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Calculation of Remanent Dose Rate Maps in the LHC Beam Dump Caverns

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Summary

The two dump caverns located at Point 6 of the LHC are expected to be among the most radioactive areas when the LHC will be in operation. The two beam dumps are used to fast extract the beam at the end of the physics runs or in case of abnormal situations. Consequently, an important fraction of the beam particles will be stopped in the dump cores which will lead to the activation of the core itself as well as of the surrounding shielding and of the cavern structure. Since repair and maintenance interventions in the caverns may be required, it is necessary to have a thorough knowledge of the expected remanent dose rate to optimize the work procedure which will be applied. The FLUKA Monte-Carlo code is used to calculate three dimensions dose rate maps corresponding to different cooling times and one year of operation of the accelerator. The calculations are performed for different geometrical configurations since in case of dump core replacement the top of the shielding will be removed. The dose rate calculations will also be used to give recommendations on the procedure to be followed during the handling exercises of a dump core replacement or other dry-runs planned before LHC start up.

Keywords: LHC, beam dumps, remanent dose rate, FLUKA

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Executive summary

The remanent dose rate calculations are performed assuming one year of operation of the machine at nominal intensity which corresponds to 6×10^{16} protons per beam. The FLUKA geometry used was partly taken from the reference radiological study of the LHC beam dump [3]. Some modifications concerning the dump core itself and the connection to the beam transfer line were implemented based on the new layout of the system as described in the LHC design report and other references.

Remanent dose rate maps covering the entire cavern for 1 h, 8 h, 1day, 1week, 1 month, 4 months and 1 year were calculated for four geometrical configurations. The studied cases are the followings :

- dump assembly in its operational configuration
- dump assembly with the top shielding blocks removed and the dump core
- dump assembly with the top shielding blocks and no dump core
- bare dump core in the cavern.

1 Introduction

Since the first study of the radiological impact of the beam dumps located at Point 6, the layout of the system and above all the method to calculate dose rate with FLUKA [1, 2] have significantly changed [3]. For this reason, new assessments of remanent dose rates at different key positions of the dump cavern are necessary for a better planning of interventions such as a dump core replacement.

In this Note, two recently developed and very accurate ways to calculate dose rates with the Monte-Carlo code FLUKA are used. The first one is a general feature of FLUKA which was implemented starting in the version of 2005. It allows the calculation of radionuclide production, the transport of radioactive decay products as well as the scoring of different quantities according to a given irradiation profile and cooling time within a single simulation. With the second method [4], the dose rate is obtained in a two steps calculation, the first step consists of a pure hadronic simulation where information concerning the production of radionuclide (and eventually radioactive daughter isotopes) such as the location, the buildup and decay corresponding to a given irradiation pattern and different cooling times are stored in an external file. In the second step of the calculation, for one particular cooling time, the decay particles are transported and any dose equivalent quantity can then be scored. The advantage of the first method is that one calculation is sufficient to obtain results corresponding to several cooling times. The second method is however more flexible and it allows to perform a parametric study of the contribution to the dose rate of decay products emitted in selected regions only. It is also possible to modify the FLUKA geometry in the second step. Those two features are very useful for the study of intervention dose when some shielding elements are removed as it is the case in a dump core replacement. Both methods were applied for the dose rate calculations in the dump cavern, and the consistency of the results was verified using an identical configuration.

2 Description of the beam dump system

The two beam dump systems are located at each side of the LSS at Point 6. Each beam line is equipped with extraction kicker magnets (MKD) to deflect the beam horizontally into the septum magnets (MSD) which provide a vertical deflection to raise the beam above the LHC machine cryogenic system. After the beam is swept using dilution kickers in a rotated “e”-like shape and after a drift distance of approximately 500 m it is absorbed in the TDE assembly [5]. The TDE assembly is a 7.7 m long cylindrical graphite block with a radius of 35 cm contained in a 1.2 cm thick steel jacket. Two different kinds of graphite were chosen to ensure a good mechanical and thermal resistance of the system. A 0.7 m long block of Polycrystalline graphite (PG) with a density of 1.73 g/cm^3 is followed by 3.5 m of flexible graphite (FG) with a lower density (1.1 g/cm^3) and again by 3.5 m of PG. To enforce the core resistance the graphite is enclosed in a vacuum-tight jacket made of stainless steel. Instead of keeping the graphite core under high vacuum as the rest of the extraction line, the option of filling the dump with an inert gas with sufficient supply to stop a graphite fire was chosen. For this reason, a vacuum-tight entrance window is equipping the line to isolate the beam dump transfer line kept under high vacuum from the dump core vessel kept under a slight overpressure of 0.2 kPa [6]. To fulfill both the mechanical resistance and permeability criteria, the window is made of a 15 mm thick layer of carbon-composite (CC) covered with a 200 μm thick stainless steel foil. The window is located approximately 10 m upstream of the graphite core front face at the limit between the extraction tunnel and the UD (UD62 or UD68) caverns. The downstream end of the core vessel is closed with a leak-tight window made of titanium. In the preliminary study of the dump, the dump core was water-cooled[7, 8]. In the final design, this solution was abandoned and replaced by an air cooling system [9] which has led to several significant changes in the system layout.

Each dump is surrounded by approximately 900 tons of radiation shielding blocks. The blocks are recycled dipole magnet yokes which were partially filled with concrete. Those blocks can be remotely handled with the cranes with which the two caverns are equipped. The crane will be operated from the catwalk situated on the side of the beam cavern and no intervention is necessary to connect the shielding blocks or the dump core in case of exchange to the crane hook. Figure 1 shows the dump cavern after the shielding block installation, the top part of the shielding is removed and a graphite core with its handling frame ready to be installed can be seen at the bottom left corner of the picture. The places which are reserved for the storage of a damaged dump core as well as for the top iron blocks when the shielding has to be opened are indicated in the figure.

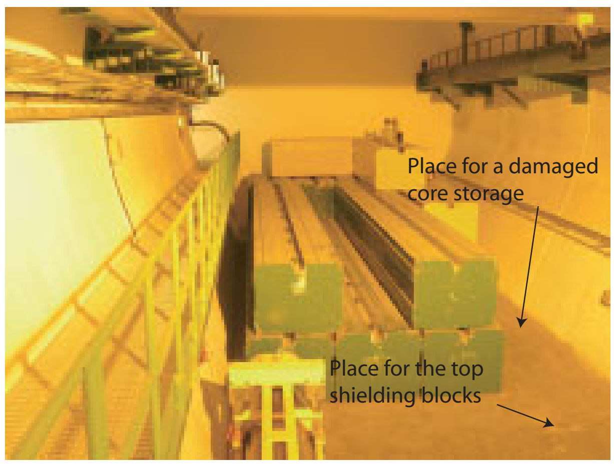


Figure 1: Picture of the dump cavern after the shielding block installation. A part of a beam dump ready to be installed can be seen at the bottom of the picture on the left.

3 The FLUKA simulation

3.1 Geometry

The different elements of the beam dump system present in the UD cavern were implemented in a FLUKA model with a high level of details. For example, the gaps between two shielding blocks or above the concrete used to fill the blocks are reproduced in the simulation since they are important for the assessment of the dose rate due to possible streaming effects. Figure 2 shows a section of the FLUKA geometry perpendicular to the beam axis to illustrate the level of details in the geometry. A right-handed coordinate frame with the x-axis pointing up and the z axis pointing in the direction of the beam was used for the geometry description. The origin of the coordinate system is located at the bottom left corner of the dump assembly front face (looking along the beam direction) as shown in Figure 2.

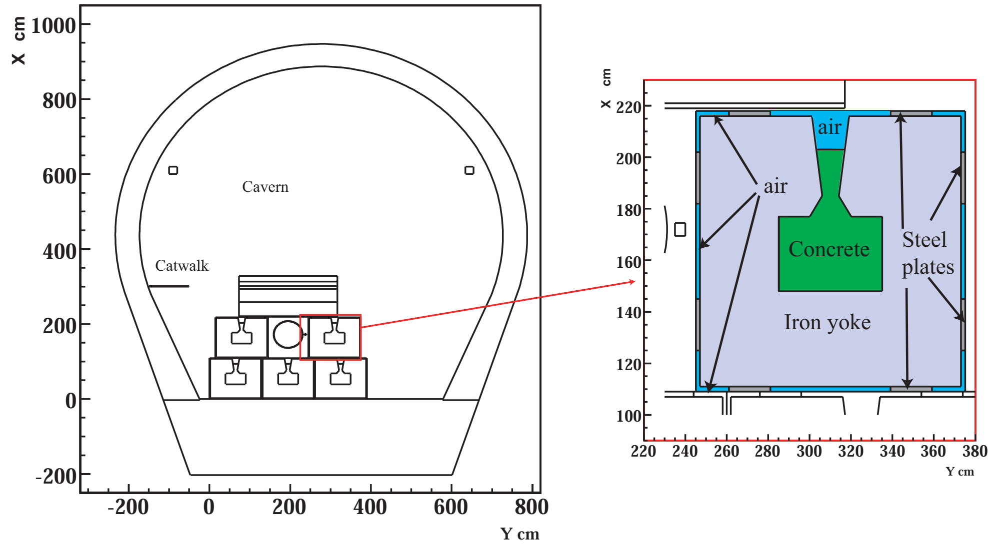


Figure 2: Section of the FLUKA geometry perpendicular to the beam direction to illustrate the level of details used for the dose rate calculations.

The catwalk is represented in the FLUKA model by a 1 cm thick iron plate along the cavern wall, the crane and its support are represented with iron blocks or bars. Figure 3 shows two longitudinal sections of the FLUKA geometry, the left figure represents a vertical section and the right one an horizontal section along the beam axis.

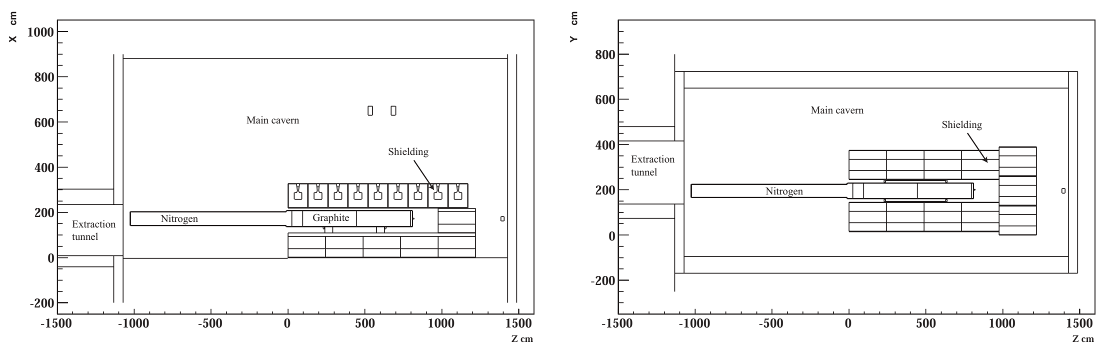


Figure 3: Longitudinal section of the FLUKA geometry used for the calculation of residual dose rate maps.

3.2 Proton source

All residual dose rate calculations were performed for one year of operation of the LHC at its nominal intensity. The fill scenario which leads to the highest number of protons in the accelerator and corresponds to a fill length of 8 hours and 3 hours of turn-around time is used for the estimation of the number of protons impinging on the dump core. In this case, it has been estimated that 2.6×10^{14} protons are sent to the dump per beam at the end of each fill. Considering 233 fills per year, the total number of protons dumped at nominal intensity is equal to 6.0×10^{16} for one beam [10, 11]. Although, in reality, protons are dumped almost instantaneously (in a few tens of μsec), for the sake of simplicity a constant rate of protons impinging on the dump core over 180 day is assumed. The consequence of this assumption is that for short cooling times like one hour after the machine shutdown (last beam dump), the calculated dose rate is underestimated. However for longer cooling times, an averaged proton intensity as used in the calculation leads to the same results than obtained with the exact irradiation profile.

In order to limit the temperature rise of the absorbing materials, the beam is swept over the graphite front face. The specific shape of the beam is used in the simulation, the positions where the 2808 bunches from the beam hit the beam core are presented in Figure 4. For each incident bunch, a vertical and horizontal Gaussian spread of the beam equal to 1.59 mm for the horizontal and to 1.36 mm for vertical components, respectively, are also taken into account [12].

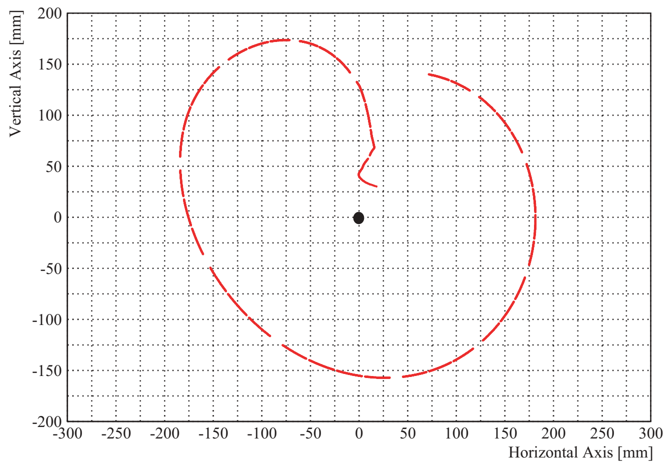


Figure 4: Positions where the different bunches of the beam hit the graphite front face with its center corresponding to the origin of the graph.

3.3 Selected positions and cooling times

Dose rates have been calculated inside the entire cavern and results are presented in two dimensional-maps. However, it is often useful to indicate doses rate also at strategic locations where persons may have to stay in case of an intervention. One of the most critical interventions will be the replacement of a dump core which requires the handling of the shielding blocks with the crane and the disconnection of the beam line. The first profile is calculated at a typical position of a human body (150 cm) above the catwalk, *ie*, where the crane operator will stand during shielding block or the graphite core handling. Other profiles are calculated along the beam direction at typical body height inside the cavern, one is on the side of the dump core steel jacket at a 5 cm distance and the two others are on each side of the shielding blocks at a 10 cm distance (second block layer). And finally, one profile is calculated along the Y direction in the back of the cavern behind the blocks at a 10 cm distance from the shielding. The different position for which the dose rate profile were calculated are indicated in Figure 5.

The dose rates are calculated for different cooling times in order to take into account the different intervention scenarios ranging from a short inspection during the physics runs period to a major intervention occurring during the annual shutdown after several weeks of cooling. The cooling times considered are 1 hour, 8 hours, 1 day, 7 days, 1 month and 4 month and for some

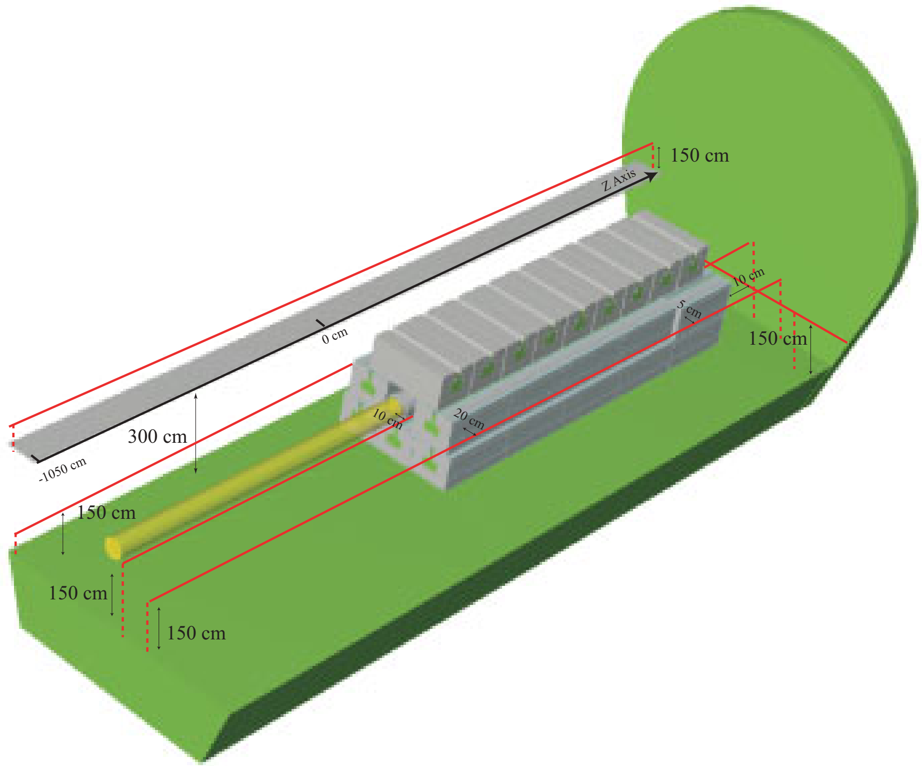


Figure 5: Selected positions indicated by red lines used to graphically show the dose rate.

cases 1 year. The dose is calculated for one year of operation of the accelerator. As mentioned above, proton losses are assumed to be constant over time while in reality one single beam dump is instantaneous, consequently for 1h and 8h of cooling the calculated doses rate are underestimated.

3.4 Dose rate calculations

To obtain the residual dose rate maps inside the dump cavern, two very accurate methods based on the transport of radioactive decay particles and on the use of energy dependent fluence to dose equivalent conversion factors are used. The factors used for the fluence to dose rate conversion are taken from the ICRP74 and Pellicciioni data and correspond to the worst possible irradiation geometry [13, 14]. The first method which allows the calculation of radionuclide and the transport of particles emitted due to the decay of the produced isotopes in a single calculation is a new feature of FLUKA which was implemented in the version of 2005. In this calculation scheme, the radiation decay emitted by the radionuclide produced in inelastic interactions are transported and their contribution to the scored quantities is weighted by taking into account a user-defined irradiation pattern and given cooling times.

The second method is not a general feature of the FLUKA code and it was developed in the past when the previous method was not available yet. The calculation in this case is performed in two steps:

1. In the first step, all characteristics concerning the production of residual excited nuclei taking into account their buildup and decay for a given irradiation pattern and different cooling times are stored in a dedicated file. Some biasing techniques can be used to limit the size of the generated files and limit the number of nuclei produced with a high probability. It is also possible to store residual nuclei only for a limited number of regions of interest.

2. In the second part of the calculation, the information concerning the residual nuclei are read from the file created during the first step of simulation. The emitted decay particles (photons, electrons and positrons) are sampled using detailed data on branching ratios, gamma energies and positron energy spectra. A pure electromagnetic transport calculation is then performed and the dose maps can be calculated using the fluence to dose conversion factors.

While both methods are identical from a physics point of view, the advantage of the first one is that dose rate maps for different cooling times can be computed in one single simulation while the second method requires first to write into files the residual nuclei characteristics and then to perform as many calculations as requested cooling times. However, the second method is more flexible since the decay products emitted in some specific areas can be selected. For the second step of the calculation, it is also possible to apply some modifications to the geometry which allows the calculation of dose rate in realistic situations, *e.g.*, in case of opening of shielding.

4 Results of the one-step calculation

4.1 Two dimensional dose rate maps

Dose rate maps were calculated considering one year of operation and cooling times of 1 hour, 8 hours, 1 day, 7 days, 1 month and 4 months. It is assumed that the number of protons interacting in the beam dump is constant over the 180 days of operation of the machine which leads to a rate of 3.86×10^9 protons / s impinging the core considering 6.0×10^{16} protons dumped per year for one beam.

To speed up the calculation, prompt electromagnetic radiation was not transported. Concerning the radioactive decays, the transport threshold was set to 50 keV and 10 keV for electrons and photons, respectively.

For each cooling time, Figures 6 to 11 present the residual dose rates averaged over a 20 cm thick slab, for horizontal and vertical sections as well as for a section perpendicular to the beam axis. The dose rate maps are centered on the point with the highest dose rate which corresponds to the slab containing the center of the dump core ($x = 172\,\mathrm{cm}$ and $y = 195\,\mathrm{cm}$) for the vertical and horizontal sections. The section perpendicular to the beam axis is centered on the maximum of the cascade which is located between 4 and 5 meters downstream of the core front face. The scale is adjusted to the range between $1\,\mu$Sv / h and 10 mSv / h. Therefore, the bins with a dose rate higher than the upper limit (10 mSv / h) appear in dark brown color and the ones with a dose rate lower than $1\,\mu$Sv / h in white.

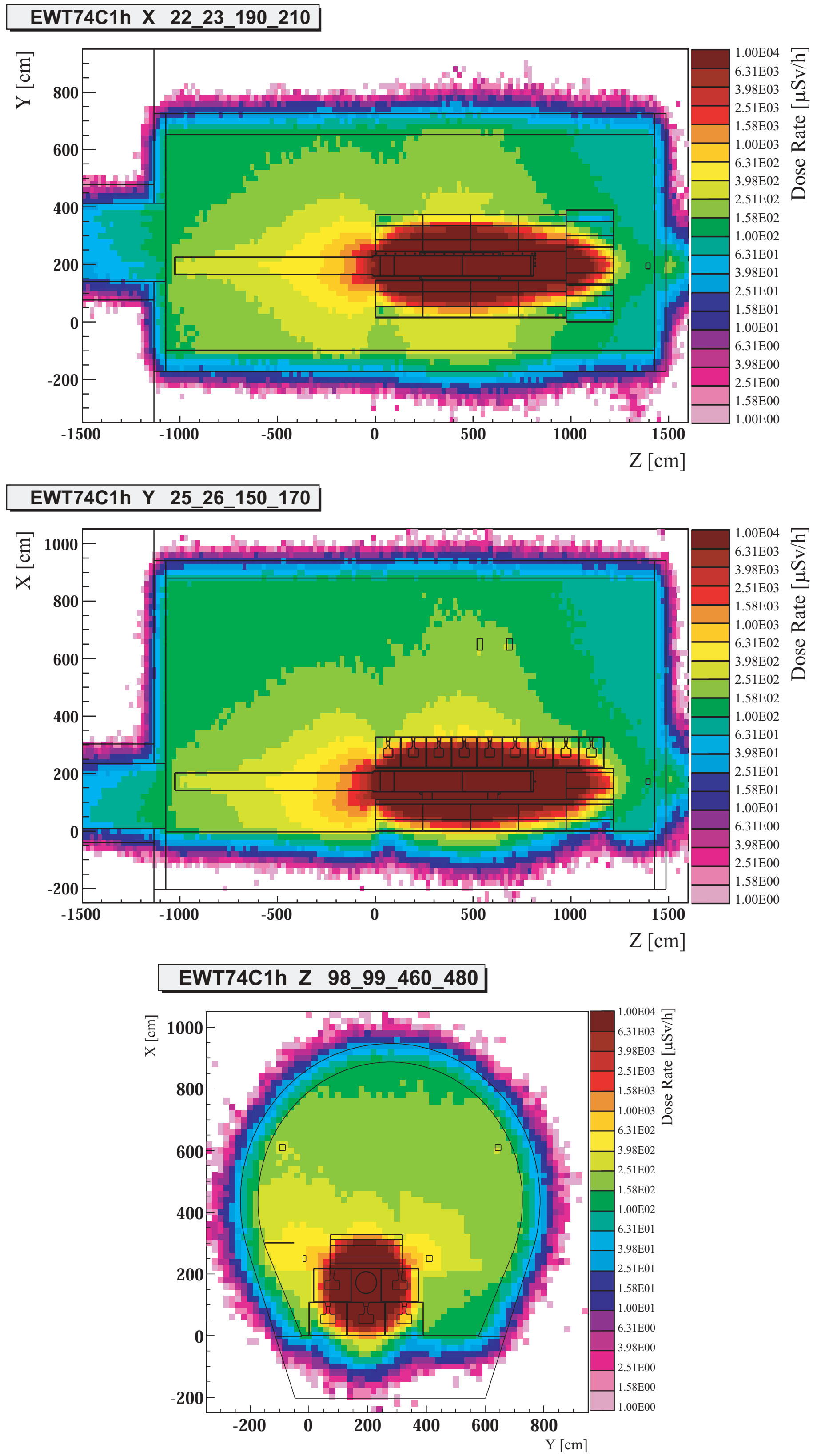


Figure 6: Dose rate maps inside the dump cavern after one hour of cooling time. The dose rate is averaged over a 20 cm thick horizontal slab (top), vertical slab (center) and transverse slab (bottom). The scale covers the range between 1 μSv/h and 10 mSv/h.

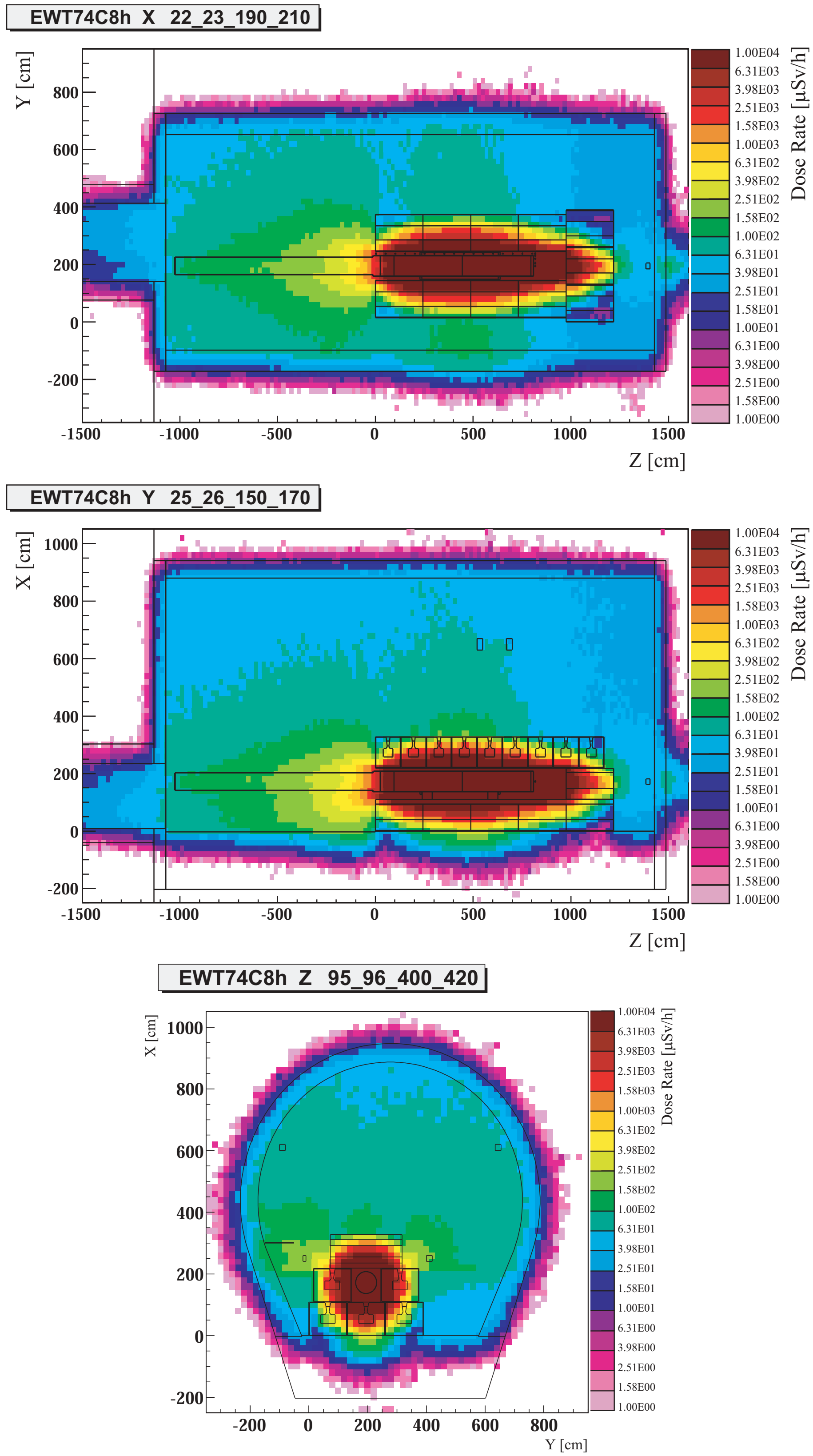


Figure 7: Dose rate maps inside the dump cavern after eight hours of cooling time.The dose rate is averaged over a 20 cm thick horizontal slab (top), vertical slab (center) and transverse slab (bottom). The scale covers the range between 1 μSv/h and 10 mSv/h.

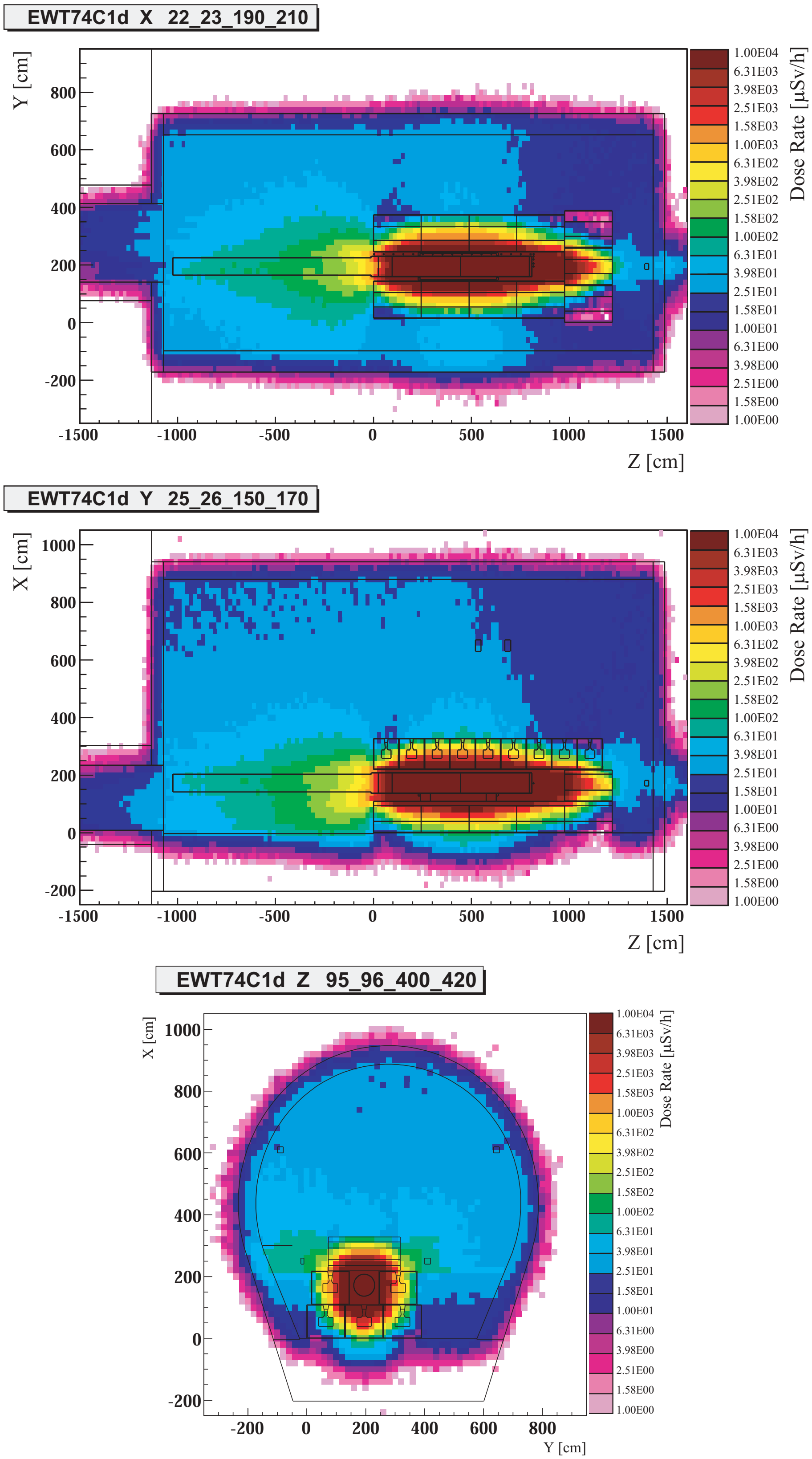


Figure 8: Dose rate maps inside the dump cavern after one day of cooling time. The dose rate is averaged over a 20 cm thick horizontal slab (top), vertical slab (center) and transverse slab (bottom). The scale covers the range between 1 μSv/h and 10 mSv/h.

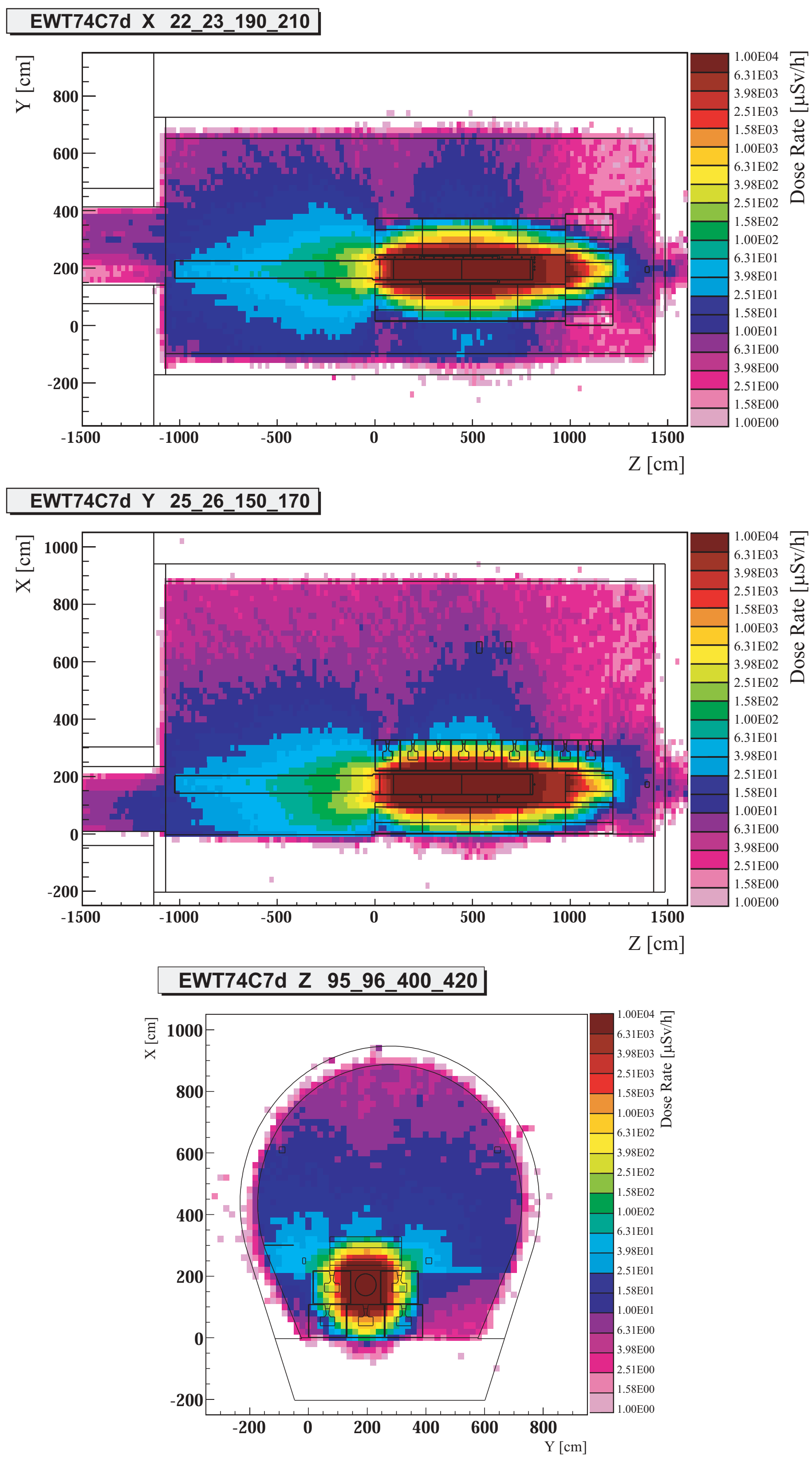


Figure 9: Dose rate maps inside the dump cavern after seven days of cooling time. The dose rate is averaged over a 20 cm thick horizontal slab (top), vertical slab (center) and transverse slab (bottom). The scale covers the range between 1 μSv/h and 10 mSv/h.

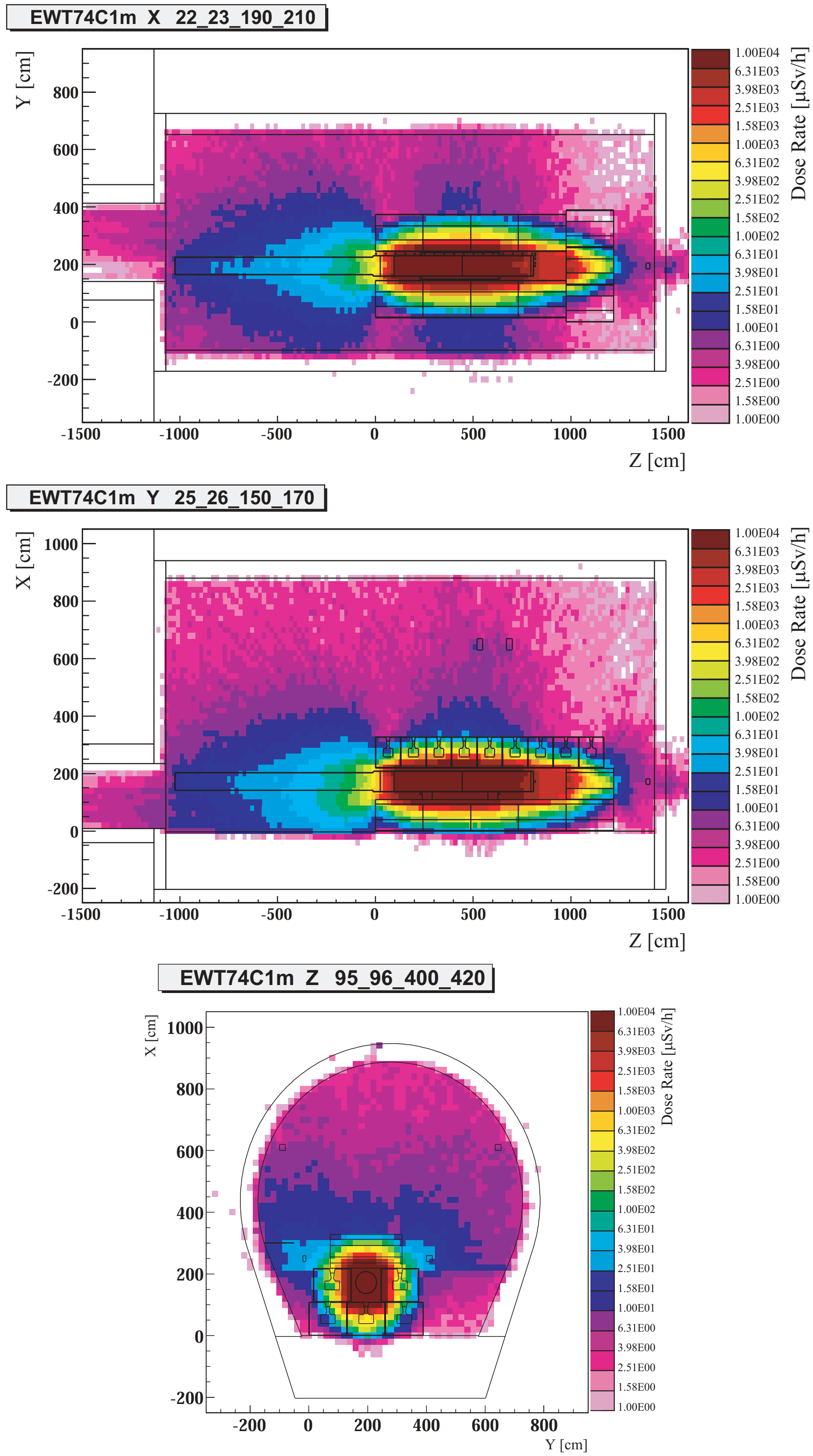


Figure 10: Dose rate maps inside the dump cavern after one month of cooling time. The dose rate is averaged over a 20 cm thick horizontal slab (top), vertical slab (center) and transverse slab (bottom). The scale covers the range between 1 μSv/h and 10 mSv/h.

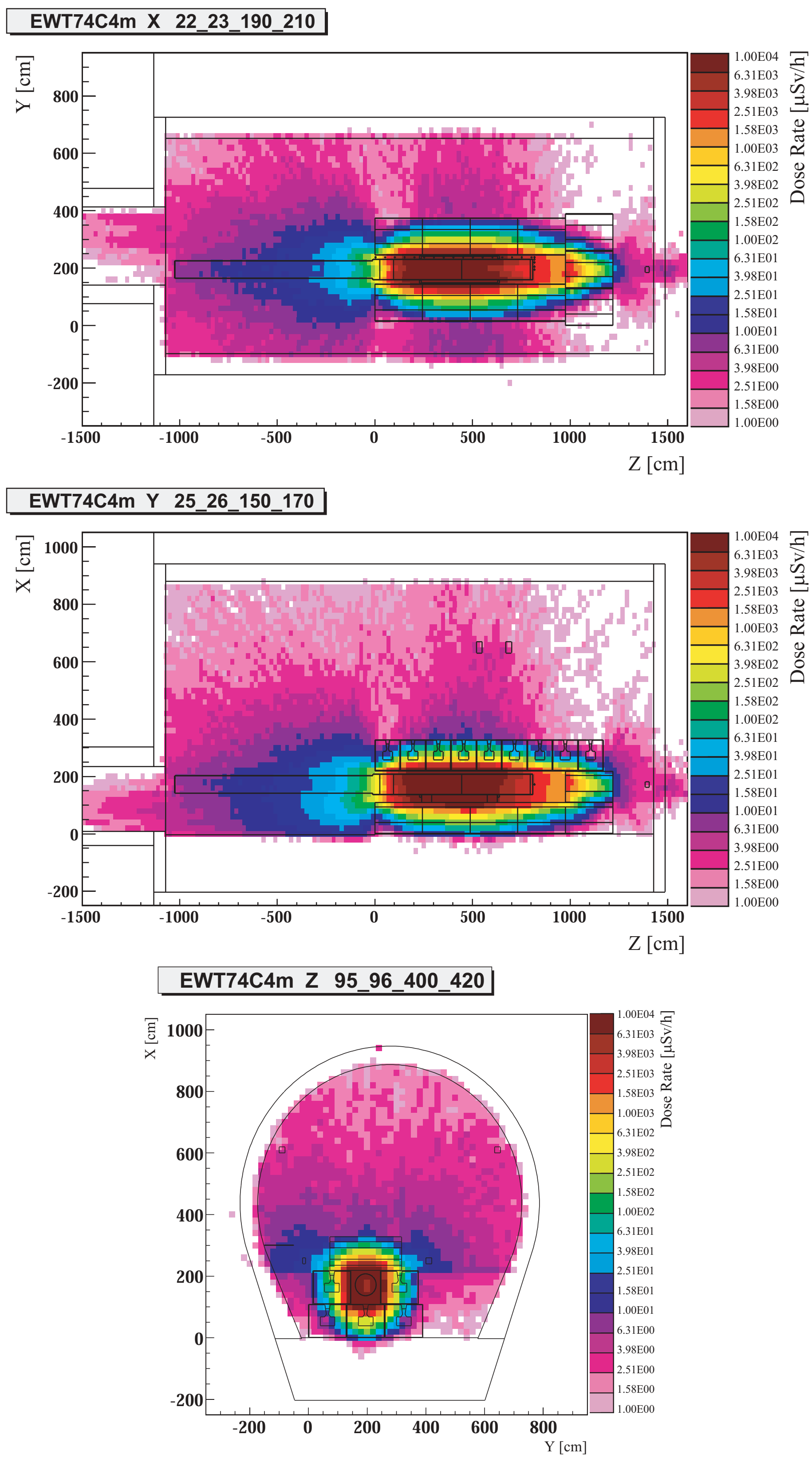


Figure 11: Dose rate maps inside the dump cavern after four months of cooling time. The dose rate is averaged over a 20 cm thick horizontal slab (top), vertical slab (center) and transverse slab (bottom). The scale covers the range between 1 μSv/h and 10 mSv/h.

4.2 Dose rate profile

As mentioned above, dose rate profiles were extracted from the three dimensional maps for several locations which are accessible during interventions in the beam dump caverns.

The dose rate along the catwalk is presented in Figure 12, the maximum for all cooling times is located 4 to 5 m downstream of the graphite block front face. After one week of cooling, the dose rate at the worst location is equal to $20\,\mu$Sv / h. It has to be noted that as it can be seen on the dose rate maps perpendicular to the beam axis in Figure 6 to 11 (bottom plot), the shielding is more efficient to limit the dose rate at cavern ground level than on the catwalk.

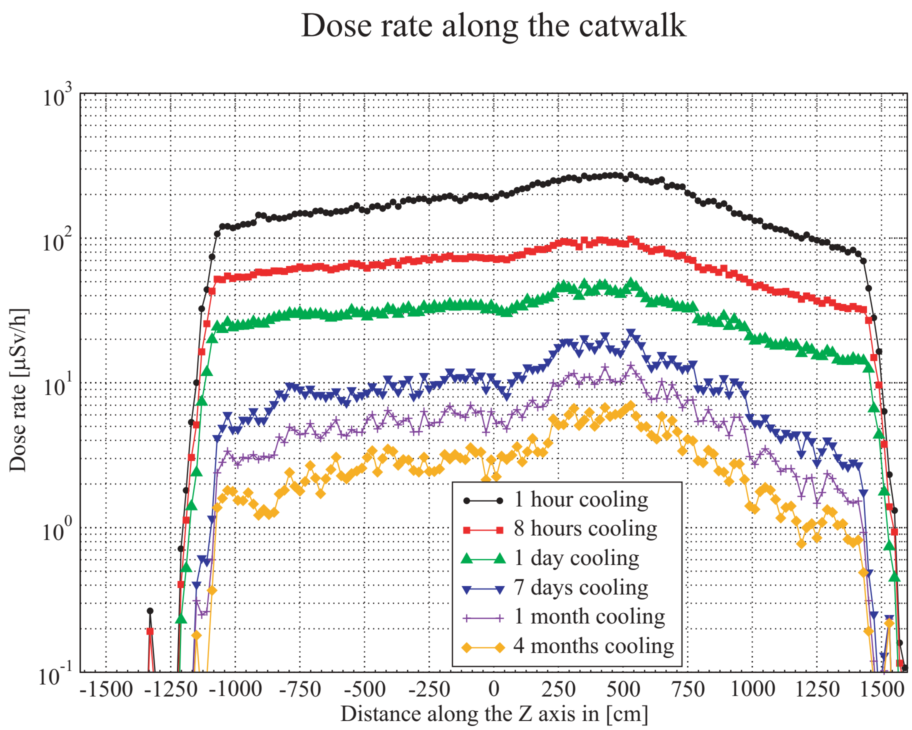


Figure 12: Dose rate along the catwalk, calculated at a height of 150 cm for different cooling times.

The dose rate along the side of the steel jacket of the core is presented in Figure 13. After one week of cooling, close to the beam the dose rate is equal to $20\,\mu$Sv / h at the end of the transfer tunnel and it reaches a value of 1 mSv / h at the interface with the shielding. Inside the shielding the dose rate reaches values up to several tens of mSv / h still for one week of cooling time. The dose rate in the back of the cavern is lower than in the front and is about $10\,\mu$Sv / h after one week of cooling.

Figure 14 presents the dose rate profiles at a 20 cm distance to the left and right of the shielding. In the front part of the cavern upstream of the core the dose rate reaches a maximum value of $30\,\mu$Sv / h for one week of cooling , along the shielding it is always lower than $20\,\mu$Sv / h and it is even lower in the back of the cavern. The dose rate on the right side of the shielding (on the right side of Figure 14) is slightly lower than the dose rate on the opposite side because more protons are impinging on the left side of the graphite core than the right side (see Figure 4). The dose rate at the beginning of the cavern z=-1100 cm (right plot) gives an indication of the expected dose rates in the beam transfer tunnel.

Figure 15 presents the dose rate profile along the shielding in the back of the cavern (along the

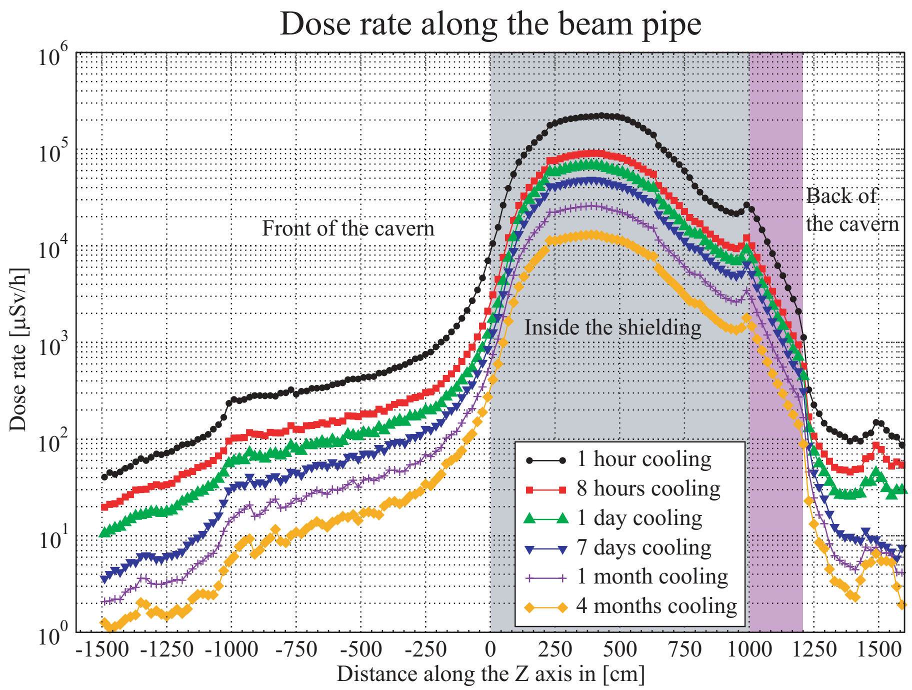


Figure 13: Dose rate along the beam pipe and the core dump for the different cooling times. For $x = 0$ cm to $x = 1220$ cm, the indicated values correspond to the ones inside the shielding .

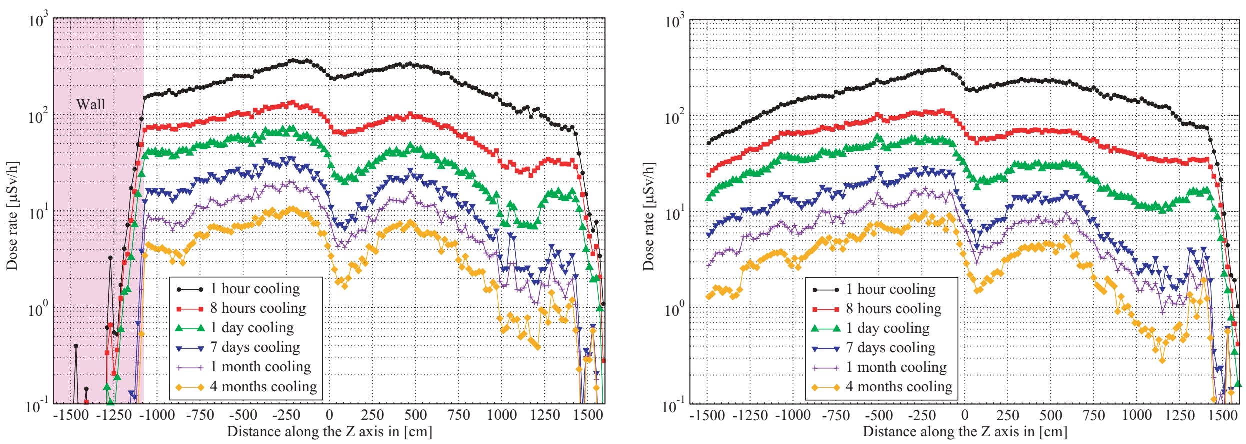


Figure 14: Dose rate on the left and right side of the shielding blocks calculated 1.50 m above the cavern floor.

Y axis, perpendicular to the beam direction). In the coordinate frame of the FLUKA geometry the graphite block is centered on $y = 195$ cm where the dose rate is peaked on a maximum value of $100\,\mu$Sv/h after one week cooling. The dose rate decreases significantly on the sides for locations which are not in the alignment of the core.

5 Comparison with the two-step method

As it was already mentioned, using the two-step method, it is possible to perform changes in the geometry and therefore to study the expected dose rate when some of the shielding blocks or the

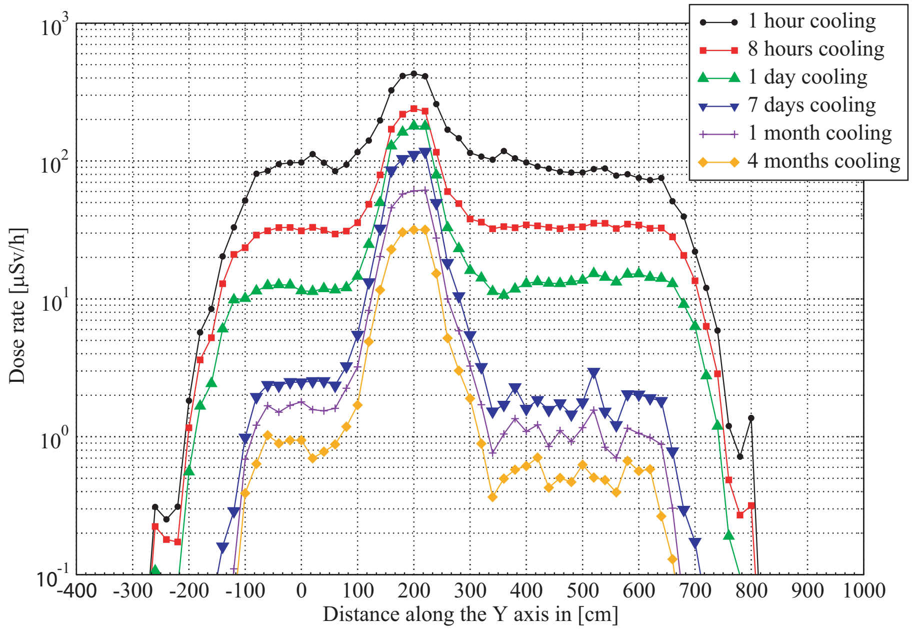


Figure 15: Dose rate in the back of the cavern calculated at 150 cm above the cavern floor and at a 30 cm distance from the shielding blocks.

dump core are removed. In the first step of the calculation, the information on the radioactive nuclei are calculated. In order to have a deeper understanding of the contribution to the residual dose of the different activated components, nuclei induced in the dump core, in the shielding and in the cavern structure itself were scored in three different calculations to investigate the contribution of the different areas as well as to limit the size of the created files. To have an idea about the statistical uncertainty and check that all regions are properly sampled, the density maps of the number of inelastic interaction above 50 MeV (stars) are plotted in Figure 17. The star density maps are normalized to one incoming protons impinging on the graphite block. It appears clearly in Figure 17 that radioactive nuclei are produced mainly in the shielding or in the graphite core itself.

In order to verify the consistency between the two methods, the contribution to the dose rate of the three subregions used in the two-step method were added and the profile along the beam dump (See Figure 5) is compared to the one obtained with the one-step method for different cooling times in Figure 16. Both methods lead to identical dose rate profiles for the three cooling times. The results obtained using the two step procedure show higher statistical fluctuations due to the fact that less particles were transported.

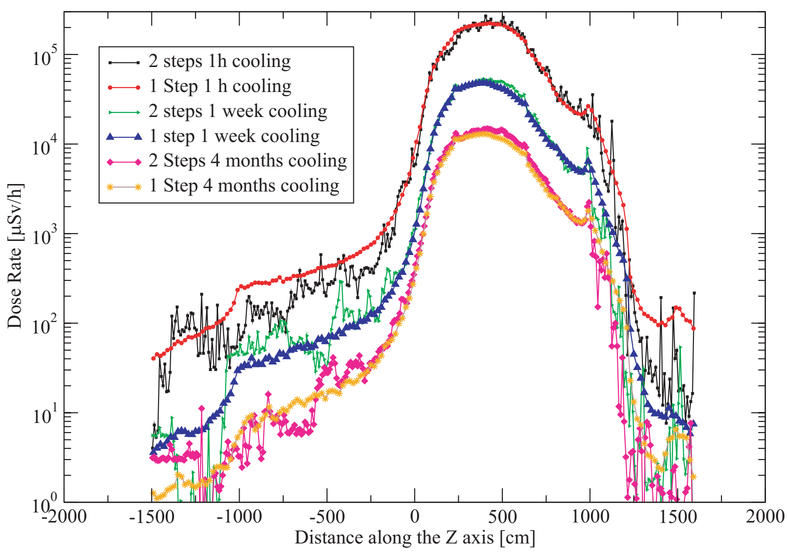


Figure 16: Comparison of the one-step and two-step methods to calculate the residual dose rate with FLUKA for cooling times of one hour, 1 week and 4 months.

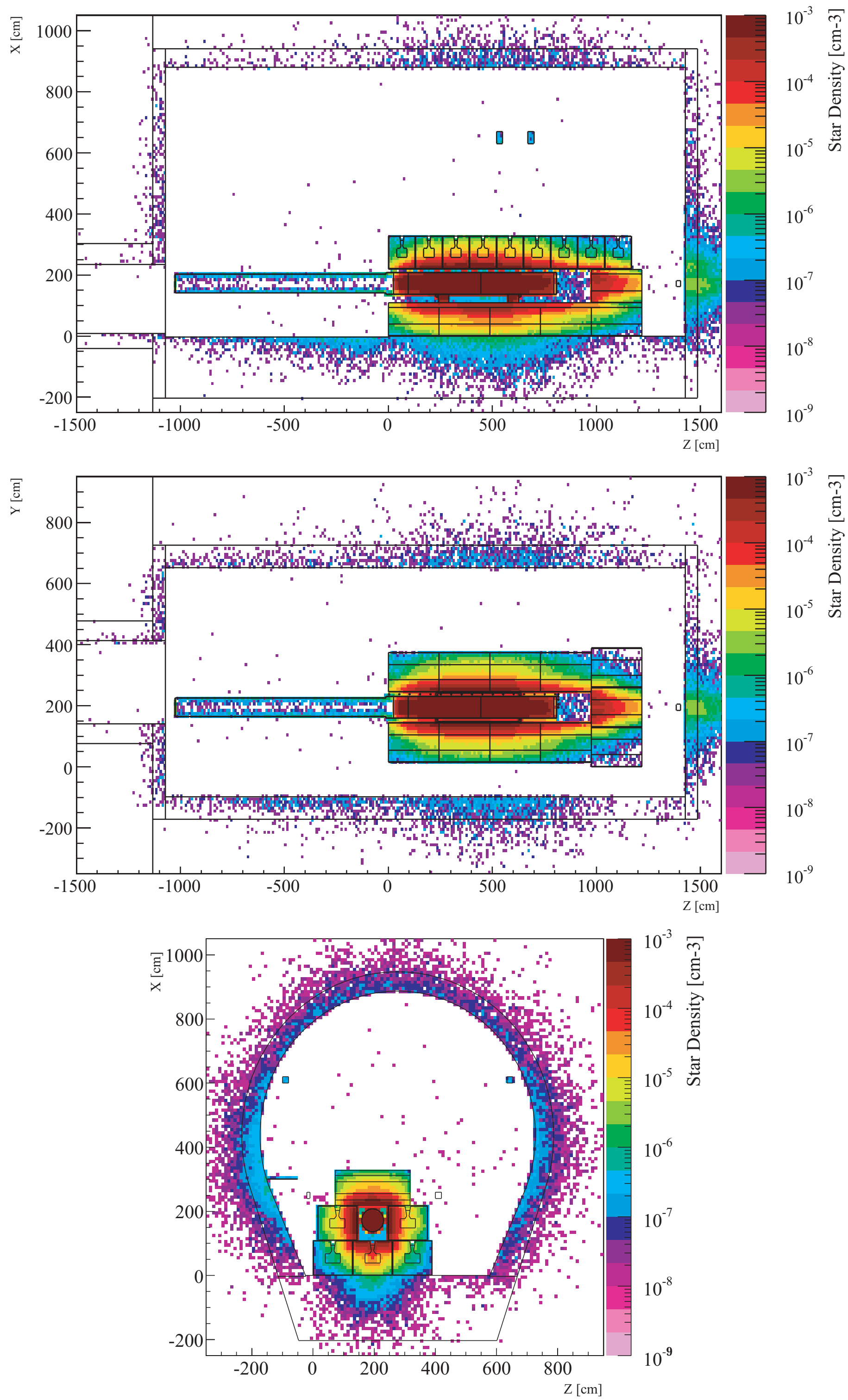


Figure 17: Star density maps for one proton impinging on the dump core. The scale covers the range between 10^{-09} stars.cm^{-3} and 10^{-03} stars.cm^{-3}.

6 Results of the two step method with the shielding in place

6.1 Remanent dose rate maps

As it was already mentioned, for the two-step method, radiations from the radioactive decay emitted in the dump core, in the shielding or in the cavern structure were treated separately. The contribution of those three areas for 1 hour, 7 days and 4 months of cooling time and one year of operation of the accelerator are represented in Figures 18, 19 and 20 for the dump core, the shielding blocks and the cavern walls and floor respectively. The activated dump contributes mainly to the dose rate in the front part of the dump cavern when the shielding is not open and the radiation cannot exit the shielding blocks. The activated shielded blocks contribute to the dose rate in the entire cavern as it is shown in Figure 19, the contribution in the front part of the cavern is as important as the one of the core assembly. The contribution from the cavern structure which includes the simplified representation of the crane is presented in Figure 20 for one hour, one week and four months cooling time. It has to be noted that for this figure the scale differs by a factor of ten from the one which was used for the Figures 18 and 19. The contribution of the cavern structure to residual dose rate is rather homogeneous and low compared to the contribution of the core assembly or the one of the shielding blocks.

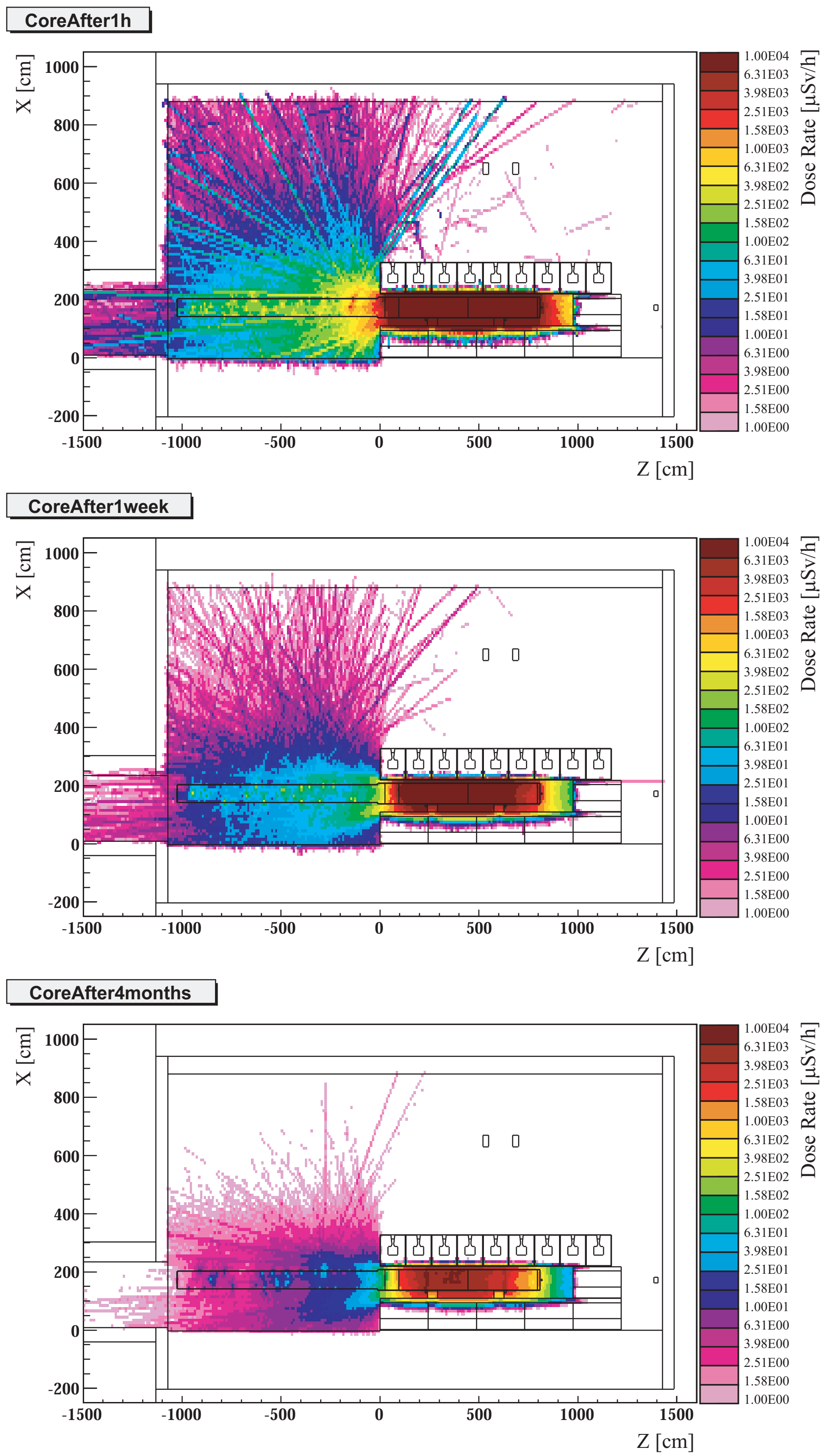


Figure 18: Dose rate inside the dump cavern due to the activated dump core after one hour (top), one week (middle) and four months (bottom) of cooling time. The dose rate is averaged over a vertical 20 cm thick slab perpendicular to the Y axis and which is centered on the dump assembly. The scale covers the range between 1 μSv / h and 10 mSv / h.

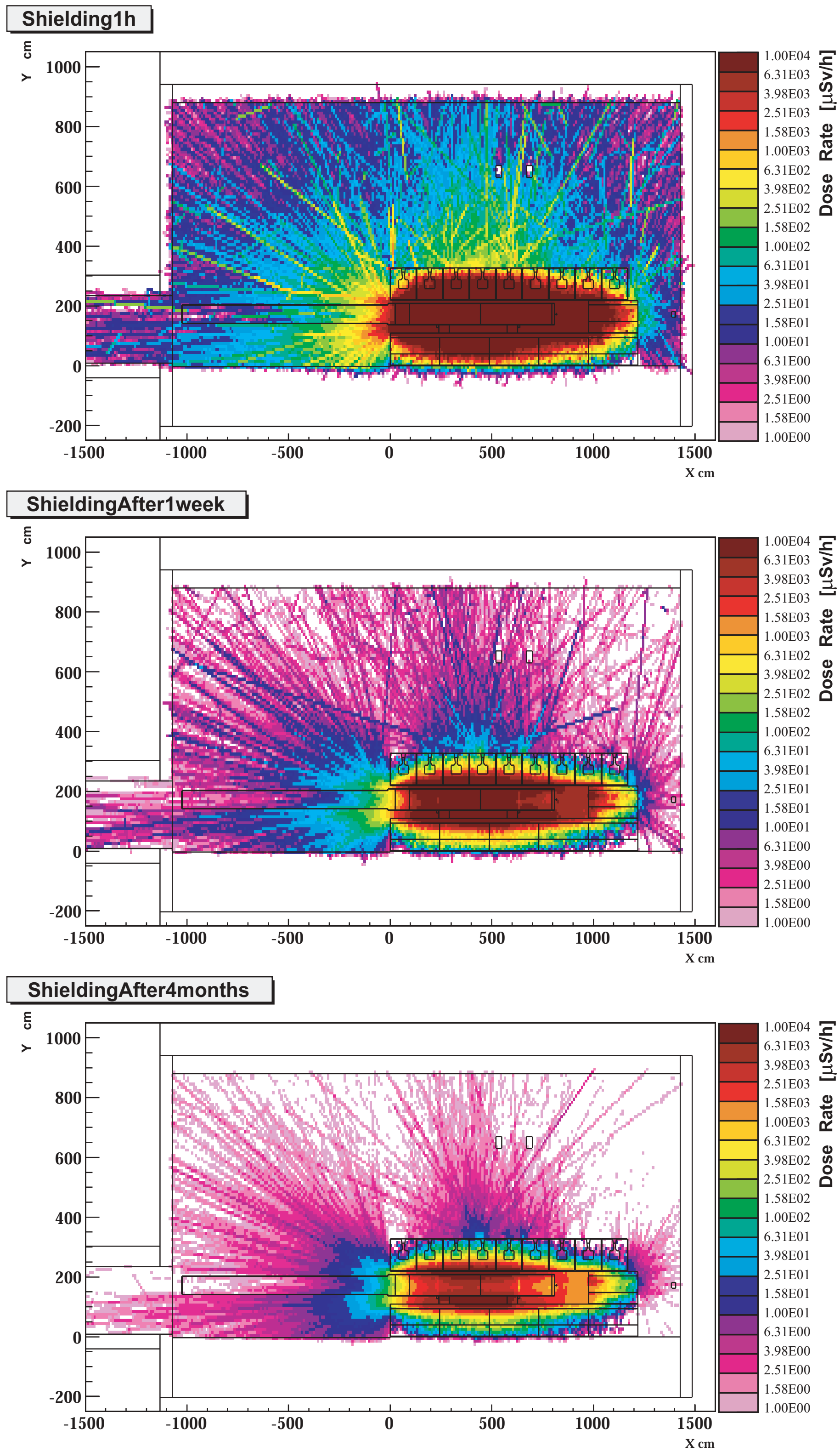


Figure 19: Dose rate inside the dump cavern due to the activated shielding blocks after one hour (top), one week (middle) and four months (bottom) of cooling time. The dose rate is averaged over a vertical 20 cm thick slab perpendicular to the Y axis and which is centered on the dump assembly. The scale covers only the range between 1 μSv / h and 10 mSv / h.

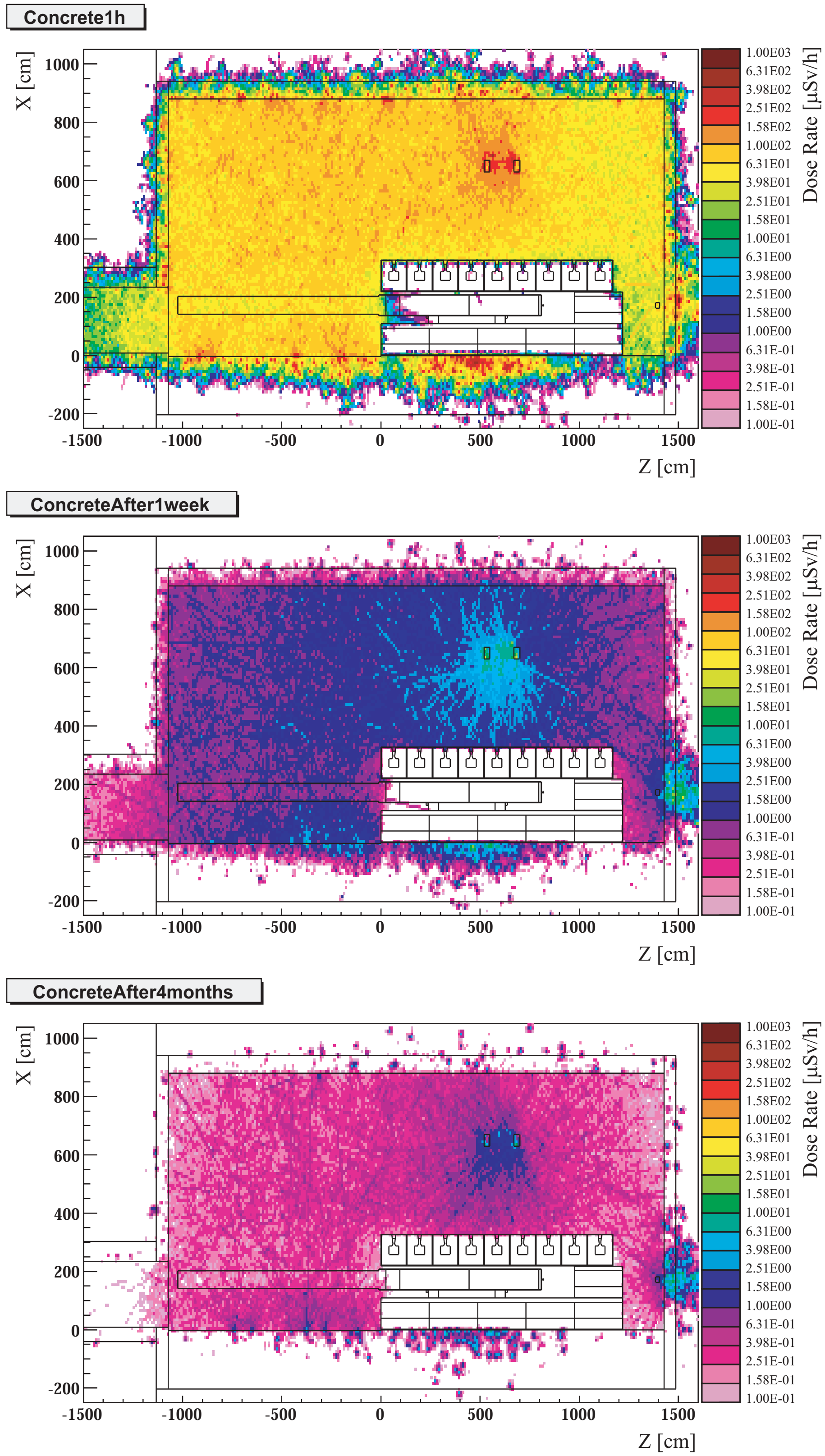


Figure 20: Dose rate inside the dump cavern due to the activated cavern structure which includes the simplified representation of the crane after one hour (top), one week (middle) and four months (bottom) of cooling time. The dose rate is averaged over a vertical 20 cm thick slab perpendicular to the Y axis and which is centered on the dump assembly. The scale covers only the range between 0.1 μSv/h and 1 mSv/h.

6.2 Dose rate profiles

The contributions of the dump core, the shielding blocks and the cavern structure to the total dose rate is represented in Figures 21, 22 and 23, for one hour, one week and four months of cooling time. The contribution to the dose rate of the cavern structure is totally negligible for cooling time above a few days since the main radioactive nuclei produced in concrete is ^{24}Na.

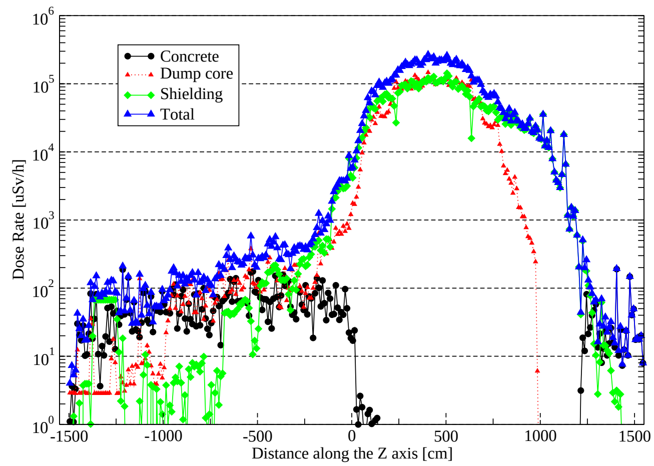


Figure 21: Contribution of the dump core, the shielding blocks and the cavern structure to the dose rate along the beam pipe for one hour cooling time.

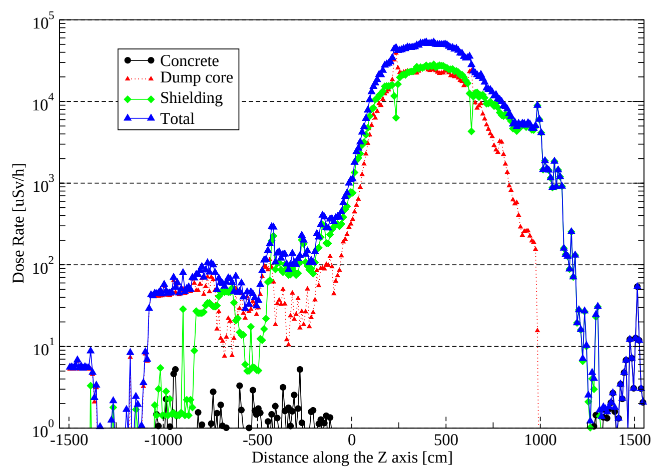


Figure 22: Contribution of the dump core, the shielding blocks and the cavern structure to the dose rate along the beam pipe after one week cooling time.

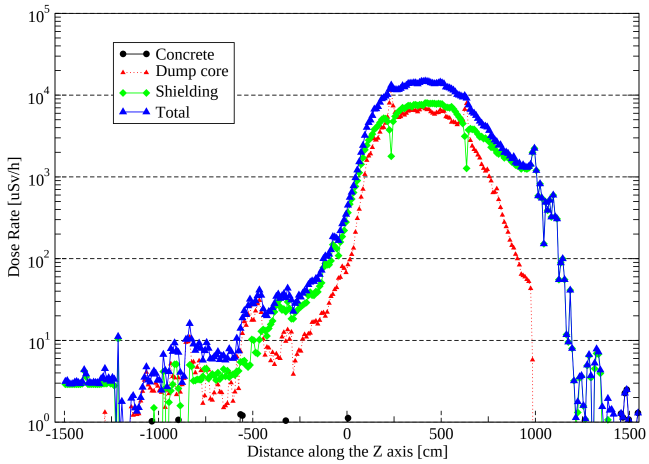


Figure 23: Contribution of the dump core, the shielding blocks and the cavern structure to the dose rate along the beam pipe after four months of cooling time.

7 Configuration with some shielding blocks removed

To fully assess the residual dose rate expected in the cavern during a major intervention such as a dump core replacement, calculations were performed with the shielding blocks removed. Three cases were studied :

1. the 9 top shielding blocks were removed from the FLUKA model and the graphite core is still in place
2. the top shielding blocks as well as the dump core is removed
3. only the dump core is present in the cavern.

Those three configurations are illustrated in Figure 24.

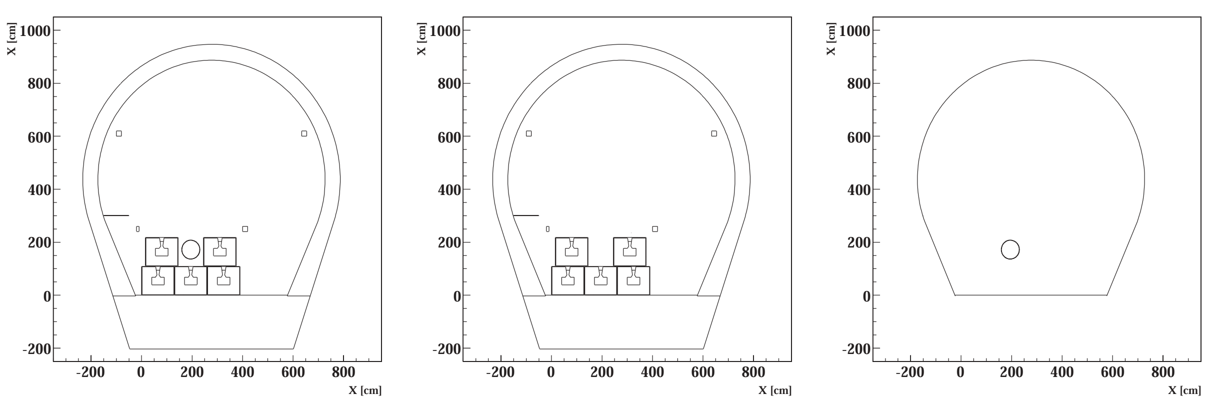


Figure 24: Three configurations with shielding blocks removed which were studied.

For those configurations, the residual dose rate is calculated for 1 week, 1 month, 4 months and 1 year of cooling time and one year of operation of the accelerator.

7.1 Configuration with the top shielding blocks removed and the dump core in place

7.1.1 Residual dose rate maps

The contribution of the two bottom rows of shielding blocks was calculated independently from the contribution of the dump core in the opened shielding configuration. The residual dose rate maps induced by the activated shielding blocks are presented in Figures 25, 26 and 27 for sections perpendicular to the X, Y and Z axis respectively and for four cooling times. The residual dose rate maps induced by the activated dump core assembly are presented in Figure 28, 29 and 30 for sections perpendicular to the X, Y and Z axis respectively and for four cooling times. The contribution of the dump core and the shielding blocks were added and the results are presented in Figures 31, 32 and 33.

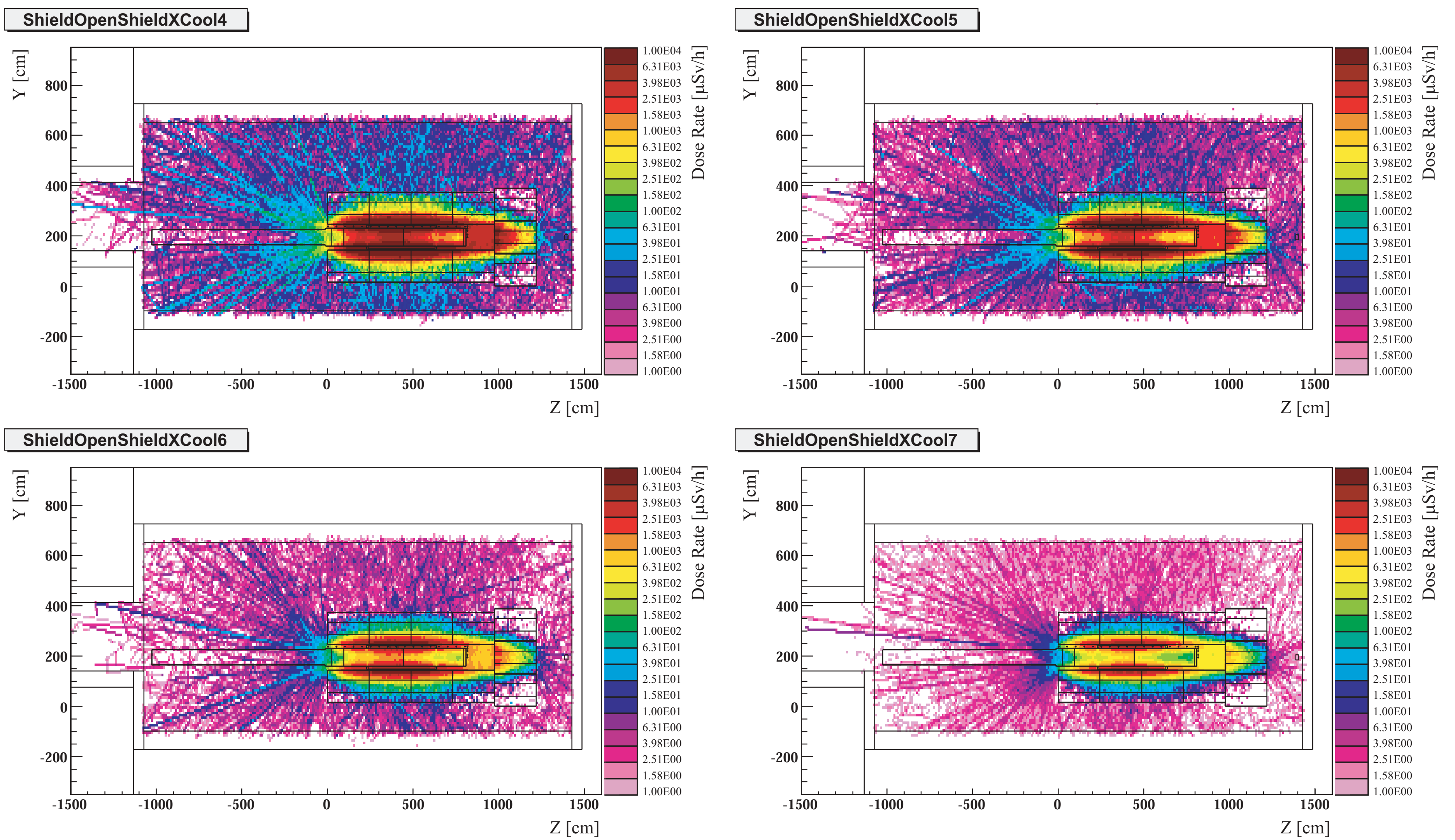


Figure 25: Residual dose rate maps perpendicular to the X axis induced by the activated shielding blocks after 1 week, 1 month, 4 months and 1 year of cooling time for the configuration with the nine top shielding blocks removed and the graphite core still in place.

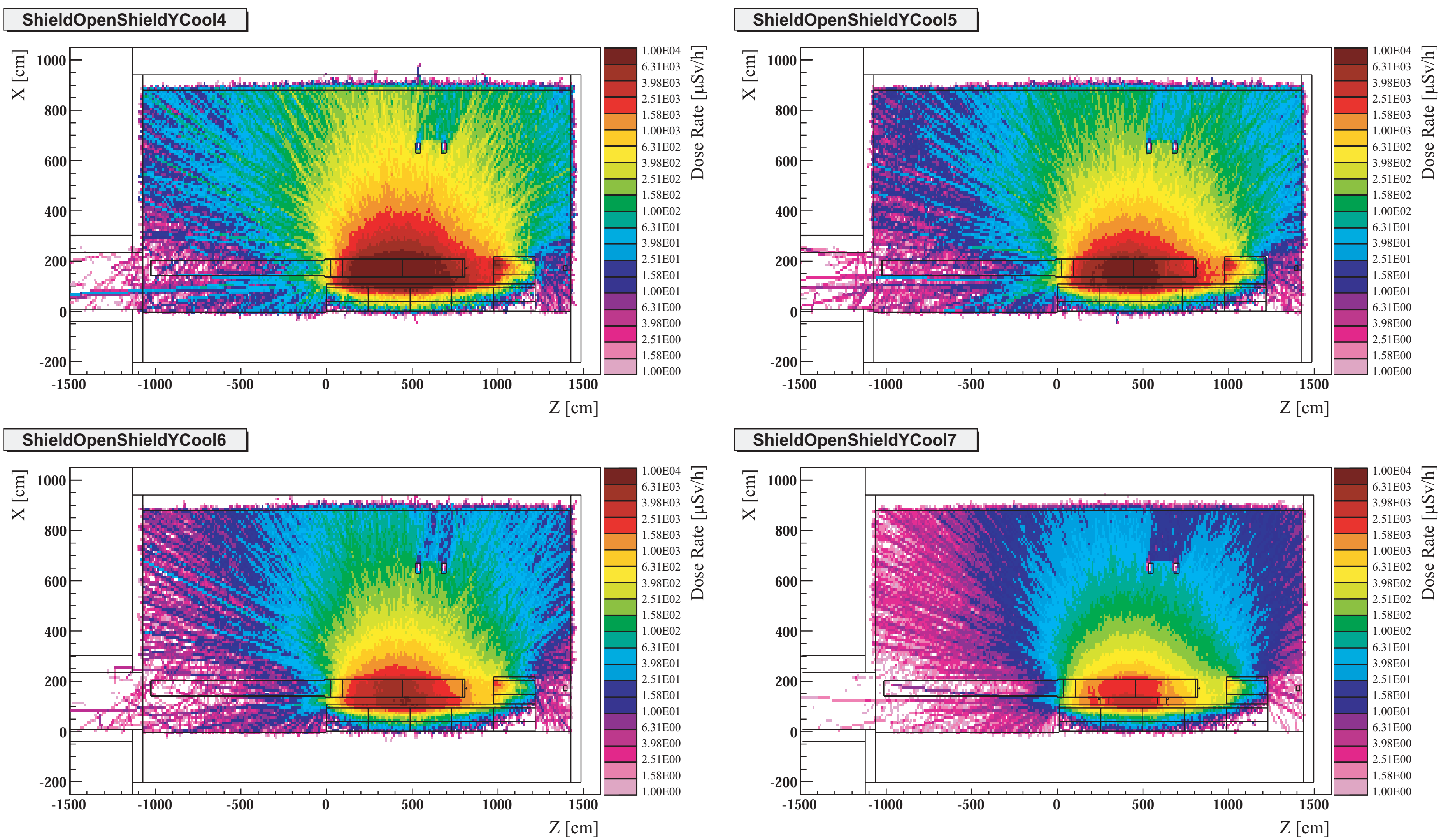


Figure 26: Residual dose rate maps perpendicular to the Y axis induced by the activated shielding blocks after 1 week, 1 month, 4 months and 1 year of cooling time for the configuration with the nine top shielding blocks removed and the graphite core still in place.

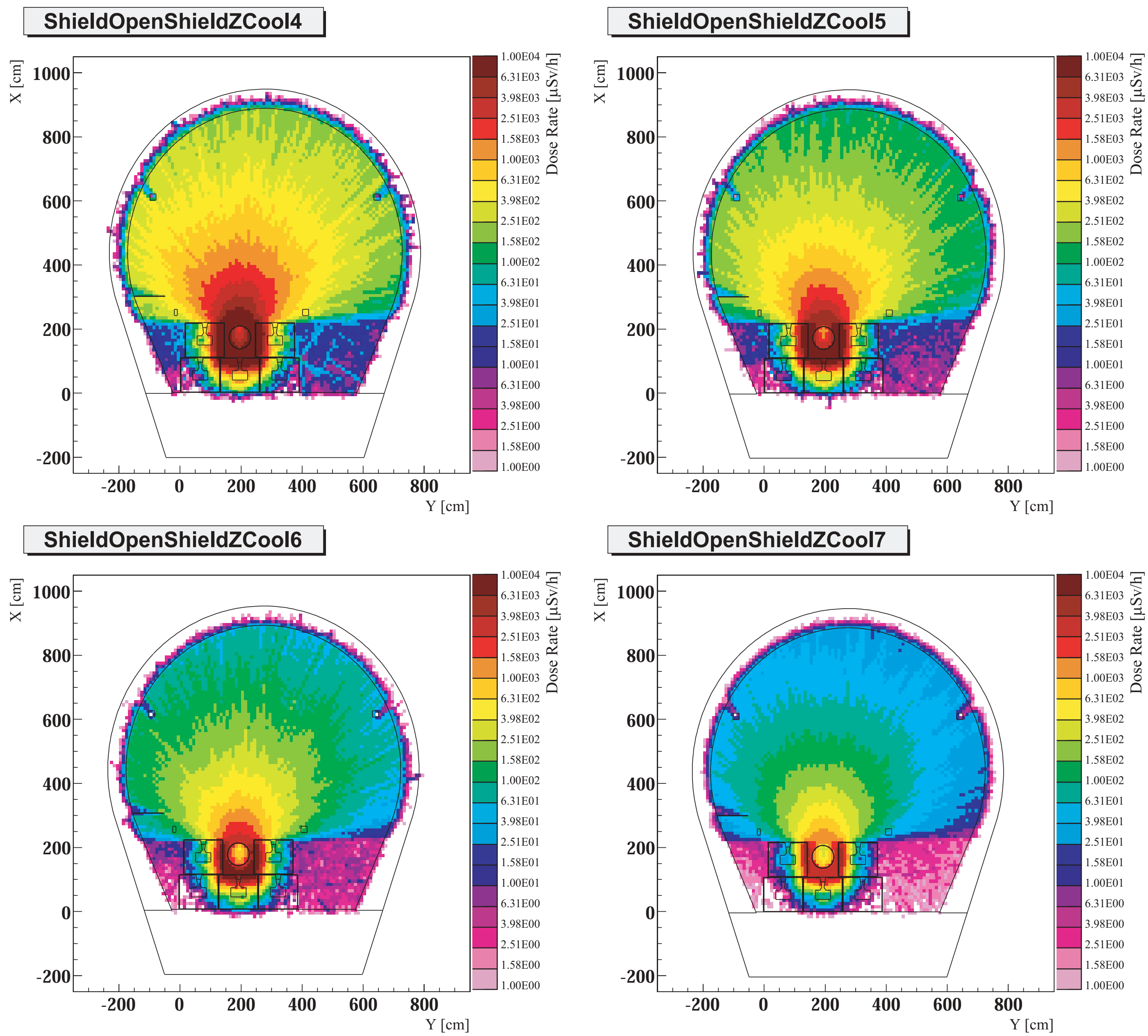


Figure 27: Residual dose rate maps perpendicular to the Z axis induced by the activated shielding blocks after 1 week, 1 month, 4 months and 1 year of cooling time for the configuration with the nine top shielding blocks removed and the graphite core still in place.

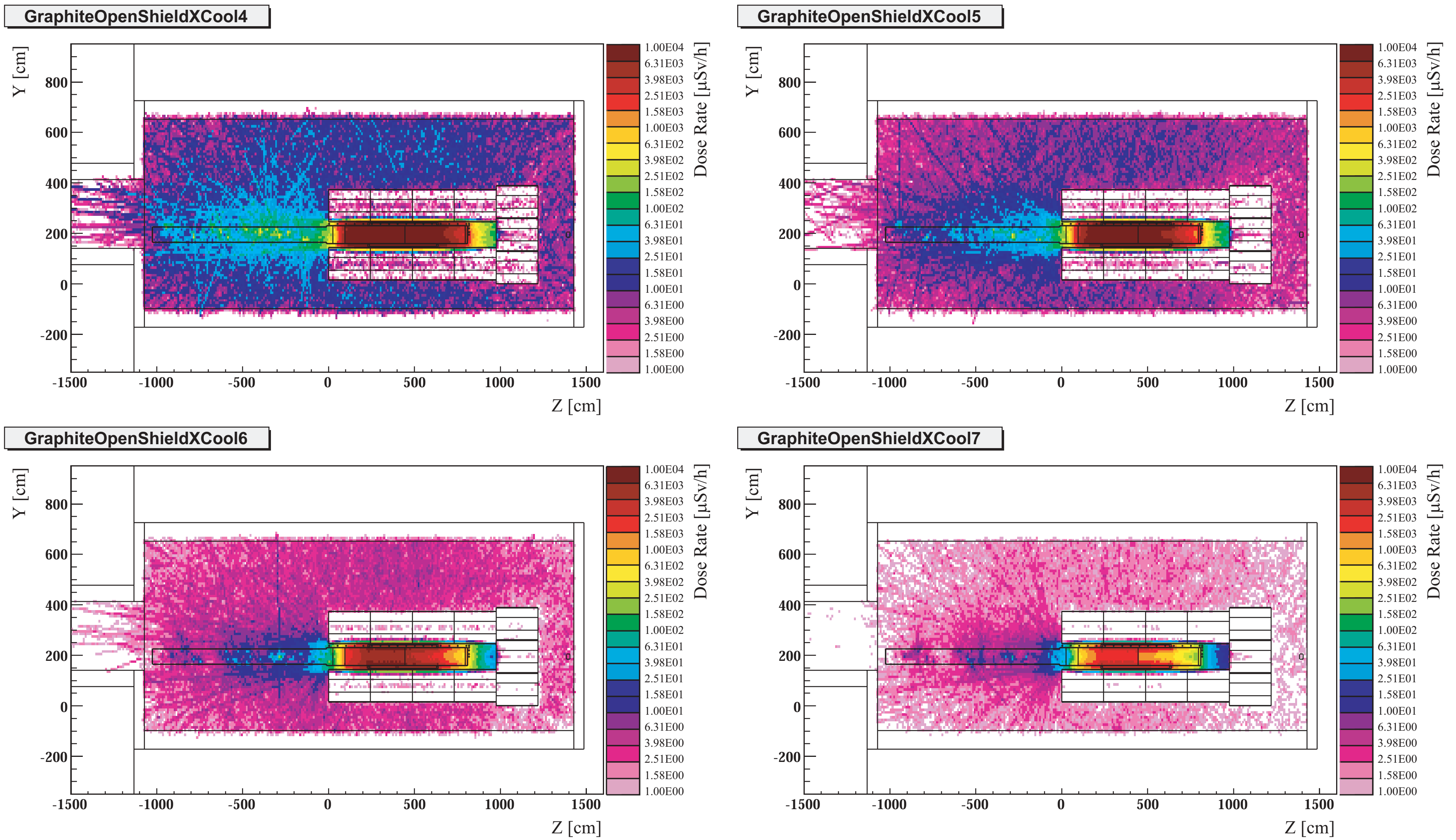


Figure 28: Residual dose rate maps perpendicular to the X axis induced by the activated dump core after 1 week, 1 month, 4 months and 1 year of cooling time for the configuration with the nine top shielding blocks removed and the graphite core still in place.

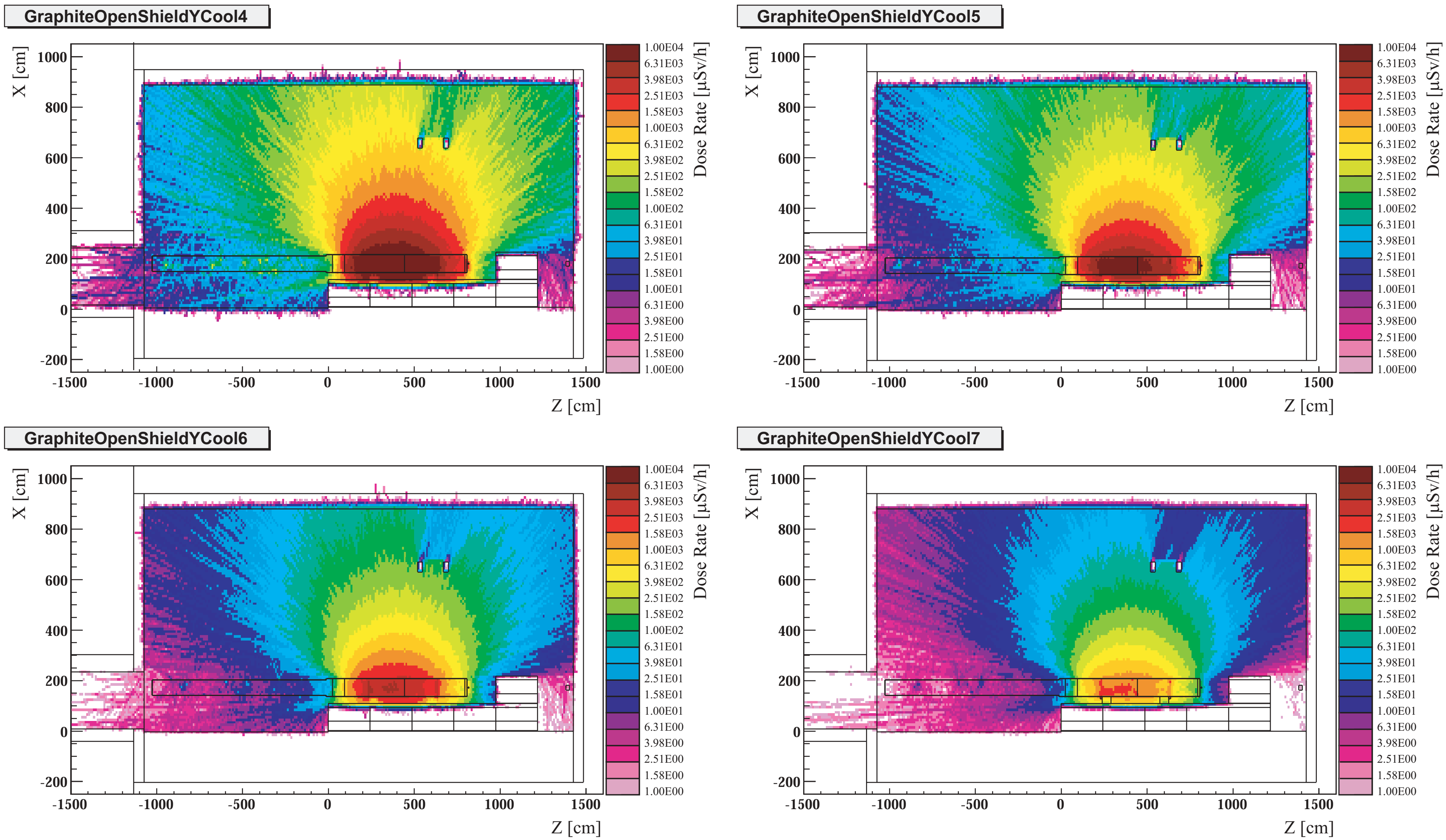


Figure 29: Residual dose rate maps perpendicular to the Y axis induced by the activated dump core after 1 week, 1 month, 4 months and 1 year of cooling time for the configuration with the nine top shielding blocks removed and the graphite core still in place.

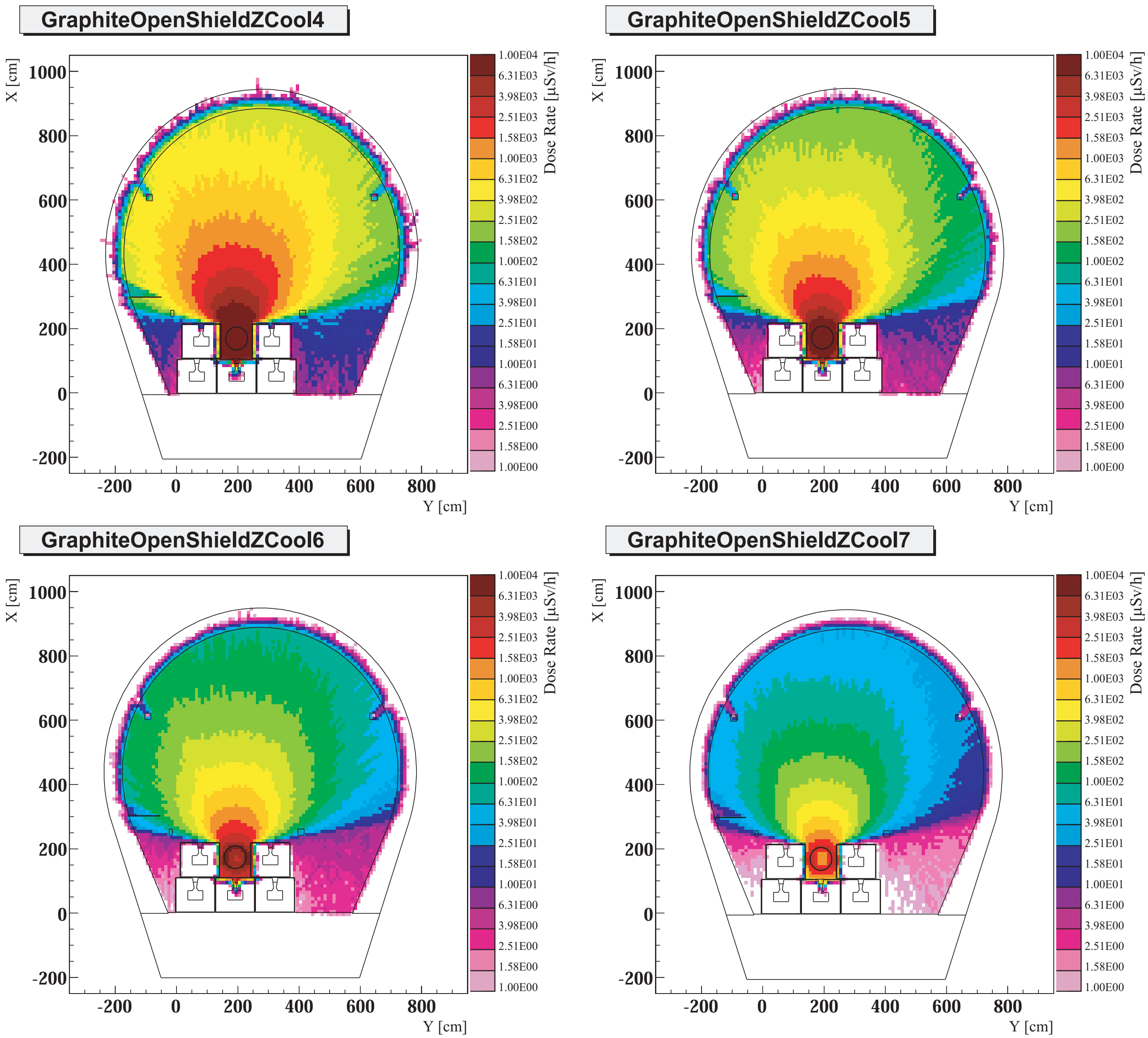


Figure 30: Residual dose rate maps perpendicular to the Z axis induced by the activated dump core after 1 week, 1 month, 4 months and 1 year of cooling time for the configuration with the nine top shielding blocks removed and the graphite core still in place.

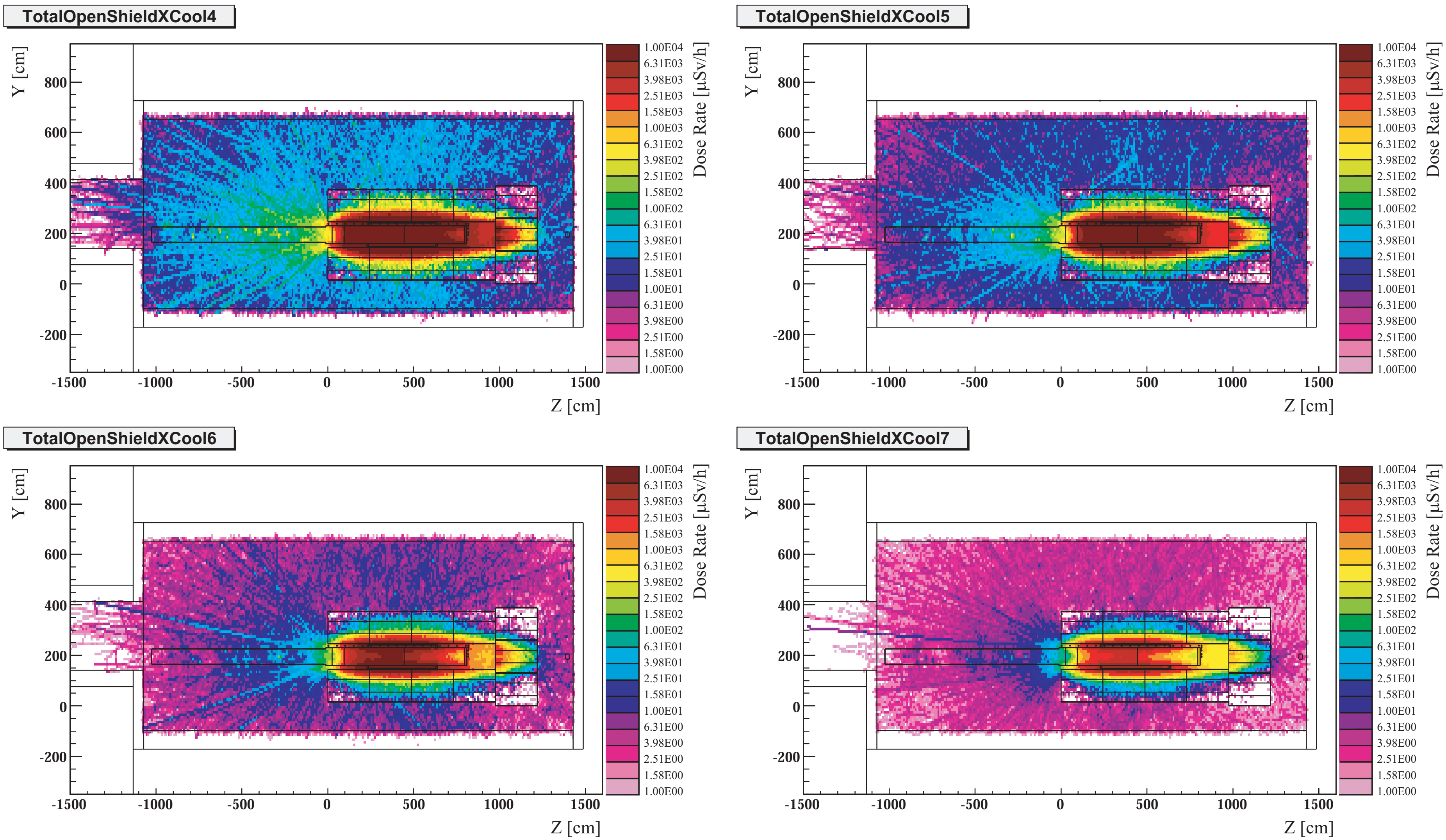


Figure 31: Residual dose rate maps perpendicular to the X axis after 1 week, 1 month, 4 months and 1 year of cooling time for the configuration with the nine top shielding blocks removed and the graphite core still in place.

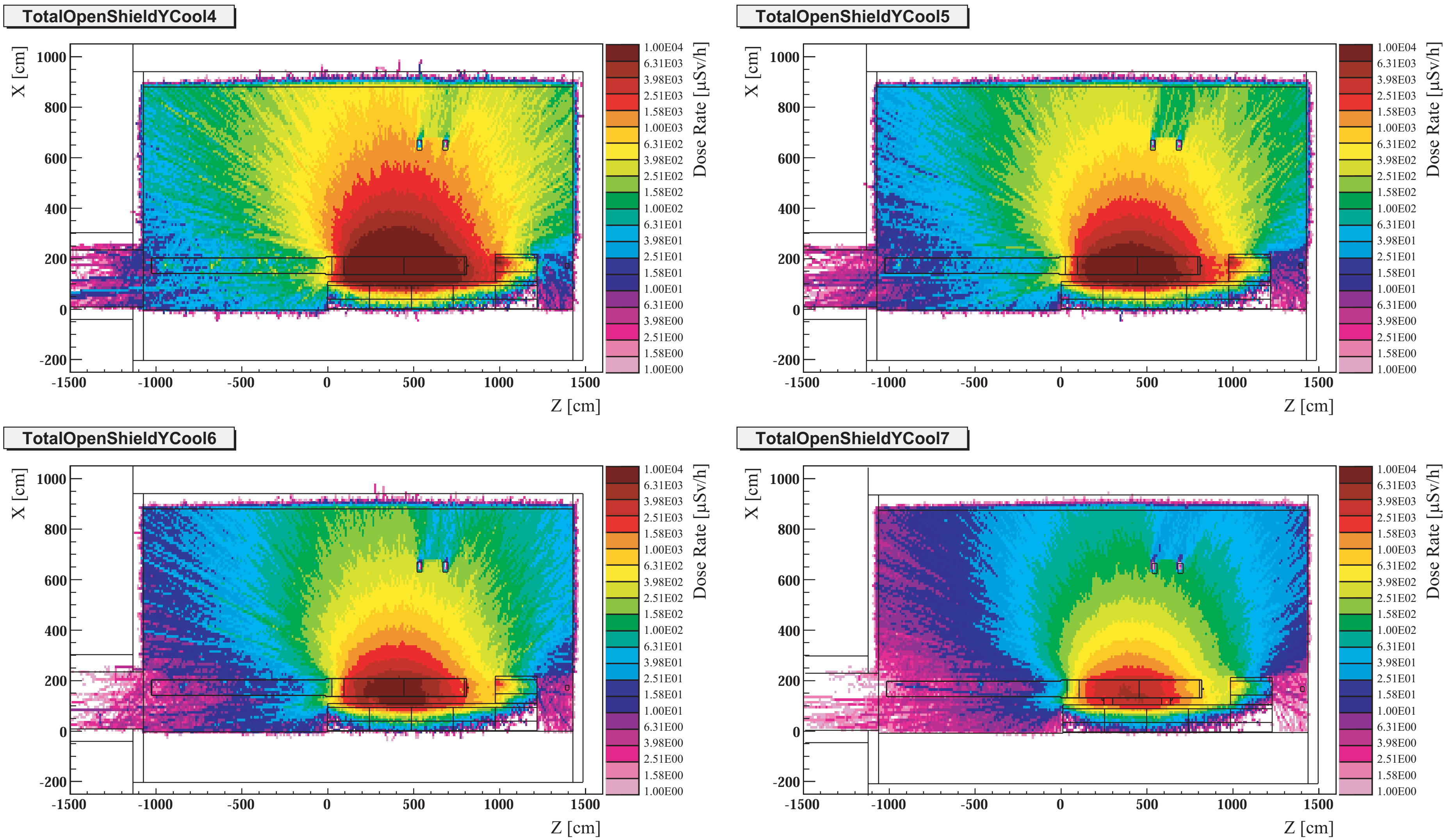


Figure 32: Residual dose rate maps perpendicular to the Y axis after 1 week, 1 month, 4 months and 1 year of cooling time for the configuration with the nine top shielding blocks removed and the graphite core still in place.

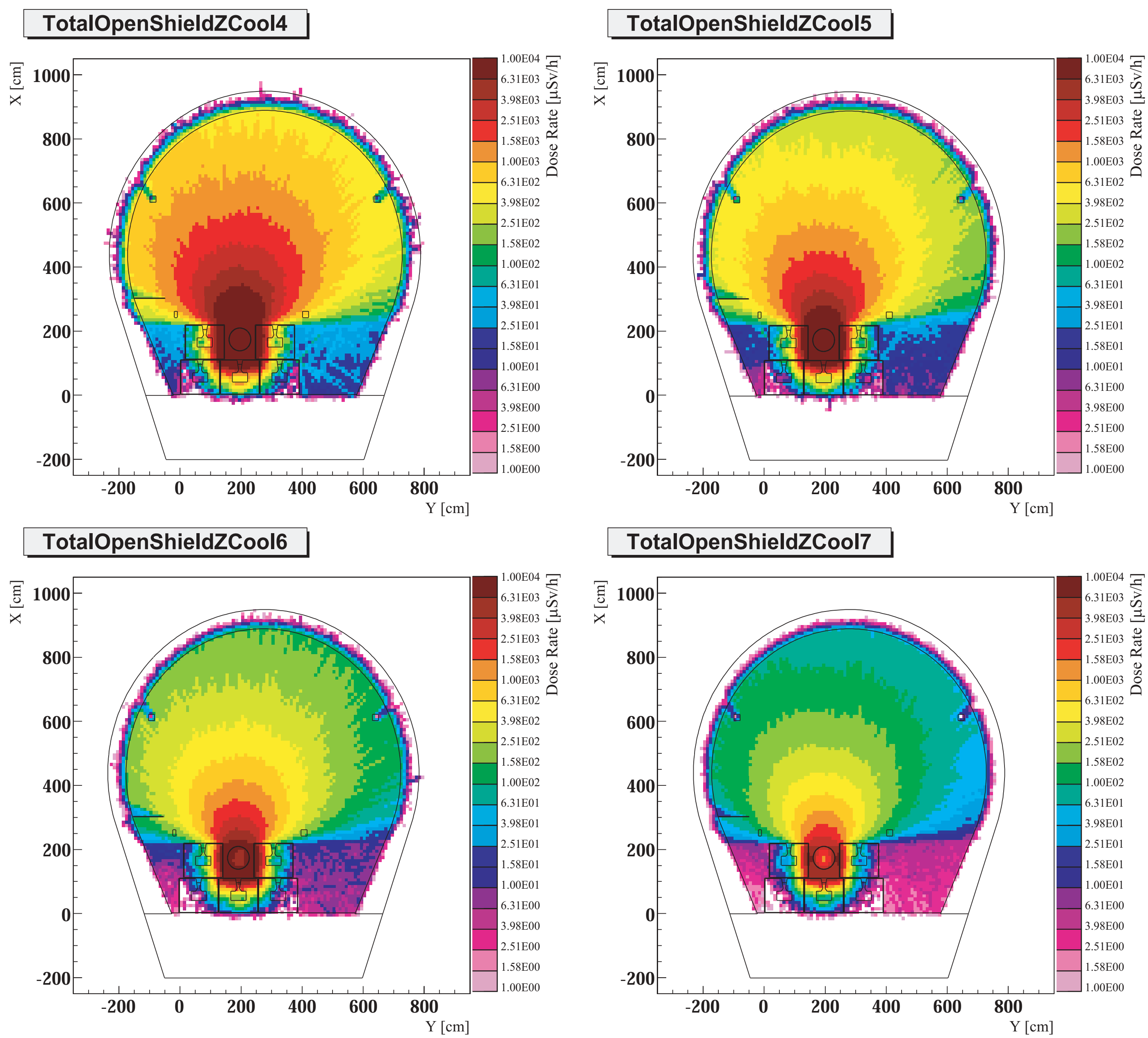


Figure 33: Residual dose rate maps perpendicular to the Z axis after 1 week, 1 month, 4 months and 1 year of cooling time for the configuration with the nine top shielding blocks removed and the graphite core still in place.

7.1.2 Dose rate profile

The dose rate along the catwalk is calculated when the nine top shielding blocks are removed (see Figure 34 on the left). In this case there is no shielding remaining between the dump core or the inner shielding and the catwalk, therefore the dose rate is very high even for significant cooling time. After 4 months of cooling the dose rate reaches 200 μSv / h on the catwalk when the shielding blocks are removed. The profile along the beam pipe is plotted in Figure 34 (right) .The dose rate is slightly lower in this case than when all shielding blocks are in place. It must be noted that the removed blocks are temporally stored on the side of the shielding and therefore the dose rate might be important at this particular location which was not consider in the calculation. The space next to the dump will also be used to store damaged dump core, therefore the assessment of the dose rate must also consider the dose rate due to the stored core.

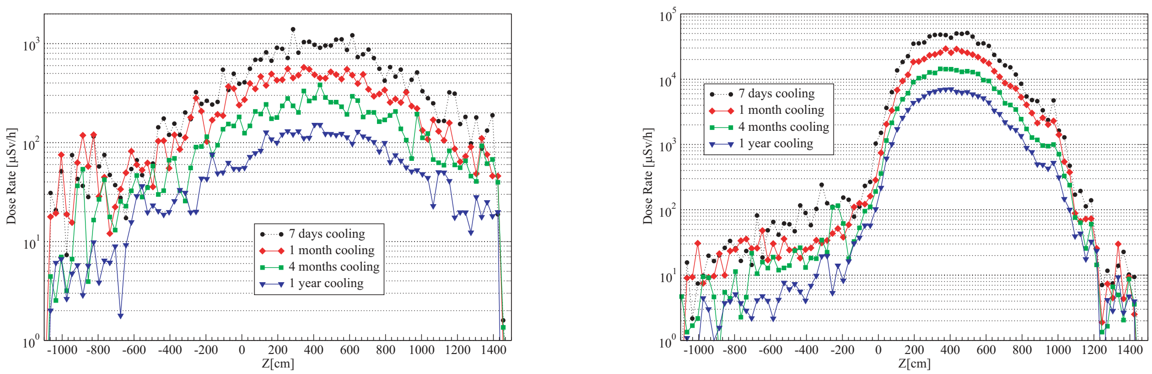


Figure 34: Dose rate profile along the catwalk (left) and close to the beam pipe (right) when the nine top shielding blocks are removed and with the core assembly still in place.

7.2 Configuration with the top shielding blocks removed and no dump core

7.2.1 Residual dose rate maps

The same calculation as in the previous section is performed but in this case only the contribution of the activated shielding blocks is taken into account. The contribution of the cavern structure is again neglected due to its low contribution to the total dose rate. Results are shown in Figures 35, 36 and 37.

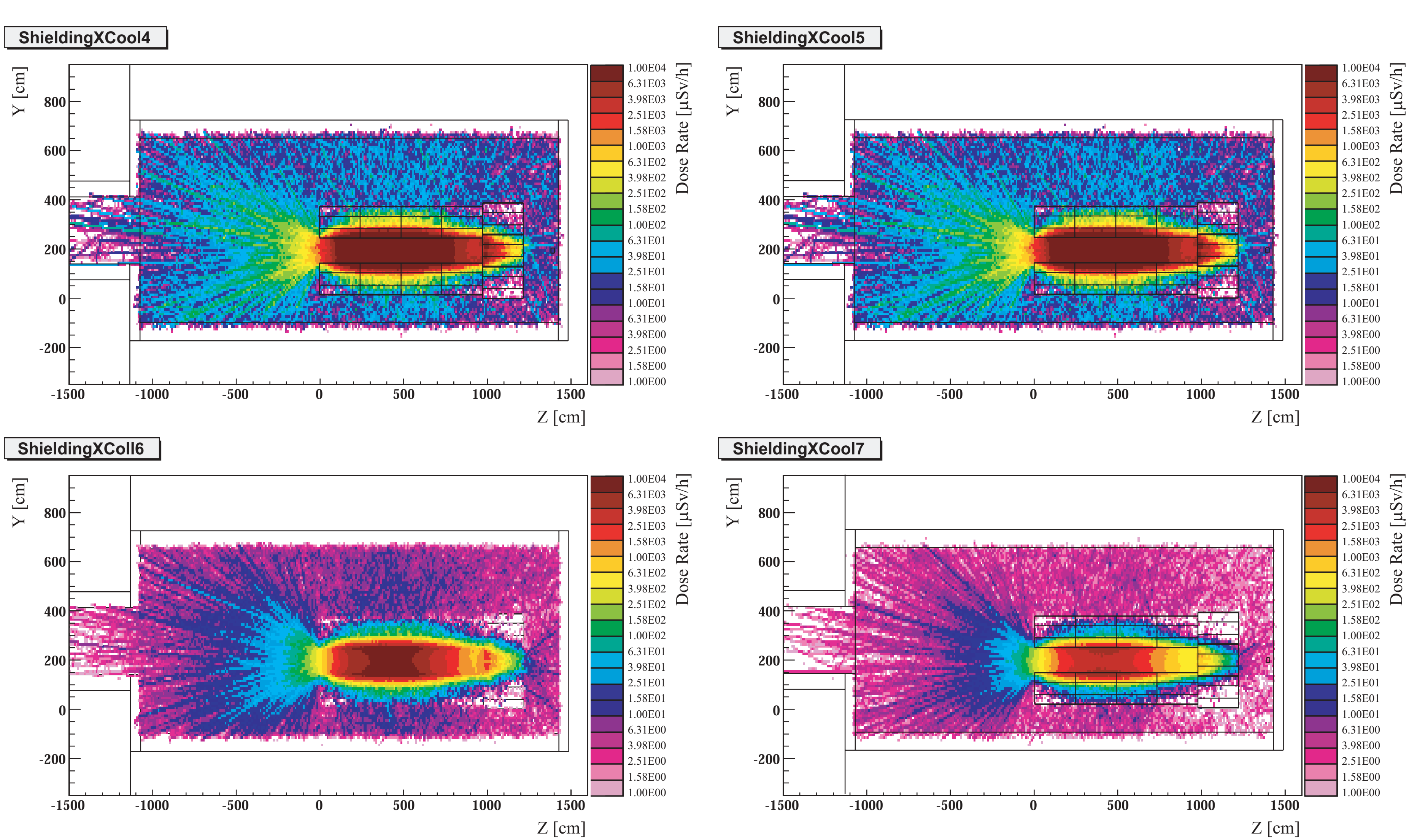


Figure 35: Residual dose rate maps perpendicular to the X axis induced by the activated shielding after 1 week, 1 month, 4 months and 1 year of cooling times for the configuration with the nine top shielding blocks removed and no dump core.

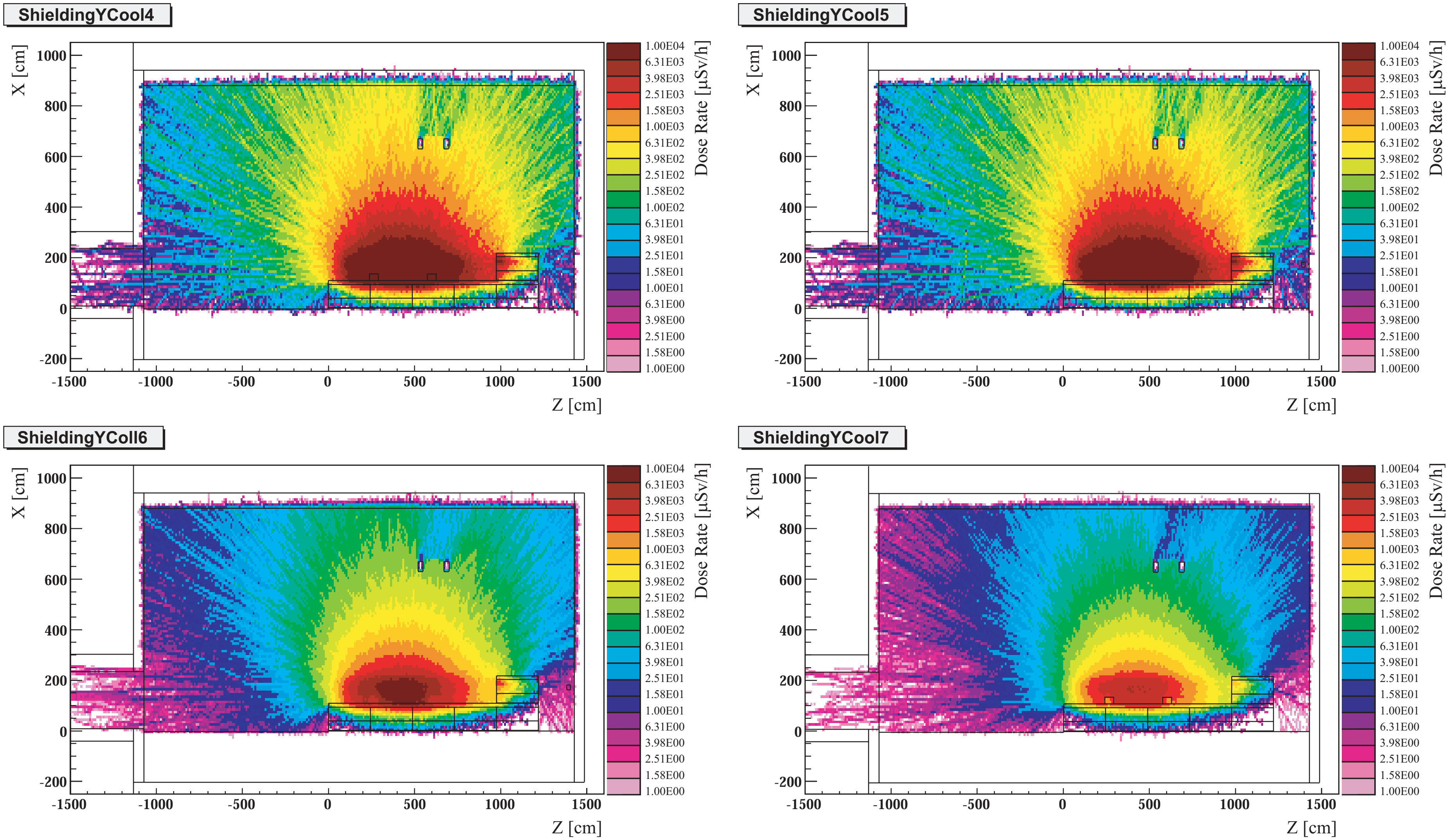


Figure 36: Residual dose rate maps perpendicular to the Y axis induced by the activated shielding after 1 week, 1 month, 4 months and 1 year of cooling times for the configuration with the nine top shielding blocks removed and no dump core.

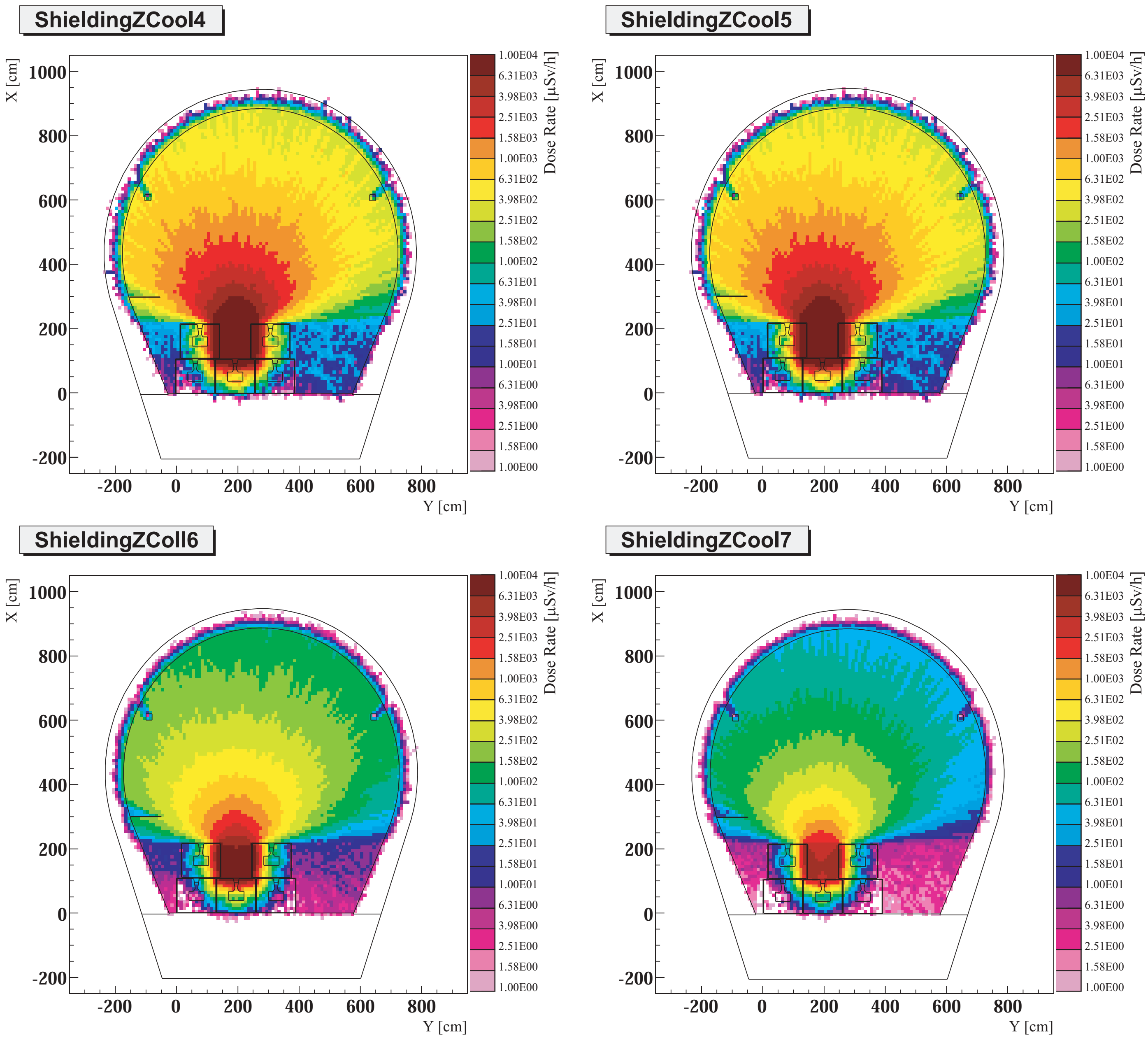


Figure 37: Residual dose rate maps perpendicular to the Z axis induced by the activated shielding after 1 week, 1 month, 4 months and 1 year of cooling times for the configuration with the nine top shielding blocks removed and no dump core.

7.2.2 Dose rate profile

The dose rate along the catwalk is calculated when the nine top shielding blocks as well as the dump core are removed. The dose rate along the catwalk is similar to the one when the dump core is in place and the shielding open. The profile along the beam pipe is plotted in Figure 38. The dose rate is slightly lower than when the graphite block is in place.

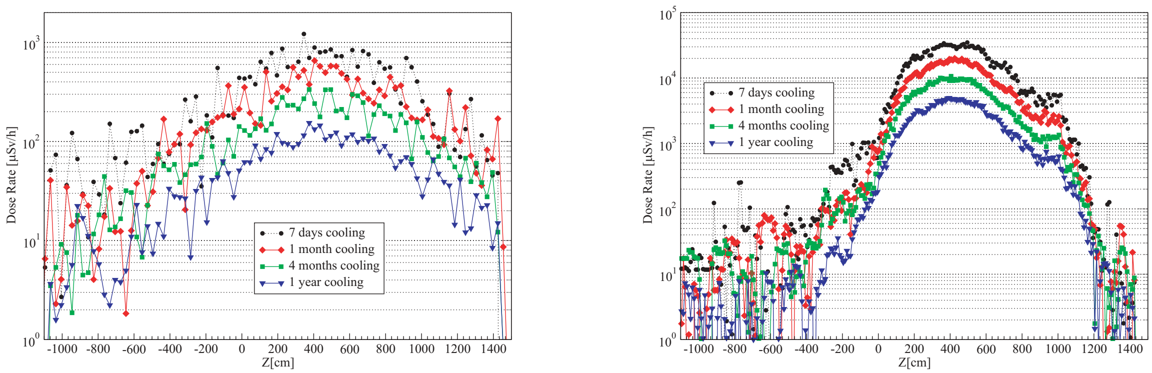


Figure 38: Dose rate profile along the catwalk (left) and along the beam pipe (right) when the nine top shielding blocks as well as the dump core are removed.

8 Dose rate around the dump core

8.1 Residual dose rate maps

All elements around the dump core were removed from the simulation to calculate the dose rate from the core itself. Results are shown in Figure 39 for a slab perpendicular to the X axis.

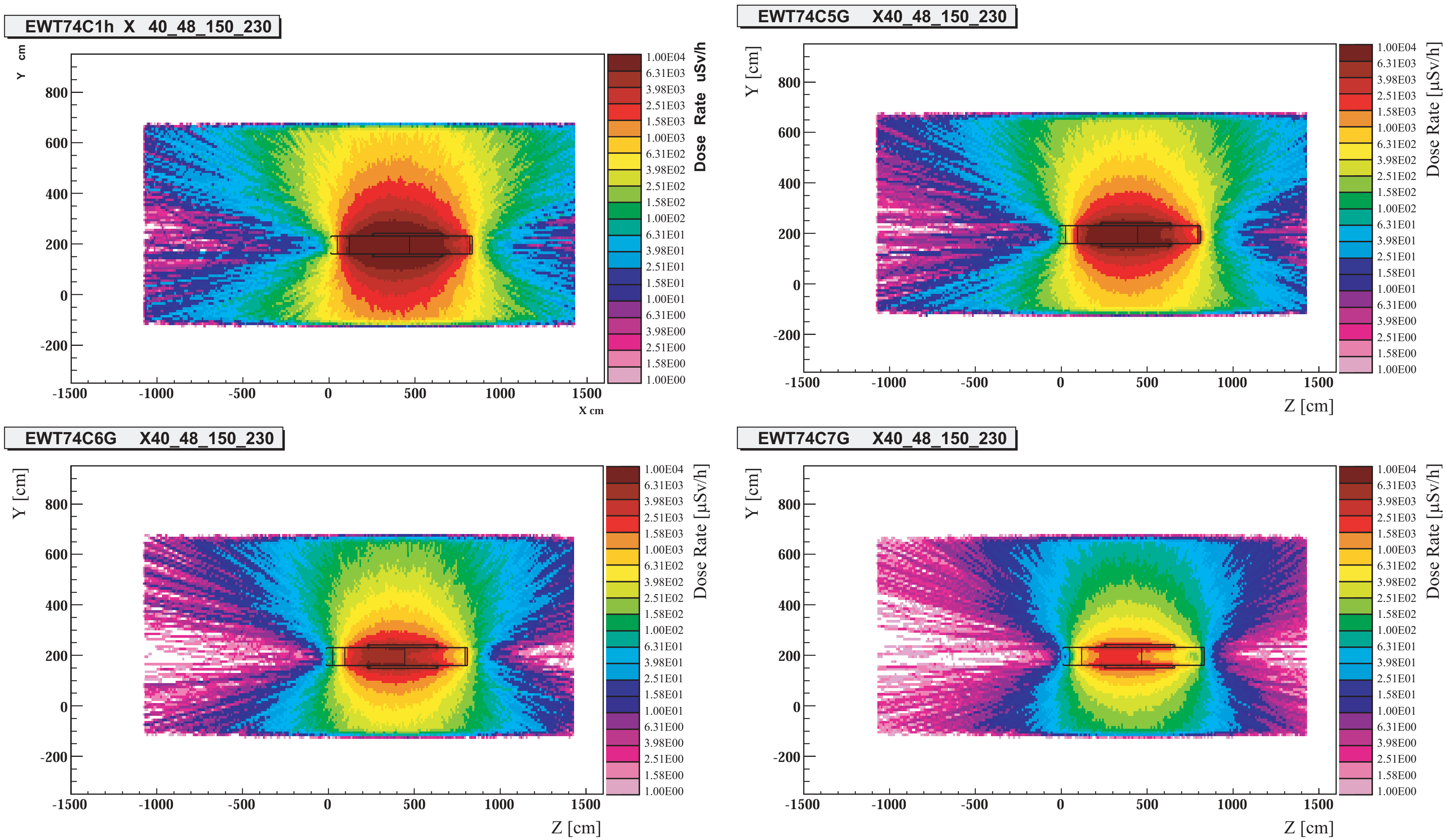


Figure 39: Residual dose rate maps perpendicular to the X axis induced by the activated dump core after 1 week, 1 month, 4 months and 1 year of cooling times.

8.2 Dose rate profile

Several profiles along the Z and Y axes in a plane perpendicular to the X axis (vertical) containing the core midplane (x=172 cm) were calculated for 1 week, one month, four months and one year of cooling time. The different positions for which the dose rate were calculated are illustrated in Figure 40 on horizontal section of the FLUKA geometry centered on the core midplane. Five profiles along the Z axis and 5 along the Y axes were considered as indicated in the figure.

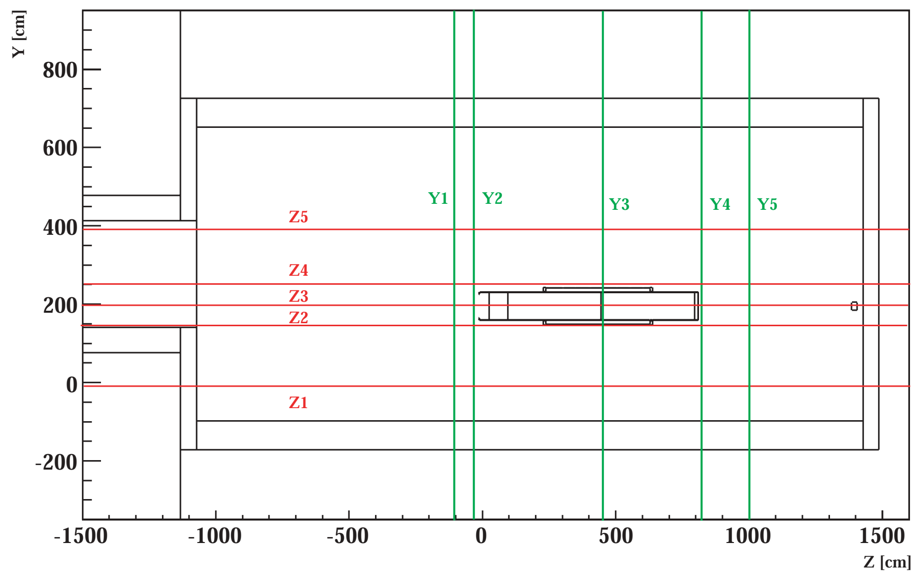


Figure 40: Positions where dose rate profiles are calculated (at a height of 172 cm which corresponds to the core center).

The profiles along the Y axis referred to as Y1 to Y5 in Figure 40 are plotted in Figure 41, 42 and 43 respectively. The profile along the Z axis referred to as Z1 to Z5 are plotted in Figures 44, 45 and 46. The dose rate is maximum on the side of the dump core, four to five meters downstream of the front face where the hadronic shower development is at maximum.

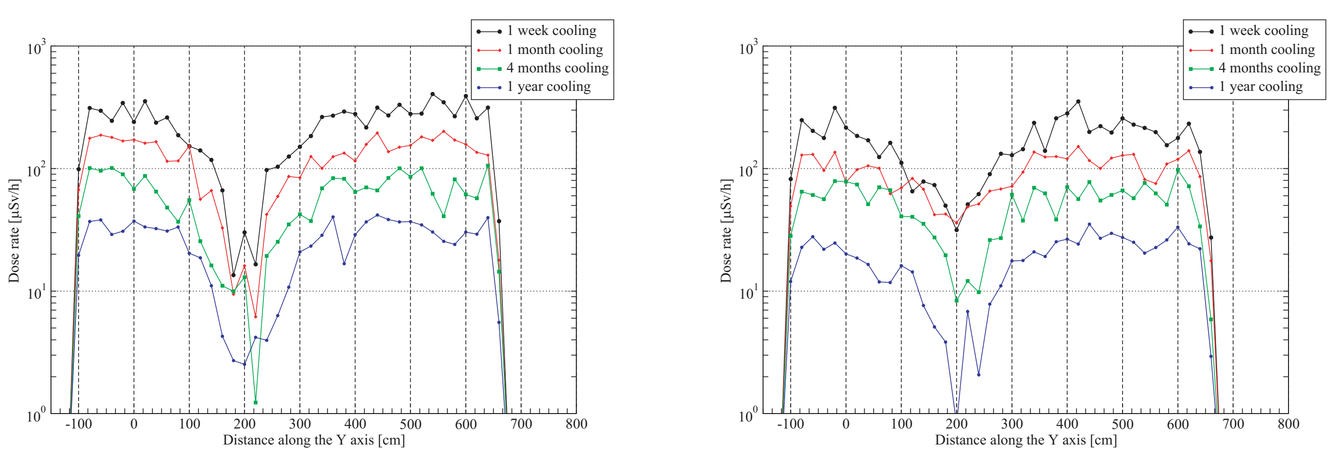
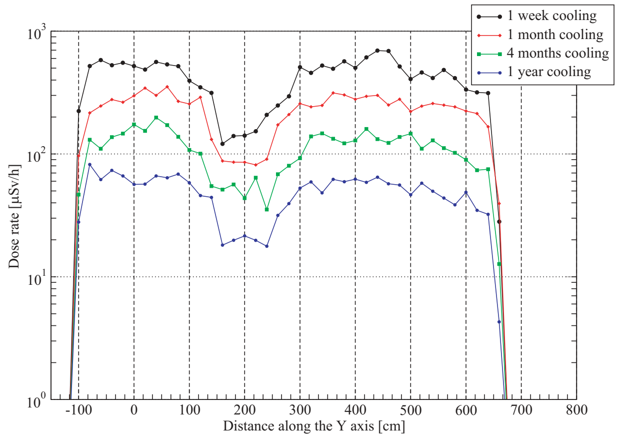


Figure 41: Dose rate along the Y1 (left z= -115 cm) and Y5 (right z=1000 cm) profiles for one week, one month, four months and one year cooling times at a 172 cm height.



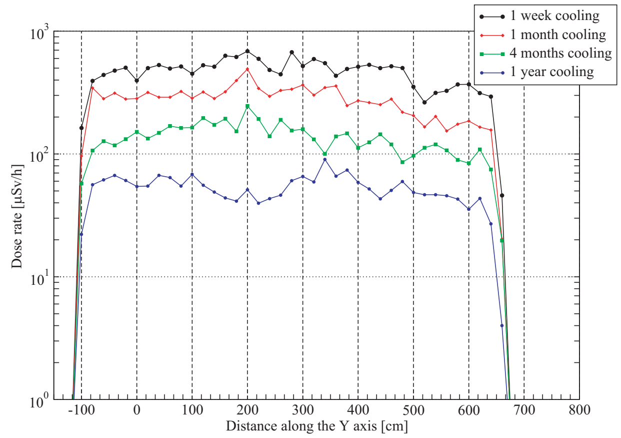


Figure 42: Dose rate along the Y2 (left z= -15 cm) and Y4 (right z=850 cm) profiles for one week, one month, four months and one year cooling times at a 172 cm height.

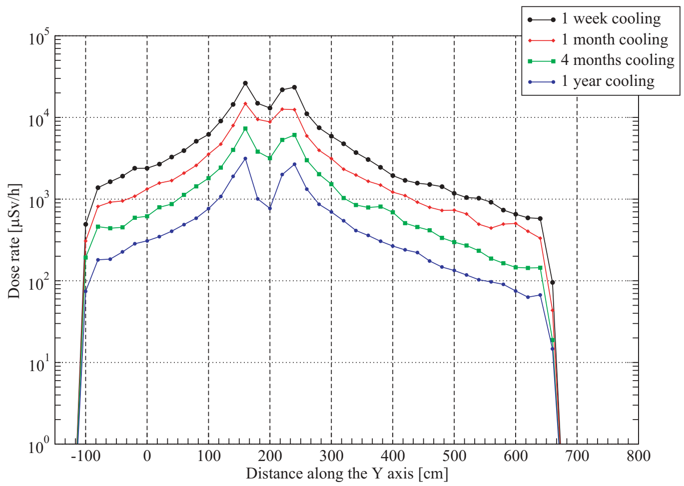


Figure 43: Dose rate along the Y3 (z= 450 cm) profile for one week, one month, four months and one year cooling times at a 172 cm height.

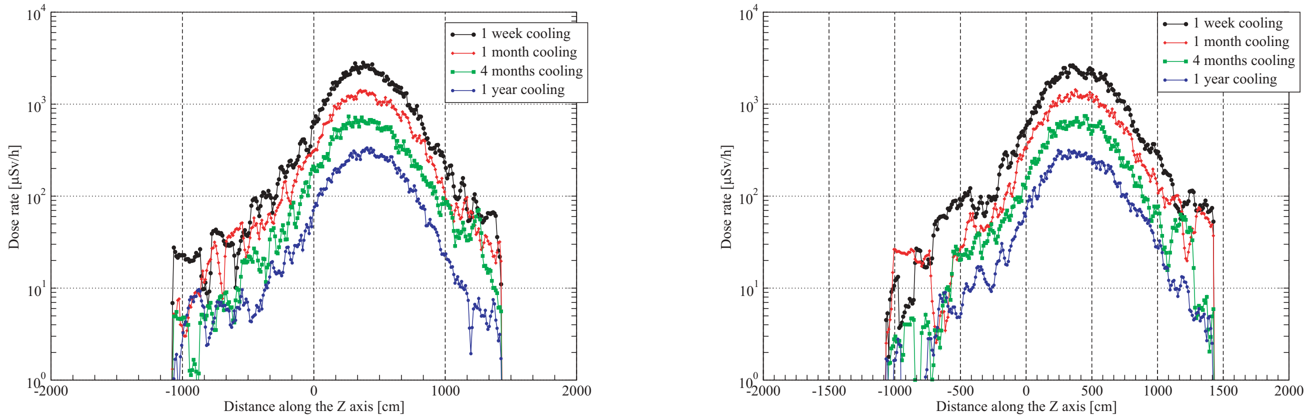


Figure 44: Dose rate along the Z1 (left y= -5 cm) and Z5 (right y=1000 cm) profiles for one week, one month, four months and one year cooling times at a 172 cm height.

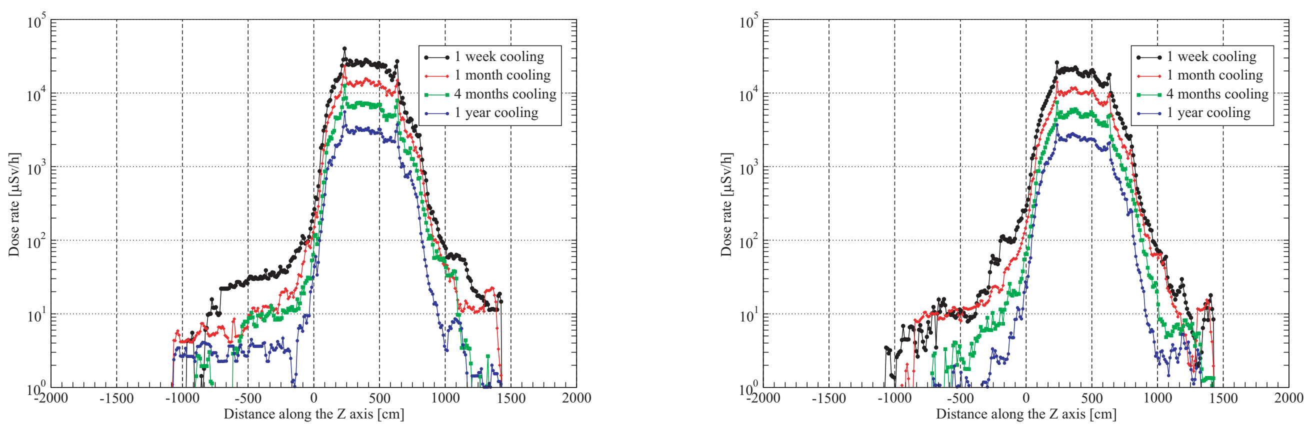


Figure 45: Dose rate along the Y2 (left y= 150 cm) and Y4 (right y=240 cm) profiles for one week, one month, four months and one year cooling times at a 172 cm height.

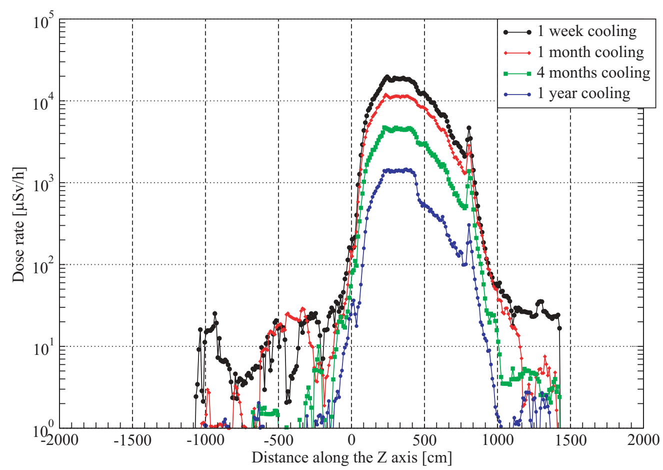


Figure 46: Dose rate along the Y3 (y= 195 cm) profile for one week, one month, four months and one year cooling times at a 172 cm height.

9 Conclusion

An important number of calculations was performed to fully assessed the dose rate in the LHC dump cavern after one year of operation of the accelerator. Several configurations ranging from the residual dose rate map around an unshielded dump core to the dose rate with the dump cavern in its operational configuration were calculated. Several cooling times were investigated since access to the cavern may be necessary for different type of interventions ranging from an inspection shortly after the accelerator shutdown to time consuming repair work after longer cooling times. The different dose rate maps or the dose rate profiles calculated will be very useful for the definition of the work procedures with the appropriate cooling time to be followed before interventions in the UD caverns.

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