SLAC RADIATION PHYSICS NOTE RP 99–15

Title: **Dose to Electronics in the NLC Beam Tunnel**

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1 Introduction

Due to instantaneous beam losses along the accelerator structures in the NLC beam tunnel showers of secondary particles - predominantly electrons, positrons, photons and neutrons - will be created. Any mechanical or electrical component installed in the beam tunnel will therefore be exposed to and possibly damaged by this secondary radiation.

In order to reduce the damage to electronic components different scenarios have been proposed. They typically differ in whether the electronics is installed inside the beam tunnel or outside, i.e. in parallel tunnels, sector alcoves, on the surface etc. Advantages and disadvantages of each scenario have to be estimated carefully since in general large cost-factors are involved. Whereas the former solutions require the installation of radiation-hard electronics and / or local shielding latter solutions allow the use of conventional, non-radiation-hard electronics but involve the construction of additional tunnels and long cable runs.

The present study aims in estimating the dose delivered to semiconductors installed at various locations *inside* the beam tunnel. In order to allow the use of Monte Carlo methods in the calculations the situation has been simplified by assuming solid “blocks” of silicon located at the respective locations of interest. In addition different scenarios of local shielding have been studied. It should be mentioned that the present study does *not* include estimates of radiation effects from so-called dark currents [1, 2].

2 The FLUKA calculations

The calculations were carried out with the ‘99 version of the particle interaction and transport code FLUKA [3, 4]. The FLUKA code has been extensively benchmarked against experimental data over a wide energy range for both hadronic and electromagnetic showers [3, 4, 5, 6, 7, 8]. For the present study the program has been used to simulate the electromagnetic and hadronic particle cascade in the NLC beam tunnel and walls as well as in various components and magnets which will be installed in the vicinity of the beam pipe.

2.1 The geometry

The complex geometry of an 8 m long section of the beam tunnel has been modelled in detail with the ALIFE geometry editor [9, 10] based on drawings obtained from [11]. The geometry is described in a right-handed orthogonal system with its origin centered in the beam pipe at the front face of the tunnel section, x as the vertical axis and z pointing down-beam.

Elevation and plan views of the FLUKA geometry are shown in Fig.1. The installations around the beam pipe include (see also the transverse sections in Fig.2): two quadrupole magnets, two electronics racks carried by hollow iron cylinders underneath the magnets, a space frame, a support structure and three ion pumps mounted on hollow cylindrical structures above the space frame. As can be seen in Fig.1b three niches in the beam tunnel wall at a height of 80 cm above beam line level were also modelled.

It was assumed that semiconductor components will be installed in following locations

- at the locations of the three ion pumps,
- at the locations of the two racks, i.e. close to the quadrupole magnets and
- in the three niches in the beam tunnel wall.

It is obvious that the semiconductor components at the locations of the ion pumps and racks but also located in the niches will be directly exposed to secondary particle radiation (predominantly electrons, photons and neutrons) caused by beam losses in the pipe. In the following we will therefore call this situation with regard to the pumps and racks *"unshielded"* and with regard to the $2' \times 2' \times 2'$ niches *"Layout 1"*.

In order to study the effect of lead-shielding to the dose delivered to the semiconductors at the pump and rack locations a second geometrical setup was considered. Here the pumps were completely covered by two inches of lead and the racks were covered from the top, front and back by four inches of lead. This setup which we will call *"shielded"* throughout this report is shown in Fig.3a.

In addition a second layout of the niches, called hereafter *"Layout 2"*, was studied (see Fig.3b). In this layout the electronics was assumed to be located inside cylindrical tubes of a length of about 70 cm and a diameter of 15 cm which are embedded in the tunnel wall under a horizontal angle of 45 degrees backwards, i.e. against the direction of the beam.

With regard to the FLUKA geometry of the beam pipe the calculations are based on two different assumptions. Initially, the calculations were based on a cylindrical pipe with 3.365 cm inner and 4 cm outer radius (see Figs.1a and 3a). In a later step however this pipe was replaced by a more realistic accelerator structure taking into account iris-substructures [12] (see Fig.4).

The beam tunnel walls, ceiling and floor were assumed to have a thickness of 2'.

2.2 Materials

All concrete shielding components were assumed to have a density of 2.35 g/cm^3 and the following chemical composition (the values in brackets give the corresponding mass fractions): oxygen (50.0%), silicon (20.0%), calcium (19.5%), aluminum (3.0%), iron (1.4%), hydrogen (0.6%), carbon (3.0%), magnesium (0.5%), sodium (1.0%) and potassium (1.0%).

In order to estimate the dose delivered to semiconductors both the pumps and racks were assumed to consist of solid silicon. Similarly, the niches were assumed to be $2' \times 2' \times 2'$ "blocks" of silicon in Layout 1 and 15 cm long silicon cylinders located at the end of the tubular niches in Layout 2.

Other materials used in the calculations include aluminum (support structure), stainless steel (space frame), copper (beam pipe and structures carrying the ion pumps) and iron (magnets).

2.3 Energy thresholds, biasing and magnetic fields

The lower energy thresholds for particle transport were set to 1 MeV and 100 keV for electrons and photons, respectively. Neutrons were followed down to 0.4 eV. The transport threshold for all other hadrons was set to 10 keV.

In order to speed up the calculations full leading particle biasing was activated in electromagnetic processes. Photo-neutron production was biased by a reduction factor of 0.02 for the inelastic interaction length of photons. It should be noted that all biasing techniques in FLUKA do *not* alter the physical result of the calculation provided the result represents an average over particle cascades caused by a sufficiently large number of primary particles (here: beam electrons lost in the beam pipe).

The magnetic fields in the two magnets have not been taken into account.

2.4 Calculated quantities

Limits on radiation damage to electronics are often given in units of rad or in units of 1 MeV neutrons per cm^2. Therefore total energy deposition and neutron fluence spectra were calculated for the racks, pumps and niches. Since the silicon "blocks" in our calculations are rather huge objects as compared to electronic components we calculated both the energy deposition averaged over the whole volume and, in addition, the dose deposited at the surface closest to the loss assuming a thickness of 1 cm (in the following called "surface dose").

Whereas the energy deposition values can be directly compared to the corresponding limit the neutron fluence spectra have to be converted to an equivalent quantity for 1 MeV neutrons. This was done by folding the neutron spectra with the energy dependent neutron kerma factors published in [13, 14] (extrapolated at high energy and normalized to the neutron kerma factors at 1 MeV) and by integrating the resulting spectrum over energy.

As an example we show in Fig.5a the average neutron fluence spectrum in the downstream rack. Folding this spectrum with the kerma factors shown in Fig.5b yields the curve plotted in Fig.5a with symbols. As expected high-energy neutrons ($E > 20$ MeV) dominate the folded spectrum.

2.5 Loss scenarios

Two beam-loss scenarios were considered: continuous losses of 500 GeV electrons over the full length of the beam pipe section (*line source*) and point losses at certain longitudinal locations in the pipe (*point source*). Whereas the former represent beam losses continuously occurring during normal operation the latter represent cases of mis-steered beam.

In calculations using the simplified version of the pipe the starting point of the transport of the primary electron was assumed to be in the copper pipe at a radial distance from the beam axis of 3.68 cm ($= (4.0 + 3.365)/2$ cm) with the electron moving parallel to the pipe.* In calculations using the more realistic pipe layout a radial distance of 0.8 cm was chosen.

FLUKA calculates particle showers on an event-by-event basis with one event being the particle shower caused by one lost electron. Results obtained from FLUKA are therefore normalized per lost electron. In order to be able to compare these results to certain limits, such as on radiation damage to semiconductors, they must be normalized to the number of electrons lost over a certain period of time. For the continuous losses we assumed that a power of 1.4 W is lost per meter for 10 years and 300 days per year. The value of 1.4 W / m was obtained in [15] from measurements combined with FLUKA calculations for the SLC LINAC tunnel which were scaled to the NLC beam power of 10 MW. The resulting factor is therefore $1.4 \times 4.494 \times 10^{10}$ electrons / m / h or 4.53×10^{15} electrons / m / 10 years. For point losses the situation is far more uncertain and depends on which lost beam power the accelerator structures can stand and for how long before they melt. This has still to be determined. In the meantime we normalize our results to 1 W lost again for 10 years and 300 days per year.

3 Results

3.1 Continuous losses

In Fig.6 the fluence of all particles is shown for a vertical section through the beam tunnel containing the beam axis. Fluence values are normalized to a loss of one electron of 500 GeV per meter. Since in the calculations the primary electrons were sampled only over a length of 720 cm (the length of the pipe section which we considered) the fluence values shown for z below about 400 cm are lacking the contributions coming from electron losses further upstream and might therefore underestimate the true value. For this reason we discuss in the following only results for rack 2, ion pump 3 and niche 3 (see Fig.1) which are all located at larger z.

*A more realistic scenario would be to assume that the electron hits the pipe under a certain angle. In those cases the material thickness the electron penetrates and the following particle shower would most likely be smaller causing less energy deposition in components etc. than in the extreme case we considered in the present work. Our interest in calculating upper limits for radiation damage to electronics however justifies our assumptions.

In Table 1 results are given for rack 2 assuming the above mentioned loss of 1.4 W/m. Dose values averaged over the whole rack and calculated for the surface pointing upstream (assuming a

Table 1: Average and surface dose rates and doses delivered to rack 2 (see Fig.1a) in the unshielded and shielded situations. Dose values are based on a total operation time of 10 years and 300 days per year and a loss of 1.4 W/m. The last two lines give fluence rates of 1 MeV neutrons averaged over the whole rack and integrated over the above period.

Rack 2		unshielded	shielded (4" Pb)
average	rad/h	257 ± 7	0.24 ± 0.04
	rad	1.9×10^7	1.7×10^4
surface	rad/h	820 ± 21	0.76 ± 0.13
	rad	5.9×10^7	5.5×10^4
neutron (1MeV)	$cm^{-2}h^{-1}$	2.7×10^9	1.4×10^9
	cm^{-2}	1.9×10^{14}	1.0×10^{14}

1 cm thick slice) as well as 1 MeV neutron fluence values are given for the unshielded and shielded scenarios. Note that the dose values contain the contributions from all transported particles. The calculations for the unshielded silicon were based on the simplified beam pipe layout whereas in the calculations for the shielded silicon the more sophisticated pipe geometry was used.† For each quantity in Table 1 the first line always shows the rate per hour whereas the second line gives the integrated value for 10 years and 300 days per year. For the dose rates we give the statistical uncertainties of the Monte Carlo calculation. The lead-shield reduces the dose rate which is mostly caused by electromagnetic particles by about a factor of 1000 but is rather inefficient, as expected, for neutrons.

In Table 2 results are shown for pump 3. Here "surface" again means a slice of 1 cm adjacent

Table 2: Average and surface dose rates and doses delivered to ion pump 3 (see Fig.1a) in the unshielded and shielded situations. Dose values are based on a total operation time of 10 years and 300 days per year and a loss of 1.4 W/m. The last two lines give fluence rates of 1 MeV neutrons averaged over the whole pump and integrated over the above period.

Ion Pump 3		unshielded	shielded (2" Pb)
average	rad/h	96 ± 9	2.2 ± 1.0
	rad	6.9×10^6	1.6×10^5
surface	rad/h	233 ± 21	5.3 ± 2.4
	rad	1.7×10^7	3.8×10^5
neutron (1MeV)	$cm^{-2}h^{-1}$	1.2×10^9	1.1×10^9
	cm^{-2}	8.8×10^{13}	7.9×10^{13}

to the upstream face of the pump. The statistical uncertainties, in particular in the surface value

†Calculations were also performed for the shielded scenario and the simplified pipe. The differences in the dose rates due to the different pipe layouts are within the statistical uncertainties.

of the shielded scenario, are higher than those for the rack since the volume of the pump is much smaller. The lead shield of two inches thickness reduces the dose rate by about a factor of 40 but has almost no effect on the 1 MeV neutron value.

Finally, in Table 3 the FLUKA predictions for niche 3 are presented. Here we give the values for the two layouts. Comparing these values for the different layouts one notices a reduction in the average dose of about 2700 and in the surface dose of about 12000. This difference is due to the fact that the surface in Layout 1 is directly facing towards the beam tunnel whereas in Layout 2 it is shielded by the backward angled niche. Neutron spectra were not calculated for Layout 1.

Table 3: Average and surface dose rates and doses delivered to niche 3 for layouts 1 and 2 (see Figs.1b and 3b). Dose values are based on a total operation time of 10 years and 300 days per year and a loss of 1.4 W / m. The last two lines give fluence rates of 1 MeV neutrons averaged over the whole niche and integrated over the above period.

Niche 3		Layout 1	Layout 2
average	rad / h	5.5 ± 0.2	$(2.0 \pm 0.3) \times 10^{-3}$
	rad	3.9×10^5	144
surface	rad / h	26 ± 1	$(2.1 \pm 0.7) \times 10^{-3}$
	rad	1.9×10^6	151
neutron (1MeV)	$\mathrm{cm}^{-2}\mathrm{h}^{-1}$	–	2.8×10^7
	cm^{-2}	–	2.0×10^{12}

3.2 Point losses

Spatial distributions of the fluence of all particles are shown for different loss points and a section in the $x - z$ plane containing the beam axis in Fig.7.

In the following, two different locations of point losses were considered: $z_{\mathrm{loss}} = 200$ cm, where one can expect dose values for pump 2 and niche 2 close to the maximum possible values and $z_{\mathrm{loss}} = 620$ cm, which is close to rack 2. Here, the calculations were only performed for the

Table 4: Average and surface dose rates as well as average 1 MeV neutron fluence rates are given for a point loss of 1 W. The loss locations are $z_{\mathrm{loss}} = 620$ cm for rack 2, $z_{\mathrm{loss}} = 200$ cm for pump 2 and $z = 200$ cm for niche 2.

		Rack 2	Pump 2	Niche 2
average	rad / h	311	30.2	0.56
surface	rad / h	1000	73.4	2.64
neutron (1MeV)	$\mathrm{cm}^{-2}\mathrm{h}^{-1}$	1.8×10^9	–	–

unshielded scenario with Layout 1 of the niches and the simplified pipe (see Fig.1). In order to allow convenient scaling a lost beam power of 1 W has been assumed. Results are given in Table 4. Realistic values for the lost power in mis-steering cases and their duration have to be estimated by beam line physicists. The time-integral of the values presented in Table 4 have then to be added to those for continuous losses discussed in the previous section.

4 Conclusions

The present study provides estimates for 1 MeV neutron fluences and dose values delivered to semiconductors at different locations in the NLC beam tunnel. Results are given for continuous losses as well as point losses and are normalized to lost beam powers of 1.4 W/m and 1 W, respectively. Whereas the former value is based on measurements performed at the SLC LINAC the latter value of 1 W is chosen in order to allow a convenient scaling for occasional mis-steering scenarios.

Any conclusions which can be drawn from this study obviously depend on limits for radiation damage to electronics. As an example we may use those published in [16]. According to these limits semiconductors would experience mild to severe damage for deposited doses between 10^3 and 10^7 rad or for 1 MeV neutrons fluences between 10^{12} and 10^{16} n/cm^2 and destruction for higher values. Comparing these limits to our calculated values one may conclude that (i) for the rack- and pump-locations the photons cause more damage than the neutrons whereas it is vice versa for the niches and (ii) for an operation period of 72000 hours only electronics in the niches of Layout 2 will survive. Conventional electronics in the other locations will be destructed or severely damaged, even if shielded with lead of thicknesses of 2” and 4”, respectively.

Finally it must again be underlined that all estimates given in this report do *not* include contributions from dark currents which can reach values of the same order of magnitude or even higher. Detailed estimations of these contributions are therefore required.

Acknowledgments

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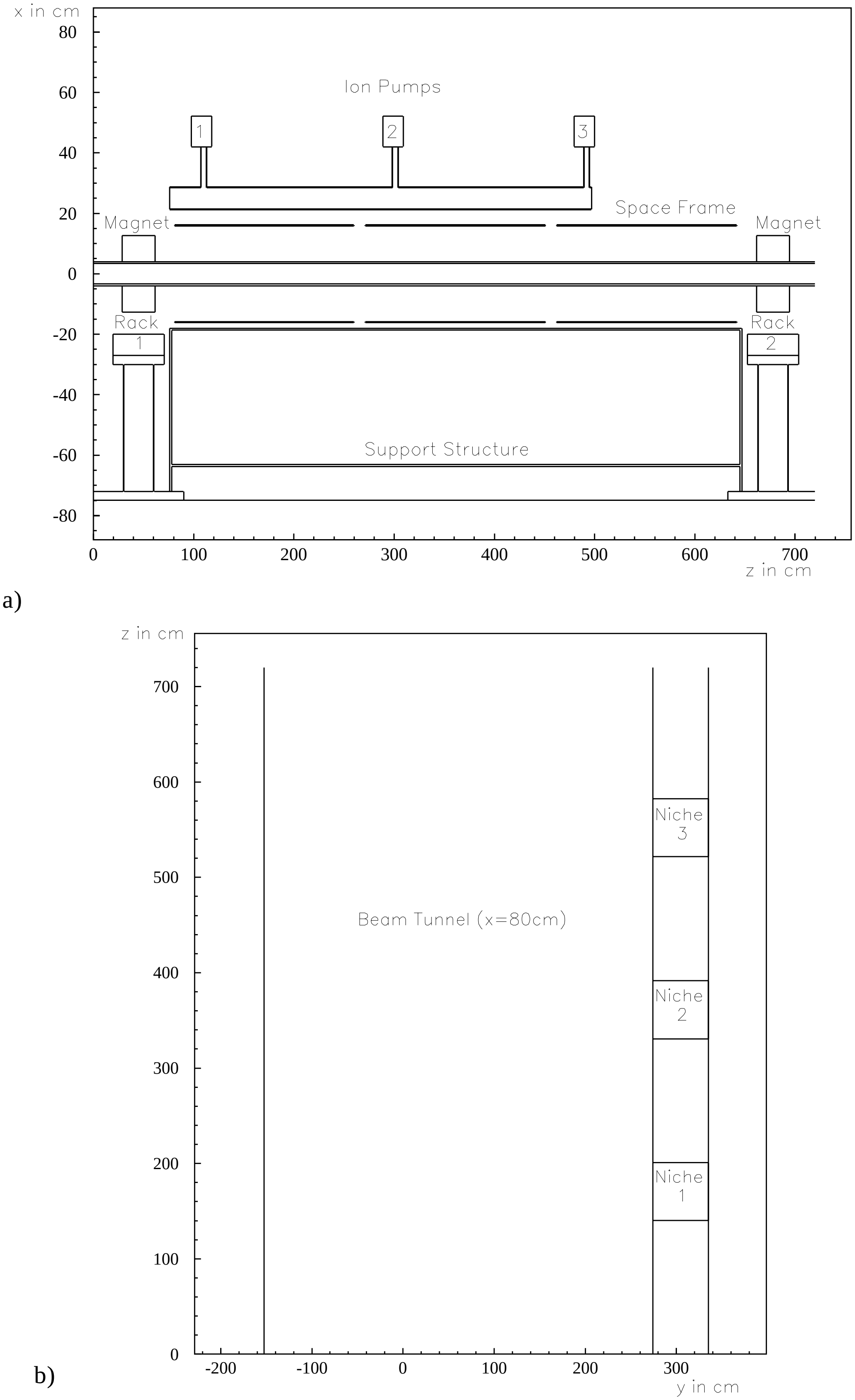


a)

b)

Figure 1: Elevation view (a) and plan view (b) of the FLUKA geometry used in the calculations. Shown in a) is the "unshielded" situation. The niches shown in b) are embedded in the concrete wall of the beam tunnel ("Layout 1").

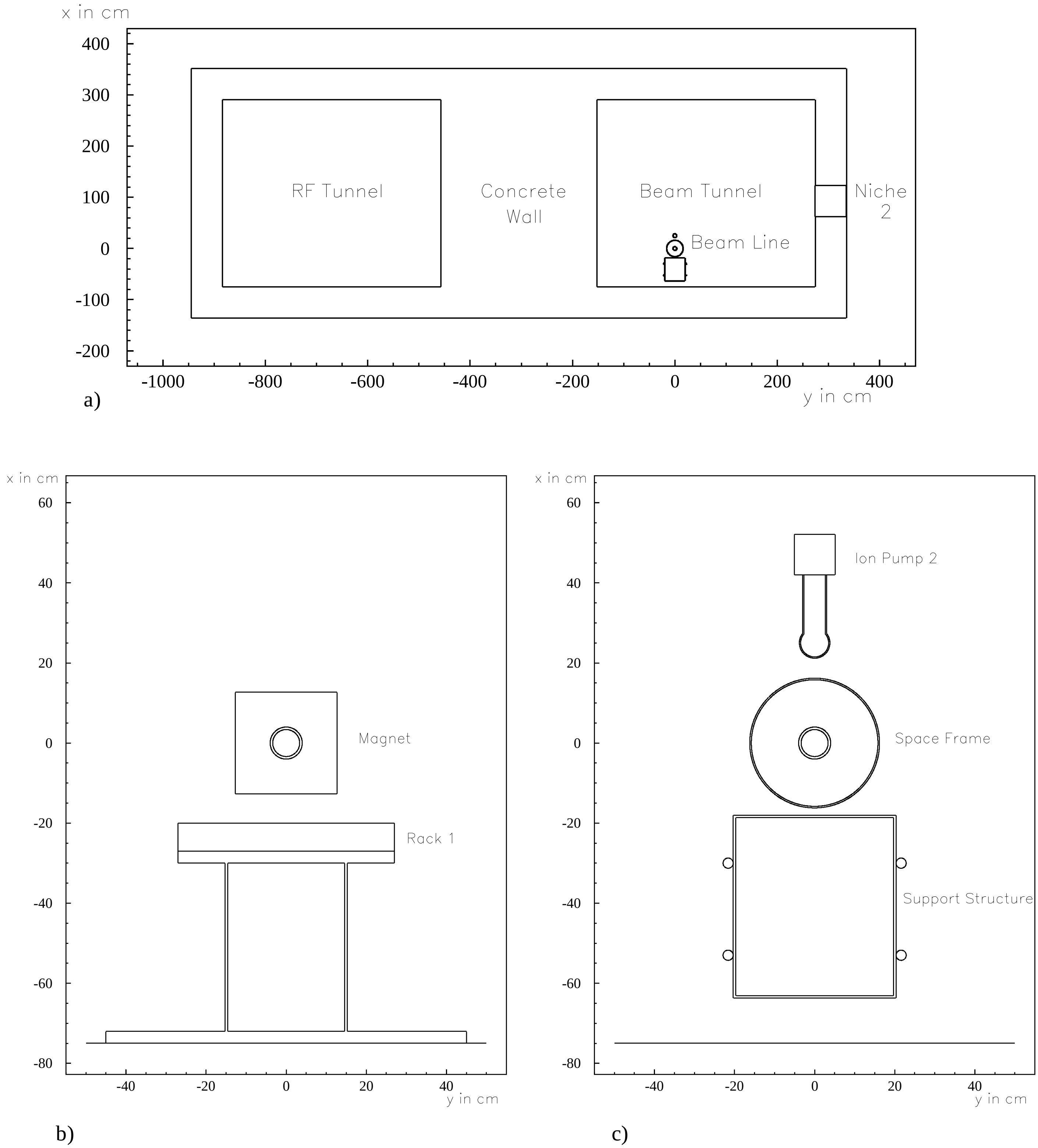
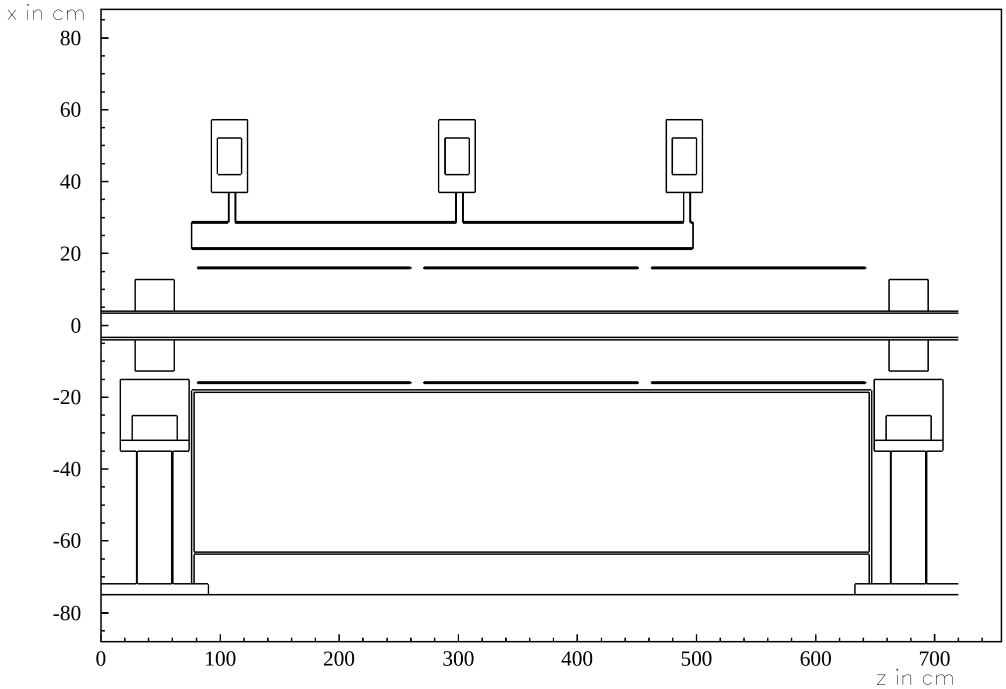


Figure 2: Elevation views (transverse to the beam line) of the FLUKA geometry used in the calculations. In a) an overall transverse view is shown with the niches in Layout 1. Sections through the first electronics rack and the second ion pump, both for the "unshielded" situation, are given in b) and c), respectively



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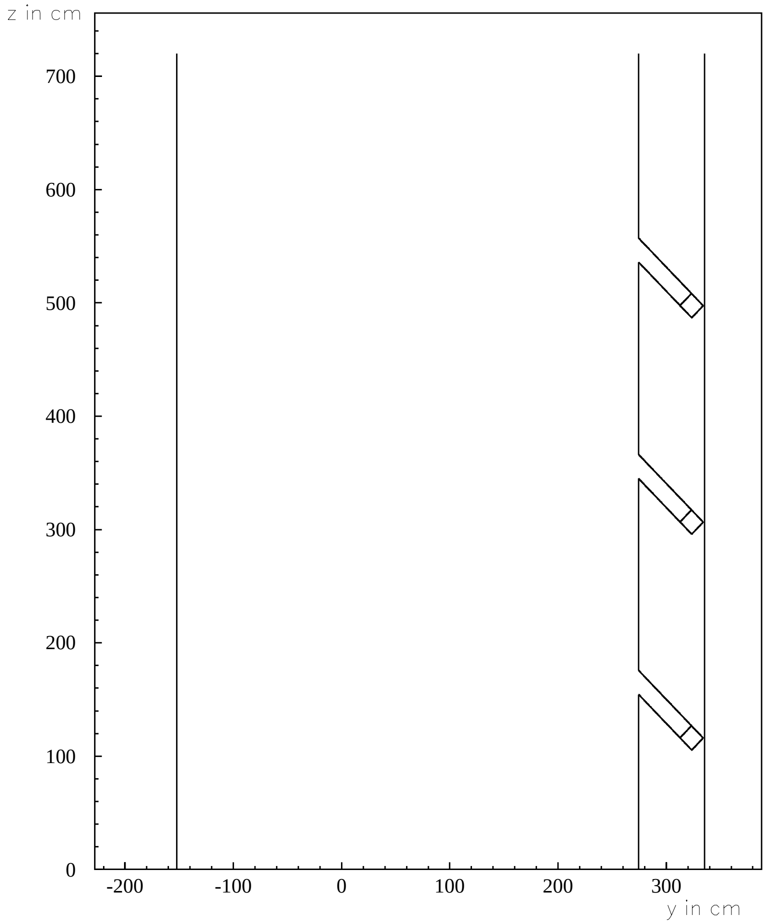


b)

Figure 3: As in Fig.1 here showing in a) the racks and pumps in the “shielded” situation and in b) the niches in Layout 2.

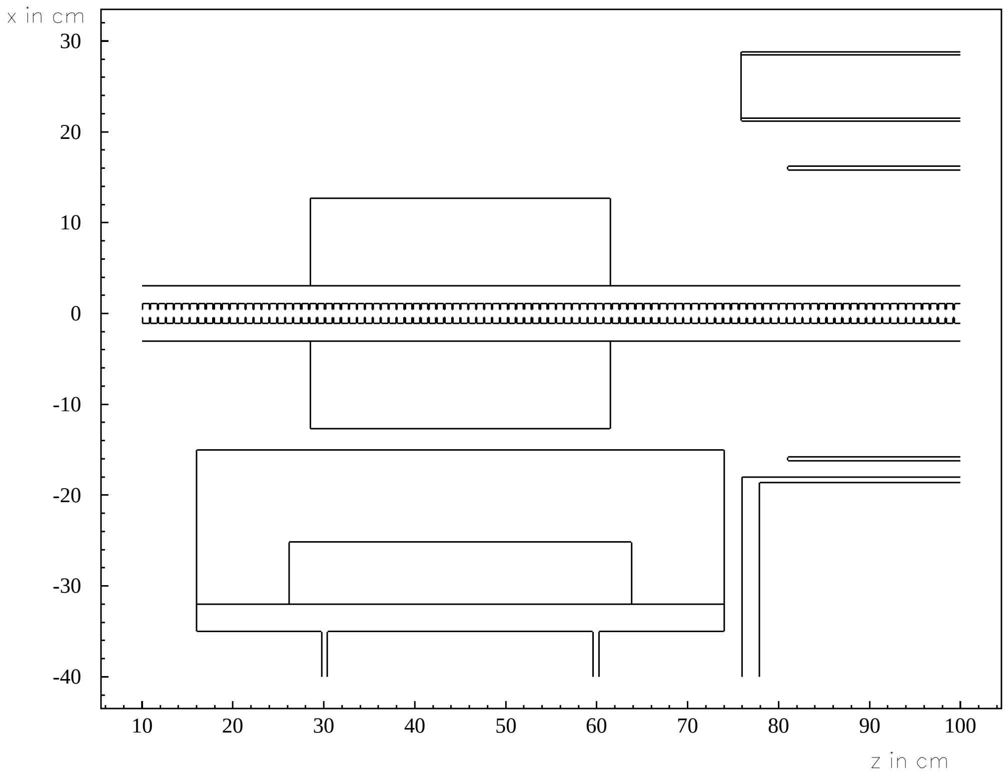
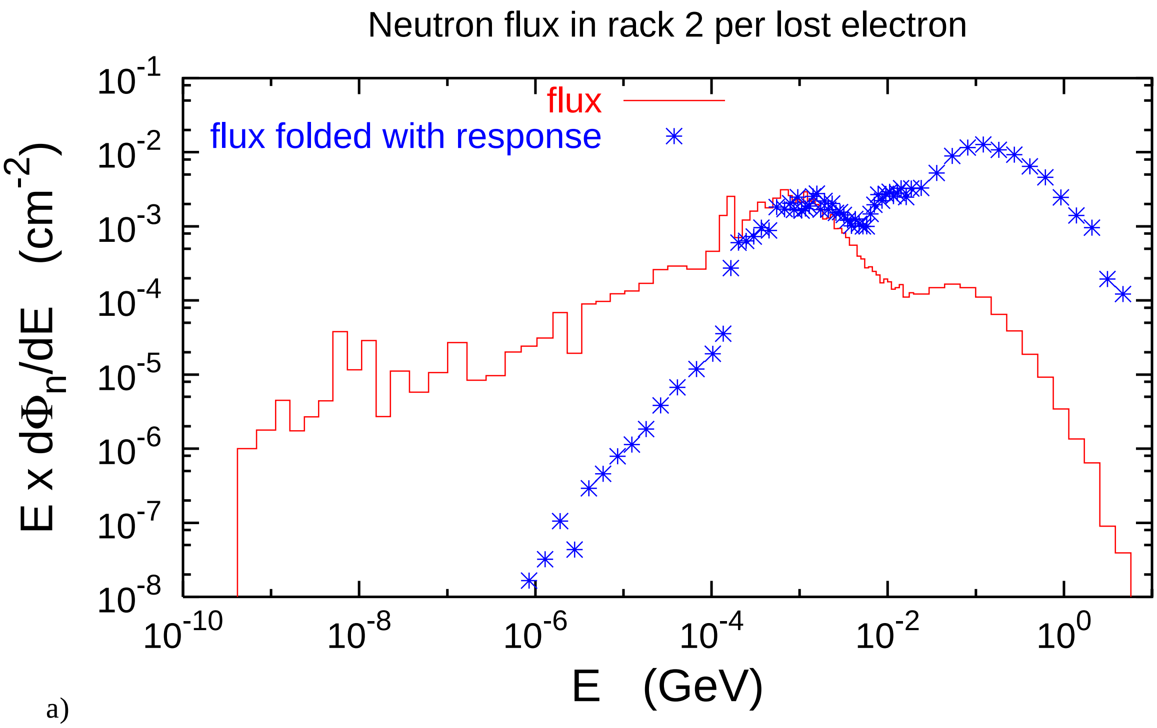
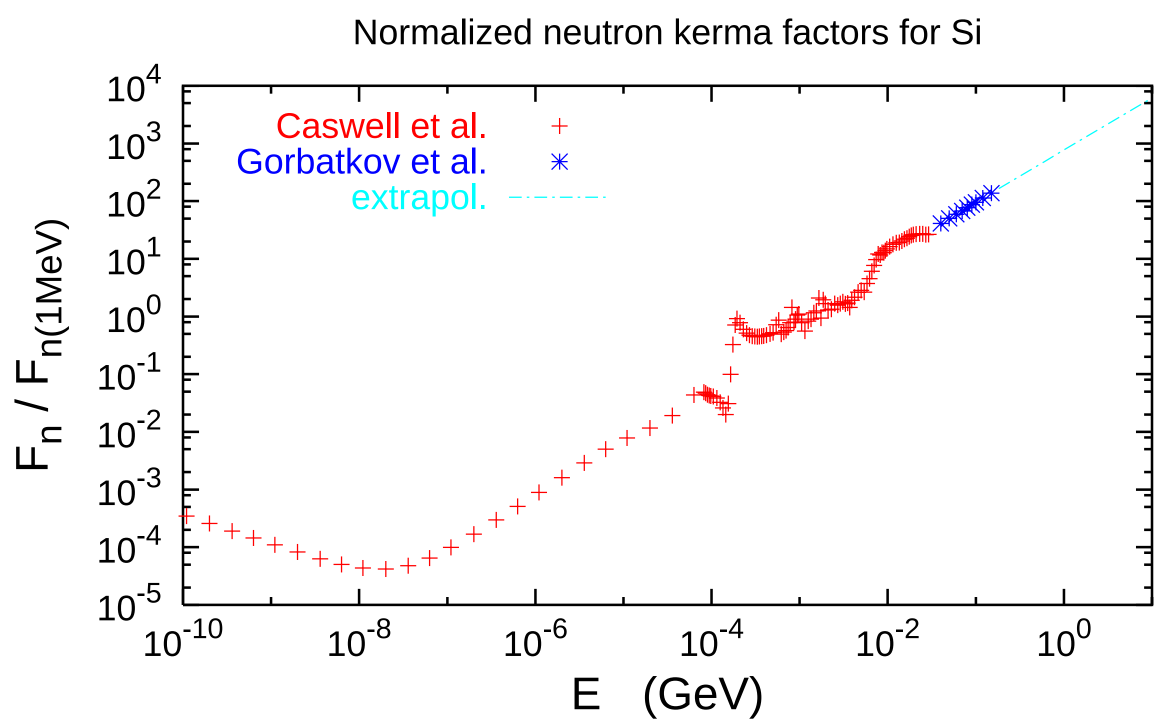


Figure 4: Zoomed elevation view of the upstream magnet, rack 1 and the beam pipe including the iris structures.



a)



b)

Figure 5: Average neutron flux spectrum in rack 2 for a loss of one electron at $z = 620$ cm (panel a, histogram). In b) neutron kerma factors normalized to the factor at 1 MeV are given for silicon [13, 14]. The neutron flux spectrum folded with these normalized kerma factors is shown in addition in a) (stars).

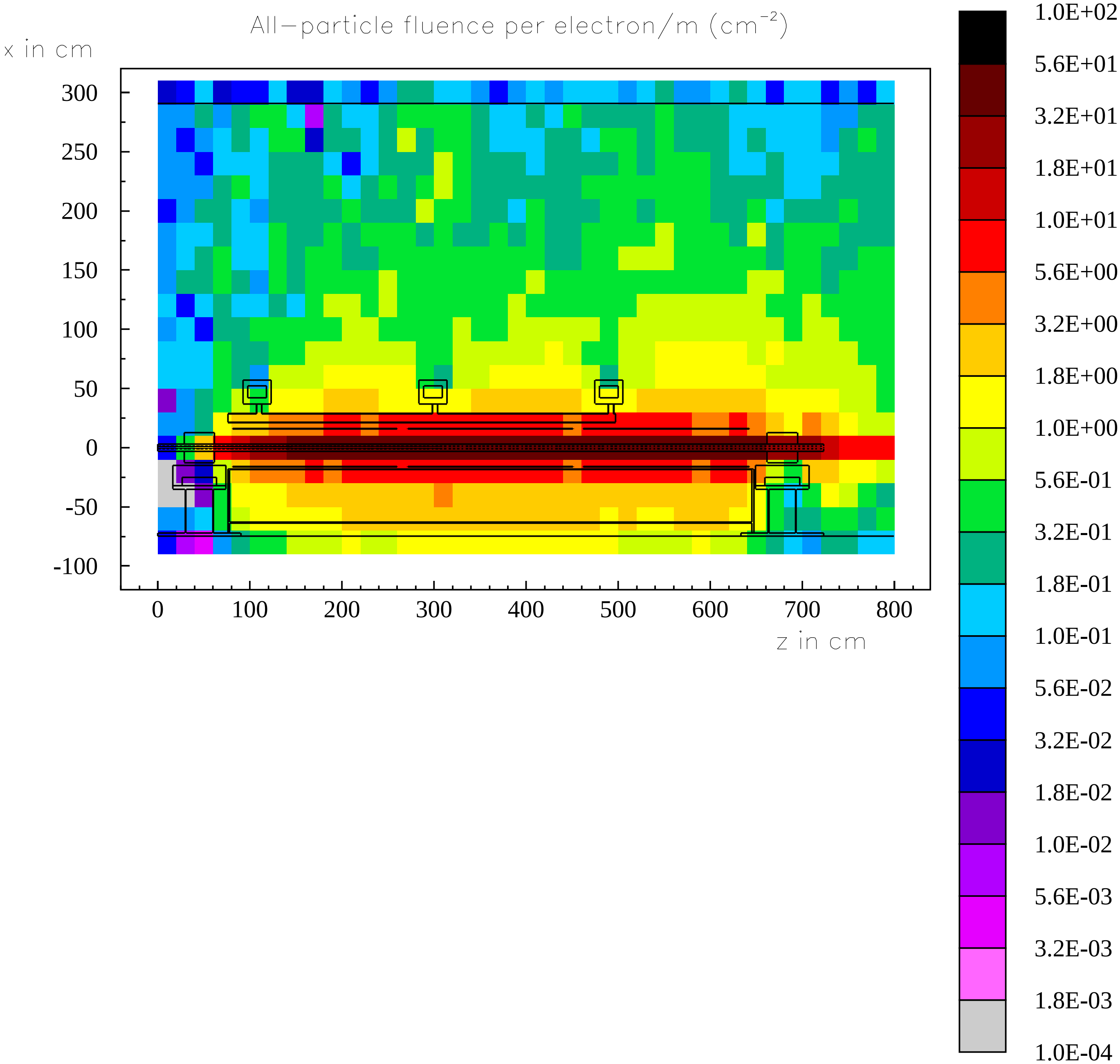


Figure 6: Average particle fluence for a loss of one electron of 500 GeV per meter in the beam pipe. Results are shown for the "shielded" situation using a beam pipe with iris structures.

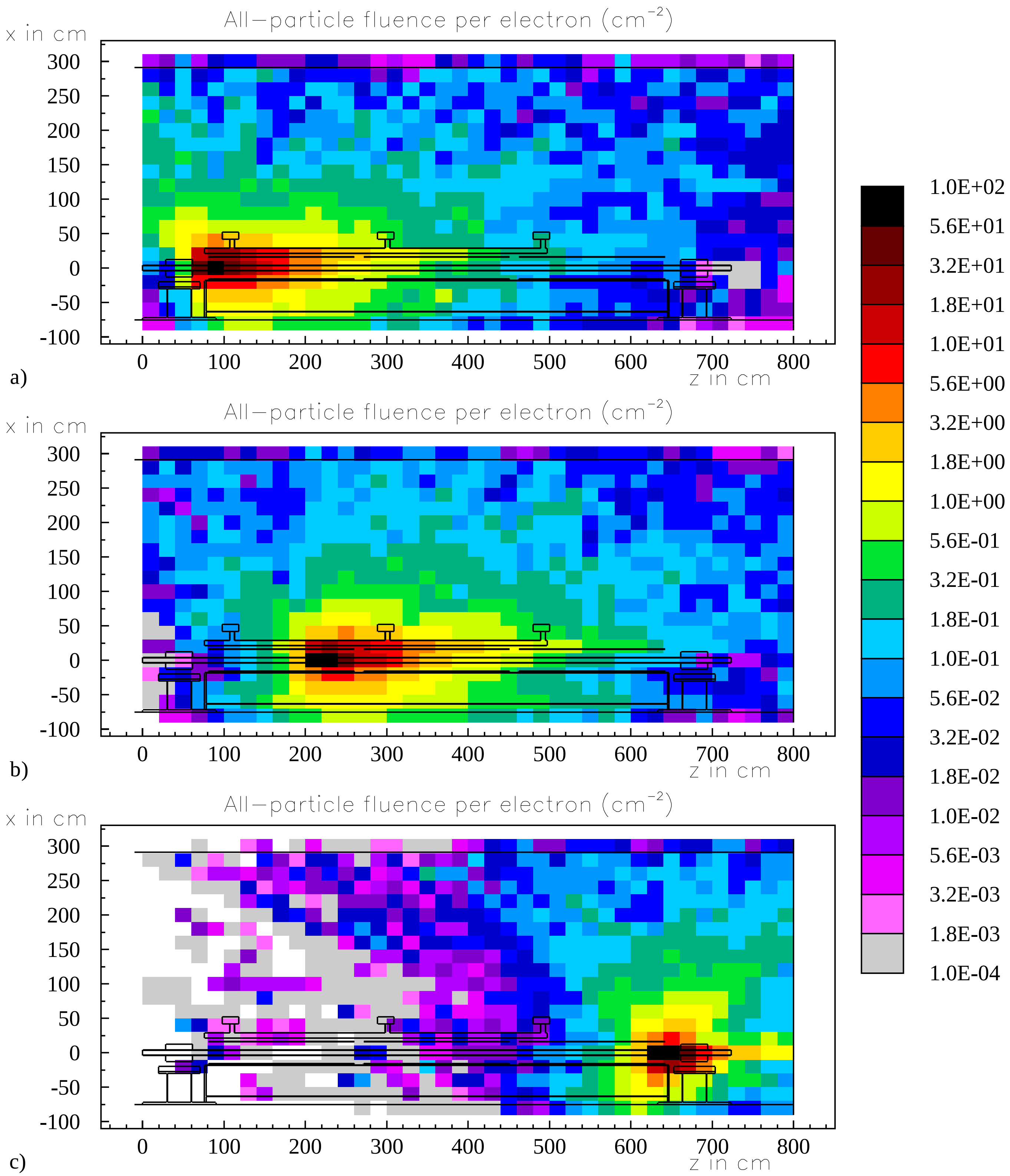


Figure 7: Average particle fluence per loss of one electron of 500 GeV in the beam pipe. The location of the losses are $z_{\text{loss}} = 61.5$ cm (a), $z_{\text{loss}} = 200$ cm (b), and $z_{\text{loss}} = 620$ cm (c). Results are shown for the "unshielded" situation using a simplified beam pipe.