Muon g-2 Preliminary Shielding Assessment

MC-1 Building and M4 Tunnel Temporary Shield Wall

Anthony Leveling
Revised 9/9/2014

A preliminary shielding assessment was originally written in June 2012 prior to construction of the MC-1 service building. The assessment is being revised post MC-1 building construction to include consideration of a temporary shield wall required to be installed in the M4 beam enclosure so that M4 beam line construction can proceed while the muon g-2 experiment takes beam. In addition, some references have been updated. The original assessment for the MC-1 service building remains unchanged.

Muon g-2 Preliminary Shielding Assessment

Contents

Muon g-2 Preliminary Shielding Assessment

Introduction

A new service building, the MC-1 Service Building, is to be built nearby the Accumulator/Debuncher Rings complex to house the muon g-2 storage ring. The Fermilab Radiological Controls Manual (FRCM) [1] requires that a preliminary shielding assessment be made prior to permitting construction of new Accelerator structures to ensure that facility design will meet all of the FRCM radiation safety requirements. The purpose of this preliminary shielding assessment is to ensure the MC-1 Service Building meets the requirements of the FRCM for operation of the muon g-2 storage ring. In addition, a new M4/M5 beam line which connects the Accumulator/Debuncher Ring enclosure to the MC-1 service building and the mu2e experiment building is discussed with regard only to the muon g-2 beam. The 8 kW, 8 GeV proton beam to be delivered to the mu2e experiment is the subject of a separate shielding assessment.

The Debuncher Ring of the Accumulator/Debuncher Rings complex is being repurposed to provide beams for muon campus experiments. The Debuncher Ring name has been changed to the Delivery Ring, in part, to indicate the change in the functionality of the Ring.

The purpose of the muon g-2 experiment [4] is to observe the decay of muons collected in the g-2 storage ring. Muons are to be produced utilizing the Antiproton Source Target Hall as follows: 8 GeV beam originating in the Booster accelerator is transported through the MI8 line into the Recycler Ring where each Booster batch will be divided into 4 individual beam bunches. One of the four bunches is extracted from the Recycler Ring and transported through the P1 line, P2 line, and the AP1 line to the Antiproton Source Target Hall. The 8 GeV beam pulse strikes the target; the resulting positive, secondary beam is focused by the lithium lens, momentum selected (3.094 GeV/c +/- 2%) by the 3 degree pulsed bending magnet and is transported to the Delivery Ring through a new M2 beam line. After a number of passes around the Delivery Ring, the secondary beam, now consisting mostly of positive muons, will be extracted from the Delivery Ring into a new M4 beam line and will be transferred and injected into g-2 storage ring located in the new MC-1 Service Building. This process is to be repeated 16 times every Main Injector cycle or every 1.33 seconds. Muons accumulate and then decay continuously while circulating in the muon g-2 storage ring.

Proton and pion contamination of the muon beam entering the g-2 storage ring is undesirable. Pions are to be eliminated primarily by allowing sufficient time for their eventual decay to muons. The decay time is optimized by extending their travel through multiple passes of the Delivery Ring. Protons with the same momentum as the muons are separated from the muons in time naturally because of their different energies. A kicker system in the Delivery Ring removes the protons rendering the muon beam relatively free of pions and protons.

Beam Parameter Summary

Each Booster batch injected into the Recycler Ring contains about 4E12 protons. Recycler Ring RF manipulations divide the beam into four bunches consisting of about 1E12 protons. The partial, momentum selected, secondary yield [7] resulting from each bunch of 1E12 protons on target along with beam energy and beam power is shown in Table 1. The incident beam power

on the production target is about 15 kW, about a factor of 5 lower than the beam power used for pbar production. The off momentum secondary beam is mainly absorbed in the target station at the collimator, pulsed magnet laminations, and the primary proton dump.

Particle type	Secondary yield of 3.094 GeV/c +/-2%	Secondary beam energy (GeV)	Lorenz factor	Beta	Secondary beam power (watts)
Protons	2E7	2.295	3.445844328	0.956964612	0.088
Pions	1E7	2.958	22.19060262	0.998984096	0.057
Muons	1E5	2.990	29.30012699	0.999417417	0.001

Table 1:   Yield of secondary beam per 1E12 protons on target determined from MARS simulations [**Error! Reference source not found.**]. The beam energy and beam power of each particle type is also given.

Site Description

As shown in Figure 1, a new M4/M5 beam line connects the Delivery Ring to the MC-1 service building and to the Mu2e experimental area. A temporary shield wall is required to be installed in the M4 beam line to permit personnel access to the downstream M4 beam line during muon g-2 operation.
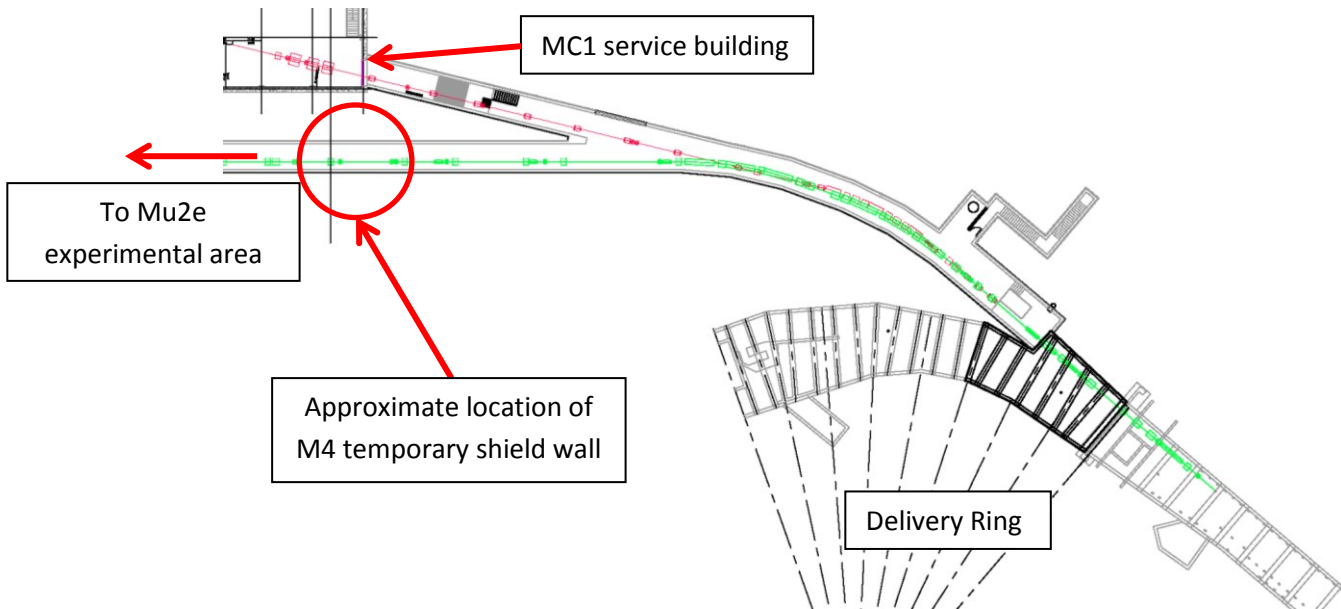

Figure 1: Layout of the M4/M5 beam lines between the Delivery Ring, MC1 service building, and the Mu2e experimental area (not shown). M5 beam line magnets Q017 and Q018 are located adjacent to the opening of the M4 tunnel. Beam line components of the M4 line re indicated in green while those of the M5 line re indicated in red. It is desirable to allow personnel access to the left of the indicated M4 temporary shield wall while excluding personnel access to the right of it.

A detailed analysis of the M4 temporary shield wall has been completed in a separate MARS simulation and is documented in Reference 10. The M4 temporary shield wall meets all requirements of the FRCM is not considered further in this work.

The MC-1 Service Building is to be located adjacent to the former Antiproton Source Accumulator/Debuncher Rings enclosure at a site designated as the Muon Campus. A partial plan view of the MC-1 Service building is shown in Figure 2. Partial elevation views are shown in Figure 3 and Figure 4. The muon g-2 storage ring is to be placed on a concrete floor at elevation 734'6" with the beam elevation at 738'1". The minimum ground elevation around the MC-1 Service Building is 746'6", about 12 feet above the storage ring floor. Two foot thick concrete walls 29 feet high form the perimeter walls of the MC-1 service building. The concrete walls rise above the local minimum grade by about 17 feet. The unshielded service building extends an additional 23 feet above the top of the 2 foot thick concrete perimeter walls. The space directly above the muon g-2 storage ring is unshielded. The complete set of available drawings for the MC-1 Service Building is contained in Reference 2.
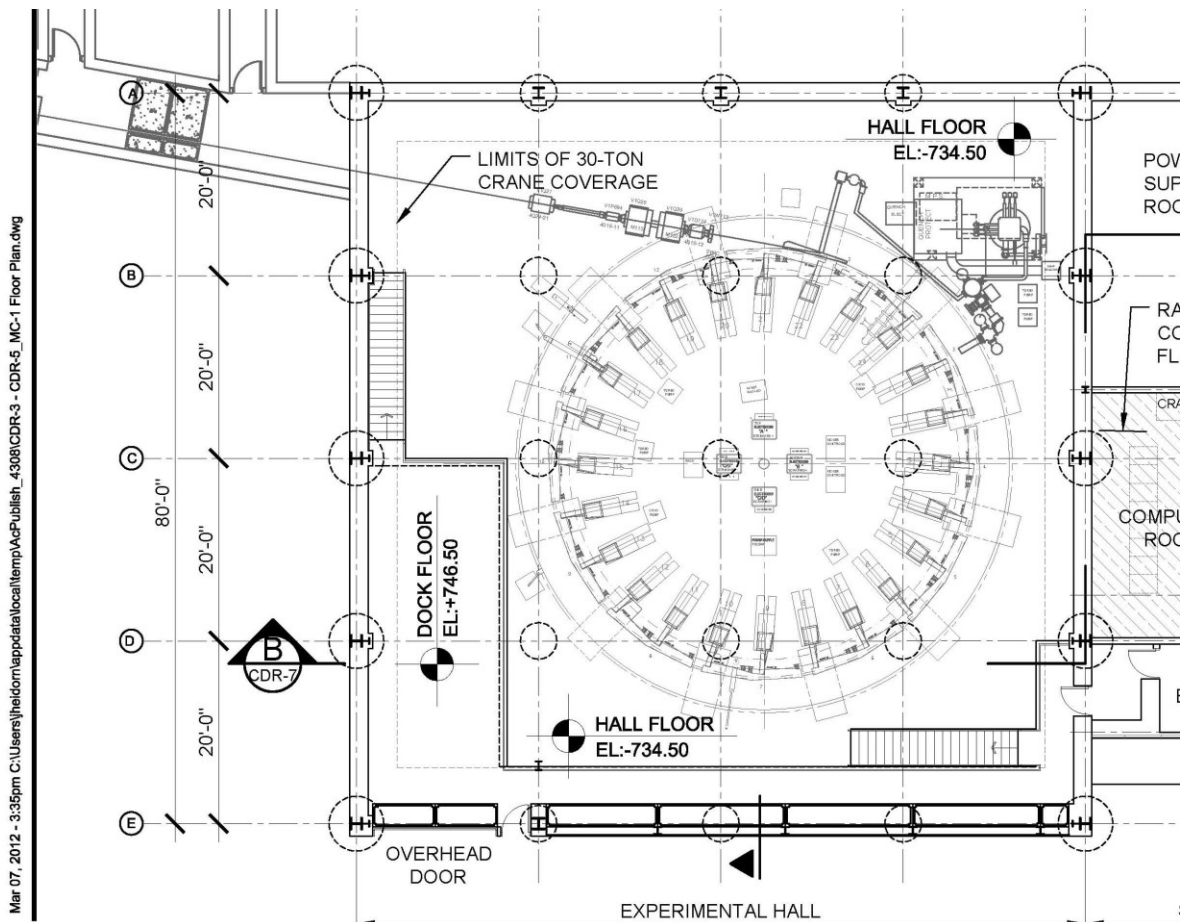

Figure 2: Plan view of MC1 service building

Figure 3: Elevation view of MC1 service building facing project east
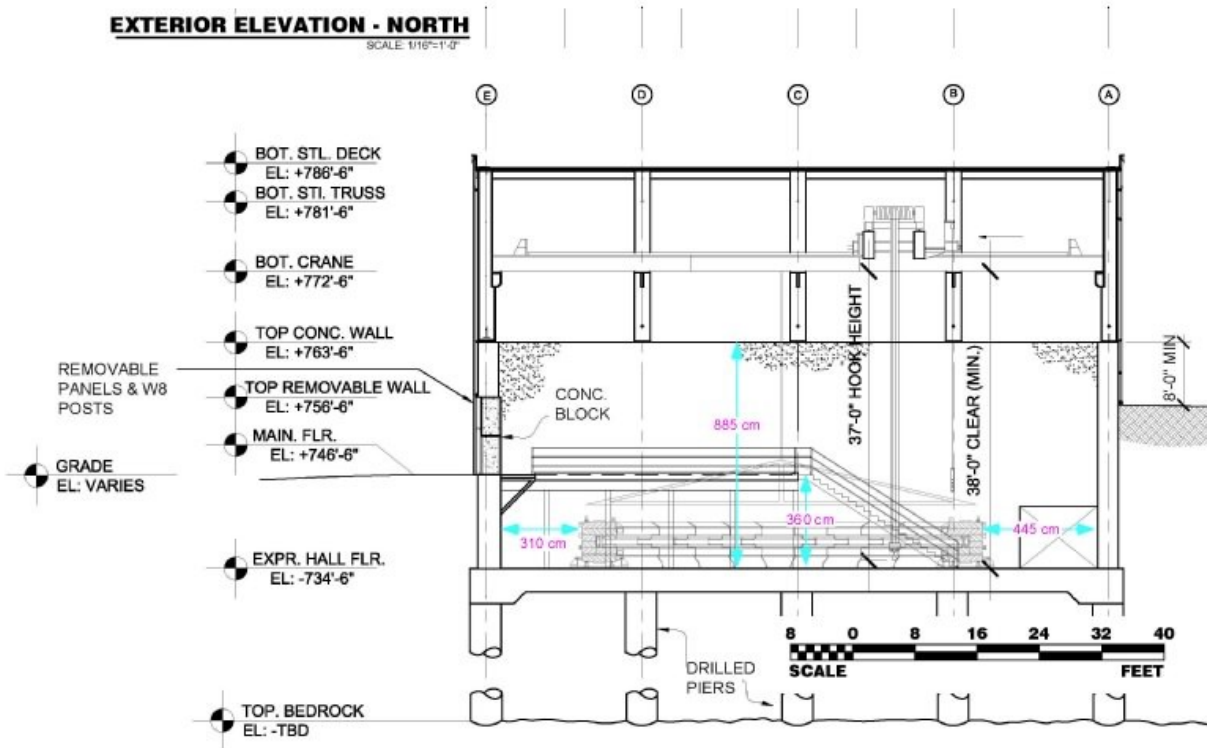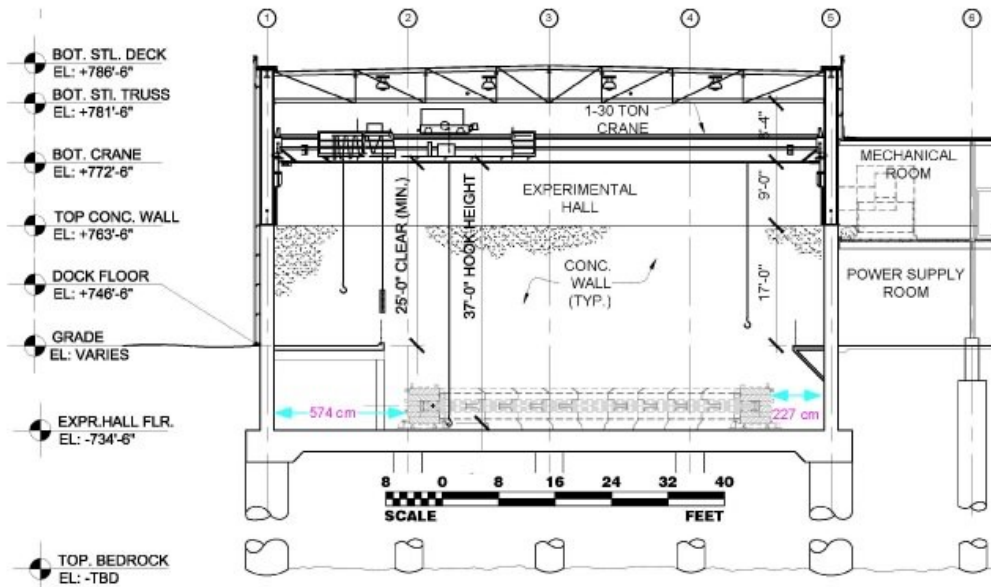
Figure 4: Elevation view of MC-1 service building facing project south

Figure 5 shows a cross section of the muon g-2 storage ring obtained from Reference 5. That image was imported into a drawing program and the dimensions of all major magnet steel components for the storage ring was determined as shown in Figure 6. Reference 5 also provides the radius of the central orbit of the storage ring as 711.2 cm
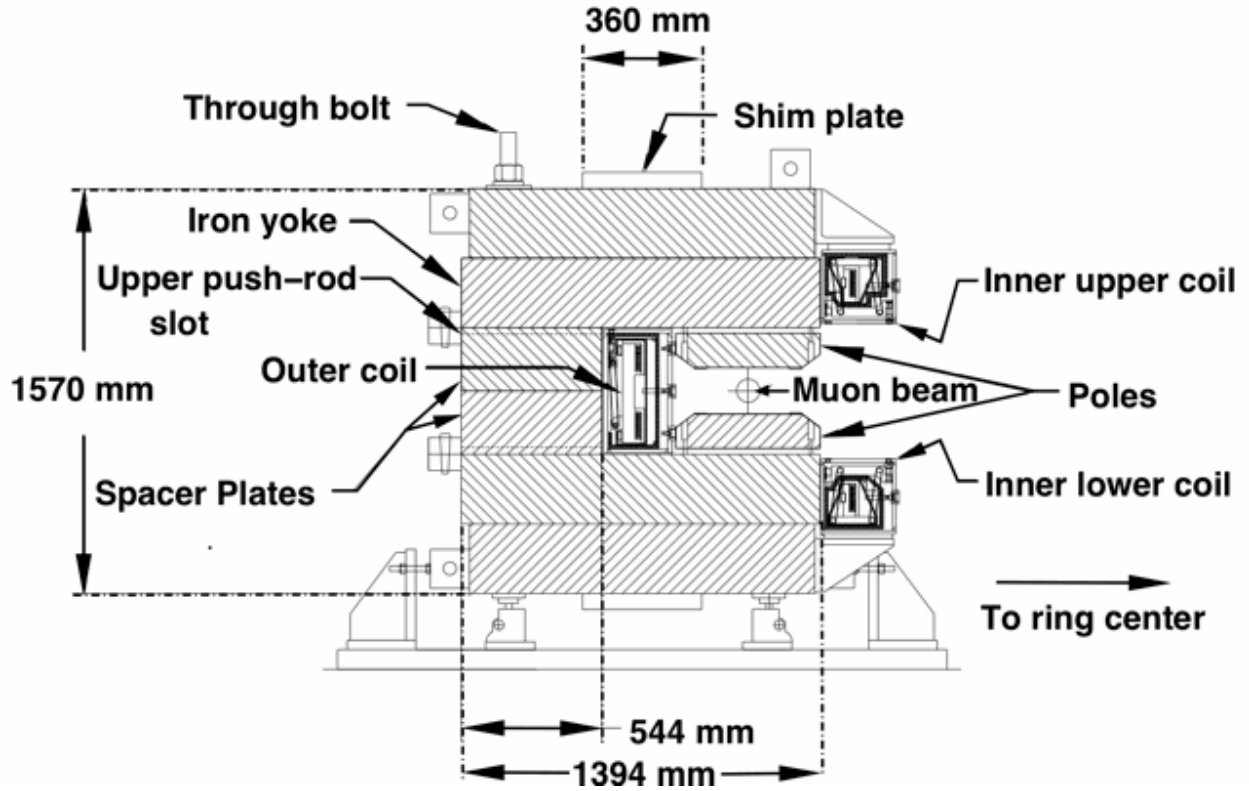
Figure 5: Cross section of muon g-2 storage ring from reference 5.
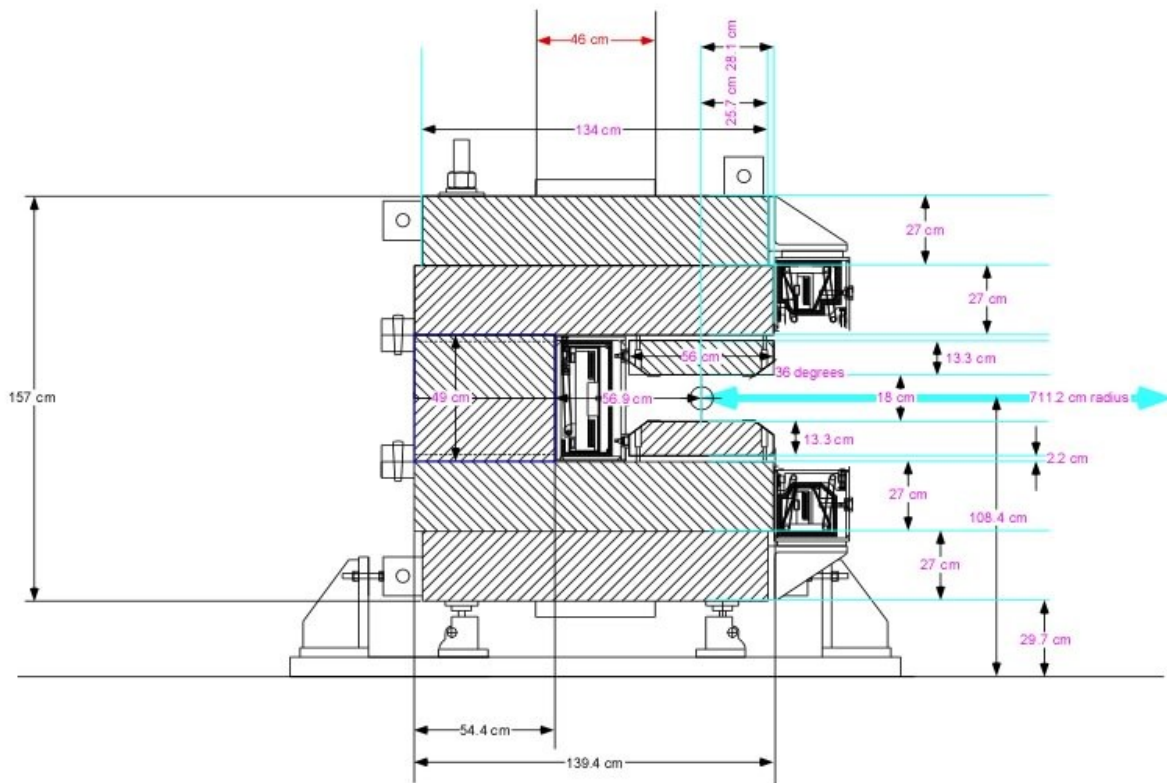
Figure 6: determination of magnet steel dimensions used in MARS model

Method of Assessment

A secondary particle is to be transported and injected into the muon g-2 storage ring. As can be seen by the anticipated beam power for the facility listed in Table 1, the beam power is << 1 watt. The existing pbar facilities were previously assessed for 13 watts and so no further consideration of the Antiproton Source facility shielding for existing facilities is given in this preliminary assessment. The MARS Code System is used to model the MC-1 service building problem and estimate for effective dose rate due to various types of beam losses.

The ring cross section and radius shown in Figure 5 was used to create a model of g-2muon storage ring in MARS as shown in Figure 6. Figure 7 shows a plan view of the MARS model for the MC-1 Service Building along with the muon g-2 storage ring at the beam elevation. All MARS user input files created for this assessment are included in Appendix 1 through 5.

To explore the worst case operating conditions for the muon g-2 storage ring, the MARS model is set up without a magnetic field. Beam is simply injected on the central orbit at 10 degrees from the horizontal axis and is allowed to drift on a tangent of the ring radius until it interacts with the center outer magnet steel, the yellow mass shown in Figure 7. Figure 8 shows the incoming beam path (black trace) and the resulting shower, primarily neutrons (green traces).
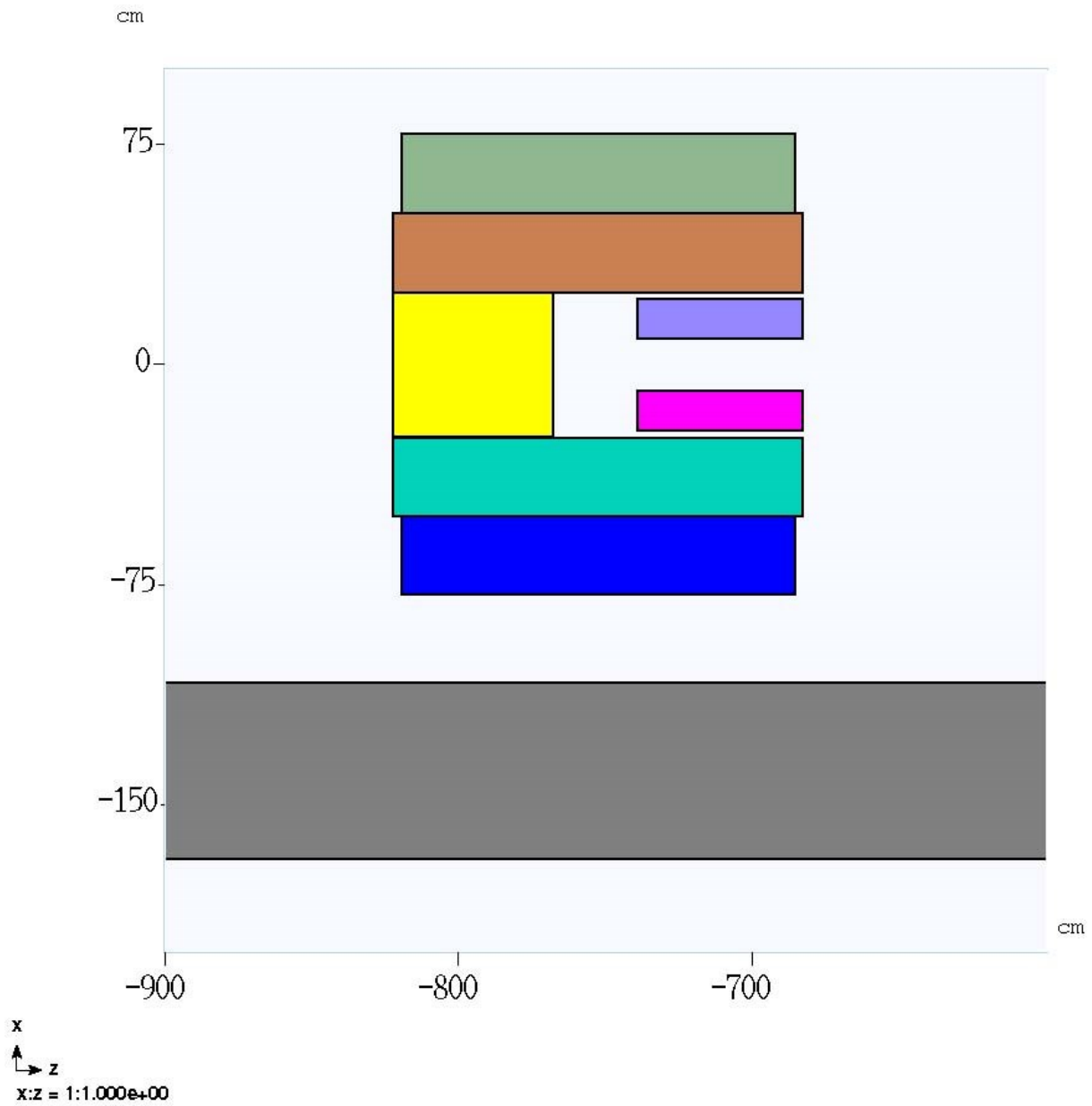
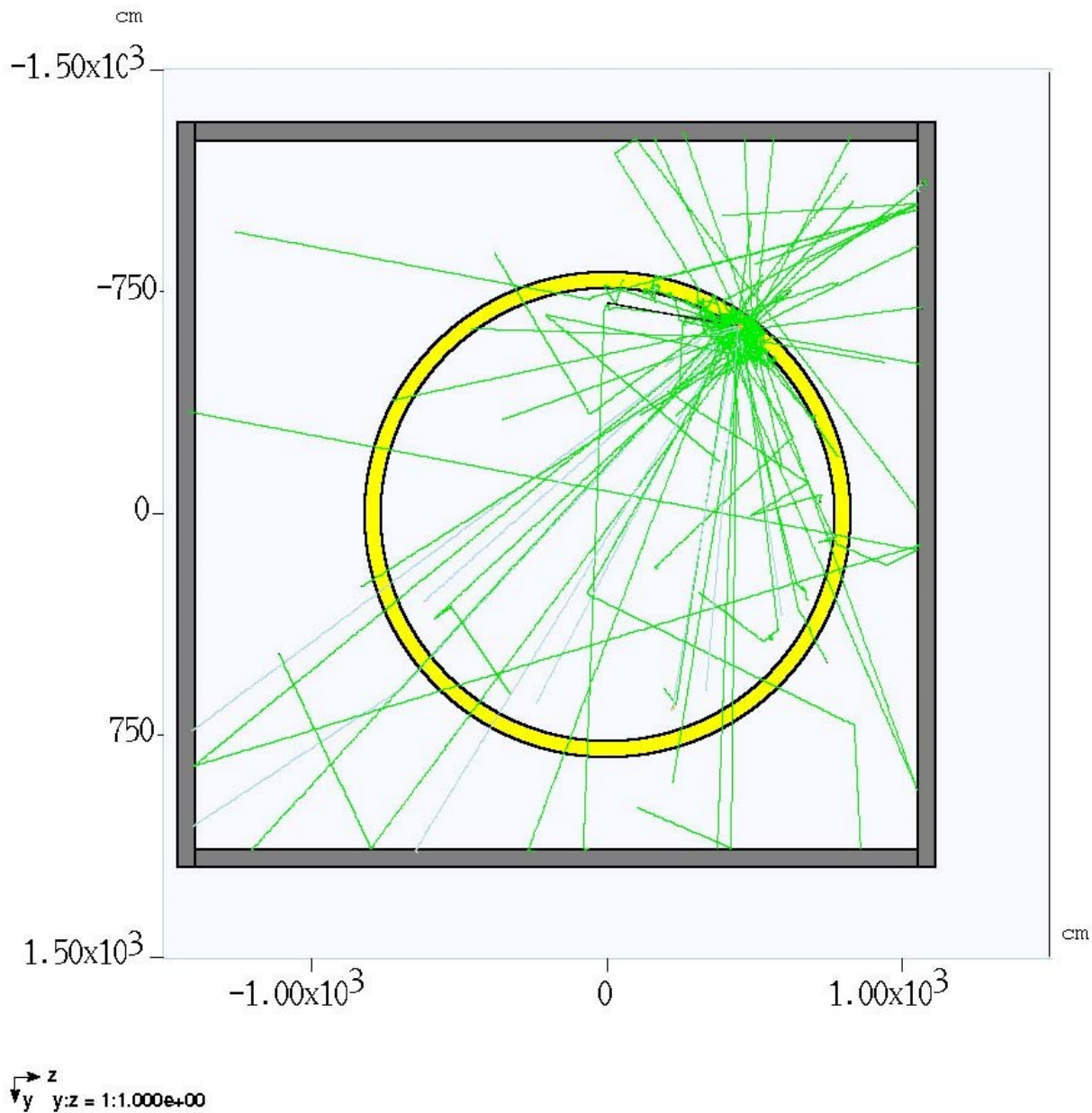Figure 7: Elevation view of muon g-2 storage ring MARS model.

Figure 8: Plan view of muon g-2 storage ring and concrete enclosure walls at beam elevation. The black trace indicates the incoming secondary particle beam while the green traces indicate neutrons resulting from secondary beam collision with the muon g-2 storage ring.

To estimate the radiation dose rates as a function of position around the MC-1 service building room where the muon g-2 storage ring is located, 5 tissue equivalent detectors are used. A top detector, 8 cm thick, covers the area at the elevation where the 2 foot thick concrete vertical walls end. Each of the four walls has an 8 cm thick tissue equivalent detector which starts at the top of the 2 foot concrete wall, extends downward about 17 feet, and spans the entire length of the respective walls. Each of the 5 detectors is subdivided into 50 X 50 bins. Figures 9, 10, 11, and 12 show some of the details of the 5 tissue equivalent detectors used in the MARS model.

Figure 9: Elevation view looking south

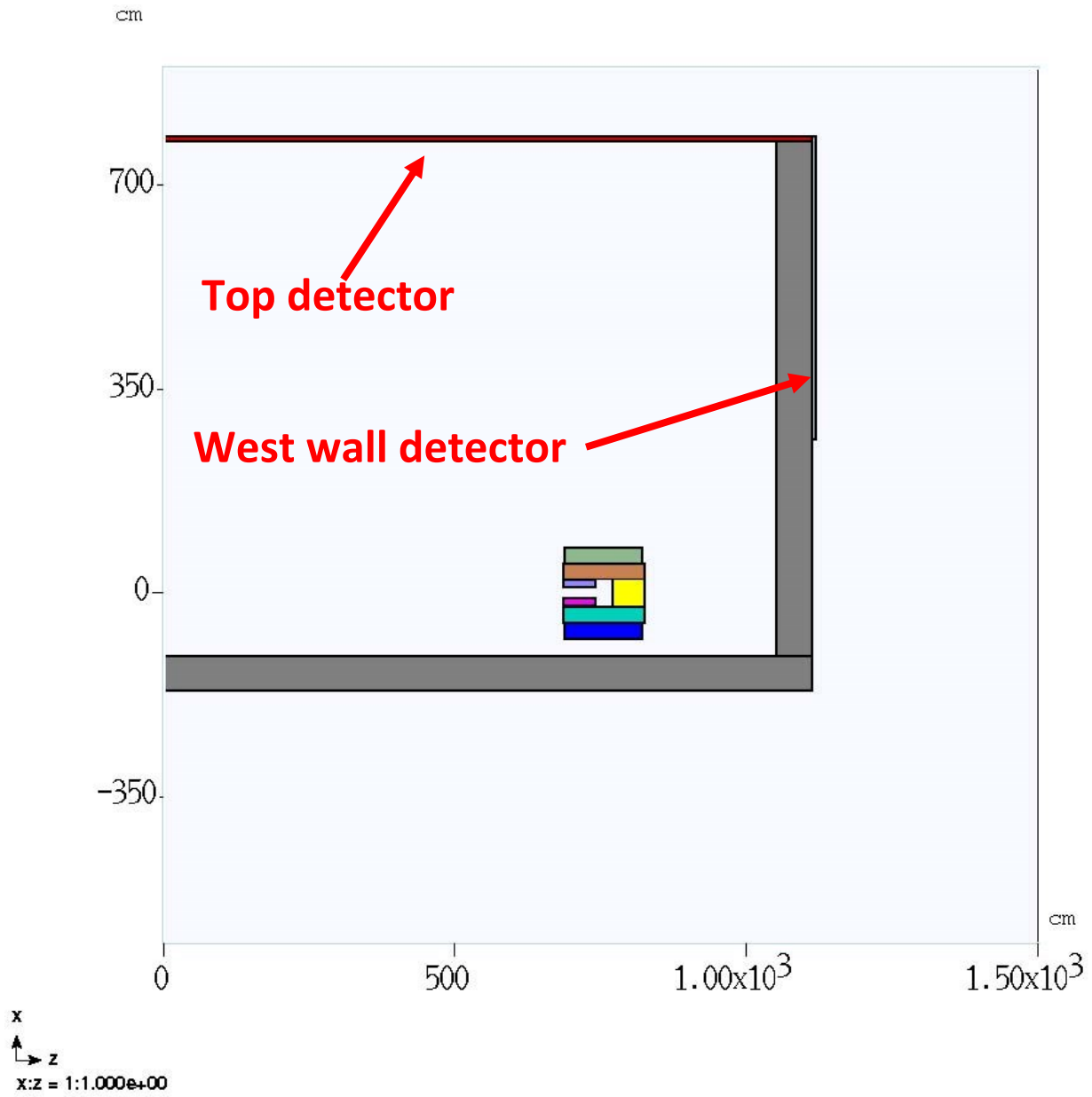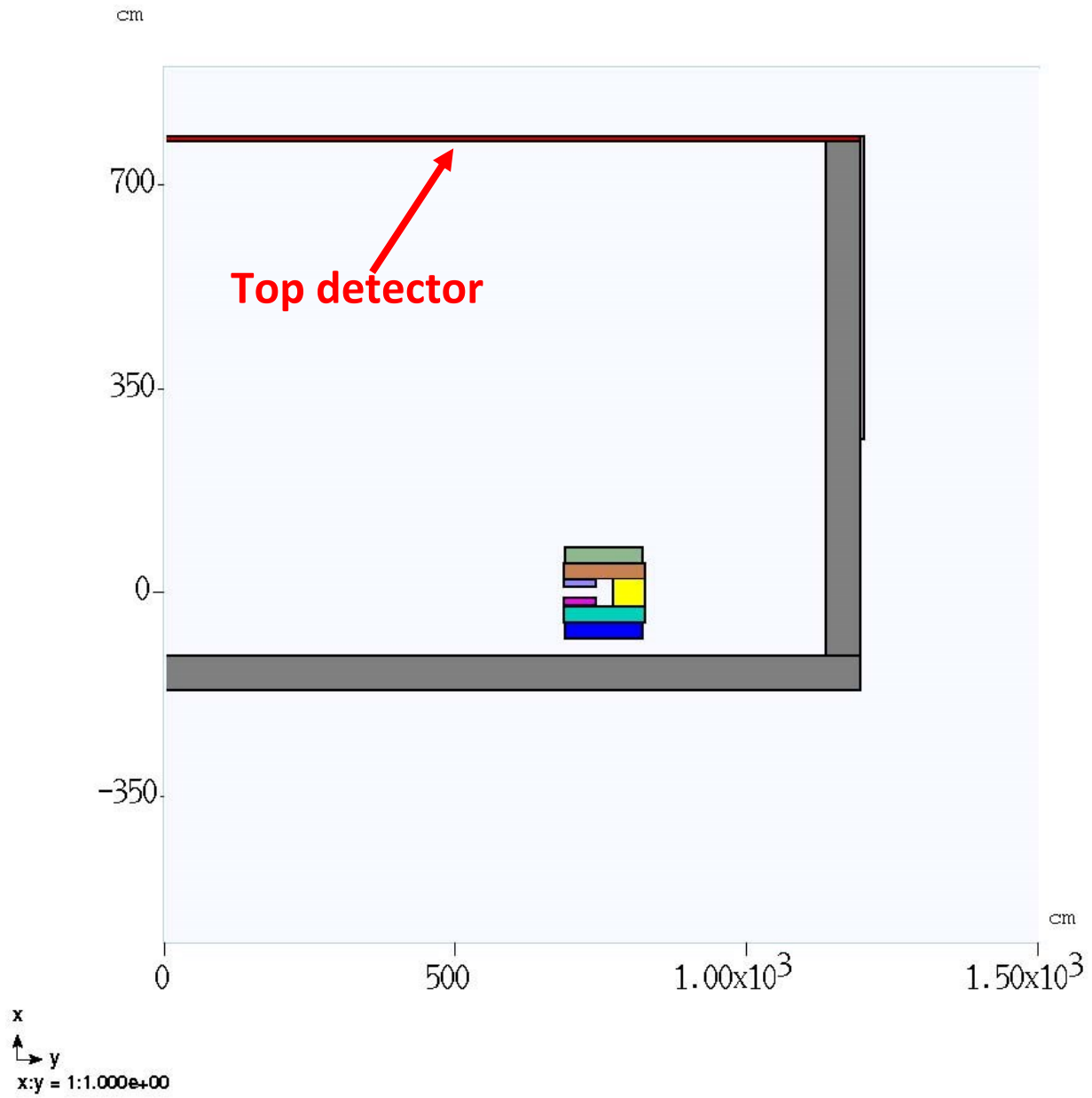Figure 10: Elevation view looking west
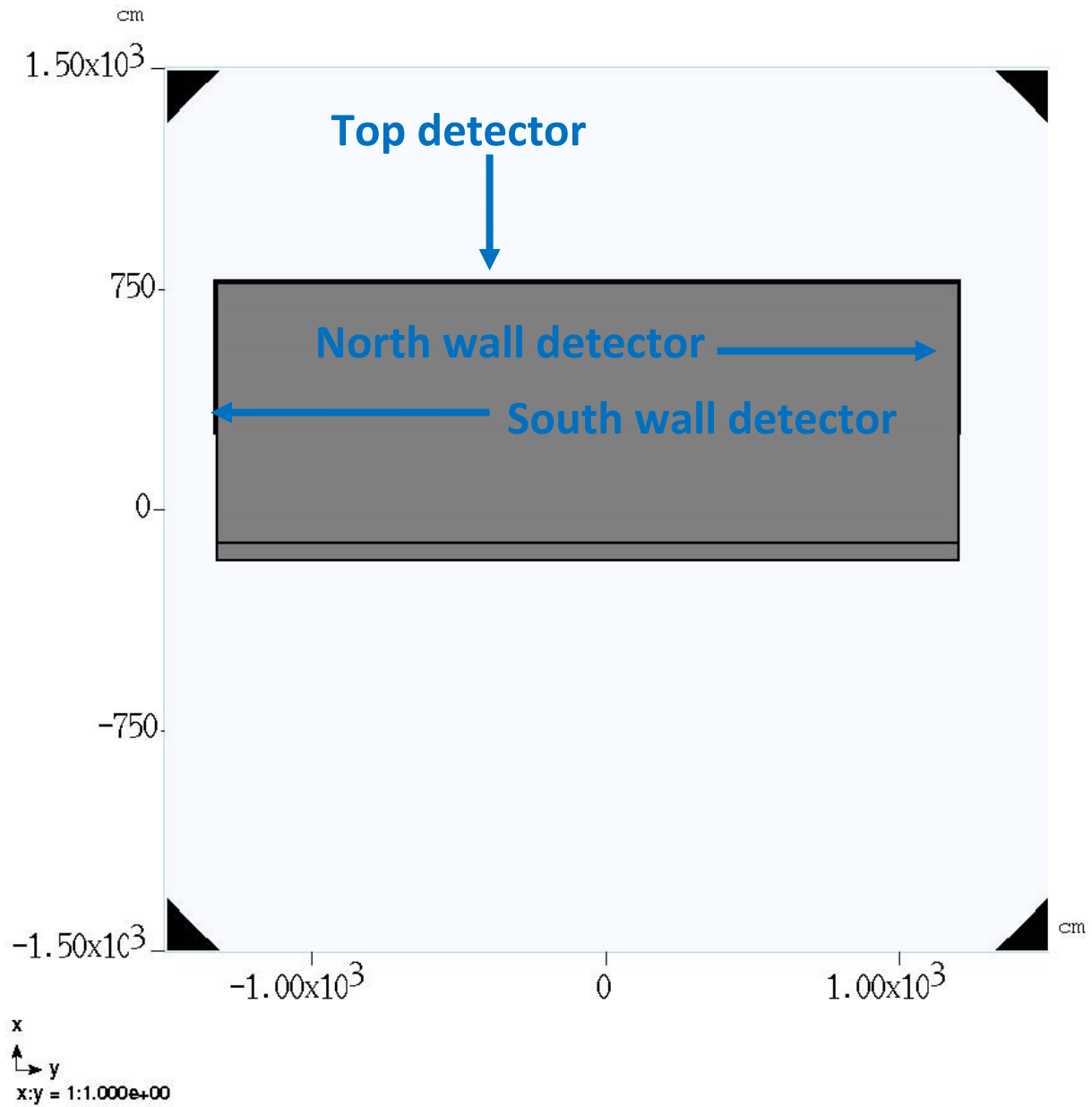
Figure 11: Elevation view of west concrete wall and relative position of tissue equivalent detectors
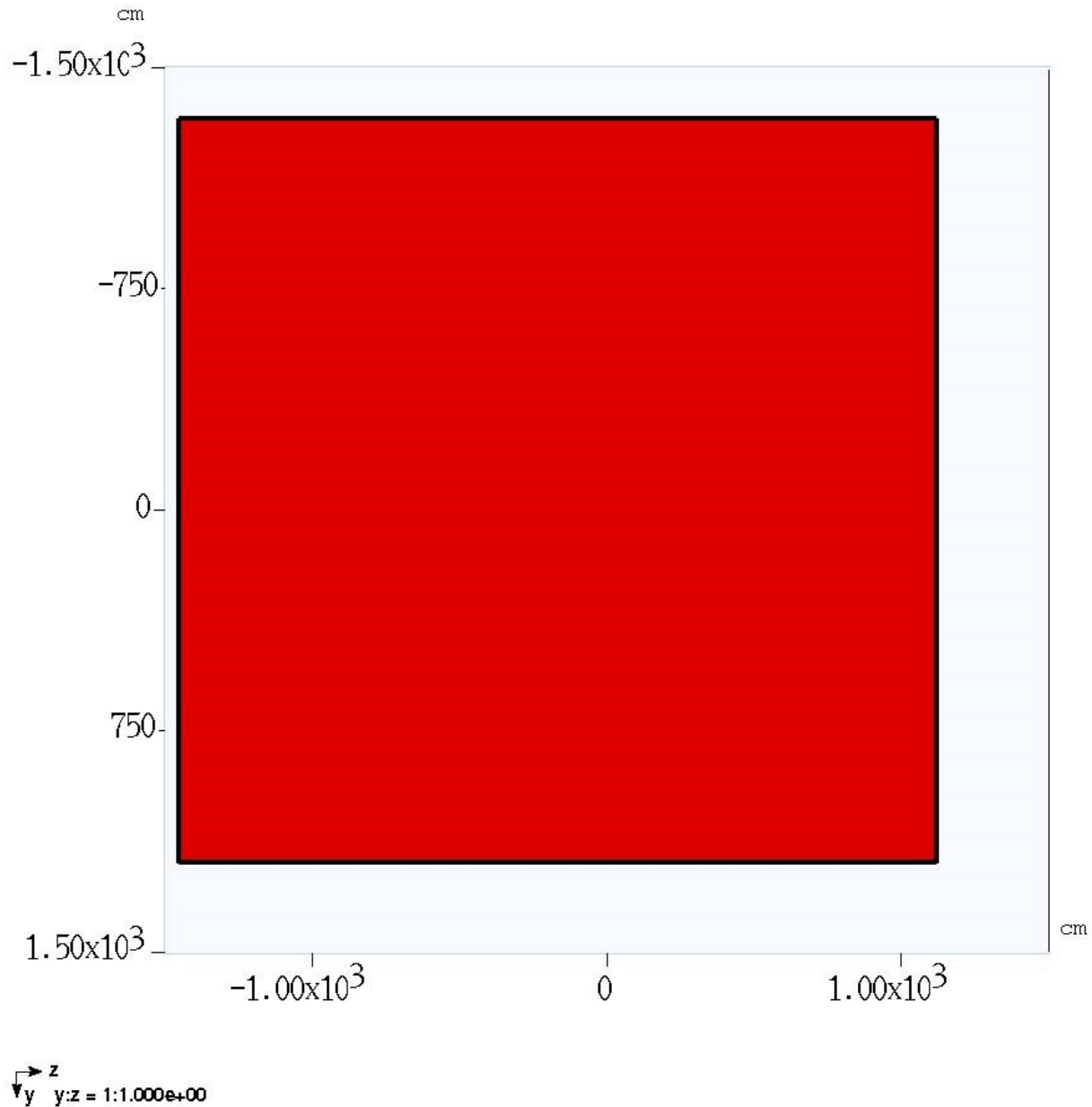
Figure 12: Plan view of top detector which covers extends over the top of the muon g-2 storage ring enclosure

Assessment Parameters

The beam types and intensities listed previously in Table 1 are used in three separate MARS runs to look at resulting radiation dose rates for the three types of particles that can potentially enter the muon g-2 storage ring. The muon beam is the working beam for the g-2muon experiment and should be considered the normal running condition. While small numbers of pions and protons will be entering the storage ring during normal operation, significant effort will be applied to ensure that pions and protons produced at the target station are to be

minimized or eliminated before reaching the muon g-2 storage ring [8]. Protons are to be kicked out of the Delivery Ring into the abort line after the muon and proton beams are separated naturally by time of flight through the M2/M3 line and through some number of turns of the Delivery Ring. Pion flux will be reduced by decay depending upon the length of the beam transport path taken as discussed below.

The full production of correct momentum protons produced in the target station and delivered to the muon g-2 storage ring is one accident to consider. The full production of decay-corrected pions produced in the target station and delivered to the muon g-2 storage ring is a second accident condition. Of the two possible accident scenarios, the proton case is more severe.

In principle, it may be possible to deliver primary protons from the Booster to the muon g-2 storage ring. Since the MC1 service building is designed only for very low power beams, the delivery of protons from the Booster to the g-2 storage ring will need to be prevented through the Radiation Safety System by the use of critical devices. Muon Campus critical devices have been determined and defined [9]; as a consequence, the possibility of primary beam delivery to the muon g-2 storage ring is eliminated.

Determination of the g-2 Normal and Accident Condition Beam Losses at MC1 service building

Based upon simulations at the AP0 target station, the secondary yield of 3.094 GeV/c protons, pions, and muons from an incident beam of 8 GeV protons on target has been determined and is shown in Table 1. The secondary beam leaves the target in a 120 ns wide pulses with a calculated time distribution shown in Figure 12. As the secondary beam travels toward the muon g-2 storage ring, two things happen: 1.) the various particle types separate in time due to their differing energies, and 2.) pions decay to muons. While the separation between pions and muons is relatively slow,   particle separation between the protons and pions/muons occurs more rapidly.

Pions produced at the target station will decay to muons by the relationship:

$$\Phi = \Phi_0 * e^{-\left(\frac{x}{\gamma c \tau}\right)}$$

where x is the decay length in meters, γ is the Lorenz factor, and cτ is 7.8045 meters [6]. The distance for various operating scenarios along with the remaining fraction of pions which would arrive at the muon g-2 storage ring is given in Table 2.

Operating Scenario	Length (meters)	Remaining fraction
AP0 directly to muon g-2 storage ring	425	8.5949%
AP0 to storage ring via Delivery Ring 1 turn	930	0.4654%
AP0 to storage ring via Delivery Ring 2 turn	1435	0.0252%
AP0 to storage ring via Delivery Ring 3 turn	1940	0.0014%
AP0 to storage ring via Delivery Ring 4 turn	2445	0.0001%

Table 2: Pion decay lengths and remaining fractions for some beam line operating scenarios

The minimum decay time is the time of flight between the AP0 target station and the injection region of the muon g-2 storage ring and results in the maximum number of pions reaching injection at the muon g-2 storage ring or about 8.6E5 pions per pulse. Longer decay times are made possible by circulating the pions in the Delivery Ring which leads to reduced numbers of pions reaching the muon g-2 storage ring. For example after one turn in the Delivery, the maximum number of pions which can reach the muon g-2 storage ring is about 4.6E4 pions per pulse. For purposes of this shielding assessment, the direct injection case for pions to the muon g-2 storage ring is considered the worst case.

Secondary protons produced at the AP0 target station are to be removed from the beam prior to entering the muon g-2 storage ring because they produce an undesirable flash in the muon decay detection system. Secondary protons have a somewhat lower energy than muons and, consequently, the protons lag behind the muons. Figure 13 shows the amount of drift between the centroid of the proton distribution and muon distributions as they travel from the AP0 target station to the muon g-2 storage ring under various scenarios.
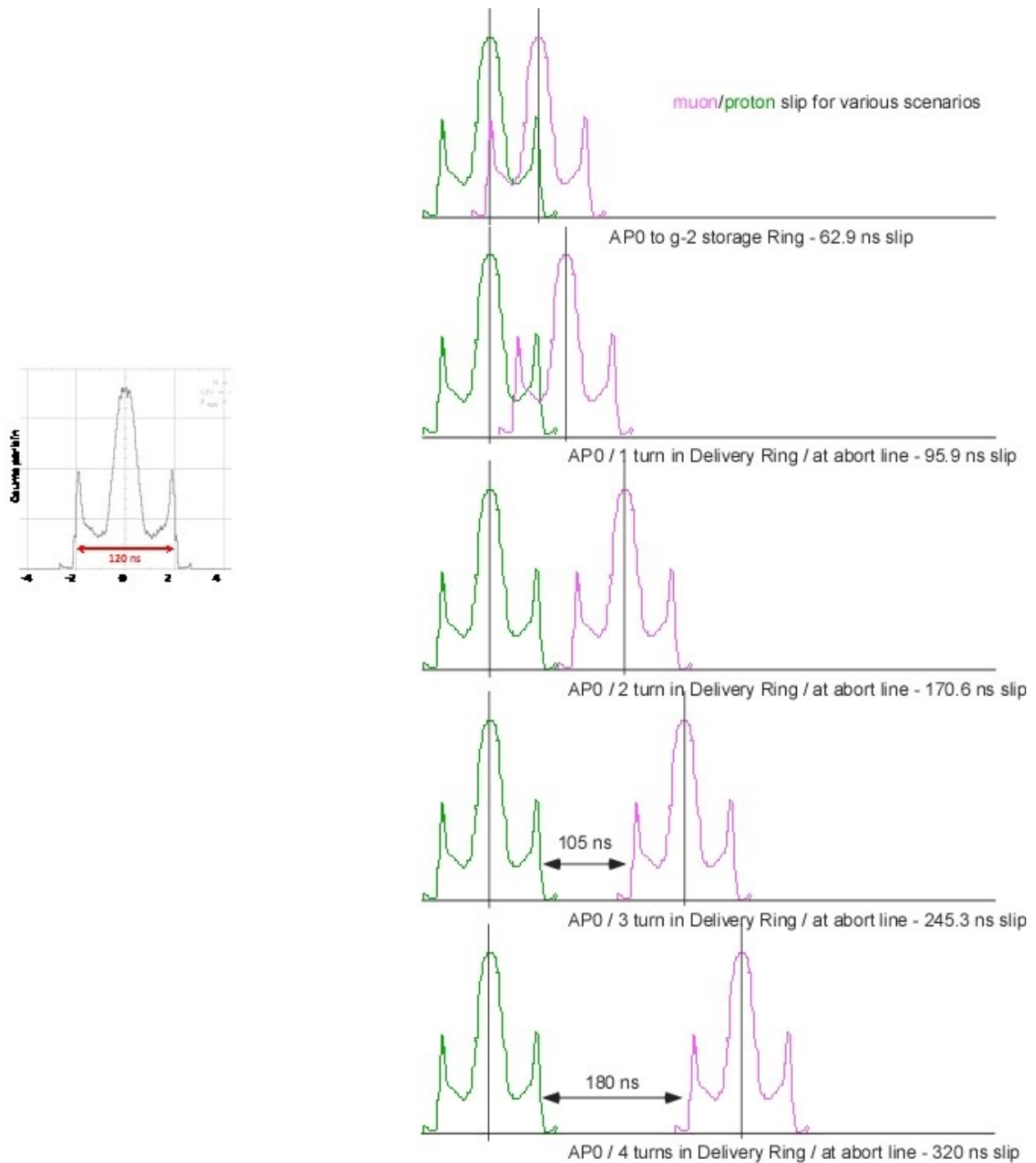
Figure 13: Proton slipping due to energy difference between protons and muons produced at the AP0 target station at the AP50 abort line as a function of turns into the Delivery Ring. The gap is necessary to cleanly extract the protons at the AP50 beam abort line.

If injection occurs directly from the AP0 target station into the muon g-2 storage ring with passing through the Delivery Ring, a Wein filter technique may be used in the M2/M3 line to remove a significant fraction of the undesirable proton beam.

The beam intensities of the various particle types for which this shielding assessment is based are listed in Table 3 for both normal and accident conditions. The maximum muon flux is desirable for normal operation of the experiment.

Particle type	Secondary yield at AP0 ppp	Remaining fraction	Normal condition	Accident condition	comment
Protons	2E7	0.1	<2E6	2E7	Actual reduction factor depends upon effectiveness of proton removal kicker system
Muons	1E5	1	1E5	1e5	Success of experiment depends upon maximizing injected muons
Pions	1E7	0.086	8.6E5	8.6E5	Direct injection from AP0 to muon g-2 storage ring
Pions	1E7	0.0046	4.6E4	4.6E4	1 transit of Delivery Ring
Pions	2E7	0.0025	2.5E3	2.5E3	2 transits of Delivery Ring

Table 3: Normal and accident beam loss conditions for various particle types and, if applicable, as a function of decay length

MC-1 Service Building Occupancy and Radiological Posting Design Goals

The design goals for radiation dose rates in and around the MC1 service building are listed in this section. The locations and intended radiation dose rates limits for normal and accident conditions are included below in Table 4. The areas listed in Table 4 can be located on drawings included in Reference 2. In general, the design goal is to require no occupancy limits for the MC-1 service building. Controlled area postings would be used for spaces including the Experiment Hall and spaces adjacent to the Experiment Hall.

Location	Radiation Dose Rate limit (mrem/hr) Normal/Accident	Permitted FRCM Occupancy	Required FRCM Radiological Postings
Experiment Hall	<0.25/<5	Exclusion Area during operations	Controlled Area
Power supply room	<0.25/<5	Minimal occupancy no time limits	Controlled Area
Computer room	<0.25/<5	Minimal occupancy no time limits	Controlled Area
Refrigeration room	< 0.05/< 1	Unlimited	No posting required
Control Room	< 0.05/< 1	Unlimited	No posting required
HVAC mechanical Room	<0.25/<5	Minimal occupancy no time limits	Controlled Area
Storage room	<0.25/<5	Minimal occupancy no time limits	Controlled Area
Shop area	< 0.05/< 1	Unlimited	No posting required
Outside building perimeter	<0.05/< 1	No occupancy limits	No posting required

Table 4: Intended occupancy and radiological postings for the MC-1 service building

Shielding Assessment

In this section, the results of MARS simulations for the three particle fluxes described above are given. The main approach used is to consider that the particle fluxes determine in Table 3 are injected into the muon g-2 storage ring which has no magnetic field. Instead of injecting the beam onto the injection orbit and circulating it, beam is injected into the ring with no magnetic field. The worst case condition, total beam loss on the muon g-2 ring and concentrated at a single point, is considered. All MARS user input files created for this assessment are included in Appendix 1 through 5.

Protons

The results of the MARS calculations for three, 8 cm thick, tissue equivalent detectors are in Figures 14, 15, and 16. The radiation dose rates shown are for the continuous loss of 2E7 protons per pulse at a single point at injection which is the worst case accident condition. The average radiation dose rate on the surface of the roof shown in Figure 14 is about 2 mrem/hr. The South Wall and West Wall radiation dose rates are shown in Figures 15 and 16.
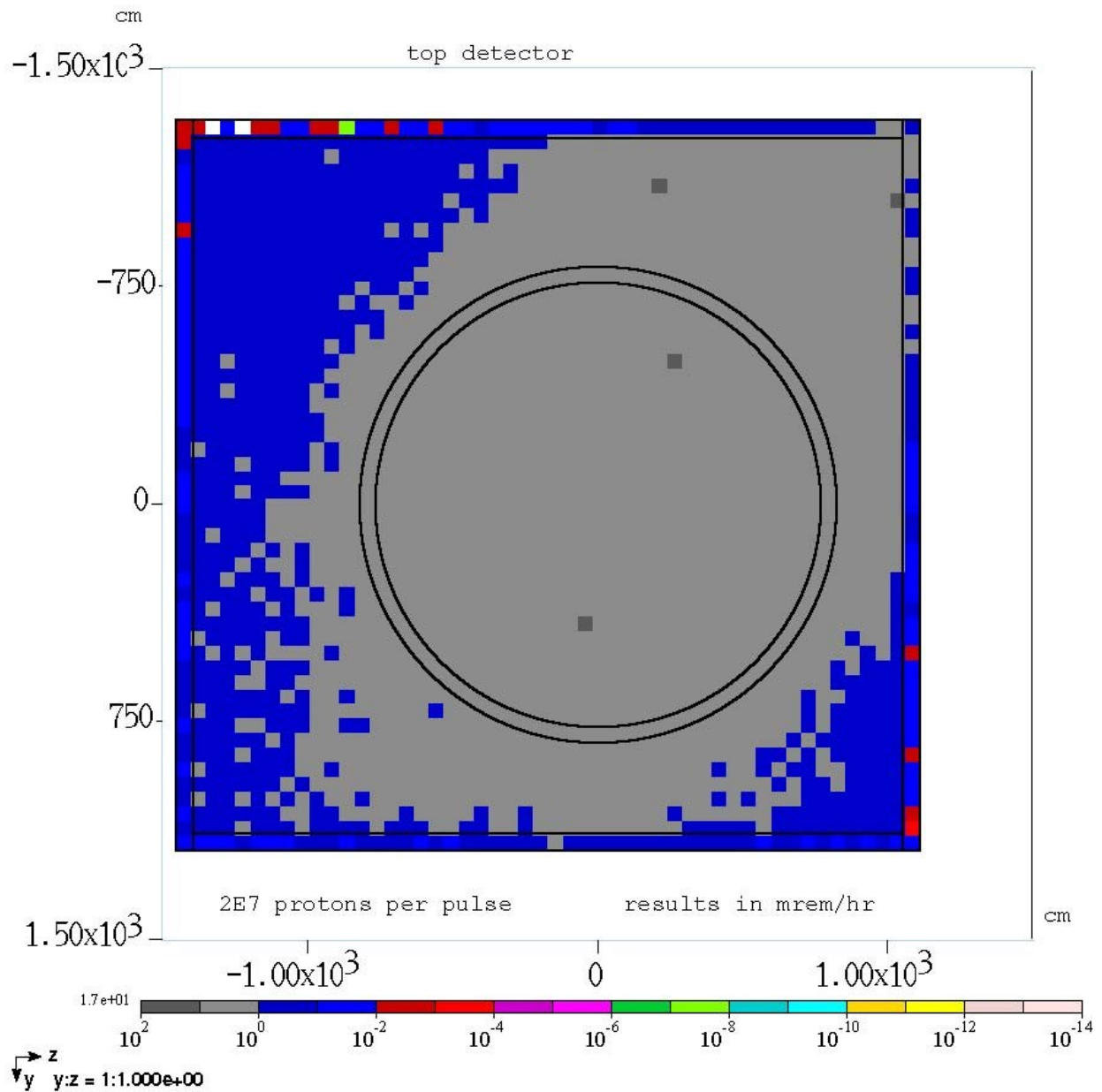
Figure 14: Tissue equivalent detector over the MC-1 service building muon g-2 storage ring under worst case accident conditions for protons. The South Wall is at the top and the West Wall is at right in the Figure. The average dose rate is 2.1 mrem/hr.

Figure 15: Tissue equivalent detector adjacent to the MC-1 service building muon g-2 storage ring South Wall under worst case accident conditions for protons. The average dose rate is 0.3 mrem/hr.
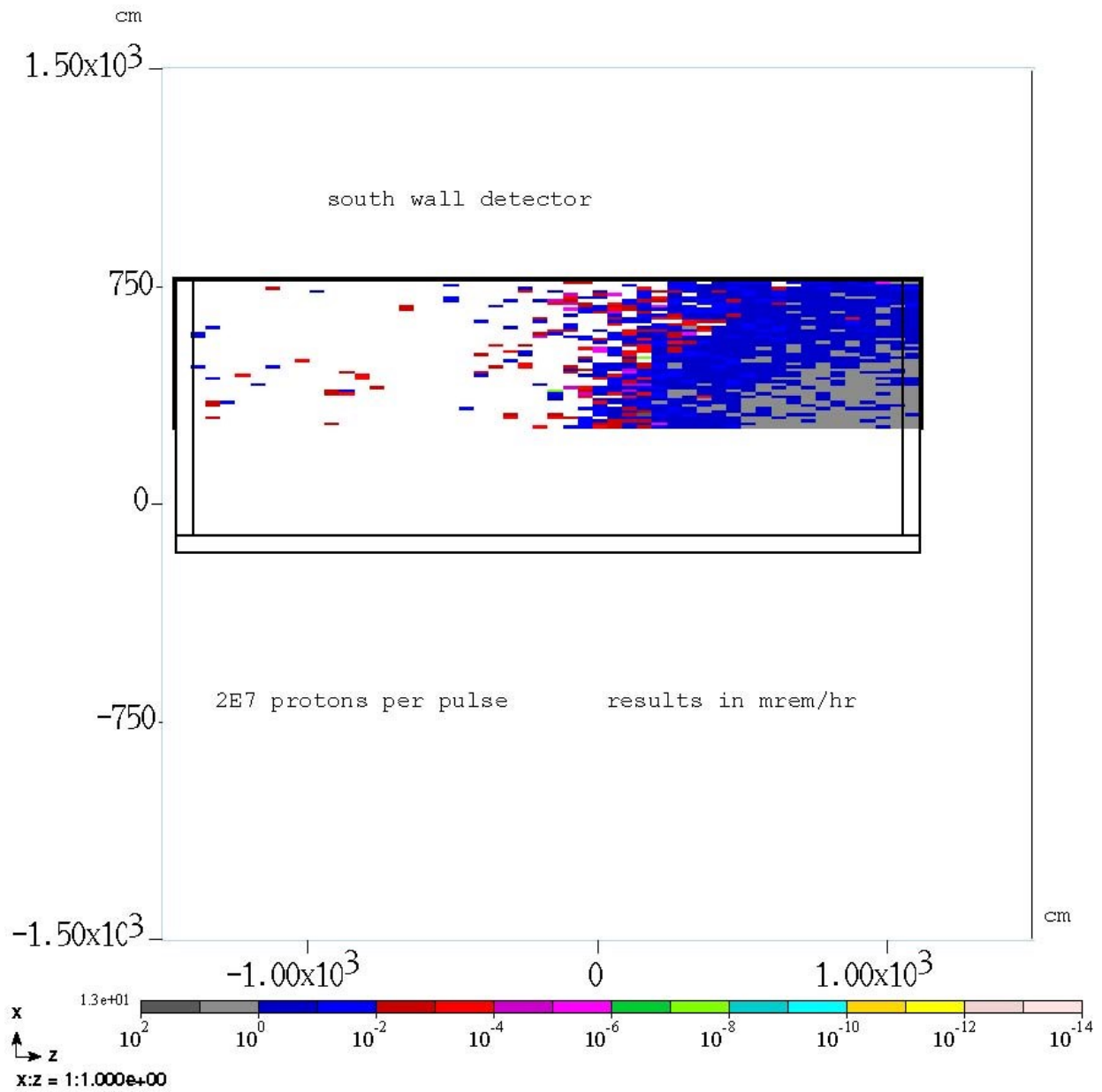
Figure 16: Tissue equivalent detector adjacent to the MC-1 service building muon g-2 storage ring West Wall under worst case accident conditions for protons. The average dose rate is 0.6 mrem/hr.

Pions

The results of the MARS calculations for three, 8 cm thick, tissue equivalent detectors are in Figures 17, 18, and 19. The radiation dose rates shown are for the continuous loss of 8.6E5 pions per pulse at a single point at injection which is the worst case accident condition. The average radiation dose rate on the surface of the roof shown in Figure 17 is about 0.1 mrem/hr. The South Wall and West Wall radiation dose rates are shown in Figures 18 and 19.
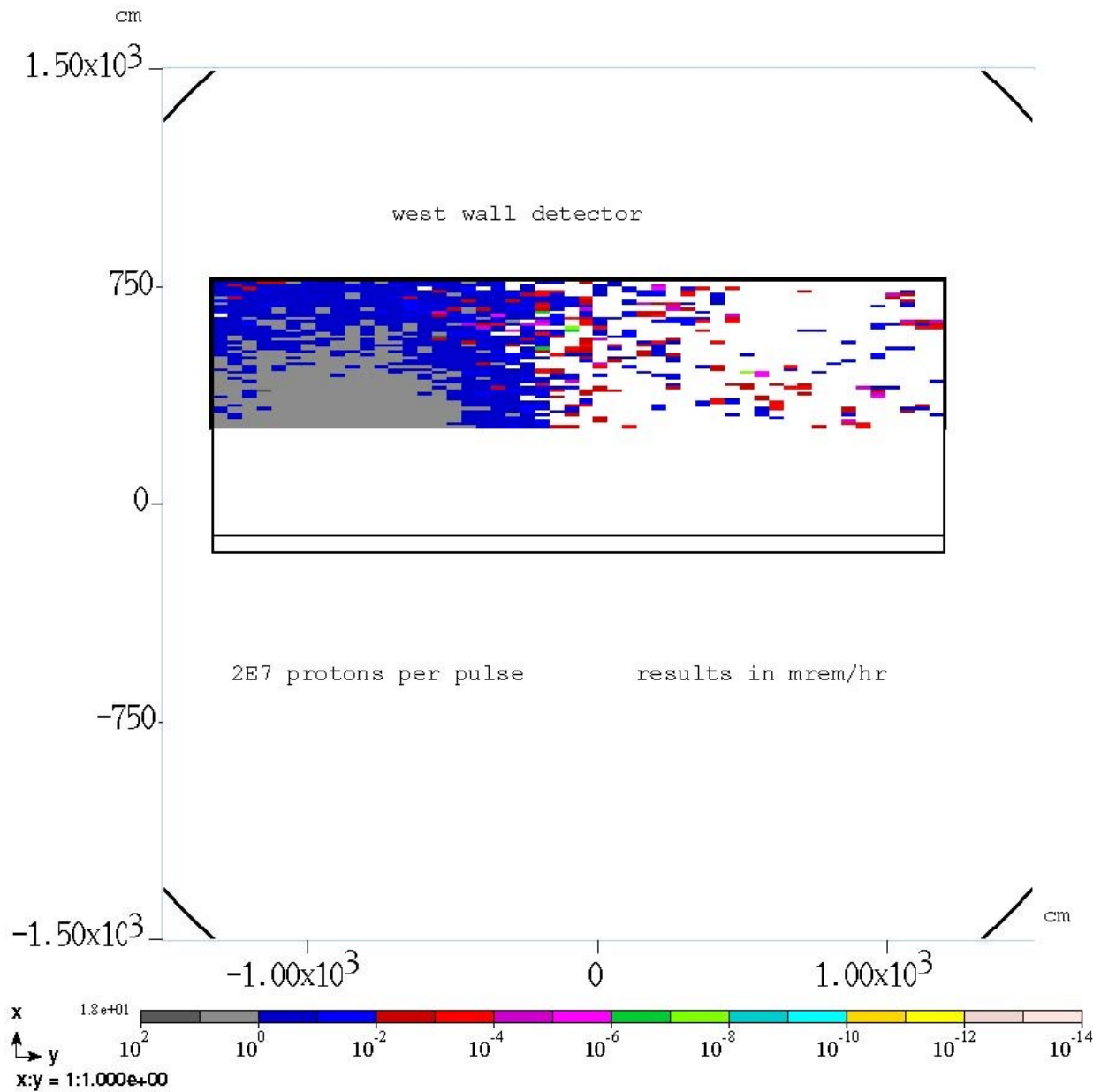
Figure 17: Tissue equivalent detector adjacent to the MC-1 service building muon g-2 storage ring West Wall under worst case accident conditions for pions. The average dose rate is 0.1 mrem/hr.
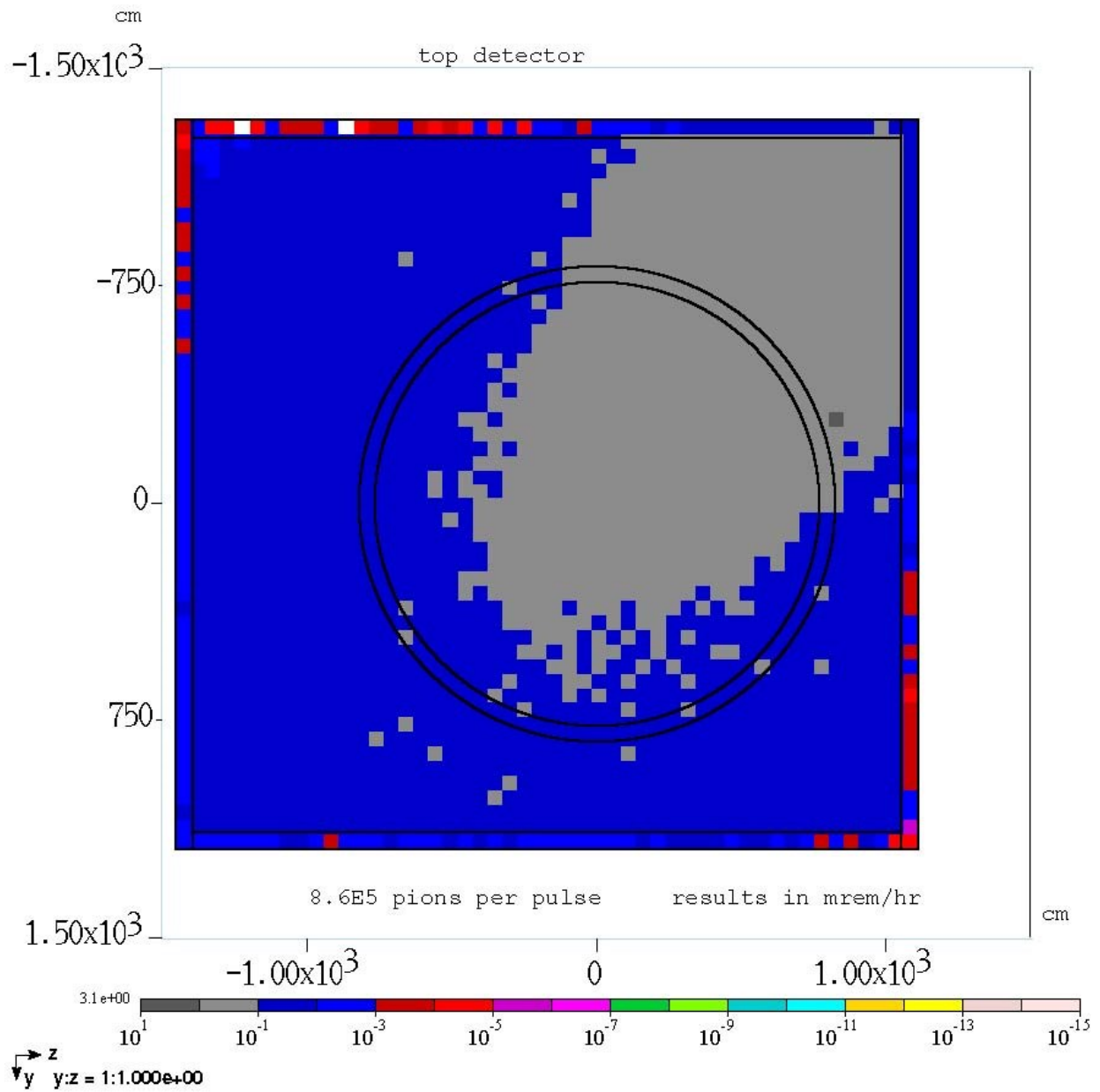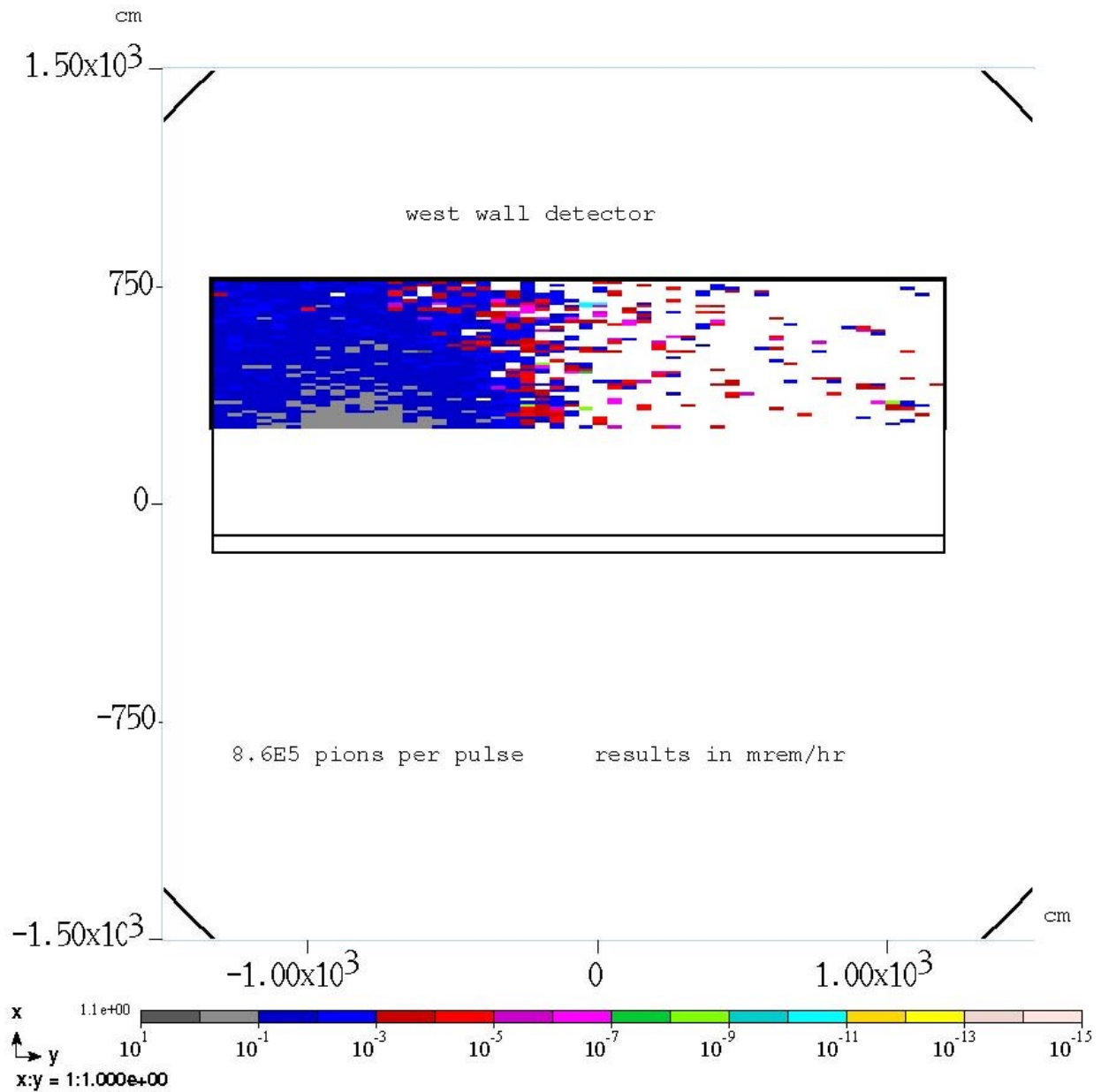
Figure 18: Tissue equivalent detector adjacent to the MC-1 service building muon g-2 storage ring West Wall under worst case accident conditions for pions. The average dose rate is 0.02 mrem/hr.

Figure 19: Tissue equivalent detector adjacent to the MC-1 service building muon g-2 storage ring South Wall under worst case accident conditions for pions. The average dose rate is 0.01 mrem/hr.

Muons

The results of the MARS calculations for three, 8 cm thick, tissue equivalent detectors are in Figures 20, 21, and 22. The radiation dose rates shown are for the continuous loss of 1E5 muons per pulse at a single point at injection which is the worst case accident condition. The average radiation dose rate on the surface of the roof shown in Figure 20 is about 0.01 mrem/hr. The South Wall and West Wall radiation dose rates are shown in Figures 21 and 22.

Figure 20: Tissue equivalent detector over the MC-1 service building muon g-2 storage ring under worst case condition which is the normal condition for muons. The South Wall is at the top and the West Wall is at right in the Figure. The average dose rate is 0.01 mrem/hr.
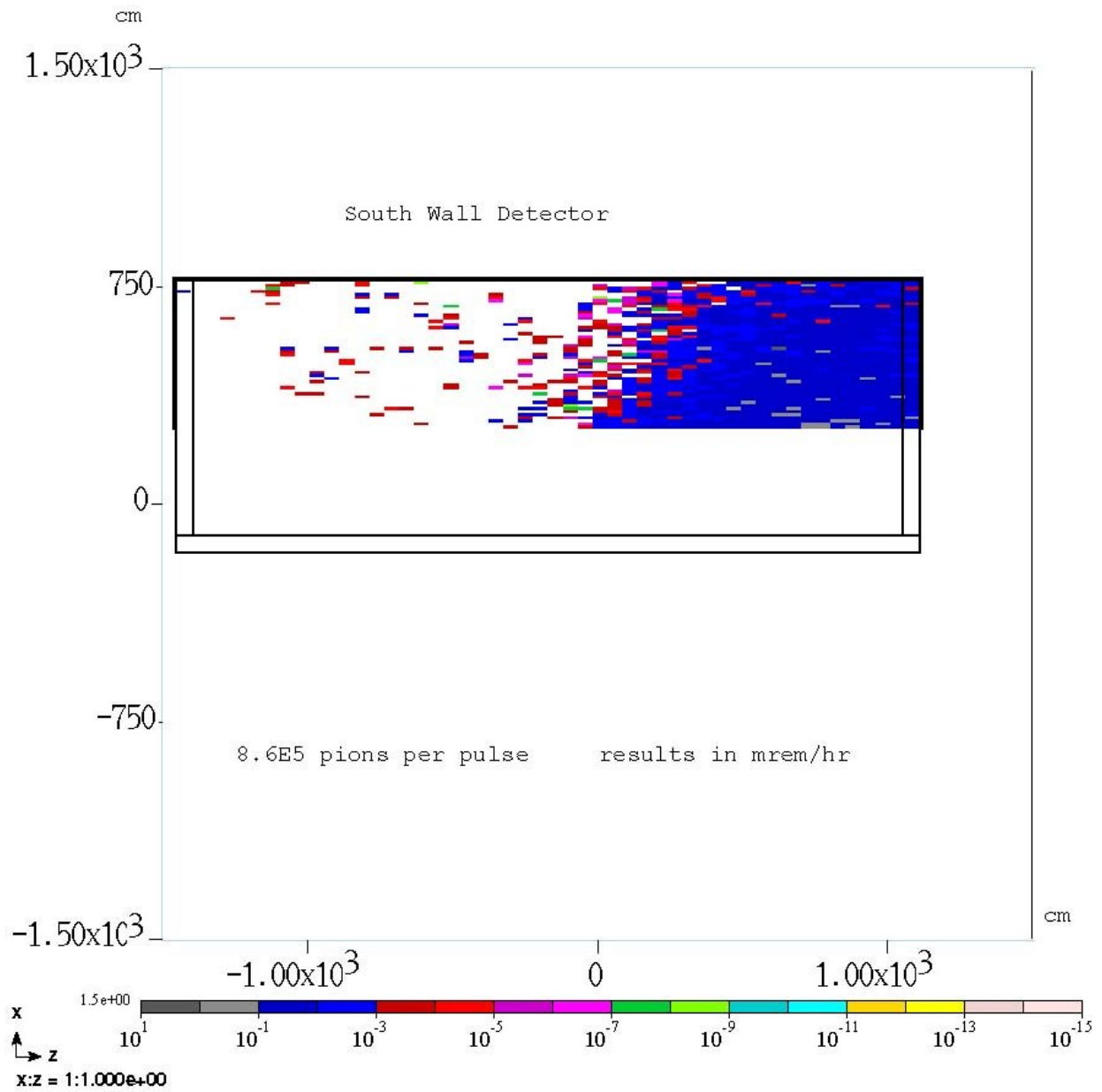
Figure 21: Tissue equivalent detector adjacent to the MC-1 service building muon g-2 storage ring South Wall under worst case conditions which is the normal condition for muons. The average dose rate is 0.001 mrem/hr.
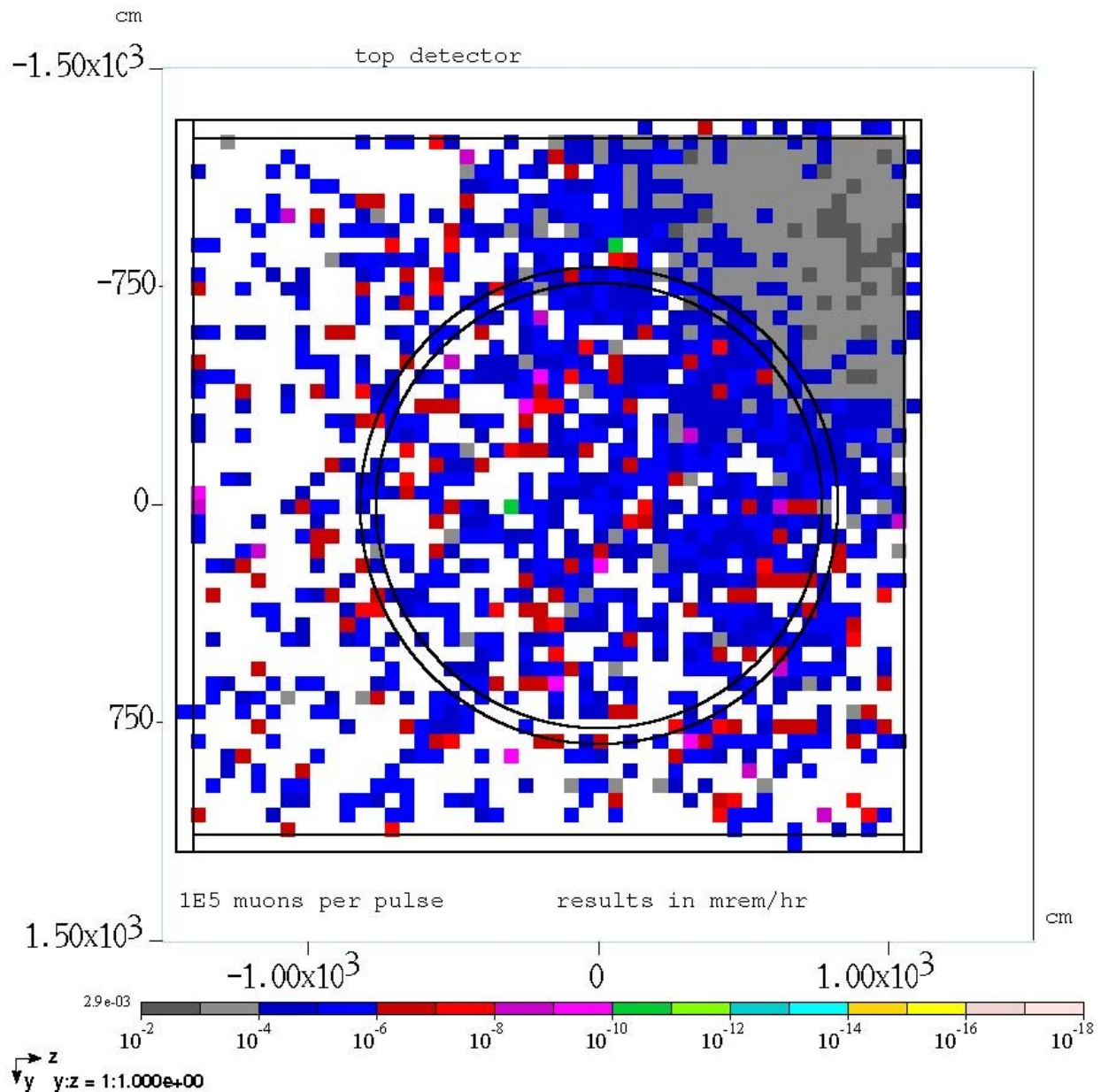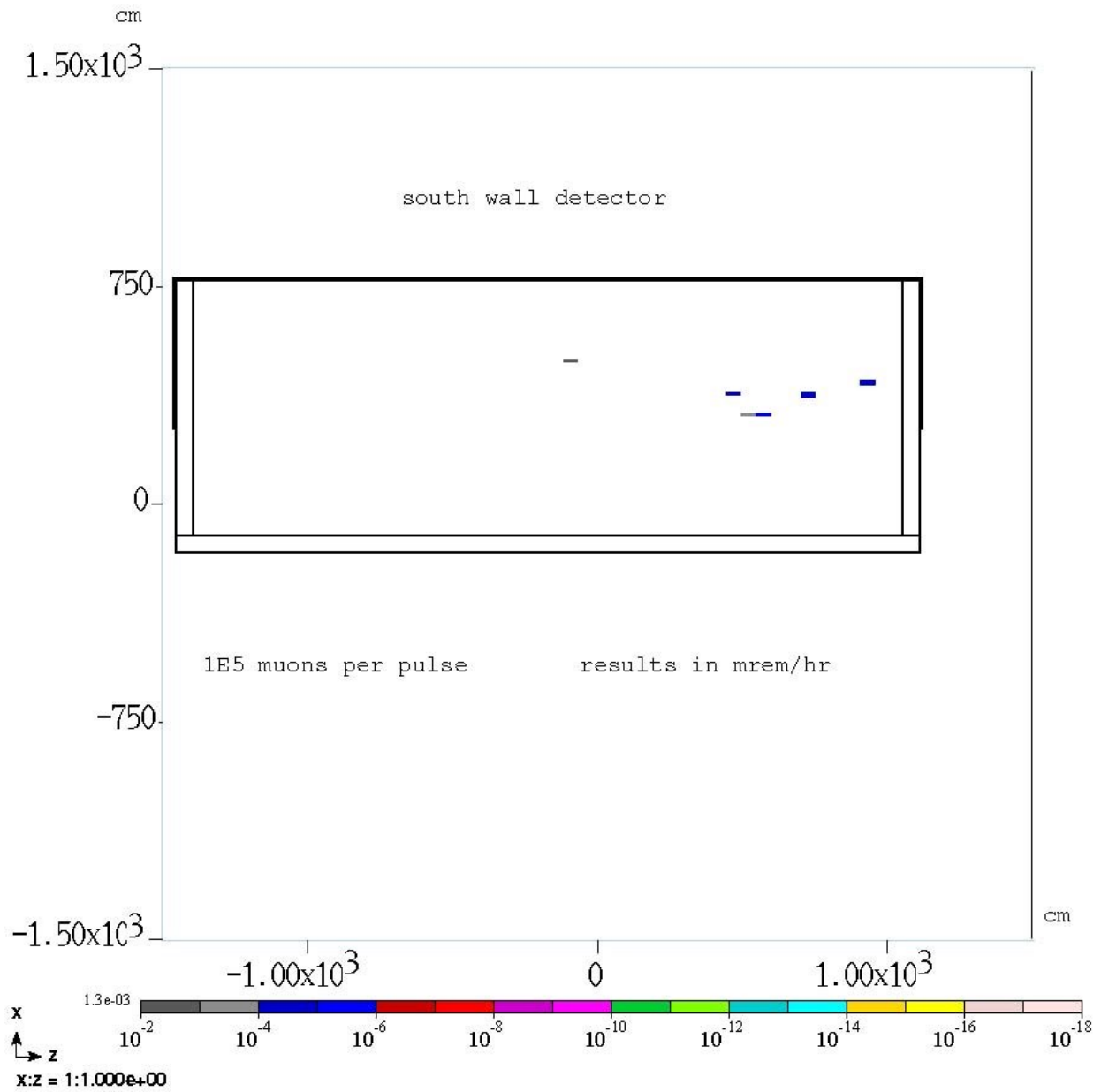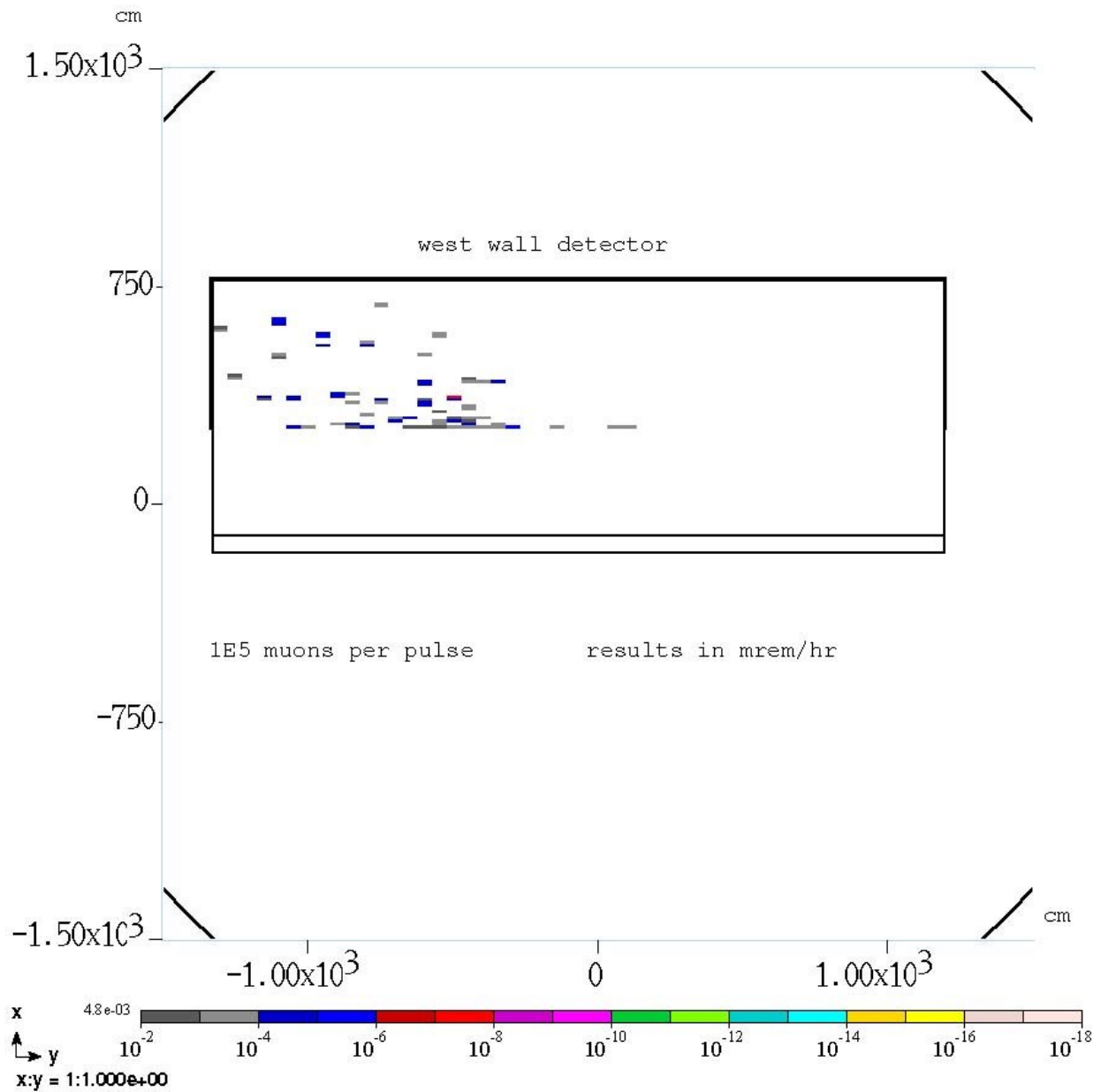
Figure 22: Tissue equivalent detector adjacent to the MC-1 service building muon g-2 storage ring West Wall under worst case conditions which is the normal condition for muons. The average dose rate is 0.003 mrem/hr.

Shielding calculation summary

The results of the MARS calculations for the normal operation of the muon g-2 storage ring show that the MC-1 Service Building design meets the requirements for the desired occupancy described in Table 4. A flash in the muon g-2 storage ring detector signal due to the injection of protons and pions is undesirable. A scheme to remove protons from the secondary beam before arrival at the muon g-2 storage ring has been developed to eliminate most protons from the secondary yield at the AP0 target station. Pions are all but eliminated as a by-product of the proton elimination scheme by circulating the secondary beam in the Delivery Ring. The contribution of radiation dose from the injection of protons and pions depends upon the final details of the proton removal scheme which remains to be determined.

Ground water, surface water, air activation

The interaction of protons and neutrons with the air inside the MC-1 Service Building at the muon g-2 storage ring enclosure can produce airborne radioactive isotopes that can be carried to the site boundary. There is an annual limit for the quantity of radionuclides that can be released off site by the laboratory.

The secondary beam anticipated to be introduced into the MC-1 Service Building is of extremely low power. As a consequence, no significant activation of groundwater, surface water, and air will be possible.

Residual Radioactivation of the muon g-2 ring

Prolonged exposure to beam can result in a buildup of radioactive isotopes in beam line elements. However, for the peak beam power to be achieved at the muon g-2 storage ring, no serious residual activation problems are possible. The level of activation which might be observed will depend upon the actual beam loss distribution of protons and pions. It is anticipated that only very limited activation of structural components will be observed.

Interlocked Radiation Detectors

No interlocked radiation detectors should be required for protection of the MC-1 Service Building. However, it would be prudent to install a small number of interlocked radiation detectors for verification purposes.

Muon g-2 Critical Devices

Critical devices will be required to prevent the introduction of primary beam into the MC-1 Service Building experimental hall from the M4 beam line. Muon Campus critical devices have been defined and are described in Reference 9.

Experimental Hall Interlocks

While the radiation dose rates produced as a result of beam loss during operation of the muon g-2 storage ring will be relatively low, a typical radiation safety system should be required to prohibit personnel access to the ring while secondary beam injection is possible.

Radiation Skyshine at the MC-1 Service Building

Due to very low available beam power, radiation skyshine would not be an issue for normal operation of the muon g-2 experiment.

Conclusion

This preliminary shielding assessment for the MC1 service building, evaluated for normal and accident conditions, demonstrates that the facility can be operated in accordance with all FRCM requirements. The facility should be capable of continuous operation at beam intensities listed in Table 3. A shield design for a temporary shield wall in the M4 enclosure has been completed which permits personnel access to the M4 beam line during muon g-2 operation.

References

1. Fermilab Radiological Control Manual http://esh.fnal.gov/xms/FRCM
2. Project Plan for the conventional construction of the MC-1 Building, FESS/Engineering Project No. 6-10-20, March 2012
3. N.V. Mokhov, "The Mars Code System User's Guide", Fermilab-FN-628 (1995); O.E. Krivosheev, N.V. Mokhov, "MARS Code Status", Proc. Monte Carlo 2000 Conf., p. 943, Lisbon, October 23-26, 2000; Fermilab-Conf-00/181 (2000); N.V. Mokhov, "Status of MARS Code", Fermilab-Conf-03/053 (2003); N.V. Mokhov, K.K. Gudima, C.C. James et al, "Recent Enhancements to the MARS15 Code", Fermilab-Conf-04/053 (2004); http://www-ap.fnal.gov/MARS/.
4. The New (g – 2) Experiment: A Proposal to Measure the Muon Anomalous Magnetic Moment to ±0.14 ppm Precision, February 2009 GM-2 doc 1-v1 http://gm2-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=1
5. The Brookhaven muon storage ring magnet, Nuclear Instruments and Methods in Physics Research A 457 (2001) 151}174
6. Particle Data Group, (URL: http://pdg.lbl.gov)
7. G-2 Yield Beam Study Results, April 2012, Dean Still, G Minus 2 Experiment Document 430-v6, July 27, 2012
8. Muon g-2 Technical Design Report, G-2 Experiment Document 2055-v2, July 2014
9. Muon Campus Critical Devices, Beams Document 4494-v2, December 2013
10. M4 beam line shielding labyrinth for Muon g-2 operation, G Minus 2 Experiment Document 624-v2, September 2014

APPENDIX 1 GEOM.INP File for all runs

```
g-2 ring    05/30/12
OPT
part1   -2   1   1  0.   0.      0.    685.5  819.5  13.5 1   1 !bottom layer
part2   -2   2   2  0.   0.      0.    683.1  822.5  13.5 1   1 !second layer
part3   -2   3   3  0.   0.      0.    768.1  822.5  24.5 1   1 !third layer
part4   -2   4   4  0.   0.      0.    683.2  739.2  6.75 1   1 !bottom pole
part5   -2   5   5  0.   0.      0.    683.2  739.2  6.75 1   1 !top pole
part6   -2   6   6  0.   0.      0.    683.1  822.5  13.5 1   1 !second from top
part7   -2   7   7  0.   0.      0.    685.5  819.5  13.5 1   1 !top layer
concflr -1   0   9 -138.4      -67.5 -173.5    30. 1260. 1283. 1 1 1 !concfloor
eastwll -1   0  10  333.56     -67.5 -1426.5  442. 1260.  30. 1 1 1 ! US wall
sothwll -1   0  11  333.56  -1297.5 -173.5    442.   30. 1223. 1 1 1 ! Southwall
nortwll -1   0  12  333.56   1162.5 -173.5    442.   30. 1223. 1 1 1 ! Northwall
westwll -1   0  13  333.56     -67.5 1079.5   442. 1260.  30. 1 1 1 ! westwall
eastdet -1   0  14  525.       -67.5 -1460.5  259. 1260.   4. 1 1 1 ! east detector
westdet -1   0  15  525.       -67.5 1113.5   259. 1260.   4. 1 1 1 ! west detector
soutdet -1   0  16  525.    -1331.5 -173.5    259.   4. 1283. 1 1 1 ! south detector
nortdet -1   0  17  525.     1194.5 -173.5    259.   4. 1283. 1 1 1 ! north detector
topdet  -1   0   8  780.       -67.5 -173.5     4.    1260. 1283. 1   1   1 !top
detector
! inject     2   0   0 711.2   0. -1000.     0. 7.5 1000. 1    1 !vacuum injectio
! TRn     XT    YT    ZT     a     b     c
  TR1  -65.2   0.    0.    0.   90.    0.
  TR2  -38.2   0.    0.    0.   90.    0.
  TR3    0.    0.    0.    0.   90.    0.
  TR4  -15.65  0.    0.    0.   90.    0.
  TR5   15.65  0.    0.    0.   90.    0.
  TR6   38.2   0.    0.    0.   90.    0.
  TR7   65.2   0.    0.    0.   90.    0.
Stop
```

APPENDIX 2 MARS.INP File for proton run

```
g-2 ring   02/24/12
/home/mokhov/restricted/mars15/dat
INDX F 2=T 3=T 5=T
CTRL 0
ENRG 2.294867 4=2.e-4
c TAPE 18
NEVT 500000 100
INIT  0. -711.2 0. 0. 0.173648 0.984808
IPIB 1
NHBK 1
ZMIN -1500.
ZSEC 1500.
RSEC 2000.
NMAT 17
MATR 'MATER.INP'
STOP

*MCNP START
m1 26000 1.0 cond=1
m2 26000 1.0 cond=1
m3 26000 1.0 cond=1
m4 26000 1.0 cond=1
m5 26000 1.0 cond=1
m6 26000 1.0 cond=1
m7 26000 1.0 cond=1
m8 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374
m9  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
m10  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
m11  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
m12  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
m13  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
m14 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374
m15 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374
m16 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374
m17 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374

*MCNP END
```

APPENDIX 3 MARS.INP File for pion run

```
g-2 ring   02/24/12
/home/mokhov/restricted/mars15/dat
INDX F 2=T 3=T 5=T
CTRL 0
ENRG 2.957576 4=2.e-4
c TAPE 18
NEVT 500000 100
INIT  0. -711.2 0. 0. 0.173648 0.984808
IPIB 3
NHBK 1
ZMIN -1500.
ZSEC 1500.
RSEC 2000.
NMAT 17
MATR 'MATER.INP'
STOP


*MCNP START
m1 26000 1.0 cond=1
m2 26000 1.0 cond=1
m3 26000 1.0 cond=1
m4 26000 1.0 cond=1
m5 26000 1.0 cond=1
m6 26000 1.0 cond=1
m7 26000 1.0 cond=1
m8 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374
m9  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
m10  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
m11  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
m12  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
m13  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
m14 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374
m15 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374
m16 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374
m17 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374

*MCNP END
```

APPENDIX 4 MARS.INP File for muon run

```
ring   02/24/12
/home/mokhov/restricted/mars15/dat
INDX F 2=T 3=T 5=T
CTRL 0
ENRG 2.990145 4=2.e-4
c TAPE 18
NEVT 500000
INIT  0. -711.2 0. 0. 0.173648 0.984808
IPIB 7
NHBK 1
ZMIN -1500.
ZSEC 1500.
RSEC 2000.
NMAT 17
MATR 'MATER.INP'
STOP


*MCNP START
m1 26000 1.0 cond=1
m2 26000 1.0 cond=1
m3 26000 1.0 cond=1
m4 26000 1.0 cond=1
m5 26000 1.0 cond=1
m6 26000 1.0 cond=1
m7 26000 1.0 cond=1
m8 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374
m9  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
m10  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
m11  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
m12  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
m13  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
m14 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374
m15 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374
m16 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374
m17 1001 -0.1077 6000 -0.1283 8016 -0.7266 7014 -0.0374

*MCNP END
```

APPENDIX 5 XYZHIS.INP File for all runs

```
XYZ histo test with histo list  1-JUNE 2012

xyz  776. 784. -1327.5 1192.5 -1456.5 1109.5 1 50 50 topdetector
DET DEP DEN DEG DEE

xyz  266. 784. -1327.5 1192.5 -1464.5 -1456.5 50 50 1 eastdetector
DET DEP DEN DEG DEE

xyz  266. 784. -1327.5 1192.5 1109.5 1117.5 50 50 1 westdetector
DET DEP DEN DEG DEE

xyz  266. 784. -1335.5 -1327.5 -1456.5 1109.5 50 1 50 southdetector
DET DEP DEN DEG DEE

xyz  266. 784.  1190.5 1198.5 -1456.5 1109.5 50 1 50 northdetector
DET DEP DEN DEG DEE
stop
```