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Radiation Safety Analysis of E-163 - Laser acceleration of electrons in vacuum

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Abstract

The feasibility of laser based high gradient acceleration of charged particles has been demonstrated in the Laser Electron Acceleration Project ("LEAP") at Stanford Campus. E-163 experiment will continue research in that field by using the same technology installed in End Station B at the Stanford Linear Accelerator Center. In this note, the radiation safety analysis for E-163 is presented.

Radiation Safety Analysis of E-163 -
Laser acceleration of electrons in vacuum

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1 Introduction

The E163 experiment will require two major changes to the Next Linear Collider Test Accelerator (NLCTA) from a radiation safety standpoint. First, the thermionic injector will be replaced by a laser-driven radiofrequency electron gun. Second, beam will be kicked out of the NLCTA by an extraction dipole and into a second shielded enclosure running parallel to the NLCTA, within which the E163 experiments will be conducted.

2 Radiation shielding criteria

In the shielding analysis that follows, the following criteria should be satisfied for normal and for mis-steered beam. Note, maximum credible beam power is equal to the mis-steered beam power and does not pose an additional concern.

Normal loss scenario:	< 1.0 mrem/h outside the enclosure but < 1000 mrem/y
	< 3 mrem/hr on the roof
Mis-steering scenario:	< 400 mrem/h outside the enclosure without any BCS devices

3 Description of modifications to the NLCTA facility

A concrete and steel shielding enclosure of approximately 600 square feet has been constructed immediately to the north of and sharing a common wall with the NLCTA enclosure, and will house the E163 experiment. The enclosure geometry is shown in Figure 1.
Four penetrations of 6” or less have been drilled through the NLCTA shielding walls to pass electron beam, rf, laser, and Cerenkov light. The penetration for the beam consists of a 6” diameter hole running 25.5^o to the NLCTA beamline, originating at the position of the Faraday Cup FARC1140 will be used for the extraction beamline. Two additional penetrations will connect the E163 shielding enclosure to a laser room. Steel and poly plugs are presently locked in place and marked as radiation protection items in the beamline-height penetration.
The electron source will be replaced by an s-band rf photoinjector, essentially identical to that presently operating at the GTF and planned for operation at the LCLS. The gun is a 1.5 cell microwave structure powered for ~2 μs at 10 Hz to a gradient of 120 MV/m or less. Electrons are generated by striking the rear surface of the gun cavity with UV light, and are then rapidly accelerated to 7 MeV with microwaves.

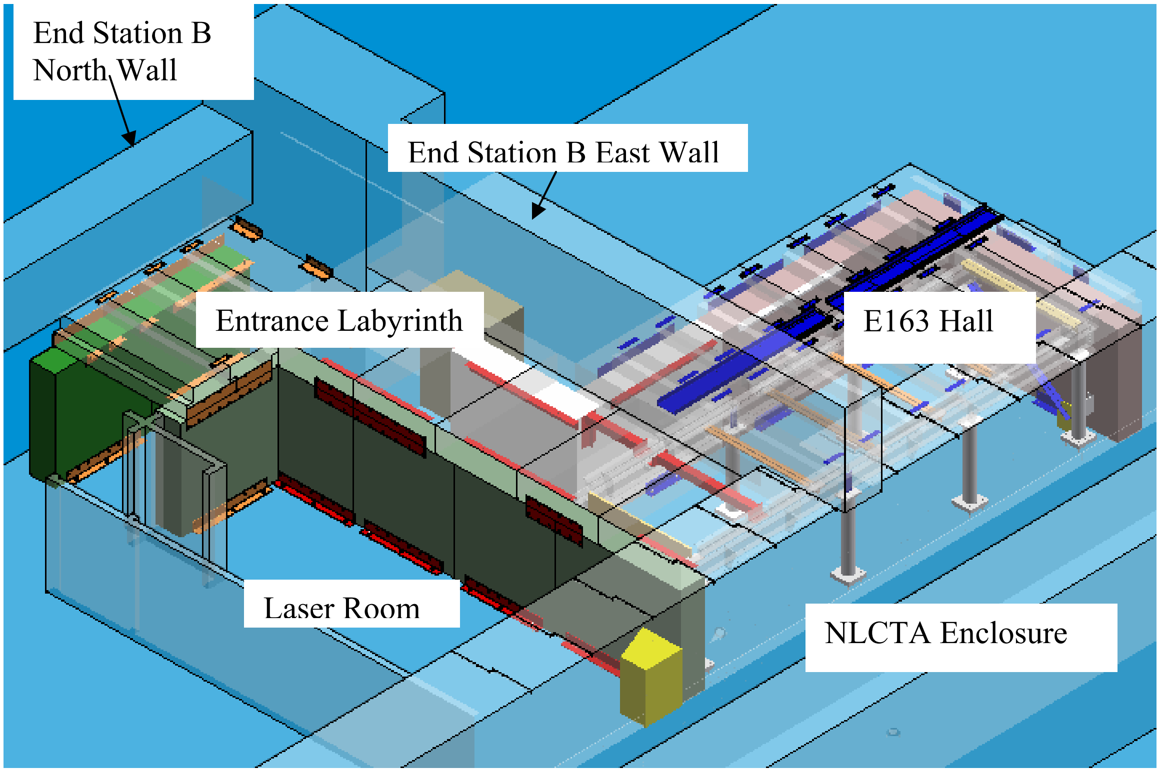

Figure 1: CAD sketch of completed E163 enclosure, viewed looking northeast. All walls and roof blocks are at least 24 inches of concrete. The wall separating the southeast corner of the laser room from the southwest corner of the shielding enclosure has an additional 2" of steel plate shielding.

4 Beam parameters and mode of operations

The facility will be operated either in "Tune-up", as is typical of the commissioning phase and much of the running phase and "Experiment" mode, when the experiment is taking data. Both modes are described below. The beam charge is controlled by a laser intensity striking the photocathode of the E163 gun. Note, that the maximum charge that can be emitted from the E-163–gun under normal running conditions is around 1nC.

4 .1 Description of "Tune up" Mode

For tune-up, the following charge and energy will be used: 60 MeV, 1 nC, 10 Hz (0.6 W). Tuning up usually requires that the beam intercepts with a screen, often for extended periods of time. Six screens are planned for the E163 beamline, see Figure 2.

Screens will be the most frequently used intercepting device during the tune-up. Two types are likely to be used: a phosphor screen, which typically is a metal plate coated with fluorescent material, and a fluorescent crystal. The former was modeled in the simulation simply as a 1 mm thick aluminum plate (X_o=24.01 gm/cc and X_o/ρ=8.9 cm), and the latter was made of a 1 mm thick $Y_3Al_5O_{12}$ for which the computed radiation length is X_o=16.11 gm/cc and X_o/ρ=3.54 cm.

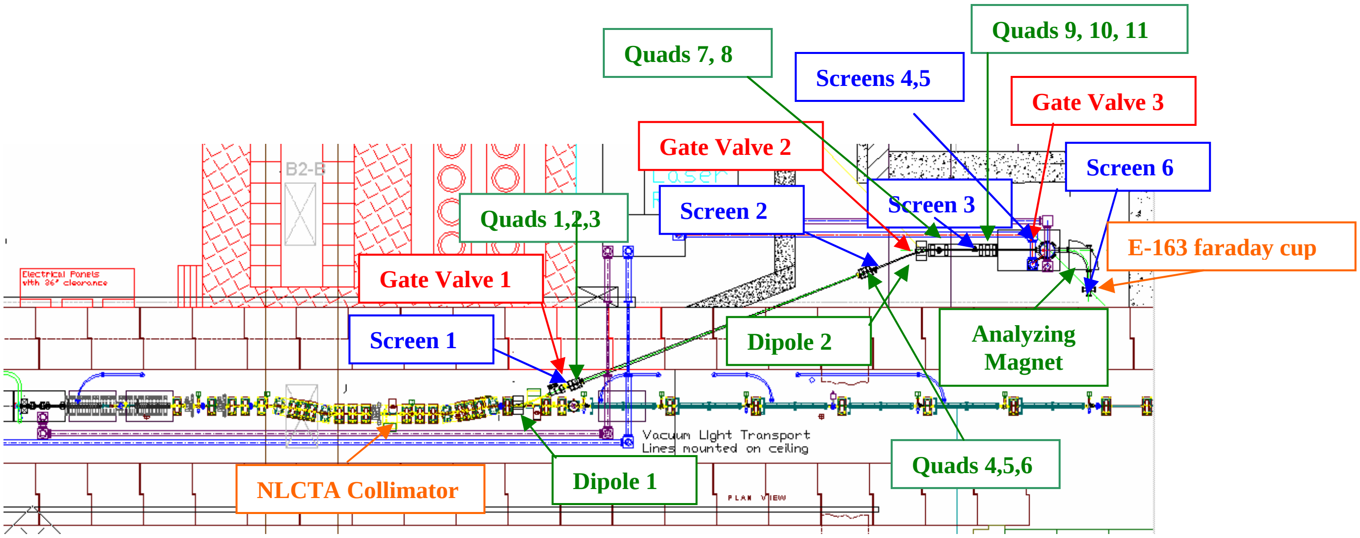

Figure 2: NLCTA and E163 enclosures, showing beamline component locations.

4.2 Description of "Experiment" Operation

Under normal experimental circumstances, ~60 MeV, **~50 pC**, 10 Hz (0.03 Watts) beam will exit the NLCTA enclosure via a +25.5^o bend dipole placed immediately downstream of the NLCTA chicane. The beam passes through the NLCTA shielding wall into the E163 enclosure, is bent –25.5^o, and is focused into the experiment vacuum chamber, where it interacts with the laser fields at the accelerator cell (fused silica X_o=27.05 gm/cc, X_o/ρ=12.3 cm). The beam is then bent –90^o in an energy analyzing spectrometer, strikes a thin (1 mm) Ce:YAG fluorescent screen, and passes on through and into a beam dump.

Finally, E-163 tests "short" laser accelerator structures during the E163 program, with expected energy gains of no more ~1 MeV total for the small group of particles that is successfully trapped in the accelerating mode, of order 10^5 or less. This means the accelerated beam will have a power of 10 Hz*10^5*e*61 MeV ~ 10 µW, and will not produce a significant increase in radiation compared to the unaccelerated case.

4.3 "Mis-steering" Beam Loss Scenarios

Equipment failure and operator error can lead to unintentional radiation production. Failure of the bend magnets and unintended closure of vacuum gate valves is considered here for illustrative purposes. Failure of a screen, causing it to be unintentionally inserted, has the same radiation distribution as for the tune-up cases above. A conservative value of 1 W total beam power has been used for the analysis.

5 Details about the Calculation

The 2003 version of the FLUKA Monte-Carlo code was used to determine the effective dose rates at the E-163 facility for normal and mis-steering condition as discussed later.

Co-ordinate system: The geometry is described in a right-handed orthogonal system with the vertical x-axis perpendicular to the beam axis. The z-axis is pointing in beam direction and the y-axis is horizontal and is pointing towards the right - looking along the beam direction.

Energy thresholds: For the simulation the threshold for particles transport was set to 0.5 MeV for electrons and positrons, Neutrons are followed down to thermal energies and for photons an energy cut-off threshold of 300 keV was used.

Biasing: Leading particle biasing was activated for all photons and all electrons. Further, the inelastic interaction length of photons was reduced by a factor of 0.02 in order to enhance the statistical significance of photonuclear reactions. Importance biasing was used in concrete shielding walls of E-163.

Scoring: The particle fluence was weighted during the scoring procedure by energy- and particle type-dependent conversion factors using the EWTMP option in FLUKA. This uses fits to the data from M. Pellicioni and the concept of the WORST value of effective dose for any body orientation.

6 Shielding requirements

The shielding of E-163 consists of 24 inch of concrete blocks and one 20 ft long 2 inch thick steel plate inside the west wall. Local shielding around beam line components will be added as described in the following paragraphs.

6.1 Tune up and Normal operation

For tune up and normal operation the following criteria had to be satisfied:

- $\leq$ 1.0 mrem/h outside the enclosure and $\leq$ 1000 mrem/y
- $\leq$ 3 mrem/hr on the roof

6.2 Beam loss scenarios

Beam loss scenarios considered in this note are described below (a summary table with dose rate outside the enclosure are given in Table I).

6.2.1 Dark Current

Field emission or “dark current” from the new photoinjector will be generated, and owing to its large energy spread and poor beam quality will be almost entirely lost in the first 2 meters of the NLCTA accelerator. Operational experience with existing guns suggests losses on the order of 1 mA or less. This loss distribution was calculated assuming 2.9 mA of dark current and is shown in Figure 3 (left graph) below, reproduced from reference [1]. The beam power loss distribution (right graph) is also shown, and gives some 83 mW total loss power per milliampere of dark current emitted. Beyond the narrow acceptance NLCTA collimator, there is negligible dark current transmission.

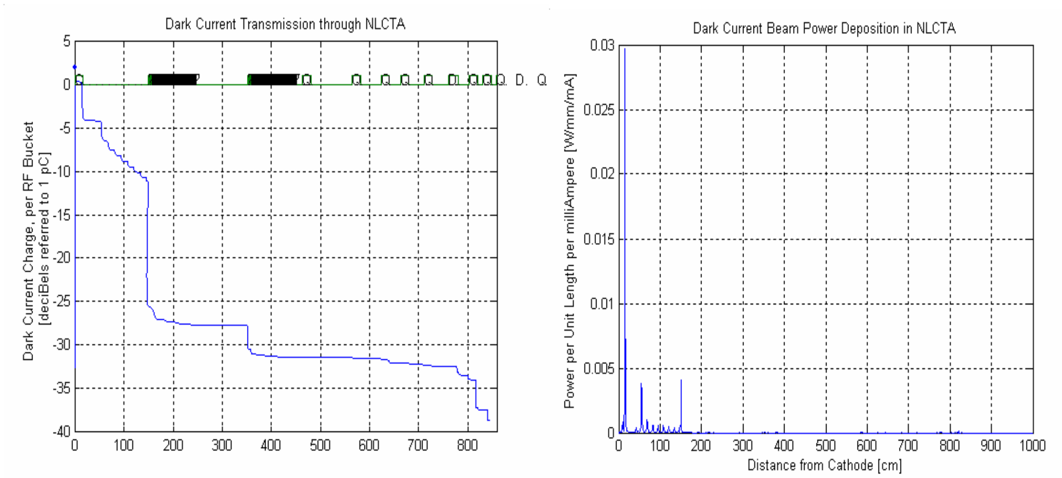

Figure 3: (Left) Dark current transmission through the NLCTA beamline, shown on a logarithmic scale, referenced to 1 pC (=0 dB) per rf bucket. A drop of 10 dB in transmission means that 90% of the current has been lost. (Right) Dark current beam power deposition in Watts per mA per millimeter of beam line. Note, that the extraction point to the E-163 enclosure is located at ~1600 cm.

6.2.2 NLCTA collimator loss

During tune up mode, the whole beam could be lost unintentionally on the NLCTA collimator. Based on SHIELD11 calculations, the existing six feet of concrete shielding of the NLTCA tunnel reduces the dose rate to 5 μrem/hr in the laser room it that case.

6.2.3 Beam intercepting screens

The tune up phase requires frequent insertions of one of the six screens into the beam line. Two different types of screens will be used; a phosphor screen, which typically is an aluminum plate coated with fluorescent material, and a fluorescent crystal $Ce:Y_3Al_5O_{12}$.

Part of the E-163 experimental setup was modeled within FLUKA to calculate the dose rate at the facility when beam intercepts with the screens, see Figure 4.

First calculations indicated that the dose rate outside the E-163 enclosure will considerable exceed the dose limit of 1 mrem/hr when a 70 MeV, 0.7 W electron beam is intercepting with the screen 3. The dose rate outside the enclosure of more was calculated to be 100 mrem/hr, see Figure 5. To reduce the dose rate either shielding along the beam line or a back-up stopper is required immediately downbeam of the screen. The latter one was preferred by E-163 Experimenters. The back-up stopper will be inserted always together with the screen. A sketch of the backup stopper is depicted in Figure 6.

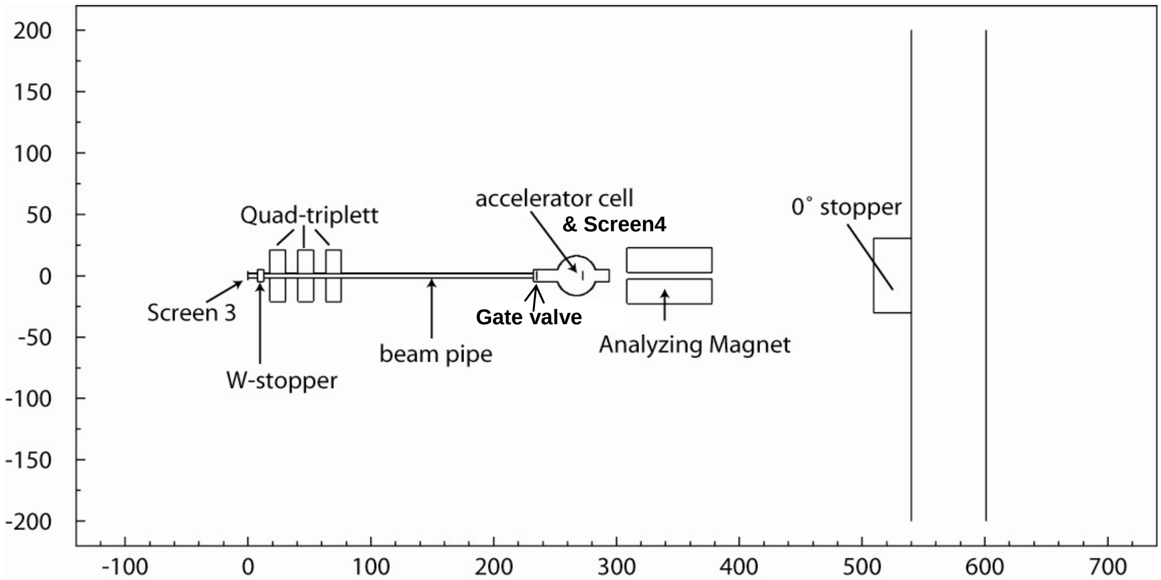

Figure 4: FLUKA geometry of beam components of E-163. Used for calculations when beam intercepts screen 3, 4 and accelerator cell. Units are in cm.

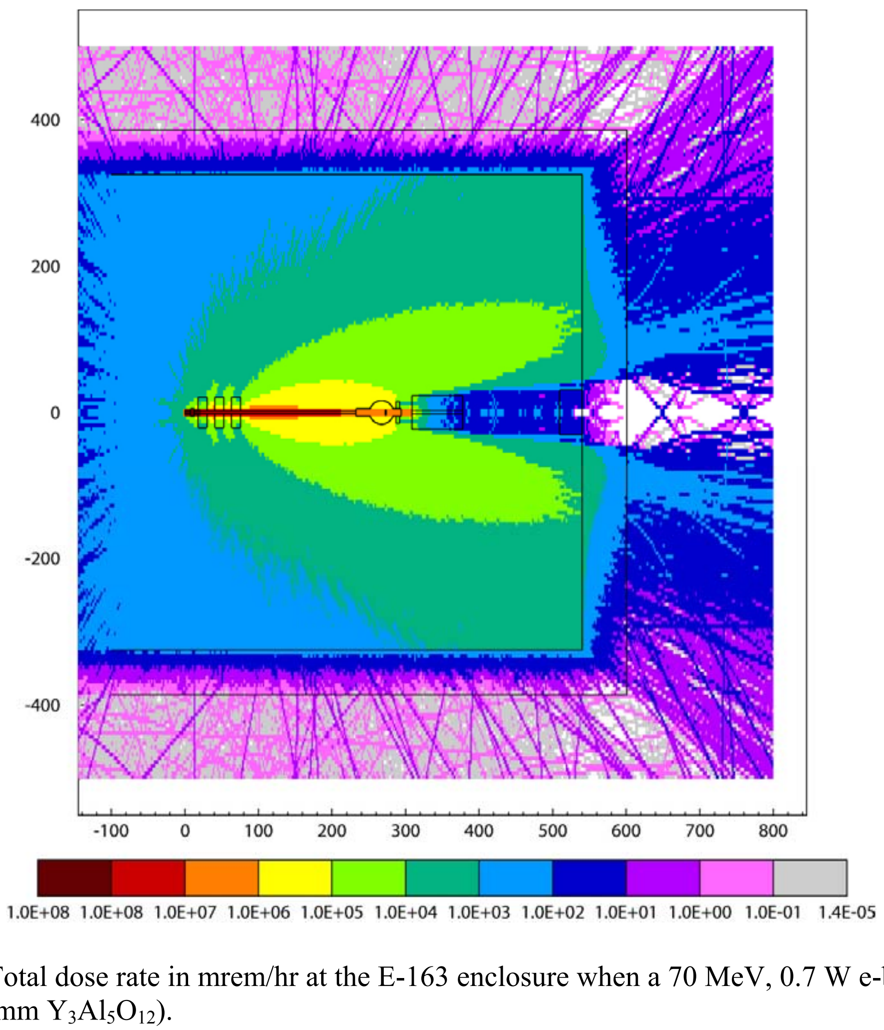

Figure 5: Total dose rate in mrem/hr at the E-163 enclosure when a 70 MeV, 0.7 W e-beam hits screen3 (1 mm $Y_3Al_5O_{12}$).

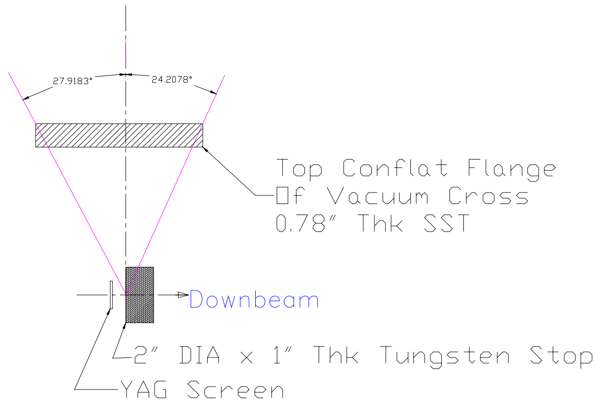

Figure 6: Ce:YAG Screen and Tungsten Stop with an iron shield on top. Backstop shield is required for screens 2 and 3 only.

The backup solution, screen plus tungsten-stopper, reduces the forward dose significantly but also increases the dose rate perpendicular to the beam line from 0.1 mrem/hr to 2.0 mrem on the side (Figure 7). On the roof the dose values goes up to 4.6 mrem/hr (shorter distance) – Figure 8. Nevertheless, as discussed later, mis-steering studies require 2“ of steel on the north side which reduces the dose rate below 0.7 mrem/hr. The screens are placed inside a vacuum cross which has a 0.78” thick steel flange on top. This reduces the dose rate on the roof to 3 mrem/hr.

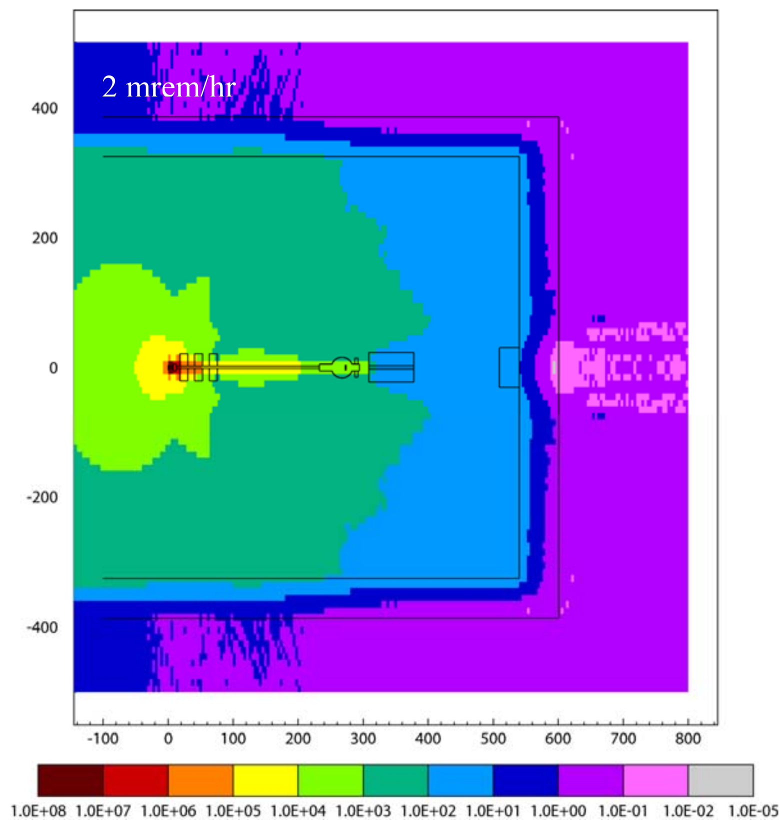

Figure 7: Plan view - Dose rate in mrem/hr at the E-163 enclosure when a 70 MeV, 0.7 W e-beam hits screen 3 (1 mm $Y_3Al_5O_{12}$) with tungsten back shield (2 inch diameter and 1 inch thick).

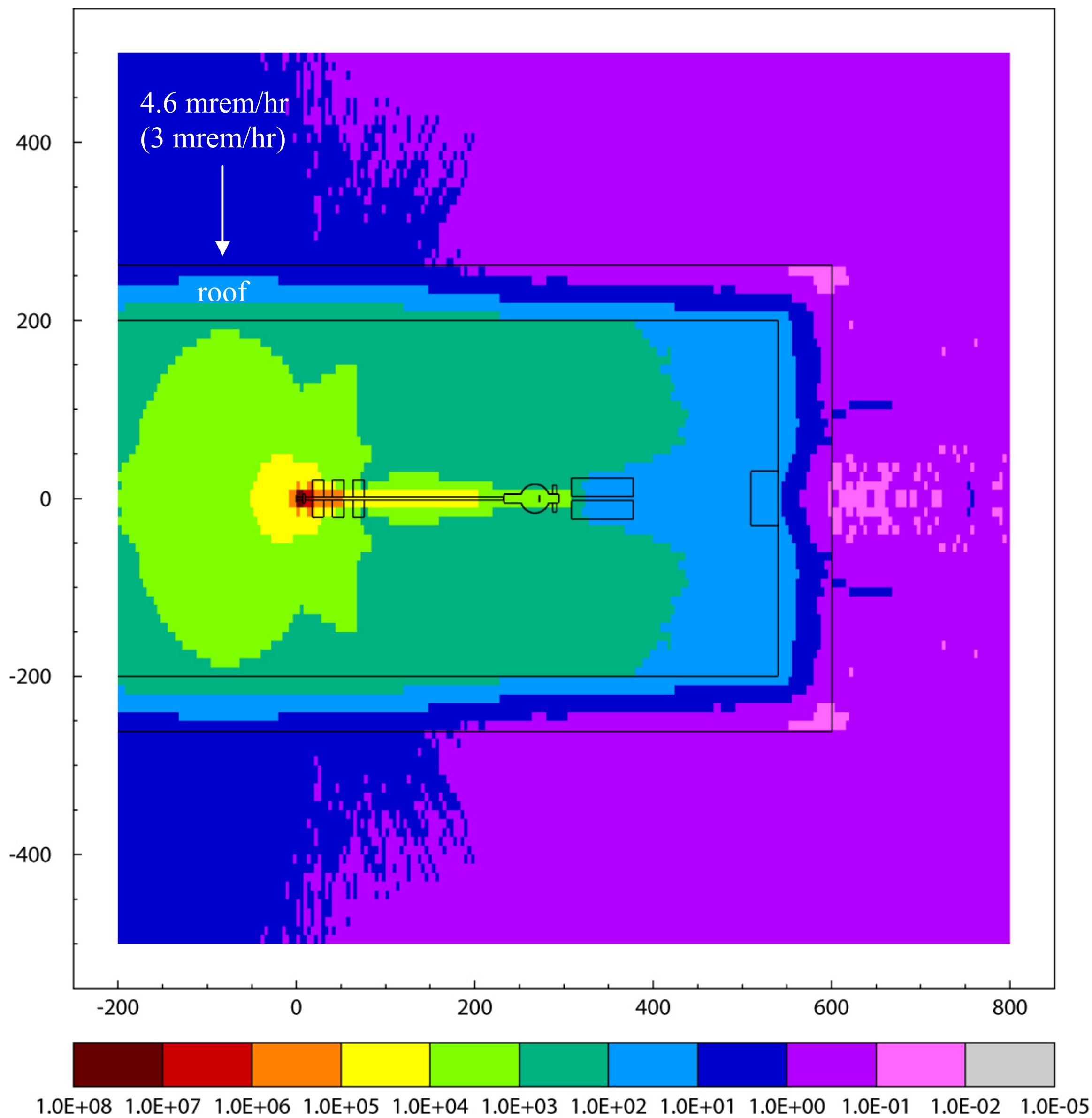

Figure 8: Elevation view - Dose rate in mrem/hr at the E-163 enclosure when a 70 MeV, 0.7 W e-beam hits screen 3 (1 mm $Y_3Al_5O_{12}$) with tungsten back shield (2 inch diameter and 1 inch thick). The value in parenthesis is the dose rate with 0.78" thick steel flange on top of the tungsten shield.

The FLUKA geometry for simulating intercepting of beam with screen 2 is shown in Figure 9. The dose rate distribution at the facility when a 70 MeV 0.6 W e-beam intercepts with screen 2 is shown for all particles, photon and neutron separately in Figure 10 to 12. It can be seen that, the dose rate outside the enclosure is always below the limit of 1 mrem/hr. At the E-163 entrance maze a dose rate was calculated to be much lower than 1 mrem/hr namely 3 only μrem/hr.

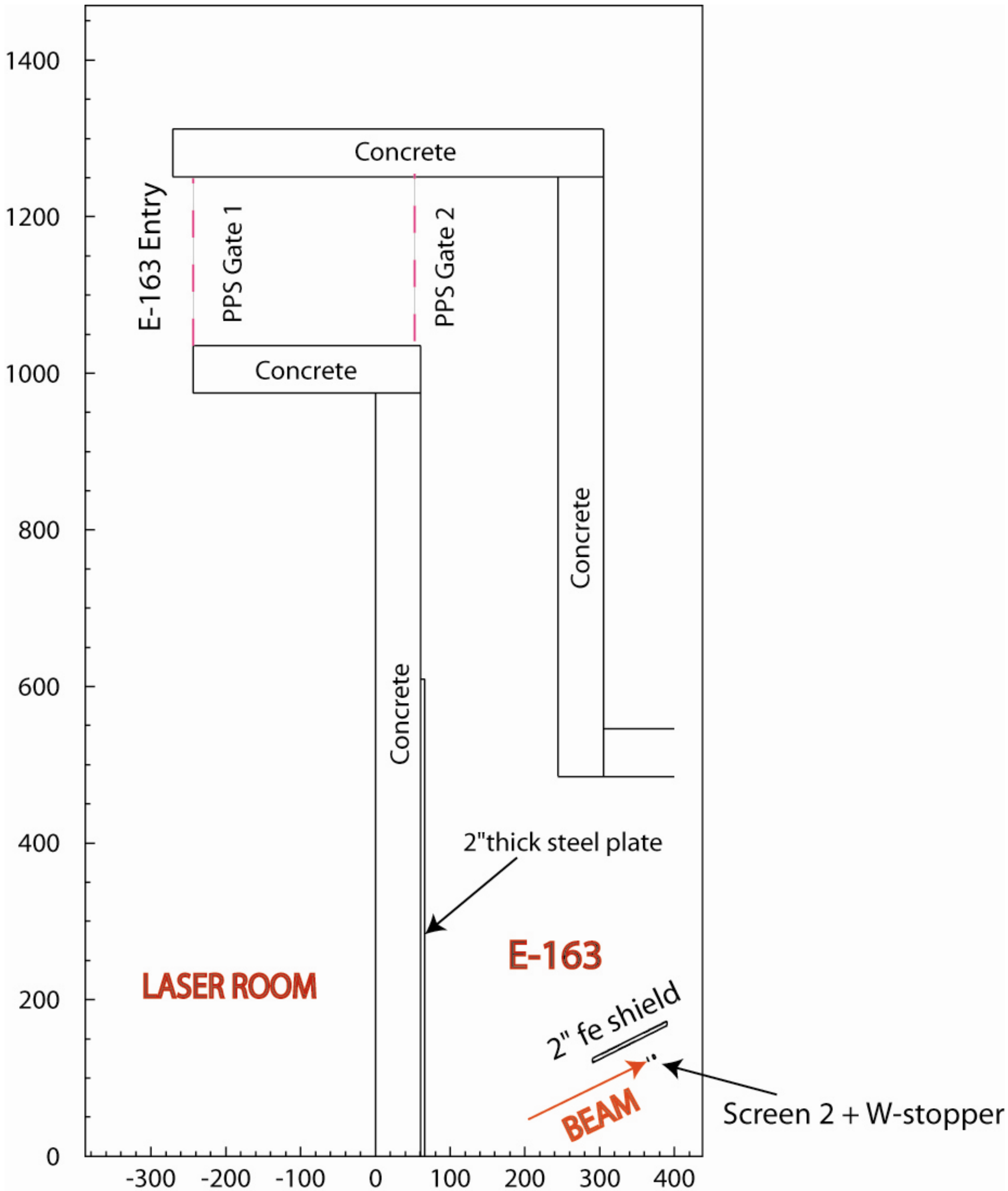

Figure 9: FLUKA geometry used to determine dose rates at the E-163 facility when beam intercepts with screen 2. Units are in cm.

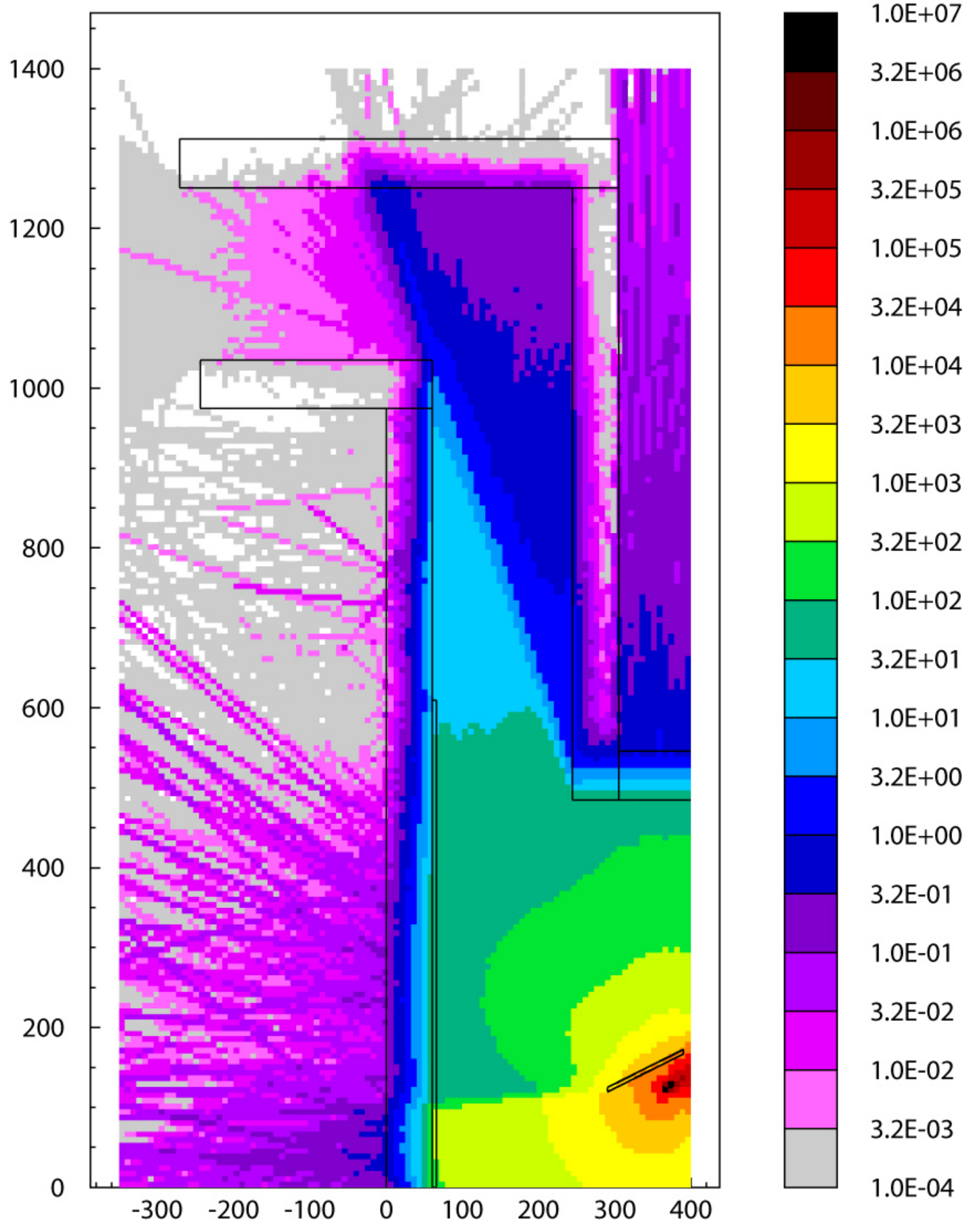

Figure 10: Total dose rate in mrem/hr - Beam intercepting with screen 2. A tungsten back up shielding is located behind the screen.

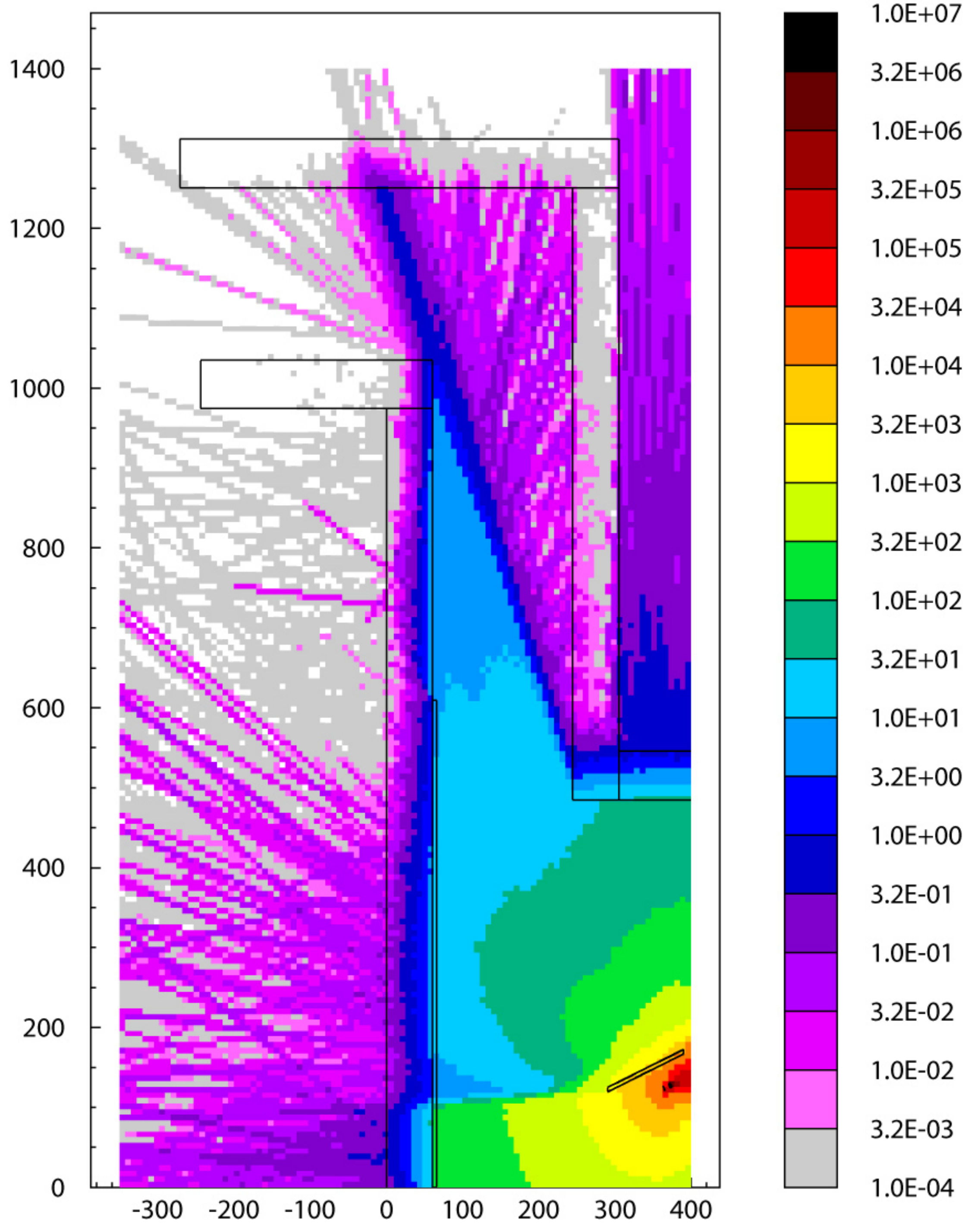

Figure 11: Photon dose rate in mrem/hr - Beam intercepting with screen 2. A tungsten back-up shielding is located behind the screen.

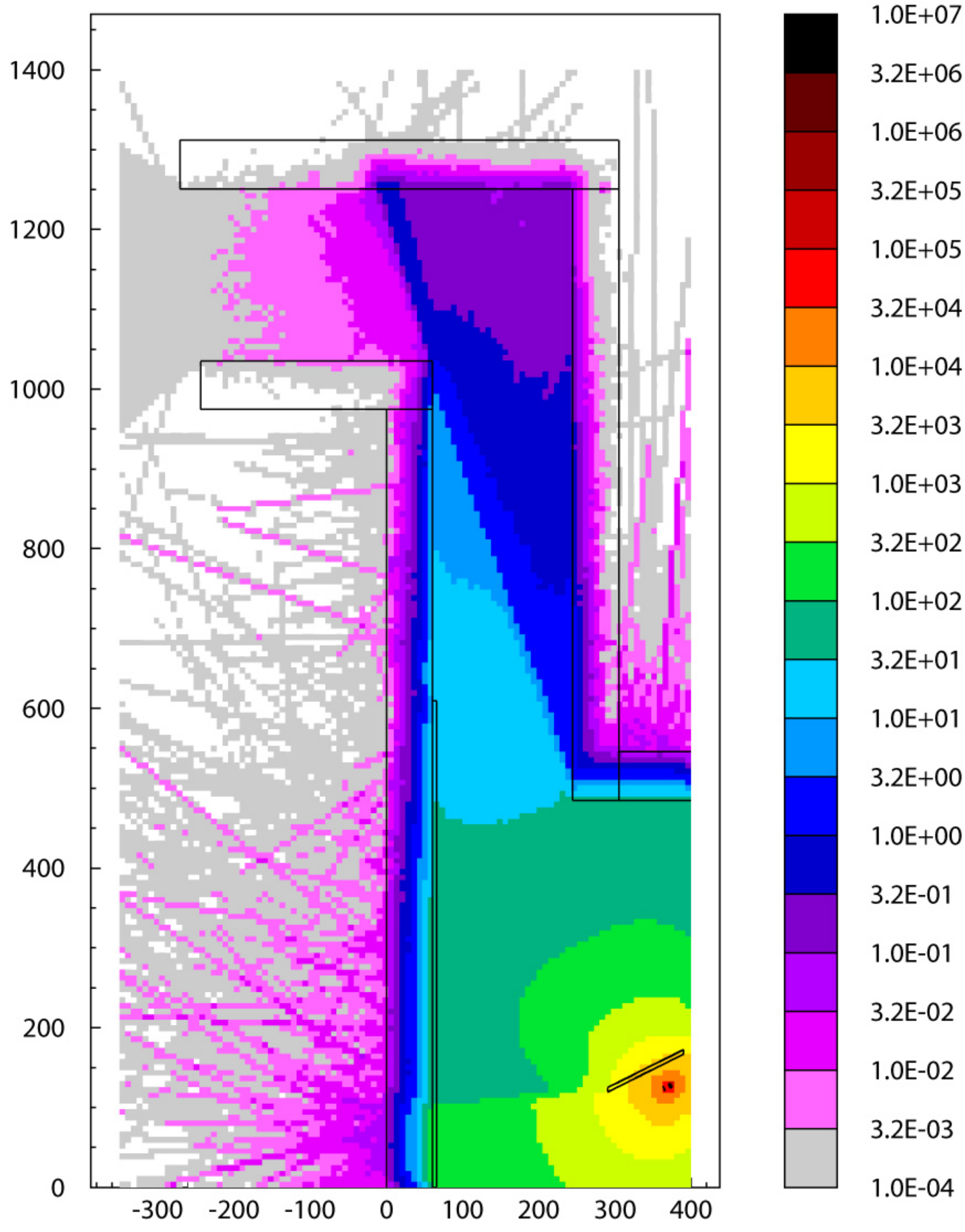

Figure 12: Neutron dose rate in mrem/hr - Beam intercepting with screen 2. A tungsten back-up shielding is located behind the screen.

Interception of a 70 MeV, 0.6 W beam with screen 4 and the accelerator cell was also simulated with FLUKA in details. For screen 4 and 5 a tungsten backup shield is not required. Figure 13 shows the components as implemented into the FLUKA geometry. In a first set of calculations electrons and positrons reaching the analyzing magnet were just discarded. It turned out that detailed transport of charged particles through the magnetic field is necessary to identify the required shielding configuration at 0-degree correctly.
Total equivalent dose rates at the enclosure is shown in Figure 14. Contribution to the dose from electrons, positrons, photons and neutrons are given in Figures 15-18, separately. It can be seen that a bulk part of positrons and neutron are actually generated by interaction with the analyzing magnet and the main dump and not be interaction with the screen it self.

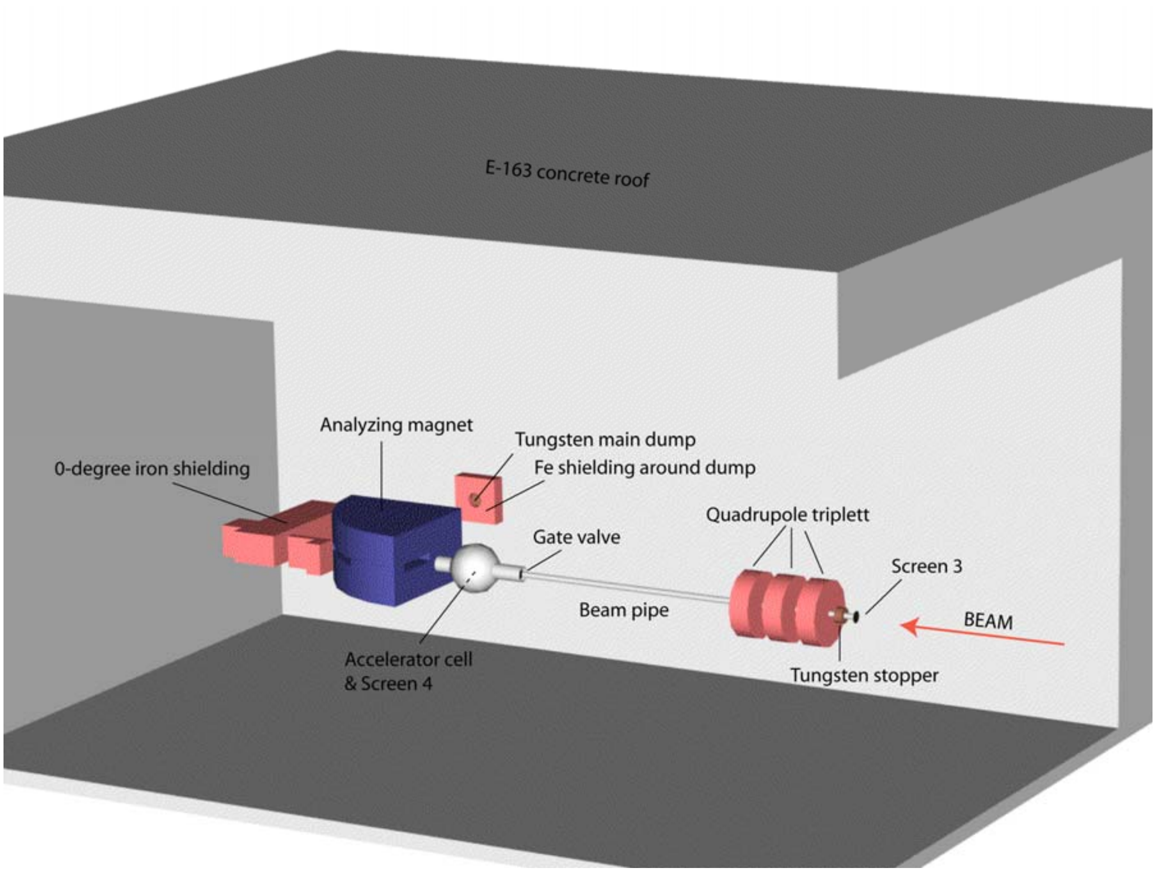

Figure 13: FLUKA geometry

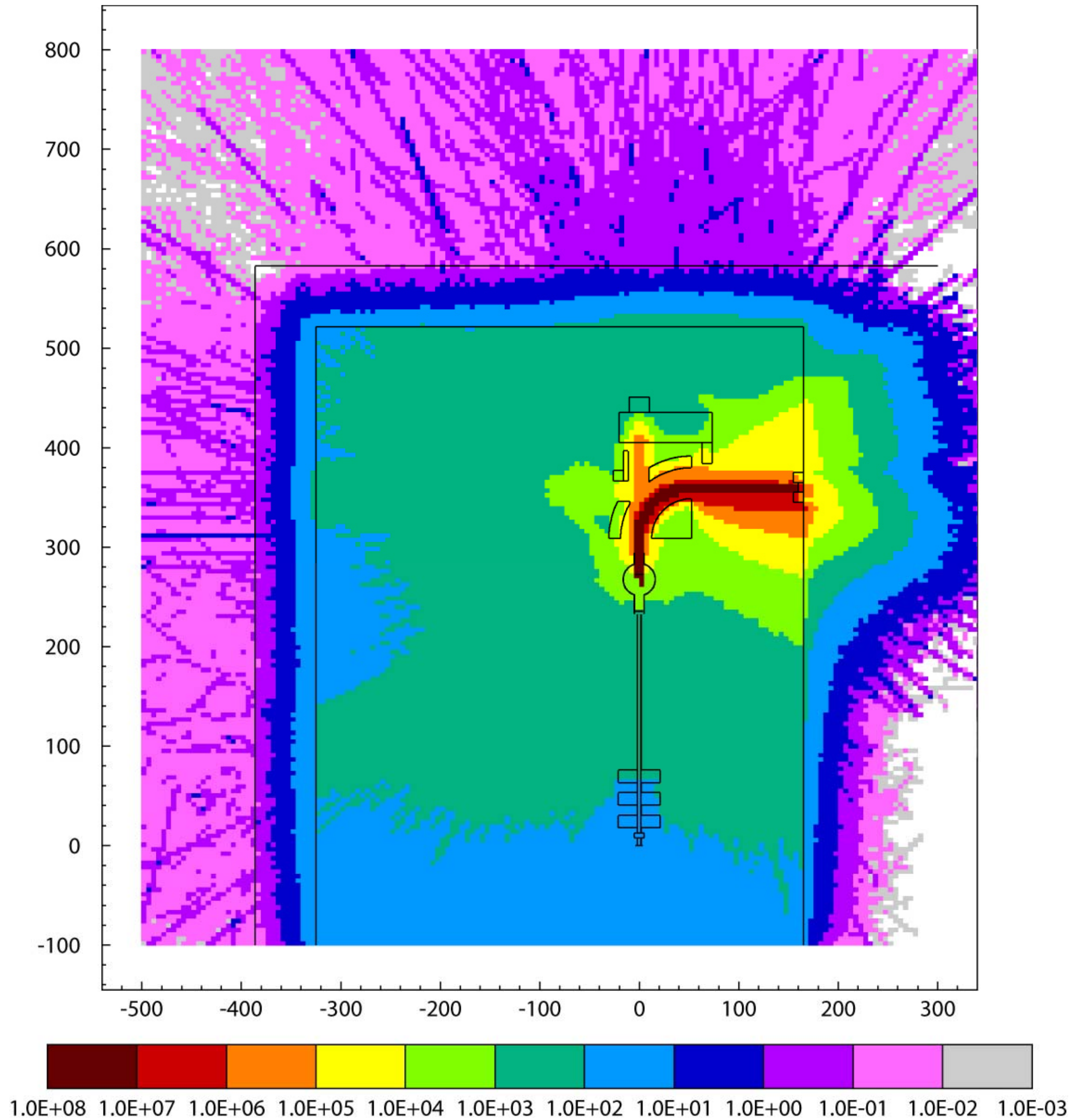

Figure 14: Total dose rate in mrem/hr at the E-163 enclosure when a 70 MeV e-beam (0.6W) intercepts screen 4.

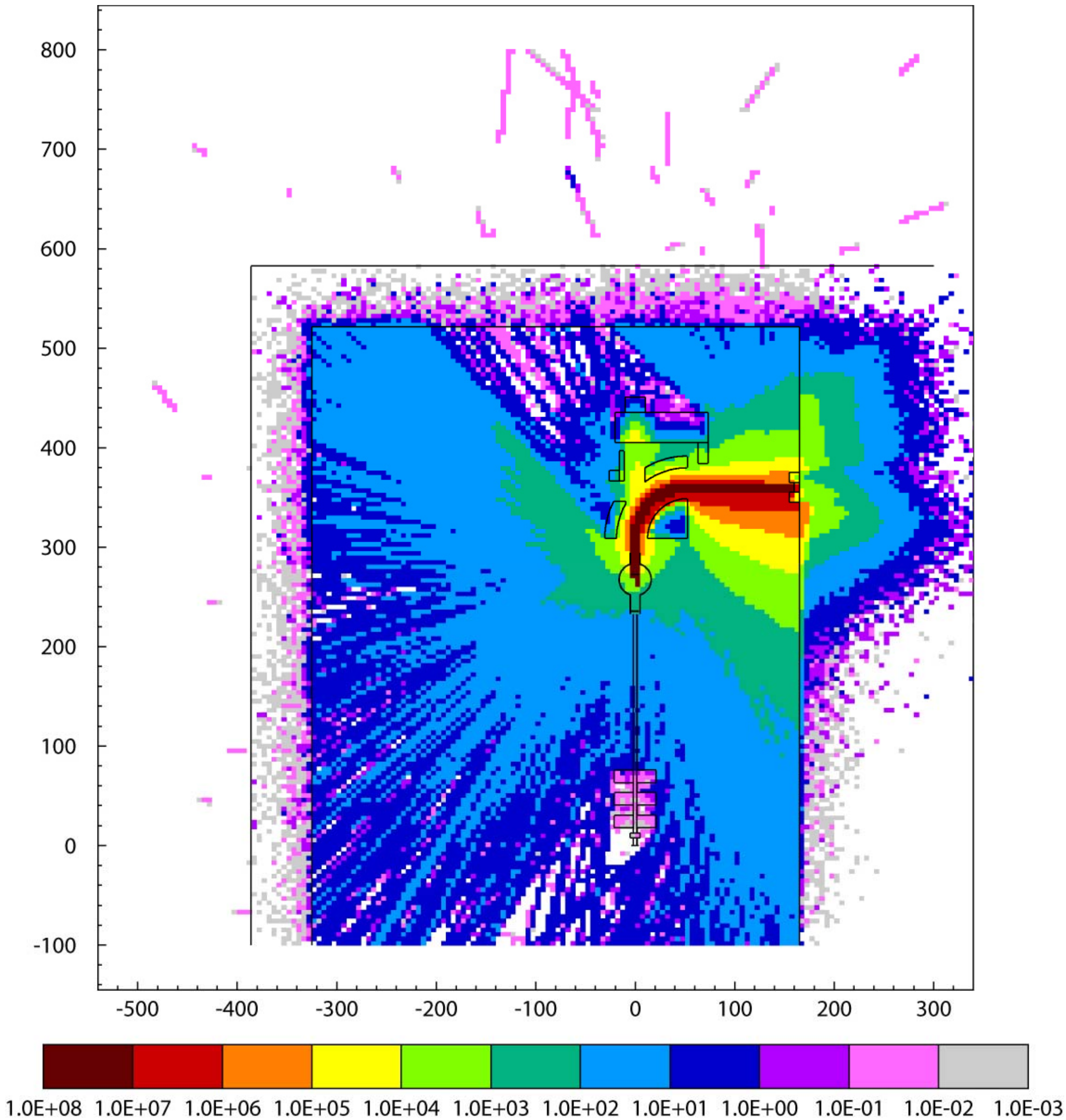

Figure 15: Electron dose rate in mrem/hr at the E-163 enclosure when a 70 MeV e-beam (0.6W) intercepts screen 4.

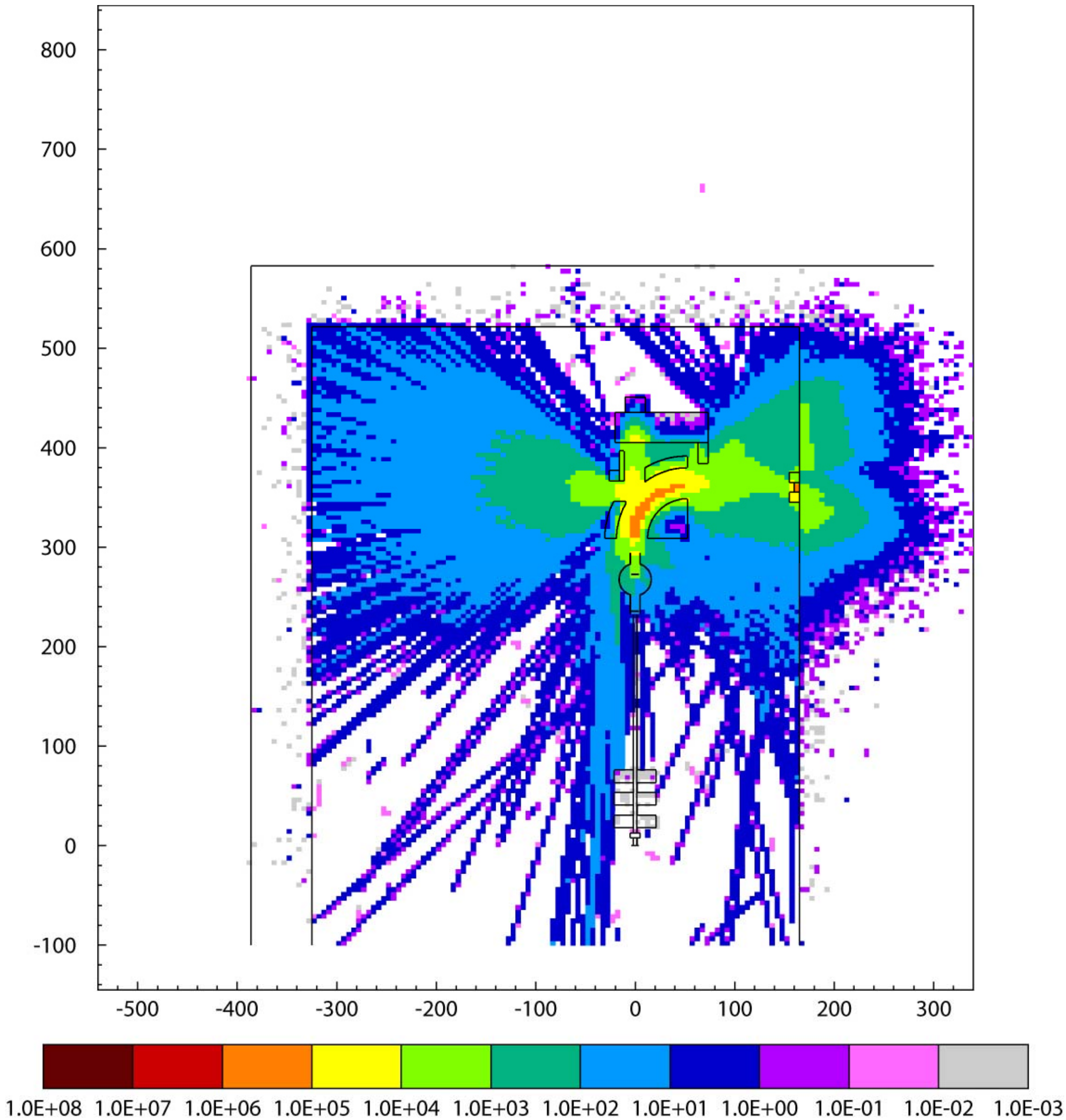

Figure 16: Positron dose rate in mrem/hr at the E-163 enclosure when a 70 MeV e-beam (0.6W) intercepts screen 4.

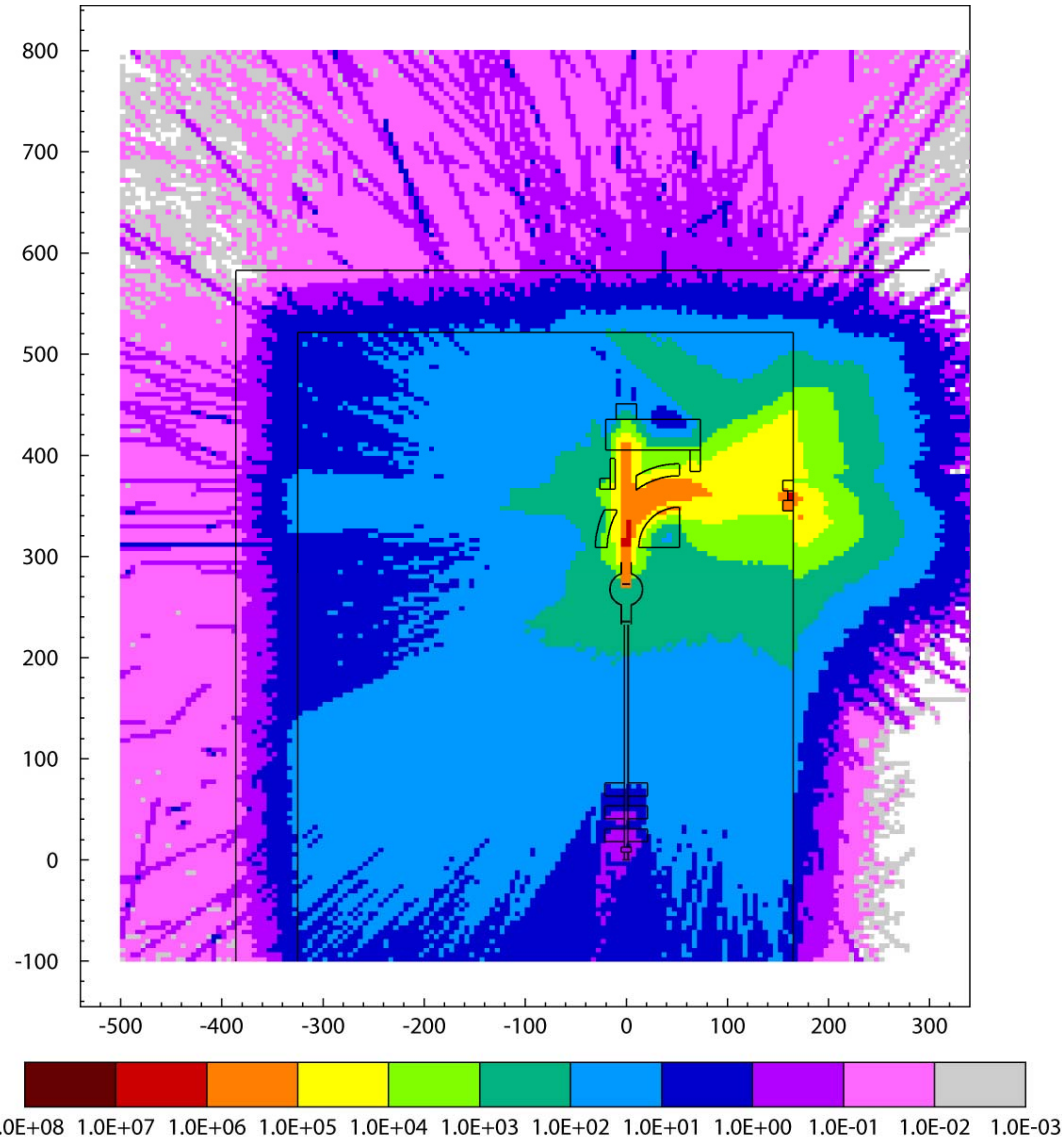

Figure 17: Photon dose rate in mrem/hr at the E-163 enclosure when a 70 MeV e-beam (0.6W) intercepts screen 4.

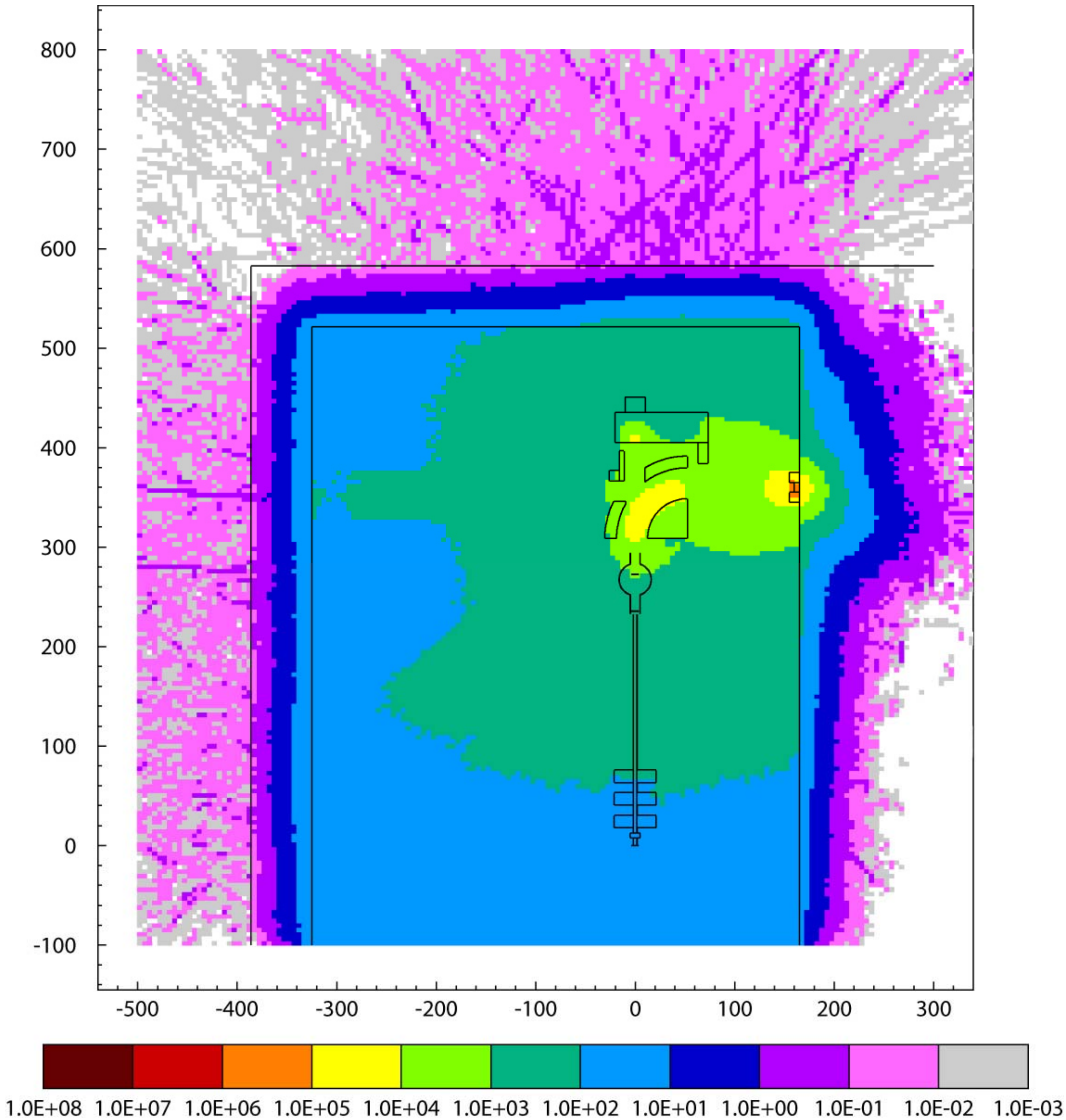

Figure 18: Neutron dose rate in mrem/hr at the E-163 enclosure when a 70 MeV e-beam (0.6W) intercepts screen 4.

6.2.4 Accelerator Cell

During normal operation a 30mW electron beam can intercept with the accelerator cell (fused silica X_o=27.05 gm/cc, X_o/ρ=12.3 cm). As shown in Figure 19, the dose rate outside the facility is below the limit of 1 mrem/hr.

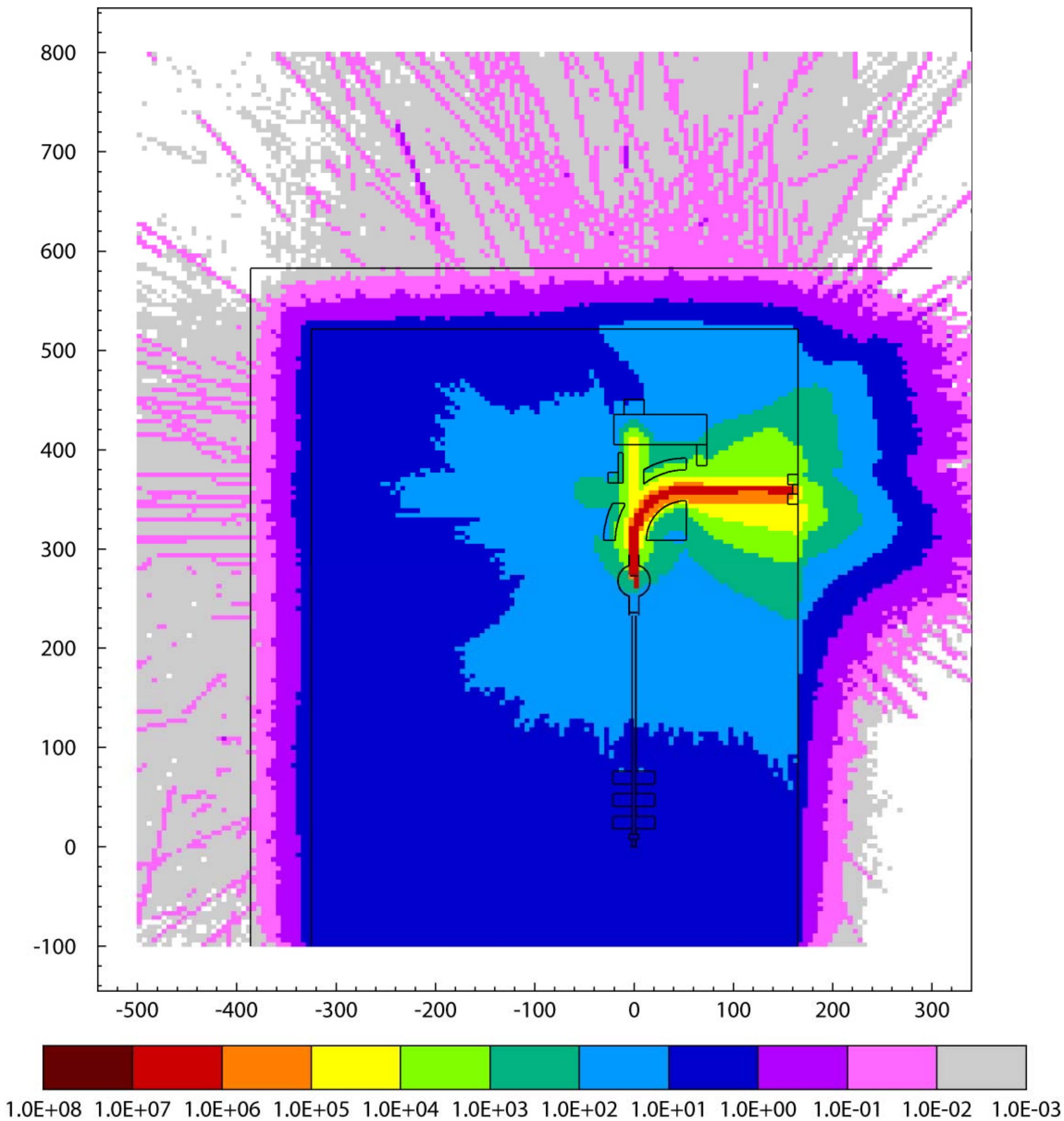

Figure 19: Dose rate in mrem/hr at the E-163 enclosure when a 70 MeV e-beam (0.03W) intercepting with the accelerator cell.

6.2.5 Screen 6 and Faraday cup after screen 6

The faraday cup, a tungsten cylinder 2" thick by 3.8" diameter, can be inserted into the beam line. Calculations indicated that shielding on the right side on the Faraday cup is required in this case to reduce the dose rate to the allowed limit of 1 mrem/hr. The shielding consists of 2 iron shielding blocks as depicted in Figure 20. The FLUKA geometry is shown in Figure 21 and the dose rate distribution at the enclosure in Figure 22.

For screen 6, a tungsten back-up stopper is not required. The dose rate outside the E-163 concrete east wall is below 1 mrem/hr when the beam intercepts with the screen, see Figure 23.

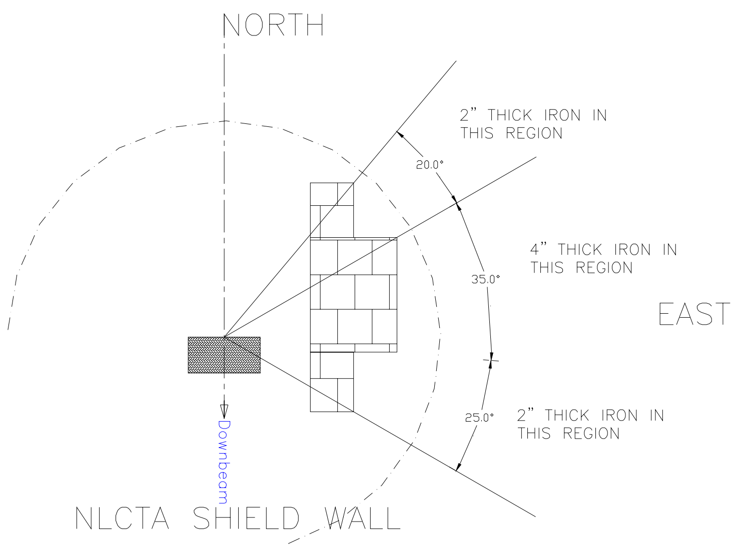

Figure 20: Faraday cup east shielding wall requirements. Wall height coverage 45 degrees up and 25 degrees down (shadows east wall floor to ceiling).

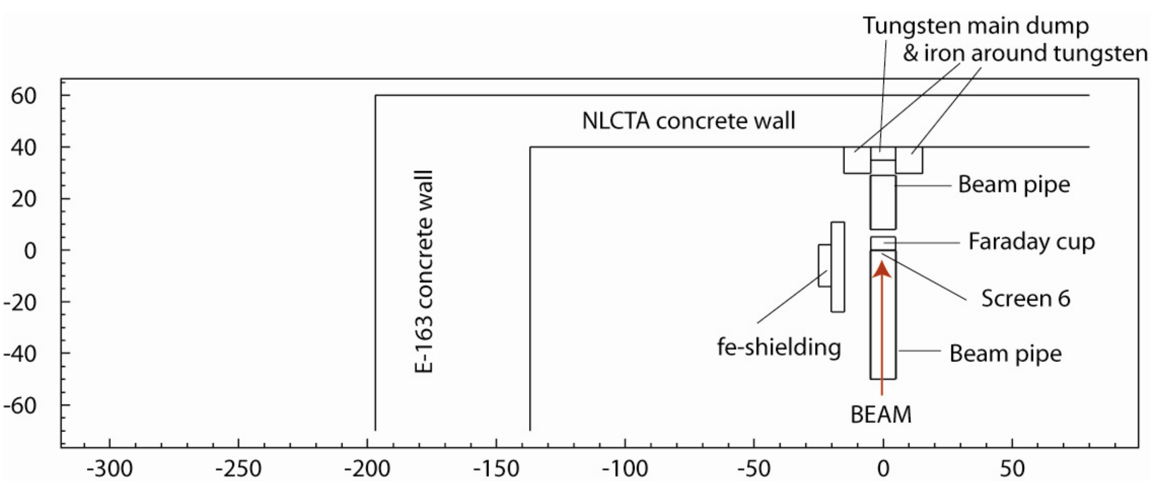

Figure 21: FLUKA geometry

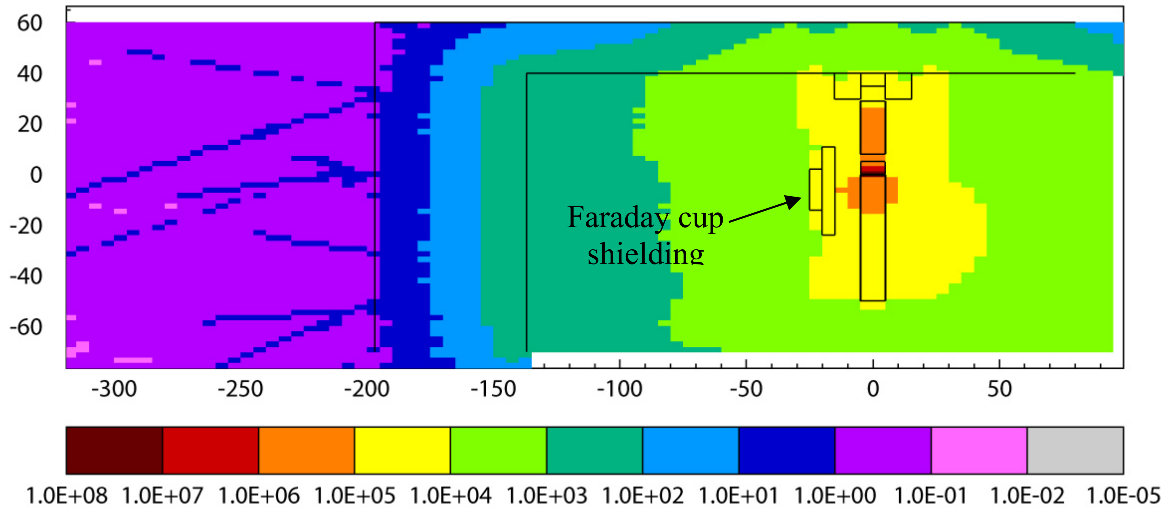

Figure 22: Dose rate in mrem/hr at the E-163 enclosure when a 70 MeV, 0.6 W e-beam hits E-163 Faraday cup

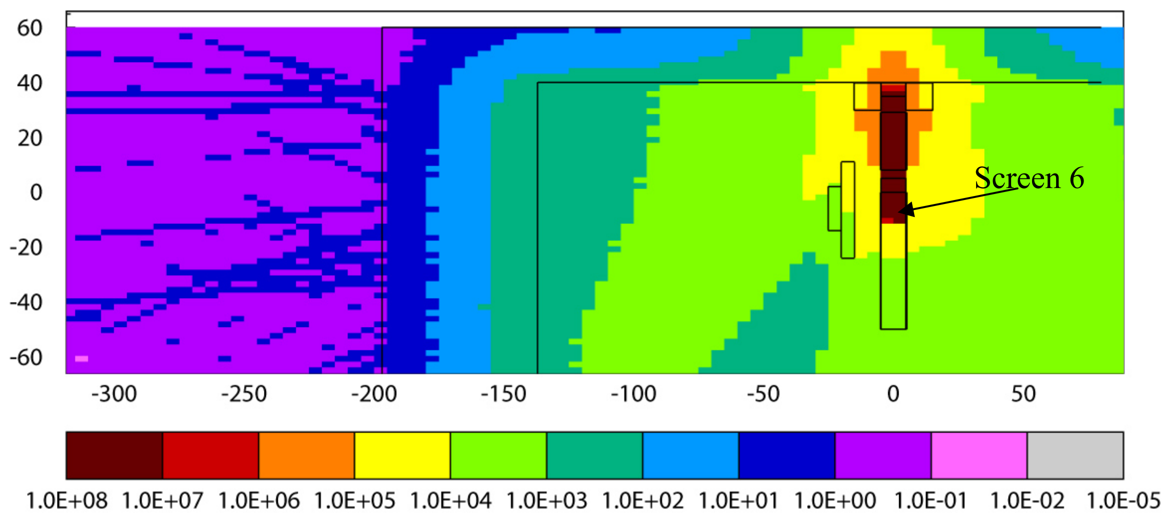

Figure 23: Dose rate in mrem/hr at the E-163 enclosure when a 60 MeV, 0.6 W e-beam intercepts with screen 6

6.2.6 Main dump

The main dump of the E-163 facility consists of a 2" diameter, 2" long tungsten stopper that is surrounded by an iron plate as shown in Figure 24. Dose rate at the enclosure when a 0.6 W 70 MeV electron beam is send to the dump is given in Figure 25.

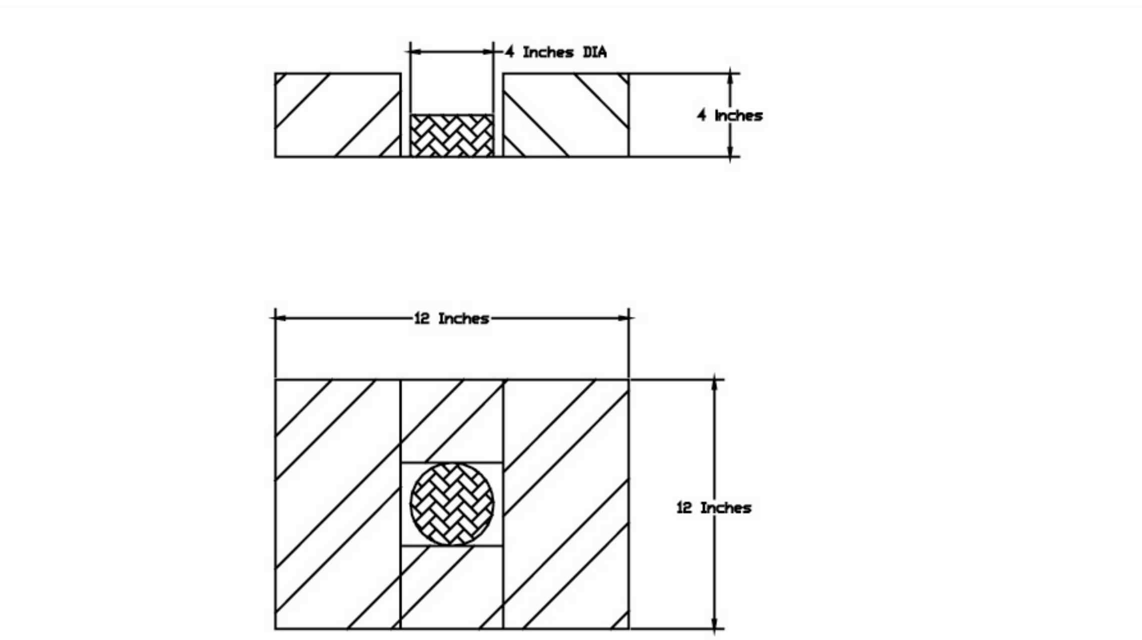

Figure 24: E-163 main dump design: A 4" diameter tungsten dump is surrounded by 12" of steel.

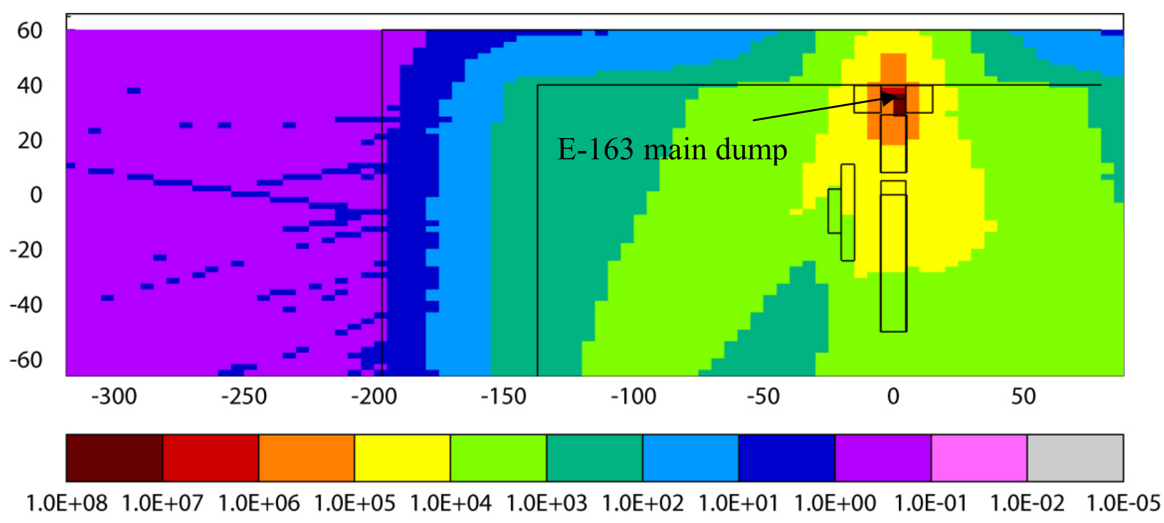

Figure 25: Dose rate in mrem/hr at the E-163 enclosure when a 70 MeV, 0.6 W e-beam is send to the main dump.

6.2.7 Penetrations

Two 4” diameter penetrations will be drilled through the West wall of the E-163 concrete enclosure to the laser room. The holes will be at a height of ~ 2.5m. The dose rate in the laser room at the penetration was calculated as 0.24 mrem/hr - source term at the opening inside the enclosure is 54 mrem/hr calculated with FLUKA and an attenuation factor obtained from [2] of 4.4×10^{-3}.
Two 4” diameter holes drilled near ceiling height and running 90^o to the NLCTA beamline will be used for optical transport vacuum tubes. The expected dose rate in the laser room due to 0.6 W, 60 MeV electrons hitting the NLCTA collimator is <0.03 mrem/hr.

6.2.8 Summary of beam losses during “normal running conditions

Table I: Summary of beam power losses during “normal running conditions

	Experiment Mode 60 MeV, 50 pC, 10 Hz 30 mW *Dose rate limit :* ***1 mrem/hr***	**Tune-up Mode** 60 MeV, 1 nC, 10 Hz 0.6 W *Dose rate limit :* ***1 mrem/hr***	**Dose rate in mrem/hr** [1] outside E-163 enclosure - except roof	**Dose rate in mrem/hr** [1] outside E-163 enclosure - on the roof
Duration	**500 hours/year**	**500 hours total**		
Dark Current Loss	240 mW in first 2 m of NLCTA injector		Negligible	Negligible
NLCTA collimator Loss	30 mW	Up to 0.6 W	0.005*	<0.005*
	Intentional Beam Loss Scenarios			
Screen 2		0.6 W	0.32	3
Screen 3		0.6 W	0.7	3
Screen 4		0.6 W	0.9	0.3
Screen 5		0.6 W	0.9	0.3
Screen 6		0.6 W	0.9	0.5
Accelerator Cell	30 mW		0.05	<0.05
Bend-Line Dump		0.6 W	0.9	0.5

* Shield11

6.3 Mis-steering

Mis-sterring cases have been analyses for the following cases. The dose rate limit is 400 mrem/hr.

6.3.1 Quads short at start of extraction line

A 1 watt beam loss on the beam chamber immediately adjacent the SW corner of the laser room was assumed. Calculations based NCRP-51 give a dose rate of 3 mrem/hr in the laser room.

6.3.2 Dipole 2 fails or is set incorrectly

A 1 watt beam loss on beam chamber near dipole 2 would result in a dose rate outside the concrete wall of 100 rem/hr, see Figure 26, which is 250 times over the limit for mis-steering and accident. A two inch thick shielding parallel to the beam pipe (i.e. actual path length is 4.6 inch) reduces the dose rate to values below the limit of 400 mrem/hr (Figure 27).

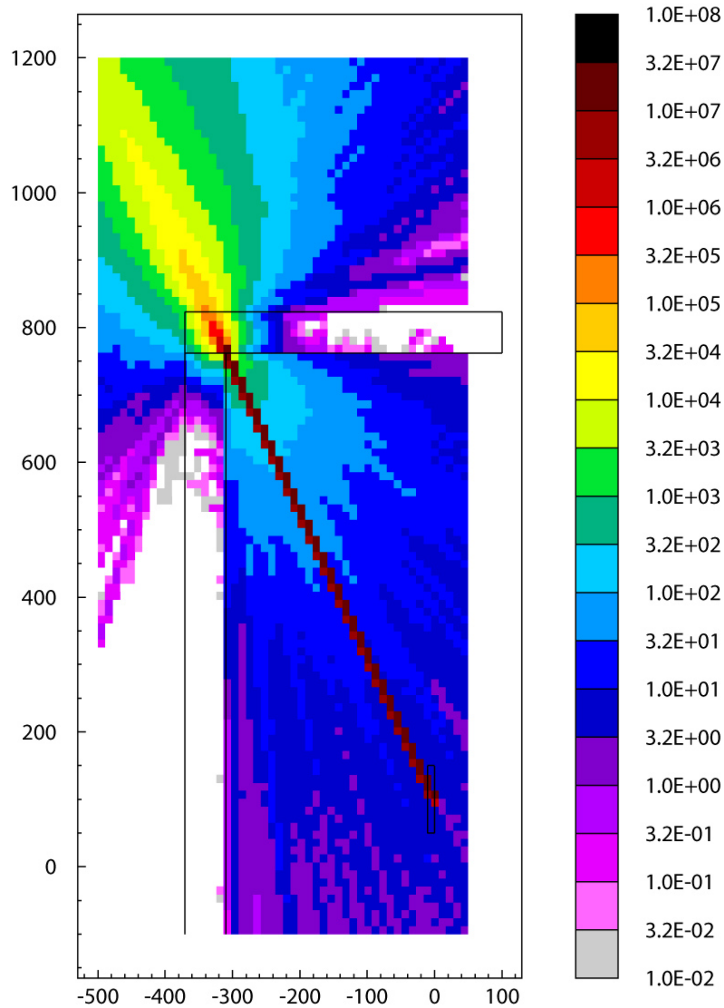

Figure 26: Dose rate in mrem/hr – Dipole 2 fails and beam hits NE corner of E-163 concrete enclosure.

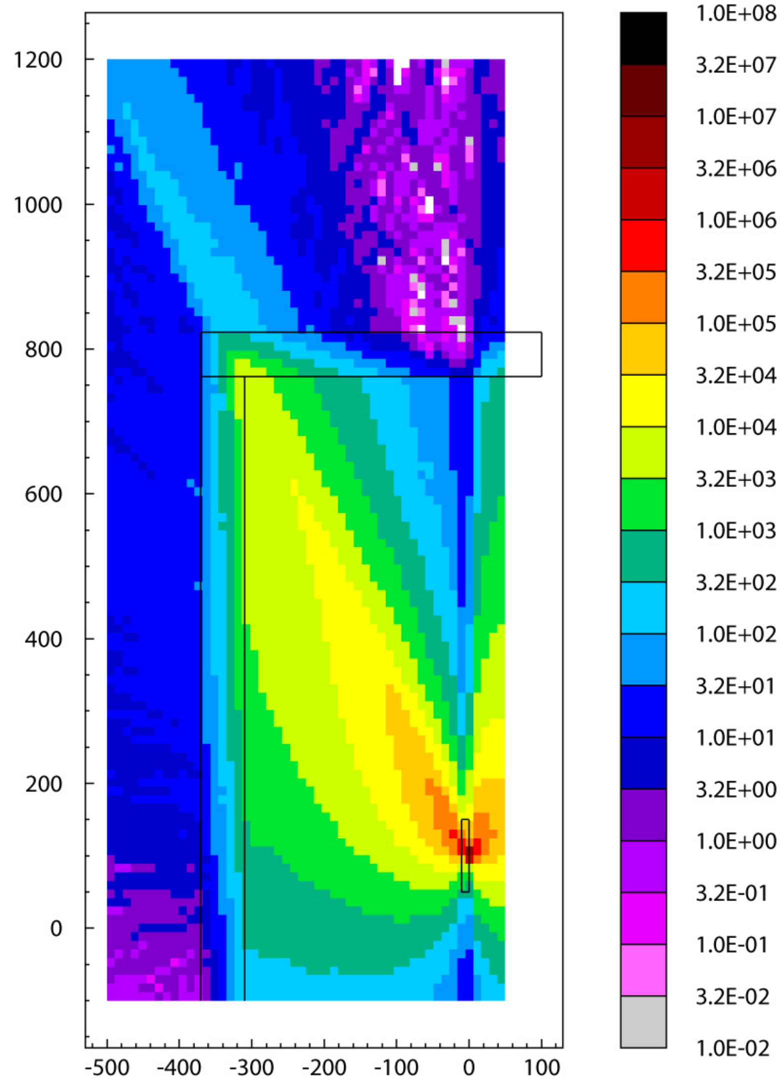

Figure 27: Dose rate in mrem/hr – Dipole 2 fails and beam hits a 2" iron shield (actual path length 4.6 ").

6.3.3 Spectrometer failure

In the case of a spectrometer failure, the beam will be stopped in a thick iron stopper, located at the 0-degree line after the spectrometer. Three different cases were studied.

- A 1 W 70 MeV Beam hits iron shielding behind spectrometer magnet.
- A 1 W 70 MeV beam intercepts with screen 4 or 5 during magnet failure.
- A 1 W 70 MeV beam intercepts with gate valve #3 (7 mm stainless steel) during magnet failure

The dose rate for these cases are depicted in figures 28-30. The case when the beam intercepts with the accelerator cell and the spectrometer magnet fails is similar to the case when screen 4 or 5 is intercepting with beam.

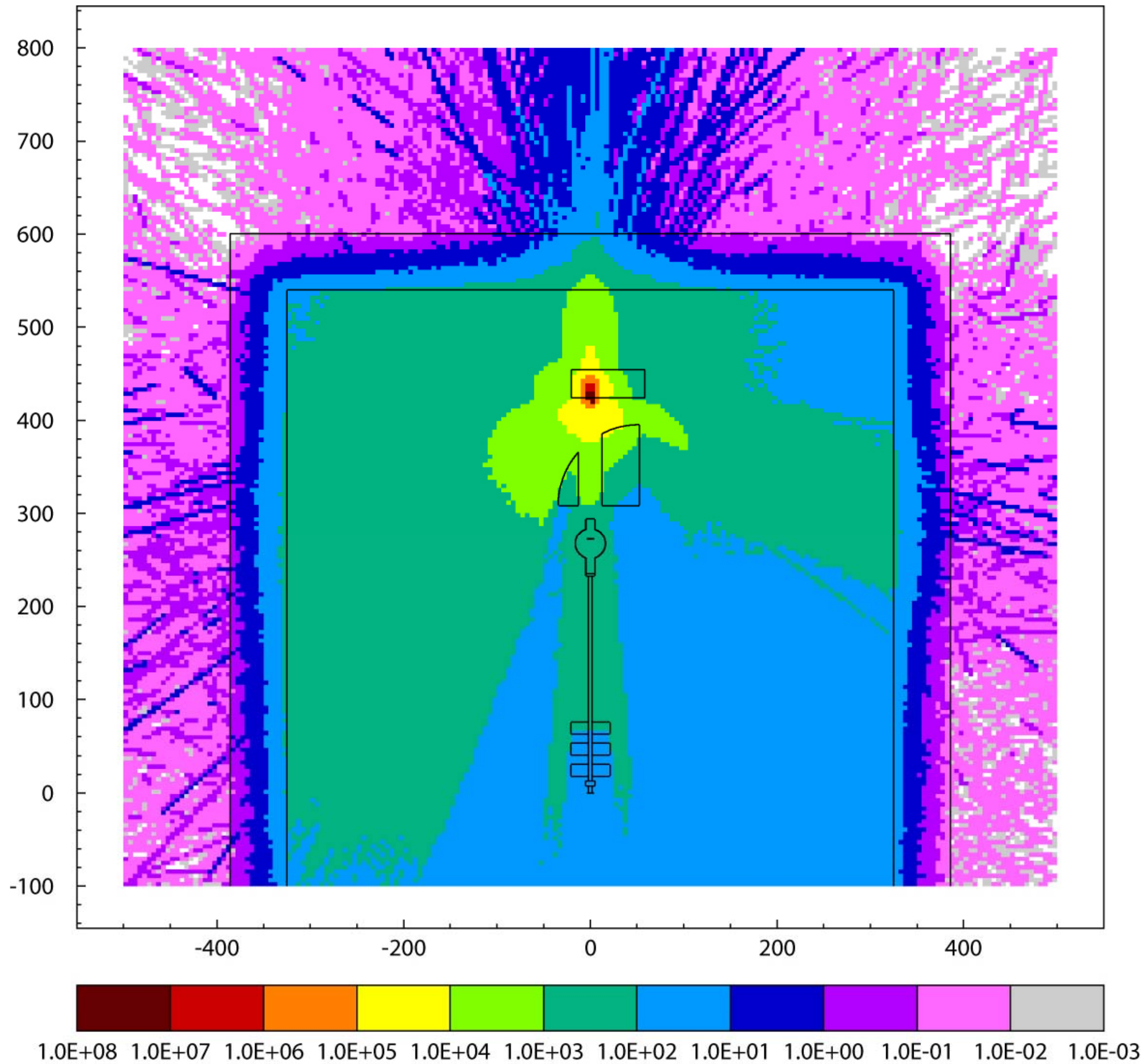

Figure 28: Dose rate in mrem/hr. Spectrometer failure - 1 Watt, 70 MeV beam strikes on a 12" thick iron shielding behind the spectrometer magnet.

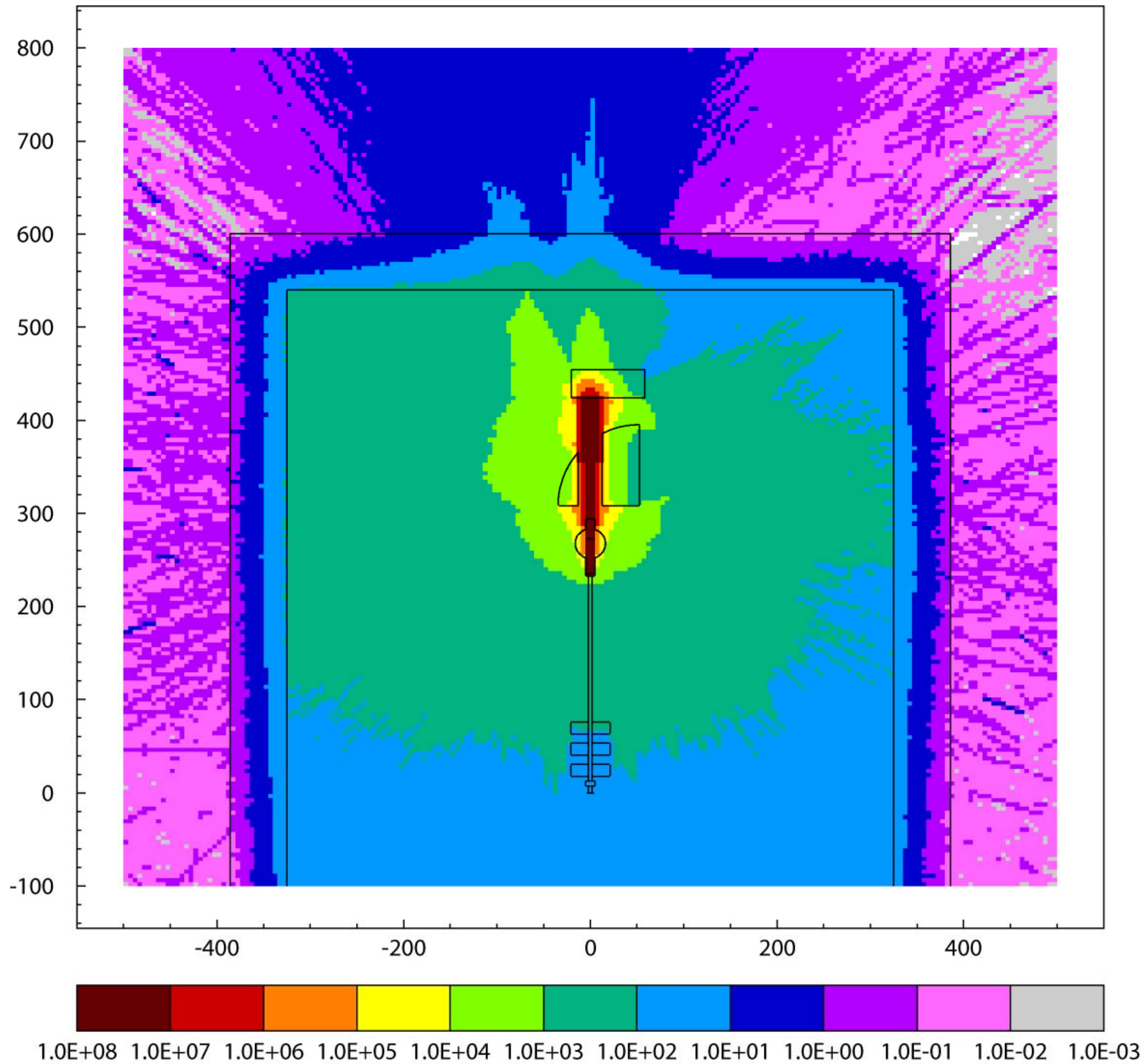

Figure 29: Dose rate in mrem/hr - A 1W, 70 MeV beam intercepts with screen 4 and the spectrometer magnet fails.

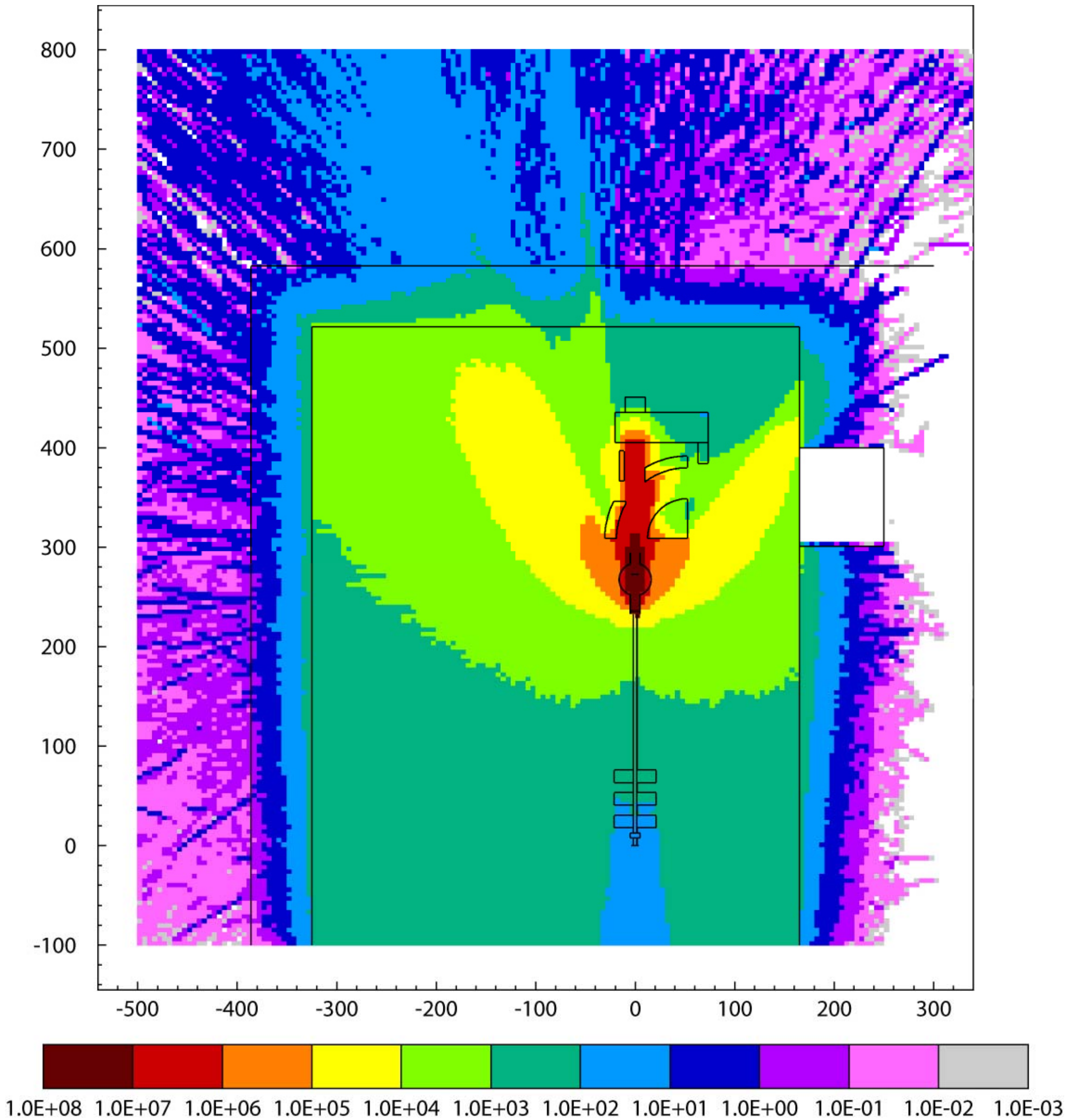

Figure 30: Dose rate in mrem/hr - A 1W, 70 MeV beam intercepts with a 7 mm thick stainless steel gate valve and the spectrometer magnet fails.

6.3.4. Gate Valve

Next, a 1 W 70 MeV beam intercepting with gate valve #3 (7 mm stainless steel) without a magnet failure of the spectrometer was studied. The dose rate outside the enclosure, as shown in Figure 31, is below 100 mrem/hr.

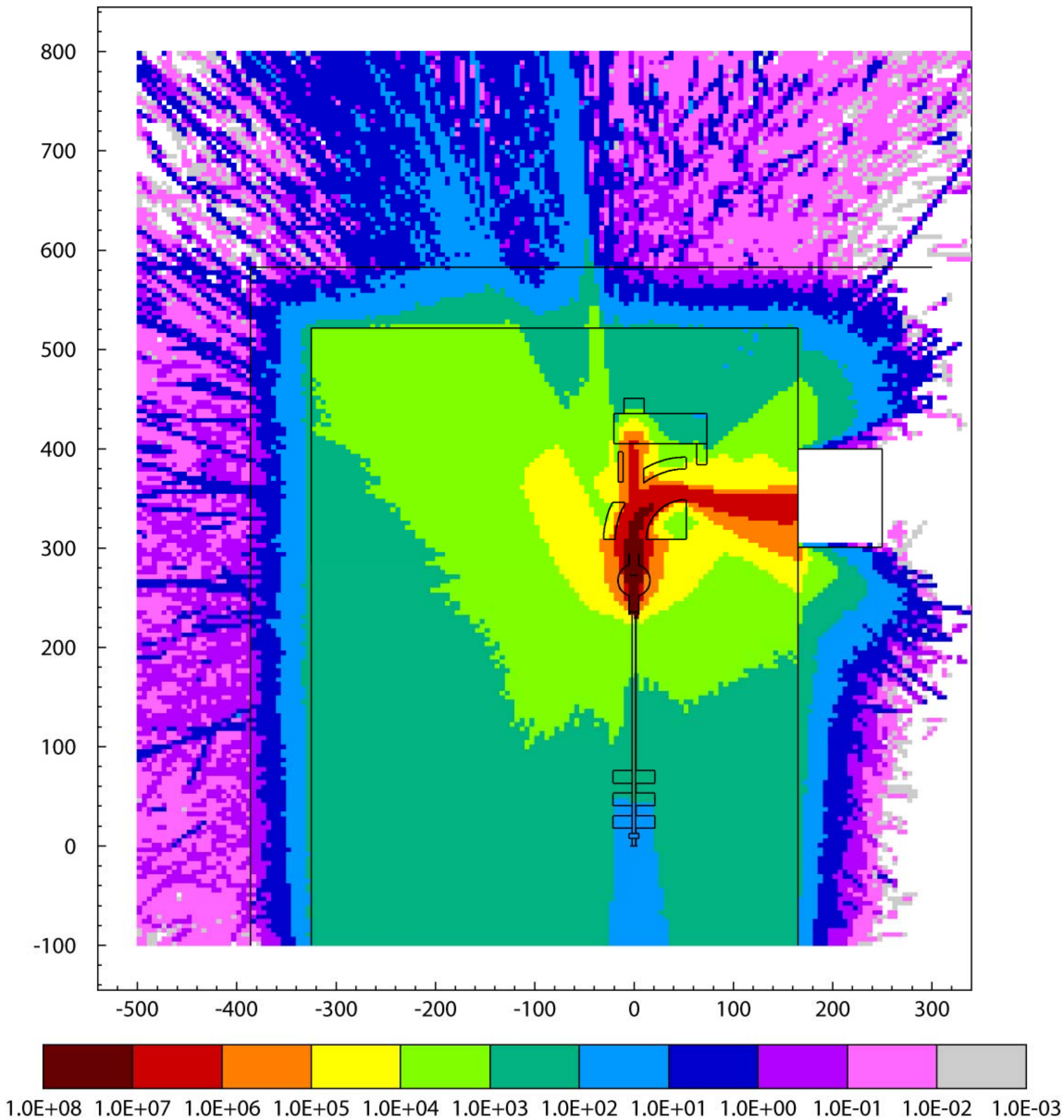

Figure 31: Total dose rate in mrem/hr - A 1W, 70 MeV beam intercepts with a 7 mm thick stainless steel gate valve; magnetic field on. Note, the main dump region was defined as Blackhole.

6.3.5 Beam stoppers in NLCTA

Two 4 inch long Tungsten stoppers will be placed inside the NLCTA tunnel approximately 4 feet away from the extraction point of the NLCTA line, see Figure 32. When the stoppers are inserted the bending magnet in the NLTCA beam line will be disabled and no beam will be kicked out onto the W-stoppers. As it can be seen in Figure 33 and Figure 34, the dose rate inside the E-163 enclosure is still below the 400 mrem/hr limit if the magnets are incidentally extracting beam into the E-163 extraction line.

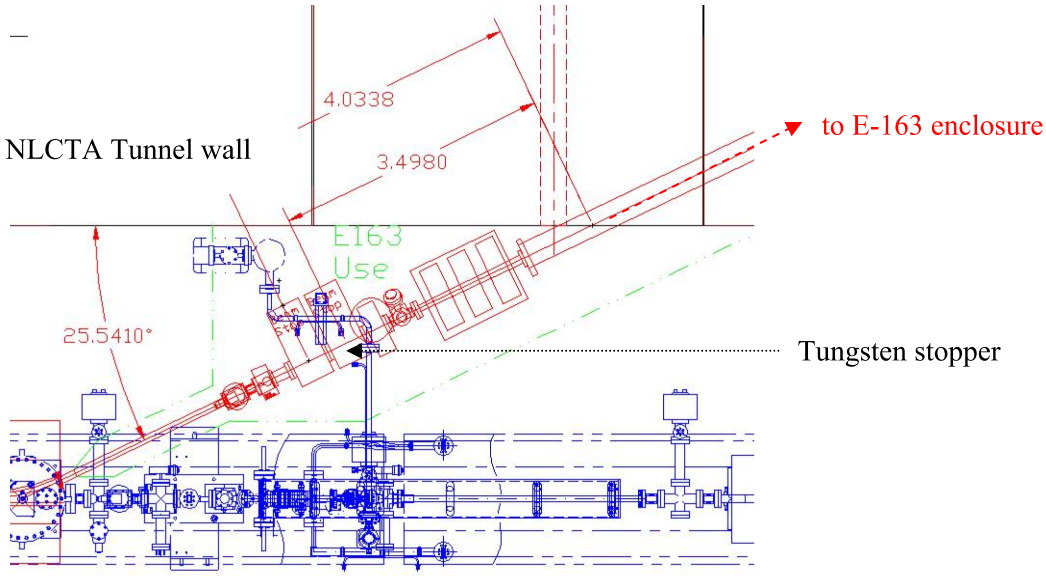

Figure 32: Location of Tungsten Stoppers in the NLCTA tunnel

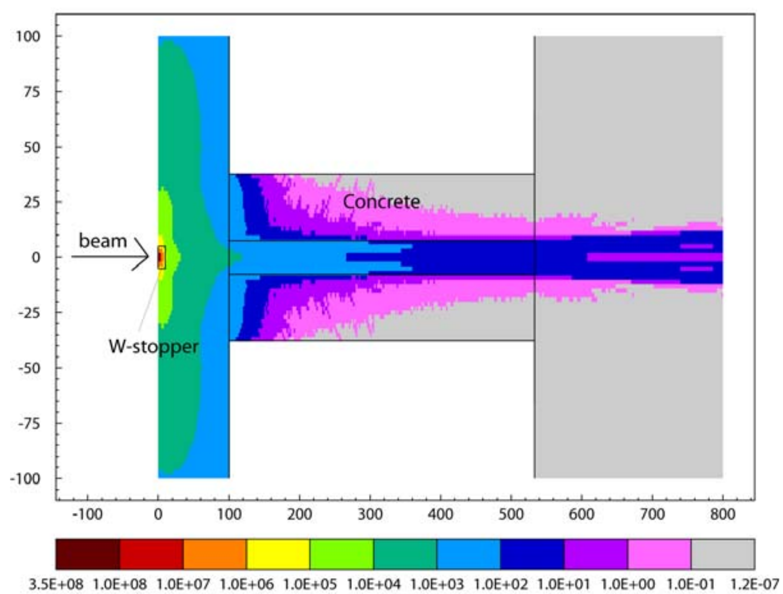

Figure 33: Dose rate in mrem/hr when 0.7 W, 70 MeV e- are hitting a 4 " W-stopper. Note, that E-163 uses two 4" long W-stoppers.

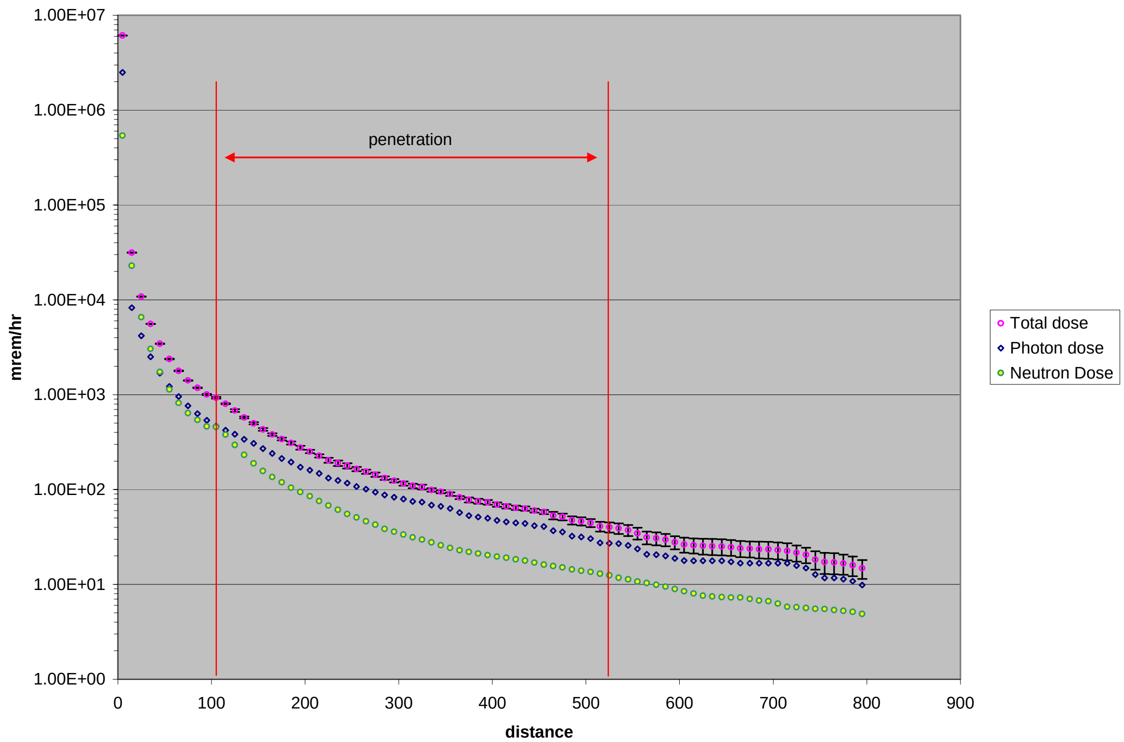

Figure 34: Dose rate behind a 4" tungsten stopper as a function of distance.

6.3.6 Failure of Quadrupoles

Ray tray studies were performed by E. Colby to identify mis-steered beam. FLUKA calculations were performed to determine the minimum thickness of shielding around these quads. The following shielding is required (see also figure 35):

- *Quads 4, 5 & 6* : 4"fe down beam, 2" on north-west, 2" above 2" south-east (to shadow east wall)
- *Quads 7 & 8* : 7" fe down beam, 2" fe north and 2" above
- *Quads 9, 10 & 11* : 8" fe down beam, 2" fe north and 2" above

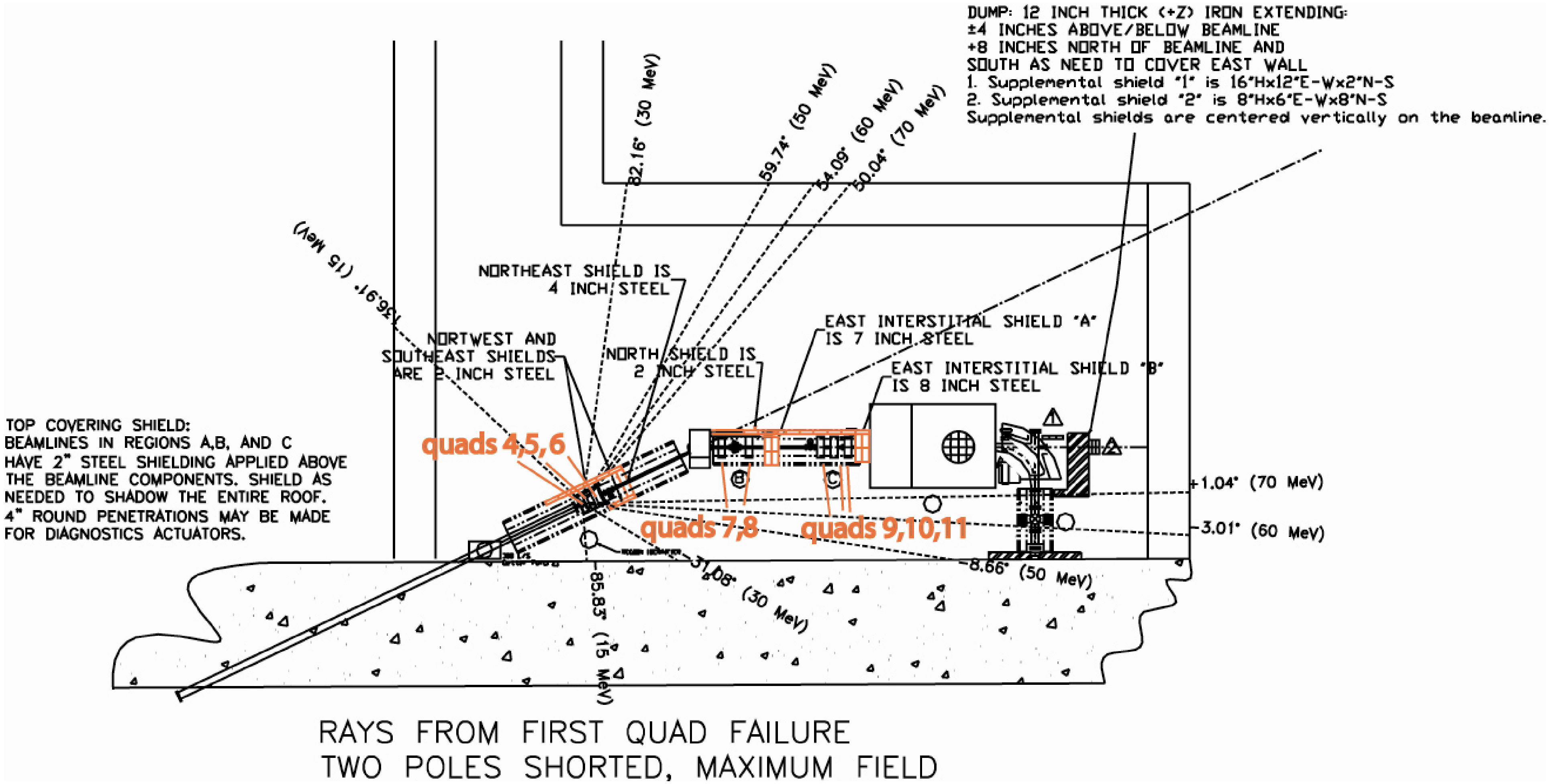

Figure 35: Shielding requirements for E-163 due to quadrupole failures (required shielding is shown in orange, note that 2" fe top covering shielding is also needed).

6.3.7 Summary of beam power losses during "mis-steering" conditions

Table II: Summary of beam power losses during "mis-steering" conditions.

Mis-steering beam loss scenarios: Dose rate limit 400mrem/hr		
Description	**Worst Case**	**Dose rate in mrem/hr** outside E-163 enclosure
Quads short at start of extraction line	1 watt on beam chamber immediately adjacent the SW corner of the laser room	3
Dipole 2 fails	1 watt on beam chamber near dipole 2	320
Dipole 2 set incorrectly*	1 watt on any of the yokes of quads 7,8,9,10, or 11	<320
Spectrometer fails	1 watt on straight ahead dump	100
Spectrometer set incorrectly*	1 watt on either the yoke of the spectrometer or the bend-line dump	<100
Screen 2	1 watt on Screen 2	0.53
Screen 3	1 watt on Screen 3	1.17
Screen 4	1 watt on Screen 4	1.5
Screen 5	1 watt on Screen 4	1.5
Screen 6	1 watt on Screen 6	1.5
Accelerator Cell	1 watt on accelerator cell + spectrometer failure	25
Gate Valve 1 closes	1 watt on gate valve 1	<320
Gate Valve 2 closes	1 watt on gate valve 2	<320
Gate Valve 3 closes	1 watt on gate valve 3	20
Quad 4,5, 6 fail	1 watt on beam chamber near quads 4,5 or 6	380
Quad 7, 8 fail	1 watt on beam chamber near quads 7 or 8	320
Quad 9,10,11 fail	1 watt on beam chamber near quads 8,9 or 10	240

*Polarity has to be checked before operation and signed off in BAS.

6.4 SUMMARY – Local shielding requirements for E-163

- E-163 beam stoppers in NLCTA -tunnel:
    - *2x 4" long Tungsten stopper*
- Quadrupoles 4, 5 and 6:
    - *2 " fe north-west, 4" fe down beam, 2" fe above and 2" fe south-east to shadow E-163 east concrete wall*
- Quadrupoles 7 and 8:
    - *2 " fe north, 7" fe down beam and 2" above*
- Quadrupoles 9, 10 and 11:
    - *2 " fe north, 8" fe down beam and 2" fe above*
- Screen 2 and 3:
    - *Tungsten back up stopper – 2" dia, 1" long. Note, that the shielding added at quadrupoles 4 to 11 acts also acts as shielding for screens 2 and 3.*
    - *Above: 0.78" fe*
- 0°-dump:
    - *12 inch thick iron*
    - *±4 inches above/below beamline*
    - *+8 inches north of beamline and south as needed to cover east wall*
    - *Supplemental fe shield between Spectrometer and dump on the north side - 8"Hx12"E-Wx2"N-S*
    - *Supplemental fe shield between Spectrometer and dump on the north side - 8"Hx4"E-Wx8"N-S*
    - *Supplemental fe shield behind dump - 8"Hx6"E-Wx8"N-S*
    - *Supplemental shields are centered vertically on the beamline.*
- Faraday cup:
    - *East: 2" fe from 60-80 degrees with respect of collimator and beamline, 4" fe from 85-120 degrees, 2" fe from 120-140 degrees. Wall height coverage +45° up, -25° down*
    - *Above: 0.78" fe*

- Main dump:
    - *4 inch diameter tungsten stopper, 2 inch long, surrounded by 4 inch thick fe (12×12 inches)*

7 References

[1] Eric Colby, "*Explosive Electron Emission (EEE) Loss Calculations for E-163)*", SLAC memorandum, 5/8/2003.

[2] R. Thomas and G. R. Stevenson, *"Radiological Safety Aspects of the Operation of Proton Accelerators"*, International Atomic Energy Agency, Vienna 1988