ESTIMATION OF RADIATION FIELD FOR BDF/SHIP AT CERN

D. O. Wasik*, C. Ahdida, R. Cala', J. A. Coleman-Smith, L. S. Esposito, M. Ferro-Luzzi, M. Fraser,
R. Franqueira Ximenes, G. Frisella, J.-L. Grenard, G. Humphreys, R. Jacobsson, G. Lerner,
M. Parkin, O. Pinto, P. Santos Diaz, CERN, Geneva, Switzerland

Abstract

The Beam Dump Facility (BDF) will host the Search for Hidden Particles (SHiP) experiment at CERN's Super Proton Synchrotron. BDF/SHiP is designed to search for feebly interacting particles in a region of mass and coupling accessible only with a dedicated beam-dump configuration. With a beam intensity of 4×10^{19} protons on target (POT) per year at 400 GeV/c, the High-Intensity ECN3 (HI-ECN3) Project will enable this search, while the radiation field is envisaged to be used for parasitic programmes in nuclear astrophysics, materials science, and radiation-to-electronics research. High-momentum protons impinging on a tungsten target generate an intense radiation field, leading to, among other features, cumulative and single-event effects to nearby equipment. In this work, the radiation environment and its impact on electronics of the detectors and associated infrastructure were evaluated through simulations performed with FLUKA Monte Carlo code. The results show that proposed optimisation solutions for shielding reduce radiation levels, keeping most effects within acceptable limits. It is also observed that modifications made to the magnetic field and geometry of the muon shield, which controls the deflection of muons produced in the beam dump to reduce flux reaching the detector, influence muon and neutrino backgrounds.

INTRODUCTION

The Search for Hidden Particles (SHiP) experiment, dedicated to exploring physics beyond the Standard Model, will be hosted by the Beam Dump Facility (BDF) at CERN's Super Proton Synchrotron [1, 2]. The High-Intensity ECN3 (HI-ECN3) Project [3] will operate under the beam conditions summarised in Table 1 (in which POT stands for protons on target), establishing one of the most intense proton-driven beam-dump environments at CERN. The tungsten target is optimized to enhance interactions of beam protons, while promoting the re-absorption of pions and kaons and thereby minimizing the resulting muon and neutrino backgrounds [1].

The simulation study of the radiation environment at BDF/SHiP and its implications for electronics reliability was performed using the FLUKA Monte Carlo code [4–6]. Results from the previous BDF/SHiP design study [7] indicated that the recommended radiation to electronics (R2E) limits could be exceeded in several locations within the ECN3 cavern, mainly in the compressors and superconducting magnet (SM) cryocoolers areas, see Figure 1. In particular, the thermal neutron equivalent fluence was found to exceed recommended thresholds in all assessed locations, highlighting the need for dedicated neutron shielding using borated shielding materials [8]. The updated BDF/SHiP model, shown in Figure 1, features several design elements aimed at reducing radiation exposure in critical areas and improving the confinement of secondary particles: (1) a new muon shield (MS) design, featuring a geometry with twice the volume, and an updated magnetic field map; (2) the addition of 5 cm of 30% borated polyethylene into the confinement walls around the target complex composed of 2 cm of steel, covering the entire TCC8 cross-section; (3) the addition of concrete shielding around Magnetized Hadron Stopper (MHS); (4) a target diameter of 25 cm. In addition, the effect of a vacuum window located approximately 10 m upstream of the target, as well that of an optional mask installed in the beam pipe upstream of the target, is assessed. The implications of these changes are evaluated in terms of their impact on particle transport downstream of the shielding structures and background to the experiment.

Table 1: Beam Parameters for the BDF/SHiP [1]

Parameter	Value	Unit
Proton momentum	400	GeV/c
Nominal beam intensity	4×10^{13}	POT/spill
Integrated extracted intensity	4×10^{19}	POT/year
Total cycle length	7.2	s
Spill duration	1.0	s
Circular dilution radius	50	mm
Beam sigma (H,V)	16, 16	mm

RADIATION TO ELECTRONICS

Protons with a momentum of 400 GeV/c impinging on a 150 cm-long tungsten target generate a strong radiation field. This leads to cumulative effects, i.e. deterministic damage caused by ionising dose and displacement damage, quantified in this study by the total ionising dose (TID) and the silicon 1-MeV neutron equivalent fluence (Si1MeVNE). It also induces Single Event Effects (SEE), i.e. stochastic effects that may be destructive or non-destructive, characterised by the high energy hadron equivalent fluence (HEHeq) and the thermal neutron equivalent fluence (ThNeq) [9, 10]. The objective of this study was to assess the risk that the installation of BDF/SHiP in TCC8 and ECN3 may require, either: (i) placing non-radiation tolerant commercial electronics in designated R2E-safe areas; or (ii) using radiation-tolerant equipment. To this end, the quantities reported in Table 2 are used to define the general requirements for classifying a given zone as an R2E-safe area.

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* dominika.oliwia.wasik@cern.ch

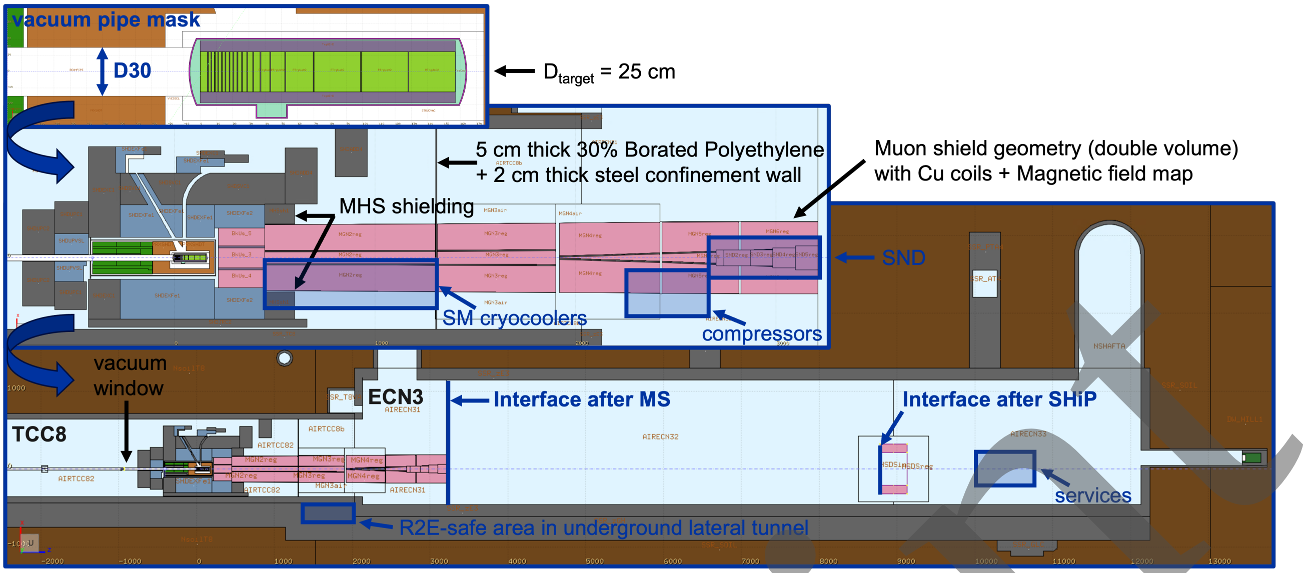

Figure 1: BDF/SHiP model in the TCC8/ECN3 beam facility with progressively zoomed regions of interest.

Table 2: General R2E limits derived from LHC experience defined to characterize an area as radiation-safe for electronics [11].

Effects	R2E quantity	Limit value	Unit
Cumulative	TID	1	Gy/(10 years)
	Si1MeVNE	10^{10}	cm^{-2}/(10 years)
SEE	HEHeq	3×10^6	cm^{-2}/year
	ThNeq	3×10^7	cm^{-2}/year

The spatial distributions of the radiation levels in ECN3 reported in Figure 2 show that radiation is strongly localised near the target complex and the first section of the MS, where particle production is most intense. Downstream, all quantities decrease rapidly along the beam direction due to attenuation in the MS and surrounding concrete structures. The TID map highlights the muon sweeping and characteristic fan-like structures produced by secondary particle transport. The new MS design confines the muon fluence within its structure, resulting in significantly reduced fluence outside the shield compared to the previous model. Radiation levels in ECN3, particularly at the locations of the Scattering Neutrino Detector (SND), electronics services, and the underground lateral tunnel, are expected to remain below the R2E limits requiring special mitigation measures, indicating that standard electronics can be used without the need for additional radiation-hardening. However, higher levels are observed along the muon plumes, the MS region and, in the case of ThNeq, its surroundings. The optimized shielding configuration comprising of concrete blocks and a confinement wall, effectively reduces radiation effects. In particular, the ThNeq decreases by approximately two orders of magnitude beyond the wall, and the geometry, enclosed by the additional concrete shielding around the MHS, helps to prevent HEH leakage. Further studies might be required for the areas of compressors and SM cryocoolers, where R2E limits are partially or fully exceeded.

MUON AND NEUTRINO BACKGROUND TO SHIP

Figure 3 presents the simulated muon and neutrino momentum distributions evaluated downstream of the MS and at the SHiP detector. Muons surviving the MS at the detector acceptance are of particular interest, as they represent the residual muon background after shielding and can contribute to the detector background either directly or through secondary particle production. A momentum threshold of 1 GeV/*c* is applied, as low-energy muons are efficiently absorbed in the surrounding material and low-energy neutrinos have negligible interaction probabilities, resulting in a minimal contribution to the detector background. Two beam configurations are considered: the full beam, parametrized as in Table 1, and a beam-tail configuration, represented by a weighted annular distribution, used to evaluate the impact of the beam tail on the beam pipe mask. The annular beam samples the halo region within a defined radial range (Rmin = 10 cm, Rmax = 20 cm) using a uniform transverse distribution, while weights are assigned based on a fit to the radial profile of the realistic beam distribution, ensuring that the correct halo population is reproduced [12]. For the full beam, the dependence on the target diameter has been studied in the previous FLUKA model for values of 25, 30, and 35 cm. The muon spectra downstream of the MS show negligible variation across these configurations, indicating that increasing the target diameter may not be required from the performance perspective. In the updated FLUKA model, the revised magnetic field map significantly modifies the muon momentum distribution, suppressing a dip previously observed in the range of approximately 3–30 GeV/*c*. This reflects the improved description of the magnetic field and its impact on muon transport through the shield. The new model also shows a reduction in the high-momentum component of the muon spectrum due to the redesigned MS. Over its ~28 m length, muons lose approximately 20–40 GeV while

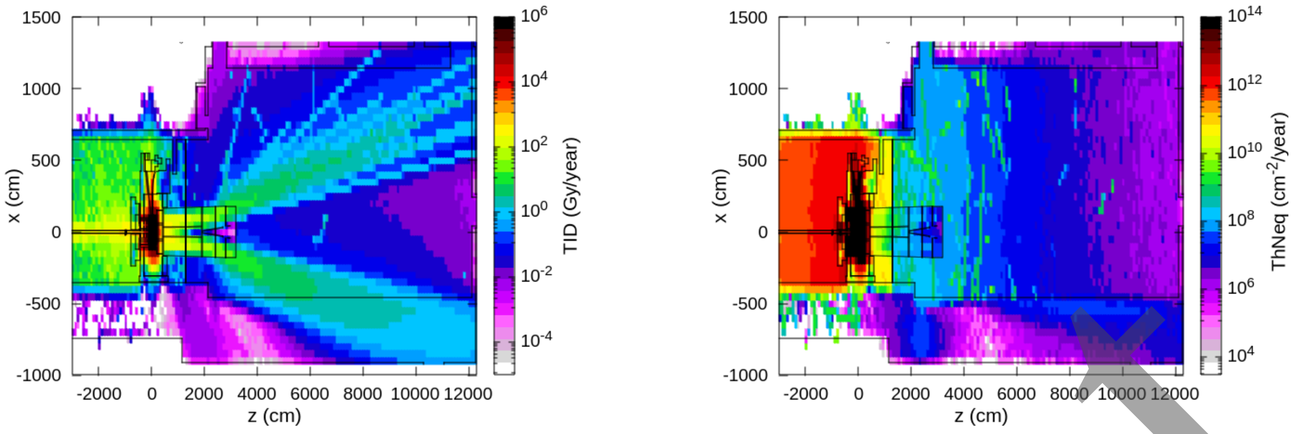

Figure 2: Total ionising dose (left) and thermal neutron equivalent fluence (right) estimation in the new FLUKA model of BDF in the TCC8/ECN3 beam facility for nominal BDF operation of 4×10^{19} POT/year. Values shown in the xz plane, averaged over $y \in [-75, 75]$ cm (beam line at $y = 0$ cm).

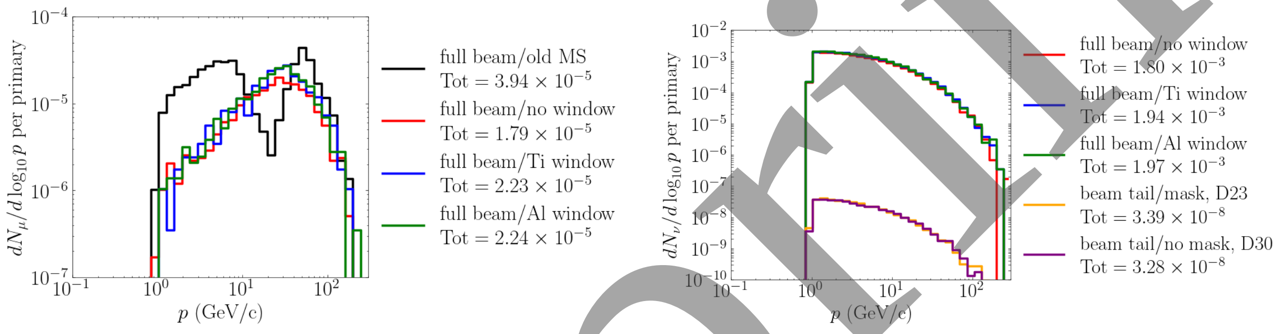

Figure 3: Muon momentum distributions downstream of the MS (left), illustrating the impact of the MS modifications and the vacuum window for the full beam. Neutrino momentum distributions at the SHiP detector (right), showing the effect of the vacuum window for the full beam and the contribution from beam-tail interactions with a beam pipe mask.

the increased transverse size improves their containment, leading to a deficit in the high-momentum tail. In total, the improved model produces approximately 60% fewer muons downstream of the MS than the previous model. The neutrino momentum distributions remain essentially unchanged across different target diameters in the previous model and after the updates, as neutrinos are unaffected by magnetic fields and interact only weakly with matter. The presence of a vacuum window introduces an additional contribution to the background. For the full beam, it increases the total muon yield at the MS by approximately 25% and the neutrino yield at the SHiP interface by about 9%. This represents a non-negligible contribution to the overall background, particularly for increased window thicknesses. The considered configurations include a 0.5 mm-thick Ti window and a 1 mm-thick Al window; a 1 mm-thick Be window is expected to exhibit similar behaviour based on comparable nuclear interaction probabilities and the required thickness. The contribution is expected to scale linearly with thickness, highlighting the need to minimise the window thickness. The effect of the beam pipe mask has been evaluated using the beam-tail configuration. Reducing the mask diameter from 30 cm to 23 cm leads to an increase of approximately 4% in the neutrino yield. However, the contribution of the mask remains negligible, at the level of $\sim 10^{-5}$ of the full-beam neutrino yield, and it can therefore be implemented if protection of sensitive equipment is required.

CONCLUSION

The simulation study demonstrates that the proposed shielding configuration for BDF/SHiP effectively mitigates radiation effects on electronics while maintaining controlled and well-understood background conditions. The redesigned MS and a borated polyethylene confinement wall achieve a significant reduction in secondary particle leakage, including a 60% decrease in muon flux and a two-order-of-magnitude drop in thermal neutron fluence. While specific areas such as cryocooler locations may require further localized optimization, the overall environment is expected to remain within safe R2E limits. This suggests that commercial electronics hardware can be used for the target system services and associated infrastructure. This study provides a quantitative basis for evaluating system performance under nominal high-intensity beam conditions and supports further optimisation of the shielding design and background performance.

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