SLAC-PUB-8490
June 2000

RADIATION DAMAGE TO ELECTRONICS IN THE BEAM TUNNEL OF THE NEXT LINEAR COLLIDER *

S. Roesler, J. C. Liu and S. H. Rokni
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

Abstract

Radiation damage to electronics in the Linac tunnel of the Next Linear Collider due to ionizing and non-ionizing effects has been estimated with detailed FLUKA simulations. Results for total dose deposited in silicon and for displacement damage by neutrons, protons and charged pions are presented. It is shown that non-radiation-hard electronics could be severely damaged unless sufficiently shielded against radiation. A scenario is proposed in which the electronic components are located in niches in the beam tunnel wall which are shielded by layers of polyethylene.

Presented at the Fifth Specialists Meeting on
Shielding Aspects of Accelerators, Targets and Irradiation Facilities, SATIF-5,
Paris, France, July 17–21, 2000

* Work supported by Department of Energy contract DE-AC03-76SF00515

Introduction

Due to beam losses along the accelerator structures in the Main Linac tunnel of the Next Linear Collider (NLC) [1] 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 radiation damage to semiconductors installed at various locations *inside* the beam tunnel. In particular, the installation of the electronics in niches in the beam tunnel wall is proposed. Ionizing and non-ionizing cumulative effects on electronics are estimated by calculating the total dose delivered to silicon and the displacement damage by hadrons using the Monte Carlo code FLUKA [2]. Single event effects are not considered in this study.

The FLUKA Calculations

The calculations were carried out with the '99 version of the particle interaction and transport code FLUKA. 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. In the following, details of the calculations are discussed which are of importance for the present study.

The Geometry and Materials

The complex geometry of a 12-m-long section of the beam tunnel has been modelled in detail with the ALIFE geometry editor [3, 4]. 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. An elevation view of the geometry is shown in Fig.1. The installations close to the beam pipe include: two quadrupole magnets, two electronics racks supported 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. A three-dimensional view of the FLUKA geometry is shown in Fig.2.

As can be seen in Figs.2 and 3 three cylindrical niches in the beam tunnel wall at a height of 90 cm above beam line level were also modelled. They are embedded in the wall under a horizontal angle of 45 degrees backwards, i.e., against the direction of the beam and have a length of about 70 cm. Two different diameters were studied: 15 cm and 30 cm (Fig.3 shows the

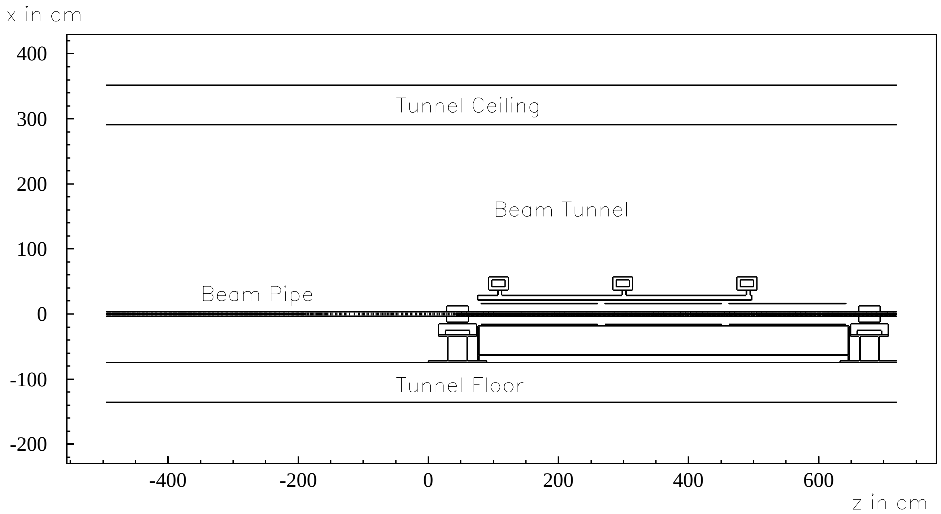

Figure 1: Vertical section through the geometry of the NLC beam tunnel used in the FLUKA calculations.

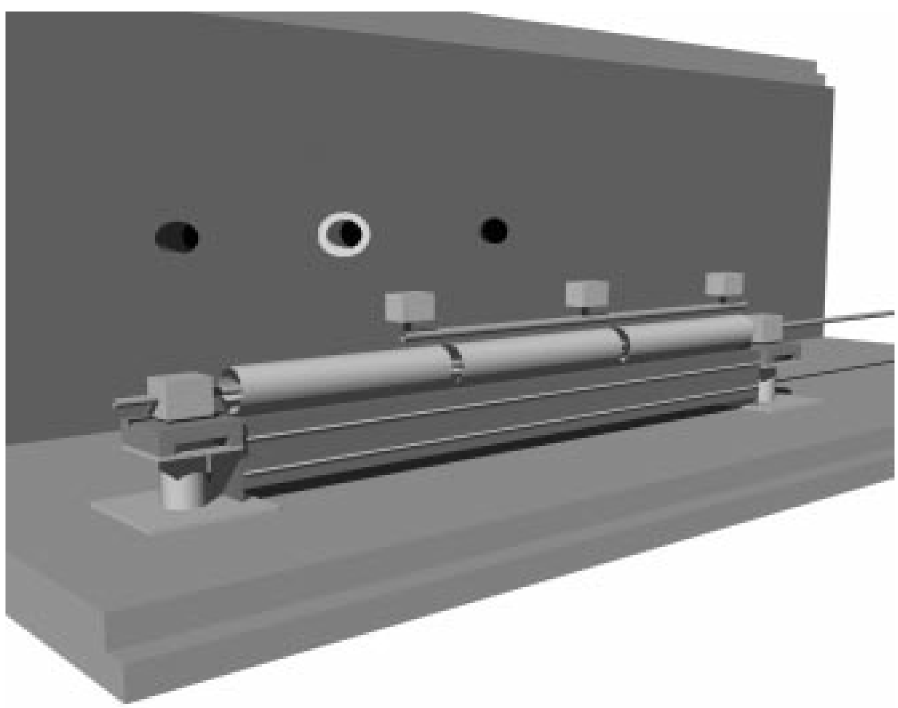

Figure 2: Three-dimensional representation of the FLUKA geometry created using FLUKACAD [5] and AutoCAD. In this view the z axis is pointing from the right to the left.

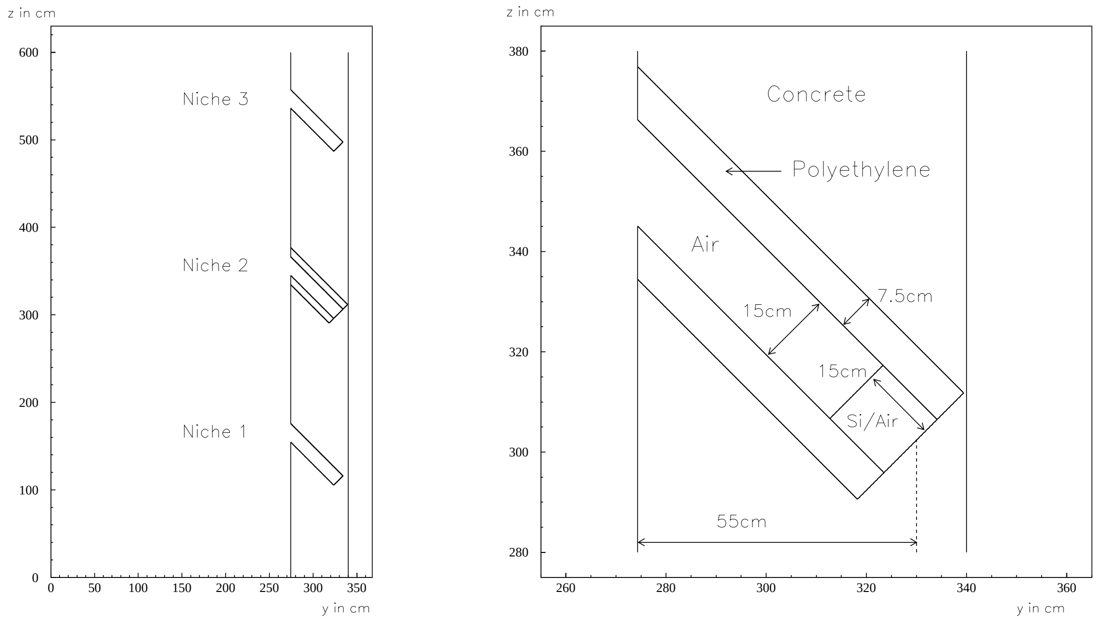

Figure 3: Horizontal section through the geometry of the niches used in the calculations (left figure). The setup with niches of a diameter of 15 cm is shown. Niche 2 (right figure) is shielded by a layer of polyethylene.

15 cm niches). In both cases niche 2 was shielded by a layer of polyethylene of 7.5 cm thickness.

Three locations for electronics installations were considered (see Figs. 3 and 4): (i) at the ion pumps above the beamline, (ii) on racks below the magnets and (iii) in the tunnel-wall niches. In addition, the effect of shielding on the damage levels at the pump and rack locations was studied by assuming the pumps to be completely enclosed by 5 cm of lead and the racks to be covered by 10 cm of lead from the front, top and back. This setup, shown in Figs. 1 and 2, will be refered to below as "shielded" whereas the one without additional lead shielding (Fig. 4) as "unshielded". In case of the niches the electronics was assumed to be located within the last 15 cm at the end of each niche (see Fig. 3).

In order to estimate the total dose delivered to semiconductors, both the pumps and racks consisted completely of silicon. Similarly, in the niches 15 cm long silicon cylinders with the same diameter as the one of the niches were used.

Calculated Quantities

The damage by ionizing radiation was estimated by calculating the total dose (electromagnetic and hadronic) to silicon at the respective locations in the tunnel.

Displacement damage is proportional to the Non-Ionizing Energy Loss (NIEL) of a particle in the semiconductor lattice and can be expressed in terms of a displacement damage function $D(E)$. In order to characterize the damage efficiency of any particle for a given energy E, the values of D are usually normalized to the ones for 1-MeV-neutrons (95 Mb mb). Figure 5 shows a compilation of damage efficiency functions for silicon [6, 7] which are widely used to estimate radiation damage at LHC experiments (see for example [8]) and were also applied in

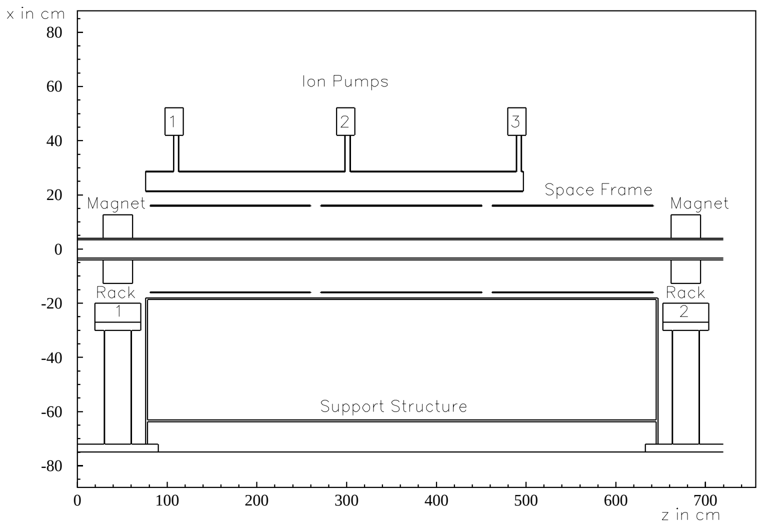

Figure 4: Vertical section through the simulated beamline installations. The three ion pumps and two racks were assumed to be possible locations for electronics.

this work. These data were implemented as a FLUKA user-subroutine. This allowed to fold

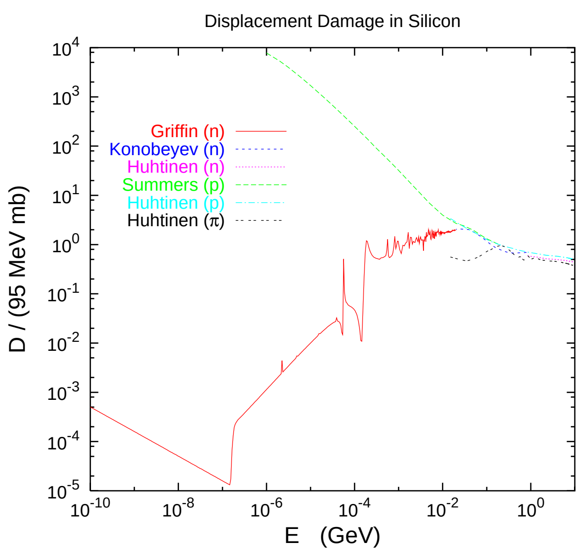

Figure 5: Silicon displacement damage functions for neutrons, protons and pions [7] (see also [6] and references therein). Values are normalized to the displacement damage by 1-MeV-neutrons (95 MeVmb).

the hadron fluence Φ with the 1-MeV-neutron displacement damage function

$$\Phi_{\rm eq}^{\rm 1MeV} = \int dE \, \frac{D(E)}{\rm 95MeVmb} \Phi(E) \tag{1}$$

and to score it in a three-dimensional mesh for any location in the NLC beam tunnel. The quantity $\Phi_{\rm eq}^{\rm 1MeV}$ (in units of $\rm cm^{-2}\ s^{-1}$) can be considered as the equivalent 1-MeV-neutron fluence producing the same bulk damage.

Energy Thresholds and Biasing

In order to save CPU-time energy thresholds for the transport of electrons and photons in the displacement damage calculations were set higher than in the dose calculations. Since in the former calculations only the hadronic cascade was of interest the threshold for electron / positron transport was set to 20 MeV and the one for photon transport to 6 MeV which corresponds approximately to the lower energy threshold for Giant Dipole Resonance interactions. For dose calculations the thresholds were lowered to 1 MeV and 100 keV for electrons / positrons and photons, respectively.

Full leading particle biasing was activated in electromagnetic processes. Photonuclear interactions were biased with a reduction factor of 0.02 for the inelastic interaction length of photons. Particle splitting by region importance biasing was used in the concrete wall around the niches in order to enhance the statistical significance of the results in the niches.

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 the calculations, the primary 500 GeV electrons were assumed to move parallel to the z-axis in positive z-direction hitting the accelerator irises at a distance from the z-axis of 0.8 cm.

Concerning the lost beam power the following assumptions were made: A power of 1.4 W is lost continuously per meter for 10 years and 300 days of NLC operation per year. This value was obtained in a study [9] from measurements combined with FLUKA calculations for the SLC LINAC tunnel which were scaled to the NLC beam power of 10 MW. Estimates for the maximum power which can be lost at a point are not available at present. In order to allow easy scaling the arbitrary assumption of a loss of 1 W was made.

Damage to Electronics near the Beamline

Results for the total dose deposited in silicon at the locations of rack 2 and pump 2 (see Fig.4) are given in Table 1. Note that results are average values for rather large silicon volumes (as compared to the size of electronics) of 2106 cm^3 for the pump and 20022 cm^3 (27540 cm^3) for the shielded (unshielded) rack and the actual dose value might therefore be underestimated due to self-attenuation in the silicon.

The equivalent 1-MeV-neutron fluence $\Phi_{\rm eq}^{\rm 1MeV}$ was scored for neutrons, protons and charged pions in a mesh covering the whole tunnel section with a bin-size of $10{\rm cm}\times 10{\rm cm}\times 10{\rm cm}$. Figure 6 shows the results for neutrons for a vertical section through the beam tunnel containing the beam pipe. Values are averaged over 20 cm in y, i.e., over two bins in y from $y = -10$ cm to $y = 10$ cm. At any location shown the values have to be interpreted as the displacement damage a silicon material (e.g. semiconductor) would experience over ten years at that location. Studying the variation along z (keeping x fixed at, for example, 100 cm) it can be observed that the values increase (decrease) for $z < -200$ cm ($z > 500$ cm). This can be explained by the fact that only losses over a 12-m-long section of the beam line were considered. Hence,

Table 1: Total dose to silicon at the location of rack 2 and pump 2. The second row under "continuous loss" gives the values integrated over 10×300 days of NLC operation.

Rack 2		unshielded	shielded (10 cm Pb)
continuous loss	Gy/h Gy	2.6 ± 0.1 1.9×10^5	$(2.4 \pm 0.4) \times 10^{-3}$ 170
point loss ($z = 620$cm)	Gy/h	3.0	–
Pump 2		**unshielded**	**shielded (5 cm Pb)**
continuous loss	Gy/h Gy	1.0 ± 0.1 7.2×10^4	0.02 ± 0.01 1600
point loss ($z = 200$cm)	Gy/h	0.3	–

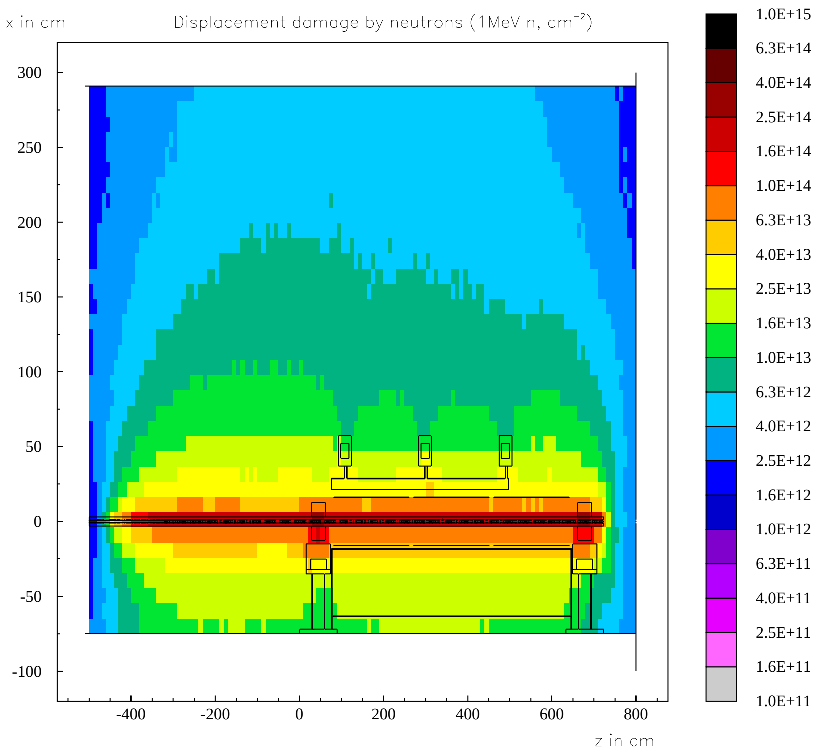

Figure 6: Displacement damage by neutrons in silicon for a loss of 1.4 W/m and 10×300 days of operation. Values are given for a vertical section through the NLC Main Linac tunnel containing the beam pipe.

contributions from losses up-(down-)stream of the considered section are missing at locations $z < -200$ cm ($z > 500$ cm). Values vary from about 1×10^{14} cm^{-2} close to the beam pipe to 5×10^{12} cm^{-2} underneath the tunnel ceiling. At the locations of the pumps and racks (shielded scenario) the 1-MeV-neutron fluence is about 2×10^{13} cm^{-2} and 4×10^{13} cm^{-2}, respectively. Displacement damage due to other hadrons is negligible as compared to that by neutrons (two orders of magnitude lower).

Damage to Electronics in the Niches

Dose to Electronics in the Niches

As mentioned above, in order to estimate the dose to electronics to be installed in the niches the last 15 cm of the niches were assumed to consist of silicon (see Fig. 3). The corresponding silicon-volumes are 2651 cm^3 and 10603 cm^3 for the 15-cm- and 30-cm-diameter niches, respectively. Dose values for the three niches and the two different diameters are listed in Table 2. The quoted errors reflect only the statistical uncertainties of the calculations.

Table 2: Total dose deposited in silicon in the three niches. Values are given for a continuous loss of 1.4 W/m and 10×300 days of operation. Units are in Gy.

Diameter	15 cm		30 cm	
	Value	Error (stat.)	Value	Error (stat.)
Niche 1	33.0	15%	29.0	11%
Niche 2	56.0	13%	47.0	8%
Niche 3	38.0	9%	45.0	12%

Comparing the three values for either of the two diameters to each other it can be seen that the value for niche 1 is lowest. This can be explained by the fact that most of the dose ($> 90\%$) is deposited by the electromagnetic cascade which is strongly peaked in forward direction. Doses for niche 1 are therefore underestimated because contributions from primary electrons lost upstream of the considered beam pipe section are missing. Furthermore, the energy deposition in niche 2 is the highest of the three niches. This is somewhat misleading because the polyethylene around niche 2 replaces what is concrete in case of the other two niches. Since concrete has a density which is about 2.5 times higher than that of polyethylene, replacing concrete by polyethylene effectively results in a reduction of the attenuation of the cascade component penetrating through the concrete.

Comparing the results for the two diameters to each other one would at first expect the doses to be larger the larger the diameter of the opening is. In contrast, the results are comparable to each other within their statistical uncertainties. This can be attributed to an artifact of averaging over the silicon cylinder and of keeping in addition the axes of the niches at the same locations: Due to the forward-peaked electromagnetic cascade the contribution to the total dose from particles penetrating through the concrete as compared to those streaming directly through the opening is therefore significant. Hence, doubling the diameter of the opening has a relatively small effect on the total dose. On the other hand, by increasing the diameter of the silicon cylinder and keeping the axis at the same place part of the additional silicon is now closer to the wall surface and part is deeper in the wall effectively leading to the same average doses.

As already mentioned above the fact that the values quoted in Table 2 were obtained by averaging over rather large silicon volumes results in an underestimation of the dose to electronics which are of much smaller sizes due to self-attenuation in the silicon. Self-attenuation can however be corrected for if it is known for silicon. Here it is assumed that silicon and concrete have similar properties so that the dependence of energy deposition in the concrete wall around the niches on the depth calculated with FLUKA can be used which decreases exponentially with depth with a slope of $0.063\mathrm{cm}^{-1}$. Assuming furthermore that the location inside the silicon cylinder which corresponds to the average value is shielded by at most 15 cm of silicon the resulting correction factor would be $e^{0.063\mathrm{cm}^{-1}\times 15\mathrm{cm}} = 2.6$. Using this factor the actual dose delivered to an electronic component in niche 2 (30 cm diameter) is 2.6×47.0 Gy$= 122$ Gy.

Displacement Damage

Figures 7 and 8 show the results of the FLUKA calculations for niches 1 and 2, respectively. In contrast to the dose calculations there was no need for the silicon volumes and the niches were left empty (i.e., the silicon was replaced by air). The equivalent 1-MeV-neutron

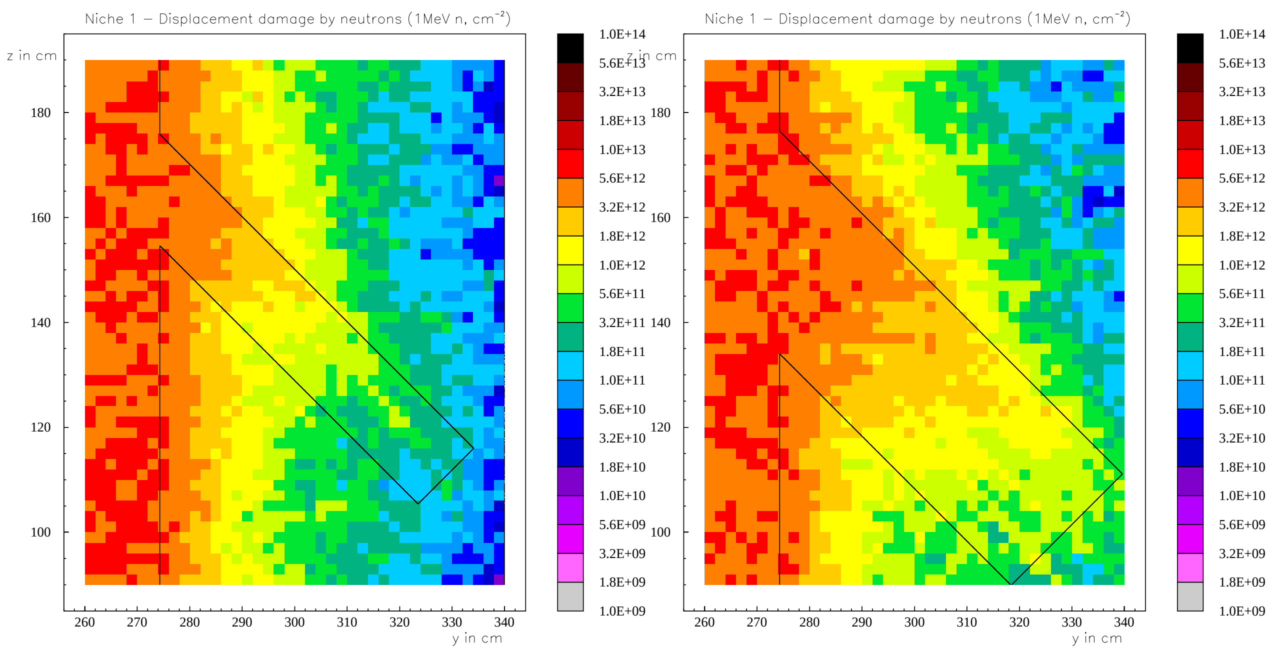

Figure 7: Displacement damage by neutrons in silicon for Niche 1 (left figure: 15 cm diameter, right figure: 30 cm diameter) and a loss of 1.4 W / m during 10×300 days of operation.

fluence caused by neutrons was scored in three meshes around the three niches with bin-sizes of 2cm$\times$2cm$\times$2cm. The results are shown for horizontal sections and are averaged over 12 cm in x (i.e., vertically), from $x = 87$ cm to $x = 99$ cm (cf. the niches are centered at $x = 92.7$ cm).

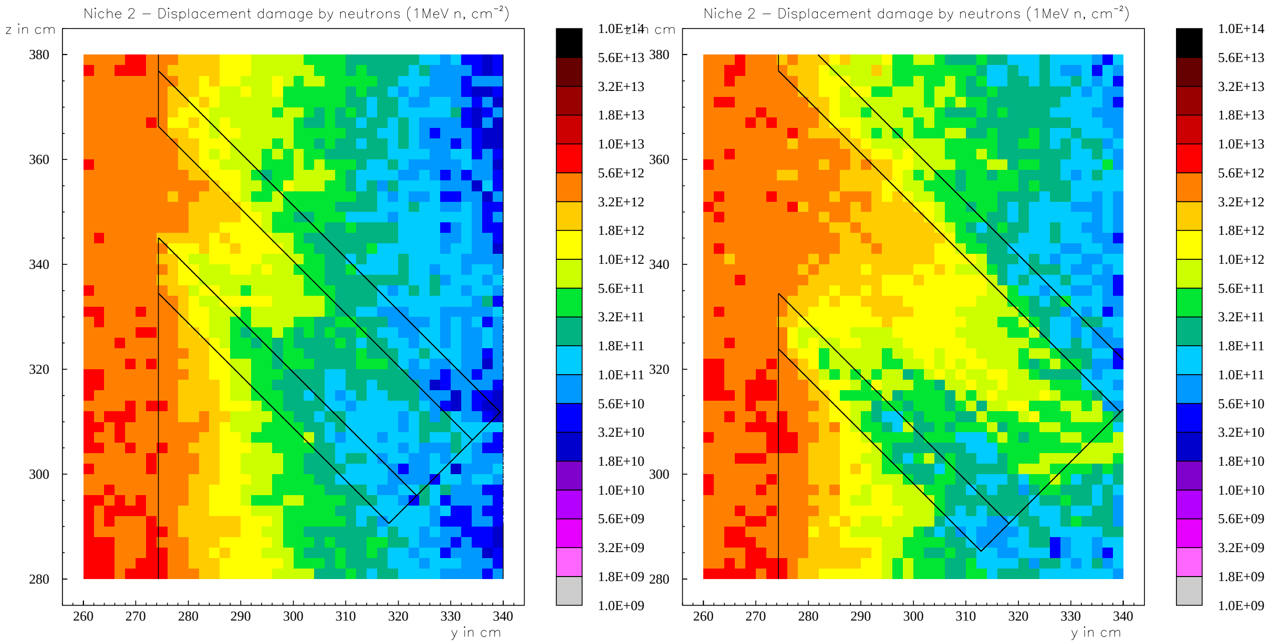

Figure 8: As in Fig. 7, here for niche 2.

Two sources of radiation contribute to the displacement damage in the niches: (i) radiation penetrating through the shielding wall and (ii) radiation streaming through the niche openings. First of all it can be seen that the present design of the niches reduces the displacement damage by roughly an order of magnitude, from about 5×10^{12} cm^{-2} at the entrance to about 5×10^{11} cm^{-2} at the innermost locations. Furthermore the larger the diameter the bigger is the contribution from neutrons steaming directly through the opening and also the bigger is the contribution through the concrete. The latter, of course, is due to the fact that the niche axes were kept at the same positions and only the diameter was changed. This causes the effective concrete shield to be thinner for the larger diameter providing less attenuation for neutrons.

From a comparison of Figs. 7 and 8 the effect of the polyethylene layer (thickness: 7.5 cm) can be seen. Whereas it is rather efficient in case of the 15-cm-diameter, for the 30-cm-diameter niche it only provides a “shadow” of about 7 cm on the side of the niche closest to the tunnel and its effect is compensated by the contribution steaming through the opening further inside.

In order to estimate the average displacement damage a silicon semiconductor might experience in these niches values were averaged over the innermost 15 cm of each niche and the whole diameter. As an example, the average spectral neutron fluence rates obtained for niche 1 and a diameter of 30 cm is shown in Fig. 9. The spectral fluence rates have the typical shape of neutron spectra behind concrete shields: a $1/E$ behavior below 1 MeV, a peak at about 1 MeV due to nuclear evaporation processes and a peak at about 80-100 MeV. The latter is due to the interplay of a decreasing (with increasing energy) inclusive neutron production spectrum with a mean free path distribution which has a broad minimum around 100-300 MeV and a steep decrease towards larger energies. In order to study which neutron energies cause most of the displacement damage the fluence rate in each energy bin was multiplied by the respective value $D(E)/95\mathrm{MeVmb}$ of the damage efficiency function (see Fig.5). This gives the equivalent 1-MeV-neutron spectral fluence rates $\Phi_{\mathrm{n}}(1\mathrm{MeV})$ which are also shown in Fig.9. It follows that

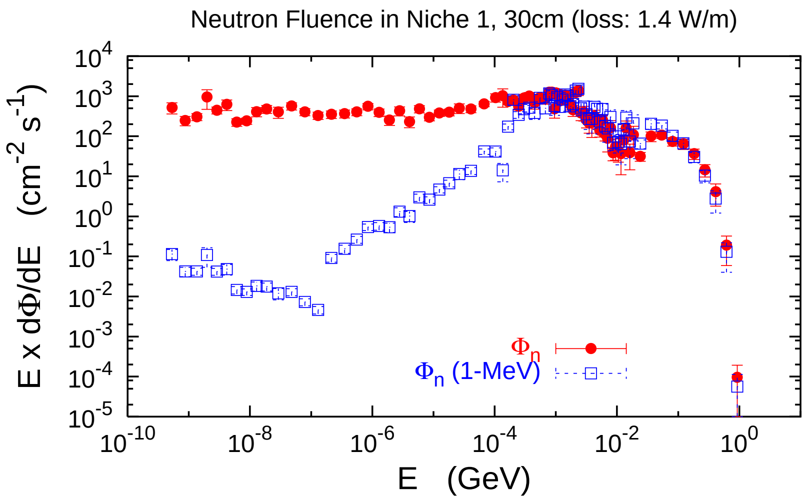

Figure 9: Neutron energy spectra in niche 1 for the 30 cm diameter and a continuous beam loss of 1.4 W/m (circles). In addition, the energy spectra multiplied with the silicon displacement damage function (see Fig.5) are given (squares).

low-energy neutrons with energies below about 100 keV are relatively unimportant and most of the damage is caused by neutrons of higher energies ($1 - 100$MeV).

Integrating Φ_n(1MeV) over all energies and over 10 years of operations yields the values listed in Table 3. As mentioned above the values for niche 3 underestimate the actual values

Table 3: Equivalent 1-MeV-neutron fluence Φ_{eq}^{1MeV} in silicon for neutrons at the locations of the three niches. Values are given for a continuous loss of 1.4 W/m and 10×300 days of operation. Units are in cm^{-2}.

Diameter	15 cm		30 cm	
	Value	Error (stat.)	Value	Error (stat.)
Niche 1	2.5×10^{11}	12%	7.4×10^{11}	7%
Niche 2	1.3×10^{11}	12%	4.1×10^{11}	9%
Niche 3	2.1×10^{11}	12%	4.8×10^{11}	6%

since losses downstream of the simulated tunnel section that would also contribute to the fluence in that niche are not considered. Those are low-energy neutrons mainly streaming in backward direction directly through the niche opening. Therefore, the difference between niches 1 and 3 is more pronounced for the larger (30 cm) opening. The differences between the values for niche 1 and 2 are due to the polyethylene layer at niche 2 which reduces the equivalent 1-MeV-neutron fluence by about a factor of 1.8. It should again be emphasized that these values are *averages* over rather large volumes and that local values can be higher or lower by a factor of two as can be seen in Figs. 7 and 8.

Conclusions

The present study provides estimates for the radiation damage to electronics in the Main Linac tunnel of the NLC due to cumulative effects. Total doses delivered to silicon and equivalent 1-MeV-neutron fluences are calculated with FLUKA for different locations in the 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 arbitrarily chosen in order to allow a convenient scaling for occasional mis-steering scenarios.

During 10 years of 300 days of operation of the NLC electronics installed close to the beamline might receive a total dose of more than 200 kGy which can only be reduced by significant lead shielding. For example, a shielding thickness of 10 cm reduces this value for rack 2 by about three orders of magnitude.

On the other hand, the average dose values to silicon in the niches are only of the order of 50 Gy. Realistic (surface) dose values may reach 150 Gy. These values are mainly due to energy deposition by electromagnetic particles and could be reduced by additional lead shielding. The equivalent 1-MeV-neutron fluence is estimated to be about 7.4×10^{11} cm^{-2} for a 30-cm-diameter niche and 2.5×10^{11} cm^{-2} for a 15-cm-diameter niche. A layer of 7.5 cm polyethylene reduces these values by about a factor of two. No attempt has been made to estimate Single-Event Effects [10].

Acknowledgements

The authors are grateful to Alfredo Ferrari for providing the FLUKA code and to Martin Breidenbach and Alberto Fassò for many stimulating discussions. This work was supported by the Department of Energy under contract DE-AC03-76SF00515.

References

[1] The NLC Design Group, *Zeroth-Order Design Report for the Next Linear Collider*. SLAC Report 474, 1996.

[2] A. Fassò, A. Ferrari, J. Ranft and P. R. Sala, *New developments in FLUKA modeling of hadronic and EM interactions*. In *Proceedings of The Third Workshop on Simulating Accelerator Radiation Environments (SARE-3)*, KEK, Tsukuba, Japan, 1997, p. 32, 1997.

[3] A. Morsch, *ALIFE: A geometry editor and parser for FLUKA*, November 1997.

[4] A. Morsch and S. Roesler, *Radiation studies for the ALICE environment using FLUKA and ALIFE*. In *Proceedings of The Fourth Workshop on Simulating Accelerator Radiation Environments (SARE-4)*, Knoxville, Tennessee, U.S.A., 1998, p. 229, 1998.

[5] H. Vincke, *Flukacad/Pipsicad: 3-dimensional Interfaces between FLUKA and AutoCAD*, this proceedings.

[6] G. Lindström, M. Moll and E. Fretwurst, *Radiation hardness of silicon detectors - a challenge from high-energy physics*. Nucl. Instrum. Meth. A426 (1999) 1.

[7] M. Huhtinen, private communication, 2000. The data-tables were downloaded from the WWW (http://sesam.desy.de/˜gunnar/Si-dfuncs-general.html).

[8] P. A. Aarnio and M. Huhtinen, *Hadron fluxes in inner parts of LHC detectors*. Nucl. Instrum. Meth. A336 (1993) 98.

[9] S. Rokni, J. C. Liu and S. Mao, *Preliminary Estimates of the Radiation Levels inside the Next Linear Collider Linac Tunnel*. SLAC Radiation Physics Note RP-98-14, 1998.

[10] M. Huhtinen and F. Faccio, *Computational method to estimate Single Event Upset rates in an accelerator environment*. Submitted to Elsevier Preprint (see http://atlas.web.cern.ch/Atlas/GROUPS/FRONTEND/radhard.htm).