FERMILAB: ACCELERATOR DIVISION

M4 Beam Line Upstream Labyrinth Shield for Muon g-2 Operation

MARS Simulation

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9/8/2014

It is envisioned that the mu2e branch of the M4 beam line will be under construction while the muon g-2 experiment takes beam at the MC-1 building. The purpose of this document is to determine a shield requirement for the mu2e branch of the M4 beam line which will permit personnel access in the mu2e portion of the M4 beam line during muon g-2 operation.

Introduction

Version 1 of this shield calculation was made in December 2012 before the final geometry of the M4/M5 beam line was established by FESS. In the present work, the M4/M5 tunnel arrangement has been defined (Reference 1 and Figure 1) and is modeled in a MARS simulation [6] to determine the efficacy of a shielding arrangement which would:

- Permit worker access to the M4 beam enclosure downstream of the M4 upstream shield wall during Muon g-2 beam operation
- permit the movement of LQ magnets past the shield wall when Muon g-2 beam is off for maintenance periods without deconstruction of the shield wall

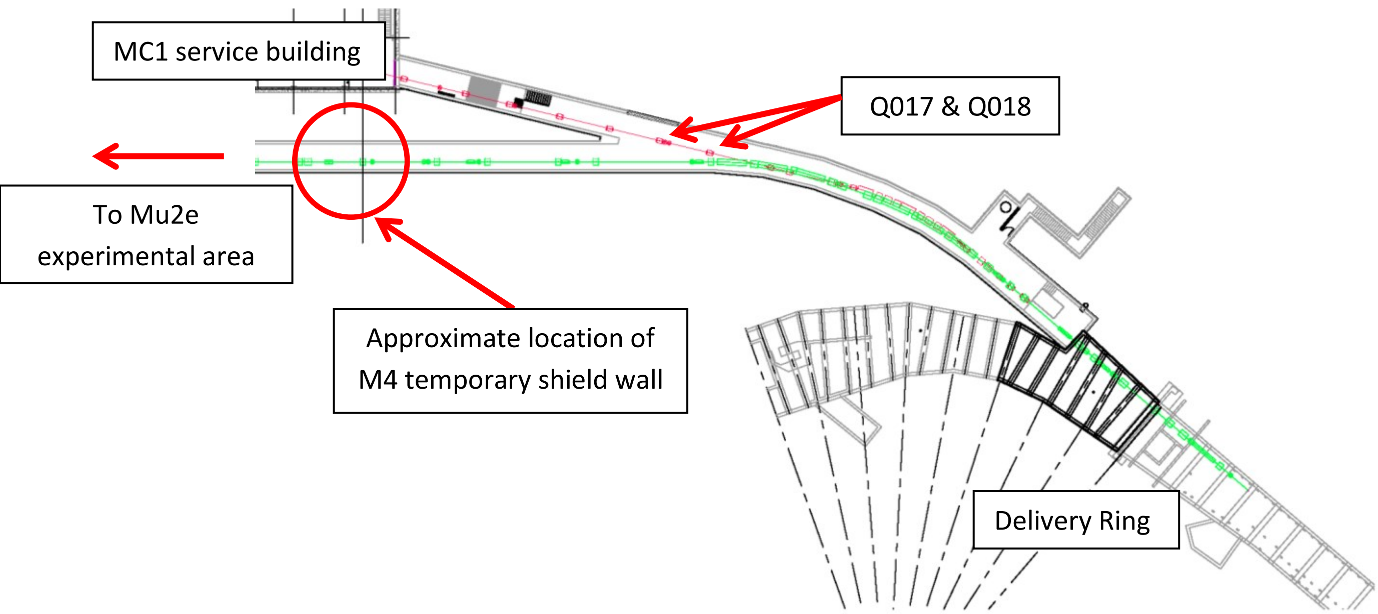

Figure 1: Layout of the M4/M5 beam lines between the Delivery Ring, MC1 service building, and the Mu2e experimental area (not shown). Magnets Q017 and Q018 are present in the M5 tunnel adjacent to the opening of the M4 tunnel. Components of the M4 line re indicated in green while those of the M5 line are indicated in red.

M5 Beam power considered for the temporary M4 shield wall

Beam delivered to the muon g-2 experiment originates from the pbar target station which is to be repurposed for this use. A 15.4 kW primary proton beam of energy 8 GeV is brought to the pbar target station. Calculations and measurements of the secondary yield from this primary beam have been reported [3] and are summarized in Table 1.

Table 1: Secondary yield of protons, and pions determined from beam studies and calculations.

Particle type	Secondary yield of 3.094 GeV/c +/-2%	Secondary beam energy (GeV)	Lorenz factor	Beta	Secondary beam power (watts)
Protons	2.4E7	2.295	3.445844328	0.956964612	0.106
Pions	9.9E7	2.958	22.19060262	0.998984096	0.564

While the secondary beam power appears to be dominated by pions, the maximum pion beam power is drastically reduced as beam is transported toward the MC-1 experimental hall. Various pion transport scenarios are considered in Table 2. For the shortest route to the MC-1 experiment hall, only 8.6% of pions remain in the beam. By the time the secondary beam reaches the M4 beam line, the limiting beam power loss case, shown in Table 3, is due to protons.

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

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 3: Normal and accident beam loss conditions for various particle types and, if applicable, as a function of decay length in the M4 beam line.

Particle type	Secondary yield at AP0 ppp	Remaining fraction	Normal condition	Accident condition	comment
Protons	2.4E7	<0.05	<2.4E6	2.4E7	Actual reduction factor depends upon effectiveness of proton removal kicker system
Muons	2.1E5	1	1E5	1e5	Success of experiment depends upon maximizing injected muons
Pions	8.5E6	0.086	8.6E5	8.6E5	Direct injection from AP0 to muon g-2 storage ring

In the conceptual design of the muon g-2 experiment, protons are to be removed almost entirely by a kicker system in the Delivery Ring as described in Reference 4. Several worst case accident conditions are considered for this preliminary assessment. It is assumed that the proton kicker system has failed and that the entire 2.3 GeV proton beam is lost continuously at full intensity listed in Table 3 and at the average duty cycle of 12 Hz for 1 hour on:

- A 65 mil thick, 4” diameter beam pipe
- On Q017, a 4Q24 magnet in the M5 beam line, and
- On Q018, another 4Q24 magnet in the M5 beam line

This set of circumstances is a conservative, worst case set of accident conditions considered for the upstream M4 shield design in this work. Muon Campus critical devices [5] prevent delivery of higher beam power beams while personnel access to the downstream M4 tunnel enclosure is possible.

Description of simulation effort (blog)

8/26/14

Copied the tunnel geometry for the m4/m5 from the grid for the M5 shield wall job. Had to correct the ceiling height at the Y. It was 10’ in the original model and has been increased to 12’ as is the current plan.

Put a 4” beam pipe at 10’ from the enclosure floor and 30” from the M5 enclosure. Put a 2.3 GeV proton beam with 2.88E8 p/s lost on a 65 mil thick beam pipe. Eventually can put a magnet in the enclosure and see if that is a better or worse case.

The beam pipe is 2’ above the ceiling of the M4 enclosure, so there is a shadow cast by any beam loss condition from the M5 line into the M4 line. The worst case beam power loss is about 100 mW.

Ran a trial version with 2 shield walls, the first setback by 10 feet and the second set back by 50 feet. Preliminary results for these two runs are shown in the following images. Pushing the wall away from the opening is obviously better.

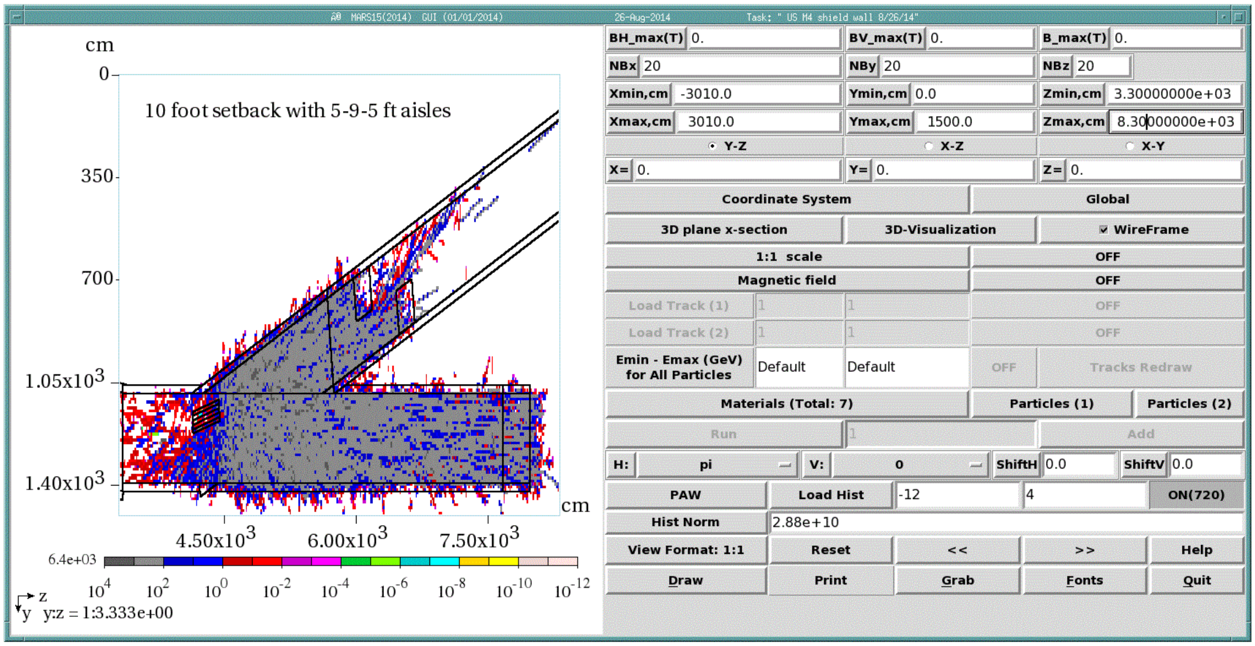

Figure 2: Plan view of M4/M5 line with shield labyrinth beginning 10' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe.

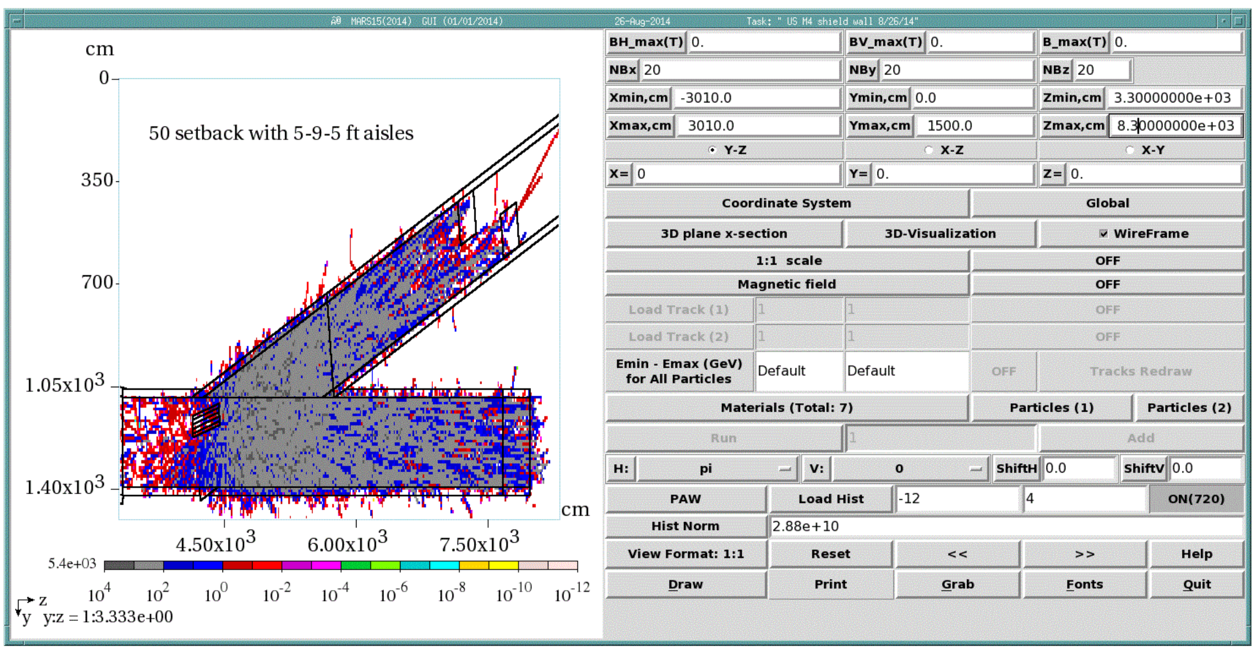

Figure 3: Plan view of M4/M5 line with shield labyrinth beginning 50' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe.

8/27/14

Talked over the above options with Jim Morgan, Dean Still, and Steve Werkema. The placement of the shield wall determines how much of the M4 beam line can be constructed while muon g-2 operates. The part of the M4 enclosure cannot be constructed while Muon g-2 operates. At this time, the length of the upstream section is not critical , so the idea to move it downstream, even at 100' does not cause scheduling concerns. At 100 feet, the tunnel is completely in the shadow of the beam and so the shield wall labyrinth just needs to stop scattered radiation from the M5 line; there would be no direct loss component stopped by the shield walls. Dean mentioned that he would want to move 6-4-120 magnets through the labyrinth which wouldn't fit the existing labyrinth which was intended to pass LQs. After some discussion, Dean said he would plan to move the 6-4-120s into position before the US shield wall is built. In fact, one wall could be built before passage of 6-4-120 magnets was precluded.

By building a shield wall that does not require relocation to pass through equipment (especially LQ magnets), costs of moving the wall can be saved and instead, resources could be spent building the US beam line. The DS M4 beam line can be built while muon g-2 takes beam. The US M4 beam line would need to be built only during periods when muon g-2 is not taking beam.

Steve is concerned that losses on Q019 just downstream of the Y could cause high losses at the M4 US wall. I will do several runs with different types of losses to check the efficacy of the shield. Candidate loss conditions are: scraping on the beam pipe (as currently modeled) and losses in a 4Q24 magnet at locations Q017, Q018, and/or Q019 (for Steve).

So the next step is to move the shield walls to 100' from the opening and begin simulations with low statistical errors. A sketch of the tunnel geometry modeled for the MARS simulation is shown in the following figure.

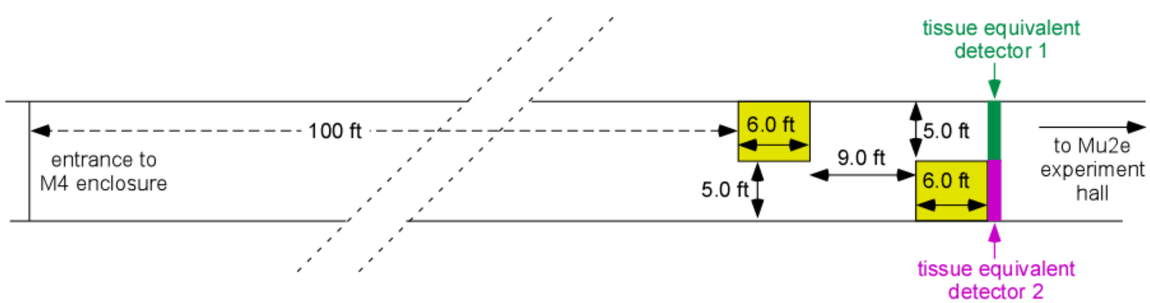

Figure 4: Sketch of concrete shield arrangement used in the MARS simulation. The first shield wall placement is 100 feet from the M4 tunnel where the ceiling height transitions from 12 feet to 8 feet. Two tissue equivalent detectors 8' high x 5' wide x 1' thick are used to determine the average effective dose rate at each side of the tunnel. An interlocked gate is to be located just downstream of the second shield wall at the position indicated by detector 1. An interlocked chipmunk in integrating mode, mounted on the gate, could be used to guarantee compliance with FRCM limits, e.g., 1 mrem/hr (unlimited occupancy, accident condition).

8/28/14

Finished setting up the shield walls and added a TE detector downstream of the walls. During trial runs this morning discovered that I had inadvertently set ENRG 5=1.E8 instead of 1.0E-12. The job had been running pretty quickly but now 50,000 ip takes about 9700 seconds. I've set the IP per job at 75,000 to set the job run time at about 4 hours. I've launched 1000 jobs which should yield low statistical error (<20%).

```
Cluster          njobs    running
17653355         500      83
17653363         500      0
```

The next job will be to build the 4Q24 subsequent runs mentioned above.

8/29/14

999 jobs have finished. The remaining one has been running 17+ hours and probably won't make it. Below are results in mrem/hr for various histograms starting at the M5 line elevation and working downward toward the floor. Each histogram layer is 1 foot thick. Table 4 lists the 10 histograms from each run along with elevation. Since the M5 beam line is partially shield by the change of ceiling height at the entrance of the M4 enclosure, the effective dose rate as a function of elevation increases moving from the ceiling elevation toward the floor elevation. All results are normalized to 2.88E8 protons per second and units in all histograms are **mrem/hr.**

Table 4: MARS simulation output histogram numbers with corresponding elevation in the simulation

Histogram number	Histogram thickness	Elevation relative to M5 beam line
702	1 foot	0 feet
704	1 foot	-1 foot
706	1 foot	-2 feet
708	1 foot	-3 feet
710	1 foot	-4 feet
712	1 foot	-5 feet
714	1 foot	-6 feet
716	1 foot	-7 feet
718	1 foot	-8 feet
720	1 foot	-9 feet

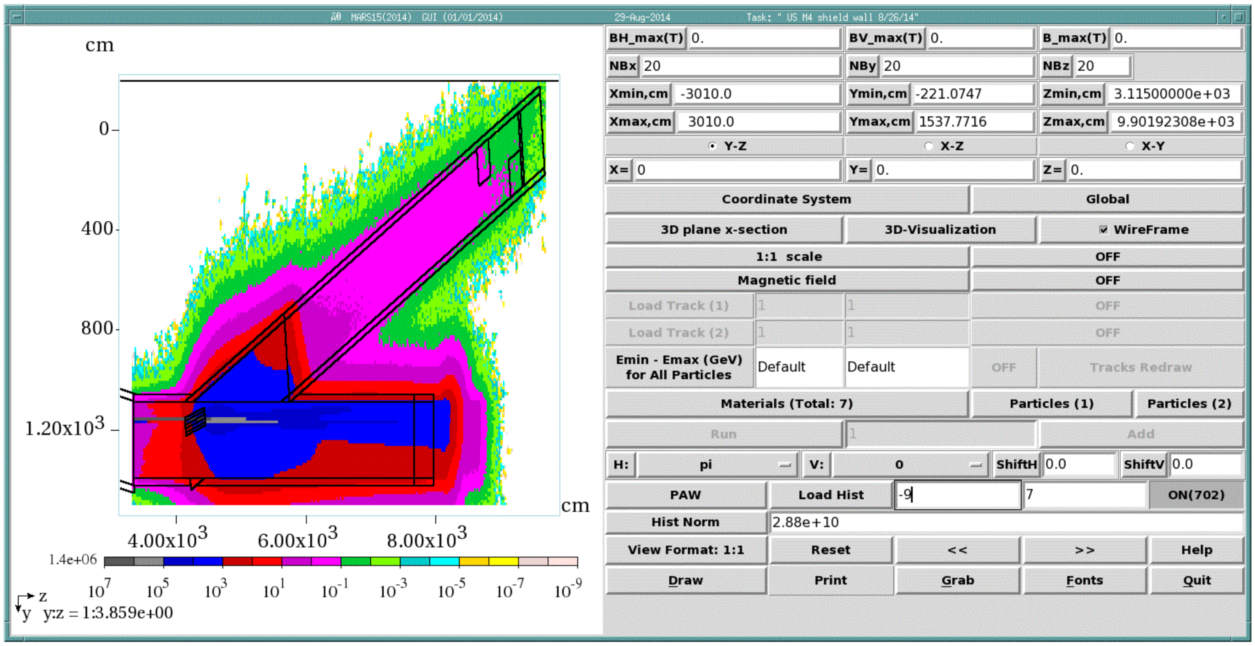

Figure 5: (Histogram 702) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe. The histogram represents the average effective dose rate for a 1 foot high region, centered at the elevation of the M5 beam line. Results are in mrem/hr.

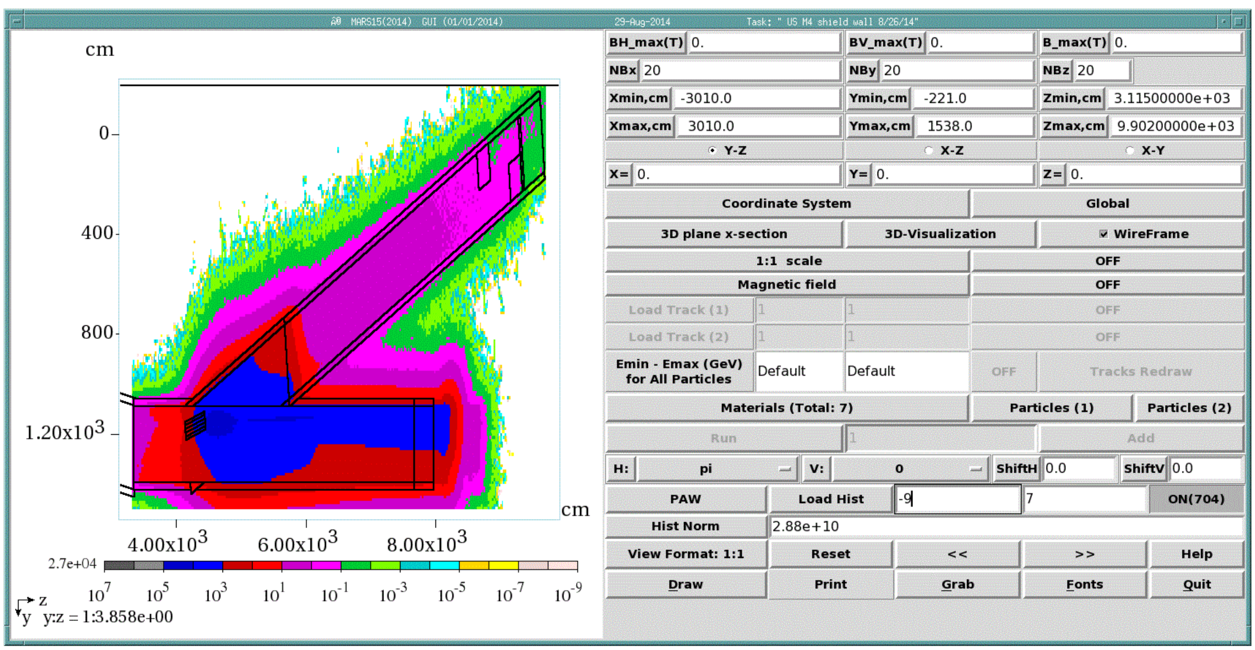

Figure 6: (Histogram 704) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe. The histogram represents the average effective dose rate for a 1 foot high region, centered 1 foot below the elevation of the M5 beam line. Results are in mrem/hr.

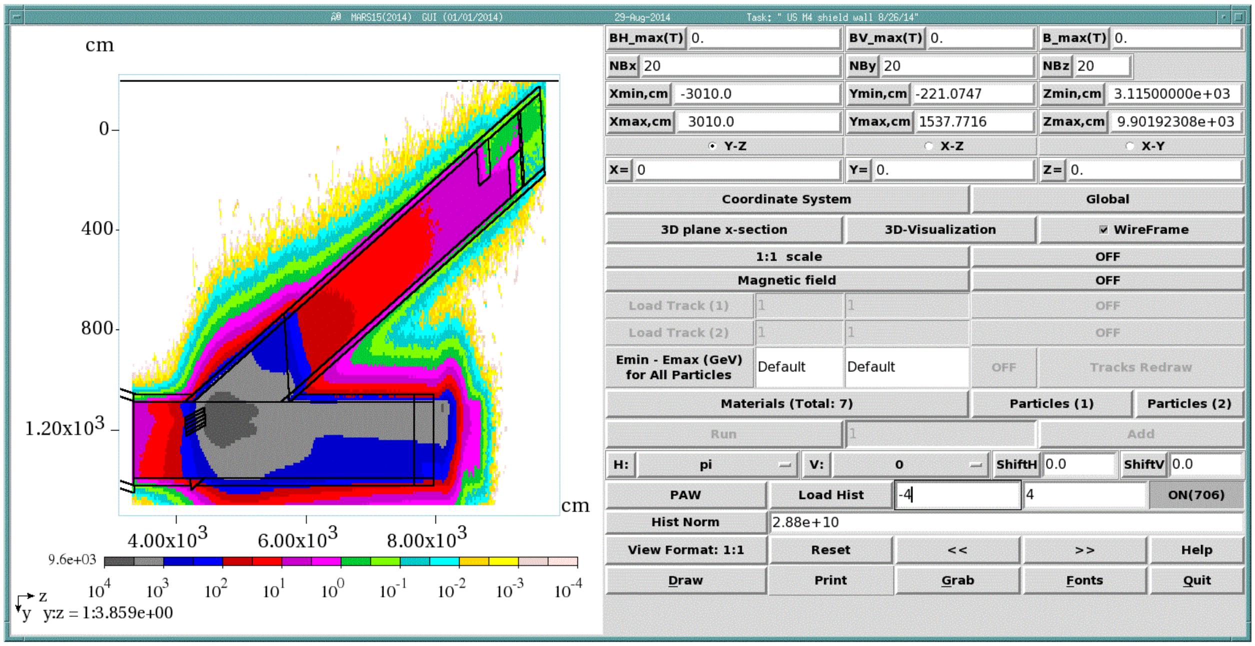

Figure 7: (Histogram 706) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe. The histogram represents the average effective dose rate for a 1 foot high region, centered 2 feet below the elevation of the M5 beam line. Results are in mrem/hr.

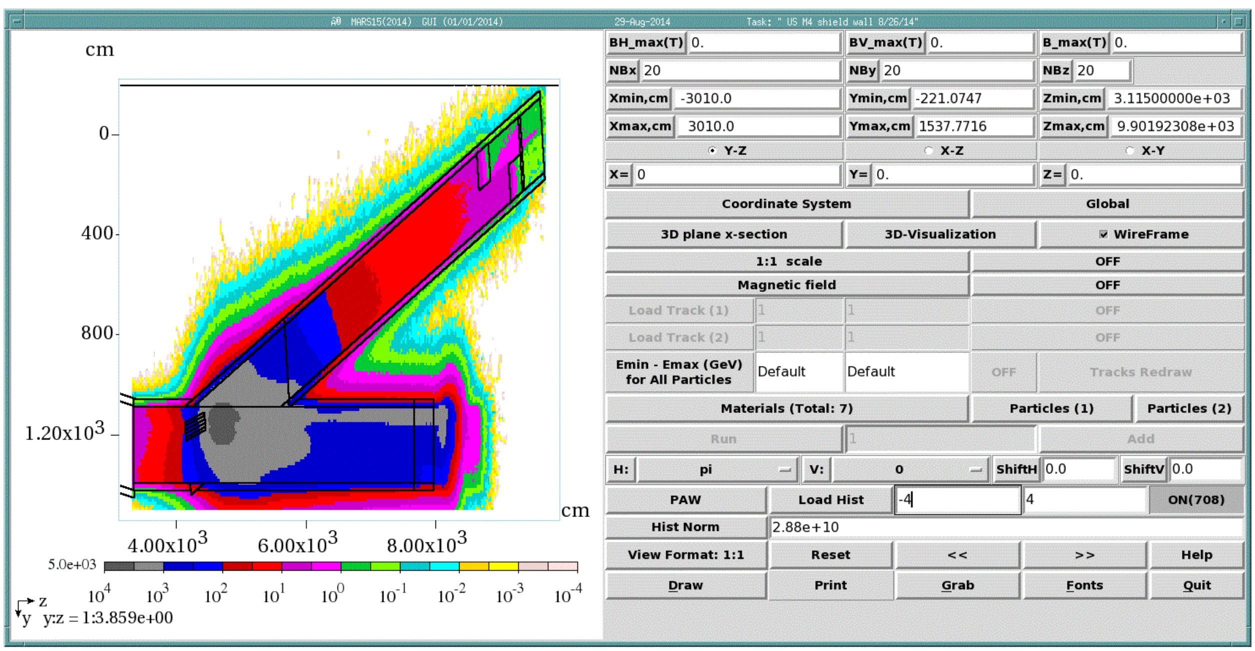

Figure 8: (Histogram 708) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe. The histogram represents the average effective dose rate for a 1 foot high region, centered 3 feet below the elevation of the M5 beam line. Results are in mrem/hr.

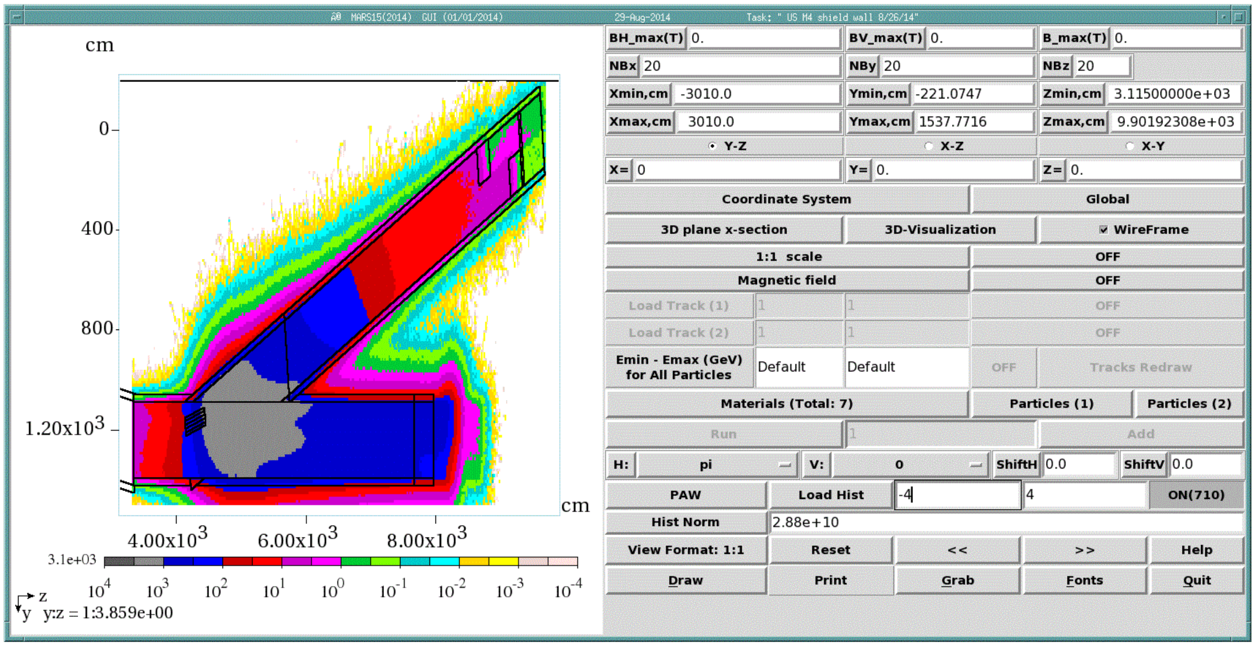

Figure 9: (Histogram 710) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe. The histogram represents the average effective dose rate for a 1 foot high region, centered 4 feet below the elevation of the M5 beam line. Results are in mrem/hr.

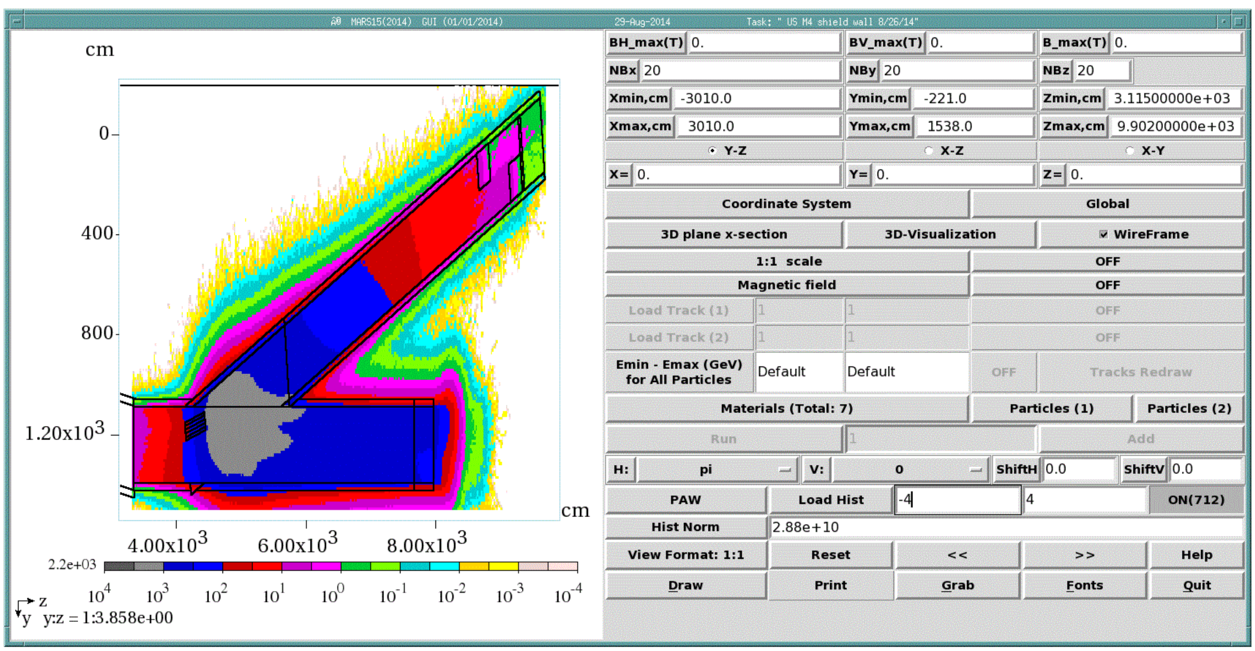

Figure 10: (Histogram 712) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe. The histogram represents the average effective dose rate for a 1 foot high region, centered 5 feet below the elevation of the M5 beam line. Results are in mrem/hr.

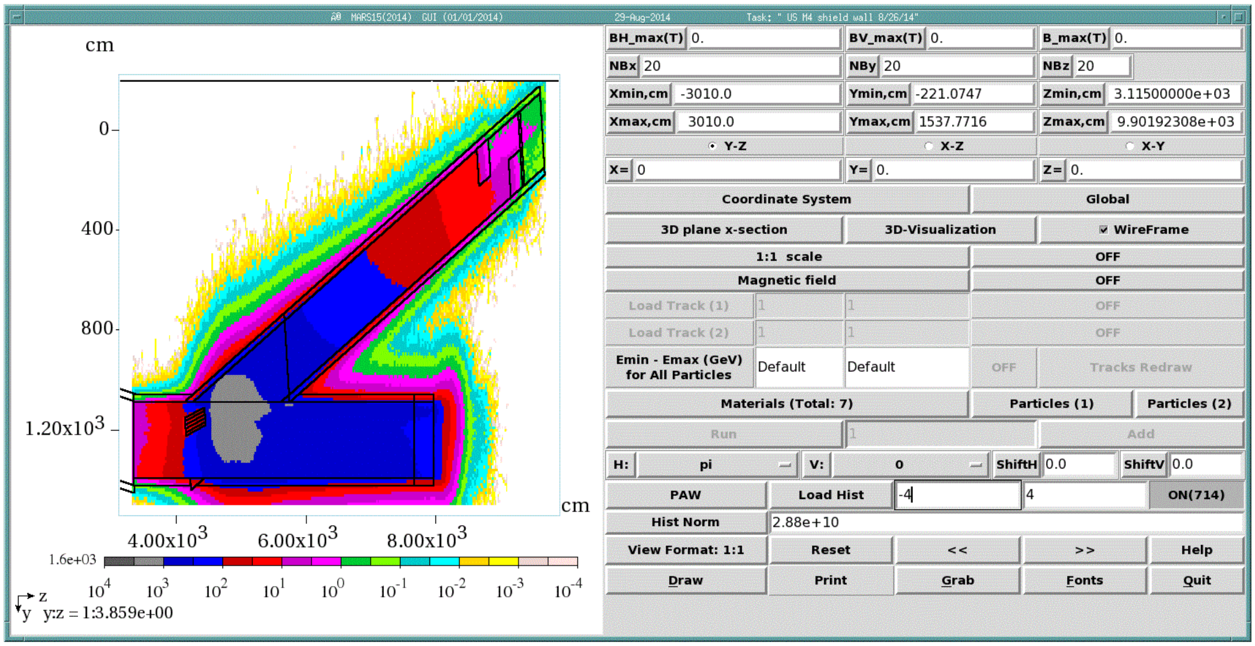

Figure 11: (Histogram 714) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe. The histogram represents the average effective dose rate for a 1 foot high region, centered 6 feet below the elevation of the M5 beam line. Results are in mrem/hr.

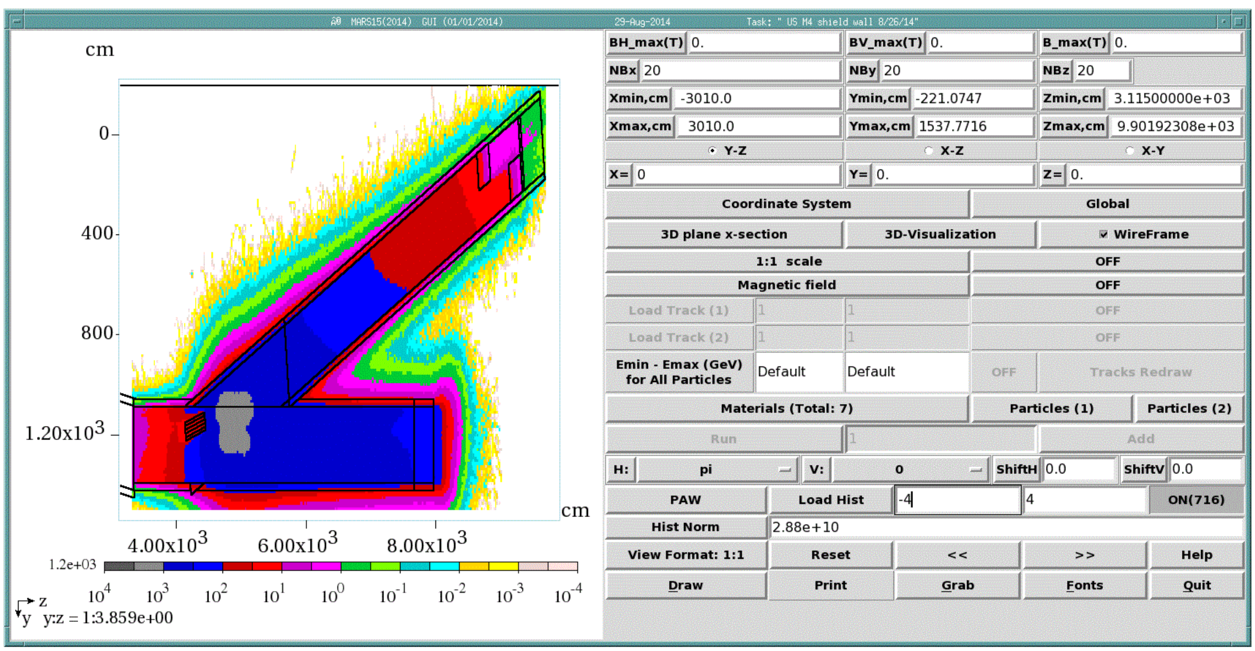

Figure 12: (Histogram 716) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe. The histogram represents the average effective dose rate for a 1 foot high region, centered 7 feet below the elevation of the M5 beam line. Results are in mrem/hr.

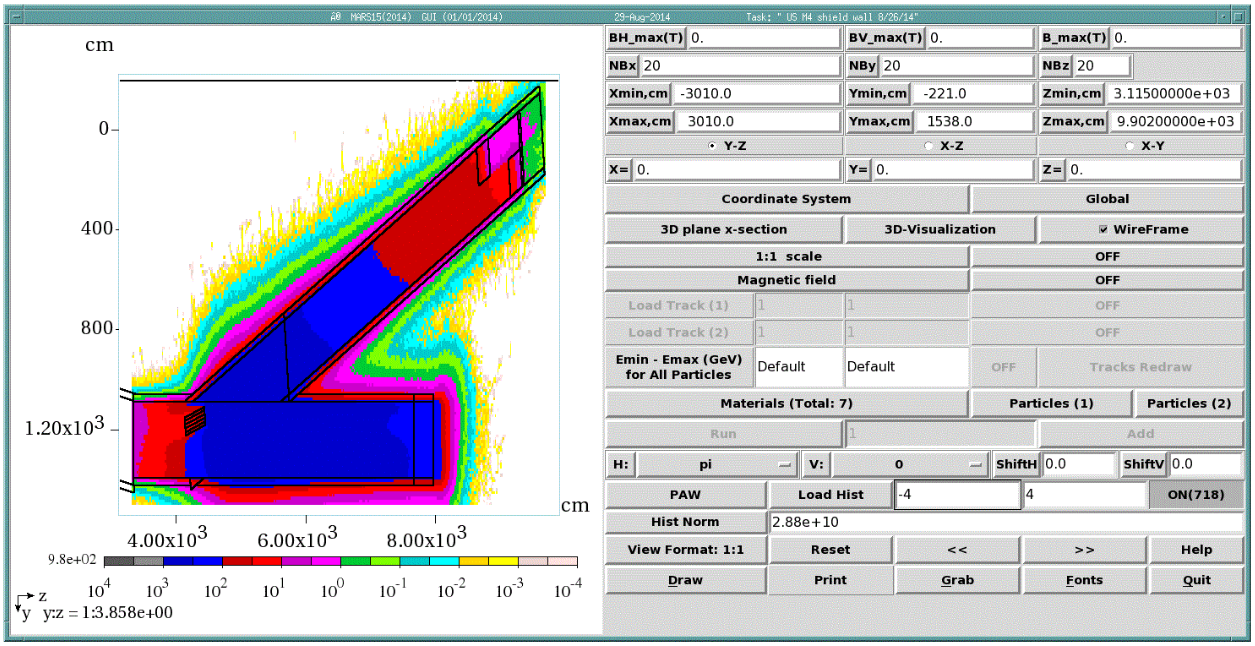

Figure 13: (Histogram 718) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe. The histogram represents the average effective dose rate for a 1 foot high region, centered 8 feet below the elevation of the M5 beam line. Results are in mrem/hr.

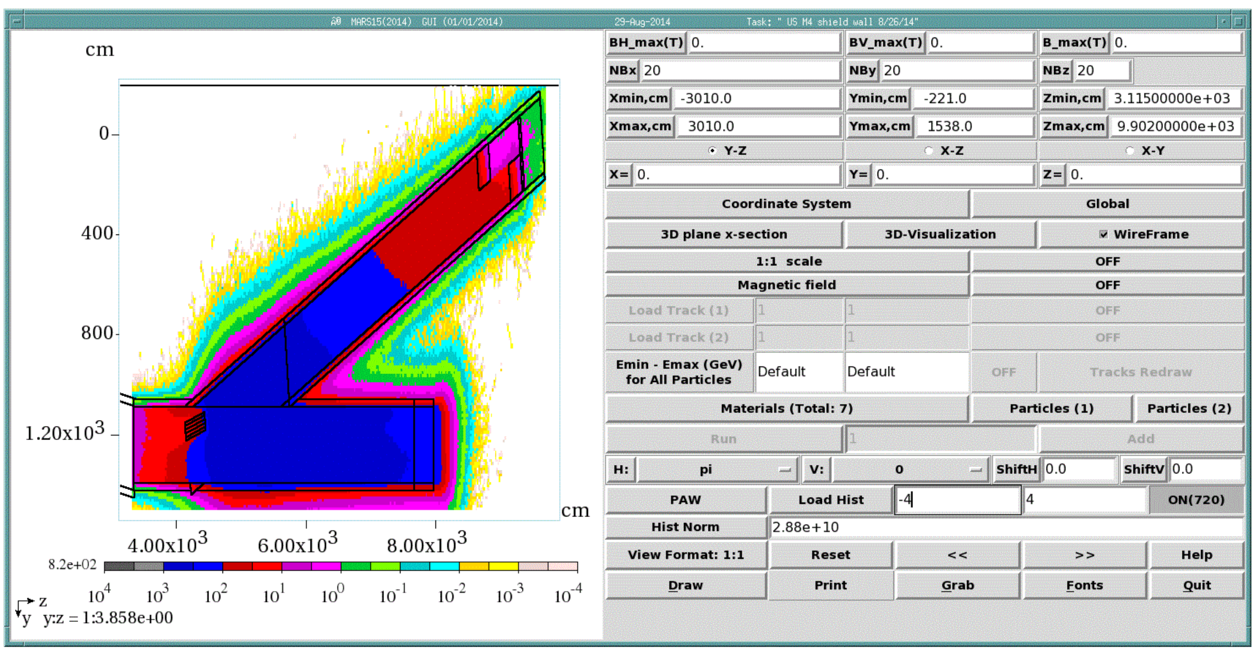

Figure 14: (Histogram 720) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe. The histogram represents the average effective dose rate for a 1 foot high region, centered 9 feet below the elevation of the M5 beam line. Results are in mrem/hr.

The effective dose rate in the two detectors downstream of the shield wall are:

Left side detector: 1.484E-14 mSv/p with an error 2.172E-16 (1.5%)
@ 2.88E8 protons/second is 1.5 mrem/hour

Right side detector: 6.905E-15 mSv/p with an error 1.434E-16 (2.1%)
@ 2.88E8 protons/second is 0.7 mrem/hour

9/2/14

Resumed work on the problem, this time with a 4Q24 in the M5 line. Created the model from images provided by Jim Morgan [2]. The following are images taken from the model:

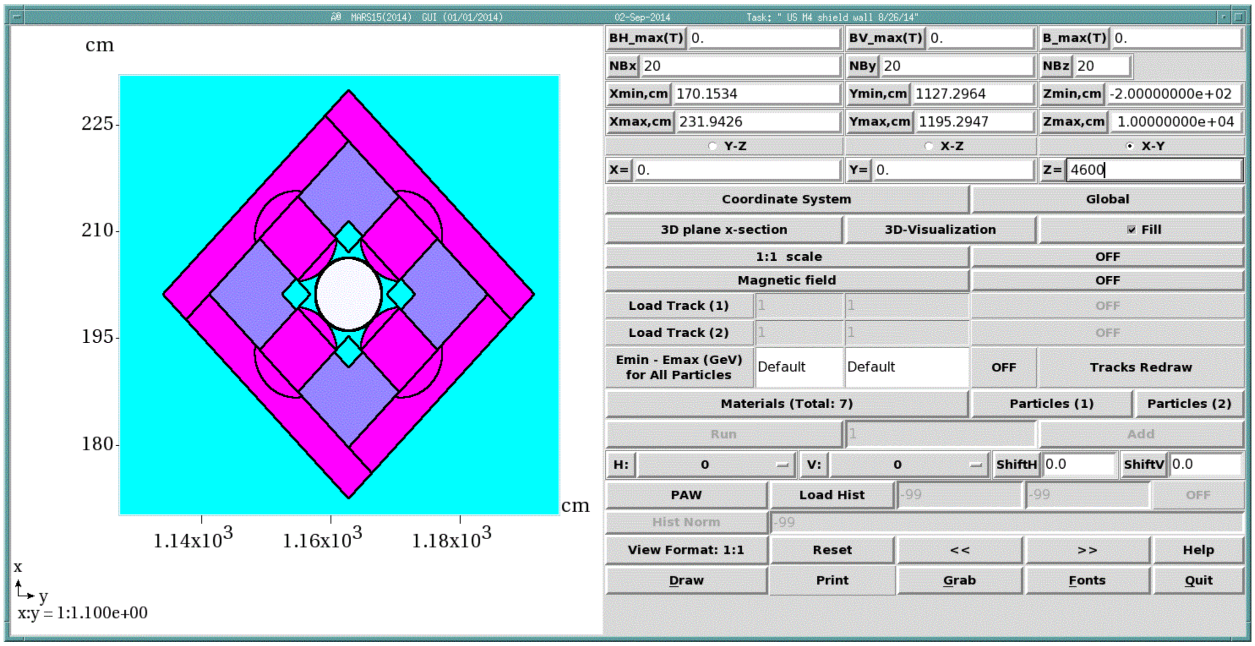

Figure 15: cross section of 4Q24 magnet used in MARS simulation

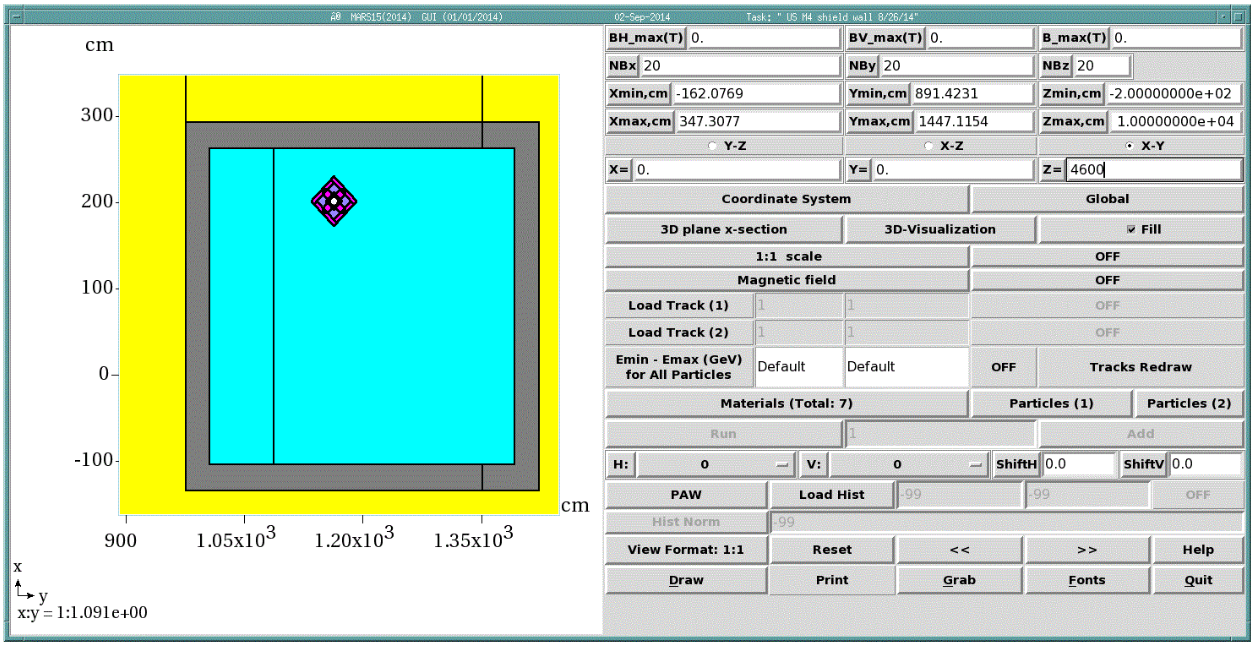

Figure 16:4Q24 magnet placement in M4/M5 enclosure

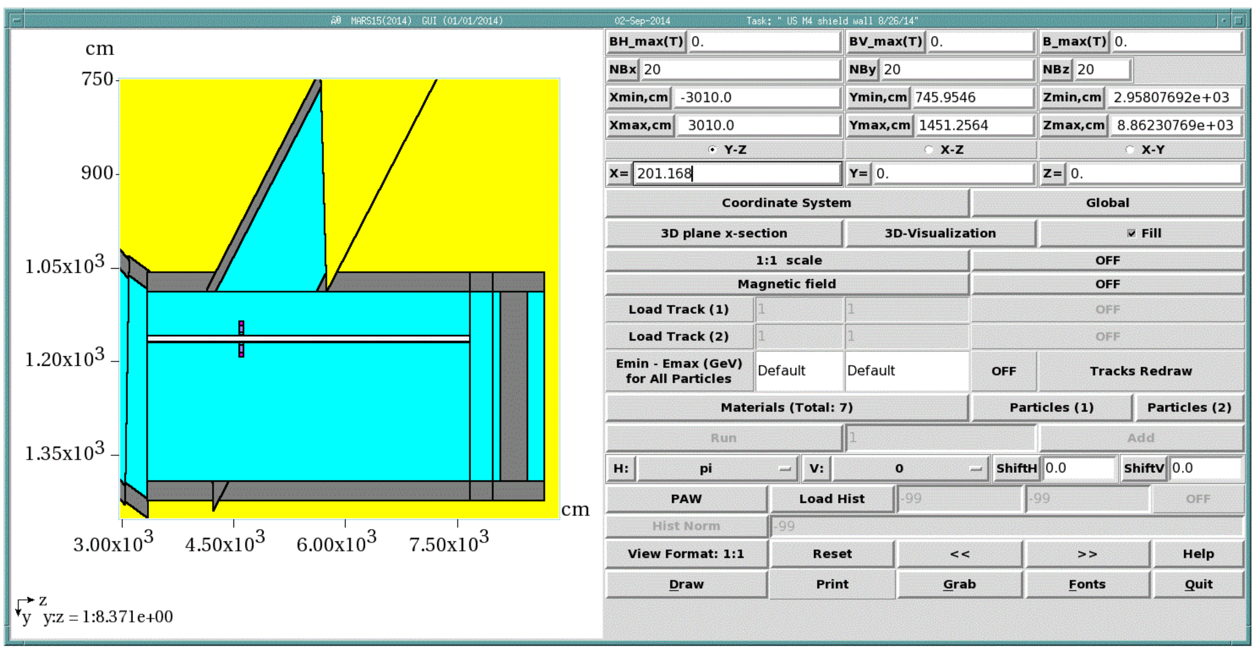

Figure 17: Plan view of Q017 in M4/M5 enclosure adjacent to entrance of the M4 enclosure. The cyan/yellow boundary indicates the location of the enclosure ceiling height change from 12 feet to 8 feet at the upstream end of the M4 tunnel.

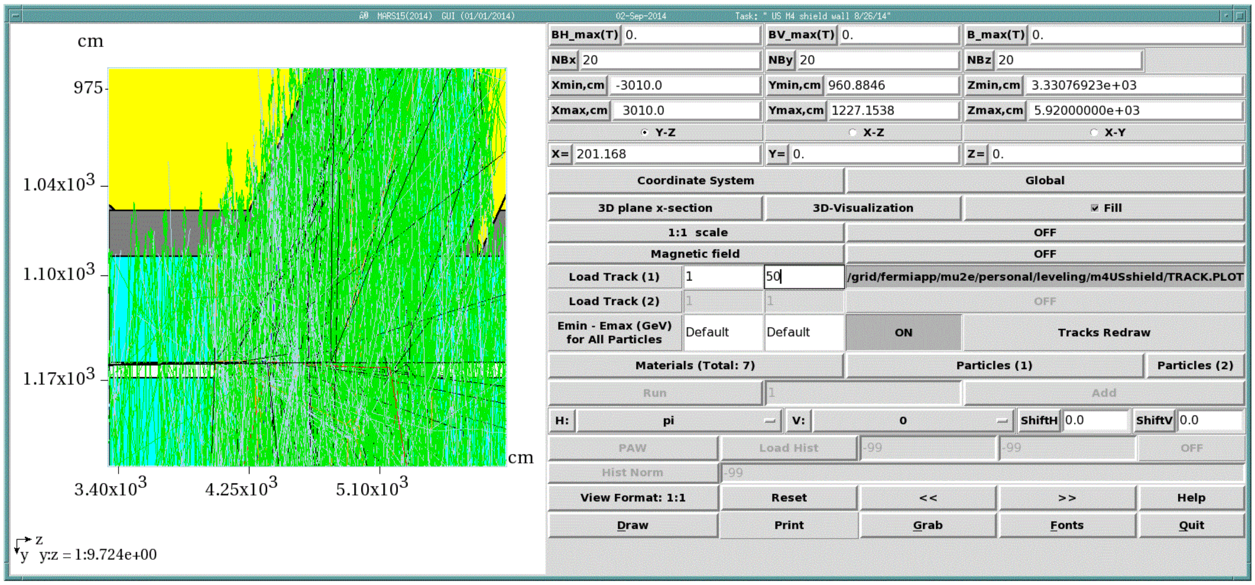

Figure 18: Plan view of Q017 with particle tracks in the vicinity

The magnet is 24" long with a 4" diameter beam tube. The magnet is modeled without a magnetic field. Used the same beam profile but used TRACK.PLOT to have significant shower intercept the magnet. The magnet windings are treated as copper with a density of 6.56 g/cc; there is no water included in the magnet coils. Moved the beam loss point US about 60 cm to have the shower more fully intercept the 4Q24 magnet. The magnet is placed in the beam enclosure using a pdf drawing provided by FESS which shows the currently envisioned positions of the beam line magnets included in the enclosure. Magnet volumes have been calculated for subroutine vfan. A trial run was launched at about 1130 following completion of the magnet modelling effort.

The 10,000 ip job took 2524 seconds. Launched 1000 jobs with 75,000 IP as was the case with the pipe scraping. The jobs will take about 5.25 hours to run. Here are the job numbers:

```
Cluster          njobs    running
17705834         500      0
17705835         500      0
<mu2egpvm02.fnal.gov>
```

9/3/14

All jobs finished up at 1847 on 9/2.

Here are the detector histograms again for the Q017 case. Results are similar to the beam pipe scraping simulation. Again, all histogram units are normalized to 2.88E8 protons per second and histogram units are **mrem/hr**.

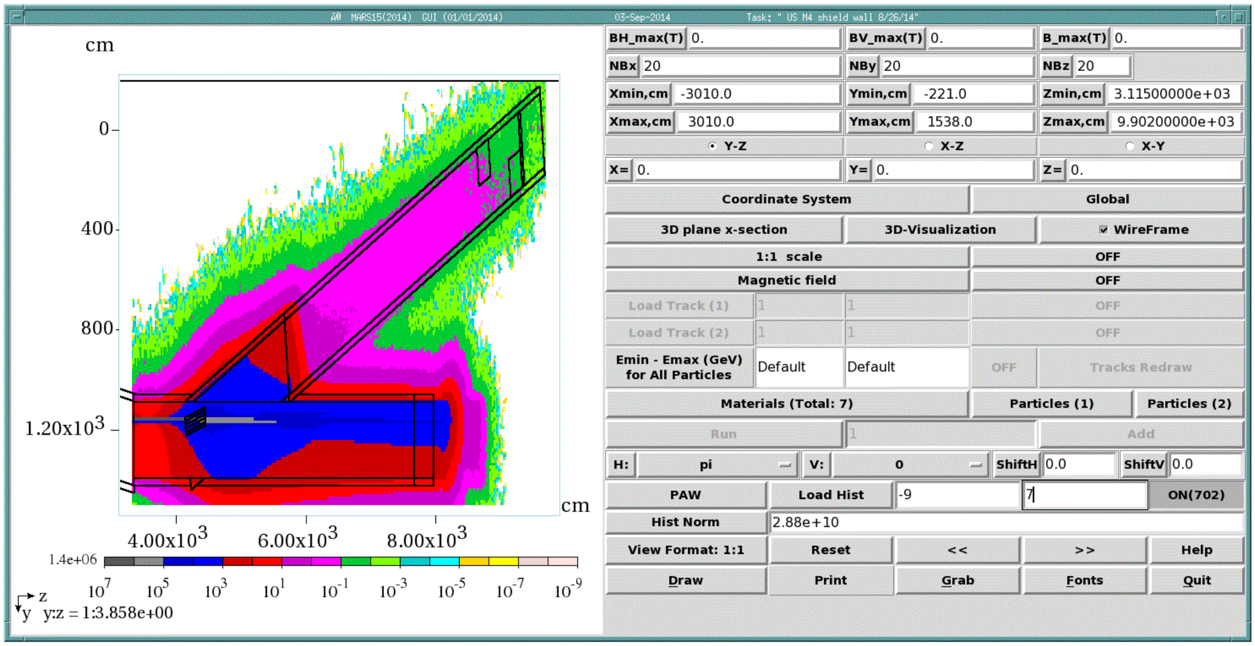

Figure 19: P(Histogram 702) lan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q017. The histogram represents the average effective dose rate for a 1 foot high region, centered at the elevation of the M5 beam line. Results are in mrem/hr.

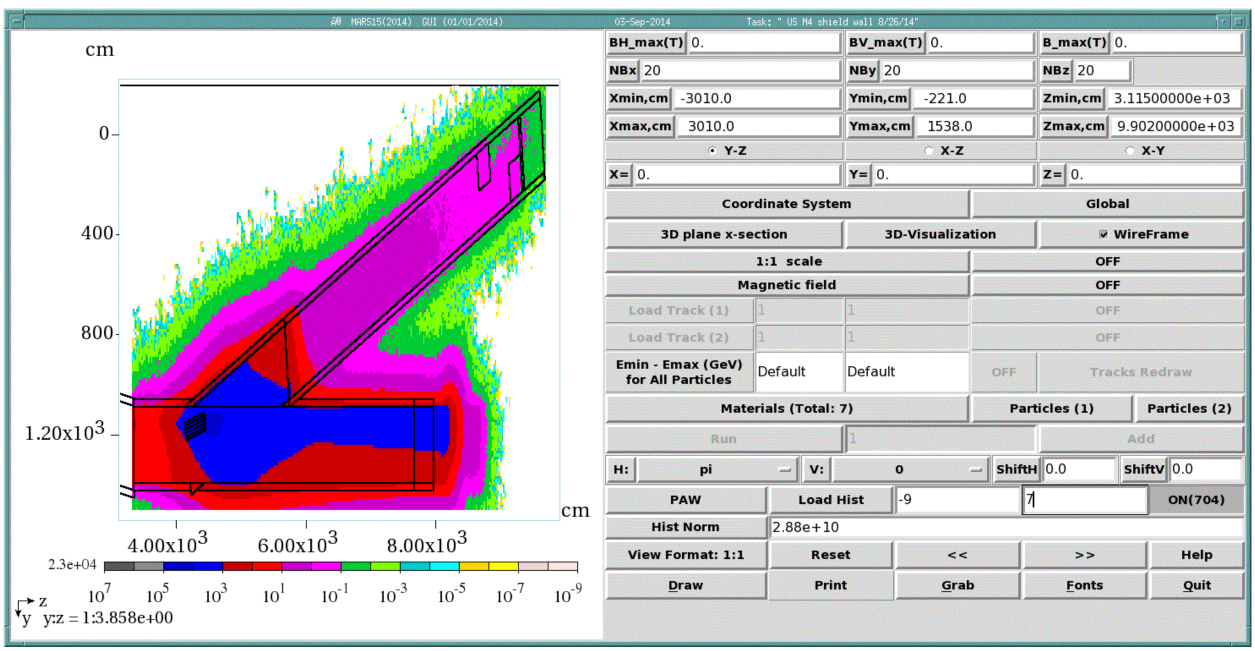

Figure 20: (Histogram 704) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q017. The histogram represents the average effective dose rate for a 1 foot high region, centered 1 foot below the elevation of the M5 beam line. Results are in mrem/hr.

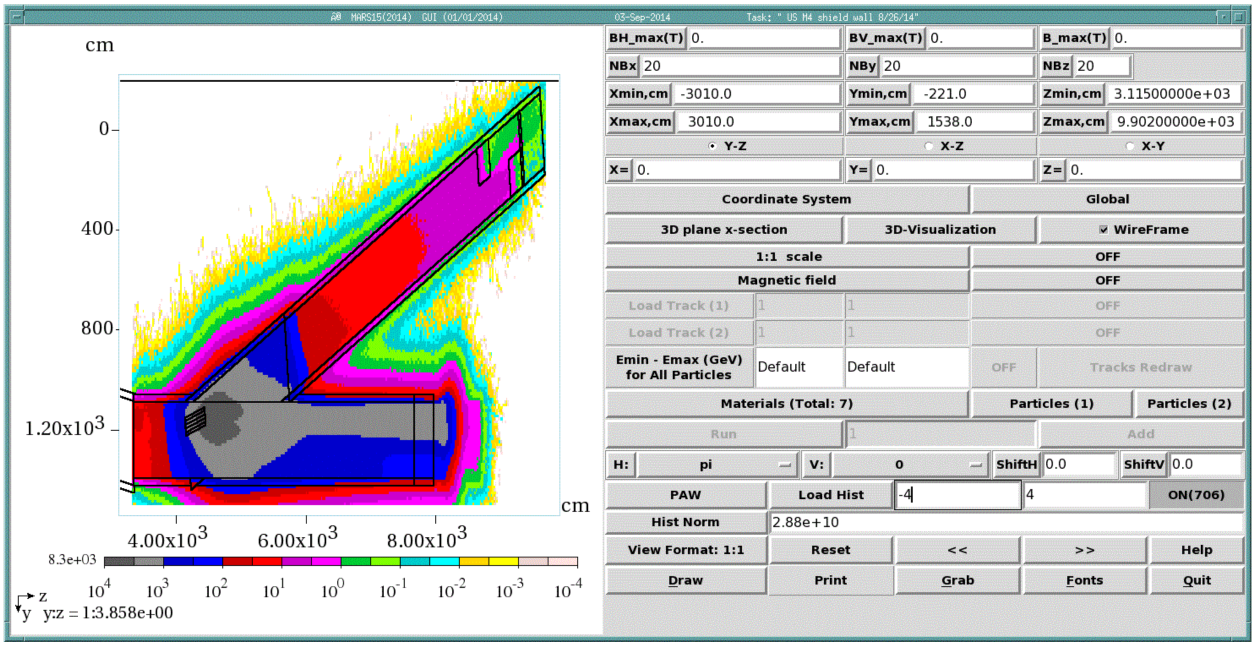

Figure 21: Plan(Histogram 706) view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q017. The histogram represents the average effective dose rate for a 1 foot high region, centered 2 feet below the elevation of the M5 beam line. Results are in mrem/hr.

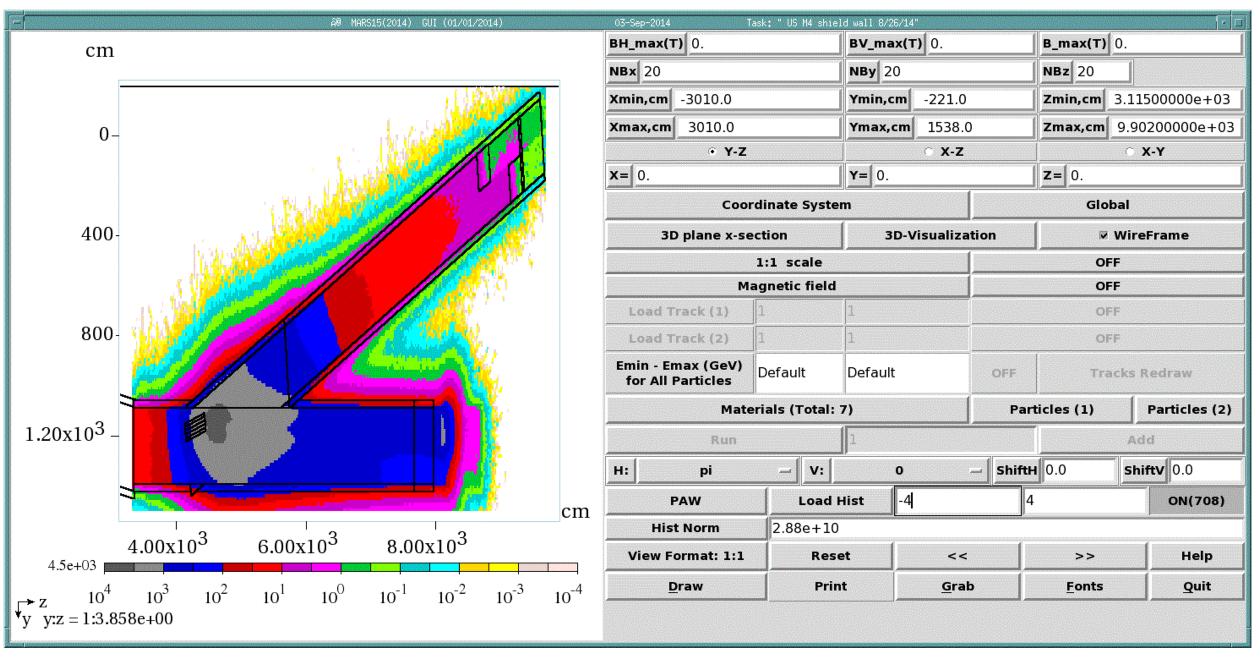

Figure 22: (Histogram 708) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q017. The histogram represents the average effective dose rate for a 1 foot high region, centered 3 feet below the elevation of the M5 beam line. Results are in mrem/hr.

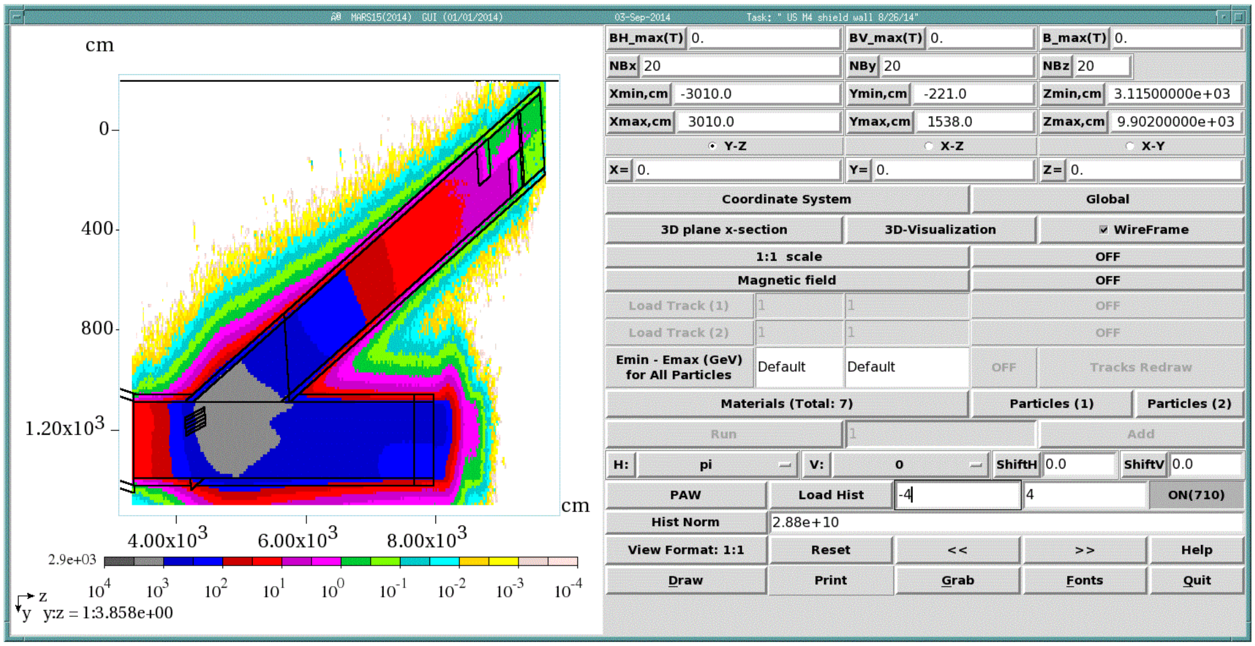

Figure 23: (Histogram 710) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q017. The histogram represents the average effective dose rate for a 1 foot high region, centered 4 feet below the elevation of the M5 beam line. Results are in mrem/hr.

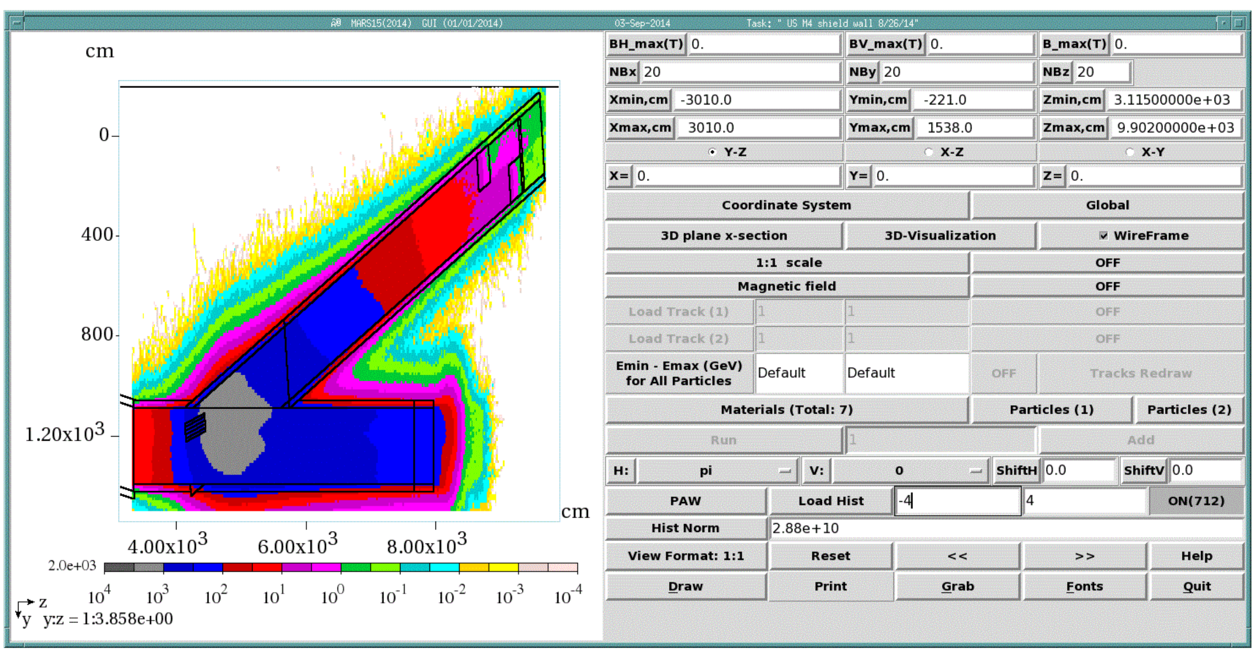

Figure 24: (Histogram 712) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q017. The histogram represents the average effective dose rate for a 1 foot high region, centered 5 feet below the elevation of the M5 beam line. Results are in mrem/hr.

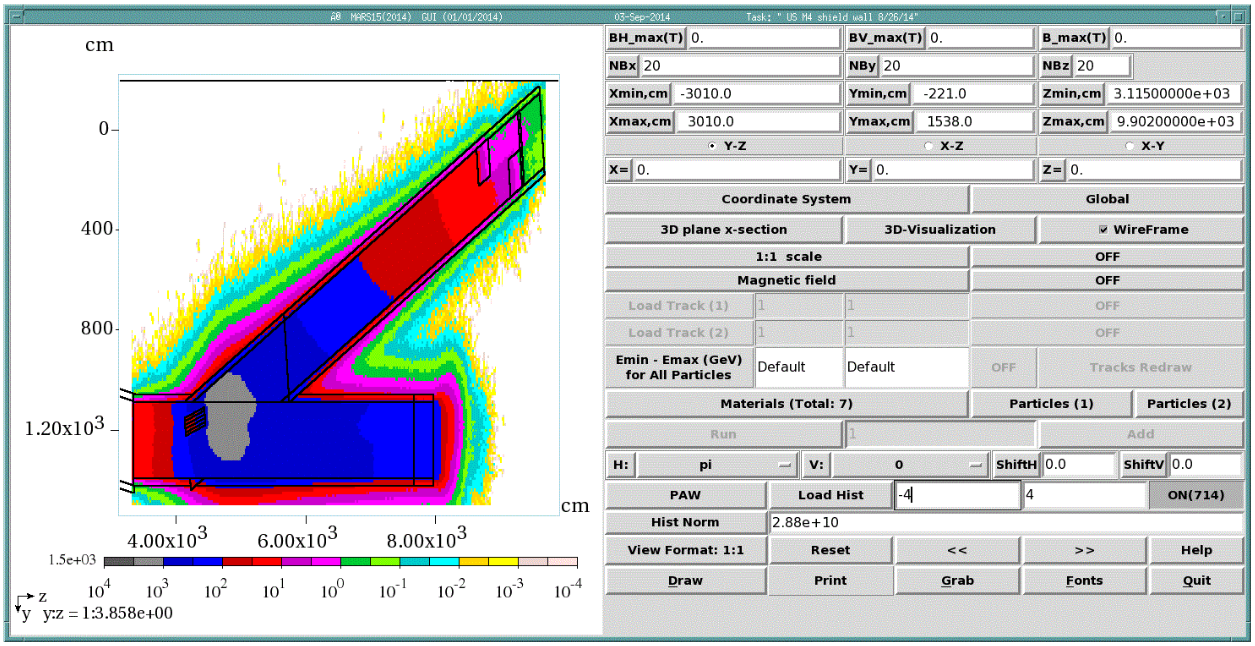

Figure 25: (Histogram 714) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q017. The histogram represents the average effective dose rate for a 1 foot high region, centered 6 feet below the elevation of the M5 beam line. Results are in mrem/hr.

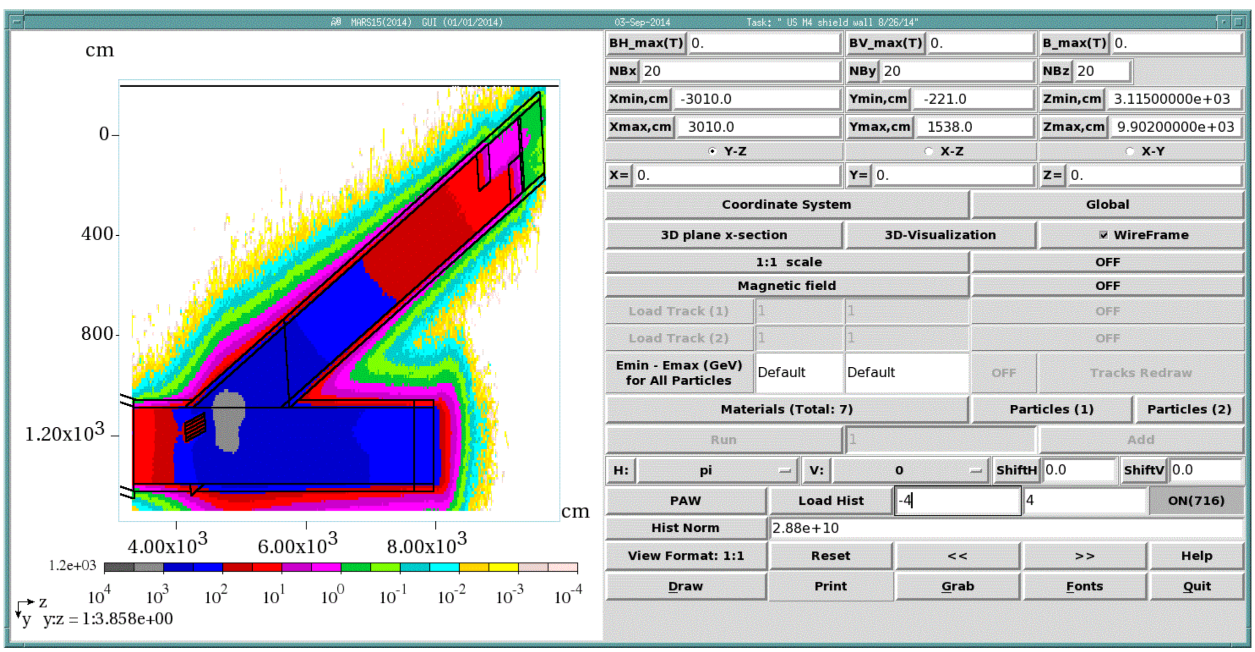

Figure 26: (Histogram 716) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q017. The histogram represents the average effective dose rate for a 1 foot high region, centered 7 feet below the elevation of the M5 beam line. Results are in mrem/hr.

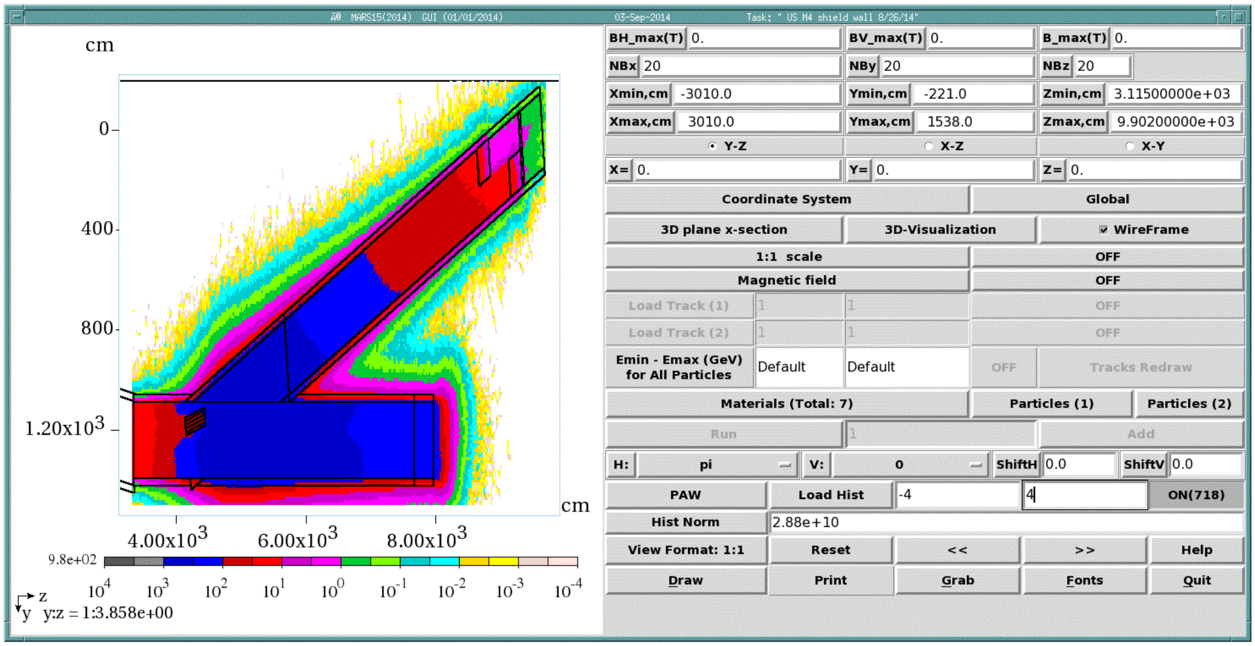

Figure 27: (Histogram 718) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q017. The histogram represents the average effective dose rate for a 1 foot high region, centered 8 feet below the elevation of the M5 beam line. Results are in mrem/hr.

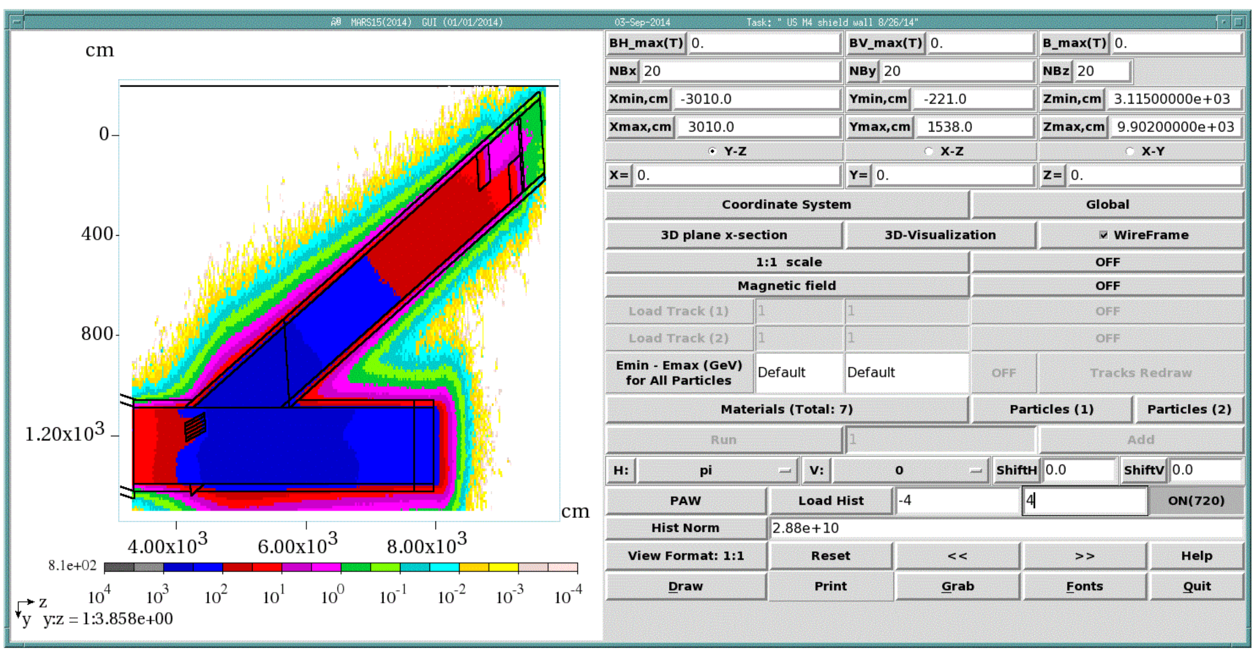

Figure 28: (Histogram 720) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q017. The histogram represents the average effective dose rate for a 1 foot high region, centered 9 feet below the elevation of the M5 beam line. Results are in mrem/hr.

The effective dose rate in the two detectors downstream of the shield wall for the Q017 run are:

Left side detector: 1.3E-14 mSv/p with an error 1.957E-16 (1.5%)
@ 2.88E8 protons/second is 1.35 mrem/hour

Right side detector: 6.731E-15 mSv/p with an error 1.344E-16 (2.0%)
@ 2.88E8 protons/second is 0.7 mrem/hour

Next, the quad is moved to Q018, about 6 meters DS of Q017. The beam is moved DS 6.3 meters. The magnet is modeled without a magnetic field.

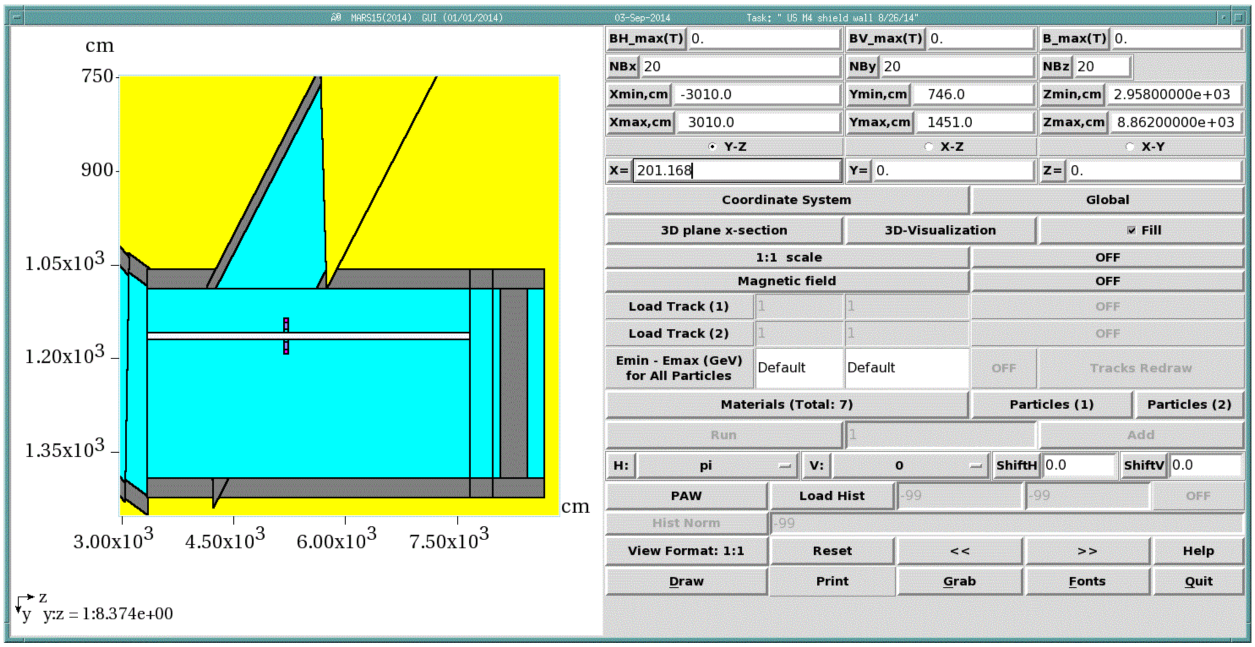

Figure 29: Q018 position in the M5 line

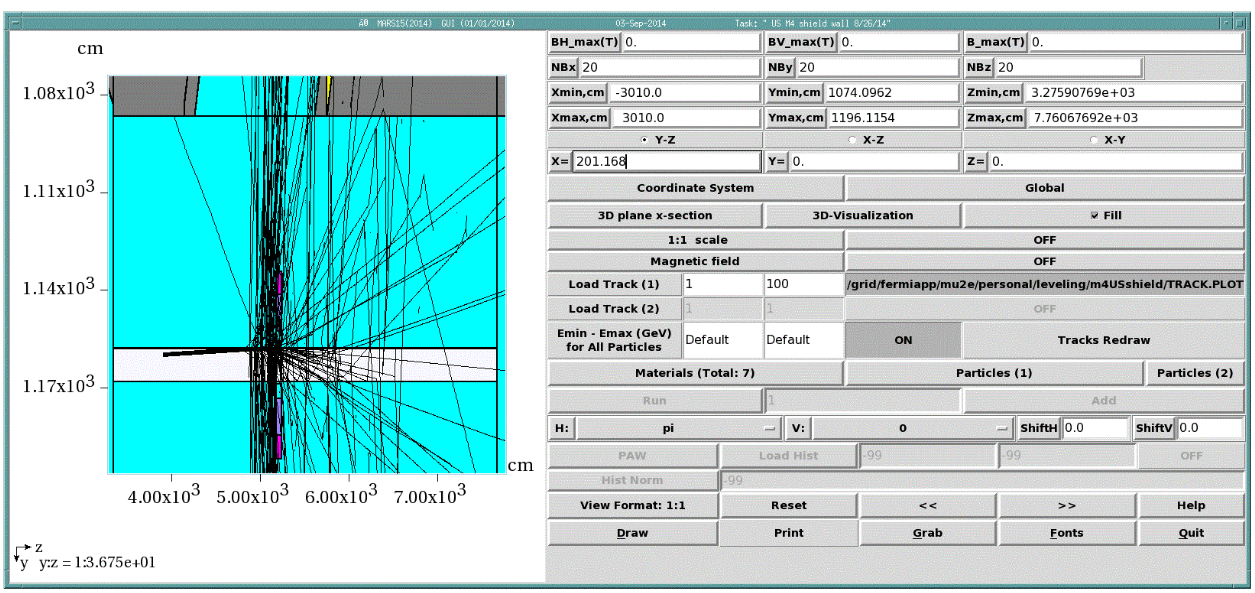

Figure 30: Q018 with beam loss occurring just upstream of the magnet

Launched the Q018 jobs at 0747 on 9/3/14. The jobs numbers are:

```
Cluster        njobs   running
17710603       500     0
17710604       500     0
```

All jobs finished up by 1317 on 9/3/14. The results are normalized to 2.88E8 protons per second and histogram results are reported in **mrem/hr**.

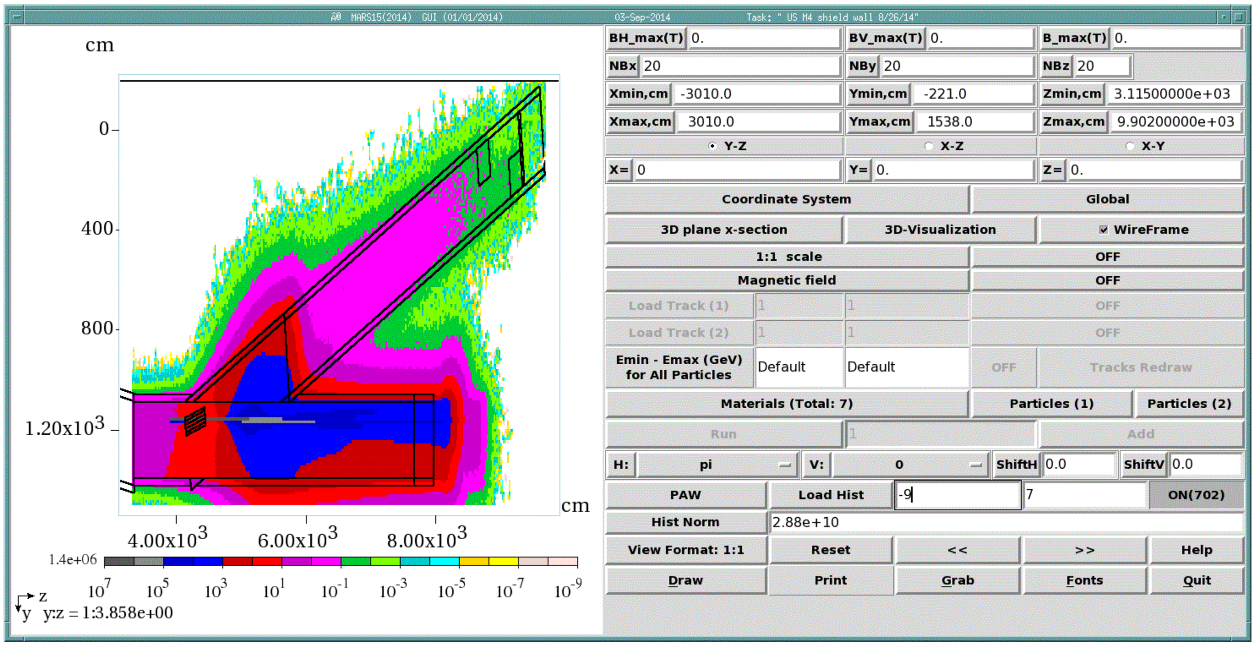

Figure 31: (Histogram 702) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q018. The histogram represents the average effective dose rate for a 1 foot high region, centered at the elevation of the M5 beam line. Results are in mrem/hr.

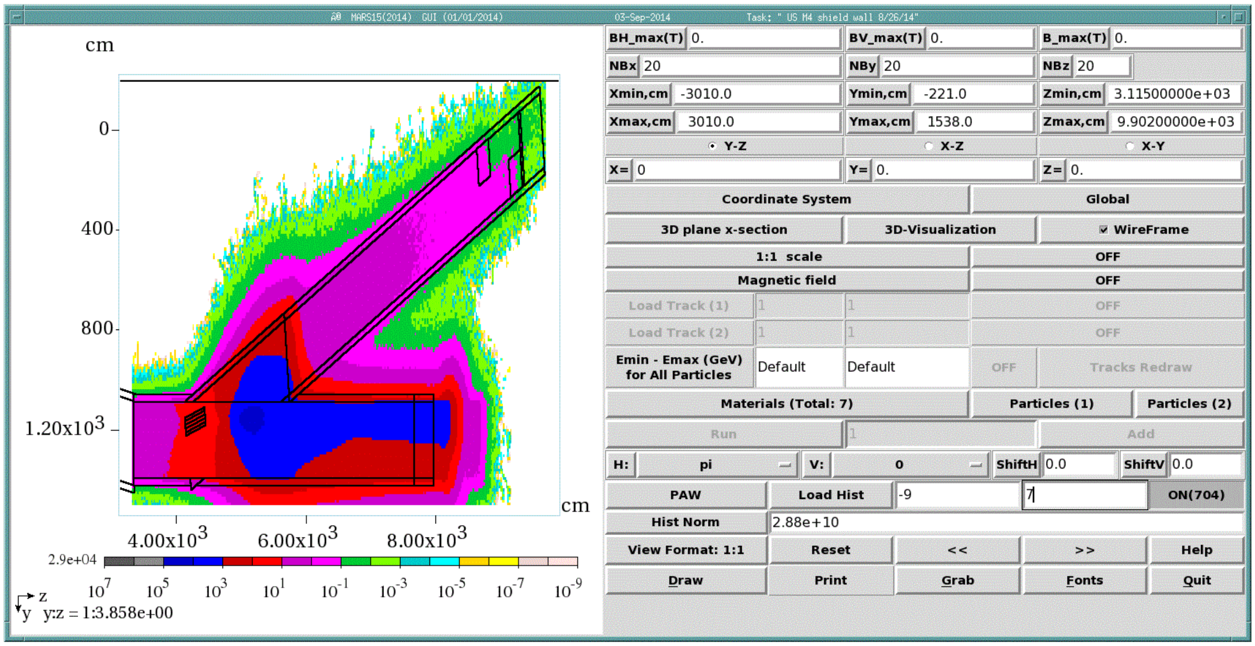

Figure 32: (Histogram 704) Plan view of M4/M5 line with shield labyrinth beginning 100’ from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q018. The histogram represents the average effective dose rate for a 1 foot high region, centered 1 foot below the elevation of the M5 beam line. Results are in mrem/hr.

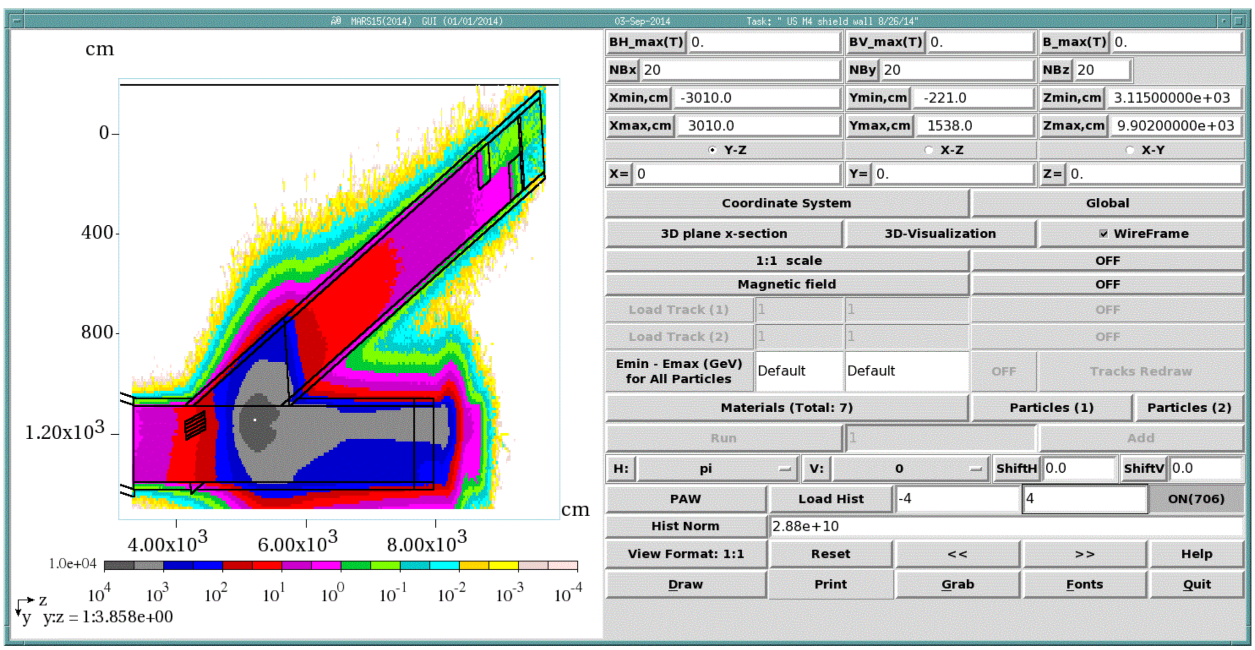

Figure 33: (Histogram 706) Plan view of M4/M5 line with shield labyrinth beginning 100’ from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q018. The histogram represents the average effective dose rate for a 1 foot high region, centered 2 feet below the elevation of the M5 beam line. Results are in mrem/hr.

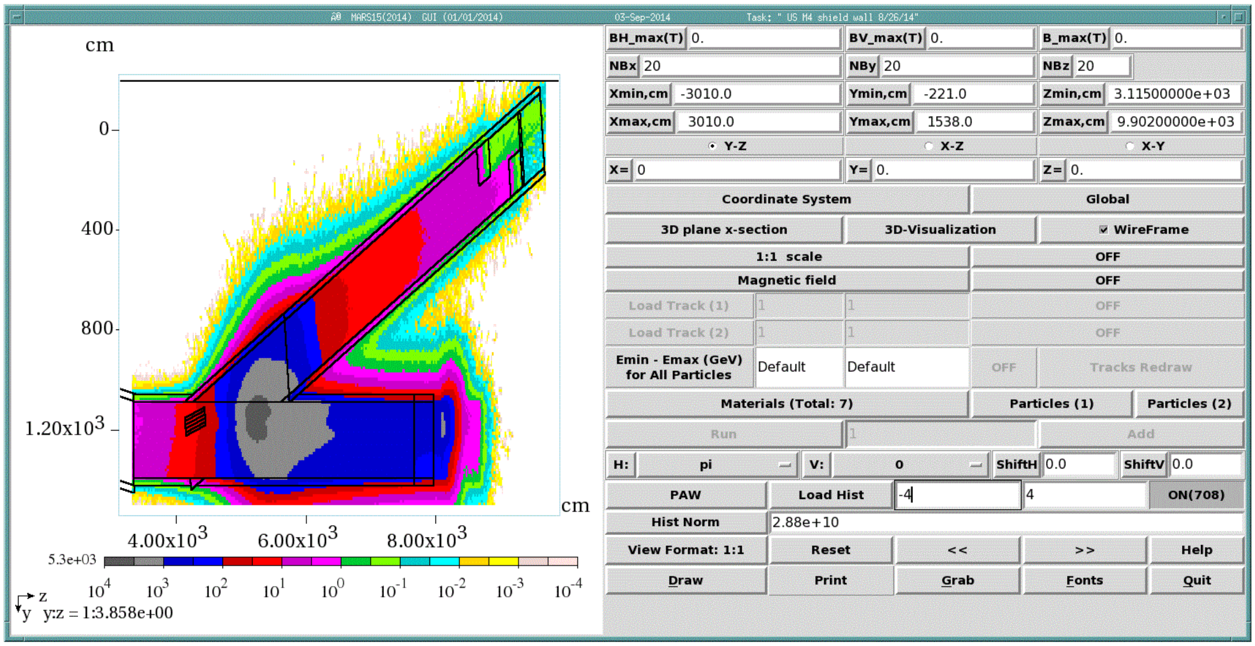

Figure 34: (Histogram 708) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q018. The histogram represents the average effective dose rate for a 1 foot high region, centered 3 feet below the elevation of the M5 beam line. Results are in mrem/hr.

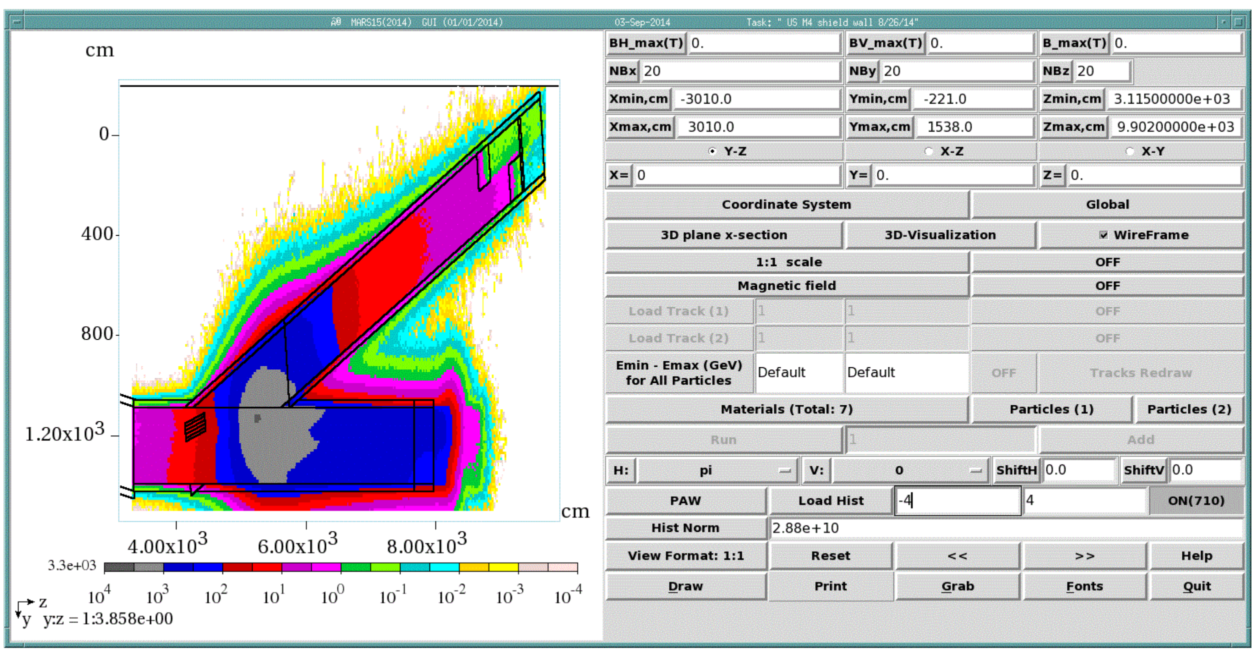

Figure 35: (Histogram 710) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q018. The histogram represents the average effective dose rate for a 1 foot high region, centered 4 feet below the elevation of the M5 beam line. Results are in mrem/hr.

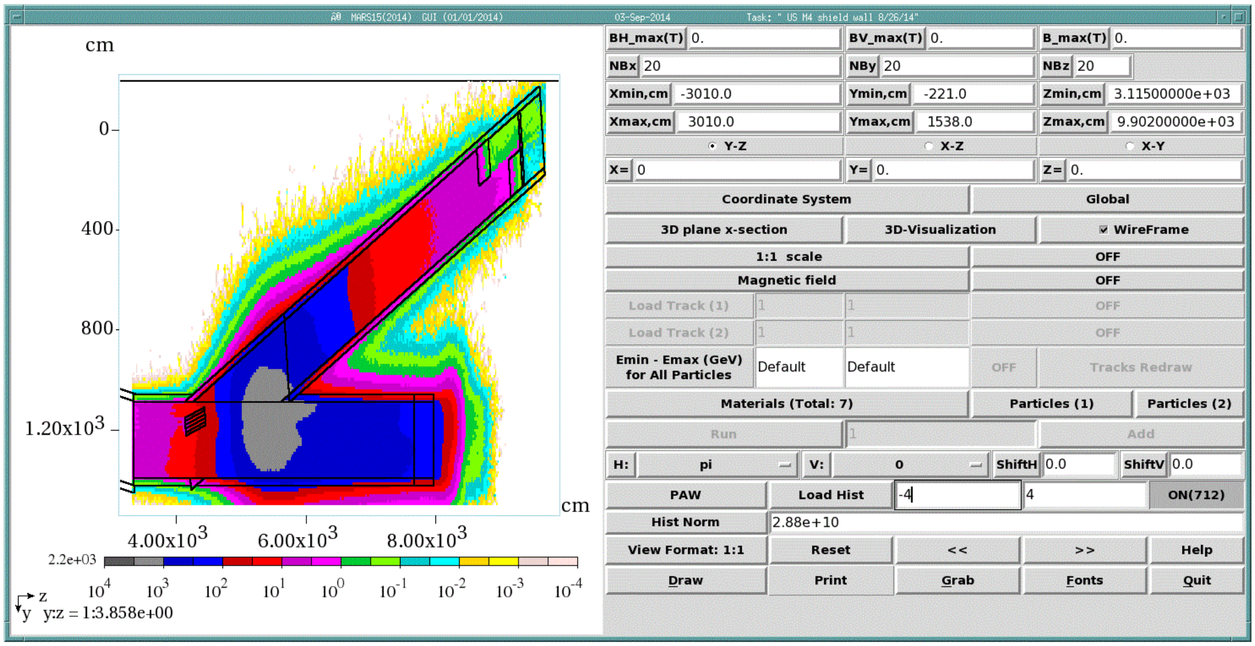

Figure 36: (Histogram 712) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q018. The histogram represents the average effective dose rate for a 1 foot high region, centered 5 feet below the elevation of the M5 beam line. Results are in mrem/hr.

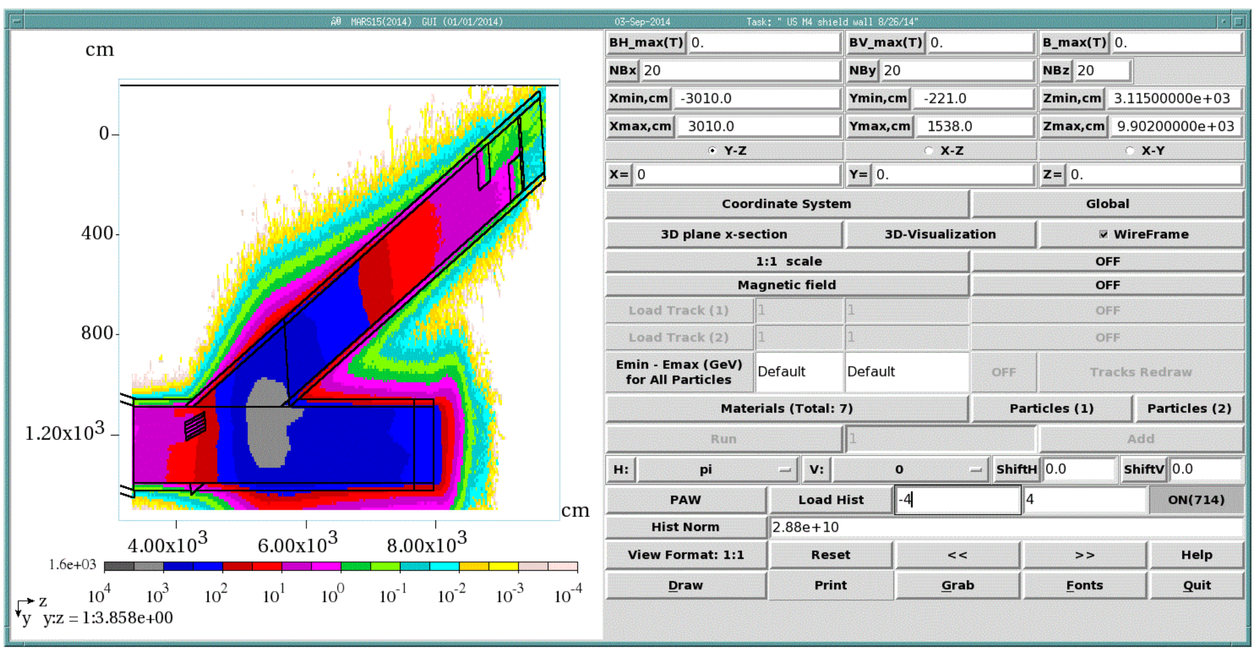

Figure 37: (Histogram 714) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q018. The histogram represents the average effective dose rate for a 1 foot high region, centered 6 feet below the elevation of the M5 beam line. Results are in mrem/hr.

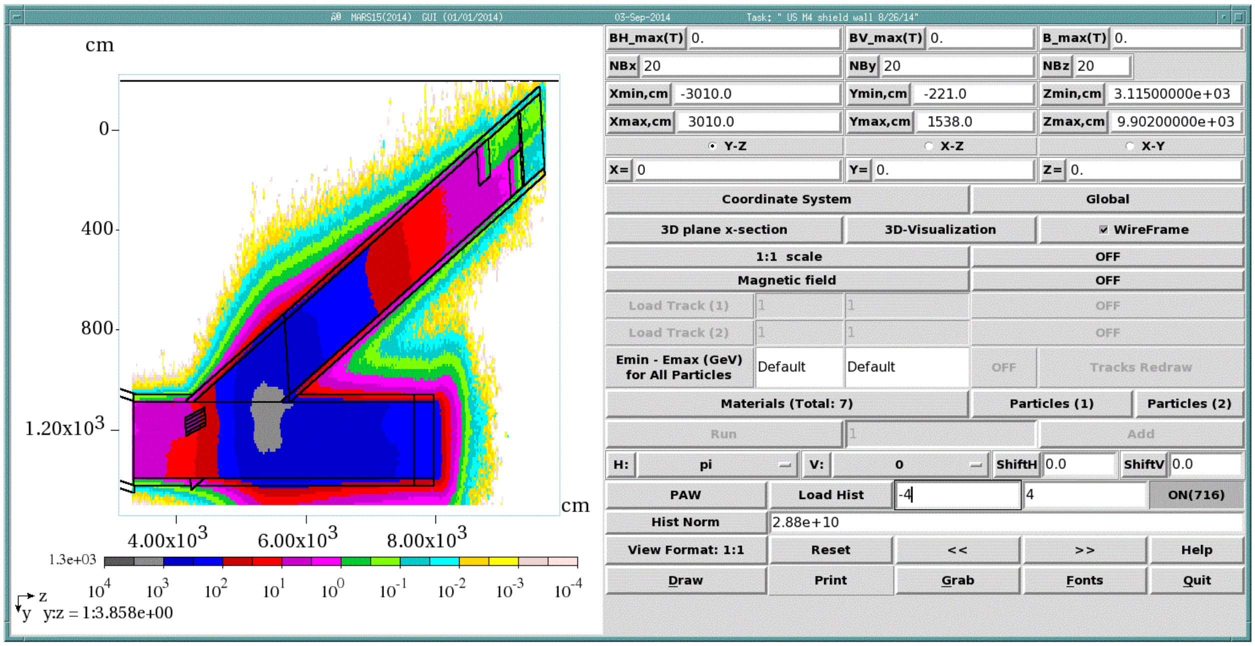

Figure 38: (Histogram 716) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q018. The histogram represents the average effective dose rate for a 1 foot high region, centered 7 feet below the elevation of the M5 beam line. Results are in mrem/hr.

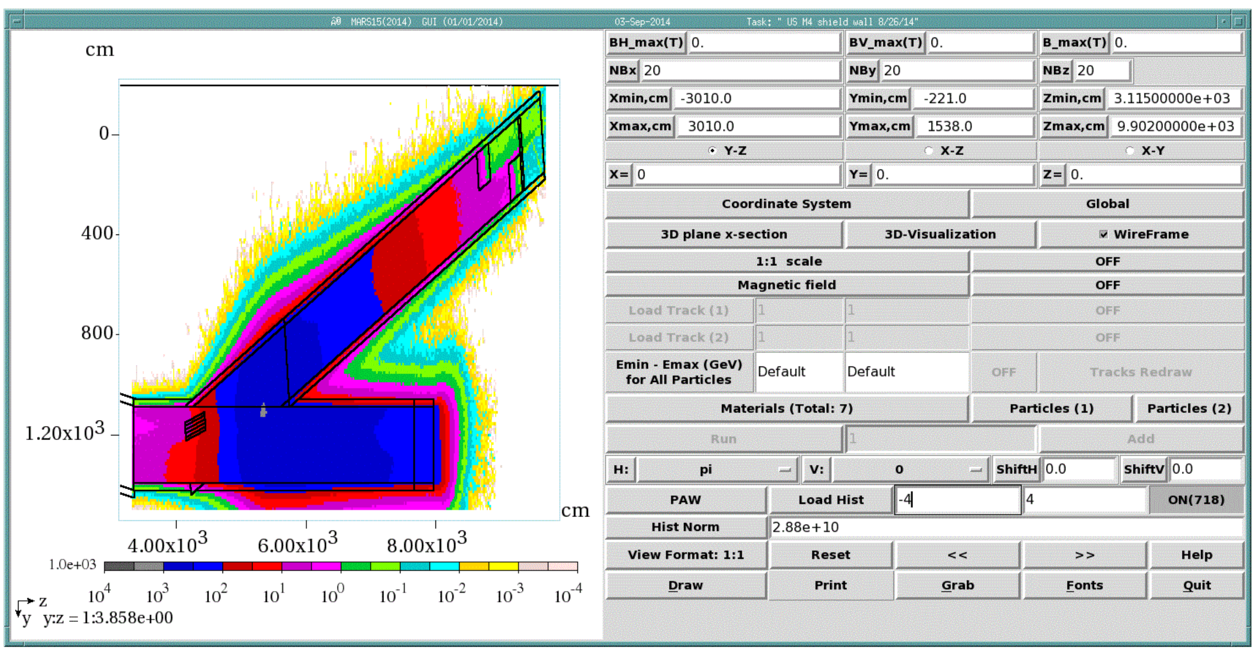

Figure 39: (Histogram 718) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q018. The histogram represents the average effective dose rate for a 1 foot high region, centered 8 feet below the elevation of the M5 beam line. Results are in mrem/hr.

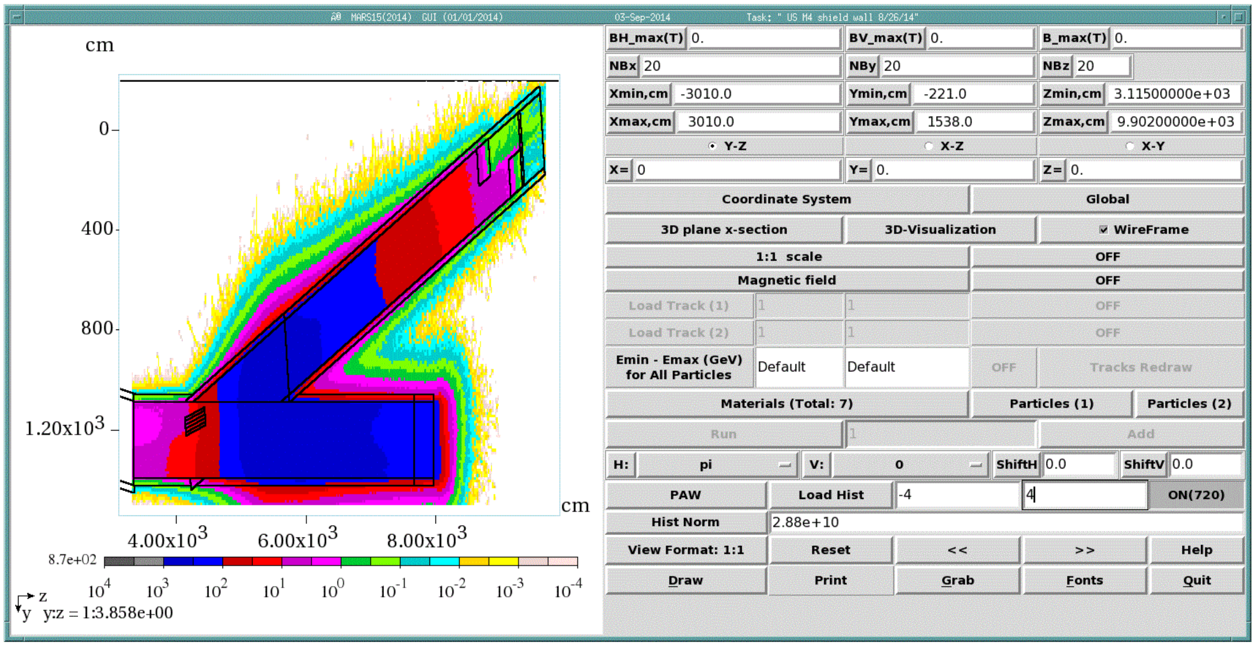

Figure 40: (Histogram 720) Plan view of M4/M5 line with shield labyrinth beginning 100' from the upstream end of the M4 line. The beam loss is due to beam scraping the M5 beam pipe just upstream of Q018. The histogram represents the average effective dose rate for a 1 foot high region, centered 9 feet below the elevation of the M5 beam line. Results are in mrem/hr.

The effective dose rate in the two detectors downstream of the shield wall for the Q018 run are:

Left side detector: 4.08E-15 mSv/p with an error 1.098E-16 (2.7%)
@ 2.88E8 protons/second is 0.4 mrem/hour

Right side detector: 6.967E-16 mSv/p with an error 4.493E-17 (6.4%)
@ 2.88E8 protons/second is 0.07 mrem/hour

It is fairly clear that the shower is diminished between the Q-17 and Q018 runs. An additional run with a beam loss at Q019 would be simply academic; it is clear that the shower will be extinguished by the intervening shield between the M4 and M5 walls.

Conclusions

A temporary shield wall is required in the M4 line to allow the muon g-2 experiment to operate concurrently with construction of the M4 beam line. Some magnets will be required to pass by the shield wall during muon g-2 shutdown periods. A solution has been found which allow LQ magnets to pass through a labyrinth consisting of 2 concrete shield walls 5 feet wide, 6 feet thick, and 8 feet high. A summary of calculated effective dose rates for three accident conditions is summarized in

Table 5: Summary of effective dose rates (with statistical errors) determined for three accident conditions in MARS simulations

Accident condition	Incident beam parameters	Detector 1 mrem/hr (error)	Detector 2 mrem/hr (error)
Beam pipe scraping loss	2.88E8 protons/s	1.5 (1.5%)	0.7 (2.1%)
Beam lost at Q017	2.88E8 protons/s	1.35 (1.5%)	0.7 (2.0%)
Beam lost at Q018	2.88E8 protons/s	0.4 (2.7%)	0.07 (6.4%)

The magnet moves can take place on shutdown days by simply unlocking a gate placed at the downstream side of the second shield wall. As indicated in Figure 4, the shield wall closest to the M5 beam line would be positioned at the left (south) side of the M4 tunnel, 100 feet from the start of the 8' x 10' M4 beam line. The second 5' wide x 6' long shield would be placed on the right (north) side of the M4 tunnel starting 9' downstream of the end of the first wall. The peak effective dose rate downstream of the temporary shield wall is calculated to be <2 mrem/hr under the most extreme beam loss condition, 2.88E8 protons/second. An interlocked radiation detector (e.g., a chipmunk) could be placed downstream of the shield walls to guarantee compliance with limits of the FRCM.

References

1. FESS drawings for bid, SC S-SET_6-10-22-(ISSUED FOR BID), included with this document in the G Minus 2 doc.db 624-v2
2. 4Q24 magnet partial drawing set included with this document in the G Minus 2 doc.db 624-v2
3. G-2 Yield Beam Study Results – April 2012 (Table 5), Muon g-2 Document 430-v6, August 2012
4. Muon g-2 MC-1 Service Building Preliminary Shielding Assessment, G Minus 2 Experiment Document 403-v1, July 2012
5. Muon Campus Critical Devices, Beam Document 4494-v2, December 2013
6. N.V. Mokhov, "The Mars Code System User's Guide", Fermilab-FN-628 (1995); N.V. Mokhov, S.I. Striganov, "MARS15 Overview", Fermilab-Conf-07/008-AD (2007) in Proc. of Hadronic Shower Simulation Workshop, Fermilab, September 2006, AIP Conf. Proc. 896, pp. 50-60 (2007); http://www-ap.fnal.gov/MARS/