Estimation of the Dose Equivalent Rate from Induced Radioactivity in the Region near the Fast Coupling System of the CNGS Magnetic Horn

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Abstract

At the CNGS facility at CERN an intense and powerful muon-neutrino beam will be generated and directed towards the underground Gran Sasso laboratory in Italy, 732 km away from CERN. There, large, complex detectors will allow long-baseline neutrino oscillation searches. Two magnetic lenses namely the horn and the reflector will focus the secondary particles generated in the target station. These two focusing elements are two coaxial lenses similar in length but different in shape. The outer conductor of the horn has a cylindrical shape while the inner conductor is generated by the rotation of a parabola around its axis, with a hole at the vertex.

In the lifetime of the CNGS project it has to be anticipated to replace the horn at least once. In the horn exchange procedure, a human intervention is necessary in the region near the fast coupling system (FCS). To estimate the radiation levels from induced radioactivity in this region the Monte-Carlo simulation program FLUKA has been used. The results obtained are presented in this report.

Outline

1. Introduction

In the lifetime of the CNGS project it has to be anticipated to replace the horn at least once. In the horn exchange procedure, a human intervention is necessary in the region near the fast coupling system (FCS). A schematic view of the layout of horn, stripline and shielding is shown in Figures 1 and 2. The horn is installed very close to the target and is fully shielded (the roof shielding, made of iron, is not shown in Figure 1).

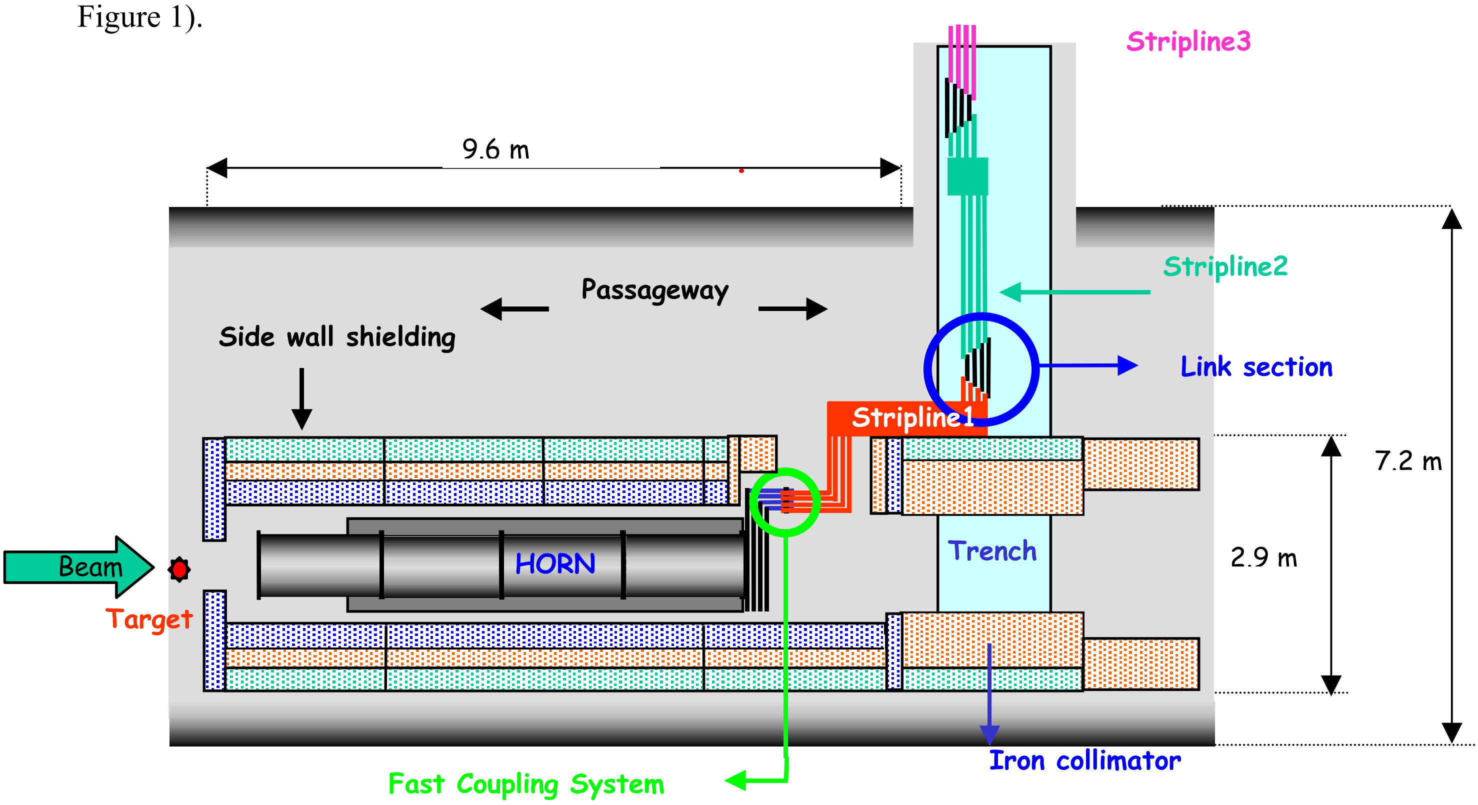


Figure 1: Schematic view (top view) of the horn region

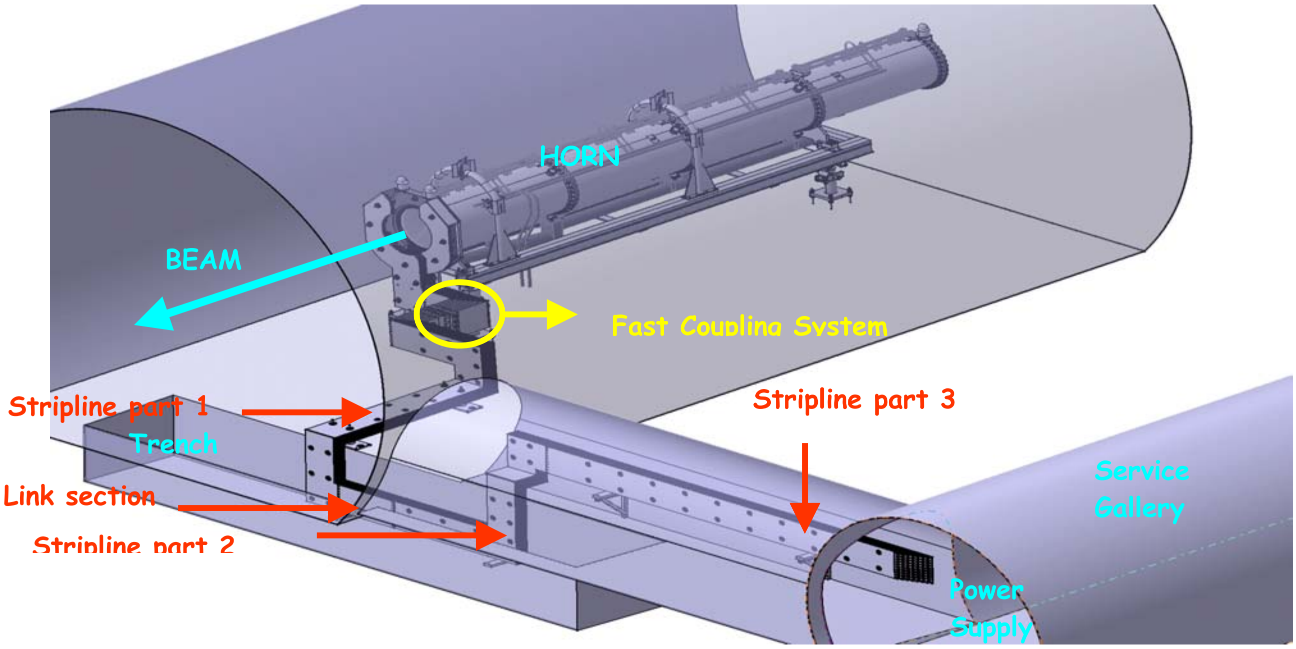


Figure 2 Artistic view of the fast coupling system region, this view does not show the shielding of the horn (Courtesy M. Briere/LAL)

The present layout of the stripline results from recommendations made at the 2003 CNGS Review: in order to reduce beam heating of the stripline, it is installed away from the beam axis and to a large extent outside the shielding. This solution requires making an opening or hole in the shielding near the downstream end of the horn, as shown in Figure 1.

The stripline connects the horn to the pulse transformer located in the service gallery (as shown in Figure 2). This set of plates is built from several sections, in general of aluminum. A special segment built of copper, the FCS, allows disconnecting / connecting quickly the horn and the striplines. Changing a horn consists in a number of steps, some of which are presently planned to be performed by a human intervention rather than a robot. In order to replace the horn, a crane is used to lift it. Before doing that, the horn has to be disconnected manually from the stripline part 1; five bolts have to be unscrewed in the fast coupling system, an operation that is estimated to take 4-5 minutes (see [1] for a more detailed description). This step of unscrewing five bolts from the "Fast Coupling System" (FCS) is shown in Figure 3 (on the top left and marked with 1). The next step consists of removing manually the link section located in the trench and disconnecting the cooling water flexible tube. Without the link section, the stripline 1 can be slid downstream 100 mm (part 3 of Figure 3). The next steps are performed with a crane, first the roof of the shielding has to be removed and also part of the lateral shielding in order to be able to lift and extract the horn from the shielding (see part 4 and 5 of Figure 3). Finally the horn is lifted with the crane and put onto a trailer, this trailer will transport the horn upstream to the storage chamber.

For the scenario of the human intervention during the replacement of the horn, simulations have been carried out in order to evaluate an adequate waiting period (cooling time) for this intervention. In this report, results are presented of the dose equivalent rate in the passageway near the fast coupling system.

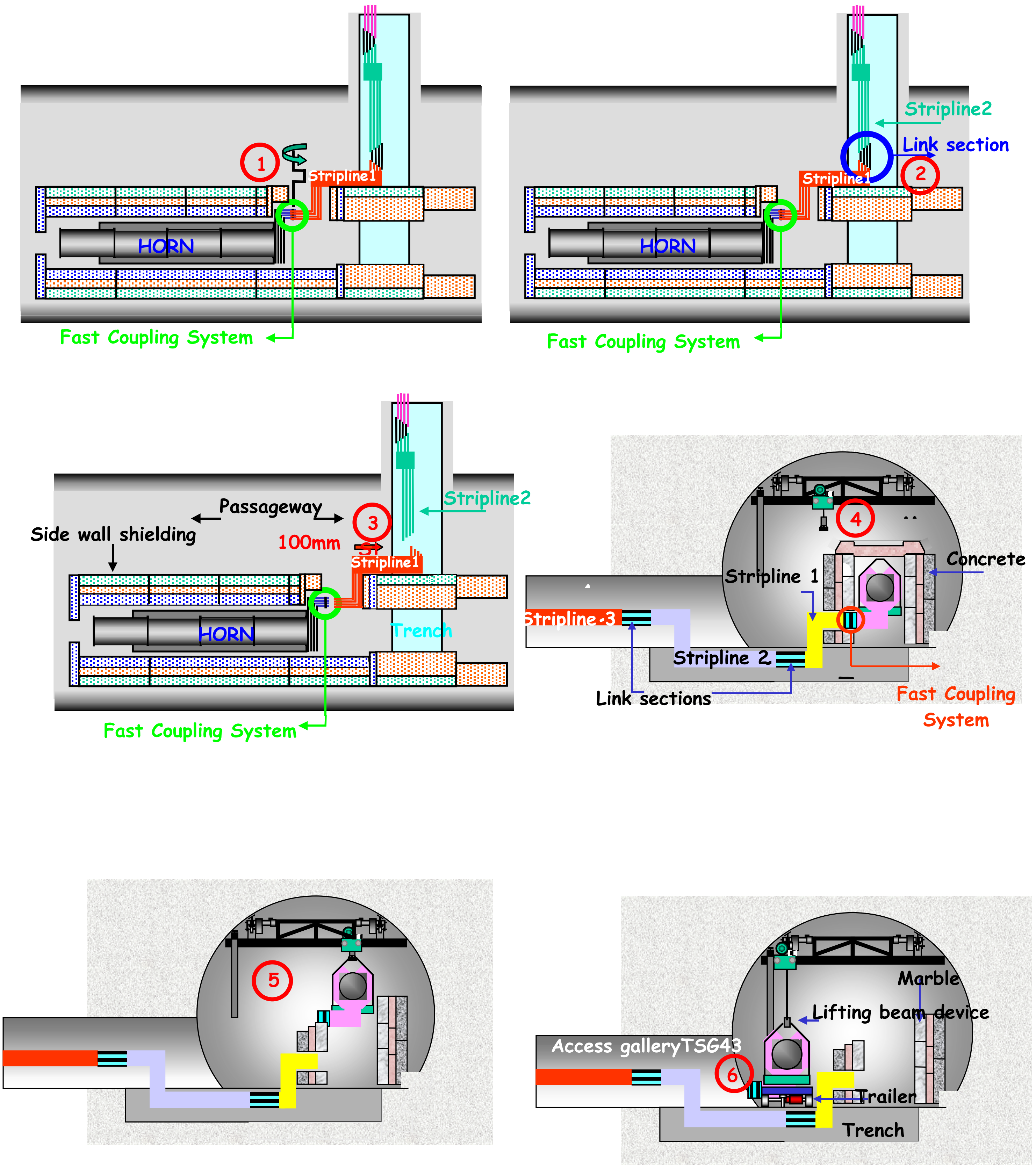


Figure 3 Sequence of steps necessary to replace the horn

1.1 Geometry of the Region near the FCS

The region of interest is shown in the layout of Figure 4 (taken from [2]). The focal point is taken as origin of the coordinate frame, x axis towards aisle, y axis upwards and z axis along beam axis (see the right side of Figure 4). The focal point is located at 50 cm downstream of the beginning of the first graphite rod of the target. The opening of the horn shielding extends in length from z =919cm to z = 1100cm, in width from x=70cm to x=150cm and in height from y = -140cm to y = -70cm.
In the region near the FCS the dose equivalent rate has been calculated. This region is located at the end of the horn tube just before the marble block and collimator (see Figure 5).

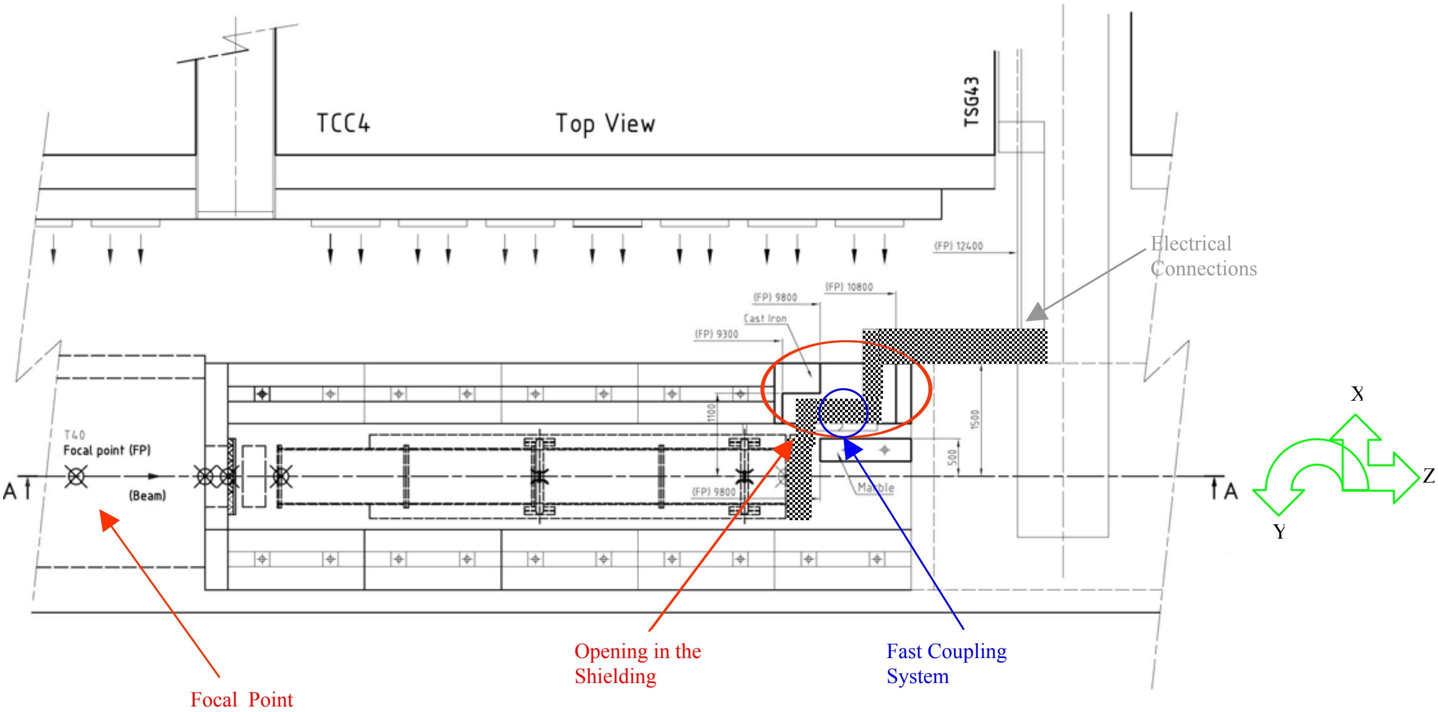


Figure 4: Present layout of the horn area

1.2 FLUKA Model of the CNGS Layout

For the calculations the version 2003 of the FLUKA Monte-Carlo computer code (see [3] and [4]) has been used.
The coordinate frame used for the FLUKA geometry input and for the FLUKA results has its origin in the center of the target, which happens to be 50 cm downstream of the focal point in the present layout, x axis towards aisle, y axis upwards and z axis along beam axis.
Two existing FLUKA geometry input files of the CNGS installation have been merged into a new single FLUKA input file. One of the input files[1] has been taken as a basis for the new input file. The target station of the other input file[2] was integrated into this new input.

[1] Fluka input of the CNGS installation by A. Ferrari, P. Sala.

[2] Fluka input of the CNGS installation by S. Roesler

Various additions and modifications have been made to this new input file. Concerning the simulations of this report the following additions and modifications are of interest (see Figure 5):

Additions:

- the marble upstream and downstream the horn
- the shielding on the top and on the sides of the horn
- the feet of the horn support
- the plates of the horn support
- the opening in the horn shielding downstream the horn tube, partially filled with iron blocks as it can be seen under opening in the shielding in Figure 4
- the electrical connections (only the section near the FCS, sections in the trench still missing)

Modifications:

- the inner and outer conductors of the horn
- the iron collimator after the horn
- the shape of the cavern wall (cylindrical with a straight part at the bottom).

The thickness of the different layers of the shielding is given in Table 1 and the composition of the materials of the shielding is shown in Table 2. Figure 5 and Figure 6 show the two sections for which the dose equivalent rates are presented in this report: (a) vertical plane at the center of the opening to access the five bolts of the FCS, (b) horizontal plane at the location of the FCS.

	Thickness (cm)
Iron roof shielding of the horn	30
Lateral concrete shielding of the horn	30
Lateral iron shielding of the horn	20
Lateral marble shielding of the horn	30
Concrete shielding of the collimator	40
Marble downstream of the horn	30
Concrete of the wall/floor tunnel	40

Table 1 Thickness of the different shielding materials in the horn area and of the concrete in the wall/floor tunnel

Material	Density	Composition
Iron[3]	7.15	93.48 % Fe; 3.4% C; 1.8% Si; 0.8% Mn; 0.4% P; 0.12% S
Concrete	2.42	52.9% O; 33.7% Si; 4.4% Ca; 3.4% Al; 1.6% Na; 1.4% Fe; 1.3% P; 1% H; 0.2%Mg; 0.1% C
Marble	2.7	$CaCO_3$

Table 2 Density (in g/cm^3) and composition of the materials of the shielding in the input of FLUKA (mass fraction)

[3] the actual composition (mass fraction) of the cast-iron grade used for the shielding around horn and reflector (Fonte à graphite sphéroïdale EN-GJS-400-18-LT) is as follows: Fe max. 94%; C 2.90 - 3.70%; Si 1.80 - 2.10% ; Mn max.0.10%; Cu max. 0.10%.

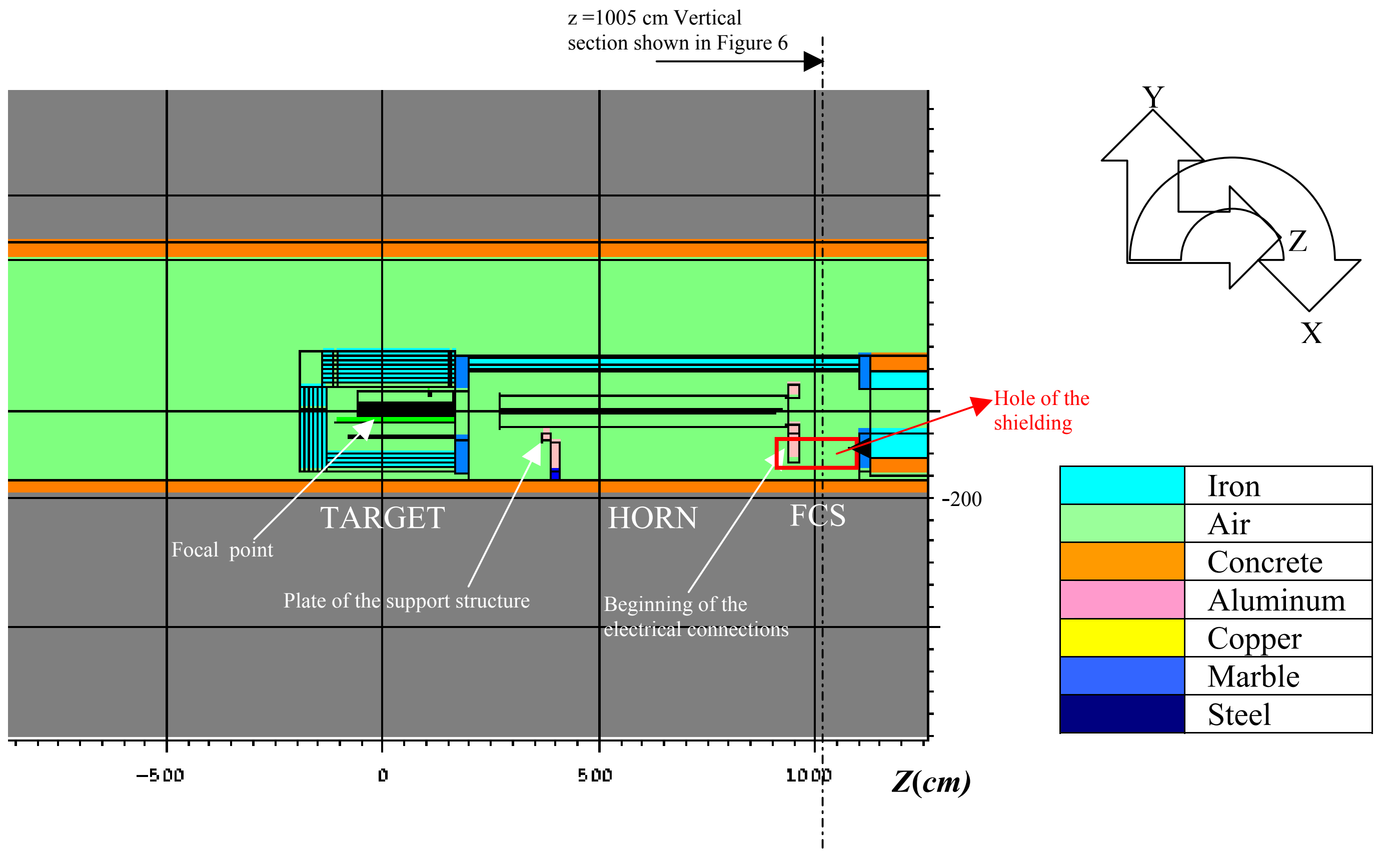


Figure 5: Vertical longitudinal section through the FLUKA geometry of target and horn

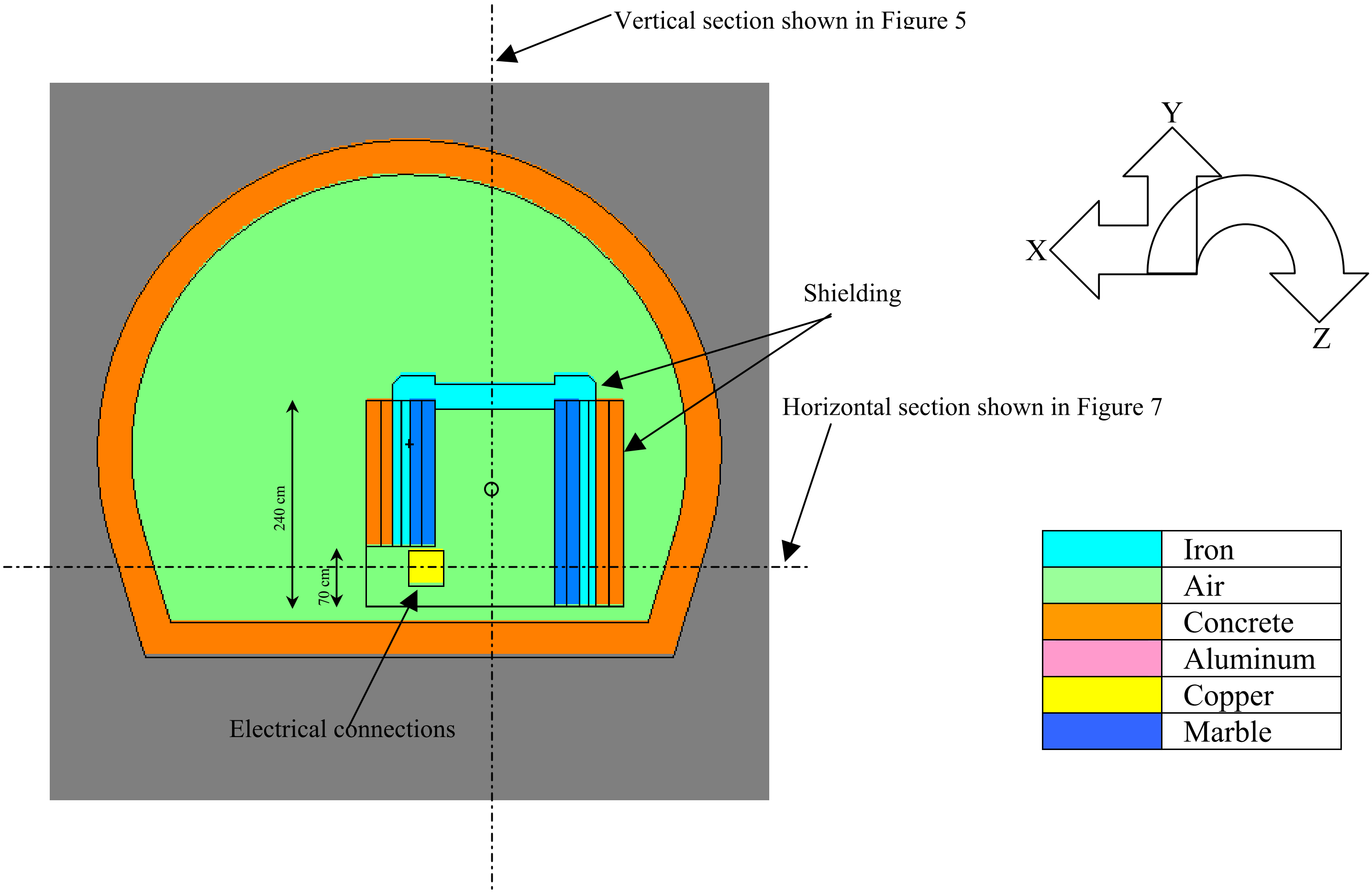


Figure 6 Vertical transverse section at the location of the FCS (z=1005cm)

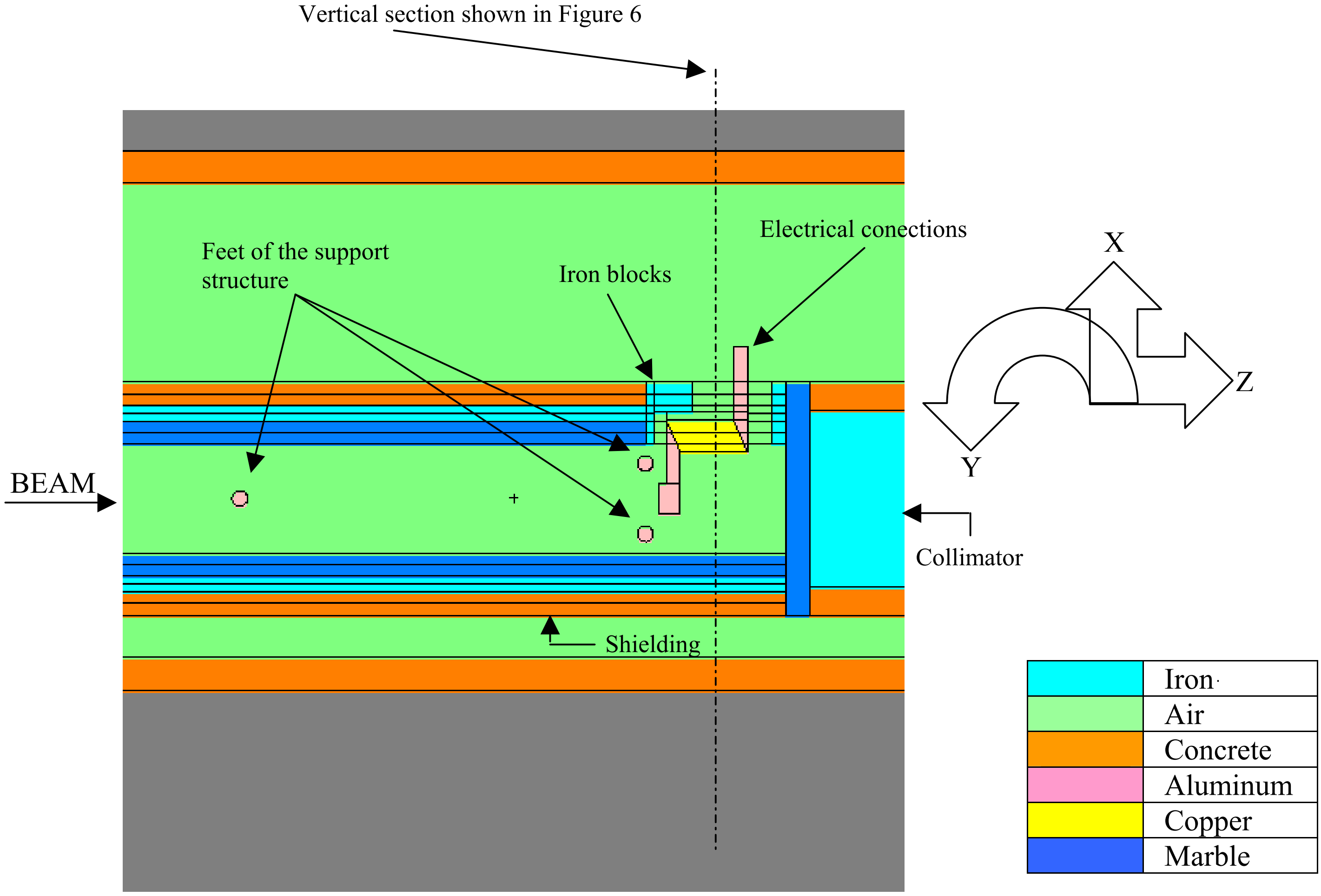


Figure 7 Horizontal longitudinal section at the height of the FCS (y =-90 cm)

2. Simulations

The simulations are based on the following beam parameters:

- Proton intensity: 8.0×10^{12} per second
- Proton beam energy: 400 GeV
- Gaussian profile of the beam ($\sigma_x=\sigma_y$ = 530 μm)
- Irradiation time: 200 days
- Cooling times: 1 day, 1 week, 1 month, 2 months, 4 months, 6 months

To obtain similar statistical uncertainties for small and big regions in the contribution to the total activation, the task of obtaining the remanent radiation has been divided into several independent simulations (see reference [7]). Each of them simulates the contribution of some materials/regions to the total amount of radiation. The results of the different contributions are finally added up to the final result. For the horn region five different contributions have been considered:

1. Concrete of the cavern walls/floor
2. Shielding in the horn area
3. Horn and adjacent structures
4. Materials near or inside the opening of the horn shielding
5. Collimator downstream the horn

The concrete of the tunnel extends from -950 cm to 10079 cm (taking the origin, the focal point, at 50 cm downstream of the beginning of the first graphite rod).
The shielding in the horn area extends from 198 cm to 1099 cm. This contribution includes also a 30 cm thick marble block downstream of the horn.
The third contribution includes the horn outer and inner conductors, the three feet of the horn support structure, the plates of the support structure and the first segment of the stripline.
The fourth contribution includes the iron, which partially fills the hole of the shielding and the rest of the electrical connections, including the copper part (FCS) (see Figure 7).
The fifth contribution includes the iron and concrete materials of the collimator downstream the horn (see Figure 7).

For each of these five components two steps of Monte-Carlo simulations (see references [5] and [6]) have been carried out. In a first step the information on the produced isotopes of each of the five contributions is stored in external files. In a second step, with the previous file used as input, the photons and positrons from the radioactive decay at a certain cooling time are sampled. This is used for the simulation of the electromagnetic cascade induced by these particles and finally the dose equivalent rate at any point of interest and for each cooling time can be obtained.

In the next paragraphs results are shown for three different kind of fillings in the opening of the horn shielding. The first one corresponds to the present layout of Figure 4, the other two are possible alternatives.

2.1 Simulation with Iron Blocks in the Opening of the Shielding

Figure 7 shows a plot of the elements implemented in the FLUKA geometry in accordance with the layout of [2] (see Figure 4). Inside the hole there are the striplines and air and a small part of the hole has been filled with iron blocks. The dose equivalent rates obtained in the simulations are shown for different cooling times in Figures 8-13.Table 3 shows a summary of results for the selected points shown in Figure 8.

From one day to one week the dose rate decreases strongly as seen in Figure 8 and Figure 9. This is due to the influence of the concrete contribution during this period. Beyond one week, the variations are small as shown in the Figures 8-13.

The opening in the shielding leads to an increase of the dose rate in the aisle by at least a factor of two. This can be seen comparing the left with the right part (where the shielding is complete) outside the shielding or comparing the rows for the locations 2 and 5 in Table 3. This clearly demonstrates the necessity of an efficient shielding in the area of the fast coupling system.

	1 day	1 week	1 month	2 months	4 months	6 months
Location 1	80	3	2	2	1	0.7
Location 2	100	8	6	6	3	3
Location 3	100	70	25	22	18	14
Location 4	450	220	100	100	85	70
Location 5	45	2	1.5	1.5	0.7	0.5

Table 3 Values of dose equivalent rate (mSv/h) in the locations shown in Figure 8, with z=1005cm and location 1 at x=350cm, location 2 at x=200cm, location 3 and 4 at x=0cm and location 5 at x=-170cm. Average values in a cube of 20x20x20 cm^3.

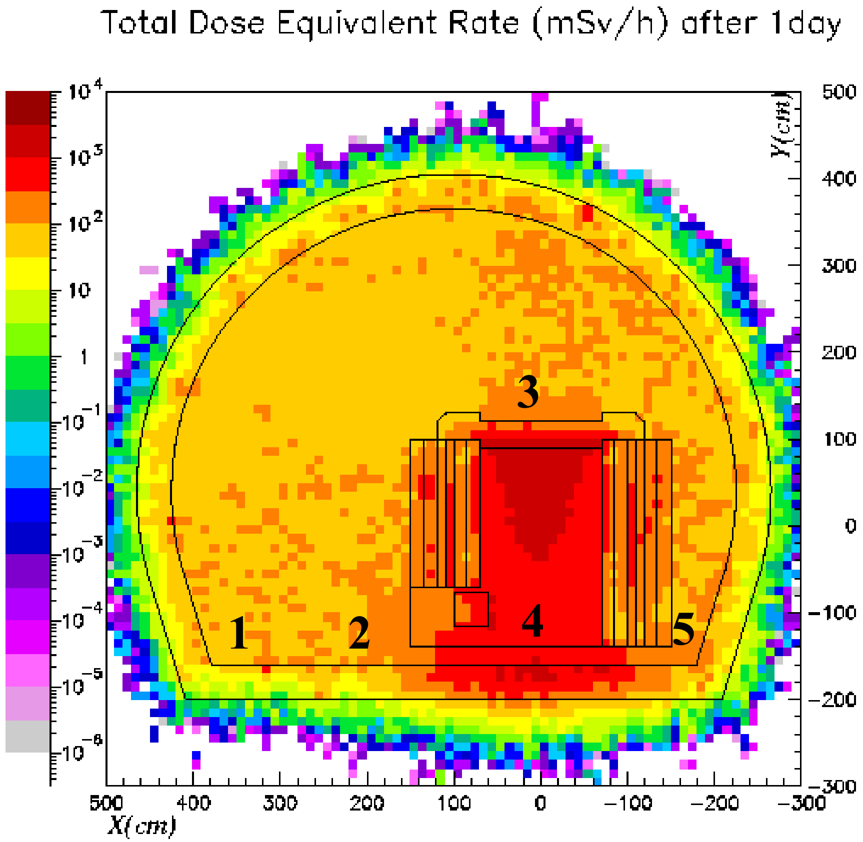


Figure 8 Dose equivalent rate (mSv/h) after a cooling time of one day

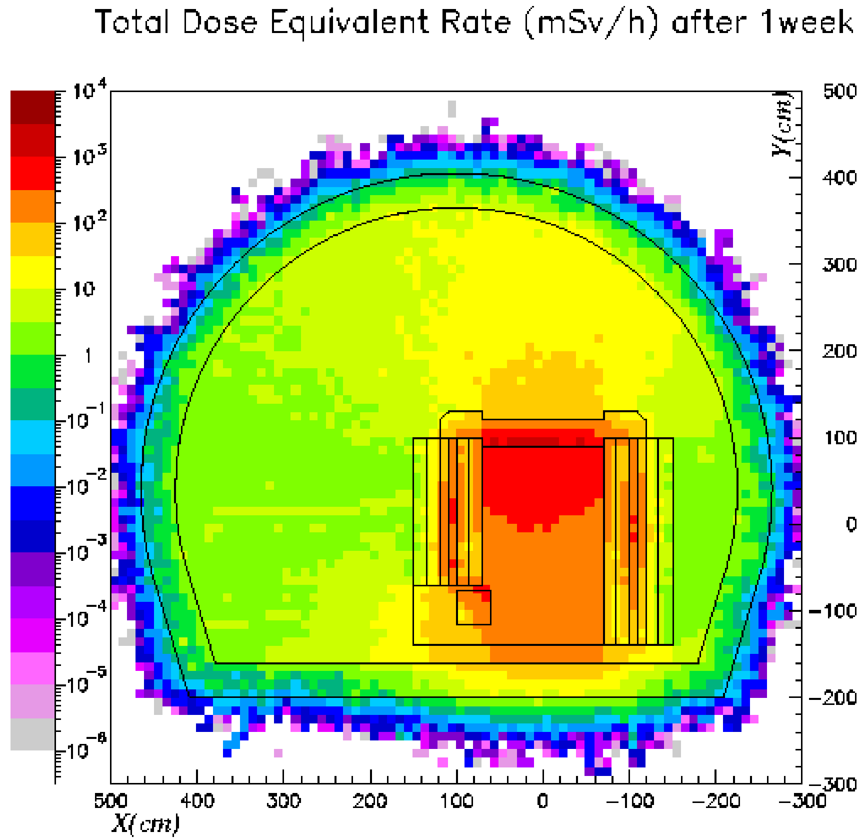


Figure 9 Dose equivalent rate (mSv/h) after a cooling time of one week

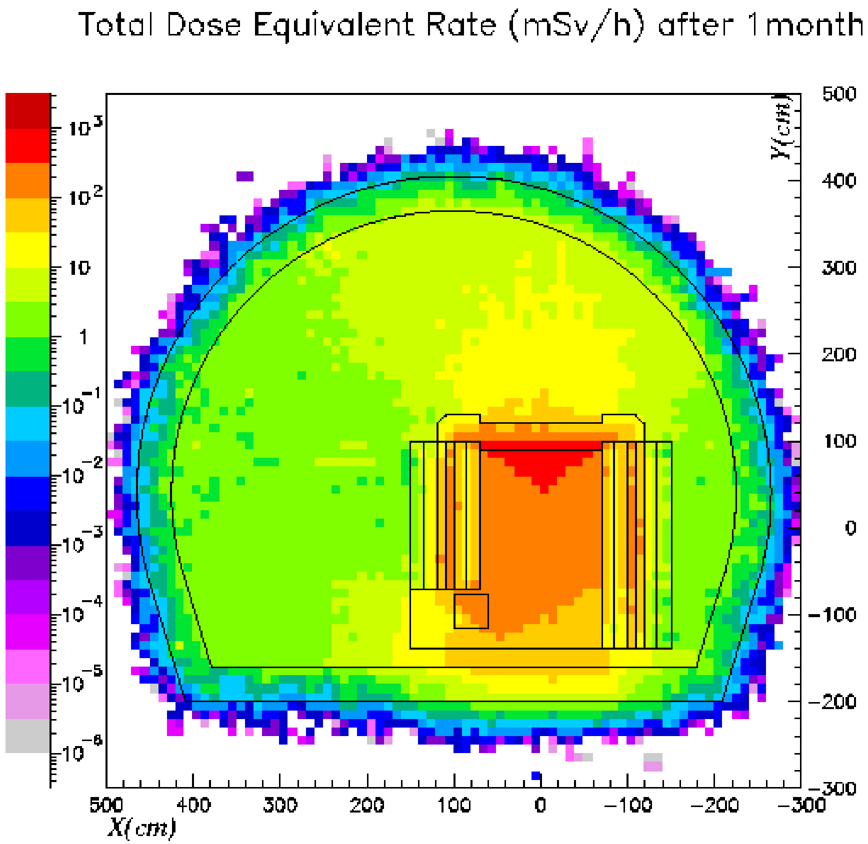


Figure 10 Dose equivalent rate (mSv/h) after a cooling time of one month

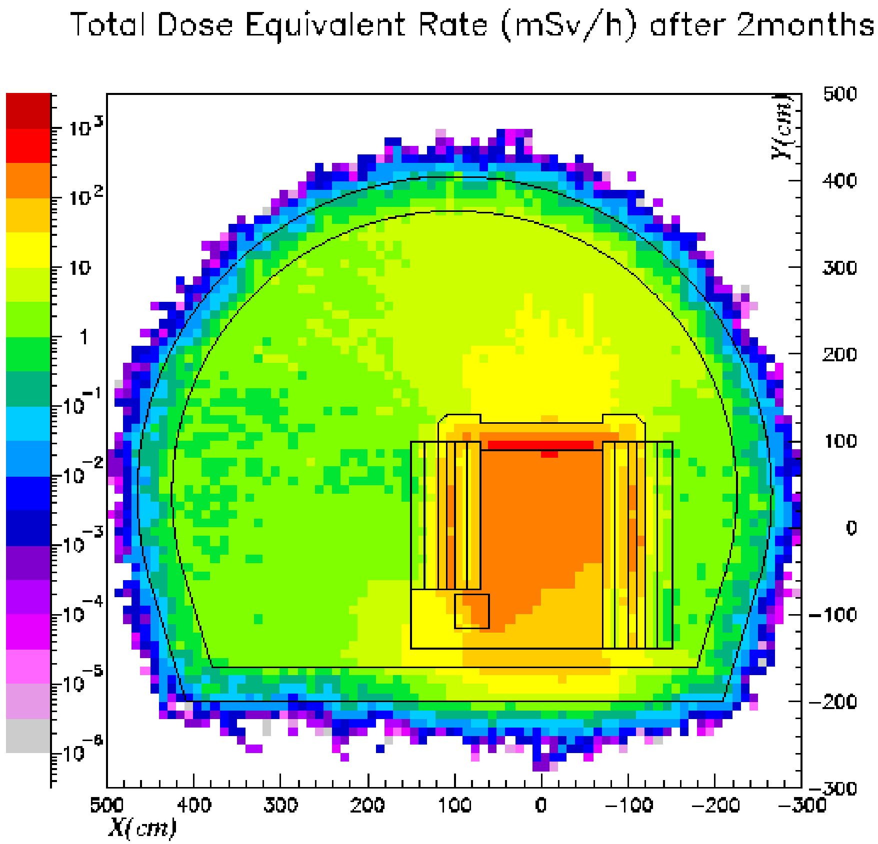


Figure 11 Dose equivalent rate (mSv/h) after a cooling time of two months

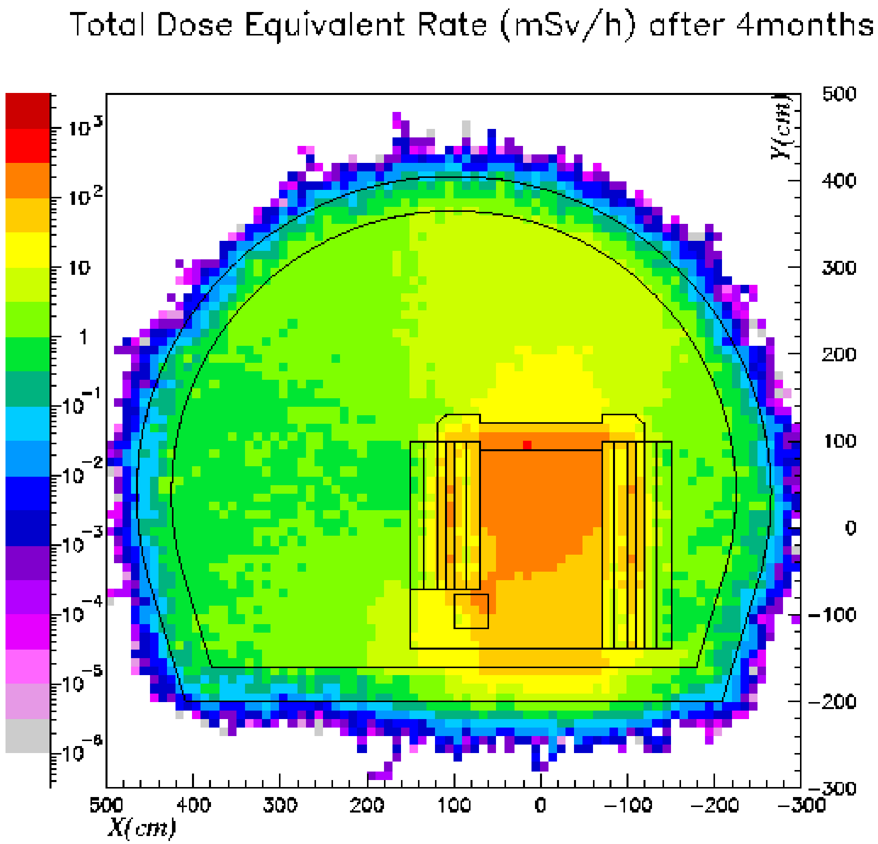


Figure 12 Dose equivalent rate (mSv/h) after a cooling time of four months

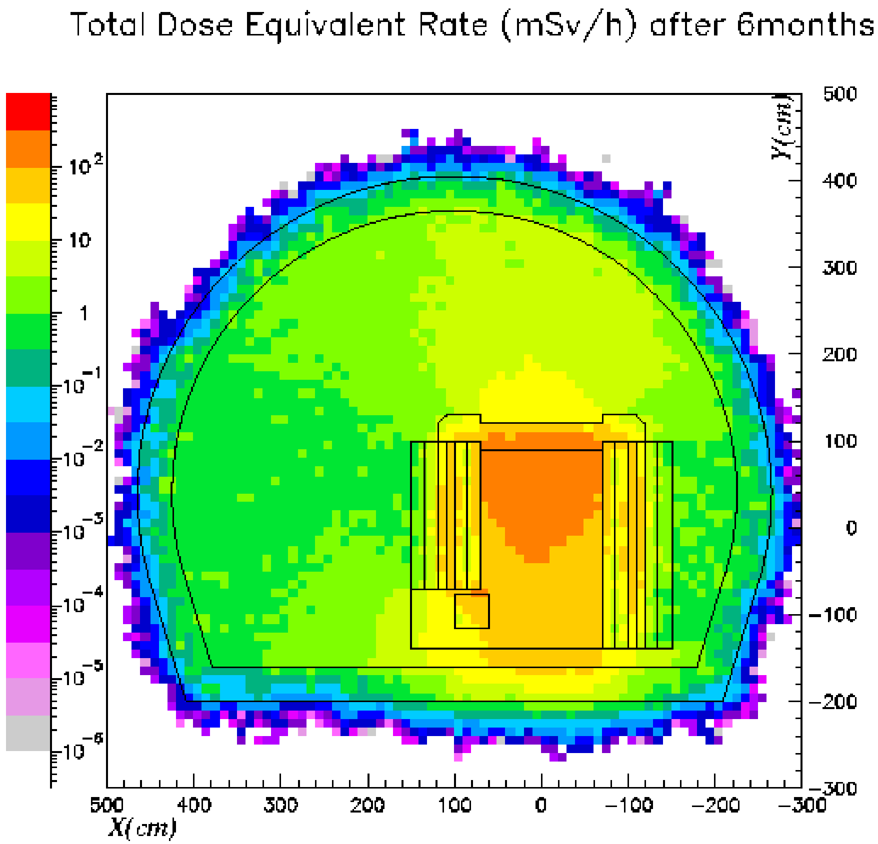


Figure 13 Dose equivalent rate (mSv/h) after a cooling time of six months

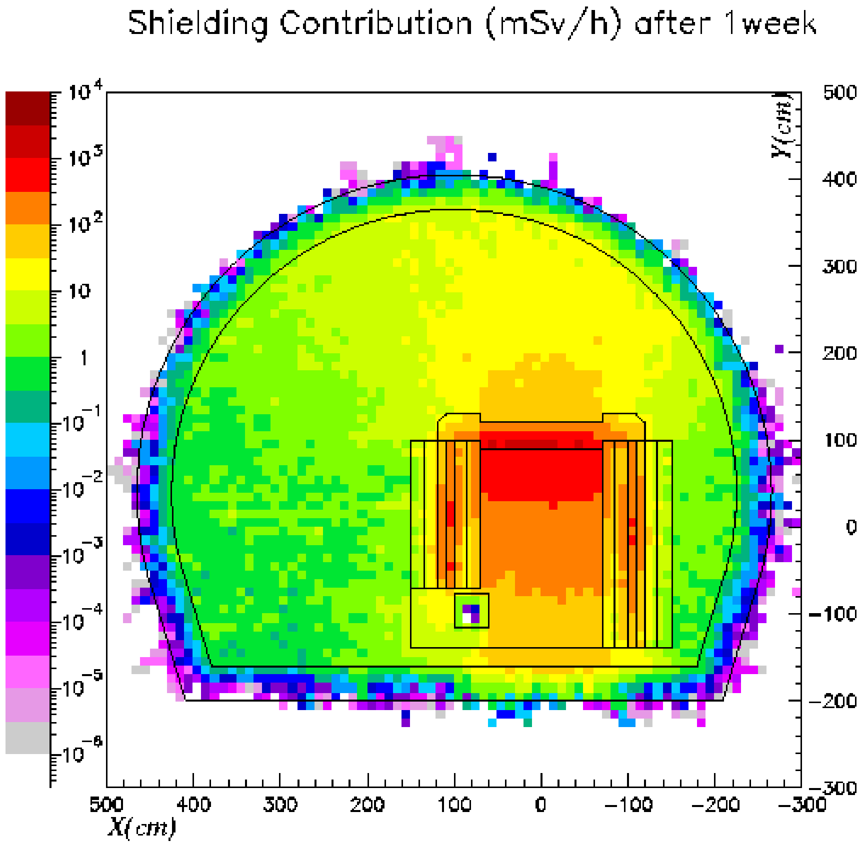
In order to show the importance of the different contributions to the total value of dose rate in the passageway, the example of a cooling time of one week has been chosen. The results of these contributions are shown in Figures 14-18. In the passageway, the main contributions to the total dose rate come from the following parts:

- The contribution of the horn shielding (see Figure 14) is non uniform. In the top part of the cavern above the horn shielding this contribution reaches its maximum value, in the passageway it reaches an average value of 1 mSv/h.
- The contribution of the concrete of the wall/floor of the cavern (see Figure 15) is uniformly distributed over the cavern outside the shielding with a value of 0.7 mSv/h.
- The contribution of the collimator (see Figure 16) is generally very small; in the passageway an average value of 0.05 mSv/h has been calculated.
- The contribution of the materials around the hole of the shielding, including the copper part of the stripline, (see Figure 17) varies from the maximum at the hole (20 mSv/h), to an average value in the passageway of 1 mSv/h.
- The contribution of the horn itself (see Figure 18) is very small except near the floor level in the passageway, where it reaches an average value of 0.7 mSv/h. In the passageway an average value of 0.25 mSv/h is obtained.

The total dose is about 3 mSv/h after a cooling time of one week. These results are summarized in Table 4.

Cooling Time 1 week	Shielding of the Horn	Materials of the Hole	Concrete of Walls/Floor	Horn Tube	Collimator	Total
Dose equivalent Rate (mSv/h)	1	1	0.7	0.25	0.05	3

Table 4 Contributions to the dose equivalent rate in the passageway near the FCS after a cooling time of one week.



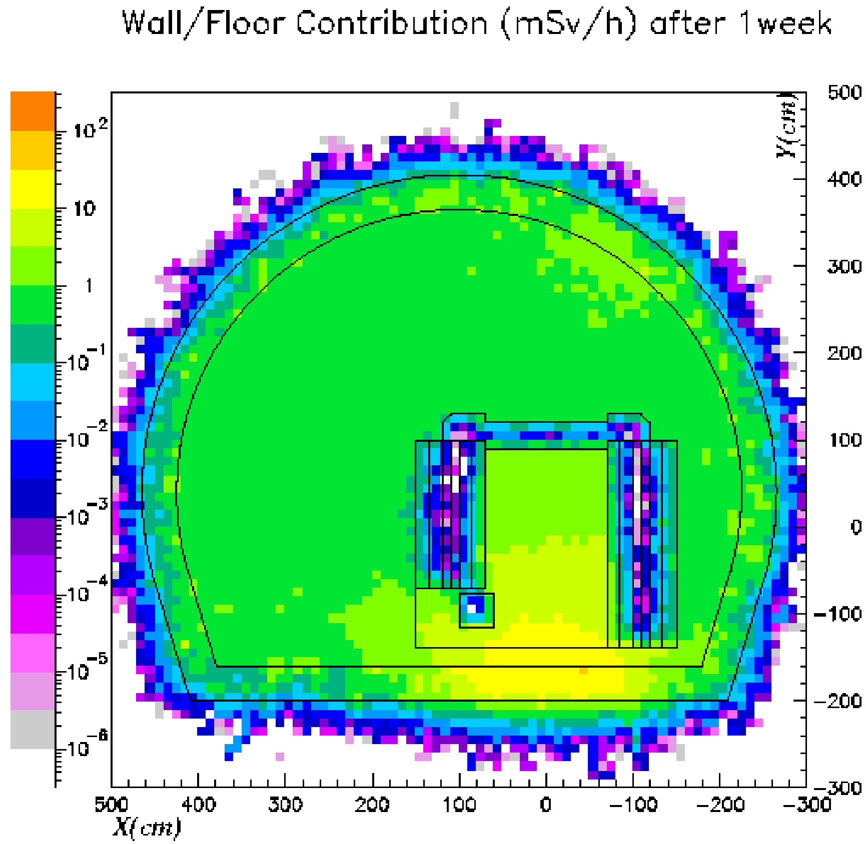


Figure 14 Shielding contribution (mSv/h) after a cooling time of one week

Figure 15 Wall/Floor contribution after a cooling time of one week

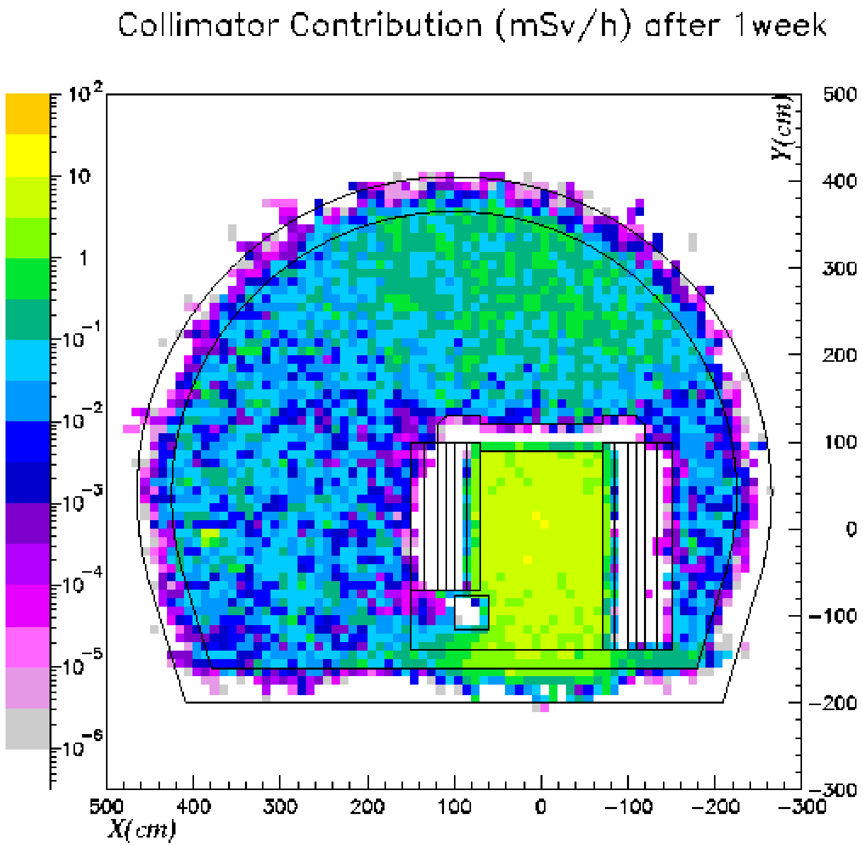


Figure 16 Collimator contribution (mSv/h) after a cooling time of one week

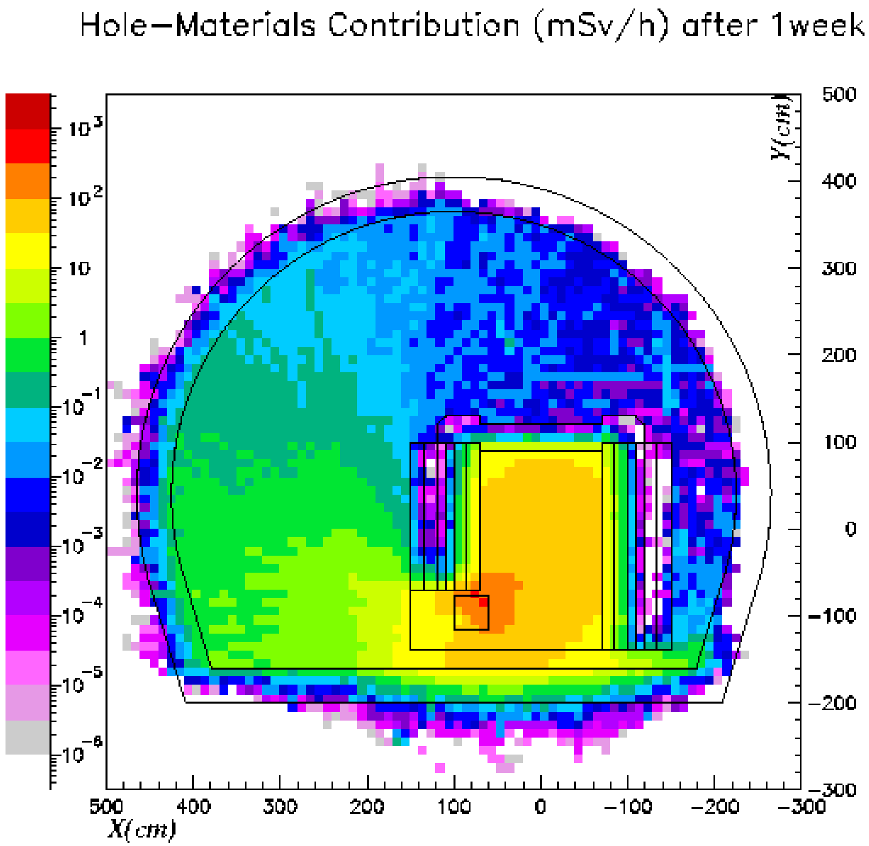
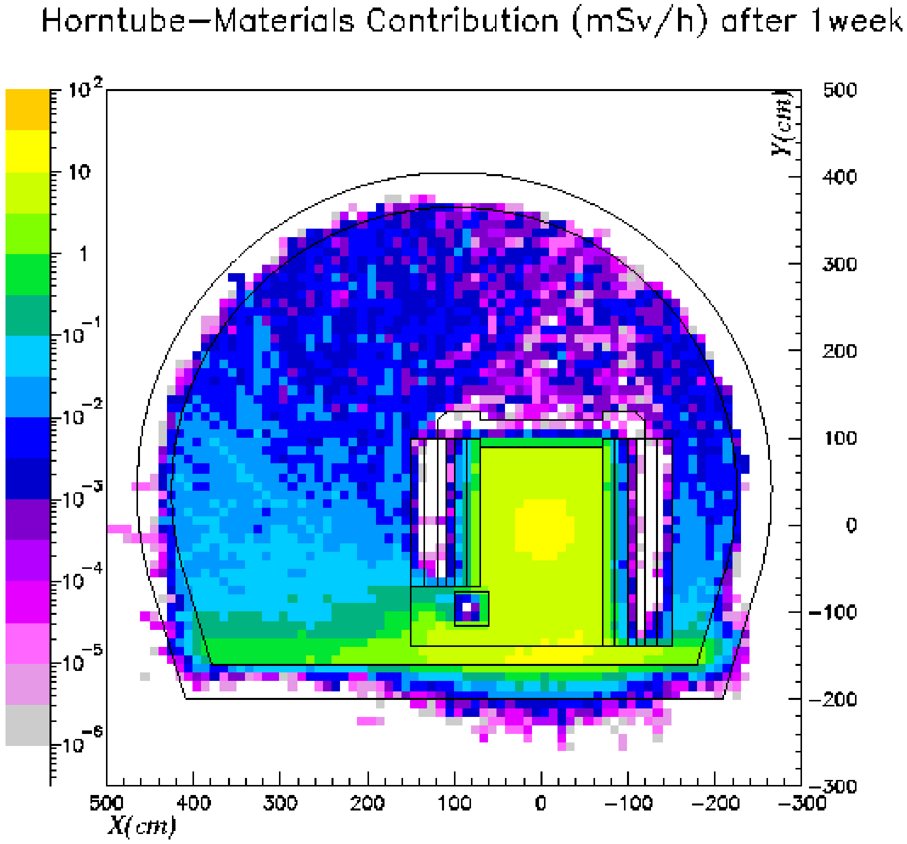


Figure 17 Hole materials contribution after a cooling time of one week



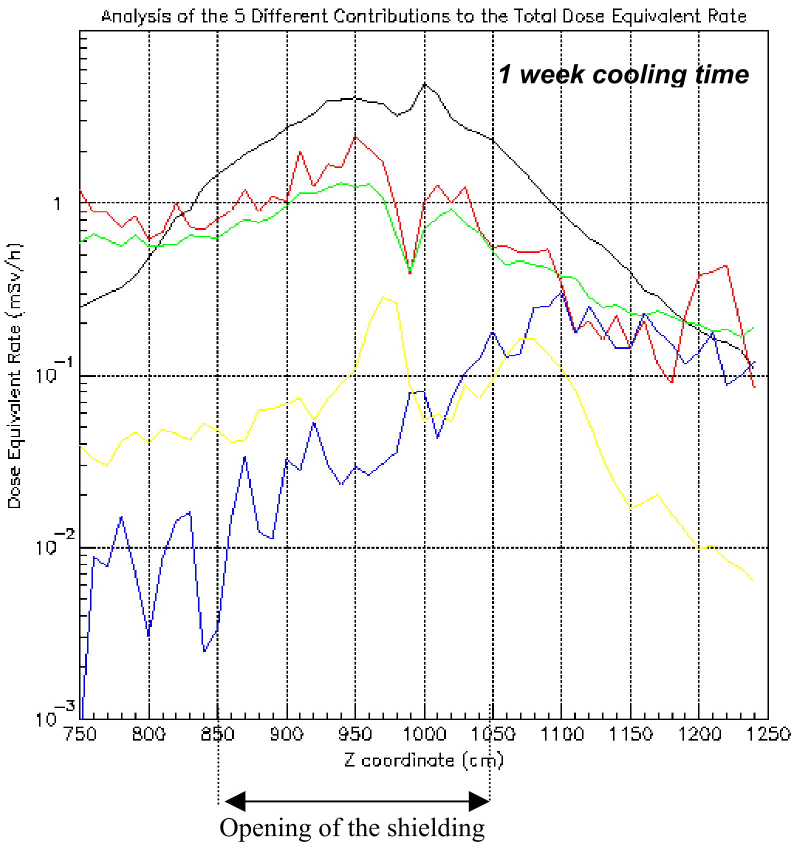


Figure 18 Collimator contribution (mSv/h) after a cooling time of one week

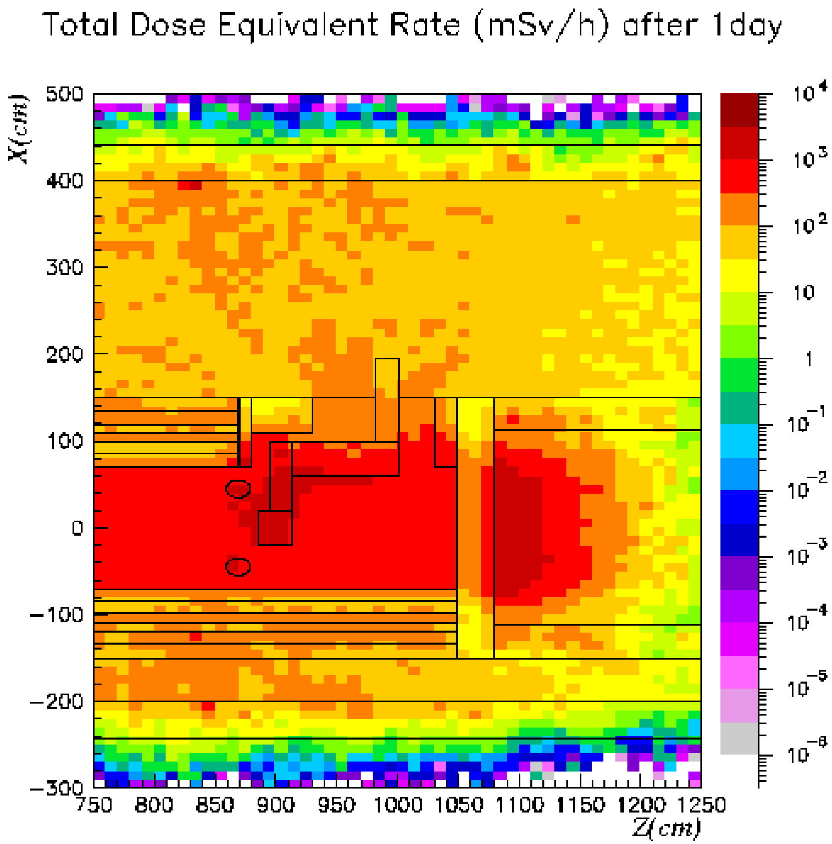
Figure 19 Comparison among different contributions along the passageway, average values in a bin centered at y=-90 cm (20cm long) and x=200 cm (40 cm long). In black contribution of the opening of the shielding, in red contribution of the shielding, in green contribution of the concrete wall/floor, in yellow contribution of the horn tube and in blue the contribution of the collimator.

Figure 20 and 21 show values of the total dose equivalent rate (after summing all the contributions) for a horizontal section at a coordinate y=-90 cm.

The red spots on Figure 21 (see points 1, 2 and 3) correspond to the induced radioactivity of the iron in the collimator, of the iron in the filling of the hole as well as of the copper in the electrical connections.

In Figures 22-25 the sum of all contributions is shown for cooling times of 1, 2, 4 and 6 months.

In Figure 26 there is a comparison of the total contribution after one week with the contribution of the materials of the hole. It can be seen that the most important contribution to the total dose rate near the hole of the shielding is the contribution of the elements inside the hole. Inside the shielding other contributions like the contribution of the concrete floor and the contribution of the shielding are more important. Values of the total dose equivalent rate at a coordinate x =200cm along the passageway are represented in Figure 27.



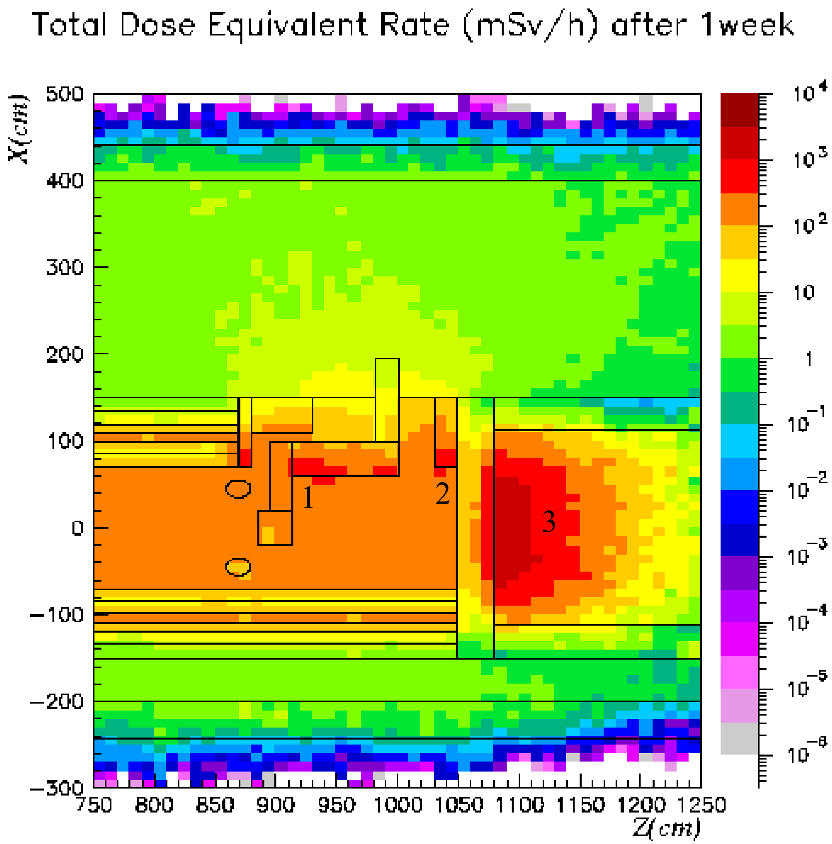


Figure 20 Dose equivalent rate after a cooling time of 1day

Figure 21 Dose equivalent rate after a cooling time of 1 week

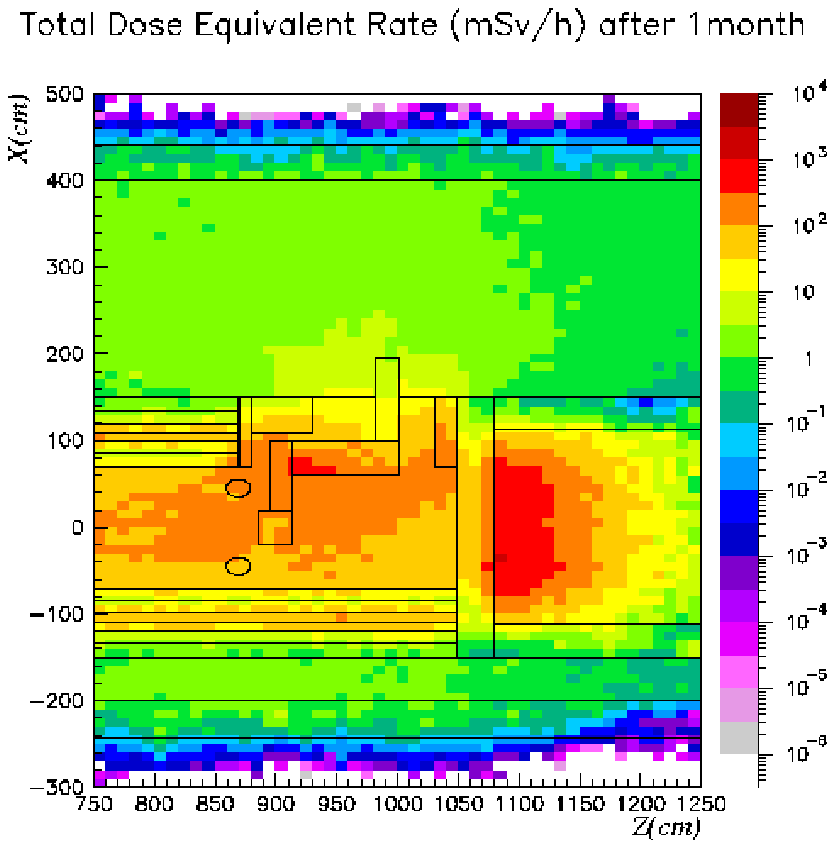


Figure 22 Total dose equivalent rates after a cooling time of 1month

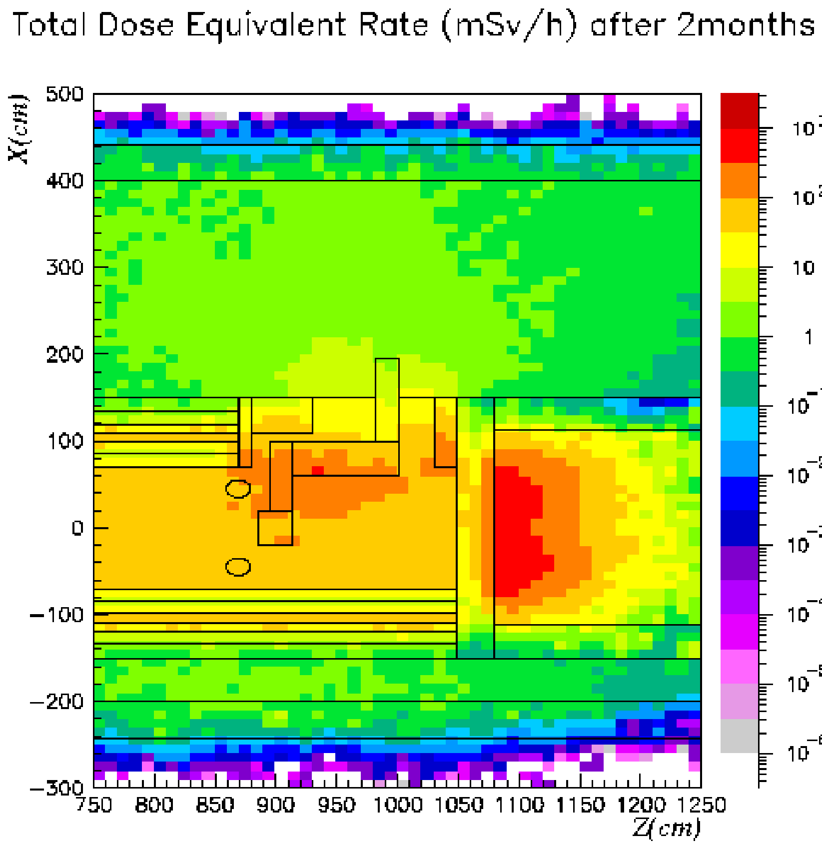


Figure 23 Total dose equivalent rates after a cooling time of 2 months

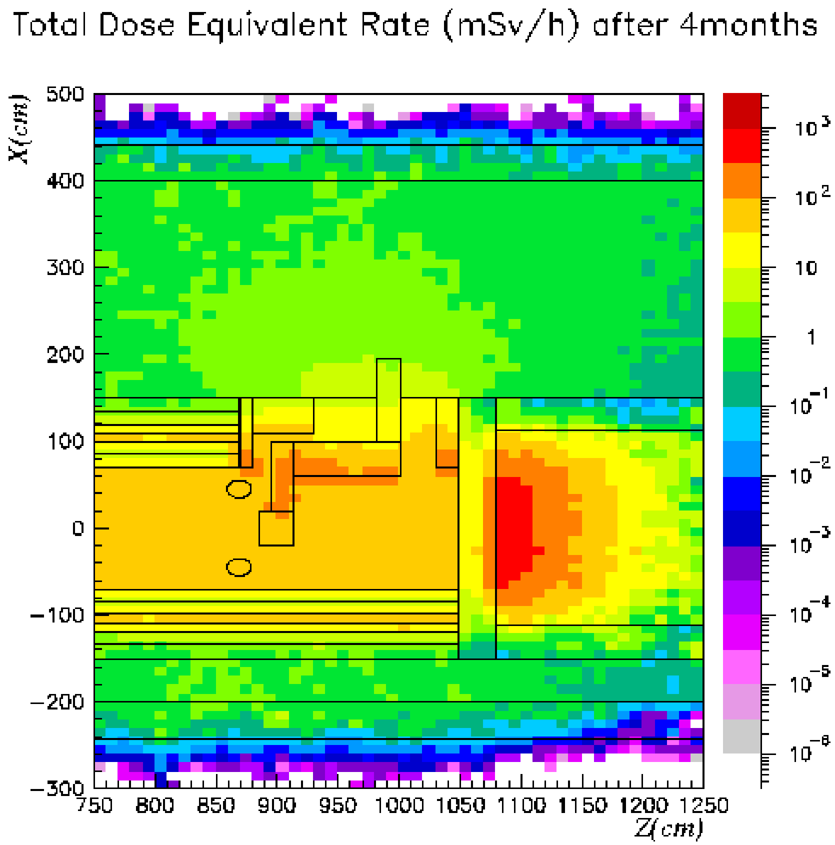


Figure 24 Total dose equivalent rates after a cooling time of 4month

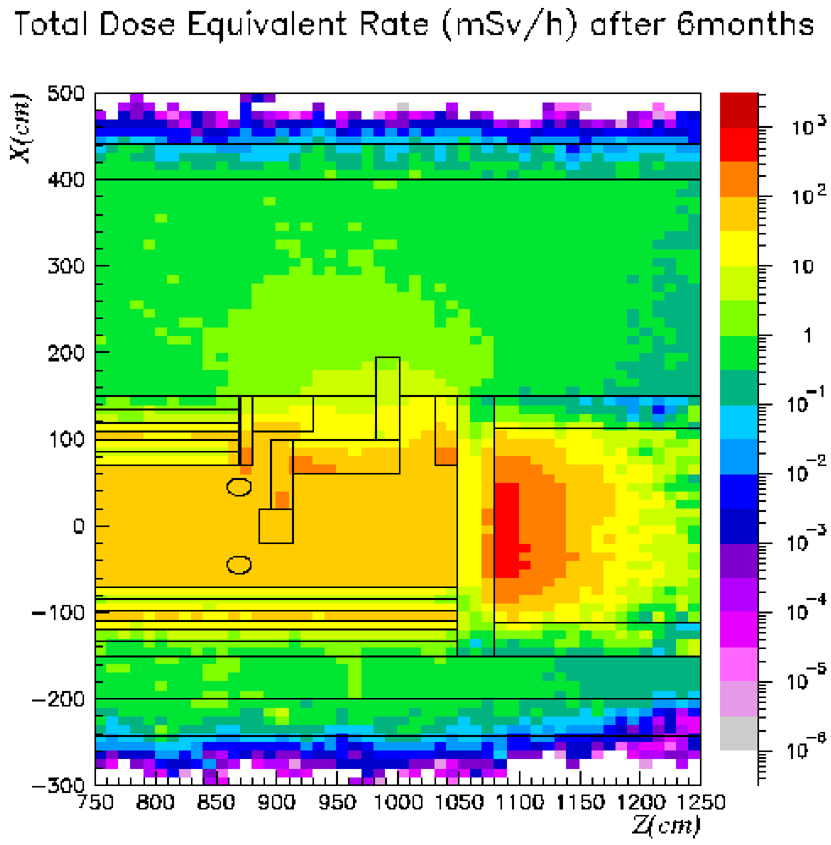


Figure 25 Total dose equivalent rates after a cooling time of 6 months

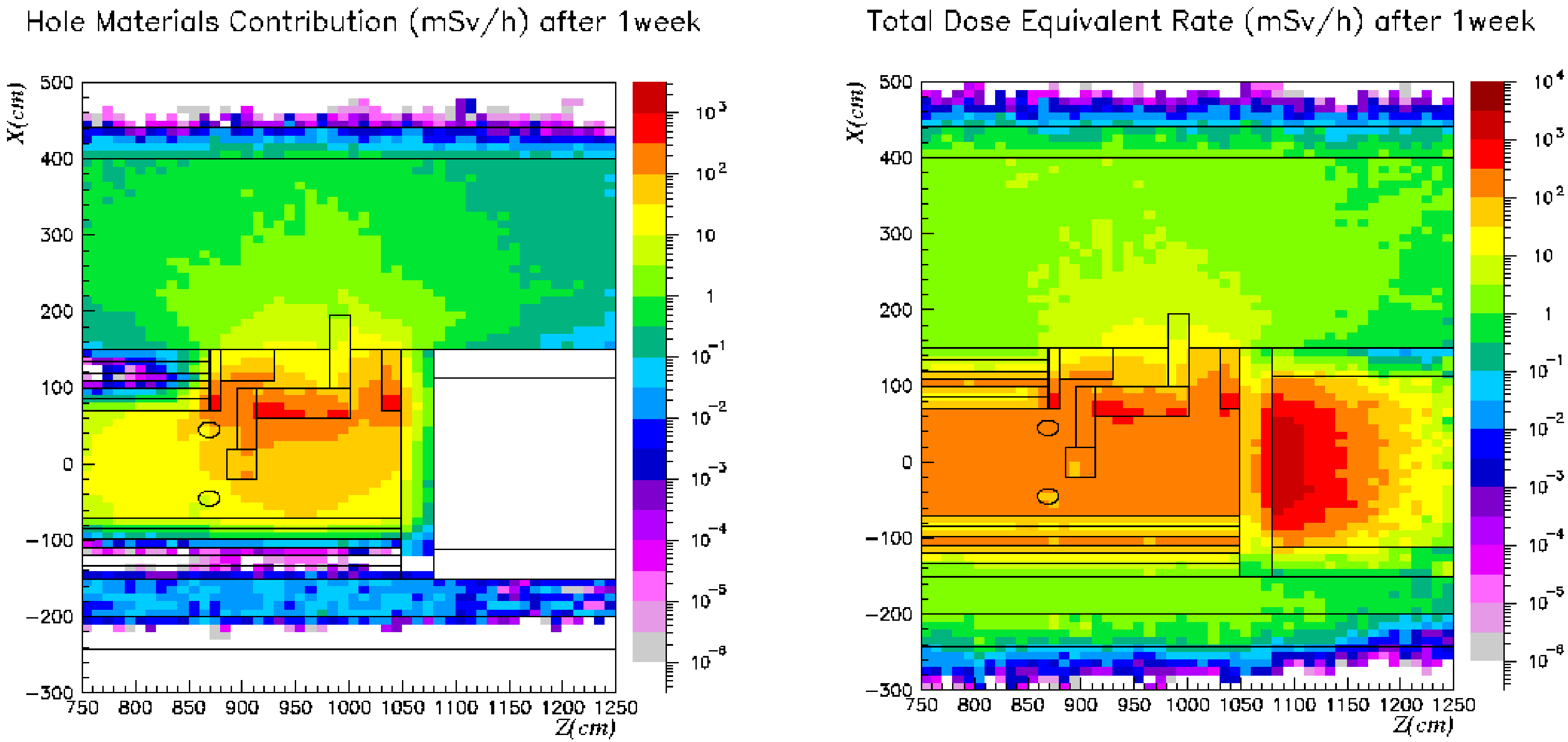


Figure 26 Comparison between the dose rate contribution of the materials inside the hole (left side) and the sum of all contributions (right side)

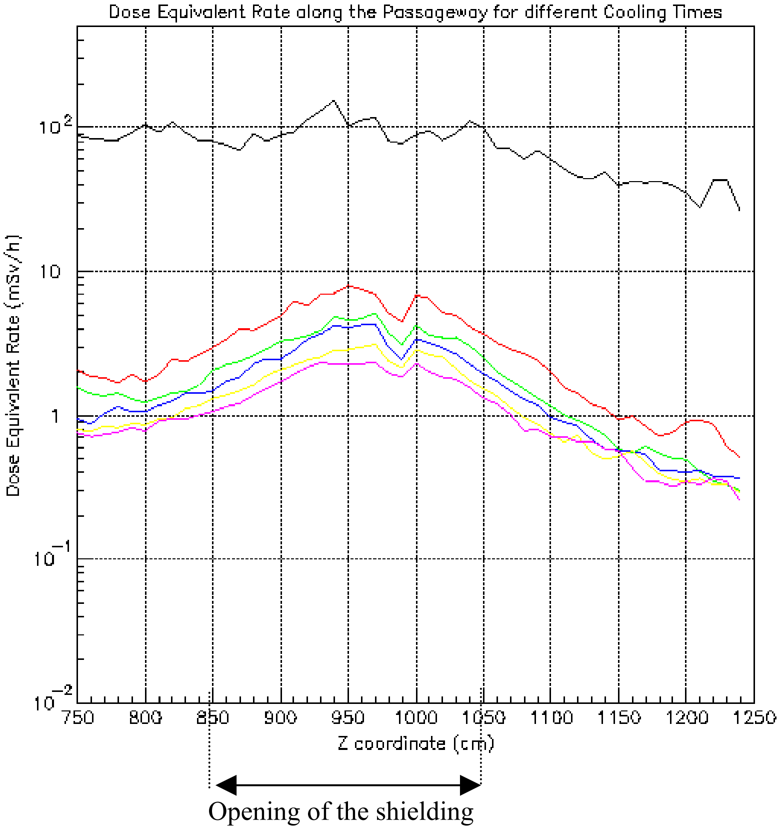


Figure 27 Average values in a bin centered at y=-90 cm (20cm long), x=200 cm (40 cm long), in black after a cooling time of 1 day and the other colors after cooling times of 1 week, 1 month, 2 months, 4 months and 6 months

2.1.1 Accumulated Dose

Table 5 and Table 6 show accumulated dose values for an intervention of 4 minutes at distances of 200 cm and 300 cm of the beam axis. From one month cooling time onwards the radiation levels do not change significantly. Therefore it appears reasonable to postpone the human interventions concerning the replacement of the horn after at least one-month cooling time.

To further decrease the levels of radiation and in order to keep the radiation levels as low as reasonable achievable (ALARA), an analysis should be made of new shielding models of the horn area. It could for example be considered to include some marble blocks in the passageway in a similar way as the marble blocks inserted on the left side of the target shielding. In the passageway near the target, with the shielding structure consisting of 80 cm thick iron blocks and of 40 cm marble blocks, it is observed a notable reduction of the dose equivalent rate (see [5]). The dose equivalent rate in the passageway near the target is 10 times less after 1 week and longer cooling periods compared to the horn in the equivalent area for the same cooling period.

Studies will also be needed to find the best arrangement of e.g. lead shielding plates to protect the workers during the interventions near the opening of the shielding.

X=200cm Y=-90 cm		Dose Equivalent Rate (mSv/h)					
		1 day	1 week	1 month	2 months	4 months	6 months
		100	10	7	7	3	3
Operation	Duration	Accumulated Dose (mSv)					
Unscrew bolts in FCS	4 minutes	7	0.7	0.5	0.5	0.2	0.2

Table 5 Dose equivalent rate and accumulated dose for a 4 minutes intervention at x=200 cm, y=-90 cm, z=1005 cm (at the location of the FCS)

X=300cm Y=-90 cm		Dose Equivalent Rate (mSv/h)					
		1 day	1 week	1 month	2 months	4 months	6 months
		80	3	2	2	1	0.7
Operation	Duration	Accumulated Dose (mSv)					
Unscrew bolts in FCS	4 minutes	6	0.3	0.2	0.2	0.1	0.07

Table 6 Dose equivalent rate and accumulated dose for a 4 minutes intervention at x=300 cm, y=-90 cm, z=1005 cm (at the location of the FCS)

Comparing Table 5 and Table 6 it is seen that for cooling times longer than 1 week the values of dose equivalent rate fall more than a 50 % at a distance of 300 cm from the beamline compared with the values at a 200 cm distance.

2.2 Simulation with a Sandwich-like Shielding in the Opening of the Shielding

For this simulation a sandwich-like structure (30 cm of concrete, 20 cm of iron and 30 cm of marble except in front of the FCS where there is no marble) has been added in the FCS area, i.e. alongside the copper part of the stripline (see Figure 28 and compare it with Figure 7). The downstream part of the hole is air to permit the free movement of the stripline when replacing the horn.

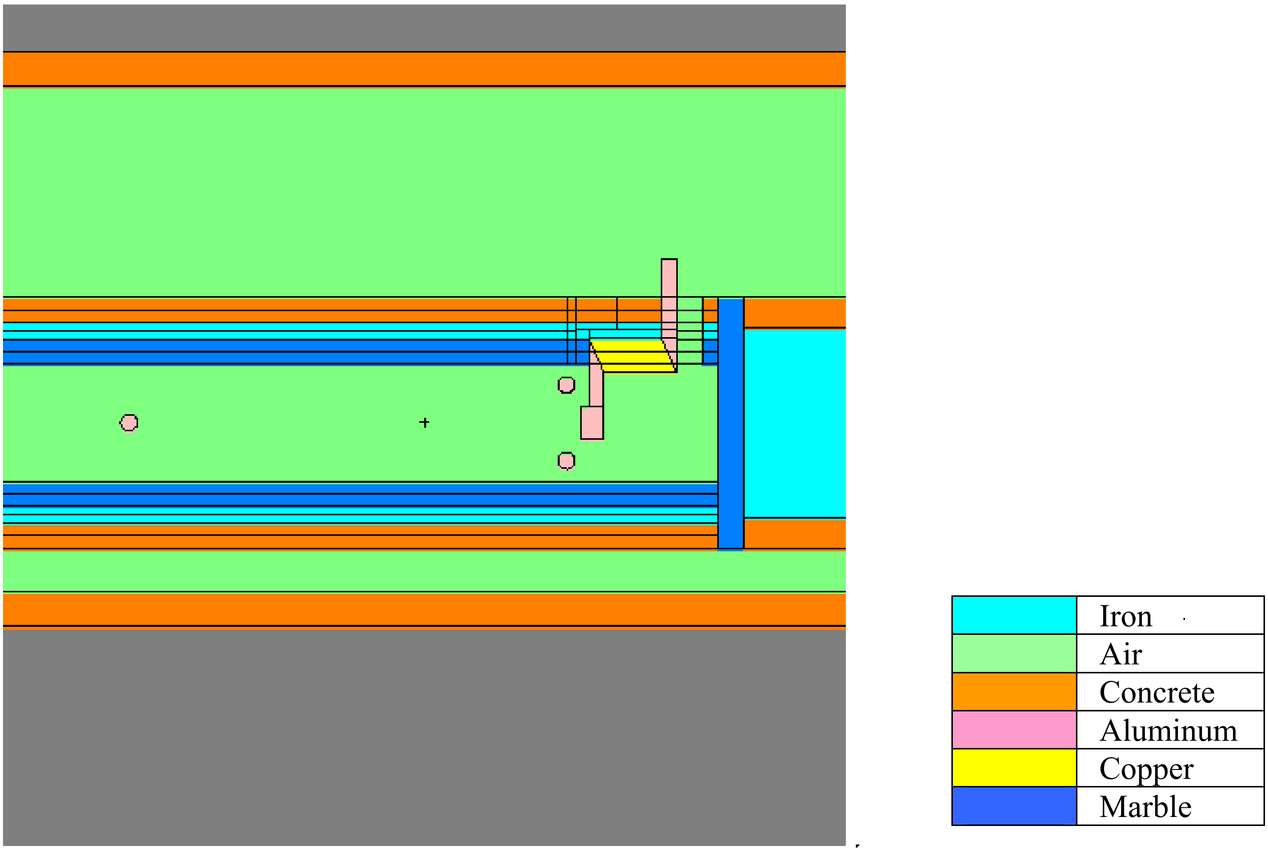


Figure 28 Horizontal longitudinal section at a coordinate Y=-90 cm

The results of these simulations are shown in the Figures 29-34. Comparing these results with the values shown in the Figures 20-25, a decrease in the dose equivalent rate in the region near the opening of the horn shielding is observed. This comparison is shown graphically in Figures 37 and 38. Values of the total dose equivalent rate at a coordinate x =200cm along the passageway are represented in Figure 35.

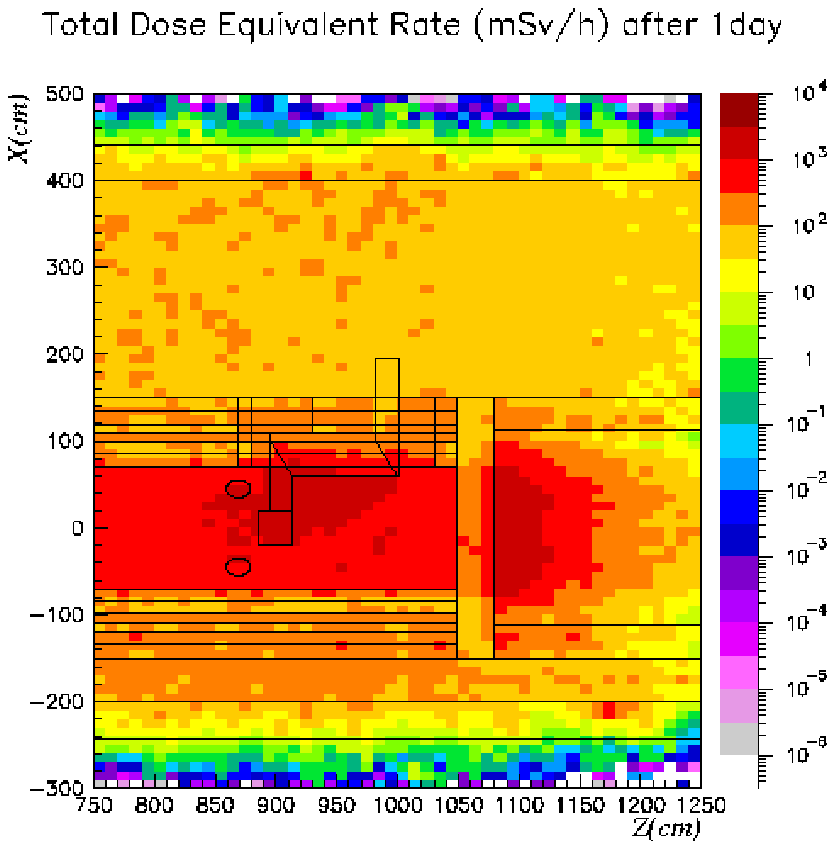


Figure 29 Total dose equivalent rates after a cooling time of 1 day

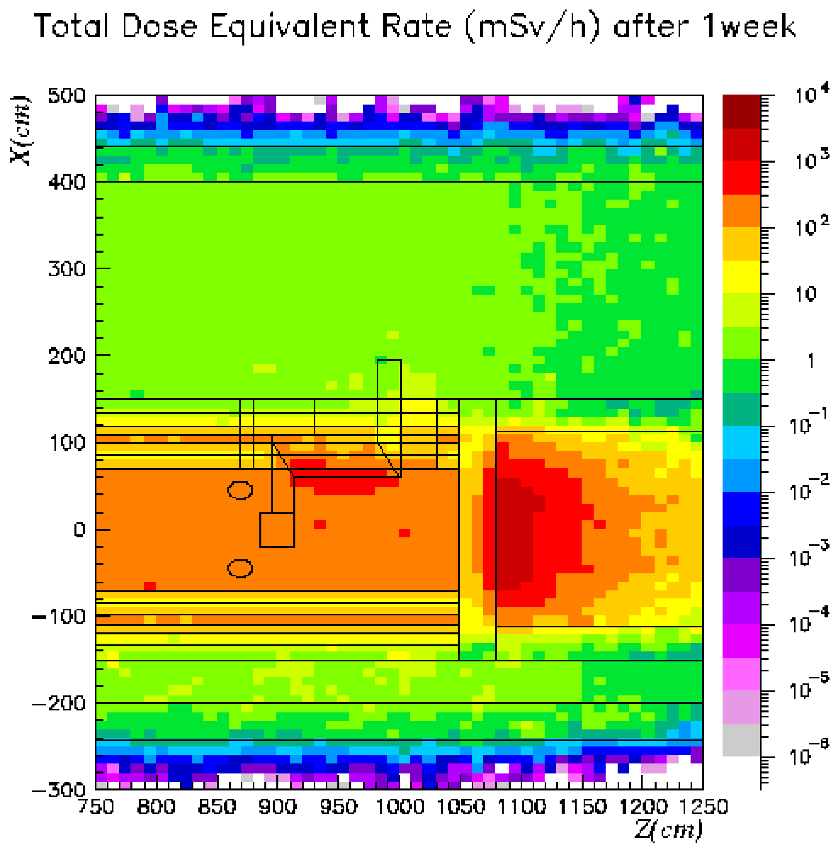
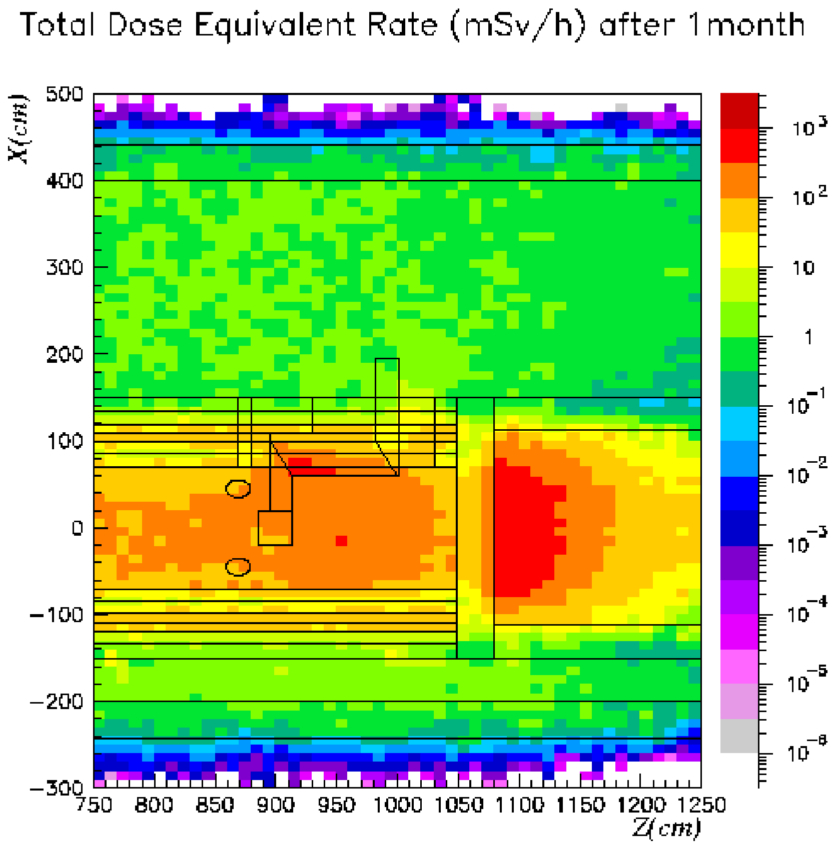


Figure 30 Total dose equivalent rates after a cooling time of 1 week



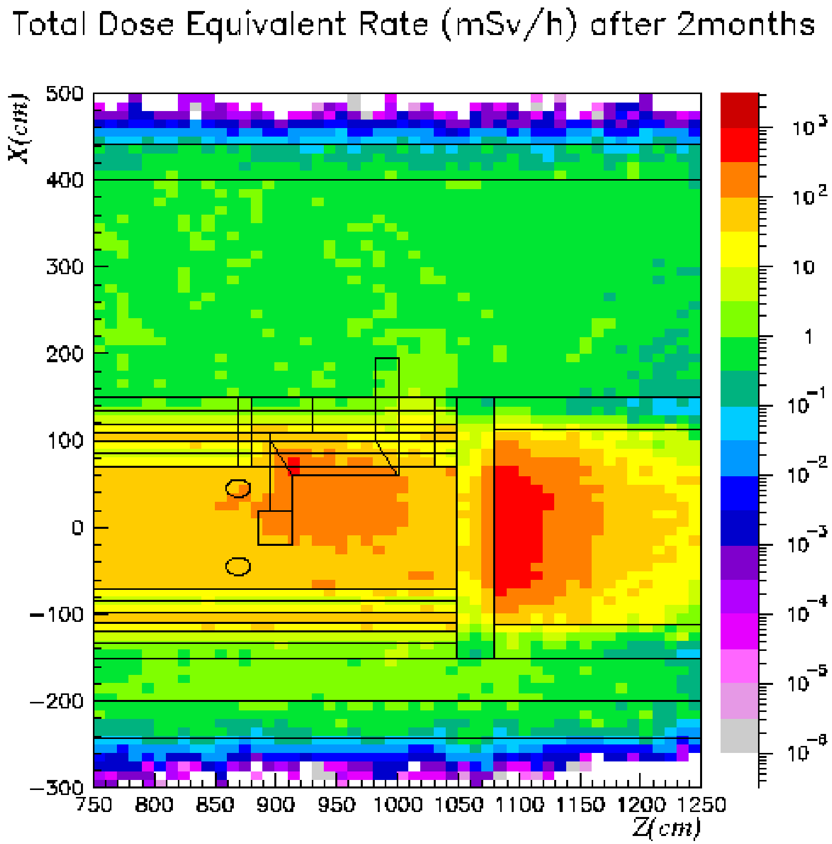
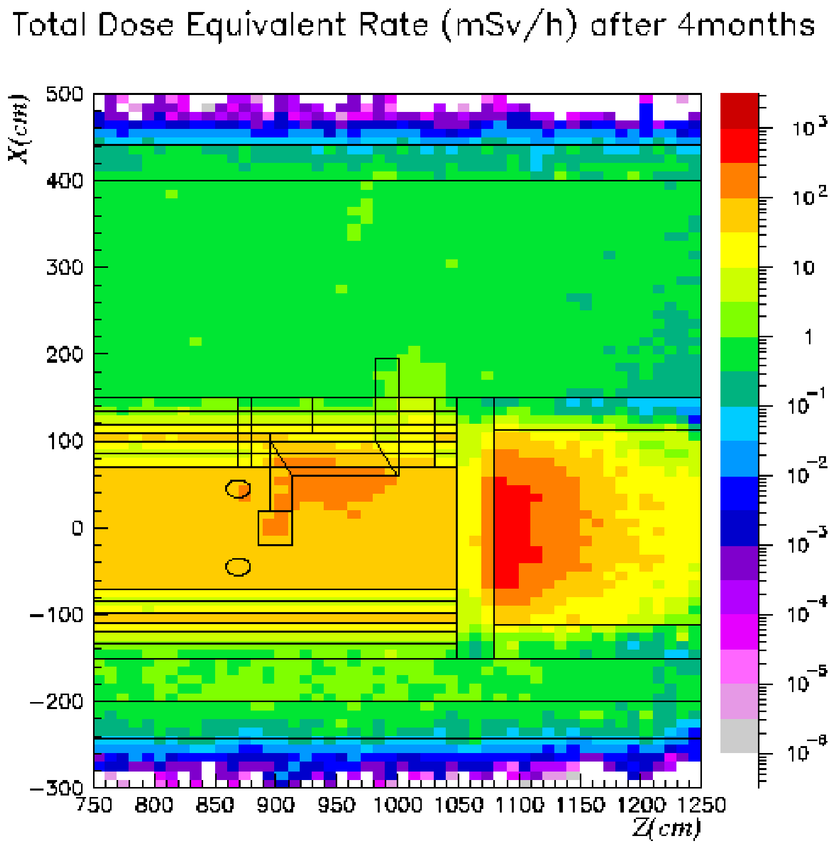


Figure 31 Total dose equivalent rates after a cooling time of 1 month

Figure 32 Total dose equivalent rates after a cooling time of 2 months



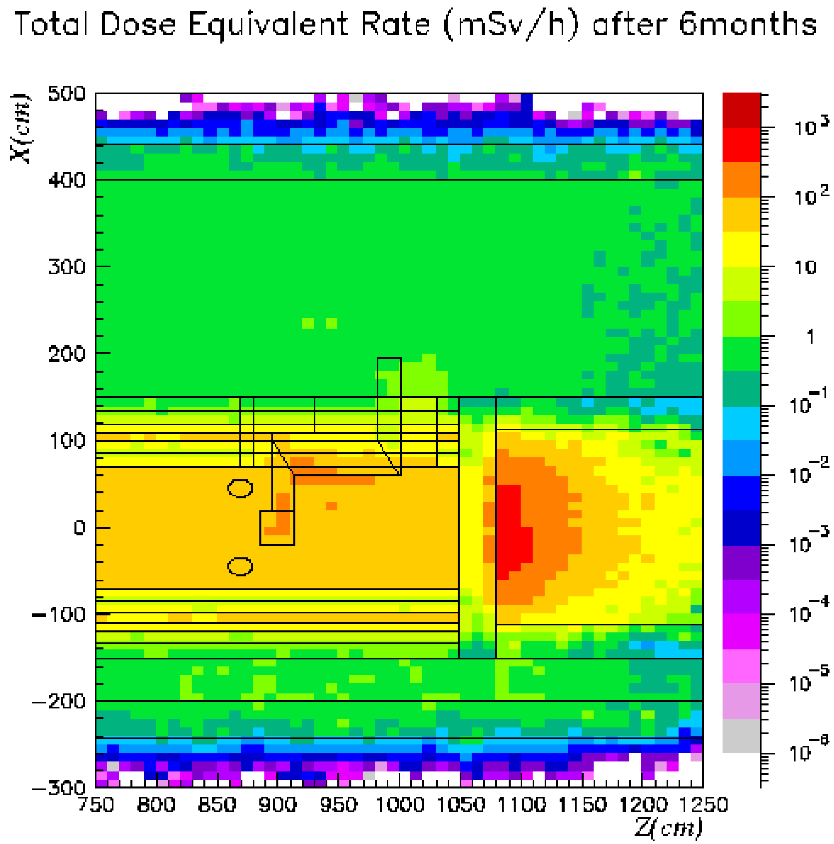


Figure 33 Total dose equivalent rates after a cooling time of 4month

Figure 34 Total dose equivalent rates after a cooling time of 6 months

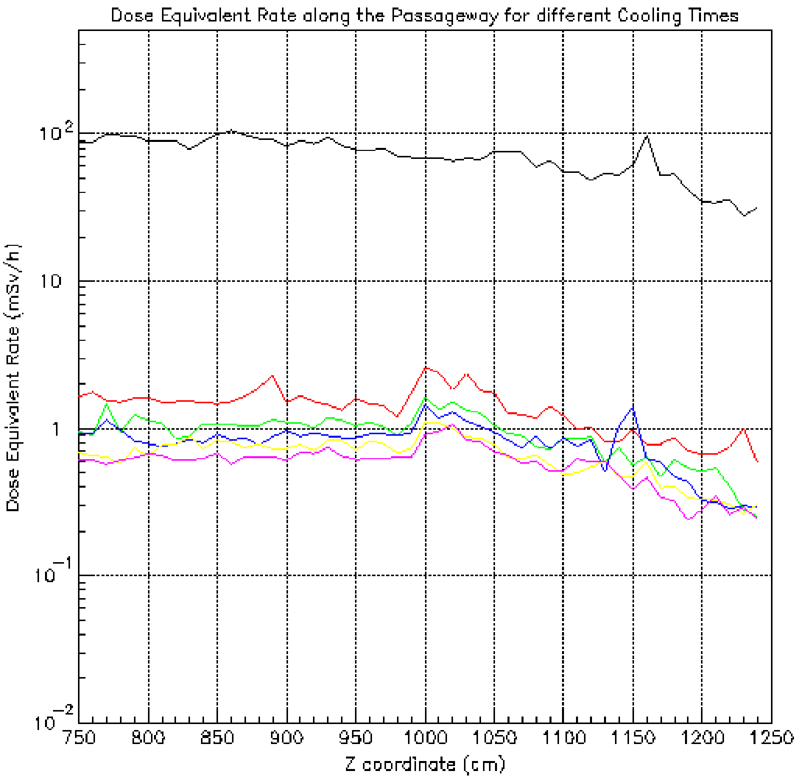


Figure 35 Average values in a bin centered at y=-90 cm (20cm long), x=200 cm (40 cm long), in black after a cooling time of 1 day and the other colors after cooling times of 1 week, 1 month, 2 months, 4 months and 6 months

2.3 Simulation with the Hole completely filled in a Sandwich Structure

In this case the hole is completely filled with materials (30 cm of concrete, 20 cm of iron and 30 cm of marble, in this case there is marble also downstream the FCS) as indicated in Figure 36. This case has been analyzed to see as reference the case with minimal levels of radiation near the fast coupling system structure (see Figure 36 and compare it with Figure 7 and Figure 28).

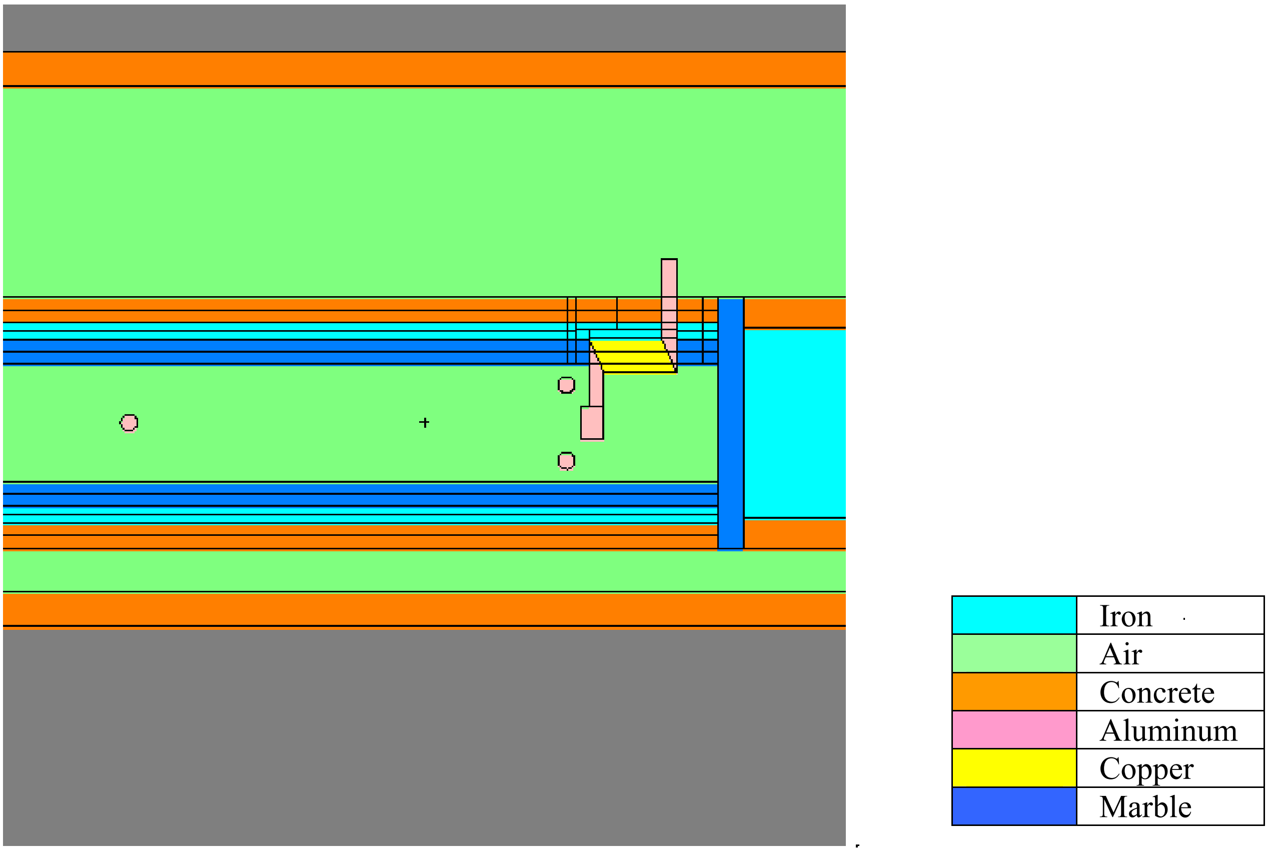


Figure 36 Horizontal longitudinal section at a coordinate Y=-90 cm

Comparing the dose equivalent rates in the Figures 39-44 with the values of the Figures 20-25, it is seen that the dose rate values are clearly smaller in the region near the FCS for the case of an opening of the horn shielding which is filled with more materials.

The simulations of the last two sections show that in order to keep the radiation levels as low as reasonable achievable, it is advisable to fill the opening of the horn shielding as much as possible with shielding elements. This can be seen also in Figures 37 and 38, where a comparison is shown of the dose equivalent rates for the three considered configurations of the shielding in the FCS region and for three different cooling times. For a cooling time of one month the dose equivalent rates reduce more than a 50% with a shielding in front of the FCS. Values of the total dose equivalent rate at a coordinate x =200cm along the passageway are represented in Figure 45.

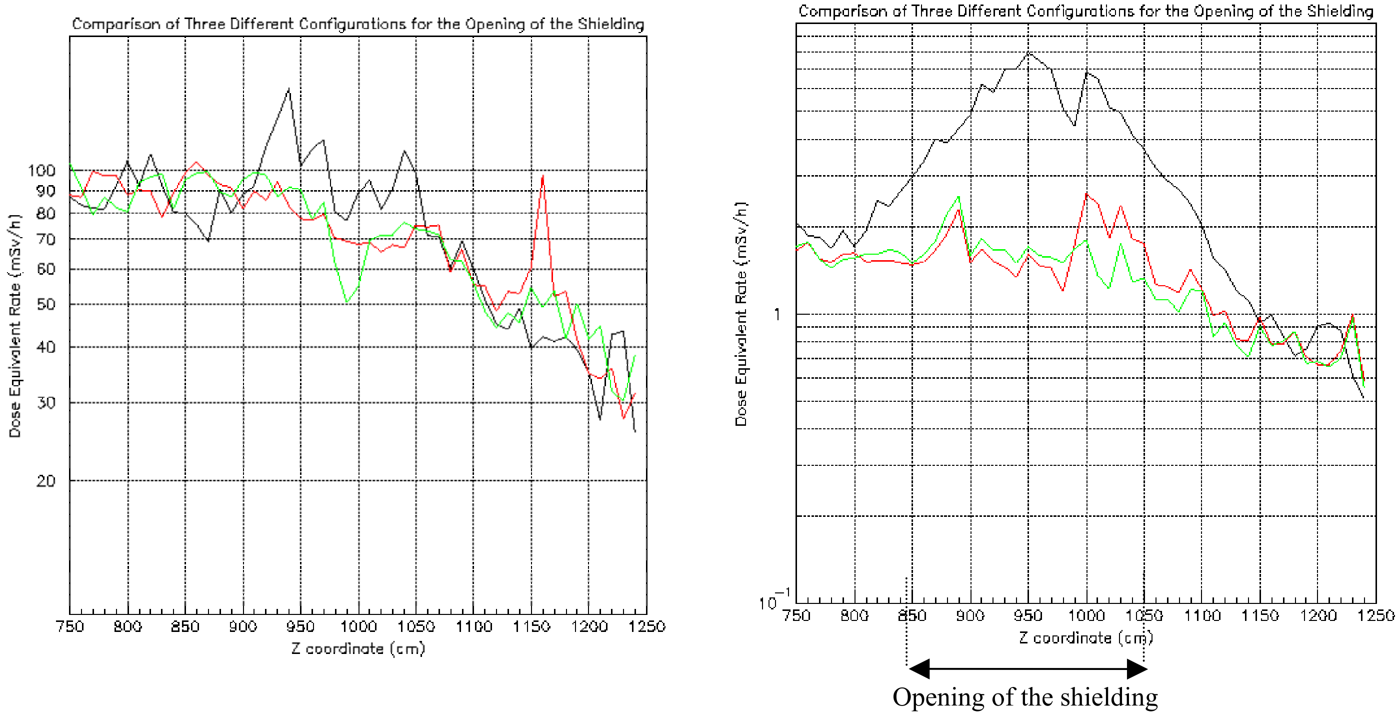


Figure 37 Average values in a bin centered at y=-90 cm (20cm long), x=200 cm (40 cm long) along the passageway, in black the layout of Figure 7, in red the layout of Figure 28 and in green the layout of Figure 36 after a cooling time of <u>1 day</u> (left) and after a cooling time of <u>1 week</u> (right).

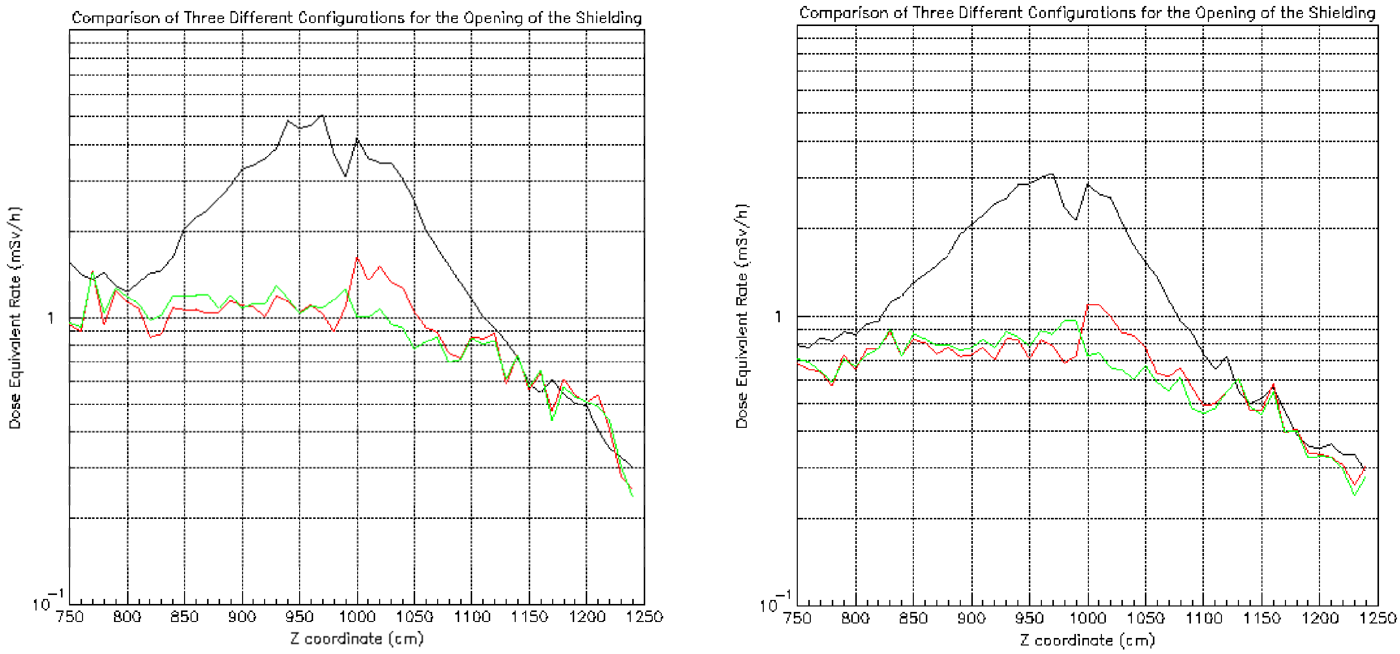


Figure 38 Average values in a bin centered at y=-90 cm (20cm long), x=200 cm (40 cm long) along the passageway, in black the layout of Figure 7, in red the layout of Figure 28 and in green the layout of Figure 36 after a cooling time of <u>1 month</u> (left) and after a cooling time of <u>4months</u> (right).

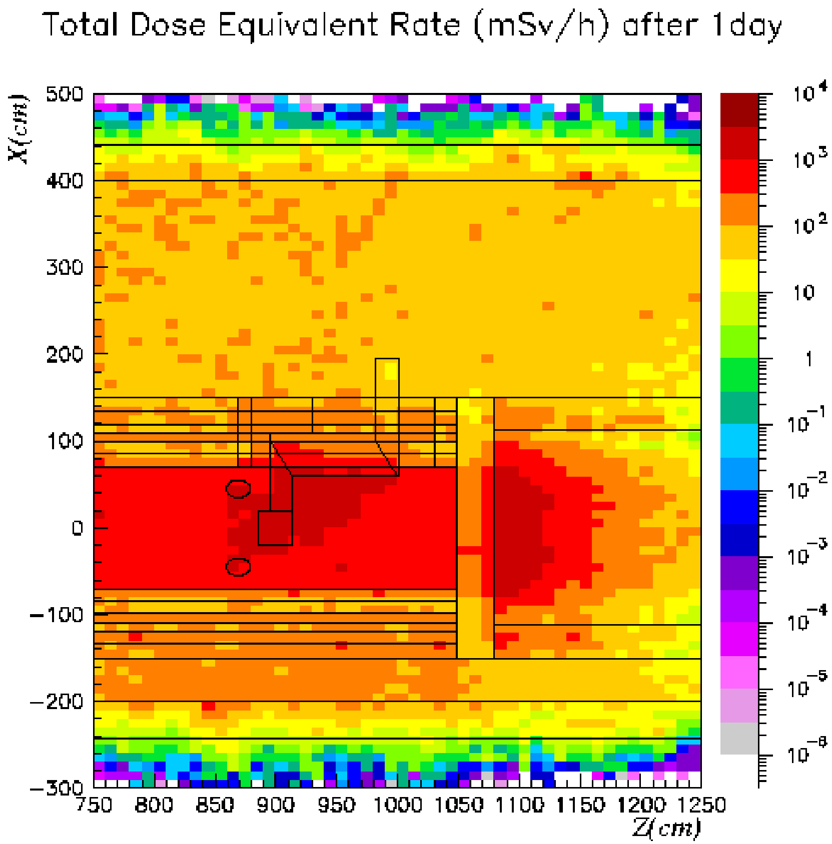


Figure 39 Total dose equivalent rates after a cooling time of 1 day

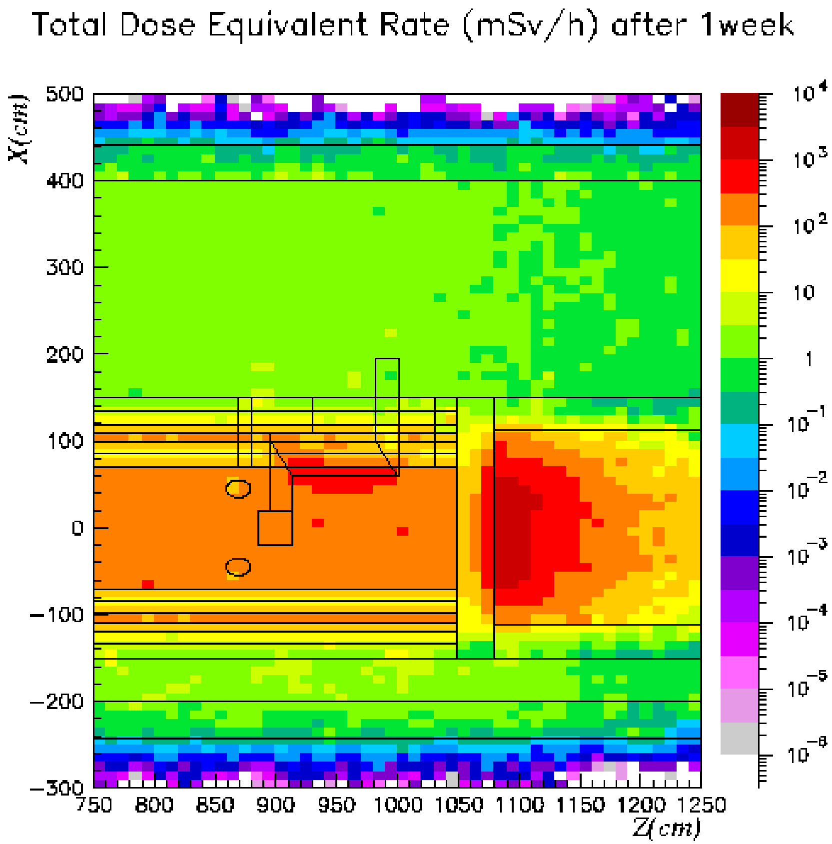


Figure 40 Total dose equivalent rates after a cooling time of 1 week

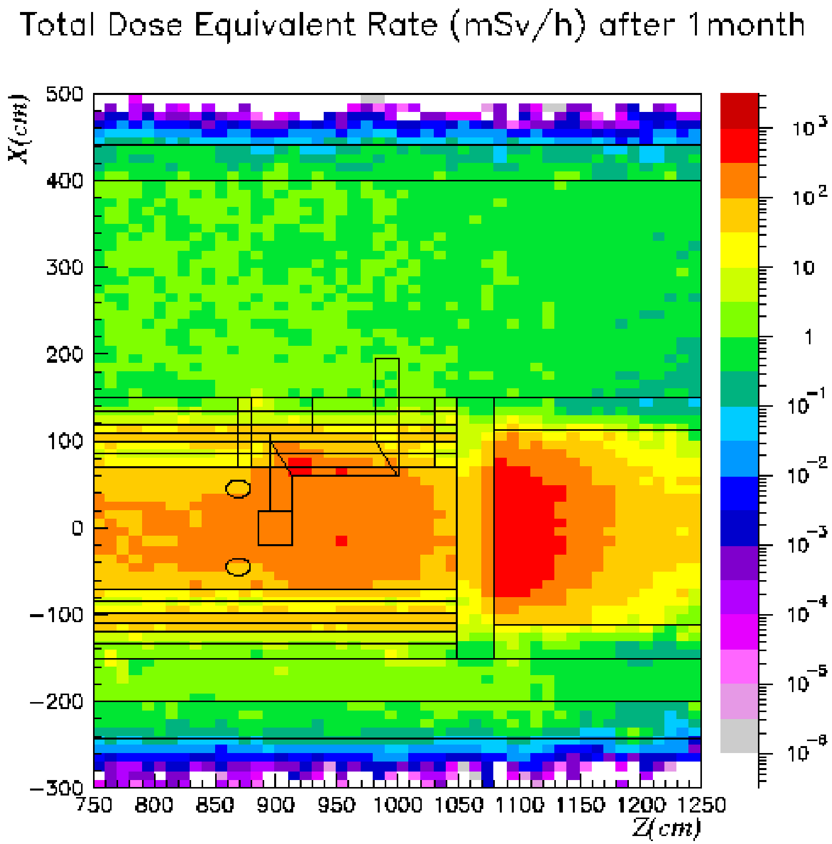


Figure 41 Total dose equivalent rates after a cooling time of 1 month

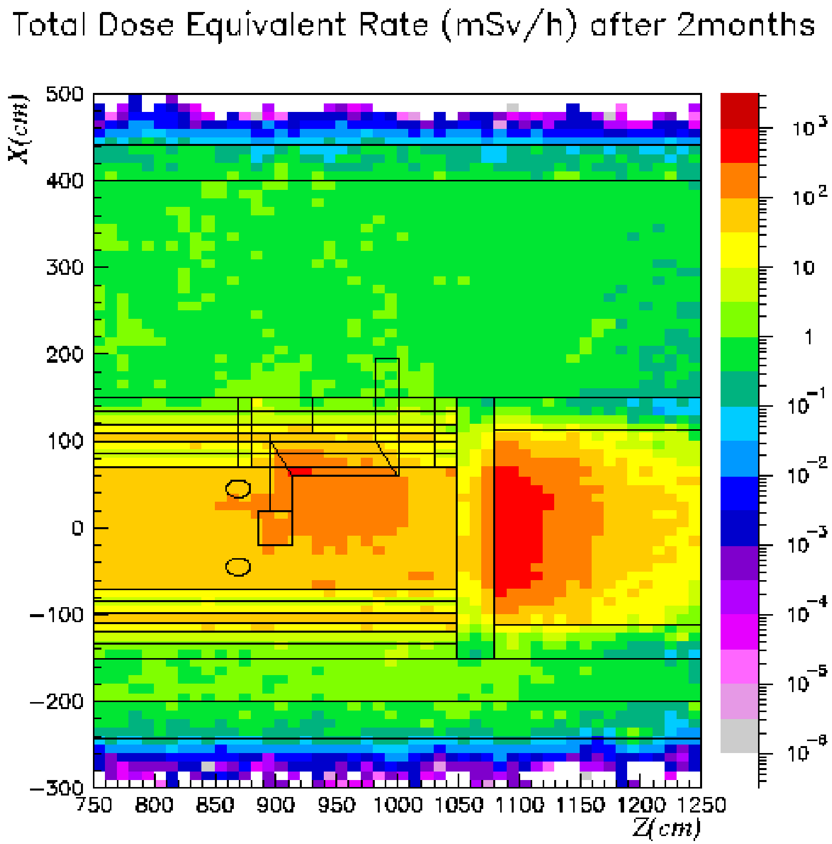


Figure 42 Total dose equivalent rates after a cooling time of 2 months

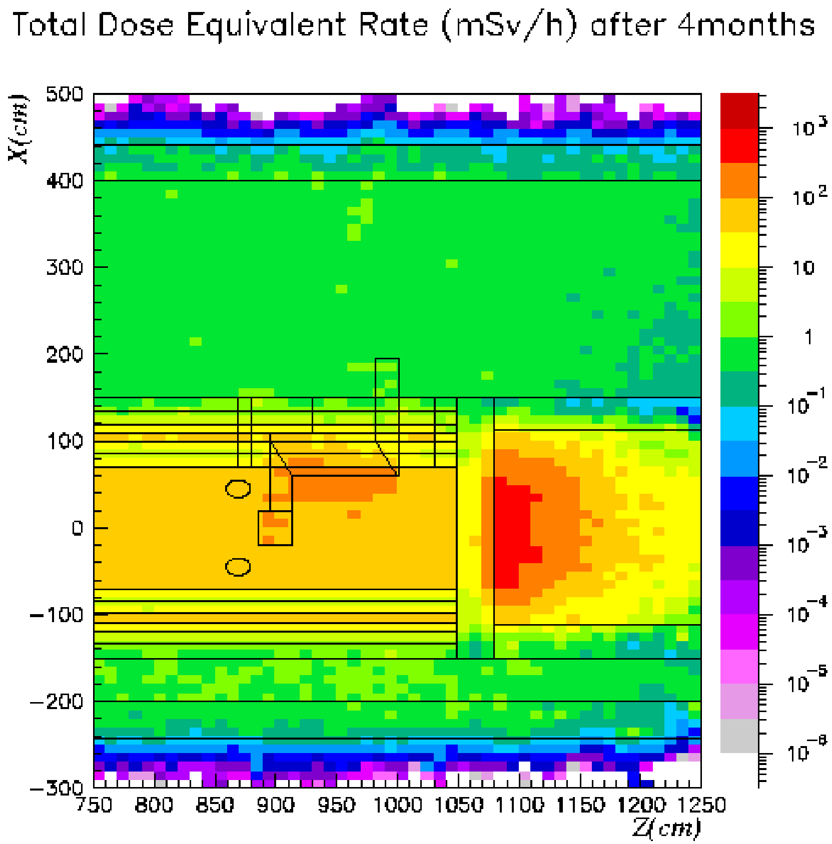


Figure 43 Total dose equivalent rates after a cooling time of 4month

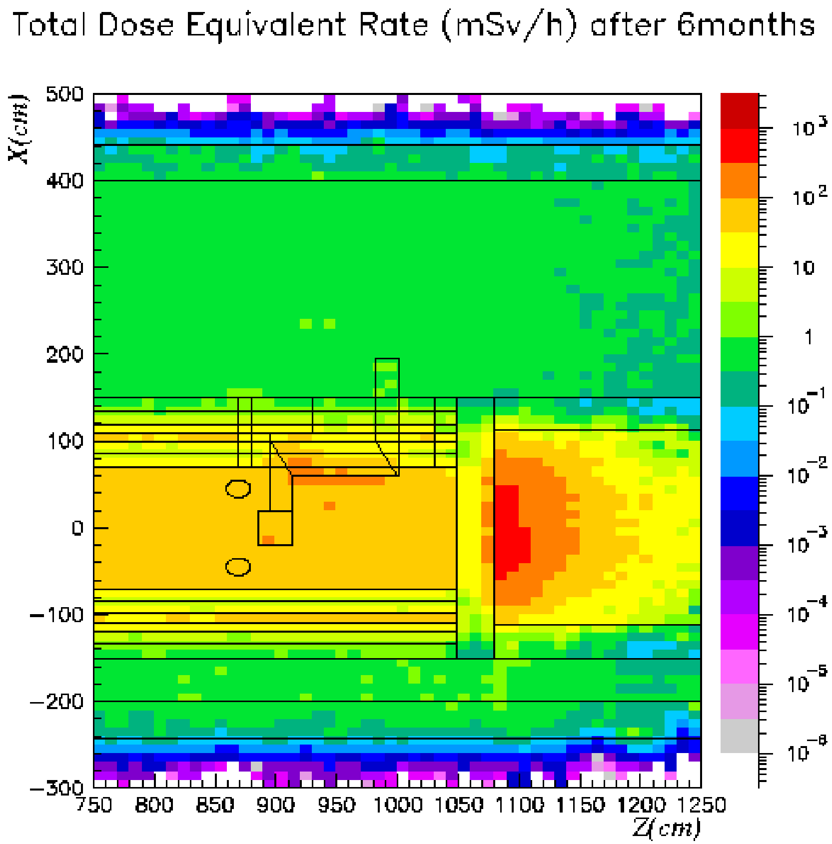


Figure 44 Total dose equivalent rates after a cooling time of 6 months

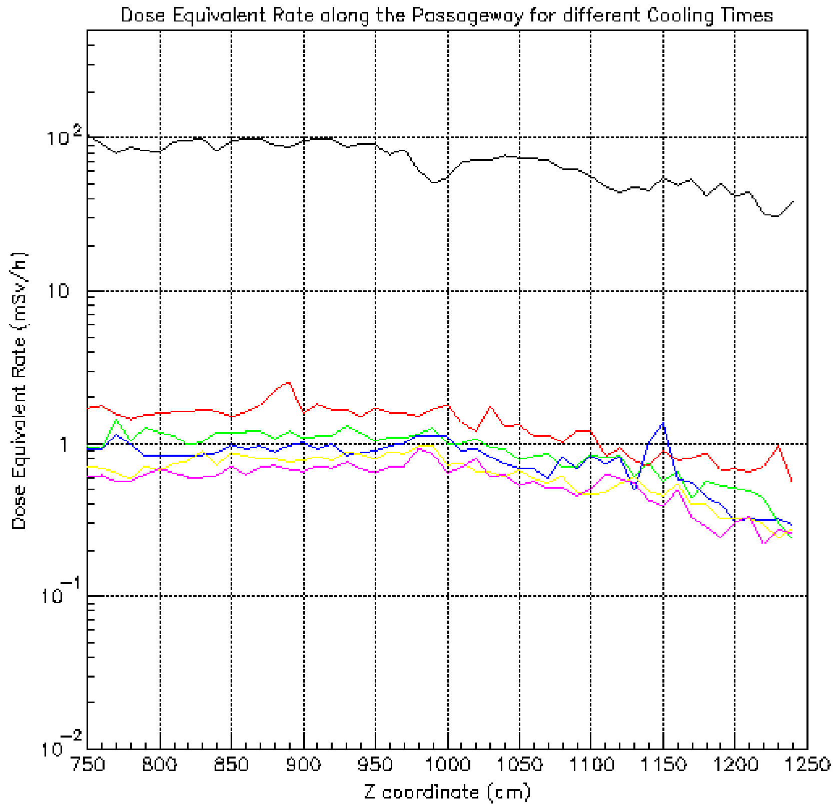


Figure 45 Average values in a bin centered at y=-90 cm (20cm long), x=200 cm (40 cm long), in black after a cooling time of 1 day and the other colors after cooling times of 1 week, 1 month, 2 months, 4 months and 6 months

3. Conclusions and Future Tasks

3.1 Conclusions

- With cooling times of one week and beyond, the major contributions to the dose equivalent rate near the FCS are the one of the materials inside the hole and the one of the shielding materials.
- Large variations of the dose equivalent rates around the horn region are observed for cooling times of one day and one week. For longer cooling times the variations are small.
- With the proposed shielding structure a cooling time of one month seems to be reasonable for a human intervention. In any case the intervention should not be performed before one week when the accumulated dose is still bigger than 2 mSv (CERN design criterion). Some other shielding structures should be studied to decrease further the dose equivalent rates.
- With a sandwich shielding structure in front of the fast coupling system it is observed a reduction of the levels of radiation near the opening of the shielding. For example the dose equivalent rates near the FCS decreases by 50% after one month of cooling time and even more for other cooling times.
- It is therefore recommended to fill the opening of the horn shielding as much as possible with shielding elements in order to keep the radiation levels as low as reasonable achievable.

3.2 Future Tasks

- Improve the accuracy of the simulations by modeling the copper block of the electrical connections as layers of air and copper instead of the present solid block of copper.
- Some other shielding structures of the horn area, for example a similar marble block such as in the case of the target, might be studied in order to keep the radiation levels as low as reasonable achievable.
- Related with the replacement of the horn a human intervention is also foreseen in the trench area. In order to calculate the radiation levels in this area, the geometry of the trench area has to be included in the new FLUKA input of the CNGS installation.

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