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Design and construction of Faraday cup ion detectors using thin film deposition

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Abstract

Thin film Faraday cup detectors can provide measurements of fast ion loss from magnetically confined fusion plasmas. These multilayer detectors resolve the energy distribution of the lost ions in addition to giving the total loss rate. Past detectors were assembled by stacking discrete foils and insulating sheets. Outlined here is a design and fabrication methodology for those detectors using thin film deposition. The intention is to use detectors fabricated by this method on JET, NSTX-U and the LHD. The detectors will consist of alternating layers of aluminum and silicon dioxide. The thicknesses of the films have been designed to isolate energies of interest. Thin film deposition offers the advantage of relatively simple and more mechanically robust construction compared to other methods, as well as precise control of film thickness. Furthermore, this depositional fabrication technique places the layers in intimate thermal contact, providing for 3D conduction and dissipation of the ion-produced heating in the layers rather than the essentially 2D heat conduction in the discrete foil stack implementation.

1 Introduction

For magnetically confined fusion plasmas, the confinement of energetic ions, be they neutral beam ions, ion cyclotron heated tail ions, or alpha particles produced by deuterium-tritium (DT) fusion, is important for efficient plasma heating, as well as to protect the plasma-facing walls from damage due to potentially high fluxes of fast ions. Measuring the ions that do escape the plasma can give vital insights as to which conditions promote good ion confinement, and can give some information as to what internal plasma processes can lead to ion loss. Thus, there are both engineering and physics reasons that motivate measurement of these losses. Faraday cup detectors have been used on several occasions[1, 2, 3, 4], including thin foil detectors in JET to measure this ion loss. The JET detector design in this work is intended to replace currently existing thin foil detectors, and will work in conjunction with a previously installed scintillator detector[5]. Construction of detectors using thin film deposition has been proposed and utilized in earlier works[2, 6]. Earlier thin foil Faraday cup detector designs, such as that for JET, involved assembling the detector from discrete foils and insulating sheets. This construction technique requires painstaking attention to assure that the metal layers do not short to one another in the final assembled system. The JET detectors used 2.5 um phlogophite mica sheets as the insulators, and these were found to be prone to cracking during handling in assembly. It was sometimes the case that the cracks were small enough to be invisible to the unaided eye, yet large enough to cause foil-to-foil shorts, which were sometimes only evident after a stack had been fully assembled and placed under compression. In practice, assembly by stacking individual foils is only feasible for detectors working in the MeV energy range. This corresponds to micron scale penetration depths of the ions into the detector. Below about 1 um thickness, the foils and insulating sheets become virtually impossible to handle due to their delicacy. Consequently, this assembly technique would not workable if the aim were a detector for 100 keV ions. In contrast, thin film deposition allows deposition of both conducting and insulating layers with thicknesses well below 1 um, with good uniformity and control of layer thickness. This, in turn, entails good control over the energy range detected by each layer and the ability to provide maximal discrimination in energy for pre-selected energy populations. In addition to the assembly advantages mentioned above, using thin film deposition would allow for the construction of a detector as a single piece, which would eliminate contact heat resistance between layers, and which, in turn, would allow for 3D conduction and dissipation of ion induced heating. The resulting detector would also be more mechanically sound than previous constructions.

2 Design Goals

Three variations of thin foil Faraday cup detectors have been designed; two for the measurement of neutral beam ions on NSTX-U and LHD and another for the measurement of alpha particles produced by D-T fusion on JET. The design goal common to all detectors was to provide some level of energy resolution for lost particles. In the case of NSTX-U with 90 keV deuteron beam ions, this translated into a desire to discriminate between the one-third, one-half, and full energy ions with less than 25% uncertainty. The LHD detector had similar goals, except the beam energy of interest is 120 keV, and the one-fourth energy particles were also of interest. The JET detector would have to have enough resolution to show the energy distribution of the lost alpha particles, dividing the energy range from the birth energy of 3.5 MeV down to near zero energy into four or five bins. Both designs would also have to survive a vacuum bake and, perhaps, operate at elevated vessel temperatures (150 C for NSTX-U and 250 C for JET). In addition, they would need to function in an intense neutron/gamma radiation environment. The designs also had to include a sufficient thickness of insulation between the foils to prevent a large incidence of defects that would cause shorts between foils. This, in practice, sets a minimum thickness for the insulating layers. An opposing consideration, though, is that the insulators be thin enough so that the resolution of the detector would not be negatively impacted by ions stopping in the insulators instead of the conducting foils.

3 Design Methodology

SRIM[7] calculations were used extensively to determine the material and thicknesses of the foils. Aluminum was chosen as the conductive material because it is the lowest-Z conducting material that did not present any significant health or chemical hazards. Lower-Z materials were found to have improved resolution, a lower ratio of straggling to total range for particles. This allowed for the isolation of energies differing by only 15 keV, in this case the one-third and one-half neutral beam ions. A combination of silicon dioxide and silicon nitride was chosen as an insulator because of the ease at which it can be selectively etched when used in conjunction with aluminum, and the significantly reduced incidence of pinholes that propigate through the insulating layer. The insulating layers were designed to be as thin as possible (.1 μm) without significant risk of shorts between adjacent foils for the NTSX-U and LHD designs and to be twice as thick (.2 μm) for the JET design, to further reduce the failure rate per layer. The thicknesses of the conducting foils were chosen by varying the thicknesses in SRIM until the desired energies were isolated to stop in separate foils.

4 NSTX-U design

The NSTX-U design consists of four aluminum foils alternated with layers of a silicon dioxide and silicon nitride insulator. The thicknesses of the aluminum foils are .1 μm, .2 μm, .2 μm, .4 μm from plasma facing to the rear of the detector. An additional aluminum foil will be included at the back of the detector to measure intrinsic noise of the system so it can be subtracted from the data collected by the other foils. The insulating layers are all .1 μm thick in total, consisting of a .04 μm silicon nitride layer between two .03 μm silicon dioxide layers. The first aluminum foil is designed to screen the rest of the detector from UV-rays emitted by the plasma, which could cause false readings by inducing photoelectric electron loss. The remaining foils are for the detection of 30 keV, 45 keV and 90 keV deuterons, respectively. These thicknesses were optimized by varying the thicknesses of the foils across multiple SRIM runs. Due to the small variation in the range of the 30 keV and 45 keV ions, and the relatively large straggling, a fair portion (about 36%) of the 30 keV deuterons will stop in the second insulating layer instead of the designated foil. It is hypothesized that this will cause the forward side of the insulator to become positively biased, which will in turn pull electrons out of the 30 keV foil, leading to the same current that would have occurred if the ions had stopped in the foil. If this hypothesis is incorrect, the performance of the detector could suffer considerably. Thin conducting films have been used previously to effectivly pull charge off of ion-bombarded insulators.[8] The ions stopping in the silicon dioxide and silicon nirtride will, over time, lead to significant damage in the insulator, including cracking and void formation, which could cause shorts between the foils.[9] This will limit the effective lifespan of the detectors.

5 JET design

The JET design consists of eight aluminum foils alternated with layers of a silicon dioxide and silicon nitride insulator, with a protective gold front foil. The thicknesses of the aluminum foils are .6 μm, 1.1 μm, 1.2 μm, 1.4 μm, 1.6 μm, 1.9 μm, 2.1 μm, and 2.3 μm from plasma facing to the rear of the detector. An additional aluminum foil will be included at the back of the detector to measure intrinsic noise of the system so it can be subtracted from the data collected by the other foils. The insulating layers are all .2 μm thick in total, consisting of a .08 μm silicon nitride layers between two .06 μm silicon dioxide layers and the gold foil is .1 μm thick. The foil thicknesses were designed so as to have a bin size of .5 MeV, e.g. the first collection foil would collect ions from .25 MeV to .75 MeV. The insulator thickness was increased for this design to decrease the probability of pinhole formation that could lead to shorts between foils, and the increase of thickness would have little effect on the overall resolution for this design. Due to the shear number of layers in the design, even a low failure rate per layer would cause a prohibiatively large failure rate for the detectors as a whole. The same procedure used to optimize the NSTX-U foil thicknesses was used for the JET detector.

6 LHD design

The LHD design consists of five aluminum foils alternated with layers of a silicon dioxide and silicon nitride. The thicknesses of the aluminum foils are are .1 μm, .2 μm, .2 μm .2 μm, .6 μm from plasma facing to the rear of the detector. An additional aluminum foil will be included at the back of the detector to measure intrinsic noise of the system so it can be subtracted from the data collected by the other foils. The insulating layers are all .1 μm thick. The first aluminum foil is designed to screen the rest of the detector from UV-rays emitted by the plasma, which could cause false readings by inducing photoelectric electron loss. The remaining foils are for the detection of 30 keV, 45 keV, 90 keV, and 180 keV deuterons, respectively. These thicknesses were optimized by varying the thicknesses of the foils across multiple SRIM runs. The same issue with the differenciation between 30 keV and 45 keV deuterons in the NSTX-U design were also encountered in this design, with similar results.

7 Acknowledgements

Fabrication and technical support by Dr. George Watson, Mr. Joe Palmer, and Mr. Bert Harrop of Princeton University's Micro and Nano Fabrication Laboratory was greatly appriciated. Conversations with Dr. K. Ogawa of the National Institute for Fusion Science, Toki, Japan concerning neutral beam ion loss measurement objectives for LHD are also appreciated. This work supported by US DoE contract DE-ACO2-09CH11466.

References

[1] O.N. Jarvis, et al., Fus Tech 39, 84 (2001).

[2] F.E. Cecil, et al., Rev. Sci. Instrum. 70, 1149 (1999).

[3] Darrow D.S. et al, Rev. Sci. Instrum. 75, 3566 (2004).

[4] V. Basiuk et al, Nucl. Fusion 44 181 (2004)

[5] Darrow, D. S., Rev. Sci. Instrum., 79 (2008).

[6] F.E. Cecil, et al, Rev. Sci. Instrum. 72, 792 (2001).

[7] The code SRIM 2008, Stopping and Range of Ions in Matter, was written by J. F. Zeigler and J. Biersack, IBM-Research, Yorktown Heights, New York 10598. (SRIM is freely available at http://www.srim.org.)

[8] Kim, J., et al., Journal of the Korean Physical Society, 43(4), 582-584, (2003).

[9] Primack, W. Journal of Nuclear Materials, 53, 238-245 (1974).

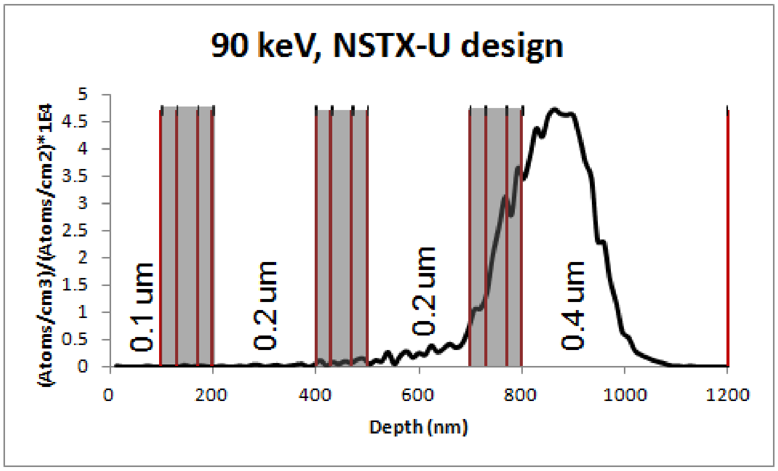

Figure 1: 90 keV deuterons into NSTX-U detector design SRIM simulation. The aluminum layers are labeled with their thickness, and the shaded layers are a composite insulator composed of two .03 um silicon dioxide layers on either side of a .04 silicon nitride layer.

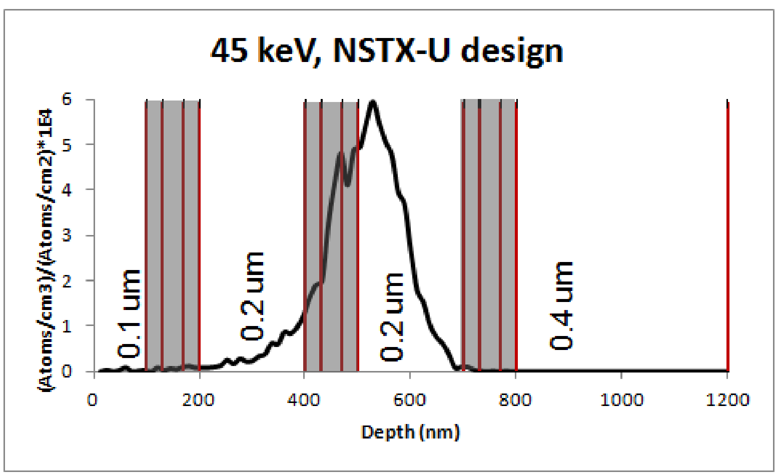

Figure 2: 45 keV deuterons into NSTX-U detector design SRIM simulation.. The aluminum layers are labeled with their thickness, and the shaded layers are a composite insulator composed of two .03 um silicon dioxide layers on either side of a .04 silicon nitride layer.

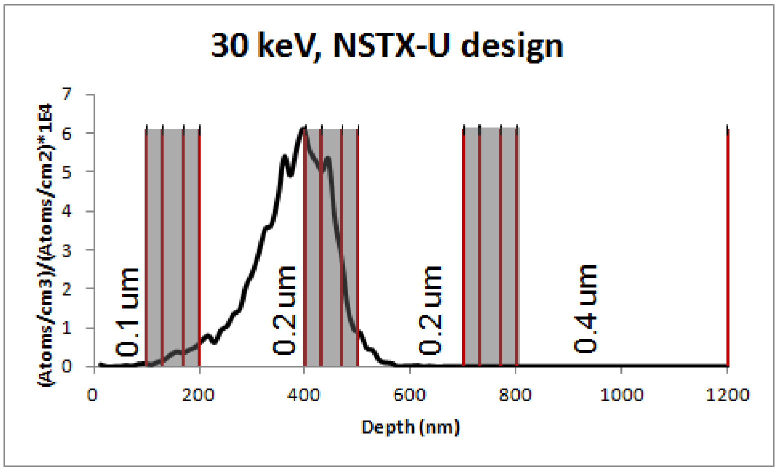

Figure 3: 30 keV deuterons into NSTX-U detector design SRIM simulation. The aluminum layers are labeled with their thickness, and the shaded layers are a composite insulator composed of two .03 um silicon dioxide layers on either side of a .04 silicon nitride layer.

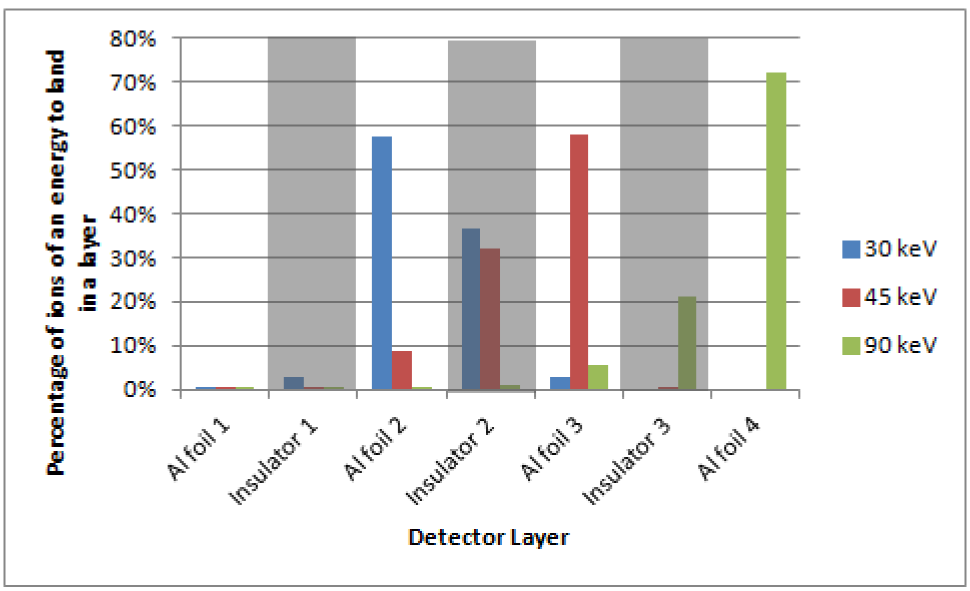

Figure 4: Percentage of incident ions to land in specified layers by ion energy for NSTX-U detector. Shaded layers represent silicon dioxide layers

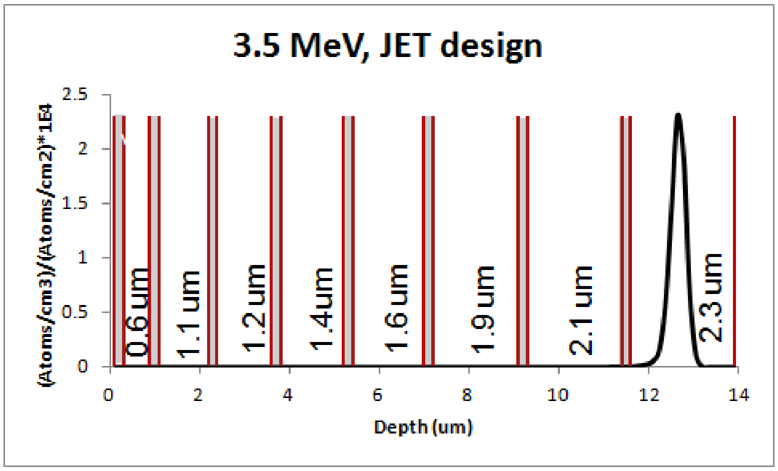

Figure 5: SRIM calcuations for 3.5 MeV alpha particles into JET detector design. The rear most foil (for detecting noise) is not shown, as it was unnecessary for the SRIM calculations.Each aluminum foil (with the exception of the first) has been designed to capture ions in a .5 MeV energy range. The conducting aluminum layers are labeled with their thickness. The front most layer is the .1 um gold screen. The shaded layers are a composite insulator composed of two .06 um silicon dioxide layers on either side of a .08 silicon nitride layer.

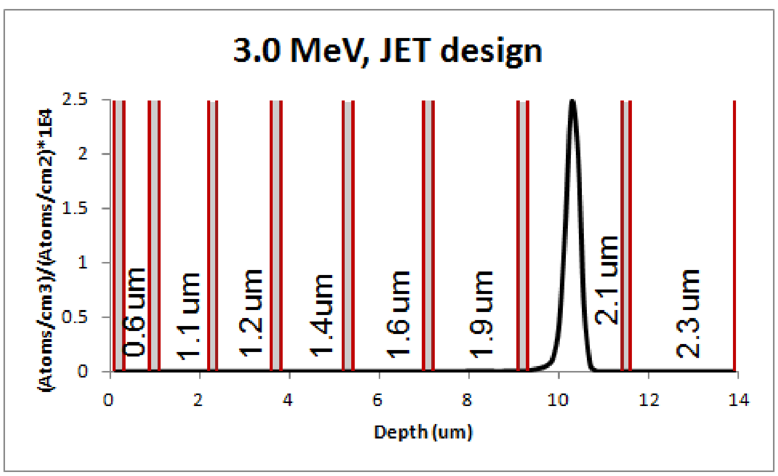

Figure 6: SRIM calcuations for 3.0 MeV alpha particles into JET detector design. The rear most foil (for detecting noise) is not shown, as it was unnecessary for the SRIM calculations. The conducting aluminum layers are labeled with their thickness. The front most layer is the .1 um gold screen. The shaded layers are a composite insulator composed of two .06 um silicon dioxide layers on either side of a .08 silicon nitride layer.

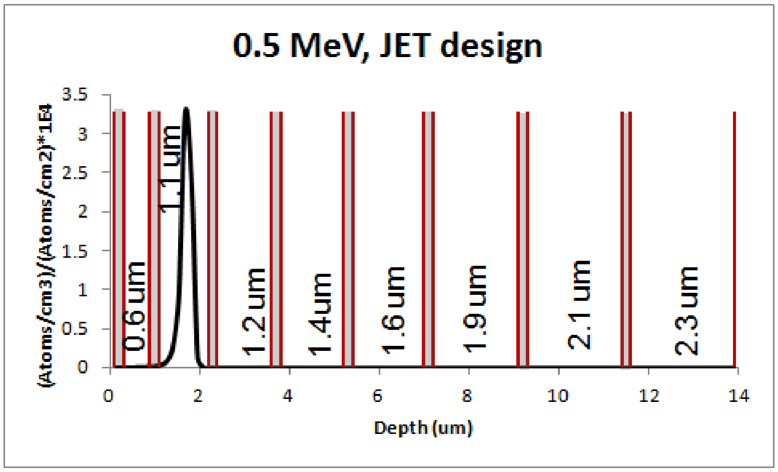

Figure 7: SRIM calcuations for 0.5 MeV alpha particles into JET detector design. The rear most foil (for detecting noise) is not shown, as it was unnecessary for the SRIM calculations. The conducting aluminum layers are labeled with their thickness. The front most layer is the .1 um gold screen. The shaded layers are a composite insulator composed of two .06 um silicon dioxide layers on either side of a .08 silicon nitride layer.

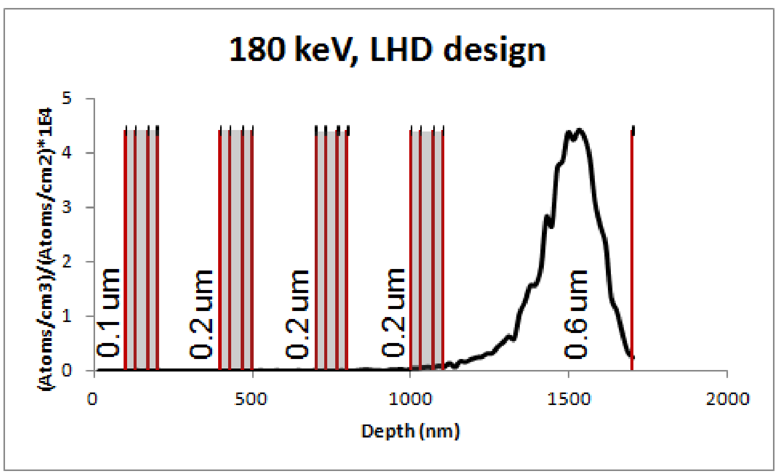

Figure 8: 180 keV deuterons incident into the proposed LHD thin film detector. Aluminum layers are labeled with their thickness, the shaded layers are a composite insulator composed of two .03 um silicon dioxide layers on either side of a .04 silicon nitride layer.

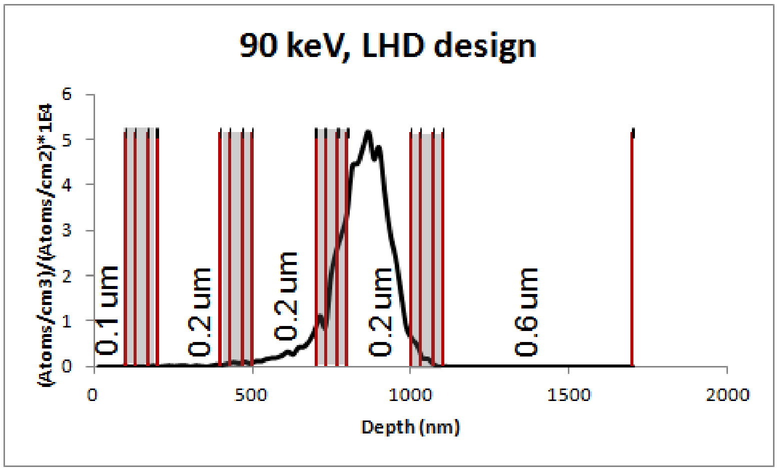

Figure 9: 90 keV deuterons incident into the proposed LHD thin film detector. Aluminum layers are labeled with their thickness, the shaded layers are a composite insulator composed of two .03 um silicon dioxide layers on either side of a .04 silicon nitride layer.

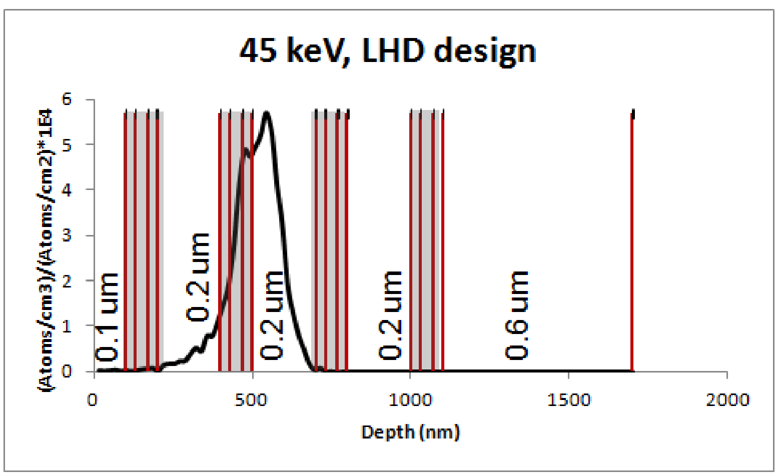

Figure 10: 45 keV deuterons incident into the proposed LHD thin film detector. Aluminum layers are labeled with their thickness, the shaded layers are a composite insulator composed of two .03 um silicon dioxide layers on either side of a .04 silicon nitride layer.

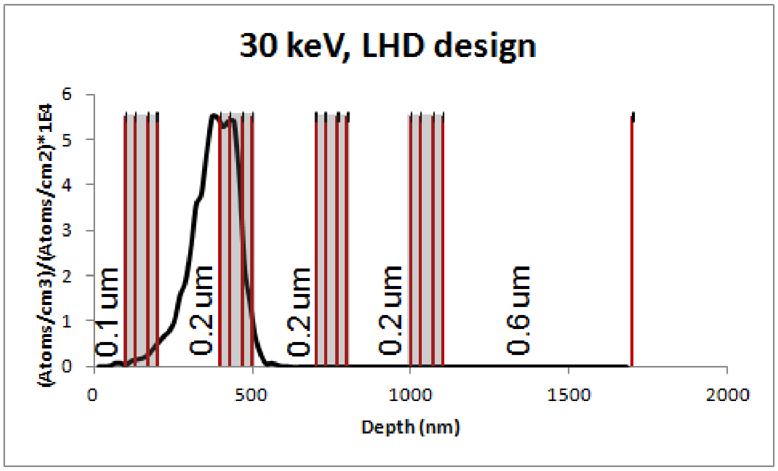

Figure 11: 30 keV deuterons incident into the proposed LHD thin film detector. Aluminum layers are labeled with their thickness, the shaded layers are a composite insulator composed of two .03 um silicon dioxide layers on either side of a .04 silicon nitride layer.

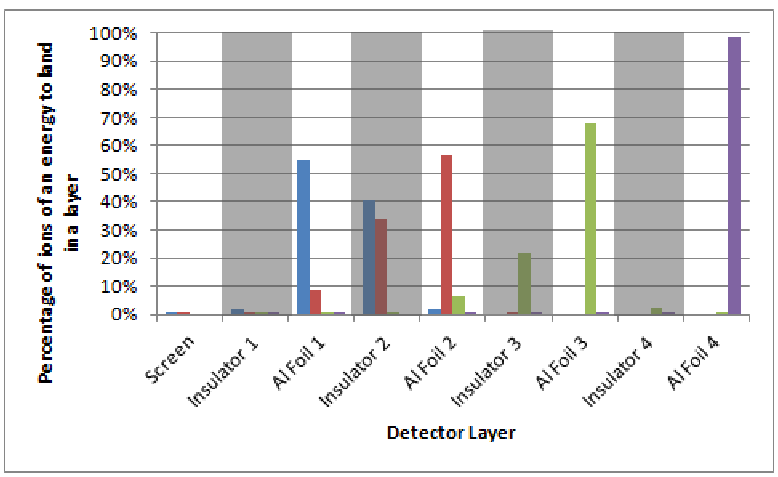

Figure 12: Percentage of incident ions to land in specified layers by ion energy for the LHD detector. Shaded layers represent a composite insulator composed of two .03 um silicon dioxide layers on either side of a .04 silicon nitride layer.

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