
SLAC RADIATION PHYSICS NOTE RP-00-04

TITLE: **Initial Estimates of the Activation Concentration of the Soil and Groundwater around the NLC Beam Delivery System Tunnel.**

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Abstract : The activity concentration for various radionuclides produced in the soil around the collimation section of the Beam Delivery System for the Next Linear Collider is calculated using the FLUKA Monte Carlo code. Different methods are used to calculate the activity concentration of ^{3}H, ^{22}Na and ^{7}Be in soil. The activity concentration of ^{3}H and ^{22}Na in groundwater are also calculated and compared with the applicable limits.

1. Introduction

Over the last two decades SLAC has been leading the international efforts in the design of the Next Linear Collider (NLC). The initial studies have resulted in a collider with an initial center-of-mass energy of 500 GeV, expandable to 1 TeV [1]. The proposed collider consists of two separate accelerators for electrons and positrons each having the following subsystems: injector, linac and the Beam Delivery System (BDS). These systems will be placed in a 33 km long,1 km wide campus, as shown in Fig. 1.

At the end of the main NLC linac, the 5 km long BDS will focus the beams and bring them to collision. The BDS for each accelerator consists of a collimation section, a switchyard, the final focus, the Interaction Point (IP) and the dumps. The collimation section of the BDS eliminates particles at large amplitude that could cause unacceptable levels of background in the detector placed at the IP. The collimation section consists of a series of spoilers and absorbers that are designed to absorb 0.1% (10 kW) of the total average beam power and is one of the main sources of secondary radiation and radioactivity.

The accelerator will be shielded sufficiently to reduce the prompt radiation levels from machine operation to levels below the regulatory limits. Earth would comprise a large part of the shield around the tunnel. Since the earth shielding is hydrologically connected to the groundwater, calculation of the concentration levels of induced radioactivity in the soil that could be leached out and eventually reach the public drinking water supplies is an important factor in design of shielding for such a facility. Several studies [2,3,4,5] have shown that only ^{3}H and ^{22}Na contribute significantly to the activation of the groundwater and need to be considered. Other radionuclides either have very short half-lives, or are strongly absorbed in the soil [4] (e.g. ^{7}Be, ^{45}Ca, ^{54}Mn).

This paper describes the methods used in deriving the activity concentration of different radionuclides in soil, and gives the initial estimates for activity concentration of ^{3}H and ^{22}Na in the groundwater around the collimation section of the BDS.

2. The FLUKA calculations

The activity concentration of different radionuclides in the soil outside the shielding walls of the BDS is calculated using the FLUKA Monte Carlo particle interaction and transport code [6]. The FLUKA code has been used widely and benchmarked extensively with experimental data in studies of nuclear cascades induced by high-energy particles in matter over a wide range of energy [7]. FLUKA has also been used in estimating the residual activity in proton accelerators [8,9] and more recently in electron accelerators [10]. It should be noted that the physics implemented in the code does not include a nuclear multi-fragmentation model which could result in an underestimation of yield of nuclides with mass numbers far from the parent nuclei in medium-mass targets.

FLUKA is used to estimate the following 3 quantities in the soil: the neutron fluence, the direct production of residual-nuclei and the density of the inelastic neutron interactions with energies greater than 50 MeV. From these data the production rates of some of the radionuclides which are radiologically significant in the soil and groundwater are estimated.

Description of the geometry

The 300 meter long collimation section is modeled with the ALIFE [11] geometry editor and parser using a simple cylindrical geometry to approximate the tunnel, spoilers, collimators and magnets. Figs. 2 a,b show a cross section along the beam direction of the geometry used in the calculation, and an expanded view of a section of the beam line. A right-handed Cartesian coordinate system with its origin at the center of the front face of the first vertical absorber was used. The beam direction is along the z-axis. The tunnel is assumed to be a concrete cylinder (inner radius=100 cm, outer radius=130 cm) surrounded by a 100-cm-thick layer of soil. The collimation region is comprised of six sections, each one having a spoiler (vertical/horizontal) and an absorber (horizontal/vertical) followed by a quadrupole magnet (focusing/de-focusing). The spoiler (inner radius=0.0061 cm, length=0.357 cm) is followed by an absorber (inner radius=0.05 cm, length=50 cm) located 2200 cm down-beam that is protecting a quadrupole (inner radius=0.7 cm, length=100 cm) located 50 cm after the absorber. The beam pipe is assumed to be a cylinder (inner radius=0.5 cm, outer radius=0.6 cm). The outer radii of the spoilers, absorbers and the magnets are assumed to be 10 cm.

Materials

Spoilers, absorbers are assumed to be made of copper; the beam pipe and the quadrupole magnets are assumed to be made of iron, air fills the rest of the tunnel. The concrete was assumed to have a density of 2.35 g/cm^{3}. The concrete chemical composition and mass fractions were assumed to be: oxygen (50.0%), silicon (20.0%), calcium (19.5%), aluminum (3.0%), sodium (1.0%), iron (1.4%), hydrogen (0.6%), carbon (3.0%), magnesium (0.5%) and potassium (1.0%). For soil, density=2.1 g/cm^{3}, the chemical composition and mass fractions that were used in the SLAC, and other studies [4,9] are listed in the following table:

Table 1: Chemical composition of soil at SLAC and DESY, and molasse at CERN (all values are given in percent).

Element	SLAC	DESY	CERN
O	54.6	53	49.2
Si	30.7	32	19.8
Al	4.2	4	6.4
K	2.5	1	1.9
Fe	1.8	2	4.1
Mg	1.7	2	3.5
H	1.6	-	-
Na	1.3	1	0.57
Ca	1.2	3	9.3
Mn	0.003	0.5	0.14
C	-	1	4.9

Other elements are also assumed to be in the soil (barium, boron, cobalt, copper, chromium, nickel, titanium, vanadium, zirconium) with mass fractions of less than 1%. Based on the hydrogen mass fraction in the soil (1.6%) at SLAC, the water content of the soil by volume is calculated to be 29.4% (14.2% by mass fraction).

Simulations

The lower kinetic energy transport cut-off for electrons, positrons and for photons was set at 5 MeV(EMFCUT), below the threshold for the production of the Giant Resonance neutrons in most of the radionuclides. Neutrons were transported down to the lowest thermal group of the 72 energy-group neutron cross-section of the ENEA data set. The transport threshold for all other hadrons was set to be 10 keV. Muons were discarded in the simulations. The threshold for scoring the hadron inelastic reactions was set at 50 MeV. The interaction length for nuclear inelastic interactions of primary photons was biased by a factor of 50 in all materials to increase photo-neutron production (LAM-BIAS). Full leading particle biasing (EMF-BIAS) was activated for all electromagnetic processes for photons, electrons and positrons below 500 GeV in all regions. The region importance biasing (BIASING) for neutrons was activated in concrete and soil. The magnetic field option in FLUKA (MGNFIELD) was used with a user-written subroutine to set the field gradient of ± 9.56 kG/cm for focusing and de-focusing quadrupole magnets. Beam is assumed to have a δ-function size and strikes the first vertical spoiler at x=0.0066, y=0.0 and z=299.99 parallel to the z-axis. A total of 24 runs were submitted on a 450 MHz PENTIUM II processor using the LINUX version of FLUKA 99, with each run having 100,000 primary 500 GeV electrons. All the results are normalized per primary particle.

3. Results of FLUKA calculations

The activity concentration for various radionuclides was calculated in a small cylindrical shell in the soil (inner radius = 130 cm, outer radius=140 cm, length = 50 cm, starting at Z=5000). This region is across the absorber that intercepts most of the scattered beam and has therefore the highest activity concentration. The following three methods were used to calculate the activity concentration in the scoring region; results obtained with these methods are then compared to each other:

1-The saturation activity (number of nuclei per gram of soil) of ^{3}H, ^{7}Be and ^{22}Na in the scoring region per primary electron was calculated using the relation:

$$A_s = n \int \sigma(E)\Phi(E)dE$$

where n is the number target atoms per gram of soil, Φ(E) (n/cm^{2}/GeV per incident electron) is the neutron flux density in the soil in the energy interval dE. The neutron track-length as a function of energy was scored using the USRTRACK option in FLUKA. Φ(E) is obtained by dividing the neutron track-length by the volume of the scoring region. σ(E) is the nuclear cross section (cm^{2}) for different reactions leading to the ^{3}H, ^{7}Be and ^{22}Na on target nuclei. Since the tunnel is shielded with a 30-cm thick concrete layer, the activation of the soil outside this shield is mainly due to the neutron interaction with its constituents, mainly oxygen and silicon [4]. Contributions from other hadrons are not expected to be significant; Liu et al. [12] have also shown that the contribution of photons to the production of ^{3}H in soil and water samples are negligible as compared to the contribution of neutrons.

The experimental data for the neutron-induced reactions cross section on different nuclei are very scarce and where exist are limited to energies below 20 MeV. The cross sections used in this work are from Tesch's evaluation [4] of the existing data and are based on various approximations and have large uncertainties associated with them. Fig. 3a shows the cross sections that are used for the ^{16}O(n,x)^{3}H and ^{28}Si(n,x)^{3}H reactions. These values are based on fits to the cross sections for the proton-induced reactions on oxygen and silicon leading to ^{3}H [4]. Fig. 3b shows the cross sections for reactions on the same nuclei leading to ^{7}Be.

Fig. 4 shows the neutron fluence in the soil per incident electron. The two main features in this figure are a high-energy peak, the so-called "spallation neutrons" around 100 MeV, and the low-energy peak around 1 MeV that corresponds to the evaporation reaction. Fig. 5 shows the results of ^{3}H activity in soil from folding of the neutron fluence spectrum with the above cross sections. Only the spallation neutrons contribute to the activation from oxygen and silicon; at energies below ~10 MeV, the reaction cross sections are negligible and at energies higher than ~100 MeV the neutron fluence drops significantly. The ^{3}H activity concentration in the soil from this method is calculated to be 2.8x10^{-9} atoms/cm^{3} per incident electron.

To calculate the activity of ^{7}Be in soil, the cross sections for the ^{16}O(p,2α 2n)^{7}Be and ^{28}Si(p,x)^{7}Be reactions were substituted for the neutron induced reactions on the same isotopes. ^{22}Na is produced from the interaction of neutrons with ^{28}Si, ^{23}Na, ^{27}Al and ^{24}Mg isotope. The activity of ^{22}Na in soil was calculated using the cross section for the

$^{28}Si(p,\alpha\ p\ 2n)^{22}Na$ reaction. This value was then scaled with the ratio of ^{22}Na activity produced in the same reaction to the total activity of ^{22}Na in soil from Tesch [4].

2-The concentration of different radionuclides were scored directly with the RESNUCLE option in FLUKA. For tritium, the number of nuclei in the scoring region in the soil outside the collimator is 0.5x10^{-9} atoms/cm^3 per incident electron.

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3-The activity concentration can also be obtained by multiplying the star density with the number of radionuclides per star in a particular region. Stars have been defined as the inelastic interactions of hadrons with kinetic energies greater than 50 MeV which are calculated in FLUKA with the SCORE option. The number of radionuclides per star can be calculated from the ratio of measured partial cross sections leading to a radionuclide to the total inelastic cross section, or obtained from the ratio of the measured (or calculated) activity to the calculated number of stars [13, 14]. The relation between the star density and the induced activity is well established for proton accelerators [8, 9, 13, 14] but has not been used widely in electron accelerators. However, outside the thick shield where the high-energy neutrons dominate the radiation field, a similar approach as for proton accelerators can be considered. Hofert et al. have used the star density calculated with an earlier version of the FLUKA [15] with the radionuclides production probabilities that were based on measurements at CERN [8, 14]. For the NLC calculations, the total number of stars (stars produced by neutrons and other hadrons) in the soil outside the concrete shield of the entire BDS is 1.10 ± 0.2% per incident electron which is only 5% higher than the number of neutron-induced stars in the same large region, 1.05 ± 0.2 %. This confirms the assumption stated earlier that most of the stars generated in the soil are due to neutron-induced reactions.

The production probability (atoms/star) can also be calculated from the star density and the activity concentration calculated in this work with the second method described above. The results are listed in the column labeled as SLAC in Table 2 which also lists the original [8,9] and the more recent data [9] from CERN on molasse labeled as CERN 87 and CERN 99, respectively. The values marked by (*) are based on experimental data from CERN99 which are in good agreement with the results of FLUKA calculations.

Table 2: Comparison of the production probability (atoms/star) for different radionuclides in soil and molasse.

Nuclide	**CERN 87**	**SLAC**	**CERN 99**
^{3}H	0.05	0.013	0.03
^{7}Be	0.003	0.005	0.012*
^{22}Na	0.011	0.007	0.0084*
^{24}Na	-	0.485	-
^{45}Ca	0.006	0.028	0.007
^{54}Mn	0.004	0.004	0.0045*
^{55}Fe	-	0.106	0.023

The difference between the two sets of CERN values is attributed by Vincke et al. [9] to ambiguities in the composition of the soil in the original CERN calculations. The overall agreement between the SLAC and the CERN99 results for the radiologically significant isotopes of ^{3}H, ^{7}Be and ^{22}Na is within a factor of 3. Some of the differences (e.g. ^{55}Fe, ^{45}Ca) could be due to different chemical composition of soil at SLAC and molasse at CERN. However, the oxygen and silicon contents used in the two studies are not very different. One explanation that needs to be investigated further is that the neutron spectra for the CERN and SLAC studies could be different. The concentration activity for ^{3}H from this method using the CERN 99 data is $1.2\text{x}10^{-9}$ atoms/cm^{3} per incident electron.

The following table shows the activity concentration for ^{3}H, ^{7}Be and ^{22}Na calculated by the methods described above and for the other radionuclides calculated with methods 2 and 3. The percentage values represent the statistical uncertainty of the results. For the column labeled "Star Density", the values of atom per star from the CERN99 have been multiplied by the number of stars that are produced by all particles in the scoring region, (0.016 ± 1.5 % stars per incident electron).

Table 3: Comparison of radionuclide production rate (atoms/cm^{3} per incident electron) in the small scoring region in soil around the BDS calculated with different methods.

Nuclide	**Spectrum**	**Direct Isotope Production**	**Star Density**
^{3}H	$2.8\text{ x}10^{-9}$	$5.0\text{ x}10^{-10}$ (8 %)	$1.2\text{x}10^{-9}$
^{7}Be	$5.1\text{x}10^{-10}$	$1.8\text{ x}10^{-10}$(19 %)	$4.6\text{x}10^{-10}$
^{22}Na	$6.1\text{x}10^{-10}$	$2.9\text{ x}10^{-10}$(6 %)	$3.2\text{x}10^{-10}$
^{45}Ca	-	$1.1\text{ x}10^{-9}$ (13 %)	$2.7\text{x}10^{-10}$
^{54}Mn	-	$1.5\text{ x}10^{-10}$(22 %)	$1.7\text{x}10^{-10}$
^{56}Fe	-	$4.1\text{ x}10^{-9}$(22 %)	$8.9\text{x}10^{-10}$

The values listed in the column labeled as “Spectrum” in Table 3 use proton-induced reaction cross sections [4] that could be different from cross sections for reactions initiated by neutrons. This difference can be seen in Fig. 6 which shows a comparison of the cross section for the ^{16}O(n,x)^{3}H reaction from Tesch [4] with the cross sections for proton and neutron induced reactions on the same target evaluated by Huhtinen [16] based on FLUKA calculations and experimental data.

For the values listed in the “Star Density” column, the production probabilities (atom per star) from CERN99 are used. While these values are based on results from FLUKA calculations that are in close agreement with the measurements (which only exist for some of the radionuclides), the neutron fluence spectra used for the CERN and the NLC calculations may differ. Thus, instead of using a “universal” set of production probability for various radionuclide in soil (e.g. values for atoms per star from CERN99), in the rest of this work the results that are based on the direct production of radionuclides with

FLUKA (column labeled SLAC in Table 2) are used. This is in part due to observed agreement between the measurements and calculations that use the RENUCLE option of FLUKA as shown by Viencke [9] and Fasso [10].

4. Soil Activation

The results in Table 3 are calculated in the small ($4.24\text{x}10^5$ cm^3) scoring region in the soil around the collimator which intercepts the highest amount of the beam power, and is meant to check the consistency of different methods of calculating production rates of radionuclides in soil. For radiation protection purposes a more realistic approach should be used, that is to consider the average induced activity in a larger volume of soil. In the rest of this note, activity concentrations for different radionuclides have been averaged over the entire 300 meter-long, 100 cm-thick soil layer (volume = $3.39\text{x}10^9$ cm^3) that surrounds the collimation section. The total number of stars produced in the soil (1.1 stars per electron), and the radionuclides per star form this work (column labeled SLAC in Table 2) are used for the calculations. Fig. 7 shows the star distribution throughout the entire geometry. In scaling the production probability of different radionuclides with the ratio of the number of stars in the entire geometry to the number of stars in the scoring region, it is assumed that the shape of the neutron spectrum remains unchanged throughout the soil.

The other two methods could not be applied to the large soil region readily. The cross sections for neutron induced spallation reactions are not available for most of the radionuclides to use the first method described above. Calculation of the activity using the RESNUCLE in the entire region is more CPU intensive than using the star density with the appropriate production probabilities.

Assuming that 0.1% of the beam intensity ($1.25\text{x}10^{11}$ electrons /second) is lost on the first spoiler, the average activity concentration for different radionuclides at saturation is then calculated. Table 4 shows the activation for various nuclei after 10 years of NLC operation (6000 hours of continuous operation followed by 2760 hours of down-time per year is assumed) and 4 different cool-off periods. The natural activity concentration of soil varies with the type of the soil. For TESLA the magnitude of the natural activity concentration of the soil varies from 0.3 to 1 Bq/gm [5], much smaller than the total induced activity immediately after the shut-down. However, this value is dominated by ^{24}Na which has a 15 hour half-life and would decay away in less than a week. Ten years after shut down the total induced activity is close to the natural background with only ^{3}H, ^{22}Na and ^{55}Fe contributing to the soil activity. With 50 years of cool-off, the total induced activity in the soil is much less than the natural activity of the soil. Some of the radionuclides (e.g. ^{3}H) leach out of the soil and add to the activity of water, thus the activity in the soil would be reduced even further. It should be pointed out that currently there are no limits for the soil activation in the federal, state or local government regulations in the U.S.

Table 4: Average activity concentration for the radiologically significant radionuclides in the1 meter-thick, 300 meter long region of soil around the BDS tunnel.

Nuclide	**Half-Life**	**Activity Concentration (Bq/gm)**				
		Saturation	**Shut-down**	**1 year**	**10 years**	**50 years**
^{3}H	12.3 y	0.25	0.07	0.07	4.2x10^{-2}	4.5x10^{-3}
^{7}Be	53.3 d	0.09	0.09	-	-	-
^{22}Na	2.6 y	0.14	0.10	0.07	6.6x10^{-3}	1.6x10^{-7}
^{24}Na	15.0 h	9.37	9.37	-	-	-
^{45}Ca	163.8 d	0.55	0.45	0.10	8.9x10^{-8}	-
^{54}Mn	312.1 d	0.08	0.06	0.03	1.7x10^{-5}	1.5x10^{-19}
^{55}Fe	2.7 y	2.05	1.34	1.04	1.1x10^{-1}	4.1x10^{-6}
Total Activity concentration		12.53	11.48	1.31	1.5x10^{-1}	4.5x10^{-3}

5. Groundwater Activation

The activity in water is mainly due to ^{3}H and ^{22}Na [2,3,4,5]; here, it is assumed that 100% of the ^{3}H and 15% of ^{22}Na is leached out of the soil [5] and is dissolved in the water(all of the produced ^{7}Be remains in the soil). Assuming these leaching factors and 30% for water content of the soil, the activity concentration for ^{3}H and ^{22}Na in the entire volume of soil (100 cm thick, 300 meter-long) around the collimation section are calculated to be 1.75 Bq/cc and 0.15 Bq/cc, respectively. Tritium is also produced in the interaction of neutrons with the oxygen nuclei in the water and should be added to the ^{3}H leaching out of the soil. Nelson et al. [17], and Dawson et al [8] have shown that the activity concentration (Bq/cc) in water and soil are nearly the same. This is due to the following facts: 1-the star density in soil is approximately twice that in water, 2-the tritium production probability in water is twice of that in soil. The ^{3}H average activity concentration at saturation is calculated to be 2.3 Bq/cc.

The operation profile of most of the high-energy accelerators is such that ^{3}H or ^{22}Na would not reach saturation values. For the NLC, after 10 years of operation (6000 hours of continuous operation followed by 2760 hours of down-time per year) the activities of these two radionuclides will be 0.68Bq/cc and 0.10 Bq/cc, respectively. It is unlikely that there will be drinking water wells close to the NLC tunnel. However, should that be the case, the calculated tritium concentration is below the EPA standard for the tritium concentration in drinking water [18], 0.74 Bq/cc. The calculated concentration level for the ^{22}Na in water outside the BDS is also below the DOE Derived Concentration Guide of 0.37 Bq/cc for ^{22}Na in drinking water [19].

Dilution and the residence time of water have not been considered here. These factors could reduce the concentration of radionuclides in water significantly. For the SLC Final Focus dump, Nelson et al.[17] have estimated a residence time factor of 20; Tesch [4], has estimated a dilution factor of about 500 for TESLA. To estimate the same factors for the NLC, hydrological information about the water movement of the site is needed. It is expected that with the inclusion of these factors the concentration of the induced activity in water would be reduced to levels well below the EPA drinking water limit. The total activity of ^{3}H and ^{22} Na in the water (1.0 x10^{9} cc) outside the entire BDS is 0.8 GBq at the shut-down which is far lower than the 185 GBq limit of release to waste water per year set in California Code of Regulation [21].

6. Conclusions

The FLUKA Monte Carlo particle interaction and transport code has been used to calculate the concentration of induced activity in the soil around the collimation section of the NLC Beam Delivery System. Different methods are used to calculate the activity concentration for ^{3}H, ^{7}Be and ^{22}Na. Following 10 years of NLC operation, the activity concentration in the soil drops to the same level as the natural background after a 10 year cool-off period. The activity concentration for ^{3}H and ^{22}Na in groundwater are also calculated. After 10 years of operation, the concentration levels for ^{3}H is below the EPA drinking water limit. Dilution factors, not considered here, are expected to lower the concentration levels significantly below the EPA limit. The total activity in water is far below the limit for release to waste water. It should be emphasized that the results presented here are preliminary and need to be repeated when information on the composition of the soil and the groundwater movement and its use near the tunnel are available.

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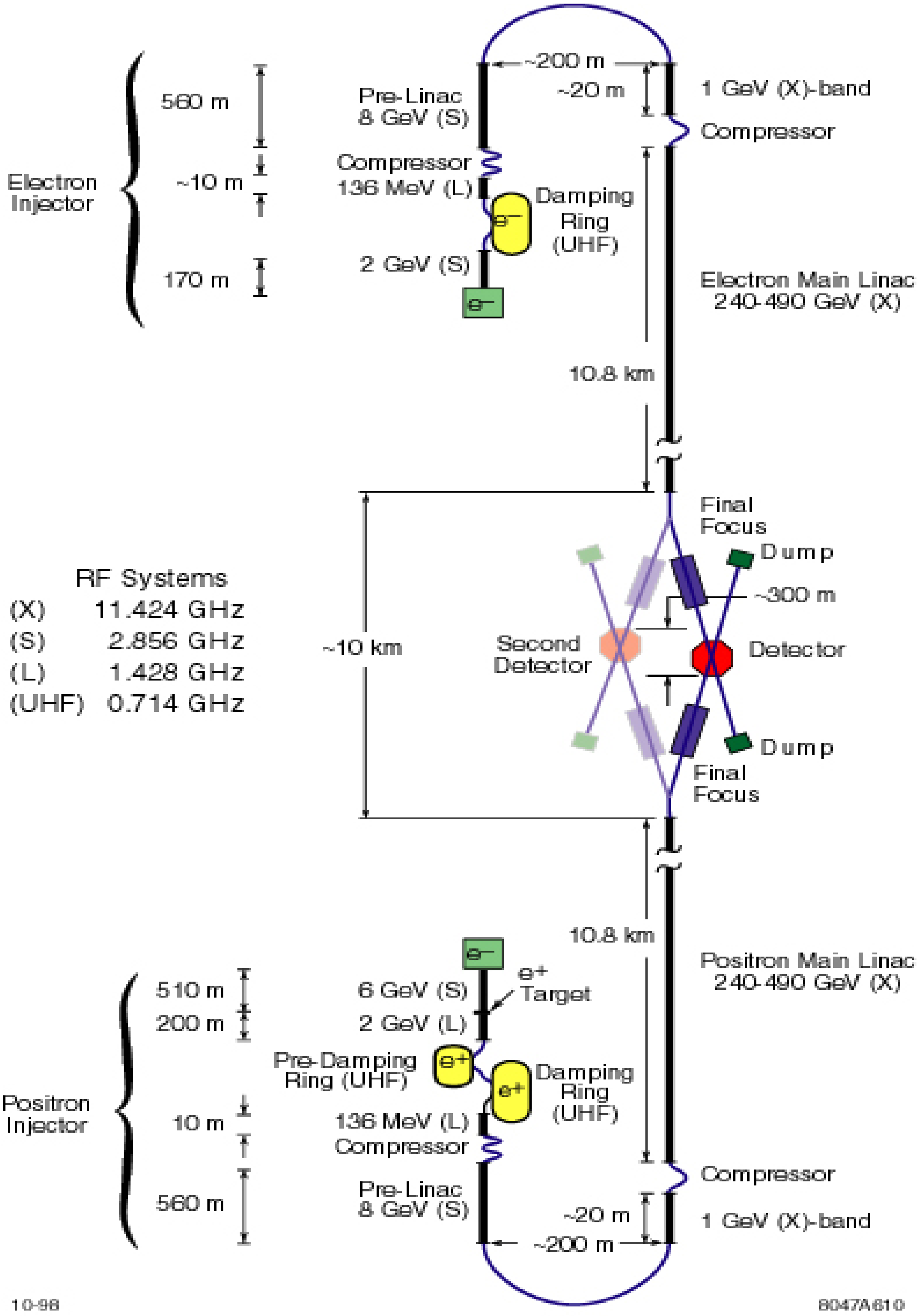

Fig. 1 The conceptual lay-out of the Next Linear Collider

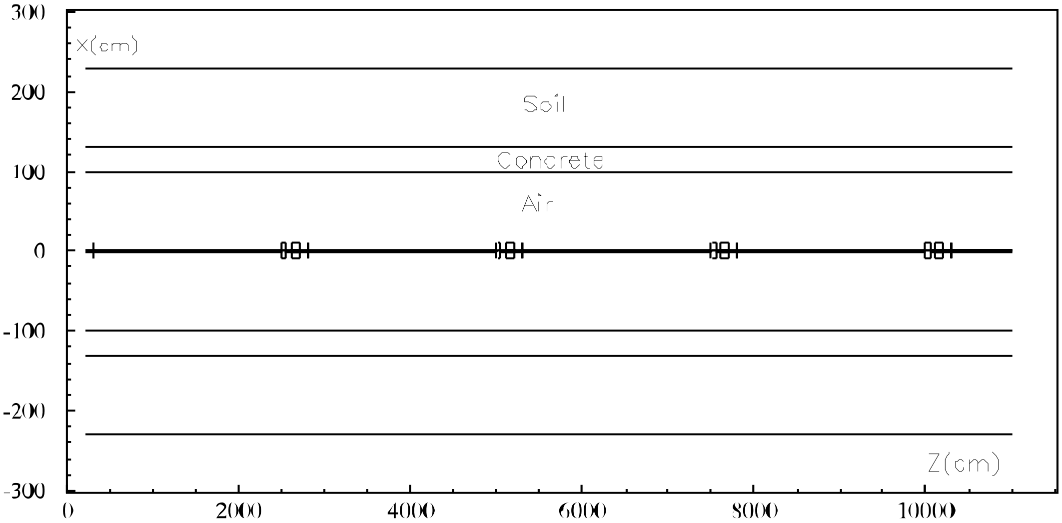

Fig. 2a. Cross sectional view of the NLC Beam Delivery System tunnel.

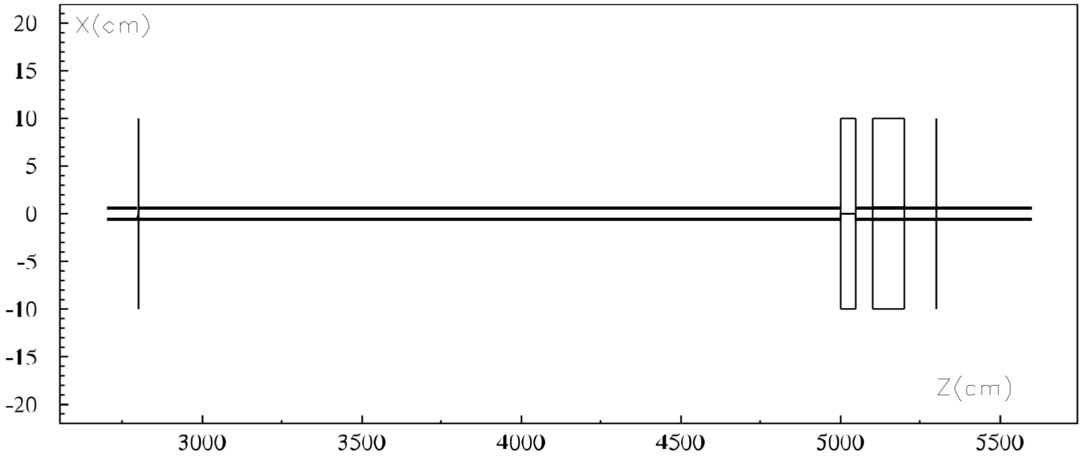

Fig. 2b. Cross sectional view of a section of the BDS showing a spoiler, an absorber, and a magnet followed by the spoiler for the next section.

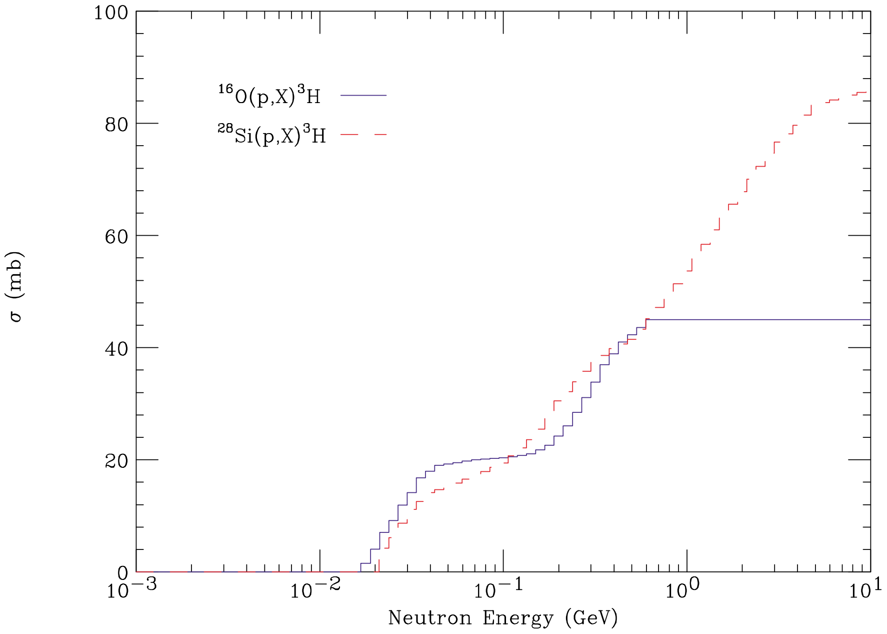

Fig.3a. Cross sections used to calculate tritium production from silicon and oxygen in the soil.

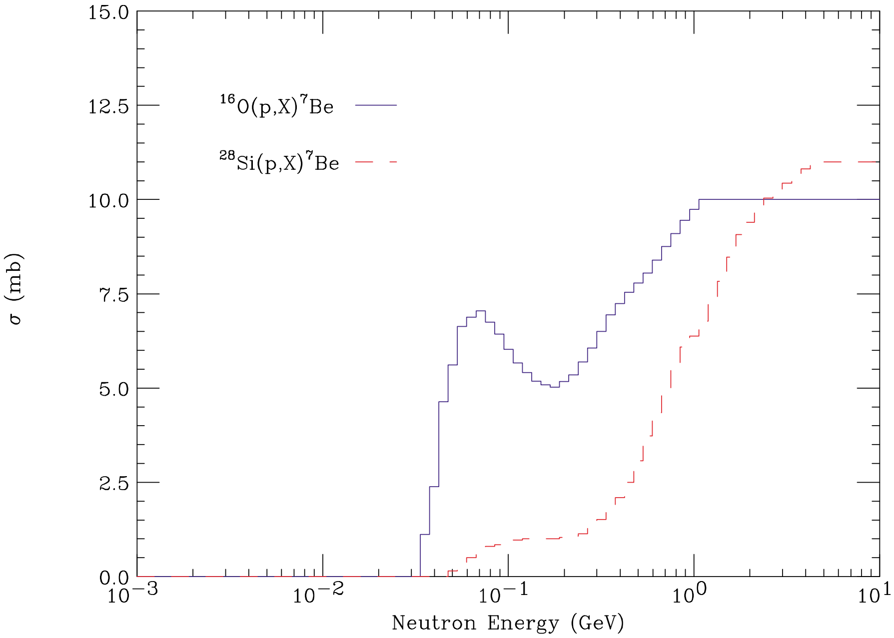

Fig.3b. Cross sections used to calculate Beryllium production from silicon and oxygen in the soil.

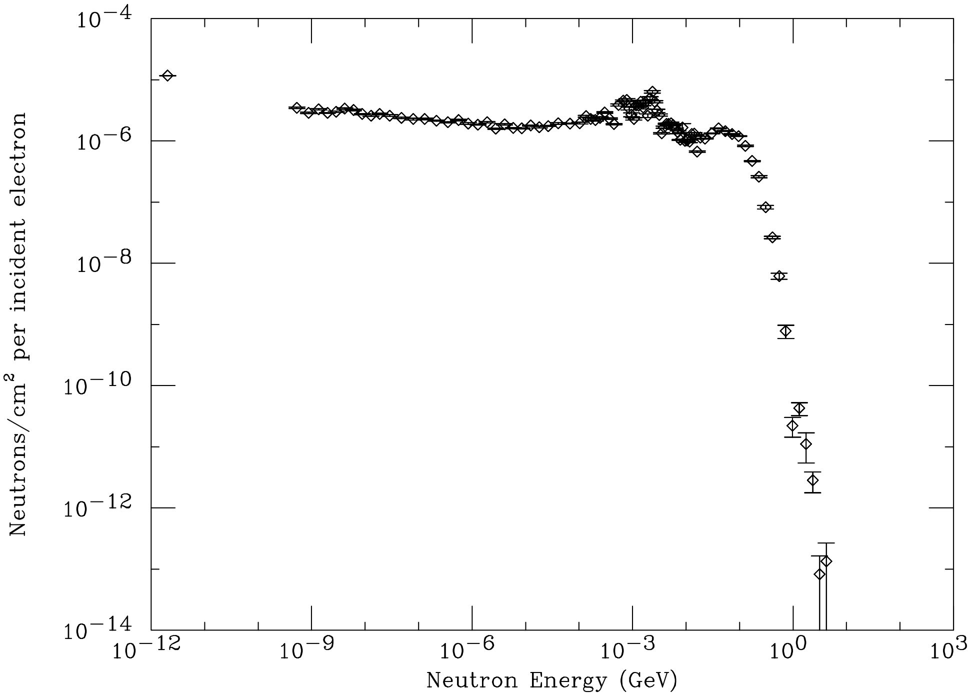

Fig. 4. Calculated neutron fluence in the scoring region .

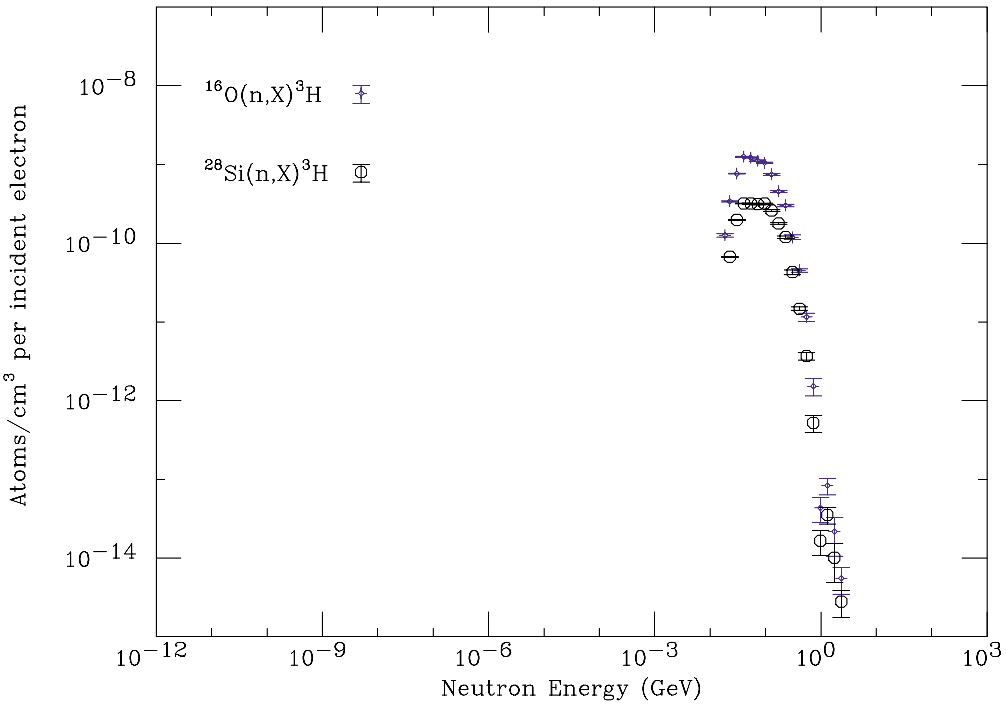

Fig. 5. Contribution of oxygen and silicon to the activity of tritium in soil.

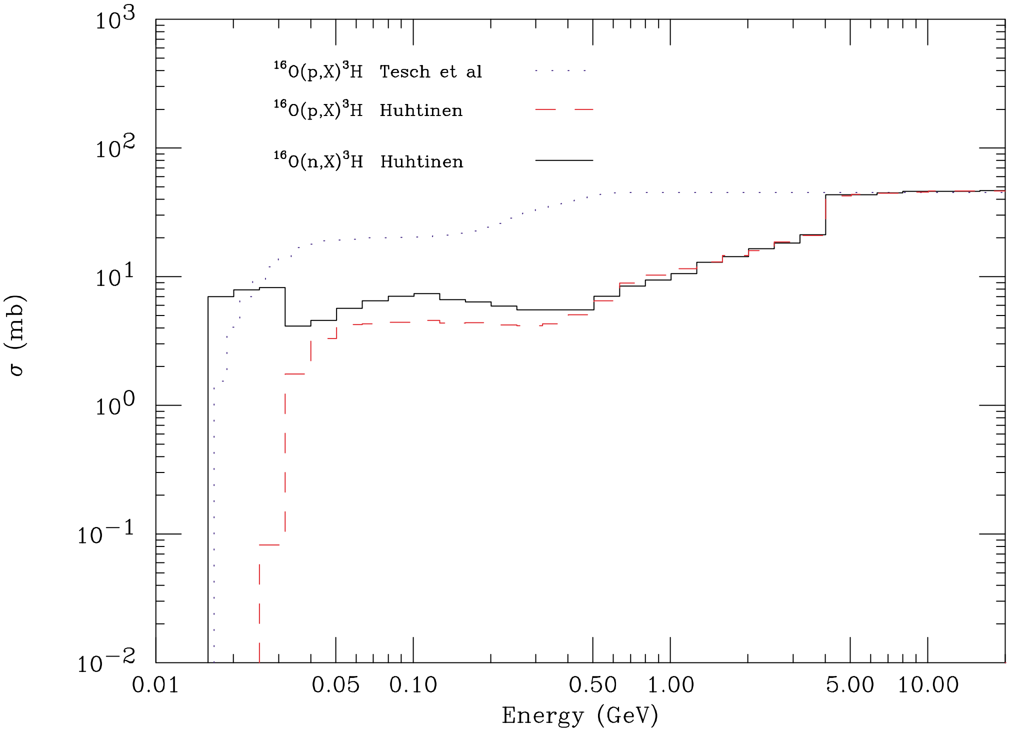

Fig. 6. High energy cross section for production of ^3H from Oxygen.

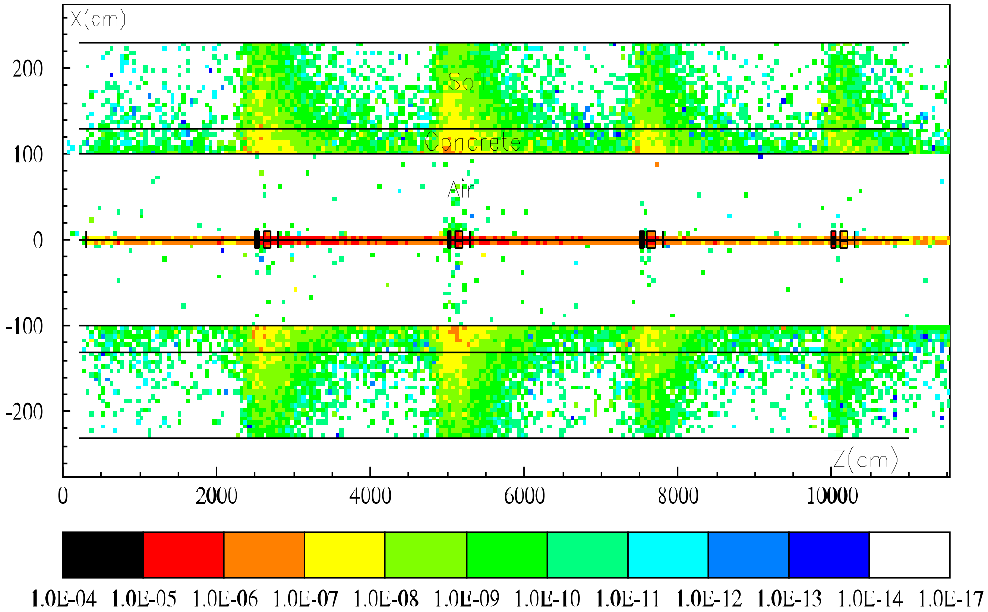

Fig. 7. Density of neutron generated stars with energies above 50 MeV.