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Design of Faraday cup ion detectors built by 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 can 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 together. Outlined here is a design methodology for those detectors using thin film deposition. The intention is to use detectors created by this method on JET and NSTX-U. 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 three dimensional conduction and dissipation of the ion-produced heating in the layers rather than the essentially two dimensional 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 heating, as well as to protect the plasma-facing walls from unnecessary damage. 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 regarding what internal plasma processes can lead to ion loss. Faraday cup detectors have been used on several occasions[1-5], including thin foil detectors in JET to measure this ion loss. The first and second generation JET fast ion loss detector designs involved assembling the detector from discrete foils and insulating sheets. The JET device design proposed below is intended to replace some of these currently existing thin foil detectors, and will work in conjunction with a previously installed scintillator detector[6]. Construction of detectors using thin film deposition has also been proposed in prior work[7,8]. Using thin film deposition would allow for the construction of a detector as a single piece, much reducing the contact heat resistance between layers, which, in turn, would allow for three dimensional conduction and dissipation of ion induced heating. The resulting detector would also be more mechanically sound than those using the older design. (Indeed, it is believed that some of the existing JET detectors have failed due to cracking or breakage of the mica insulating sheets within, allowing adjoining foils to come into electrical contact.) The use of thin film deposition also gives a large amount of control as to the thicknesses of the foils, providing much better discrimination between specific energy ions.

2 Design Goals

Two variations of thin foil Faraday cup detectors have been designed; one for the measurement of neutral beam ions on NSTX-U and the other for the measurement of alpha particles produced by D-T fusion on JET. The design goal common to both 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 JET detector would have to have enough resolution to show the energy distribution of the lost alpha particles with ~30 percent accuracy. Both designs would also have to operate at elevated vessel temperatures (150° C for NSTX-U and 250° C for JET), and 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. The insulators would also have to 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

An extensive set of calculations were made with the code SRIM (Stopping and Ranges of Ions in Matter)[9] to optimize the material choices and thicknesses for each layer. 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. Silicon dioxide was chosen as an insulator because of the ease at which it can be selectively etched when used in conjunction with aluminum. The insulating layers were designed to be as thin as possible (100 nm) without significant risk of shorts between adjacent foils for the NTSX-U design and to be twice as thick (200 nm) for the JET design. This choice was made to further reduce the failure rate per layer. The thicknesses of the conducting foils were chosen by varying those in the SRIM model until the different ion energy components were found to stop in separate foils.

4 NSTX-U design

The NSTX-U design consists of four aluminum foils alternated with layers of silicon dioxide. The thicknesses of the aluminum foils are 100 nm, 200 nm, 200 nm, and 400 nm 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 100 nm 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 and 90 keV deuterons, respectively. Fig. 1 shows the deposition vs.

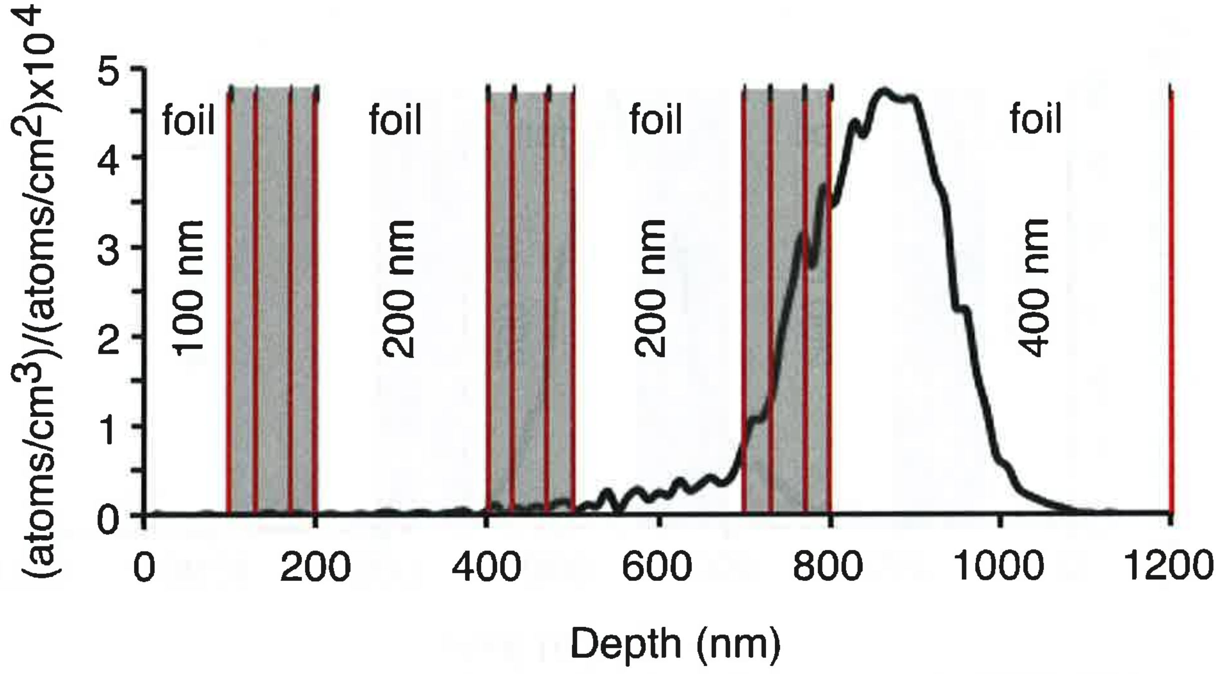

Figure 1: The SRIM computed deposition profile of 90 keV deuterons in the NSTX-U detector, shown along with the various layers of the sensor. The white bands are the aluminum layers, while the gray regions denote the insulating layers. The latter are composite structures, with two 30 nm silicon dioxide layers sandwiching a 40 nm silicon nitride layer. The red lines in the insulator region denote the boundaries between the different layers.

depth of 90 keV full energy beam deuterium beam ions in the detector. Nearly all the deposition is in the third foil, as desired. Fig. 2 displays the deposition of the 45 keV half energy deuterons in this structure. Due to the small variation between the range of the 30 keV and 45 keV ions, and the relatively large straggling, a fair portion (about 41%) 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. The ions stopping in the silicon dioxide will, over time, lead to significant damage in the insulator, including cracking and void formation, which could cause shorts between the foils.[10,11] This will limit the effective lifespan of the detectors.

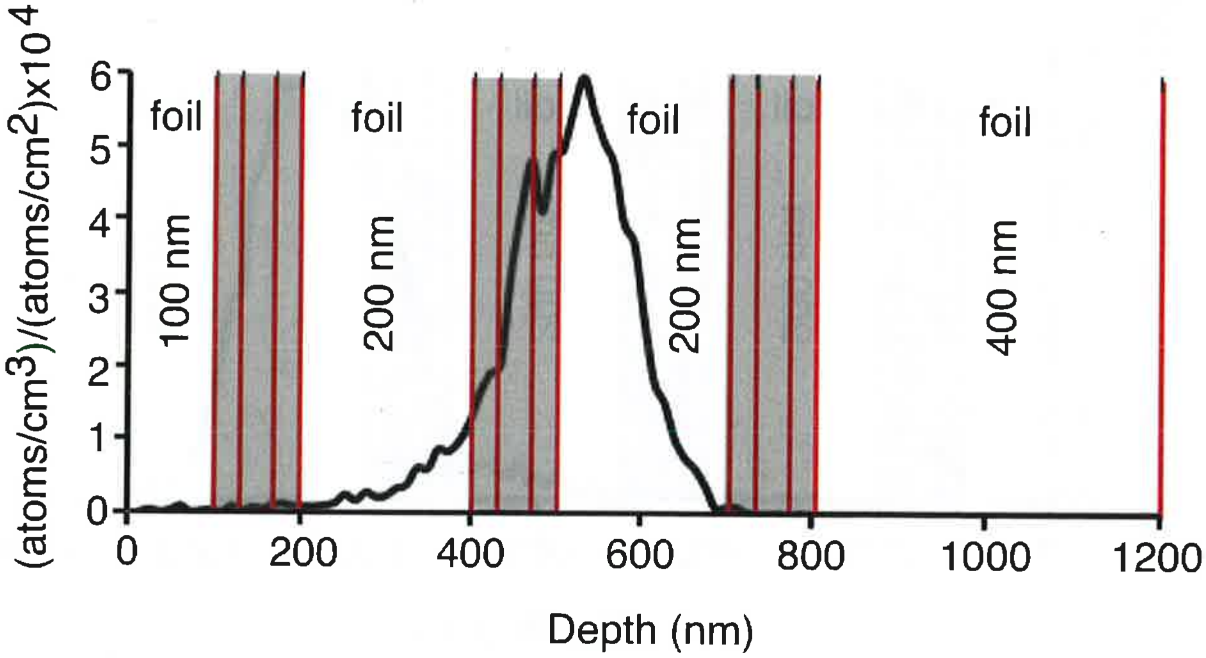

Figure 2: The SRIM computed deposition profile of 45 keV deuterons in the NSTX-U detector, shown along with the various layers of the sensor. The detector is the same one depicted in Fig. 1 and the shading and color scheme is also the same. Note that the majority of the incident ions are deposited in the third foil (second active foil), as desired.

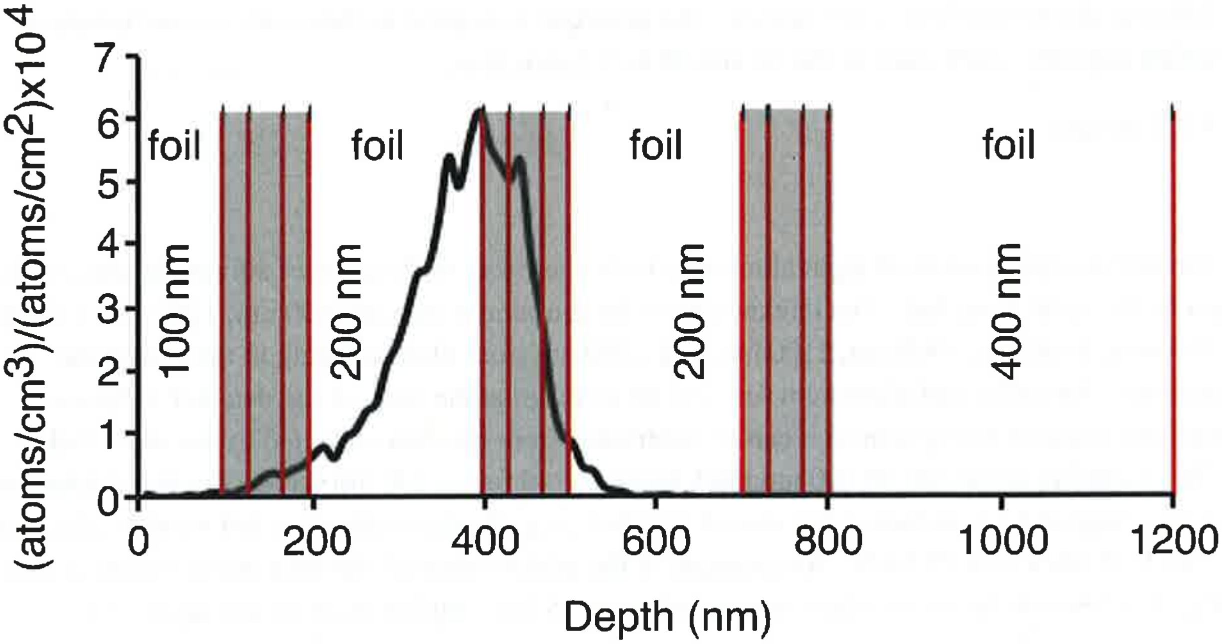

Figure 3: The SRIM computed deposition profile of 30 keV deuterons in the NSTX-U detector, shown along with the various layers of the sensor. The detector is the same one depicted in Fig. 1 and the shading and color scheme is also the same. Note that the majority of the incident ions are deposited in the second foil (first active foil), as desired.

Fig. 4 depicts the fraction of each energy component of the incident beam that appears in each

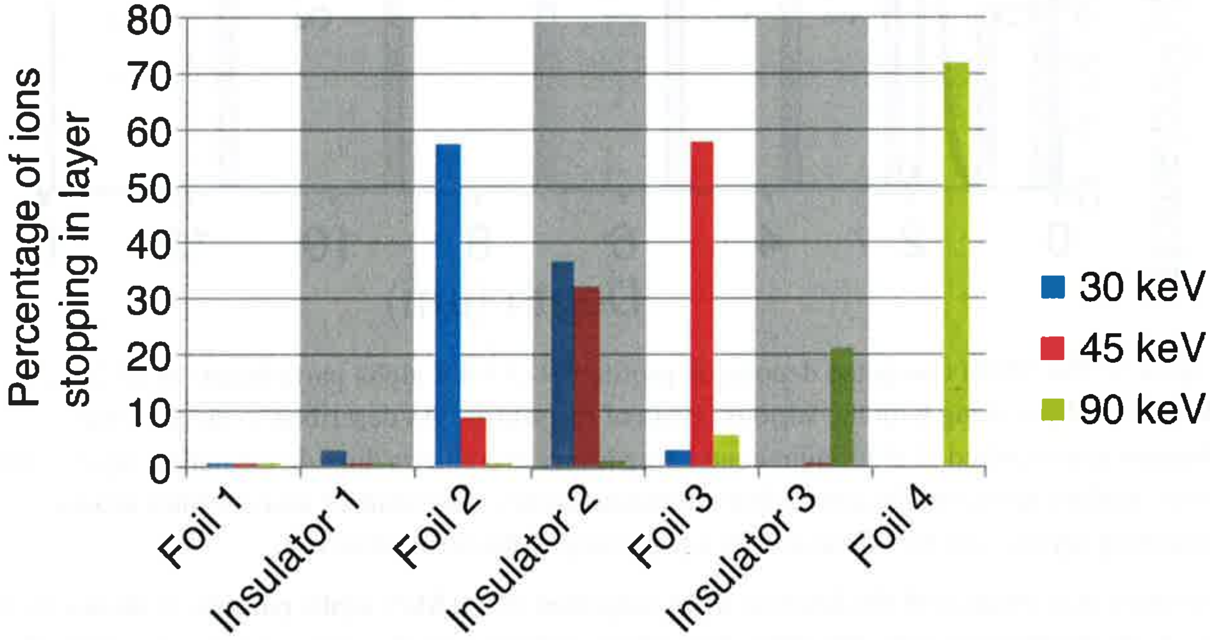

Figure 4: The SRIM computed deposition profile of 30 keV deuterons in the NSTX-U detector, shown along with the various layers of the sensor. The detector is the same one depicted in Fig. 1 and the shading and color scheme is also the same. Note that the majority of the incident ions are deposited in the second foil (first active foil), as desired.

detector layer, including the intervening insulators. As can be seen in this figure, the design does a fairly good job of causing the different energy components of the beam to be deposited into different aluminum foils in the device. The principal exception to this is the second insulator, which captures ~30% each of the 30 and 45 keV beam ions.

5 JET design

The JET design consists of eight aluminum foils alternated with layers of silicon dioxide, with a protective gold front foil. The thicknesses of the aluminum foils are 600 nm, 1100 nm, 1200 nm, 1400 nm, 1600 nm, 1900 nm, 2100 nm, and 2300 nm 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 200 nm thick and the gold foil is 100 nm thick. The foil thicknesses were designed so as to have a bin size of 0.5 MeV, e.g. the first collection foil would collect ions from 0.25 MeV to 0.75 MeV. An example of the performance of this first active foil is shown in Fig. 5, where all the current from a population of 0.5 MeV alphas stops in this layer. The modeled performance of the detector when subjected to 3.0 MeV alpha particles is shown in Fig. 6. As in the previous case, the entire population of these particles stops completely within the

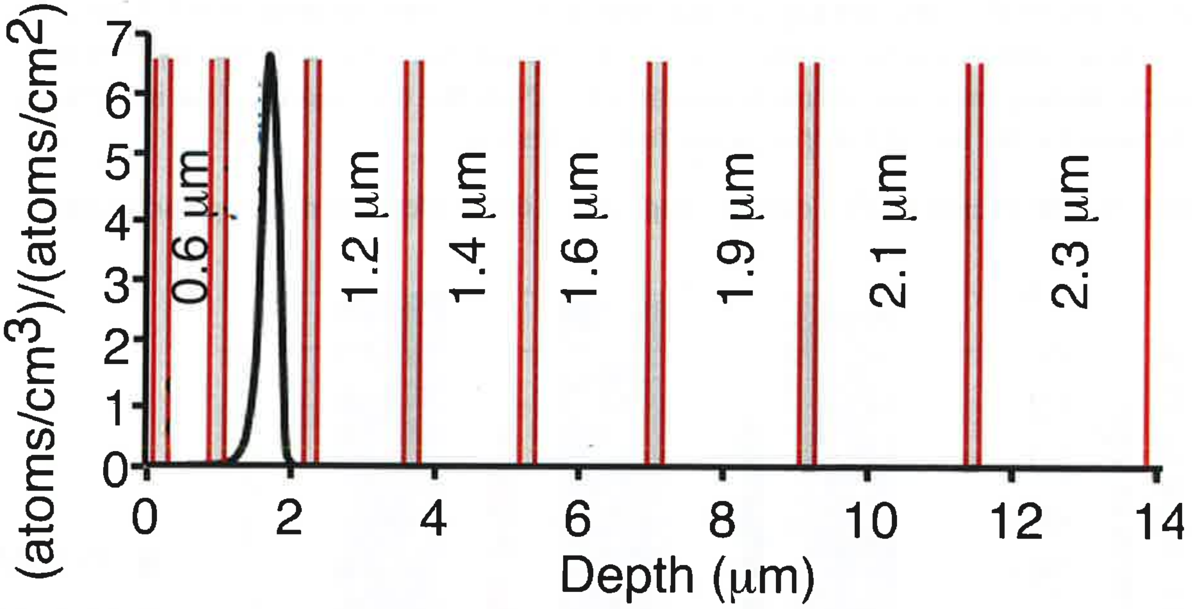

Figure 5: The SRIM computed deposition profile of 0.5 MeV alpha particles in the JET detector, shown along with the various layers of the sensor. As described in the text, the detector is comprised of aluminum conducting layers and silicon dioxide insulating layers. The white regions represent the conductive aluminum layers. The shading and red lines are the insulating layers. All the alphas of this energy stop in the first active foil.

designated layer. Finally, Fig. 7 displays the computed deposition profile of 3.5 MeV alphas in

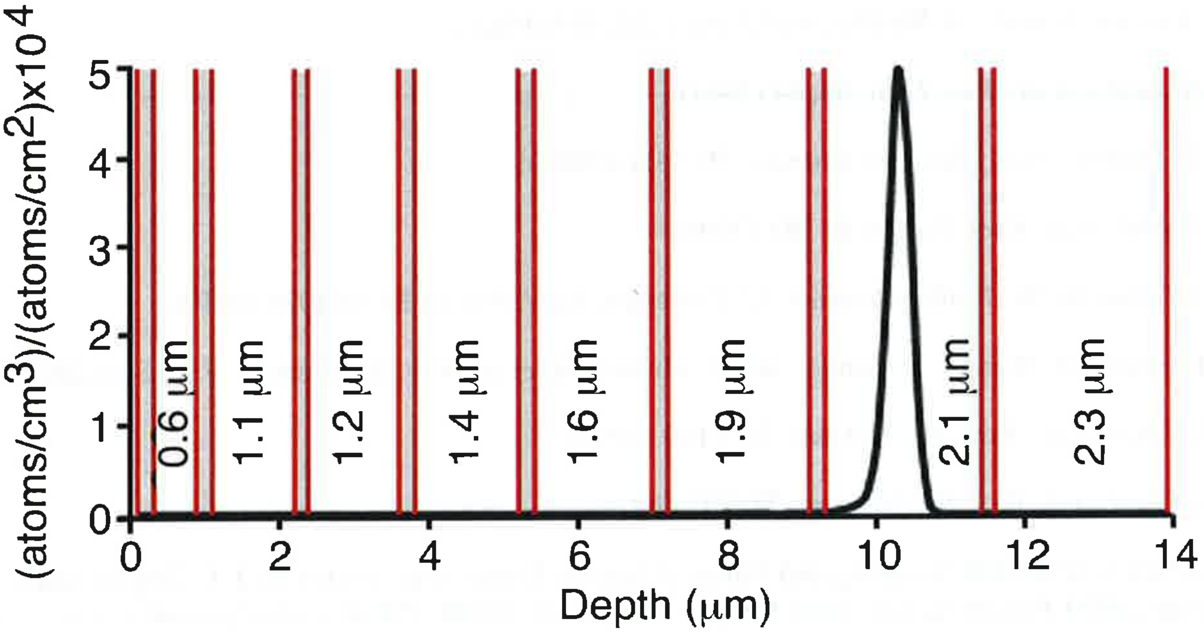

Figure 6: The SRIM computed deposition profile of 3.0 MeV alpha particles in the JET detector, shown along with the various layers of the sensor. The coloring and shading are as in the previous figures. All the alphas of this energy stop in the sixth active foil.

the detector. 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 sheer number of layers in the design, even a low failure rate per layer would cause a prohibitively 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.

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