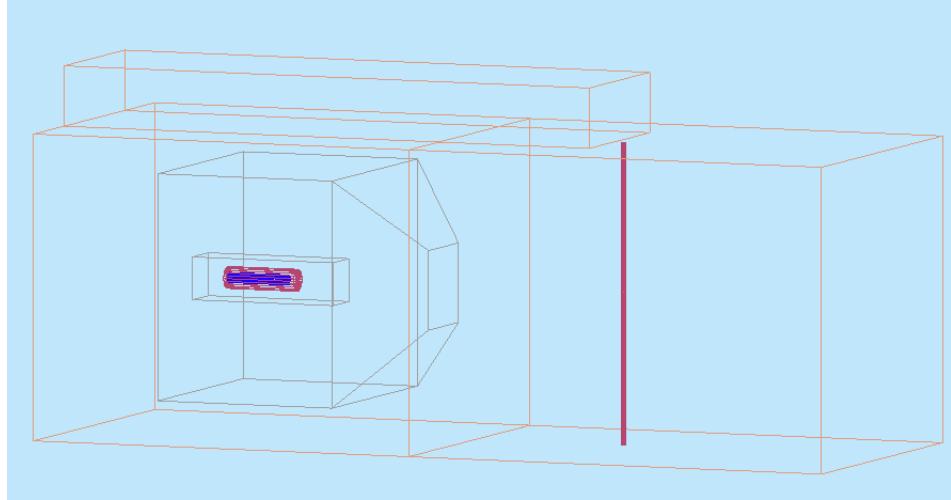


Figure 4: The geometry/composition of the beam-dump, the sourraunding concrete bunker and the soil as implemented in GEMC. The drawings also shows the pipe used to lower the BDX-Hodo detector at the beam-line depth.

- we used a low statistic sample of EOT to simulate the interaction of the 11 GeV electrons with the beam-dump;
- we sampled the muon flux distribution in momentum, azimuthal angle and transverse position

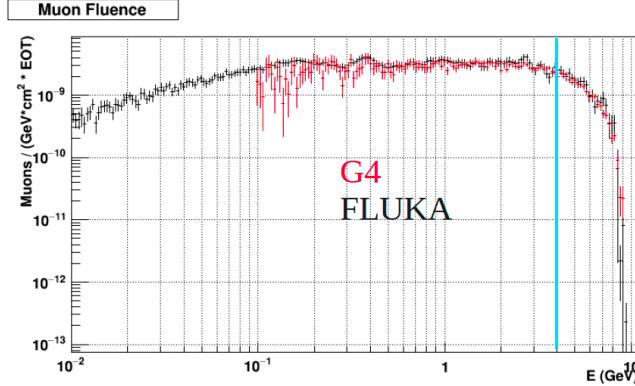


Figure 5: Muon fluence downstream of the beam-dump obtained by FLUKA (black) and GEMC (red). The GEMC simulations started at $E_\mu = 100$ MeV.

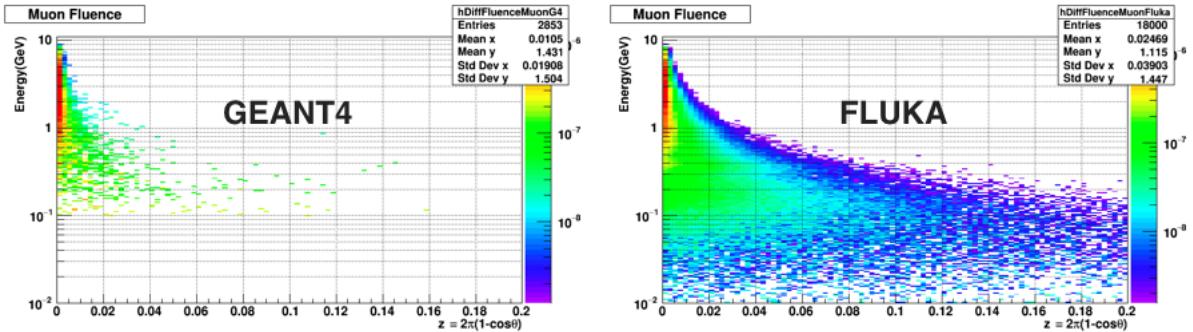


Figure 6: Energy vs. azimuthal angle of muons crossing the flux detector located downstream of the beam-dump obtained by FLUKA and GEMC.

on a flux detector located downstream of the beam-dump;

- we used distributions obtained in the previous step as input of a custom event-generator to produce a high statistic muon sample;
- we used GEMC to transport muons downstream of the beam-dump all the way down to the desired location(s) of BDX-Hodo (see Section 3.2 for details);
- we implemented the BDX-Hodo response in GEMC to realistically describe the muon detection.

The area where muons are sampled from the primary beam/dump interaction and used as source in the custom-made event generator is shown in Fig. 7.

Figure 8 shows the muon distributions (energy vs azimuthal angle and radial distance from the beam line) downstream of the beam-dump, as obtained by the full GEMC simulation of 11 GeV electrons hitting the beam-dump. The left panel of Fig. 9 shows the distributions obtained by running the full simulation with GEMC compared to the custom event generator results. As a check, the right panel of the same figure shows the comparison in the location of interest (~ 20

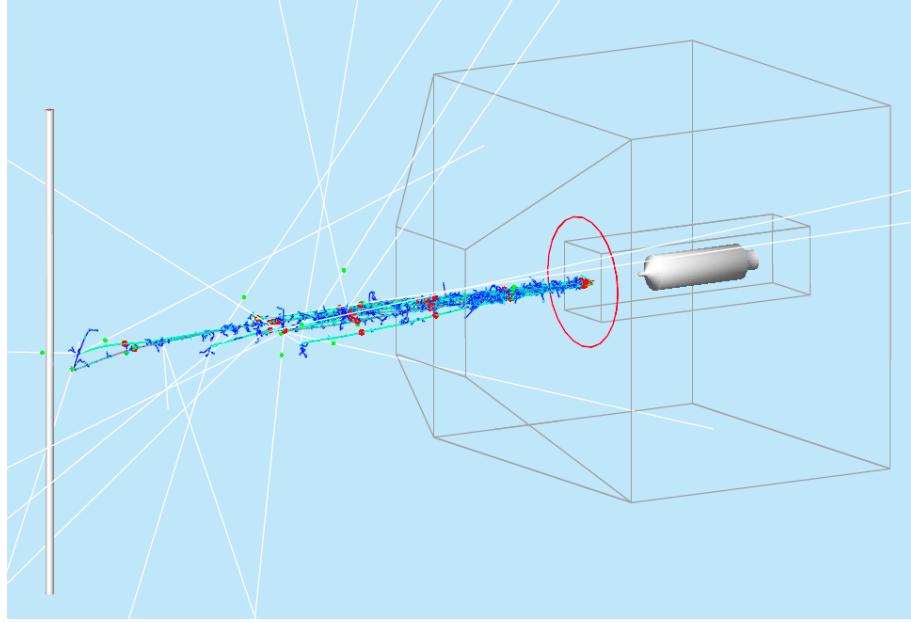


Figure 7: The μ sampling/generation area is the surface enclosed by the magenta circle.

m downstream of the beam-dump). The difference in the error bar size indicates the improvement obtained by adopting this procedure.

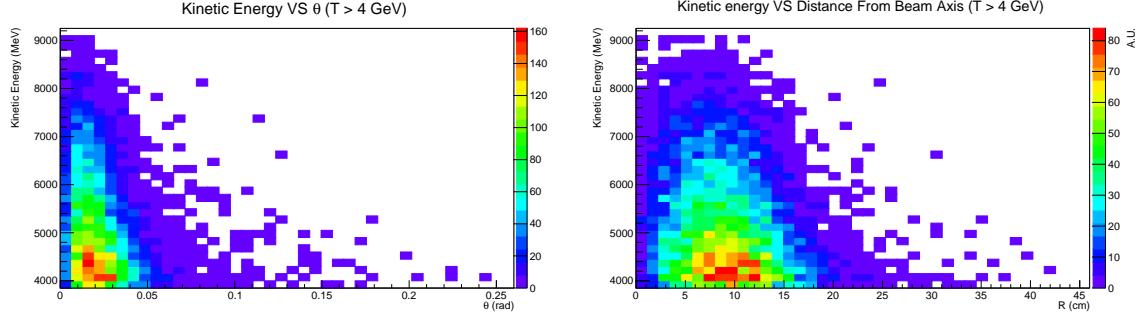


Figure 8: Muon kinetic energy vs. azimuthal angle (left) and distance (right) from the beam-line axes as obtained by the full GEMC simulation.

2.5.2 Background - FLUKA

We used FLUKA to estimate the background expected in the BDX-Hodo detector. We simulated an 11 GeV electron-beam interacting with the beam-dump, propagate all particles to the location of interest obtaining the fluence on the CsI(Tl) surface. Figure 10 shows the resulting fluence per EOT as a function of energy for all particles (black) and muons only (red). As expected, muons are the only high energetic particles reaching the crystal while other species (neutrons mainly) account

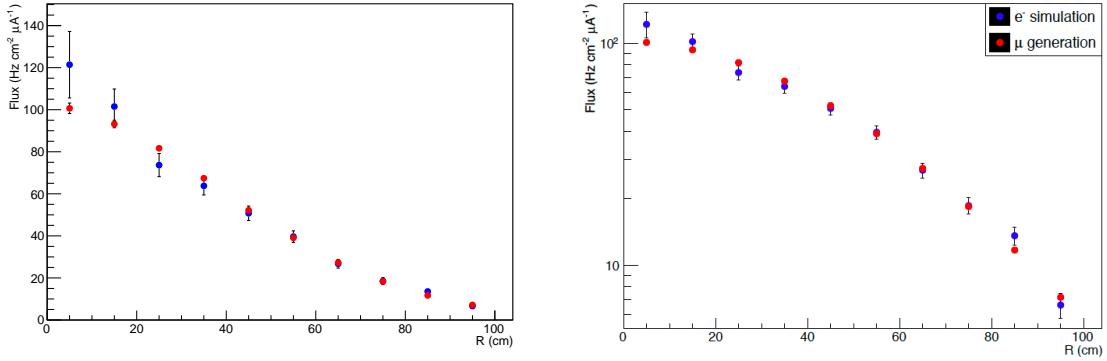


Figure 9: Muon flux as a function of the radial distance from the beam axes obtained by GEMC (blue) and by the custom event-generator (red) at the sampling/generation location (left) and in the region of interest (right), ~ 20 m downstream of the beam-dump.

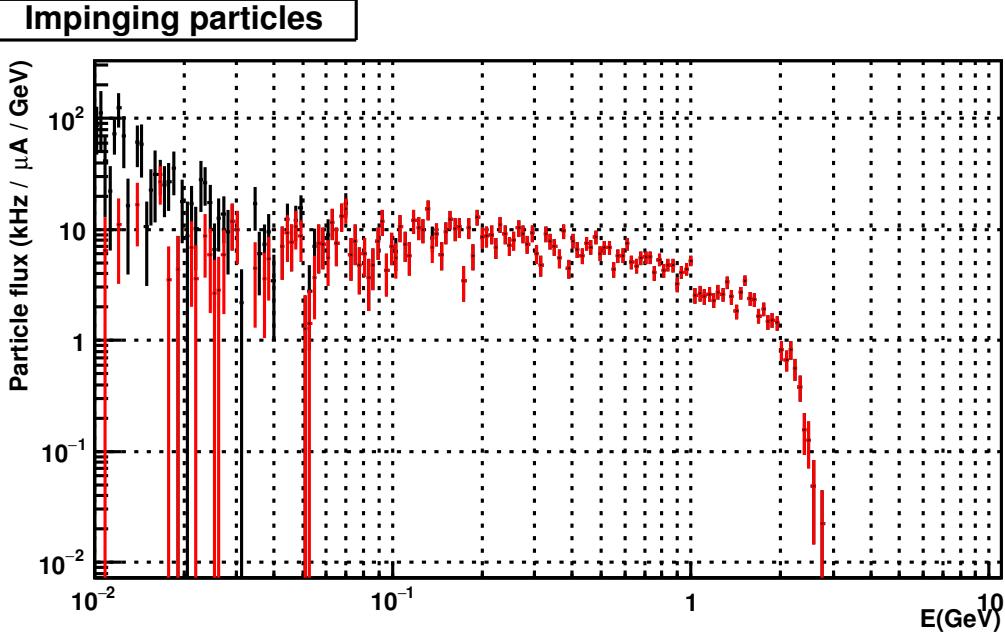


Figure 10: Fluence on CsI(Tl) crystal of all crossing particles (black) and muons only (red). The crystal is located in the region of interest ~ 20 m downstream of the beam-dump.

for the low energy of the spectrum. More details are reported in Sec. 4.

It's interesting to note that the spectrum of high energy neutrons, $T_n > 100$ MeV, (sampled downstream of the dump) obtained by GEMC is in good agreement with FLUKA (see Fig. 11). The agreement indicates that, in this energy range, both simulation tools are reliable.

Another interesting aspect of the neutron spectrum is shown in Fig. 12. The energy spectrum

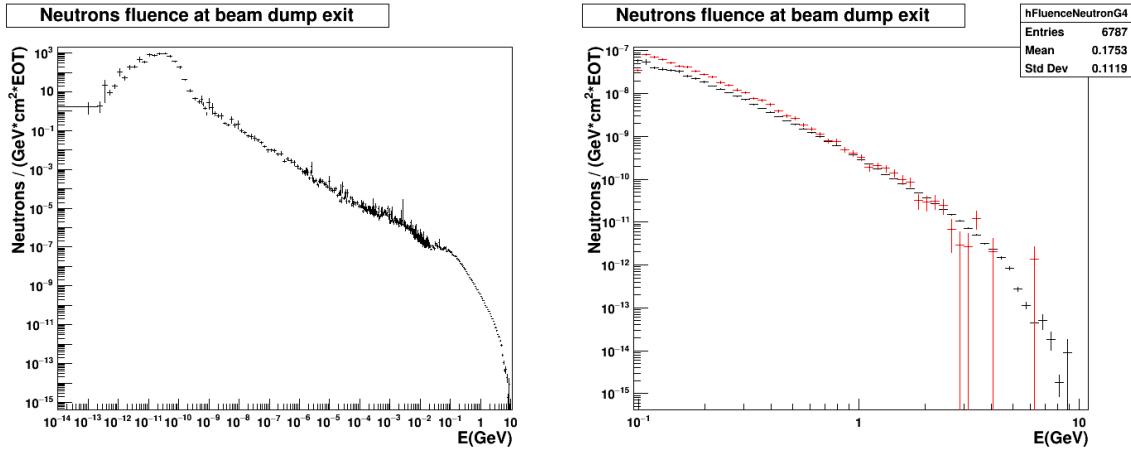


Figure 11: Neutron spectrum downstream of the the dump obtained by full FLUKA simulation (left). The right panel shows the comparison between FLUKA (black) and GEMC (red) for the high energy part pf the spectrum.

(sampled downstream of the dump) obtained by FLUKA by RadCon (Ref. [2]) is compared to the same plot obtained by our FLUKA simulations. The two models differ in the implementation of the beam-dump vault: a detailed description of the material surrounding the dump, that includes air and concrete, versus a simplified geometry/material description. The effect is clearly visible in the low energy part of the spectrum (while the high energy part is almost identical) proving that a detailed description of the dump enclosure is necessary to correctly describe the low energy backgrounds.

Figure 12: Neutron differential fluence downstream of HPBD

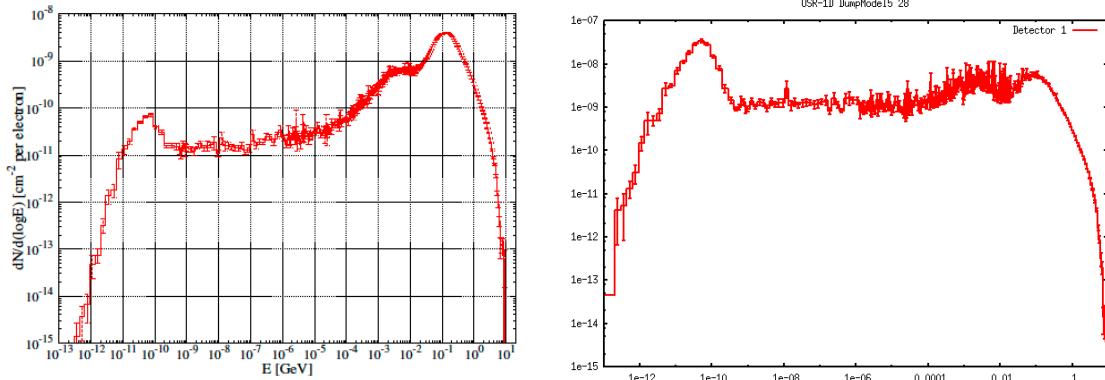


Figure 12: Comparison of neutron energy spectrum obtained by FLUKA, sampled downstream of the beam-dump with a simplified geometry (left) and including vault sourounding materials (right). The number of low energy neutrons significantly increases when the reflections on the wall are taken into account.

Muon and background flux at the location of interest will be discussed in details in the Sec. 4 after presenting the BDX-Hodo detector in the next Section.

3 Test set-up



Hall A Beam Dump / C1

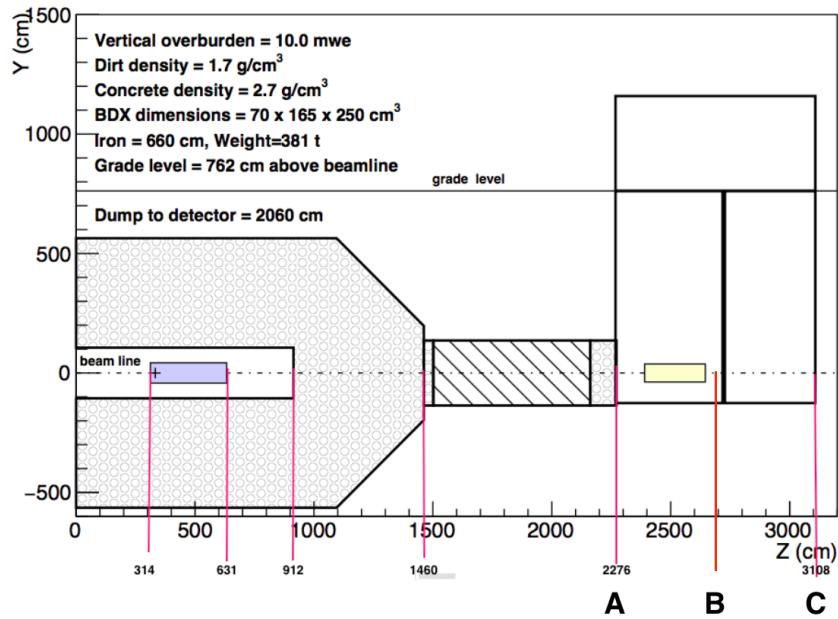


Figure 13: The area downstream of the Hall-A beam-dump and the studied test locations.

3.1 Detector location

The area downstream of Hall-A beam-dump is shown in Fig. 13 indicating test measurement locations relative to the new underground facility proposed in PR-16-001 [1]. The three positions, indicated

with markers **A**, **B** and **C**, correspond to the hall entrance (22.4 m downstream of the beam-dump entrance), a point in the middle (25.2 m) and the exit (28 m), respectively. The experimental set-up we are proposing requires digging a well and inserting a pipe in one (or more) of these locations. The BDX-Hodo detector will be lowered in the pipe and the muon flux sampled at different heights wrt. nominal beam height. The muon flux profiles in Y (vertical direction), measured in different locations in Z (distance from the dump), will allow us to compare the absolute and relative MC predictions.

3.2 The BDX-Hodo detector

The detector used to measure the beam-on-related muon radiation and the background in the proximity of the new BDX underground facility will make use of a BDX ECal CsI(Tl) crystal sandwiched between a set of segmented plastic scintillators. A CAD representation as well as a vertical and horizontal cut with dimensions are shown in Fig. 14. The front of the crystal will be equipped with two

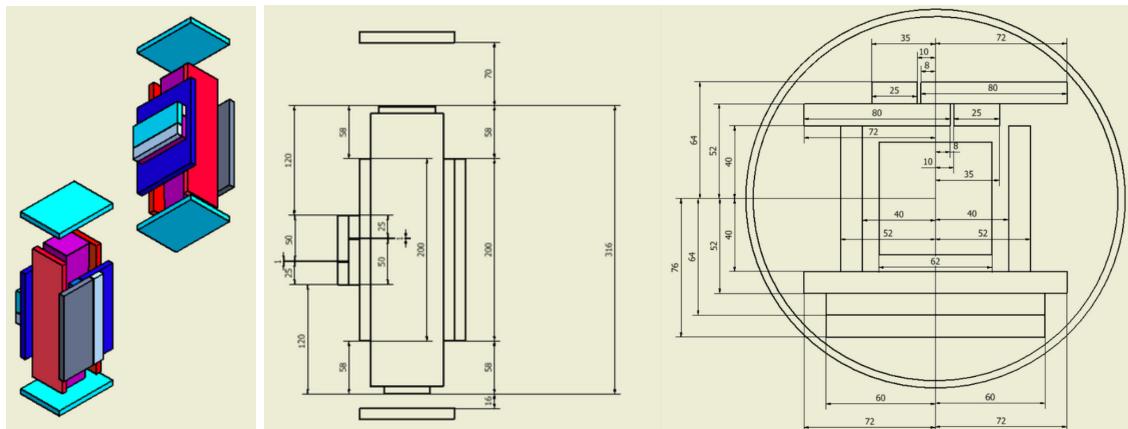


Figure 14: The CAD representation of the BDX-Hodo detector and some drawings with geometry and sizes.

layers of plastic scintillators, each composed by a large and a small 1 cm-thick scintillators strips. The overlap of the four paddles (each 20 cm long in Y) results in three independent 2.5 cm channels along the X (horizontal) direction. The same concept was applied to the back side of the crystal but with paddles tilted by 90 degrees to define three 2.5 cm independent channels along the Y (vertical) direction. The requirement of a hit in both front and back paddles defines a 3x3 matrix of $2.5 \times 2.5 \text{ cm}^2$ pixels providing a cm-like muon XY position resolution. The addition of a larger paddle ($20 \times 14.4 \text{ cm}^2$) on the back provides an enhanced sensitivity in the unlikely case rates will be much lower than what estimated by MC simulations. Four more paddles covering the left/right sides and the top/bottom of the crystal will be used to veto cosmic rays and other radiation not associated to the beam direction. The crystals will be coupled, on the large side, to a $6 \times 6 \text{ mm}^2$ Hamamatsu S13360-6025 SiPM as described in Sec. 3.2.1 of PR-16-001 [1]. The scintillator paddles will be made with extruded plastic, each read out via a WLS fiber coupled to a $3 \times 3 \text{ mm}^2$ Hamamatsu S12572-100 SiPM sharing the same technology used in the BDX Inner Veto detector (described in details in Sec. 3.2.2 of PR-16-001). The detector will be contained in a 20-cm diameter stainless-steel cylindrical vessel, covered on top and on the bottom by steel lids. The whole assembly will be water-tight to prevent any water from leaking inside the vessel. A stainless-steel extension on the top cover will be

used to run cables (signal and power) from the detector to the ground-level. The extension, made by a 1-inch stainless steel pipe, rigidly attached to the whole assembly, will be also used to remotely control the cylinder orientation providing correct the alignment of the BDX-Hodo wrt. the beam axes.

To record the 13 (scintillators) + 1 (crystal) channels a single 16ch fADC board and a VME crate will suffice. A loose condition on the CsI(Tl) crystal will trigger the DAQ to record signals from all SiPMs. Off-line, muons produced by the electron beam will be identified by requiring a 5-fold coincidence (two front paddles + CsI(Tl) crystal + two back paddles). The full DAQ system (crate + pc) will be shielded in a van parked close to the well entrance. The power will be provided by a diesel power generator to minimize the requirements of long extension cords.

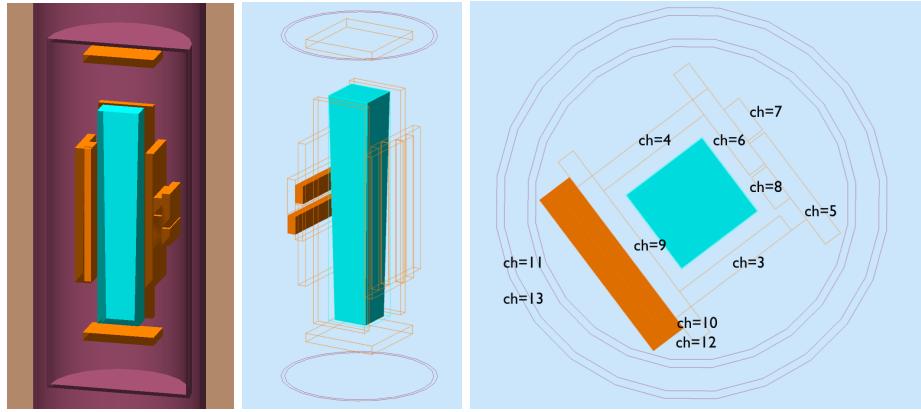


Figure 15: The GEMC implementation of the BDX-Hodo detector.

The detector geometry as well as the realistic response of the CsI(Tl) crystal and plastic scintillators have been implemented in GEMC (see Appendix B.2 of PR-16-001 [1] for details about the detectors response parametrisation). Figure 15 shows the BDX-Hodo implementation in GEMC. To estimate rates, we assumed a detection threshold of 10 phe in scintillators and 100 phe in the crystal corresponding to 400 keV and 2 MeV of deposited energy respectively*.

*MIPs release ~ 50 phe (~ 2 MeV) and 1670 phe (~ 32 MeV) respectively.

4 Results

Muons and beam-related background were generated by the 11 GeV electron beam interaction with the beam-dump and propagated in the region of interest as described in Sec. 2.5.

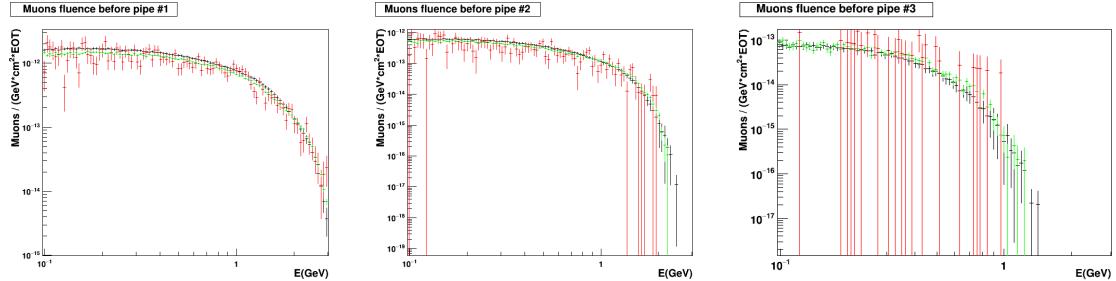


Figure 16: Differential fluence of muons at the three locations of interest (A, B and C). Beam dump interactions using FLUKA (black), GEMC (red) and the high statistic custom μ event generator with GEMC propagation (green). The agreement between FLUKA and the high statistics GEMC calculations is very good.

4.1 Muon detection

Fig. 16 shows the muon flux crossing the BDX-Hodo as obtained by GEMC and FLUKA in the three locations of interest (**A**, **B** and **C**). The flux has been sampled assuming the BDX-Hodo is centered on the beamline. Results are reported for muons generated at high statistic by the custom μ event generator and propagated using GEMC (green points in the figure). The number of event generated at the dump correspond to $(1.2 \pm 0.1) 10^{12}$ EOT or one second of $0.2 \mu\text{A}$ current. Rates in crystal, scintillators and requiring a 5-fold coincidence of the two front/back layers of plastic with the crystal are reported in Tab. 1 for a beam current of $10 \mu\text{A}$ and detection thresholds as listed in the previous Section. Results show a drop in rate by about one order of magnitude when moving from one location to the next. Table 2 shows the expected rate measured in position **C** when the BDX-Hodo detector is off-axes by $40/80$ cm. The measurement of muon rate at different heights (angles) wrt to the beam-line (beam-dump) will provide further information to validate simulations. Fluxes in position **C** (or/and **B**) are large enough to be detectable (significantly higher than cosmic muons and beam-dump neutron background) and manageable by crystal, SiPms and front-end electronics (no pile-up effects expected). These two locations are close to the paved road and easily accessible by the drilling machine and related equipment. Similar conclusions (scaling rates by 10) hold if the beam current drops/increases by one order of magnitude (between 1 and $100 \mu\text{A}$) making the test feasible in parallel to any 11 GeV operation of Hall-A.

4.2 Muon flux above-the-ground

For the sake of completeness, the muon flux has also been evaluated using FLUKA in the closest locations above ground illuminated by the beam-dump vault. This set-up located the detector above ground with no drilling required, largely simplifying the test. Due to the CPU-time necessary to track muons at such large angle (with respect to the beam axis) we used a two-step procedure. Firstly, the 11 GeV electron beam interacting in the beam-dump produced muons, which were sampled on the roof of the vault at four different locations (shown in Fig. 17-left). A high statistic

Table 1: Beam-on muon rates expected in BDX-Hodo for $I_{beam}=10\mu A$ in locations **A**, **B**, and **C**.

| Location | Rate _{Crystal} (kHz) | Rate _{Front-Back Scint} (kHz) | Rate _{Coin} (kHz) | Rate _{XY ch} (kHz) |
|----------|-------------------------------|--|----------------------------|-----------------------------|
| A | 120 | 120/40 | 24 | 4.5 |
| B | 20 | 22/8 | 3.7 | 0.7 |
| C | 2.8 | 2.5/1 | 0.5 | 0.1 |

Table 2: Beam-on muon rates expected in BDX-Hodo for $I_{beam}=10\mu A$ in position **C** sampled at different vertical distance from the beam-line.

| Vertical distance | Rate _{Crystal} (kHz) | Rate _{Front-Back Scint} (kHz) | Rate _{Coin} (kHz) | Rate _{XY ch} (kHz) |
|-------------------|-------------------------------|--|----------------------------|-----------------------------|
| 0 (nominal) | 2.8 | 2.5/1 | 0.5 | 0.1 |
| 40 cm | 1.4 | 2.5/1.5 | 0.17 | 0.04 |
| 80 cm | 0.6 | 0.6/0.3 | 0.08 | 0.02 |

sample of muons were then generated according to the sampled distributions and propagated to the outside. Applying a conservative hypothesis (the muons are propagated perpendicular to the beam axis crossing the minimal amount of concrete and dirt) muons with energy higher than 4.5 GeV (the minimum to penetrate earth and concrete around beam dump) were propagated and sampled in the four perpendicular outdoor positions. Figure 17-right shows the four locations (A_{Ext} , B_{Ext} , C_{Ext} , and D_{Ext}) on top of the hill. Integrating over the surface of the BDX-Hodo detector ($\sim 100 \text{ cm}^2$) and considering as a reference a beam current of $10 \mu A$, no sizeable muon flux would be detected (Rate_{Max} < 3 Hz). Rates in the different outdoor locations are listed in Tab. 3.

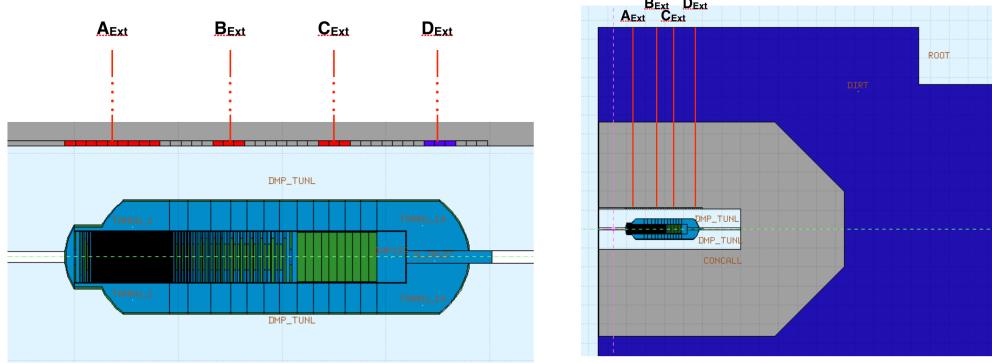


Figure 17: Left: In red are shown the points on the roof where muon flux has been sampled. Right: A_{Ext} , B_{Ext} , C_{Ext} , and D_{Ext} are the four location outdoor where the muon flux has been evaluated.

Table 3: Beam-on muon rate expected outdoor, on top of the beam-dump hill.

| Location | Rate _{Crystal} (Hz / (cm ² μA)) |
|------------------|---|
| A _{Ext} | 2.2 10 ⁻³ |
| B _{Ext} | 4.7 10 ⁻⁴ |
| C _{Ext} | 1.9 10 ⁻³ |
| D _{Ext} | negligible |

4.2.1 Beam-related background

Beside muons, other particles are produced in the 11 GeV electron beam interaction with the dump. The majority (electrons, gamma, nuclei and fragments) are ranged-out well before to reach the region of interest but some (low energy neutrons, mainly) may propagate through concrete and dirt reaching the BDX-Hodo detector. Fig. 18 shows the neutron flux in the three locations of interest as obtained by FLUKA simulations.

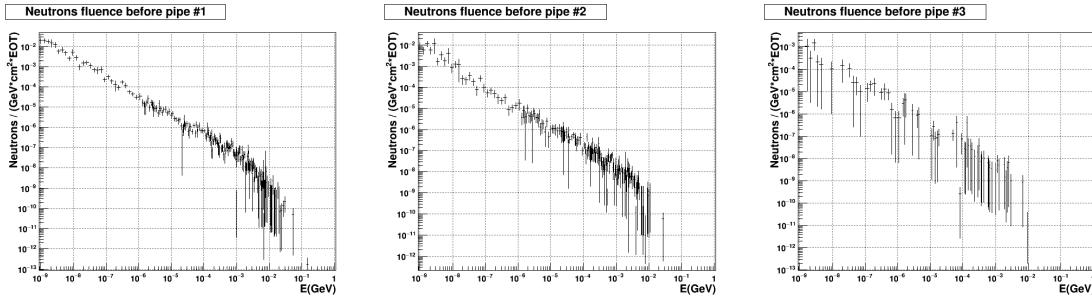


Figure 18: Neutron differential fluence at the three locations of interest. Spectra are obtained from electron beam interaction with the beam-dump using FLUKA.

For a complete understanding of the low energy (< MeV) background in the BDX-Hodo crystal, particles produced in the dump can not be tracked separately since some of them are produced along the way (e.g. by energetic muons or neutrons in the proximity of the detector). On top of that, neutral particles (in particular low energy/thermal neutron) do not directly interact with the crystal but deposit a visible energy via secondary interactions (e.g. gamma from nuclear capture in the surrounding material) making hard, if not impossible, to track back the background source. For all the above mentioned reasons we evaluated the background by running the full FLUKA simulation of 11 GeV electrons interaction with the beam-dump recording the deposited energy in BDX-Hodo crystal. Figure 19 shows the fluence of all particles (black) and muons only (red) on the CsI(Tl) surface. As already noticed, the high energy range of the spectrum is saturated by muons. Figure 20 shows the deposited energy in the CsI(Tl) crystal (located in the three position of interest). Muons (shown in red) almost saturate the highest energies (the MIP peak is clearly visible around $E_{Dep} = 32$ MeV) while the contribution from other particles (neutrons) accumulates at low energies.

The crystal integrated rate is reported in Fig. 21 as a function of the deposited energy (and detected photoelectrons). Considering that the experiment only records events with a deposited

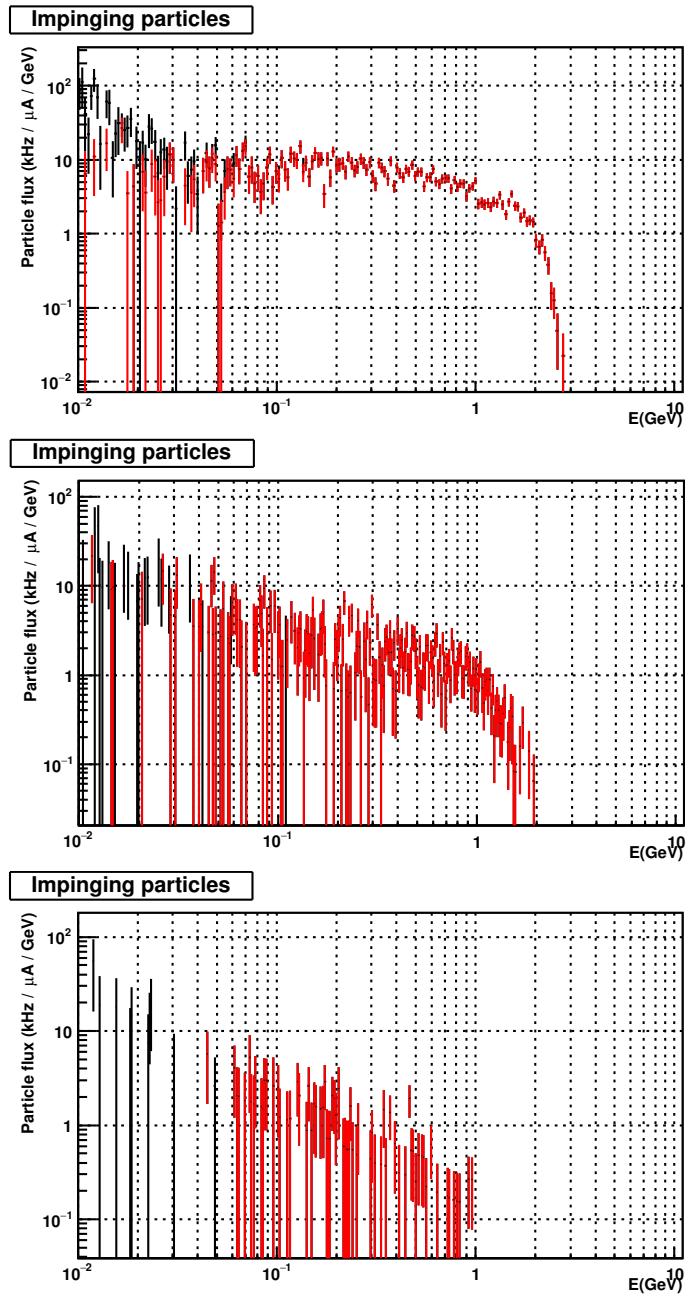


Figure 19: Fluence of all particles (black) and muons only (red) hitting the CsI(Tl) crystal. Plots refer to the crystal located in **A** (top), **B** (middle), and **C** (bottom).

energy in the crystal larger than 1 MeV (25 pe), the expected rate is in the range of 10 kHz.

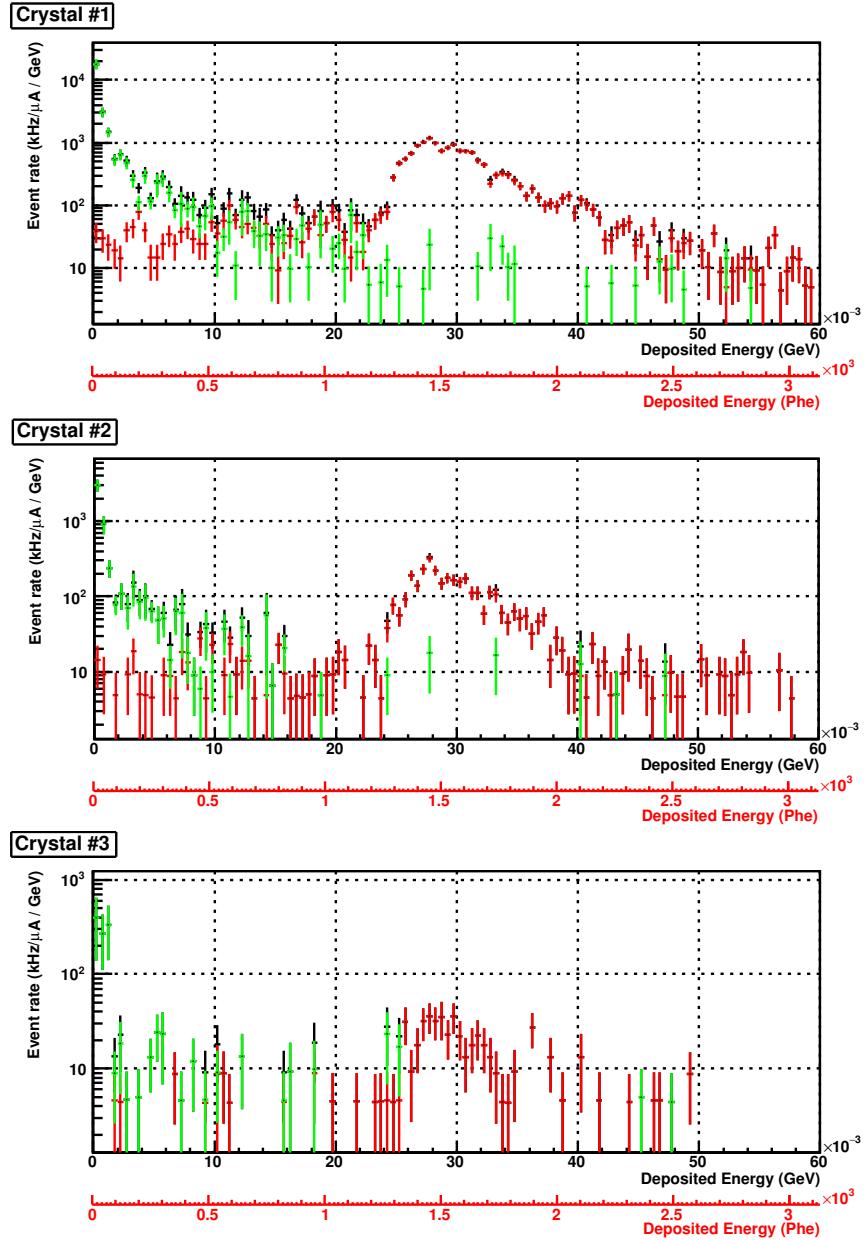


Figure 20: Distribution of energy deposited in the CsI(Tl) crystal by all particles (black), muons only (red) and the rest (green). The three plots refer to the crystal located in **A** (left), **B** (center), and **C** (right).

4.2.2 Cosmic background

The cosmic muon background in the BDX-Hodo has been evaluated using GEMC. This is the same cosmic flux generator used in PR-16-001 [1]. The muon energy spectrum has been divided in different

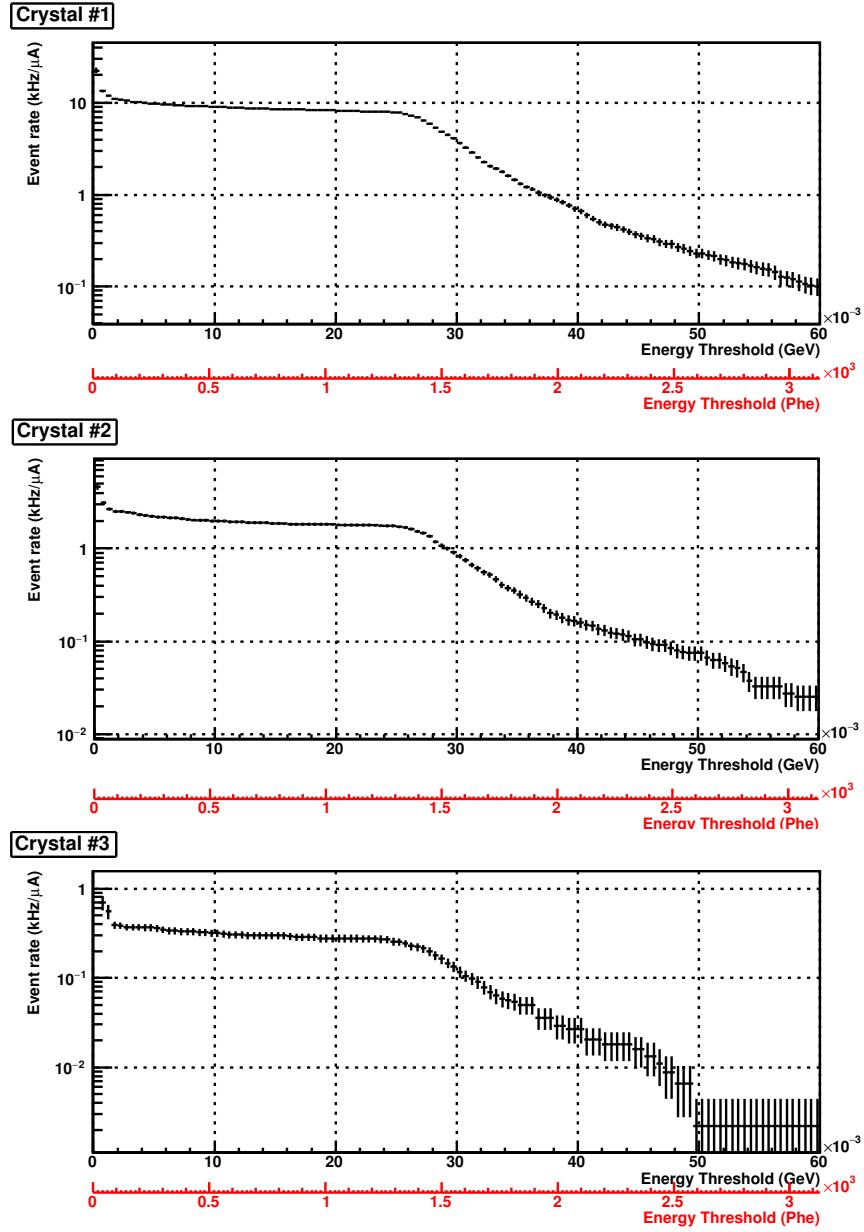


Figure 21: Crystal integrated rate as function of deposited energy. Plots refer to the crystal located in **A** (left), **B** (center), and **C** (right).

ranges and correctly weighted to estimate the full rate expected on the detector. Rates have been evaluated for CsI(Tl) crystal, Top scintillator, and for the coincidence of the front/back scintillator with the crystal to mimic the condition used to identify and account for beam-on muons. We assumed the same detection thresholds used in the other rate estimates (10 phe and 100 phe for

scintillators and crystal respectively). Tab. 4 shows the results of this study. The cosmic muon rate is negligible (in every condition < 1 Hz) well below the expected rate of muons from the electron beam interacting in the beam dump.

The same procedure was used to generate and sample cosmic neutrons. The corresponding rate in the CsI(Tl) crystals of hits over threshold were found to be negligible (< 0.1 Hz).

No attempts were made to evaluate the environmental background since the soil composition is poorly known.

Table 4: Cosmic rate expected in different components of BDX-Hodo

| Energy range (GeV) | Rate _{Crystal} (Hz) | Rate _{Top Scintillator} (Hz) | Rate _{Coincidence} (Hz) |
|--------------------|------------------------------|---------------------------------------|----------------------------------|
| 0.2 - 2 | 0.01 | 0.02 | 0 |
| 2 - 10 | 0.2 | 0.25 | 0.01 |
| 10 - 100 | 0.35 | 0.4 | 0.01 |
| Cosmic muon rate | 0.56 | 0.67 | 0.02 |

4.3 Test configuration and practical details

Practical details (drilling technology, costs and schedule) and a work plan for the proposed test configuration are reported in the Appendix.

4.4 Summary

We simulated the interaction of a 11 GeV electron beam with the Hall-A beam-dump studying the radiation field in the beam-dump vault and ~ 20 m downstream in the area of the new underground facility required by the BDX experiment. Two different simulation tools (GEMC and FLUKA) were used. For some locations, results were compared with JLab Radiological Control Group estimates. Here are the main outcome:

- our results are consistent with those obtained by RadCon;
- we confirm that only (high energy) muons and (mainly thermal/low energy) neutrons propagates trough the beam-dump vault concrete walls and dirt reaching the region of interest;
- no sizeable flux was found outdoor in the closest locations above-ground;
- for energies greater than 100 MeV, muon and neutron flux estimates with FLUKA and GEMC are in agreement;
- for energies lower than 100 MeV, FLUKA (using the biasing technique) is much more efficient in terms of running time.

To validate MC tools and gain confidence in the beam-on background shielding optimization for the BDX experiment we propose to measure the muon flux in the region where the new underground facility will be located. We itemize the proposed test set up and the expected results:

- muons produced in the dump can be measured by placing a detector downstream of the dump at beam height, i.e. below ground;
- a detector (BDX-Hodo) based on one CsI(Tl) crystal from the BDX ECal, sandwiched between layers of scintillator counters will be specifically built for this measurement;
- two wells equipped with 10' pipes will be drilled 25.2 m and 28 m downstream of the beam-dump and the BDX-Hodo detector will lowered into a pipe down to beam height;
- rates of beam-on muons measured by BDX-Hodo are expected to be sizeable for a beam current of $10 \mu A$ (~ 3 kHz and ~ 20 kHz in the two locations respectively);
- given the count rates reported above, this measurement could be done with a variety of beam current ($1 - 100 \mu A$) making the test fully parasitic wrt the Hall-A plans;
- this measurement was found to be insensitive to the cosmic muon background and other backgrounds (mainly) neutrons generated in the dump;
- the use of a BDX CsI(Tl) crystal will validate the proposed technology in a background-rich environment without the additional shielding needed for the BDX experiment[†];
- once the pipes are installed, tests will run for about a week, parasitically to any 11 GeV 1-100 μA , Hall-A run; This test, measuring the muon flux (absolute and relative) at two locations in Z (distance from the dump) and several in Y (vertical) will address the concern expressed by PAC44 report about the beam-on backgrounds in the BDX experiment.

[†]The BDX experiment foresees an optimized shielding that will drastically reduce any possible background.

5 Appendix

5.1 Cost estimates

The cost estimates for drilling pipes downstream of the Hall A beam dump are based on a budgetary bid for a single 16" pipe at location C indicated in Fig. 13. A cross section of the pipe (or "well") is shown in Fig. 22. The budgetary quote was adjusted by Suresh Chandra (JLab Facilities) to account for additional effort/work needed to complete the project. The resulting cost estimate is shown in Fig. 23. The following items were included in the cost:

- concrete slab on grade as a base for experimental test
- ground exploration in advance of drilling
- air blower to keep the well dry during test
- drilling of the hole proper; installing a pipe suitable for use as a guide for the detector apparatus
- backfill and compaction
- generator (on loan from facilities) to provide temporary power for one-week test (3KVA).

Based on the budgetary bid, two cost estimates were made for 10" pipes based on previous experience with such similar projects. The estimates are shown in Figs. 24 and 25 at locations B and C of Fig. 13. Given that the muon rate changes considerably with distance to the dump, we believe that two pipes are necessary to reliably understand the rate measurements. The estimated cost to drill two 10" pipes is \$40k. The typical time schedule for completing the project would be 8 weeks to prepare the contract, 6 weeks to award, and 6 weeks to complete the work, i.e. five months total.

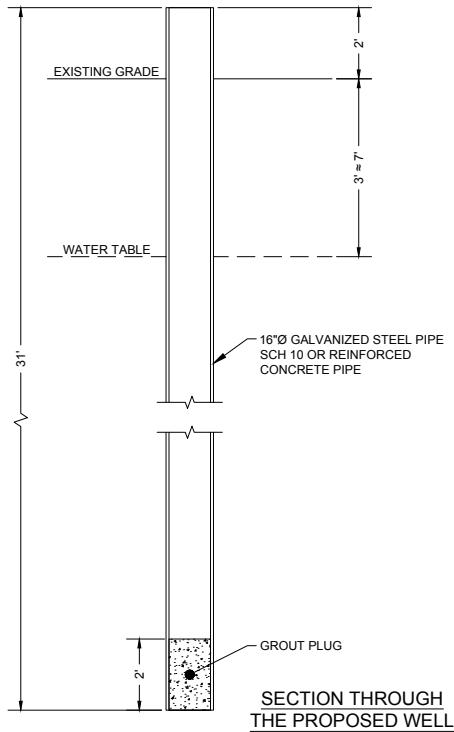
5.2 Work- & time-plan

The two wells will be drilled in locations **B** and **C** in the area downstream of the Hall-A beam-dump as shown in Fig 13 by inserting a 10" pipe as described in the previous Section. The test would run during the day, approximately for 4 calendar days [‡]. The test would be conducted during a time that 11-GeV beam with relatively steady current (between 1 and 100 μ A) is delivered to Hall A. The detector will be lowered in the pipe and positioned at different depths measuring counting rates at each setting. Table 5 shows the expected CsI(Tl) rates and collected statistics. The beam-on status and the beam current are the only relevant accelerator information, accessible off-line by EPICS values stored in the database [§]. About 10 minutes of stable beam ($\frac{\Delta I_{Beam}}{I_{Beam}} < 10\%$) will be enough to asses the relationship between beam current and detected muon rate and establish a normalization factor. Data with beam-off will be taken opportunistically to asses the beam-unrelated background in the detector [¶]. If possible we would like to take data at more than one beam current to check that the count rates scale. This would require 1h of dedicated beam-time coordinated with the Hall-A physics program to change the beam current by a factor of 10. Since the pipes will remain in place, it is worth noting that it will be possible to plan other opportunistic measurements with different Hall-A beam current/energy set-ups.

[‡]Assuming 8h day shifts only and 50% efficiency of CEBAF, this corresponds to less than 1 PAC days.

[§]Synchronisation between BDX-Hodo DAQ and EPICS data is required at level of 1s.

[¶]The background associated to cosmic muons is expected to be dominant wrt cosmic neutrons and environmental background. The status of the other experimental Halls will be recorded to asses the presence of further low energy neutron source.



Date: 1/27/17

Cost Estimate for BDX Experiment - One 16" Well

| NUMBER | DESCRIPTION | QUANTITY | UNITS | RATE | AMOUNT | Sub's O&P | Contingency | Total |
|-------------|---|----------|-------|----------|----------|-----------|-------------|----------|
| 1 | Well Installed 16" diameter - (Budgetary Bid + 5% for safety training & JLab work conditions) | 1.00 | Ea. | \$15,750 | \$15,750 | | 25% | \$19,688 |
| 2 | Backfill & compaction | 1.00 | Ea. | \$3,000 | \$3,000 | 25% | 25% | \$4,688 |
| 3 | Generator | 1.00 | Ea. | \$1,000 | \$1,000 | 25% | 25% | \$1,563 |
| 4 | Concrete slab on grade 5'x5'x6" (To act also as Wt. against uplift) | 1.00 | Ea. | \$500 | \$500 | 25% | 25% | \$781 |
| 5 | Ground exploration | 1.00 | Ea. | \$1,200 | \$1,200 | 25% | 25% | \$1,875 |
| 6 | Air Blower to keep the well dry | 1.00 | Ea. | \$1,000 | \$1,000 | 25% | 25% | \$1,563 |
| Grand Total | | | | | | | | \$30,156 |

NOTES:

- 1) The Estimate is based on the assumption that **no radioactive contamination** of underground soil or water is encountered during drilling of the well.
- 2) Ground exploration will need to be done before detailed design done. This will also be used to ascertain no radioactive contamination in the well area.

Figure 23: Preliminary cost estimate for a single 16" pipe.

Date: 1/27/17

Cost Estimate for BDX Experiment - One 10" Well

| NUMBER | DESCRIPTION | QUANTITY | UNITS | RATE | AMOUNT | Sub's O&P | Contingency | Total |
|-------------|---|----------|-------|----------|----------|-----------|-------------|----------|
| 1 | Well Installed 10" diameter (Cost Based on bid for 16" well) | 1.00 | Ea. | \$12,000 | \$12,000 | | 25% | \$15,000 |
| 2 | Backfill & compaction | 1.00 | Ea. | \$2,500 | \$2,500 | 25% | 25% | \$3,906 |
| 3 | Generator | 1.00 | Ea. | \$1,000 | \$1,000 | 25% | 25% | \$1,563 |
| 4 | Concrete slab on grade 5'x5'x6" (To act also as Wt. against uplift) | 1.00 | Ea. | \$500 | \$500 | 25% | 25% | \$781 |
| 5 | Ground exploration | 1.00 | Ea. | \$1,200 | \$1,200 | 25% | 25% | \$1,875 |
| 6 | Air Blower to keep the well dry | 1.00 | Ea. | \$1,000 | \$1,000 | 25% | 25% | \$1,563 |
| Grand Total | | | | | | | | \$24,688 |

NOTES:

- 1) The Estimate is based on the assumption that **no radioactive contamination** of underground soil or water is encountered during drilling of the well.
- 2) Ground exploration will need to be done before detailed design done. This will also be used to ascertain no radioactive contamination in the well area.

Figure 24: Preliminary cost estimate for a single 10" pipe.

Date: 1/27/17

Cost Estimate for BDX Experiment - Two 10" Wells

| NUMBER | DESCRIPTION | QUANTITY | UNITS | RATE | AMOUNT | Sub's O&P | Contingency | Total |
|--------|--|----------|-------|----------|----------|-----------|-------------|----------|
| 1 | Well Installed 10" diameter (Cost Based on bid for 16" well) | 2.00 | Ea. | \$10,000 | \$20,000 | | 25% | \$25,000 |
| 2 | Backfill & compaction | 2.00 | Ea. | \$2,000 | \$4,000 | 25% | 25% | \$6,250 |
| 3 | Generator | 1.00 | Ea. | \$1,000 | \$1,000 | 25% | 25% | \$1,563 |
| 4 | Concrete slab on grade 5'x5'x6" (To act also as Wt. against uplift) | 2.00 | Ea. | \$500 | \$1,000 | 25% | 25% | \$1,563 |
| 5 | Ground exploration | 1.00 | Ea. | \$1,200 | \$1,200 | 25% | 25% | \$1,875 |
| 6 | Air Blower to keep the well dry | 2.00 | Ea. | \$1,000 | \$2,000 | 25% | 25% | \$3,125 |
| | Grand Total | | | | | | | \$39,375 |

NOTES:

- 1) The Estimate is based on the assumption that **no radioactive contamination** of underground soil or water is encountered during drilling of the well.
- 2) Ground exploration will need to be done before detailed design done. This will also be used to ascertain no radioactive contamination in the well area.

Figure 25: Preliminary cost estimate for two 10" pipes.

References

- [1] The BDX Collaboration. Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab, 2016. <https://arxiv.org/abs/1607.01390>. 1, 3, 4, 12, 13, 14, 19
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- [3] Ungaro, M. CLAS12 GEANT4 Simulation Package GEMC, 2016. <http://gemc.jlab.org>. 4