MARS Calculations for MIPP(FNAL-E907) Shielding Assessment

M.A. Kostin

Fermi National Accelerator Laboratory P.O. Box 500, Batavia, Illinois 60510

December 16, 2003

Abstract

We present the results of MARS calculations of beam induced radiation in the MIPP beamline for MIPP shielding assessment.

1 Model

In order to estimate the beam induced effects for MIPP running conditions a model of the MIPP beam line and beam enclosure has been established within the MARS14 framework [1]. The optics of the beam line is governed by an "optics" file that is an output of the MAD code [2]. The MAD "optics" file is read and translated to MARS14 format by the recently improved and refined MAD-MARS Beam Line Builder (`MMBLB`) [3]. The use of the `MMBLB` makes it possible to easily synchronize changes in both the MAD and MARS14 models.

Two views of the system studied are shown in Fig. 1 and 2, which depict the MIPP beamline in the MC6 hall. Shown are a segment of the primary beamline leading up to the primary target cage followed by the secondary beamline. The MAD-like axis orientation has been used for the MARS14 model, that is the axis Y points upwards and Z – downstream. This axis convention is not native to MARS14, where the axis X points upwards. This leads to cross-section plots rotated by $\pi/2$ clock-wise for all such plots in this document.

A number of simplifications have been made in the model. Concrete magnet stands have not been included. The stands represent a significant amount of material and should result in even smaller radiation doses in the system when accounted for. Effects of the gaps between concrete blocks that form the walls of the beam enclosure in MC6 have not been studied. Such gaps may result in higher dose rates, especially in places where walls are relatively thin (roof of MC6).

The following material densities are used. The density ρ for shielding steel is taken to be 7.2 g/cc, which is 92% of the nominal one. This takes into account the gaps between the shielding sheets. The density ρ for soil is taken to be 2.24 g/cc, that of Fermilab wet dirt. The heavy concrete has the density of 4 g/cc and the same chemical composition as

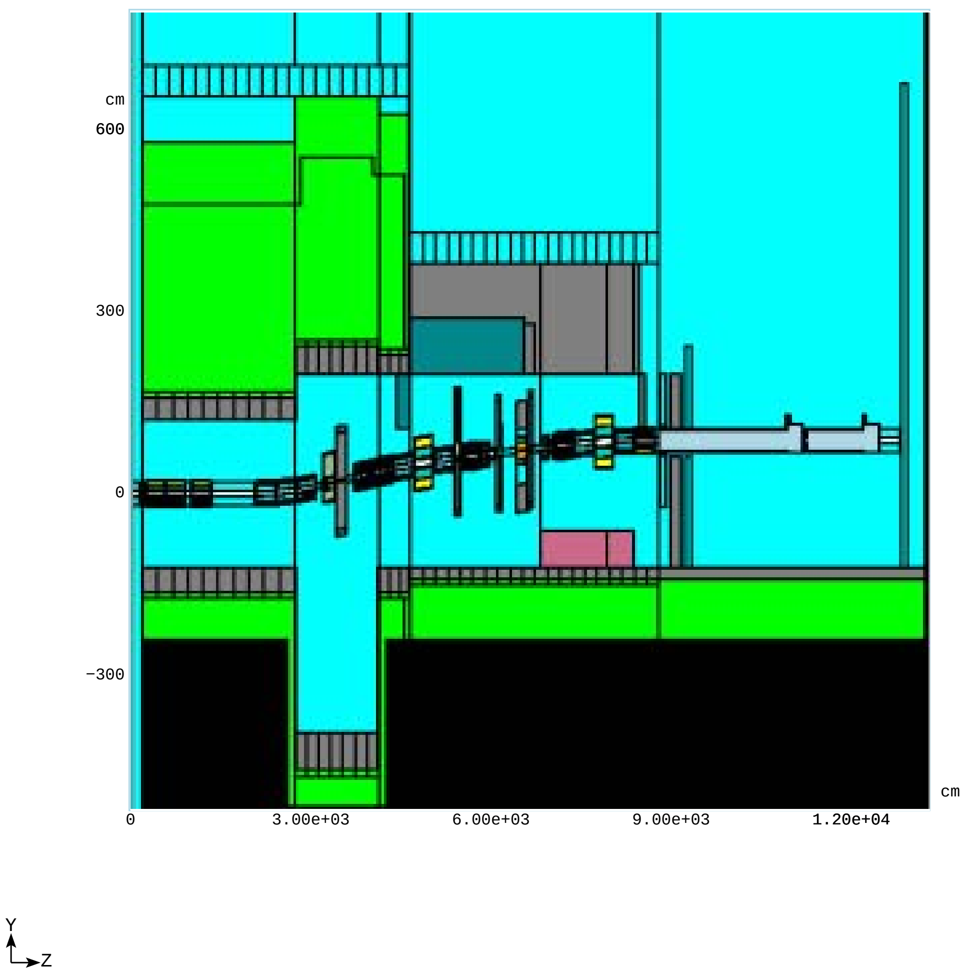

Figure 1: YZ view of the MARS14 model.The primary beam line segment in M05 is shown that leads to the primary target cage at ≈ 3.75e+03 cm. The secondary beam line is shown all the way up to the MIPP experimental hall, ending with the beam Cerenkov counters.

the standard MARS14 heavy concrete. All the other materials in the model are with the standard densities (as in MARS14).

The following beam induced effects have been studied:

- Energy deposition in element coils
- Sump water activation
- Residual dose rates on accessible surfaces of elements
- Prompt dose rates outside of the MIPP beam enclosure.

The items above require different normalizations. The proton intensity is used to normalize MARS14 results for both the residual dose and prompt dose rates, whereas a total number of protons is important for the energy deposition and sump water activation. To be conservative, we assume that the repetition period is 2.9 sec, that is the "double spill" scheme [4]

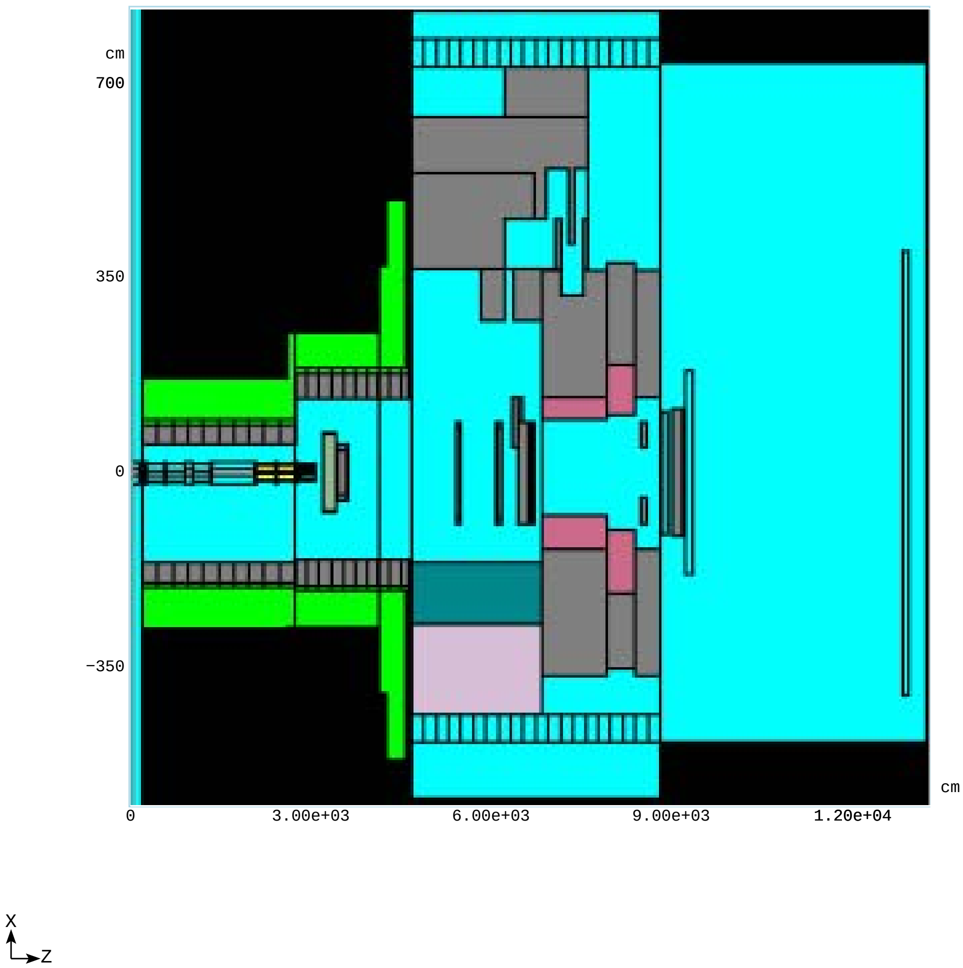

Figure 2: XZ view of the MARS14 model. The slice is through the primary target and the secondary beamline which rises above this plane is not shown.

Beam Momentum GeV	Spill intensity (protons/spill)	Average Intensity (protons/sec)	total protons	Total spills	total time days
-90	7.62E+10	2.63E+10	3.43E+15	45092	1.5
-70	1.38E+10	4.75E+09	9.56E+14	69478	2.3
-50	5.73E+09	1.98E+09	5.46E+14	95394	3.2
-25	2.77E+09	9.54E+08	2.77E+14	100112	3.4
-15	3.78E+09	1.30E+09	3.79E+14	100112	3.4
-5	1.49E+10	5.14E+09	1.21E+15	81137	2.7
5	9.66E+09	3.33E+09	7.55E+14	78100	2.6
15	2.10E+09	7.23E+08	2.10E+14	100112	3.4
25	1.08E+09	3.73E+08	1.08E+14	100112	3.4
50	5.76E+08	1.99E+08	5.44E+13	94390	3.2
70	3.43E+08	1.18E+08	2.67E+13	78038	2.6
90	2.67E+08	9.20E+07	1.55E+13	57923	1.9
		Total	7.97E15	10.0E6	33.6

Table 1: Beam intensities (assuming "double spill") and number of protons required for runs with various beam momenta. Each double slow spill lasts 2.9sec with 1 sec flattop. With this high rate of data taking, the total experiment lasts 33.6 days! In practice, the beam delivery rates are likeliy to be lower and the run is likely to last a year.

does work.

The beam intensities and number of protons required for the MIPP runs for various beam momenta are summarized in Table 1. The total number of protons over all the physics data taking runs is 7.97×10^{15}. This does not include MINOS running, which will require a separate shielding assessment. We have not explicitly included time spent on commissioning the experiment and tuning the beam, which is expected to take several weeks, during which the beam intensity would be small and unpredictable. However, for the safety assessment document, we use a conservative figure of 2E16 total protons for the non-MINOS part of the experiment and the numbers used in the SAD have been scaled up accordingly from those in this document. A graphical representation of the beam intensities versus momenta is show in Fig. 3.

2 Energy Deposition in Element Coils

The energy deposition distribution in magnet coils is shown in Fig. 4, assuming normal running. A point on the plot represents the deposited energy averaged over a coil segment. The energy distribution within a coil of one element has not been studied. The distribution shown in Fig. 4 is a sum of energy deposition dependencies for all the beam momenta weighted with the total number of protons for each momenta. As one can see, the deposited energy does not exceed 1 Mrad in the peak. A typical life-time limit for coil insulation and epoxy is about 400 Mrad.

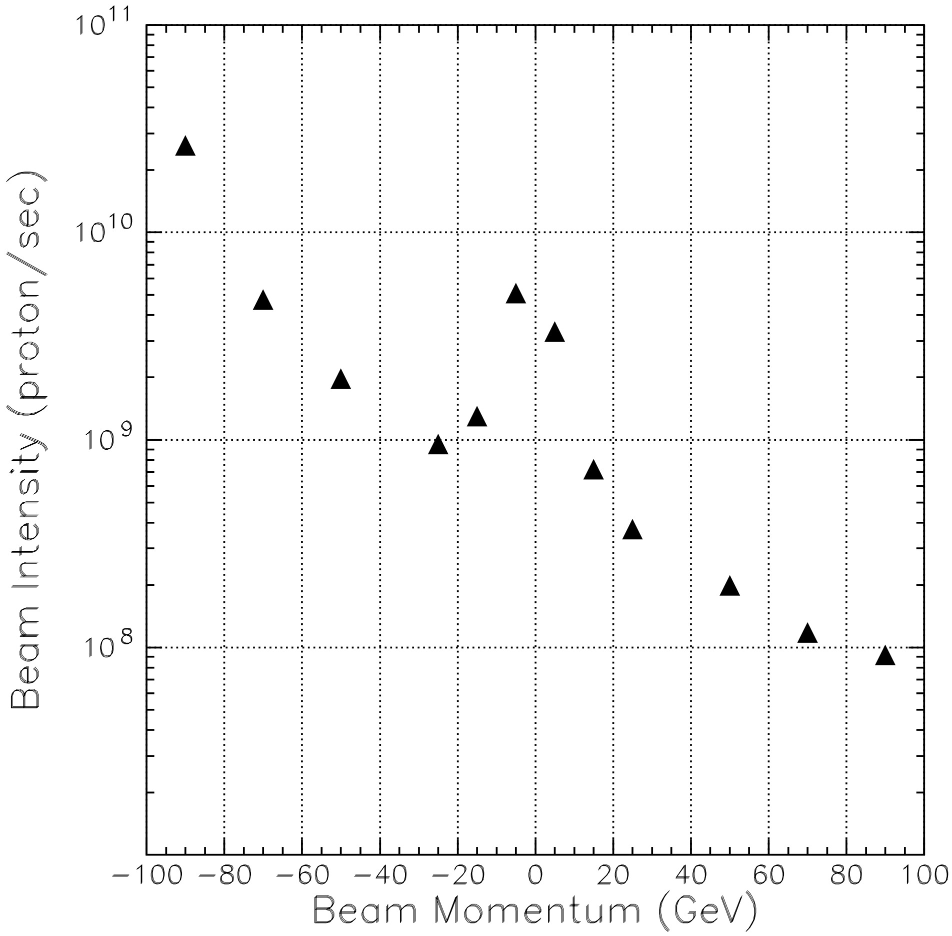

Figure 3: Beam intensities for various beam momenta.

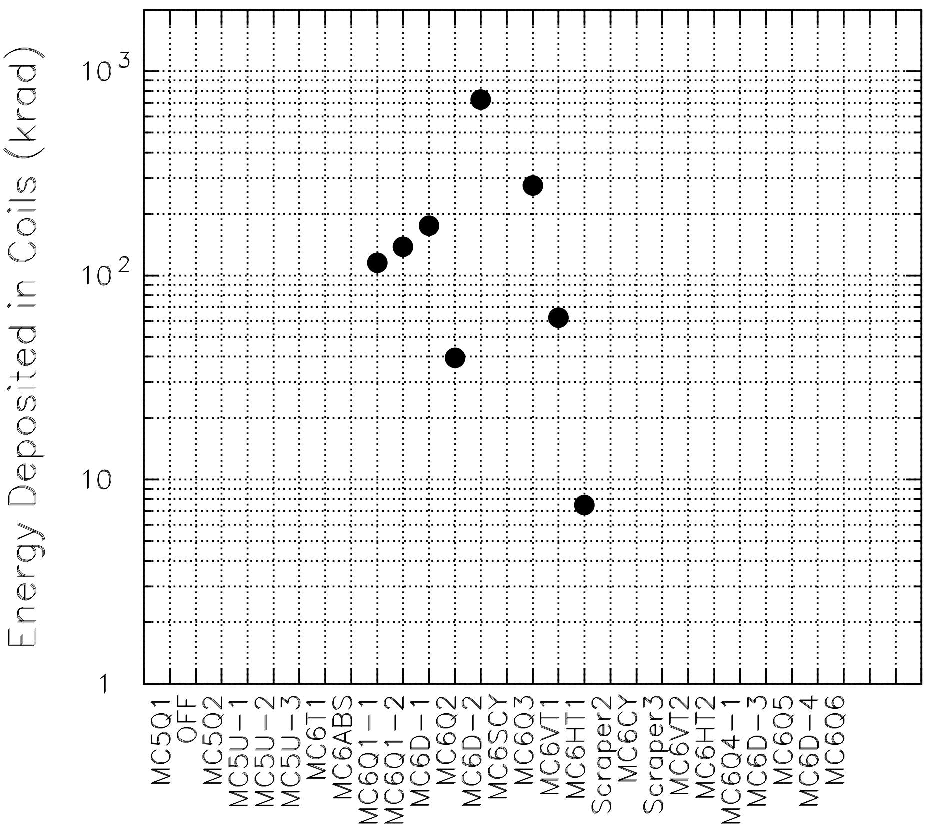

Figure 4: Energy deposited in magnet coils after all the data taking runs.

3 Sump Water Activation

The sump water activation is normally measured in numbers of so-called "stars" per cm^3 per running period (typically a year). The resulting star density distribution has been calculated with a similar method described in the previous section, i.e. star density distributions were calculated for each beam momentum run and then the distributions were summed up with weights equal to number of protons specific for each run. There are two peaks found in the resulting star density distribution. The first peak is in an area that is a short distance downstream of the primary target. The star density for this place was found to be 8.04×10^8 star/(running period)/cm^3. The second peak is induced by primary protons dumped onto the beam line elements. The star density for that is 9.78×10^8 star/(running period)/cm^3. A maximal allowed star density for sump water is 5.96×10^{10} star/year/cm^3 [5].

A beam enclosure cross-section and star density distribution for a -90 GeV run at the location of the first peak are shown in Fig. 5 and 6. The star density distribution is normalized to one proton on target. This distribution is similar to others at other secondary momenta, since it is formed by the particles coming out of the primary target and its shielding and is not affected by the field of the downstream magnets, i.e. the momentum of the secondary beam.

4 Residual Dose Rates

The residual dose rates on contact (at 0 cm) on accessible surfaces of beam elements after 30 days of irradiation and 1 day of cooling ("30 days/1 day/0 cm") for various beam momenta are shown in Fig. 7 and 8. The doses were calculated with the use of so-called "omega factors". The method is known to give a possible bias from experimentally measured doses by a factor of 2-3. Therefore, the plots can be multiplied by that factor for a conservative estimate. One can see, that runs at some beam momenta result in the residual dose rates above the radiation area limit of 100 mrem/hr. Those runs are for 90, 70 and 5 GeV negative momenta and 5 GeV positive one. However, the total running time at these momenta, with a double spill every 2.9 seconds is considerably less than 30 days as can be seen from Table 1. The curves here have to be renormalized downwards by the factors given in Tables 2 and 3 if a double slow spill is fully active. In practice, we may run in a mode that has less slow spill delivered, which will ameliorate these numbers further.

There two examples shown in Fig. 9 and 10. The figures exhibit "30 days/1 day/0 cm" residual dose distributions for the target shielding for a -90 GeV run and for the momentum collimator shielding for +90 GeV.

One should note that a "30 days/ 1 day/ 0 cm" dose rate is practically same as "100 days/ 4 hours/ 30 cm" one. For those who are interested in other irradiation/cooling terms, there are two renormalization tables below for both the regular concrete and yoke material.

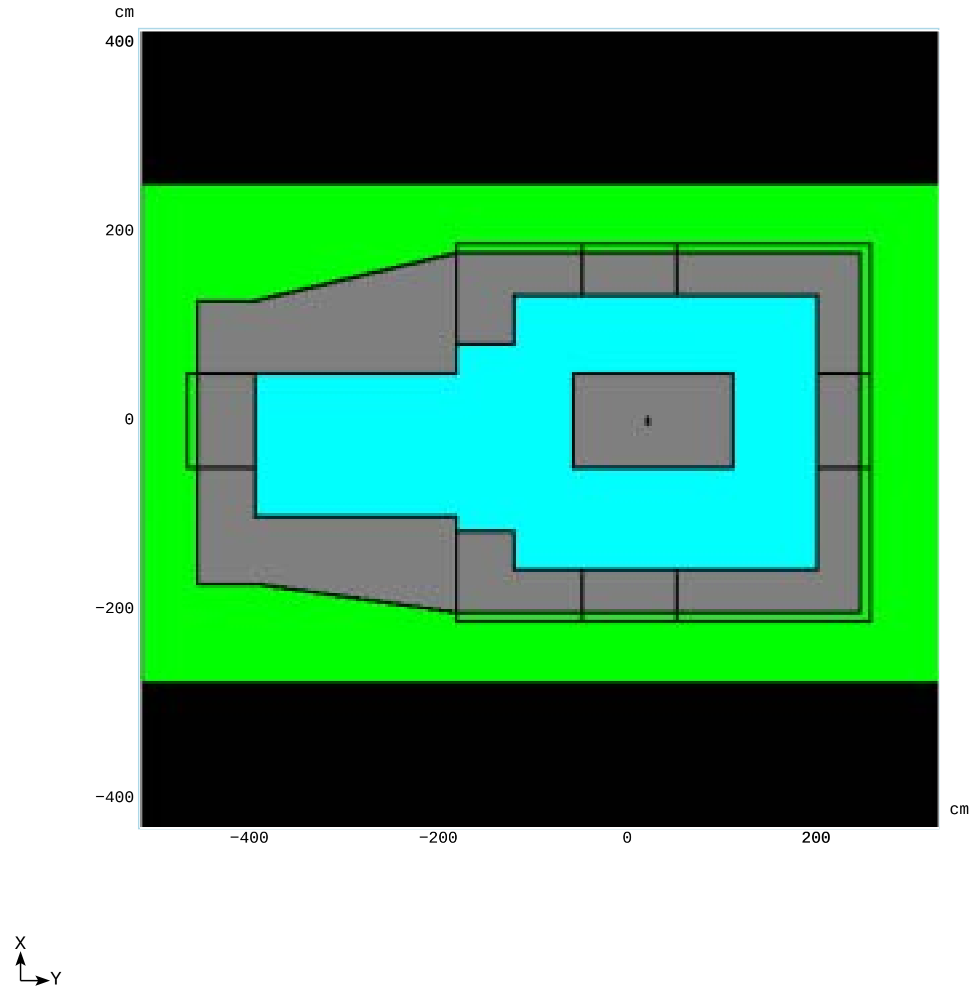

Figure 5: A cross-section of the MIPP beam enclosure at the location of first star density peak. Materials are color-coded. Blue – air, grey – concrete, green – soil.

5 Prompt Dose Rates

There are three distinguished areas for prompt dose calculations:
- In the front of the Meson Building
- Inside of the Meson Building, area MC6
- Area MC7.

5.1 Prompt Dose Rates In the Front of the Meson Building

The prompt dose in this areas is governed mostly by the interactions in the primary target and surroundings. This means that the dose is scalable with the primary beam intensity, with the worst case scenario for -90 GeV secondary beam. The maximal prompt dose in

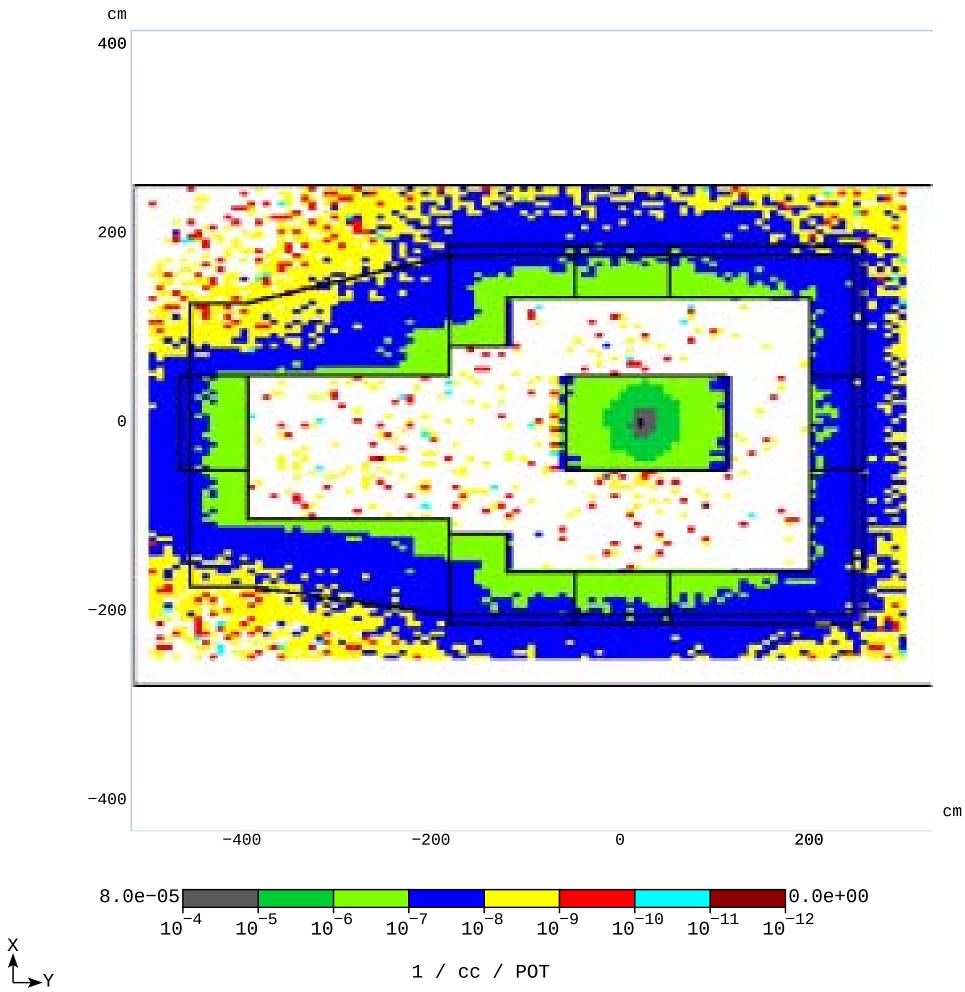

Figure 6: Star density distribution for a - 90 GeV run at the location shown in Fig. 5. The distribution is normalized to one proton on target.

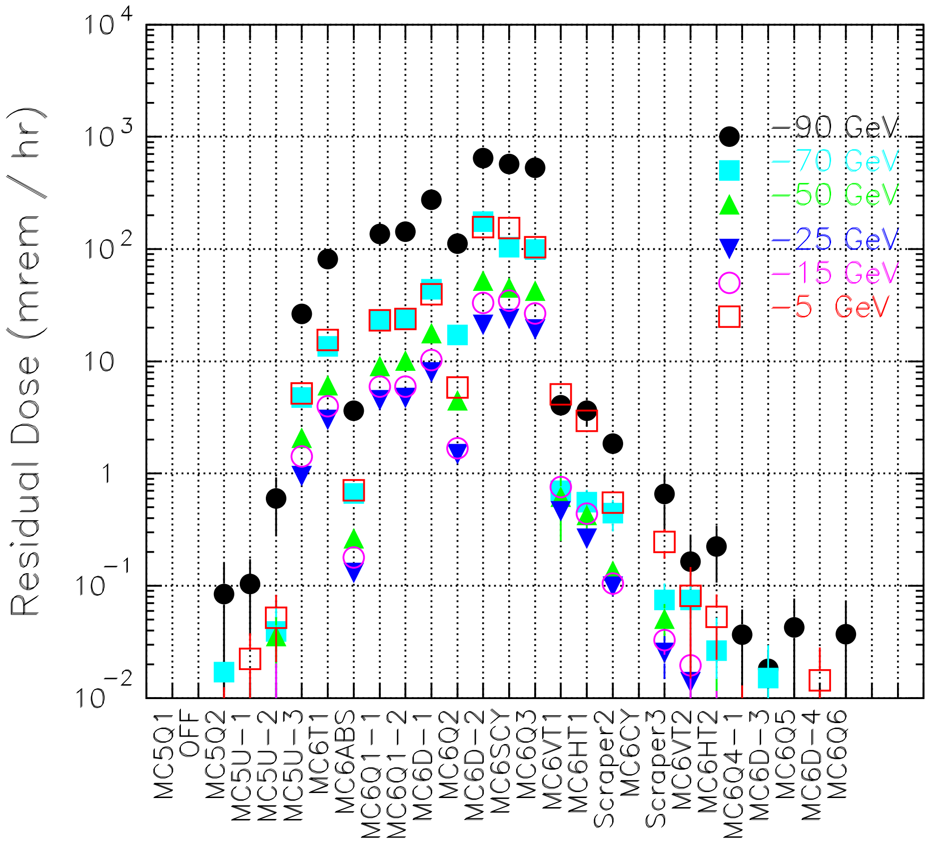

Figure 7: "30 days/1 day/0 cm" residual dose rates for beam elements for negative momenta. The fluxes of protons used are as given in Table 1.

this case is 5 mrem/hr with the statistical uncertainty of 50%. The dose does not exceed the limit of 100 mrem/hr for the given area. Fig. 11 and 12 show a cross-section and prompt dose distribution at a z-position where the prompt dose is maximal. The distribution demonstrates a well-established dose rate dependence: 1 m of wet dirt (or similarly for regular concrete) provide a dose rate reduction of 10 times.

5.2 Prompt Dose Rates Inside of the Meson Building, area MC6

The prompt dose distributions shown in Fig. 13 – 18 are driven by the primary beam dumped onto the beam line elements. On these plots, the z-coordinate equal to 0 corresponds to the beginning of the Meson Building. The prompt dose is the highest for a run with maximal beam intensity, i.e. -90 GeV, at ≈ 10 m downstream from the beginning of the Meson Building.

The Fig. 19 and 20 show a cross-section and prompt dose distribution in the place of maximal prompt dose rate.

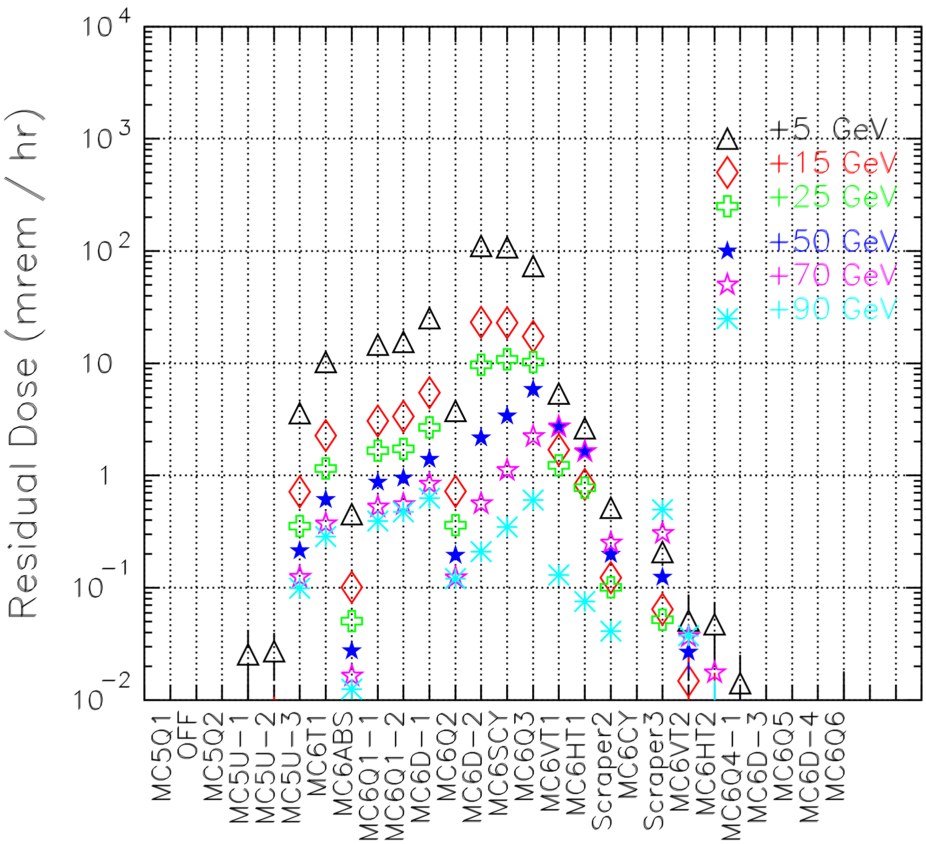

Figure 8: "30 days/1 day/0 cm" residual dose rates for beam elements for positive momenta. The fluxes of protons used are as given in Table 1.

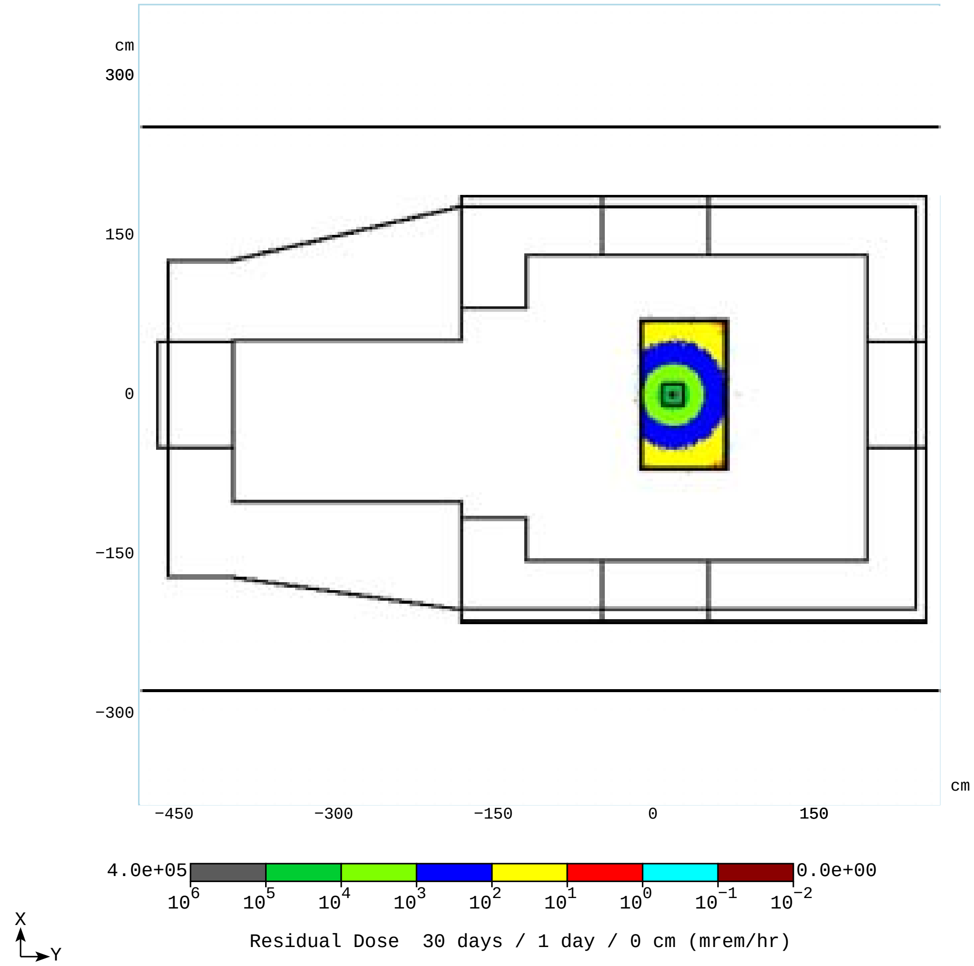

Figure 9: Distribution for “30 days/1 day/0 cm” residual dose in the target shielding for a -90 GeV run.

5.3 Prompt Dose Rates in the Area MC7

The prompt dose in the area MC7 is driven mostly by muons and accompanying photons. The prompt dose distribution downstream of the concrete wall that divides the areas MC6 and MC7 and analogous distribution at the MIPP detector are shown in Fig. 21 and 22. The maximal dose rates are obtained for a -90 GeV run. 2-D distributions for the prompt dose for the above locations for a -90 GeV run are shown in Fig. 23 and 24. The 2-D distributions for other beam momenta look similar to the ones above.

6 Places for monitoring

Suggested places for monitoring devices:
• 10 m from the beginning of the Meson Building, right side

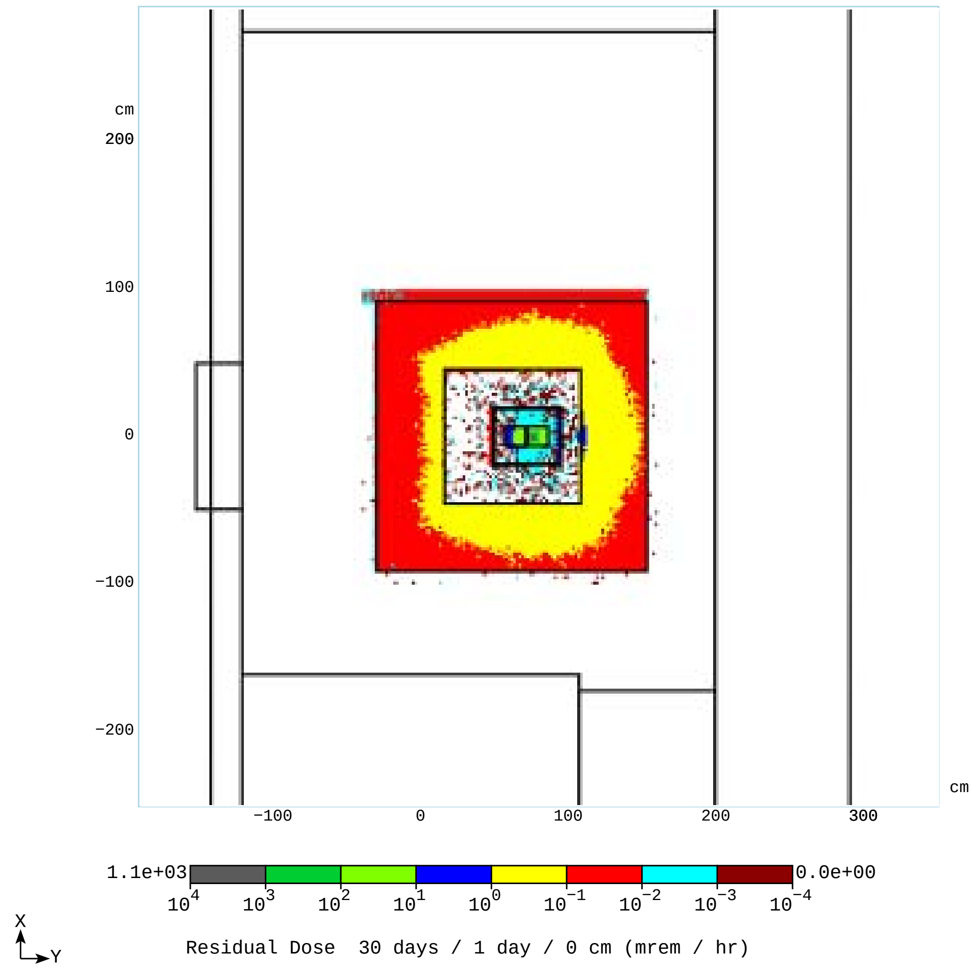

Figure 10: Distribution for “30 days/1 day/0 cm” residual dose in the momentum collimator shielding for a +90 GeV run.

Tcool	Irradiation times 1/2day	1day	5day	30day	100day	1yr	20yr
1sec	2.130E+00	2.257E+00	2.664E+00	3.245E+00	3.679E+00	4.221E+00	4.821E+00
1min	1.963E+00	2.090E+00	2.493E+00	3.079E+00	3.512E+00	4.054E+00	4.654E+00
10min	1.614E+00	1.738E+00	2.128E+00	2.725E+00	3.155E+00	3.702E+00	4.303E+00
0.5hr	1.293E+00	1.414E+00	1.788E+00	2.400E+00	2.824E+00	3.374E+00	3.975E+00
1hr	1.027E+00	1.142E+00	1.498E+00	2.124E+00	2.545E+00	3.099E+00	3.699E+00
2hr	7.381E-01	8.433E-01	1.175E+00	1.820E+00	2.235E+00	2.796E+00	3.395E+00
4hr	4.361E-01	5.278E-01	8.301E-01	1.498E+00	1.908E+00	2.479E+00	3.081E+00
6hr	3.020E-01	3.843E-01	6.655E-01	1.340E+00	1.741E+00	2.314E+00	2.913E+00
12hr	1.266E-01	1.939E-01	4.367E-01	1.121E+00	1.505E+00	2.092E+00	2.691E+00
1day	6.728E-02	1.219E-01	3.286E-01	1.000E+00	1.370E+00	1.966E+00	2.564E+00
2days	4.739E-02	8.975E-02	2.645E-01	8.890E-01	1.250E+00	1.846E+00	2.443E+00
7days	2.356E-02	4.602E-02	1.551E-01	6.031E-01	9.303E-01	1.517E+00	2.107E+00
30d	5.750E-03	1.139E-02	4.748E-02	2.332E-01	4.716E-01	1.016E+00	1.576E+00
0.5yr	1.197E-03	2.393E-03	1.168E-02	6.819E-02	1.832E-01	5.322E-01	9.306E-01
1yr	6.880E-04	1.375E-03	6.752E-03	3.972E-02	1.105E-01	3.322E-01	5.999E-01
2yr	2.892E-04	5.779E-04	2.846E-03	1.679E-02	4.739E-02	1.446E-01	2.679E-01
5yr	2.650E-05	5.296E-05	2.611E-04	1.542E-03	4.388E-03	1.353E-02	2.958E-02
10yr	1.270E-06	2.539E-06	1.262E-05	7.519E-05	2.351E-04	8.017E-04	4.906E-03
20yr	4.511E-07	9.022E-07	4.508E-06	2.702E-05	8.925E-05	3.225E-04	2.886E-03
30yr	3.298E-07	6.593E-07	3.295E-06	1.976E-05	6.552E-05	2.379E-04	2.260E-03

Table 2: Residual dose rate normalization factor for "yoke" like material. The plots for 30day/1 day/0cm/ have to be renormalized by the factors given in the table for different exposures and cooling times. For instance a 1 day exposure followed by a 1 day cooling time has a normalizing factor of 0.1219

- 10 m from the beginning of the Meson Building, left side
- at the exit door from the beam enclosure (MC6)
- downstream surface of the concrete wall dividing MC6 and MC7, above the beamline

References

[1] N.V. Mokhov, "The MARS Code System User's Guide", Fermilab-FN-628 (1995); N.V. Mokhov, O.E. Krivosheev, "MARS Code Status", Proc. Monte Carlo 2000 Conf., p. 943, Lisbon, October 23-26, 2000; Fermilab-Conf-00/181 (2000); `http://www-ap.fnal.gov/MARS/`.

[2] H. Grote, F.C. Iselin, "The MAD program (Methodical Accelerator Design)", CERN/SL/90-13.

Tcool	Irradiation times						
	1/2day	1day	5day	30day	100day	1yr	20yr
1sec	4.504E+01	4.566E+01	4.613E+01	4.666E+01	4.684E+01	4.704E+01	4.793E+01
1min	2.322E+01	2.383E+01	2.430E+01	2.483E+01	2.501E+01	2.520E+01	2.611E+01
10min	6.900E+00	7.521E+00	7.968E+00	8.511E+00	8.686E+00	8.887E+00	9.780E+00
0.5hr	2.985E+00	3.593E+00	4.022E+00	4.571E+00	4.748E+00	4.948E+00	5.836E+00
1hr	1.781E+00	2.373E+00	2.786E+00	3.333E+00	3.507E+00	3.709E+00	4.597E+00
2hr	1.247E+00	1.811E+00	2.201E+00	2.735E+00	2.906E+00	3.112E+00	3.997E+00
4hr	9.858E-01	1.495E+00	1.849E+00	2.346E+00	2.515E+00	2.724E+00	3.608E+00
6hr	8.615E-01	1.330E+00	1.659E+00	2.126E+00	2.294E+00	2.502E+00	3.386E+00
12hr	6.216E-01	9.780E-01	1.240E+00	1.620E+00	1.784E+00	1.996E+00	2.879E+00
1day	3.562E-01	5.641E-01	7.372E-01	1.000E+00	1.157E+00	1.375E+00	2.254E+00
2days	1.225E-01	1.959E-01	2.830E-01	4.388E-01	5.825E-01	8.117E-01	1.687E+00
7days	4.701E-03	9.010E-03	3.085E-02	1.226E-01	2.383E-01	4.873E-01	1.356E+00
30day	1.346E-03	2.675E-03	1.192E-02	6.283E-02	1.532E-01	3.998E-01	1.251E+00
0.5yr	5.098E-04	1.019E-03	5.025E-03	2.968E-02	8.893E-02	2.893E-01	1.042E+00
1yr	3.877E-04	7.754E-04	3.846E-03	2.288E-02	7.061E-02	2.372E-01	8.893E-01
2yr	2.731E-04	5.461E-04	2.715E-03	1.618E-02	5.044E-02	1.713E-01	6.647E-01
5yr	1.135E-04	2.269E-04	1.129E-03	6.738E-03	2.116E-02	7.243E-02	2.926E-01
10yr	2.949E-05	5.897E-05	2.934E-04	1.751E-03	5.510E-03	1.891E-02	7.799E-02
20yr	2.120E-06	4.239E-06	2.109E-05	1.258E-04	3.968E-04	1.364E-03	6.012E-03
30yr	2.023E-07	4.046E-07	2.016E-06	1.205E-05	3.854E-05	1.346E-04	8.207E-04

Table 3: Residual dose rate normalization factor for concrete. The plots for 30day/1 day/0cm/ have to be renormalized by the factors given in the table for different exposures and cooling times. For instance a 1 day exposure followed by a 1 day cooling time has a normalizing factor of 0.564

[3] M.A. Kostin, O.E. Krivosheev, N.V. Mokhov, I.S. Tropin, “An Improved MAD-MARS Beam Line Builder: User’s Guide”, FERMILAB-FN-738, 2003.

[4] For a description of the “double slow spill scheme”, see “A scheme to extract a low intensity slow spill Main Injector beam to the Meson Area without compromising antiproton production rate”, C.S.Mishra, C.T.Murphy, R.Raja, FN-TM-213, October 2000. The document may be found at

http://ppd.fnal.gov/experiments/e907/Beam/ramp.pdf.

Note that this document assumes a design repetition rate of 1.467 seconds for proton shots for anti-proton production. To date, this has not been achieved, so the repetition rate of the double slow spill will be slower than what is assumed in this document, making the assumptions in this document even more conservative.

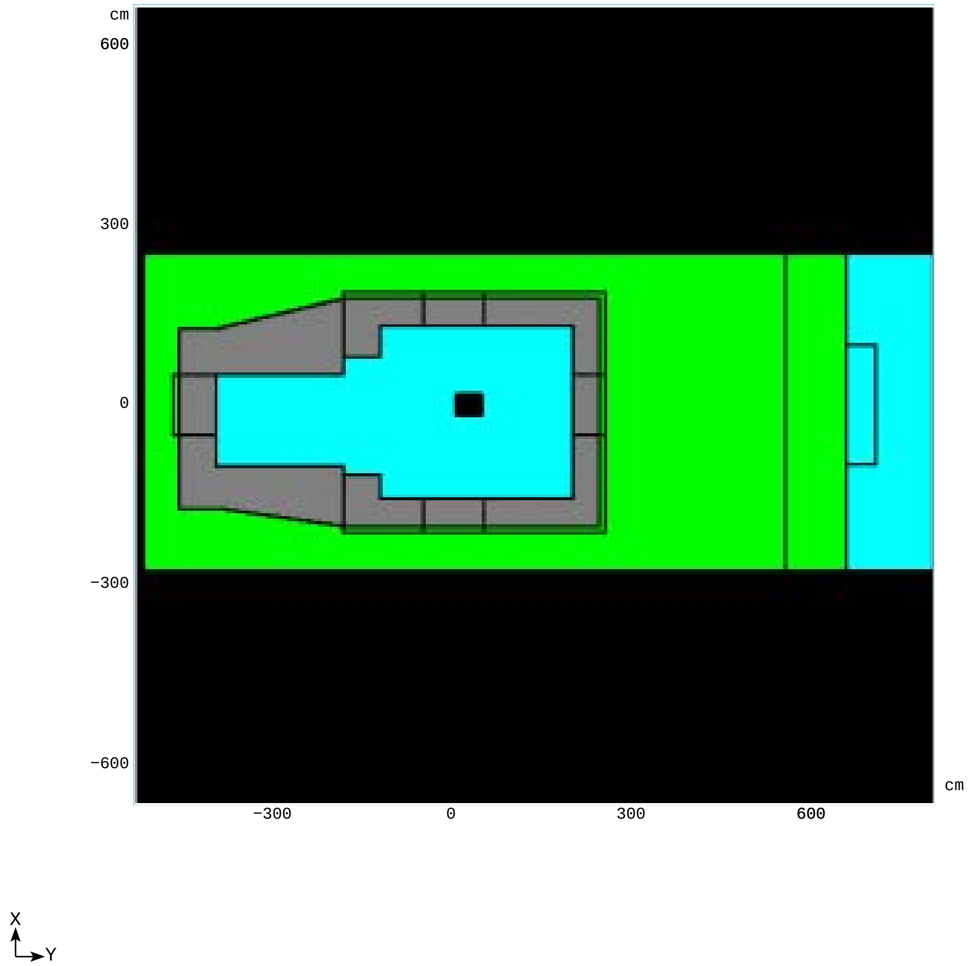

Figure 11: A cross-section at a z-position where the prompt dose rate is maximal in MC05. The materials are color-coded. Blue – air, grey – concrete, green – soil. The black square in the middle is a beamline element.

[5] See Appendix MC5-B of the MIPP Safety Analysis Document.

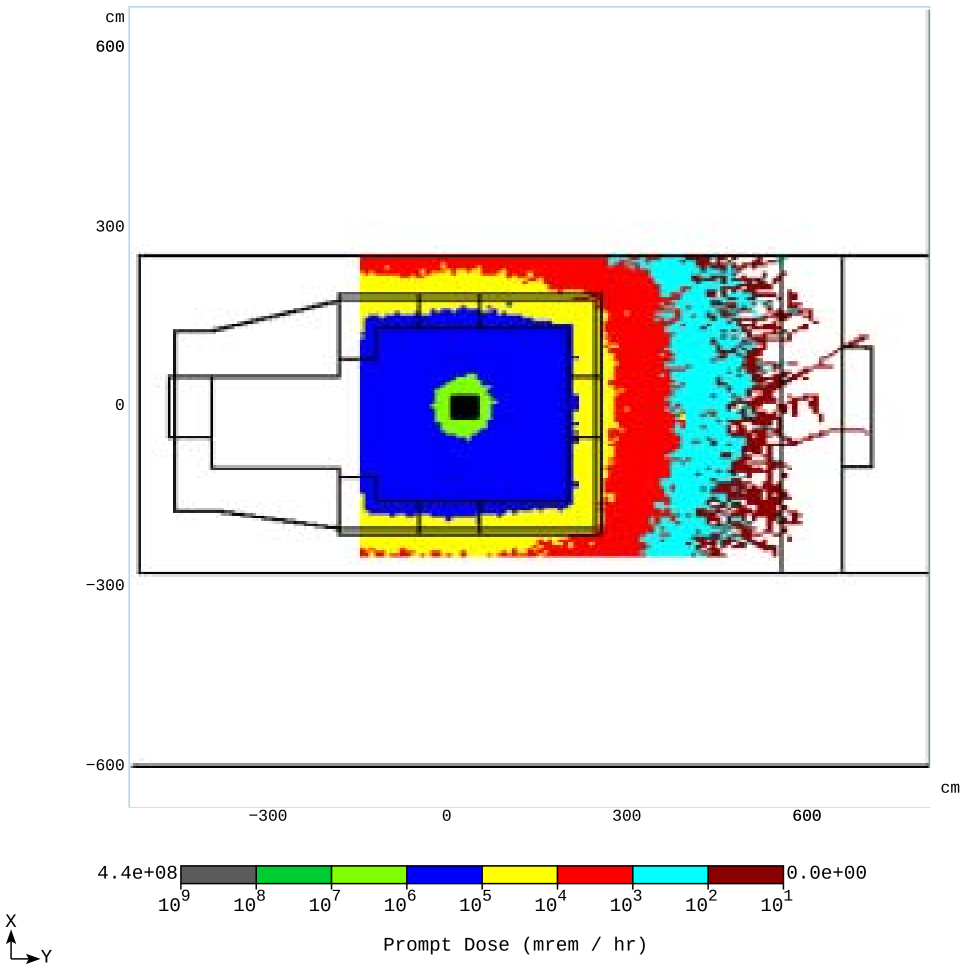

Figure 12: Prompt dose distribution in the location shown in Fig. 11.

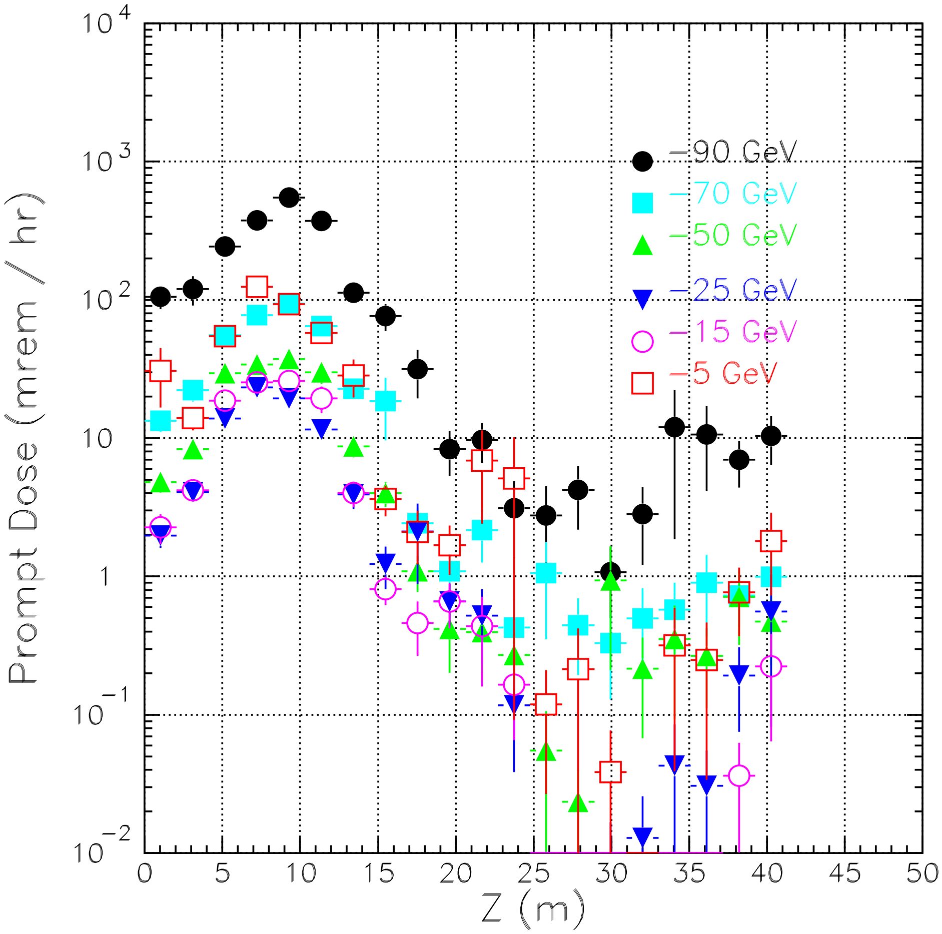

Figure 13: Prompt dose on the top of the concrete roof.

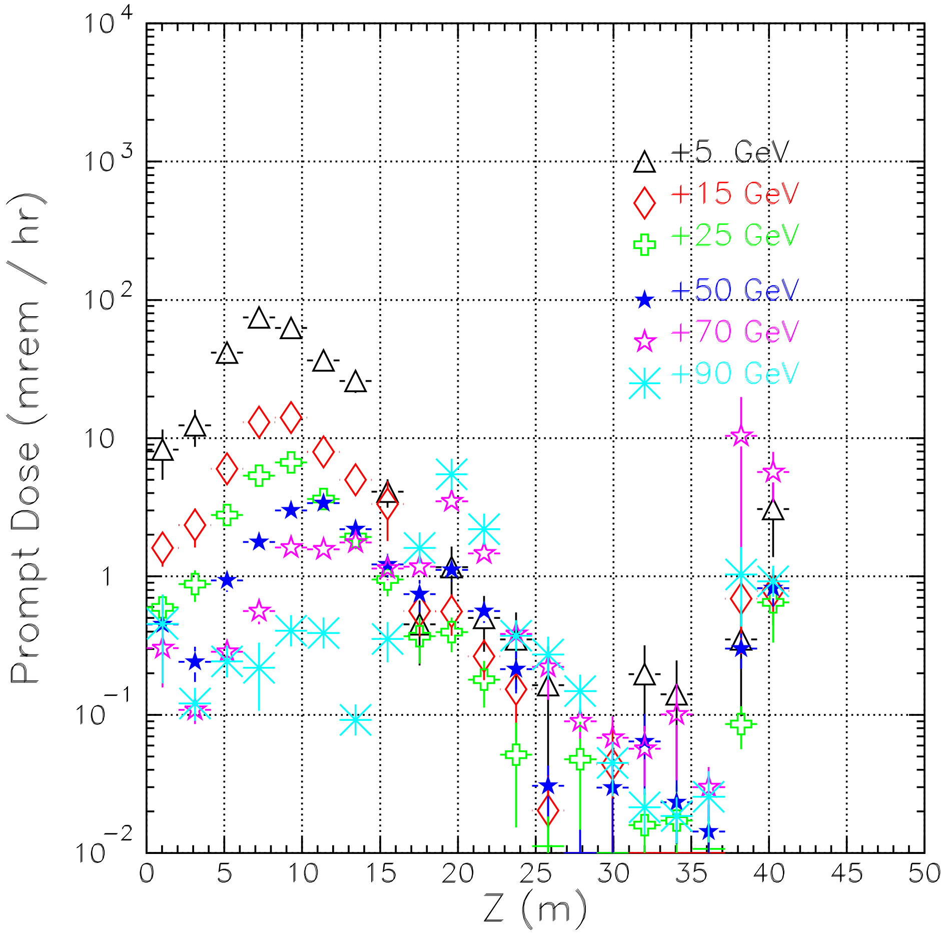

Figure 14: Prompt dose on the top of the concrete roof.

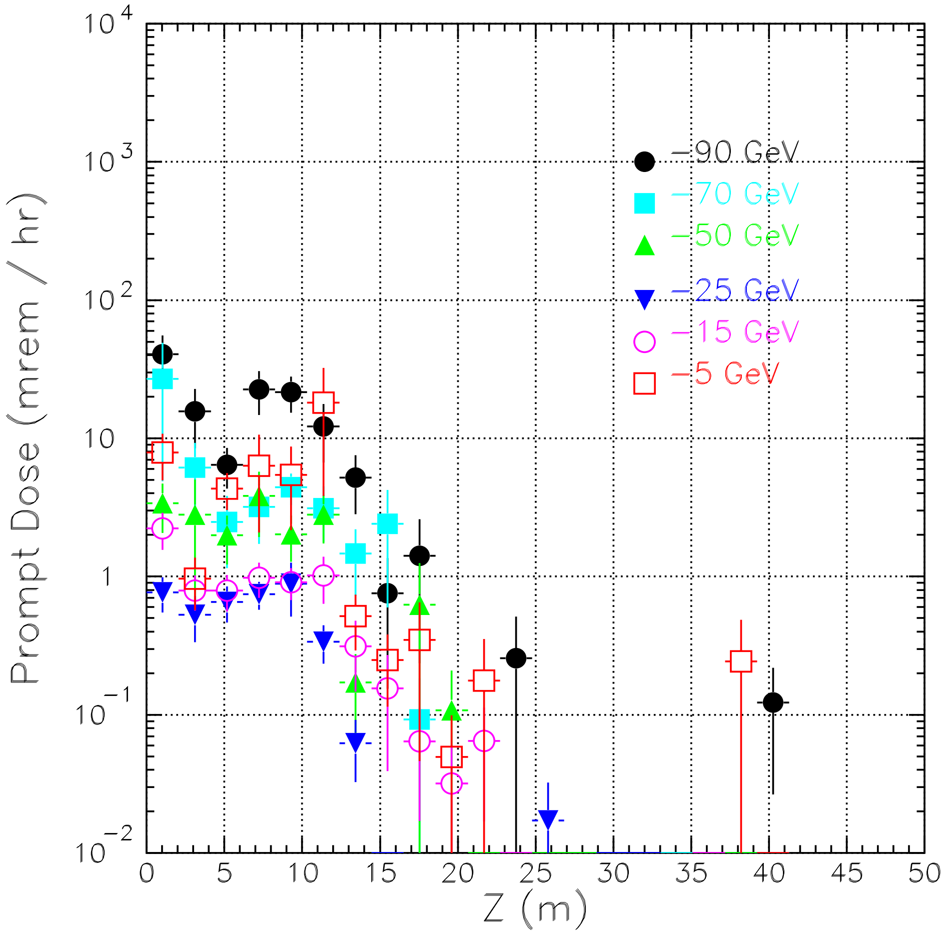

Figure 15: Prompt dose on the right side of beam enclosure in the Meson Building (looking downstream).

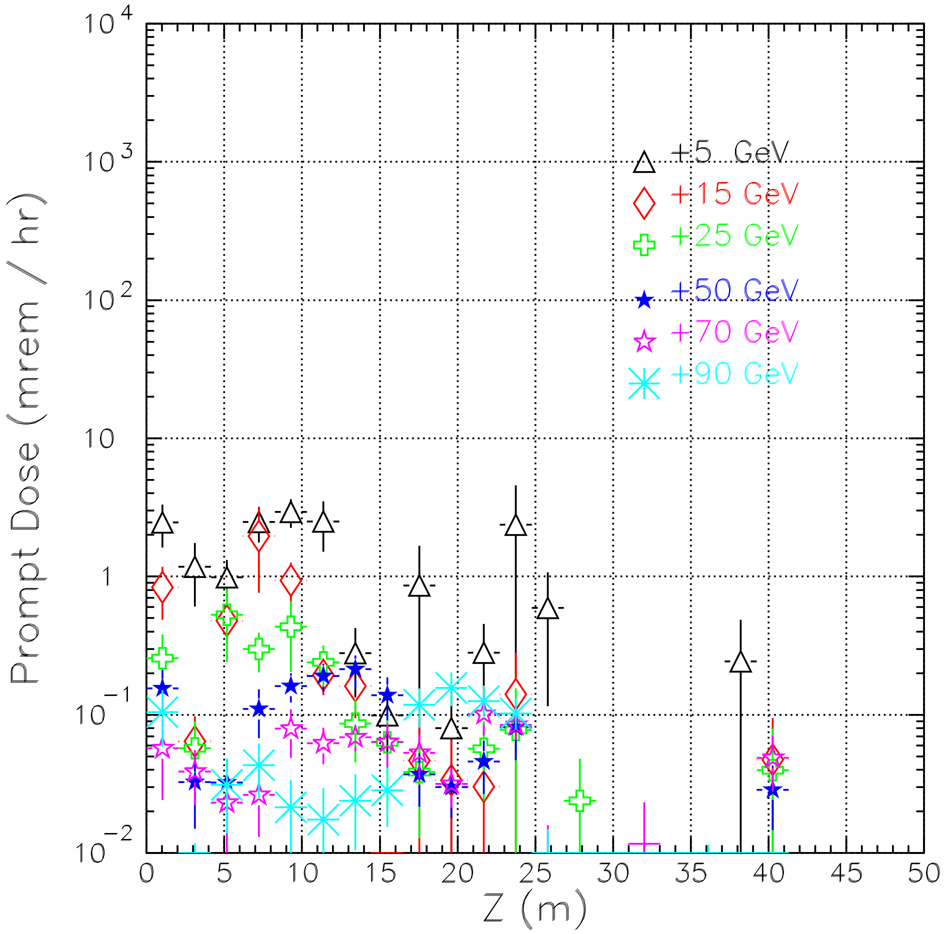

Figure 16: Prompt dose on the right side of beam enclosure in the Meson Building (looking downstream).

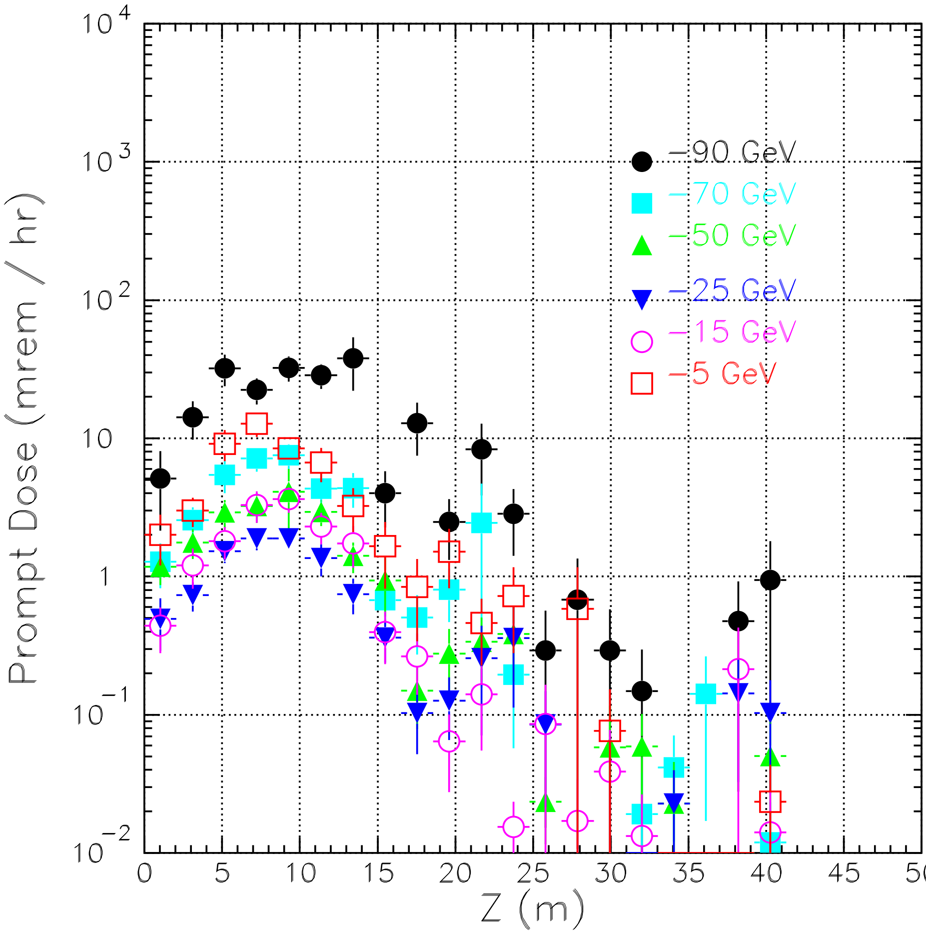

Figure 17: Prompt dose on the left side of beam enclosure in the Meson Building (looking downstream).

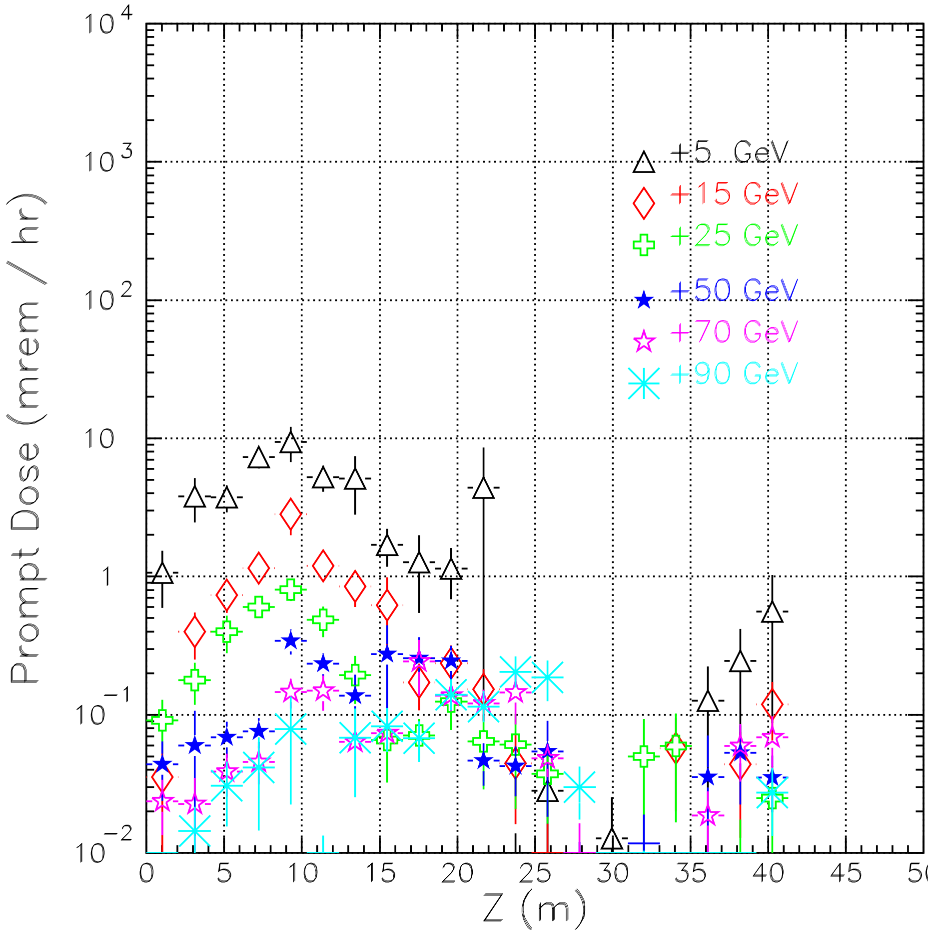

Figure 18: Prompt dose on the left side of beam enclosure in the Meson Building (looking downstream).

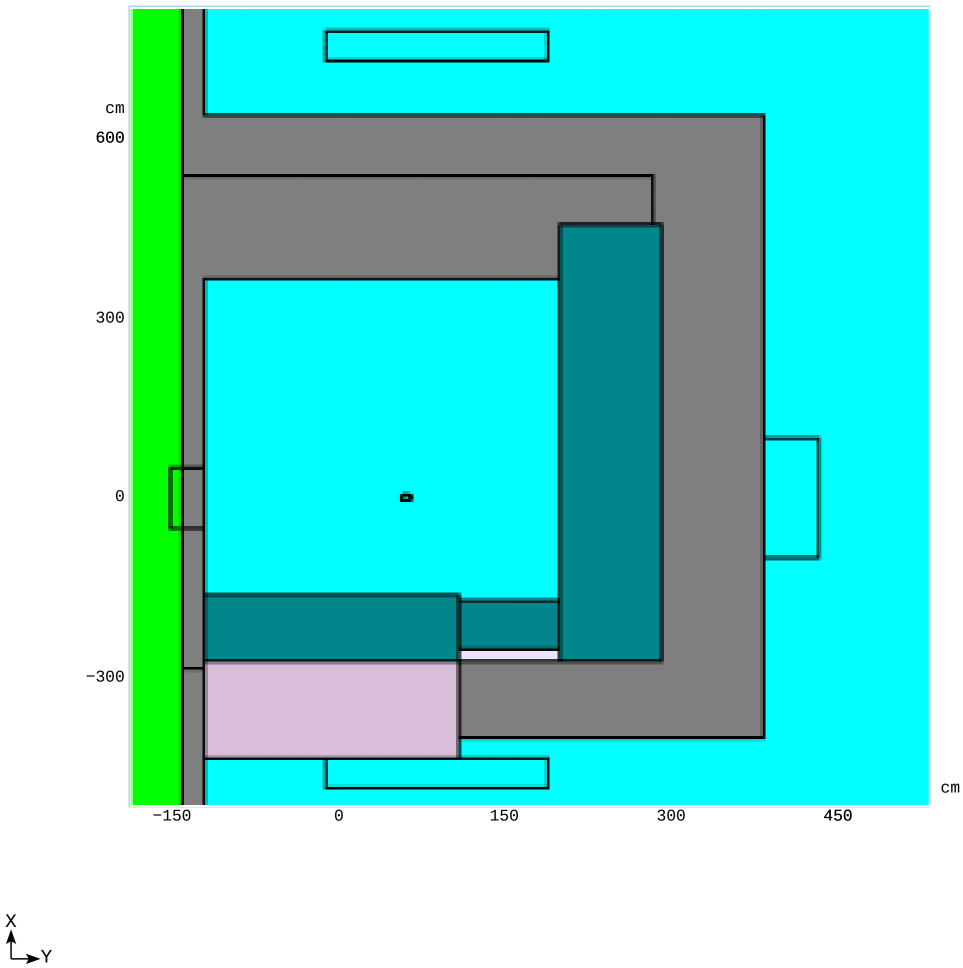

Figure 19: A cross-section of the beam enclosure in the Meson Building in the place of maximal prompt dose rate. The material are color-coded. Blue – air, grey – regular concrete, dark blue – heavy concrete, white – steel, light violet – heavy concrete.

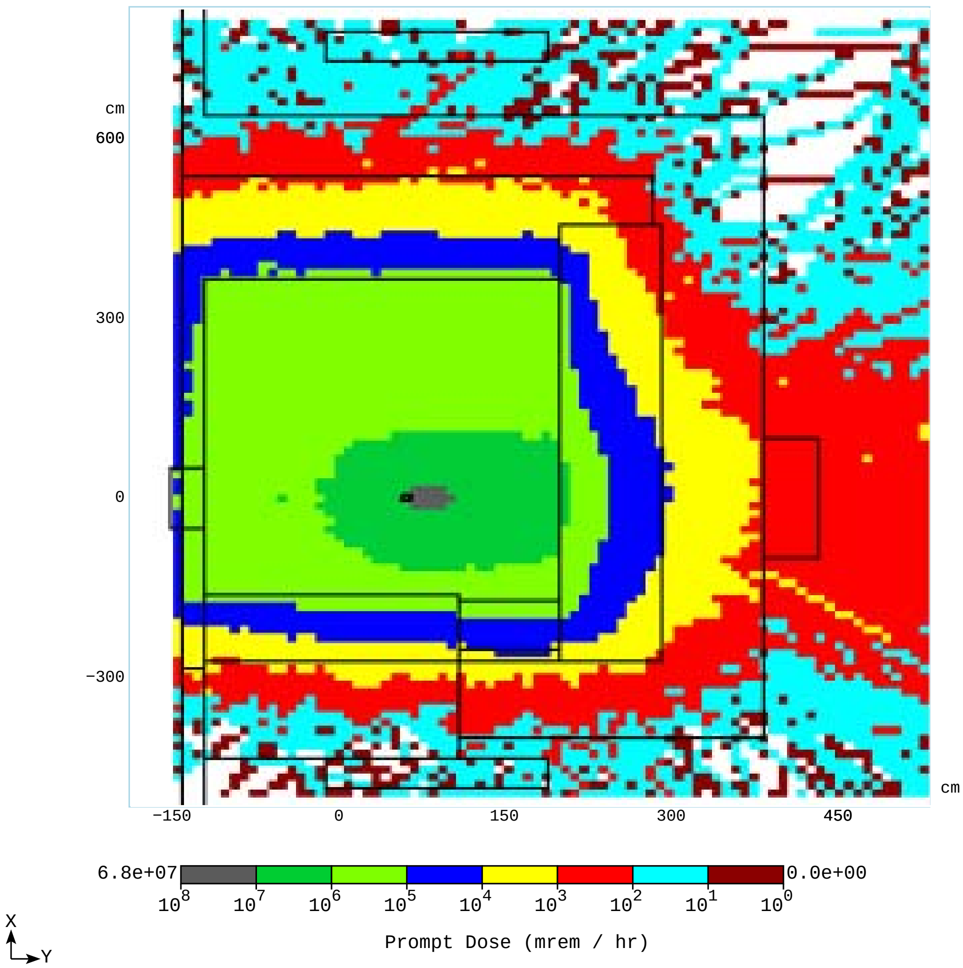

Figure 20: Prompt dose distribution in the location shown in Fig. 19.

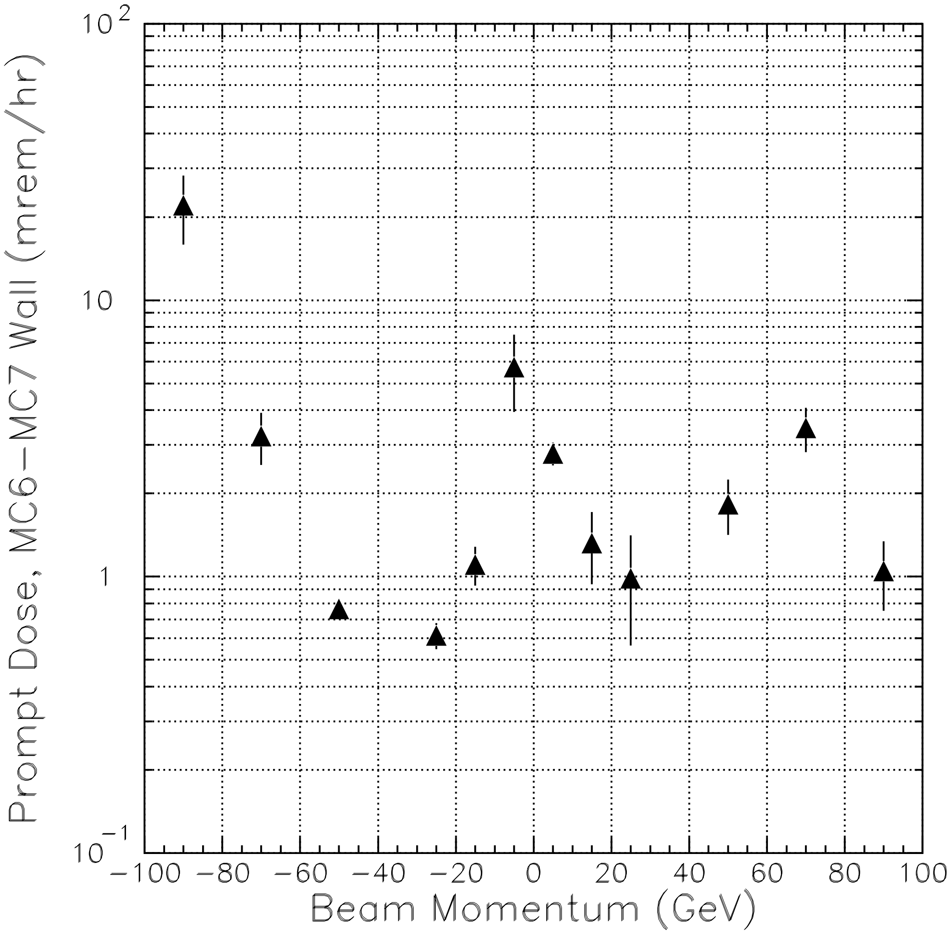

Figure 21: Prompt dose downstream of the concrete wall dividing the areas MC6 and MC7.

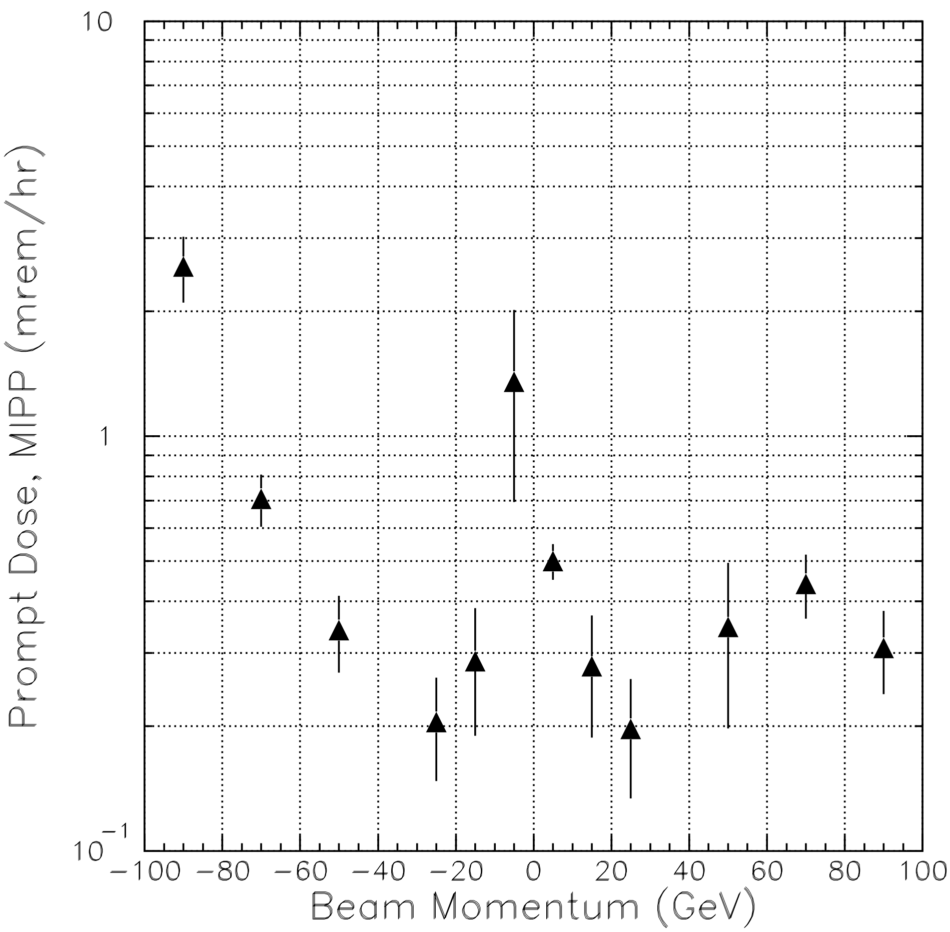

Figure 22: Prompt dose at the MIPP detector.

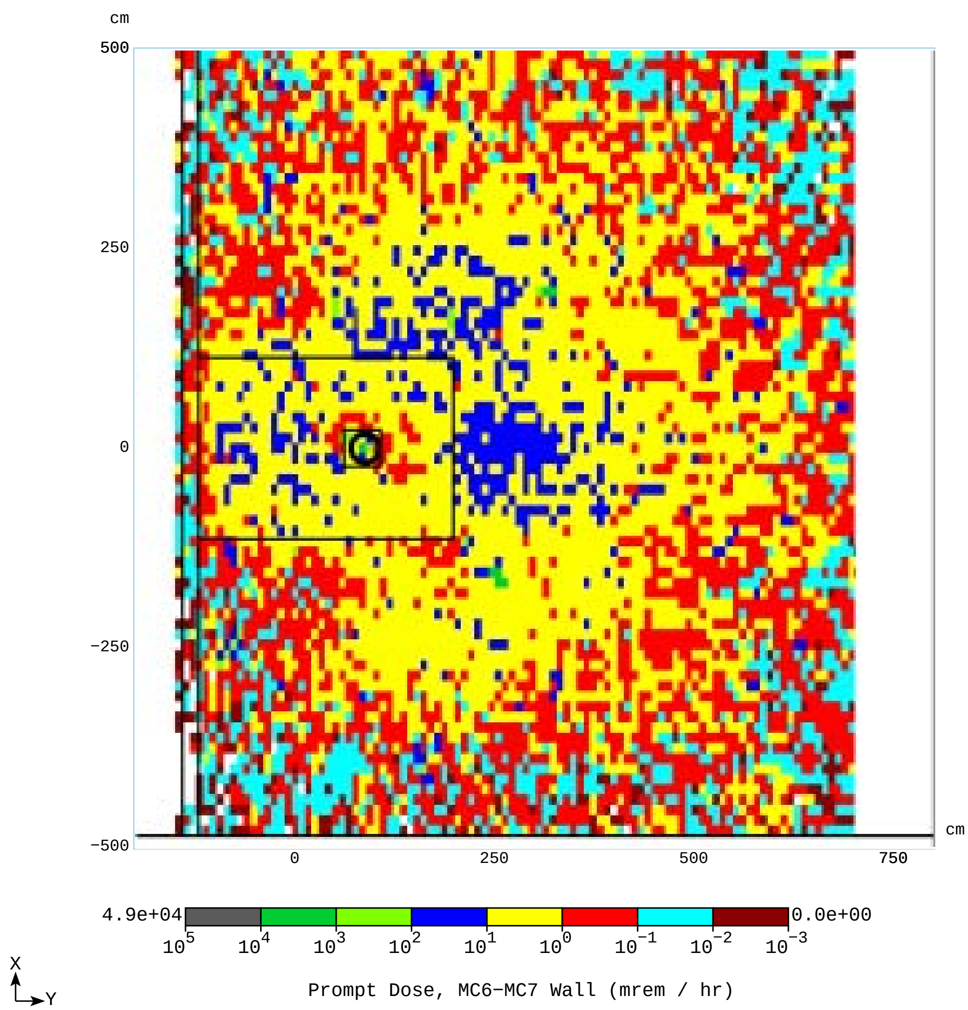

Figure 23: Prompt dose downstream of the concrete wall that divides the areas MC6 and MC7 for a run with the beam momentum of -90 GeV. A box corresponds to a profile of the wall.

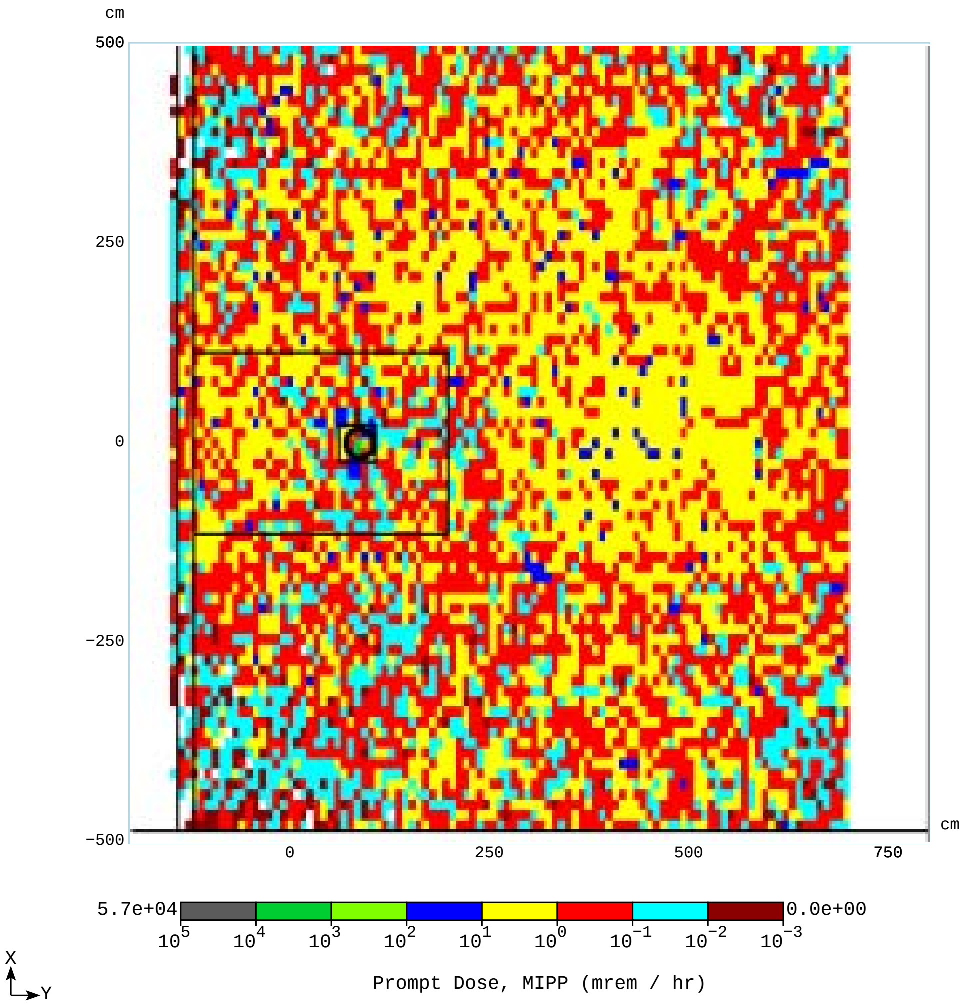

Figure 24: Prompt dose at the MIPP detector for the beam momentum of -90 GeV. A box corresponds to a profile of the wall that divides the areas MC6 and MC7. The box is kept for the sense of scale.