FERMILAB ACCELERATOR DIVISION

Site Riser Penetration Design for the M4 Beam Line

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The M4 beam line design includes a 16 foot earth equivalent berm. Site riser penetrations through the shielding berm are required for various alignment tasks. This document describes the design considerations for such penetrations in order to meet the requirements of the Fermilab Radiological Controls Manual.

Introduction

A MARS simulation of the M4 beam line was created to model performance of the 16 foot earth shield covering the M4 beam line. The M4 beam line tunnel is nominally 8 feet high by 10 feet wide. An MDC magnet is to be used as a switching magnet between the mu2e experiment and the M4 beam line diagnostic absorber. While the cross section of the magnet is used in this model, the nominal sagitta of the MDC magnet is not. The use of the magnet cross section without sagitta permits a direct comparison of the MARS simulation with the laboratory standard shielding criteria. An 8 inch diameter site riser penetration utilized at the Anti-proton Source facility is incorporated into the model. The magnet centerline is positioned 3 feet to the right of the left enclosure wall and 4 feet above the enclosure floor. The center of the site riser penetration is conservatively positioned 4 feet to the left of the right side enclosure wall. A trial MARS simulation was run to determine the position of the highest flux longitudinally relative to the MDC magnet. The peak occurs at z=3 meters as indicated in Figure 6. Images from the MARS GUI are included as Figures 1 through 4 to indicate the relative position of model features.

Input files used in the MARS simulation are included at the end of this document.

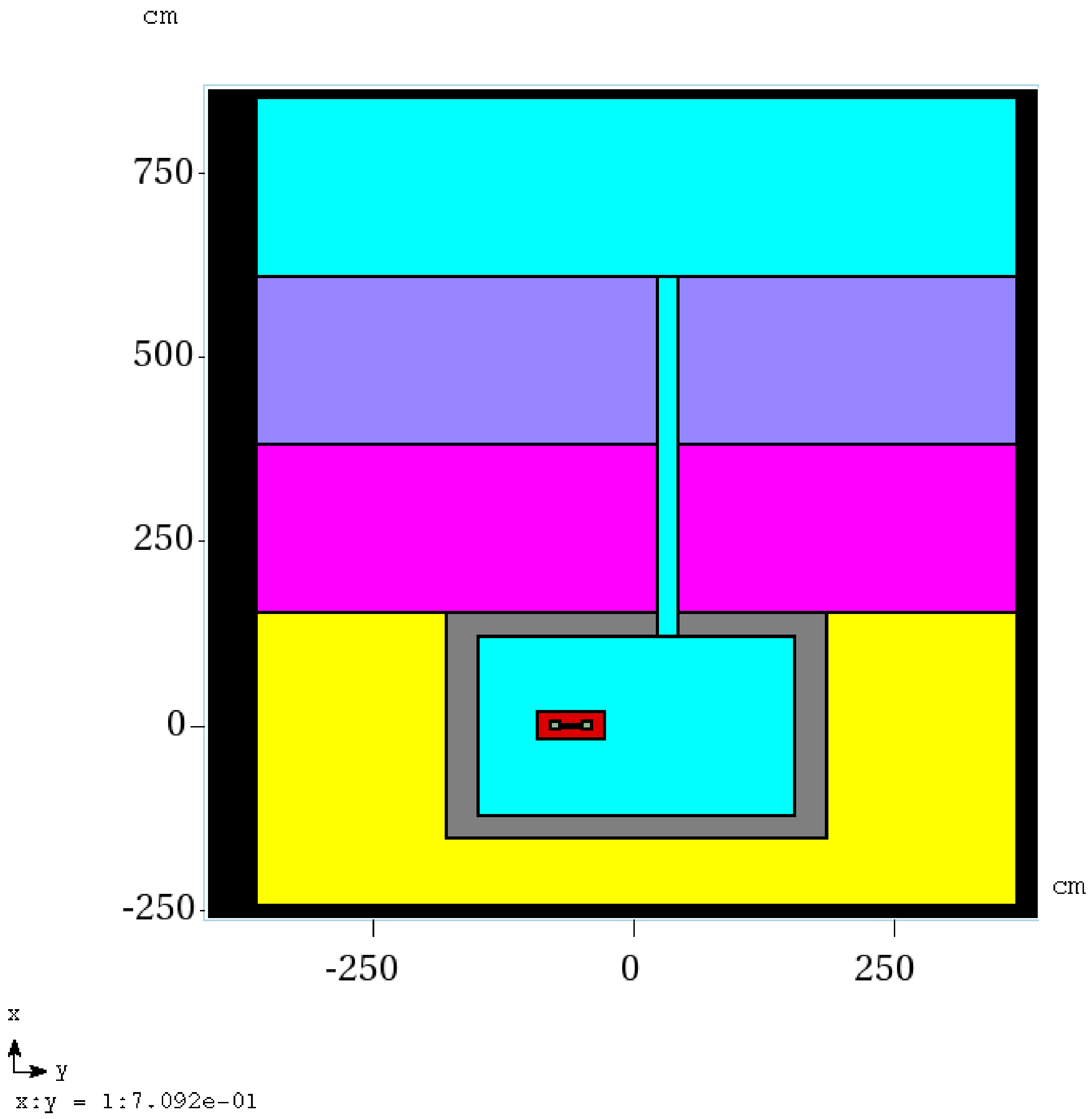

Figure 1: Elevation cross section of the MDC magnet, the concrete tunnel, site riser penetration, and various layers of gtil used in the model. The cyan layer at the top indicates the air above the berm surface. The 16 foot shield includes the 1 foot thick tunnel ceiling. Color codes indicated are: yellow, gtil; grey, concrete; cyan, air; red; magnet laminations; pink, gtil; and purple, gtil.

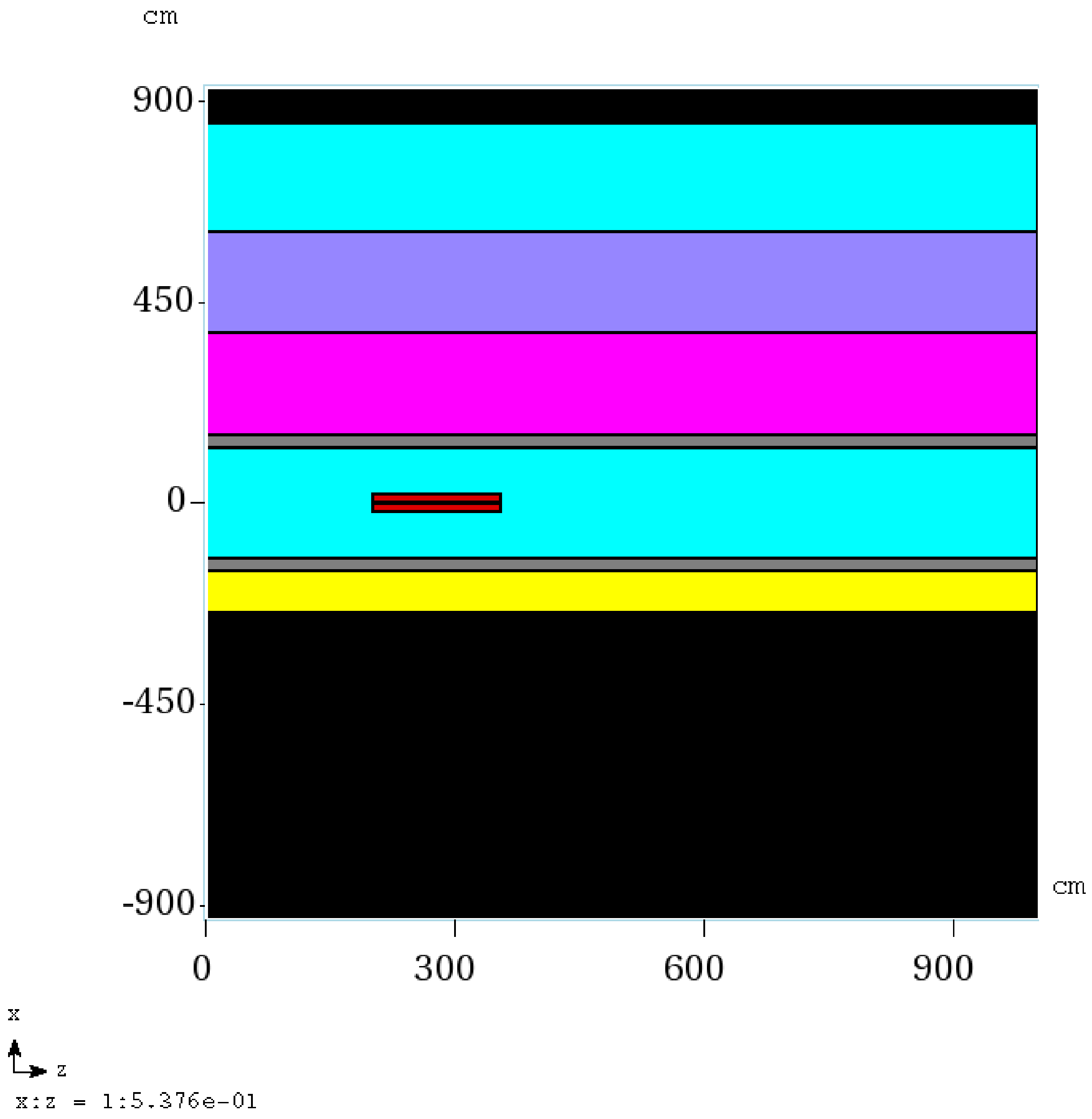

Figure 2: Elevation view of the model. The site riser penetration is out of the indicated plane by 4 feet. The magenta and violet layers are each 7.5 foot layers of the shielding berm. The MDC magnet is indicated as the red box. Color codes indicated are: yellow, gtil; grey, concrete; cyan, air; red; magnet laminations; pink, gtil; and purple, gtil.

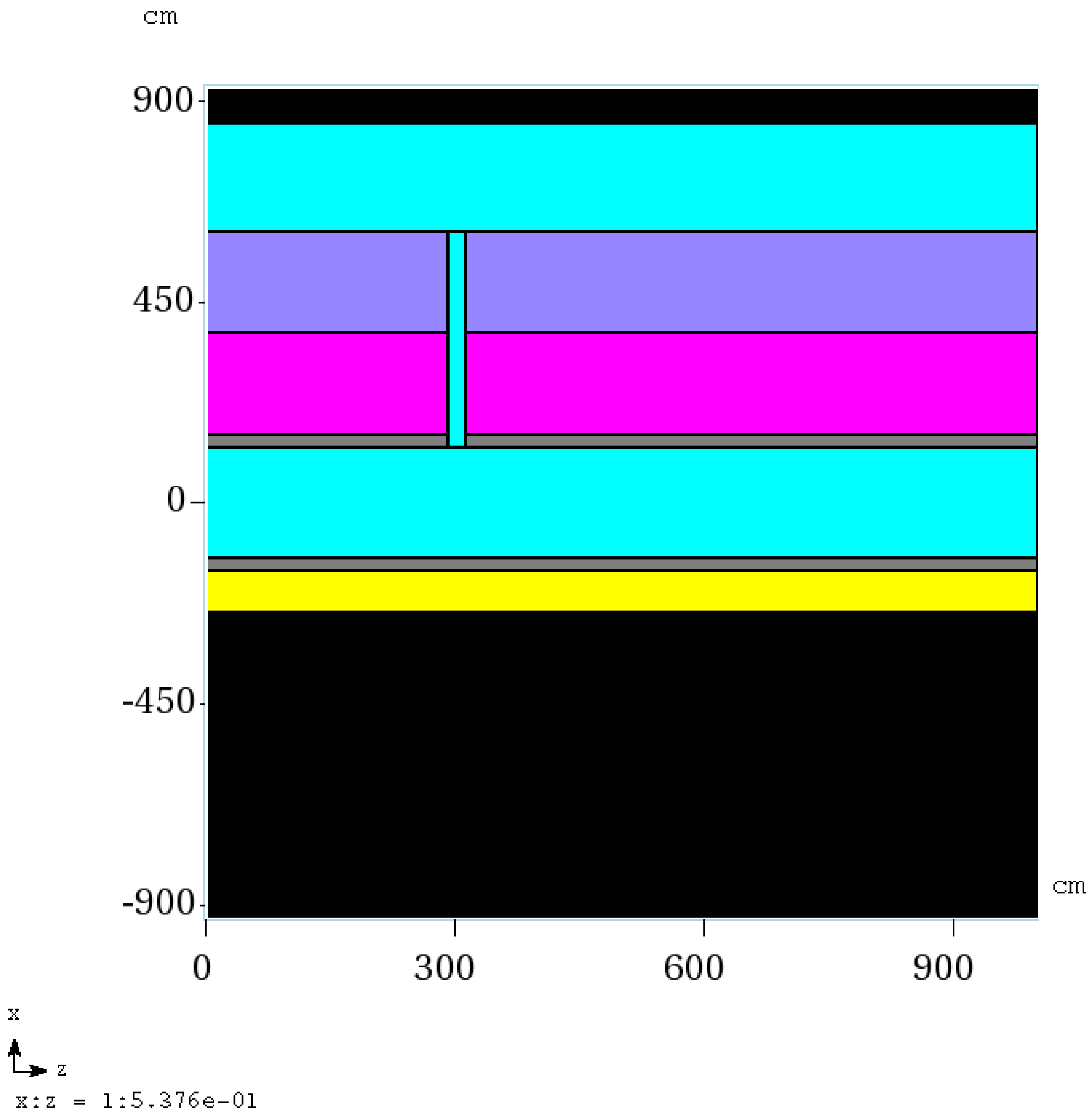

Figure 3: This elevation view is similar to Figure 2 except that it is 4 feet to the right of the beam line. Color codes indicated are: yellow, gtil; grey, concrete; cyan, air; pink, gtil; and purple, gtil.

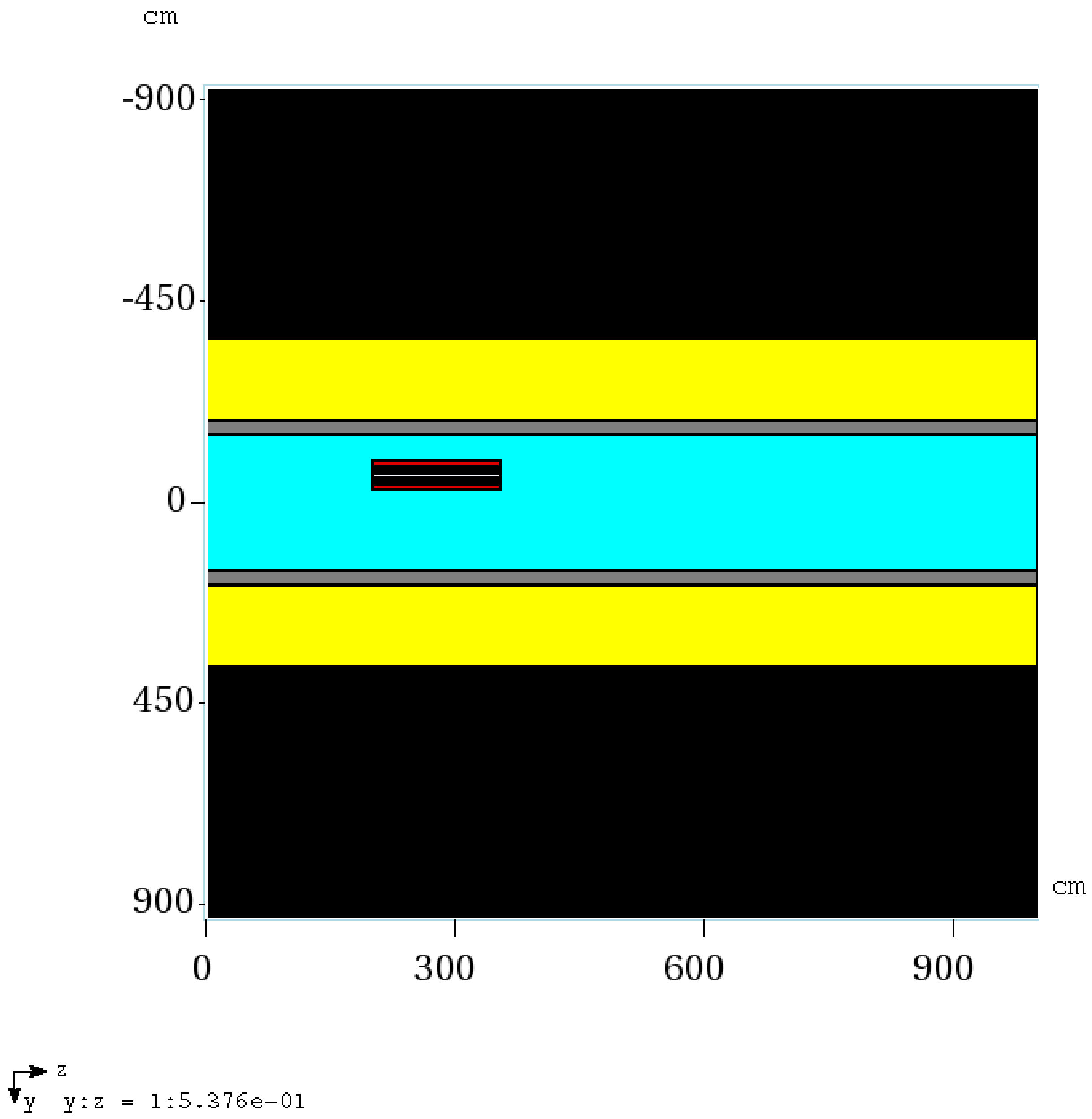

Figure 4: Plan view of the MARS simulation through the centerline of the beam line. Color codes indicated are: yellow, gtil; grey, concrete; cyan, air; and red; magnet laminations.

Beam Parameters

The generic shielding criteria [2] provides the beam geometry used in MARS simulations to produce the earth equivalent shielding required for the various control levels in the FRCM [1]. The beam centroid is placed at a distance of 1 sigma from the surface at which the beam interacts. The beam is directed with a Gaussian distribution, with no angular spread, parallel to the beam line element. For this work, a MARS simulation was made with a surface perpendicular to the beam axis at the exit of the MDC magnet with the dimensions of the vacuum chamber. 1,000 incident particles were used with a sigma of 0.25 cm. The distribution of unaffected protons is shown in Figure 5. A total of 848 - 8 GeV protons were collected on the surface indicating the portion of the incident beam lost is 15.2%. A plan view of particle tracks generated by the beam in the vicinity of the MDC magnet is shown in Figure 6. All results reported in this paper are based upon an 8 kW, 8 GeV beam with a resulting beam power loss of about 1.2 kW.

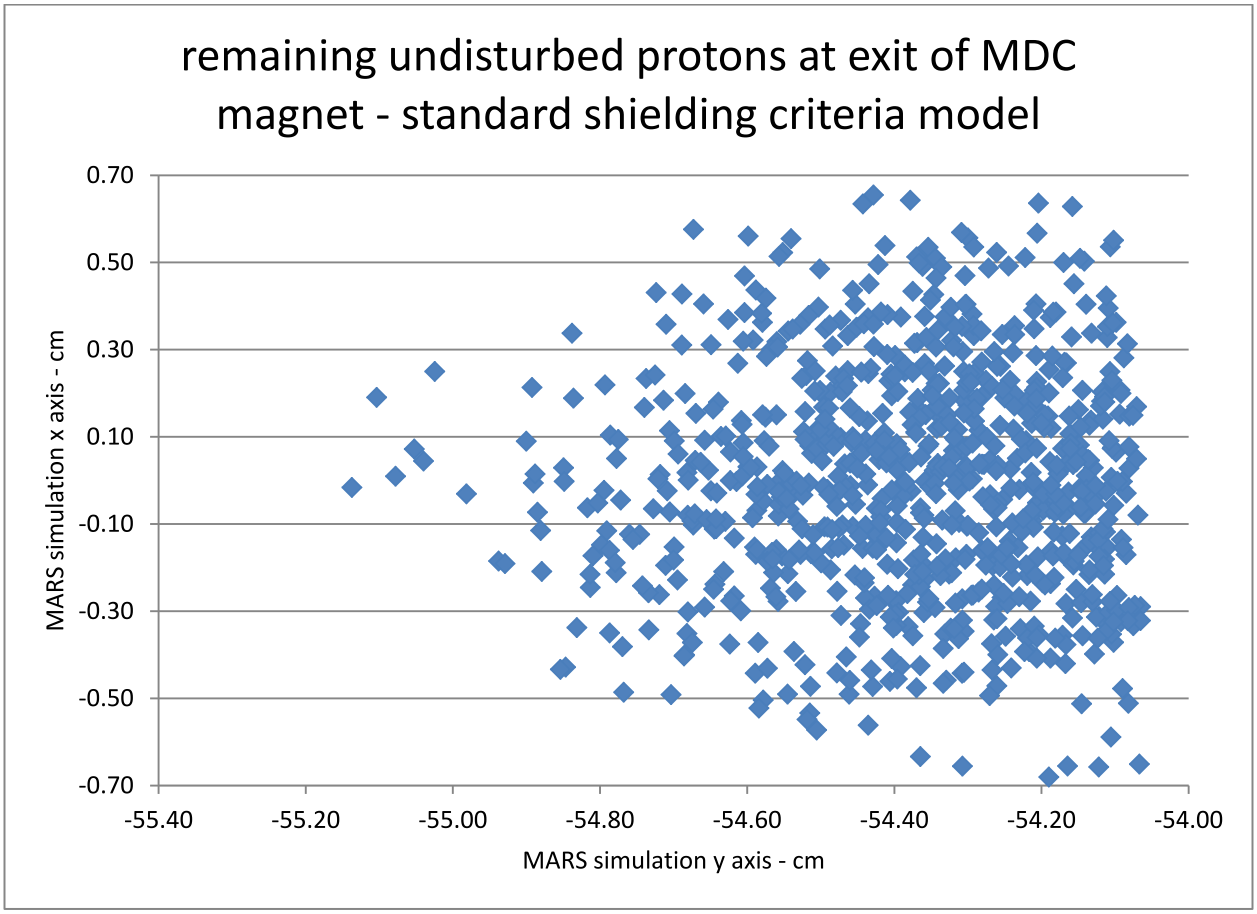

Figure 5: Distribution of protons exiting the MDC magnet without interacting in the MDC magnet. 848 of 1000 incident particles go through the magnet without interacting. This is equivalent to a 15.2% beam loss. The horizontal center of the vacuum chamber is at y=-60.96 cm and the right edge is at y=-54.0588 cm.

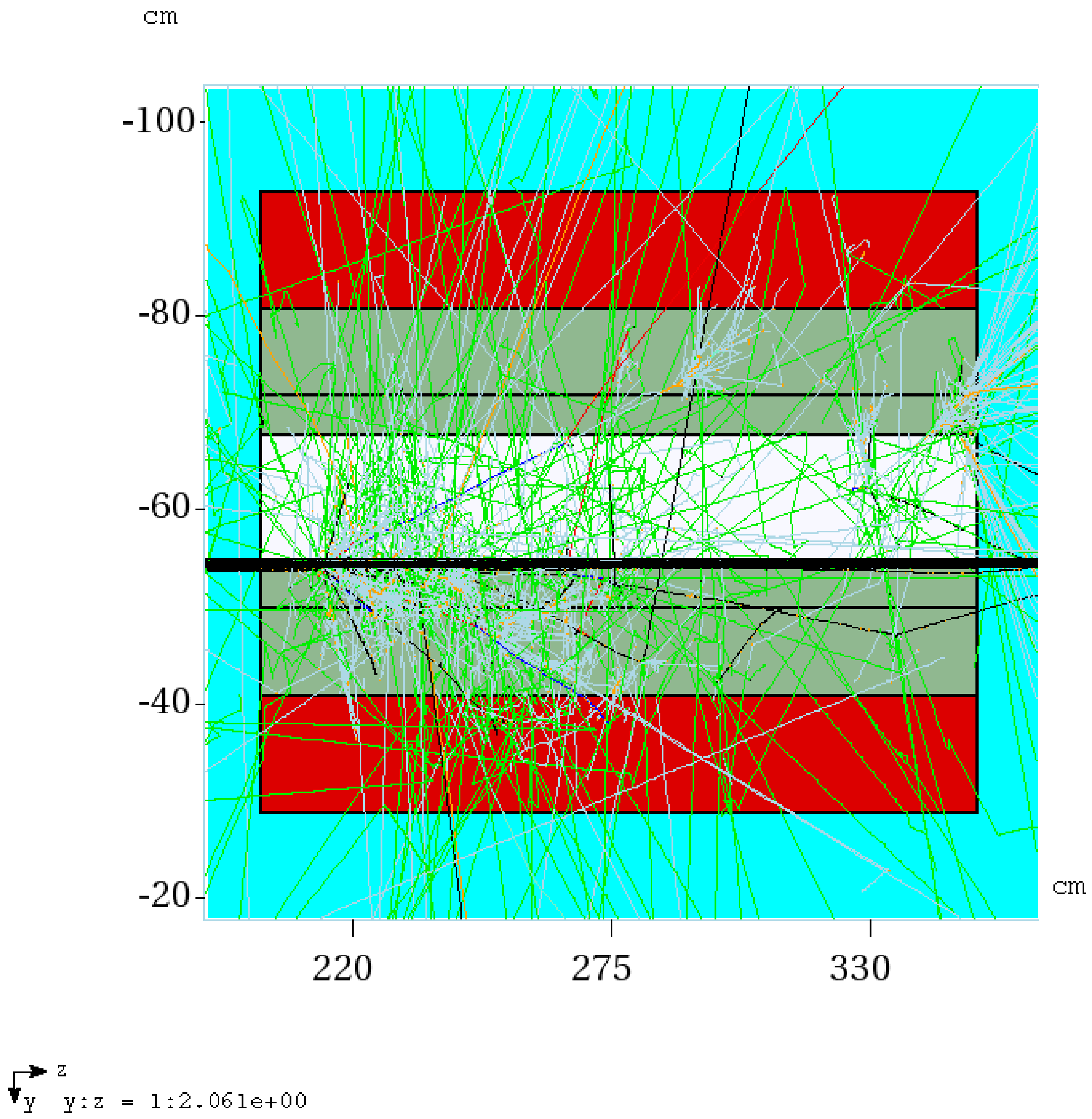

Figure 6: Particle tracks generated in the MARS simulation from 20 incident particles. About 15% of the beam strikes the upstream pole face of the magnet while the remaining 85% passes through the magnet aperture without scattering. Color codes indicated are: cyan, air; red; magnet laminations; green, magnet coils; and white, vacuum. The major particle track colors are; black, protons; and green, neutrons; grey, photons; red, pions; and orange, electrons.

Simulation procedure and results – Stage 1

For thick shielding problems, it is recommended that the simulation be broken into multiple runs. For this calculation, a particle surface was created at x=381.0 cm for a stage 1 run. A trial run was made to determine the total number of 8 GeV incident protons required to produce about 5E5 particles for a stage 2 run. The determination of running parameters is illustrated in Table 1.

Table 1: Test run parameters, estimate of required incident particles and running time, and the chosen stage 1 run parameters

	Test run	
ip	10000	
lines	32	
runtime	335	seconds
	target	
desired lines	500000	
required ip	156250000	
required runtime	1456	hours
	Stage 1 parameters	
assume	500	jobs
ip per job	312500	

The total number of incident particles for the stage 1 run was 1.5625E8 (PRIME). The stage 1 run produced 500 mars.hbook files containing histograms which were statistically combined with the r_average fortran routine into a single mars.hbook file. The run also resulted in 500 fort.71 files which, when concatenated, produced a particle source file of 583,233 particles (STACK). The run time for each of the 500 jobs was less than 3 hours.

Figure 7 shows the resulting total flux at the tunnel ceiling while Figure 8 shows the prompt effective dose rate there. The placement of the site riser at z=300 cm in the model springs from the results of the figures. The site riser was placed in the model to create the largest possible source to the penetration entrance.

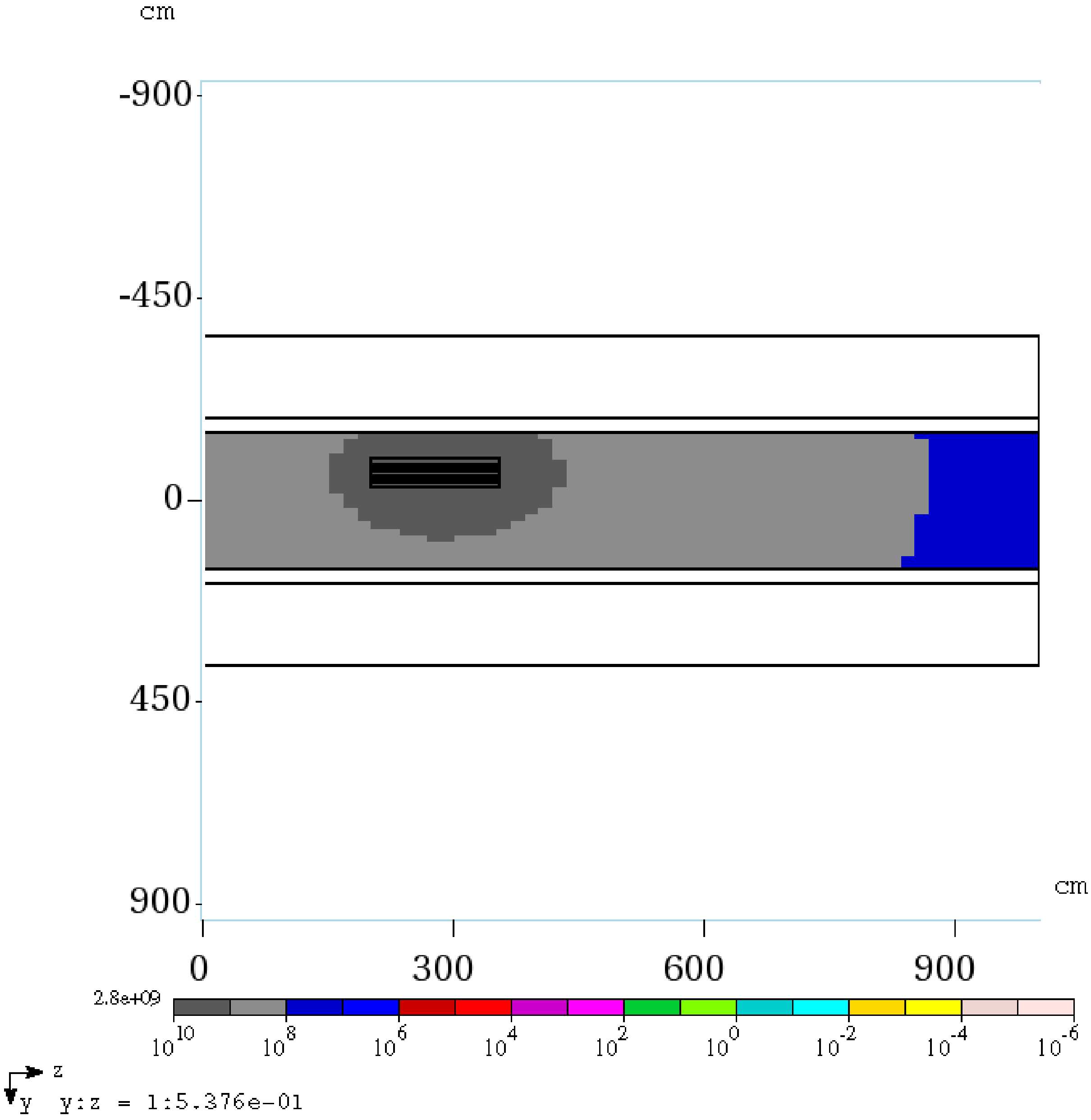

Figure 7: Stage 1 result showing the total flux at tunnel ceiling

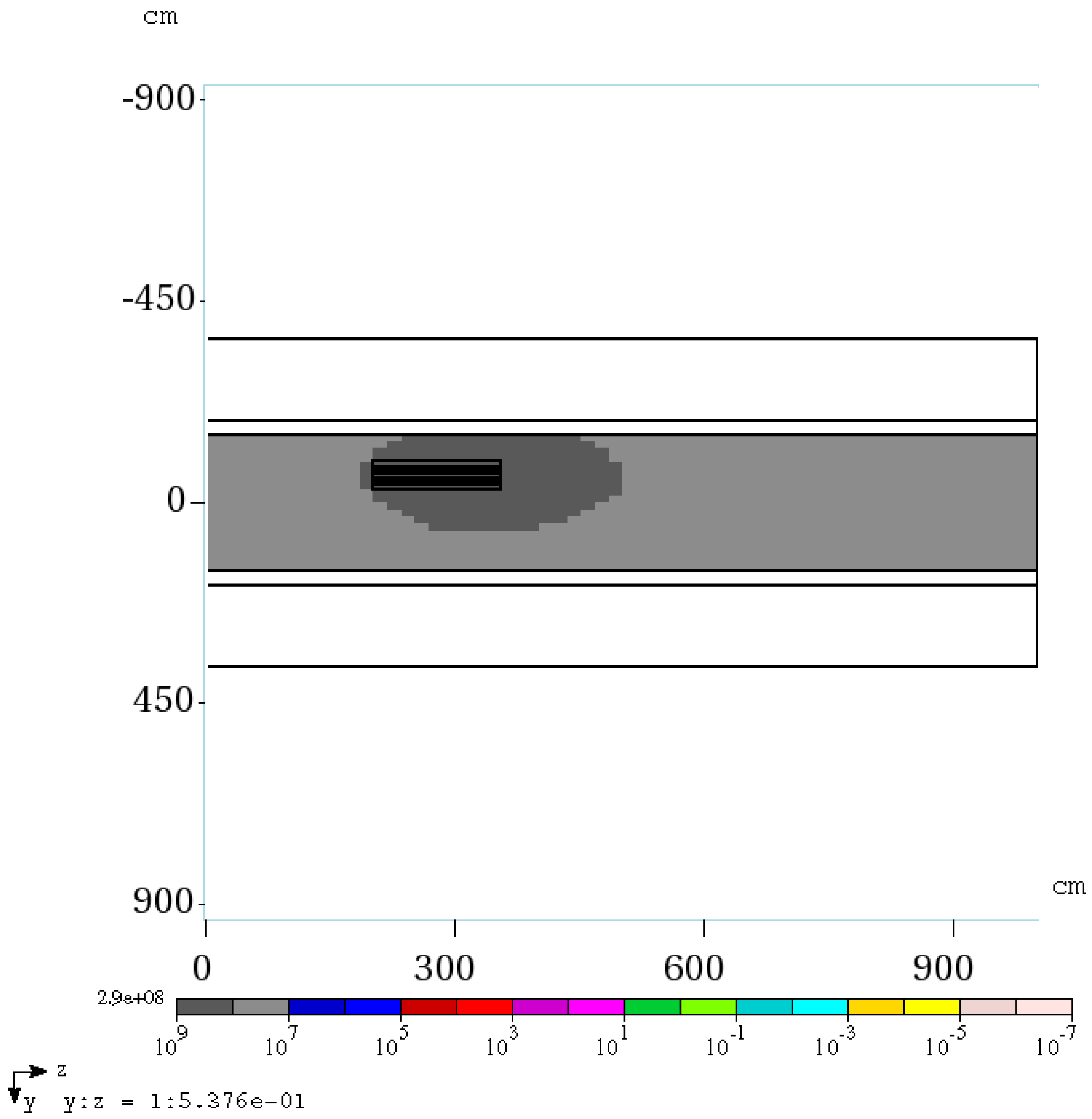

Figure 8: Stage 1 tunnel ceiling effective dose rate in units of mrem/hr normalized to an 8 kW beam with a 15% beam loss.

The total flux for 2 longitudinal, elevation views are shown in Figure 9 and Figure 10. The histograms scales for these 2 figures are made identical intentionally to make enable comparisons for the two longitudinal slices. The determination of prompt effective dose rates on the shielding berm and at the exit of the penetration is made in the stage 2 run.

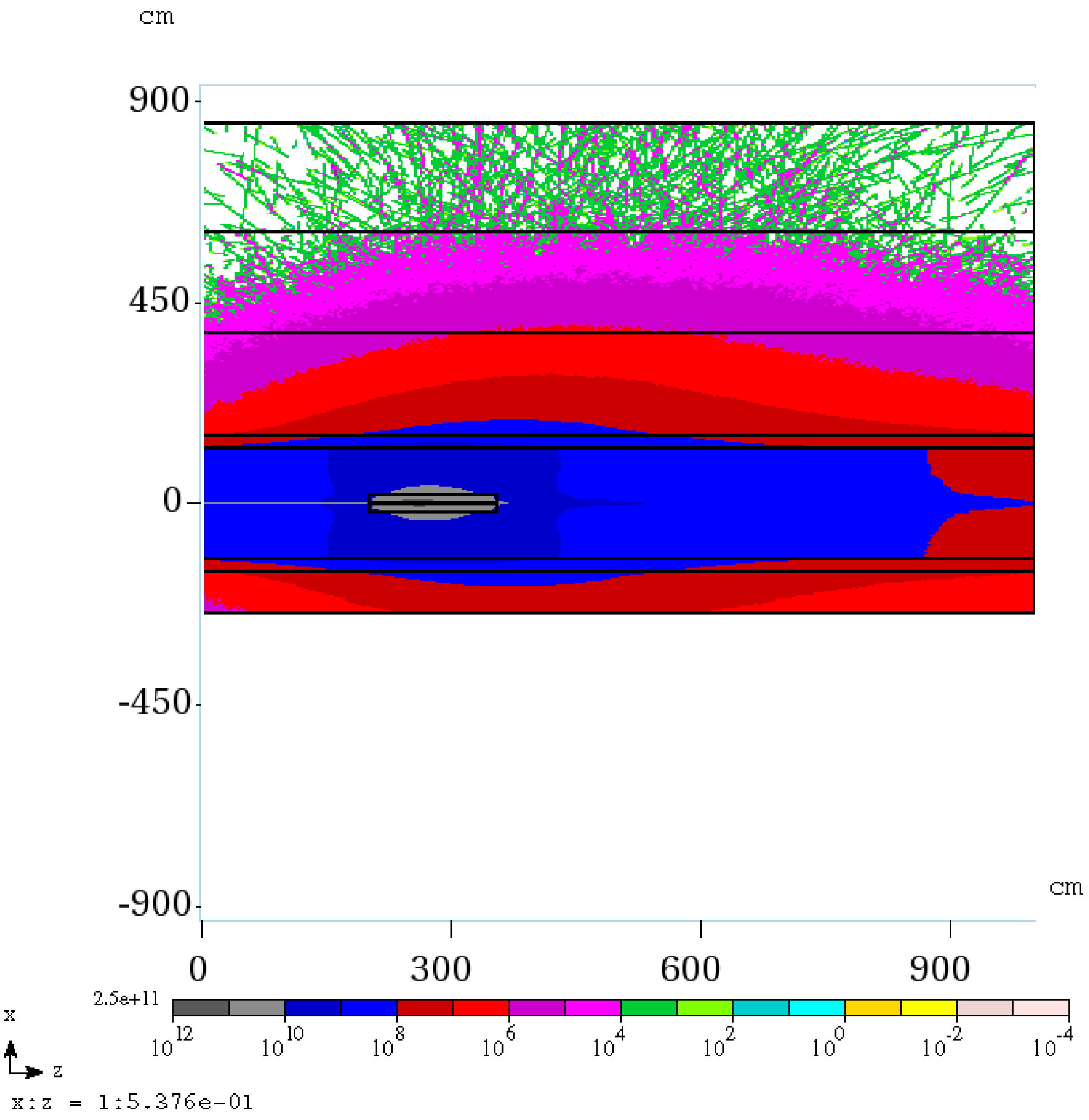

Figure 9: Stage 1 flux elevation view around the magnet beam loss

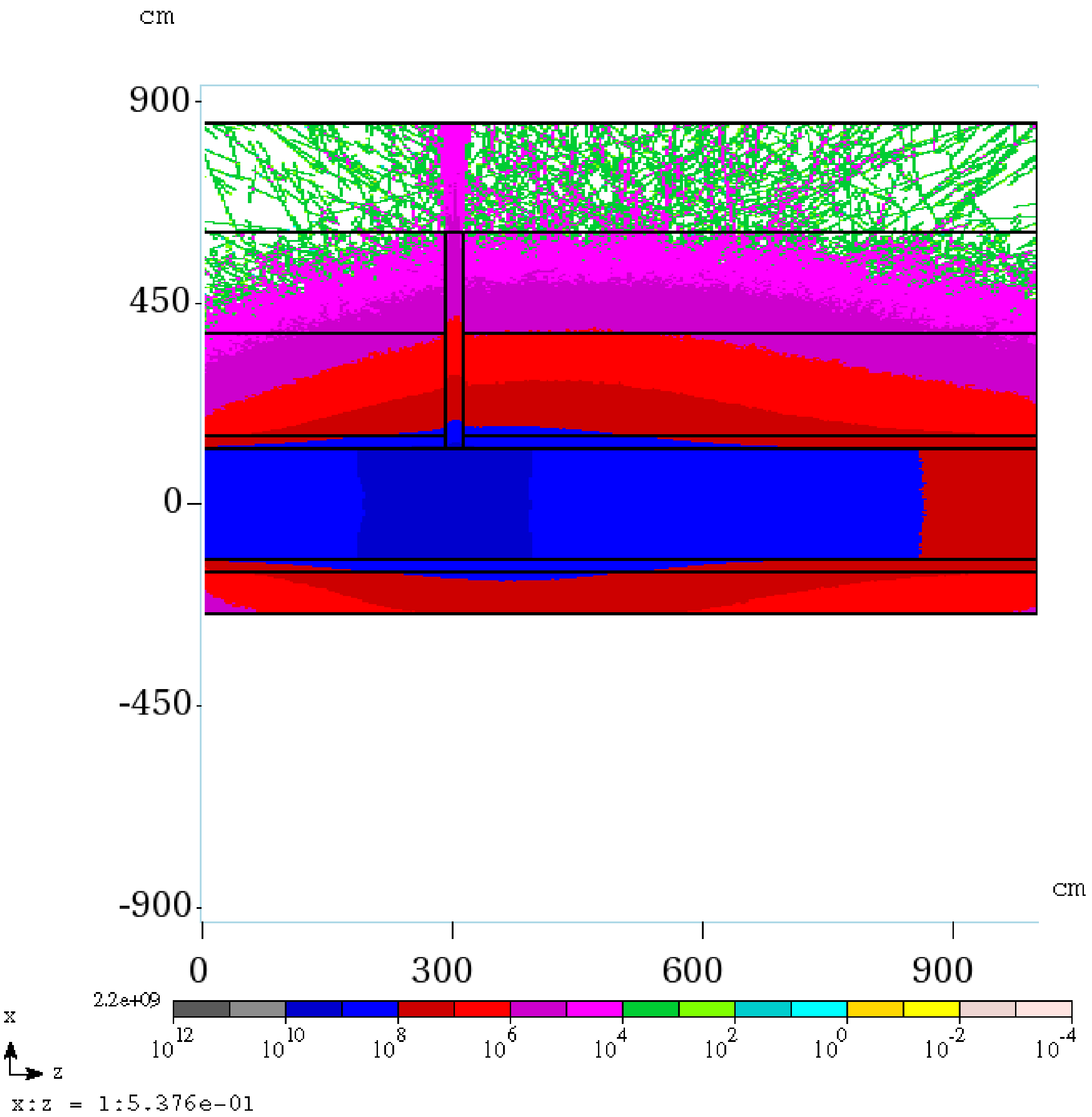

Figure 10: Stage 1 flux elevation view in plane of the site riser. Elevated flux at the 8” site riser penetration is clearly illustrated.

Simulation procedure and results – Stage 2

The particle file generated in the Stage 1 run was used as a source term for the Stage 2 run. The particle file source is the surface at x=381.0 cm. The particle file containing 583,233 particles was run through exactly one time for each of 500 jobs. A weighting factor, determined by the ratio STACK/PRIME is applied to each particle in the file. The run time per job on the grid was well under 2 hours. The result of the Stage 2 run produced 500 mars.hbook files which were statistically combined into one mars.hbook file using the r_average fortran routine.

Figure 11 and Figure 12 show longitudinal, elevation views of the resulting total flux along the beam line and along the plane containing the penetration, respectively. These figures can be compared with the previous Figure 9 and Figure 10. Note that the statistics in the Stage 2 run are very good in the outer shield layer compared with the Stage 1 run. The scales for these 4 figures are made identical for comparison purposes.

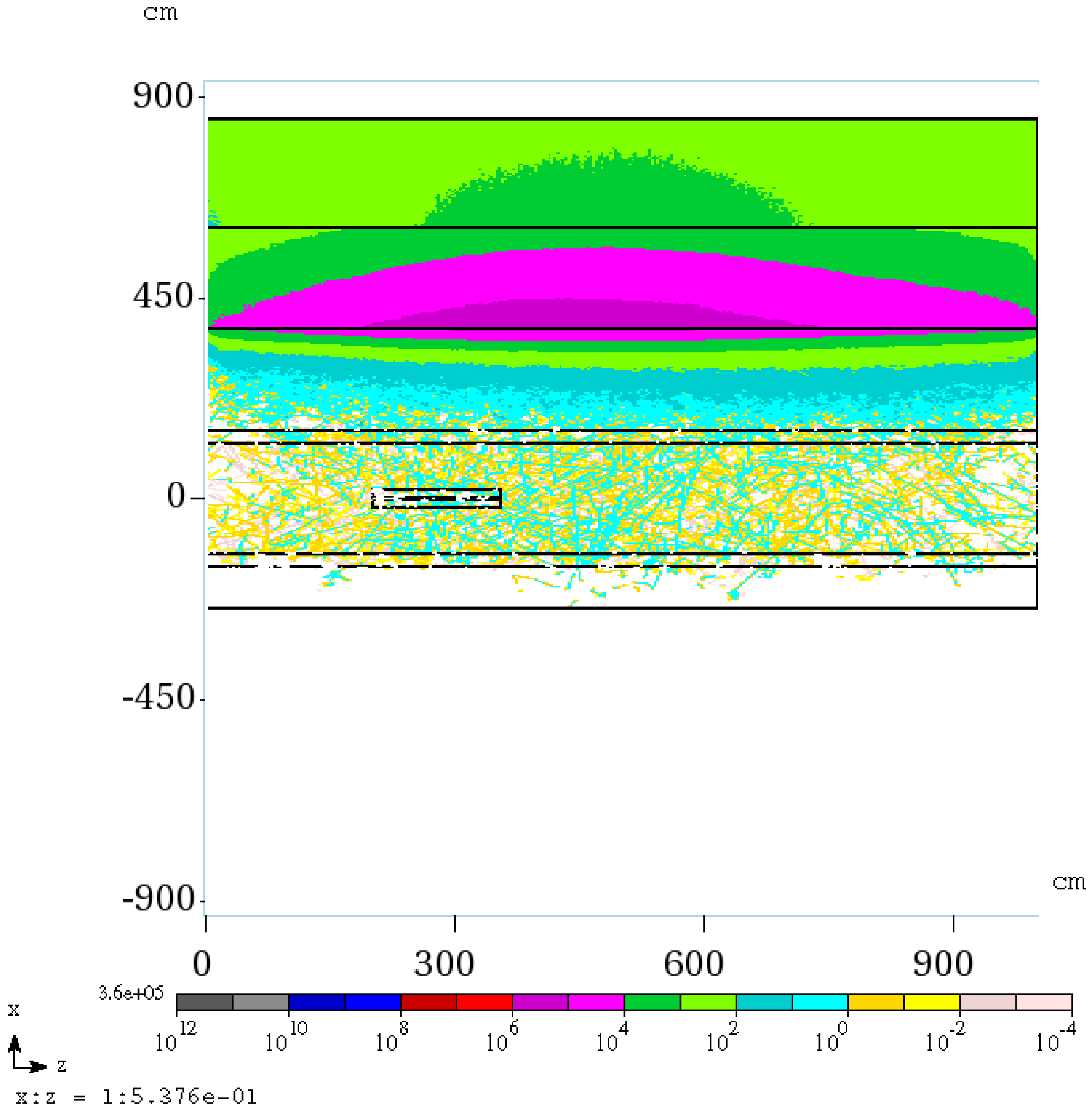

Figure 11: Stage 2 flux result in the longitudinal, elevation view in plane of the beam line

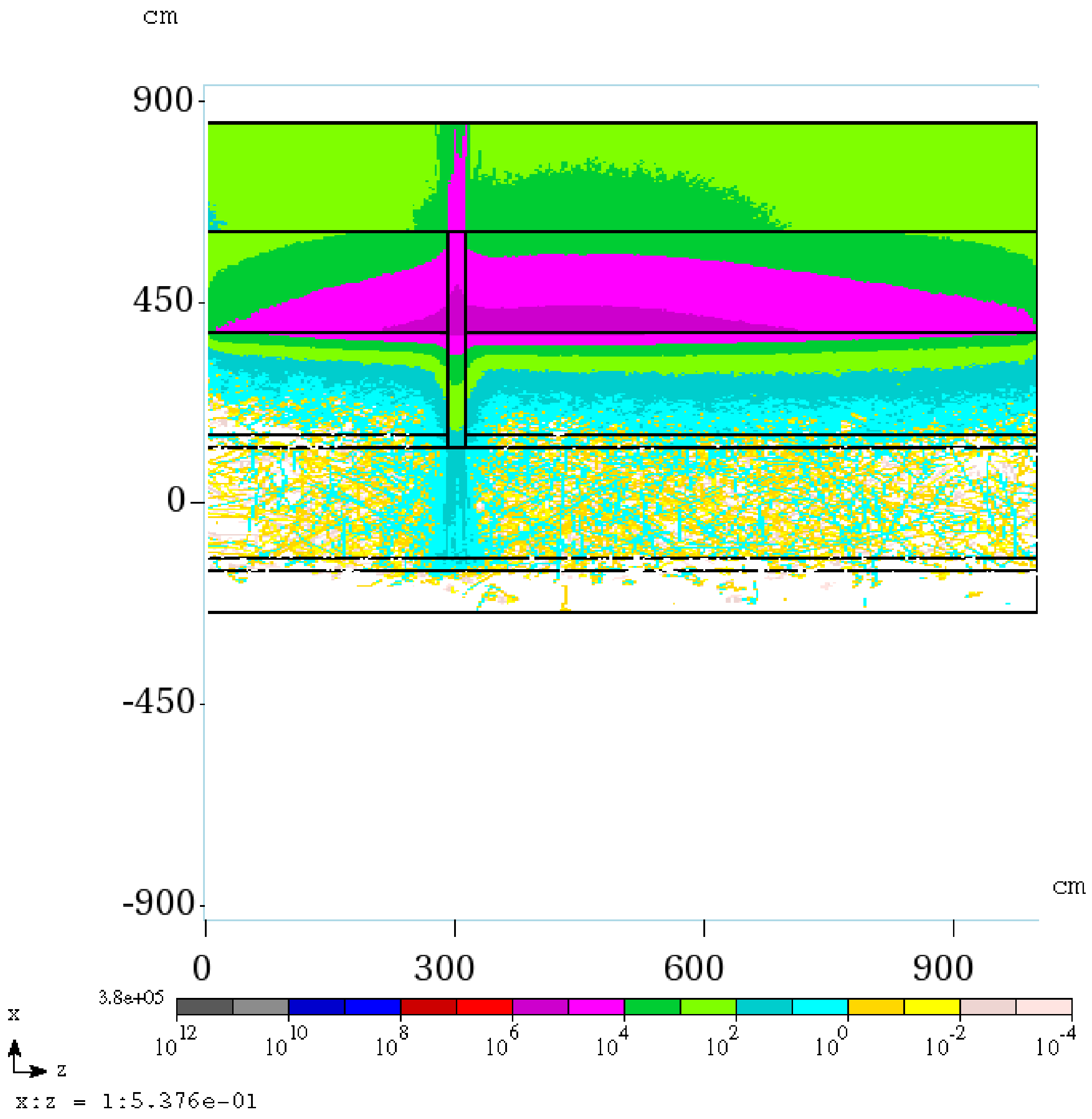

Figure 12: Stage 2 flux result in the longitudinal, elevation view in plane of the site riser

Figure 13 and Figure 14 are histograms of prompt effective dose rate for the surface on the berm and for the surface over and around the site riser penetration, respectively. The peak dose rates along the vertical plane directly above the beam line are 200 to 300 mrem per hour. As indicated in Figure 14 the peak effective dose rate over the penetration is 5,800 mrem per hour.

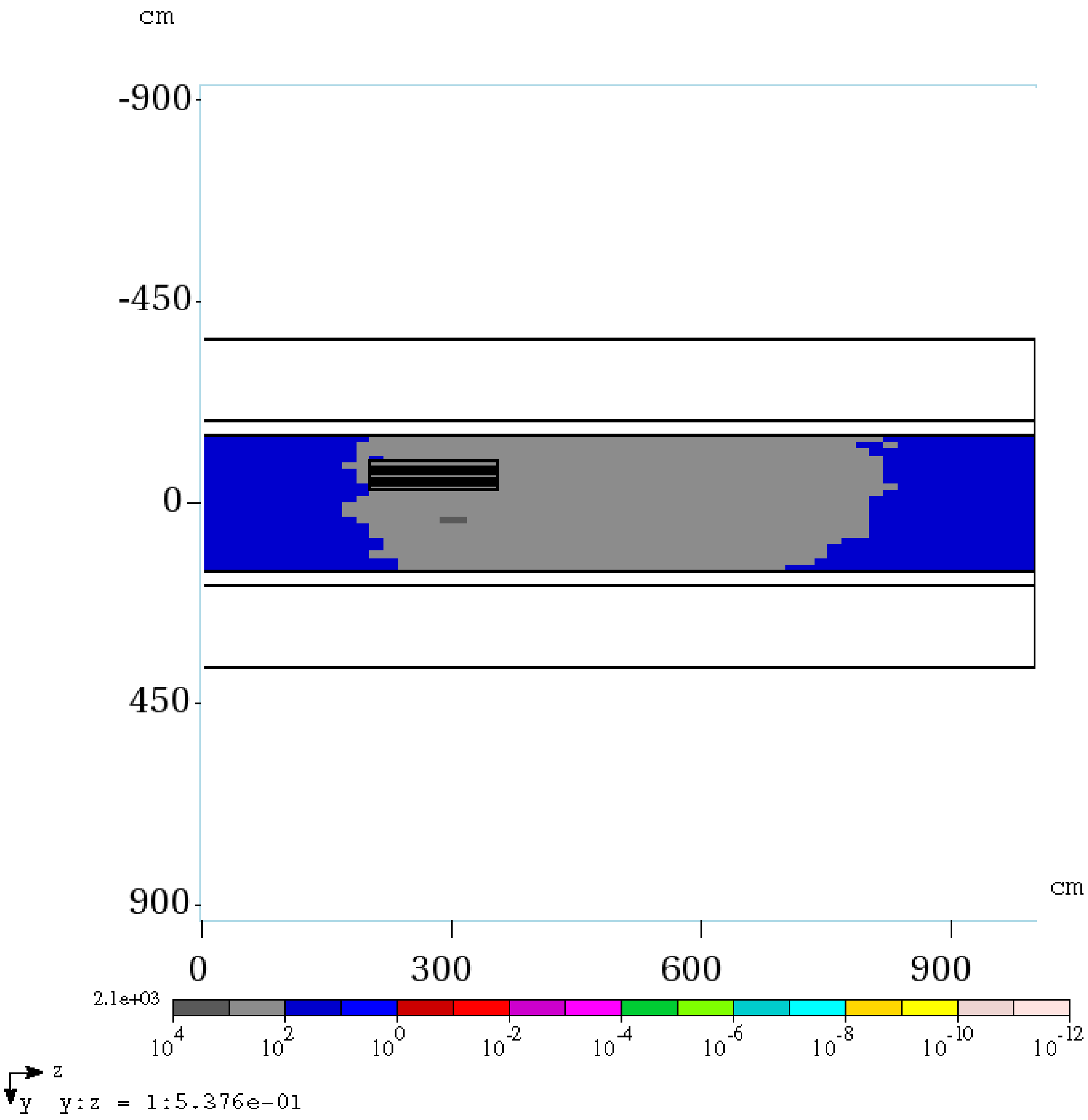

Figure 13: Stage 2 effective dose rate on surface of berm. The average rates along the beam line are approximately 200 to 300 mrem per hour. The indicated peak effective dose rate of 2.1E3 mrem per hour occurs at the 8" site riser penetration.

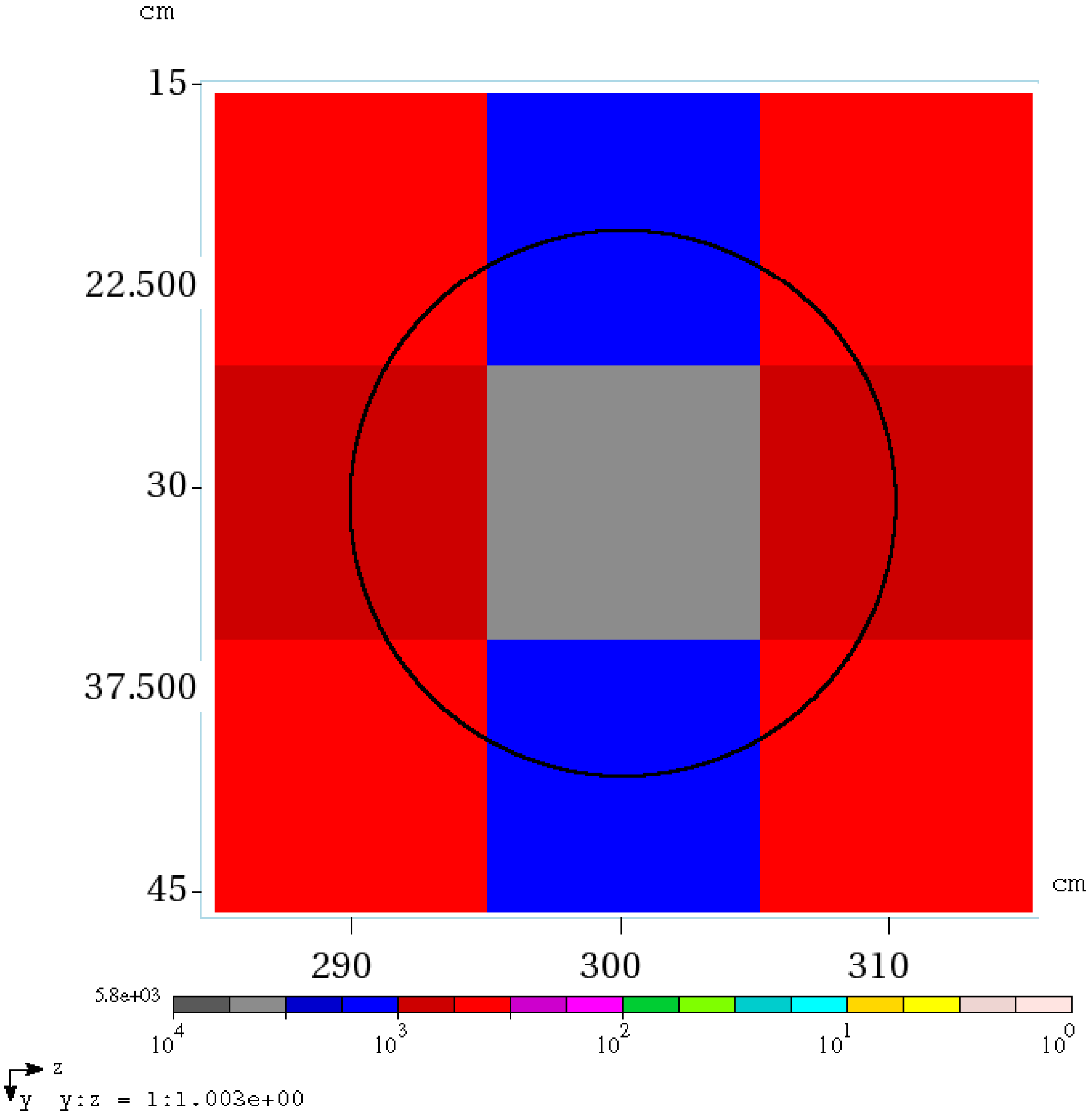

Figure 14: Stage 2 effective dose rate on berm surface at penetration in mrem/hr. The peak, prompt, effective dose rate directly over the penetration in the center pixel is of the 3 x 3 array is 5,800 mrem per hour. The dimension of each pixel is 8" x 8". The black circle indicates the ID of the penetration.

Comparison of MARS simulation with lab wide shielding criteria

An excerpt from the lab wide shielding criteria for an 8 kW, 8 GeV beam for a beam loss on "Magnet in Enclosure" is shown in Table 2. The expected effective dose rate for 16.2 feet of shielding is 5 to 100 mrem per hour. The MARS simulation result is 200 to 300 mrem per hour as shown in Figure 13. The results agree within a factor of 2 to 3 considering the upper end of the lab wide shielding criteria. This factor of 2 to 3 is within the nominal expectation of such comparisons.

Table 2: Excerpt from lab wide shielding criteria for an 8 kW beam loss

	A. Beam on Magnet in Enclosure		
		Standard	Scaled
	Category	(e.f.d.)	Thickness
D < 1mrem	1A	30.5	23.0
1 ≤ D ≤ 5 mrem	2A	28.1	20.6
1 ≤ D ≤ 10 mrem	1SE-A	27.1	19.6
1 ≤ D ≤ 10 mrem	2SE-A	27.1	19.6
5 ≤ D ≤ 100 mrem	3A	23.7	16.2
100 ≤ D ≤ 500 mrem	4A	21.3	13.8
500 ≤ D ≤ 1000 mrem	5A	20.3	12.8
D < 1mrem	6A	18.9	11.4
1 ≤ D ≤ 5 mrem	7A	16.5	9.0
5 ≤ D ≤ 100 mrem	8A	12.1	4.6
100 ≤ D ≤ 500 mrem	9A	9.7	3.0
500 ≤ D ≤ 1000 mrem	10A	8.7	3.0

Maximum Effective Dose Rate Limitation by Total Loss Monitoring System

The shield design of the M4 beam line for the mu2e experiment includes the use of interlocked radiation detectors [4]. The TLM system is the first option under consideration to provide this function. The upper limit of radiation effective dose rate chosen by the mu2e project is 5 mrem per hour. As indicated in the previous section, the calculated radiation effective dose rate averages 250 mrem/hr on the surface of the berm assuming a 1,200 watt beam loss. A protection factor of 50 would reduce the beam power loss to 24 watts at a single point with a resulting upper effective dose rate of 5 mrem per hour. A 24 watt beam power loss of 8 GeV protons is equivalent to 1.88E10 protons per second. The TLM response to an 8 GeV beam loss has been determined to be about 3 nC/1E10 protons. A TLM trip level of 338 nC/minute would therefore limit the maximum effective dose rate anywhere on the berm protected by the TLM to 5 mrem per hour. Nominally, it is expected that losses would be distributed along the length of the TLM and, consequently the peak radiation effective dose rate along the berm should be << 5 mrem/hr.

The effective dose rate at the exit of the penetration for a 1,200 watt beam loss was determined to be 5,800 mrem per hour. With the protection factor of 50 provided by the TLM system, the exit effective dose rate would be limited to 116 mrem per hour.

Penetration shield

It is very unlikely that an effective dose of 116 mrem could be delivered over a period of one hour at a site riser penetration. However, mitigation in the form of a simple shield would entirely eliminate the possibility. The site riser modeled in the MARS simulation has an inside diameter of 8 inches. A site riser shield with the following characteristics has been included in the MARS simulation:

- length 6 feet
- type – PVC, schedule 80, 6 inch diameter pipe
- nominal OD of 6.625”
- Fill - polyethylene beads
- Position – the top of the 6 foot length of pipe would end at the berm surface

It is not necessary for the shield to completely fill the site riser pipe either in its length or its diameter. It is necessary that the end of the shield be positioned near the berm surface since polyethylene would not be as effective a shield, for example, at the bottom of the site riser. The suggested penetration shield arrangement is shown in Figure 15.

The resulting flux in longitudinal, elevation view through the penetration is shown in Figure 16 and can be compared with the no shield case shown in Figure 12.

The resulting effective radiation dose rate on the surface of the berm is shown in Figure 17. This result, normalized to an 8 kW beam, can be compared with Figure 13. The hot spot at the site riser penetration is removed.

The resulting effective dose rate over the penetration is shown in Figure 18 and can be compared with the result in Figure 14. The proposed shield achieves a reduction factor of 16.6 with the resulting dose rate reduced to 350 mrem/hr. The additional protection provided by the TLM system reduces the dose rate to 7 mrem per hour. Again, since it is most unlikely that the losses sensed by the TLM system would be concentrated at a single point, the effective dose rate at the penetration should be << 7 mrem/hr.

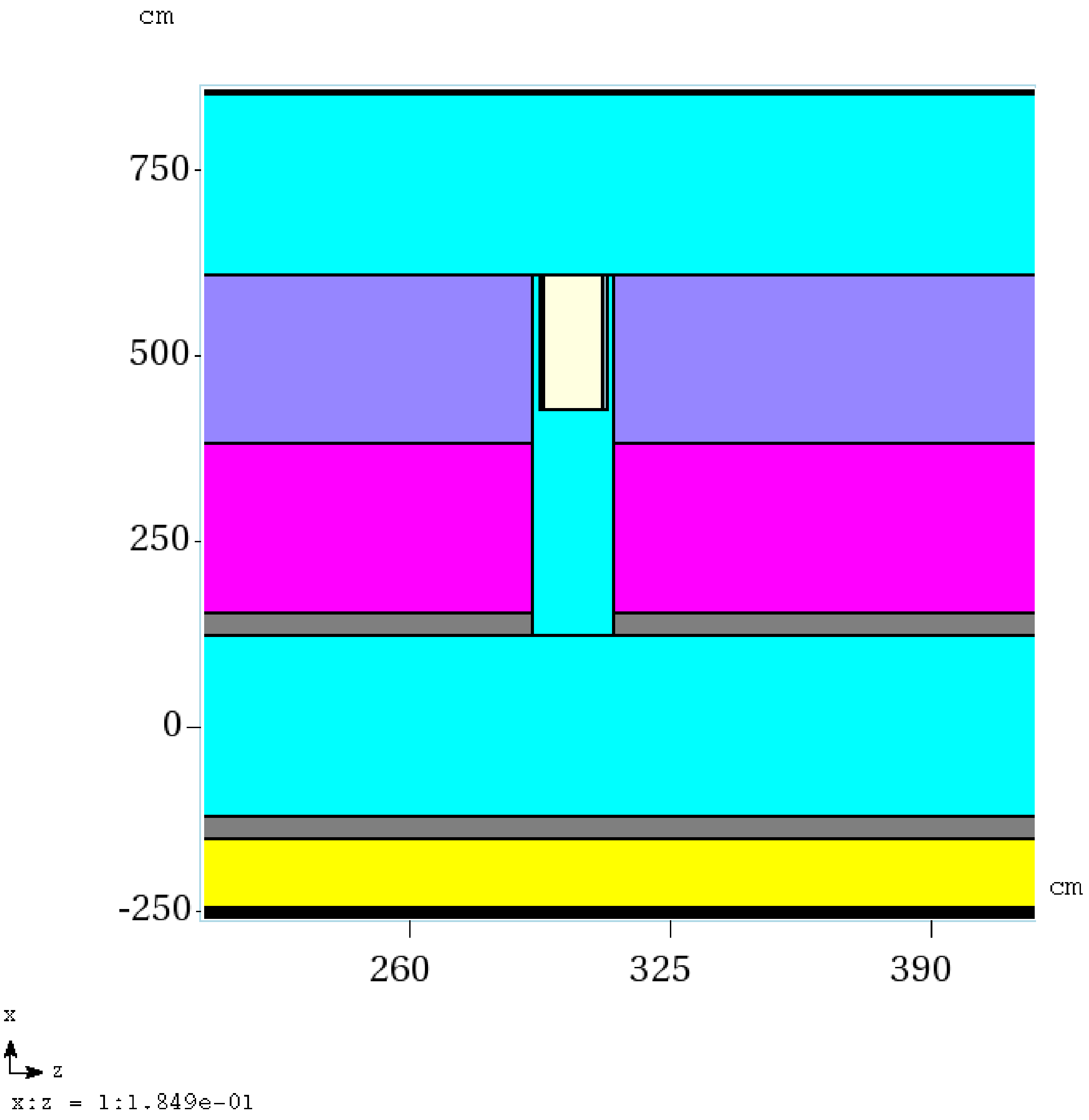

Figure 15: Elevation view of site riser with 6 foot length of 6 inch diameter, PVC, schedule 80 pipe, filled with polyethylene beads. The shield would be very effective for low energy neutrons expected at the pipe exit.

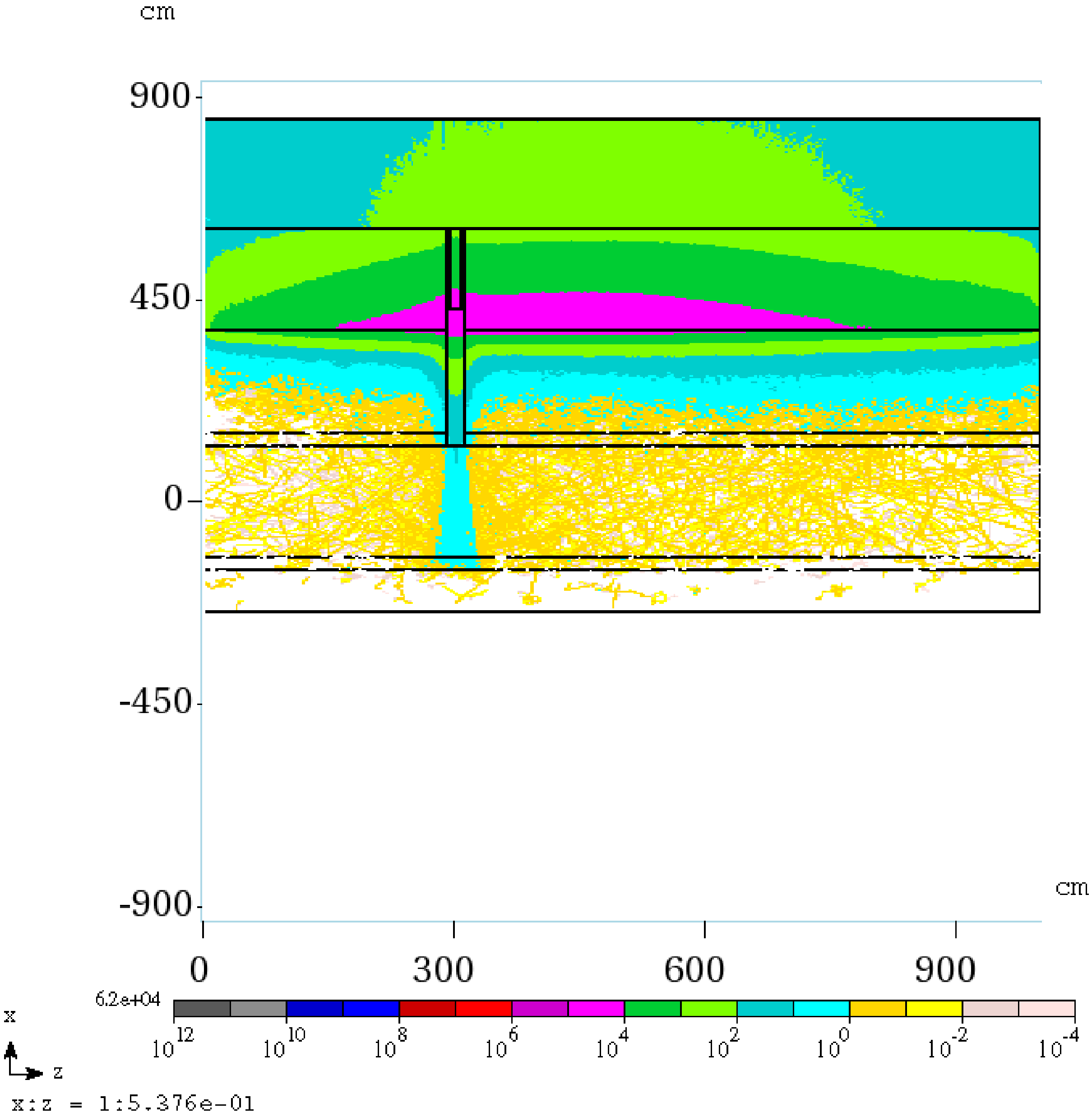

Figure 16: This longitudinal elevation view of the site riser penetration shows the effect of the polyethylene shield. This result can be compared with Figure 12.

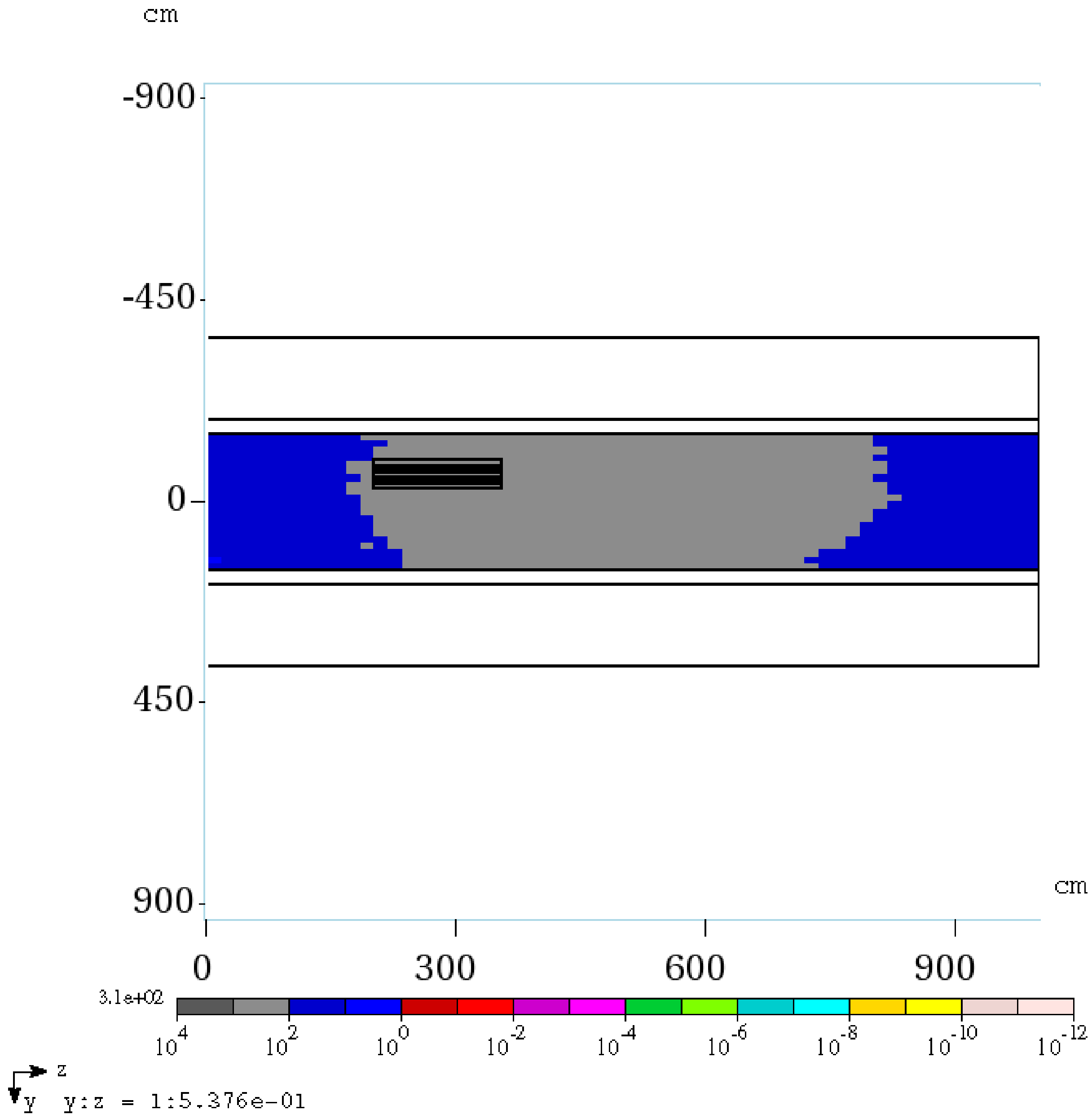

Figure 17: Plan view of the berm surface histogram in mrem/hr normalized to and 8 kW beam is shown here. The small hot spot seen above in Figure 13 at the site riser penetration is removed.

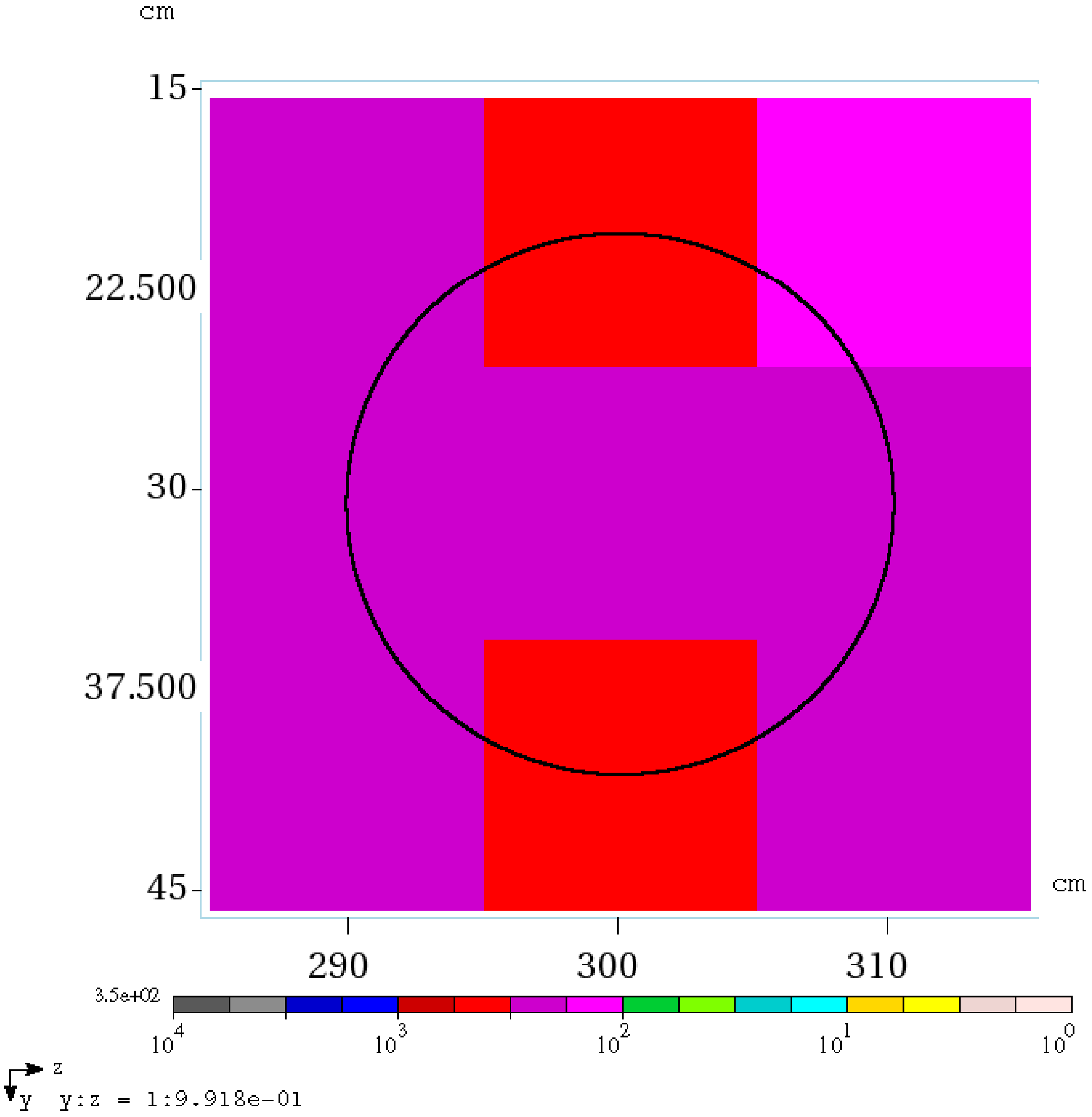

Figure 18: This result shows the Stage 2 effective dose rate on berm surface at the shielded penetration in mrem/hr. The peak, prompt, effective dose rate directly over the penetration in the center pixel is of the 3 x 3 array is 350 mrem per hour. The dimension of each pixel is 8" x 8". The black circle indicates the ID of the penetration. This result can be compared with the unshielded penetration shown in Figure 14.

Conclusions

A model including an MDC magnet located near a site riser penetration in the M4 beam line tunnel with a 16 foot earth equivalent shield has been created. The beam loss mechanism used in the calculation is the one prescribed by the generic shielding criteria. An interlocked radiation detector, the TLM system, would limit radiation effective dose anywhere along the length of berm it protects to < 5 mrem/hour.

Under very unlikely conditions, the effective radiation dose rate at a proposed site riser penetration could reach 116 mrem/hr. A penetration shield design is proposed which, in conjunction with TLM interlocked radiation detector, would reduce the site riser penetration effective dose rate to <<7 mrem hr.

References

1. Fermilab Radiological Controls Manual, http://esh.fnal.gov/xms/ESHQ-Manuals/FRCM
2. S. D. Reitzner, Update to the Generic Shielding Criteria, FERMILAB-TM-2550-ESH, 23 October 2012
3. N.V. Mokhov, “The MARS Code System User’s Guide”, Fermilab FN-628 (1995); N. V. Mokhov, S. I. Striganov, “MARS15 overview,” Proc. Hadronic Shower Simulation Workshop, Batavia, Illinois, USA, 6-8 September, 2006, Vol. 896, pp. 50-60, American Institute of Physics, Melville, NY (2007); http://www-ap.fnal.gov/MARS/
4. A.F. Leveling, “muon campus preliminary shielding assessment – part 1”, Beams Document 4513-v1

GEOM.INP

```
  m4 line penetration 1/19/14

!OPT

!shield fill poly beads
polybeads  2  1  10  426.72  30.48  300.  0.       7.31647  182.88  1  1  1
!end of penetration shield pipe


!penetration shield pipe
penshield  2  1  9  426.72  30.48  300.  7.31647  8.41375  182.88  1  1  1
!end of penetration shield pipe

!site riser
siteriser  2  1  1  121.92  30.48  300.  0.  10.16  487.68  1  1  1
TR1  0.  0.  0.  0.  90.  0.

!MDC MAGNET
MDCmagvac 1  0   0   0.    -60.96    200.   2.8397   6.9012  152.4 1 1 1 !vacuum chamber
incoil    1  0   7   0.    -60.96    200.   2.8397  11.0058  152.4 1 1 1 !inner coil
loutcoil  1  0   7   0.    -76.4565  200.   5.3975   4.4907  152.4 1 1 1 !left outer coil
routcoil  1  0   7   0.    -45.4635  200.   5.3975   4.4907  152.4 1 1 1 !right outer coil
MDCiron   1  0   8   0.    -60.96    200.  18.0848  32.0548  152.4  1 1 1 !MDC steel
!TR16  0.  0.  0.  1.125  0.  0.
!end of MDC

tunair  1  0  1    0.      0.  0.  121.92 152.4   1000.  1  1  1
tuncon  1  0  2    0.      0.  0.  152.4  182.88  1000.  1  1  1
1stgtil 1  0  3  -45.72    0.  0.  198.12 365.76  1000.  1  1  1
2ndgtil 1  0  4  266.70    0.  0.  114.3  365.76  1000.  1  1  1
3rdgtil 1  0  5  495.30    0.  0.  114.3  365.76  1000.  1  1  1
atmosph 1  0  6  731.52    0.  0.  121.92 365.76  1000.  1  1  1
blackho 2  0 -1    0.      0.  0.    0.   957.    1000.  1  1  1
stop
```

MARSBASE.INP

```
  m4 line penetration 1/19/14

INDX 3=T 5=T

CTRL 0
C RZVL 0. 121.92  200. 355.  5=5.E7
C TAPE 18
C NEVT 10000
NEVT 583233
ENRG 5=1.E-12
C ENRG 8.0

C VARS 4=6.25E12
C IPIB 1 2.
C BEAM 0.25 0.25
C INIT    0. -54.3088  0. 0.  0.  1.

SMIN 1.E-3 5.

ZSEC 1000.
NHBK 1
NLTR 1
RSEC 930.
C NOBL 1
MATR 'MATER.INP'

STOP
*MCNP START
m1 7014 -0.746 8016 -0.240 18000 -0.013 1001 -0.001 gas=1
m2 1001 -0.006 6000 -0.030 8016 -0.500 11023 -0.010 13027 -0.030 &
   14000 -0.200 19000 -0.010 20000 -0.200 26000 -0.014
m3 26000 -0.1610 19000 -0.0282 14000 -0.1417 13027 -0.0972 &
   12000 -0.1752  8016 -0.3800  1001 -0.0167
m4 26000 -0.1610 19000 -0.0282 14000 -0.1417 13027 -0.0972 &
   12000 -0.1752  8016 -0.3800  1001 -0.0167
m5 26000 -0.1610 19000 -0.0282 14000 -0.1417 13027 -0.0972 &
   12000 -0.1752  8016 -0.3800  1001 -0.0167
m6 7014 -0.746 8016 -0.240 18000 -0.013 1001 -0.001 gas=1
m7 29000 -0.56  1001  -0.021261 8016 -0.267980 12000 -0.117348
m8 26000 1.0 cond=1
m9 1001  -0.069770  6000  -0.558140  8016 -0.372090
m10 6000 -0.856285  1001  -0.143715
*MCNP END
```

MATER.INP

```
  m4 line penetration 1/19/14

1 'AIR'
2 'CONC'
3 'GTIL' 2.24
4 'GTIL' 2.24
5 'GTIL' 2.24
6 'AIR'
7 'HOLW'
8 'FE'
9 'ACRL'
10 'CH2'  0.70

STOP
```

XYZHIS.INP

```
  m4 line penetration 1/19/14

xyz    91.92   121.92  -152.4   152.4     0.   1000.   1   20 60 tun_prompt_rates
DET  FLT
xyz   609.6    640.08  -152.4   152.4     0.   1000.   1   20 60 surf_prompt_rates
DET  FLT
xyz    -243.84  853.44  -71.12  -50.8    0.   1000. 300  1  300  long_elev_flux
FLT
xyz    -243.84  853.44  20.32  40.64     0.   1000. 300  1  300  pen_long_elev_flux
FLT
xyz   609.6    640.08    15.24   45.72  284.76  315.24 1   3  3 penexit_prompt_rates
DET  FLT
stop
```

XYZHIS.TAB

```
   m4 line penetration 1/19/14

  XYZ HISTOGRAMS: NXYZDET=    5,   NXYZHIS=    8  normalized per AINT (p/s)



      To speed up, minimize amount of histograming:

      keep the numbers of detectors, types and bins as small as possible!



  ID  NF NDT GLBL  V-H   Title       NGLB   Eth(GeV)  Nb_V Nb_H  V_min(cm)   V_max(cm)
H_min(cm)   H_max(cm)       < Slice (cm) >      Description

  701  2  3  XYZ:  Y-Z   DET (mSv/hr)   0  0.000E+00   20   60 -1.5240E+02  1.5240E+02
0.0000E+00  1.0000E+03  9.1920E+01  1.2192E+02  tun_prompt_rates

  702  2  3  XYZ:  Y-Z   FLT (1/cm2/s   0  0.000E+00   20   60 -1.5240E+02  1.5240E+02
0.0000E+00  1.0000E+03  9.1920E+01  1.2192E+02  tun_prompt_rates

  703  2  3  XYZ:  Y-Z   DET (mSv/hr)   0  0.000E+00   20   60 -1.5240E+02  1.5240E+02
0.0000E+00  1.0000E+03  6.0960E+02  6.4008E+02  surf_prompt_rates

  704  2  3  XYZ:  Y-Z   FLT (1/cm2/s   0  0.000E+00   20   60 -1.5240E+02  1.5240E+02
0.0000E+00  1.0000E+03  6.0960E+02  6.4008E+02  surf_prompt_rates

  705  1  2  XYZ:  X-Z   FLT (1/cm2/s   0  0.000E+00  300  300 -2.4384E+02  8.5344E+02
0.0000E+00  1.0000E+03 -7.1120E+01 -5.0800E+01  long_elev_flux

  706  1  2  XYZ:  X-Z   FLT (1/cm2/s   0  0.000E+00  300  300 -2.4384E+02  8.5344E+02
0.0000E+00  1.0000E+03  2.0320E+01  4.0640E+01  pen_long_elev_flux

  707  2  3  XYZ:  Y-Z   DET (mSv/hr)   0  0.000E+00    3    3  1.5240E+01  4.5720E+01
2.8476E+02  3.1524E+02  6.0960E+02  6.4008E+02  penexit_prompt_rates

  708  2  3  XYZ:  Y-Z   FLT (1/cm2/s   0  0.000E+00    3    3  1.5240E+01  4.5720E+01
2.8476E+02  3.1524E+02  6.0960E+02  6.4008E+02  penexit_prompt_rates
```

Subroutine mfill – for particle counting downstream of MDC magnet

```
      if(ihtyp.eq.2) then
      if(jj .ne. 1)return
      if(E2 .lt. 7.9D0)return
       vert = abs(X2)
       hor = abs(Y2)
       if(Z2 .ge. 352.4D0 .and. Z1 .le. 352.4D0) then
       if((X2 .le. vert) .and.(Y2 .le. hor)) then
            write(71,100)JJ,E1,W,X1,Y1,Z1,DCX,DCY,DCZ !particle screen at end of MDC
            return
       end if
       end if
       end if
 100  format (1i7,8(1pe13.5))
```

Subroutine mfill – for stage 2 particle source

```
       if(ihtyp.eq.2) then
       if((jj .ge. 18) .and. (jj .le. 21)) return
       if((X2 .ge. 381.0D0) .and.(X1 .lt. 381.0D0)) then
           write(71,100)JJ,E1,W,X1,Y1,Z1,DCX,DCY,DCZ !stage 2 particle surface crossing
           return
       end if
       end if
 100  format (1i7,8(1pe13.5))
```

Subroutine BEG1

```
      PRIME=1.56250D8  !number of IP in stage 1 run
      STACK=583233.D0  !number of lines in stage 2 input file

          W0=STACK/PRIME

20     READ(46,*,END=100)JJ,E,W,X,Y,Z,DCX,DCY,DCZ

      W=W0*W

      RETURN
100    REWIND(46)
      GOTO 20
     END
```