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TECHNICAL NOTE

Prompt, Activation and Background radiation studies for the HiRadMat facility of CERN/SPS

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Abstract

HiRadMat (High Irradiation to Materials) is a new facility under construction at CERN designed to provide high intensity beams in order to test raw materials and accelerator components with respect to the effect caused by the impact of pulsed, high intensity particle beams. In the present note detailed Monte-Carlo simulations studies using the FLUKA code have been performed for prompt dose equivalent rates in the corresponding tunnel structure as well as surface buildings, residual dose rates (after seven cooling times) for an exemplary irradiation of an LHC collimator, as well as for the remnant background dose in the tunnels after one year of operating the facility. Moreover, calculations of the possible activation of the cooling water in the dump have been performed.

The scope of this document includes the operational aspects of the facility but does not cover experiment specific hazards or waste issues as they need to be studied on an individual basis.

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Contents

Short Summary

Quantities calculated:	• Ambient Dose Equivalent (H*(10)) in the TNC, TJ7, TA7, PA7 and BA7 tunnels and buildings in prompt, activation (after several cooling times) and background (without the irradiated objects) scenarios • Prompt charged hadrons over 20MeV fluence, in the TNC and TJ7 tunnels • Prompt silicon 1MeV neutron equivalent fluence, in the TNC and TJ7 tunnels • Activation of the dump's cooling water
Simulation Code:	Fluka version 2010.2 (Developer's version)
Conversion Coefficients:	• The conversion coefficients of Pelliccioni are used to fold the particle fluence to ambient dose equivalent. [Fluence-to-dose conversion coefficients by M. Pelliccioni, Radiat. Prot. Dosim. 88, pp. 279-297, (2000)]
Geometry layout:	2010
Assumed Scenarios:	• Prompt studies: A cylindrical copper target, placed at the focal point 1, was being hit by the beam. The results are normalized for two SPS cycles, the long (duration: 44s) and the short (duration: 16.8s), as well as for an operational envelope scenario of 4.89 x 10^{15} protons over 100 extractions of 20 s each. • Activation studies: A collimator, placed on the specifically designed irradiation table, was intercepting the beam. The irradiation profile used was the nominal one with the short SPS cycle (10^{15} protons over 504 s, that is 1.98 x 10^{12} p/s). • Background studies: A copper target placed at the focal point 3 as well as the collimator with the table were simulated to be irradiated with 10^{16} protons over one year, which represents the usual operational scenario of the facility. • For the water circuit activation calculations two scenarios were calculated: a) The beam directly hits the TED core (worst case scenario for the activation of the water) for an irradiation profile of i) 10^{16} protons over 1 year and ii) 10^{17} protons over 10years and b) The beam impinges on a collimator (operational scenario) for the same aforementioned irradiation profiles.
Beam energy:	• The nominal SPS beam parameters were used. That is, particle momentum of 450 GeV/*c*, a flat distribution of Δp equal to 0.585, and a Gaussian shape of 0.5 x 0.5 mm^2.
Transport thresholds:	• Prompt studies: The general FLUKA transport of all particles is set (via the DEFAULTS card) at 100 keV (low energy neutrons down to 10^{-14} GeV). Also the electromagnetic cascades were turned off for the prompt studies, via the card EMF-OFF.
	• Activation & background studies: The threshold for electrons was set via EMFCUT at 100 keV for electrons/positrons and 10 keV for photons. The electromagnetic cascade was switched ON since it represents the main contribution to the residual dose rate. In addition the new evaporation model of the code (with heavy fragmentation) and the coalescence model (PHYSICS cards) were enabled as recommended in the FLUKA manual.
Results:	• During the operation of the facility, access to all underground areas must be prohibited, while access to the surface buildings will be possible. • The residual dose rate in the TNC and the TJ7 tunnels should be monitored carefully if the activated object is still in the tunnel and access should be required • In case of access to the TNC attention should be paid also to the activation of the dump, which will contribute significantly to the residual background dose rate in the experimental area, especially after the irradiated object has been removed .The risk of water activation in the dump cooling circuits is very low.

	• A worst-case accident scenario has been studied by placing an optimum target (99.9% interaction rate) in an underground location in TJ7, which is closest to the access shaft. This set up is used to resemble a conservative case of an accidental beam loss on a magnet in the presumably worst location. It was found that in publicly accessible locations the highest expected dose equals 2E-15 uSv/lost proton +/- 25%. Consequently, the improbable scenario of losing the full maximum proton load of an experiment should yield a total dose below 10 uSv, which can be considered as sufficiently low.

1. Introduction

HiRadMat (High Irradiation to Materials) facility is a new facility, under construction at CERN designed to provide high-intensity pulsed beams to an irradiation area where raw materials, as well as accelerator components can be tested. The facility uses a 450 GeV/*c* proton beam extracted from CERN's SPS with a pulse length of 7.2 µs to a maximum pulse power of 3.4 MJ. The facility is built in the old WANF (1) tunnel. A CATIA model of the area can be found in Figure 1, while in Figure 2 the corresponding FLUKA (2), (3) model can be seen.

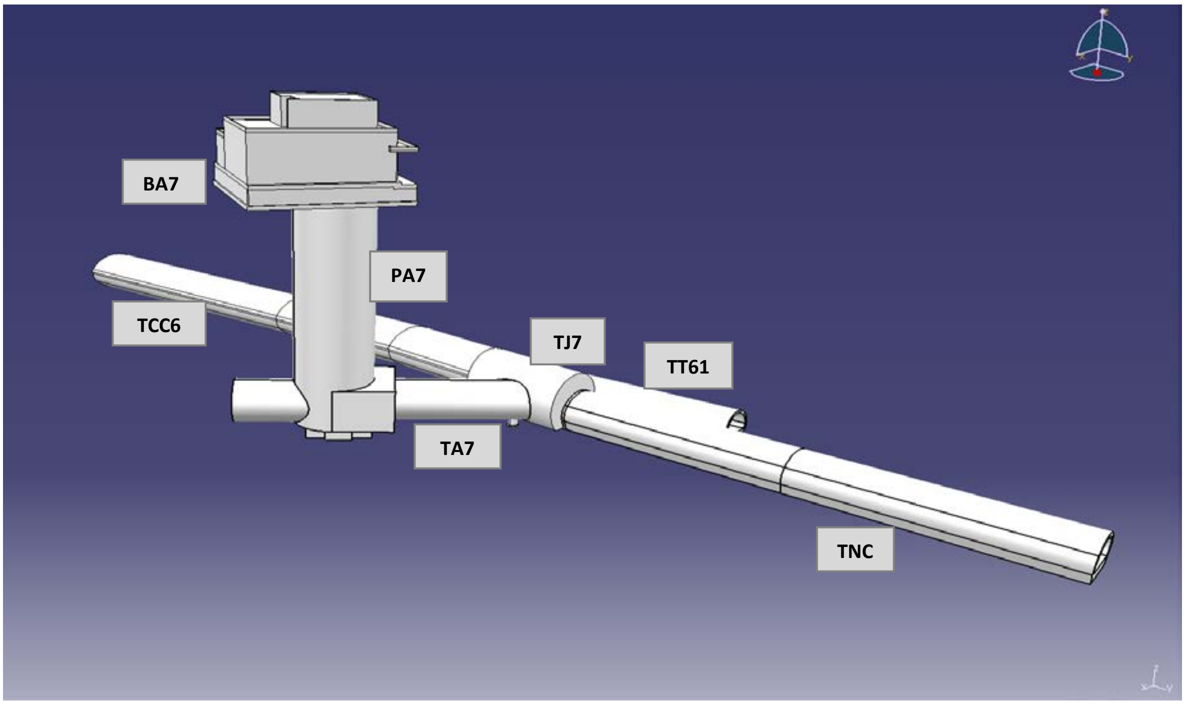


Figure 1: A CATIA layout of the tunnels including the respective identifiers. The HiRadMat irradiation area will be located in the TNC tunnel at the place of the old WANF area.

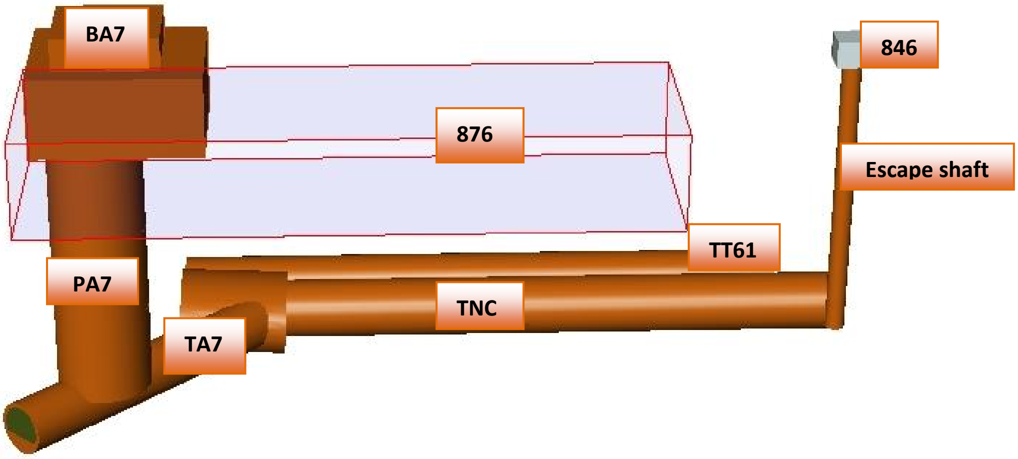


Figure 2: The corresponding FLUKA model for the tunnel geometry. The TCC6 tunnel was not modelled. The 3D visualisation was done with the solid modelling program SimpleGeo (4)

The model, built with the GUI interface for FLUKA (FLAIR) (5), was very accurate in terms of dimensions according to the civil engineering plans. Small differences exist due to the fact that is not always possible to model the exact physical geometry in terms of fixed shapes and regions as it is required in a Monte – Carlo program. A table with the inter-comparison of the dimensions between the drawings and the corresponding FLUKA model can be found in Table 1.

Table 1: The corresponding differences in the dimensions between the actual geometry and the model are negligible. The slope of the TNC tunnel was assumed zero with respect to the beam line, and all the slopes were calculated assuming the TNC tunnel and beam line being horizontal.

	Drawings	*FLUKA model*
TJ7 tunnel		
Shape	*Elliptical*	*Elliptical*
Rx [mm]	*6000*	*6000*
Ry [mm]	*4150*	*4145*
Length [mm]	*13000*	*12980*
Slope [degrees]	*2.66*	*2.66*
TNC tunnel		
Shape	*Elliptical*	*Elliptical*
Rx [mm]	*3250 / 3000 (not absolute)*	*3250*
Ry [mm]	*3250 / 3000 (not absolute)*	*3000*
Length [mm]	*65000*	*65000*
Slope [degrees]	*0*	*0*
TA7 tunnel		
Shape	*Cylindrical*	*Cylindrical*
Rx [mm]	*2650*	*2650*
Ry [mm]	*2650*	*2650*
Length [mm]	*40415*	*40000*
Slope	*45*	*45*
PA7 tunnel		
Position (x, z)	*-21237, -21237 (45 degrees angle)*	*-21250,-21370 (45 degrees angle)*
Shape	*Cylindrical*	*Cylindrical*
Rx [mm]	*4550*	*4550*
Ry [mm]	*4550*	*4550*
Length [mm]	*34972*	*35000*

Four different sets of simulations have been performed with the FLUKA (2010) code, in order to assess the radiological risk from several operational and worst-case scenarios of the HiRadMat facility.

- Prompt ambient dose equivalent rate calculations

  In the prompt calculations scenario, the nominal beam is simulated to impinge on a cylindrical copper target (density: 8.96 g/cm^3) placed at focal point 1 of the irradiation area (see Figure 3 in the next page). This position was chosen because it represents the closest one of the experimental positions with respect to the surface building (BA7) which should be accessible by personnel during the operation of the facility. The quantities scored in all the tunnels (TNC, TJ7, TA7) as well as at the surface area in building BA7 were:

  - The Ambient Dose Equivalent (H*(10)) (6), given in terms of [µSv/h], normalized with respect to two SPS cycles: The long one (a total 10^{15} protons spread over 30 extractions, with the duration of the supercycle equal to 44 seconds) and the short one (a total 10^{15} protons spread over 30 extractions, with the duration of the supercycle equal to 16.8 seconds). In addition an operational envelope scenario (worst-case) was utilized, of a total of 4.89 x 10^{15} protons spread over 100 extractions, each one of them had a duration of 20 s (7).

- The 1 MeV equivalent neutron fluence in TNC, TJ7 and TA7 tunnels
- The hadrons > 20MeV fluence in the TNC, TJ7 and TA7 tunnels

For these calculations the electromagnetic cascades were turned off (EMF-OFF) since the electromagnetic cascade at high energy accelerators typically contributes to the total dose equivalent only by about 20% around bends or behind shielding, while it may be extremely time-consuming in terms of CPU time.

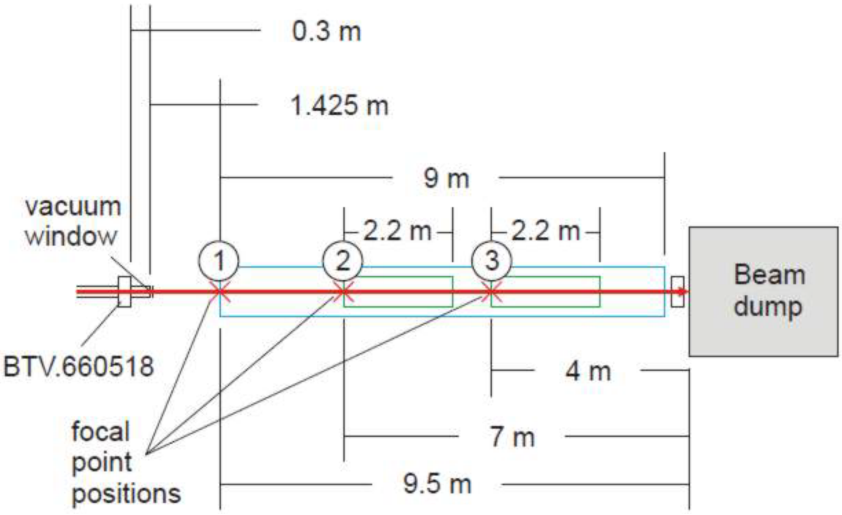


Figure 3: The focal points of the irradiation area. In the prompt studies the copper target was simulated to be at focal point 1 (the nearest one to TJ7 and TA7 tunnels as well as BA7 building) while in the activation and background studies the table and the collimator were simulated to be at focal point 3, due to the particular interest of the possible dump activation.

- Residual dose rate calculations

For the residual dose rate calculations the activation of a collimator (see Figure 4 & Figure 5) placed on an aluminum table at focal point 3 was studied after seven different cooling times (1 hour, 12 hours, 1 day, 2 days, 1 week, 1 month, 2 months). The irradiation profile chosen for this scenario was the short SPS cycle (10^{15} protons over 504 s) as this represents the maximum amount of particles within the shortest available time and as such, denotes the worst case scenario with respect to the activation. For this type of simulations the electromagnetic cascade was turned on (EMF-ON) for the decay radiation (defined with the RADDECAY card) in order to allow for the calculation of residual dose rates based on the produced radioactive isotopes. The production thresholds of electron-positrons and photons were set (via the EMFCUT card) at 100 and 10 keV respectively. Moreover, the new evaporation and coalescence model of the code were activated via the PHYSICS card.

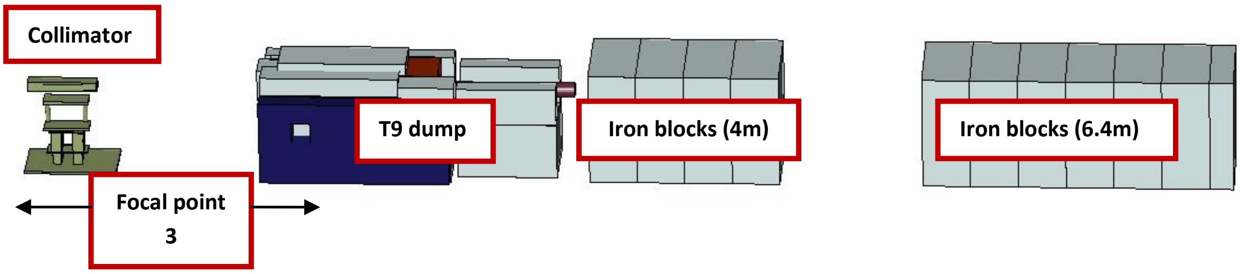


Figure 4: Detail of the FLUKA model of the irradiation area. The table and the collimator used for the activation and background studies are placed at the focal point 3.

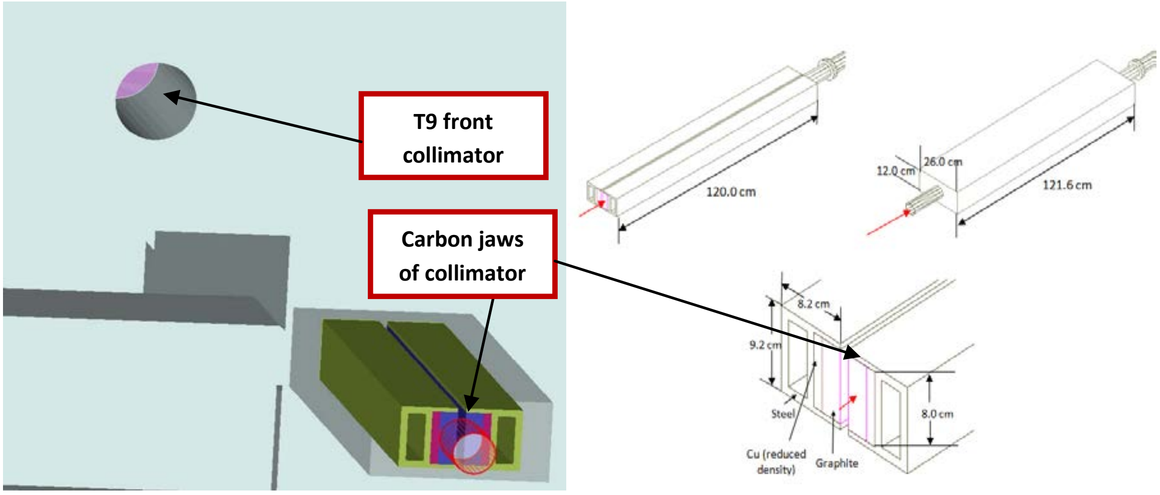


Figure 5: Detail of the collimator geometry, as modelled in FLUKA. The beam impact was simulated to hit exactly 1 mm "inside" the right jaw of the collimator. On the left the collimator placed in front of upstream collimator of the T9 beam dump is shown. On the right details of the collimator are depicted (8).

- Background calculations

With a new feature of the FLUKA (2010) code calculations of the remnant (background) radiation in the tunnel were performed, assuming that the activated target objects (e.g., a collimator) have been removed. Two scenarios were studied this way:

- The beam hitting the jaw of the collimator, which is removed afterwards.
- The beam hitting a cylindrical copper target placed at focal point 3, which is removed afterwards.

The irradiation profile used in this scenario was 10^{16} protons over one year, representing the average total number of protons in the experimental area within one year’s time.

- Cooling water activation

An estimate of the induced radioactivity in the cooling water pipes was carried out for two different irradiation scenarios in order to predict the possible activation of the water in the cooling pipes of the dump (see Figure 6). In addition its compliance with the limits of the Swiss legislation has been checked in order to determine whether the water would have to be classified as radioactive. The two scenarios used were:

- 10^{16} particles over one year
- 10^{17} Particles over ten years.

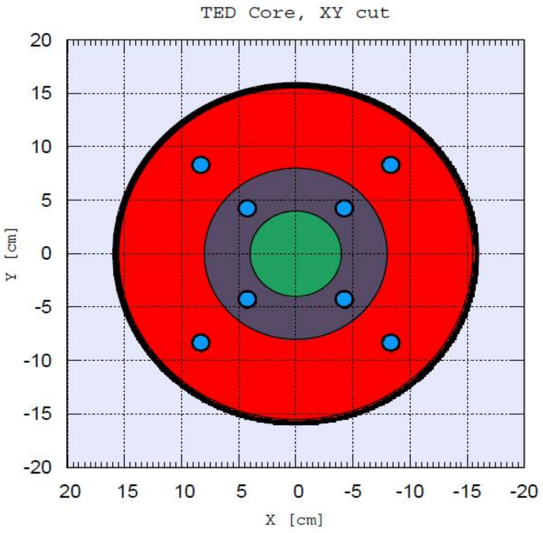


Figure 6: The FLUKA model of the TED core. The green color represents carbon, gray is antico, red is copper. In the antico and copper layers there are four steel pipes for the cooling water circulation (9).

2. Prompt Calculations

For the prompt calculations a cylindrical copper target with a radius 3 cm and a length of 1 meter, placed exactly at focal point 1 (the position closest to the BA7 building), was intercepting the full beam. This scenario represents the worst case in which almost all the beam particles will interact with the copper rod (copper interaction length: 15.32 cm) and produce secondary particles. The ambient dose equivalent H*(10) in the TA7 access tunnel, and the control building BA7 at the surface was scored. The following results are normalised per experiment for three cases: an operational envelope scenario, a scenario involving the long SPS cycle (30 extractions x 44 s each = 1320 s) and one involving the short SPS cycle (30 extractions of 16.8 s each = 504 s). In the following plots, the results are given in terms of [μSv/h]. The code gives the results for the dose equivalent in [pSv/p]. In order to convert this in [μSv/h] we had to multiply with a normalization factor, calculated as follows:

$$\frac{pSv}{p} \cdot \frac{\#p}{\#extr \cdot duration} \cdot 3.6 \cdot 10^{-3} = \frac{\mu Sv}{h}$$

Three cases were studied.

- The operational envelope scenario: $4.89 \cdot 10^{15}$ protons, over 100 extractions of 20 s each. The normalisation factor in this case is: $8.8 \cdot 10^{9}$

- The case of long SPS cycle (10^{15} protons over 30 extractions of 44 s each). The normalisation factor in this case is: $2.73 \cdot 10^{9}$

- The case of short SPS cycle (10^{15} protons over 30 extractions of 16.8 s each). The normalisation factor in this case is: $7.14 \cdot 10^{9}$

In order to facilitate the understanding of the subsequent graphs Figure 14 shows a picture of the FLUKA geometry including indications of the respective underground tunnels as well as the BA7 surface building in relation to the experimental area.

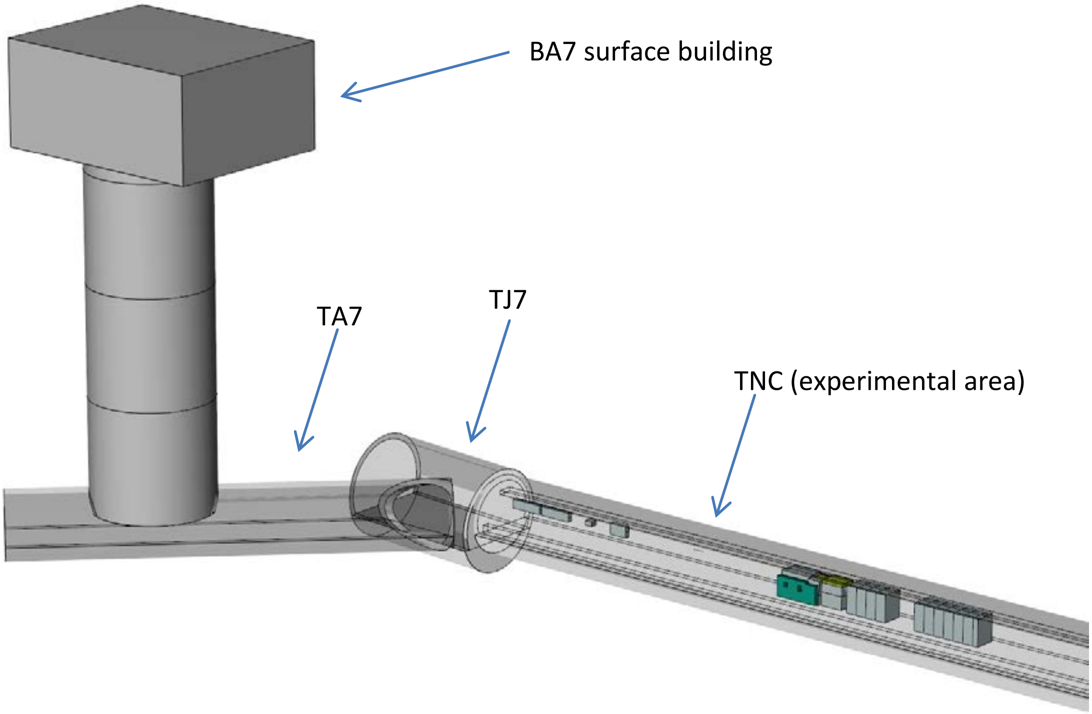


Figure 7: The FLUKA model of the tunnel geometry. The surrounding soil as well as the tunnel walls have been removed from the figure for visualisation purposes.

i. TA7 tunnel prompt dose calculations

a) Operational envelope scenario - $4.89 \cdot 10^{15}$ protons over 100 extractions of 20s each

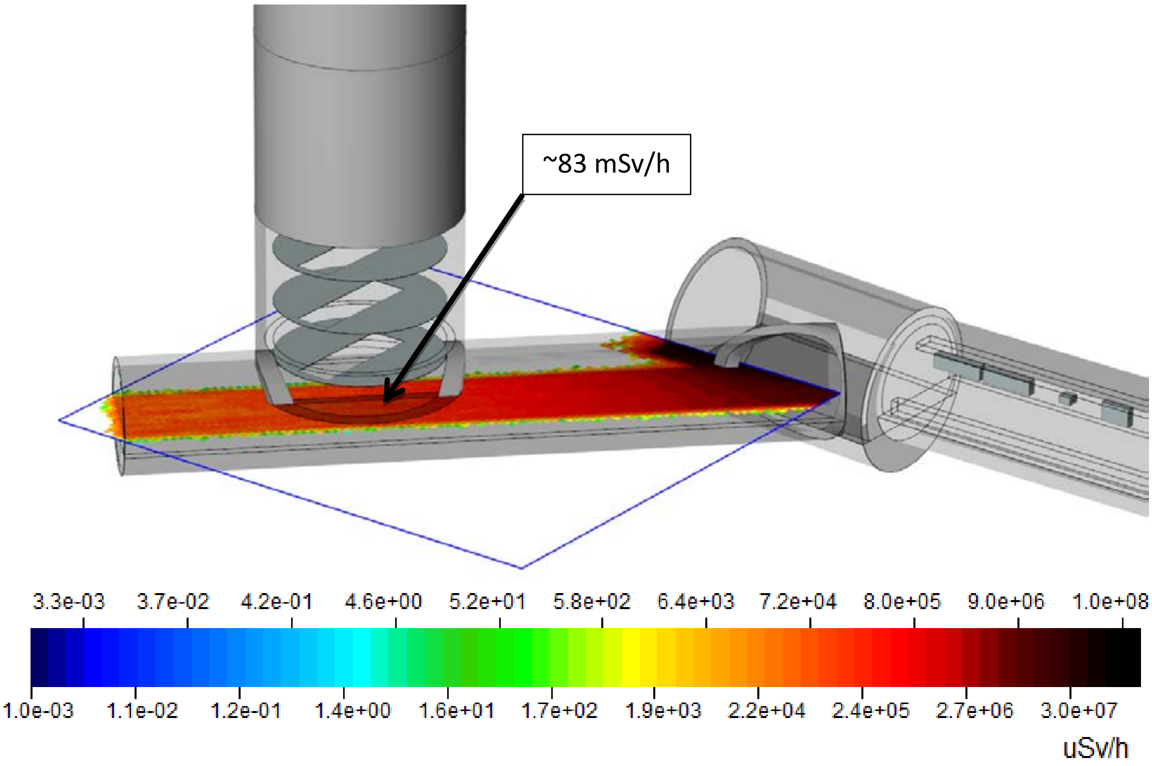


Figure 8: The prompt ambient dose equivalent rate in the TA7 tunnel for the operational envelope scenario. The average dose equivalent rate at the bottom of the shaft is 83 mSv/h +/- 20%.

b) Short SPS cycle scenario - 10^{15} protons over 30 extractions of 16.8 s each

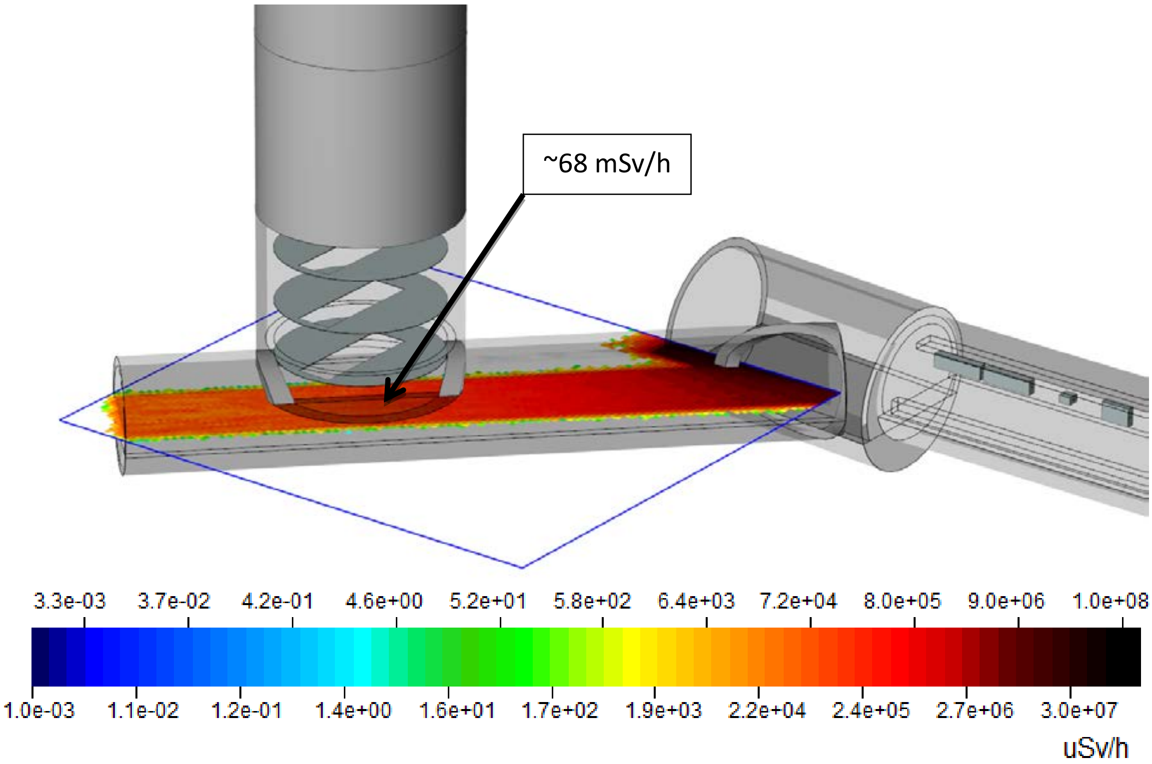


Figure 9: The prompt ambient dose equivalent rate in the TA7 tunnel, for the short SPS cycle scenario. The average dose equivalent rate at the bottom of the shaft is ~68 mSv/h +/- 20%.

c) Long SPS cycle scenario - 10^{15} protons over 30 extractions of 44 s each

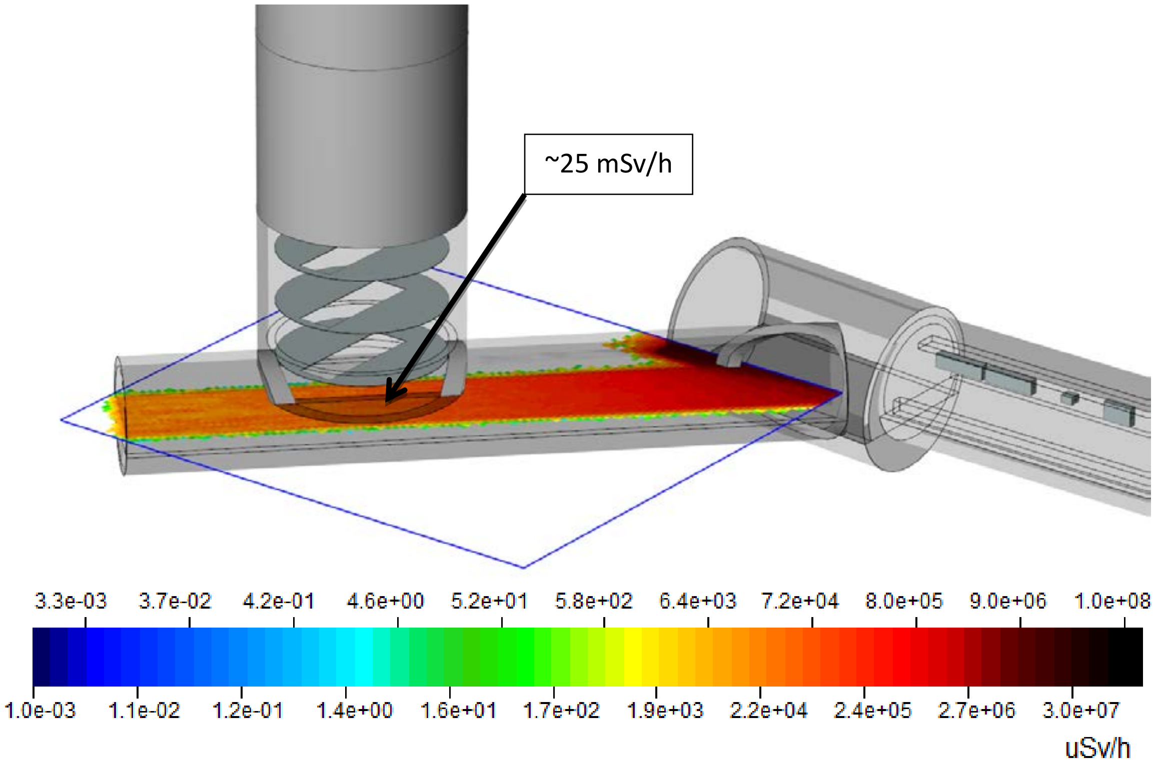
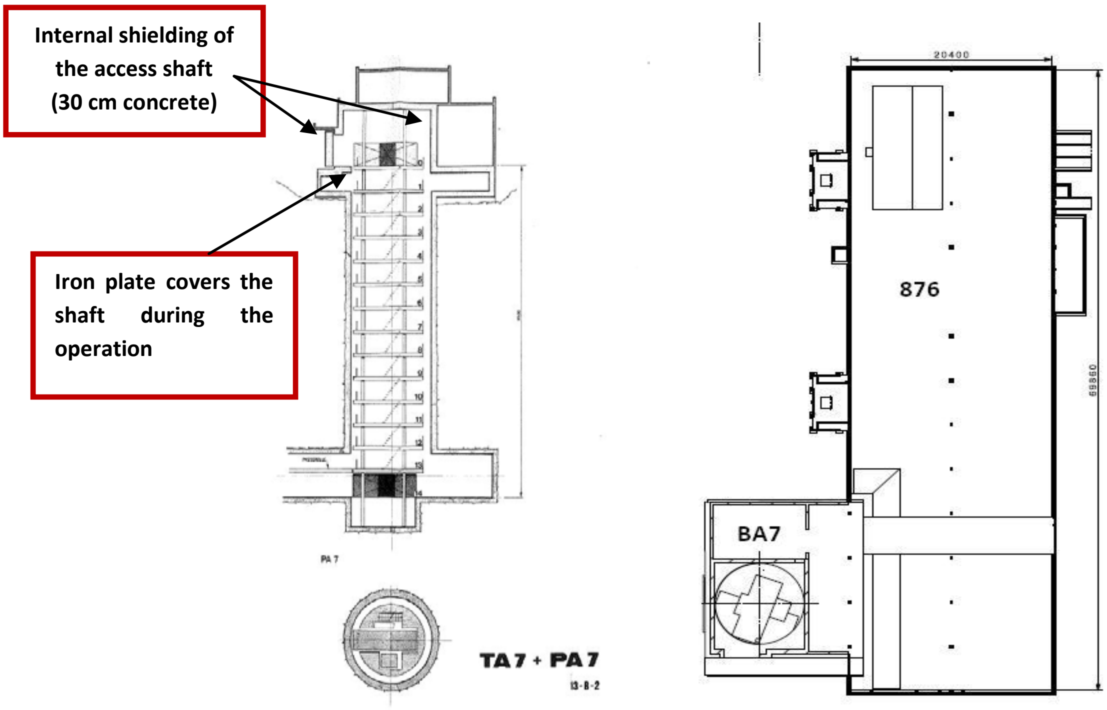


Figure 10: The prompt ambient dose equivalent rate in the TA7 tunnel, for the short SPS cycle scenario. The average dose equivalent rate at the bottom of the shaft is ~25 mSv/h +/- 20%.

ii. BA7 building prompt dose calculations

As the BA7 surface building will host the control room and lab-space for HiRadMat, the prompt dose equivalent levels have to be studied carefully. The building was modelled in detail (as can be seen in Figure 18), and variance reduction techniques (splitting and Russian roulette) were implemented in order to improve the statistics of the calculations. Without the application of appropriate biasing techniques the results would be of insufficient statistical significance even after 15 days of CPU time and 500.000 primary particles, which could easily lead to misinterpretation of the radiological circumstances. The statistical information for BA7 can be seen in Figure 21.



Internal shielding of the access shaft (30 cm concrete)

Iron plate covers the shaft during the operation

Figure 11: The civil engineering drawings for the buildings BA7 and 876

In the implemented FLUKA model the stair-case floor was modelled as being constructed out of iron and having a thickness of 1 cm. Moreover, in order to include the possible contribution by the electromechanical infrastructure (cables, etc. surrounding the shaft) in the dose estimates a second material layer was added between the air and the wall as a compound of copper and air (30% of the volume was copper, as a contribution of the electric cables, and 70% of the volume was assumed to be air, representing the space between the cables). Inside the building BA7 the shaft was modelled to be covered by an iron plate with a thickness of 1cm. In Figures 19, 20 details of the model can be seen.

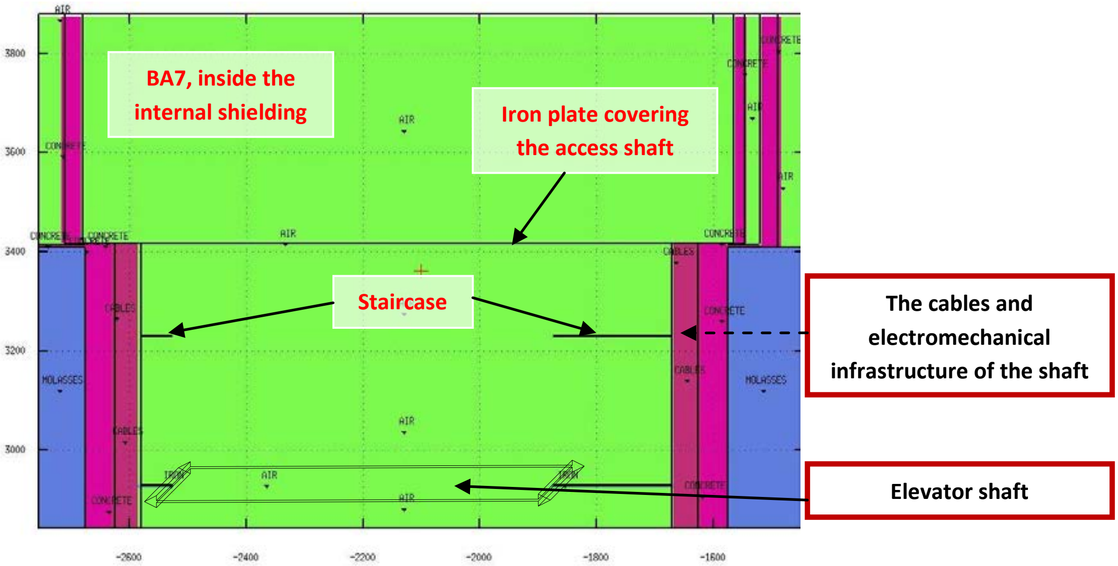


Figure 12: Detailed view of the FLUKA model of the intersection between the PA7 (shaft) and BA7 building.

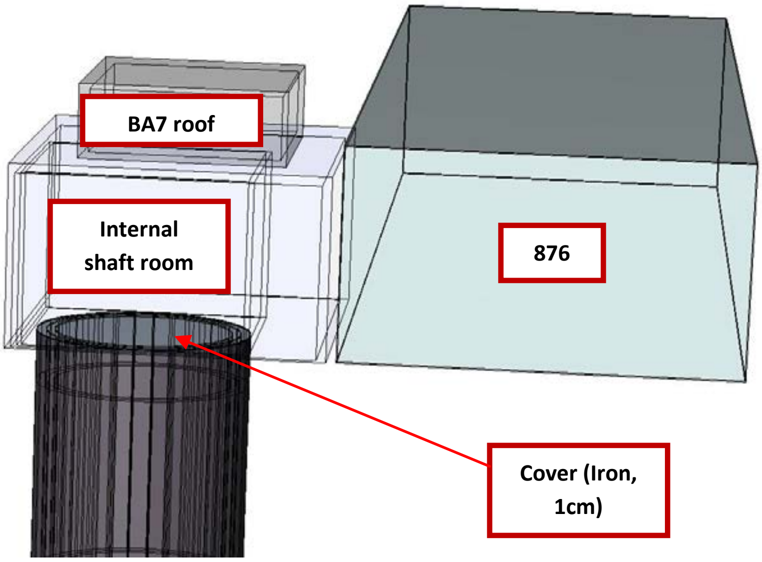


Figure 13: Detailed view of the FLUKA model of BA7 and 876 buildings.

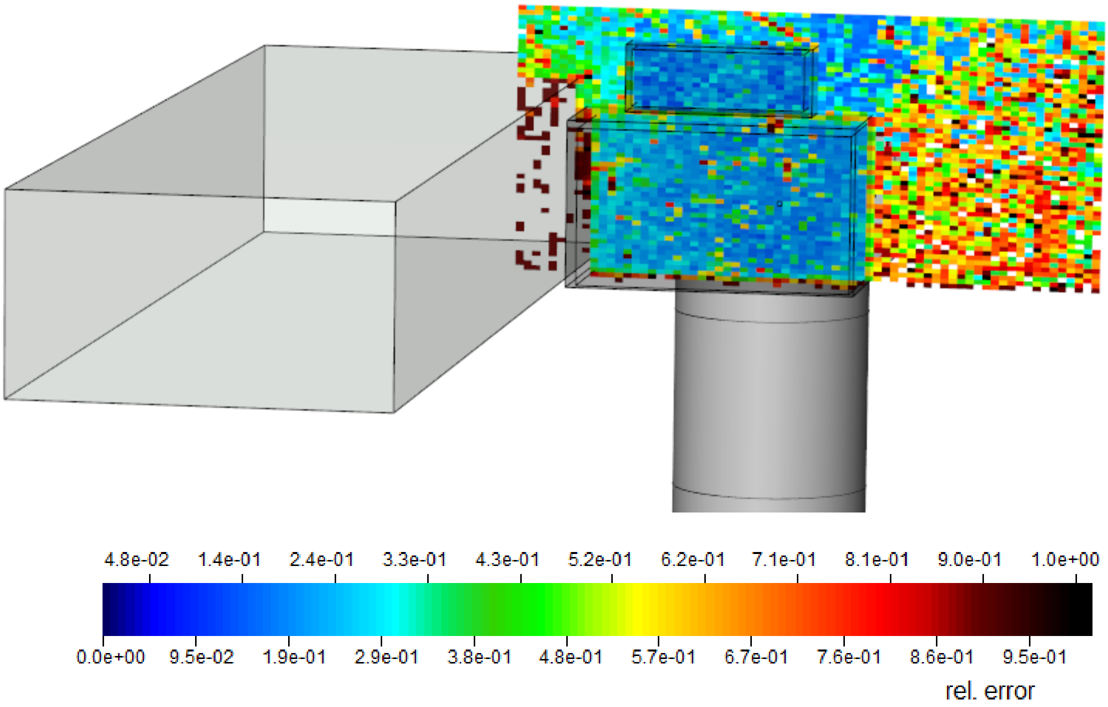
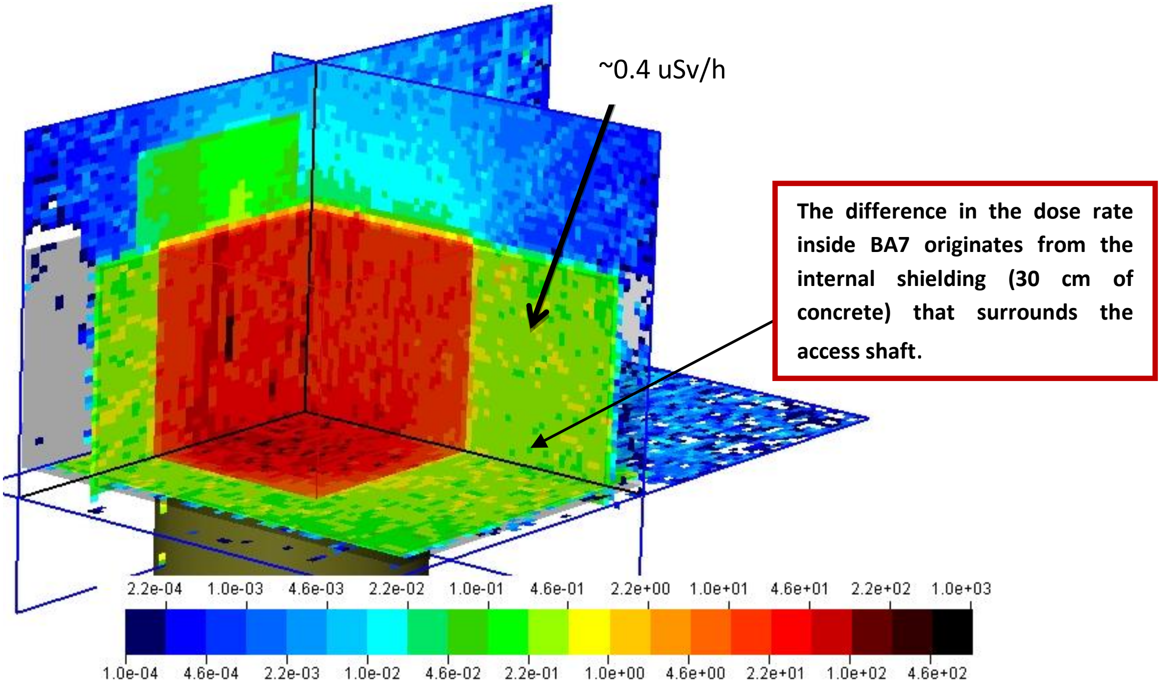


Figure 14: The statistical information for the dose rate in BA7 building. The error is fluctuating around 30% for the space outside of the internal shielding located in BA7.

a) Operational envelope scenario - $4.89 \cdot 10^{15}$ protons over 100 extractions of 20s each (all the results are in [µSv/h]



~0.4 uSv/h

The difference in the dose rate inside BA7 originates from the internal shielding (30 cm of concrete) that surrounds the access shaft.

Figure 15: The prompt ambient dose equivalent rate inside the BA7 building for the operational envelope scenario. The results are given in terms of [µSv/h]. The average dose rate outside the internal shielding inside BA7 is 0.4 uSv/h +/- 30%.

b) Short SPS cycle scenario - 10^{15} protons over 30 extractions of 16.8 s each

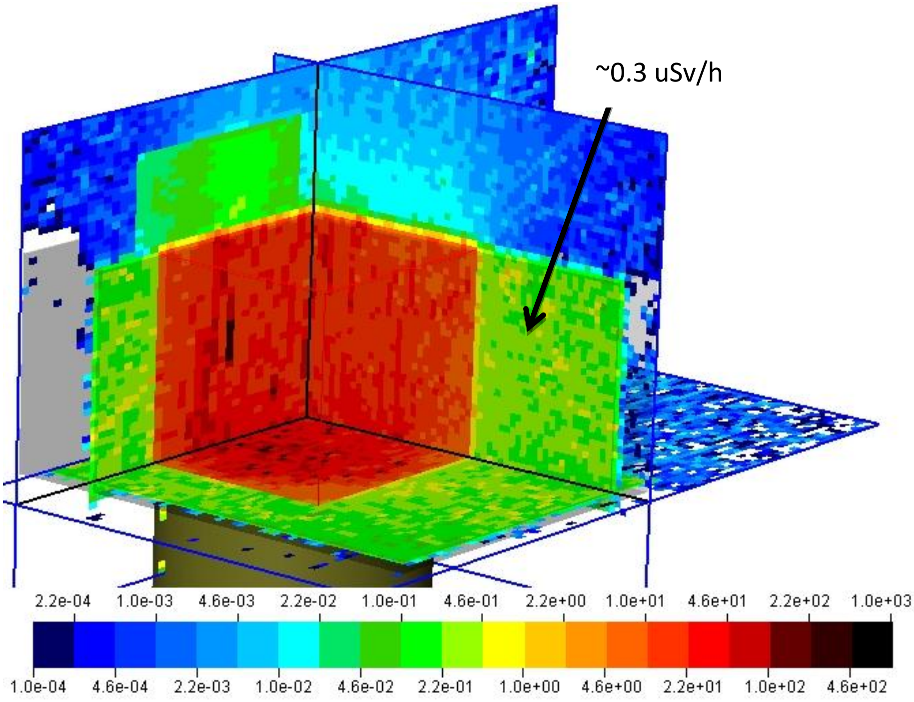


Figure 16: The prompt ambient dose equivalent rate inside the BA7 building for the short SPS cycle scenario. The results are given in terms of [µSv/h]. The average dose rate outside the internal shielding in BA7 is 0.3 uSv/h +/- 30%.

c) Long SPS cycle scenario - 10^{15} protons over 30 extractions of 44 s each

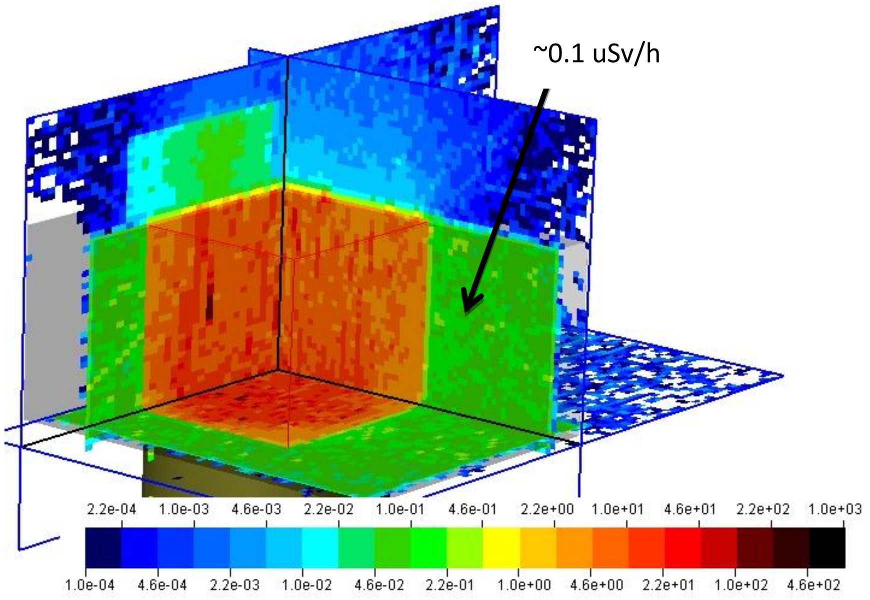


Figure 17: The prompt ambient dose equivalent at BA7 building for the long SPS cycle scenario. The results are given in terms of [µSv/h]. The average dose rate outside the internal shielding in BA7 is 0.1 uSv/h +/- 30%.

In Figures 22 to 24, it can be seen that the internal shielding of the shaft is necessary as without it the dose rates would be too high for the classification of a supervised radiation area, which is the classification usually strived for in accessible experimental areas at CERN. However, outside of this internal shielding the dose rates are low enough (<2.5 uSv/h low-occupancy) to allow for a classification as a low-occupancy non-designated area. In addition the accessible area next to BA7, where it is foreseen to have lab-space, is monitored with an active RAMSES monitor (10).

iii. BA7 building roof calculations

Access to the roof of BA7 is usually blocked with a pad locked ladder. However, one cannot fully exclude the possibility of an access during operation which could be unknown to the operators. Therefore, the dose rates at the roof have been studied as well. For the operational envelope scenario discussed above the dose rate on top of the roof shielding of building BA7 can be seen in Figure 25.

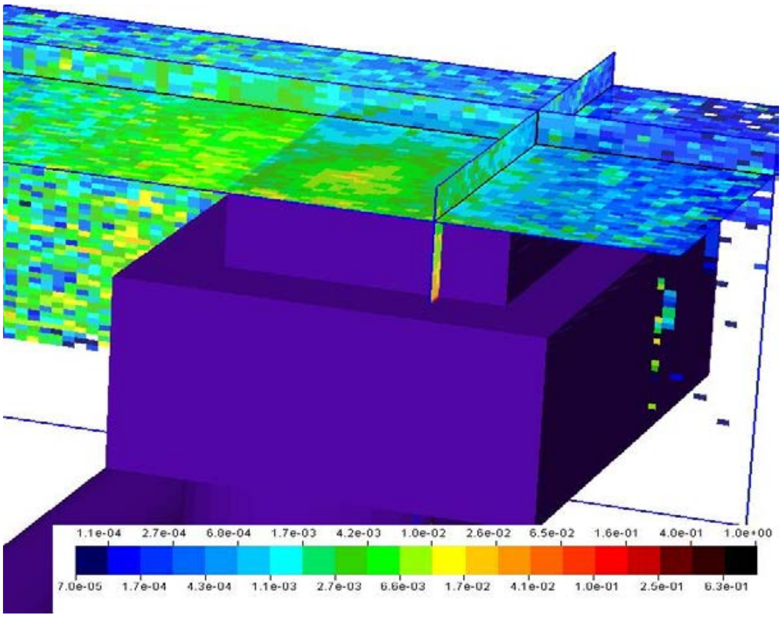
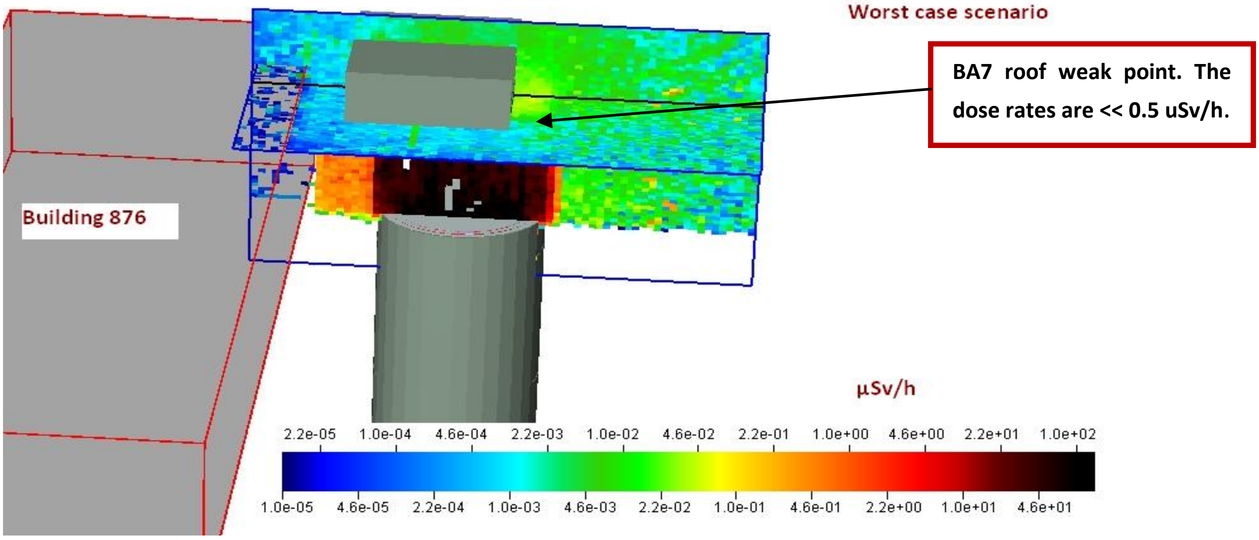


Figure 18: The prompt ambient dose equivalent at BA7 building roof for the operational envelope scenario. The results are given in terms of [µSv/h]

The additional rectangular shielding on top of BA7 building, as can be seen in Figure 18 (left) does not fully cover the access shaft through which radiation will stream to the surface. This creates a potentially weak point on the roof of BA7 building which had to be checked carefully. As can be seen in Figure 26 the shielding is still sufficient as the dose rates are expected to be significantly below 0.5 uSv/h.

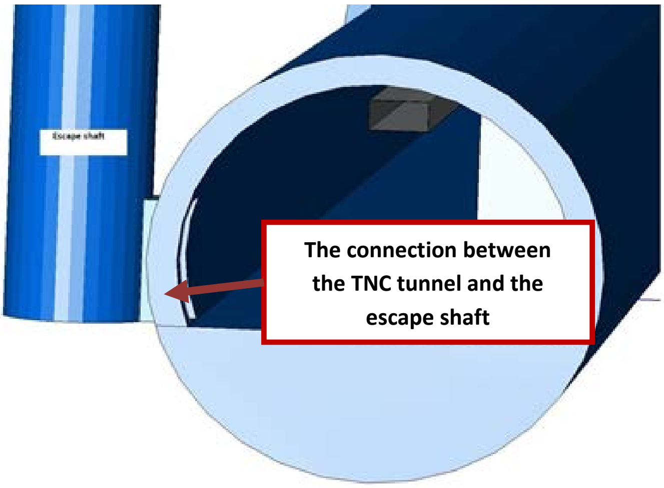

Worst case scenario

BA7 roof weak point. The dose rates are << 0.5 uSv/h.

Figure 19: The prompt ambient dose equivalent rate at BA7 building roof for the operational envelope scenario. The results are given in terms of µSv/h.

iv. Building 846 (escape shaft) calculations

Since the escape shaft is connected to the TNC tunnel hosting the experimental area the occurring prompt dose rate at the exit of the shaft need to be studied as well. Thus, a model of the shaft and the surface building 846 was created. The escape shaft is connected to the TNC tunnel through a concrete door of 30 cm thickness. A detailed view of the geometry model implemented can be seen in the following figure.



The connection between the TNC tunnel and the escape shaft

Figure 20: Detail of the geometry model concerning the escape shaft.

The irradiation scenario for estimating the dose rate in the escape shaft was the same as for the dose estimation in building BA7, that is 4.89 x 10^{15} protons over 100 extractions of 20s each. In the following Figure 28 the dose rate in the escape building 846 and the escape shaft is shown.

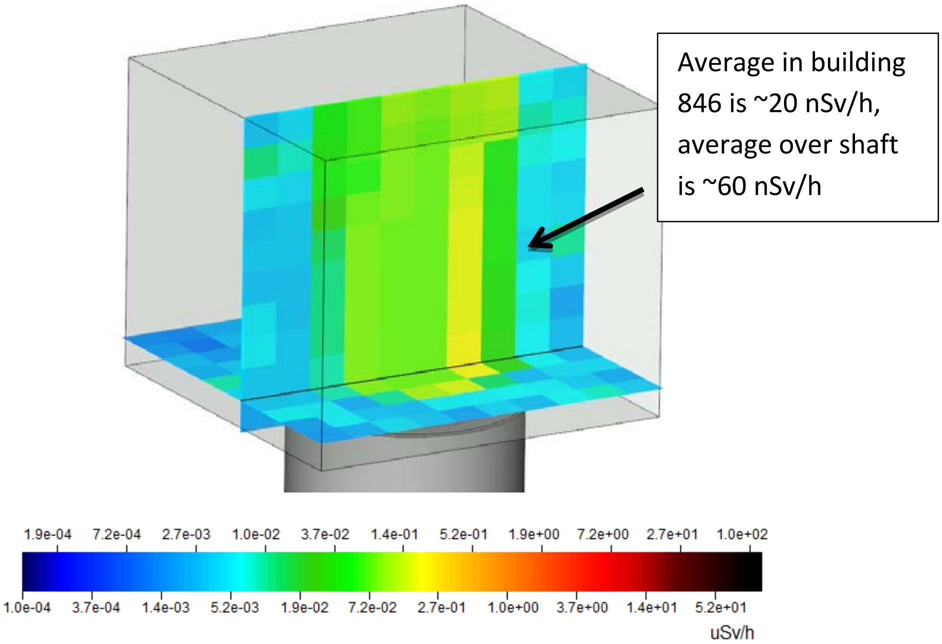

Average in building 846 is ~20 nSv/h, average over shaft is ~60 nSv/h

Figure 21: The ambient dose equivalent on the surface building of the escape shaft (bt. 846). The results are given, for the operational envelope scenario, in terms of [μSv/h]. The highest values can be found directly over the shaft with an average of 60 nSv/h +/- 30% while the average of the building is 20 nSv/h +/- 30%.

As can be seen from the figures above, the prompt dose rate in the surface building 846 should be negligible during the operation of the facility, even for the operational envelope scenario (4.89 x 10^{15} protons over 2000 seconds).

3. Accident scenario

In order to assess safe operation of the HiRadMat facility a worst-case accident scenario had to be studied as well. The highest doses in accessible non-designated areas around BA7 are to be expected in case of a beam loss on equipment, *e.g.*, a magnet, which is located in TJ7 and as such, closest to the access shaft leading to the surface buildings. In order to simulate such a situation under worst-case conditions a so-called “optimum target” (copper rod of 1.0 m length and a radius of 3 cm) was placed in TJ7, right in line of sight with respect to the access tunnel TA7. This “optimum target” configuration yields an interaction probability of 99.9% and thus, can be regarded as the envelope case for a beam loss. Figure 33 illustrates the total dose equivalent per lost proton in the accessible areas around BA7 for the worst case accident scenario. It was found that in publicly accessible locations the highest expected dose equals 2 x 10^{-15} uSv/lost proton +/- 25%. In the improbable case that the full proton load of one experiment (10^{15}) is lost unnoticed, the total dose for such an event is expected to be below 10 uSv in accessible areas. Doses higher than 10 uSv (inside the cyan contour line) are found only inside the shielded area of the access shaft, which is inaccessible during the operation. A total dose of 10 uSv or less can be considered as negligibly low for an accident. In addition to the theoretical assessment an IG5 ionization chamber (PAB72) is located next to the entrance of the access shaft in BA7 (see Ref. (10) for details). In case radiation levels for low-occupancy non-designated areas are exceeded (< 2.5 uSv/h) this monitor would raise an alarm in the control room. In addition one can foresee the possibility to include this monitor in the interlock chain of the beam line.

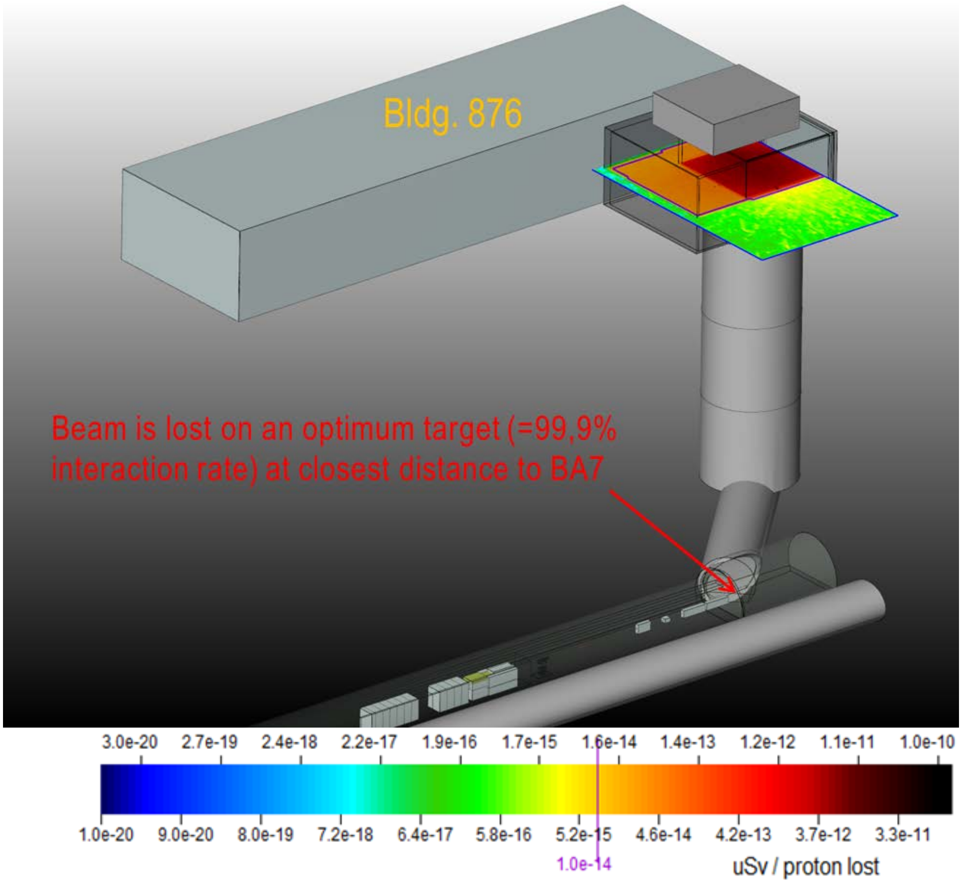
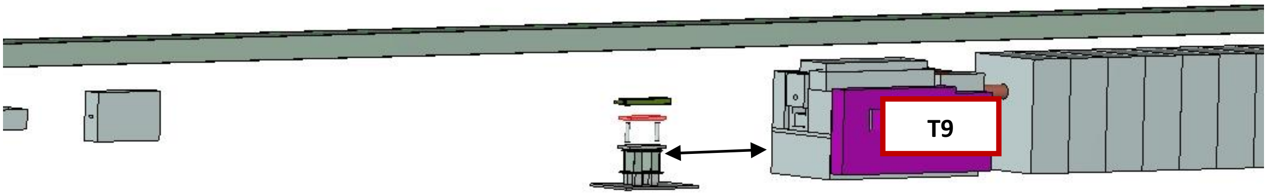


Figure 22: Total dose equivalent per lost proton in the accessible areas around BA7 for the worst case accident scenario. It was found that in publicly accessible locations the highest expected dose equals 2 x 10-^{15} uSv/lost proton +/- 25%. In the improbable case that the full proton load of one experiment (10^{15}) is lost, the total dose for such an event would be below 10 uSv in accessible areas. Doses significantly higher than 10 uSv (inside the cyan contour line) are found only inside the shielded area of the access shaft, which is inaccessible during the operation.

4. Activation calculations

In order to calculate the induced residual dose rate in the tunnels as well as the experimental area an exemplary operational scenario was chosen. In this operational scenario the beam was simulated to hit the carbon jaw of the collimator, exactly at 1 mm distance from the inner boundary, depicted in Figure 5. The irradiation profile chosen for this simulation was the short SPS cycle, that is $1.98 \cdot 10^{12}$ p/s for 504 s, which equals a total number of 10^{15} impinging particles within the shortest possible time frame. The dose rate [µSv/h] in all the tunnels was calculated for 7 different cooling times (1 hour, 12 hours, 1 day, 2 days, 1 week, 1 month and 2 months). All the results are normalised in terms of [µSv/h][1].



The test stand was modeled to be at focal point 3.

Figure 23: The FLUKA model used for the activation calculations.

i. TNC tunnel activation dose calculations

a) Cooling time of 1 hour

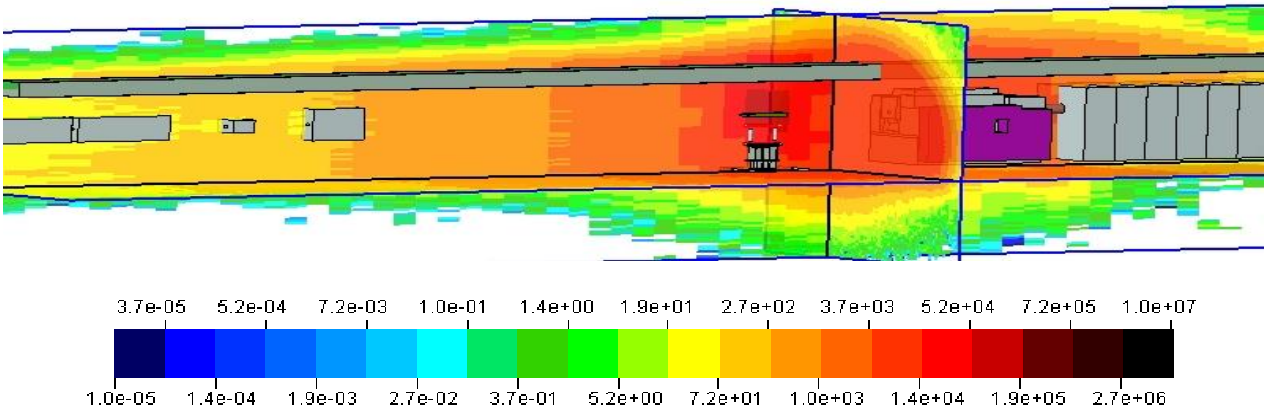


Figure 24: Dose rate in the TNC tunnel after a cooling time of 1 hour. The results are given in terms of [µSv/h].

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[1] The code gives the results for the several decay times in [pSv/s]. So, in order to convert in [µSv/h] the correct normalization factor is: 3.6E-03.

b) Cooling time of 12 hours

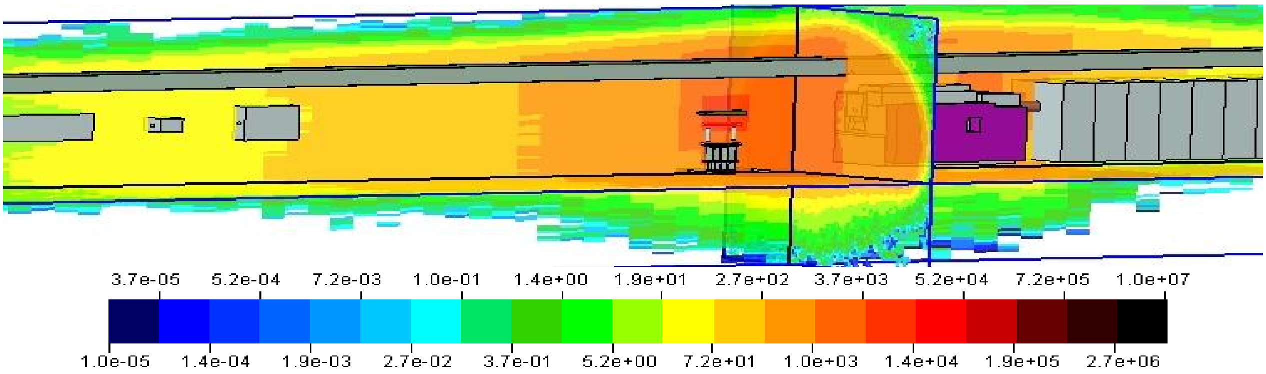

Figure 25: Dose rate in the TNC tunnel after a cooling time of 12 hours. The results are given in terms of [µSv/h].

c) Cooling time of 1 day

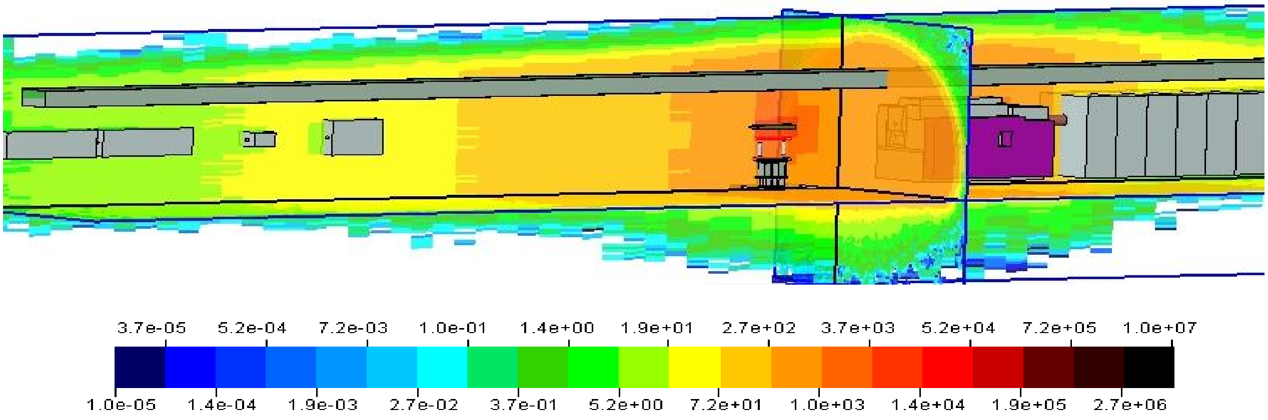

Figure 26: Dose rate in the TNC tunnel after a cooling time of 1 day. The results are given in terms of [µSv/h].

d) Cooling time of 2 days

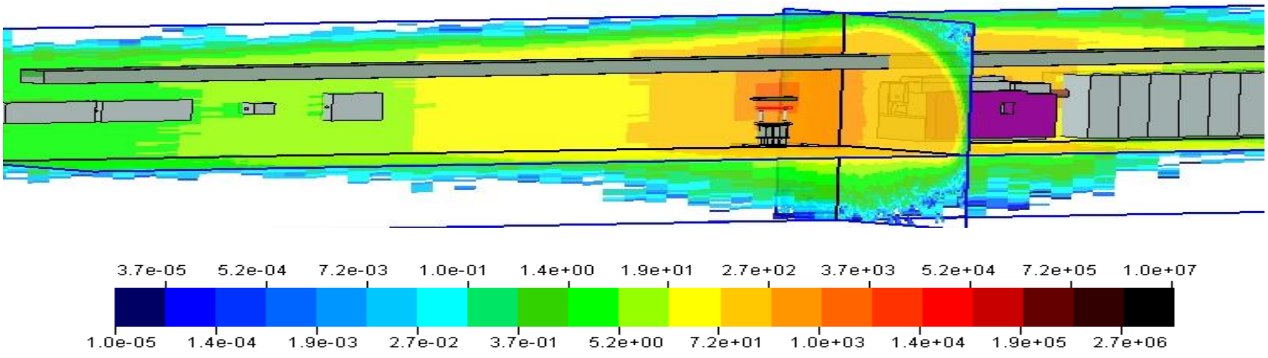

Figure 27: Dose rate in the TNC tunnel after a cooling time of 2 days. The results are given in terms of [µSv/h].

e) Cooling time of 1 week

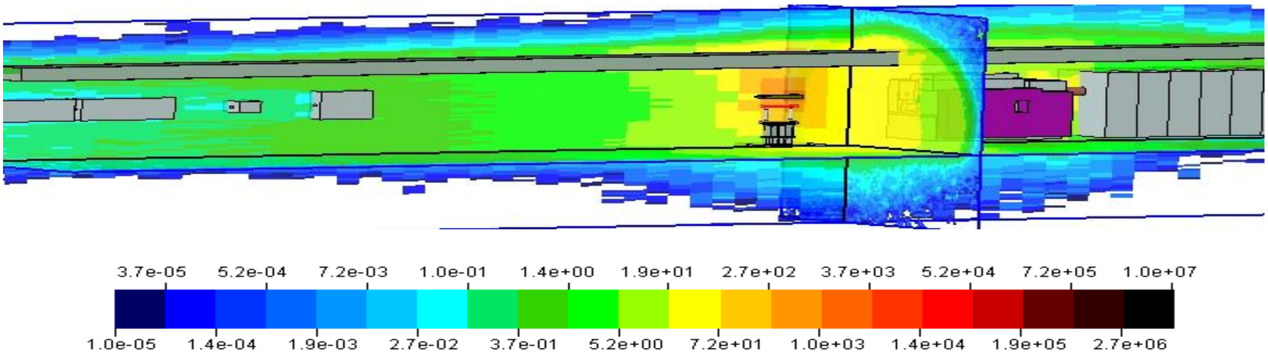

Figure 28: Dose rate in the TNC tunnel after a cooling time of 1 week. The results are given in terms of [µSv/h].

f) Cooling time of 1 month

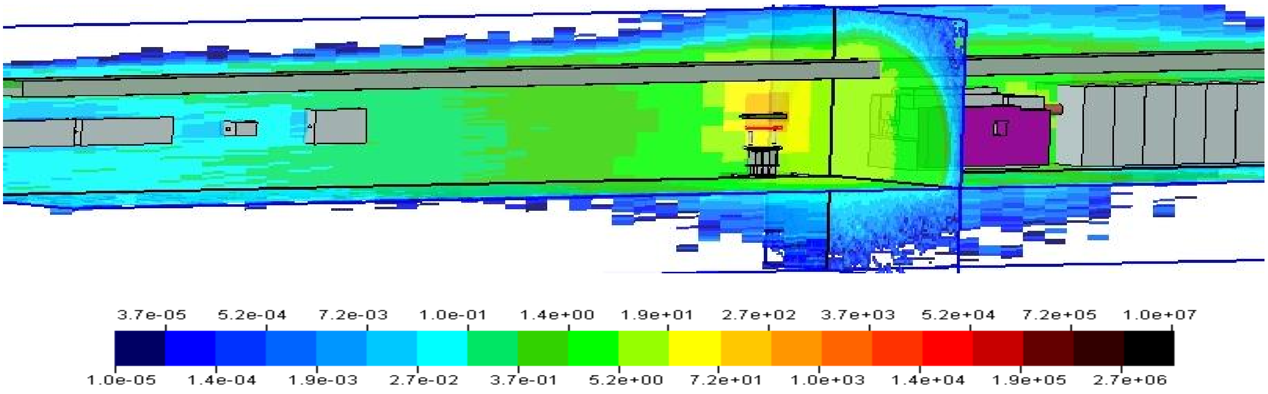

Figure 29: Dose rate in the TNC tunnel after a cooling time of 1 month. The results are given in terms of [µSv/h].

g) Cooling time of 2 months

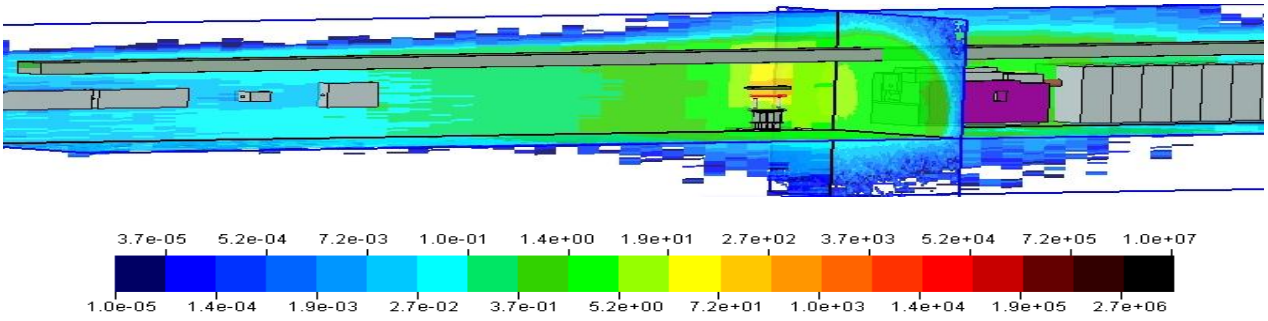

Figure 30: Dose rate in the TNC tunnel after a cooling time of 2 months. The results are given in terms of [µSv/h].

As human interventions might be carried out in the vicinity of the activated collimator 3 distances were chosen near the collimator, upstream and downstream, in order to assess the levels of the residual dose rates after the 7 cooling times. More specifically:

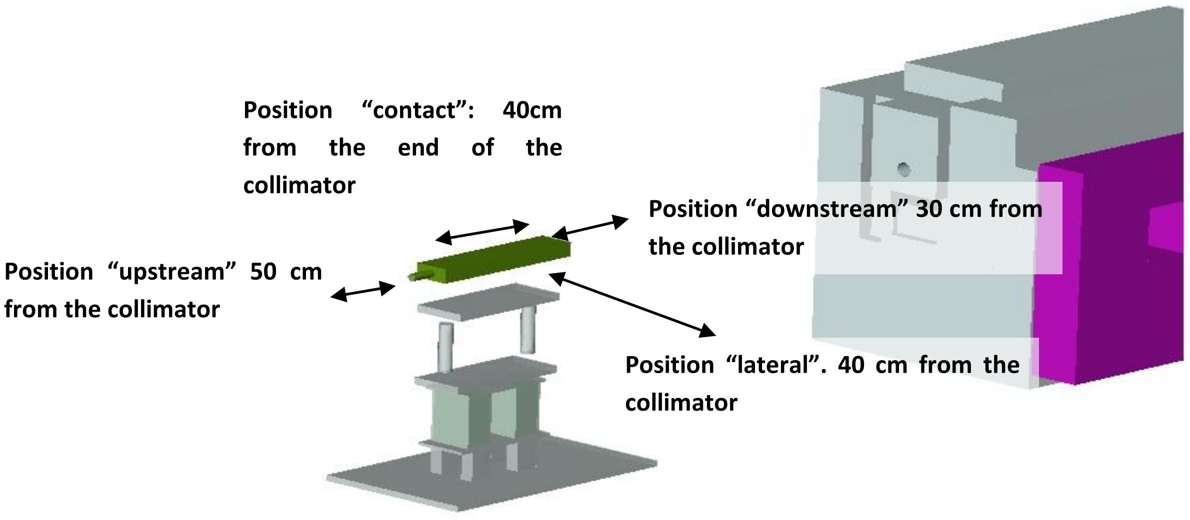

Figure 31: The reference positions of the dose rate near the collimator. The collimator was modelled to be at test stand 3.

The corresponding dose rates can be found in Table 2 [µSv/h] :

Table 2: Ambient dose equivalent rate in uSv/h near the activated collimator for the seven corresponding cooling times.

Position/Cooling time	*Position "upstream"*	*Position "contact"*	*Position "downstream"*	*Position "lateral"*
1 hour	$4 \cdot 10^4$	10^6	$3 \cdot 10^4$	$7 \cdot 10^4$
12 hours	$1.5 \cdot 10^3$	$4 \cdot 10^4$	$2 \cdot 10^3$	$4.5 \cdot 10^3$
1 day	800	$2 \cdot 10^4$	10^3	$2.5 \cdot 10^3$
2 days	360	10^4	500	$1 \cdot 10^3$
1 week	90	$5 \cdot 10^3$	130	450
1 month	20	10^3	30	110
2 months	10	550	15	50

As can be seen from the values for the "contact" position in Table 2 (which actually corresponds to the dose rate encountered at the surface in the middle of the collimator), the irradiated object itself remains quite radioactive even after a cooling period of 2 months. Significantly lower values can be found for the upstream, downstream and lateral locations. In general, it is foreseen to keep human intervention close to the irradiated objects to a bare minimum, as the irradiated objects should be handled and removed remotely. However, if the need for such an intervention should arise the values in Table 2 as well as the active RAMSES monitoring can be used to implement proper work and dose-planning. The required waiting time before the access will have to be decided taking the urgency as well as the radiation hazard into account. However, it is obvious from the calculations that several days of waiting yield a significant reduction in terms of residual dose rate. It should be noted that in addition to the calculations several PMI ionization chambers are installed in the experimental area for accurate surveillance of the residual dose rate (10).

ii. TJ7 tunnel activation dose calculations

Figure 43 to Figure 49 show the residual dose rate in the TJ7 tunnel while the irradiated collimator is still in place in the adjacent TNC tunnel.

a) Cooling time of 1 hour

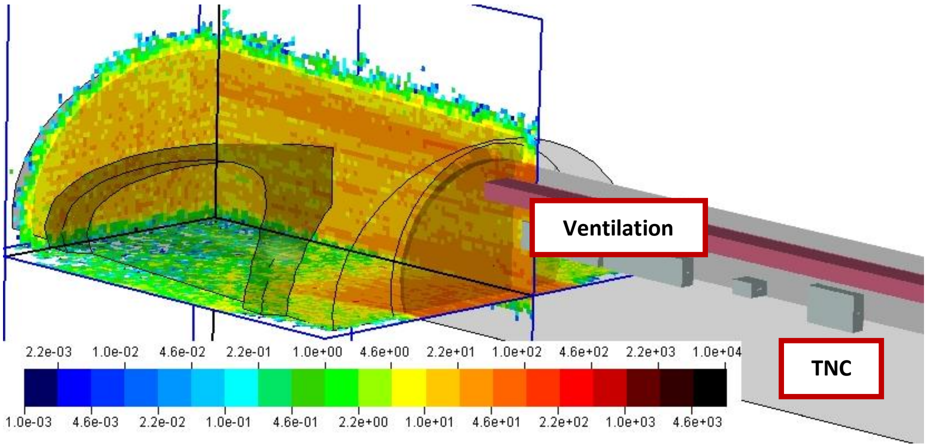

Figure 32: Dose rate in the TJ7 tunnel after a cooling time of 1 hour. The results are given in terms of [µSv/h]. Current levels of background radiation are not taken into account!

b) Cooling time of 12 hours

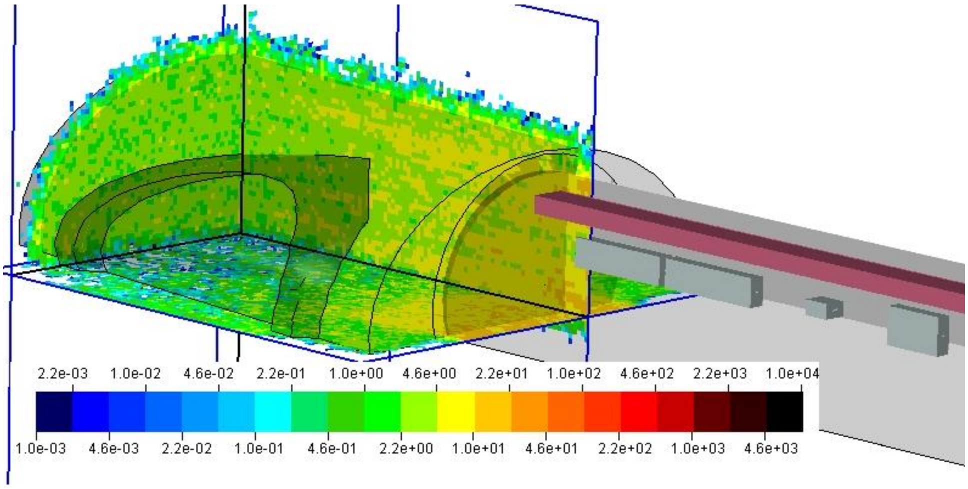

Figure 33: Dose rate in the TJ7 tunnel after a cooling time of 12 hours. The results are given in terms of [µSv/h]. Current levels of background radiation are not taken into account!

c) Cooling time of 1 day

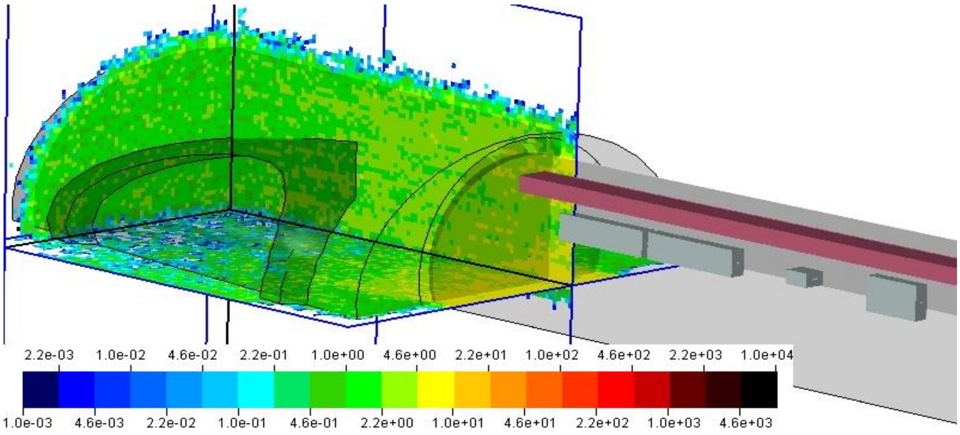

Figure 34: Dose rate in the TJ7 tunnel after a cooling time of 1 day. The results are given in terms of [µSv/h]. Current levels of background radiation are not taken into account!

d) Cooling time of 2 days

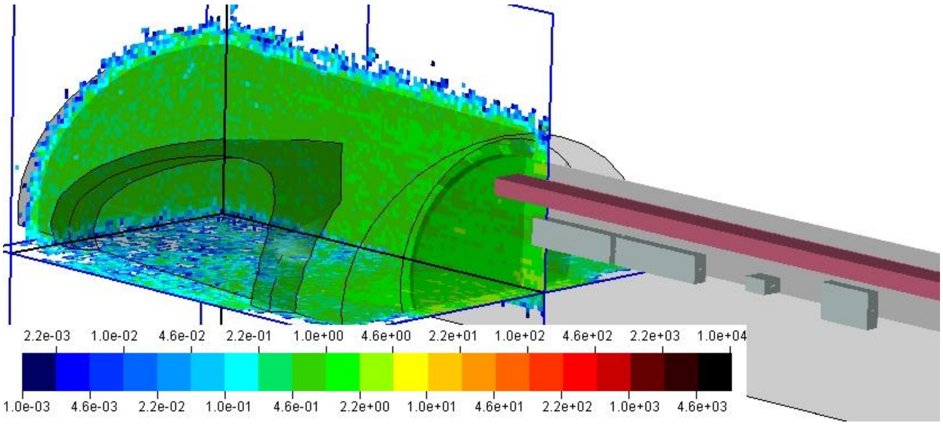

Figure 35: Dose rate in the TJ7 tunnel after a cooling time of 2 days. The results are given in terms of [µSv/h]. Current levels of background radiation are not taken into account!

e) Cooling time of 1 week

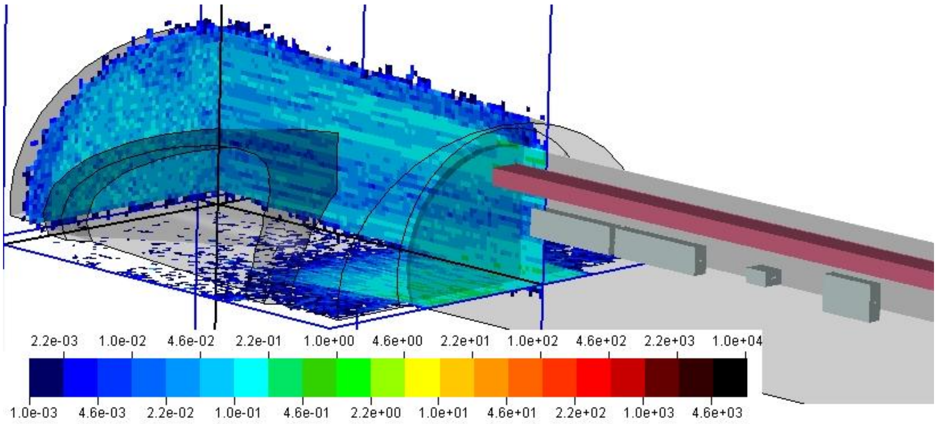

Figure 36: Dose rate in the TJ7 tunnel after a cooling time of 1 week. The results are given in terms of [µSv/h]. Current levels of background radiation are not taken into account!

f) Cooling time of 1 month

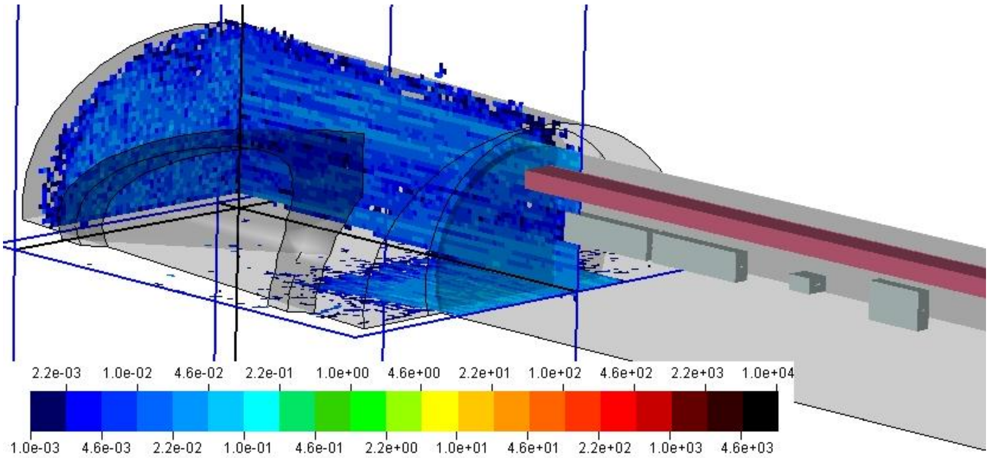

Figure 37: Dose rate in the TJ7 tunnel after a cooling time of 1 month. The results are given in terms of [µSv/h]. Current levels of background radiation are not taken into account!

g) Cooling time of 2 months

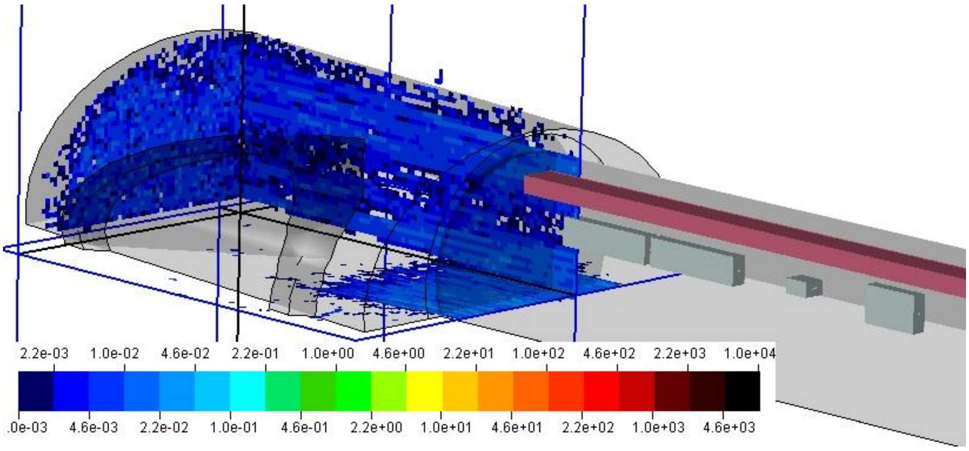

Figure 38: Dose rate in the TJ7 tunnel, after a cooling time of 2 months. The results are given in terms of [µSv/h]. Current levels of background radiation are not taken into account!

From the figures above it can be clearly seen that the dose rate in the TJ7 tunnel decreases from about 70 µSv/h (excluding current background radiation levels of a few µSv/h) after a cooling time of 1 hour toabout 12 µSv/h after a cooling time of ½ day. After 1 week the dose rate would have reached levels of <0.1 µSv/h, which is even lower than current radiation levels in TJ7 of a few µSv/h, originating from its use for the former WANF neutrino facility.

It is clearly favorable to remove the irradiated object to the storage area at the end of the TNC before public access to the underground tunnels adjacent to the TNC, like TJ7, is granted. If urgent access is really needed (e.g. passage to TCC6) and it is demonstrably impossible to remove the irradiated object beforehand, then a period of at least 12 hours of cool down should be respected and access to the TNC has to be precluded by the access system.

4. Background radiation

With a new feature of the FLUKA code it was possible to calculate the remnant (background) radiation in the tunnels for the seven different cooling times used as before, but with the activated object removed. This scenario allows for estimating of the dose rate that technicians and personnel will be exposed to after the end of an experiment and while installing the next one. It should be noted that the calculations do not include current background radiation levels due to the use of the tunnel as the former WANF neutrino facility.

Two scenarios were studied:

- A copper target of radius 3 cm and a length of 15 cm was placed at focal point 3. After the irradiation the target was removed and the decay radiation was calculated without the target for the 7 cooling times. The irradiation profile chosen was 10^{16} protons over 1 year. This scenario represents a nominal scenario of about 10 experiments per year.
- Instead of the aforementioned copper target an exemplary collimator mounted on a table was simulated.

i. Background radiation after irradiating a copper target, 15 cm length

➢ TNC tunnel calculations

a) Cooling time of 1 hour

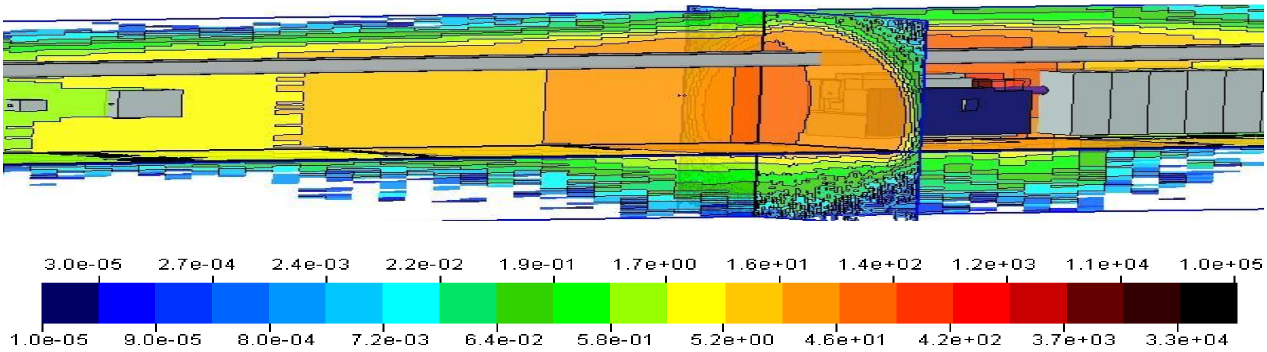

Figure 39: Background radiation for the TNC tunnel in the case of the copper target after a cooling time of 1 hour. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

b) Cooling time of 12 hours

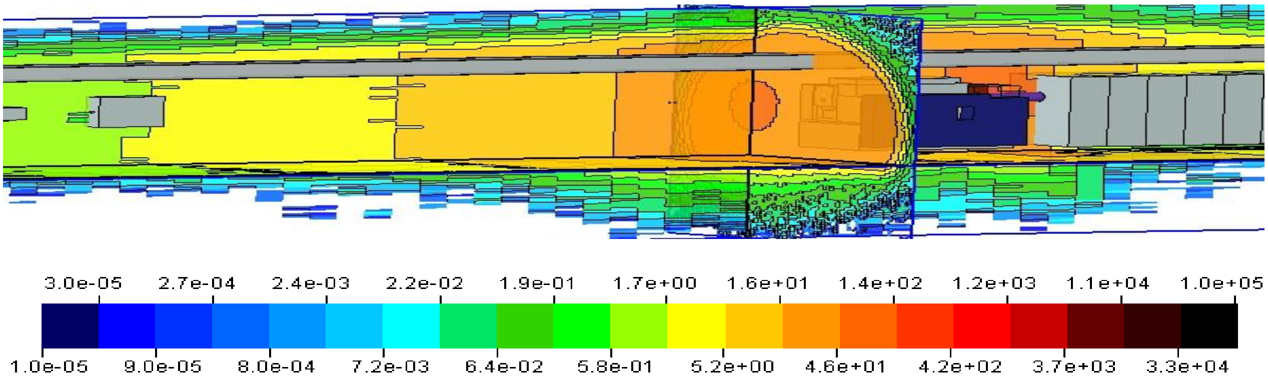

Figure 40: Background radiation for the TNC tunnel in the case of the copper target after a cooling time of 12 hours. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

c) Cooling time of 1 day

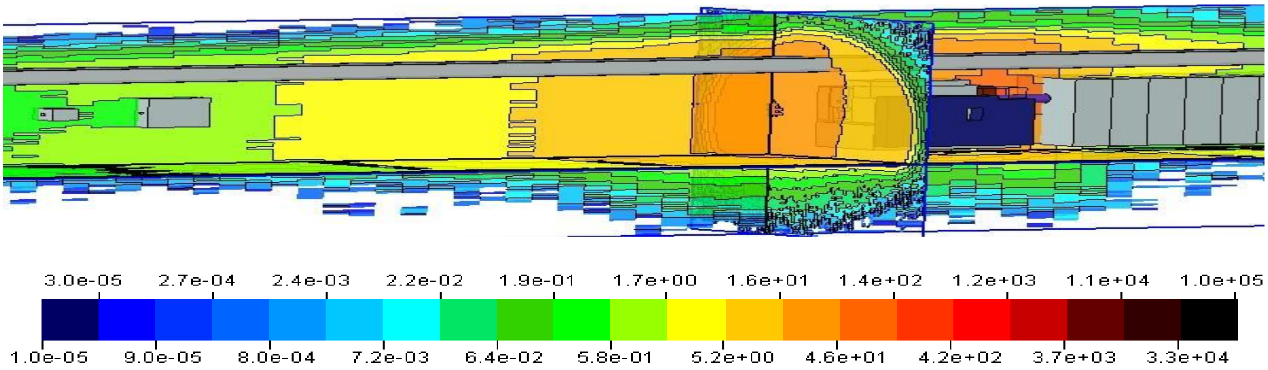

Figure 41: Background radiation for the TNC tunnel in the case of the copper target after a cooling time of 1 day. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

d) Cooling time of 2 days

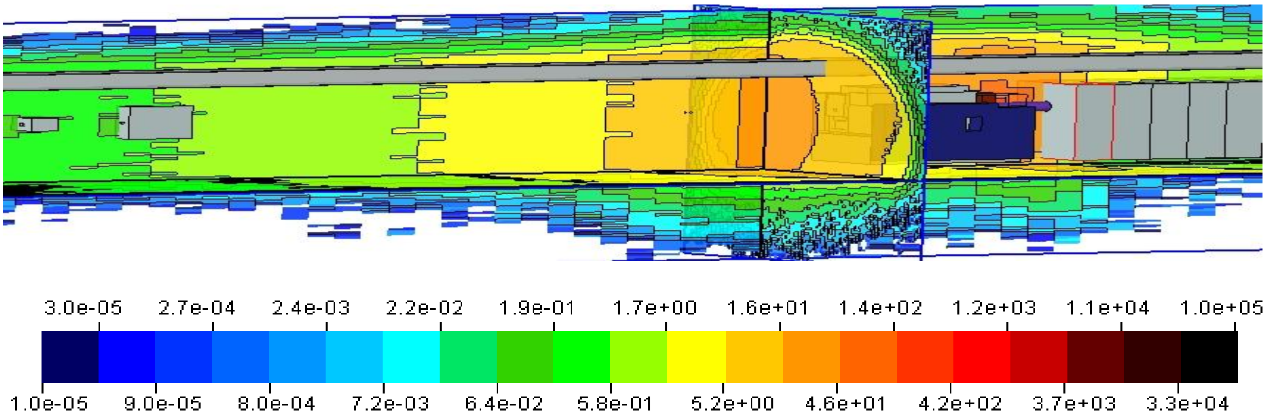

Figure 42: Background radiation for the TNC tunnel in the case of the copper target after a cooling time of 2 days. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

e) Cooling time of 1 week

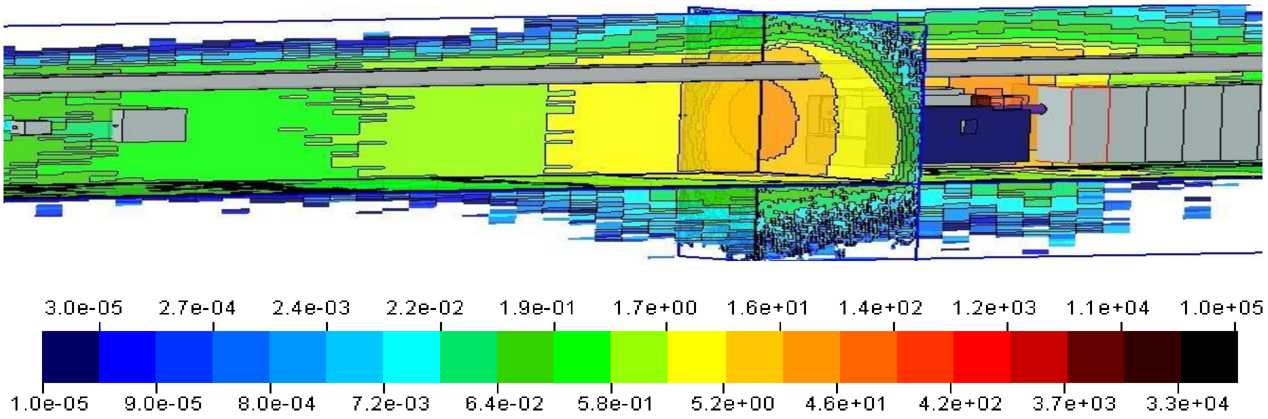

Figure 43: Background radiation for the TNC tunnel in the case of the copper target after a cooling time of 1 week. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

f) Cooling time of 1 month

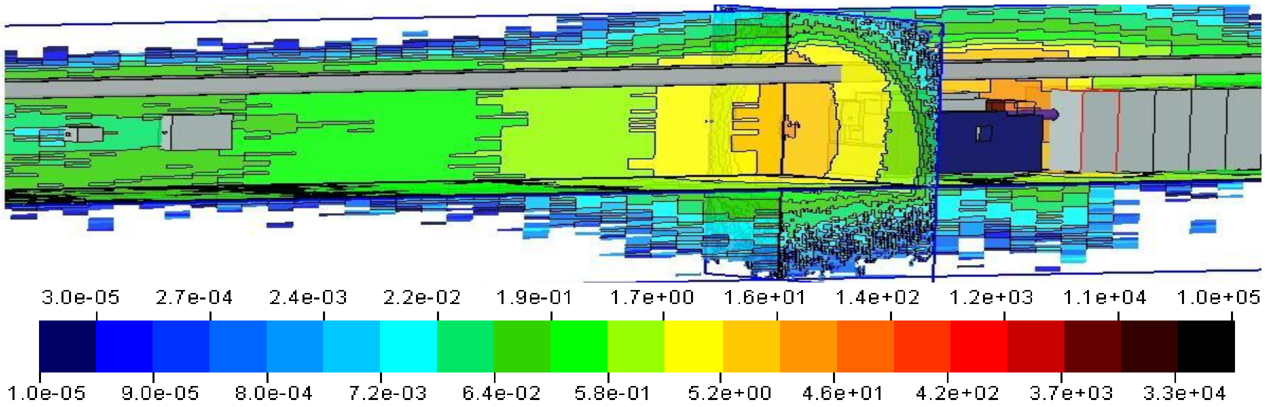

Figure 44: Background radiation for the TNC tunnel in the case of the copper target after a cooling time of 1 month. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

g) Cooling time of 2 months

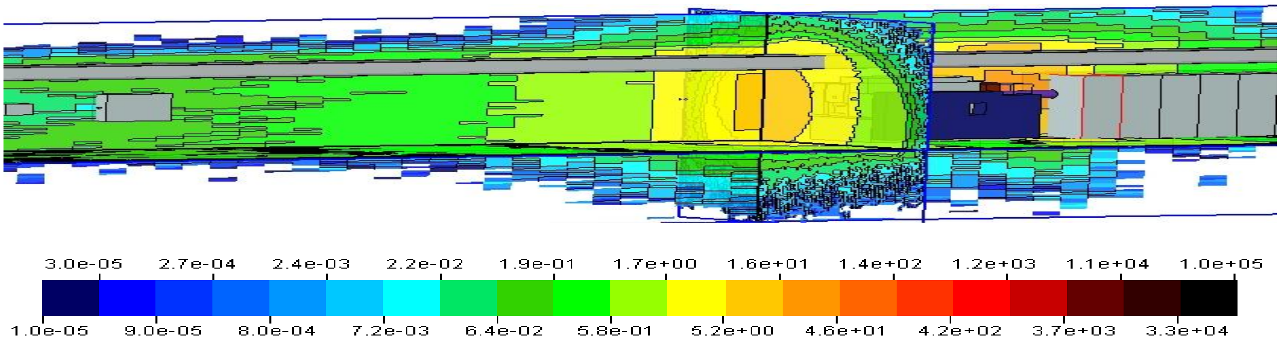

Figure 45: Background radiation for the TNC tunnel in the case of the copper target after a cooling time of 2 months. The results are given in terms of [µSv/h].

From Figure 56 to Figure 62 it can be see that even after the removal of the irradiated copper target the background radiation levels remain elevated near the dump. Current radiation levels near the dump's front face are already in the range of ~80 uSv/h and it can be clearly seen that even a waiting time of 2 months would not yield significant changes in comparison to the current situation. Including the contribution of the current radiation level and the background from one year of HiRadMat operation one would expect ambient dose rates of 90-100 uSv/h near the dump's front face.

- TJ7 tunnel calculations

a) Cooling time of 1 hour

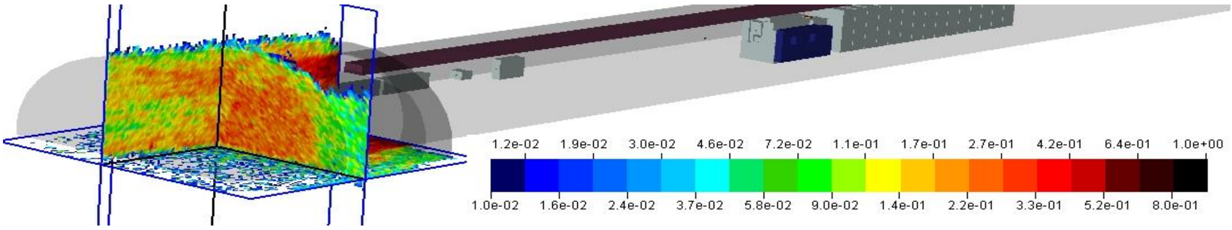

Figure 46: Background radiation for the TJ7 tunnel, in the case of the copper target after a cooling time of 1 hour. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

b) Cooling time of 12 hours

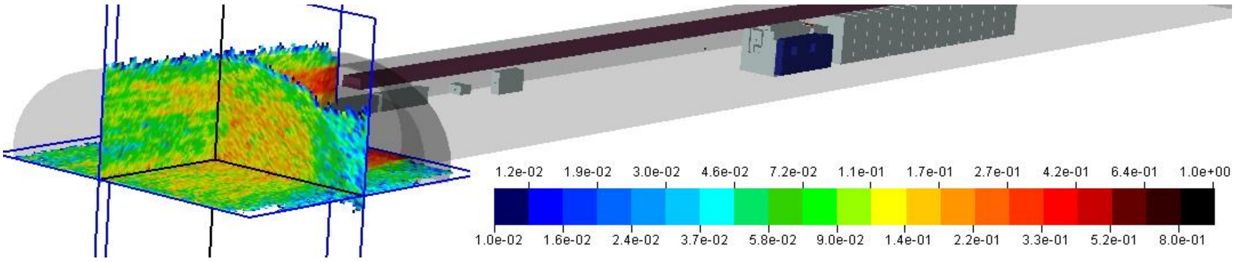

Figure 47: Background radiation for the TJ7 tunnel in the case of the copper target after a cooling time of 12 hours. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

c) Cooling time of 1 day

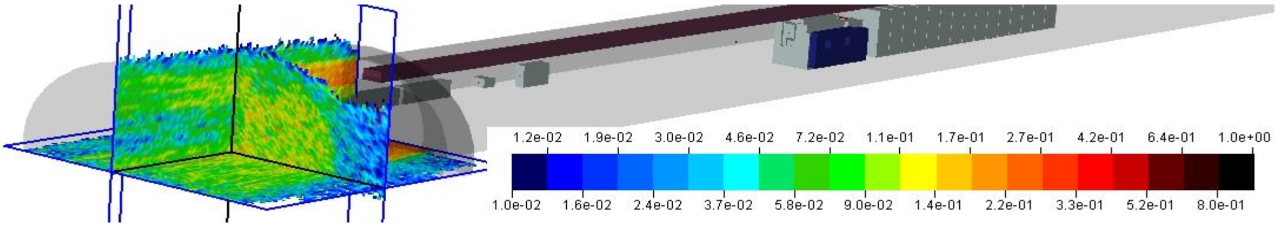

Figure 48: Background radiation for the TJ7 tunnel, in the case of the copper target, after a cooling time of 1 day. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

d) Cooling time of 2 days

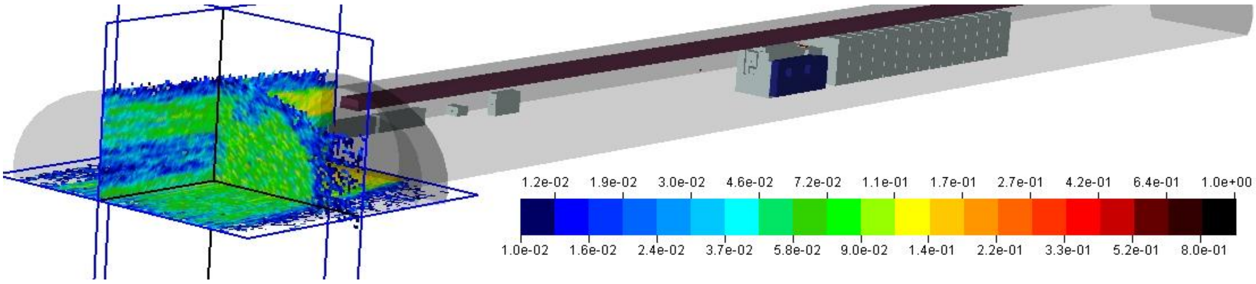

Figure 49: Background radiation for the TJ7 tunnel in the case of the copper target after a cooling time of 2 days. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

e) Cooling time of 1 week

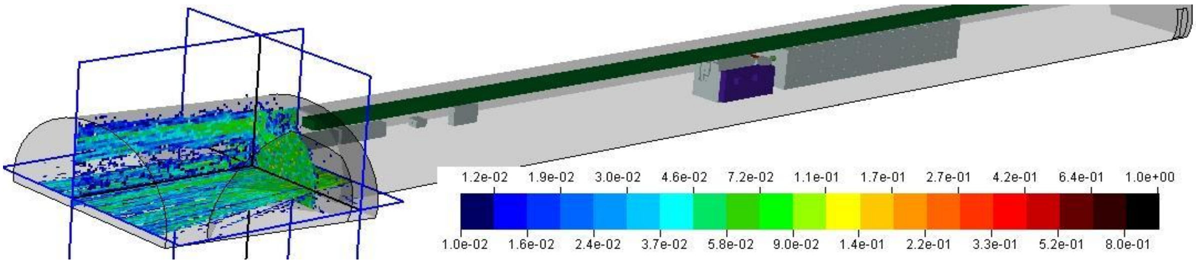

Figure 50: Background radiation for the TJ7 tunnel in the case of the copper target after a cooling time of 1 week. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included! Please note also that the legend color scale has changed from the previous picture.

f) Cooling time of 1 month

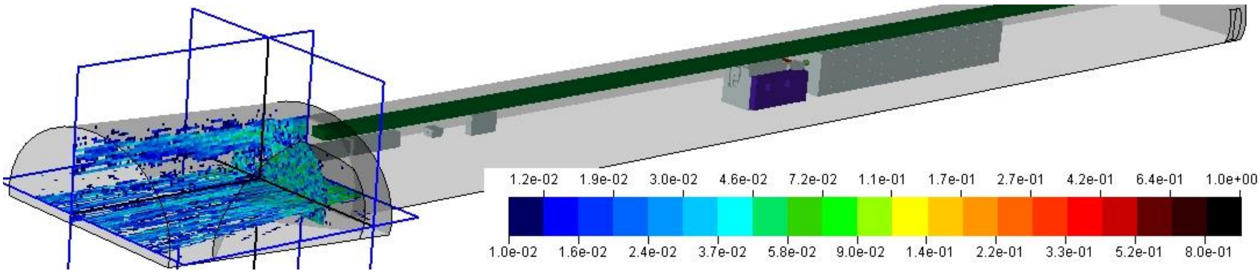

Figure 51: Background radiation for the TJ7 tunnel in the case of the copper target after a cooling time of 1 month. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

g) Cooling time of 2 months

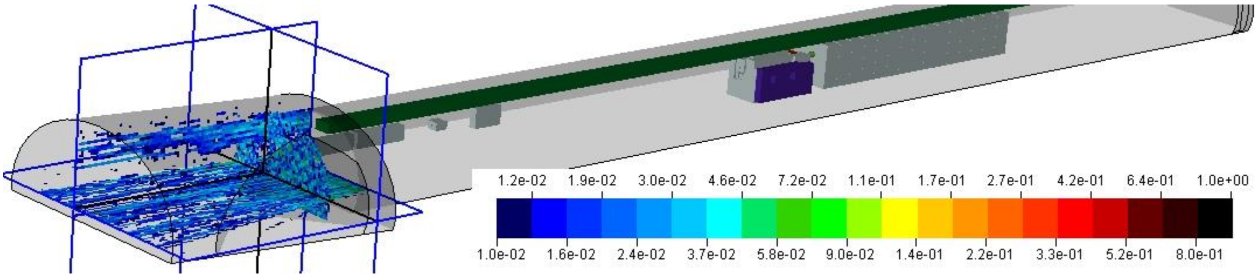

Figure 52: Background radiation for the TJ7 tunnel in the case of the copper target after a cooling time of 2 months. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

As can be seen from Figure 63 to Figure 69, one full year of operation is not expected to have any significant impact on the residual dose rate levels in TJ7. Even after one hour of cooling the dose rate would already be below 1 μSv/h, which is in the order of the current background of a few μSv/h, originating from the former WANF installation.

ii. Background radiation after irradiating a collimator.

- TNC tunnel calculations

a) Cooling time of 1 hour

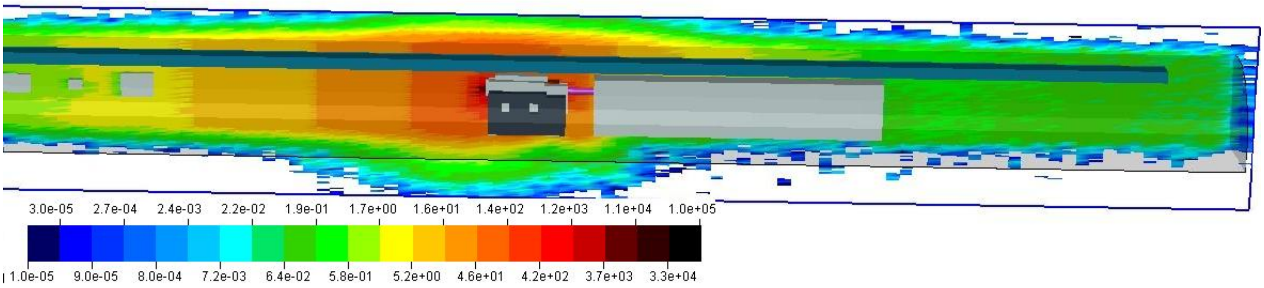

Figure 53: Background radiation for the TNC tunnel in the case of the table and the collimator irradiation after a cooling time of 1 hour. The results are given in terms of [μSv/h]. Current background radiation levels from former use of the tunnel are not included!

b) Cooling time of 12 hours

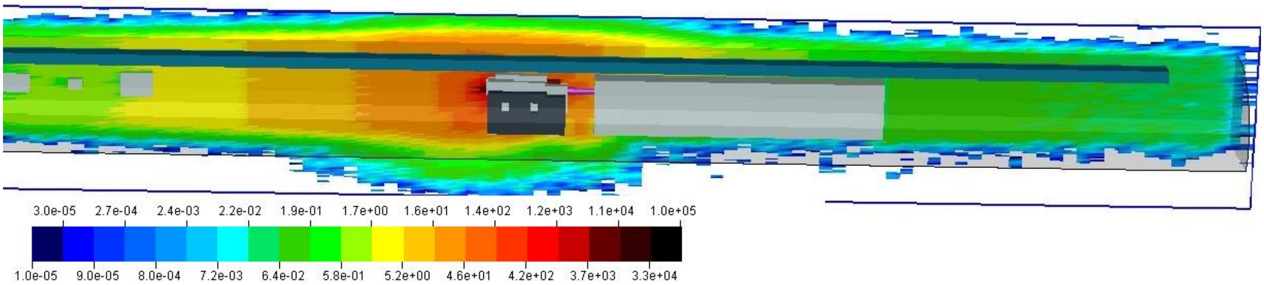

Figure 54: Background radiation for the TNC tunnel in the case of the graphite collimator irradiation after a cooling time of 12 hours. The results are given in terms of [μSv/h]. Current background radiation levels from former use of the tunnel are not included!

c) Cooling time of 1 day

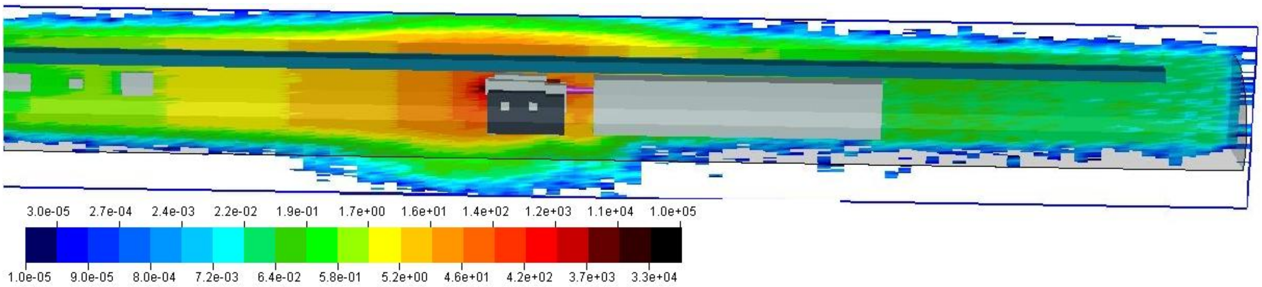

Figure 55: Background radiation for the TNC tunnel in the case of the graphite collimator irradiation after a cooling time of 1 day. The results are given in terms of [μSv/h]. Current background radiation levels from former use of the tunnel are not included!

d) Cooling time of 2 days

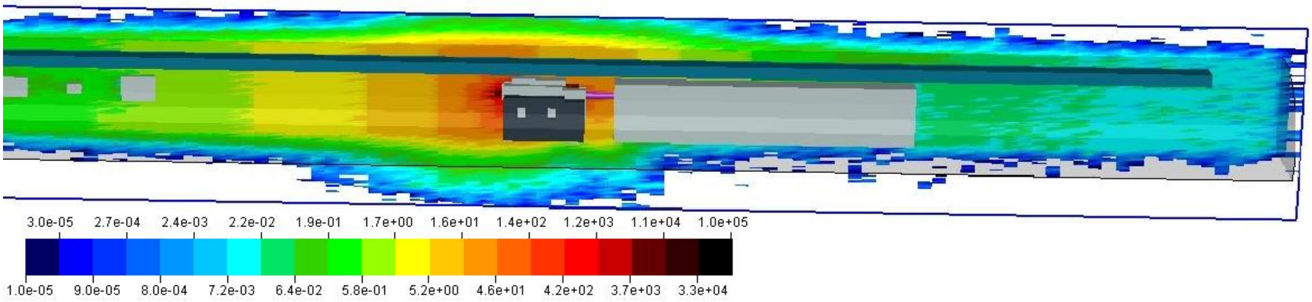

Figure 56: Background radiation for the TNC tunnel in the case of the graphite collimator irradiation after a cooling time of 2 days. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

e) Cooling time of 1 week

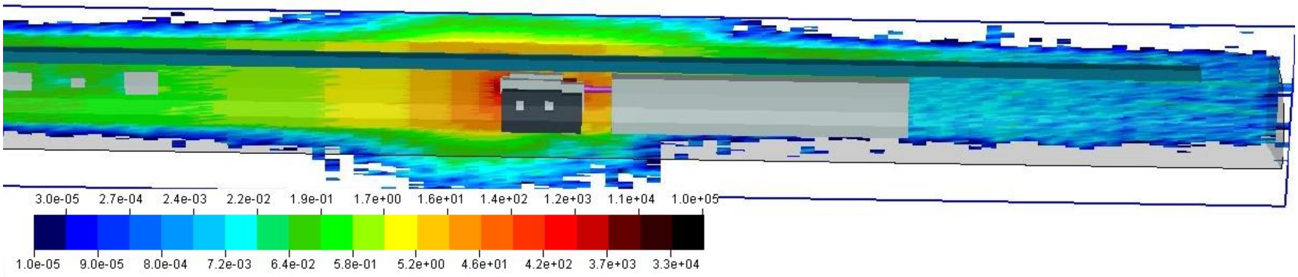

Figure 57: Background radiation for the TNC tunnel in the case of the graphite collimator irradiation after a cooling time of 1 week. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

f) Cooling time of 1 month

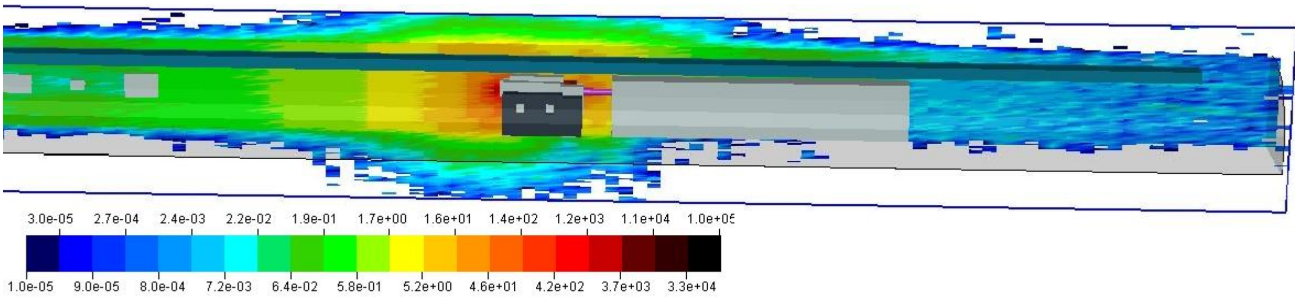

Figure 58: Background radiation for the TNC tunnel in the case of the graphite collimator irradiation after a cooling time of 1 month. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

g) Cooling time of 2 months

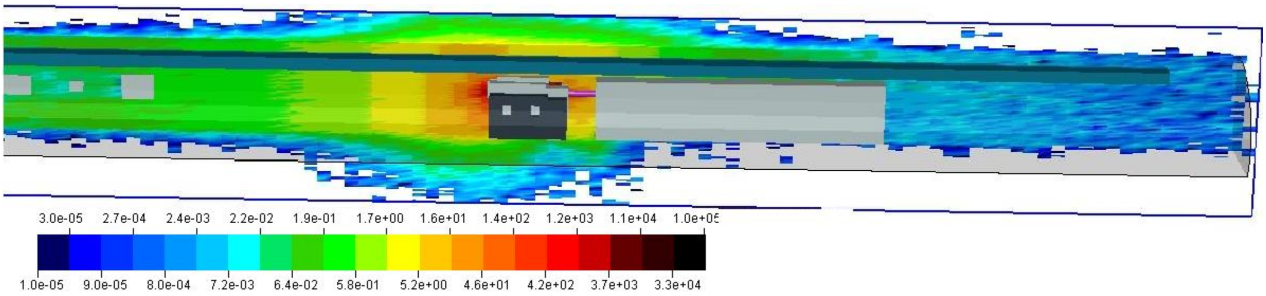

Figure 59: Background radiation for the TNC tunnel in the case of the graphite collimator irradiation after a cooling time of 2 months. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

From Figure 70 to Figure 76 we can see that as expected the main source of background radiation is the activation of the dump.

- TJ7 tunnel calculations

a) Cooling time of 1 hour

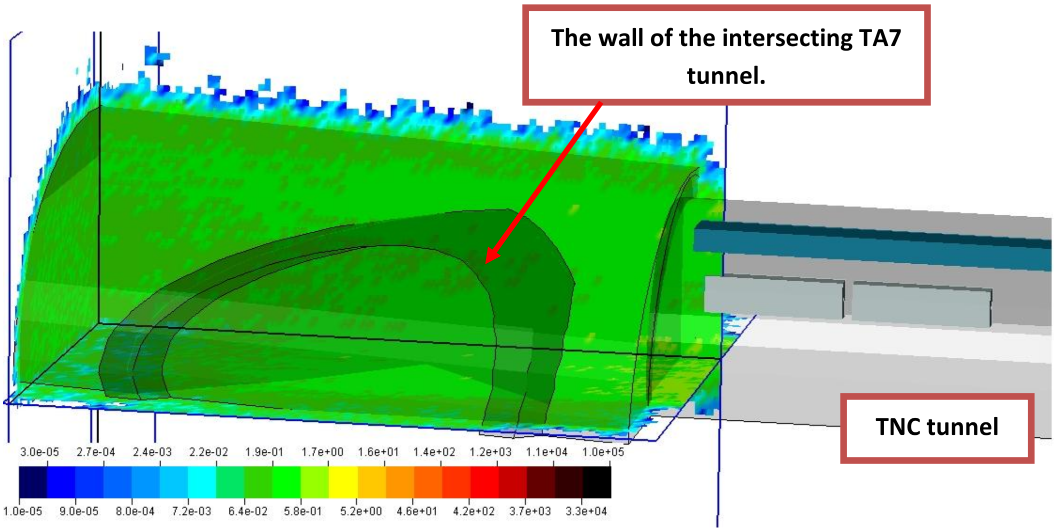

Figure 60: Background radiation for the TJ7 tunnel in the case of the graphite collimator irradiation, after a cooling time of 1 hour. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

b) Cooling time of 12 hours

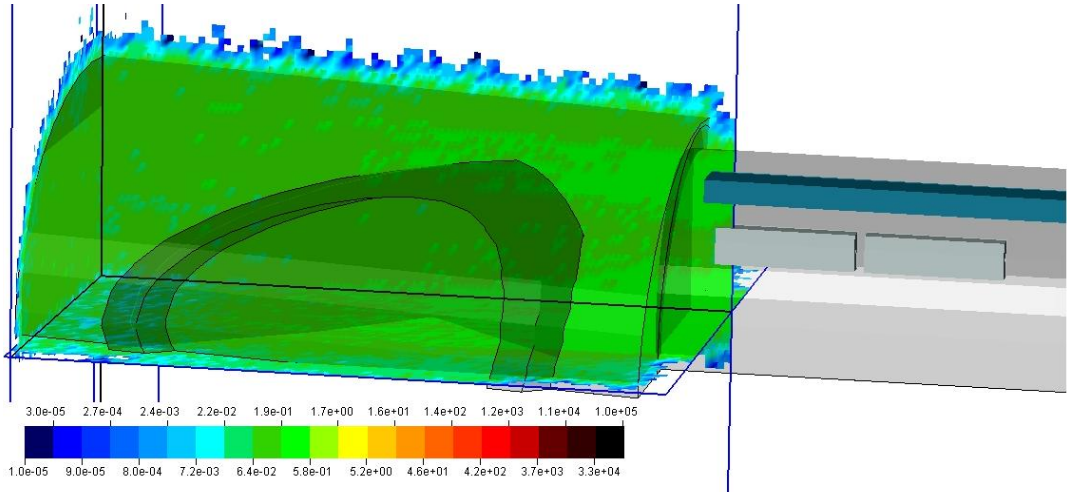

Figure 61: Background radiation for the TJ7 tunnel in the case of the graphite collimator irradiation after a cooling time of 12 hours. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

c) Cooling time of 1 day

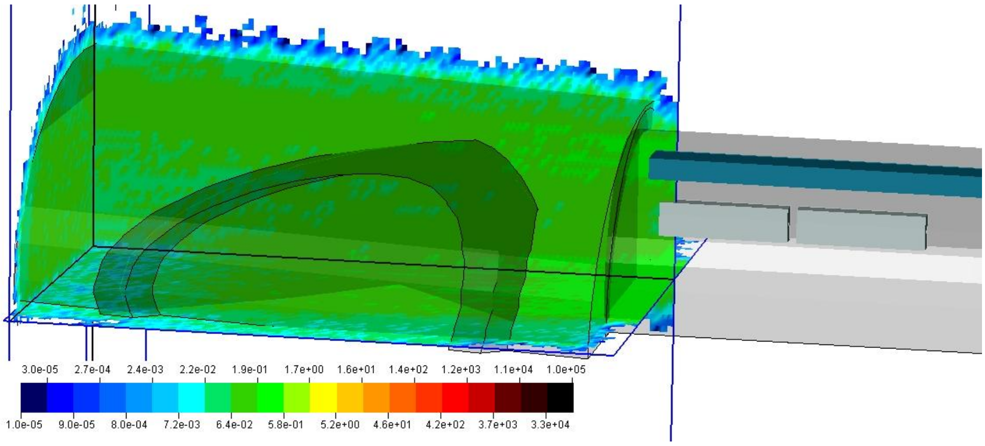

Figure 62: Background radiation for the TJ7 tunnel in the case of the graphite collimator irradiation after a cooling time of 1 day. The results are given in terms of [μSv/h]. Current background radiation levels from former use of the tunnel are not included!

d) Cooling time of 2 days

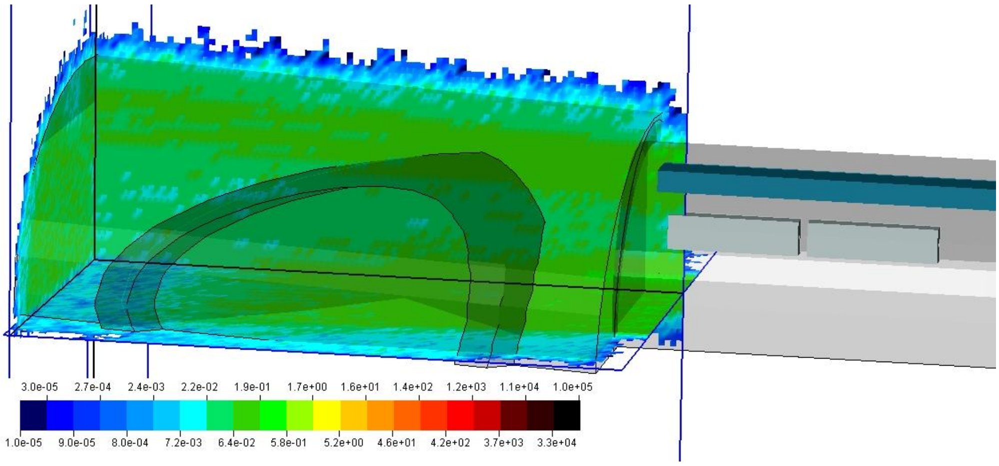

Figure 63: Background radiation for the TJ7 tunnel in the case of the graphite collimator irradiation after a cooling time of 2 days. The results are given in terms of [μSv/h]. Current background radiation levels from former use of the tunnel are not included!

e) Cooling time of 1 week

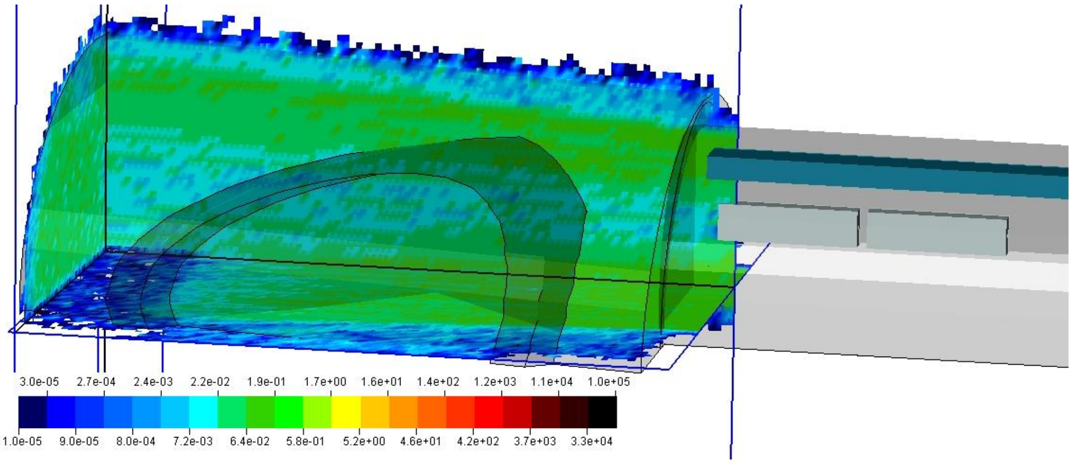

Figure 64: Background radiation for the TJ7 tunnel in the case of the graphite collimator irradiation after a cooling time of 1 week. The results are given in terms of [μSv/h]. Current background radiation levels from former use of the tunnel are not included!

f) Cooling time of 1 month

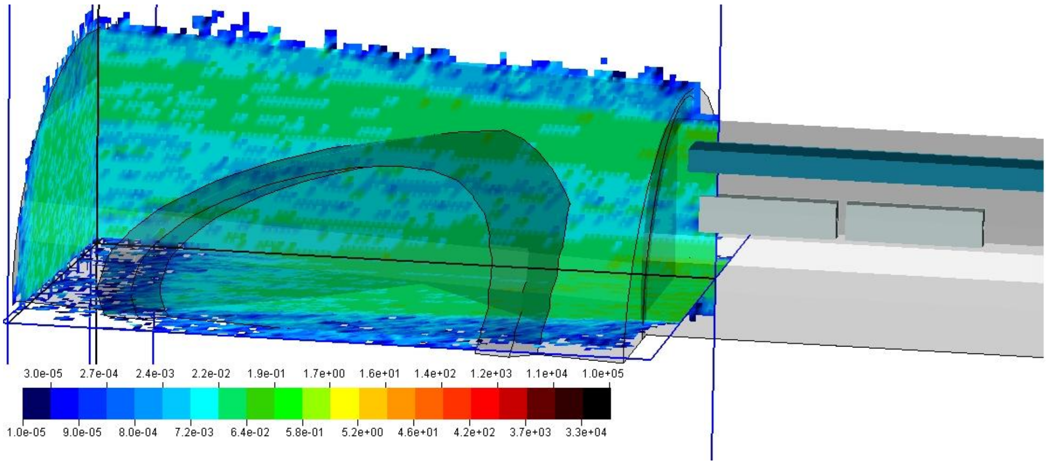

Figure 65: Background radiation for the TJ7 tunnel in the case of the graphite collimator irradiation after a cooling time of 1 month. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

g) Cooling time of 2 months

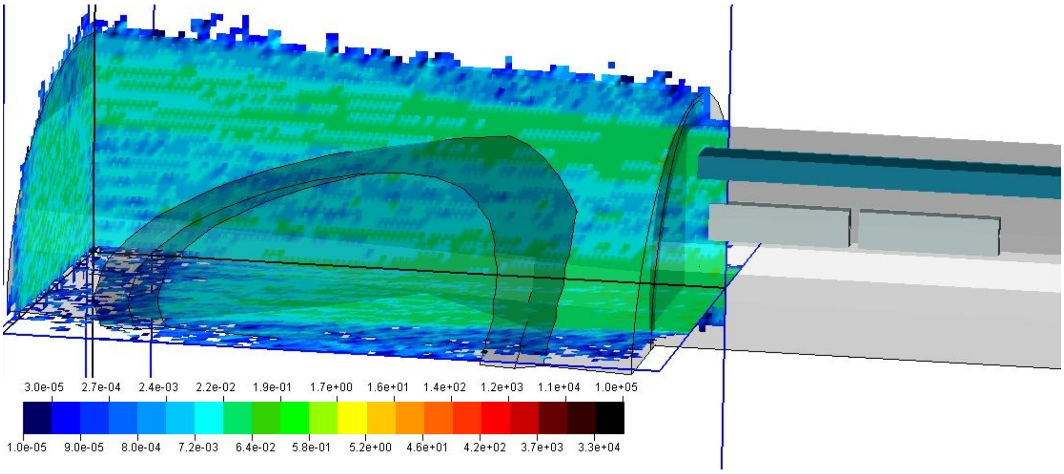

Figure 66: Background radiation for the TJ7 tunnel in the case of the graphite collimator irradiation after a cooling time of 2 months. The results are given in terms of [µSv/h]. Current background radiation levels from former use of the tunnel are not included!

5. Water activation calculations

In order to estimate the activation of the water in the cooling circuit of the dump an estimator of the residual nuclei produced in the water was used. Two different beam-impact scenarios were studied:

- The full beam was simulated to hit directly on the TED core which is an admittedly worst-case scenario for the activation of the water
- The beam was simulated to impinge on a graphite collimator located at the focal point 3, which represents a normal operational scenario

Moreover, two different irradiation profiles were used:

- An average number of 10^{16} protons over one year, which represents a nominal “operational” scenario of the facility

- An average number of 10^{17} protons over 10 years, which represents a long-term scenario

In order to estimate the water activation three basic assumptions were made:

- The activated (in the dump) volume of water is assumed to be homogenously mixed with the rest of the water-cooling circuit.
- The total volume of the water in the circuit is 60000 l while the volume of the water being instantaneously inside the dump is 4.779 l. Therefore, a dilution factor of $d = \frac{4.779}{60000} = 7.97 \cdot 10^{-5}$ is obtained.
- According to previous studies (11), FLUKA underestimates the production of ^{3}H by a factor of 2.54. This was taken into account in the calculations.

i. Operational Scenario (beam on the collimator)

- 10^{16} protons over one year

Table 3: The specific activity from ^{3}H and ^{7}Be, during an operational scenario (10^{16} protons over one year)

Isotope	$\tau_{1/2}$	*Specific Activity [Bq/l]*
^{3}H	12.4 y	45
^{7}Be	53.3 d	88

- 10^{17} protons over ten years

Table 4: The specific activity from ^{3}H and ^{7}Be for a long-term operational scenario (10^{17} protons over ten years)

Isotope	$\tau_{1/2}$	*Specific Activity [Bq/l]*
^{3}H	12.4 y	353
^{7}Be	53.3 d	89.5

ii. Worst case scenario (beam sent directly in the dump core)

- 10^{16} protons over one year

Table 5: The specific activity from ^{3}H and ^{7}Be for a worst case scenario (10^{16} protons over one year)

Isotope	$\tau_{1/2}$	*Specific Activity [Bq/l]*
^{3}H	12.4 y	102
^{7}Be	53.3 d	198

- 10^{17} protons over ten years

Table 6: The specific activity from ^{3}H and ^{7}Be for a long-term worst-case scenario (10^{17} protons over ten years)

Isotope	$\tau_{1/2}$	*Specific Activity [Bq/l]*
^{3}H	12.4 y	1020
^{7}Be	53.3 d	1999

According to the Swiss legislation (12) effluents are considered as radioactive if the following conditions are met: the specific activity exceeds 1% of the exemption limit (LE) as a weekly mean and the total activity release is larger than 100 times the exemption limit. In the case of water the levels of tritium ^{3}H (HTO) and ^{7}Be are usually critical. The value of 1% of the LE value for ^{3}H is found to be 6000 Bq/l and 100 times the LE value for the total activity equals 60 MBq. In the case of ^{7}Be the respective values are 4000 Bq/l and 40 MBq. As can be seen neither in the operational nor in the worst-case scenario the limits should be exceeded. As the half-life of ^{7}Be is significantly lower than for ^{3}H a worst-case short-term scenario was studied as well, because in this case the level of ^{7}Be can be expected to be higher than for using for example 10^{16} protons over one whole year. Therefore, a calculation of the ^{7}Be levels has been performed for an unrealistic scenario during which 10 consecutive experiments would have been performed within the shortest possible time. For this case 10^{16} protons have been assumed to directly hit the beam dump within 5040 seconds (10 experiments x 16.8 s super-cycle * 30 extractions). This yields a maximum of 946 Bq/l obtained after 30 minutes of decay, which is still below the applicable limit of 4000 Bq/l.

6. Summary & conclusions

The prompt dose rate levels during the operation of the facility were calculated for three different irradiation scenarios, one representing the operational envelope and the two additional ones corresponding to the nominal conditions with either a short (16.8 s) or a long (44 s) SPS super-cycle. Naturally, the dose rate levels in the underground areas exclude access while the facility is operating. As the shaft to the underground area is enclosed by an internal shielding the dose rates in the accessible areas of BA7 and as well as the adjacent building 876 are low enough to classify them as “non-designated area”. In addition there is constant surveillance by ionization chambers of the RAMSES monitoring system.

A worst-case accident scenario has been studied as well, which was simulated by placing an optimum target (99.9% interaction probability) in TJ7 in direct line of sight with respect to the access shaft that leads to the surface buildings.

In the improbable case that the full proton load of an experiment (10^{15} protons) would be lost on this optimum target the total dose for the event would be < 10 uSv in accessible areas around BA7. This value can be regarded a sufficiently low. In addition a RAMSES monitor located next to the access shaft would raise an alarm if the radiation levels exceed the limits applicable to non-designated areas in this case (< 2.5 uSv/h). Furthermore, it can be foreseen to include this monitor in the interlock chain of the beam line.

Human intervention in the vicinity of the irradiated objects is foreseen to be kept at a bare minimum, as the handling should be done in a fully remote way. If the urgent need of an access should arise the residual dose rate levels for a typical experiment involving a collimator have been calculated and can be used for a first work- and dose planning. In addition several radiation monitors (PMI detectors) are located directly in the experimental area to obtain accurate on-the-spot measurements. In general the irradiated object should be moved to the storage area before access to the underground tunnels like TJ7 will be granted. Even with the actual test objects removed one still has to pay attention to the residual dose rates originating from the beam dump.

The risk of water activation in the beam dump cooling circuits is below the applicable limits, even in the worst – case scenario that the beam directly hits the TED core for up to 10 full years. Estimates for nominal operation show values which are significantly below the applicable limits as shown in Tables 3 & 4.

Acknowledgements

The authors would like to thank Stefan Roesler for his attention to detail and his valuable comments.

Appendix A

In addition to quantities that are important for operational radiation protection, like ambient dose equivalent, also a number of results have been calculated that can be used to assess damage to electronics. In the following sections 1 MeV neutron equivalent as well as high energy hadron fluence can be found for the different underground tunnels.

i. Silicon 1 MeV neutron equivalent fluence & Hadrons > 20MeV fluence

The Silicon 1 MeV neutron equivalent fluence is a quantity used widely to evaluate the damage of electronics (consisting of Silicon) in a radiation environment. It is defined by:

$$\Phi_{eq1MeVSi} = \frac{\int_{E_0}^{E_{\max}} \Phi(\mathrm{E})\mathrm{K}(\mathrm{E})dE}{K(1MeV)}$$

Where:

Φ(E): Differential fluence

K(E): Displacement KERMA factor by fluence unit

K(1 MeV) = displacement KERMA factor by fluence unit at 1 MeV

FLUKA converts the fluence of particles to the fluence of 1 MeV neutron equivalent fluence online by application of the NIEL scaling hypothesis (13).

Another very useful quantity for the determination of the damage of electronics is the fluence of hadrons over 20MeV. These two quantities were scored and are being presented in Figure 29 - 35, for TNC, TJ7 and TA7 tunnels.

For these two quantities the results are given in [particles/cm^2/primary proton]

TNC Tunnel Silicon 1MeV neutron equivalent fluence

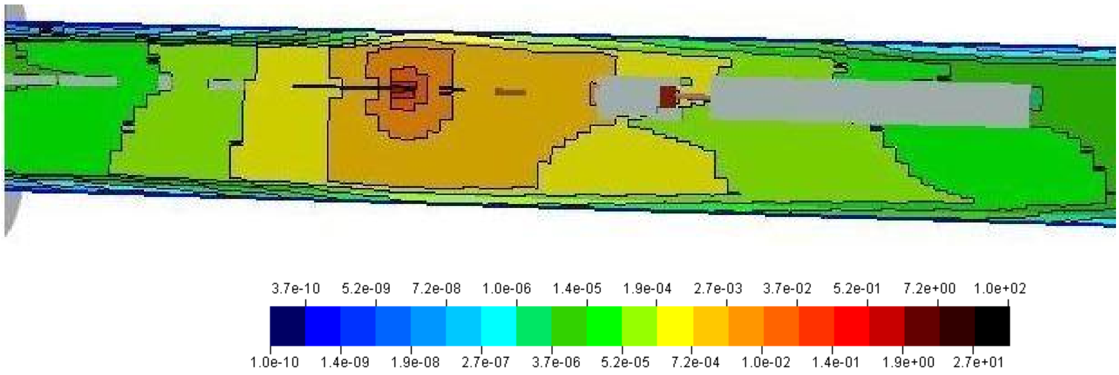

Figure 67: The Silicon 1 MeV neutron equivalent fluence for the TNC tunnel. The results are given in particles/cm^2/primary proton

TJ7 Tunnel Silicon 1MeV neutron equivalent fluence

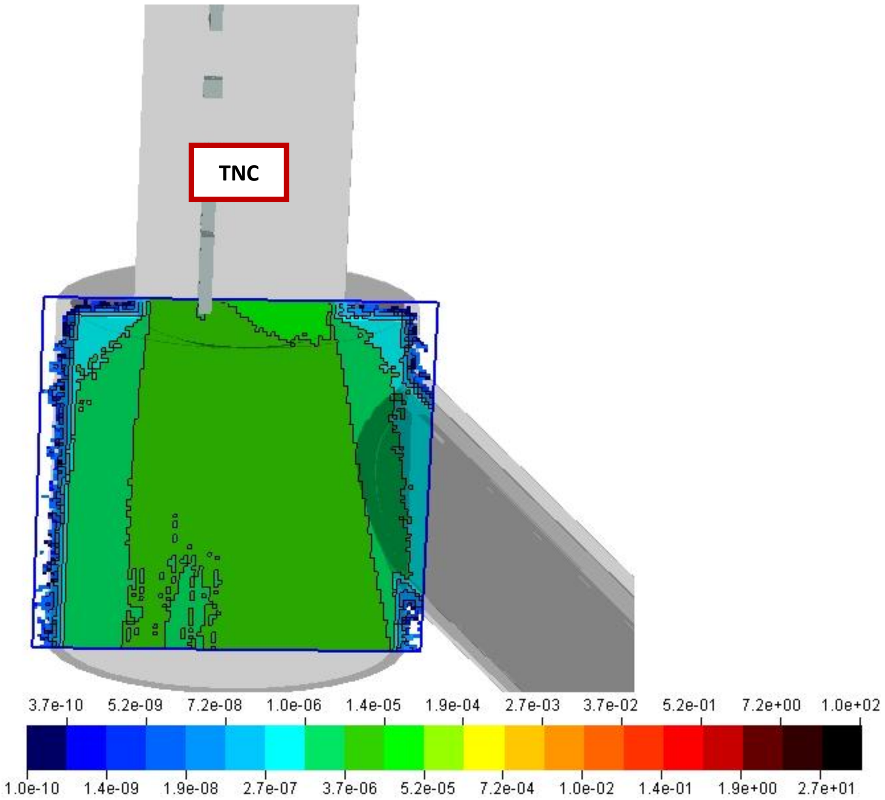

Figure 68: The Silicon 1 MeV neutron equivalent fluence for the TJ7 tunnel. The results are given in particles/cm2/primary proton

TNC tunnel hadrons >20MeV fluence

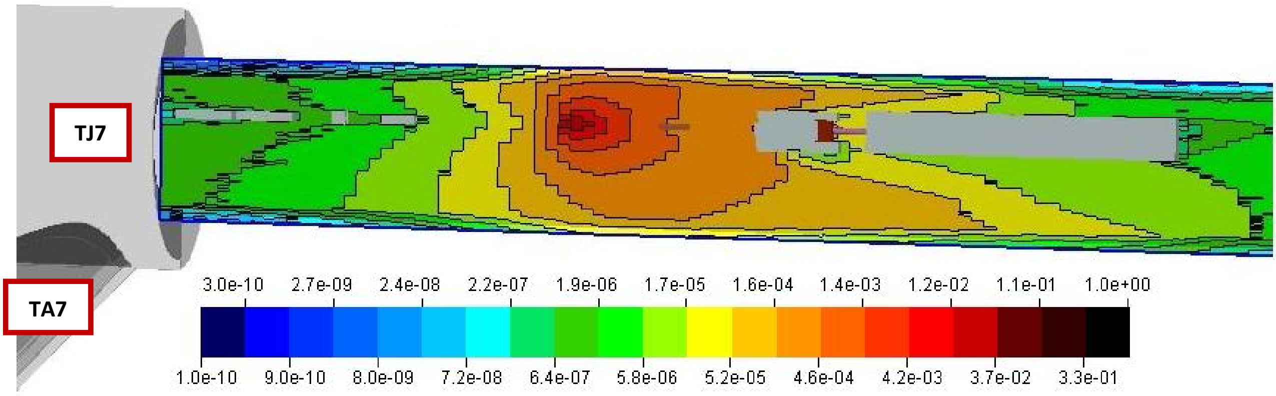

Figure 69: The hadrons > 20MeV fluence for the TNC tunnel. The results are given in particles/cm^2/primary proton

TJ7 tunnel hadrons >20MeV fluence

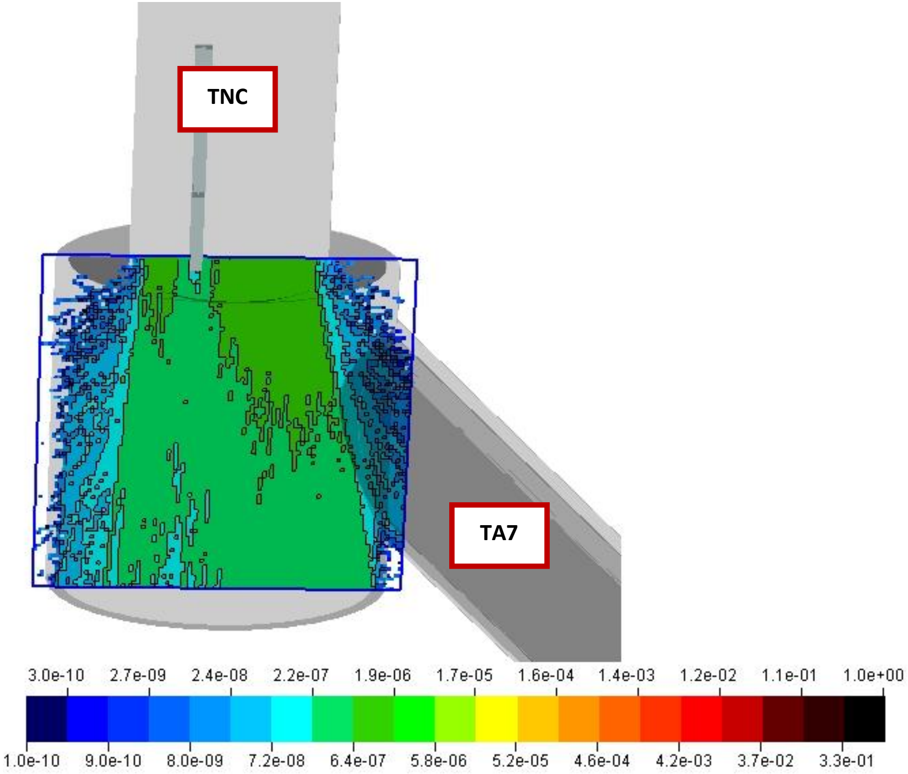

Figure 70: The hadrons > 20 MeV fluence for the TNC tunnel. The results are given in particles/cm^2/primary proton

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