RADIATION PROTECTION STUDY FOR THE SHIELDING DESIGN OF THE LINAC4 BEAM DUMP AT CERN

J. Blaha* and J. Vollaire, CERN, Geneva, Switzerland

Abstract

The aim of this study is to determine an optimal shielding of the LINAC4 beam dump fulfilling the radiation protection requirements. Therefore a detailed Monte-Carlo calculation using FLUKA particle transport and interaction code has been performed and the relevant physics quantities, such as particle fluences, neutron energy spectra, residual and prompt dose rates, air and water activation have been evaluated for different LINAC4 operation phases.

INTRODUCTION

The new linear accelerator LINAC4 [1] which is designed to provide a pulsed 160 MeV H^- beam is currently being constructed at CERN. The LINAC4 is going to replace the present 50 MeV proton accelerator LINAC2 as injector to the Proton Synchotron Booster (PSB). Thus the LINAC4 will become an essential component of the whole CERN accelerator complex, especially considering the future increase of the LHC luminosity.

The LINAC4 is terminated by a dump collecting the beam which is not intended for further utilization, i.e. during the accelerator commissioning phase, during the measurement operation as well as in case of degraded situations. When beam ions interact with the material of the dump core hadronic showers are initialized and mixed radiation fields with large numbers of neutrons and other highly penetrating particles are produced. In addition, the material of the dump is highly activated. Therefore an effective shielding surrounding the dump needs to be established in order to limit activation of the structures placed in dump proximity and to protect personnel accessing the machine.

METHODOLOGY

A detailed Monte-Carlo calculation using the FLUKA code [2] has been performed and the relevant physics quantities, such as particle fluences, neutron energy spectra, residual and prompt dose rates, and induced activation have been calculated for different irradiation profiles (operation phases) and several cooling times in order to optimize the choice of shielding material and its design in accordance with the ALARA principle. Furthermore, the airborne radioactivity as well as the activation of the beam dump cooling water have been calculated using FLUKA and simplified laminar flow models. The aim of this study is to determine an optimal shielding design fulfilling the radiation protection requirements for the LINAC4 main dump. The proposed shielding must take into account different accelerator operational phases, the space constraints inside the accelerator vault and the decommissioning of the installation at the end of its lifetime.

* jan.blaha@cern.ch

FLUKA GEOMETRY MODEL

The main dump is placed at the intersection of the LINAC4 tunnel and the LINAC4 transfer line, about 12 m below ground level. A detailed geometry of the beam dump as well as the LINAC4 civil engineering site have been implemented in the simulation, see Fig. 1. Thus the prompt dose rate can be evaluated not only in dump proximity, but also in accessible locations as the connection with the LINAC2.

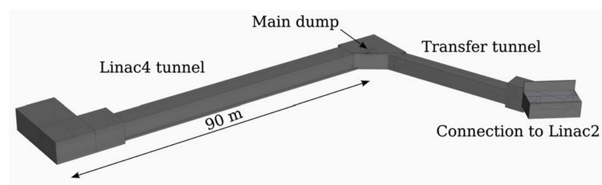

Figure 1: FLUKA geometry of the tunnel enclosure.

Dump and Shielding Design

The dump has cylindrical shape and it consists of a graphite core and stainless jacket. A length of the core is 75.4 cm and with a radius of 10.85 cm. Considering a backscattering trap on the core front side, the effective depth is 60 cm, see Fig. 2. The jacket covers the core and also incorporates a water cooling system.

Several shielding design options were tested for different materials and geometry configuration and their basic radiological parameters were compared to one another in order to select the most suitable one for a complete study. The proposed shielding consists of iron blocks which surrounds the dump core and borated concrete blocks used as the outermost layer. The borated concrete with a 0.9% mass fraction of natural boron was chosen to enhance its shielding properties against neutrons and to lower the residual dose due to induced activation. In order to obtain required boron content, colemanite, a natural mineral that contains boron oxide, was added to the concrete composition. Overall dimensions of the shielding are $240 \times 200 \times 224$ cm^3 (length$\times$width$\times$high), and the total weigh of the dump with shielding is about 36.3 tons. The air volume between the dump and its shielding (see Fig. 2) is reserved for supporting mechanical structures that will allow easy and fast dump replacement in case of failure.

ISBN 978-3-95450-122-9

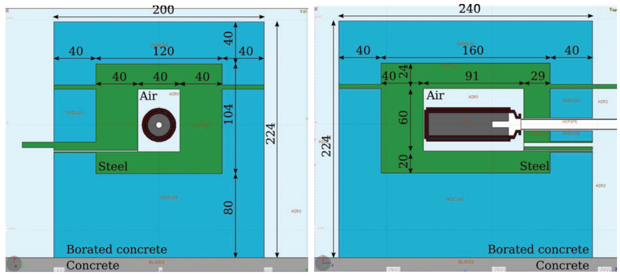

Figure 2: Front (left) and side (right) view of the dump and its shielding as implemented in FLUKA. Dimensions are in cm. Supporting structures for dump removal and some openings for dump services are also a part of the model.

OPERATION SCENARIOS

LINAC4 provides a pulsed beam of 160 MeV H^- ions. The pulse structure of the beam was approximated by an average beam intensity calculated for each irradiation period, preserving of the total number of impinging protons. Three operation phases of LINAC4 are taken into account: 1 month commissioning phase with a nominal beam power of 2.84 kW, 9 months reliability run with a 1/4 of the nominal power to asses the operational availability of the machine and potentiality weakness before connection to the PSB, and 30 years of normal operation (LINAC4 life time) when the dump is exposed to the beam only occasionally.

PHYSICS SETTINGS

Simulation were performed with FLUKA particle transport and interaction code. Predefined setting for precision simulations was chosen. A 10 keV energy transport cut-off was set to all particles except neutrons for which is by default 1E-5 eV. The production and transport energy thresholds for electrons/positrons and photons were set to 100 keV and 50 keV, respectively. Energy transport cut-off were increased by a factor of 10 for prompt electromagnetic radiation originated from decayed nuclei at the requested cooling time. Moreover, to achieve accurate results for residual nuclei production, the new evaporation model of the heavy fragments and the coalescence mechanism were explicitly activated for all simulations. Finally, the region importance biasing was used to optimize the CPU time of calculation and to obtain a sufficient statistic.

RESULTS

Residual Radiation

Residual dose rates maps inside the dump cavern have been calculated for different cooling times and for each operation phase. As shown in Fig.3 the ambient dose equivalent rate falls down steadily as the radiation induced ^{24}Na ($T_{1/2}$=15 h) in concrete decays, and reaches a level of several μSv/h at 1 m distance after 1 day of cooling in case of normal operation. Similar radiation levels are acquired after 1 week of cooling for commissioning and reliability run, respectively. Hence, the dump area can be accessible for an intervention after relatively short cooling times.

Prompt Radiation

Ambient dose equivalent rates during LINAC4 operation at a nominal beam power at LINAC4 level and at the junction of the LINAC4 and LINAC2, which will be accessible during commissioning and reliability run is shown in Fig. 4. The contribution from LINAC4 to the dose rates on LINAC2 side will stay under 10 μSv/h, which comply well with dose limits and work place classification in this area.

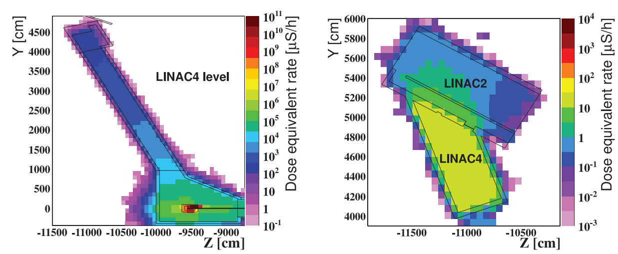

Figure 4: Ambient dose equivalent rates due to prompt radiation during operation at a nominal power of 2.84 kW at LINAC4 level (left) and at the junction to LINAC2 (right).

Water Activation

Activity of cooling water inside the dump was calculated from the production yield of the radiation induced nuclides in a water circuit. The results are summarized for the most important contributors, ^{3}H and ^{7}Be, in Tab. 1. Specific activity can be than scaled accordingly knowing the total volume of the whole cooling circuit and its water flow rate.

Table 1: Production yield and activity in 2.5 l of cooling water inside the dump after commissioning (C), reliability run (R), and normal operation (NO).

	Half life	Yield $[ncl/proton]$	Activity $[MBq]$ C	R	NO
^{3}H	12.32 y	6.01E-6	1.56	7.13	7.83
^{7}Be	53.26 d	1.32E-6	23.91	26.65	1.76

Air Activation

Radionuclide production yields in air have been delivered by folding the track-length spectra computed by FLUKA for different hadrons (n, p, π^+, π^-) with the production cross section of the target nuclide [3]. From the production yields the activity time evolution was calculated for a full set of produced radionuclides assuming a simple laminar flow model with a partial air exchange. The total annual activity released into atmosphere during LINAC4 operation at the nominal power is estimated to be about 2.6 TBq. The residual activity inside the tunnel immediately after the beam stop is about 38.7 MBq (29.1 kBq/m^3).

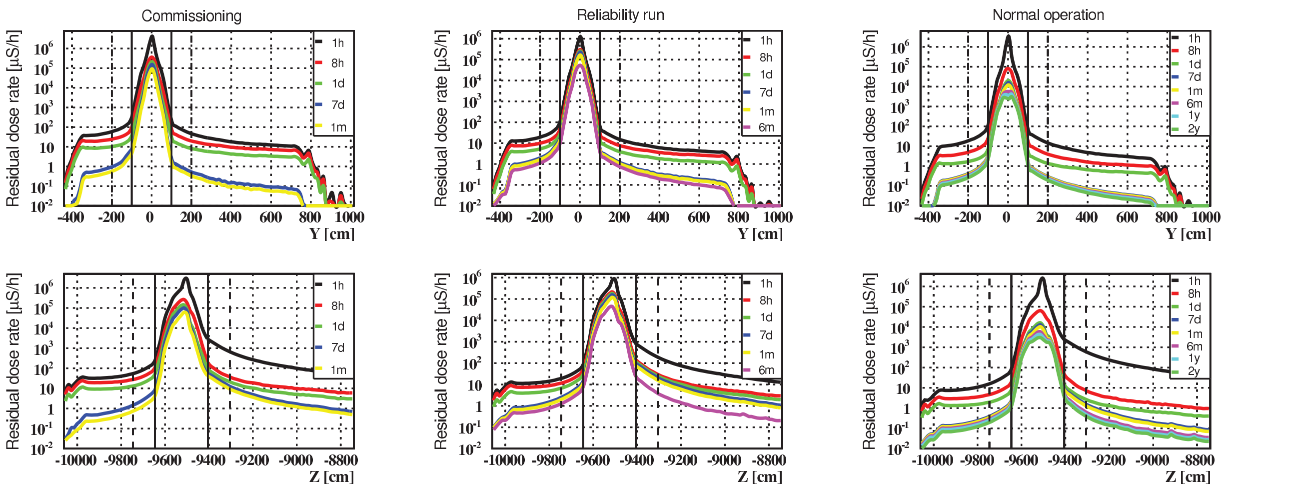

Figure 3: Ambient dose equivalent rates after several cooling times on an imaginary plane at center of the dump perpendicular (top) and along the beam direction (bottom) for three operation phases. Full vertical lines indicates the shielding boundary and dashed lines mark a 1 m distance from the shielding.

The contribution to the effective dose due to the airborne radioactivity for a personnel accessing the tunnel after a short cooling time is very low and an additional air flush will not be necessary.

Radioactive Waste and Radionuclide Inventory

Waste zoning calculations have been performed to identify which parts of the dump will became radioactive and thus treated as a radioactive waste. Figure 5 shows that after 30 years of operation and 2 years of cooling time, according to Swiss legislation [4] and also more restrictive CERN norms [5], practically whole dump assembly will be radioactive and an appropriate disposal will be required.

Complete inventory of radionuclides has been established for each dump component and will be used as an important input for the radioactive waste management. The expected activity is listed in Tab. 2.

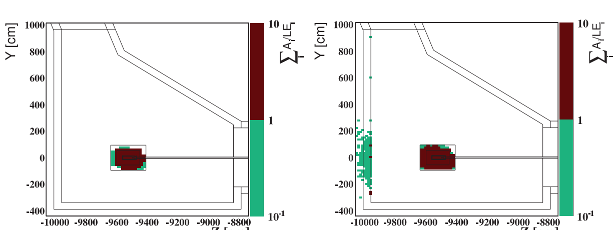

Figure 5: Radioactive (brown) and non-radioactive material (green and white) in the dump area based on Swiss legislation (left) and CERN norms (right) after 30 years of operation and 2 years of cooling time.

SUMMARY AND CONCLUSION

Residual dose rates show that the dump area can be accessible after a short cooling time. The prompt radiation

Table 2: Mass and specific activity for the LINAC4 dump after 30 years of operation and 2 years cooling time.

Component	Material	Mass [$tons$]	Activity [Bq/kg]
Dump core	Graphite/steel	0.34	3.60E+08
Inner shielding	Steel	15.89	8.72E+05
Outer shielding	Borated concrete	20.07	2.31E+03
Beam pipe	Aluminum	0.02	5.65E+03

at the area accessible during the beam-on is at the acceptable level and hence no further actions are required. Radionuclides production in water has been quantified for the dump cooling water system. Activity released into the atmosphere has been estimated and effective dose due to airborne radioactivity has been found to be under the legislation limits for workers accessing the tunnel. Waste zoning and radionuclide inventory for all dump materials have been established and will be considered further in the decommission scenario of the LINAC4. Generally, the dump shielding design consisting of steel iron and borated concrete fulfills well the CERN radiation protection requirements.

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ISBN 978-3-95450-122-9