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A Radiation Shielding Study for the Meson Test Beam Facility at Fermilab*

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Abstract

In this study the results of Monte Carlo radiation shielding calculations performed for the M03-MT6 area in the Meson Test Beam Facility (MTBF) are described.

1 Introduction

The MTBF was designed in order to test equipment and detectors in a beam of moderate energy particles (5-120 GeV) [1]. It is a versatile beam line available to users participating in various projects. An upgrade to the beam line has been approved in order to provide a test beam for the detector R&D for the International Linear Collider [2]. This upgrade implies, in particular, installation of a new target, collimator, and beam absorber which will be strong sources of secondary radiation. In order to design an appropriate shielding for the area, the radiation shielding calculations were performed with the MARS15 [3] code. It is assumed that the intensity of the initial proton beam is equal to 10^{12} protons per minute at an energy of 120 GeV.

2 Geometry Model

The model developed for this region extends from the target up to 150 m downstream and includes the target itself, collimator, beam absorber, shielding blocks, a number of dipoles and quadrupoles, and the tunnel. A Cartesian right-handed coordinates system is used in the model (see Fig. 1). Thus, the positive direction for the X-axis is upward while for the Z-axis it follows the direction of the beam (if one ignores the bends of the beam line and the target offset relative to the origin of the coordinate system, (0,0,0), that are obsreved in the Figure). The color scheme employed in the first three Figures that describe the geometry

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model is the following: white, violet, green, grey, blue, and red (or brown) colors represent vacuum, aluminum, soil, regular concrete, air, and steel, respectively.

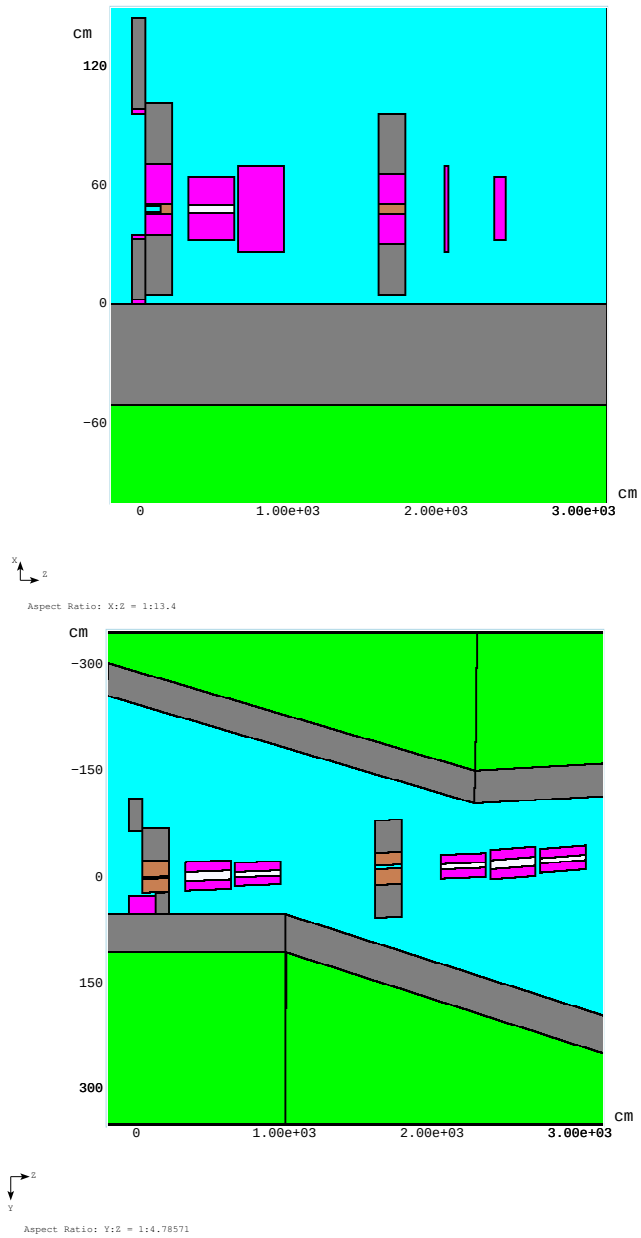

Figure 1: A fragment of the MARS model 'as built' for the tunnel with first elements of the beam line (target, collimator, beam absorber, several dipoles and quadrupoles, and shielding blocks): elevation view at $Y = 0$cm (top) and plan view at $X = 48$cm (bottom).

In order to determine the groundwater activation, the star density was calculated according to the geometry model that features the beam line elements and shielding components 'as built' and for the region where the major beam loss occurs. It is shown below that the region of major beam loss extends from the target up to the beam absorber (see Fig. 1).

The target—an aluminum cylinder 30 cm in length and with a cross section of 0.635cm $\times$ 0.635cm—is surrounded by concrete and steel shielding blocks (see Fig. 2) and is followed by a 180-cm collimator with a rectangular aperture 2.54cm $\times$ 2.54cm. The center of the upstream end of the target is at the point (X,Y,Z)=(48.3cm,-0.44cm,-2.54cm). The upstream end of the 180-cm beam absorber is placed at $Z = 18$m (see Fig. 1). The absorber has a rectangular aperture 5.08cm $\times$ 2.54cm inside its steel core 45.7cm $\times$ 35.6cm which, in turn, is surrounded by concrete blocks.

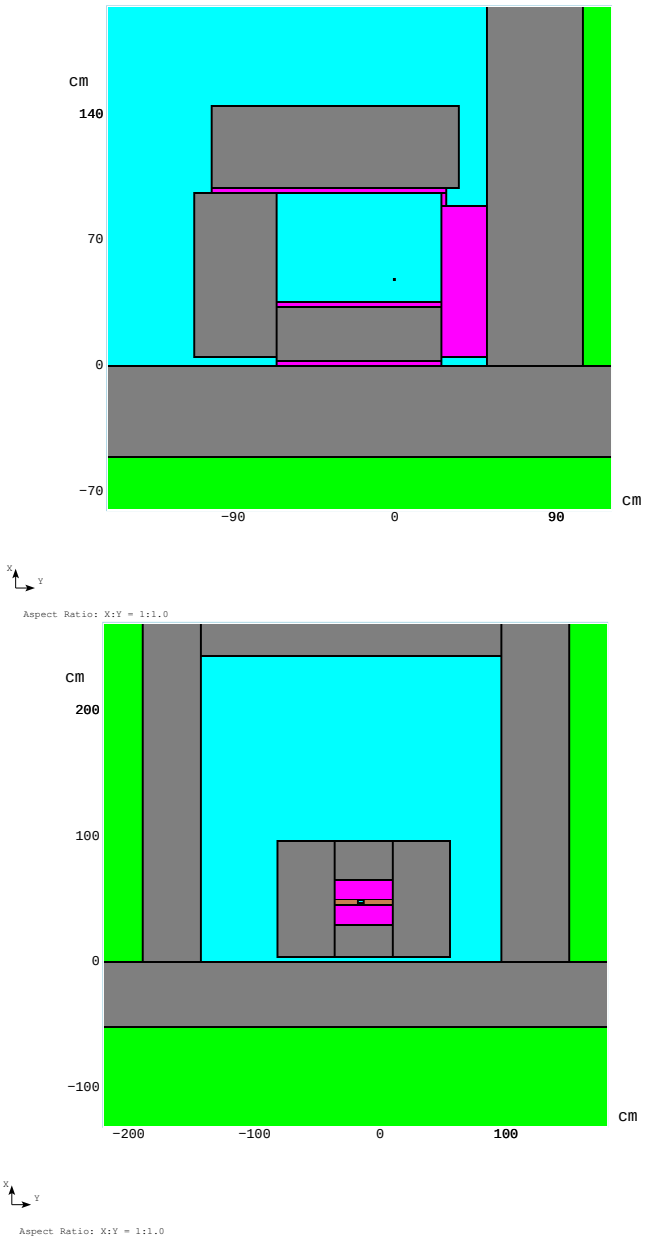

Figure 2: A cross section of the shielding blocks surrounding the target (top) and cross section of the tunnel with the beam absorber downstream of the target and collimator (bottom).

In order to predict the prompt dose rate in the control room at the users area, one has to take into account the realistic multiple bends of the tunnel and beam line which help to provide shielding against muons as the most penetrating radiation in the test area (see Fig. 3). The entrance to the users area is approximately at the point (Y,Z) = (2m,170m) and is not shown on the Figure.

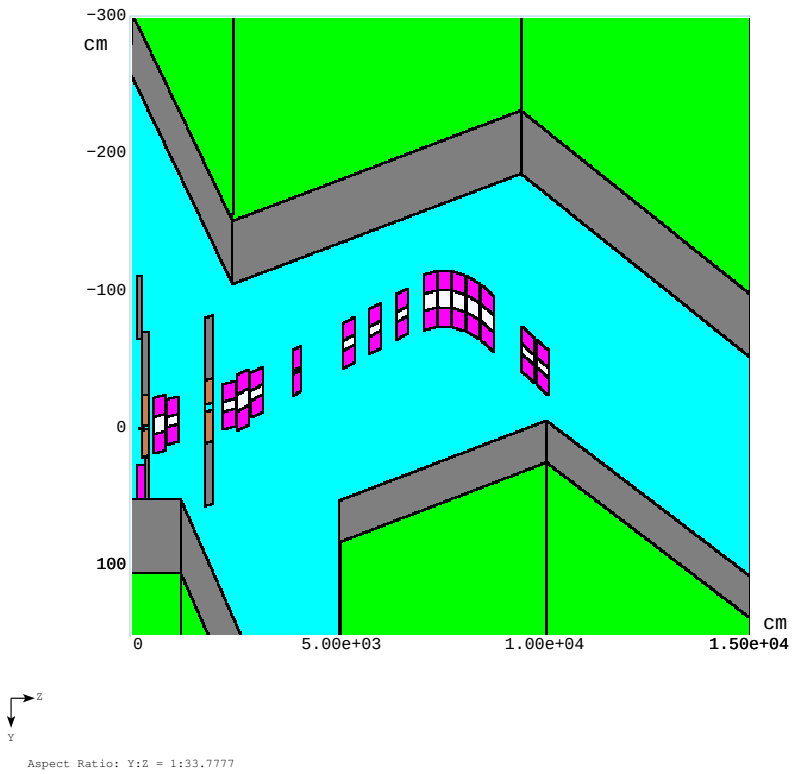

Figure 3: A plan view of the model 'as built' for the area with the bent beam line from the target up to 150 m downstream.

3 Results of Calculations

3.1 Groundwater activation

The calculated distributions of star density around the collimator and beam absorber, *i.e.* in the region where the major beam loss occurs, are shown in Figs. 4 and 5. One can see that the maximum star density observed in the soil under the concrete floor under the beam absorber is equal to 1.4×10^{-6} cm^{-3} per proton. This data gives rise to an estimate of the groundwater activation with tritium and sodium that does not exceed the EPA limits for more than *ten years* of continuous operation at normal conditions [4] and at the level of 1.2×10^{17} protons per year. In other words, after 10 years of continuous operation at the level of 1.2×10^{17} protons per year the groundwater activation will be at the 65% level of the EPA limit.

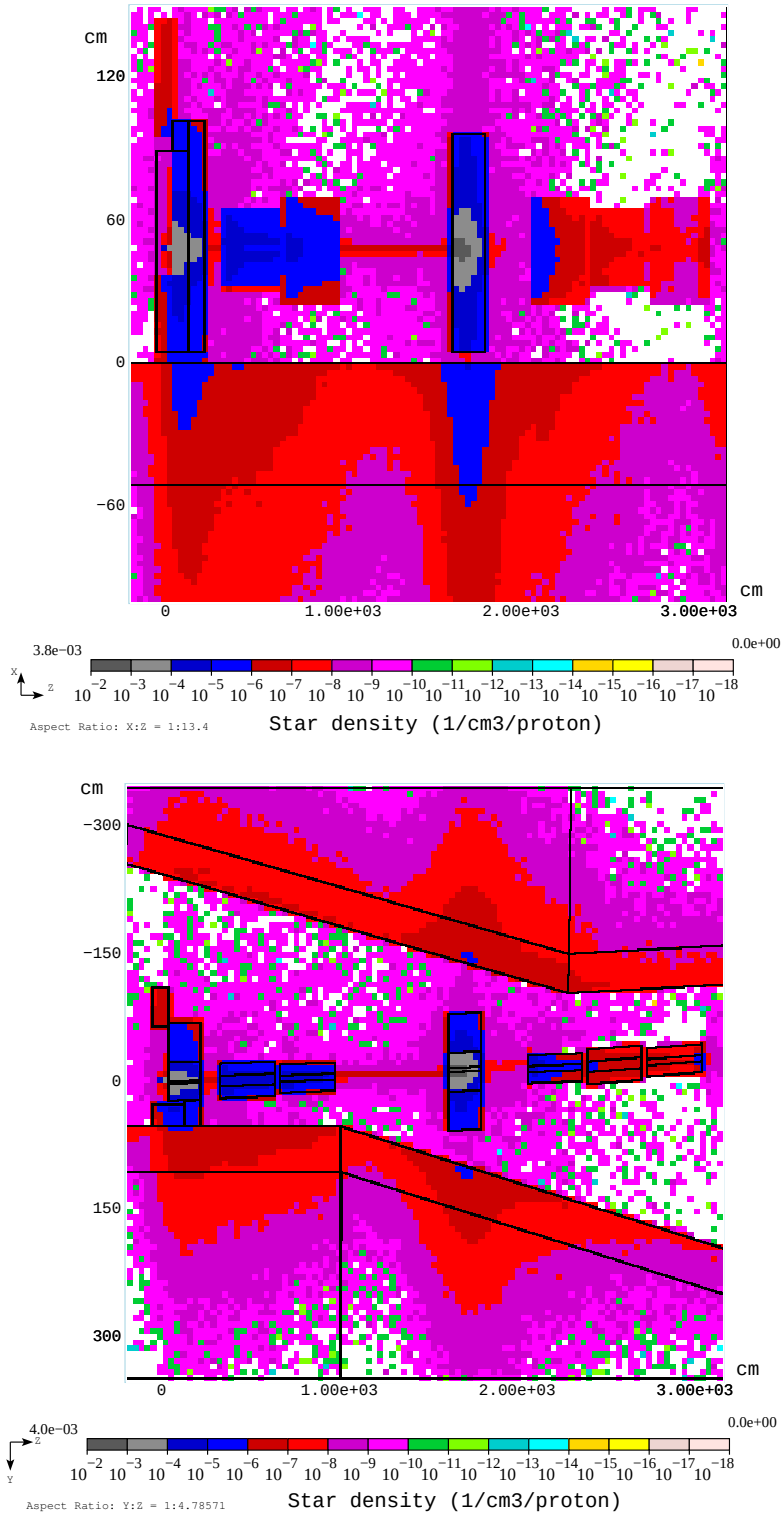

Figure 4: The calculated distributions of star density in the region where the major beam loss is observed: elevation view at $Y = 0$cm (top) and plan view at $X = 48$cm (bottom).

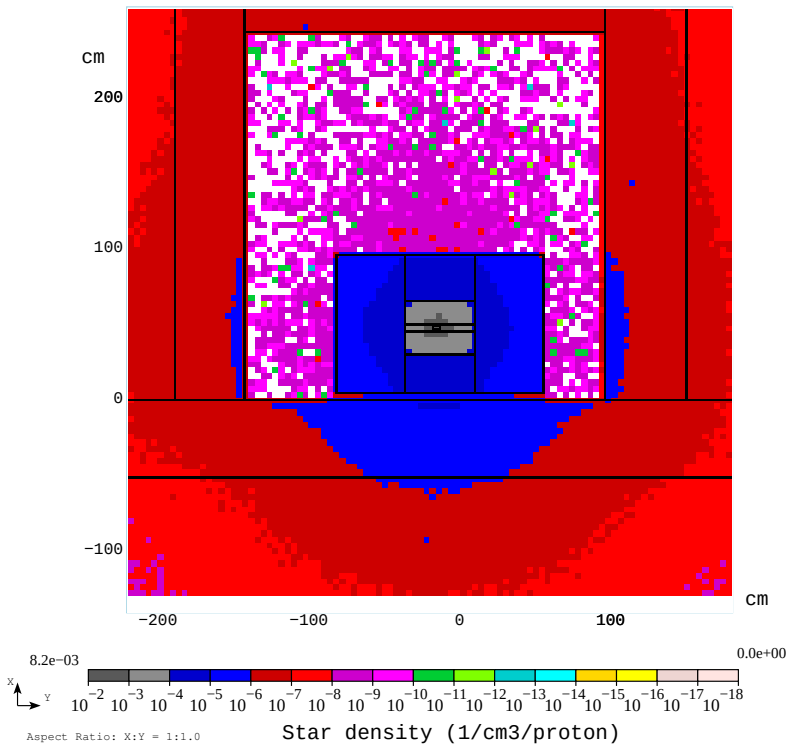

Figure 5: The calculated distribution of star density over a cross section of the tunnel with the beam absorber where the shower maximum is observed.

The estimate of the groundwater activation was based on the assumption that the maximum-to-average ratio for the star density distributions is equal to 50 [4]. According to the current ES&H rules at Fermilab, the averaging of the star density should be performed over a soil volume that contains 99% of stars. In order to verify the ratio for this particular study, a separate calculation was performed for the test area. The volume corresponds to -2m $< Z <$ 32m longitudinally and 1.5m of dirt immediately outside of the tunnel concrete walls laterally. Averaged over four sides–left, right, top, and bottom–it gives us $< S >$ = 3.0$\times 10^{-8}$ cm^{-3} per proton. Therefore, the maximum-to-average ratio turns out to be 47 and the 6-% difference confirms high reliability of the used ratio of 50.

3.2 Residual contact dose

The calculated distribution of the residual contact dose rate in the region of maximum beam loss is shown in Fig. 6. One can see that there are several very hot spots in the beam line: (i) front and back of the collimator; (ii) front and back of the beam absorber; (iii) front of the first quadrupole (MT4Q2) downstream of the absorber. In order to determine extra shielding against the high residual radiation and plan on various maintenance procedures, cooling curves were calculated for the hottest spots (see Figs. 7 thru 11).

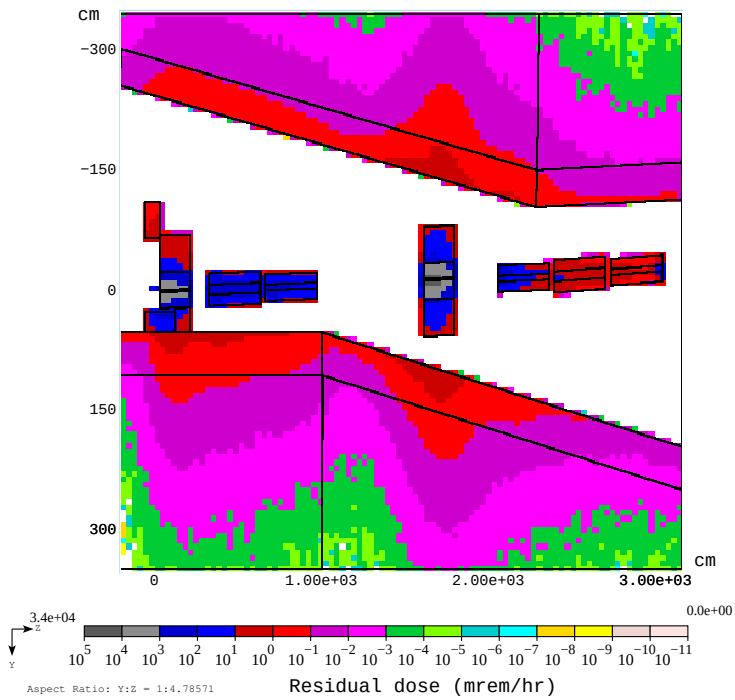

Figure 6: The calculated distribution (plan view) of the residual contact dose rate in the region where the major beam loss is observed and after a 30-day irradiation and 1-day cooling.

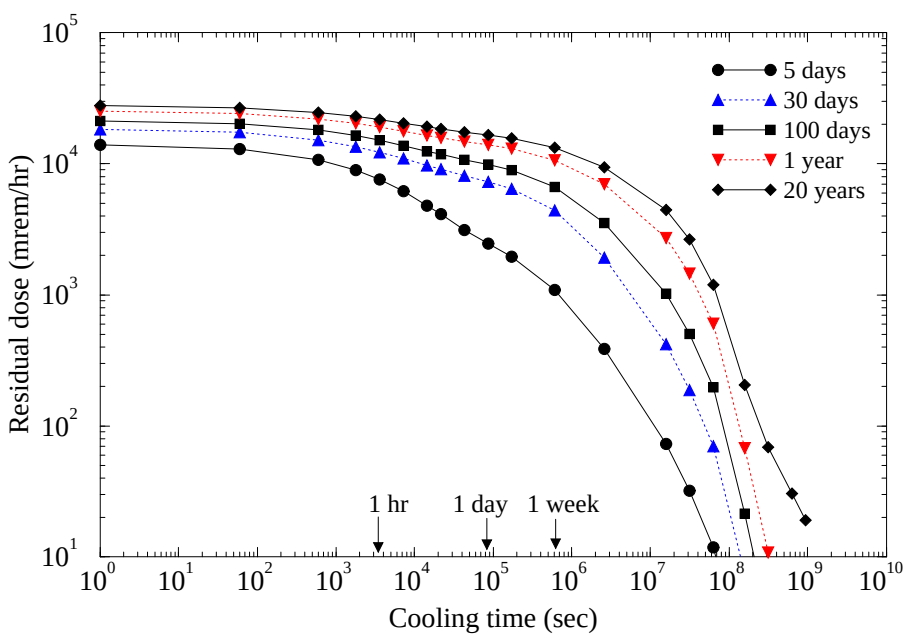

Figure 7: The calculated residual contact dose on the front surface of the collimator for several irradiation times.

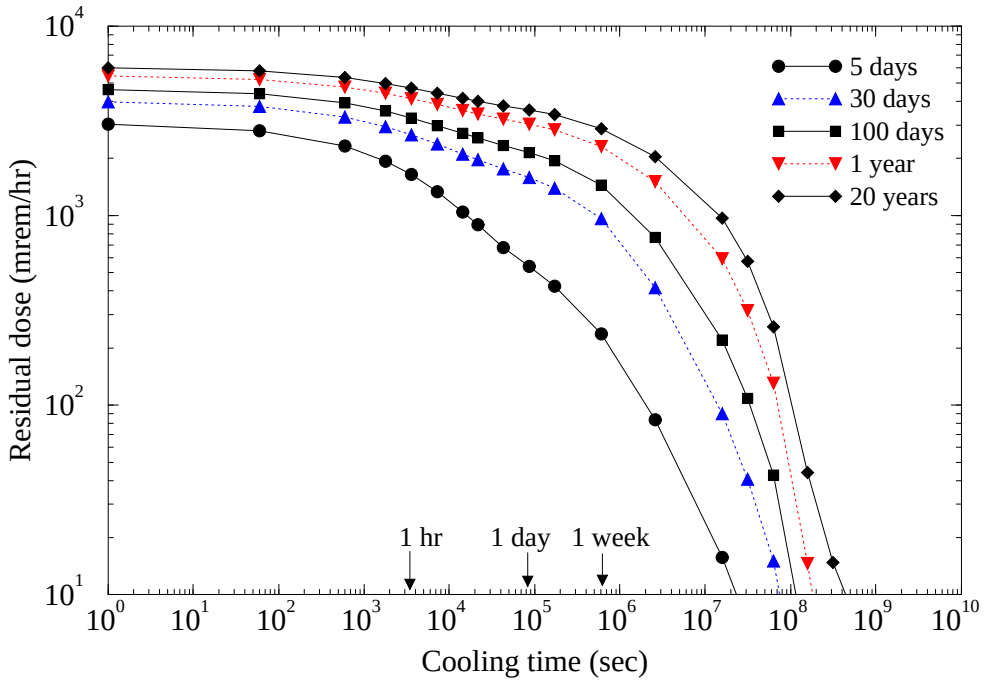

Figure 8: The calculated residual contact dose on the back surface of the collimator for several irradiation times.

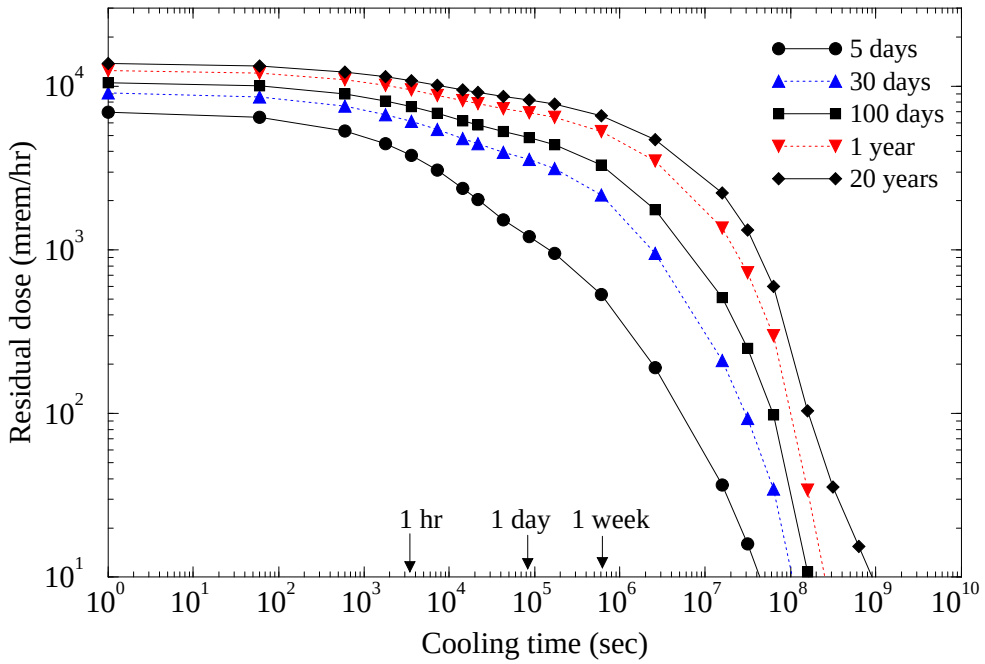

Figure 9: The calculated residual contact dose on the front surface of the absorber for several irradiation times.

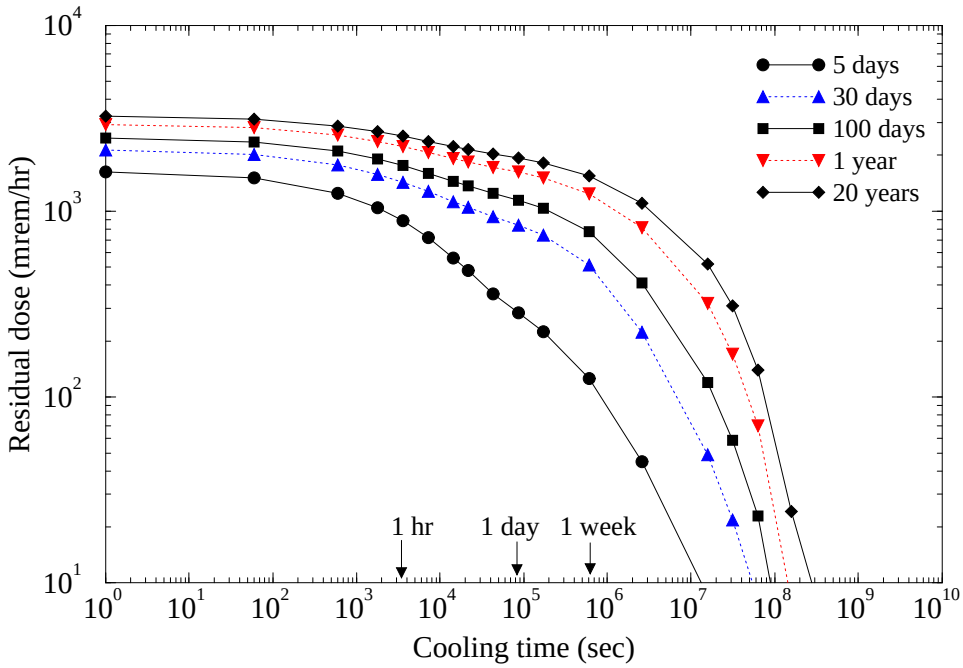

Figure 10: The calculated residual contact dose on the back surface of the absorber for several irradiation times.

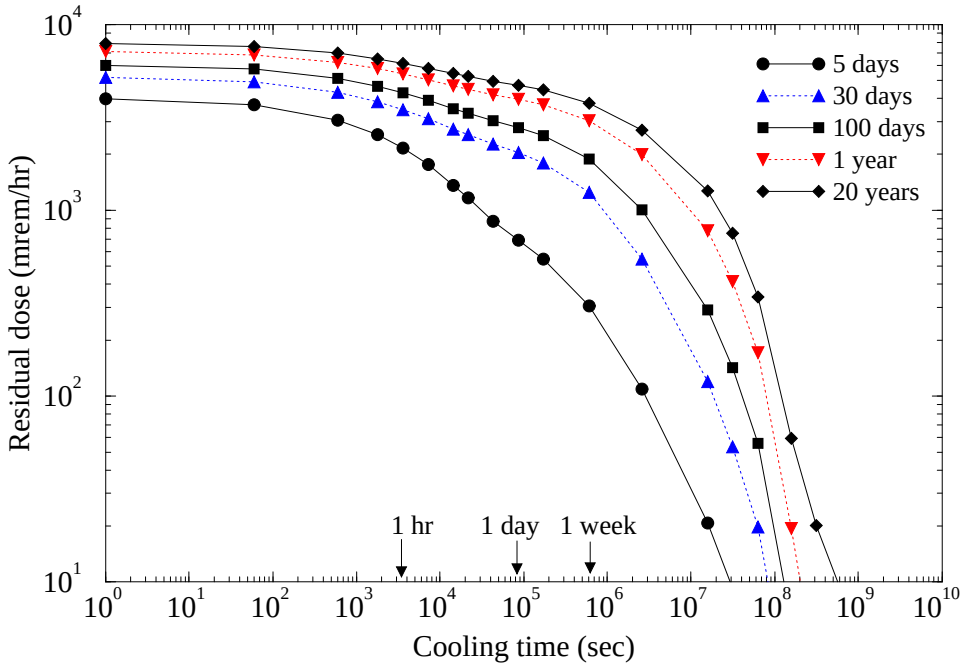

Figure 11: The calculated residual contact dose on the front surface of the quadrupole MT4Q2 for several irradiation times.

3.3 Prompt dose rate in control room

The calculated distribution of the prompt dose in the tunnel at normal operation is shown in Fig. 12. The control room is in the MS4 service building and the distance from it to the target is a bit more than 170 m. In addition, the room is off-axis by about 300 cm and surrounded by a 90-cm concrete wall.

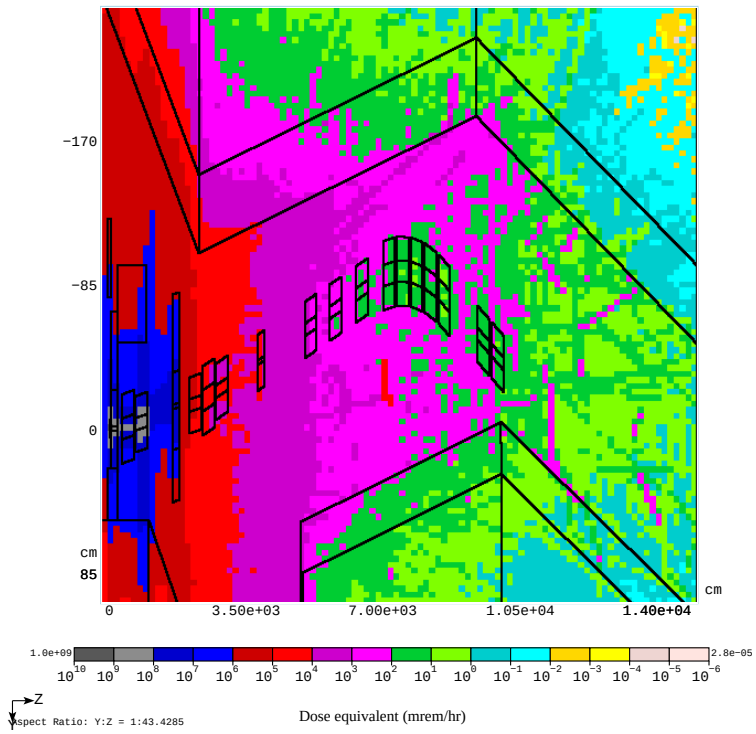

Figure 12: The calculated distribution (plan view) of the prompt dose in the tunnel from the target up to 150 m downstream.

In order to determine the prompt dose rate in the control room, another calculation has been performed with a 90-cm concrete wall placed at 110 m downstream of the target. It enabled us to estimate the dose attenuation due to such a wall and gave rise to the dose of about 1 mrem/hr at 150 m downstream of the target. Two additional observations should be taken into account as well: (i) the dose in the tunnel drops off by a factor of 10 as we go from 110 up 150 m; (ii) the remnants of the radiation going straightforward, that can be seen in Fig. 12, should be ignored because the radiation is directed into the wall and soil behind it, not into the users area. The calculation was performed for a slightly different shielding around the target when compared to the shielding shown in Figs. 1 thru 3. The difference is mostly in the extra concrete block on left side of the target ($-1m < Y < -0.5m$) and does not influence our speculations on radiation transport downstream to the control room.

Taking all that into account, one can state that the prompt dose rate in the control room at normal operation at the level of 10^{12} protons per minute will not exceed 0.3 mrem/hr. This is a conservative estimate that does not take into account the fact that the energy

spectrum of the radiation that will hit the real concrete wall of the control room will be softer than that at $Z = 110$m due to additional scattering in the air on the way downstream to $Z = 170m$, and the softer spectrum means increased absorption in the wall. Minor shileding updates around the control room might be required in order to provide the dose rate in the room not exceeding 0.25 mrem/hr which corresponds to a *Controlled Area of unlimited occupancy* [5].

4 Conclusions

It has been shown that the proposed shielding design around the target at M03 location gives rise to the following radiation levels around the test area at normal operation: (i) the prompt dose rate in the control room in the MS4 service building will not exceed 0.25 mrem/hr with minor shielding updates around the room; (ii) residual activity of the tunnel walls around the area is well under 100 mrem/hr; at the same time there are several hot spots with high residual contact dose rate in the beam line around the collimator and beam absorber (well above 1000 mrem/hr after a 30-day irradiation and 1-hr cooling) that require extra local shielding; (iii) the groundwater contamination with tritium and sodium will not exceed the EPA limits for more than ten years of continuous operation at the level of 1.2×10^{17} protons per year.

5 Acknowledgements

The author is thankful to Charles Brown, Rick Coleman, and Bill Higgins for helpful discussions.

References

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[2] http://ilc.fnal.gov.

[3] N.V. Mokhov, “The MARS Code System User’s Guide”, Fermilab-FN-628 (1995); N. V. Mokhov, O. E. Krivosheev, “MARS Code Status”, Proc. of the Monte Carlo 2000 Conference, Lisbon, October 23-26, 2000, Springer, p. 943; Fermilab-Conf-00/181 (2000); http://www-ap.fnal.gov/MARS/.

[4] K. Vaziri, Private communication, Fermilab (2006).

[5] “Fermilab Radiological Control Manual”, http://www-esh.fnal.gov/FRCM/.