Title
Radiological Protection Studies For NGLS XTOD

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RADIOLOGICAL PROTECTION STUDIES FOR NGLS XTOD

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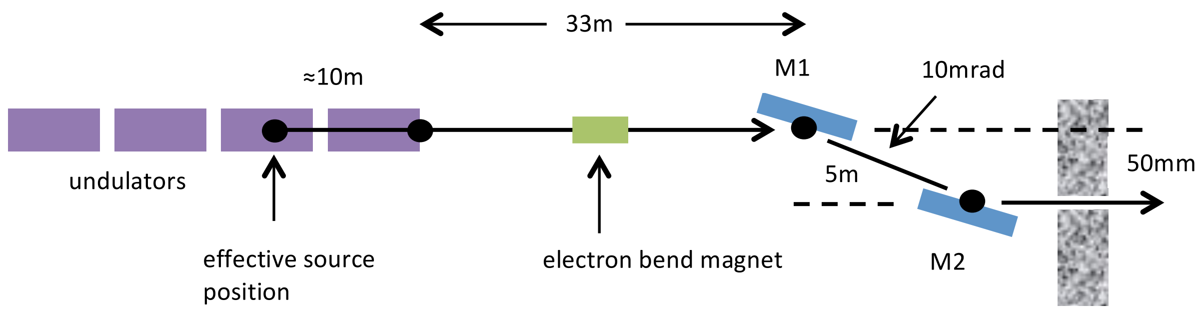
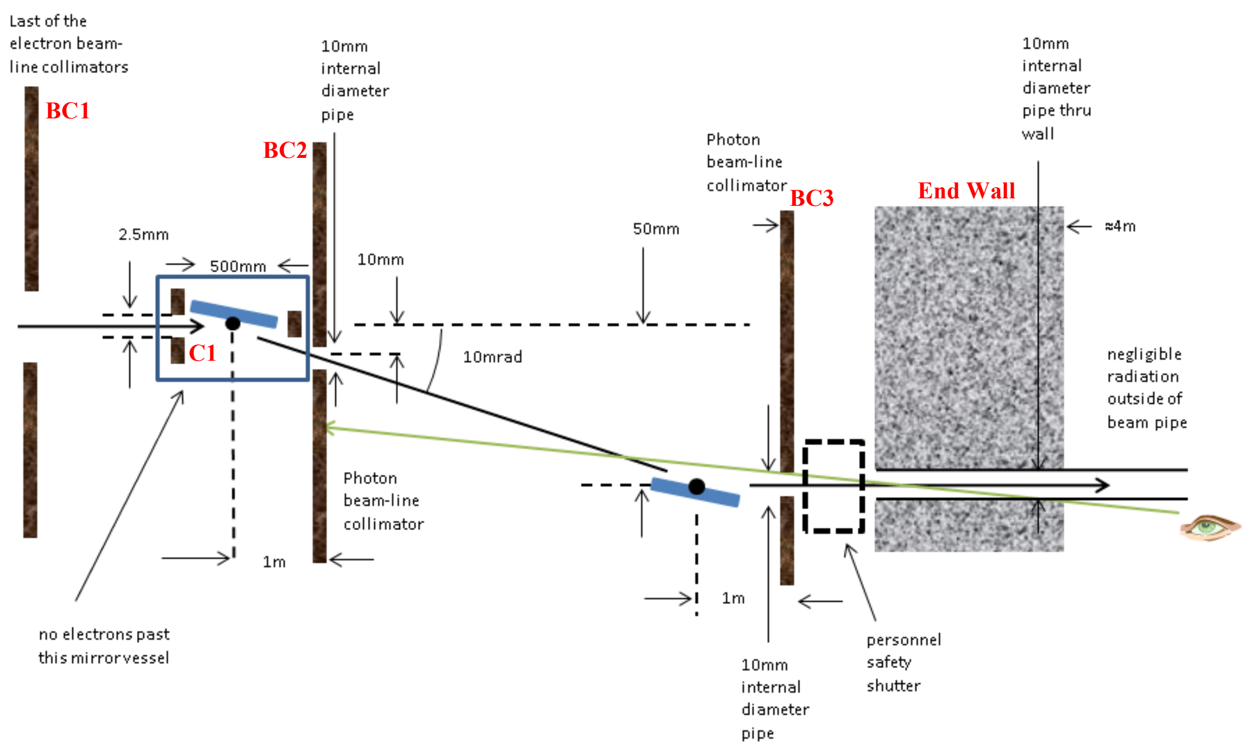
1 Introduction and Fundamental Parameters

The X-ray transport, optics and diagnostic system (XTOD) starts from the end of bending magnets sending electrons to the main dump and ends at the end wall separating the accelerator tunnel from the user experimental hall (hereafter referred as EH wall), as shown in Figure 1. Figure 1.a shows the general schematic and Figure 1.b shows the initial layout with possible shielding components. This document summarizes the extensive studies on the shielding and collimator system design necessary to meet the radiation protection requirements.



(a) Schematic view from undulators to end wall



(b) Closed view with shielding pieces

Figure 1 Fundamental layout of NGLS X-ray transport and diagnostic system

The primary electron beam delivers 720 kW at 2.4 GeV. In normal conditions, electrons will be sent to the main dump, while certain amount of bremsstrahlung (generated by electron beam interactions with beam line apertures and residual gas) will enter XTOD. The power and spectrum of bremsstrahlung was analyzed in Section 3.1 and Section 4.

The agreed upon radiation dose limit for the experimental hall is 200 mrem for 2000 hours yearly operation, i.e. 0.1 mrem/h in normal conditions. Also, a hutch-less beamline design is expected, and users should be able to access the vicinity of the beam pipe when beamlines are open. Therefore the radiation dose around the beam pipe (at 30 cm distance) should also be limited at 0.1 mrem/h.

This document first analyzes the worst accident case, in which electrons are not bent by the main dipoles, as this unambiguous case is instrumental to define the range of the main shielding parameters. The shielding is then defined and tested against the bremsstrahlung in normal operations based on a simplified foil source model. In parallel to these calculations, the leakage of radiation through beam-lines is thoroughly surveyed for both accident and normal beam loss scenarios. A somewhat realistic normal beam loss (at the bends) is then studied to estimate the limit on electron beam losses. All simulation result figures are put together in Appendix A. Appendix B and Appendix C list the material definitions and other physics parameters used in simulations. Appendix D gives an example of a FLUKA input that includes bending magnet and XTOD components, and Appendix E lists the source codes of FLUKA user subroutines.

2 Radiation Protection for Direct Electron Beam in Accident Scenarios

In normal situations, electron beams are deflected by the main bends into the underground dumps, and only a small amount of radiation (mainly bremsstrahlung photons) from electron-beam interactions at the bend and at previous apertures make it to the optics section. In this section we analyze an accident scenario where the electron beam is not deflected by the main bends (power supply failure, magnet shortage, operator error, etc.). In that case the full electron power goes straight into the optics section and hits some XTOD component. High-energy showers generated in that component then penetrate, to some extent, through the EH wall, or leak through the beamlines towards EH. At SLAC, for such accidents, dose rates of up to 25 rem/h are accepted, as safety systems should shut the beam off very quickly.

First we present the penetration of radiation through shielding components, which was used to parameterize the wall thickness that was then tested also for normal losses in Sections 3.2. Next, the beam line layout defined in Sections 3.5 will be tested against radiation leakage for accident case.

2.1 Direct dose penetration into EH for un-steered electrons

The resulting amount of dose penetrating through the EH bulk into the experimental hall will depend on the shielding thickness of BC2, on the EH wall material and dimensions, and on the relative distance between the two.

FLUKA simulations explored the sensitivity of the dose in EH to the different parameters in play. A *2.5 GeV* beam was sent directly into BC2 (M1 mirror is ignored for conservative estimation), located at different distances (5, 10, 15 and 20 m) from the wall, and of variable thickness (0, 5, 10, 20 and 30 cm). Results, normalized to 720 kW beam power, were then gnu-plotted into common graphs, to better compare effects.

Figure 12.a shows the trade-off between the BC2 and the EH concrete wall thicknesses for a distance (between the front faces of each) of 5 m. For such separation (which is within the initial range provided by LBNL), a 3 m thick wall would be sufficient if the stopper was 30 cm thick. If BC2 were 20 cm thick, then the wall would have to be 3.5 m thick, while if BC2 was only 10 cm thick, then EH wall should have

a thickness of 4 m. From extrapolation of the curves, it can be deduced that a 5 cm thick BC2 would need a 4.5 m wall, while a 5 m wall would be required if no BC2 was used.

In Figure 12.b the effect of distance is analyzed for a 30 cm thick BC2 stopper. For any wall thickness we observe that the dose in EH is reduced within a factor ~4-5 when distance grows from 5 to 20 m. Thus, the accident dose in EH is approximately inversely proportional to the distance between BC2 and EH wall.

Figure 13 shows that the dose in EH is dominated by neutrons if BC2 is thin (10 cm), while if BC2 is thick enough (30 cm), then the dose through EH wall after some thickness (2.5 m) is largely dominated by photons. In any case, unlike for higher energy facilities (15 GeV in LCLS-I), the contribution of muons is limited to a few percent.

Using the parameterization presented here, with feedback from NGLS, dimensions of BC2 and of EH2 wall are defined in section 3.2, after analysis of the basic normal loss scenario.

2.2 Radiation leakage through the beamline for un-steered electrons

In the case of bend magnets failure, electron beams will pass C1 and hit M1 directly, as sketched by the dashed line in Figure 2. Figure 14 shows the total dose when the 720 kW 2.4 GeV electron pencil beams hit M1 under the configuration defined in Section 3.5: 5 cm horizontal offset between M1 and M2, 1" OD pipes, and 10 mm diameter collimator apertures. The dose rate inside the experimental hall is very high, 800 rem/h at 30 cm from beam pipe, meaning the radiation leakage is very strong. Figure 15 shows the dose by assuming all collimators, EH wall and the air inside tunnel are "black holes" (=perfect absorbers), in which case the dose rate inside the experimental hall is still as high as 650 rem/h at 30 cm from the beam pipe. This indicates that the major radiation leakage is from the direct transport along beam pipes. Figure 16 shows the dose when the offset of two mirrors is increased to 10 cm (by moving M1 5-meters upstream). The increased offset helps reduce the dose rate at the experimental down to 250 rem/h, which is only a moderate reduction. Figure 17 shows the dose when the aperture of collimators is reduced to 5 mm diameter. The experimental hall dose is then reduced greatly to 30 rem/h, which indicates the collimators are the most effective control on radiation leakage.

To mitigate the radiation leakage to the experimental hall, a small permanent magnet, 50 cm long with 0.16 T magnet field (starting from Z[1] = -1350 cm and giving 10 mrad bend for 2.4 GeV electrons) in following simulations, is proposed to bend electrons toward ground, as indicated by the arrow in Figure 2.

The electron beams will hit the beam pipe (at $Z \approx -1200$ cm) due to the magnetic field. Figure 18 shows the dose due to the radiation shower of the bent electron beams on the beam pipe. Figure 18.a shows that the dose at the beam height is low and that there is no noticeable leakage through the beam pipe, but Figure 18.b shows there are strong radiation fields under the beam height, therefore BC2 should be extended toward ground to cover the range. Because of the high beam power of 720 kW, it is very likely that electron beams will burn through the beam pipe and then hit BC2 directly, as shown in Figure 19. There is still no noticeable leakage from the beam pipe and the dose behind the end wall is below limitation also. Overall, a small permanent bending magnet will be able to reduce the dose inside the experimental hall in accident scenarios.

[1] In all of the following simulations, the upstream surface of the end wall is set as the reference point Z = 1000 cm in FLUKA models.

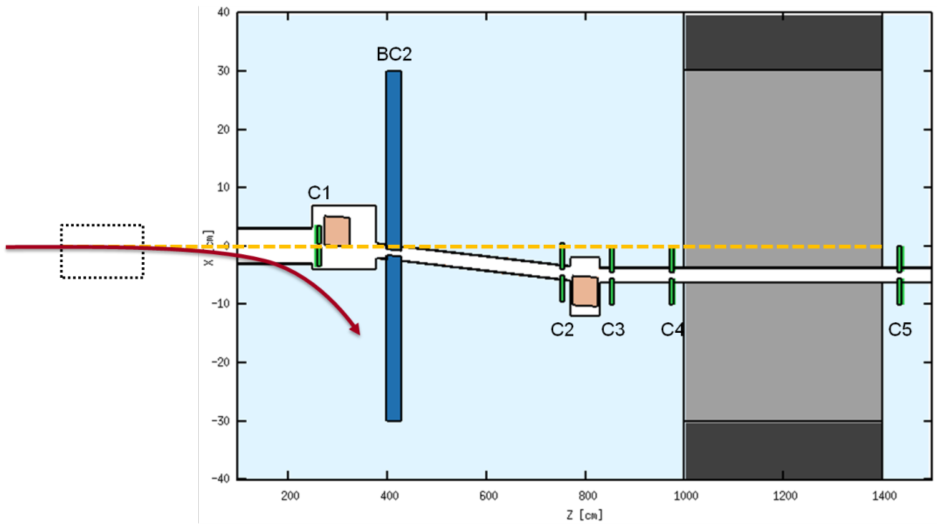


Figure 2 Top view of the basic configuration for radiation leakage simulations

3 Radiation Protection for Bremsstrahlung in Normal Operations

Electrons generate bremsstrahlung radiation through different interaction mechanisms along the beam line, i.e., collisions with residual gas molecules, energy acceptance losses at the end bends, and beam interception by diagnostic objects such as wire scanners or screens. In this section, a simplified model was used to simulate a generic bremsstrahlung source (Section 3.1). The bremsstrahlung source was then sent to XTOD and a fraction of the resulting showers reached the end wall. Section 3.2 studies shielding to reduce the radiation dose behind the end wall. On the other hand, secondary particles from the interaction of bremsstrahlung photons and XTOD components may leak along beam pipes and enter the experimental hall. Section 3.3 captures various sensitivity studies of different parameters that were conducted towards the minimization of the radiation leakage into the experimental hall based on the initial layout. Section 3.4 studies the shielding requirement inside the experimental hall in case the leakage is strong and Section 3.5 gives a proposed design modified from the initial layout with small leakage dose inside the experimental hall. All these studies are based on the simplified foil source model. The actual power of bremsstrahlung was studied in a more realistic model in Section 4.

3.1 Simplified foil source model of bremsstrahlung generation

In the simplified foil source model of bremsstrahlung generation, 2.4 GeV electron beams hit a Titanium foil and then all particles other than photons are discarded. Titanium foils with different thicknesses: 0.1 mm, 1 mm, 2 mm and 5 mm, were used to explore the distribution of bremsstrahlung photons.

Figure 20 shows the *angular* distributions of bremsstrahlung photon intensity and power density from titanium foils of different thicknesses. All distributions are normalized to a total of 1 Watt photons. The figure shows that bremsstrahlung photons are concentrated within 1 mrad, and that the thicker foil generates the more angularly divergent distribution. For 0.1 mm foil, 90% of photons and power are concentrated within 1 mrad polar angle.

Figure 21 shows the *energy* distributions of bremsstrahlung photons from the titanium foils. Distributions are also normalized to the total 1 Watt photons. Photon intensities are exponentially proportional to energies and the photon power distributions are approximately uniform between 1 MeV and 100 MeV. For 0.1 mm foil, photons in the range of 200 MeV – 2.4 GeV contribute 90% of total power.

Overall, bremsstrahlung generated from 0.1 mm foil is more forward-focused than that from a thicker foil, but has similar energy spectrum. Therefore the 0.1 mm foil was used to generate bremsstrahlung for dose simulations in the rest of this section.

Table 1 lists the bremsstrahlung yield (fraction of incident electron energy converted to bremsstrahlung) for different thicknesses. The table shows (as expected), that the yield is proportional to the foil thickness for thin foils (compared with the radiation length of titanium, 3.6 cm).

Table 1 Bremsstrahlung yield for different thickness of foils

Ti foil thickness	Bremsstrahlung yield
0.1 mm	0.28%
1 mm	2.7%
2 mm	5.3%
5 mm	12.5%

3.2 BC2 and the end EH wall thickness

A simplified model as Figure 3 was used to study the shielding requirements for BC2 and the EH wall. The bremsstrahlung source from 0.1 mm Ti foil was set at $Z = -1500$ cm, and BC2 (starting at $Z = 500$ cm) was added to help reduce the thickness of EH wall. In the following simulations, a 4 meters thick concrete EH wall ($Z = 1000 – 1400$ cm) was used, and all dose results were normalized to 1 Watt photons. The dose behind EH wall should be reduced to less than 0.1 mrem/h.

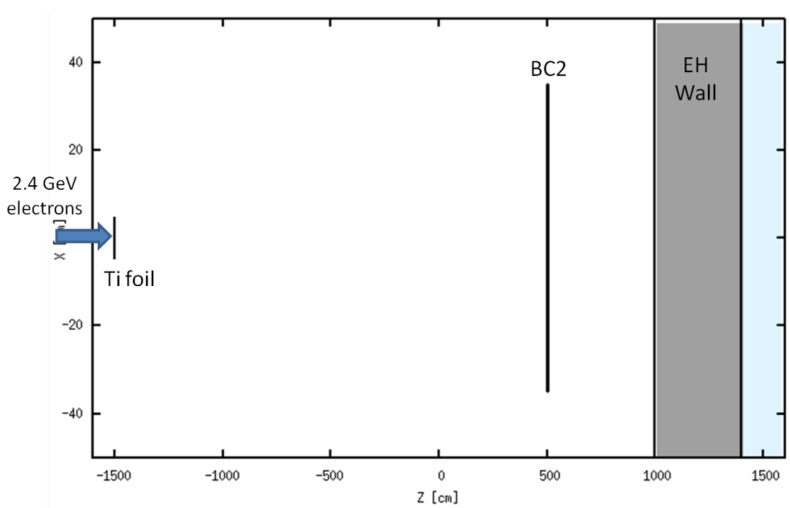


Figure 3 Basic model for EH wall thickness

Three different configurations of BC2 were studied: 10 cm A36 steel, 30 cm A36 steel and 10 cm heavy tungsten alloy (WHA). All dimensions above were along the primary beam direction (*Z*) and the transverse extension of BC2 (disk) was arbitrarily set as $R = 35$ cm. Figure 22, Figure 23 and Figure 24 show dose distributions for the three BC2 configurations. Figure (a) is the top view of total dose distribution in the *R*-*Z* coordinate system. Figure (b), (c) and (d) show the dose curve along the *Z*-direction within the range of $R \leq 5$ cm for total dose as well as the photon and neutron contributions.

The 10 cm steel BC2 is not enough to attenuate all high energy photons, thus a large amount of secondary neutrons are generated inside EH wall (Figure 22.d), although photons still dominate the dose behind the wall. This configuration is acceptable for up to 1 W bremsstrahlung source for the *0.1 mrem/h* limit.

The 30 cm steel BC2 can reduce the total radiation dose before the wall by a factor 100 with respect to the 10 cm steel configuration (Figure 23.b vs. Figure 22.b). The 10 cm WHA BC2 produces 10 times less photon doses (Figure 24.c vs. Figure 23.c) but twice as high neutron doses (Figure 24.d vs. Figure 23.d) at the upstream of the end wall, compared with 30 cm steel BC2 configuration. But behind the wall, the total doses from the two configurations are almost the same (Figure 24.b and Figure 23.b), and neutrons are the major contributors to the remaining dose for both cases[2]. With a 4-meter end EH wall, both configurations (30 cm steel or 10 cm WHA) are acceptable for up to 50 W bremsstrahlung sources. Alternatively, with a 3-meter EH wall, the 10 cm WHA BC2 is acceptable for up to 5 W bremsstrahlung, while 30 cm steel BC2 is acceptable for up to 2 W only. Note the radiation leakage from beam pipe is not considered yet here.

3.3 Parametric studies on the collimator system to reduce radiation leakage from beam pipe

The initial layout including mirrors and collimators was setup in FLUKA, as shown Figure 4, to simulate the radiation leakage along beam pipe to the experimental hall. A baseline model was set for the parametric studies. The two mirrors (centers at Z = 300 cm and 800 cm, respectively) are both 50 cm long (Z), 5 cm thick (X) and 5 cm wide (Y) silicon blocks with a reflection angle of 5 mrad (horizontal reflection) and the horizontal offset between the two mirrors is 50 mm. All beam pipes have 0.8 mm thick stainless steel wall unless otherwise specified, but mirror tanks are not included. The baseline shielding was set as:

- 30 cm thick A36 steel BC2 with 70 cm × 70 cm transverse cross section (upstream Z = 400 cm, i.e. 600 cm upstream of the wall)
- 8 cm thick WHA collimator C1 with 3.5 cm radius and 3 mm aperture[3] (upstream Z = 260 cm)
- 8 cm thick WHA collimator C12 with 25 cm × 20 cm cross section (upstream Z = 750 cm)
- 8 cm thick WHA BC3 with 35 cm × 30 cm cross section (downstream Z = 900 cm)
- 4 m thick concrete wall (upstream Z = 1000 cm)

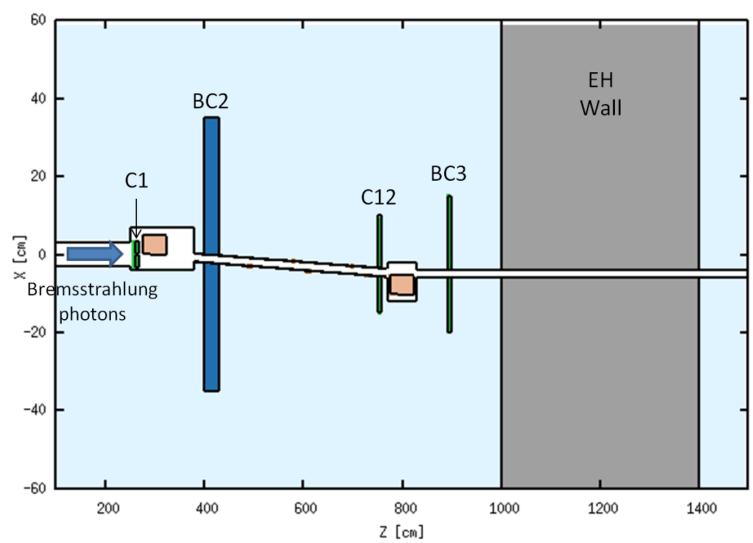


Figure 4 Top view of NGLS XTOD model

[2] Tungsten in WHA has high GDR photoneutron production cross sections, which explain the higher neutron dose, but those neutrons have low energy (~10-40 MeV), and therefore are attenuated by the wall.
[3] Aperture size is the diameter in this report. C1 aperture in the initial layout (Figure 1) is 2.5 mm. Use 3 mm in simulations for tolerance and conservative studies.

The transverse extension of the above shielding was set arbitrarily. In the initial configuration, the outer diameter (OD) of beam pipe matches the aperture of BC2, C12 and BC3. And there was a 1-cm thick iron target inside beam pipe at Z = 1500 cm (inside experimental hall) to scatter leaking particles.

A set of configurations was simulated. The corresponding dose distributions are displayed in Figure 25 through Figure 48. The beam power inside the beam pipe carried by all particles from the bremsstrahlung source was also tracked along XTOD for all configurations, as listed in Table 2 (all results were normalized to 1 Watt bremsstrahlung from 0.1 mm Ti foil). The following sections discuss the effect of different components on reducing the radiation leakage based on the leakage powers along XTOD in Table 2 (the "#" indicates the configuration corresponding to Table 2) and the dose distribution in figures.

Table 2 Power inside beam pipe along NGLS XTOD for different configurations, all results normalized to 1 W bremsstrahlung from 0.1 mm foil

Pipe ID (mm)		Configuration*	Leave M1 Tank (mW)	Enter M2 Tank (μW)	Leave M2 Tank (μW)	Enter Wall (μW)	Enter EH+ (μW)
10	1.	10 mm pipe default setting	2.10	85.3	47.4	1.33	0.079
	2.	Include C12	2.10	83.7	46.3	1.27	0.079
	3.	10 cm thick BC2 including C12	2.09	84.8	46.4	1.24	0.069
	4.	No BC3	2.09	85.5	47.5	1.24	0.080
	5.	"Blackhole" BC2 & BC3 & Air in tunnel	2.01	81.0	44.8	1.22	0.073
	6.	"Blackhole" EH wall	2.10	86.4	48.3	1.26	0.077
	7.	"Blackhole" BC2 & BC3 & Air & EH wall	2.01	80.6	44.8	1.23	0.079
	8.	C1 aperture = 5 mm	3.66	152	84.3	2.14	0.14
	9.	C1 aperture = 10 mm	42.1	264	145	3.65	0.22
	10.	Mirror offset = 40 mm	2.10	141	75.4	0.736	0.083
	11.	Mirror offset = 60 mm	2.09	56.9	32.2	5.88	0.079
	12.	Very thin pipe wall	2.09	72.5	59.3	3.20	0.085
	13.	1.6 mm pipe wall	2.09	85.3	47.8	1.29	0.079
	14.	10 mm pipe wall	2.09	84.2	46.6	1.30	0.074
	15.	Copper mirror	1.54	71.2	38.6	0.865	0.047
12.5	16.	12.5 mm pipe default setting	3.32	140	80.4	3.92	0.22
15	17.	15 mm pipe default setting	15.5	214	120	9.70	0.54
20	18.	20 mm pipe default setting	23.7	403	222	46.1	2.27
	19.	Include C12	23.7	404	223	45.7	2.17
	20.	Include C12 at Z = 500 cm	23.7	403	222	46.6	2.21
	21.	Stopper inserted	23.8	403	220	0.016	0.0003
	22.	BC2 & BC3 aperture = 10 mm	23.8	317	184	23.6	0.64
	23.	"Blackhole" BC2 & BC3	23.7	402	220	45.8	2.15
Misc	24.	25.4 mm pipe to EH and other pipe 10 mm; BC3 aperture = 10 mm; add one collimator before wall with 10 mm aperture.	2.10	86.3	68.4	0.978	0.28

* Shielding components that are not described specifically in a row will use the default setting (see Section 3.3). Collimator C12 was not included in simulations except for in Configuration #2, #3, #19 and #20.

+ The standard deviations are around 10%. For all configurations, electrons with the average energy of 300 – 400 MeV contribute about 70% of power entering the experimental hall and photons with the average energy of 30 – 50 MeV contribute the remaining 30%. Neutrons, muons and other particles carry less than 10^{-4} of the total power.

3.3.1 The collimator between two mirrors (C12)

Simulations were performed for both 10 mm (#1 in Table 2, Figure 25 vs. #2 in Table 2, Figure 26) and 20 mm (#18 in Table 2, Figure 42 vs. #19 in Table 2, Figure 43) inner diameter (ID) pipe with and without C12, the collimator between two mirrors. Results show that with and without C12, the leakage powers and dose distributions inside the experimental hall are equal within the statistic uncertainty of Monte Carlo simulations.

Comparisons were also made between cases when C12 is moved closer to the 2nd mirror (#19 in Table 2, Figure 43) or set at the central position between two mirrors (#20 in Table 2, Figure 44). The corresponding leakage powers and dose distributions inside the experimental hall are also equal. Therefore **C12 does not help reduce the radiation leakage,** and was not included in the following studies.

3.3.2 BC2 and BC3

Both 30 cm thick steel BC2 (#2 in Table 2, Figure 26) and 10 cm thick steel BC2 (#3 in Table 2, Figure 27) were simulated based on the configurations with 10 mm ID pipe. The leakage powers and dose distributions inside the experimental hall are equal within statistic uncertainty. Thus, **the thickness of BC2 has little effect on the radiation leakage.** 30 cm thick BC2 was used in most simulations unless otherwise specified.

In another simulation BC3 was not implemented (#4 in Table 2, Figure 28) for 10 mm ID pipe to compare with the baseline setting (#1 in Table 2, Figure 25). The leakage powers along XTOD were found to be equal, as well as the dose distributions inside the experimental hall. This leads to conclude that **BC3 is not necessary to reduce radiation leakage**.

It was also studied how much the scattering from BC2 and BC3 contributes to the radiation leakage. The analysis was carried out by comparing the default configuration of 20 mm ID pipe (#18 in Table 2, Figure 42) with an identical setup except that scattering is artificially suppressed by discarding all particles reaching BC2 and BC3 (#23 in Table 2, Figure 47). The leakage powers along XTOD were equal and the dose distributions inside the experimental hall are also same. Thus, **the scattering from BC2 and BC3 contributes little to the radiation leakage**.

Several other extreme configurations were also implemented. These extreme configurations assume: (1) all collimators and the air inside tunnel are "black holes" (#5 in Table 2, Figure 29); (2) the EH wall is "black hole" (#6 in Table 2, Figure 30); (3) the combination of both (#7 in Table 2, Figure 31). In all extreme configurations, there are only little changes on the radiation leakage power. So the radiation leakage is largely dominated by the direct view along beam pipes (determined by collimator apertures and size of pipes), while the contribution from scattering on collimators and EH wall is negligible.

3.3.3 Beam pipe size

Configurations of beam pipes with different inner diameters were studied: 10 mm (#1 in Table 2, Figure 25), 12.5 mm (#16 in Table 2, Figure 40), 15 mm (#17 in Table 2, Figure 41), and 20 mm (#18 in Table 2, Figure 42). It is obvious that the power of radiation as well as doses inside the experimental hall increase with the beam pipe size. For 10 mm pipe, the leakage power reduction factor from the 2nd mirror to the wall aperture is about 40 and then the 4-meter long concrete wall reduces leakage by another factor 15. When the beam pipe size increases, the reduction factor from the 2nd mirror to the wall aperture decreases: 20 for 12.5 mm, 10 for 15 mm and 5 for 20 mm. Meanwhile, since particles entering a bigger pipe are more divergent, the reduction factor of the 4-meter long wall slightly increases from 15 to 20.

To understand better the role of beam pipe size and collimator aperture, two more configurations were studied. The first one used 20 mm pipe while both BC2 and BC3 apertures were 10 mm (#22 in Table 2, Figure 46). The second one used 10 mm pipe between the two mirrors and 25.4 mm (1") pipe from the 2nd mirror to the experimental hall, BC3 aperture was 10 mm and another collimator with 8 cm tungsten and 10 mm aperture was set just upstream of the end wall (#24 in Table 2, Figure 48). The dose distributions from the combined situations are the compromise of beam pipe size and collimator aperture. The doses inside the experimental hall with different beam pipe sizes and apertures were compared in Figure 5.

Overall, beam pipe size is the main factor related to radiation leakage. **The leaking power increases very fast with the pipe size**. **Inserting collimators with a small aperture on a large pipe can help reduce the some of the leakage**, but the remaining leakage will still be more than that from a pipe with the size of the small collimator aperture.

3.3.4 C1 aperture

According to the initial layout (Figure 1), the distance from the electron bending magnets to the upstream end of M1 is about 16 m. On this location, a bremsstrahlung source with 1 mrad divergence will expand to a 32 mm diameter. With the default C1 aperture of 3 mm, only 10% of bremsstrahlung will hit the mirror directly and 90% will be attenuated by C1 (see the accumulation power curve in Figure 20). Simulations were performed not only for the baseline C1 aperture of 3 mm ((#1 in Table 2, Figure 25), but also for larger apertures of 5 mm (#8 in Table 2, Figure 32) and 10 mm (#9 in Table 2, Figure 33). Obviously, larger C1 aperture will deliver higher leakage power and, therefore, larger radiation dose inside the experiment hall. **The leakage power is almost linear with the aperture of C1 in the range of simulation trials**.

3.3.5 Offset between two mirrors

In the baseline configuration the two mirrors are separated by 5 m, and the horizontal offset is 50 mm. By moving the two mirrors closer or farther, two more layouts with 40 mm (#10 in Table 2, Figure 34) and 60 mm (#11 in Table 2, Figure 35) offsets were studied. It is interesting to notice that when mirrors are closer to each other, the leakage power leaving the 2nd mirror is larger, but the power entering the wall is also smaller because of the smaller aperture from the 2nd mirror to the pipe opening on EH wall. Also, when the collimation from M2 to wall is more effective (M2 farther from the wall), the collimation of the wall decreases. The overall effect is that the final leakage power entering the experimental hall as well as the dose distribution is almost the same for all three sets of mirror layouts. Therefore, **moving mirrors within a small range will not help reduce the radiation leakage**.

3.3.6 Pipe wall thickness

The default beam pipe wall in the simulations is 0.8 mm stainless steel 316 (#1 in Table 2, Figure 25). Simulations were also performed by assuming there was no pipe wall at all (#12 in Table 2, Figure 36), double thickness pipe wall (#13 in Table 2, Figure 37) and an extreme 1 cm thick pipe wall (#14 in Table 2, Figure 38). It is noticeable that **the leaking powers along XTOD are almost identical for different pipe wall thicknesses**, but due to the self-shielding of the beam pipe, **thicker pipe wall will help reduce doses inside the experimental hall**. More details about applying extra shielding to the beam pipe inside experimental hall will be discussed in Section 3.4.

3.3.7 Mirror material

The radiation leakage for the default silicon mirrors (#1 in Table 2, Figure 25) and for copper mirrors (#15 in Table 2, Figure 39) were also compared. **The copper mirrors deliver lower radiation leakage power, as well as smaller dose than silicon mirrors**.

3.3.8 Personal protection stopper

Personal protection stoppers are required when the photon beam pipe in experimental hall is removed and personnel may stand directly downstream of the beam. An **8 cm thick WHA stopper** right before the wall was studied for 20 mm ID pipe (#21 in Table 2, Figure 45). The leakage was reduced by a factor of 10,000 and the remaining dose is acceptable.

3.3.9 Summary of parametric studies

Figure 5 summarizes the contact doses on beam pipe and the doses 30 cm from beam pipe for typical configurations. The goal is to limit the 30 cm dose at 0.1 mrem/h. Beam pipe size and collimator aperture are the main factor to control the amount of bremsstrahlung leakage. For 1 W bremsstrahlung, the pipe size / aperture cannot be larger than 12.5 mm, and 10 mm apertures can be used for up to 2 W bremsstrahlung source. **The radiation leakage comes almost all from the direct view along beam pipes** and the scattering from collimators and wall is negligible (that is why BC2, C12 and BC3 have little help on reducing leakage). Therefore, in order to be effective, a collimator must have an aperture smaller than the inner diameter of its corresponding beam pipe.

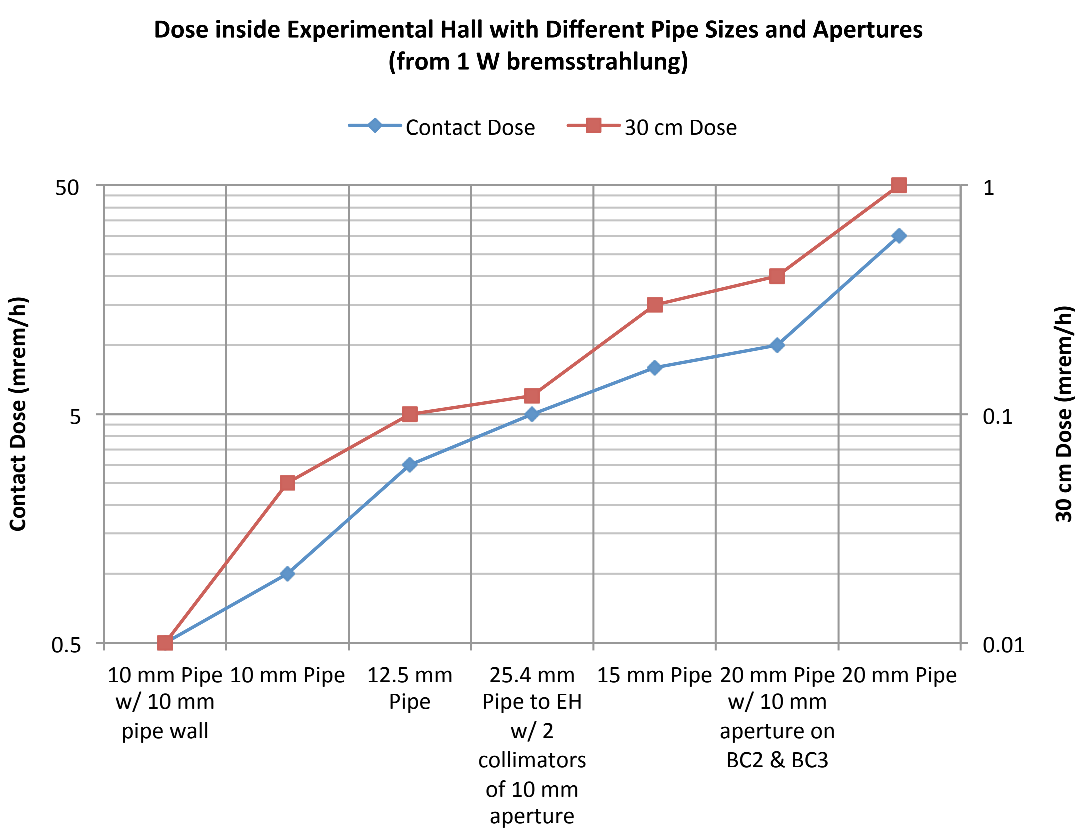


Figure 5 Total dose inside the experimental hall with different pipe sizes and apertures

3.4 Shielding on beam pipe inside experimental hall

This study focuses on answering how much shielding is needed inside the experimental hall in case of strong leakage. As commented for Table 2, leaking radiation is composed of high-energy photons and electrons, so lead is an appropriate shielding. The leakage in these simulations comes from the default setting with 20 mm ID pipe (#18 in Table 2, Figure 42).

The dose distribution with normal pipe settings is first studied to find the worst cases to be considered. Since the beam loss point is variable along the beam pipe as well as the component that may introduce losses, several cases were studied as shown in Figure 49. There is a 1 cm thick iron scattering target at Z = 1500 cm in the baseline setting (also in all parametric studies described in Section 3.3), and the radiation inside the experimental hall from such a target reaches 1.0 mrem/h at 30 cm (Figure 49.a). If there is no target, the divergence of leaking particles will also deliver up to 0.7 mrem/h at 30 cm (Figure 49.b) and it will affect a large area (30 cm dose still reaches 0.24 mrem/h at 10 m to EH wall). This means that the shielding on beam pipe may need to cover a large range. If the scattering target is more downstream, e.g. at Z = 1900 cm in Figure 49.c, the dose from target scattering is at a similar level to that from diverging particles. It is also studied that, if a thicker target (5 cm iron in Figure 49.d) is applied, the maximum dose increases slightly to 1.1 mrem/h and the self-shielding of the target actually reduces the area with large dose. Overall, the 1 cm iron target at Z = 1500 cm is a good representative to deliver large dose at the region close to the beam pipe entrance and to generate wide-spread large dose area as well. Thus, this target setting and the setting without target are used in the following studies.

Figure 50 shows the total dose distribution inside the experimental hall with and without target, when the beam pipe is wrapped by 5 or 10 mm lead. With 5 mm lead wrap, the maximum dose at 30 cm is reduced by about a factor 4, i.e. from 1.0 mrem/h to 0.25 mrem/h (or from 0.7 mrem/h to 0.14 mrem/h without target). With 10 mm lead, the maximum dose is further reduced to 0.13 mrem/h (or 0.07 mrem/h without target), which is another factor of 2.

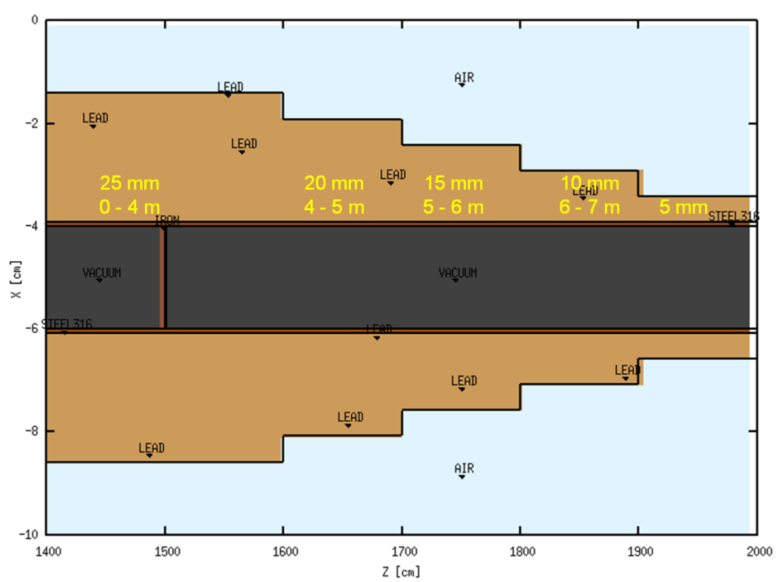


Figure 6 Configuration of stepping lead shielding

The area close to the EH wall has the largest dose and then the dose decreases along the beam direction, so a stepping lead shielding configuration[4] as shown in Figure 6 is studied. The stepping shielding is

[4] Note the last step with 5 mm lead extends to Z = 2400 cm, 10 m downstream of EH wall.

expected to provide a uniform dose distribution along the beam direction in the experimental hall. Figure 51 shows the dose distribution for the stepped shielding with and without scattering target. The maximum dose at 30 cm is 0.05 mrem/h with target and 0.03 mrem/h without target, which is the same dose level for the leakage from 10 mm ID pipe. Therefore adding lead shielding around beam pipe can help to reduce the dose in the experimental hall, but the shielding is thick and needs to cover a large region.

3.5 Proposed collimator system based on foil bremsstrahlung source

Parametric studies in Section 3.3 show that the aperture of direct view (limited by beam pipe size and collimator apertures) is the major factor defining bremsstrahlung leakage. However, there are some practical difficulties to build a small pipe through a thick wall and the optic systems expect to have a relative large beam pipe. By considering all the reasons, another XTOD collimator system, which is composed of large beam pipe and collimators with small apertures, is proposed as shown in Figure 7. Although studies in Section 3.3 show that BC2, C12 and BC3 of Figure 4, which are in the comparable location of BC2, C2, C3 and C4 in the new layout, have little help on reducing leakage as they have the same aperture of beam pipe, here all collimators have smaller apertures and are included again. The collimator C5 cannot directly reduce the amount of radiation entering the experimental hall, but it can help reduce leakage to downstream beam line and can be shielded locally if necessary.

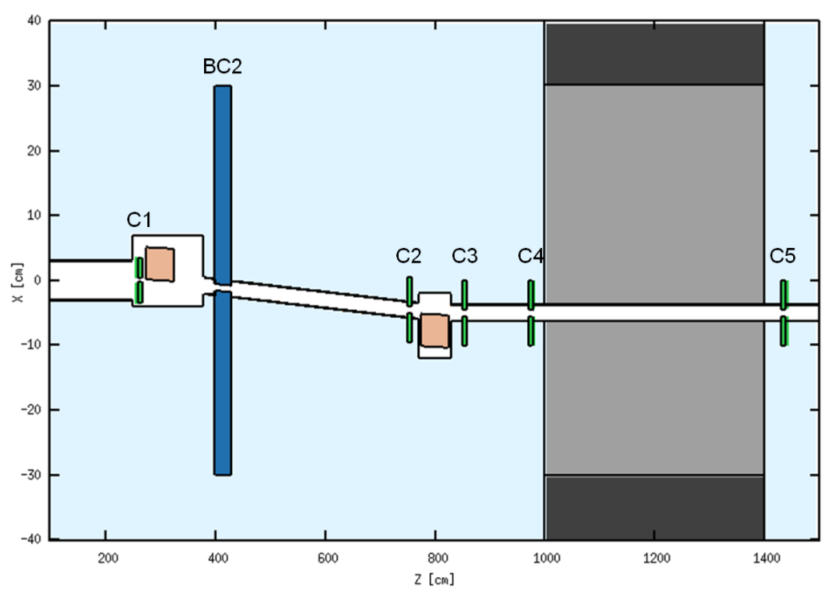


Figure 7 Top view of the proposed collimator system

The first simulation used 1” OD beam pipe and collimators have the aperture as 5 mm diameter on C1 and 10 mm diameter on others (C2 – C5 & BC2). All other parameters such as collimator outer dimensions and mirror offset are same as the baseline setting in Section 3.3. The total dose distribution from this configuration is shown in Figure 52. For 1 W bremsstrahlung source, the total power of leaking particles is 0.44 μW, and meanwhile the dose inside the experimental hall at 30 cm from beam pipe is limited at up to 0.04 mrem/h. If all collimator apertures are reduced to 5 mm diameter, the total leaking power is reduced to about 0.02 μW and there is no obvious dose from leakage as shown in Figure 53. Therefore this proposed configuration is very effective on reducing bremsstrahlung leakage and the 10 mm aperture configuration can take up to 2 W bremsstrahlung from the foil source model. Figure 8 shows the radiation leakage power along XTOD area. It shows that a mirror itself is not very effective on reducing leakage and that the main contribution is from collimators.

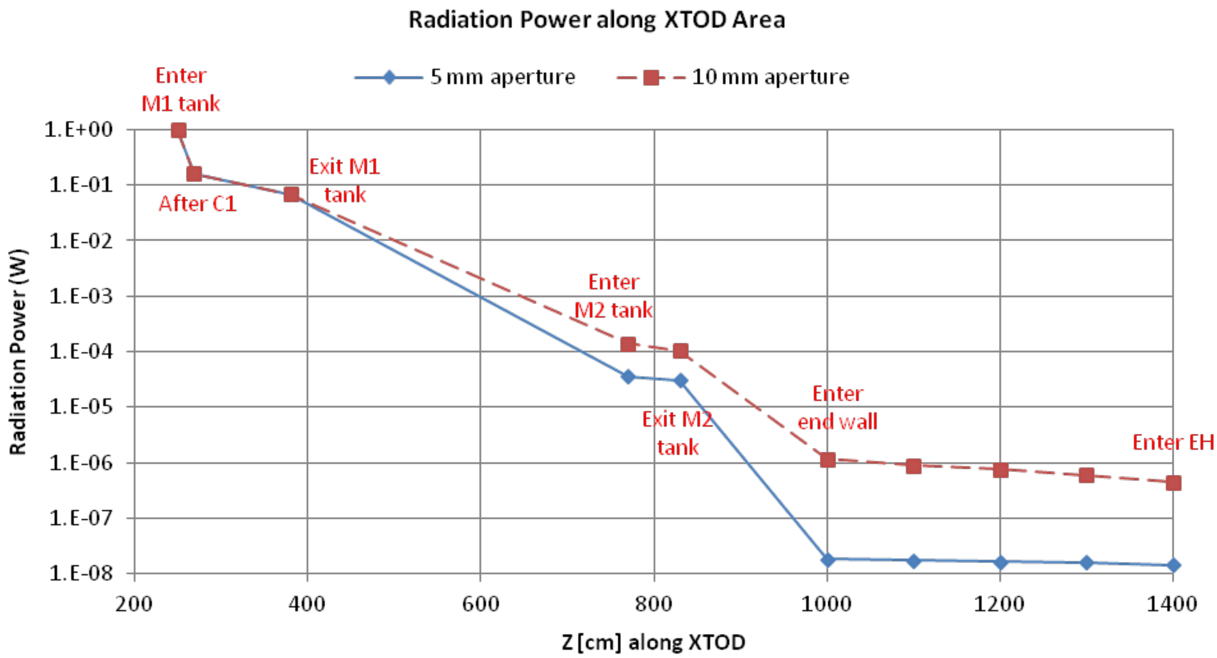


Figure 8 Change of radiation power along XTOD area for 5 mm and 10 mm aperture configurations

4 Bremsstrahlung production for a more realistic model

The calculations for normal losses in the previous sections are all normalized to the power of bremsstrahlung, which should mainly be created by electron beam interactions in the main bends. This section tries to build a relation between the power of electron losses in the main bend and the power of bremsstrahlung entering XTOD.

The main bend consists of three main bending magnets, each of which is 80 cm long with 1.16 T magnetic field to bend 2.4 GeV electron beams (20/3) degree. An elevation view of bending magnets and vacuum chambers is shown in Figure 9. Before the three main magnets, there is a soft-bend magnet, which bends electron beams 0.6 mrad toward ground. This soft-bend magnet itself is not included in the model but the bending angle is, i.e. electrons enter the first main magnet with an angle of 0.6 mrad toward ground. The *Z*-location and longitudinal dimension of the main magnets are from the MAD Deck file, but the "C-shape" transverse cross section of main magnets, as shown in Figure 10, is set arbitrarily by referring the similar design of LCLS. The vacuum chamber of the 1st magnet has a larger vertical dimension to connect both electron and photon beam lines. All vacuum chambers have 1.0 mm thick stainless steel side wall[5]. The most important parameter is the size of magnet opening and vacuum chamber.

[5] Vacuum chamber dimension in Figure 10 is the inner size. Vacuum chambers have no end wall, so vacuum pipes connecting chambers of different magnets are not included in the model and particles leaving one vacuum chamber will enter air directly.

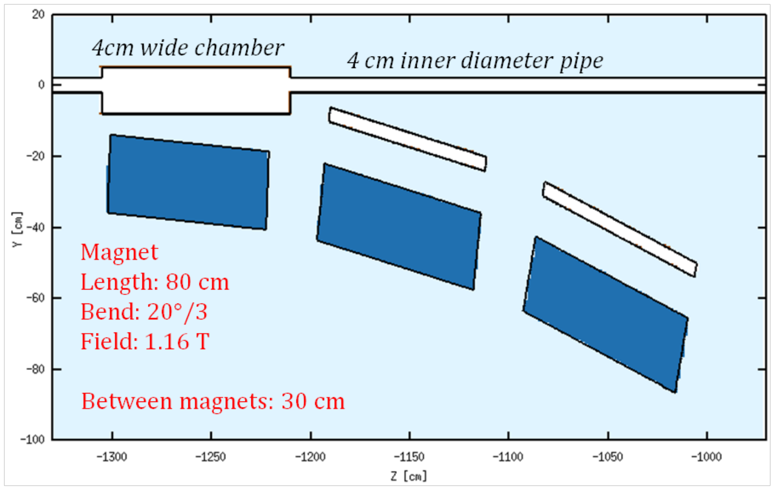


Figure 9 Elevation view of bending magnets and vacuum chambers

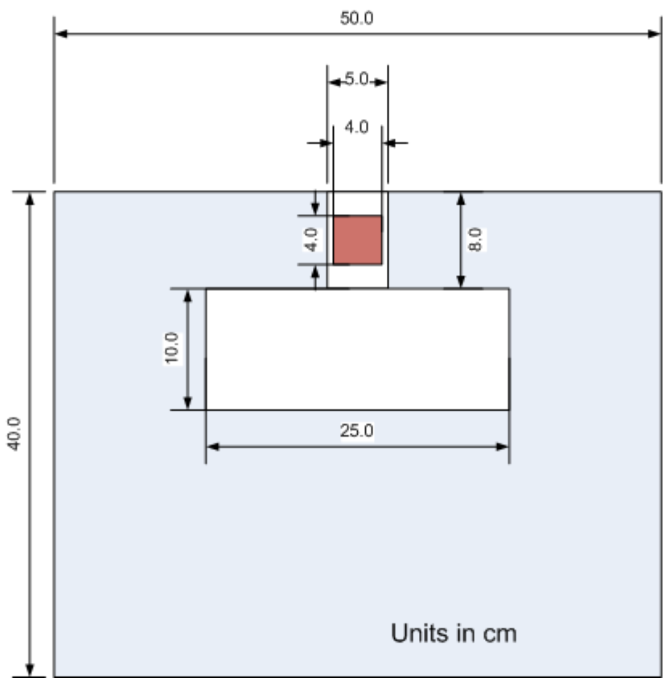


Figure 10 Transverse cross section of bending magnet and vacuum chamber

Borrowing the experience of LCLS, two beam loss models, uniform loss and point loss, are studied. The uniform loss model assumes electrons are lost uniformly along the main electron trajectory. For a same amount of electron losses, losses in the 2nd and 3rd magnets will deliver much lower radiation to XTOD due to the larger offset than losses in the 1st magnet. Therefore, the uniform loss model conservatively assumes that all losses happen in the 1st magnet. As for the point loss model, all electron losses happen at the entrance of the 1st BYD main magnet, which represents a more conservatively scenario than that of the uniform loss model. In both models, electrons are assumed hitting the side walls of the vacuum chamber with a small angle of 0.1 mrad.

Figure 54 shows the total dose around bending magnets for both uniform and point lossees. The point loss will produce a strong forward radiation along the photon beam pipe. In both cases, electrons lose only a small portion of energy and will almost follow the original trajectory after the interaction. Figure 55 shows the dose distribution for the whole XTOD area for both models. Figure 56 shows the spectrum of photons leaving the 1st magnet for both models. Photons from the uniform loss model are less forward-focused than those the from point loss model, which in turn are less forward-focused than photons from the previous foil model of section 3.

In the above simulations, the photon beam pipe connecting the 1st magnet and M1 mirror tank has a 4 cm inner diameter, thus matching the vacuum chamber inner width. Simulations for a smaller (1" OD) connecting pipe (same size as proposed in Section 3.5) were performed to study the importance of that dimension. The radiation powers at different locations for different models are listed in Table 3. The ratio of radiation entering M1 tank from point and uniform loss models is about 40 for both pipe configurations. This ratio is consistent with LCLS studies. More than 90% of the radiation entering M1 tank is photons.

NGLS XTOD has a collimator, C1, before the 1st mirror, M1. This collimator is very efficient in reducing radiation transported to M1 and beyond. Table 3 also shows that (as expected) the power of radiation through C1 varies very little between the two studied connecting pipe sizes.

In the foil bremsstrahlung source model, 1 W bremsstrahlung source would deliver 170 mW bremsstrahlung through C1. A more realistic situation could be represented by a combination of uniform and point losses at the first bend. For such case, using data in Table 3 we get that an average of 1 W electron losses deliver 0.1 mW bremsstrahlung through C1. Then **1500 W electron losses** (~0.2% of the full 720 kW beams) **in the main bend would deliver** 150 mW through C1, which is in **the similar level of radiation as from 1 W bremsstrahlung from the foil source model** used in the studies of Section 3.

Table 3 Radiation powers at different locations for different models

From 1 W e^-	4 cm ID pipe to M1		1" OD pipe to M1		1 W Brem
(mW)	Uniform	Point	Uniform	Point	from Foil
Leave 1st Magnet	16	88	10	74	---
	70% p	*Almost all p*	*65% p*	*Almost all p*	
	30% e	*<0.1% e*	*35% e*	*<0.1% e*	
Enter M1 Tank	0.5	18	0.2	10	966
	90% p	*92% p*	*92% p*	*93% p*	
	10% e	*8% e*	*8% e*	*7% e*	
Passing C1	0.011	0.37	0.012	0.45	170

5 Conclusion

There are two major radiological protection concerns on NGLS XTOD: the radiation directly penetrating the wall between XTOD and the experimental room and the radiation that leaks into the experimental room through the beam pipe. The recommended configuration is shown in Figure 11.

The direct radiation penetration to the experimental hall, without considering the radiation leakage from beam pipe, is shielded by BC2 and EH wall. Simulations show that:

In accident scenarios (Section 2.1):

- Minimum 10 cm iron/steel BC2 at no closer than 5 m from the EH wall upstream face and 4 meter thick EH concrete wall is adequate to reduce the accident dose rate to 25 rem/h;
- Alternatively, 30 cm iron/steel BC2 and 3 meter concrete wall is also adequate.

In normal operations (Section 3.2):

- 4 meter concrete wall with

  - 10 cm steel BC2 is acceptable for up to 1 W bremsstrahlung source;
  - Either 30 cm steel or 10 cm WHA BC2 is acceptable for up to 50 W bremsstrahlung sources.
- 3 meter concrete wall with
  - 10 cm WHA BC2 is acceptable for up to 5 W bremsstrahlung sources;
  - 30 cm steel BC2 is acceptable for up to 2 W bremsstrahlung sources.

Overall, **4 m concrete EH wall** with **30 cm steel BC2** are recommended to shield the *direct radiation penetration* to the experimental room.

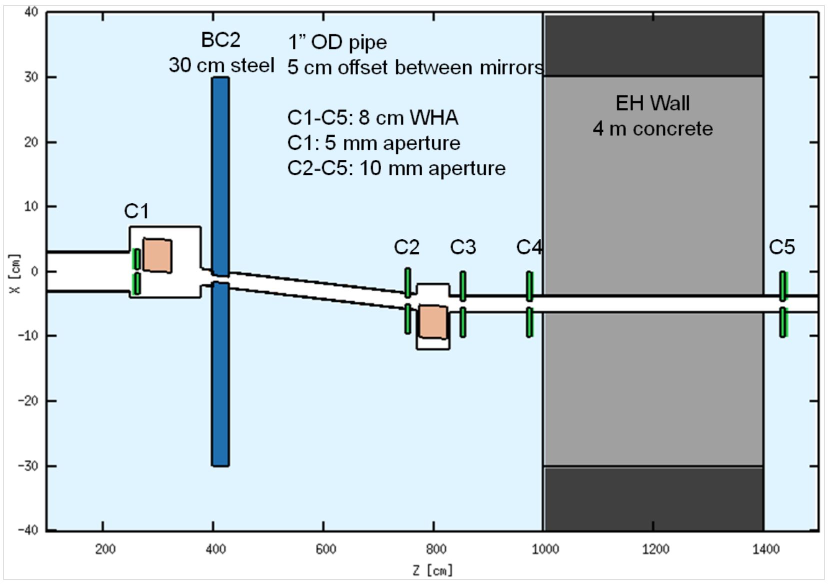


Figure 11   Recommended collimator and EH wall configuration for NLGS XTOD

Detailed parametric studies (Section 3.3) were performed to understand *the radiation leakage through the beam pipe*. As a compromise of scientific program expectation, engineering availability and radiation safety requirement, a collimator system with **1" OD beam pipe** and **collimators** of **8 cm WHA** and **10 mm diameter apertures** (except **C1 aperture is 5 mm**) is recommended (Section 3.4):

In accident scenarios (Section 2.2):

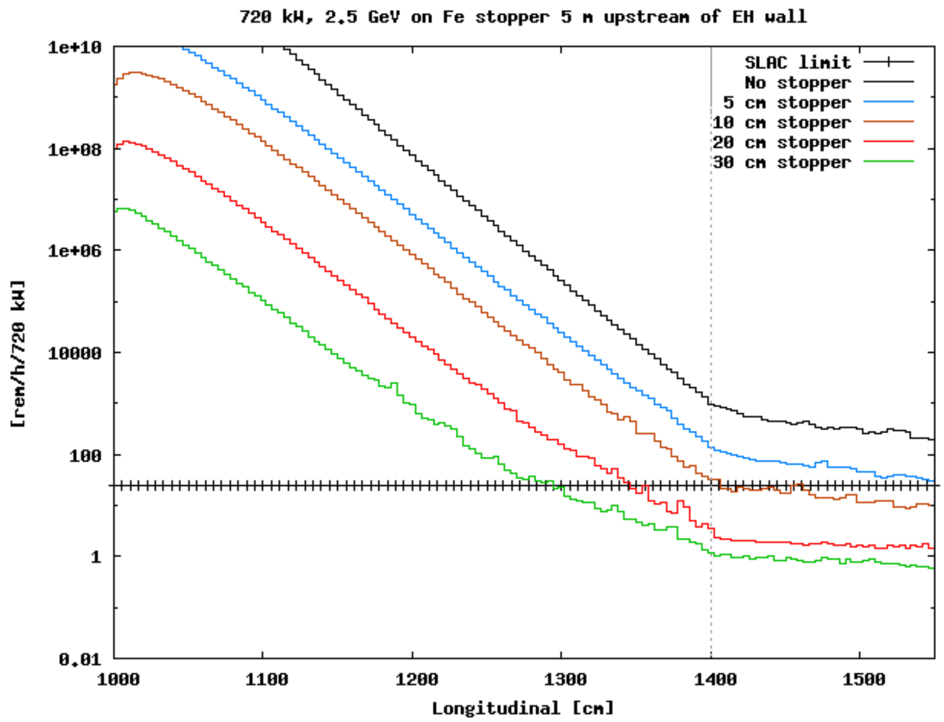
- If 720 kW 2.4 GeV electron beams hit M1 directly, it will induce to very high radiation leakage to the experimental hall;
- A small permanent magnet bending beam toward ground can help reduce radiation leakage in accident scenarios.

In normal operations (Section 3.4):

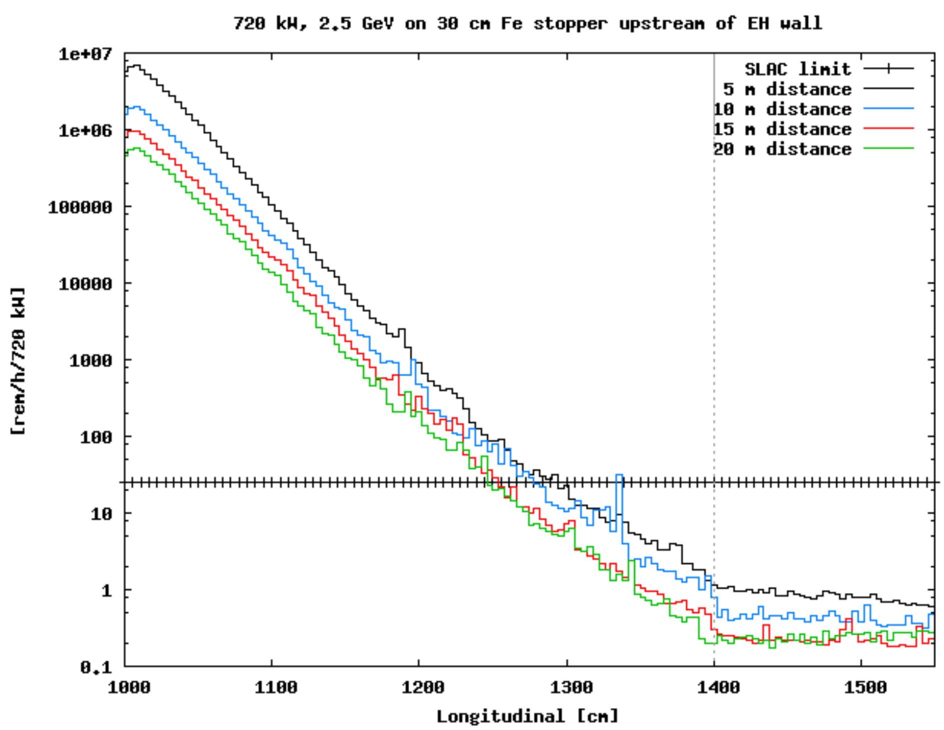
- The proposed collimator system is acceptable for up to 2 W bremsstrahlung sources.

Bremsstrahlung source in the studies for the above requirements comes from a simplified foil source model, while in reality bremsstrahlung is mainly produced by the electron losses in the main bend (bremsstrahlung from residual gas is much less). Studies in Section 4 show that **1500 W electron losses** (~0.2% of the full 720 kW beams) **in the main bend** will deliver the similar level of radiation to M1 as 1 W bremsstrahlung from the foil source model. There will be collimators between the last bending magnet and M1 tank to define the electron containment. They are not included in the current model. Experiences from LCLS-II show that these collimators can also help a lot to reduce further the radiation entering M1 tank.

Appendix A Simulation Results

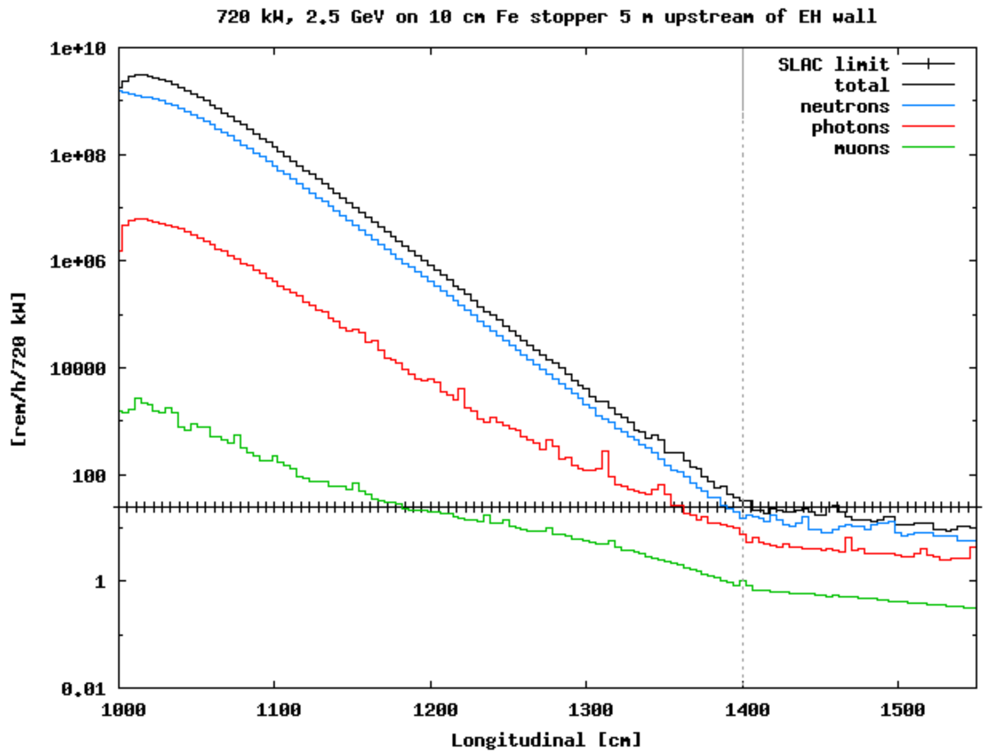


(a) BC2 of different thickness at 5 m from wall

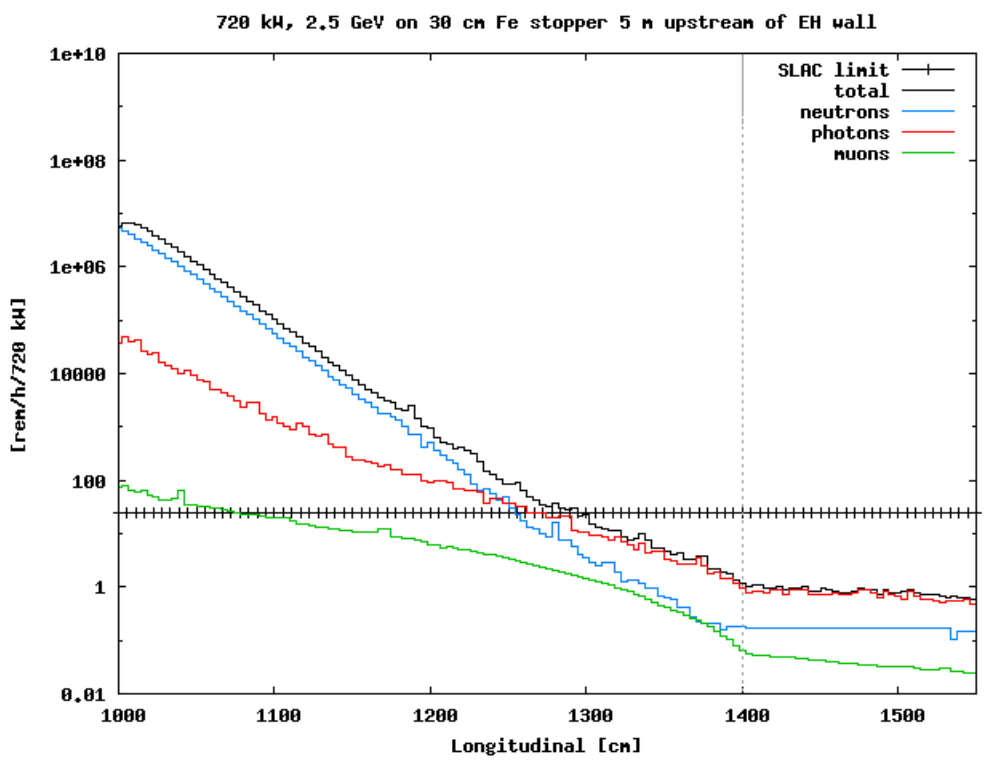


(b) 30 cm BC2 at different distances from wall

Figure 12 Maximum dose rate through EH concrete wall for 720 kW, 2.5 GeV electrons hitting an iron stopper (BC2) at different distances from the wall



(a) 10 cm BC2



(b) 30 cm BC2

Figure 13 Maximum dose rate through EH concrete wall for 720 kW, 2.5 GeV electrons hitting an iron stopper (BC2) located 5 m upstream of wall front face

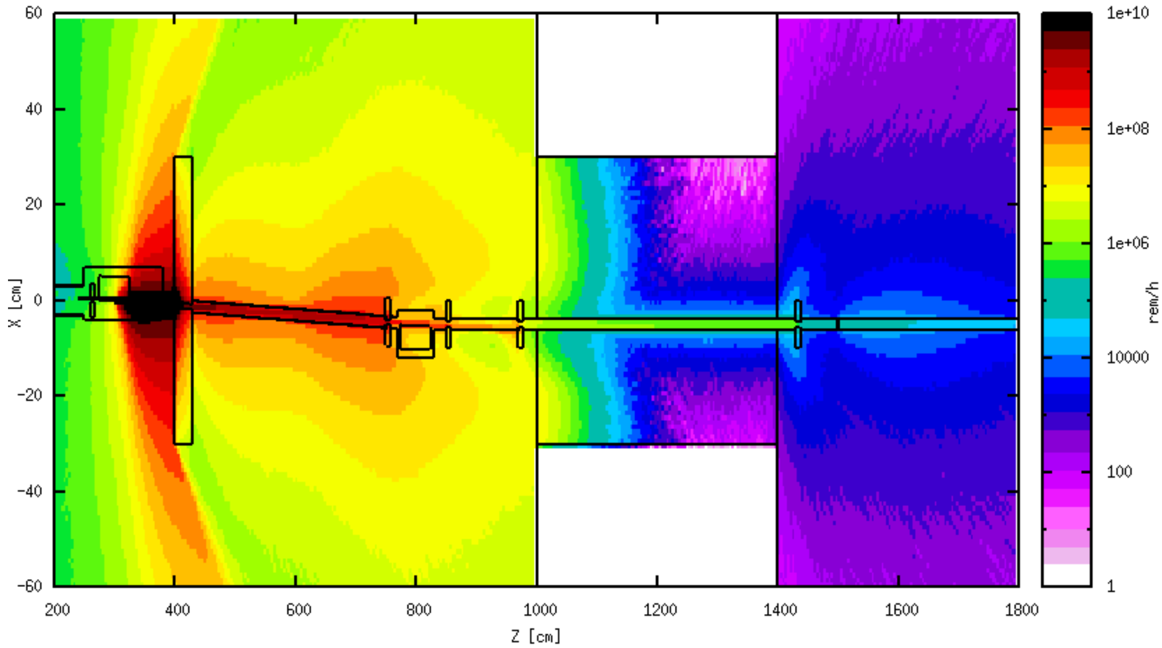


Figure 14 Top view of total dose distribution (average in ±10 cm of beam height) for 720 kW 2.4 GeV pencil beam hitting M1 directly: basic configuration with 5 cm horizontal offset between M1 and M2, 1" OD pipe and 10 mm diameter collimator aperture.

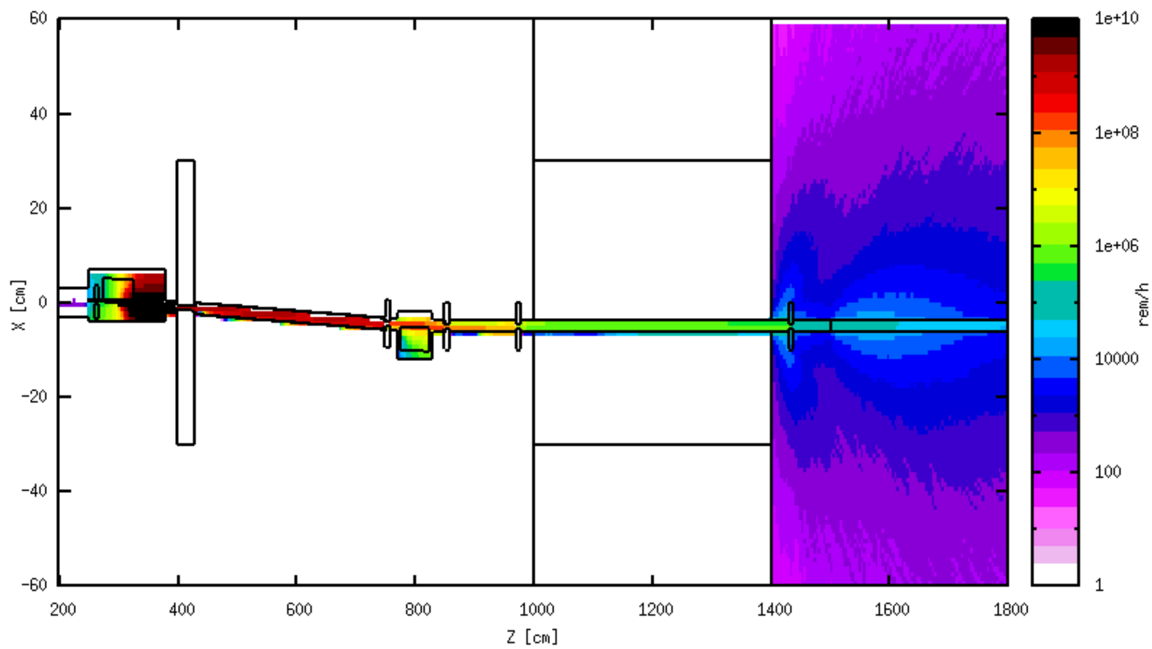


Figure 15 Top view of total dose distribution (average in ±10 cm of beam height) for 720 kW 2.4 GeV pencil beam hitting M1 directly: basic configuration, assuming all collimators, walls and air inside tunnel are "black holes".

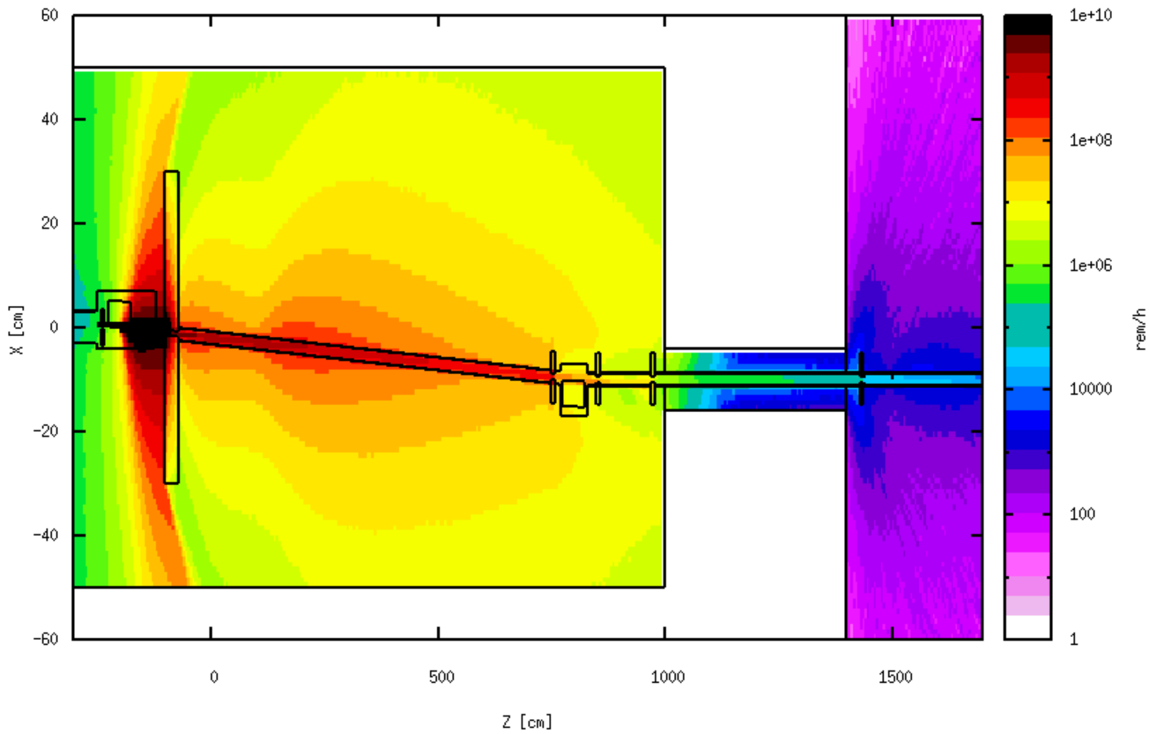


Figure 16 Top view of total dose distribution (average in ±10 cm of beam height) for 720 kW 2.4 GeV pencil beam hitting M1 directly: 10 cm offset between M1 and M2 (by moving M1 5-meters upstream).

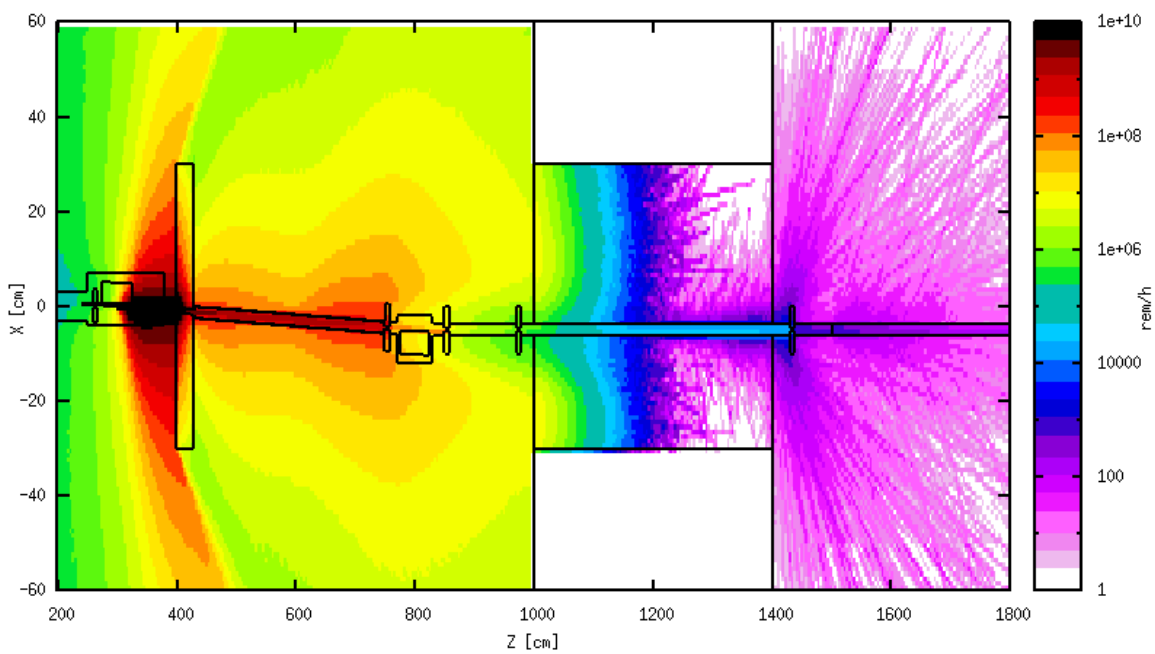
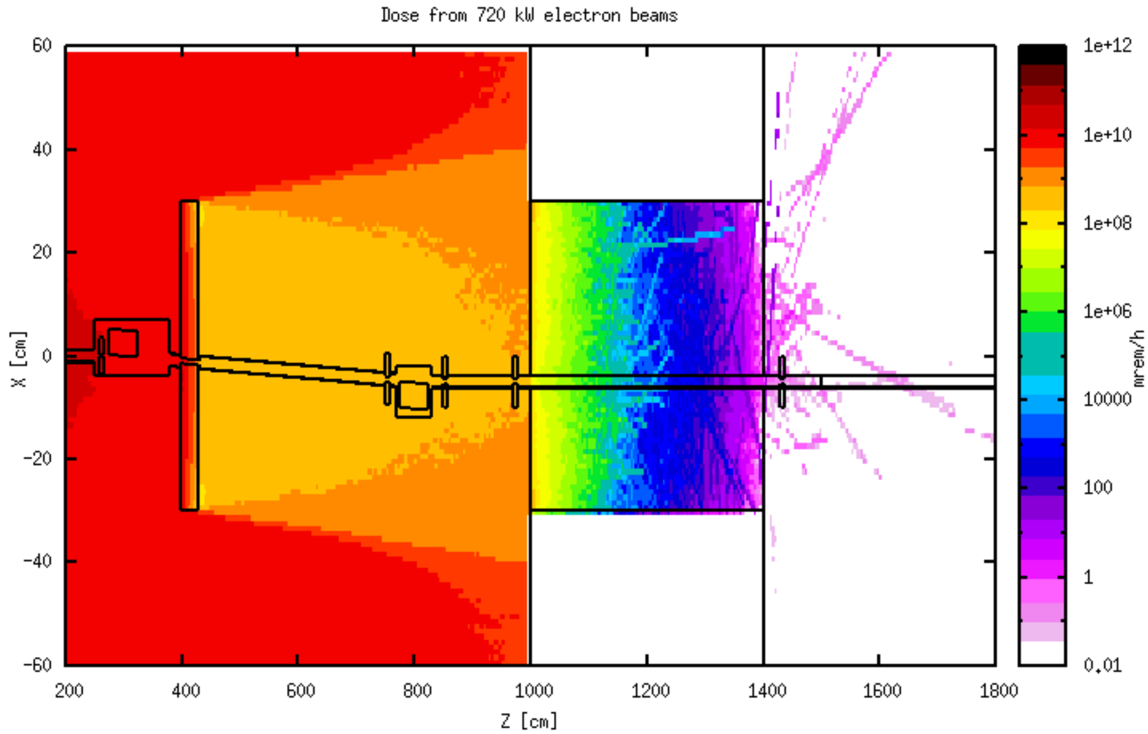
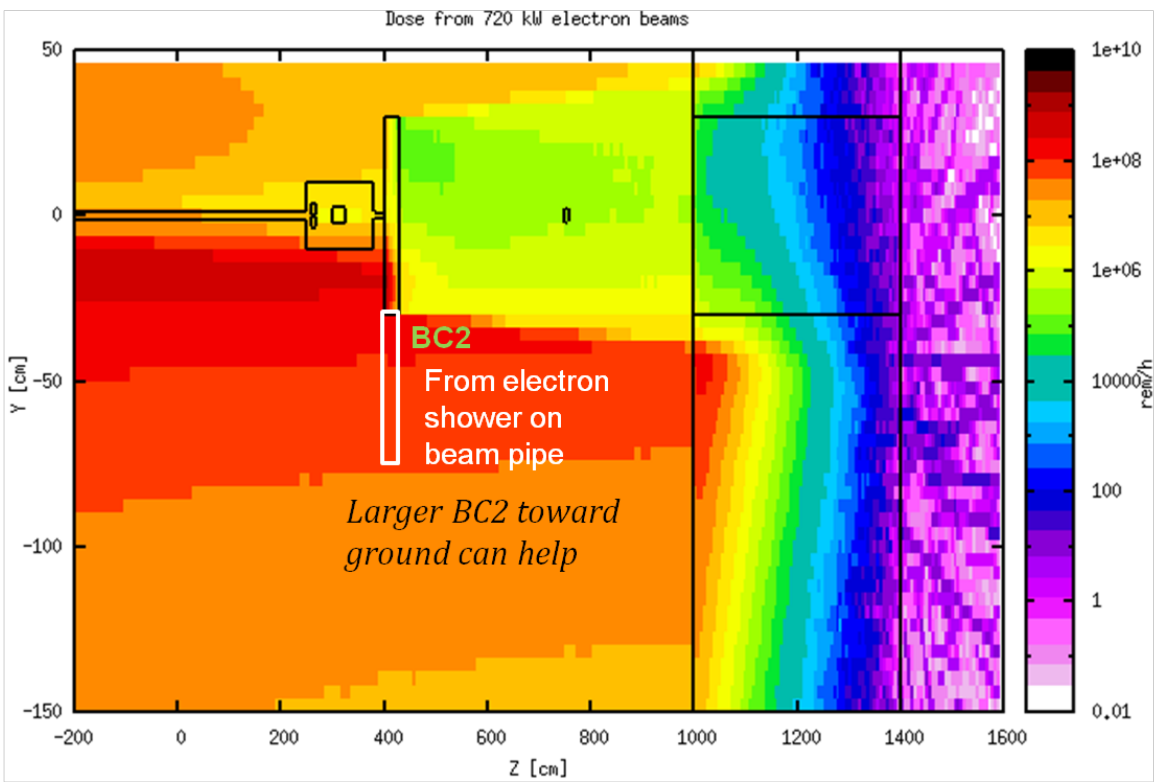


Figure 17 Top view of total dose distribution (average in ±10 cm of beam height) for 720 kW 2.4 GeV pencil beam hitting M1 directly: 5 mm diameter collimator aperture.

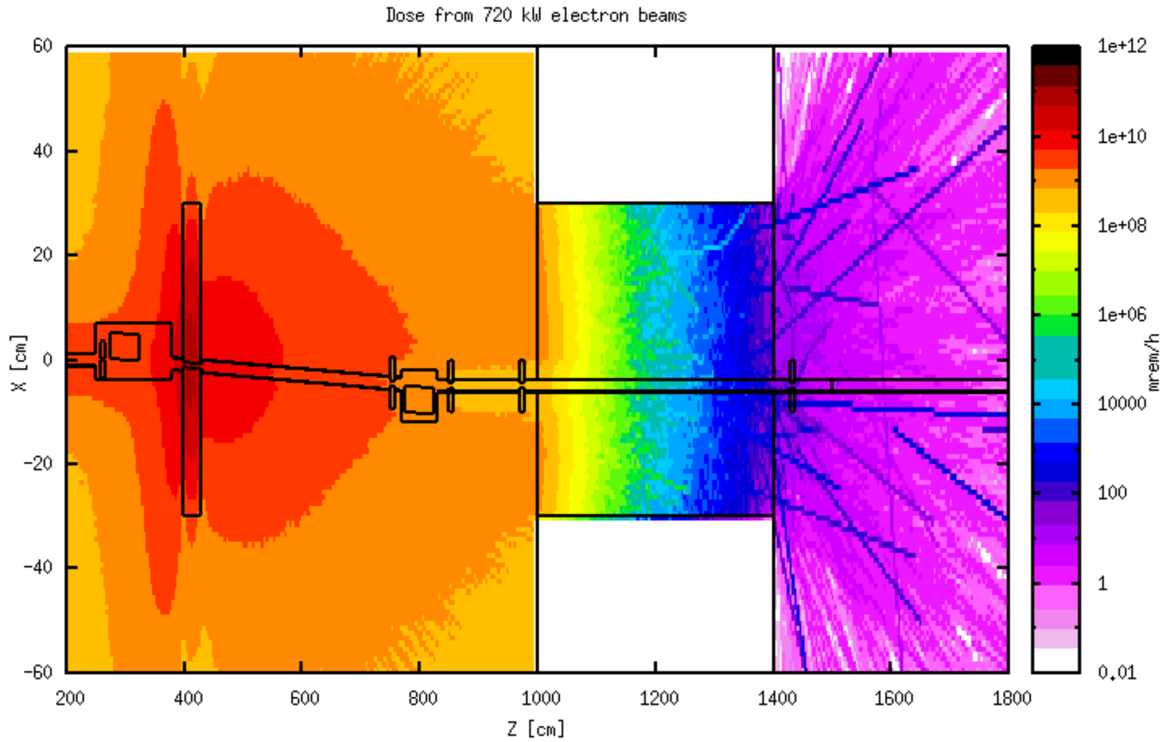


(a) Top view

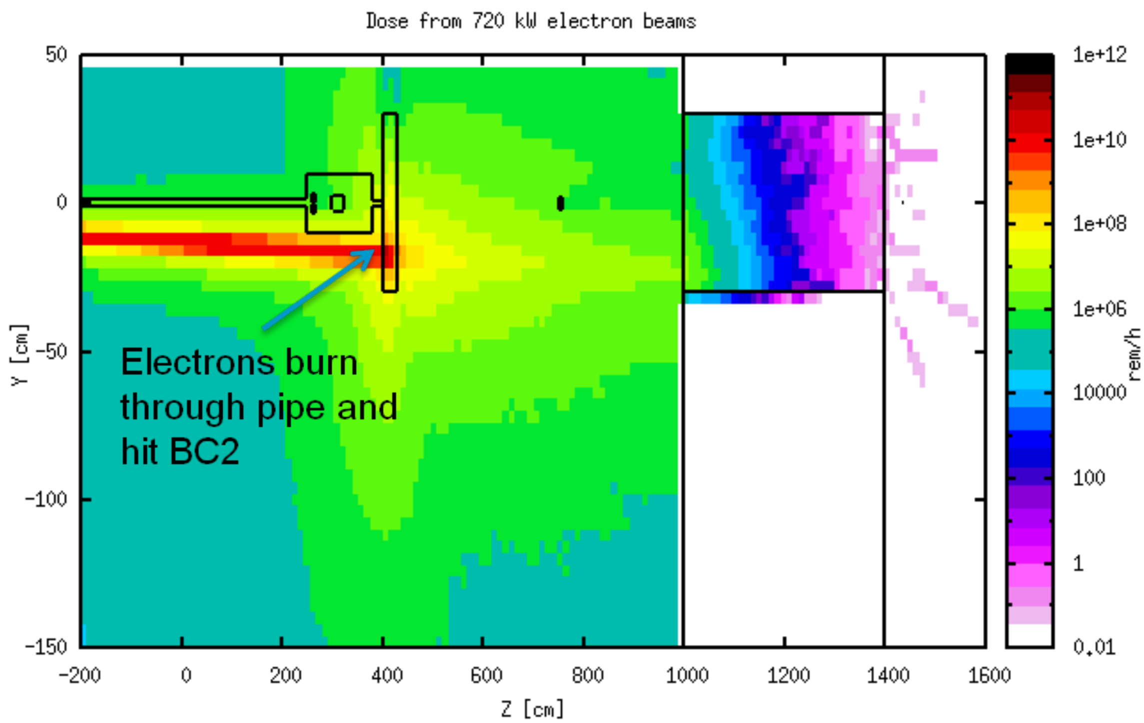


(b) Elevation view

Figure 18 Total dose distributions when 720 kW 2.4 GeV electron beams hit beam pipe (at Z ≈ -1200 cm).

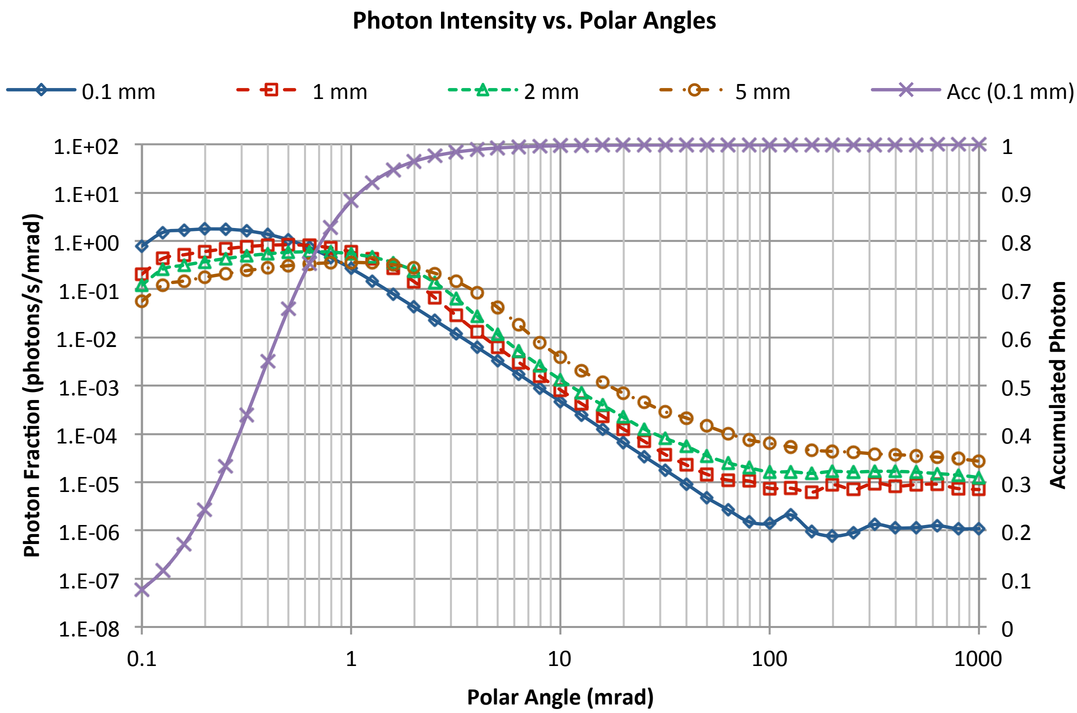


(a) Top view



(b) Elevation view

Figure 19 Total dose distributions when 720 kW 2.4 GeV electron beams burn through beam pipe and hit BC2 directly.



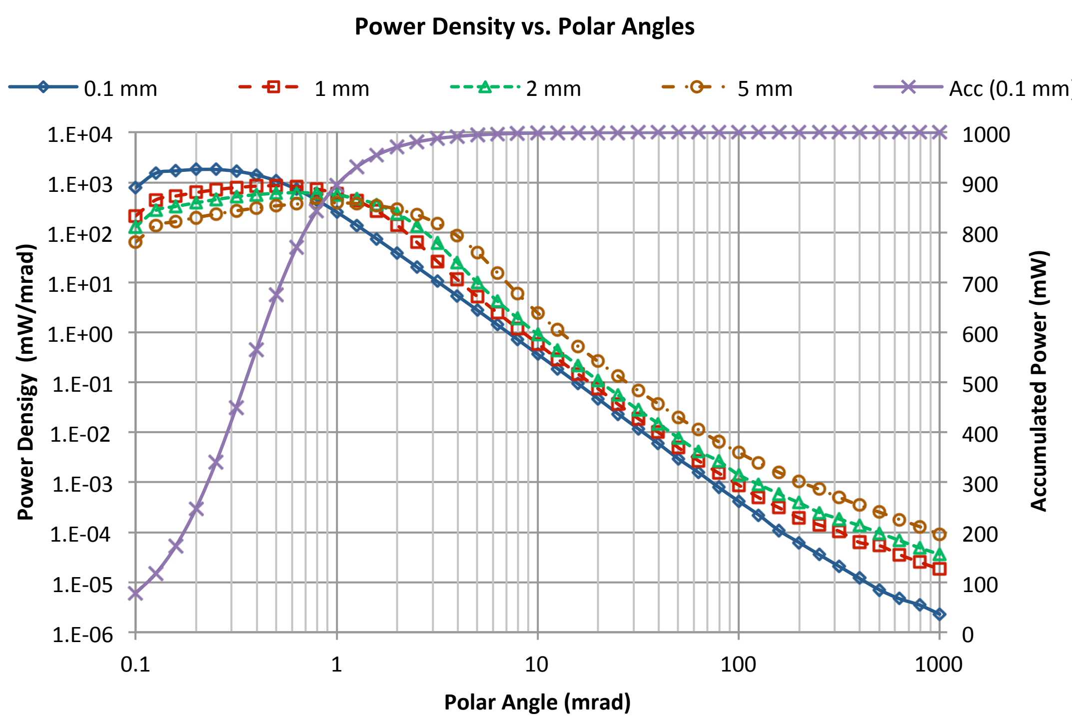
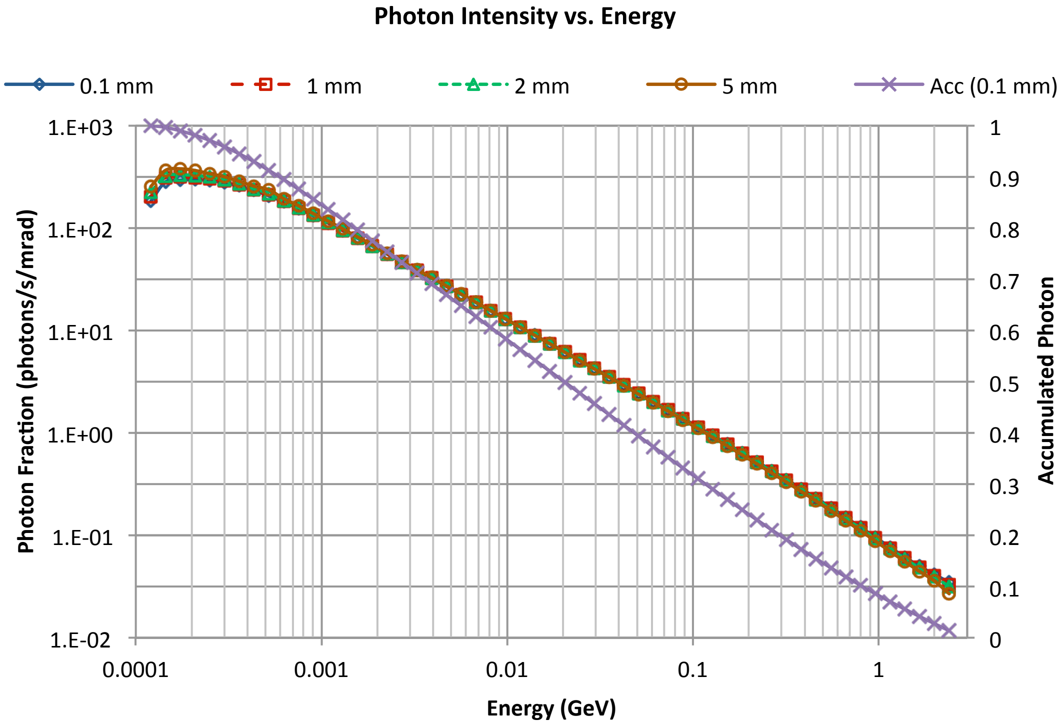


Figure 20 Angular distribution of bremsstrahlung (per 1 W photons) from Ti foils of different thicknesses. “Acc (0.1 mm)”



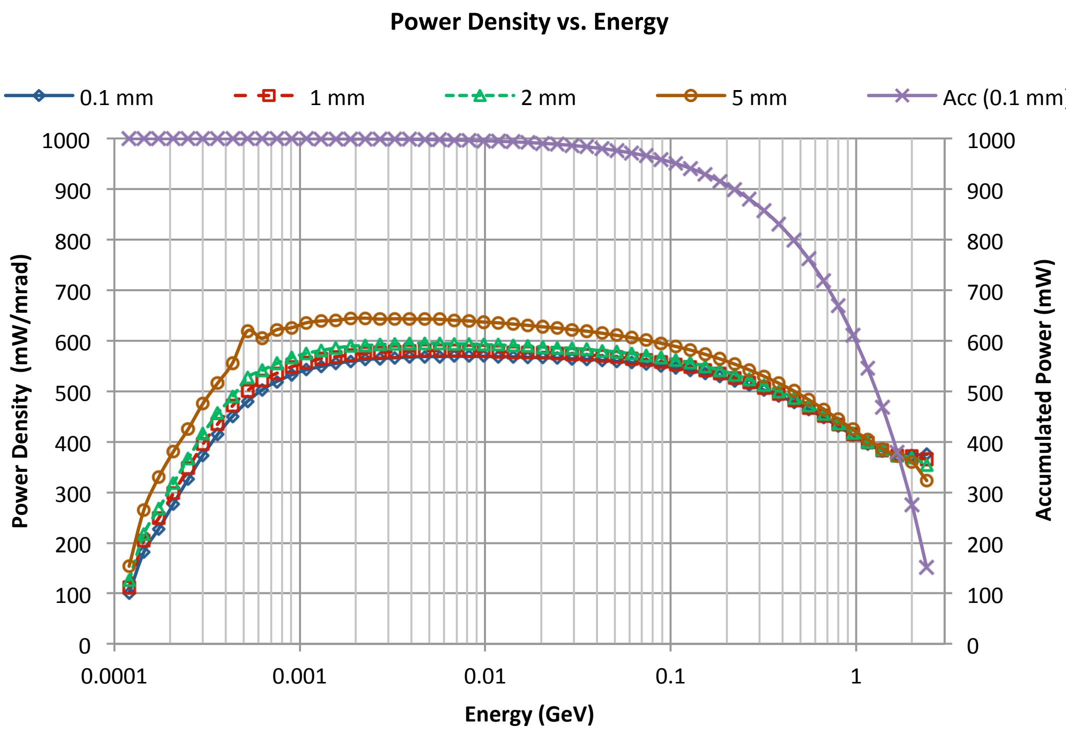
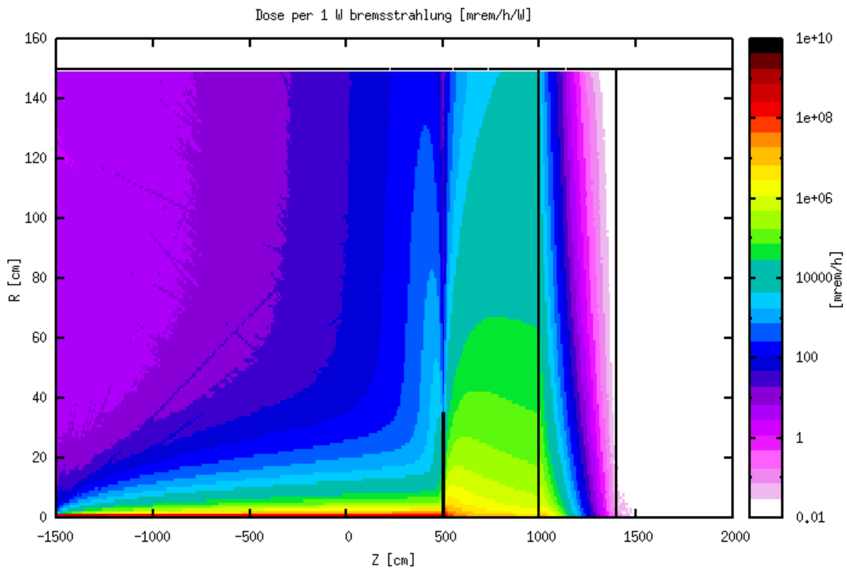
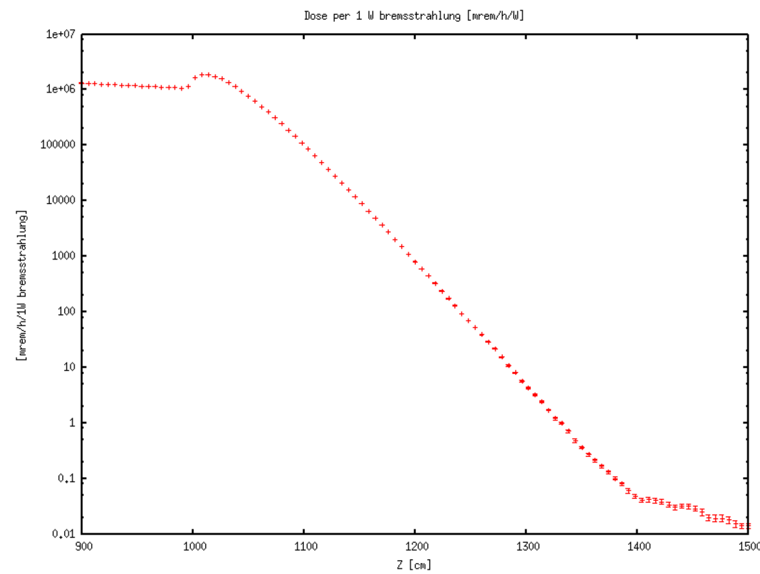


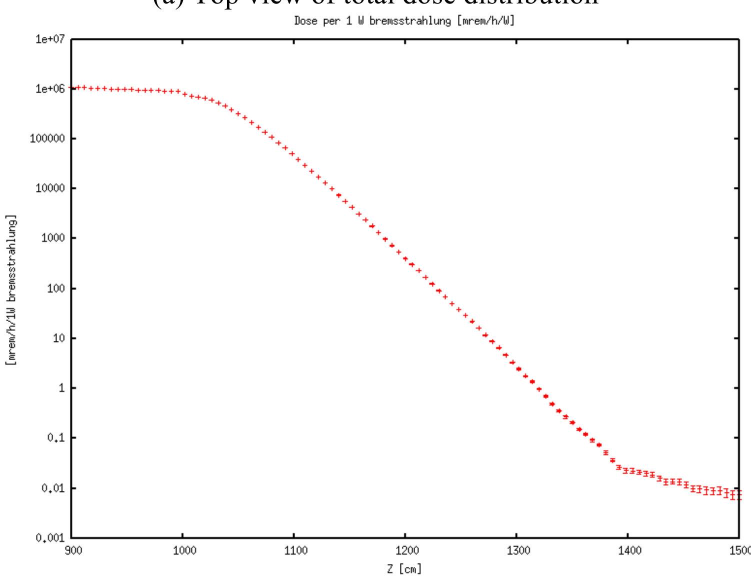
Figure 21 Energy distribution of bremsstrahlung (per 1 W photons) from Ti foils of different thicknesses



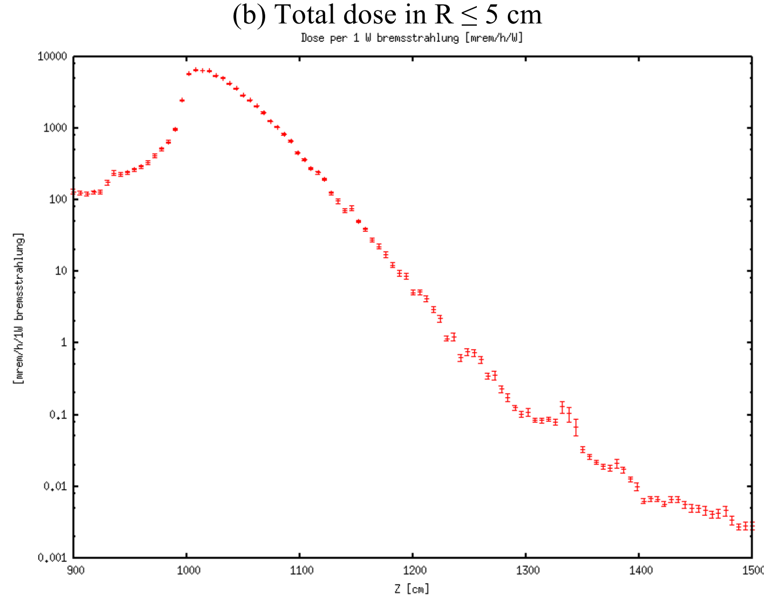
(a) Top view of total dose distribution



(b) Total dose in R ≤ 5 cm

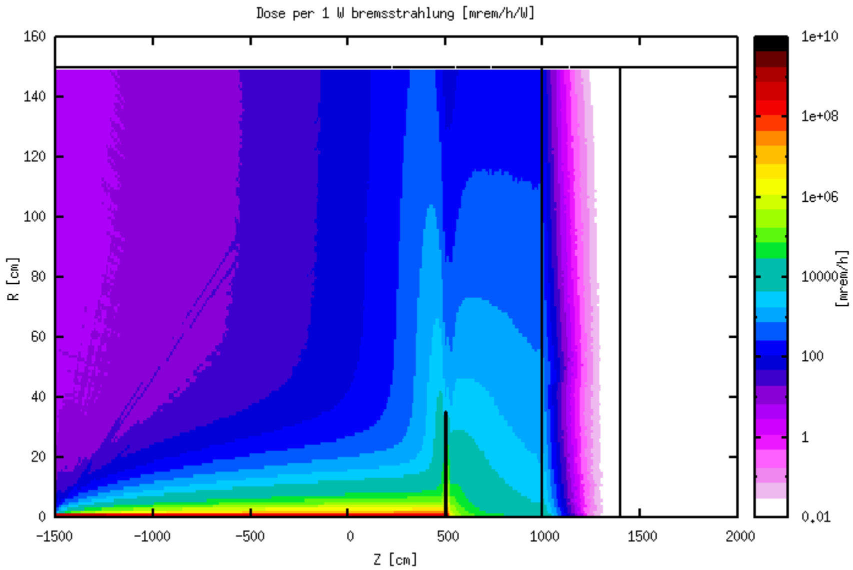


(c) Photon dose in R ≤ 5 cm

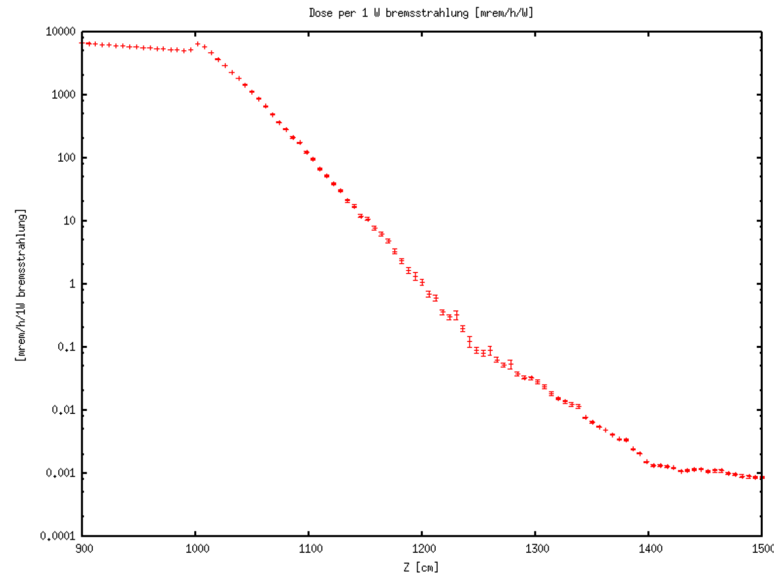


(d) Neutron dose in R ≤ 5 cm

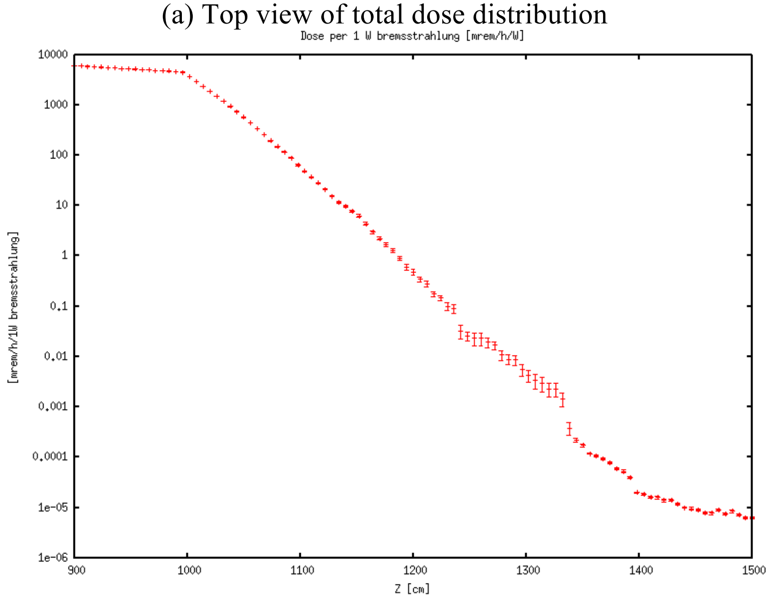
Figure 22 Dose distributions with 10 cm A36 steel BC2



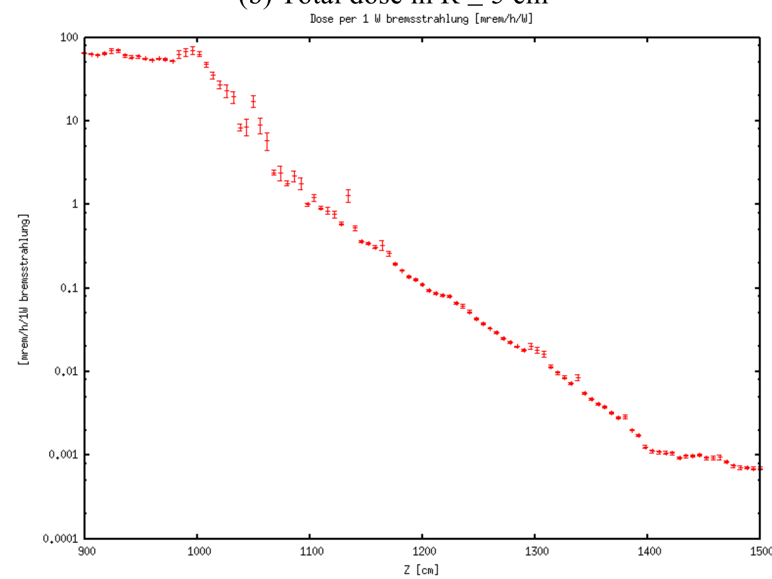
(a) Top view of total dose distribution



(b) Total dose in R ≤ 5 cm

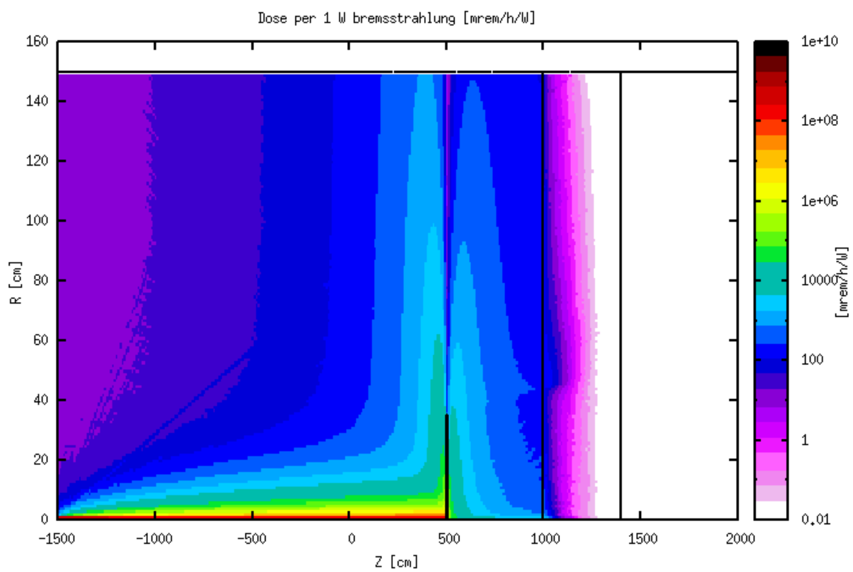


(c) Photon dose in R ≤ 5 cm

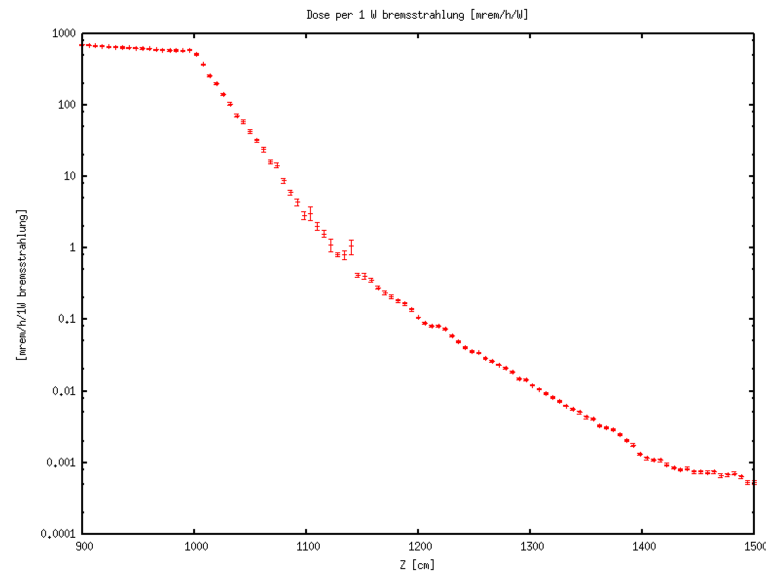


(d) Neutron dose in R ≤ 5 cm

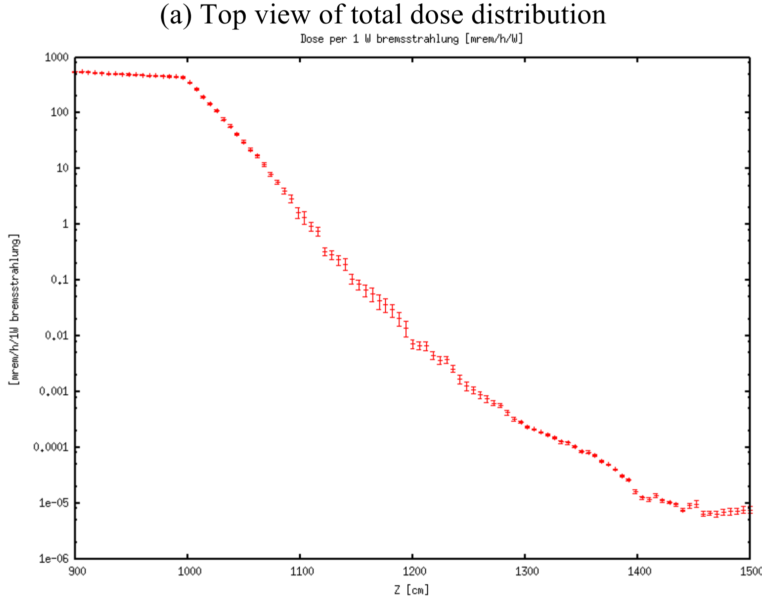
Figure 23 Dose distributions with 30 cm A36 steel BC2



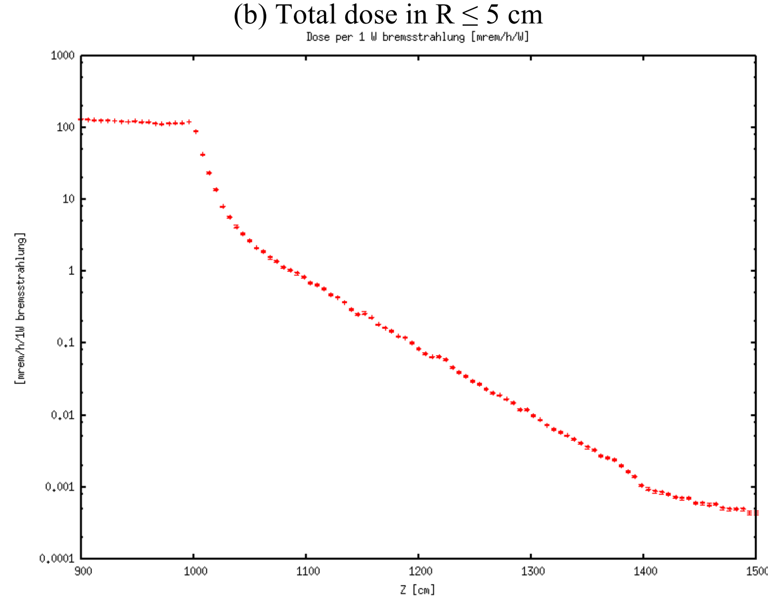
(a) Top view of total dose distribution



(b) Total dose in R ≤ 5 cm

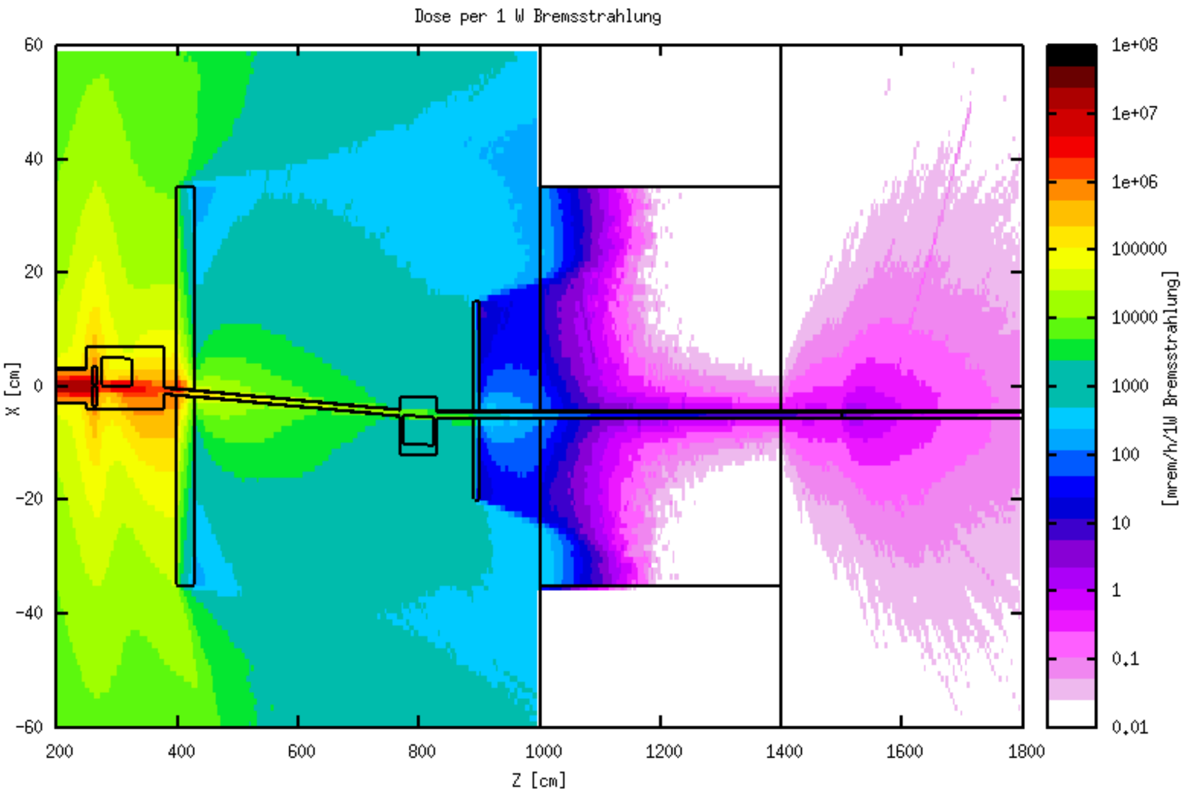


(c) Photon dose in R ≤ 5 cm

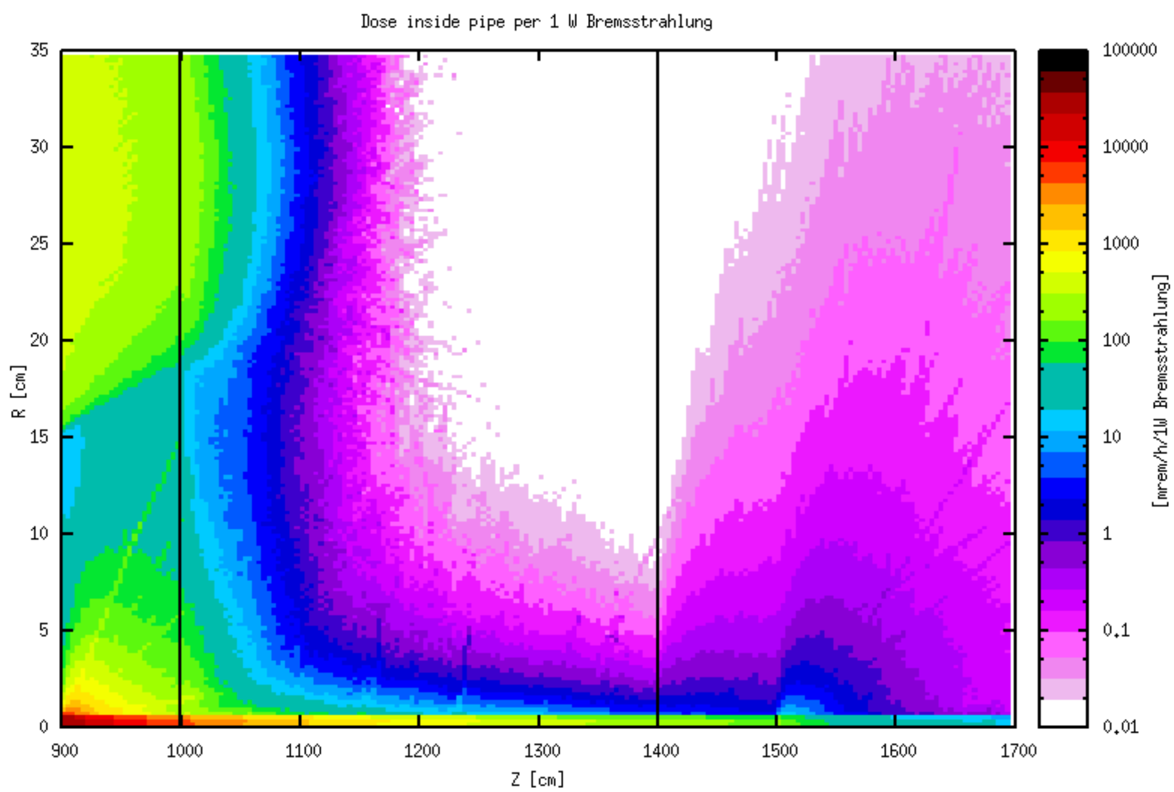


(d) Neutron dose in R ≤ 5 cm

Figure 24 Dose distributions with 10 cm WHA BC2



(a) Top view (average in ±10 cm of beam height)



(b) *R-Z* view with the center at the beam pipe entering the experimental hall

Figure 25 Total dose distributions for 10 mm ID pipe without C12 (Configuration #1)

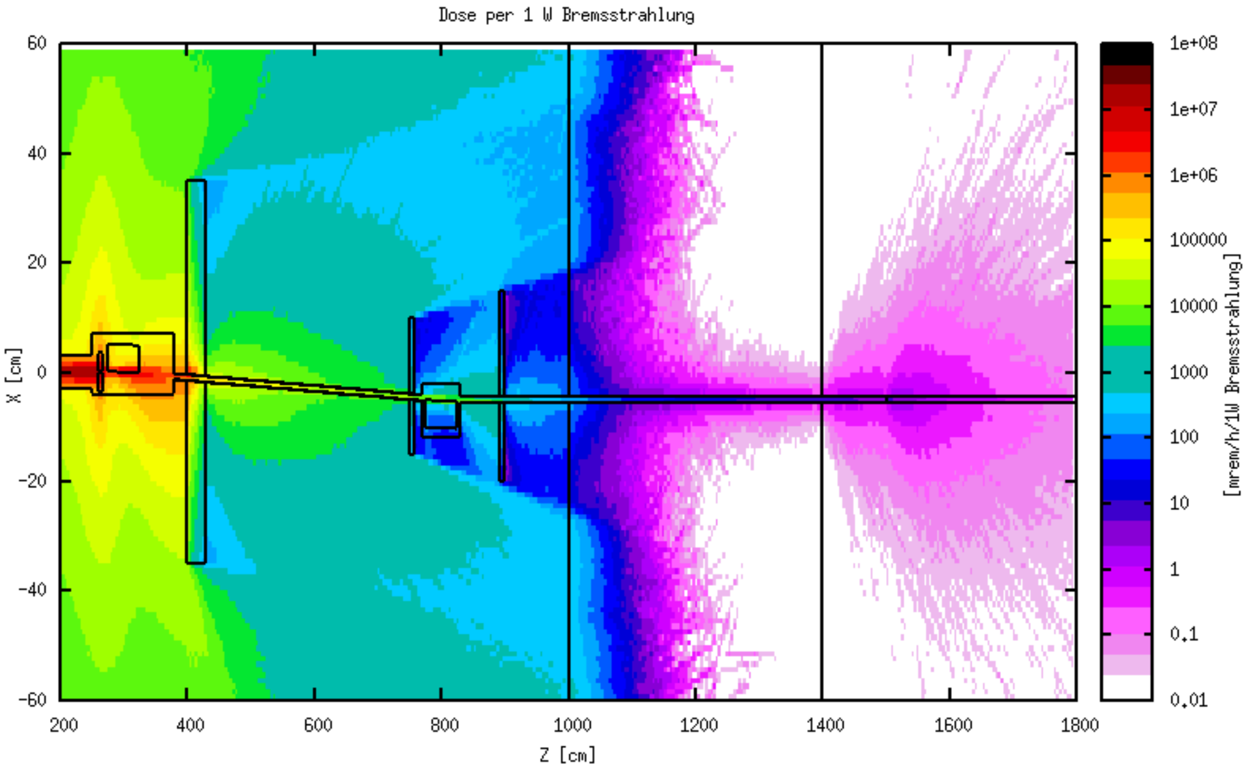


Figure 26 Top view of total dose distributions (average in ±10 cm of beam height) for 10 mm ID pipe with C12 (Configuration #2)

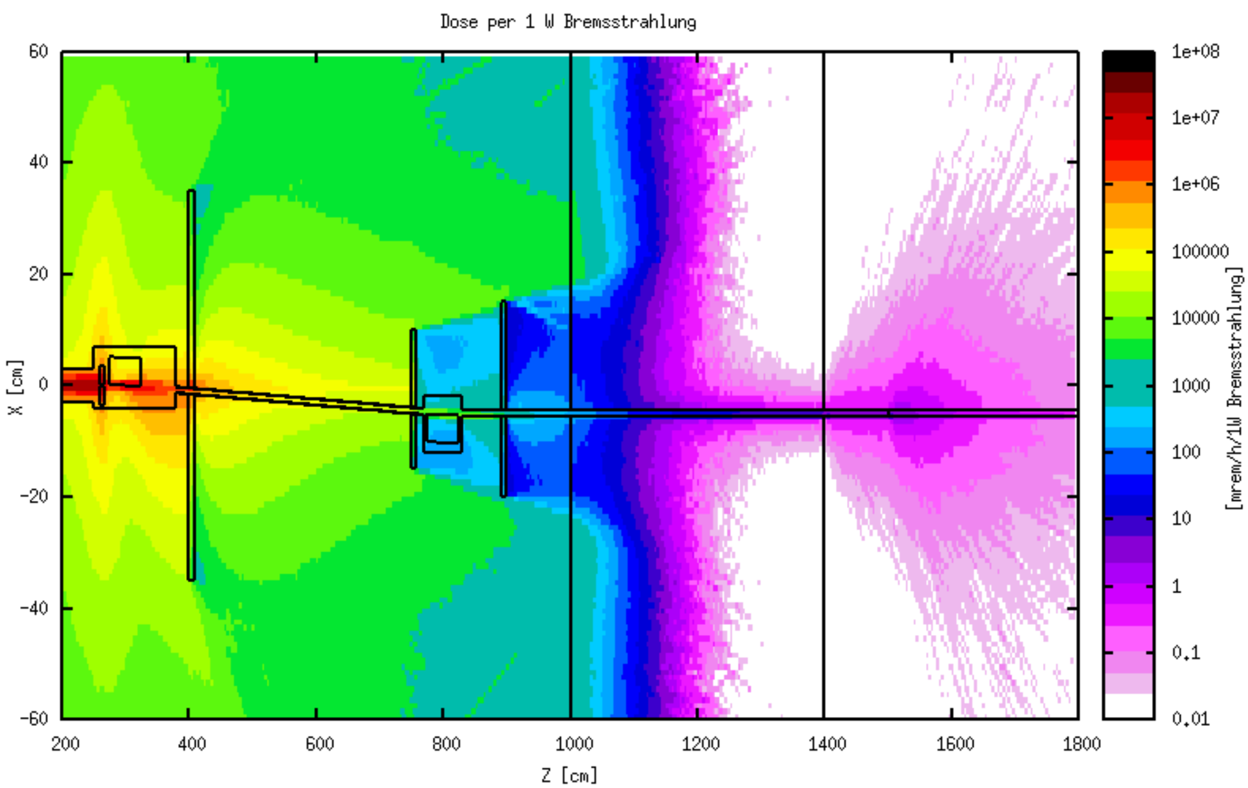
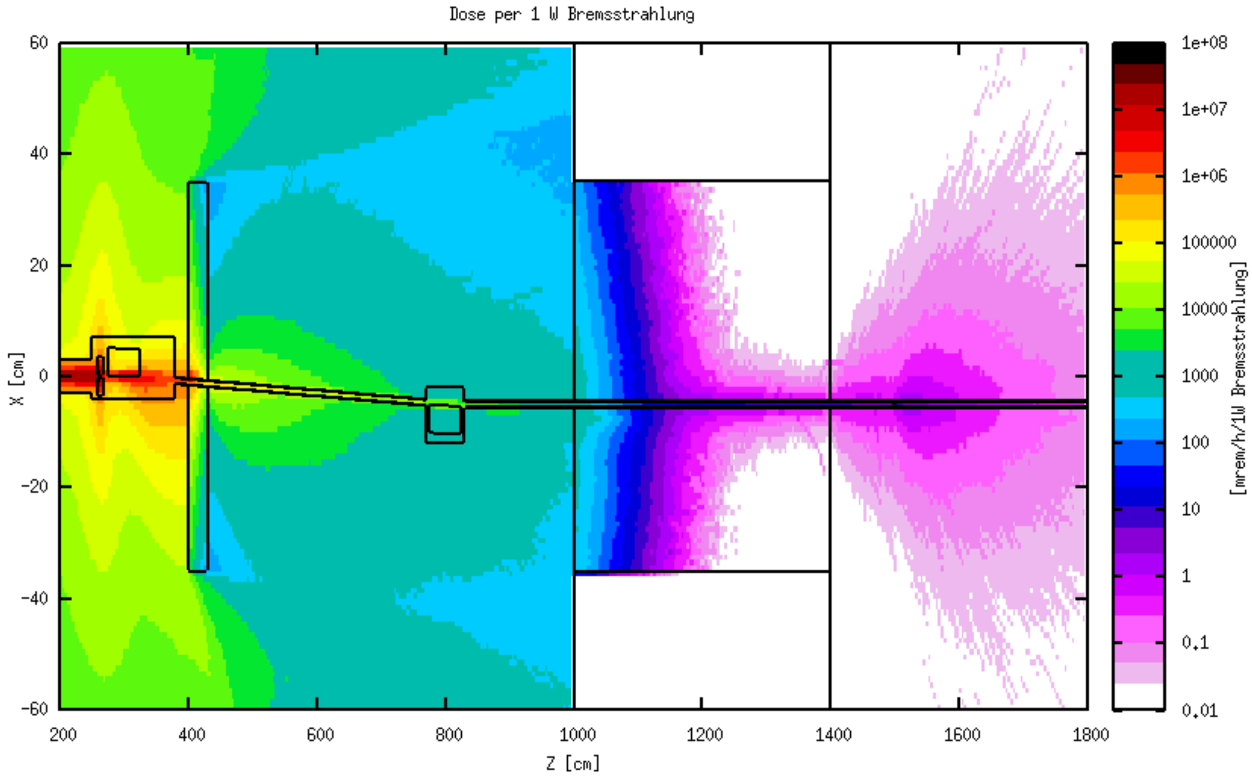
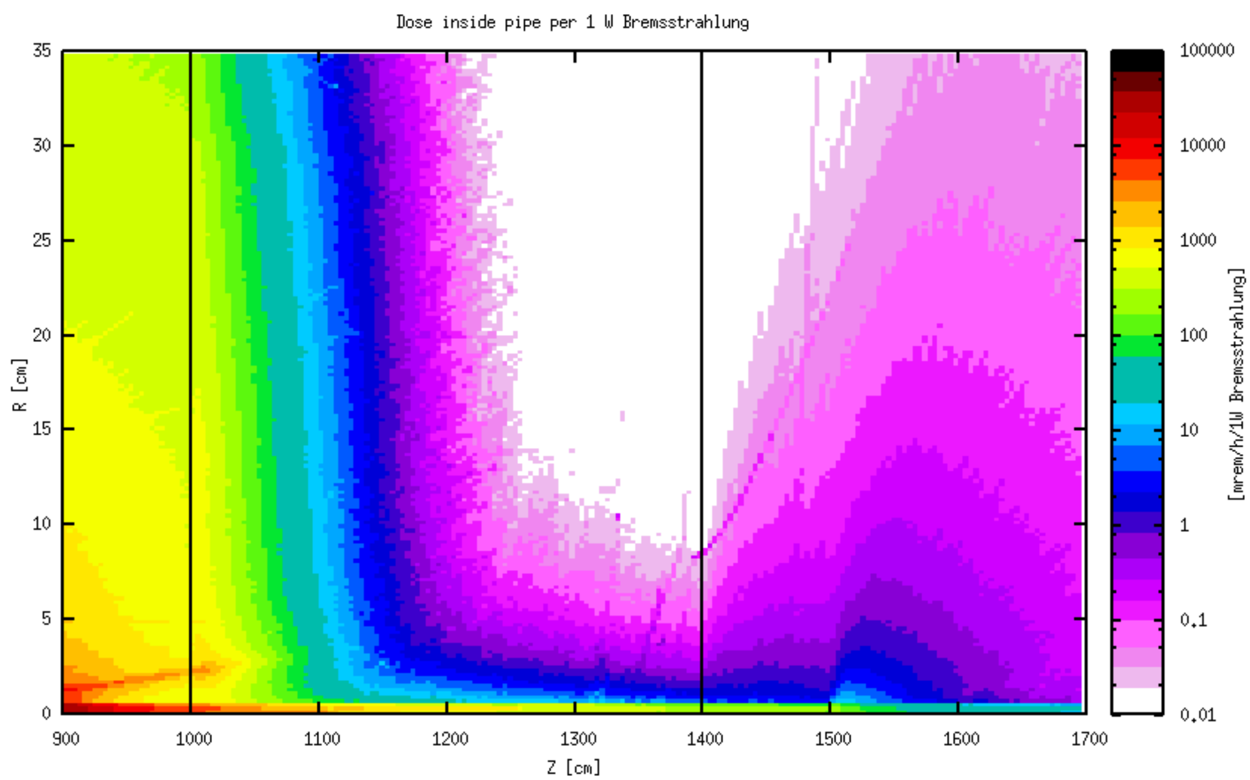


Figure 27 Top view of total dose distributions (average in ±10 cm of beam height) for 10 cm thick BC2 and 10 mm ID pipe with C12 (Configuration #3)



(a) Top view (average in ±10 cm of beam height)



(b) *R-Z* view with the center at the beam pipe entering the experimental hall

Figure 28 Total dose distributions for 10 mm ID pipe without BC3 (Configuration #4)

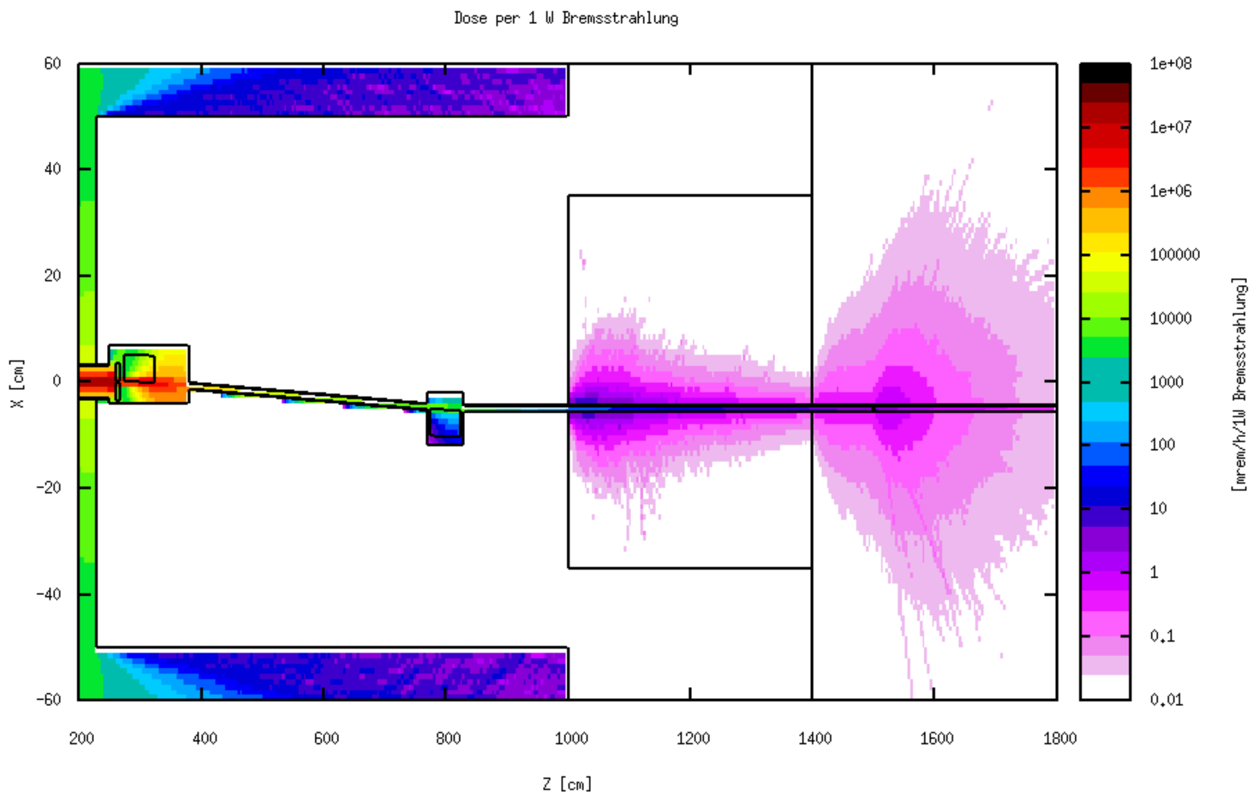


Figure 29 Top view of total dose distributions (average in ±10 cm of beam height) by assuming all collimators and the air inside tunnel are "blackhole" (Configuration #5).

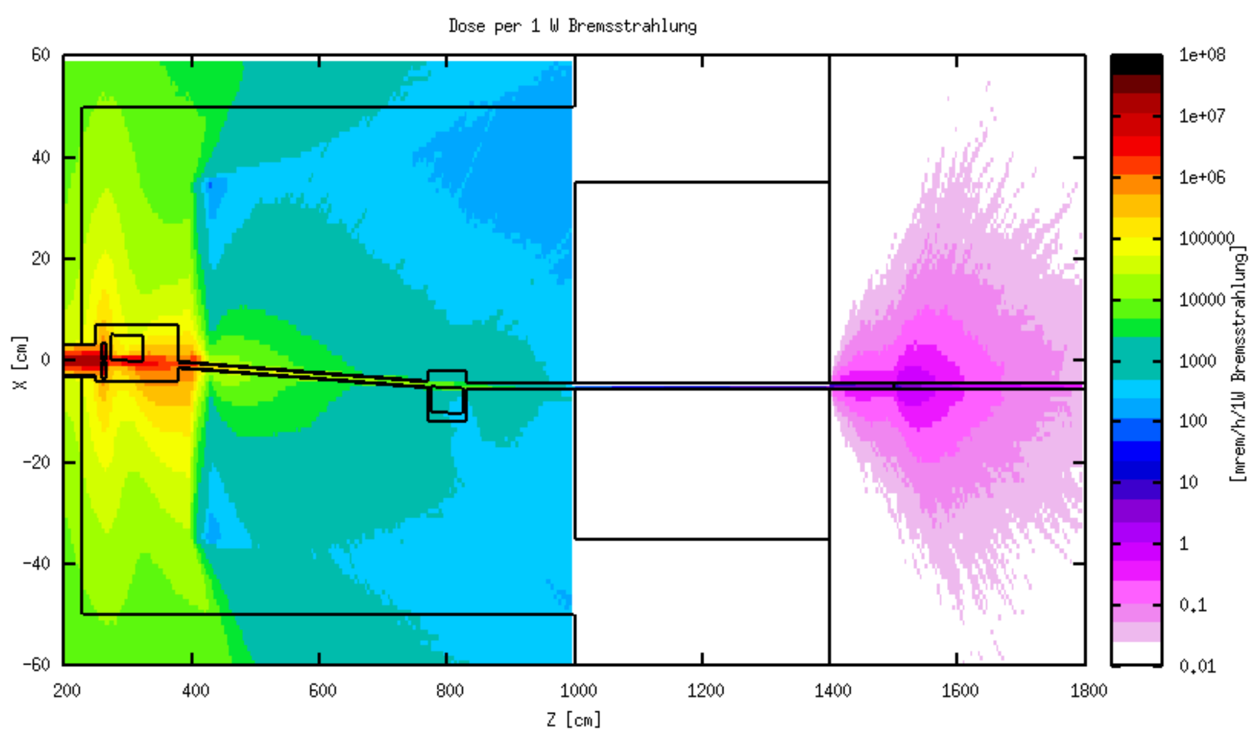


Figure 30 Top view of total dose distributions (average in ±10 cm of beam height) by assuming the end EH wall as "blackhole" (Configuration #6).

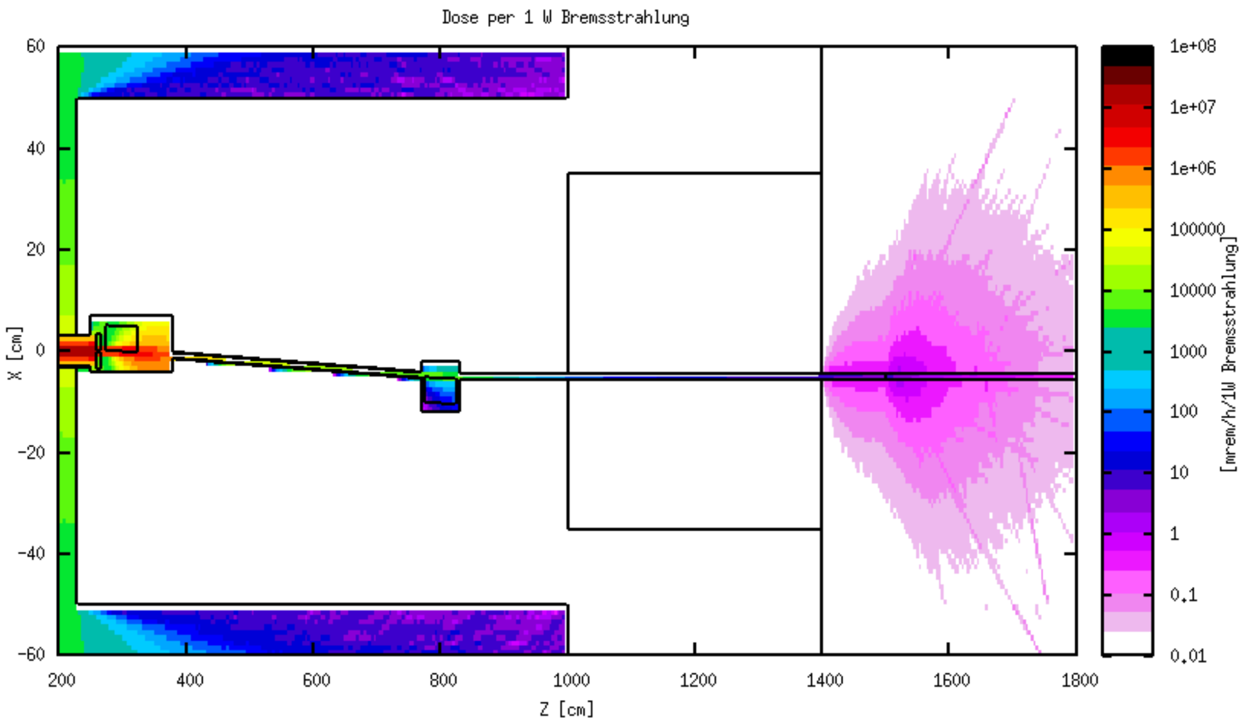


Figure 31 Top view of total dose distributions (average in ±10 cm of beam height) by assuming all collimators and the air inside tunnel and the end EH wall are "blackhole" (Configuration #7).

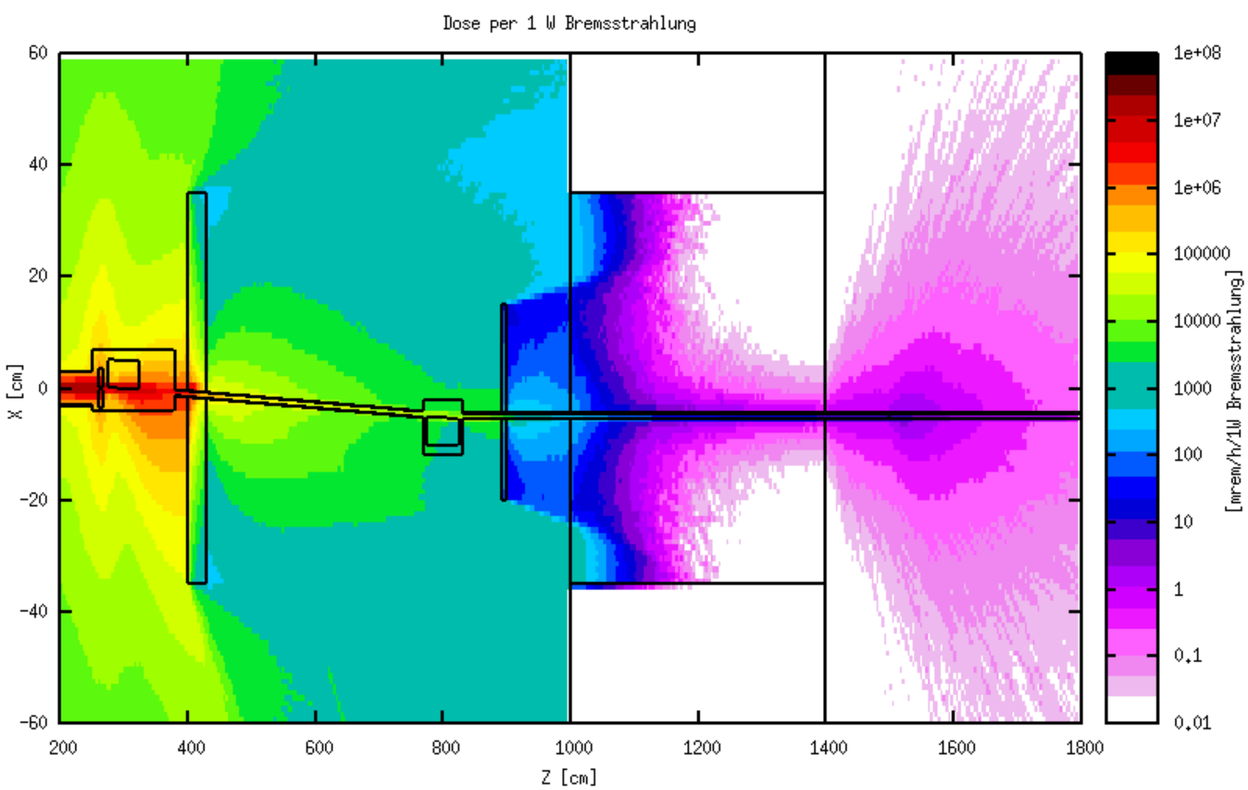


Figure 32 Top view of total dose distributions (average in ±10 cm of beam height) for 5 mm C1 aperture (Configuration #8).

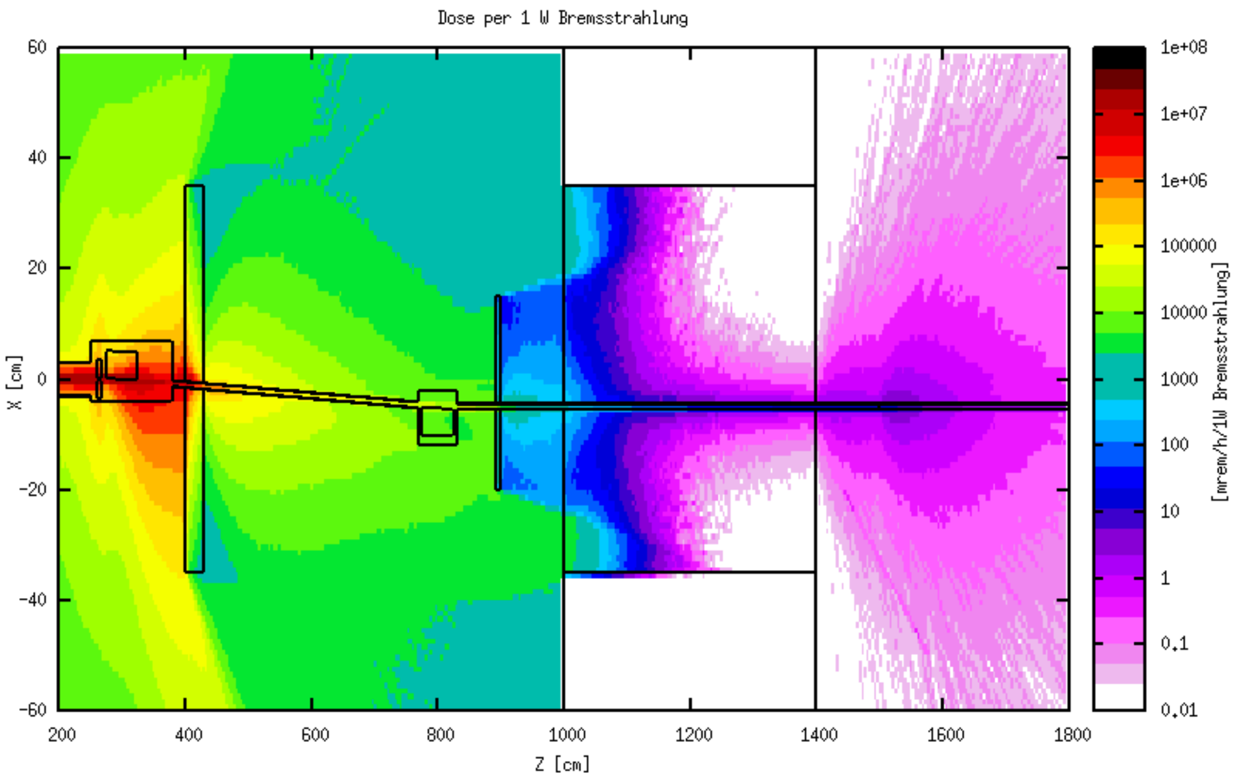


Figure 33 Top view of total dose distributions (average in ±10 cm of beam height) for 10 mm C1 aperture (Configuration #9)

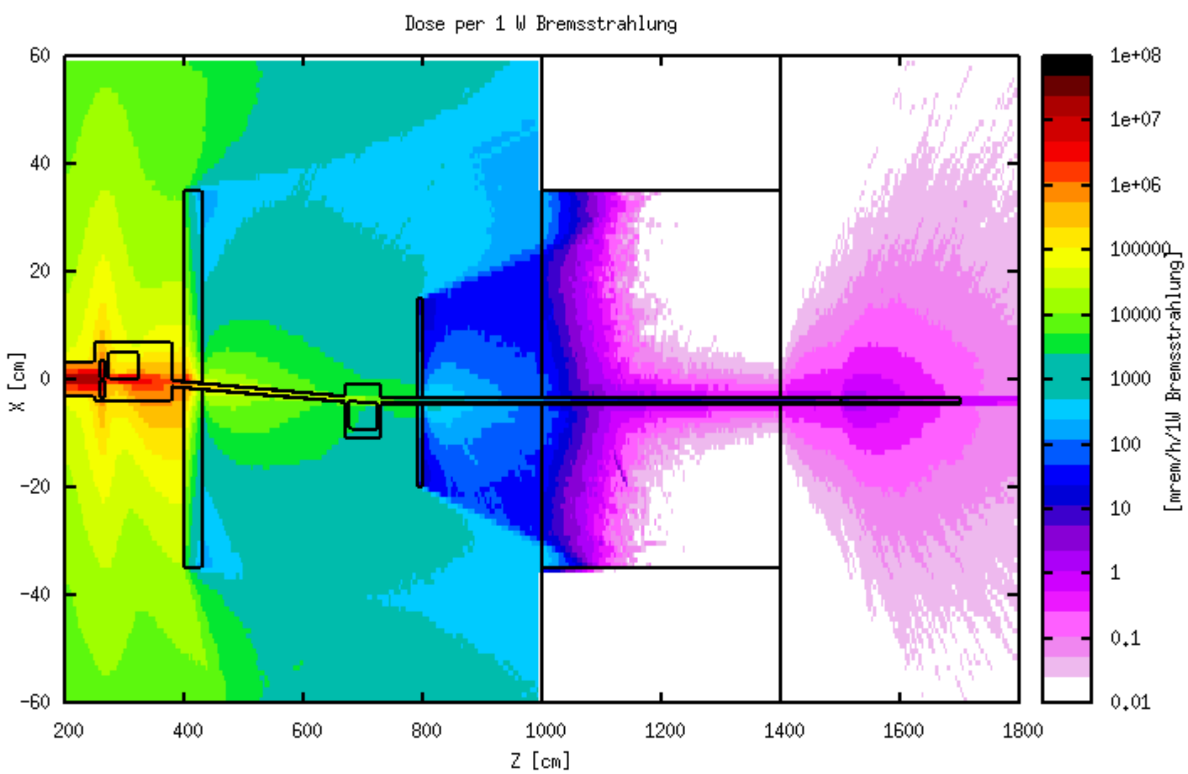


Figure 34 Top view of total dose distributions (average in ±10 cm of beam height) for 40 mm mirror offset (Configuration #10)

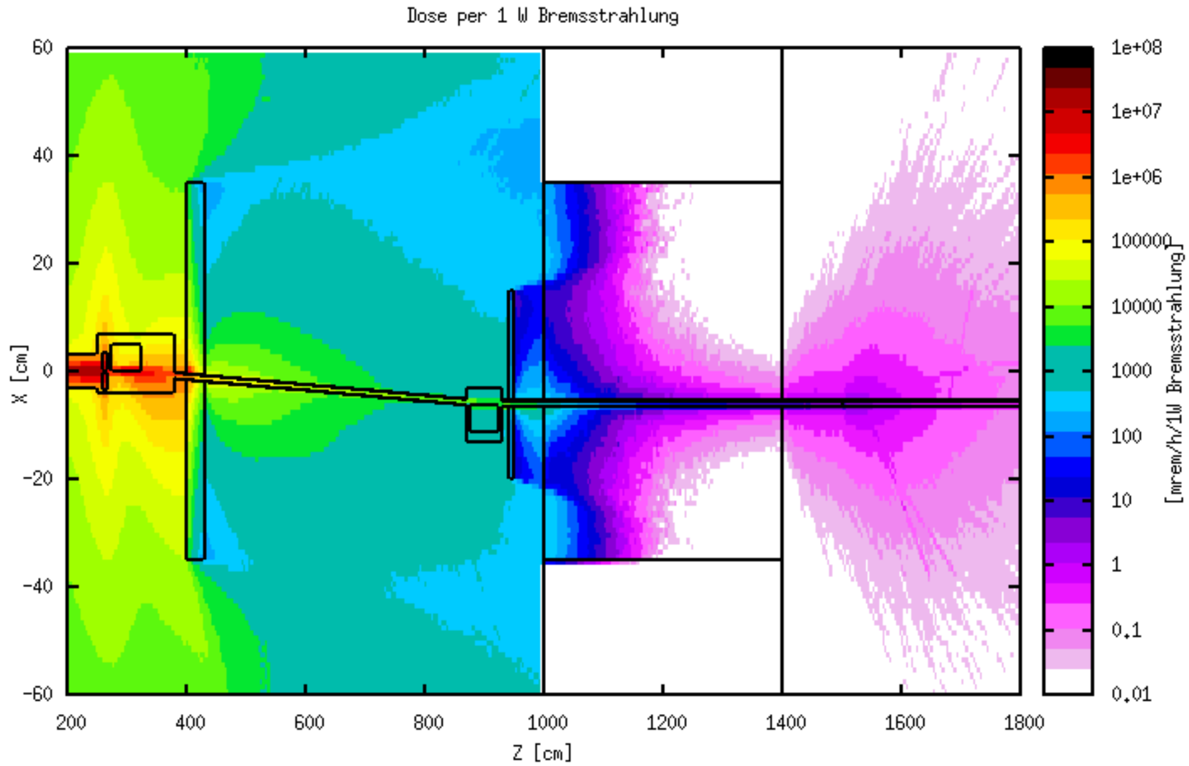
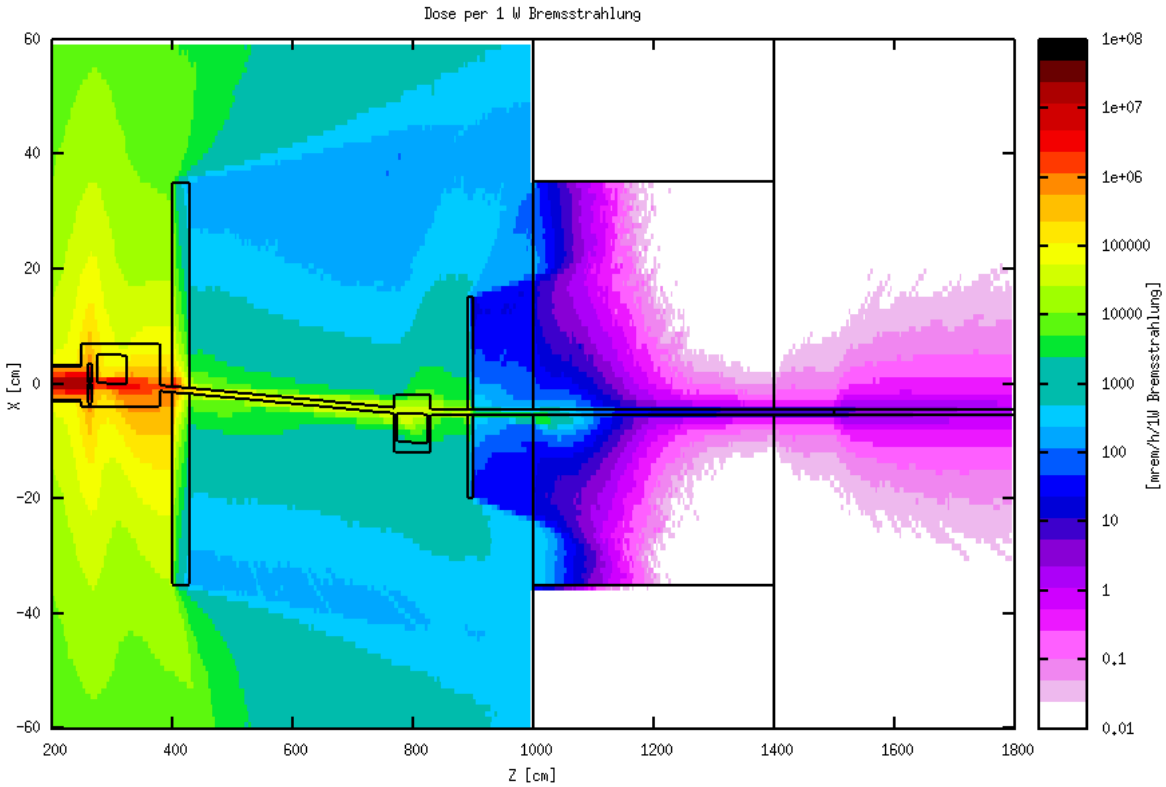
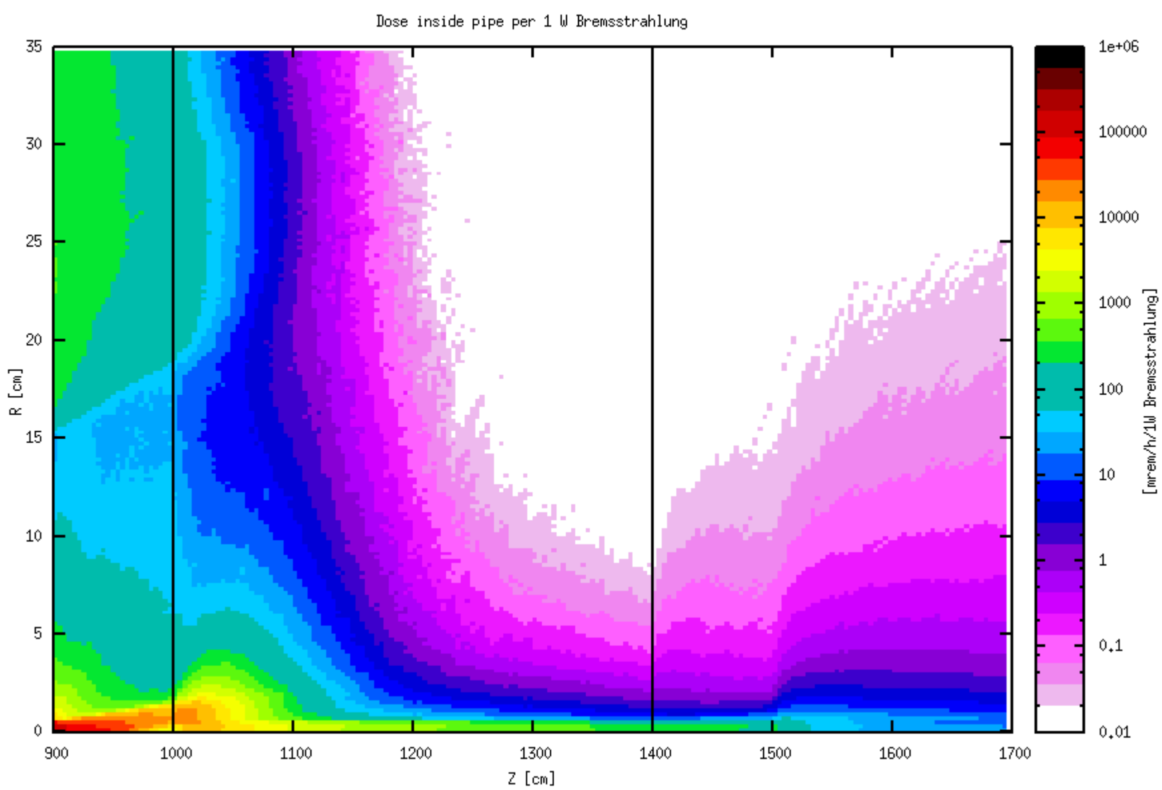


Figure 35 Top view of total dose distributions (average in ±10 cm of beam height) for 60 mm mirror offset (Configuration #11)

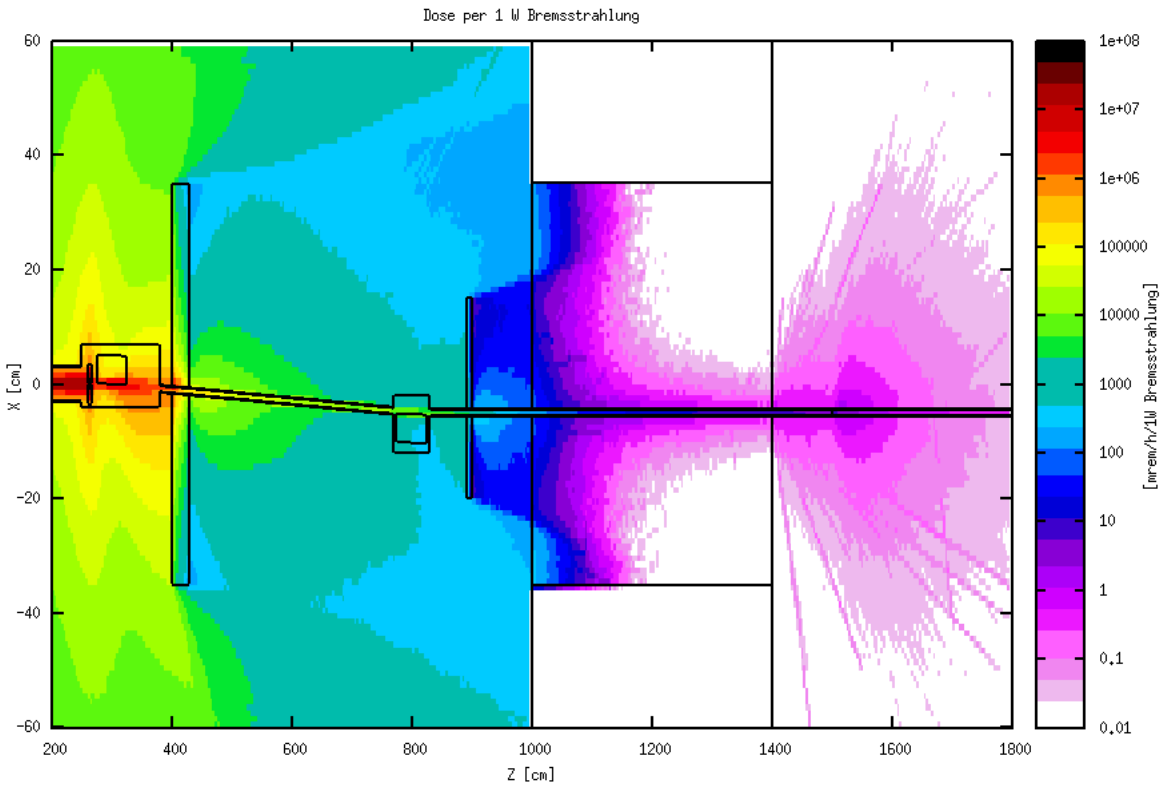


(a) Top view (average in ±10 cm of beam height)

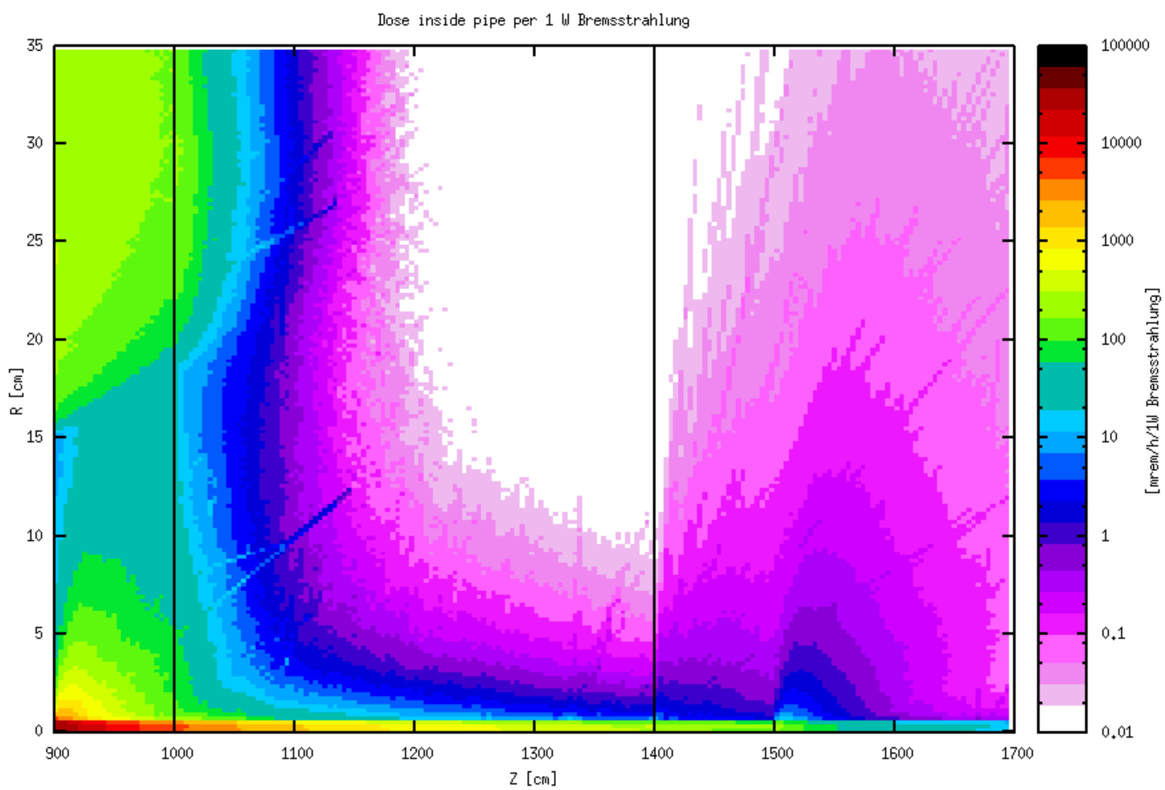


(b) *R*-*Z* view with the center at the beam pipe entering the experimental hall

Figure 36 Total dose distributions for very thin pipe wall (Configuration #12)

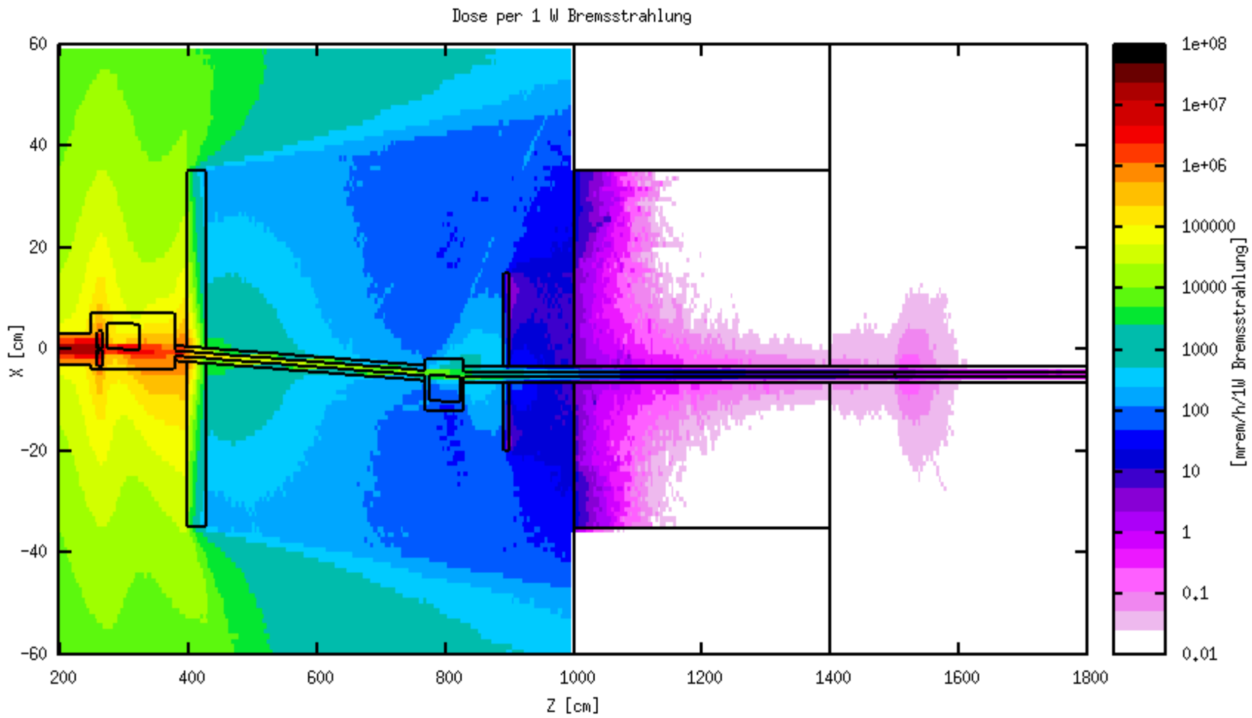


(a) Top view (average in ±10 cm of beam height)

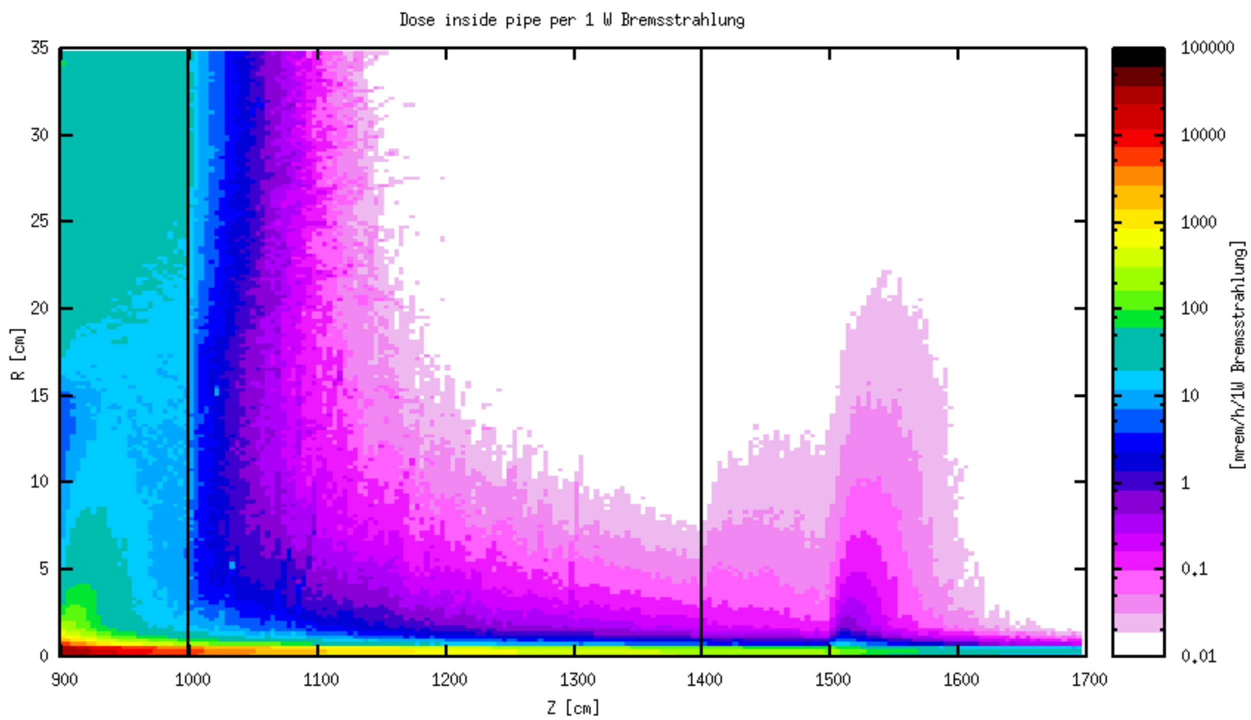


(b) *R*-*Z* view with the center at the beam pipe entering the experimental hall

Figure 37 Total dose distributions for 1.6 mm pipe wall (Configuration #13)

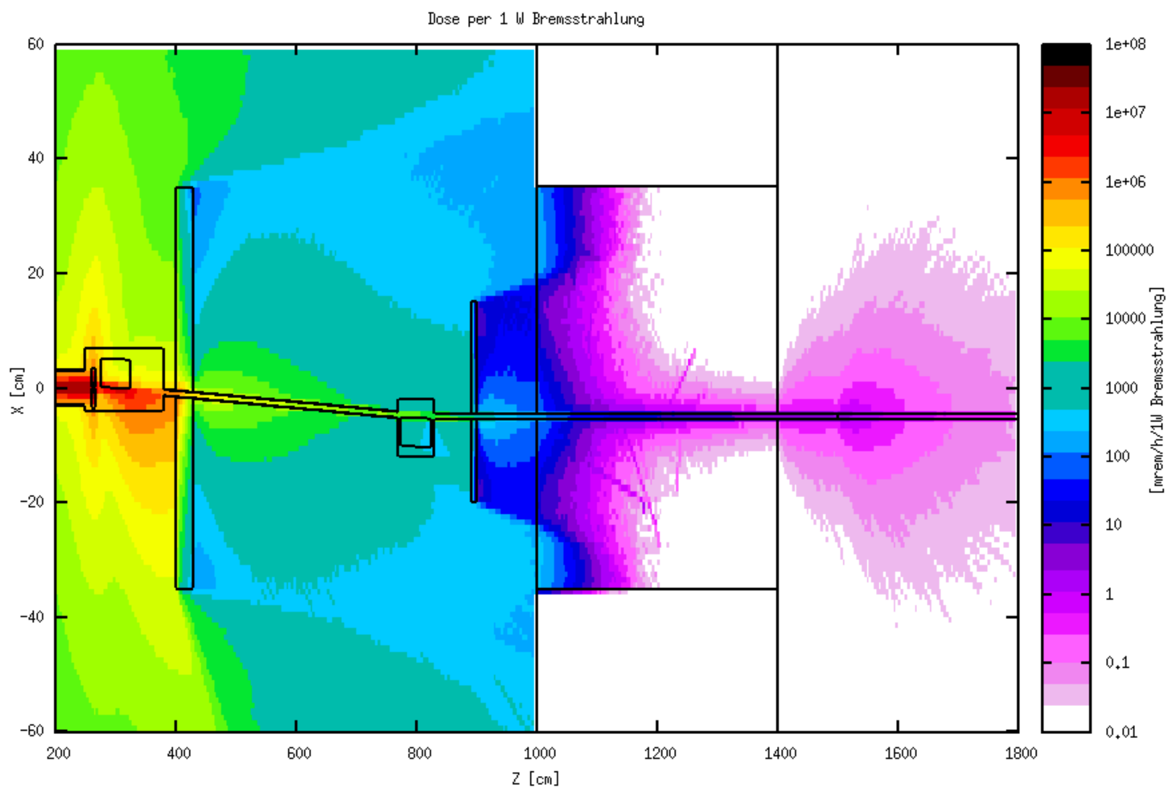


(a) Top view (average in ±10 cm of beam height)

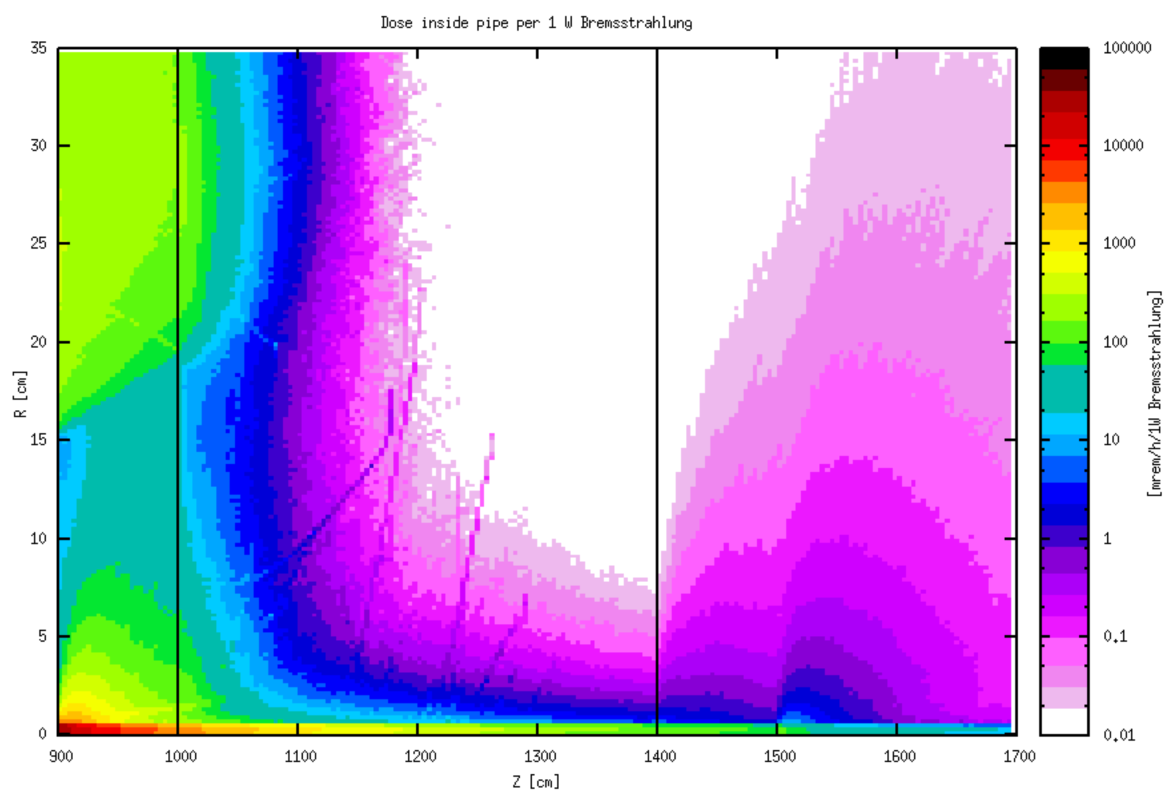


(b) *R*-*Z* view with the center at the beam pipe entering the experimental hall

Figure 38 Total dose distributions for 10 mm pipe wall (Configuration #14)



(a) Top view (average in ±10 cm of beam height)



(b) *R-Z* view with the center at the beam pipe entering the experimental hall

Figure 39 Total dose distributions for copper mirror (Configuration #15)

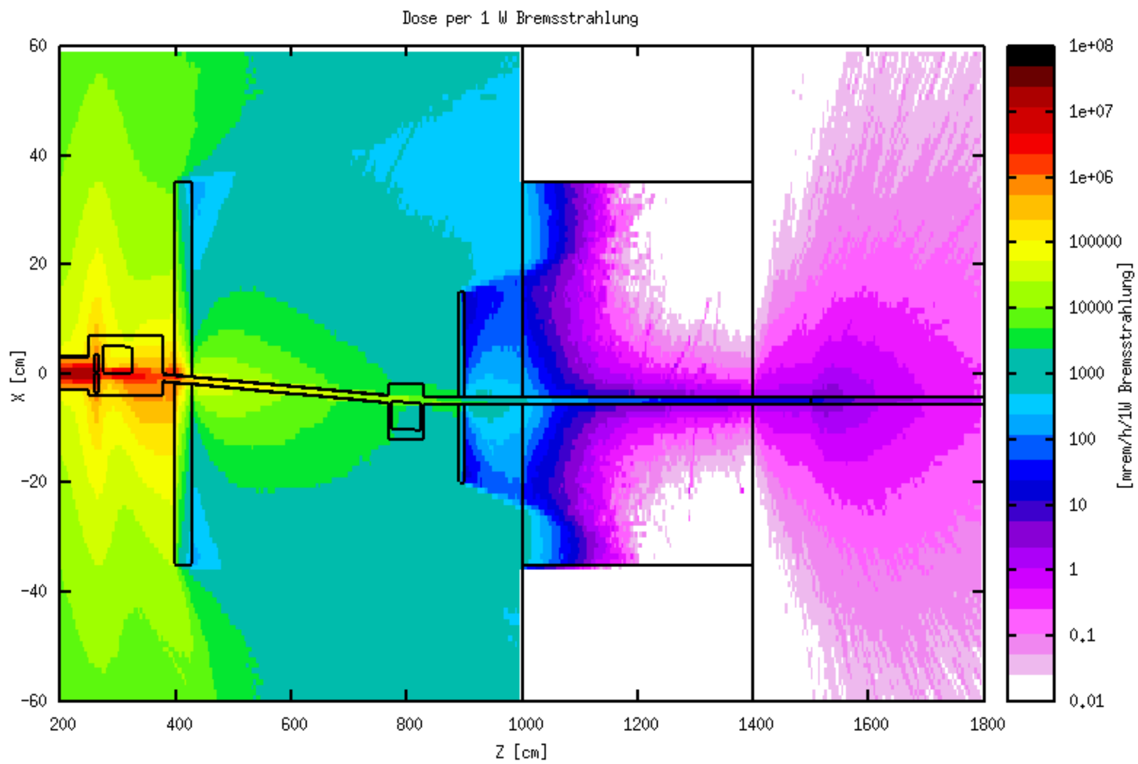


Figure 40 Top view of total dose distributions (average in ±10 cm of beam height) for 12.5 mm ID pipe (Configuration #16)

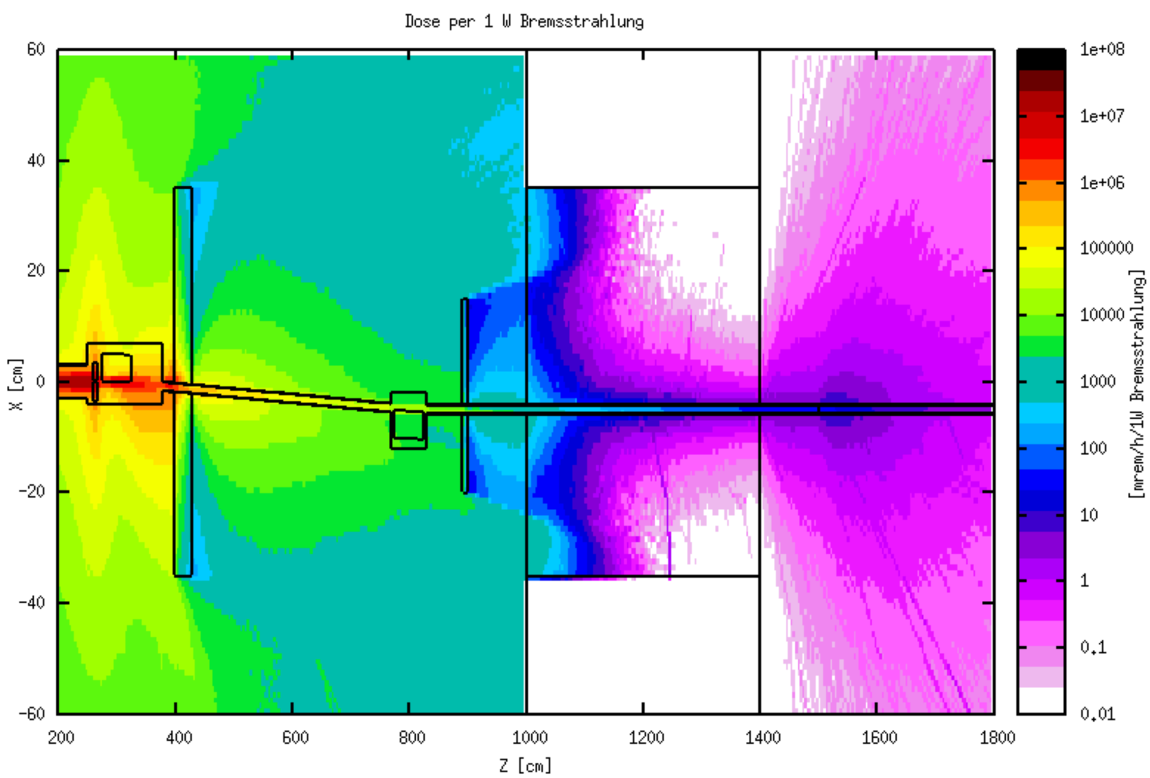


Figure 41 Top view of total dose distributions (average in ±10 cm of beam height) for 15 mm ID pipe (Configuration #17)

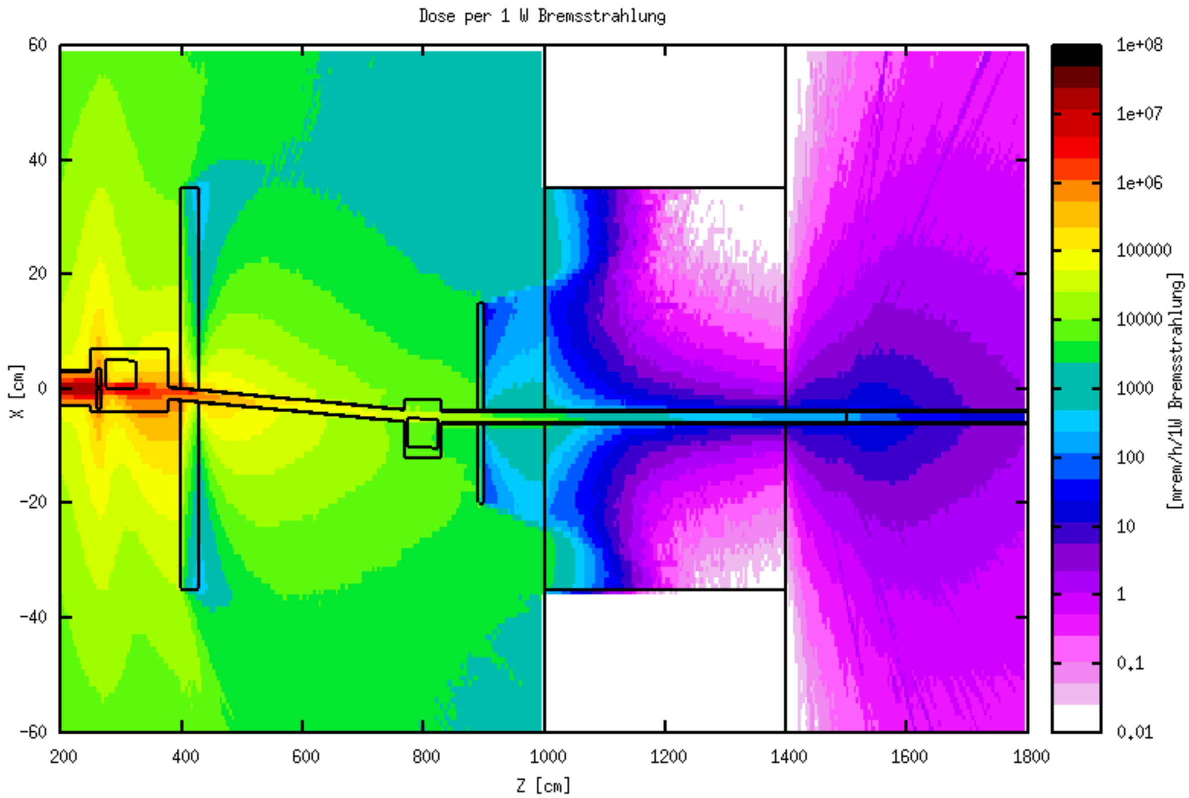


Figure 42 Top view of total dose distributions (average in ±10 cm of beam height) for 20 mm ID pipe (Configuration #18)

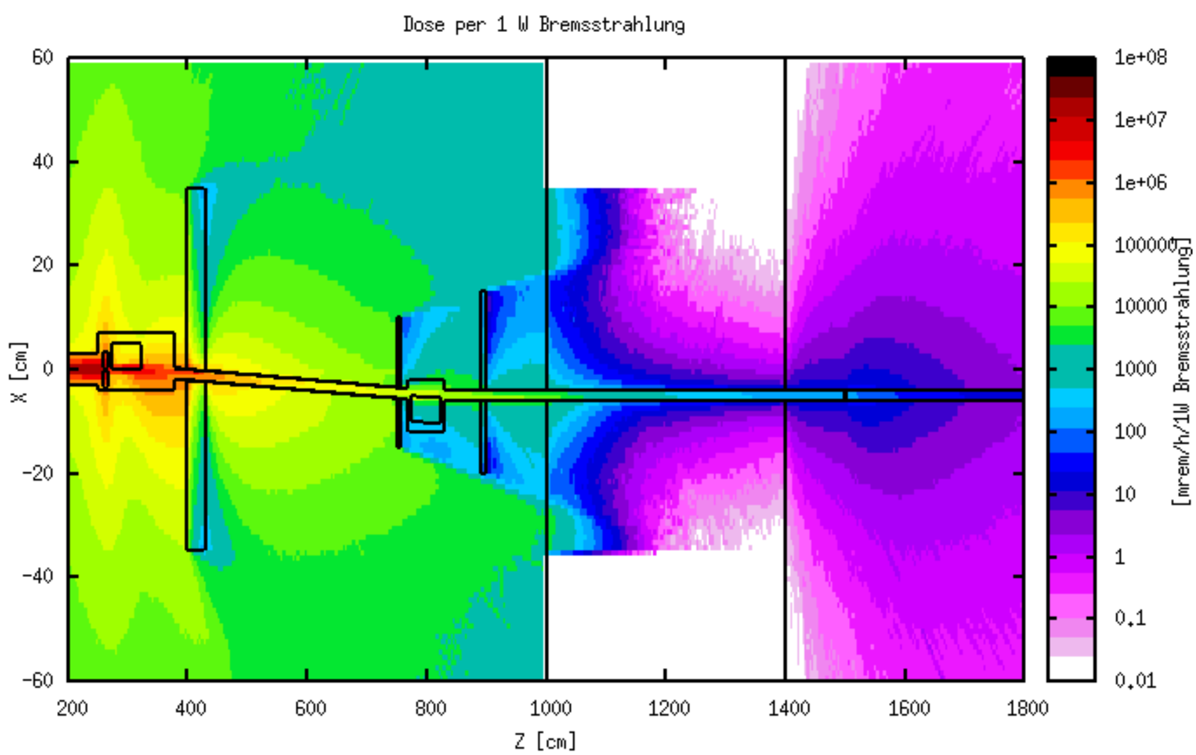


Figure 43 Top view of total dose distributions (average in ±10 cm of beam height) for 20 mm ID pipe with C12 (Configuration #19)

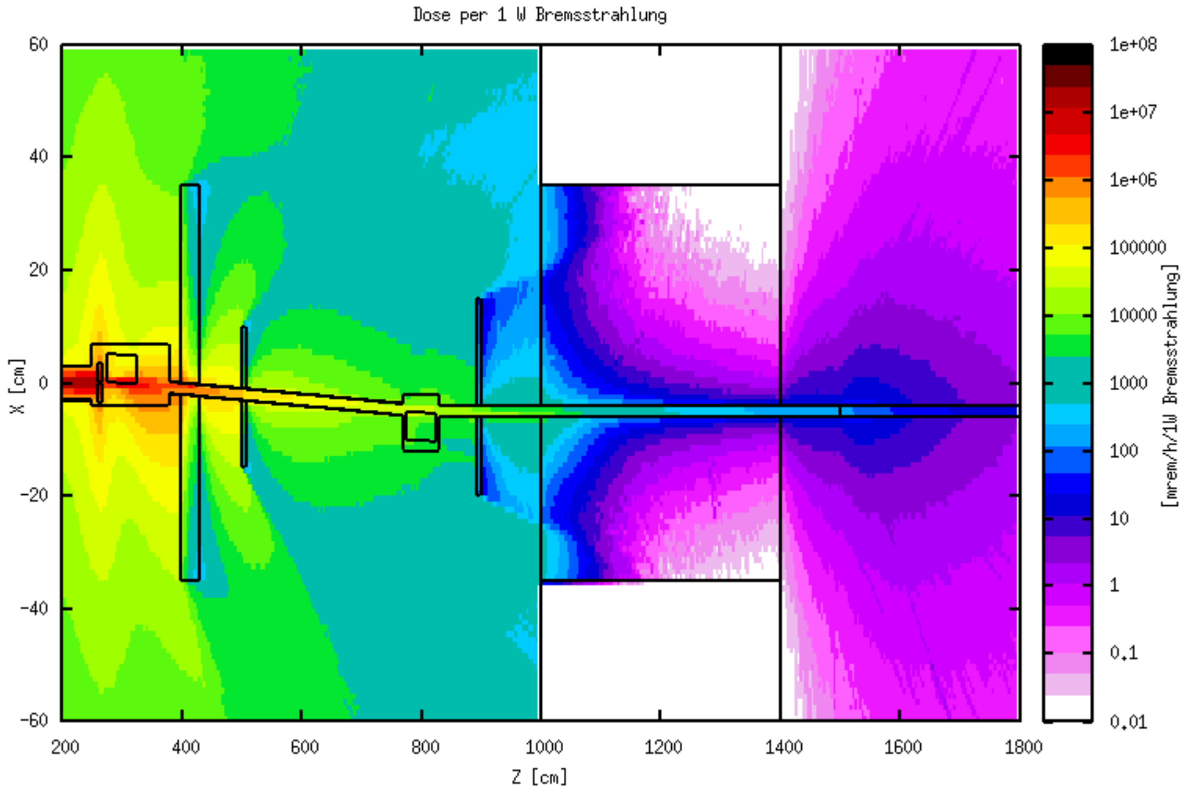


Figure 44 Top view of total dose distributions (average in ±10 cm of beam height) for 10 mm ID pipe with C12 (Configuration #20)

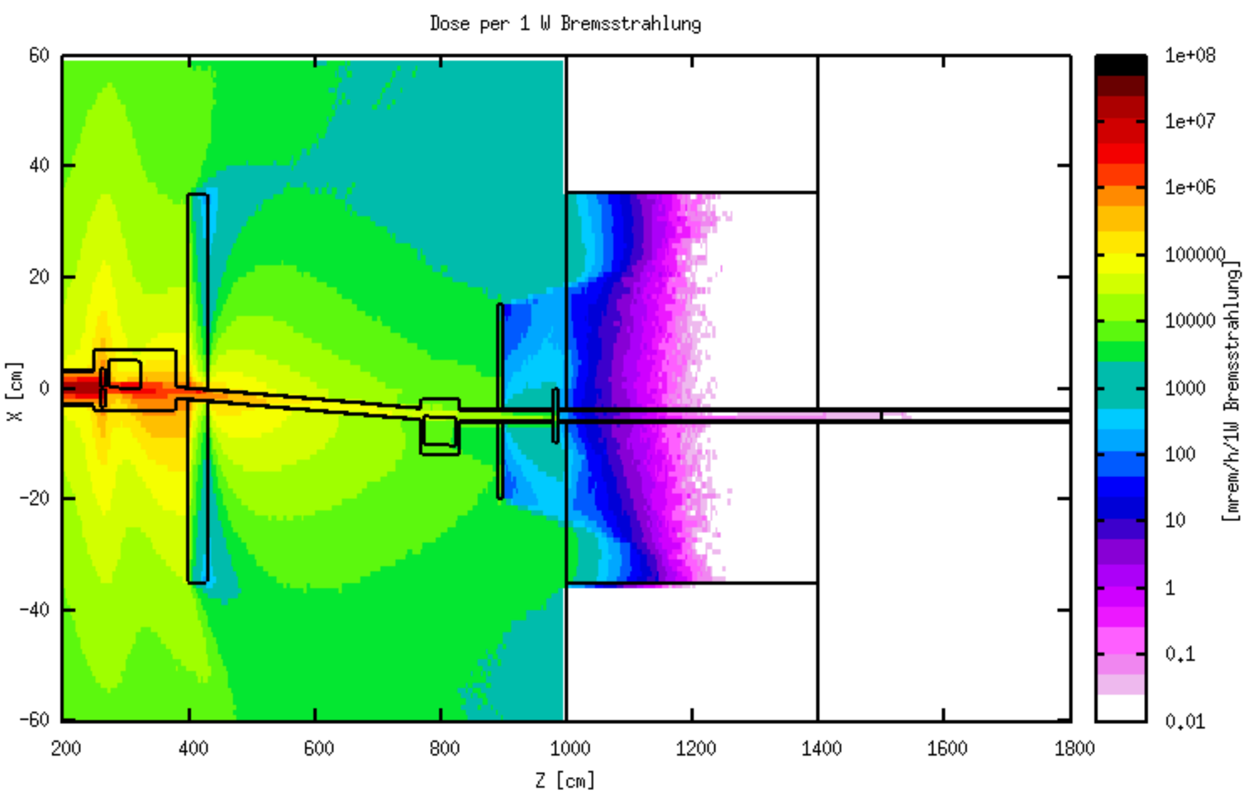


Figure 45 Top view of total dose distribution with personal protection stopper inserted (Configuration #21)

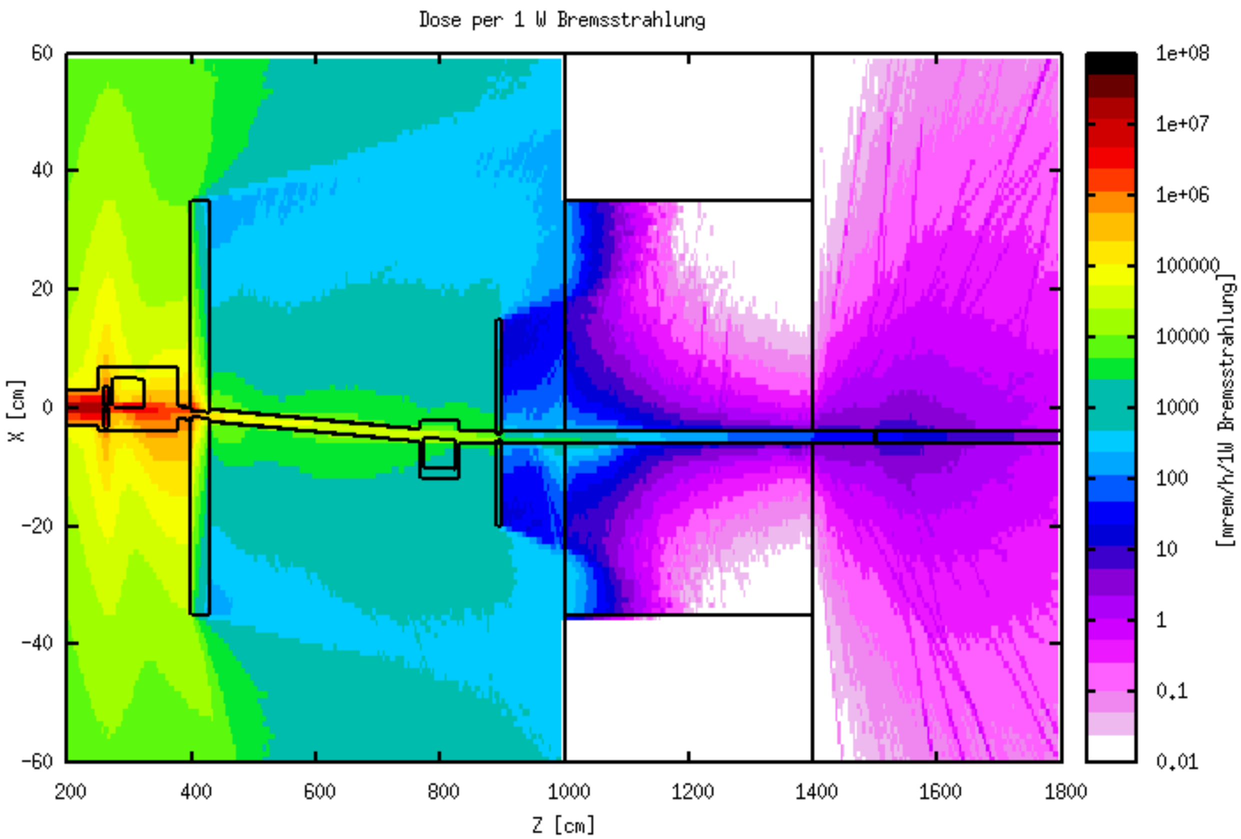


Figure 46 Top view of total dose distribution with BC2 & BC3 aperture 10 mm (Configuration #22)

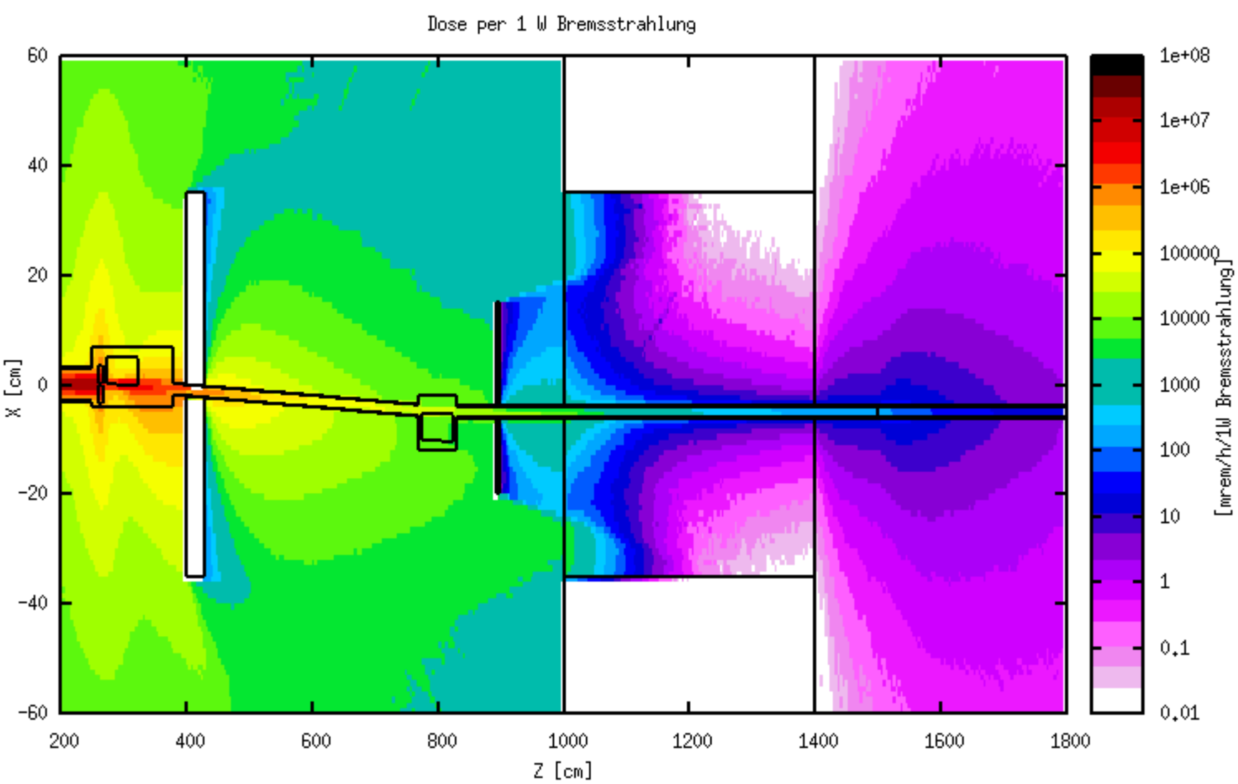
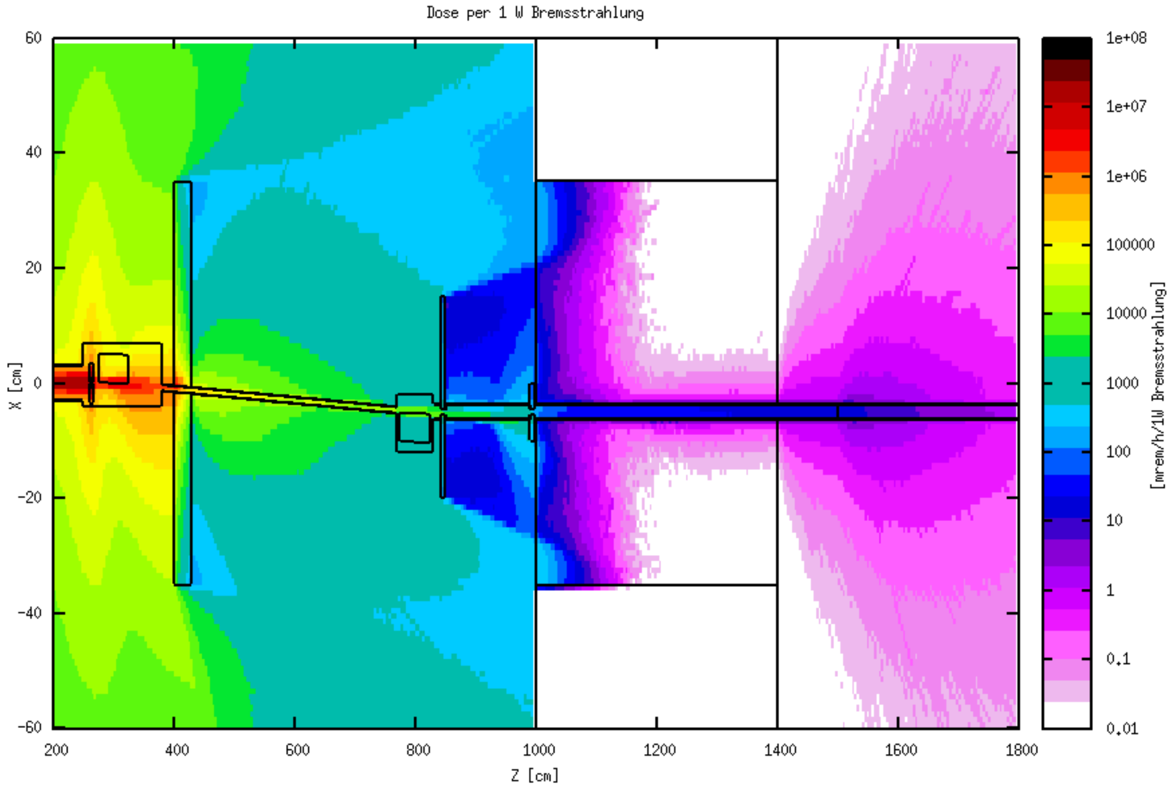
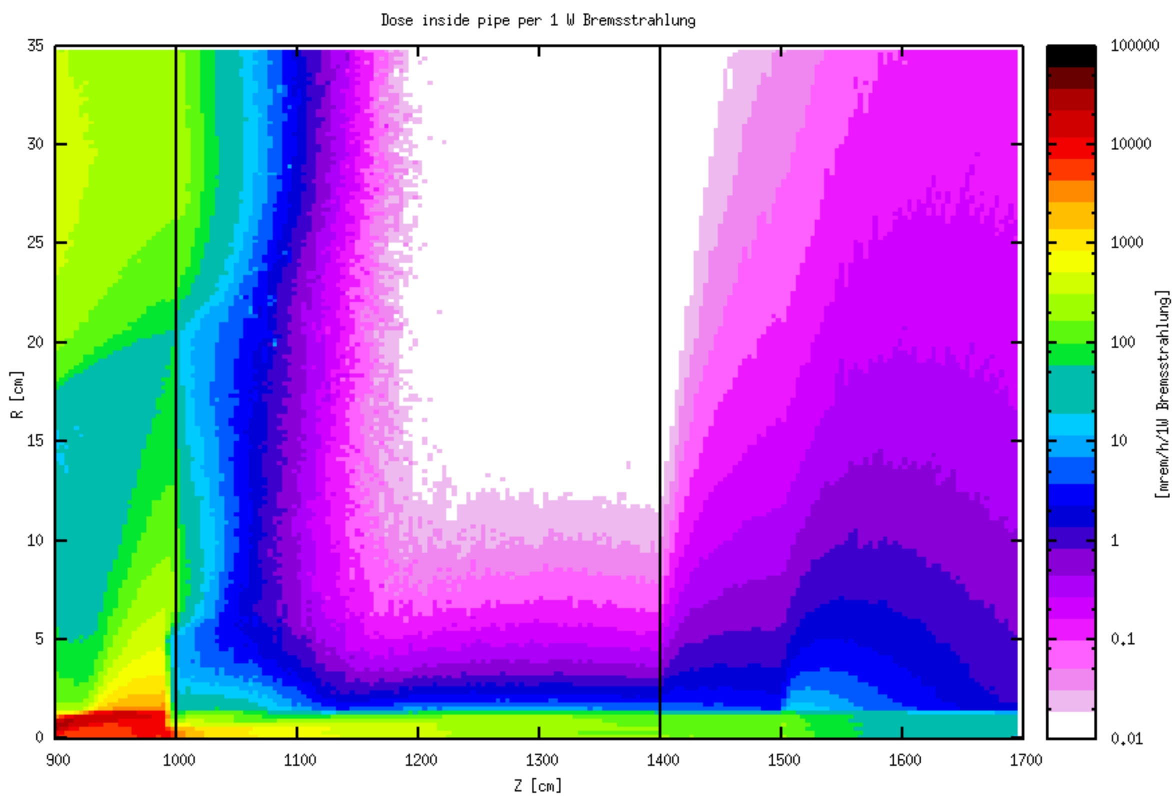


Figure 47 Top view of total dose distribution with BC2 & BC3 "Blackhole" (Configuration #23)

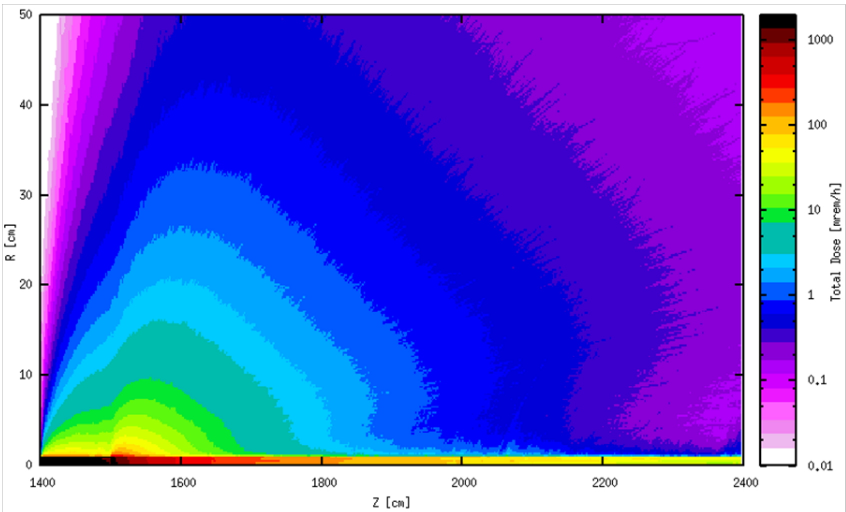


(a) Top view (average in ±10 cm of beam height)

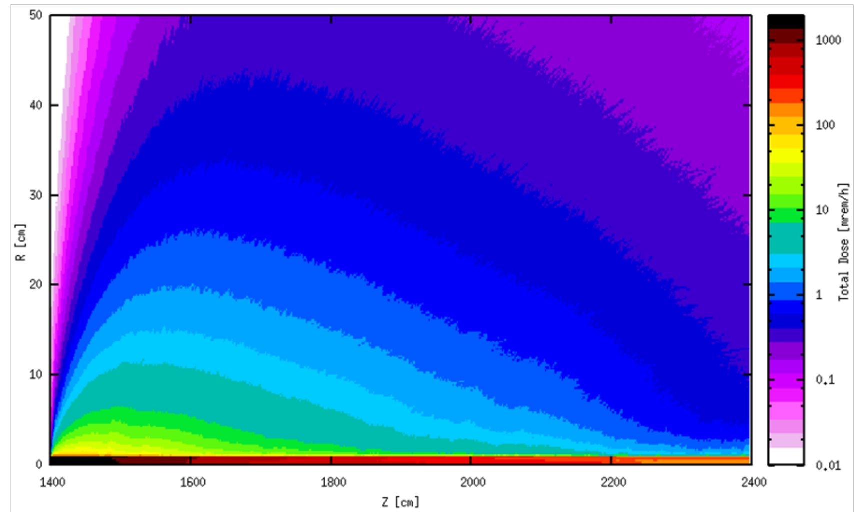


(b) *R*-*Z* view with the center at the beam pipe entering the experimental hall

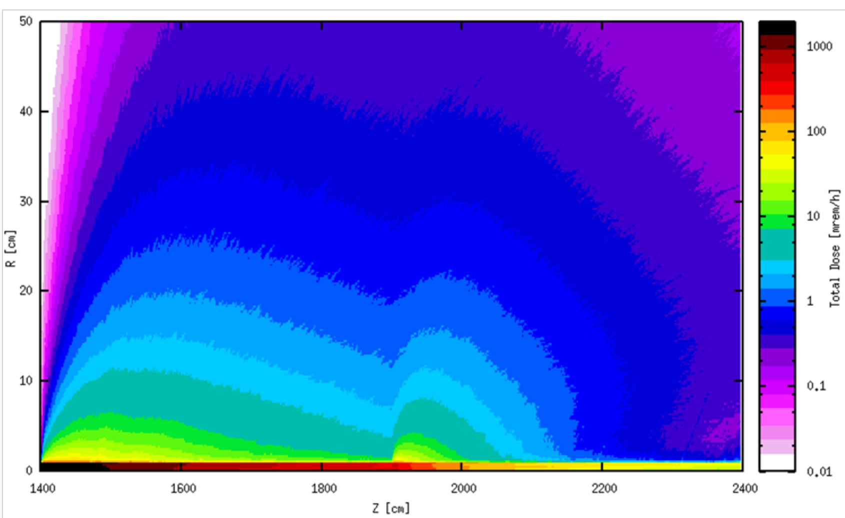
Figure 48 Total dose distributions for 25.4 mm (Configuration #24)



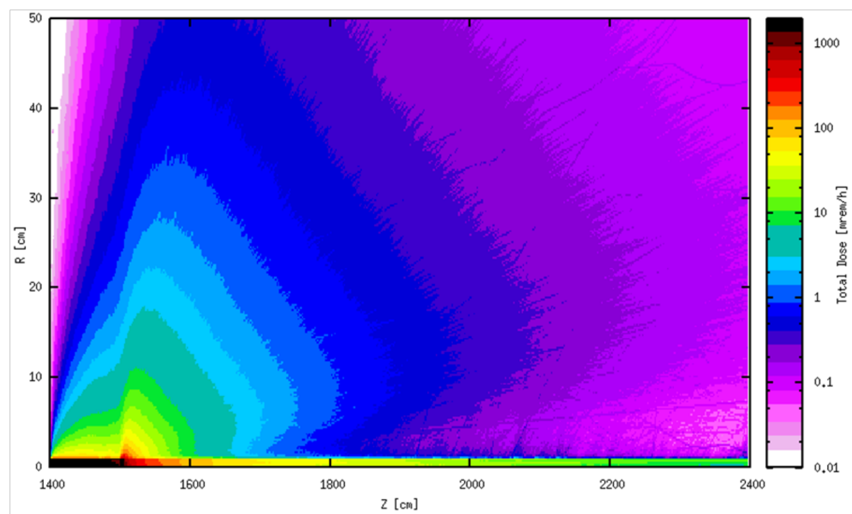
(a) 1 cm iron target at Z = 1500 cm



(b) No target

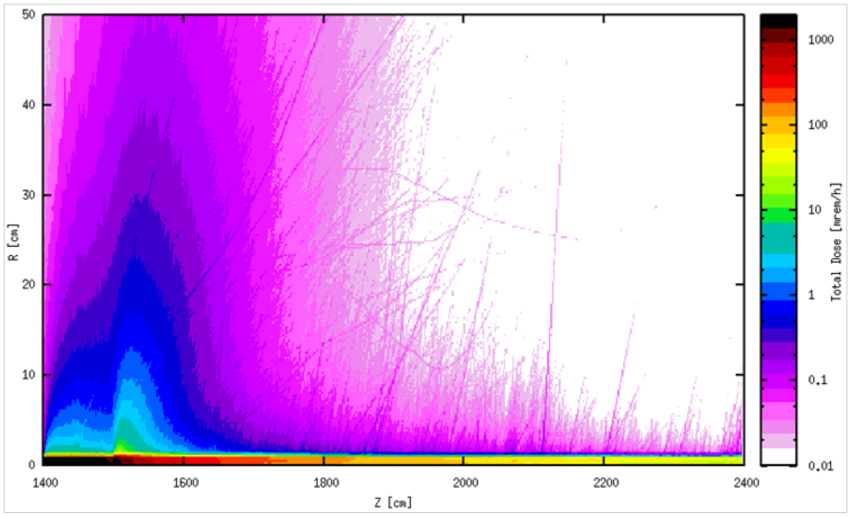


(c) 1 cm iron target at Z = 1900 cm

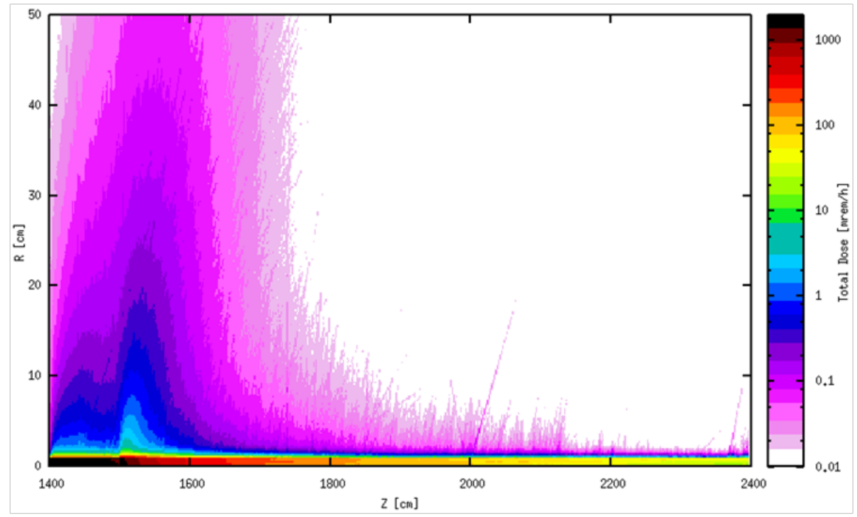


(d) 5 cm iron target at Z = 1500 cm

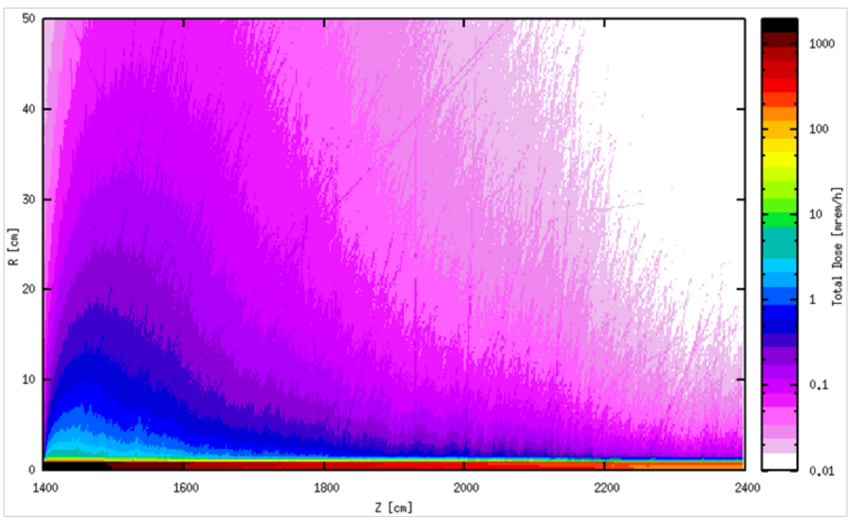
Figure 49. Total dose distribution inside the experimental hall for different target configurations



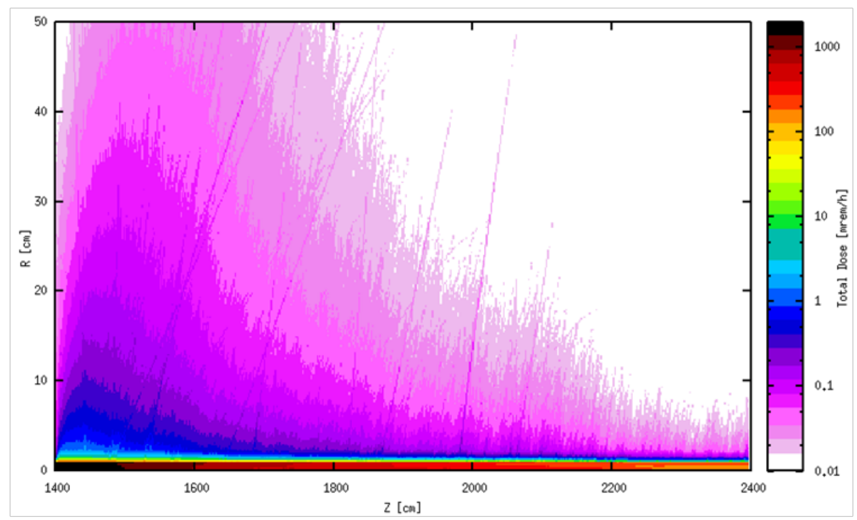
(a) 1 cm iron target at $Z = 1500$ cm with 5 mm lead wrap



(b) 1 cm iron target at $Z = 1500$ cm with 10 mm lead wrap

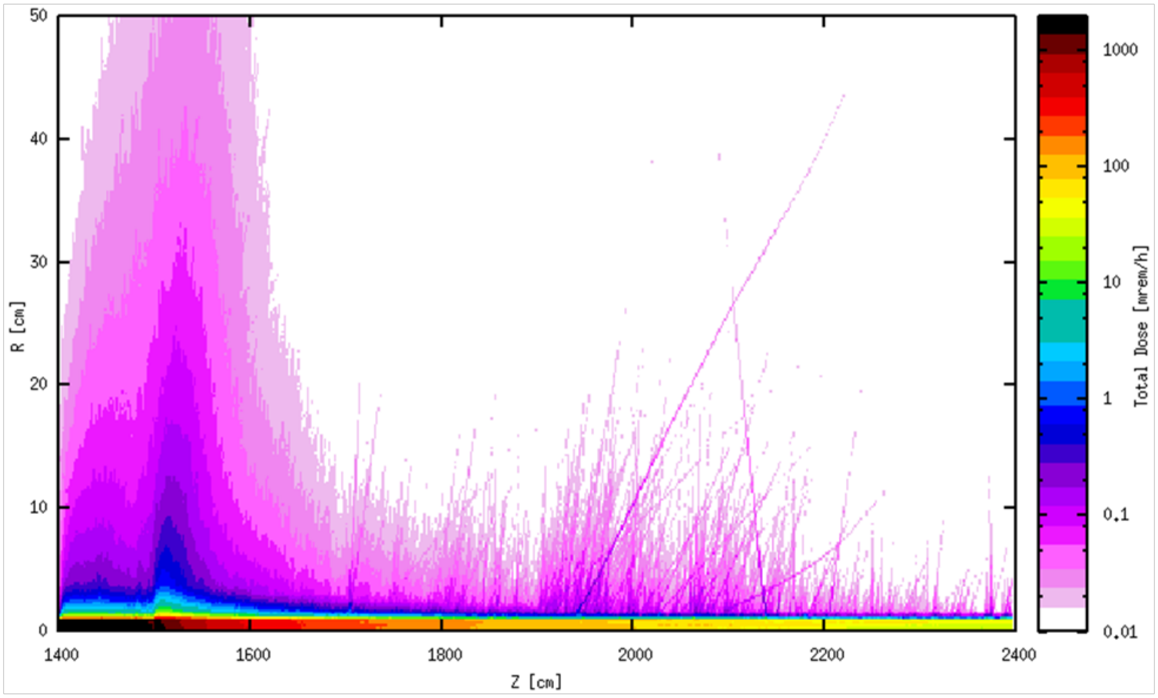


(c) No target in pipe, 5 mm lead wrap

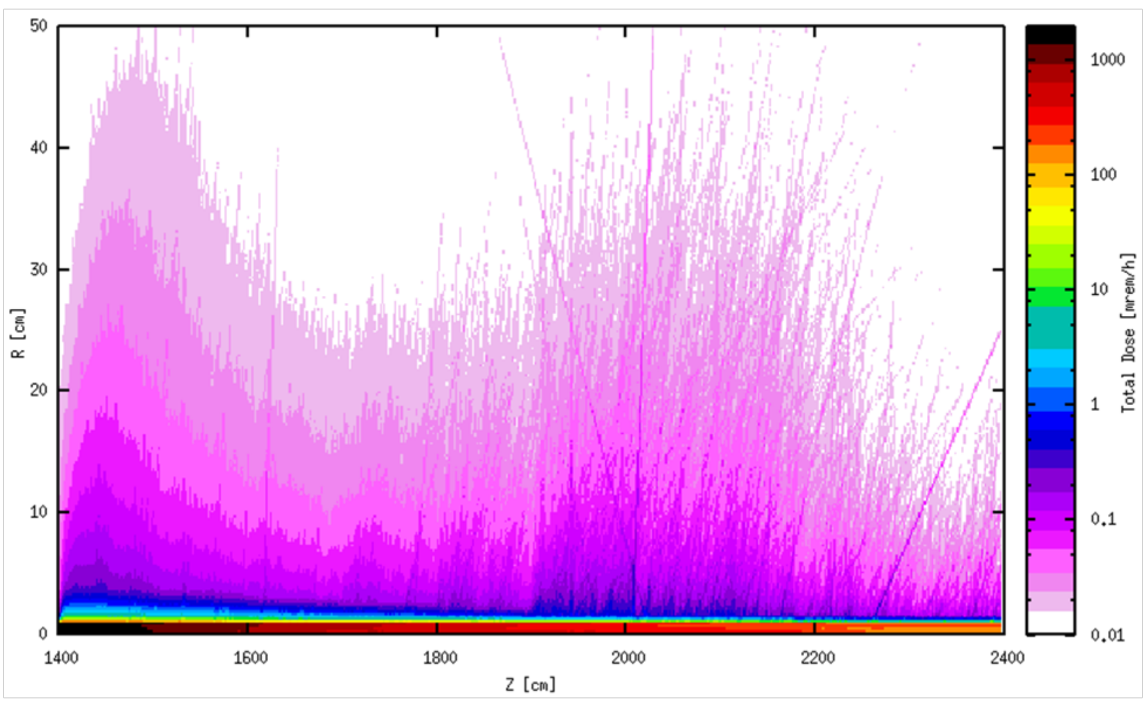


(d) No target in pipe, 10 mm lead wrap

Figure 50 Total dose distribution inside the experimental hall with different lead shielding and target configurations

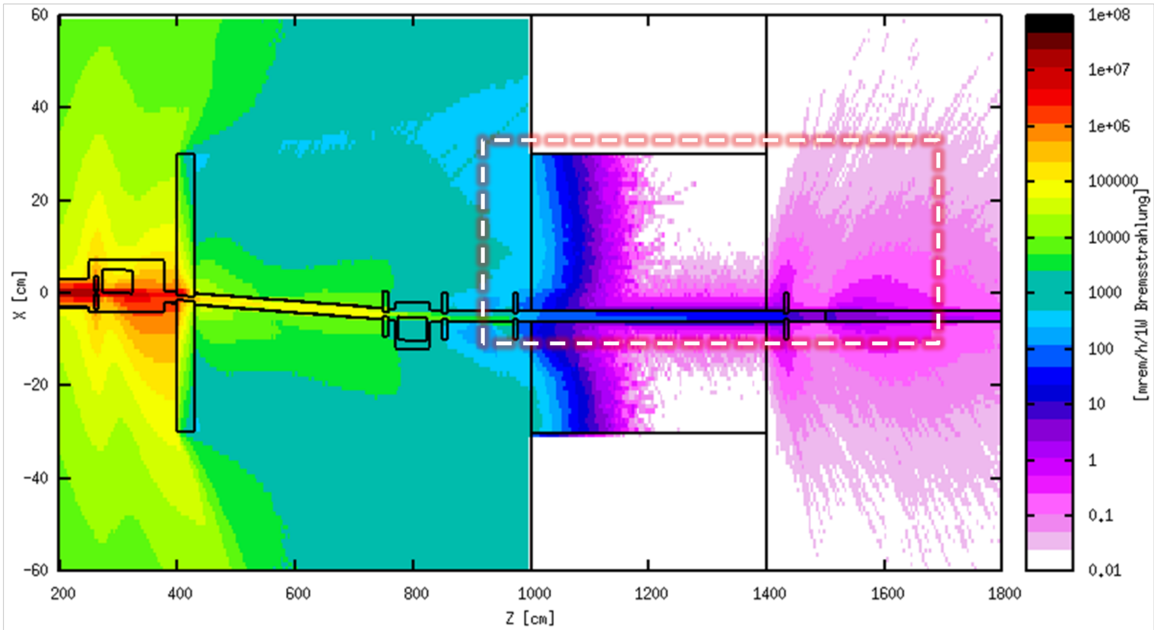


(a) 1 cm iron target at Z = 1500 cm

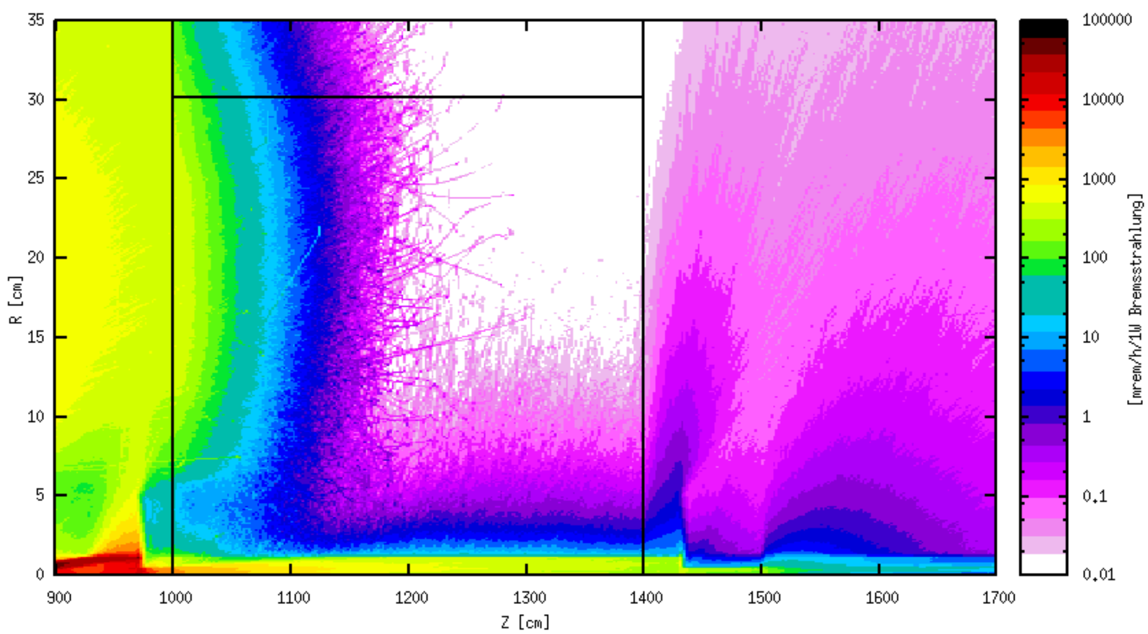


(b) No target

Figure 51 Total dose distribution inside the experimental hall with the stepping shielding under different target configurations



(a) Whole view



(b) Zoomed view of dashed area in (a), *R*-*Z* coordinates

Figure 52 Top view of total dose distribution for 1" OD beam pipe with collimator apertures at 5 mm diameter on C1, 10 mm diameter on others (C2 – C5 and BC2).

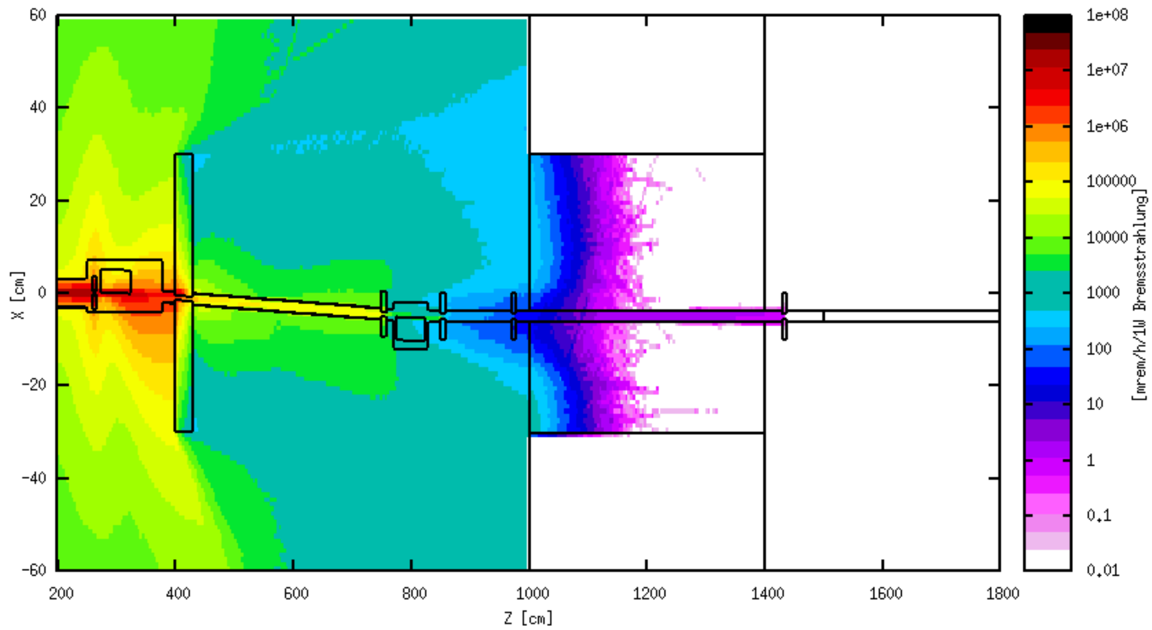
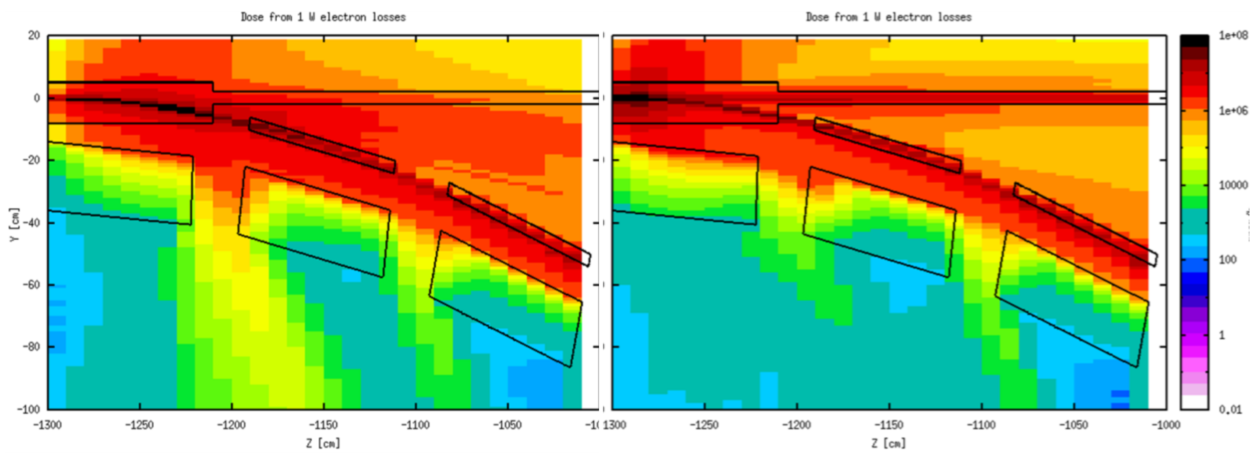
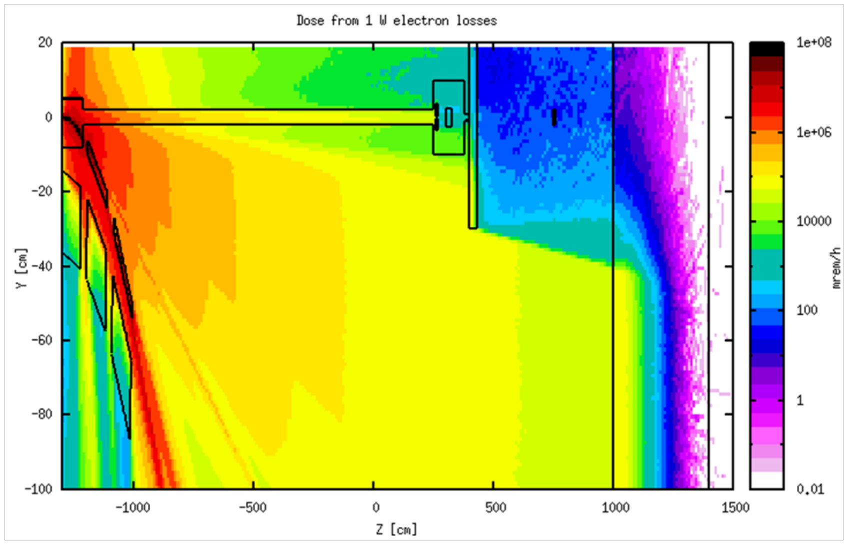


Figure 53 Top view of total dose distribution for 1” OD beam pipe with all collimators (including BC2) have the 5 mm diameter apertures.

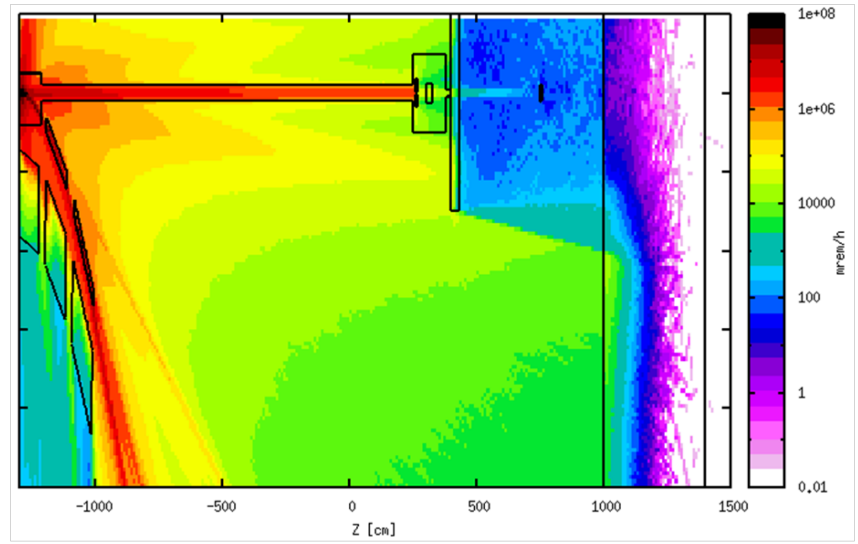


(a) uniform loss (b) point loss

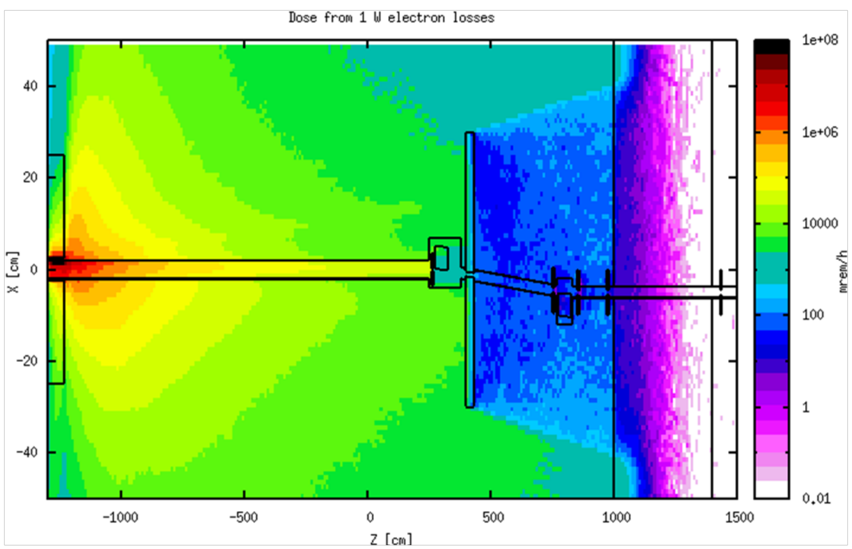
Figure 54 Elevation view of total dose around bending magnets for both uniform and point loss model

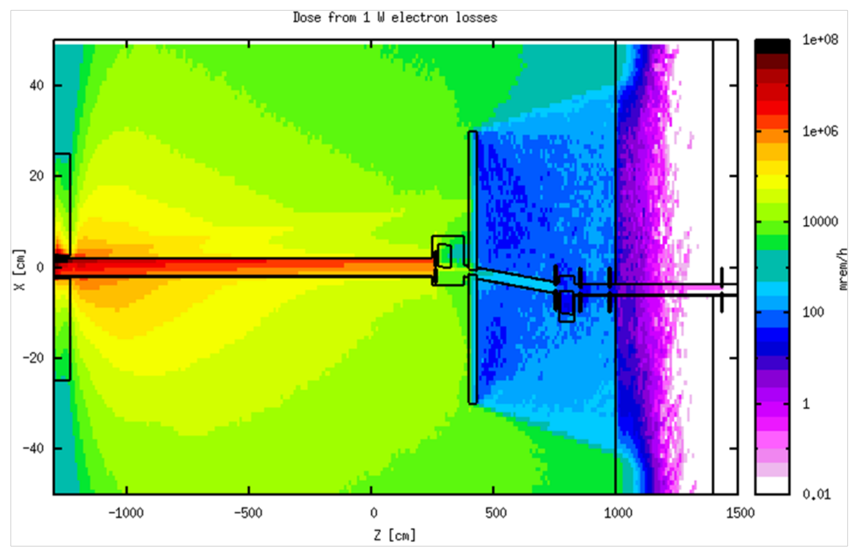


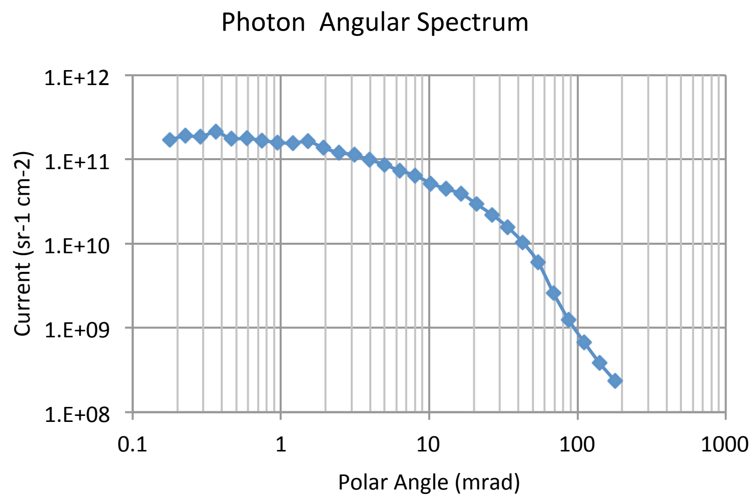
(a) Elevation view, uniform loss



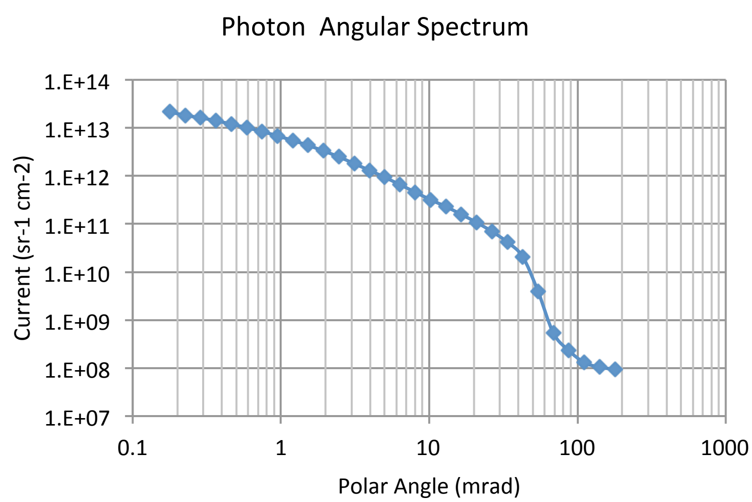
(b) Elevation view, point loss







(a) Uniform loss



(b) Point loss

Figure 56 Angular spectra of photons leaving the 1st magnet (for 4 cm ID pipe to M1)

Appendix B Material Components Used for FLUKA Simulations

List in the format of FLUKA input (elements in mass fractions)

```
* CONCRETE = H C O | Na Mg Al | Si K Ca | Fe
MATERIAL         0.0       0.0      2.35       40.                 0.CONCRETE
COMPOUND       -0.01  HYDROGEN    -0.001    CARBON -0.529107    OXYGENCONCRETE
COMPOUND      -0.016    SODIUM    -0.002  MAGNESIU -0.033872  ALUMINUMCONCRETE
COMPOUND   -0.337021   SILICON    -0.013  POTASSIU    -0.044   CALCIUMCONCRETE
COMPOUND      -0.014      IRON                                        CONCRETE

* Air
MATERIAL         0.0       0.0 0.0012048       41.                 0.AIR
COMPOUND    -1.24E-4    CARBON -0.755267  NITROGEN -0.231781    OXYGENAIR
COMPOUND   -0.012827     ARGON      -0.0                -0.0          AIR

* Stainless Steel 316
MATERIAL         0.0       0.0       8.0       42.       0.0       0. STEEL316
COMPOUND       -0.08    CARBON    -0.045   PHOSPHO     -0.03    SULFURSTEEL316
COMPOUND       -0.75   SILICON     -17.0  CHROMIUM      -2.0  MANGANESSTEEL316
COMPOUND     -65.495      IRON     -12.0    NICKEL     -0.10  NITROGENSTEEL316
COMPOUND       -2.50  MOLYBDEN                                        STEEL316

* Tungsten Heavy Alloy
MATERIAL         0.0       0.0      18.0       43.                 0.WALLOY
COMPOUND       -0.95  TUNGSTEN    -0.035    NICKEL    -0.015      IRONWALLOY

* A36 Steel
MATERIAL                            7.80       44.                    A36STEEL
COMPOUND      -98.00      IRON     -1.03  MANGANES     -0.29    CARBONA36STEEL
COMPOUND       -0.28   SILICON     -0.20    COPPER                    A36STEEL
COMPOUND       -0.10   PHOSPHO     -0.10    SULFUR                    A36STEEL
```

Appendix C Physics Parameters for FLUKA Simulations

Physics Setting

- Default: FLUKA "PRECISIOn" setting
- Photonuclear interaction are activated at all energies for all materials
- Muon pair coherent production by photons is activated

Cut-off energies:

- Hadrons and muons: 1 keV
- Neutrons: down to thermal energies as default setting
- Electromagnetic transport:
    - Default: 50 keV for electrons and 20 keV for photons
    - On titanium foil: 500 keV for electrons and 100 keV for photons
    - High cut-off on several components for fast simulation:
        - On C1: 5 MeV for electrons and 3 MeV for photons
        - On BC2: 8 MeV for electrons and 5 MeV for photons
        - On the first 2 m wall: 5 MeV for electrons and 3 MeV for photons
        - On the wall between 2.0-2.5 m: 2 MeV for electrons and 1 MeV for photons
- Electromagnetic production:
    - Default: 200 keV for electrons and 100 keV for photons
    - On titanium foil: 500 keV for electrons and 100 keV for photons

Physics biasing:

- Leading particle biasing is activated for all supported physical effects in all regions
- On titanium foil: biasing for bremsstrahlung is activated as the mean free paths are reduced by a factor 100
- The interaction length of muon production by photons is reduced by a factor 10^4
- The hadronic inelastic interaction length of particle is reduced by multiplying by 0.02 for WHA, silicon and steels and is applied to all generations. At the interaction point sampled according to the biased probability, the particle always survives with a reduced weight. Secondaries are created in any case and their weight adjusted taking into account the ratio between biased and physical survival probability.

Region biasing:

- Used along the XTOD pipes and mirrors
- EH wall is separated into layers with different weights

Appendix D FLUKA Input including XTOD (as Figure 7) and BYD Magnets (as Figure 9)

```
* --+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
TITLE
NGLS XTOD
* --+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
GLOBAL           99.
DEFAULTS                                                              PRECISION
BEAM           -2.40       0.0       0.0    0.0000    0.0000      -1.0ELECTRON
BEAMPOS          2.0       0.0   -1300.0    0.0001   -0.0006
SOURCE        689.10     0.001
*
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7...+...8
MATERIAL         19.   39.0983     0.862       26.                  0.POTASSIU
MATERIAL         26.    55.847      7.72       27.                  0.AVERAGFE
MATERIAL         27.   58.9332      8.90       28.                  0.COBALT
MATERIAL         23.   50.9415      6.11       29.                  0.VANADIUM
MATERIAL          5.    10.811      2.34       30.                  0.BORON
MATERIAL         60.    144.24      7.01       31.                  0.NEODYMIU
MATERIAL          6.    12.011     3.520       32.                  0.DIAMOND
MATERIAL         24.   51.9961      7.18       33.                  0.CHROMIUM
MATERIAL         25.  54.93805      7.44       34.                  0.MANGANES
MATERIAL         40.    91.224     6.506       35.                  0.ZIRCONIU
MATERIAL         56.   137.327       3.5       36.                  0.BARIUM
MATERIAL         16.    32.065     1.960       37.                  0.SULFUR
MATERIAL         15.  30.97376     1.823       38.                  0.PHOSPHO
MATERIAL         42.     95.94     10.22       39.                  0.MOLYBDEN
*
* * CONCRETE = H C O | Na Mg Al | Si K Ca | Fe
MATERIAL         0.0       0.0      2.35       40.                  0.CONCRETE
COMPOUND       -0.01  HYDROGEN    -0.001    CARBON -0.529107    OXYGENCONCRETE
COMPOUND      -0.016    SODIUM    -0.002  MAGNESIU -0.033872  ALUMINUMCONCRETE
COMPOUND   -0.337021   SILICON    -0.013  POTASSIU    -0.044   CALCIUMCONCRETE
COMPOUND      -0.014      IRON                                      CONCRETE
*
* Air
MATERIAL         0.0       0.0 0.0012048       41.                  0.AIR
COMPOUND    -1.24E-4    CARBON -0.755267  NITROGEN -0.231781    OXYGENAIR
COMPOUND   -0.012827     ARGON      -0.0                -0.0           AIR
*
* Stainless Steel 316
MATERIAL         0.0       0.0       8.0       42.       0.0       0. STEEL316
COMPOUND       -0.08    CARBON    -0.045   PHOSPHO     -0.03    SULFURSTEEL316
COMPOUND       -0.75   SILICON     -17.0  CHROMIUM      -2.0  MANGANESSTEEL316
COMPOUND     -65.495      IRON     -12.0    NICKEL     -0.10  NITROGENSTEEL316
COMPOUND       -2.50  MOLYBDEN                                      STEEL316
*
* Tungsten Heavy Alloy: W Ni Fe: HD18DV
MATERIAL         0.0       0.0      18.0       43.                  0.WALLOY
COMPOUND       -0.95  TUNGSTEN    -0.035    NICKEL    -0.015      IRONWALLOY
*
* A36 Steel
MATERIAL                            7.80       44.                  A36STEEL
COMPOUND      -98.00      IRON     -1.03  MANGANES     -0.29    CARBONA36STEEL
COMPOUND       -0.28   SILICON     -0.20    COPPER                  A36STEEL
COMPOUND       -0.10   PHOSPHO     -0.10    SULFUR                  A36STEEL
* --+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
GEOBEGIN                                                            COMBNAME
    0    0          Geometry of NGLS XTOD
* --+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
RPP BlaBox     -150.0  150.0  -150.0  150.0  -2000.0  2000.0
RPP outout    -5000.0 5000.0 -5000.0 5000.0  -5000.0  5000.0
*
```

```
RPP beamcho    -2.1    2.1   -8.08   5.08 -1305.08 -1210.0
RPP beamchi    -2.0    2.0   -8.0    5.0  -1305.0  -1210.08
*
* Magnets
BOX mag1body  -25.0   3.9601 -1299.7650  50.0   0.0     0.0
                0.0  -4.6995    79.8618   0.0 -39.9309 -2.3498
BOX mag1open   -2.5   3.9701 -1299.7692   5.0   0.0     0.0
                0.0  -4.7007    79.8818   0.0  -8.0062 -0.4711
BOX mag1midl  -12.5  -3.9601 -1300.2350  25.0   0.0     0.0
                0.0  -4.7007    79.8818   0.0 -10.0027 -0.5886
RPP mag1cho    -2.1    2.1   -8.08   3.08 -1305.08 -1210.0
RPP mag1chi    -2.0    2.0   -8.0    3.0  -1305.0  -1210.08
*
BOX mag2body  -25.0  -4.2944 -1189.6461  50.0   0.0     0.0
                0.0 -13.9391    78.7763   0.0 -39.3881 -6.9696
BOX mag2open   -2.5  -4.2845 -1189.6544   5.0   0.0     0.0
                0.0 -13.9426    78.7960   0.0  -7.8973 -1.3974
BOX mag2midl  -12.5 -12.1621 -1191.0466  25.0   0.0     0.0
                0.0 -13.9426    78.7960   0.0  -9.8667 -1.7459
BOX mag2cho    -2.1  -6.1653 -1189.9872   4.2   0.0     0.0
                0.0 -13.9426    78.7960   0.0  -4.1358 -0.7318
BOX mag2chi    -2.0  -6.2638 -1190.0046   4.0   0.0     0.0
                0.0 -13.9426    78.7960   0.0  -3.9388 -0.6970
*
BOX mag3body  -25.0 -25.2770 -1081.2301  50.0   0.0     0.0
                0.0 -22.9902    76.6254   0.0 -38.3127 -11.4951
BOX mag3open   -2.5 -25.2674 -1081.2373   5.0   0.0     0.0
                0.0 -22.9960    76.6445   0.0  -7.6817 -2.3048
BOX mag3midl  -12.5 -32.9300 -1083.5363  25.0   0.0     0.0
                0.0 -22.9960    76.6445   0.0  -9.5973 -2.8795
BOX mag3cho    -2.1 -27.0969 -1081.7861   4.2   0.0     0.0
                0.0 -22.9960    76.6445   0.0  -4.0228 -1.2070
BOX mag3chi    -2.0 -27.1926 -1081.8149   4.0   0.0     0.0
                0.0 -22.9960    76.6445   0.0  -3.8313 -1.1495
*
* Wall Layers
XYP PLAz000    1000.00
XYP PLAz050    1050.00
XYP PLAz100    1100.00
XYP PLAz150    1150.00
XYP PLAz200    1200.00
XYP PLAz250    1250.00
XYP PLAz300    1300.00
XYP PLAz350    1350.00
XYP PLAz400    1400.00
*
* Mirrors
RPP m1tank      -4.0  7.0 -10.0 10.0 250.0 380.0
XYP m1sep      264.0
RPP m2tank     -12.0 -2.0 -10.0 10.0 770.0 830.0
BOX m1         0.124999479 -2.5 275.0003125      0.0 5.0 0.0
              -0.249998958  0.0  49.999375       4.9999375 0.0 0.024999896
BOX m2        -5.124999479 -2.5 775.0003125      0.0 5.0 0.0
              -4.9999375    0.0  -0.024999896   -0.249998958 0.0 49.999375
*
* Pipes
RCC Pipe01O   0.0  0.0 -1599.99   0.0  0.0  1899.99  2.08
RCC Pipe01I   0.0  0.0 -1599.99   0.0  0.0  1899.99  2.0
RCC Pipe12O   0.0  0.0   300.00  -5.0  0.0   500.00  1.27
RCC Pipe12I   0.0  0.0   300.00  -5.0  0.0   500.00  1.19
RCC Pipe23O  -5.0  0.0   800.00   0.0  0.0  1000.00  1.27
RCC Pipe23I  -5.0  0.0   800.00   0.0  0.0  1000.00  1.19
*
```

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* Collimators
RCC c1o      0.0  0.0  260.0  0.0  0.0  8.0   3.5
RCC c1i      0.0  0.0  259.9  0.0  0.0  8.2   0.25
RPP bc2    -30.0 30.0  -30.0 30.0  400.0  430.0
RCC bc2i    -1.0  0.0  399.9 -0.30 0.0 30.2   0.5
RCC c2o     -4.5  0.0  750.0 -0.08 0.0  8.0   5.0
RCC c2i     -4.5  0.0  749.9 -0.08 0.0  8.2   0.5
RCC c3o     -5.0  0.0  850.0  0.0  0.0  8.0   5.0
RCC c3i     -5.0  0.0  849.9  0.0  0.0  8.2   0.5
RCC c4o     -5.0  0.0  970.0  0.0  0.0  8.0   5.0
RCC c4i     -5.0  0.0  969.9  0.0  0.0  8.2   0.5
RCC c5o     -5.0  0.0 1430.0  0.0  0.0  8.0   5.0
RCC c5i     -5.0  0.0 1429.9  0.0  0.0  8.2   0.5
*
* Air seperations
RPP AirA    -50.0 50.0  -40.0 40.0  230.0 2000.0
RPP AirB    -30.1 30.1  -30.1 30.1  379.9 2000.0
RPP AirC    -11.0  1.0  -10.1 10.1  845.0 2000.0
*
* Inside EH
RCC target    -5.0 0.0  1500.0   0.0 0.0 1.0  5.0
END
*
* --reg-----or-----or-----or-----or-----or-----or-----or-----or-----or-----
BLACKho    25 | -BlaBox   +outout
*
INSAIR     25 | +BlaBox   -AirA  -Pipe01O  +PLAz000
                -beamcho  -mag1body -mag2body -mag3body
*               -p2dumpo
MAG1BODY   25 | +mag1body -mag1open -mag1midl -beamcho
MAG1MIDL   25 | +mag1body +mag1midl -mag1cho
MAG1OPEN   25 | +mag1body -mag1midl +mag1open -beamcho
MAG1CHMO   25 | +beamcho  -beamchi  -Pipe01I
MAG1CHMI   25 | +beamchi
*
MAG2BODY   25 | +mag2body -mag2midl -mag2open
MAG2MIDL   25 | +mag2midl +mag2body
MAG2OPEN   25 | +mag2body +mag2open -mag2cho  -mag2midl
MAG2CHO    25 | +mag2cho  +mag2body -mag2chi
MAG2CHI    25 | +mag2chi  +mag2body
*
MAG3BODY   25 | +mag3body -mag3open -mag3midl
MAG3MIDL   25 | +mag3body +mag3midl
MAG3OPEN   25 | +mag3body -mag3midl +mag3open -mag3cho
MAG3CHO    25 | +mag3body +mag3cho   -mag3chi
MAG3CHI    25 | +mag3body +mag3chi
*
*P2DUMPO    25 | +BlaBox   +p2dumpo   -p2dumpi  -mag3body
*P2DUMPI    25 | +BlaBox   +p2dumpo   +p2dumpi  -mag3body
*
INAIRA     25 | +BlaBox   +AirA  -AirB  -m1tank  -Pipe01O  -Pipe12O  +PLAz000
INAIRB       25  | +BlaBox    +AirB   -AirC   -m2tank   -bc2   -c2o   -Pipe12O   -Pipe23O
+PLAz000
INAIRC     25 | +BlaBox   +AirC  -c3o -c4o  -Pipe23O   +PLAz000
OUTAIR     25 | +BlaBox   -PLAz400  -AirA
OUTAIRA    25 | +BlaBox   -PLAz400  +AirA  -AirB
OUTAIRB    25 | +BlaBox   -PLAz400  +AirB  -AirC
OUTAIRC    25 | +BlaBox   -PLAz400  +AirC  -Pipe23O  -c5o
*
* Walls
EHWALL1    25 | +BlaBox   +PLAz050  -PLAz000  -AirA
EHWALL2    25 | +BlaBox   +PLAz100  -PLAz050  -AirA
EHWALL3    25 | +BlaBox   +PLAz150  -PLAz100  -AirA
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EHWALL4     25 | +BlaBox   +PLAz200  -PLAz150  -AirA
EHWALL5     25 | +BlaBox   +PLAz250  -PLAz200  -AirA
EHWALL6     25 | +BlaBox   +PLAz300  -PLAz250  -AirA
EHWALL7     25 | +BlaBox   +PLAz350  -PLAz300  -AirA
EHWALL8     25 | +BlaBox   +PLAz400  -PLAz350  -AirA
EHWALL1A    25 | +BlaBox   +PLAz050  -PLAz000  +AirA  -AirB
EHWALL2A    25 | +BlaBox   +PLAz100  -PLAz050  +AirA  -AirB
EHWALL3A    25 | +BlaBox   +PLAz150  -PLAz100  +AirA  -AirB
EHWALL4A    25 | +BlaBox   +PLAz200  -PLAz150  +AirA  -AirB
EHWALL5A    25 | +BlaBox   +PLAz250  -PLAz200  +AirA  -AirB
EHWALL6A    25 | +BlaBox   +PLAz300  -PLAz250  +AirA  -AirB
EHWALL7A    25 | +BlaBox   +PLAz350  -PLAz300  +AirA  -AirB
EHWALL8A    25 | +BlaBox   +PLAz400  -PLAz350  +AirA  -AirB
EHWALL1B    25 | +BlaBox   +PLAz050  -PLAz000  +AirB  -AirC
EHWALL2B    25 | +BlaBox   +PLAz100  -PLAz050  +AirB  -AirC
EHWALL3B    25 | +BlaBox   +PLAz150  -PLAz100  +AirB  -AirC
EHWALL4B    25 | +BlaBox   +PLAz200  -PLAz150  +AirB  -AirC
EHWALL5B    25 | +BlaBox   +PLAz250  -PLAz200  +AirB  -AirC
EHWALL6B    25 | +BlaBox   +PLAz300  -PLAz250  +AirB  -AirC
EHWALL7B    25 | +BlaBox   +PLAz350  -PLAz300  +AirB  -AirC
EHWALL8B    25 | +BlaBox   +PLAz400  -PLAz350  +AirB  -AirC
EHWALL1C    25 | +BlaBox   +PLAz050  -PLAz000  -Pipe23O  +AirC
EHWALL2C    25 | +BlaBox   +PLAz100  -PLAz050  -Pipe23O  +AirC
EHWALL3C    25 | +BlaBox   +PLAz150  -PLAz100  -Pipe23O  +AirC
EHWALL4C    25 | +BlaBox   +PLAz200  -PLAz150  -Pipe23O  +AirC
EHWALL5C    25 | +BlaBox   +PLAz250  -PLAz200  -Pipe23O  +AirC
EHWALL6C    25 | +BlaBox   +PLAz300  -PLAz250  -Pipe23O  +AirC
EHWALL7C    25 | +BlaBox   +PLAz350  -PLAz300  -Pipe23O  +AirC
EHWALL8C    25 | +BlaBox   +PLAz400  -PLAz350  -Pipe23O  +AirC
*
* Mirrors
M1TANKU     25 | +m1tank  -m1  -c1o  +m1sep
M1TANKD     25 | +m1tank  -m1  -c1o  -m1sep
M2TANK      25 | +m2tank  -m2
M1          25 | +m1
M2          25 | +m2
*
* Pipes
PIPE01O     25 | +Pipe01O  -Pipe01I  -m1tank  -beamcho
PIPE01I     25 | +Pipe01O  +Pipe01I  -m1tank  -beamchi
PIPE12O     25 | +Pipe12O  -Pipe12I  -m1tank  -m2tank  -c2o  -bc2
PIPE12I     25 | +Pipe12O  +Pipe12I  -m1tank  -m2tank  -c2o  -bc2
PIPE2WO     25 | +Pipe23O  -Pipe23I  +PLAz000 -c3o -c4o
PIPE2WI     25 | +Pipe23O  +Pipe23I  +PLAz000 -c3o -c4o
PIPEWaO1    25 | +Pipe23O  -Pipe23I  -PLAz000 +PLAz100
PIPEWaI1    25 | +Pipe23O  +Pipe23I  -PLAz000 +PLAz100
PIPEWaO2    25 | +Pipe23O  -Pipe23I  -PLAz100 +PLAz200
PIPEWaI2    25 | +Pipe23O  +Pipe23I  -PLAz100 +PLAz200
PIPEWaO3    25 | +Pipe23O  -Pipe23I  -PLAz200 +PLAz300
PIPEWaI3    25 | +Pipe23O  +Pipe23I  -PLAz200 +PLAz300
PIPEWaO4    25 | +Pipe23O  -Pipe23I  -PLAz300 +PLAz400
PIPEWaI4    25 | +Pipe23O  +Pipe23I  -PLAz300 +PLAz400
PIPEEHO     25 | +Pipe23O  -Pipe23I  -PLAz400 -c5o
PIPEEHI     25 | +Pipe23O  +Pipe23I  -PLAz400 -c5o  -target
*
* Collimators
C1O         25 | +c1o  -c1i
C1I         25 | +c1o  +c1i
C2O         25 | +c2o  -c2i
C2I         25 | +c2o  +c2i
BC2         25 | +bc2  -bc2i
BC2I        25 | +bc2  +bc2i
C3O         25 | +c3o  -c3i
```

```
C3I        25 | +c3o  +c3i
C4O        25 | +c4o  -c4i
C4I        25 | +c4o  +c4i
C5O        25 | +c5o  -c5i
C5I        25 | +c5o  +c5i
*
TARGET     25 | +target   +Pipe23I
END
GEOEND
*
* --+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
ASSIGNMA    BLCKHOLE   BLACKho
ASSIGNMA         AIR    INSAIR
*
ASSIGNMA    A36STEEL  MAG1BODY
ASSIGNMA         AIR  MAG1MIDL
ASSIGNMA         AIR  MAG1OPEN                          1.0
ASSIGNMA    STEEL316  MAG1CHMO                          1.0
ASSIGNMA      VACUUM  MAG1CHMI                          1.0
*
ASSIGNMA    A36STEEL  MAG2BODY
ASSIGNMA         AIR  MAG2MIDL
ASSIGNMA         AIR  MAG2OPEN                          1.0
ASSIGNMA    STEEL316   MAG2CHO                          1.0
ASSIGNMA      VACUUM   MAG2CHI                          1.0
*
ASSIGNMA    A36STEEL  MAG3BODY
ASSIGNMA         AIR  MAG3MIDL
ASSIGNMA         AIR  MAG3OPEN                          1.0
ASSIGNMA    STEEL316   MAG3CHO                          1.0
ASSIGNMA      VACUUM   MAG3CHI                          1.0
*
ASSIGNMA         AIR    INAIRA
ASSIGNMA         AIR    INAIRB
ASSIGNMA         AIR    INAIRC
ASSIGNMA         AIR    OUTAIR
ASSIGNMA         AIR   OUTAIRA
ASSIGNMA         AIR   OUTAIRB
ASSIGNMA         AIR   OUTAIRC
ASSIGNMA    CONCRETE   EHWALL1
ASSIGNMA    CONCRETE   EHWALL2
ASSIGNMA    CONCRETE   EHWALL3
ASSIGNMA    CONCRETE   EHWALL4
ASSIGNMA    CONCRETE   EHWALL5
ASSIGNMA    CONCRETE   EHWALL6
ASSIGNMA    CONCRETE   EHWALL7
ASSIGNMA    CONCRETE   EHWALL8
ASSIGNMA    CONCRETE  EHWALL1A
ASSIGNMA    CONCRETE  EHWALL2A
ASSIGNMA    CONCRETE  EHWALL3A
ASSIGNMA    CONCRETE  EHWALL4A
ASSIGNMA    CONCRETE  EHWALL5A
ASSIGNMA    CONCRETE  EHWALL6A
ASSIGNMA    CONCRETE  EHWALL7A
ASSIGNMA    CONCRETE  EHWALL8A
ASSIGNMA    CONCRETE  EHWALL1B
ASSIGNMA    CONCRETE  EHWALL2B
ASSIGNMA    CONCRETE  EHWALL3B
ASSIGNMA    CONCRETE  EHWALL4B
ASSIGNMA    CONCRETE  EHWALL5B
ASSIGNMA    CONCRETE  EHWALL6B
ASSIGNMA    CONCRETE  EHWALL7B
ASSIGNMA    CONCRETE  EHWALL8B
```

```
ASSIGNMA    CONCRETE  EHWALL1C
ASSIGNMA    CONCRETE  EHWALL2C
ASSIGNMA    CONCRETE  EHWALL3C
ASSIGNMA    CONCRETE  EHWALL4C
ASSIGNMA    CONCRETE  EHWALL5C
ASSIGNMA    CONCRETE  EHWALL6C
ASSIGNMA    CONCRETE  EHWALL7C
ASSIGNMA    CONCRETE  EHWALL8C
ASSIGNMA      VACUUM   M1TANKU
ASSIGNMA      VACUUM   M1TANKD
ASSIGNMA      VACUUM    M2TANK
ASSIGNMA     SILICON        M1
ASSIGNMA     SILICON        M2
ASSIGNMA    STEEL316   PIPE01O
ASSIGNMA    STEEL316   PIPE12O
ASSIGNMA    STEEL316   PIPE2WO
ASSIGNMA    STEEL316  PIPEWaO1
ASSIGNMA    STEEL316  PIPEWaO2
ASSIGNMA    STEEL316  PIPEWaO3
ASSIGNMA    STEEL316  PIPEWaO4
ASSIGNMA    STEEL316   PIPEEHO
ASSIGNMA      VACUUM   PIPE01I
ASSIGNMA      VACUUM   PIPE12I
ASSIGNMA      VACUUM   PIPE2WI
ASSIGNMA      VACUUM  PIPEWaI1
ASSIGNMA      VACUUM  PIPEWaI2
ASSIGNMA      VACUUM  PIPEWaI3
ASSIGNMA      VACUUM  PIPEWaI4
ASSIGNMA      VACUUM   PIPEEHI
ASSIGNMA      WALLOY       C1O
ASSIGNMA      VACUUM       C1I
ASSIGNMA    A36STEEL       BC2
ASSIGNMA      VACUUM      BC2I
ASSIGNMA      WALLOY       C2O
ASSIGNMA      VACUUM       C2I
ASSIGNMA      WALLOY       C3O
ASSIGNMA      VACUUM       C3I
ASSIGNMA      WALLOY       C4O
ASSIGNMA      VACUUM       C4I
ASSIGNMA      WALLOY       C5O
ASSIGNMA      VACUUM       C5I
ASSIGNMA        IRON    TARGET
*
* --+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
MGNFIELD        10.0       0.2       0.1   1.16093       0.0       0.0
EMF-BIAS       1022.       1.0       1.0    INSAIR  @LASTREG
EMF-BIAS         0.4       0.0       0.0  STEEL316                      LAMBBREM
LAM-BIAS         0.0      0.02    WALLOY    PHOTON
LAM-BIAS         0.0      0.02    WALLOY    PHOTON                      INEALL
LAM-BIAS         0.0      0.02   SILICON    PHOTON
LAM-BIAS         0.0      0.02   SILICON    PHOTON                      INEALL
LAM-BIAS         0.0      0.02  STEEL316    PHOTON
LAM-BIAS         0.0      0.02  STEEL316    PHOTON                      INEALL
LAM-BIAS         0.0      0.02  A36STEEL    PHOTON
LAM-BIAS         0.0      0.02  A36STEEL    PHOTON                      INEALL
PHOTONUC         1.0       0.0       0.0  HYDROGEN  @LASTMAT
PHOTONUC         1.0     1.E-4       0.0  HYDROGEN  @LASTMAT            MUMUPAIR
PART-THR     -1.0E-5    PROTON   APROTON
PART-THR     -1.0E-5  ANEUTRON  @LASTPAR
DISCARD      NEUTRIE  ANEUTRIE
EMFCUT       -2.0E-4    1.0E-4       0.0  HYDROGEN  @LASTMAT            PROD-CUT
EMFCUT       -2.0E-3    1.0E-3       0.0    WALLOY                      PROD-CUT
EMFCUT       -2.0E-4    1.0E-4       0.0    INSAIR  @LASTREG
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EMFCUT       -5.0E-3    3.0E-3       0.0       C1O
EMFCUT       -5.0E-3    3.0E-3       0.0        M1
EMFCUT       -8.0E-3    5.0E-3       0.0       BC2
EMFCUT       -5.0E-3    3.0E-3       0.0   EHWALL1   EHWALL4
EMFCUT       -2.0E-3    1.0E-3       0.0   EHWALL5
EMFCUT       -5.0E-3    3.0E-3       0.0  EHWALL1A  EHWALL4A
EMFCUT       -2.0E-3    1.0E-3       0.0  EHWALL5A
EMFCUT       -5.0E-3    3.0E-3       0.0  EHWALL1B  EHWALL4B
EMFCUT       -2.0E-3    1.0E-3       0.0  EHWALL5B
EMFCUT       -5.0E-3    3.0E-3       0.0  EHWALL1C  EHWALL4C
EMFCUT       -2.0E-3    1.0E-3       0.0  EHWALL5C
EMFCUT       -2.0E-3    1.0E-3       0.0  MAG1BODY
EMFCUT       -5.0E-3    3.0E-3       0.0  MAG2BODY
EMFCUT       -8.0E-3    5.0E-3       0.0  MAG3BODY
*
USERDUMP        100.       0.0        0.        1.
*
* --+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
BIASING          0.0       1.0       1.0    INSAIR  @LASTREG           PRINT
BIASING          0.0       1.0       4.0    INAIRA
BIASING          0.0       1.0       4.0   M1TANKU
BIASING          0.0       1.0       4.0   M1TANKD
BIASING          0.0       1.0       4.0       C1O
BIASING          0.0       1.0       4.0       C1I
BIASING          0.0       1.0       4.0        M1
BIASING          0.0       1.0       8.0    INAIRB
BIASING          0.0       1.0       8.0       BC2
BIASING          0.0       1.0       8.0      BC2I
BIASING          0.0       1.0       8.0   PIPE12O
BIASING          0.0       1.0       8.0   PIPE12I
BIASING          0.0       1.0       8.0       C2O
BIASING          0.0       1.0       8.0       C2I
BIASING          0.0       1.0      16.0    M2TANK
BIASING          0.0       1.0      16.0        M2
BIASING          0.0       1.0      16.0    INAIRC
BIASING          0.0       1.0      64.0   PIPE2WO
BIASING          0.0       1.0      64.0   PIPE2WI
BIASING          0.0       1.0      64.0       C3O
BIASING          0.0       1.0      64.0       C3I
BIASING          0.0       1.0      64.0       C4O
BIASING          0.0       1.0      64.0       C4I
BIASING          0.0       1.0     256.0  PIPEWaO1
BIASING          0.0       1.0     256.0  PIPEWaI1
BIASING          0.0       1.0     512.0  PIPEWaO2
BIASING          0.0       1.0     512.0  PIPEWaI2
BIASING          0.0       1.0    1024.0  PIPEWaO3
BIASING          0.0       1.0    1024.0  PIPEWaI3
BIASING          0.0       1.0    2048.0  PIPEWaO4
BIASING          0.0       1.0    2048.0  PIPEWaI4
BIASING          0.0       1.0    4096.0   PIPEEHO
BIASING          0.0       1.0    4096.0   PIPEEHI
BIASING          0.0       1.0    4096.0       C5O
BIASING          0.0       1.0    4096.0       C5I
BIASING          0.0       1.0    4096.0    TARGET
*
BIASING          0.0       1.0       1.0   EHWALL1
BIASING          0.0       1.0       2.0   EHWALL2
BIASING          0.0       1.0       4.0   EHWALL3
BIASING          0.0       1.0       8.0   EHWALL4
BIASING          0.0       1.0      16.0   EHWALL5
BIASING          0.0       1.0      32.0   EHWALL6
BIASING          0.0       1.0      64.0   EHWALL7
BIASING          0.0       1.0     128.0   EHWALL8
```

```
BIASING          0.0       1.0       4.0  EHWALL1A
BIASING          0.0       1.0       8.0  EHWALL2A
BIASING          0.0       1.0      16.0  EHWALL3A
BIASING          0.0       1.0      16.0  EHWALL4A
BIASING          0.0       1.0      32.0  EHWALL5A
BIASING          0.0       1.0      64.0  EHWALL6A
BIASING          0.0       1.0     128.0  EHWALL7A
BIASING          0.0       1.0     256.0  EHWALL8A
BIASING          0.0       1.0       8.0  EHWALL1B
BIASING          0.0       1.0       8.0  EHWALL2B
BIASING          0.0       1.0      16.0  EHWALL3B
BIASING          0.0       1.0      16.0  EHWALL4B
BIASING          0.0       1.0      32.0  EHWALL5B
BIASING          0.0       1.0      64.0  EHWALL6B
BIASING          0.0       1.0     128.0  EHWALL7B
BIASING          0.0       1.0     256.0  EHWALL8B
BIASING          0.0       1.0      16.0  EHWALL1C
BIASING          0.0       1.0      16.0  EHWALL2C
BIASING          0.0       1.0      32.0  EHWALL3C
BIASING          0.0       1.0      32.0  EHWALL4C
BIASING          0.0       1.0      64.0  EHWALL5C
BIASING          0.0       1.0     128.0  EHWALL6C
BIASING          0.0       1.0     256.0  EHWALL7C
BIASING          0.0       1.0     512.0  EHWALL8C
*
BIASING          0.0       1.0    1024.0    OUTAIR
BIASING          0.0       1.0    2048.0   OUTAIRA
BIASING          0.0       1.0    2048.0   OUTAIRB
BIASING          0.0       1.0    4096.0   OUTAIRC
* --+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
* Global view
USRBIN          10.0   DOSE-EQ     -30.0      50.0      20.0    1500.0Dose1A
USRBIN         -50.0    -100.0   -1300.0     100.0     120.0     280.0&
AUXSCORE      USRBIN  ALL-PART              Dose1A                    EWTMP
USRBIN          10.0   DOSE-EQ     -30.0     150.0      50.0    2000.0Dose1M
USRBIN        -150.0     -50.0   -1500.0     200.0       1.0     350.0&
AUXSCORE      USRBIN     MUONS              Dose1M                    EWTMP
USRBIN          10.0   DOSE-EQ     -30.0     150.0      50.0    2000.0Dose1P
USRBIN        -150.0     -50.0   -1500.0     200.0       1.0     350.0&
AUXSCORE      USRBIN    PHOTON              Dose1P                    EWTMP
USRBIN          10.0   DOSE-EQ     -30.0     150.0      50.0    2000.0Dose1N
USRBIN        -150.0     -50.0   -1500.0     200.0       1.0     350.0&
AUXSCORE      USRBIN   NEUTRON              Dose1N                    EWTMP
USRBIN          10.0   DOSE-EQ     -30.0     150.0      50.0    2000.0Dose1E
USRBIN        -150.0     -50.0   -1500.0     200.0       1.0     350.0&
AUXSCORE      USRBIN     E+&E-              Dose1E                    EWTMP
*
* Wall
*USRBIN          10.0   DOSE-EQ     -31.0      60.0      30.0    1800.0Dose2A
*USRBIN         -60.0     -30.0     200.0     120.0       6.0     400.0&
*AUXSCORE      USRBIN  ALL-PART              Dose2A                    EWTMP
*USRBIN          10.0   DOSE-EQ     -31.0      60.0      30.0    1800.0Dose2M
*USRBIN         -60.0     -30.0     200.0     120.0       6.0     400.0&
*AUXSCORE      USRBIN     MUONS              Dose2M                    EWTMP
*USRBIN          10.0   DOSE-EQ     -31.0      60.0      30.0    1800.0Dose2P
*USRBIN         -60.0     -30.0     200.0     120.0       6.0     400.0&
*AUXSCORE      USRBIN    PHOTON              Dose2P                    EWTMP
*USRBIN          10.0   DOSE-EQ     -31.0      60.0      30.0    1800.0Dose2N
*USRBIN         -60.0     -30.0     200.0     120.0       6.0     400.0&
*AUXSCORE      USRBIN   NEUTRON              Dose2N                    EWTMP
*USRBIN          10.0   DOSE-EQ     -31.0      60.0      30.0    1800.0Dose2E
*USRBIN         -60.0     -30.0     200.0     120.0       6.0     400.0&
*AUXSCORE      USRBIN     E+&E-              Dose2E                    EWTMP
```

```
*
* Pipe
USRBIN          11.0   DOSE-EQ     -32.0      35.0       0.0    1700.0Dose3A
USRBIN           0.0      -5.0     900.0     350.0       1.0     400.0&
AUXSCORE      USRBIN  ALL-PART              Dose3A                    EWTMP
USRBIN          11.0   DOSE-EQ     -32.0      35.0       0.0    1700.0Dose3M
USRBIN           0.0      -5.0     900.0     350.0       1.0     400.0&
AUXSCORE      USRBIN     MUONS              Dose3M                    EWTMP
USRBIN          11.0   DOSE-EQ     -32.0      35.0       0.0    1700.0Dose3P
USRBIN           0.0      -5.0     900.0     350.0       1.0     400.0&
AUXSCORE      USRBIN    PHOTON              Dose3P                    EWTMP
USRBIN          11.0   DOSE-EQ     -32.0      35.0       0.0    1700.0Dose3N
USRBIN           0.0      -5.0     900.0     350.0       1.0     400.0&
AUXSCORE      USRBIN   NEUTRON              Dose3N                    EWTMP
USRBIN          11.0   DOSE-EQ     -32.0      35.0       0.0    1700.0Dose3E
USRBIN           0.0      -5.0     900.0     350.0       1.0     400.0&
AUXSCORE      USRBIN     E+&E-              Dose3E                    EWTMP
*
* Magnet
*USRBIN          10.0   DOSE-EQ     -33.0       3.0      20.0     500.0Dose4A
*USRBIN          -3.0    -100.0   -1500.0       1.0     240.0     400.0&
*AUXSCORE      USRBIN  ALL-PART              Dose4A                    EWTMP
*USRBIN          10.0   DOSE-EQ     -33.0       3.0      20.0     500.0Dose4M
*USRBIN          -3.0    -100.0   -1500.0       1.0     240.0     400.0&
*AUXSCORE      USRBIN     MUONS              Dose4M                    EWTMP
*USRBIN          10.0   DOSE-EQ     -33.0       3.0      20.0     500.0Dose4P
*USRBIN          -3.0    -100.0   -1500.0       1.0     240.0     400.0&
*AUXSCORE      USRBIN    PHOTON              Dose4P                    EWTMP
*USRBIN          10.0   DOSE-EQ     -33.0       3.0      20.0     500.0Dose4N
*USRBIN          -3.0    -100.0   -1500.0       1.0     240.0     400.0&
*AUXSCORE      USRBIN   NEUTRON              Dose4N                    EWTMP
*USRBIN          10.0   DOSE-EQ     -33.0       3.0      20.0     500.0Dose4E
*USRBIN          -3.0    -100.0   -1500.0       1.0     240.0     400.0&
*AUXSCORE      USRBIN     E+&E-              Dose4E                    EWTMP
*
*USRBIN          10.0   DOSE-EQ     -34.0       4.0       2.0   -1200.0Dose4A
*USRBIN          -4.0      -2.0   -1300.0     200.0      10.0     200.0&
*AUXSCORE      USRBIN  ALL-PART              Dose4A                    EWTMP
*
*
* Source Spectrum
*   leave Magnet 1 and enter pipe to M1
USRBDX          -2.0    PHOTON     -40.0  MAG1CHMI   PIPE01I    12.566
USRBDX           2.4     1.E-4      20.0               1.E-4      20.0&
USRBDX          -2.0     E+&E-     -40.0  MAG1CHMI   PIPE01I    12.566
USRBDX           2.4     1.E-4      20.0               1.E-4      20.0&
*   enter M1 tank
USRBDX          -2.0    PHOTON     -41.0   PIPE01I   M1TANKU    12.566
USRBDX           2.4     1.E-4      20.0               1.E-4      20.0&
USRBDX          -2.0     E+&E-     -41.0   PIPE01I   M1TANKU    12.566
USRBDX           2.4     1.E-4      20.0               1.E-4      20.0&
*   leave C1 hole
USRBDX          -2.0    PHOTON     -42.0       C1I   M1TANKD    0.7854
USRBDX           2.4     1.E-4      20.0               1.E-4      20.0&
USRBDX          -2.0     E+&E-     -42.0       C1I   M1TANKD    0.7854
USRBDX           2.4     1.E-4      20.0               1.E-4      20.0&
*
* --+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
RANDOMIZE        1.0        1.
START          1.0E5
USROCALL         1.0
STOP
```

Appendix E Facility Subroutines for FLUKA

source.f

```
      SUBROUTINE SOURCE ( NOMORE )

      INCLUDE '(DBLPRC)'
      INCLUDE '(DIMPAR)'
      INCLUDE '(IOUNIT)'
      INCLUDE '(BEAMCM)'
      INCLUDE '(FHEAVY)'
      INCLUDE '(FLKSTK)'
      INCLUDE '(IOIOCM)'
      INCLUDE '(LTCLCM)'
      INCLUDE '(PAPROP)'
      INCLUDE '(SOURCM)'
      INCLUDE '(SUMCOU)'

      LOGICAL LFIRST
      real*8  r, theta_max
      real*8  theta

      SAVE LFIRST r, theta_max
      DATA LFIRST / .TRUE. /

      IF ( LFIRST ) THEN
*  |  *** The following 3 cards are mandatory ***
        TKESUM = ZERZER
        LFIRST = .FALSE.
        LUSSRC = .TRUE.
*     Bending radius
        r  = whasou(1)
*     Max bending angle
        theta_max = whasou(2)
        write(lunout,*) "Bend radius =", r, ", theta =", theta_max
      END IF
*  |
*  +-------------------------------------------------------------------*
*  Push one source particle to the stack. Note that you could as well
*  push many but this way we reserve a maximum amount of space in the
*  stack for the secondaries to be generated
* Npflka is the stack counter: of course any time source is called it
* must be =0
      NPFLKA = NPFLKA + 1
      theta = theta_max * flrndm(tkesum)
*      write(lunout,*) "theta =", theta
*
      WTFLK(npflka) = 1
      WEIPRI = WEIPRI + WTFLK(NPFLKA)
      ILOFLK(NPFLKA) = IJBEAM
*  +-------------------------------------------------------------------*
*  |  (Radioactive) isotope:
      IF (ILOFLK(NPFLKA) .EQ. -2 .AND. LRDBEA ) THEN
         IARES  = IPROA
         IZRES  = IPROZ
         IISRES = IPROM
         CALL STISBM ( IARES, IZRES, IISRES )
         IJHION = IPROZ  * 1000 + IPROA
         IJHION = IJHION * 100 + KXHEAV
         IONID  = IJHION
         CALL DCDION ( IONID )
         CALL SETION ( IONID )
*  |
```

```
*  +-------------------------------------------------------------------*
*  |  Heavy ion:
      ELSE IF (ILOFLK(NPFLKA) .EQ. -2 ) THEN
         IJHION = IPROZ  * 1000 + IPROA
         IJHION = IJHION * 100 + KXHEAV
         IONID  = IJHION
         CALL DCDION ( IONID )
         CALL SETION ( IONID )
         ILOFLK (NPFLKA) = IJHION
*  |  Flag this is prompt radiation
         LRADDC (NPFLKA) = .FALSE.
*  |  Group number for "low" energy neutrons, set to 0 anyway
         IGROUP (NPFLKA) = 0
*  |
*  +-------------------------------------------------------------------*
*  |  Normal hadron:
      ELSE
         IONID = ILOFLK(NPFLKA)
*  |  Flag this is prompt radiation
         LRADDC (NPFLKA) = .FALSE.
*  |  Group number for "low" energy neutrons, set to 0 anyway
         IGROUP (NPFLKA) = 0
      END IF
*  |
*  +-------------------------------------------------------------------*
* From this point .....
* Particle generation (1 for primaries)
      LOFLK  (NPFLKA) = 1
* User dependent flag:
      LOUSE  (NPFLKA) = 0
* User dependent spare variables:
      DO 101 ISPR = 1, MKBMX1
         SPAREK (ISPR,NPFLKA) = ZERZER
 101  CONTINUE
* User dependent spare flags:
      DO 201 ISPR = 1, MKBMX2
         ISPARK (ISPR,NPFLKA) = 0
 201  CONTINUE
* Save the track number of the stack particle:
      ISPARK (MKBMX2,NPFLKA) = NPFLKA
      NPARMA = NPARMA + 1
      NUMPAR (NPFLKA) = NPARMA
      NEVENT (NPFLKA) = 0
      DFNEAR (NPFLKA) = +ZERZER
* ... to this point: don't change anything
* Particle age (s)
      AGESTK (NPFLKA) = +ZERZER
      AKNSHR (NPFLKA) = -TWOTWO
* Group number for "low" energy neutrons, set to 0 anyway
      IGROUP (NPFLKA) = 0
* Kinetic energy of the particle (GeV)
      TKEFLK (npflka) = SQRT(PBEAM**2 + AM(IJBEAM)**2) - AM(IJBEAM)
* Particle momentum
      PMOFLK (NPFLKA) = PBEAM
* Cosines (tx,ty,tz)
      TXFLK (NPFLKA) = UBEAM
      TYFLK (NPFLKA) = -sin(theta) * SQRT(1.0 - UBEAM*UBEAM)
      TZFLK (NPFLKA) = SQRT(ONEONE - TXFLK(NPFLKA)*TXFLK(NPFLKA)
&                             - TYFLK(NPFLKA)*TYFLK(NPFLKA))
* Polarization cosines:
      TXPOL (NPFLKA) = -TWOTWO
      TYPOL (NPFLKA) = +ZERZER
      TZPOL (NPFLKA) = +ZERZER
```

```
* Particle coordinates
      XFLK  (NPFLKA) = XBEAM
      YFLK  (NPFLKA) = YBEAM - r * (1.0 - cos(theta))
      ZFLK  (NPFLKA) = ZBEAM + r * sin(theta)
*
*      write(lunout,*) XFLK(NPFLKA), YFLK(NPFLKA), ZFLK(NPFLKA)
*      write(lunout,*) TXFLK(NPFLKA), TYFLK(NPFLKA), TZFLK(NPFLKA)
* Calculate the total kinetic energy of the primaries: don't change
      IF ( ILOFLK (NPFLKA) .EQ. -2 .OR. ILOFLK (NPFLKA) .GT. 100000 )
     &   THEN
         TKESUM = TKESUM + TKEFLK (NPFLKA) * WTFLK (NPFLKA)
      ELSE IF ( ILOFLK (NPFLKA) .NE. 0 ) THEN
         TKESUM = TKESUM + ( TKEFLK (NPFLKA) + AMDISC (ILOFLK(NPFLKA)) )
     &          * WTFLK (NPFLKA)
      ELSE
         TKESUM = TKESUM + TKEFLK (NPFLKA) * WTFLK (NPFLKA)
      END IF
      RADDLY (NPFLKA) = ZERZER
*  Here we ask for the region number of the hitting point.
*     NREG (NPFLKA) = ...
*  The following line makes the starting region search much more
*  robust if particles are starting very close to a boundary:
      CALL GEOCRS ( TXFLK (NPFLKA), TYFLK (NPFLKA), TZFLK (NPFLKA) )
      CALL GEOREG ( XFLK  (NPFLKA), YFLK  (NPFLKA), ZFLK  (NPFLKA),
     &              NRGFLK(NPFLKA), IDISC )
*  Do not change these cards:
      CALL GEOHSM ( NHSPNT (NPFLKA), 1, -11, MLATTC )
      NLATTC (NPFLKA) = MLATTC
      CMPATH (NPFLKA) = ZERZER
      CALL SOEVSV

      RETURN
      END
```

mydata

```
      integer MAXRECORD
      parameter (MAXRECORD = 12)

*     Total, Photon, Electron, Neutron, Muon
      integer MAXTYPE
      parameter (MAXTYPE = 5)

      REAL*8 powers(MAXRECORD,MAXTYPE)
      integer*4 region(MAXRECORD+1)

      common /power/ powers, region

      save /power/
```

mgdraw.f

```
      SUBROUTINE MGDRAW ( ICODE, MREG )
      INCLUDE '(DBLPRC)'
      INCLUDE '(DIMPAR)'
      INCLUDE '(IOUNIT)'
      INCLUDE '(CASLIM)'
      INCLUDE '(COMPUT)'
      INCLUDE '(SOURCM)'
      INCLUDE '(FHEAVY)'
      INCLUDE '(FLKSTK)'
      INCLUDE '(GENSTK)'
      INCLUDE '(MGDDCM)'
```

```
      INCLUDE '(PAPROP)'
      INCLUDE '(QUEMGD)'
      INCLUDE '(SUMCOU)'
      INCLUDE '(TRACKR)'
      INCLUDE '(BEAMCM)'
*
      include 'mydata'

      LOGICAL LFCOPE
      SAVE LFCOPE
      DATA LFCOPE / .FALSE. /

      real*8 tmp
      integer i, j, ierr
      integer reg_c1o, reg_c1i, reg_tank
      save    reg_c1o, reg_c1i, reg_tank
*
*----------------------------------------------------------------------*
*                                                                      *
*     Icode = 1: call from Kaskad                                      *
*     Icode = 2: call from Emfsco                                      *
*     Icode = 3: call from Kasneu                                      *
*     Icode = 4: call from Kashea                                      *
*     Icode = 5: call from Kasoph                                      *
*                                                                      *
*----------------------------------------------------------------------*
*                                                                      *
      RETURN
*
*======================================================================*
*                                                                      *
*     Boundary-(X)crossing DRAWing:                                    *
*                                                                      *
*     Icode = 1x: call from Kaskad                                     *
*             19: boundary crossing                                    *
*     Icode = 2x: call from Emfsco                                     *
*             29: boundary crossing                                    *
*     Icode = 3x: call from Kasneu                                     *
*             39: boundary crossing                                    *
*     Icode = 4x: call from Kashea                                     *
*             49: boundary crossing                                    *
*     Icode = 5x: call from Kasoph                                     *
*             59: boundary crossing                                    *
*                                                                      *
*======================================================================*
*                                                                      *
      ENTRY BXDRAW ( ICODE, MREG, NEWREG, XSCO, YSCO, ZSCO )
      IF ( .NOT. LFCOPE ) THEN
        LFCOPE = .TRUE.
        do i = 1, MAXRECORD
          do j = 1, MAXTYPE
            powers(i,j) = 0.0
          end do
        end do

        CALL GEON2R("MAG1CHMI", region(1),  ierr)
        CALL GEON2R("PIPE01I ", region(2),  ierr)
        CALL GEON2R("M1TANKU ", region(3),  ierr)
        CALL GEON2R("C1I     ", region(4),  ierr)
        CALL GEON2R("M1TANKD ", region(5),  ierr)
        CALL GEON2R("PIPE12I ", region(6),  ierr)
        CALL GEON2R("M2TANK  ", region(7),  ierr)
        CALL GEON2R("PIPE2WI ", region(8),  ierr)
```

```
        CALL GEON2R("PIPEWaI1", region(9),  ierr)
        CALL GEON2R("PIPEWaI2", region(10), ierr)
        CALL GEON2R("PIPEWaI3", region(11), ierr)
        CALL GEON2R("PIPEWaI4", region(12), ierr)
        CALL GEON2R("PIPEEHI ", region(13), ierr)

        CALL GEON2R("C1O     ", reg_c1o,  ierr)
        CALL GEON2R("C1I     ", reg_c1i,  ierr)
        CALL GEON2R("M1TANKD ", reg_tank, ierr)

        OPEN (UNIT = 85, FILE = "c1.dat", STATUS = 'UNKNOWN')
        OPEN (UNIT = 86, FILE = "after.dat", STATUS = 'UNKNOWN')
      END IF

      if(jtrack .gt. 0) then
        tmp = wtrack * (etrack - am(jtrack))
      else
        tmp = 0.d0
      end if

      do i = 1, MAXRECORD
        if(MREG.eq.region(i) .and. NEWREG.eq.region(i+1)) then
*         Summation powers
          powers(i,1) = powers(i,1) + tmp
          if(jtrack .eq. 7) then
            powers(i,2) = powers(i,2) + tmp
          else if(jtrack .eq. 3 .or. jtrack .eq. 4) then
            powers(i,3) = powers(i,3) + tmp
          else if(jtrack .eq. 8 .or. jtrack .eq. 9) then
            powers(i,4) = powers(i,4) + tmp
          else if(jtrack .eq. 10 .or. jtrack .eq. 11) then
            powers(i,5) = powers(i,5) + tmp
          end if

*    Record particles entering experimental hall
          if(i .eq. MAXRECORD) then
          write(86,100) xsco,ysco,zsco,cxtrck,cytrck,
&                       jtrack,etrack,wtrack
          endif

          exit
        end if
100     format(F7.2,F8.2,F9.2,2E14.6,I3,2E14.6)
      end do

*     Write particles leaving C1
      if((MREG.eq.reg_c1o .or. MREG.eq.reg_c1i) .and.
&       NEWREG.eq.reg_tank) then
          write(85,100) xsco,ysco,zsco,cxtrck,cytrck,
&                       jtrack,etrack,wtrack
      end if

      RETURN
*
*=======================================================================*
*                                                                       *
*     Event End DRAWing:                                                *
*                                                                       *
*=======================================================================*
*                                                                       *
      ENTRY EEDRAW ( ICODE )
      RETURN
*
```

```
*======================================================================*
*                                                                      *
*     ENergy deposition DRAWing:                                       *
*                                                                      *
*     Icode = 1x: call from Kaskad                                     *
*             10: elastic interaction recoil                           *
*             11: inelastic interaction recoil                         *
*             12: stopping particle                                    *
*             13: pseudo-neutron deposition                            *
*             14: escape                                               *
*             15: time kill                                            *
*     Icode = 2x: call from Emfsco                                     *
*             20: local energy deposition (i.e. photoelectric)         *
*             21: below threshold, iarg=1                              *
*             22: below threshold, iarg=2                              *
*             23: escape                                               *
*             24: time kill                                            *
*     Icode = 3x: call from Kasneu                                     *
*             30: target recoil                                        *
*             31: below threshold                                      *
*             32: escape                                               *
*             33: time kill                                            *
*     Icode = 4x: call from Kashea                                     *
*             40: escape                                               *
*             41: time kill                                            *
*             42: delta ray stack overflow                             *
*     Icode = 5x: call from Kasoph                                     *
*             50: optical photon absorption                            *
*             51: escape                                               *
*             52: time kill                                            *
*                                                                      *
*======================================================================*
*                                                                      *
      ENTRY ENDRAW ( ICODE, MREG, RULL, XSCO, YSCO, ZSCO )
      RETURN
*
*======================================================================*
*                                                                      *
*     SOurce particle DRAWing:                                         *
*                                                                      *
*======================================================================*
*
      ENTRY SODRAW
      RETURN
*
*======================================================================*
*                                                                      *
*     USer dependent DRAWing:                                          *
*                                                                      *
*     Icode = 10x: call from Kaskad                                    *
*             100: elastic   interaction secondaries                   *
*             101: inelastic interaction secondaries                   *
*             102: particle decay  secondaries                         *
*             103: delta ray  generation secondaries                   *
*             104: pair production secondaries                         *
*             105: bremsstrahlung  secondaries                         *
*             110: decay products                                      *
*     Icode = 20x: call from Emfsco                                    *
*             208: bremsstrahlung secondaries                          *
*             210: Moller secondaries                                  *
*             212: Bhabha secondaries                                  *
*             214: in-flight annihilation secondaries                  *
*             215: annihilation at rest   secondaries                  *
```

```
*             217: pair production        secondaries                  *
*             219: Compton scattering     secondaries                  *
*             221: photoelectric          secondaries                  *
*             225: Rayleigh scattering    secondaries                  *
*     Icode = 30x: call from Kasneu                                    *
*             300: interaction secondaries                             *
*     Icode = 40x: call from Kashea                                    *
*             400: delta ray  generation secondaries                   *
*  For all interactions secondaries are put on GENSTK common (kp=1,np) *
*  but for KASHEA delta ray generation where only the secondary elec-  *
*  tron is present and stacked on FLKSTK common for kp=npflka          *
*                                                                      *
*======================================================================*
*
      ENTRY USDRAW ( ICODE, MREG, XSCO, YSCO, ZSCO )
      RETURN
      END
```

usrout.f

```
      subroutine usrout( NOMORE )

      INCLUDE '(DBLPRC)'
      INCLUDE '(DIMPAR)'
      INCLUDE '(IOUNIT)'
      INCLUDE '(CASLIM)'

      include 'mydata'

      integer i, j, ierr
      character*8 name1, name2

      write(lunout,*) "Particle energy along XTOD (GeV * weight)"
      write(lunout,*)
      do i = 1, MAXRECORD
        CALL GEOR2N(region(i), name1, ierr)
        CALL GEOR2N(region(i+1), name2, ierr)

        write(lunout,*) "  from ", name1, " to ", name2, ": "
        write(lunout,*) "       Total:", powers(i,1)
        write(lunout,*) "      Photon:", powers(i,2)
        write(lunout,*) "    Electron:", powers(i,3)
        write(lunout,*) "     Neutron:", powers(i,4)
        write(lunout,*) "        Muon:", powers(i,5)
        write(lunout,*)
      end do

      open(UNIT = 90, FILE = "power.out", STATUS = 'UNKNOWN')
      write(90,*) ncase
      do i = 1, MAXRECORD
        do j = 1, MAXTYPE
          write(90,*) powers(i,j)
        end do
      end do
      write(90,*)
      close(90)

      end
```