EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

Radiation protection studies for the SHiP facility

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Abstract

The enlarged scope of the recently proposed experiment to search for Heavy Neutral Leptons, SPSC-EOI-010, is a general purpose fixed target facility which in the initial phase is aimed at a general Search for Hidden Particles (SHiP) as well as tau neutrino physics. This report summarizes radiation protection considerations for the SHiP facility and the primary beam extraction for SHiP.

Modifications

Revisions	Date	Pages	Description
0.0	13/03/2015	53	Creation of document
0.1	26/03/2015	53	Check of the version 0.0 by R. Jacobsson, D. Forkel-Wirth and S. Roesler
0.2	07/04/2015		Comments by R. Trant

Contents

SHORT SUMMARY

Quantities calculated:

    a) Prompt dose in the SHiP facility

    b) Stray radiation in the surrounding experimental and public areas of SHiP

    c) Residual dose in the SHiP target complex

    d) Prompt dose in the SHiP beam line

    e) Soil activation around TDC2 and TCC2

Simulation code: FLUKA version 2011.2b.5

Conversion coefficients: Fluence-to-dose conversion coefficients by M. Pelliccioni Radiat. Prot. Dosim. 88, pp. 279-297, (2000)

Assumed scenarios: 81 days (24h/24h) at 355 kW average beam power, i.e. 4.0×10^{13} protons per cycle every 7.2 seconds, 5 years overall operation with a total of 2.0×10^{20} protons on target

    The various operational and accident scenarios for evaluation of the quantities d) and e) are summarized in Section 3.2

Beam energy: 400 GeV/c protons

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1 Introduction

A new general purpose facility to Search for Hidden Particles (SHiP) has recently been proposed in which a high-intensity 400 GeV proton beam from the SPS shall be directed to a fixed-target complex in the North Area of CERN's Prévessin site [1] (see Figure 1). The target complex is located underground with the production target at a depth of about 10 m. The target is designed to contain most of the cascade generated by the primary beam interaction. It is embedded in a massive iron shielding absorbing the remaining primary protons and produced hadrons emerging from the target. The hadron absorber is followed by an active muon shield and an experimental hall, which houses the SHiP detector.

As SHiP aims at pushing the primary proton beam to a power of around 355 kW, radiation protection considerations strongly determine the design of the facility. In particular high prompt and residual dose rates call for considerable shielding and remote interventions in the target area. Also the risk and environmental impact from releases of radioactivity by air and water as well as the soil activation heavily influence the design. In order to respect the applicable CERN radiation protection legislation regarding doses to personnel as well as the environmental impact, a radiological assessment was carried out for the design of the SHiP facility. Studies include expected prompt and residual dose rates in the various accessible areas of SHiP as well as the levels of stray radiation in the surrounding experimental and public areas.

Next to the radiological assessment of the SHiP facility itself also the evaluation of its primary beam extraction from the SPS is a crucial factor. SHiP plans a slow resonant extraction from the SPS LSS2 using existing extraction equipment and transfer of the beam along TT20 up to a switch into a dedicated SHiP transfer line. The induced radioactivity in the SPS extraction region will increase in proportion to the total number of protons extracted per year - with the SHIP extraction in addition to the North Area requirement. The expected increase of the activation levels was therefore investigated. Since the dedicated SHiP beam line branches off at the top of the existing TT20, in the TDC2 cavern, further studies on prompt dose rates during beam operation in TT20 and TDC2 as well as the expected level of ground activation around TT20 and TDC2 were conducted. These are particularly relevant for the civil engineering works of SHiP (see also [2]).

To assess the above-mentioned radiation protection aspects, extensive simulations were performed with the FLUKA Monte Carlo particle transport code [3, 4]. The details of these studies and their results as well as their impact on SHiP will be summarized in this report, which represents an annex to the SHiP Technical Proposal [5]. The report is divided into two sections, which focus on the SHiP facility and the primary beam extraction for SHiP, respectively.

Additional radiation protection studies such as the releases of radioactive substances to the ambient air, a more detailed assessment of the environmental impact, dismantling of the facility, radioactive waste production, etc. have not

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been investigated to date. These will however be required at a later stage of the project.
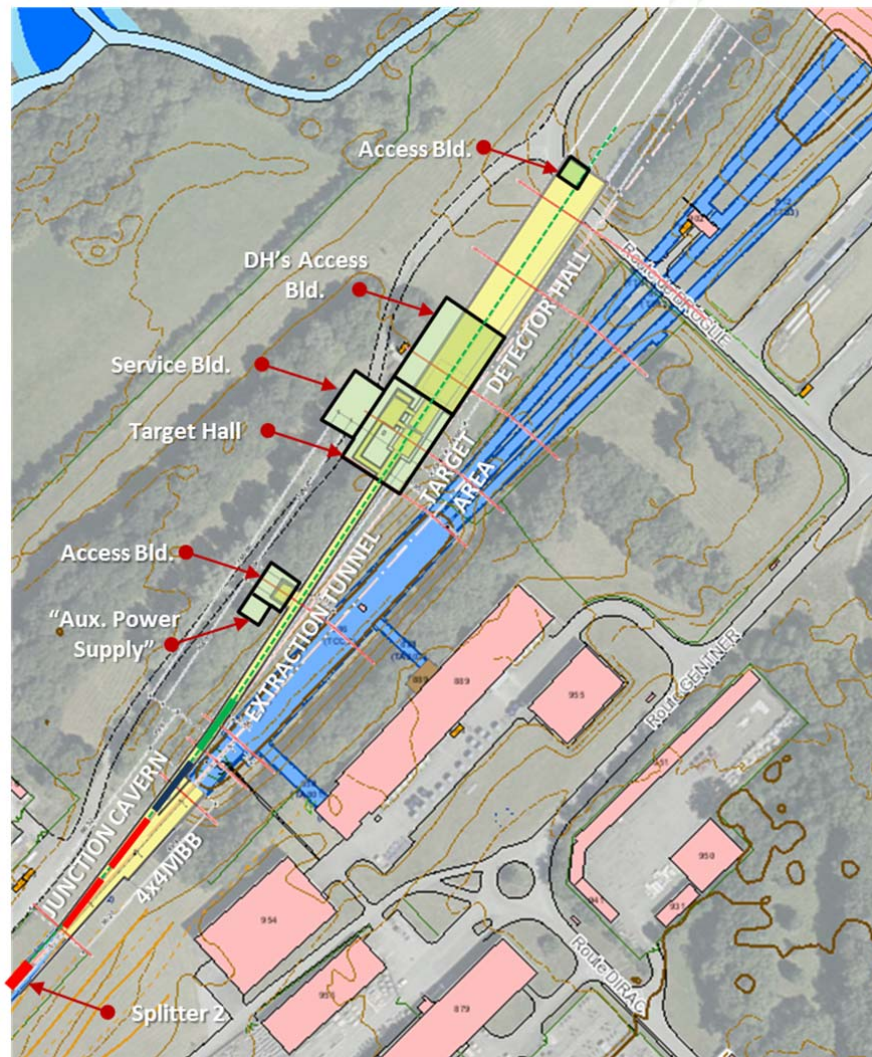

Figure 1: *Layout of the future SHiP facility in the North Area of CERN's Prévessin site.*

2 SHiP facility

This section summarizes the radiological assessment for the design of the SHiP facility. Studies include expected prompt and residual dose rates in the various accessible areas of SHiP as well as the levels of stray radiation in the surrounding experimental and public areas.

2.1 FLUKA input

The Monte Carlo particle code FLUKA was used to evaluate the radiation protection requirements for the SHiP facility. The FLUKA model of the facility was developed in collaboration with EN-STI [6]. Figures 2 - 4 depict, from a radiation protection point of view, the most critical areas of the facility: the target complex and the active muon shield. The coordinate system used in the model is a right-handed Cartesian coordinate system with origin at a depth of 32 cm within the target. The orientation of the coordinate system is defined by the width (x) and height (y) of the target complex and the beam direction (z).
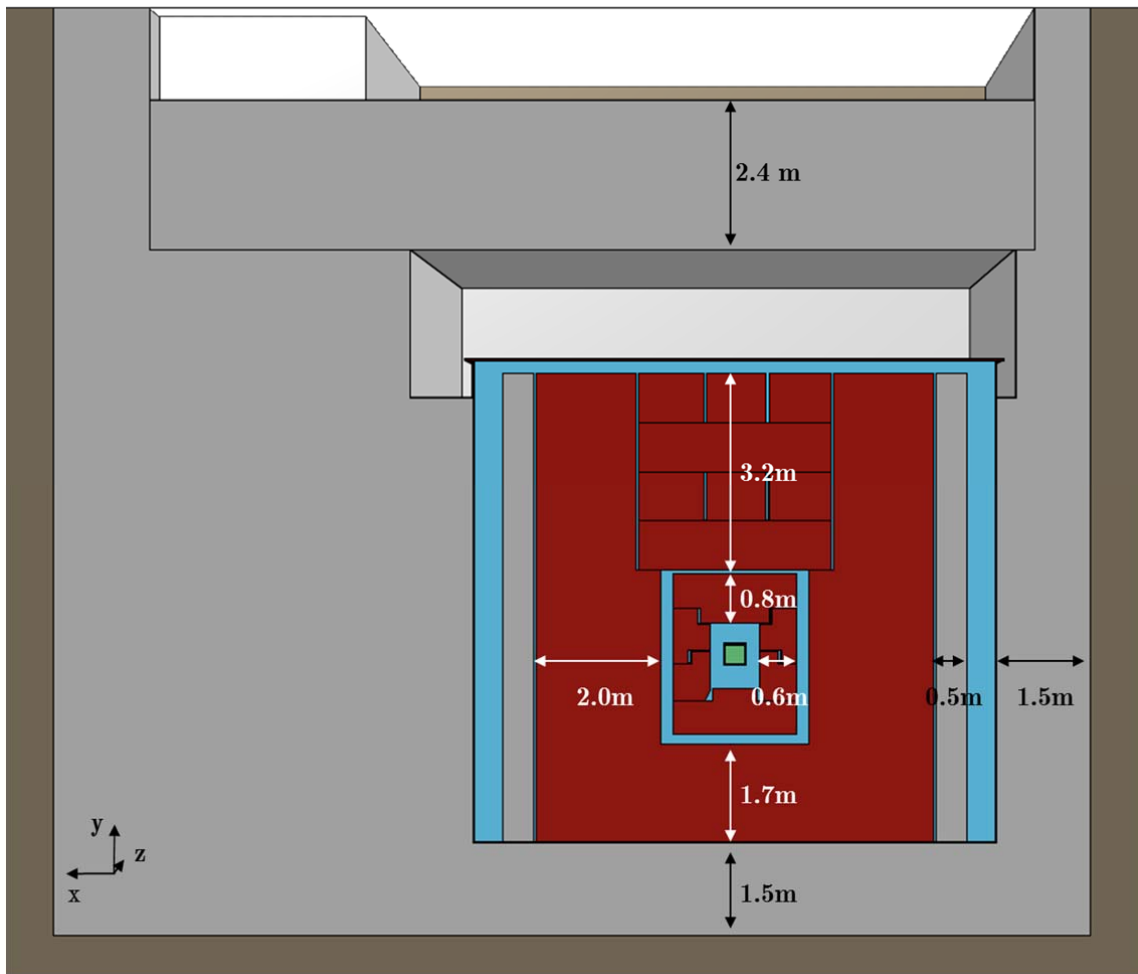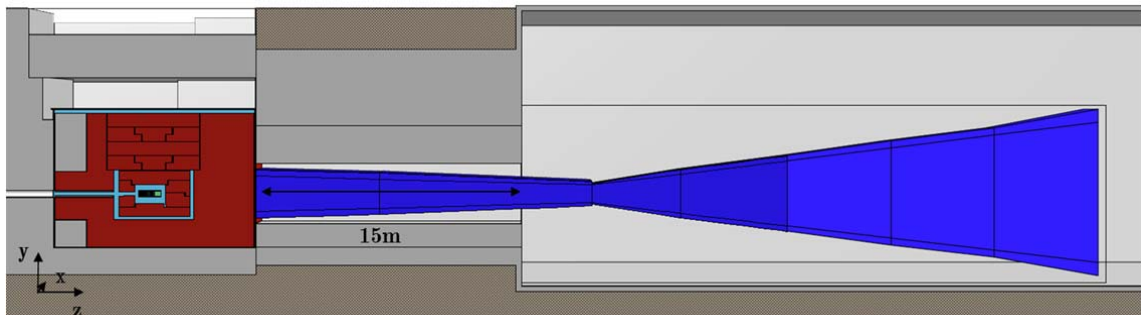

Figure 2: *Front view of the SHiP target complex as implemented in FLUKA. Cast iron is displayed in red, concrete in grey, molybdenum/tungsten in green, helium in light-blue and moraine in khaki.*
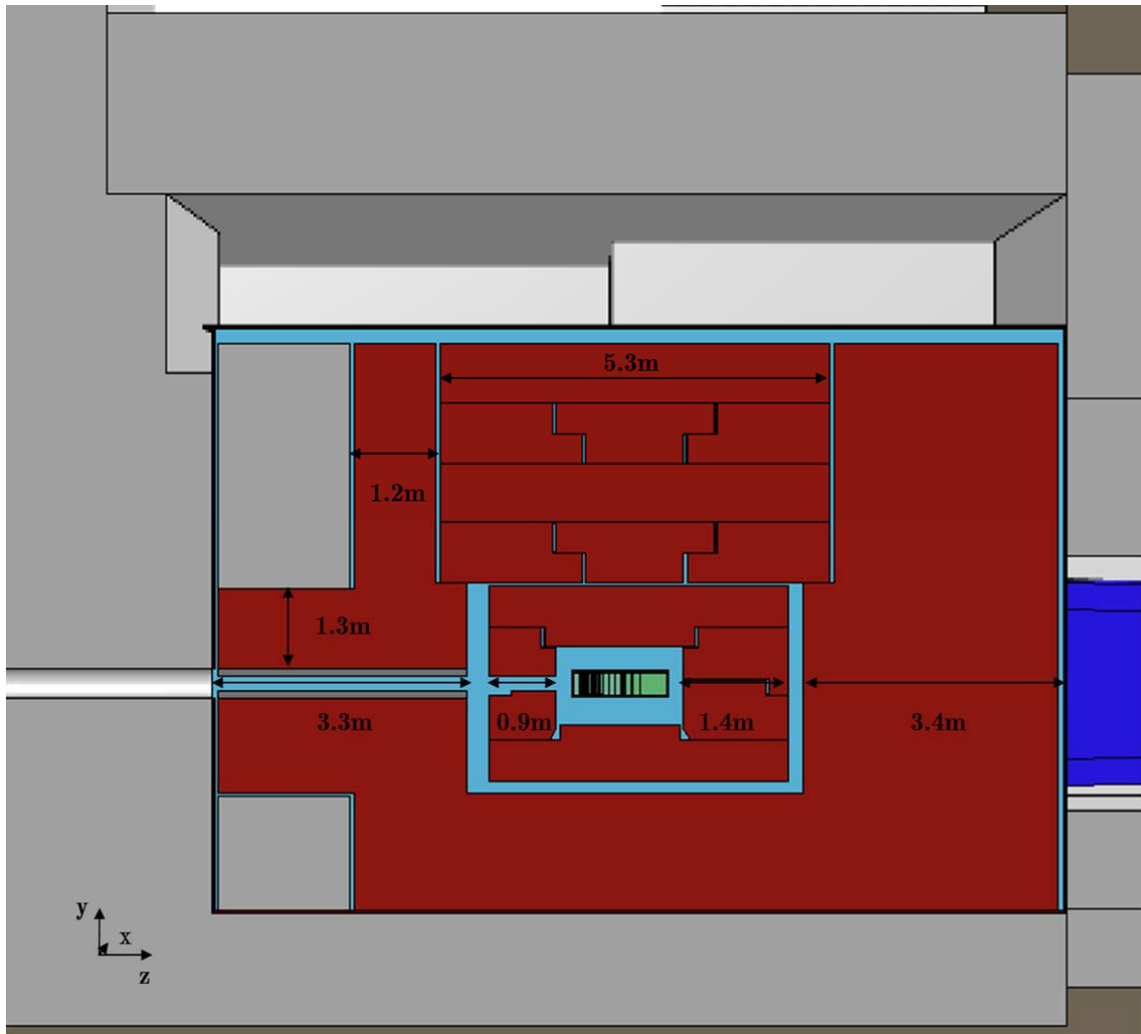
Figure 3: *Side view of the SHiP target complex as implemented in FLUKA. Cast iron is displayed in red, concrete in grey, molybdenum/tungsten in green, helium in light-blue, moraine in khaki and iron of the active muon shield in blue.*

Figure 4: *Side view of the SHiP target complex, the active muon shield and the beginning of the underground experimental hall as implemented in FLUKA. Cast iron is displayed in red, concrete in grey, molybdenum/tungsten in green, helium in light-blue, moraine in khaki and iron of the active muon shield in blue.*

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Due to the proximity of SHiP to the ground level (~10 m), other experimental facilities (~20 m[1]) and public areas (~70 m), massive shielding is required to keep the prompt radiation in the various accessible areas of the facility and the surrounding reasonably low. Next to personnel protection regarding prompt dose rates, considerable shielding is indispensable to reduce the residual dose rates and the environmental impact from activated air and soil as well as to relax radiation levels on electronics equipment (see also [6]). The shielding was consequently designed with the objective to keep the various radiological hazards originating from the operation of the SHiP facility as low as reasonably possible, while taking the constraints from the different stages of the experiment, that is the construction, operation, maintenance and dismantling, into account. The envisaged configuration is such as to avoid activation of the fixed concrete civil engineering structures simplifying not only the dismantling but also possible changes of scope of the installation.

The shielding in the target area was therefore modelled with massive iron blocks of thicknesses as specified in Figures 2 and 3. The iron blocks are specially designed for remote handling as they will become highly activated. Several 5 cm wide gaps were included in between the blocks in order to account for imperfect alignment, ducts for cooling, electronics etc. The innermost shielding blocks will include stainless steel water cooling pipes for heat removal. The water cooling circuits for these elements as well as for the target will be closed and separated from others. The downstream shielding, which has a thickness of 4.8 m, also acts as a hadron stopper with the double objective of absorbing the secondary hadrons and the residual non-interacting protons emerging from the target, and to significantly reduce the exposure of the active muon shield to radiation. The iron shielding is embedded in a helium vessel made out of iron. The remaining gaps between the iron shielding and the helium vessel structure are filled with removable concrete shielding blocks. The helium vessel is further surrounded by the fixed concrete civil engineering structures. The minimum concrete thickness from a radiation protection point of view amounts to 1.5 m, however larger thicknesses will probably be required from an engineering standpoint. The minimum concrete shielding thickness of 2.4 m towards the target hall was further estimated. The shielding upstream of the target has an aperture for the primary beam of 20 cm in radius, which is filled with a graphite collimator with an aperture of 10 cm in radius. The passage towards the primary beam line should be as small as possible to reduce the "back splash" of particles into the primary beam area, which leads to activation of the upstream beam-line components and the surrounding air. For further information about the conceptual design of the target area station please refer to [6].

The material properties employed for the shielding components were chosen such that they result in rather conservative prompt and residual dose rate estimates. The composition of the shielding materials is given in Table 1. Note that for cast

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[1] The distance between the target bunker and TT81 approximately amounts to 20 m.

iron the self-shielded low energy neutron cross-sections were utilized in order to correct for self-shielding effects. A pessimistic cobalt concentration of 0.035% was furthermore assumed. A density of 7.85 g/cm^3 and 2.34 g/cm^3 was utilized for the cast iron and concrete components, respectively [7].

Material	Element	Weight percentage [%]
Cast iron	Iron (self-shielded)	94.27
	Carbon	3.40
	Silicon	1.80
	Manganese	0.50
	Cobalt	0.04
Concrete[2]	Oxygen	40.4%
	Carbon	23.3
	Silicon	12.1
	Calcium	12.1
	Hydrogen	10.1
	Magnesium	2.0
Moraine	Oxygen	3.90E-01
	Calcium	2.41E-01
	Silicon	1.83E-01
	Carbon	5.03E-02
	Iron	4.88E-02
	Aluminium	4.35E-02
	Potassium	2.16E-02
	Magnesium	8.07E-03
	Titanium	4.46E-03
	Sodium	3.34E-03
	Manganese	1.47E-03
	Barium	9.41E-04
	Strontium	8.68E-04
	Phosphorus	6.20E-04
	Chromium	5.28E-04
	Zinc	2.92E-04
	Zirconium	2.57E-04
	Sulfur	2.32E-04
	Nickel	1.72E-04
	Vanadium	1.40E-04
	Cerium	1.32E-04
	Chlorine	1.25E-04
	Lanthanum	1.10E-04

[2] For future studies sodium should be included in the concrete composition. Nevertheless, we expect an insignificant impact with respect to the conclusions due to the fact that the design of the SHiP target complex is such that the concrete structures are well shielded by the iron shielding resulting in very low levels of concrete activation.

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Tungsten	1.05E-04
Copper	6.37E-05
Neodymium	5.48E-05
Cobalt	4.27E-05
Yttrium	4.07E-05
Lead	3.78E-05
Gold	3.48E-05
Gallium	2.54E-05
Lithium	5.73E-06
Europium	6.87E-08

Table 1: *Elemental composition of the shielding materials as defined in the FLUKA studies* **[7]**.

The soil surrounding the whole facility was modelled with a density of 1.9 g/cm^3, which is lower than the measurement performed nearby for CENF, which resulted in 2.3 g/cm^3 [8]. In this way, location-dependent density differences and a local decrease due to civil engineering works are conservatively taken into account. The chemical composition of the soil as specified in Table 1 was determined from core samples taken for CENF. A water content of 7.5% as measured from the samples was furthermore assumed. Results from the soil sample analysis can be found in [9]. The soil around the SHiP facility was modelled according to the current ground level in that area with the least distance to the SHiP beam line of 10.3 m.

The air volumes of the facility were minimized to reduce the production of airborne radioactivity. In the most critical area, that is the central region around the target and hadron absorber, the air was further replaced by a helium environment. This is motivated by the fact that pure helium gives only rise to the formation of tritium, which has a significantly lower radiological impact than the radionuclides arising from air. The service pit on top of the helium vessel, in which air activation is expected, is further separated by an airtight concrete block from the target hall to avoid unjustified exposure to personnel. In practice, however, perfect confinement by physical barriers is not feasible as some openings in the containment are necessary to allow for access, transfer of equipment, etc. To sufficiently compensate the defects of the static confinement a ventilation system according to ISO17873 guaranteeing a pressure cascade from low to high contaminated areas should additionally be employed. The ventilation circuits should be equipped with high-efficiency particle and aerosol (HEPA) filters to remove activated dust particles and aerosol-bound radionuclides from the air. Also the air exhaust should be foreseen with such filters and the airborne radioactivity released into the environment should be monitored.

The SPS beam parameters considered for the radiation protection evaluation of the SHiP facility are specified in Table 2. Note that these parameters can be considered conservative as they assume continuous operation of SHiP without taking the fixed target operation in the North Area and machine studies at low energies into account [10, 11]. Next to the standard beam scenario, also an

accident scenario with the loss of one full spill during an interruption of the muon shield magnets was studied.

Beam energy	400 GeV
Average beam power on target	355 kW
Beam intensity	$4 * 10^{13}$ p/cycle
Cycle length	7.2 s
Effective days of operation per year	81 days (24h/24h)
Overall operation	5 years
Overall POT[3]	$2 * 10^{20}$

Table 2: *Parameters of the SHiP beam scenario as employed in the FLUKA studies* **[11**, **10]***.*

2.2 Prompt dose rates

The prompt dose rates were evaluated by convoluting the fluence of neutrons, protons, charged pions and muons with the respective energy-dependent fluence-to-effective dose conversion coefficients. The contribution from photons, electrons and positrons was neglected for saving computing time. According to former studies, a dose contribution from electromagnetic processes of less than 10% of the hadronic contribution can however be expected behind the shielding [12, 13]. The results are presented in the following for the various areas of the SHiP facility and its surrounding experimental and public sites.

SHiP target complex

The SHiP target complex was designed under the condition that the target hall can be accessed during beam operation and classified as a Supervised Radiation Area with low occupancy (< 15 μSv/h) [14]. On the contrary, no access during beam operation will be permitted to the target bunker. The prompt dose rates expected in the latter were nevertheless studied, as they demonstrate the effectiveness of the various shielding components and allow for a further risk analysis of the facility.

The expected prompt dose rates in the SHiP target complex are depicted in Figure 5. As expected, the highest dose rates can be found in the region of the target reaching a few 10^{12} μSv/h. They are reduced by a few orders of magnitude in the surrounding iron shielding. Above the helium vessel enclosing the shielding, the prompt dose rates amount up to 100 mSv/h. Note that openings in the shielding were included in order to take possible weak points like feedthroughs for cooling and cabling into account. The prompt dose rates are further reduced by the above concrete shielding, such that they drop down to below a 1 μSv/h in the target hall. At the bottom and the sides of the target bunker, the dose rates drop down to below 1 mSv/h.

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[3] Protons on target.

Prompt dose, z [0:200], all particles

Prompt dose, x [145:160], z [0:200] all particles
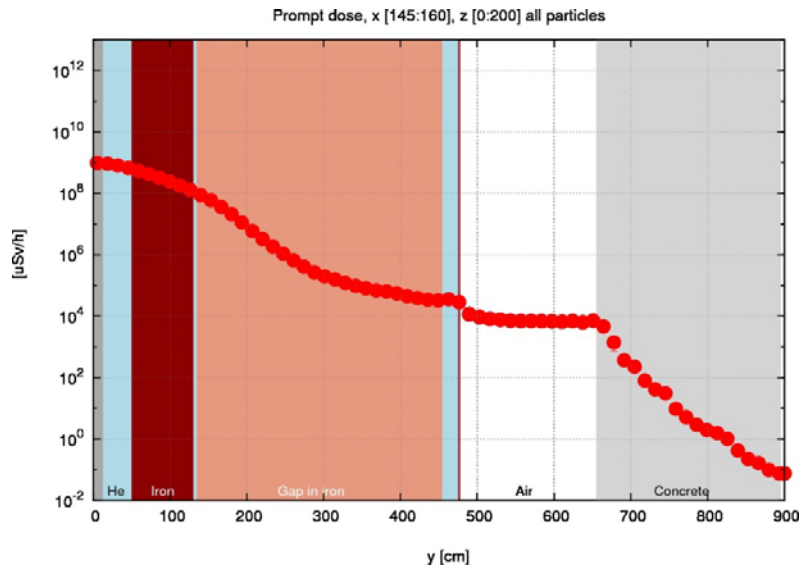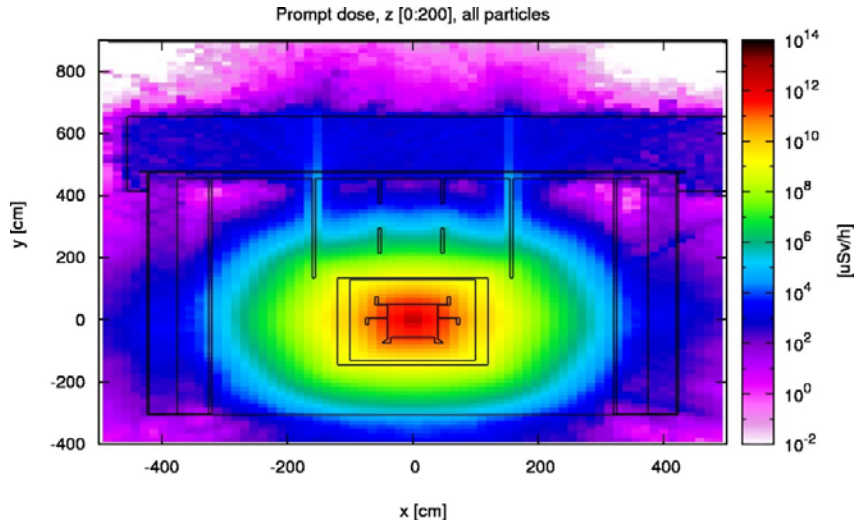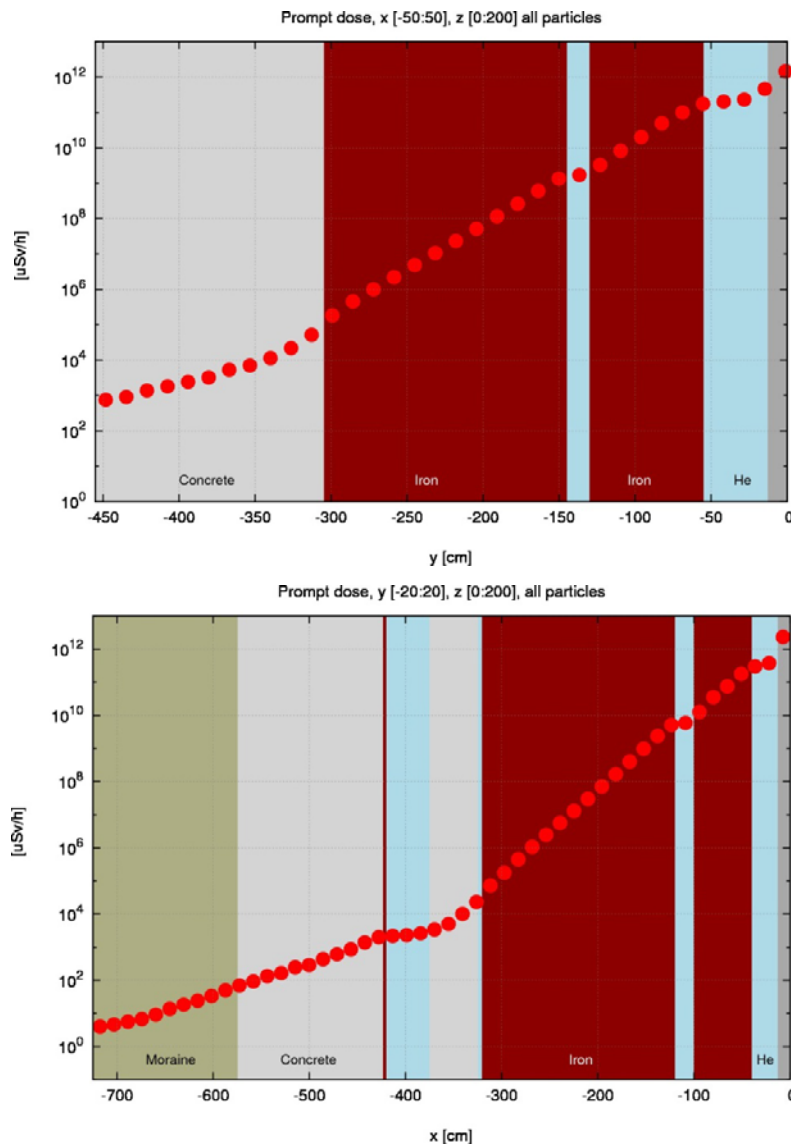
Figure 5: *Prompt dose rates (in μSv/h) in the SHiP target complex (1st: front view, 2nd: along the height at the level of the shielding gaps, 3rd: along the bottom, 4th: along the side).*

The production of radioactivity in the soil and water surrounding the SHiP facility is a significant environmental concern. Particularly soluble radionuclides likely to pass through the karstic system are critical for the protection of groundwater resources. To minimize related radiological risks, the specific activities of the leachable radionuclides H-3 and Na-22 should lie below the following design goals [15]:

- H-3 < 10 Bq/kg,
- Na-22 < 2 Bq/kg.

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The leachable radionuclide Na-24 was neglected due to the fact that it is too short-lived to survive the way from its place of creation to its place of consumption. When studying the relation between the prompt radiation and the soil activation for the CENF facility, it was estimated that the above-given limits are not exceeded with prompt dose rates of 1 mSv/h or below [12]. As mentioned above, the prompt dose rates outside of the SHiP target bunker drop down to below 1 mSv/h and thus do not exceed the envisaged limit to keep ground activation at an acceptable level.

SHiP active muon shield and underground experimental hall

Similar to the target complex, no access during beam operation will be permitted to the muon shield tunnel and the underground experimental hall. Here again, the prompt dose rates were investigated to illustrate the effectiveness of the active muon shield and provide information for a further risk analysis.

Figure 6 to Figure 8 present different views of the prompt dose rate distributions in the muon shield tunnel and the underground experimental hall which are expected from all particles[4], muons and neutrons. They demonstrate that the muons are swept away from the beam line by the active muon shield and keep their direction due to their small large-angle scattering behind the muon shield, while the neutrons show a relatively direction-independent shape. The dose rates reach a few mSv/h on the side of the experimental hall behind the muon shield and drop below 1 mSv/h in the surrounding soil. The level of soil activation is considered acceptable, particularly due to the fact that the dose rates are dominated by muons. The side view of the experimental hall illustrates that the muons are also bend towards the top of the experimental hall. In the above-ground access building to the experimental hall, a few μSv/h are reached wherefore this building should be classified as Supervised Radiation Area. For the accident scenario with the loss of one full spill during an interruption of the muon shield magnets dose below 0.1 μSv is expected in the above-ground access building.

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[4] Note again that the contribution from photons, electrons and positrons was not included.

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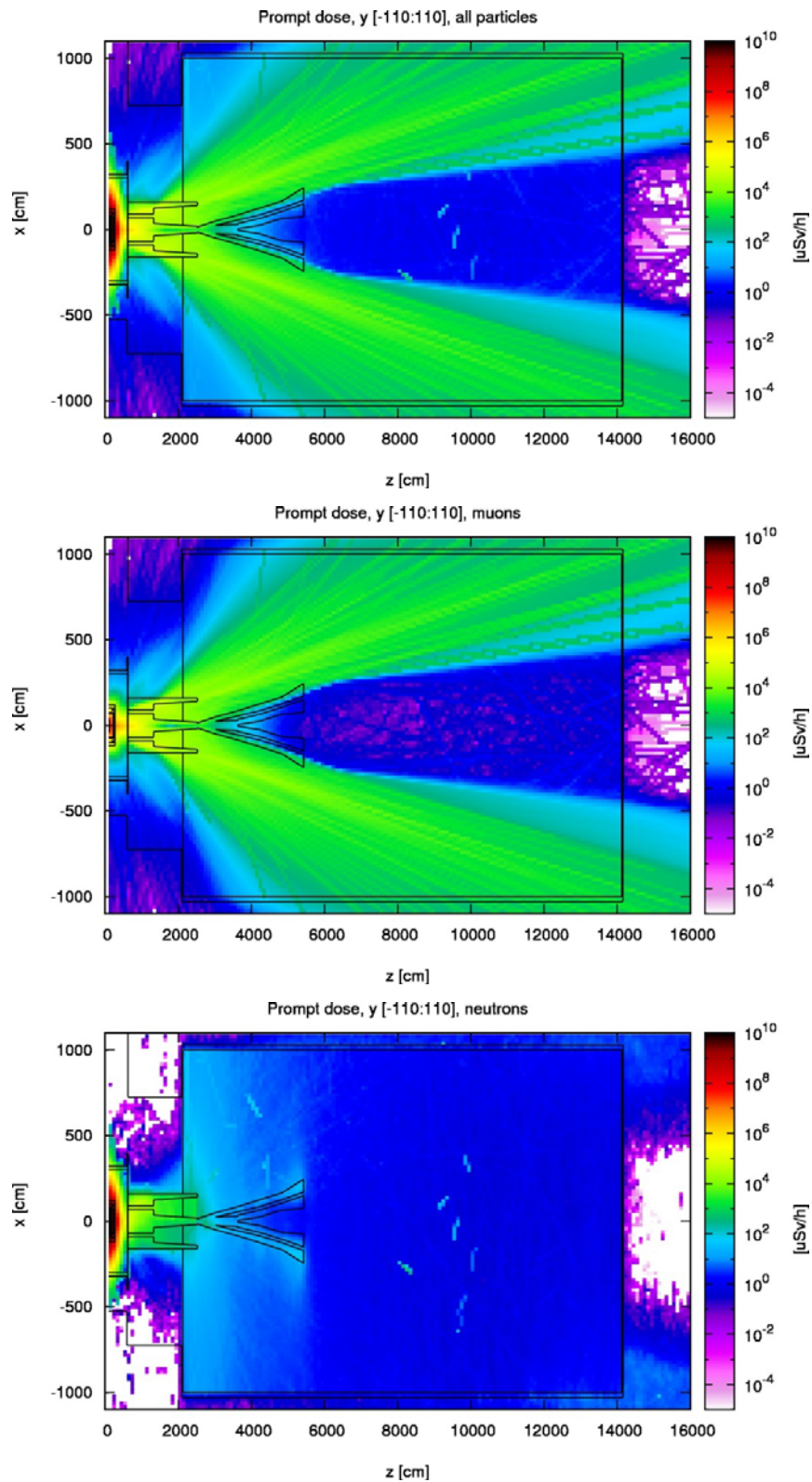
Figure 6: *Prompt dose rates (in µSv/h) in the SHiP muon shield and underground experimental hall (top view for all particles, muon and neutrons).*

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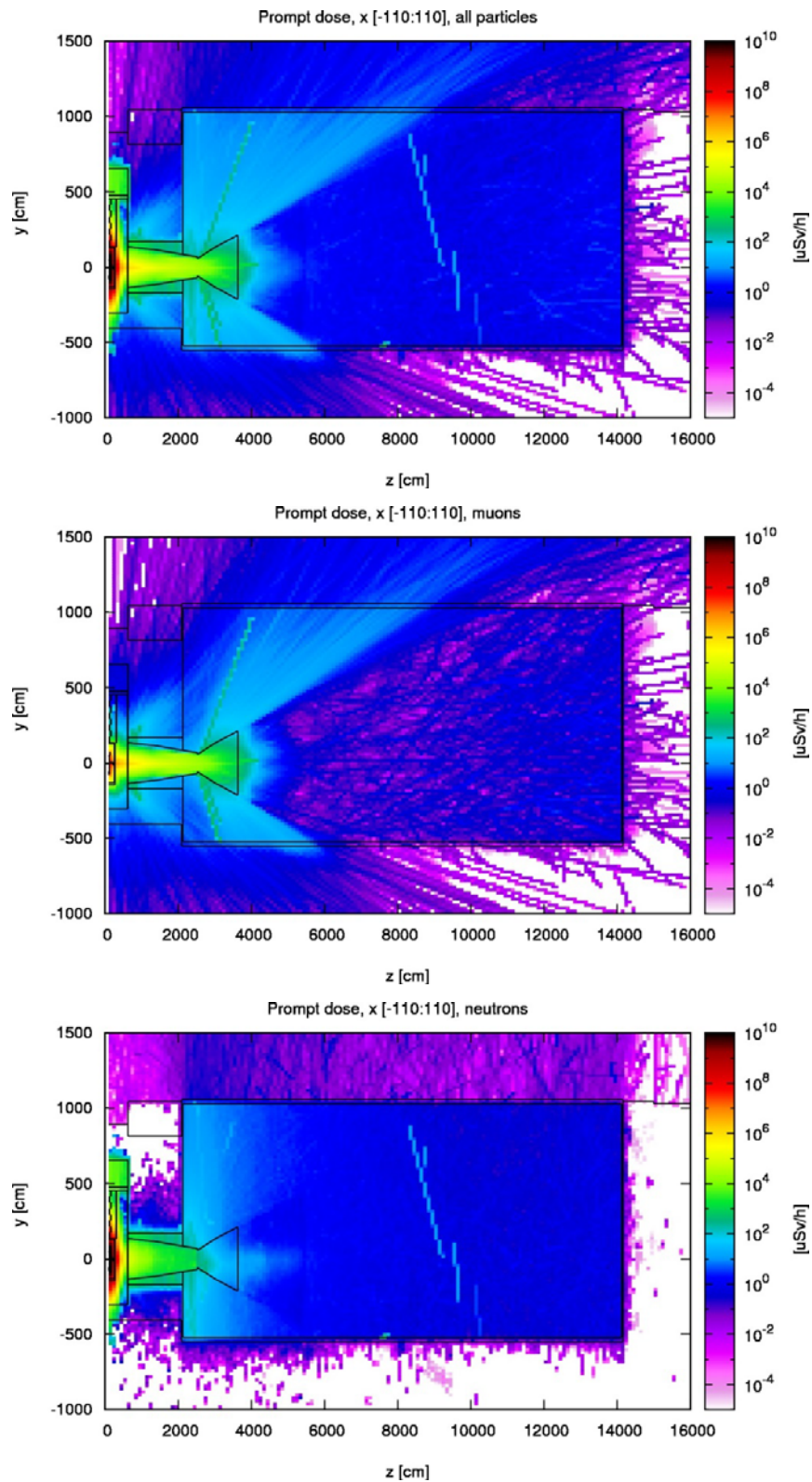
Figure 7: *Prompt dose rates (in µSv/h) in the SHiP muon shield and underground experimental hall (side view for all particles, muon and neutrons).*
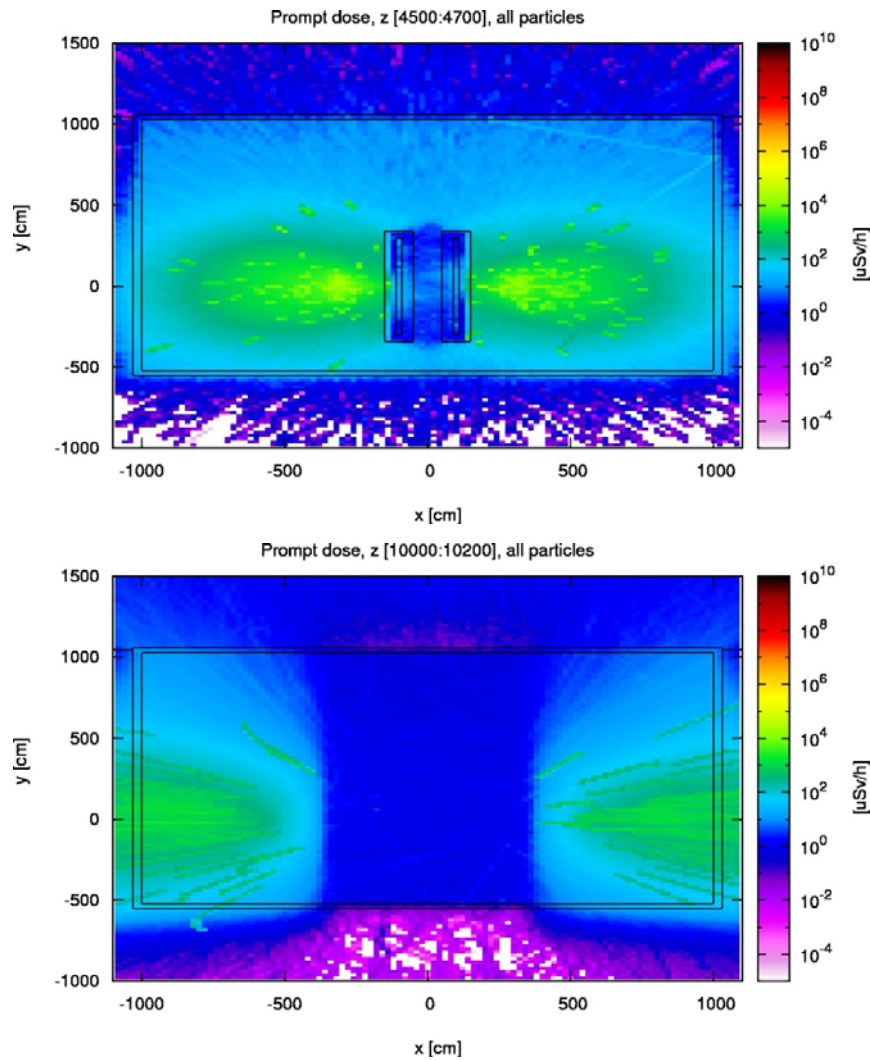
Figure 8: *Prompt dose rates (in µSv/h) as a cross view at the end of the active muon shield and in the underground experimental hall for all particles.*

Surrounding experimental areas

The prompt radiation at the ground level above the underground experimental hall was analysed in order to define the dose rates next to the access building, which covers only the first 40 m of the underground experimental hall. Figure 9 presents the aboveground prompt dose rates in the area of the experimental hall. It shows that the highest dose rates are reached behind the access building amounting to a few µSv/h until approximately 30 m behind and 5 m next to the experimental hall. This area should therefore either be fenced off, or even more favourable, the soil from the excavations should be backfilled on top of the experimental hall such that the dose rates would be further reduced down to a level allowing for a non-designated area. For the accident scenario with the loss of one full spill during an

interruption of the muon shield magnets dose rates below 0.1 µSv are expected above the experimental hall.
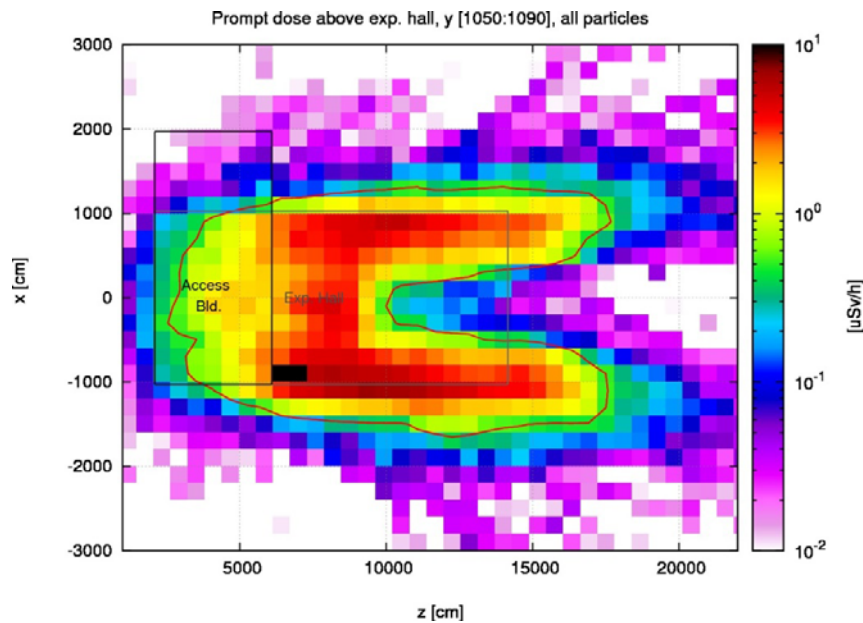
Figure 9: *Prompt dose rates (in µSv/h) above the underground experimental hall for all particles. The black and grey line indicates the access building and the underground experimental hall, respectively, and the red line the 0.5 µSv/h contour.*

Figure 10 shows the expected prompt dose rates in the ground and experimental facilities surrounding the SHiP facility. It demonstrates that the existing beam lines TT81, TT82 and TT83 are not affected by the prompt dose rates originating from the SHiP facility. The SHiP operation also does not influence the present area classification of the EHN1 experimental hall, which corresponds to a permanently occupied Supervised Radiation Area (< 3 µSv/h). One should bear in mind that the given results are conservative estimates due to the fact that a moraine density 20% lower than the measured one was assumed. The operation of the SHiP facility – as designed – should therefore not have any impact on its surrounding experimental areas.
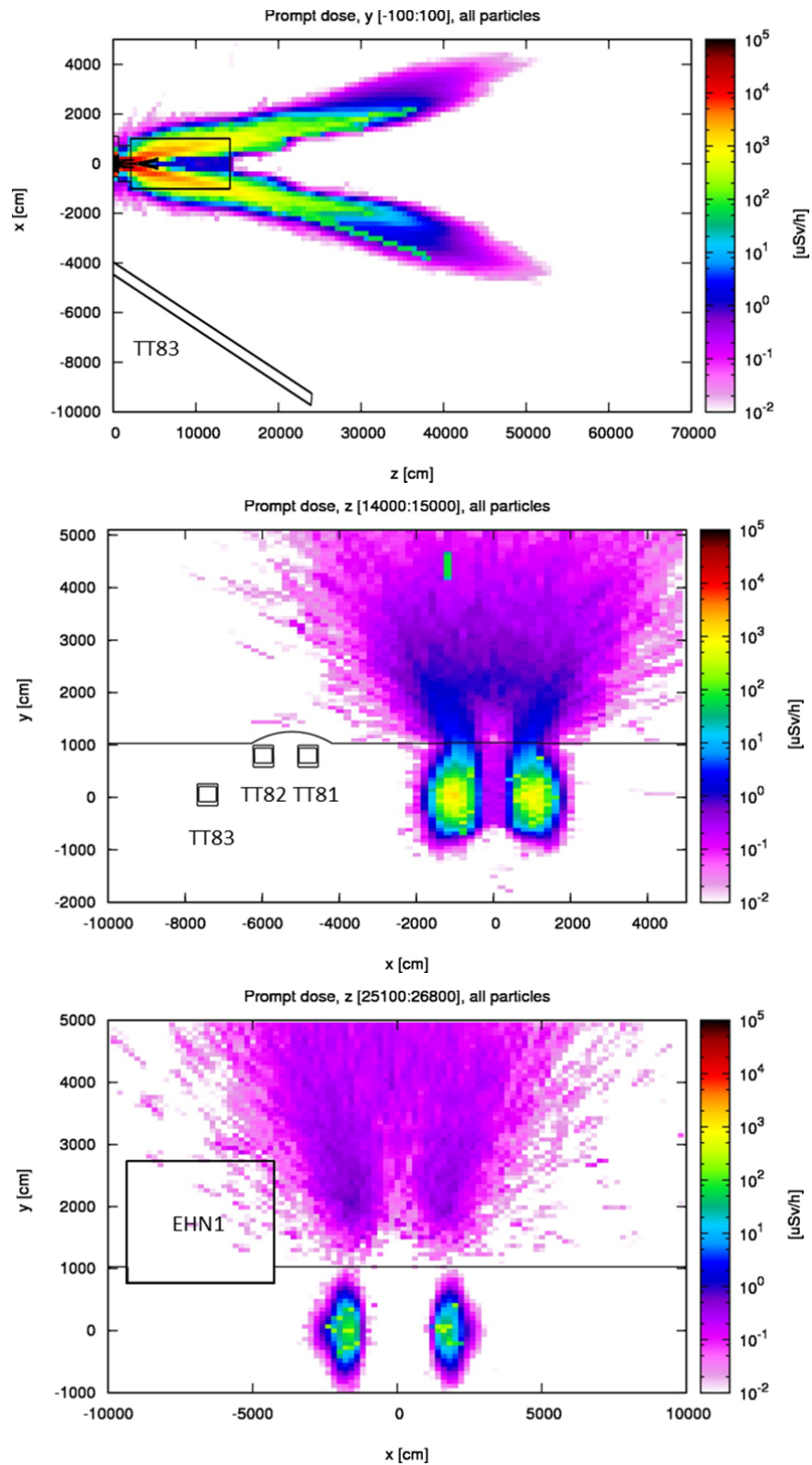
Figure 10: *Prompt dose rates (in µSv/h) in the ground and experimental facilities surrounding SHiP (top: top view at the level of the SHiP beam line, middle: cross view behind the SHiP experimental hall, bottom: cross view at the beginning of EHN1).*

Surrounding public area

According to CERN's radiation protection code F [16], if the total annual effective dose from all CERN facilities to any member of the public remains below 10 µSv/y the exposure does not require any justification and facilities are considered as optimised. In SHiP, the effective dose to members of the public is expected to be dominated by stray radiation, which means prompt radiation that still penetrates outside the shielded zones to the environment and beyond the fenced areas of CERN.

Figure 11 and Figure 12 present the preliminary annual dose rates above ground level which originate from the SHiP facility. The asymmetric shape can, besides the lack in statistics, be explained by the asymmetric concrete shielding in the target complex. At CERN's fence, which has a minimal distance of approximately 70 m to the SHiP beam line, annual dose rates are expected to be smaller than 5 µSv/y, which is an acceptable dose objective for the facility. Note that in case the soil from the excavations will be backfilled on top of the underground experimental hall, the dose rates are expected to be further reduced. A standard stray-radiation monitor for photons, muons and neutrons shall be installed at the fence closest to the most exposed area. More optimized simulations of the stray radiation and the effective dose to members of the public shall be performed at a later stage of this project.
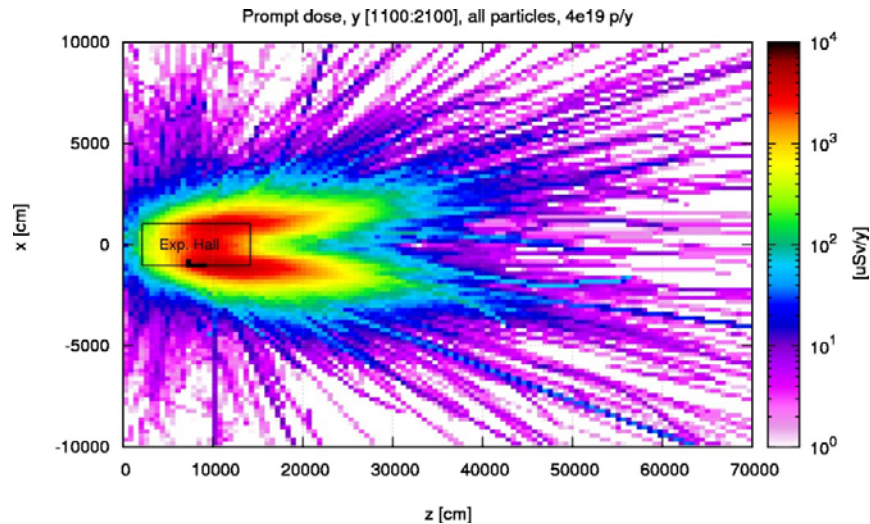
Figure 11: *Annual prompt dose rates (in µSv/y) at the ground level of the SHiP facility. The black line indicates the underground experimental hall.*

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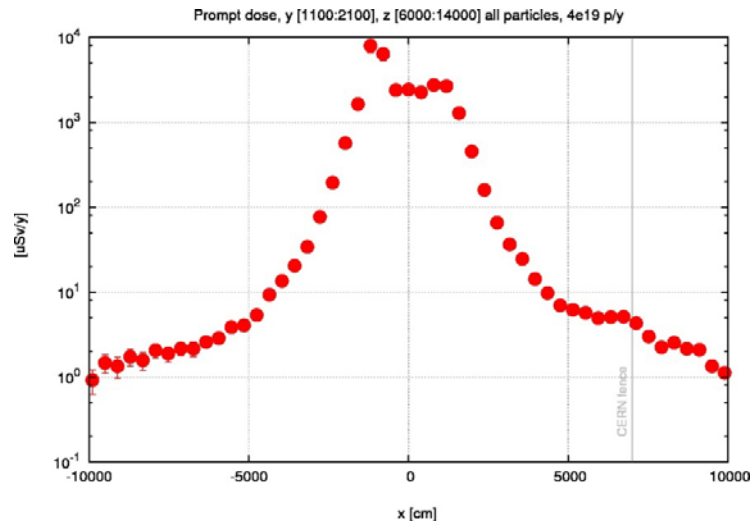
Figure 12: *Lateral cut of the annual prompt dose rates (in µSv/y) at the ground perpendicular to the beam direction. The grey line approximately indicates the CERN fence.*

2.3   Residual dose rates

The residual dose rates were conservatively estimated assuming an average beam intensity of $4 * 10^{13}$ protons per 7.2 seconds with an 81 days long operation time per year for a total of 5 consecutive years (i.e. a total of $2 * 10^{20}$ pot). They were obtained by convoluting the fluence of photons, electrons and positrons from γ- and ß-decays with the respective energy-dependent fluence-to-effective dose conversion coefficients [17]. Note that the air- and helium-filled regions were selectively set to vacuum when producing and transporting the radioactive decay products. In that way, radioactive decay products originating from the activated air and helium were ignored. This is useful since the activated air and helium are released into the environment in case of access and will therefore no longer contribute to the respective residual dose rates. The committed effective dose due to activated air and helium should be evaluated separately at a later stage of the project. When comparing the design and prompt dose rates of SHiP and CENF one can however conclude that significantly lower doses due to air and helium activation can be expected for SHIP than for CENF. For CENF, the releases of radioactive substances to the ambient air would lead to a maximum effective dose to a member of the public from a residential reference population group of 1.2 µSv/y [12, 15]. The results of the residual dose rate studies are presented in the following for the various accessible areas and different cooling times.

SHiP target complex

Figure 13 and Figure 14 show the expected residual dose rates in the SHiP target complex for different cooling times. The highest dose rates can be found in the

region of the target. They are in the order of a few 10^8 µSv/h after 1 week of cooling. The closest accessible area to it is above and next to the helium vessel enclosing the shielding. Here maximum residual dose rates of a few µSv/h after 1 week of cooling are reached considering that the helium vessel is closed and all shielding elements are in place. The residual dose rates in the target hall can further be considered negligible.

It should be noted that the residual dose levels in the adjacent CV rooms are expected to exhibit local hot spots. This is due to the fact that the ventilation and cooling units located in this area contain demineralisation cartridges which may become highly activated. Experience from the operation of the CNGS facility has shown that residual dose rates around the demineralisation cartridges may exhibit values of up to a few 10 mSv/h on contact. In order to reduce the radiological hazard arising from these units, special cartridges for fast exchange, shielded by concrete shielding blocks of 80 cm thickness should be foreseen.

Figure 13: *Residual dose rates (in µSv/h) in the SHiP target complex for different cooling times (top - bottom: 1 week, 1 month, 1 year, 5 years). Note that the air and helium activation has not been taken into account.*
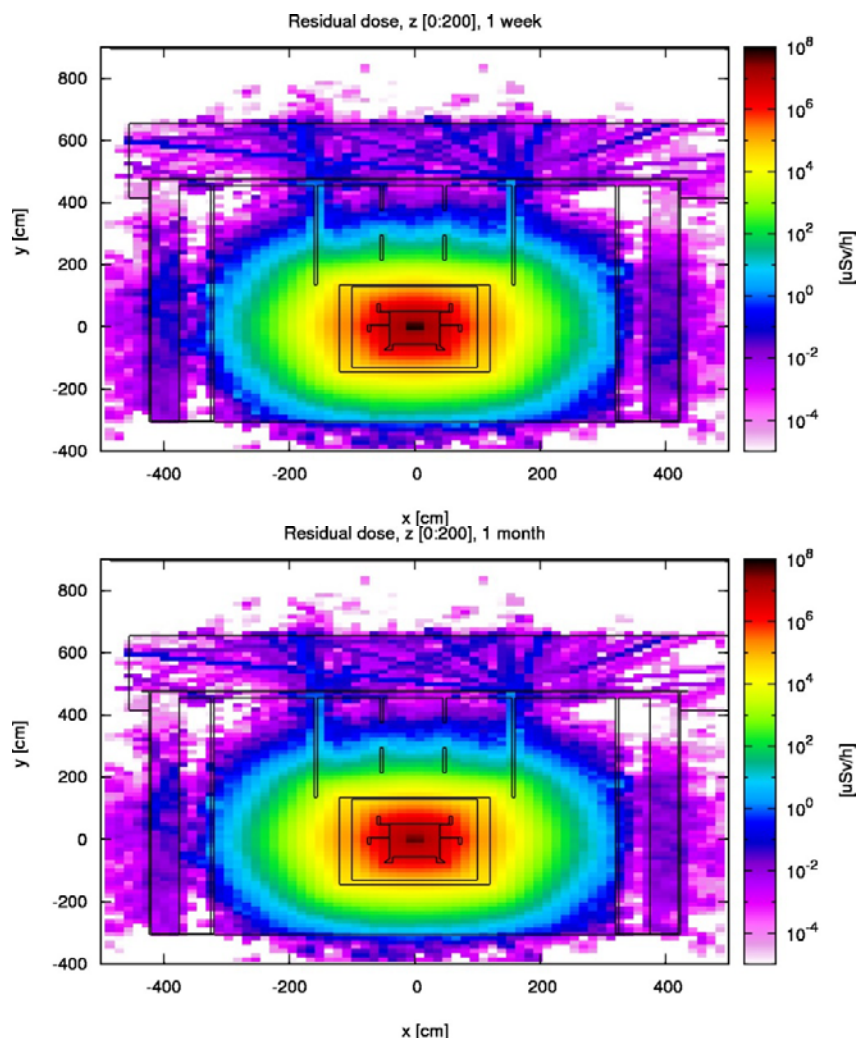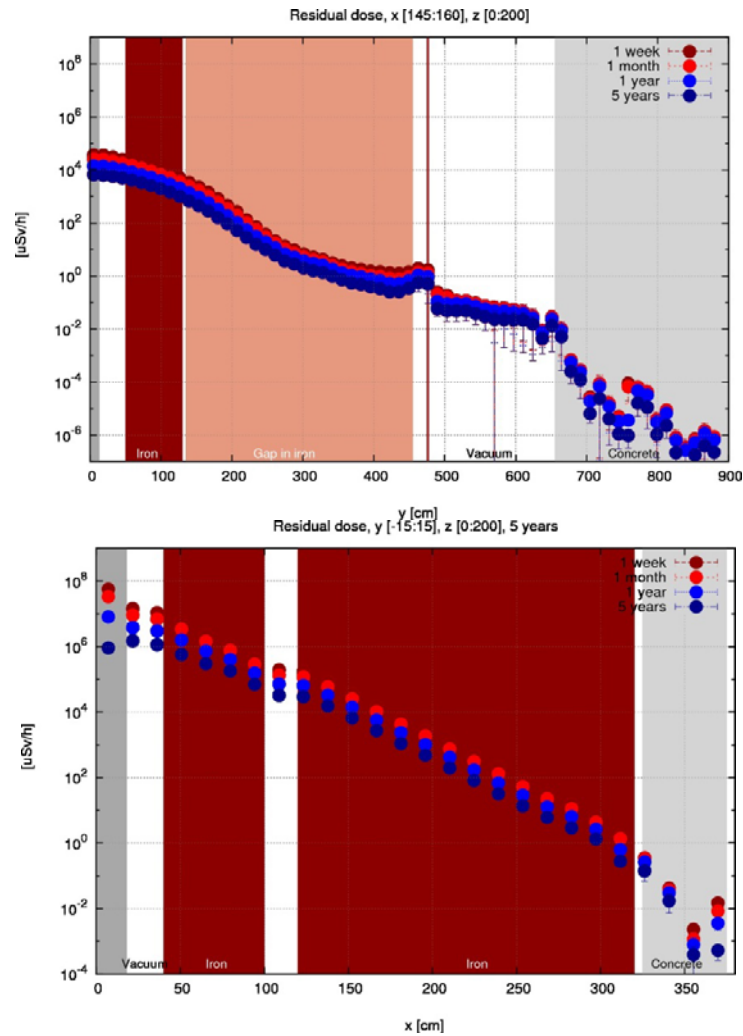
Figure 14: *Residual dose rates (in µSv/h) in the SHiP target complex for different cooling times (top: along the height at the level of the shielding gaps, bottom: along the side). Note that the air and helium activation has not been taken into account.*

Residual dose rates arising solely from the removable shielding and the target were further evaluated. This information is relevant for situations where these components must be removed from the helium vessel, e.g. in the event of a target replacement. FLUKA allows evaluating the respective emissions of an activated object in a complex environment by the possibility of selectively changing regions to vacuum when producing and transporting radioactive decay products. Radioactive decay products originating from regions switched to vacuum are ignored. Figure 15 illustrates the shielding in the target area, which was studied standalone.

Figure 15: *Outer (left) and inner (right) removable cast iron shielding in the SHiP target area, whose residual dose rates were evaluated standalone.*

Figure 16 shows the residual dose rates expected from the upper removable cast iron shielding blocks in the SHiP target area. As can be seen dose rates rapidly decrease with the distance to the target. While the bottom block exhibits dose rates of a few 10 mSv/h after 1 week of cooling, dose rates of the outer block can be considered as negligible. The studies show that the inner blocks should be handled remotely and stored in the designated shielding storage room in case of removal from the helium vessel.
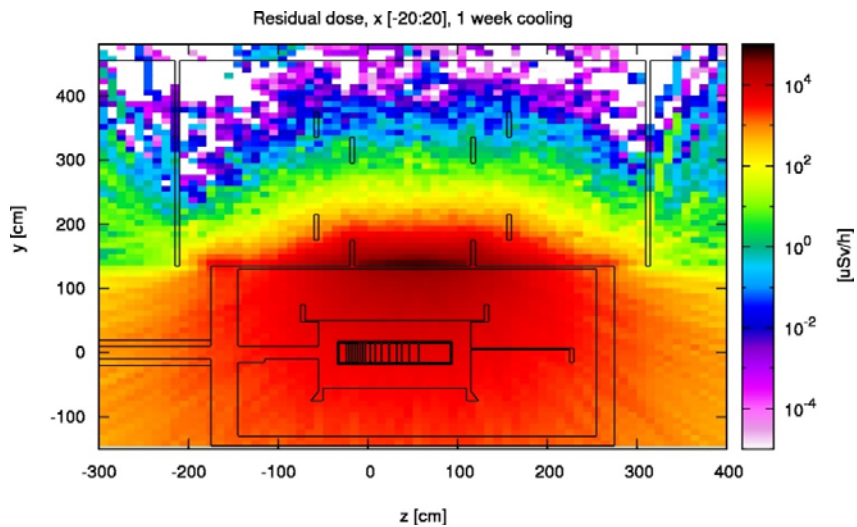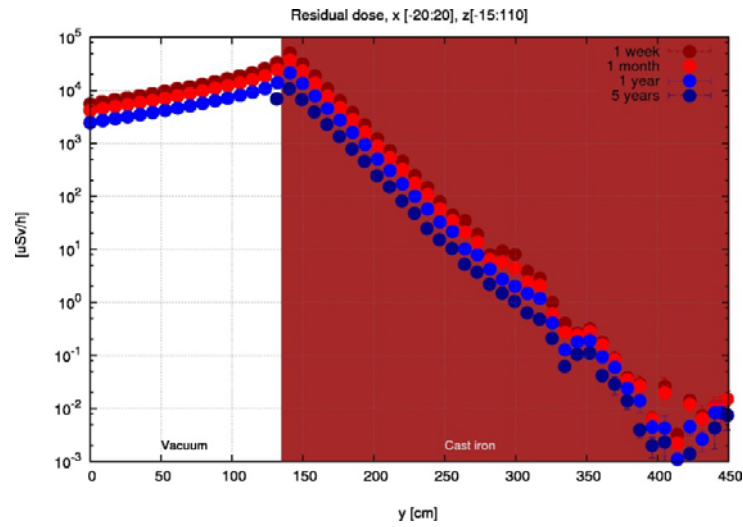
Figure 16: *Residual dose rates (in µSv/h) originating from the upper cast iron shielding blocks (top: side view after 1 week of cooling, bottom: along the height for different cooling times).*

Figure 17 illustrates the expected residual dose rates originating from the upper proximity cast iron shielding block. Here the dose rates reach up to a few 10 Sv/h after 1 week of cooling still amounting to a few 100 mSv/h at the upper, least activated, part of the block. The studies demonstrate that the proximity shielding must be handled remotely and stored in the designated shielding storage room when being removed from the helium vessel.
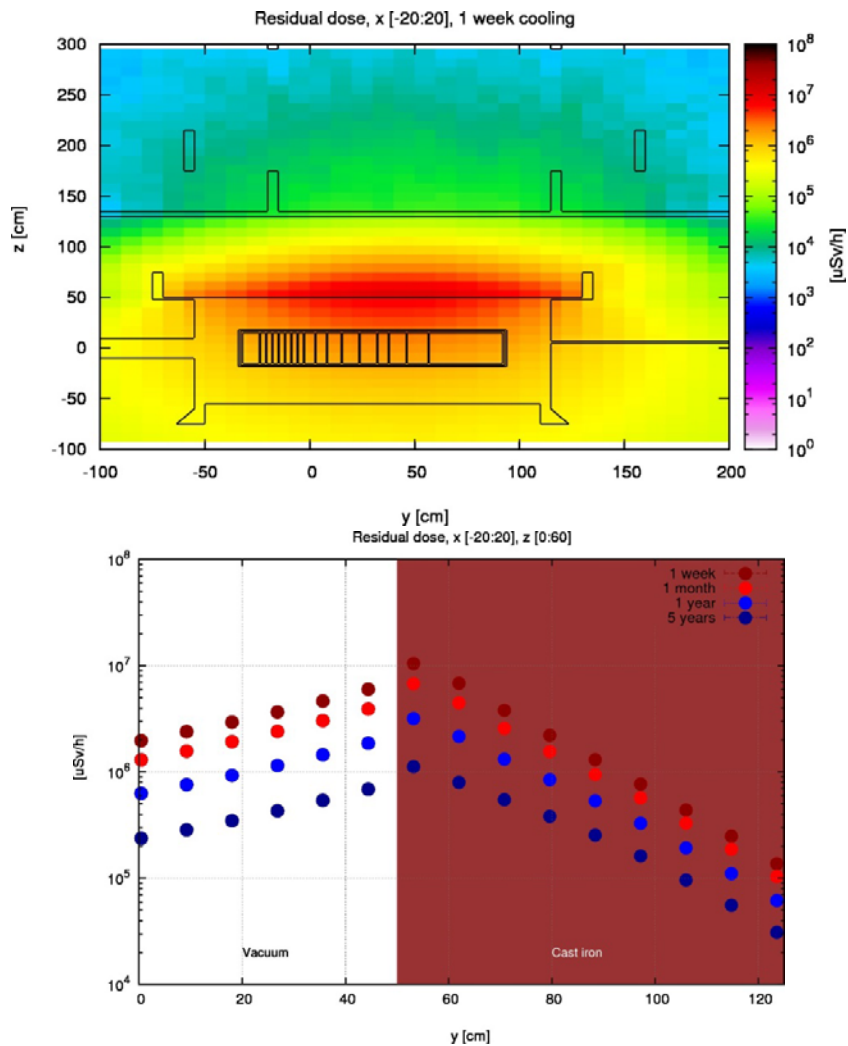
Figure 17: *Residual dose rates (in µSv/h) originating from the upper proximity cast iron shielding block (top: side view after 1 week of cooling, bottom: along the height for different cooling times).*

Figure 18 presents the residual dose rates resulting from the molybdenum-tungsten target. The dose rates originating from the first part of the target, which is the one composed of molybdenum, clearly dominate. In the molybdenum part, dose reach up to 1000 Sv/h rates dropping down to a surface dose rate of a few 10 Sv/h after 1 week of cooling. From the tungsten part a maximum surface dose rate of 10 Sv/h after 1 week of cooling is expected. Assuming that the target will be stored in a special target pit as described in [6] for a cool down period of at least one year, the surface dose rates of the target should remain below 5 Sv/h. The studies show that remote handling of the target is a crucial factor in the design. For more information about the remote handling system please refer to [6].
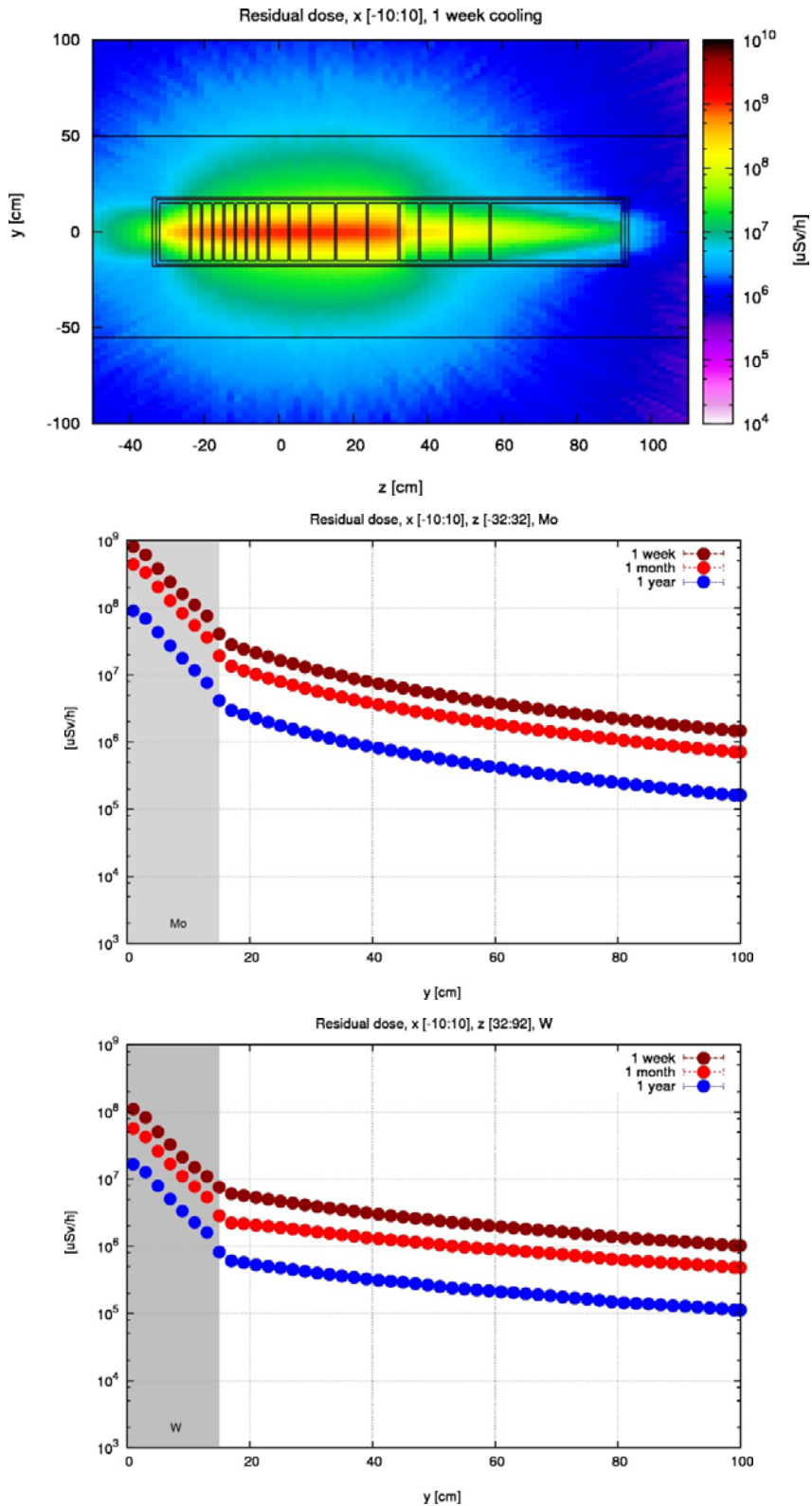
Figure 18: *Residual dose rates (in µSv/h) originating from the molybdenum-tungsten target (top: side view after 1 week of cooling, middle: along the height in the region of molybdenum, bottom: along the height in the region of tungsten).*

Furthermore the amount of shielding necessary for transporting the activated target was investigated. For this purpose it was assumed that the target would be stored in the temporary target storage for one year of cool down before being transported. For transport the target would be placed in a special transport cask which would allow reducing the remaining residual dose of 5 Sv/h down to 2 mSv/h. Table 3 summarizes the shielding thickness requirements of such a transport cask in case that it is made of iron and lead, respectively. It can be seen that molybdenum, with its main dose contribution from Y-88, is the more stringent factor calling for 26 cm of iron or 16 cm of lead shielding [6].

Shielding material	Target material	Required shielding
Iron (7.8 g/cm^3)	Tungsten	23 cm
	Molybdenum	26 cm
Lead (11.3 g/cm^3)	Tungsten	12 cm
	Molybdenum	16 cm

Table 3: *Shielding thickness requirements for different shielding materials assuming a dose rate reduction from 5 Sv/h to 2 mSv/h.*

3   SHiP primary beam extraction

The radiological assessment of the SHiP primary beam extraction involves two main topics, the SPS extraction region and the dedicated SHiP beam line. The following two chapters summarize the respective considerations for these issues.

3.1   SPS extraction

The SHiP beam extraction from the SPS will be a slow resonant extraction from the SPS LSS2 using existing extraction equipment and transfer of the beam along TT20 up to a switch into a dedicated SHiP transfer line [10]. The activation of the SPS extraction region will increase in proportion to the total number of protons extracted per year - with the SHIP extraction in addition to the North Area requirement.

To evaluate the expected increase of the activation levels, recent PMI data from BA2 were investigated. Even though the highest fluxes were by far achieved in 2007, this year was not taken as reference as it followed years with low intensity operation (2006) and no beam at all (2005) and therefore presents atypical residual dose rates. The data from 2010 with 8.7*10^{18} protons extracted to the North Area was instead considered more representative. The eight PMI monitors available were located at about 1 m from the beam axis, but not always at the most radioactive locations. Figure 19 shows the data from the PMI detector reading the highest dose rates. The data during beam operation are not useable

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due to saturation, however the data in the ion run and shutdown period are reliable. The data show that the ion runs do not contribute to a dose increase and that the cool-down is fast in the beginning, but after a few days the decrease is extremely slow, a factor of approximately 2 or lower over a month.
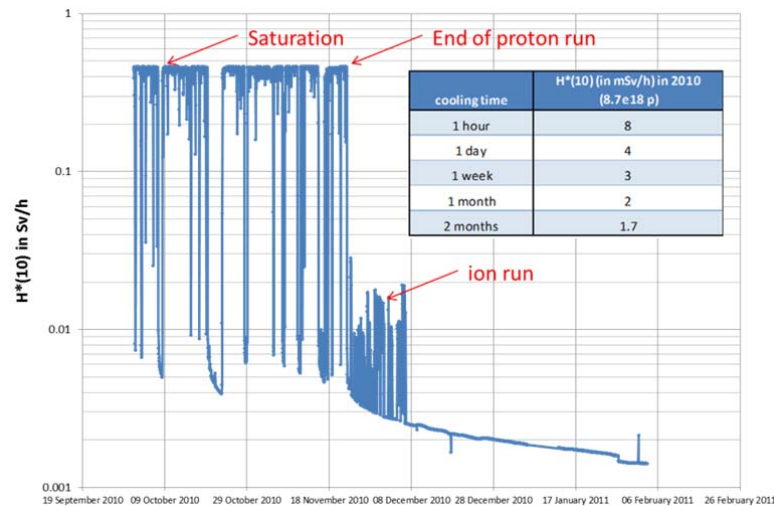
Figure 19: *Dose rate behavior in BA2 seen by the PMI detector PMIU202 in 2010 (i.e. 8.7×10^{18} protons). Other PMI readings in BA2 follow the same behavior (with slightly lower values).*

A radiation protection survey was made 17 days after the end of the 2010 proton run. The dose rates at 40 cm distance to the ZS septum were in the 10-16 mSv/h range. With the annual SHIP intensities of $4*10^{19}$ protons in addition to the North Area intensities of $1*10^{19}$ protons, this implies about 6 times higher dose rates, thus ~70 mSv/h.

The conclusion from the above studies is that it is of prime importance to reduce the losses at the ZS and the rate of failures. For information about possible measures to reduce the losses and failure rates please refer to [10]. Intervention times and methods should further be optimised, e.g. by using robots and remote handling, to lower the exposure of personnel to radiation. Also the materials used should be evaluated.

3.2 SHiP beam line

The radiological assessment of the dedicated SHiP beam line was based on FLUKA simulations. It includes the study of prompt dose and soil activation around the existing tunnels TDC2 and TCC2 as well as prompt dose expected in the new SHiP beam line due to beam operation in the North Area. These factors influence the construction work for the SHiP beam line and facility. The details and results of these studies are summarized in the following.

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Furthermore it should be noted, that for the connection of the Junction cavern of the SHiP beam line to TDC2 a 100 m long section of TDC2 is planned to be dismantled and demolished. All the concrete originating from the demolition of the TDC2 structures will be classified as radioactive. The civil engineering workers will therefore require safety trainings and will need to be individually monitored. Additionally, the CE contractor must be authorised by his national authority to send workers in radiation areas of a third party (for more information see [18]). As the civil engineering work implies radioactive dust, the work procedures and the measures to protect the work site must further be defined. Also the (temporarily) storage and disposal or, even more favourable, the reuse of the radioactive waste will have to be considered.

3.2.1 FLUKA input

The FLUKA model of the present TT20 line, which was developed by EN-STI, was supplemented with the SHiP extraction cavern and tunnel according to the 9 MBB beam line configuration. The 9 MBB configuration is, from an RP perspective, the most critical one as it implies the smallest deflection angle of the SHiP beam line with respect to the TT20 line. Expected differences to the 13 MBB and 17 MBB beam line configuration are discussed in the following. Figure 20 depicts the present and new FLUKA model. Next to the tunnel structures they include the beam splitters 1 and 2 in TDC2 as well as the primary targets T2, T4 and T6 with their nearby beam line and shielding elements in TCC2. The surrounding soil was defined like in the FLUKA model of the SHiP facility as specified in Section 2.1.
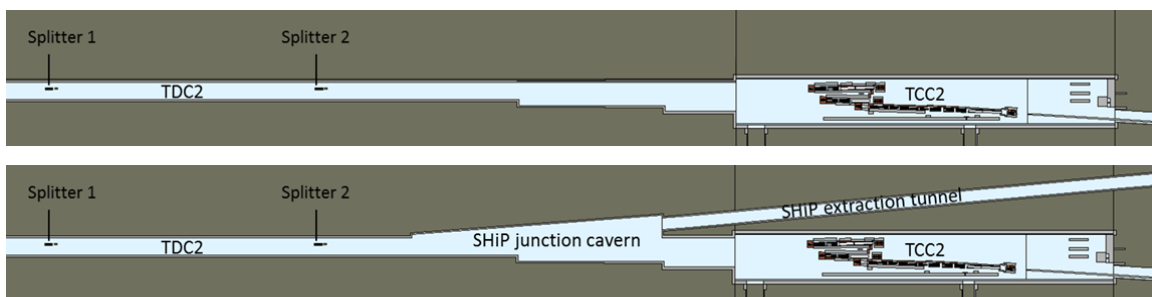
Figure 20: *Top view of the TT20 lines as of present (top) and including the SHiP extraction cavern and tunnel (bottom).*

For the evaluation of the prompt dose rates and the soil activation around TDC2 and TCC2 as well as for the prompt dose rates expected in the new SHiP beam line during beam operation in the North Area different operational and accident scenarios were used. Table 4 summarizes the main assumptions of these scenarios. For normal beam operation the contributions from continuous 5% beam loss on splitter 1 and 2 and beam impinging on the T2, T4 and T6 targets were investigated. As accident scenario the loss of a full spill on splitter 1 or 2 was considered too conservative due to the extended size of the beam and the

interlock by the beam loss monitors. Instead a beam loss of 25% of one spill on splitter 1 or 2 was deemed adequate as a worst case accident scenario.

Operational scenarios	5% beam loss at splitters	• 5% of the beam is lost each at splitter 1 and 2 in TDC2
	Beam on targets in TCC2	• Beam on T2, T4 and T6 targets in TCC2
Accident scenarios	25% beam loss at splitter 1	• For a worst case calculation 25% of the beam lost at one splitter was assumed
	25% beam loss at splitter 2	

Table 4: *Operational and accident scenarios considered for the radiological assessment of the SHiP beam line* **[19]***.*

The beam parameters employed in the given operational and accident scenarios are listed in Table 5. The average beam intensities were used to evaluate the soil activation. For a correct estimation of the long-lived radio-nuclides in the soil, a period dating back to 1976 and ending in 2017, thus before the beginning of LS2, when the civil engineering works for the SHiP extraction cavern and tunnel are foreseen, was investigated. For the evaluation of the prompt dose rates, the maximum beam intensities expected for 2015 until 2017 were instead utilized.

	Average beam intensity [pot/y]			Max. beam intensity [p/s]
	1976 – 2011	2012	2015 – 2017	2015 – 2017
T2	3.1E18	1.6E18	1.6E18	1.1E11
T4	1.6E18	8.4E17	7.8E18	5.6E11
T6	1.6E19	7.8E18	7.8E18	5.6E11
Splitter 1/2	2.2E19[5]	1.1E19[5]	1.9E19[5]	4.5E13/16.8 = 2.7E12

Table 5: *Beam parameters used for the radiological assessment of the SHiP beam lines* **[19, 20, 21]***.*

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[5] Estimated with T2+T4+T6+10%.

3.2.2 Prompt dose rates

The prompt dose rates were evaluated by convoluting the fluence of neutrons, protons, charged pions, muons, photons, electrons and positrons with the respective energy-dependent fluence-to-effective dose conversion coefficients. In contrary to the evaluation of the SHiP facility, the contribution from electromagnetic processes was included here as it is expected to be non-negligible due to the lack of shielding material inside the tunnels.

Figure 21 presents the prompt dose rates in the present TDC2 and TCC2 tunnels and the surrounding soil in case of a continuous beam loss of 5% and 10%[6] at splitter 2. The attenuation along the side of TDC2 shows that a soil thickness of at least 8 m is necessary to reduce the dose rates next to the tunnel down to 0.5 µSv/h.

From these studies it can be concluded that a minimum soil thickness of 8 m around the tunnel walls of TDC2 and TCC2 must be kept during beam operation in the North Area. How this requirement influences the construction works for the new SHiP beam line is further discussed in [2].

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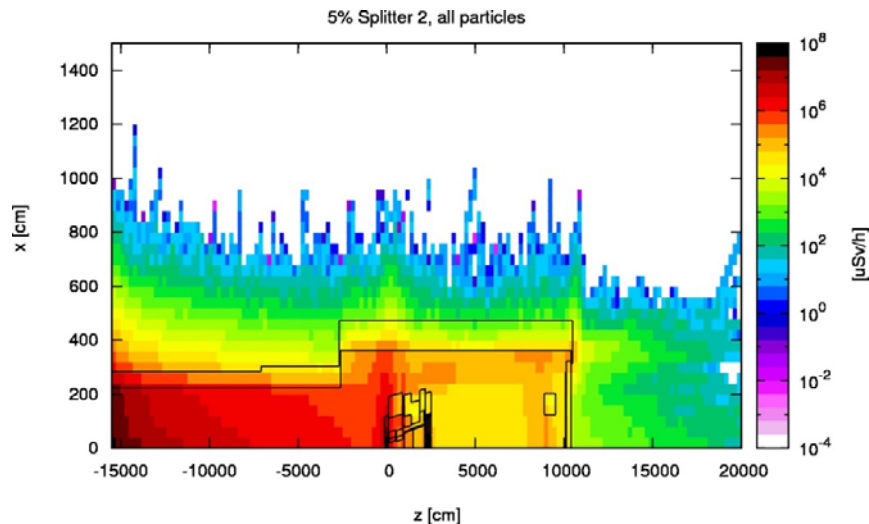
[6] 10% beam loss was assumed to further take the beam loss at splitter 1 into account.
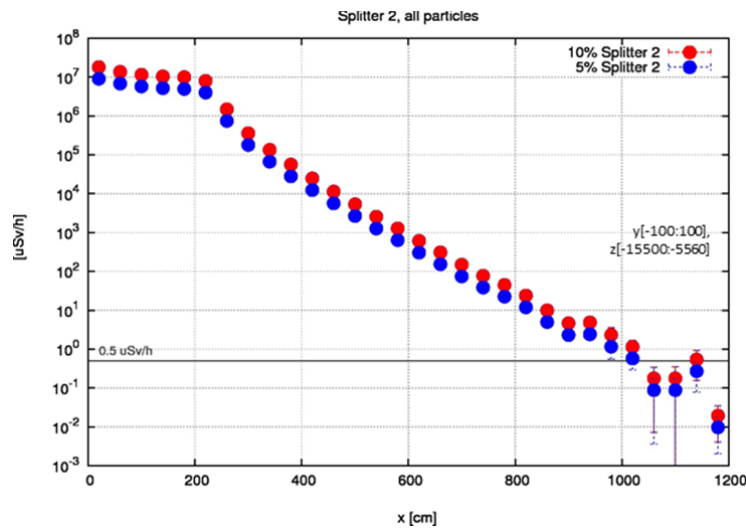
Figure 21: *Prompt dose rates (in µSv/h) around TDC2 and TCC2 in continuous beam loss at splitter 2. (top: top view of TCC2 and TDC2 for 5% beam loss at splitter 2, bottom: along the side of TDC2 for 5% and 10% beam loss at splitter 2).*

Figure 22 until Figure 24 present the prompt dose rates expected in the new SHiP extraction tunnel during beam operation in the North Area for the various operational and accident scenarios with losses at splitter 1 and/or 2 as specified in Table 4. The contribution from all particles, neutrons and muons is shown separately. All scenarios show similar distributions with doses from neutrons dominating at the beginning of the tunnel and decreasing rapidly along the tunnel length, such that after approximately 50 m doses from muons begin to prevail. While an accidental beam loss at splitter 1 and 2 yields 20 mSv and 40 mSv, respectively, a continuous 5% beam loss at splitters 1 and 2 during normal operation results in 650 mSv/h. For the latter, the contribution from muons at the beginning of the tunnel is expected to be of about 60 mSv/h. At the end of the extraction tunnel, thus the beginning of the SHiP facility, dose rates still amount to 20 mSv/h. The shielding requirements for a further reduction of the dose rates to allow for a non-designated area in the SHiP facility are discussed in the following.
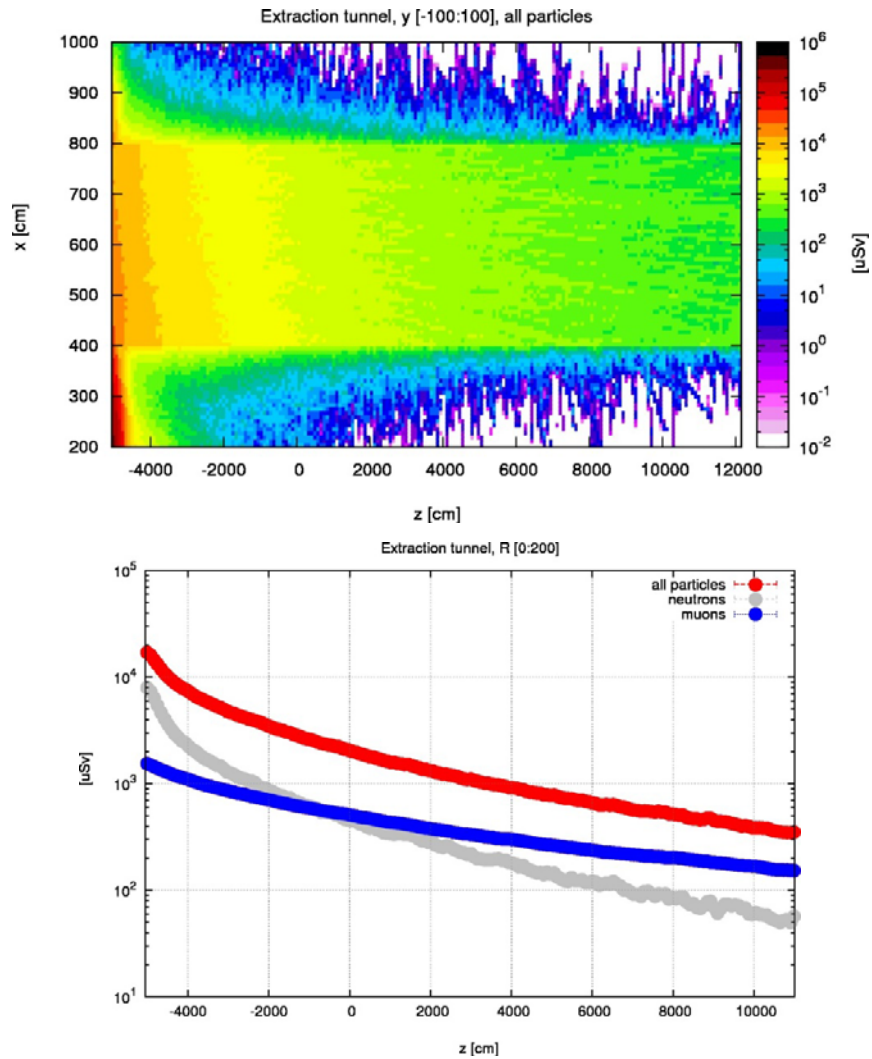
Figure 22: *Prompt dose rates (in µSv) in the SHiP extraction tunnel according to the 9 MBB beam line configuration for a loss on splitter 1 (top: top view for all particles, bottom: along the length of the tunnel for all particles, neutrons and muons).*
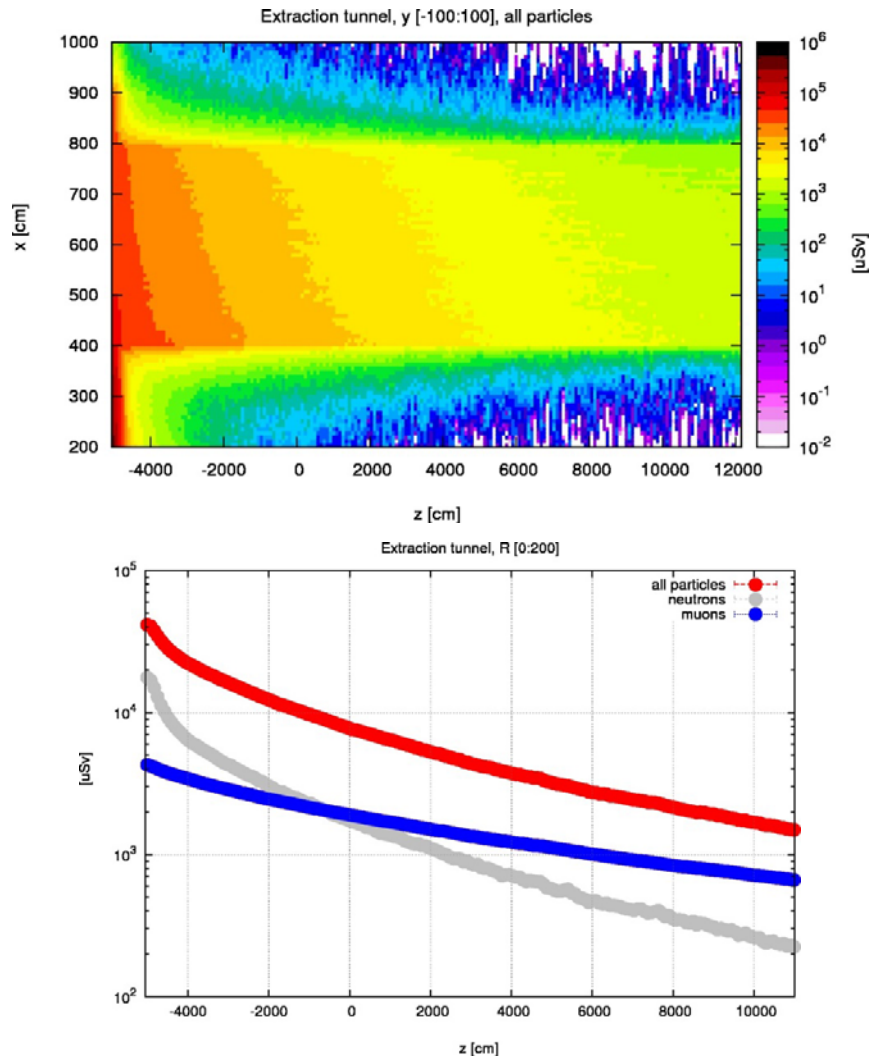
Figure 23: *Prompt dose rates (in µSv) in the SHiP extraction tunnel according to the 9 MBB beam line configuration for a loss on splitter 2 (top: top view for all particles, bottom: along the length of the tunnel for all particles, neutrons and muons).*

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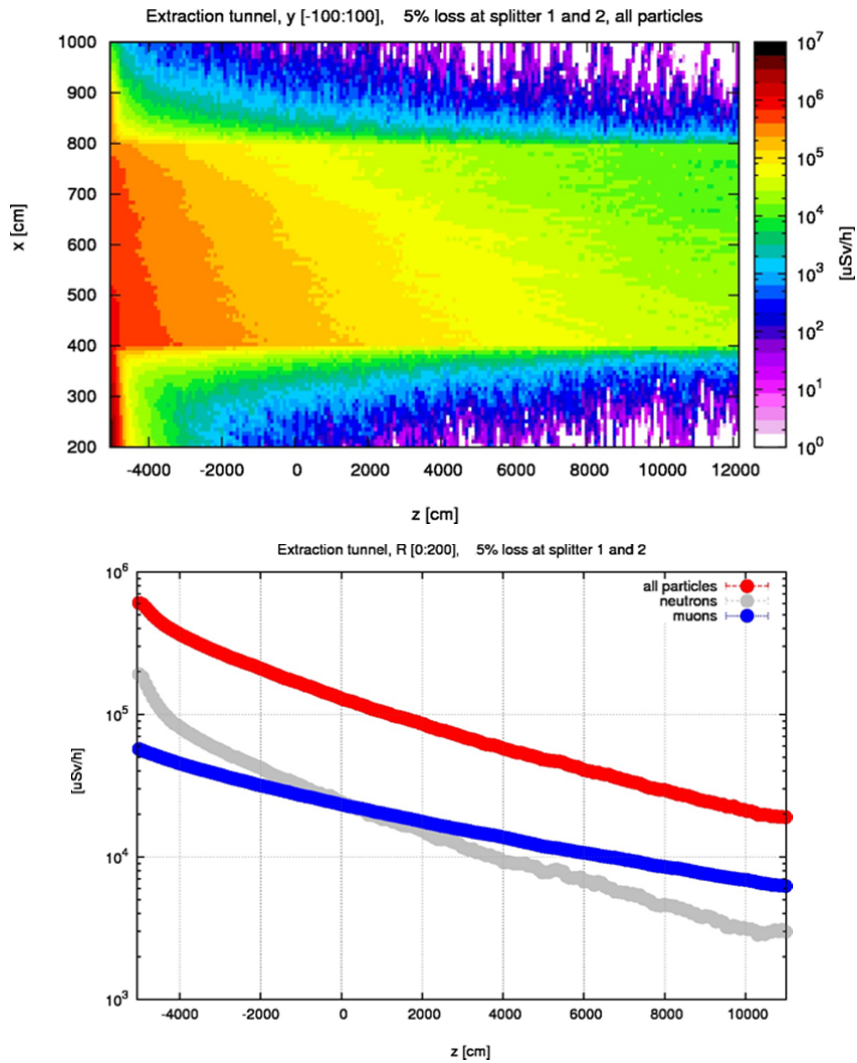
Figure 24: *Prompt dose rates (in µSv/h) in the SHiP extraction tunnel according to the 9 MBB beam line configuration for a continuous 5% beam loss at splitter 1 and 2 (top: top view for all particles, bottom: along the length of the tunnel for all particles, neutrons and muons).*

Furthermore, doses expected in the new SHiP extraction tunnel due to beam impinging on the T2, T4 and T6 primary targets were evaluated. Figure 25 illustrates the respective results, showing that the highest dose rates can again be found at the beginning of the tunnel. The contribution of back streaming of radiation from TCC2 into TDC2, where the SHiP beam line branches off, is thus larger than the one of radiation traversing the soil along the side of the tunnel. The maximum dose rates expected in the SHiP extraction tunnel are of the order of 1 mSv/h.

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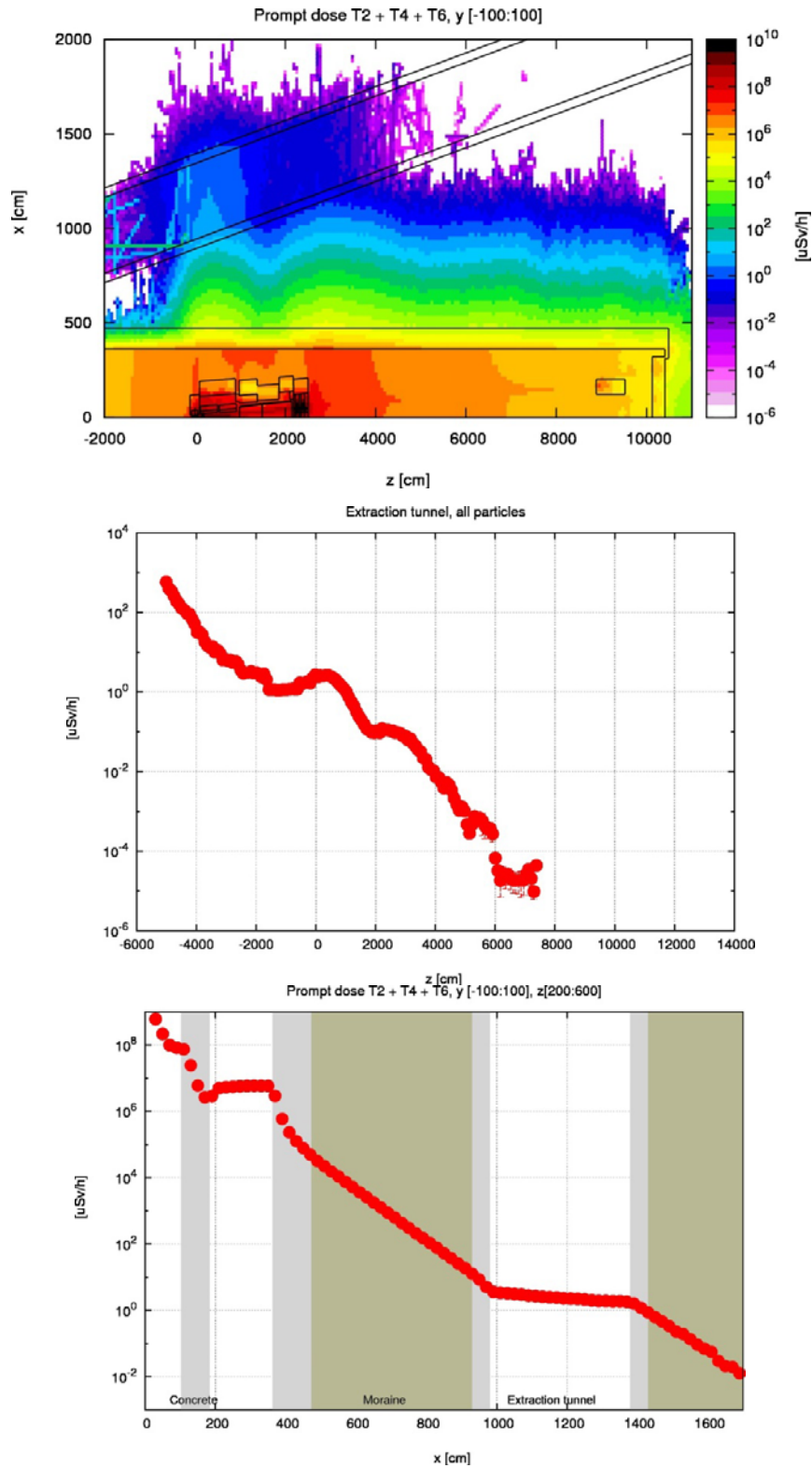
Figure 25: *Prompt dose rates (in µSv/h) for all particles in the SHiP extraction tunnel according to the 9 MBB beam line configuration for beam on targets T2, T4 and T6 (top: top view of TCC2 and the SHiP extraction tunnel, middle: along the length of the tunnel for all particles, neutrons and muons, bottom: along the side of the T2 target).*

The maximum prompt dose rates expected in the new SHiP extraction tunnel for the various operational and accident scenarios are summarized in Table 6. The operational scenario with continuous 5% beam loss at splitters 1 and 2 yielding 650 mSv/h is by far the most critical one. Note that for the 13 MBB and 17 MBB configuration the dose rates are expected to be slightly reduced due larger deflection angles of the SHiP beam line with respect to the TT20 line.

Operational scenarios	5% beam loss at splitters	650 mSv/h (60 mSv/h for muons)
	Beam on targets in TCC2	1 mSv/h
Accident scenarios	25% beam loss at splitter 1	20 mSv
	25% beam loss at splitter 2	40 mSv

Table 6: *Expected prompt dose rates at the beginning of the SHiP extraction tunnel according to the 9 MBB beam line configuration for the various operational and accident scenarios.*

The shielding requirements to allow for a non-designated area in the SHiP facility when under construction during beam operation in the North Area were further evaluated. Therefore, the attenuation in the SHiP extraction tunnel in case that it is filled with concrete was studied. Figure 26 shows the attenuation of the prompt dose rates along the length of the tunnel when filled with concrete for an accidental beam loss of 25% at splitter 2. Low-energy neutrons are quickly absorbed in the concrete, so that already after 5 m the contribution from muons dominates the total dose rates. For muons an attenuation of a factor 10 every 10 m can be deduced from the spectrum. When applying this reduction factor to the worst case scenario, which is that of a continuous 5% beam loss at both splitters, one can conclude that about 50 m of concrete or 20 m of iron would be necessary to reduce the doses down to 0.5 µSv/h. Considering an extraction tunnel cross-section of 4 x 4 m^2, a total shielding volume of 800 m^3 of concrete or 320 m^3 of iron would thus be required. The possibility of utilizing the iron shielding actually foreseen for the SHiP target facility should be investigated, which would add up to approximately 390 m^3 of shielding usable for this purpose. Once the SHiP facility would be put into operation the shielding could be installed in its actual position in the target facility. To avoid activation of the iron shielding and facilitate its installation in the target facility about 1 m of concrete should be placed upstream of it in the extraction tunnel. A total of 16 m^3 of concrete would

thus additionally be required, which could however be reused later on as shielding in the SHiP facility.
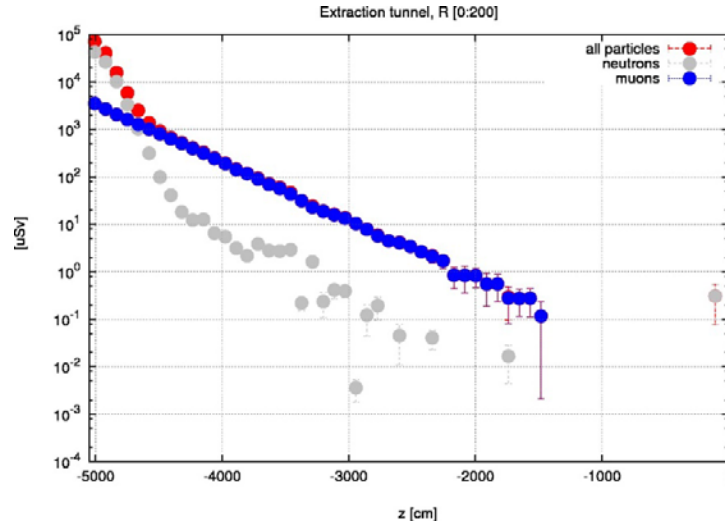
Figure 26: *Prompt dose rates (in µSv) along the length of the SHiP extraction tunnel according to the 9 MBB beam line configuration when filled with concrete for a loss on splitter 2. Contributions from all particles, neutrons and muons are shown separately.*

3.2.3 Soil activation

The soil activation around TDC2 and TCC2 was estimated with the help of the residual dose rates. The latter were evaluated assuming normal beam operation scenario in the North area dating back to 1976, as specified in Table 5, such that long-lived radio-nuclides are adequately accounted for. Doses were obtained by convoluting the fluence of photons, electrons and positrons from γ- and ß-decays with the respective energy-dependent fluence-to-effective dose conversion coefficients [17].

Figure 27 illustrates the residual dose rates around TDC2 for normal beam operation with a 5% beam loss at splitters 1 and 2. The decrease of doses next to the tunnel is given for different cooling times. Small differences between the various cooling times show that mostly long-lived radio-nuclides dominate the dose rates. After a distance of 3 m to the tunnel walls the dose rates drop below 0.1 µSv/h, which corresponds to less than 1 LE[7] [22], meaning that the soil might be considered as non-radioactive according to [23].

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[7] Exemption limits for waste characterization based on design limits representing the minimum of the recommended exemption limits by IAEA, Euratom and Swiss legislation.

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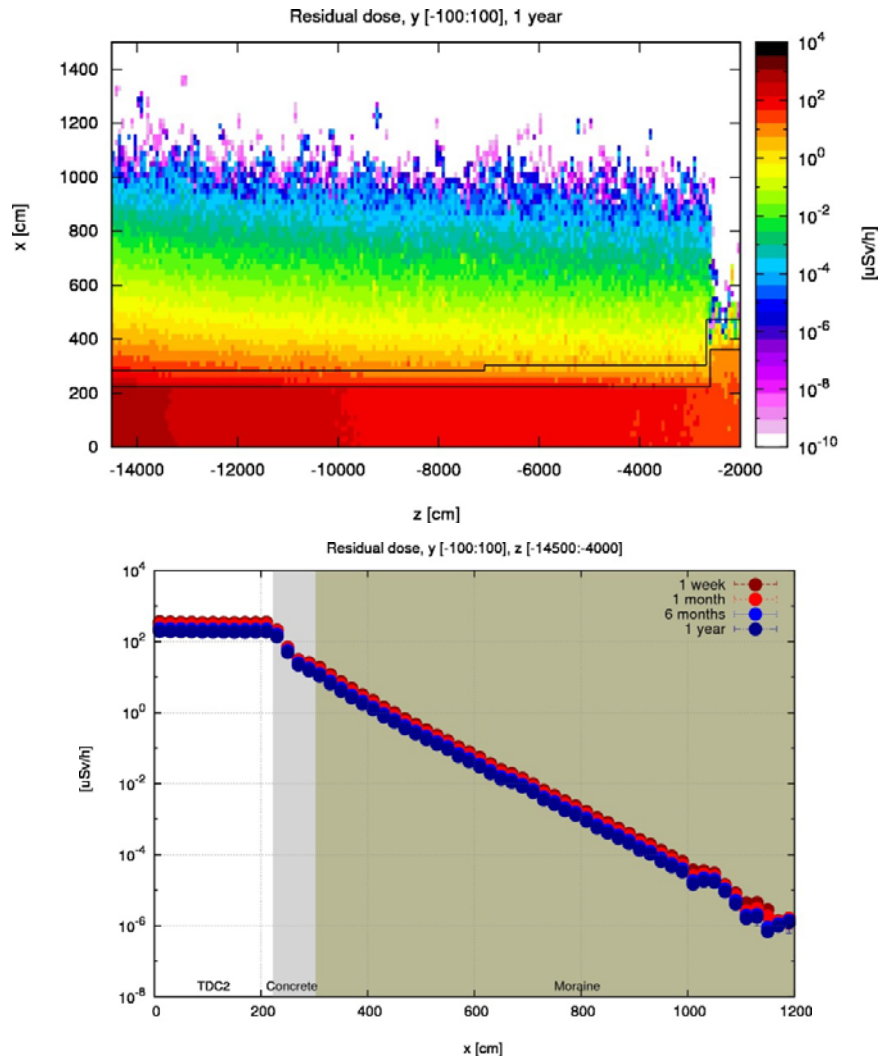
Figure 27: *Residual dose rates (in µSv/h) next to TDC2 for 5% beam loss at splitters 1 and 2 (top: top view for 1 year of cooling, bottom: along the side for different cooling times).*

Figure 28 further presents the residual dose rates around TCC2 for normal beam operation with beam impinging on the T2, T4 and T6 targets. Here again, the decrease of doses next to the tunnel is given for different cooling times, manifesting relatively small differences between the various cooling times due to long-lived radio-nuclides. After a distance of 2 m to the tunnel walls the dose rates drop below 0.1 µSv/h.
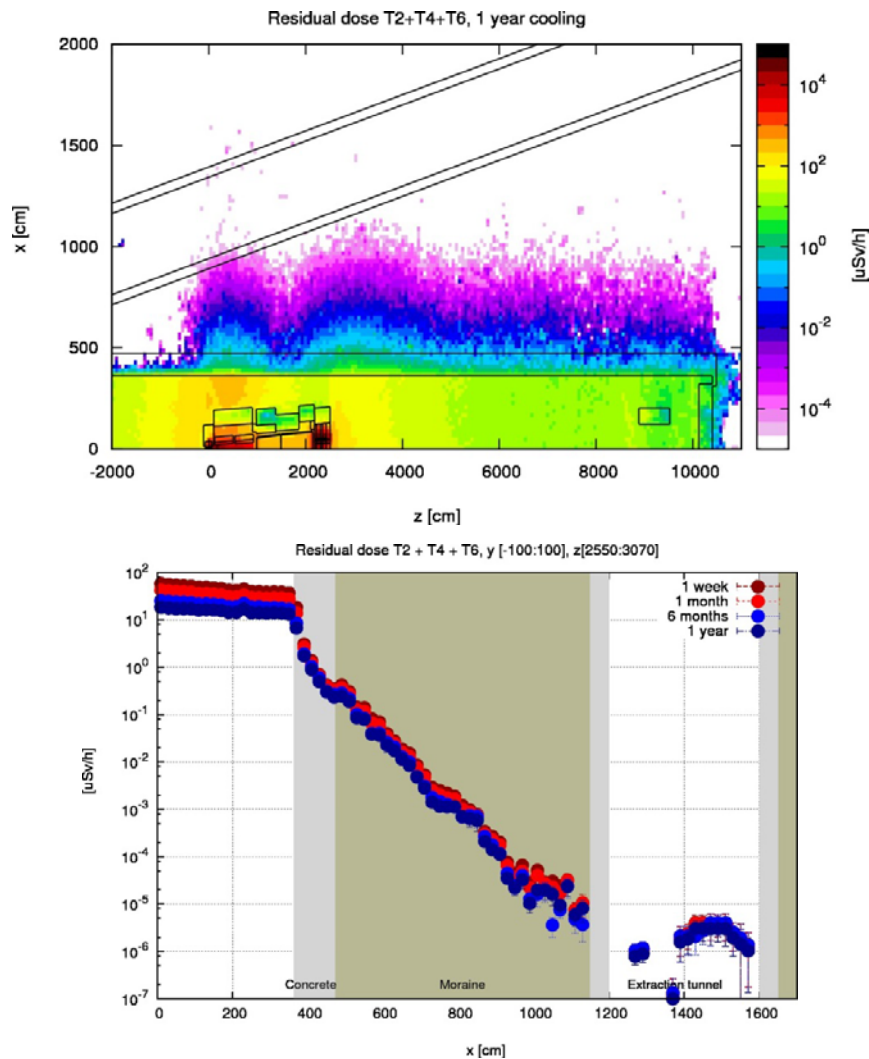
Figure 28: *Residual dose rates (in µSv/h) next to TCC2 for beam on targets T2, T4 and T6 (top: top view for 1 year of cooling, bottom: along the side for different cooling times).*

From the above studies one can conclude that the present soil activation next to TDC2 and TCC2 can be considered negligible at a respective distance of 3 m and 2 m to the tunnel walls. To verify the amount of soil activation it is advised to take soil samples in this area. Any civil engineering work beyond the above-given limits requires CE workers classified as Radiation Workers. In this case the workers need to receive all required radiation protection safety trainings and need to be individually monitored. Additionally, the CE contractor must be authorised by his national authority to send workers in radiation areas of a third party (for more information see [18]).

4 Conclusion

A radiological assessment for the design of the SHiP facility was carried out in order to respect the applicable CERN radiation protection legislation regarding doses to personnel as well as the environmental impact. The main results are summarized below:

1. The SHiP target complex was designed under the condition that the target hall and the access building to the underground experimental hall can be accessed during beam operation and classified as a Supervised Radiation Area with low occupancy (< 15 µSv/h). On the contrary, no access during beam operation will be permitted to the SHiP target bunker or the experimental hall.

2. Prompt dose rates in the soil surrounding the SHiP facility drop down to below 1 mSv/h and thus do not exceed the envisaged limit to keep ground activation at an acceptable level.

3. The area above the SHiP underground experimental hall exhibits dose rates of a few µSv/h. This area should therefore either be fenced off, or even more favourable, the soil from the excavations should be backfilled on top of the experimental hall such that the dose rates would be further reduced down to a level allowing for a non-designated area.

4. For the accident scenario with the loss of one full spill during an interruption of the muon shield magnets dose below 0.1 µSv is expected in the most affected accessible area, which is the area above the underground experimental hall.

5. Prompt dose rates originating from the SHiP facility do not affect the existing beam lines TT81, TT82 and TT83 or the present area classification of the EHN1 experimental hall, which corresponds to a Supervised Radiation Area.

6. The stray radiation at any point outside the fenced CERN site should not cause annual effective doses to any member of the public exceeding 5 µSv/y. Note that in case the soil from the excavations will be backfilled on top of the underground experimental hall, the dose rates and therefore the environmental impact of the facility are expected to be further reduced. A standard stray-radiation monitor for photons, muons and neutrons shall be installed at the fence closest to the most exposed area.

7. After 5 years nominal operation dose rates above and next to the helium vessel enclosing the shielding are of a few µSv/h, but up to a few 100 mSv/h after one week of cooling at the removable cast iron shielding. The surface dose rate of the target reaches a few 10 Sv/h after 1 week of cooling. Remote handling and designated storage areas are therefore foreseen for these elements [6].

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8. Assuming that the target will be stored in a special target pit for a cool down period of at least one year, the surface dose rates of the target should remain below 5 Sv/h. Shielding requirements were evaluated to reduce this dose to 2 mSv/h to allow for transport after at least one year of cooling in the temporary storage. The shielding thickness of such a transport cask would have to be of 26 cm of iron or 16 cm of lead.

9. The induced radioactivity in the SPS extraction region is expected to increase significantly with SHIP in addition to the North Area operation. Particularly at the ZS septum losses and failure rates should therefore be reduced. Intervention times and methods should further be optimised, e.g. by using robots and remote handling, to lower the exposure of personnel to radiation. Also the materials used should be evaluated.

10. During beam operation in the North Area a minimum soil thickness of 8 m around the tunnel walls of TDC2 and TCC2 must be respected by civil engineering.

11. The soil activation around TDC2 and TCC2 is expected to drop to below 0.1 µSv/h (corresponding to approximately 1 LE of the new design exemption limits) at 3 m and 2 m from the tunnel walls, respectively. To verify the amount of soil activation it is advised to take soil samples in this area. Any civil engineering work beyond the above-given limits requires CE workers classified as Radiation Workers.

12. The maximum prompt dose rates expected in the new SHiP extraction tunnel during beam operation in the North Area are due to continuous 5% beam loss at splitters 1 and 2 yielding 650 mSv/h.

13. The shielding requirements to allow for a non-designated area in the SHiP facility when still under construction during beam operation in the North Area were evaluated. About 50 m of concrete or 20 m of iron would be necessary to reduce the doses down to 0.5 µSv/h. A total shielding volume of 800 m^3 of concrete or 320 m^3 of iron in the extraction tunnel would thus be required. Here the iron shielding actually foreseen for the SHiP target facility could be used, which would add up to approximately 390 m^3 of shielding usable for this purpose. Once the SHiP facility would be put into operation the shielding could be installed in its actual position in the target facility. To avoid activation of the iron shielding and facilitate its installation in the target facility about 1 m of concrete should be placed upstream of it in the extraction tunnel. A total of 16 m^3 of concrete would thus additionally be required, which could however be used later on as shielding in the SHiP facility.

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Additional radiation protection studies will be required at a later stage of the project. These should include the following topics:

1. The production of radionuclides in the air and helium compartments of the SHiP facility and the consequent effective dose to personnel.

2. Optimization of the design to minimize doses for critical interventions (e.g. target exchange).

3. A detailed assessment of the environmental impact of the SHiP facility, including the impact from stray radiation, releases of radioactivity by air, releasing of water containing radioactive substances, earth activation and the risk of groundwater contamination.

4. The dismantling of the SHiP facility and the radioactive waste production.

5. The radiological issues concerning the refurbishment of TDC2 and the SPS extraction region.

A rough and very preliminary estimate of the RP manpower is given in Appendix A.

Acknowledgements

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6 List of figures

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Appendix A

	2015	2016	2017	2018	2019	2020	2021	2022	TOTAL
Staff physicists	0.30	0.25	0.25	0.30	0.30	0.30	0.20	0.20	2.10
Staff technicians	0.00	0.00	0.20	0.50	0.50	0.30	0.20	0.20	1.90
Temp technicians	0.00	0.00	0.00	2.00	2.00	0.00	0.00	0.00	4.00
Fellow	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	3.00

Table 7: *Preliminary RP manpower estimates (in FTE = man-years) for the SHiP project based on present information.*