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Simulation of Neutron Backgrounds from the ILC Extraction Line Beam Dump

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ABSTRACT

Simulation of Neutron Backgrounds from the ILC Extraction Line Beam Dump. SIVA DARBHA (University of Toronto, Toronto, ON M5S 1A1) LEWIS KELLER (Stanford Linear Accelerator Center, Menlo Park, CA 94025) TAKASHI MARUYAMA (Stanford Linear Accelerator Center, Menlo Park, CA 94025)

The operation of the International Linear Collider (ILC) as a precision measurement machine is dependent upon the quality of the charge-coupled device (CCD) silicon vertex detector. A neutron flux of 10^{10} neutrons/cm^2 incident upon the vertex detector will degrade its performance by causing displacement damage in the silicon. One source of a neutron background arises from the dumping of the spent electron and positron beams into the extraction line beam dumps. The Monte Carlo program FLUKA was used to simulate the collision of the electron beam with the dump and to determine the resulting neutron fluence at the interaction point (IP). A collimator and tunnel were added and their effect on the fluence was analyzed. A neutron source was then generated and directed along the extraction line towards a model of the BeamCal, vertex detector, and beampipe to determine the neutron fluence in the silicon layers of the detector. Scattering in the BeamCal and beampipe was studied by manipulating the composition of the BeamCal. The fluence in the first silicon layer for the current tungsten BeamCal geometry was corrected according to a 1 MeV equivalent silicon displacement damage to obtain a comparable value for the damage done to the CCD vertex detector. The IP fluence was determined to be $3.65*10^{10}$ +/- $2.34*10^{10}$ neutrons/cm^2/year when the tunnel and collimator were in place, with no appreciable increase in statistics when the tunnel was removed. The BeamCal was discovered to act as a collimator by significantly impeding the flow of neutrons towards the detector. The

majority of damage done to the first layer of the detector was found to come from neutrons with a direct line of sight from the quadrupole, with only a small fraction scattering off of the beampipe and into the detector. The 1 MeV equivalent neutron fluence was determined to be $1.85*10^9$ neutrons/cm^2/year when the positron beam was considered, or $9.27*10^8$ neutrons/cm^2/year by one beam alone, which contributes 18.5% of the threshold value in one year. Future work will improve the detector model by adding the endcap sections of the silicon detector, and will study in detail the neutron scattering off of the tunnel walls. Other sources of neutron backgrounds will also be analyzed, including electron-positron pairs, Beamstrahlung photons, and radiative Bhabha scattering, in order to obtain a complete picture of the overall neutron damage done to the vertex detector.

INTRODUCTION

The Large Hadron Collider (LHC) operating at CERN will probe a new energy scale using 14 TeV center of mass energy proton-proton collisions, and will produce a wealth of new physics, including searches for the Higgs boson and Supersymmetry [1]. The International Linear Collider (ILC) is a proposed linear electron-positron collider that will be 31 km in length and will have a center of mass energy of 500 GeV. It will have a cleaner signal to noise ratio than the LHC and will provide precision measurements for some of the physics discovered there. The electron and positron beams in the ILC will have $2*10^{10}$ particles per bunch and a bunch separation of 370 ns, with 2625 bunches in 1 ms trains at a repetition rate of 5 Hz; they will come into collision at the interaction point (IP) at a 14 mrad crossing angle [2].

The Beam Delivery System (BDS) in the ILC is responsible for transporting the electron and positron beams from the main linacs, colliding them at the IP, and discarding the spent beams to the extraction line beam dumps. The extraction line is shown in Figure 1. The beam dumps are stainless steel cylindrical containers, of 75 cm radius and 7.5 m length, with a titanium window, of 15 cm radius and 1 mm thickness, through which the beams enter; the dumps contain water at a pressure of 10 bar [3]. Water was used in the dumps since its high specific heat capacity makes it ideal to dissipate the energy of the beams. Only a minute fraction of the particles in any bunch crossing will interact, leaving the high energy electron and positron beams to be extracted from the IP in their near entirety and discarded in the water dump. The dumps are designed to absorb 17 MW of beam power at a 500 GeV center of mass energy [3].

The extracted beams will interact with the H_2O molecules in the dump, leading to EMF showering that will produce a flux of neutrons, most of which are forward directed. Some of this ‘gas’ of secondary particles is backward directed and will reach the detector, creating unwanted backgrounds in the tracking devices and calorimeters that will obscure the physics processes observed from actual collisions. The flux of neutrons may even cause displacement damage in the silicon atoms in the charge-coupled device (CCD) vertex detector, which is the innermost tracking system in the SiD detector model, if it reaches a value higher than 10^{10} neutrons/cm^2, leading to charge traps [4], [5]. The traps would degrade the performance of the detector by reducing the charge transfer along the CCD and by causing junction leakage [4], [5]. Such degradation would hinder the performance of the ILC as a precision machine and would require frequent repairs, which should be minimized to allow continuous and robust recording of data.

This paper investigates the neutron detector backgrounds from the extraction line beam dump through Monte Carlo simulations. The program FLUKA was used for the simulations due to its robustness with low energy neutron cross sections. Only the electron beam was used for the analysis, with the positron beam having symmetric and analogous results. The neutron fluences at the dump and at the detector were studied first without material near the beam line to provide a benchmark estimate. Concrete tunnel walls and a concrete collimator were then added to the simulation and their effect on the fluences was studied. Information gathered on neutron distributions during this work was used to simulate an isotropic and uniformly distributed neutron source located in the bore of the extraction line quadrupole and incident upon the beryllium beampipe and the five layers of the CCD silicon vertex detector central barrel to obtain an estimate of the real neutron fluence at the vertex detector. Particle biasing techniques were used to increase statistics on the simulated events, and the effectiveness of each bias was studied.

MATERIALS AND METHODS

The Monte Carlo program FLUKA was used for the simulations. The spent electron beam was given an initial position at the origin and was directed in the positive z-direction with an energy of 250 GeV. The beam was collided into the water dump, which was placed at z = 300 m and was modeled by a circular cylinder of water with a radius of 75 cm and a length of 5 m (see Figure 2). The stainless steel container and Ti window were ignored since they would not impede an outward flux of neutrons from inside the dump and would increase the computation time.

The neutron fluence decays exponentially as a function of cosθ for neutrons leaving the water dump in the negative z-direction, where θ is the polar angle with respect to the z-axis. The distributions were measured on the surface of the dump at A-A' in Figure 2, binned over small ranges of cosθ, and treated as isotropic in each bin (see Figure 3). The fluence was assumed to be isotropic in the range of $-1 < \cos\theta < -0.99$, which corresponds to an 8.1^{o} spread around the negative z-direction from the surface of the water dump and a circle of radius 42.7 m at z = 0.

The relevant fluence value was that measured in a circle of 1.5 cm radius at z = 0, concentric with the z-axis and parallel to the xy-plane, which is the IP fluence. The neutrons that reach this circle are the ones that will reach the vertex detector, since they have passed through the extraction line quadrupole bore and have not been impeded by collimators, magnets, or the tunnel. However, due to insufficient statistics from a scoring plane 1.5 cm in radius, a circular scoring plane 2 m in radius at z = 0 was used. The fluence calculated, per square centimeter, with this scoring plane would be the same as that measured with a 1.5 cm radius circle after a sufficiently long time due to the isotropic fluence.

As a primary benchmark estimate, 10^4 electrons were collided into the water dump and the IP fluence was measured with no material in the beamline. A concrete collimator and a concrete tunnel wall were then added to the simulation, as shown in Figure 2, and the IP fluence was measured with $5*10^4$ incident electrons. Finally, the tunnel was removed, the collimator was kept in place, and the IP fluence was measured with $5*10^4$ incident electrons to study neutrons which scatter off of the tunnel walls and towards the detector.

In order to increase the statistics on the fluence scoring, three biasing techniques were used. Firstly, leading particle biasing was activated for electrons, positrons, and photons with energy below 2.5 GeV. Since simulating a full electromagnetic shower requires long computation time, leading particle biasing traces only the most energetic secondary created by the electrons, positrons, or photons below 2.5 GeV and eliminates all others, adjusting the 'weight' of the most energetic particle accordingly. Secondly, the interaction cross section for neutron production by photonuclear interactions was increased by a factor of 50, and the 'weight' associated with each neutron produced this way was decreased by a factor of 50 to preserve particle multiplicity. Finally, the cylindrical water dump was divided into 10 adjacent regions as in Figure 3. The region at the back of the dump was given an 'importance' of 1.0, and each region progressively closer to z = 0 was given a factor of 2.0 larger importance. As photons produced in the water dump passed from one region to another, their multiplicity was increased or decreased on average by the ratio of importances on either side of the boundary. Those passing from a region of lower importance to a region of higher importance were split on average by a factor of 2.0, and if traveling in the opposite direction were terminated or transported according to Russian Roulette [6]. FLUKA adjusted the 'weight' associated with biased particles to conserve particle multiplicity when the biases were applied. The computation time and effectiveness were studied for each type of bias with 6000 incident electrons.

Production and transport cutoffs were activated to decrease simulation time. A 50 MeV cutff on both was applied to electrons and positrons, and a 10 keV cutoff on both was applied to photons. A transport cutoff of $1.0332*10^{-5}$ GeV was applied to neutrons, which in FLUKA corresponds to all low energy neutron groups with group number greater than or equal to 48. This value was chosen from Non-Ionizing Energy Loss (NIEL) scaling studies which show that neutrons below 10 keV do not have sufficient energy to create displacement damage, which are mostly from point defects and defect clusters, in the silicon bulk of the vertex detector [7]. The NIEL stopping power for neutrons in silicon also decreases with decreasing kinetic energy, and consequently neutrons below 10 keV were not a concern [8].

Once the neutron fluence at the IP was determined, the real neutron fluence at the CCD silicon vertex detector was studied, since the neutrons that reach the IP do not necessarily collide with the detector elements. The central barrel beryllium beampipe and the five layers of the Si barrel vertex detector were placed around the IP, as shown in Figure 4, and were based on the geometry specified at the Snowmass conference [9]. Figure 5 shows the full model of the detector and the nearest section of the extraction line, which consists of the quadrupole and the BeamCal. The BeamCal was modeled by a 12.5 cm thick slab of tungsten; the Si layers in it were ignored since they have a low probability of scattering the incident neutrons.

The neutron energy and 'weight' distributions at A-A' in Figure 2 were recorded from the previous simulations and were sampled from and used to generate a neutron source. Figure 6 shows the energy distribution. The initial positions of the neutrons in the source were generated randomly in the quadrupole bore at D-D' in Figure 5 in a circle of 1.5 cm radius centered at $x = -2.1$ cm and $y = 0$ cm. This starting point modeled the neutrons from the water dump that would reach the surface of the first extraction line quadrupole from the dump without being blocked by collimators, magnets, or other material. All neutrons in the source were given a 7 mrad trajectory from the z-axis.

The resulting neutron fluence at the five layers of the CCD silicon vertex detector was measured. This value was combined with the IP fluence, when the tunnel and collimator were in place, to provide an estimate of the total fluence at the vertex detector. The measurement was performed twice more, when the BeamCal was removed and when it was replaced with an infinitely absorbing material, in order to give an estimate of the BeamCal scattering. The tungsten was then returned, and the fluence as a function of the BeamCal aperture radius was studied. Finally, since the amount of displacement damage done to CCD silicon detectors by neutrons is proportional to neutron energy, a correction was applied to the fluence at the first layer of the detector, with the tungsten BeamCal in place, by scaling it to a 1 MeV equivalent silicon displacement damage (see Figure 7) [10]. This provided a normalized and comparable value for the amount of damage done to the vertex detector by neutron backscattering from the water dump. The other fluence values were left uncorrected, but could be corrected by the same method.

RESULTS

The IP fluence with no objects in the extraction line was measured to be $8.33*10^{10}$ +/- $1.50*10^{10}$ neutrons/cm^2/year. When the tunnel and collimator were added for a more accurate estimate, the fluence dropped to $3.65*10^{10}$ +/- $2.34*10^{10}$ neutrons/cm^2/year. When the tunnel was removed, there was no appreciable change in the fluence given the current level of statistics, as it remained at $3.73*10^{10}$ +/- $3.34*10^{10}$ neutrons/cm^2/year. The computation time and effectiveness of the biasing techniques used in the IP fluence scoring are shown in Table 1.

Figure 8 shows the fluence at the five layers of the inner detector for the three different modifications of the BeamCal. For the first layer, there was over an order of magnitude difference between the tungsten and no BeamCal cases, the former having a fluence of $1.79*10^{10}$

neutrons/cm^2/year and latter having one of 4.28*10^8 neutrons/cm^2/year. There was a similar difference between the tungsten and black BeamCal cases, the latter having a fluence of 2.21*10^7 neutrons/cm^2/year. In all three cases, the fluence in layers two to five dropped far below that in layer 1, implying that the first layer experiences the bulk of the neutron damage. The neutron fluence of 4.28*10^8 neutrons/cm^2/year at the first layer when the tungsten BeamCal was in place is of particular importance, since it was found for the current status of the extraction line for the first layer, and is shown circled in Figure 8. This neutron fluence at the detector is 1.2% of the fluence that reaches the IP, with the rest of the neutrons passing through the empty space in the detector or scattering off of the Be beampipe harmlessly (see Figure 4).

The energy distribution of the neutrons that contribute to this fluence shows a large number of neutrons with energy greater than 10 MeV, implying that the current nominal fluence underestimates the displacement damage power (see Figure 9). This distribution corrected with the information from Figure 8 gives the 1 MeV damage equivalent neutron fluence, which was calculated to be 9.27*10^8 neutrons/cm^2/year, more than a factor of two larger than the uncorrected value. The symmetric positron beam contributes the same amount of displacement damage, meaning the final corrected fluence is 1.85*10^9 neutrons/cm^2/year. In one year, this amounts to 18.5% of the 10^{10} neutrons/cm^2 flux that would degrade the vertex detector to the point of repair or replacement.

Figure 10 shows the fluence at the five layers of the detector as the BeamCal aperture was expanded; the fluence increases as the aperture is opened.

DISCUSSION AND CONCLUSIONS

The neutron fluence at the IP when there is no material in the extraction line, which was 8.33*10^{10} +/- 1.50*10^{10} neutrons/cm^2/year, is the highest level of background that is possible at the detector from backscattering from the beam dump if one assumes that every particle that reaches the IP will damage the vertex detector. The collimator in front of the dump blocked roughly half of this flux, since the fluence decreased by a factor of two to $3.73*10^{10}$ +/- $3.34*10^{10}$ neutrons/cm^2/year when the collimator was added. There was no appreciable increase in fluence when the tunnel was added given the current level of statistics, as it remained at $3.65*10^{10}$ +/- $2.34*10^{10}$ neutrons/cm^2/year. This should not be interpreted to mean that there is no scattering off of the tunnel walls, as the root-mean-square (RMS) deviation in the fluences once the collimator was added was more than 50% of the fluence itself. The amount of scattering is an important value to know when looking for potential solutions to reduce the backscattering problem. One solution being considered is to move the water dump out of a direct line of sight from the detector and to place a dipole immediately before the collimator to bend the trajectory of the beam towards the dump. If neutrons do not scatter off of the tunnel walls, this would be an effective solution. However, if the neutrons do scatter off of the tunnel walls and act like a gas of particles moving back towards the detector, as suspected, then bending the beam would not reduce this background source. A further study of neutron scattering is being conducted.

The computation time and effectiveness of the biasing techniques for 6000 incident electrons are shown in Table 1. As columns 6 and 7 show, that statistics increased by a factor of 203 at the surface of the dump and by a factor of 59 at the IP. This allowed the estimation of a more stable IP fluence and provided a large distribution from which to sample in order to produce the neutron source. The total ‘weight’ of the neutrons recorded at z = 300 m and z = 0 m, shown in columns 4 and 5, was preserved as the different biases were applied, meaning that the biases did not obscure the underlying physics when improving the statistics. This validated the use of these biases with 10^4 and $5*10^4$ incident electrons when estimating the IP fluence.

The sharp drop in the fluence at layer 1 of the vertex detector from $1.79*10^{10}$ to $4.28*10^8$ neutrons/cm^2/year, shown in Figure 8, implies that the BeamCal acts like a collimator and impedes the flow of neutrons through it by 97.6%. Since this large amount of collimation is not the intent of the BeamCal, the effect of the fluence on its tungsten and silicon layers are being studied in further detail. When the black BeamCal is in place, there is no direct line of sight from the quadrupole bore to the detector, and the only neutrons that can hit the detector are those that scatter off of the beryllium beampipe. Thus, the further drop in the fluence to $2.21*10^7$ neutrons/cm^2/year for the black BeamCal gives the estimate that 5.16% of the neutrons that hit the detector have scattered off of the beampipe, and the rest have hit it along their direct line of sight. Furthermore, the order of magnitude drop in the fluence between layer 1 and layers 2 to 5 of the silicon detector show that the outer layers are well shielded from the neutron fluence and are not a concern; attention should be focused on the innermost layer which takes the bulk of the displacement damage. The endcap sections of the silicon detector are being added and their effect on the fluence at all of the layers is being studied.

The neutron energy at the vertex detector is more heavily distributed above 10 MeV, as shown in Figure 9, which implies that the damage to the detector is greater than the nominal fluence. The corrected 1 MeV equivalent neutron fluence of $9.27*10^8$ neutrons/cm^2/year is properly normalized and can be compared to the threshold value of 10^{10} neutrons/cm^2. When the positron beam is considered and the fluence doubles to $1.85*10^9$ neutrons/cm^2/year, the neutron backscattering from the dump contributes 18.5% of the threshold value in one year. Even if this was the only background, the detector would degrade within 6 years; a longer lifetime is desired.

Although the current background level is not overwhelming, the relationship in Figure 10 is an important consideration when analyzing the effect of other neutron backgrounds in the detector. Two particularly important neutron backgrounds arise from electron-positron pairs produced from beam-beam interactions and synchrotron radiation produced from the quadrupoles used to focus the beams immediately before the IP; both products can hit the BeamCal and produce a neutrons through electromagnetic showers [11]. This is the dominant source of neutron background, as the neutrons produced at the BeamCal are immediately by the vertex detector and cannot be shielded. A simple method to reduce this flux would be to open the BeamCal aperture to prevent interactions. However, as Figure 10 shows, a tradeoff exists, since doing so would increase the neutron background from the extraction line beam dump. In the extreme case, the BeamCal could be opened up larger than the extraction line quadrupole aperture, and the dump background would equal 2.09×10^{10} neutrons/cm^2/year, which would require the vertex detector to be replaced every six months.

These results have directed our further studies towards analyzing the main sources of neutron backgrounds, including electron-positron pairs, Beamstrahlung photons, and radiative Bhabha scattering, in order to obtain a complete picture of the overall neutron damage done to the vertex detector and to understand the tradeoffs that exist in attempting to suppress it. The detector model will also be improved, and the effect of the neutron flux on the endcap tracking chambers and other elements will be studied. The neutron damage in the CCD silicon detector must be minimized in order to ensure detector longevity as well as minimal repairs of the detector components, allowing the ILC to effectively perform measurements and discover new fundamental physics.

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Figures

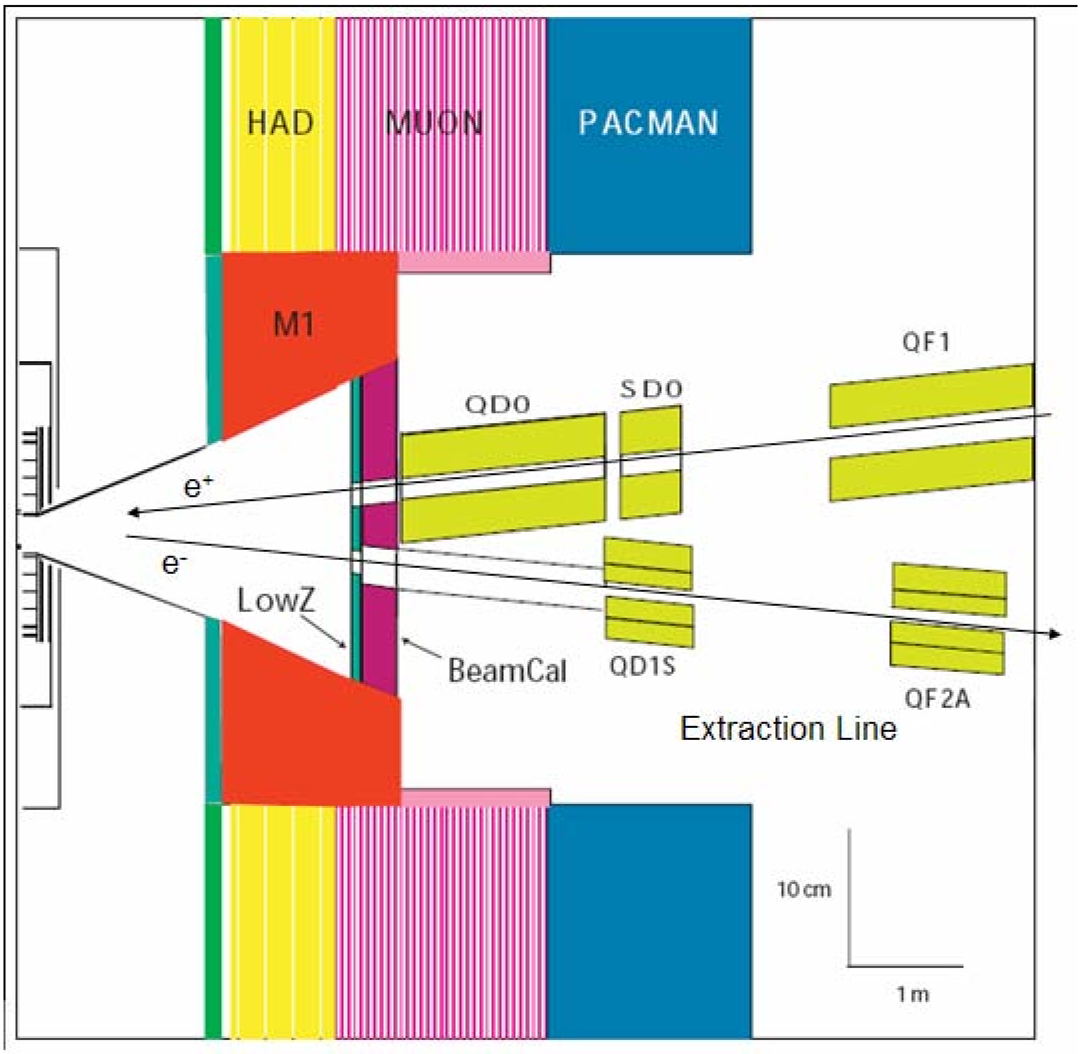

Figure 1. A Geant4 model of the extraction line. The light green indicates quadrupoles, and the water dump is located 300 m down the extraction line.

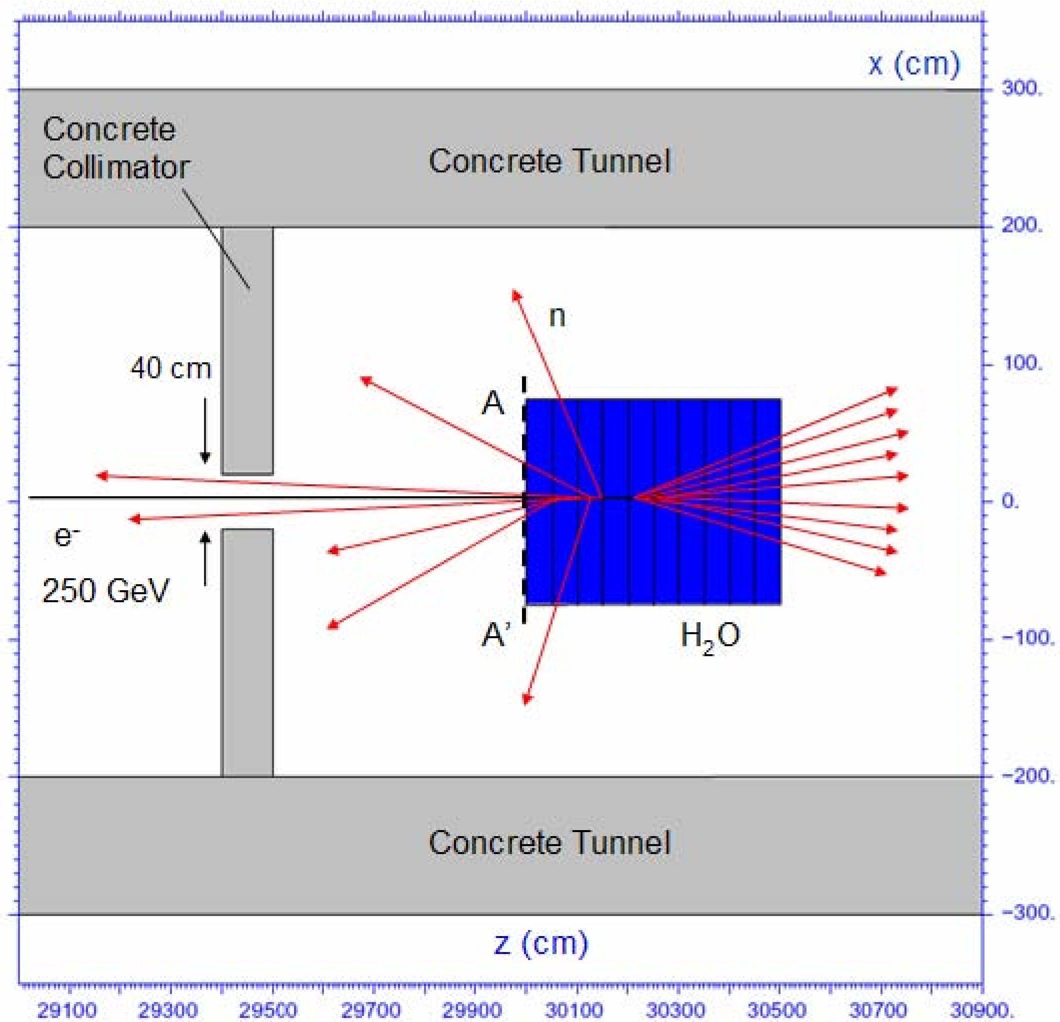

Figure 2. The FLUKA model of the beam dump with a concrete collimator and concrete tunnel in place. The 250 GeV input electron beam acts as a line source in the water dump, and the red arrows symbolize possible trajectories of the neutrons produced in the dump along that source.

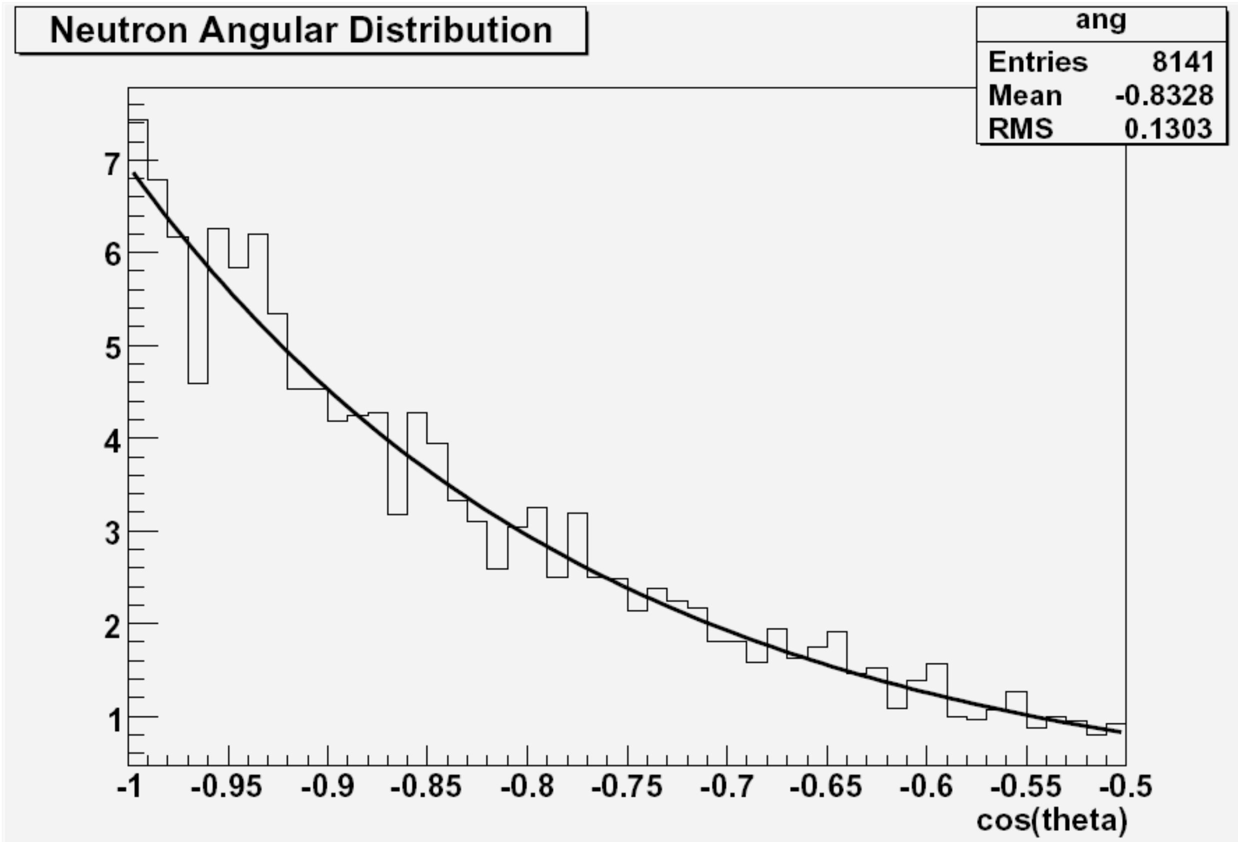

Figure 3. The neutron angular distribution at A-A' in Figure 2. The neutron fluence can be treated as isotropic in each bin. The fluence was scored at z = 0 m with a 2 m radius scoring plane with the assumption of the isotropy in the first bin (-1 < cosθ < -0.99).

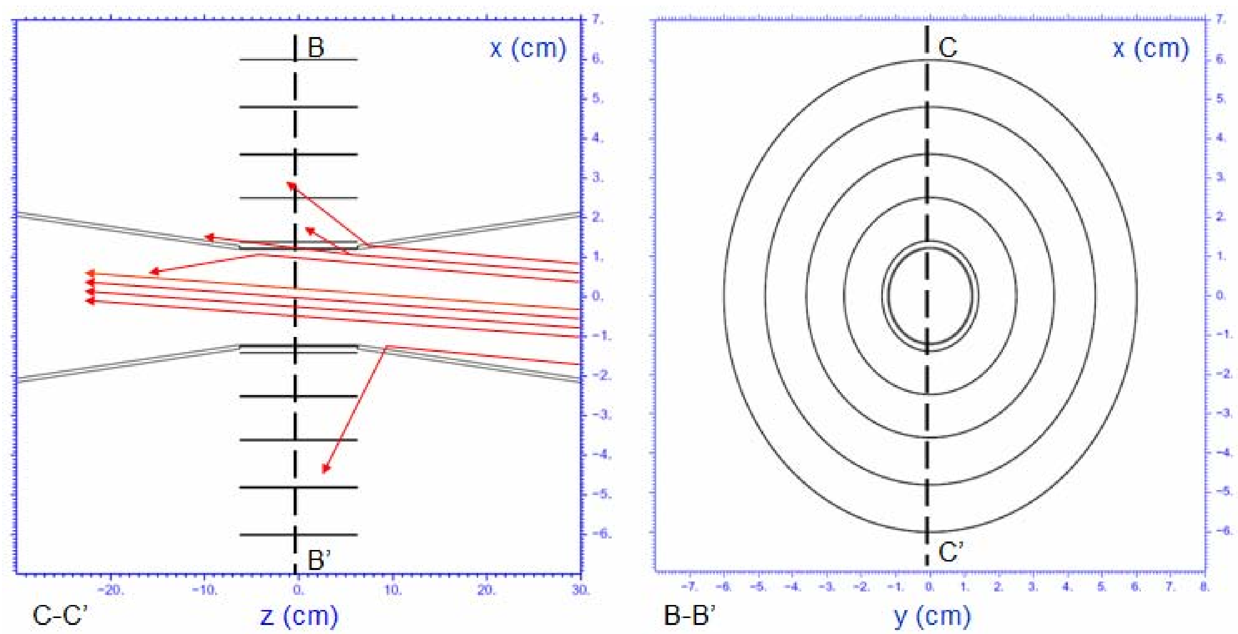

Figure 4. The CCD silicon vertex detector in the SiD detector model and the beryllium beampipe. The five layers of the detector were modeled by concentric cylinders, each 0.01 cm

thick. The beampipe barrel was made 0.04 cm thick and the conical section was made 0.1 cm thick. The left and right conical sections of the beampipe extend outward to -167.9 cm and +167.9 cm respectively, but have been truncated here at -30 cm and +30 cm [9].

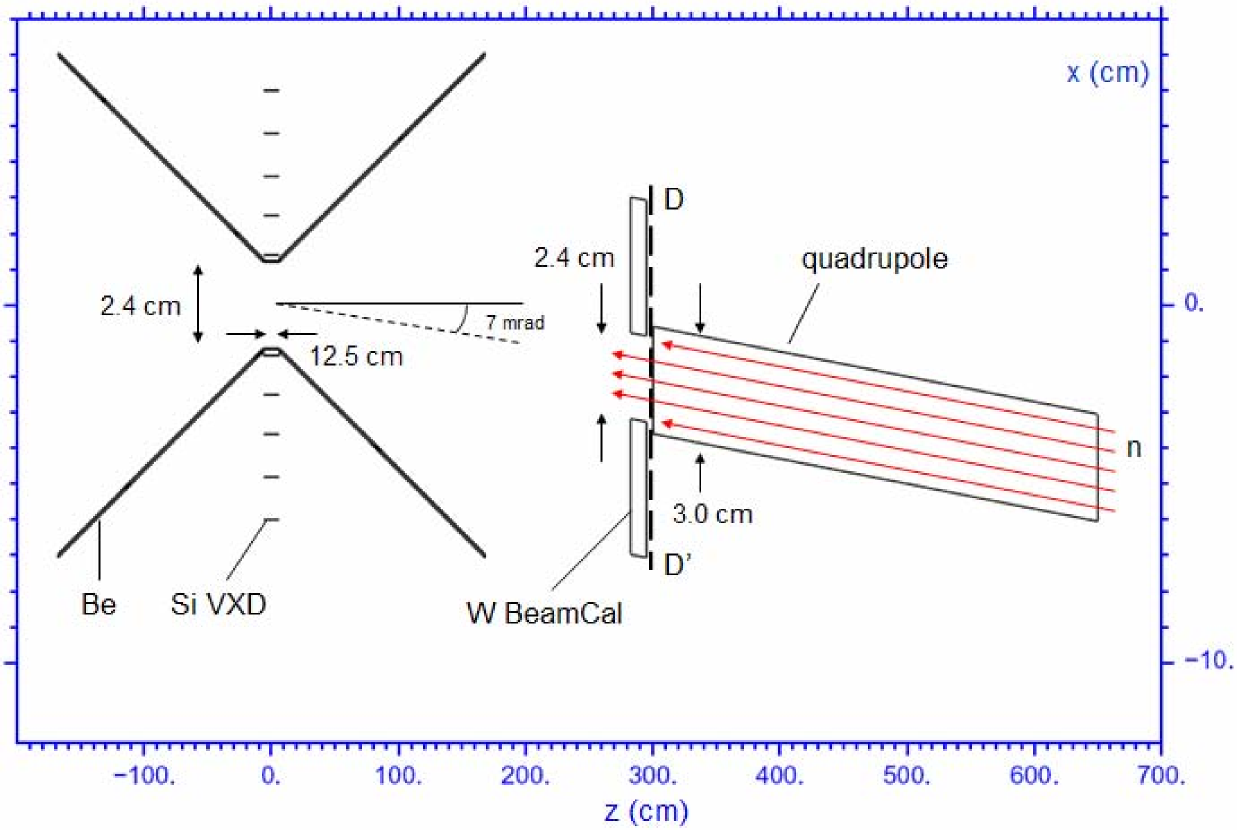

Figure 5. The full model of the extraction line. The BeamCal was modeled by a 12.5 cm thick slab of tungsten. The neutron source was evenly distribution on the surface of the quadrupole at D-D' and the neutrons were given a trajectory of 7 mrad towards the detector.

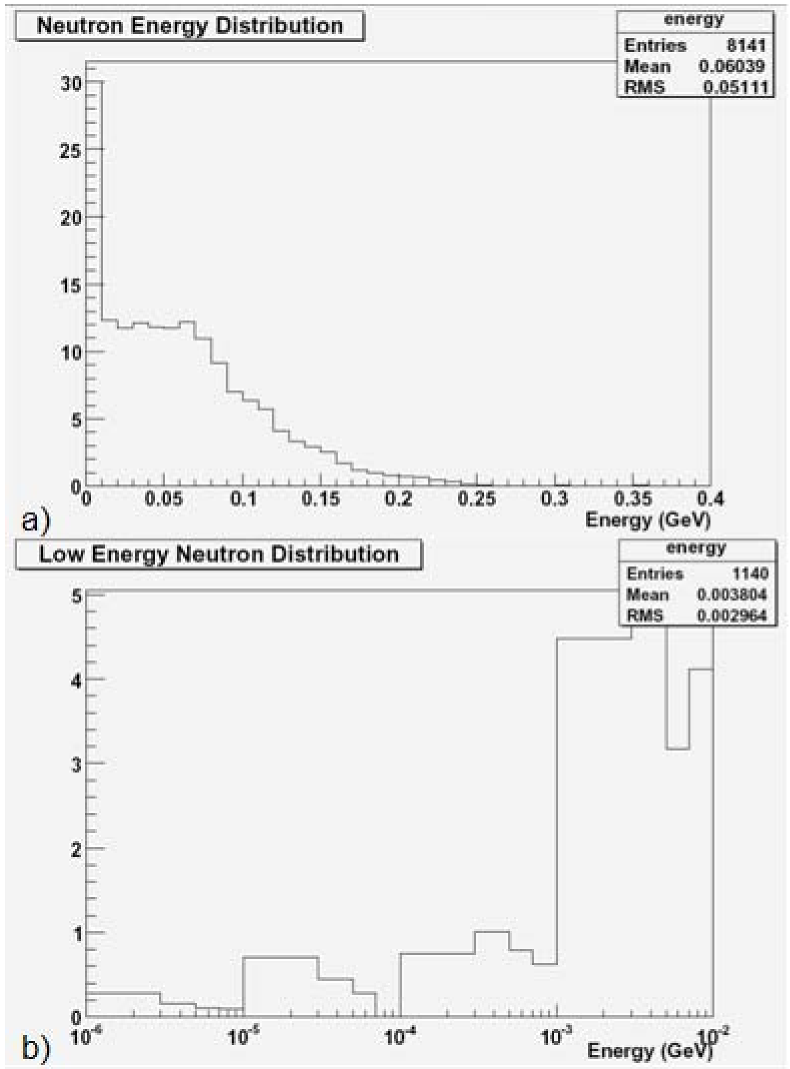

Figure 6. a) The neutron energy distribution collected at A-A' in Figure 2. b) The low energy neutron distribution for neutrons in the first bin in Figure 6a).

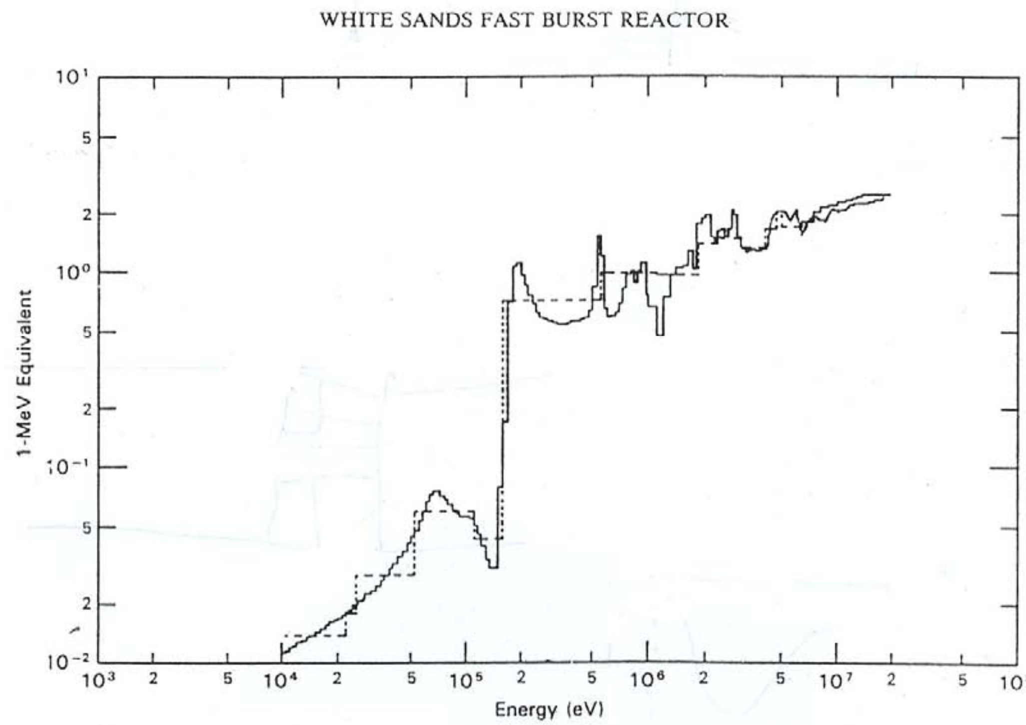

Figure 7. Silicon displacement as a function of energy. Figure was made by T. M. Flanders and M. H. Sparks [10].

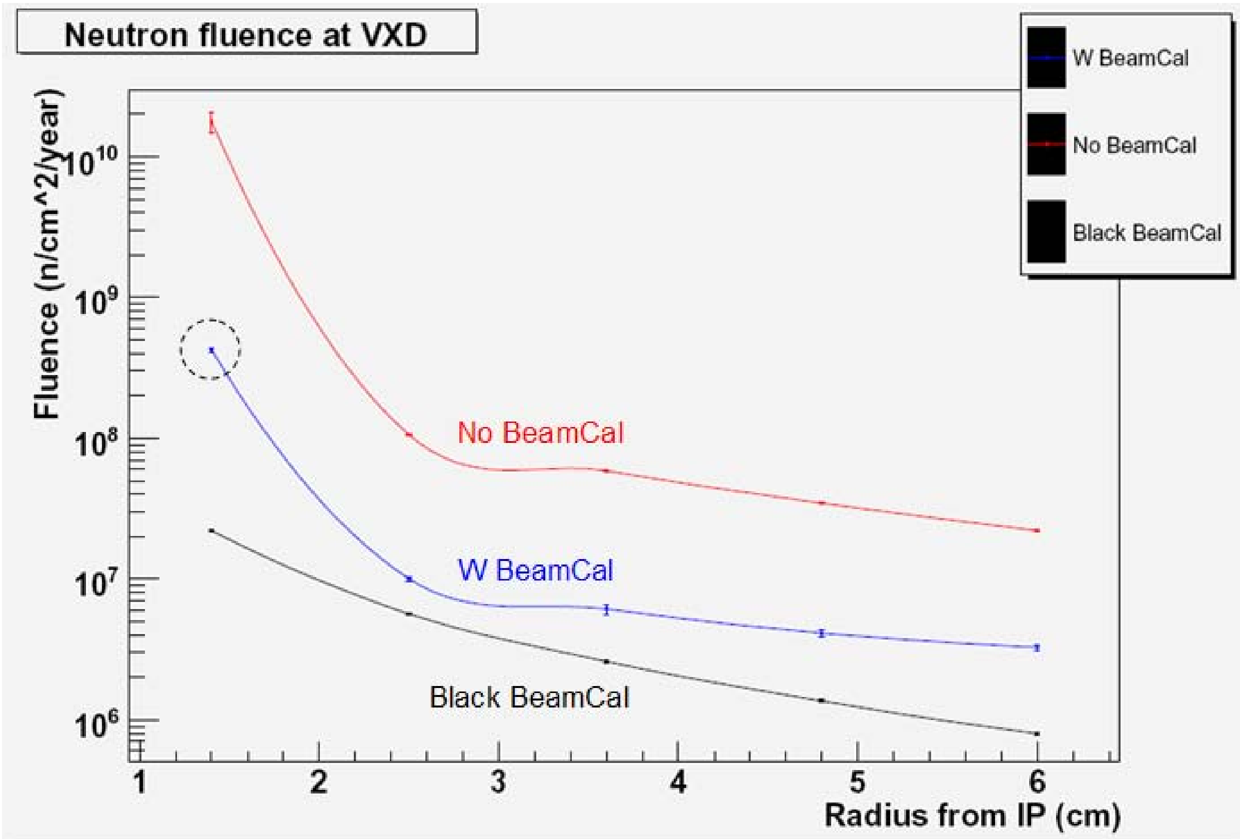

Figure 8. The fluence as a function of radius from the IP for three different modifications of the BeamCal. The circled value, $4.28*10^8$ neutrons/cm^2/year, is of particular importance, since it corresponds to the current BeamCal type and aperture radius.

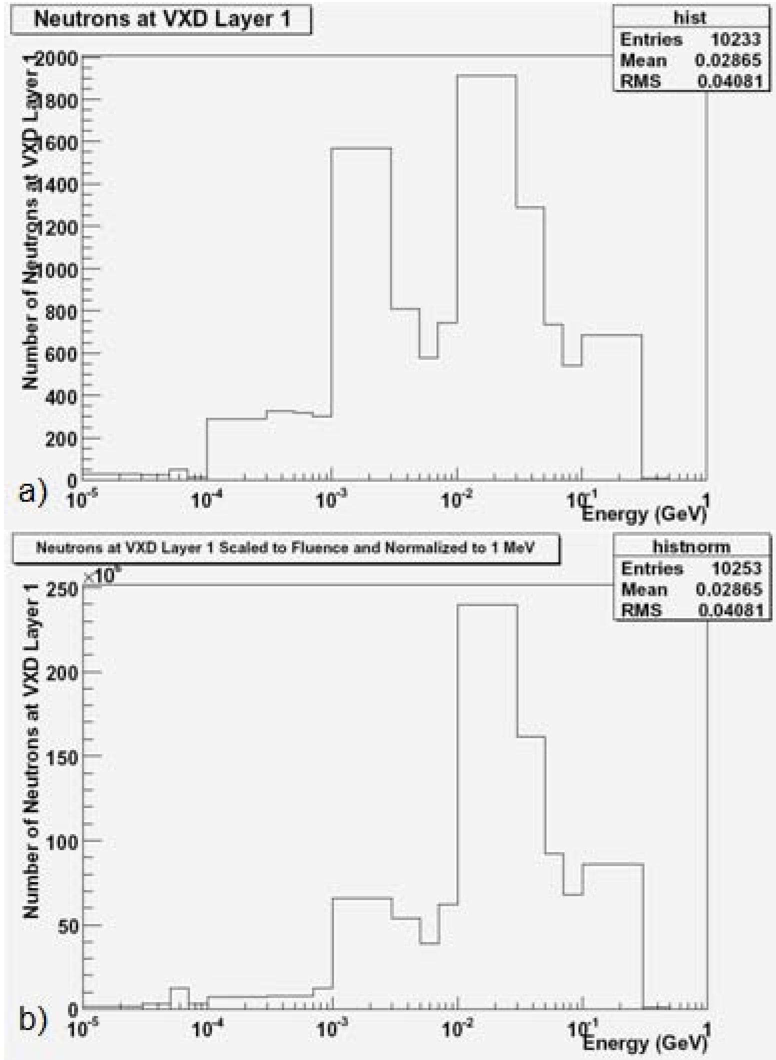

Figure 9. a) The neutron energy distribution for the flux that reaches the first layer of the silicon detector. b) The neutron energy distribution scaled to 1 MeV equivalent neutron displacement damage to CCD silicon detectors.

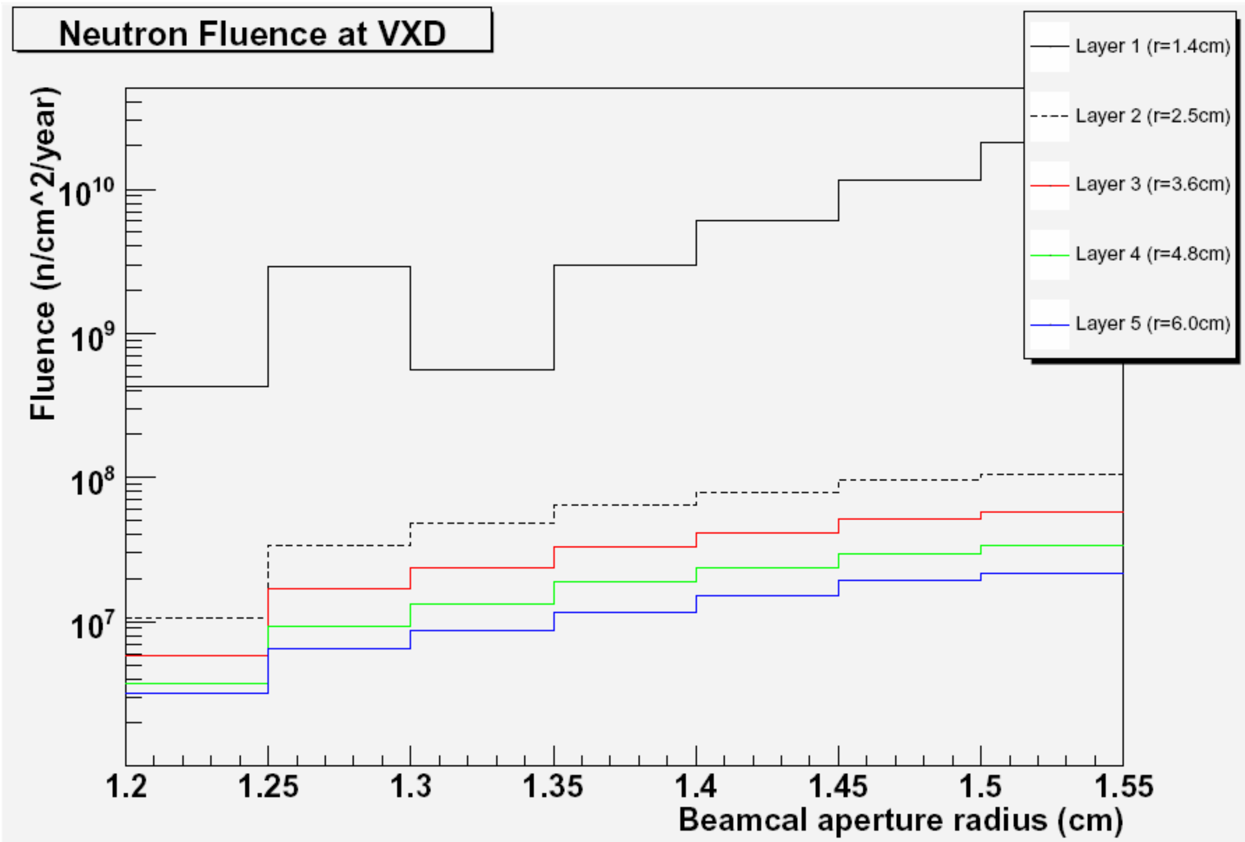

Figure 10. The neutron fluence at the five layers of the vertex detector as the aperture radius of the BeamCal is expanded. At a radius of 1.5 cm, the BeamCal does not block any of the incident neutrons.

Tables

			Neutron total 'weight'		Neutron total number	
Run Number	Type of Bias	Computation Time	At z = 300 m	At z = 0	At z = 300 m	At z = 0
1	No biasing	23 hours 35 min	82	2	82	2
2	Leading particle biasing activated for EMF particles (for e^-,e^+ < 2.5 GeV and γ < 2.5 GeV)	1 hour 36 min	103	0	87	0
3	Decay length biasing activated for photonuclear interactions (biasing factor = 0.020)	6 hours 46 min	103	0.781	5008	49
4	Splitting in waterdump activated for photons	6 hours 22 min	96.4	1.09	16619	117

	(10 regions in waterdump, factor of 2 for each region boundary)					

Table 1. Computation time and effectiveness of each bias. All runs were made with 6000 electrons incident on the water dump and each run contains the biases of all previous runs.