Gadolinium Thin Foils in a Plasma Panel Sensor as an Alternative to ^{3}He

R. L. Varner, J. R. Beene and P. S. Friedman

***Abstract*—Gadolinium has long been investigated as a detector for neutrons. It has a thermal neutron capture cross-section that is unparalleled among stable elements, because of the isotopes ^{155,157}Gd. As a replacement for ^{3}He, gadolinium has a significant defect, it produces many gamma-rays with an energy sum of 8 MeV. It also produces conversion electrons, mostly 29 keV in energy. The key to replacing ^{3}He with gadolinium is using a gamma-blind electron detector to detect the conversion electrons. We suggest that coupling a layer of gadolinium to a Plasma Panel Sensor (PPS) can provide highly efficient, nearly gamma-blind detection of the conversion. The PPS is a proposed detector under development as a dense array of avalanche counters based on plasma display technology. We will present simulations of the response of prototypes of this detector and considerations of the use of gadolinium in the PPS.**

I. Neutron detection using Gadolinium

THE isotopes ^{155,157}Gd have long been known for having among the largest thermal neutron capture cross sections of any stable isotopes [1]. This has been a curiosity of nuclear structure and an inspiration for development of neutron detectors and as an agent for neutron cancer therapy. Investigation of the use of gadolinium as a neutron detector has recently become more urgent with the anticipated depletion of the ^{3}He supply in the world. The isotopes ^{155,157}Gd have cross sections for capturing thermal (0.025 eV) neutrons of 65,000 and 255,000 barns, respectively[2]. The naturally available metal, in which ^{155}Gd is 14.8% and ^{157}Gd is 15.7%, has an average effective (n,γ) cross section of 49,000 barn. These high cross sections, much higher than that of the popular ^{3}He(n,p) reaction (5300 barn), as seen in Figure 1,

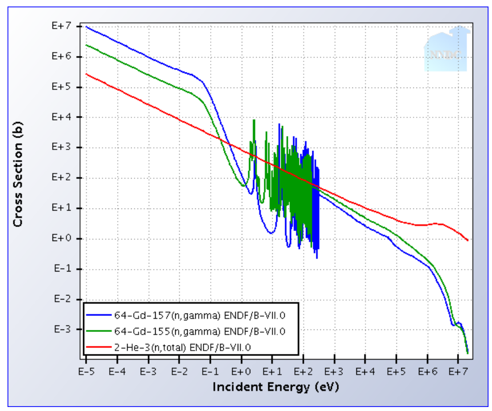

Fig. 1. Neutron capture cross section of ^{155,157}Gd compared to ^{3}He neutron reaction cross section[2].

suggest that a Gd-based detector might complement or even replace the ^{3}He tubes now widely in use for thermal neutrons.

What are the properties of a ^{157}Gd neutron detector? The cross section of 255,000 barn translates into a mean free path for the neutron of 1.3 μm. To stop 99% of the neutrons requires a thickness of 6.0 μm. The daughter nucleus, ^{158}Gd, excited to more than 8 MeV, decays by emitting a number of gamma rays that easily escape the foil. In addition, the neutron capture events decay through the 79 keV 2^+ state which itself decays 59% of the time by internal conversion [3]. The resulting electrons are emitted from K, L, and M shells of the atom at energies of 29 keV, 71 keV and 78 keV[4].

An electron with 29 keV will lose 22 keV, on average, traversing the entire 6 μm foil. If the foil is

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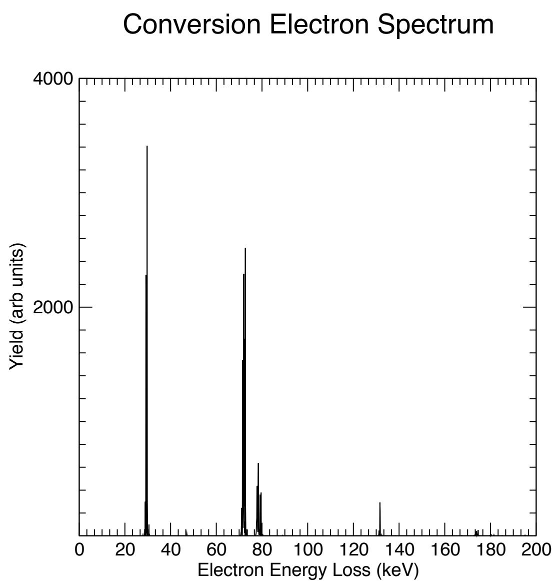

Fig. 2. Simulated ^{157}Gd(n,γ) internal conversion electron spectrum.

at the window of an electron detector, geometrically about half the electrons will enter the sensitive volume, for a net maximum efficiency of neutron detection of about 29%. This compares favorably with arrays of ^{3}He detectors, which can be as efficient as 70%. The ^{157}Gd foil efficiency can be raised to nearly 59% if the foil is placed between two sensitive detectors, as suggested by Gebauer, et al, [5] to detect electrons emitted in most directions. These calculations show that it is possible to make a highly efficient thermal neutron detector using Gd foils based on detecting only the conversion electrons. To provide an alternative to ^{3}He, we need to detect the conversion electrons and not background gamma-rays. The primary background in this kind of detector will be electrons produced by gamma-ray scattering and other processes by which an incident gamma accelerates electrons. A thin gas detector such as the plasma panel sensor (PPS) may be able to accomplish that goal. What is critical to the process is having a very small mass detector to reduce the gamma interaction probability, but very high efficiency for electron detection.

II. The Plasma Panel Sensor, a Detector of Ionizing Radiation

The plasma display panel, the basis of plasma television, is composed of 200 μm cells, with small discharge gaps of 150 μm with a 500 torr gas fill of Xe and Ne. In the display, the cells are held at electric fields just below that required to cause discharge. The display raises the field to cause a discharge, causing scintillation of phosphors lining the cell. The device is designed to limit the duration and physical extent of the discharge. Each cell discharges thousands of times per second. The low mass, fine pixelation and rapid discharge of this class of devices suggests its application to detectors of ionizing radiation[6][7][8].

Using plasma display technology to detect radiation, the Plasma Panel Sensor (PPS), shown below, is a two-dimensional array of cells facing a thin volume of inert gas, e.g. Ar. The cells are each biased into the Geiger region. With sufficient induced ionization, a cell will avalanche, producing a large amplitude pulse with a short rise time, around 1 ns. The volume of gas has a drift electrode to drive electrons into the cells. Because we operate beyond the proportional mode of the cells, the detector is not directly sensitive to the energy deposited by the electrons. If the cells are small enough and the electron range large enough, we might be able to count electron-ion pairs, giving us a signal proportional to energy.

Features:

- High Sensitivity - potential gain of 10^6 or higher
- Fine pixelation - 0.1 to 1 mm pixel separation and sizes
- Small gas volume - 0.1 to 10 mm thickness, near 1 atm operating pressure
- Low mass - dielectric substrates 0.1 to 2 mm in thickness
- Very fast time response (sub nanosecond)

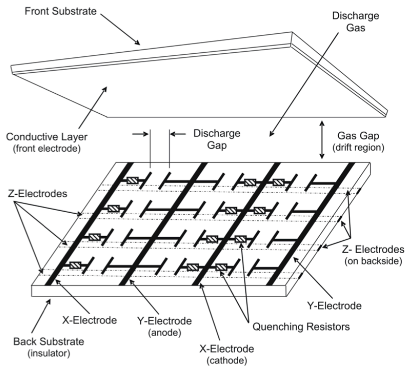

Fig. 3. Schematic of a plasma panel detector. Y and Z electrodes provide orthogonal position determination. X electrodes provide the bias needed to drive the avalanche.

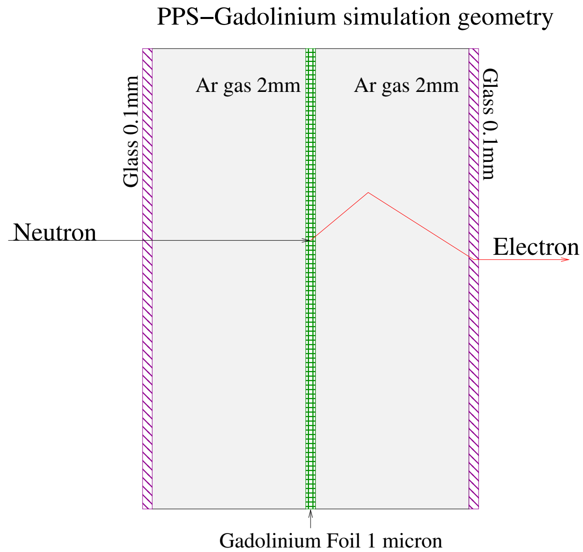

Fig. 4. Schematic of a plasma panel neutron detector. The two gas volumes provide much higher efficiency for detecting the conversion electrons.

III. Gadolinium in a Plasma Panel

Placing Gd in a plasma panel should be straight forward. It would replace the drift electrode in Fig 3, and the source of electrons, rather than being ionization in the gas, is the Gd itself. Since the conversion electrons are emitted in all directions, the preferred geometry would be one like Fig. 4, in which two panels face the same drift electrode.

A minimally thick, yet self-supporting foil of ^{157}Gd is around 1 μm thick. Such a foil has a calculated efficiency for capturing neutrons of 55%. The simulated profile of this capture in the foil is shown in Fig. 5.

As earlier stated, the internal conversion fraction of the ^{158}Gd decay is about 59%, so that this detector model has a maximum efficiency of neutron detection using internal conversion (IC) electrons of 32%. The IC electrons escaping the foil lose energy. The energy spectrum of the IC electrons entering the Ar gas volume is shown in Fig. 6

The simulations of gadolinium in a PPS were done using Geant4, version 4.9.3[9], using the appropriate low energy neutron and gamma physics. The particular geometry modeled in Fig. 4 shows a configuration to capture the electrons emitted in both forward and backward directions, using two gas volumes 2 mm thick. All our example simulations generated neutrons at 25 meV (thermal neu-

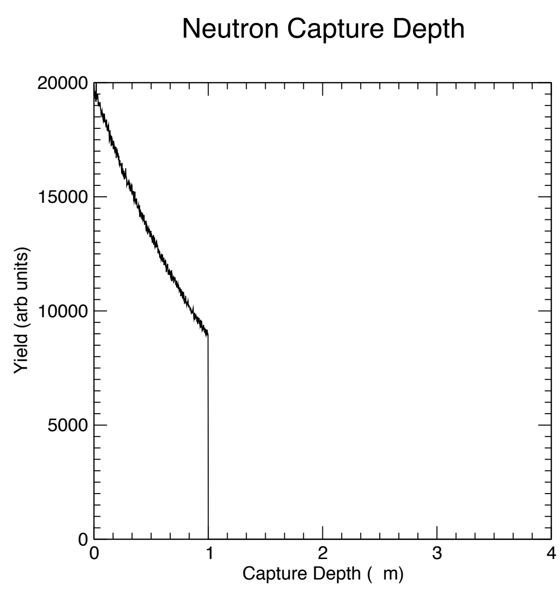

Fig. 5. Capture profile of neutrons in the ^{157}Gd foil.

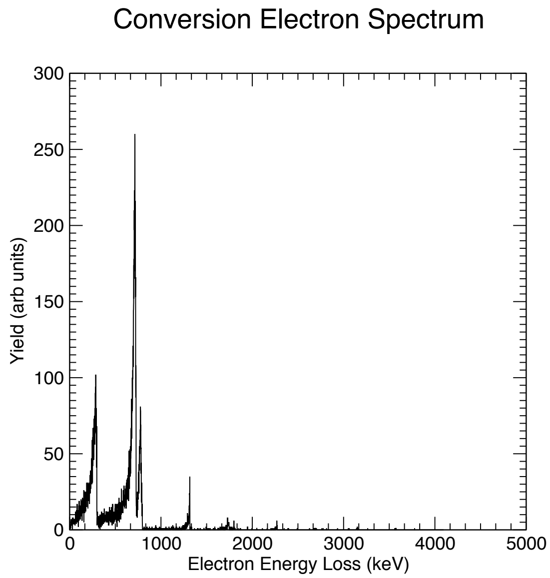

Fig. 6. Energy spectrum of the IC electrons exiting the $1 \mu m$Gd foil.

trons) directed at a 1 μm ^{157}Gd foil embedded in a similar gas volume. The outer layers of glass are the dielectric substrate on which the PPS discharge and detection occur, stimulated by ion-pair production in the gas. To estimate the gamma sensitivity of the system, we simulated the bombardment by ^{137}Cs gamma-rays.

If a Gd foil were to be placed in the sensitive volume of a PPS of 1 mm thickness, the gamma sensitivity would be small. A rough estimate for the gamma sensitivity is to calculate the probability of interaction of a photon with the materials of the detector, shown in Table I. The mass attenuation is from the NIST XCOM database for 0.662 MeV ^{137}Cs gammas.

It would appear that the glass plates defining the volume will create most of the gamma induced background in the detector. After exploring this background, we will discuss potential means to improve it.

Simulations were made for a few geometries. In all cases, the Gd foil was 1 micron thick. The results are summarized in the Table II. The "IC intrinsic electron threshold" is the energy of the low energy peak in the energy loss spectrum. As the gas stopping power increases, the threshold rises, as one would expect. The number of ion pairs produced at threshold are estimated assuming for Ar gas that 26 eV is required to produce an ion pair. The gamma/neutron sensitivity is the ratio of the number of counts in the neutron IC spectrum to the number of electron counts from a similar number of gamma rays.

In Fig. 7 and 8, for each Ar gas thickness there are two plots: one shows the energy loss spectrum of the particles in the Ar gas volume, the other the energy loss versus the initial energy. The red curves show the spectrum resulting from 100 times as many gamma rays incident on the same system. The energy loss versus incident energy spectra demonstrate the origin of some features in the energy loss spectrum and the effect of slightly thicker gas volumes on the different components of the conversion electron spectrum.

From these simulations, we have learned several things. The response of the detector to the conversion electrons varies significantly with thickness, especially for the 29 keV electrons. The 5 mm gas layer stops a significant number of these electrons, as can be seen especially in the energy-loss vs incident electron energy plots. There is not a significant difference in the forward-going to backward-going yields or spectra, as seen in Fig. 9.

The efficiency of detection, of course, depends on the threshold of the PPS, but as can be seen in Table II, column 3, the energy loss threshold is high enough that all incident electrons generate a significant number of ion-pairs. In all the simulations, the number of conversion electrons detected were consistent with the theoretical efficiencies estimated earlier in section I.

The major issue is the insensitivity of the detector to electrons from gamma scattering in the materials of the detector. Table I gives an indication of the problem, in which the glass layer defining the electrode structure has nearly two orders of magnitude more scattering of gammas than any of

TABLE I
EXPECTED PROBABILITY OF GAMMA INTERACTION IN THE DETECTOR MATERIALS

Material	*Thickness (mm)*	*Areal Density* (g/cm^2)	*Mass Attenuation* (cm^2/g)	*Probability*
Gd	0.001	7.89×10^{-4}	0.0871	6.9×10^{-5}
Ar	1	1.78×10^{-4}	0.0701	1.2×10^{-5}
Glass	0.1	2.52×10^{-2}	0.0773	1.9×10^{-3}
Si_3N_4	0.001	3.1×10^{-4}	0.0773	2.4×10^{-5}

TABLE II
RESULTS OF SIMULATIONS OF ^{157}GD IN A PPS DETECTOR.

PPS Depth (mm)	Dielectric type/thick (μm)	IC intrinsic electron threshold (eV)	Ion pairs	Gamma/n sensitivity
1	glass/100.	400	15	5.3 x 10-3
2	glass/100.	900	35	5.7 x 10-3
2	Si_3N_4/1.	900	35	5.5 x 10-4
2	none	900	35	4.5 x 10-4
5	glass/100.	2500	96	6.1 x 10-3
10	Si_3N_4/1.	6000	231	1.4 x 10-3

the other components in the detector. Table II shows the detailed results of simulations with the glass, in which the gamma-neutron detection ratio is around 5×10^{-3}, which is above the Domestic Nuclear Detection Office (DNDO) minimum standard of 1×10^{-4} [10].

It is possible to find insulators that are strong and much thinner than glass, however. One example is Si_3N_4 (silicon nitride) [11], that can be made to a thickness of $1\mu m$, withstand the pressure differential and hold printed traces for the electrodes. Simulations with Si_3N_4 are also shown in Table II, as well as in Fig. 10. Detectors using this thin window material approach the DNDO standard, limited in this case by gamma scattering in the gadolinium foil. To demonstrate this, a simulation was run with no windows, showing that the gamma/neutron sensitivity is nearly the same as with the silicon nitride windows.

IV. CONCLUSIONS

Gadolinium foils can function in a sensitive electron detector as a very efficient, low mass neutron detector. At present, it is difficult for this technology to reach the DNDO goals for field useable neutron counters. Nevertheless, the PPS has some properties which can be exploited in a controlled environment to enhance the effectiveness of gadolinium. First is its excellent timing, with a risetime of around 1 ns. Used with a pulsed beam system, the timing can help to isolate gamma-induced events from neutrons. We can also explore the utility of multiple layers of PPS and gadolinium, to increase the neutron sensitivity and examine any correlations in the energy deposition of the gamma-scattered electrons across multiple layers of PPS. It is possible also that we can adjust the threshold sensitivity of the PPS, in combination with adjustments to the thickness of the gas volume, to enhance the detection of conversion electrons compared to gamma-scattered electrons. Further investigations in this area are important, in light of the ongoing ^{3}He shortage.

ACKNOWLEDGEMENT

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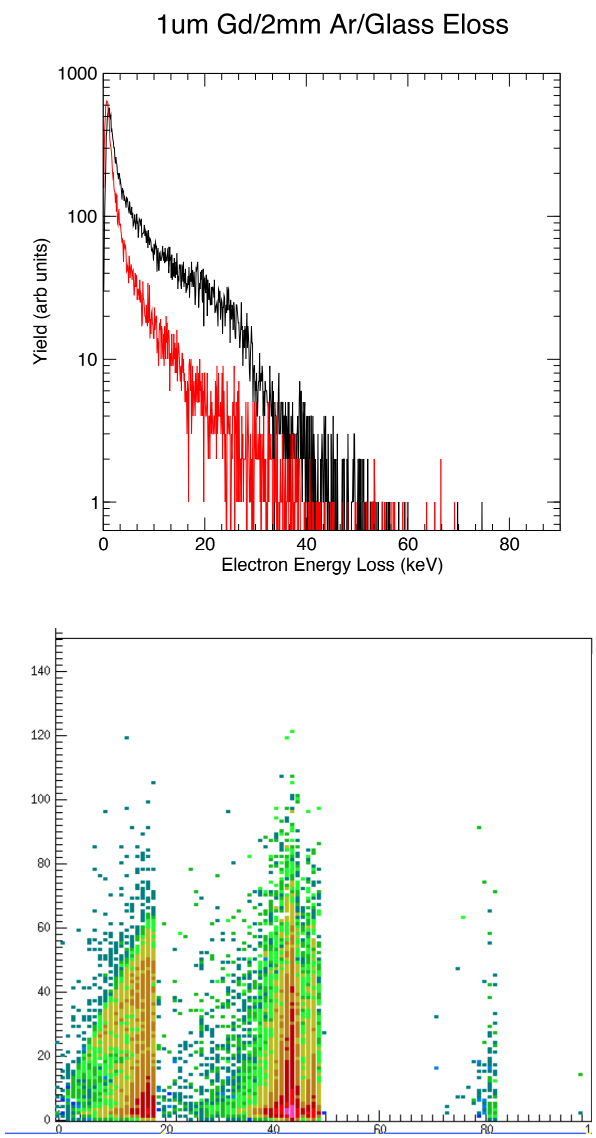

Fig. 7. Simulation of conversion electron energy deposited in 2mm of Ar gas. The red data in the upper plot is the yield of electrons scattered by gamma-rays, scaled up by 100. See the text for more detail.

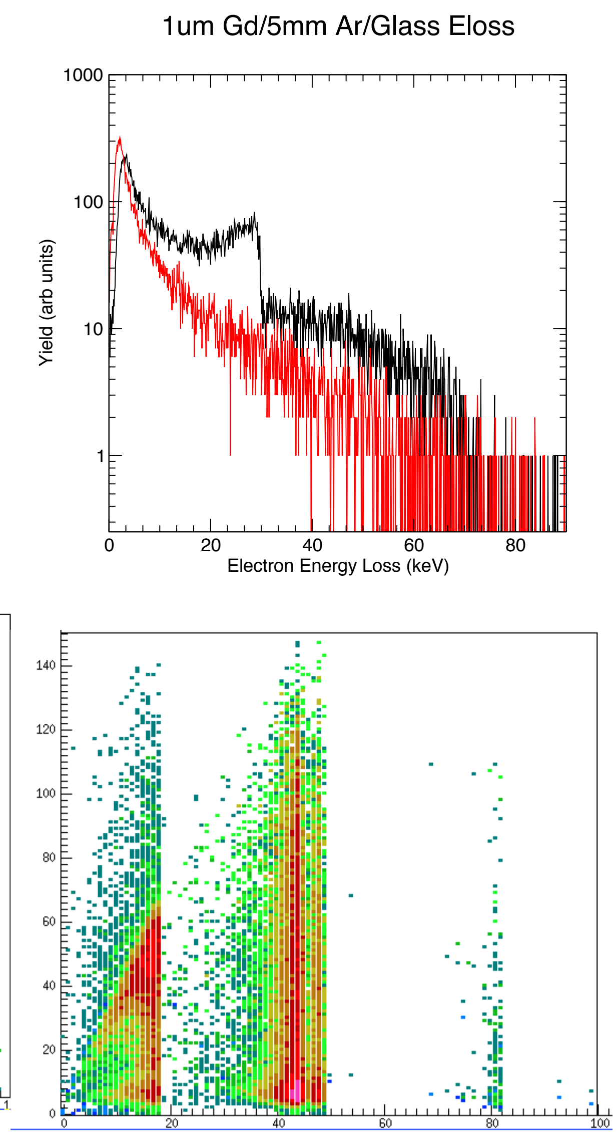

Fig. 8. Simulation of electron energy deposited in 5mm of Ar gas, as in Fig 7.

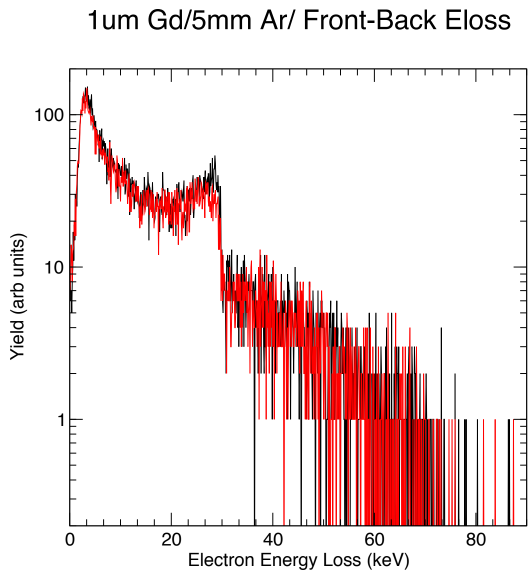

Fig. 9. Comparison of forward-going (black) to backward-going (red) conversion electron energy loss

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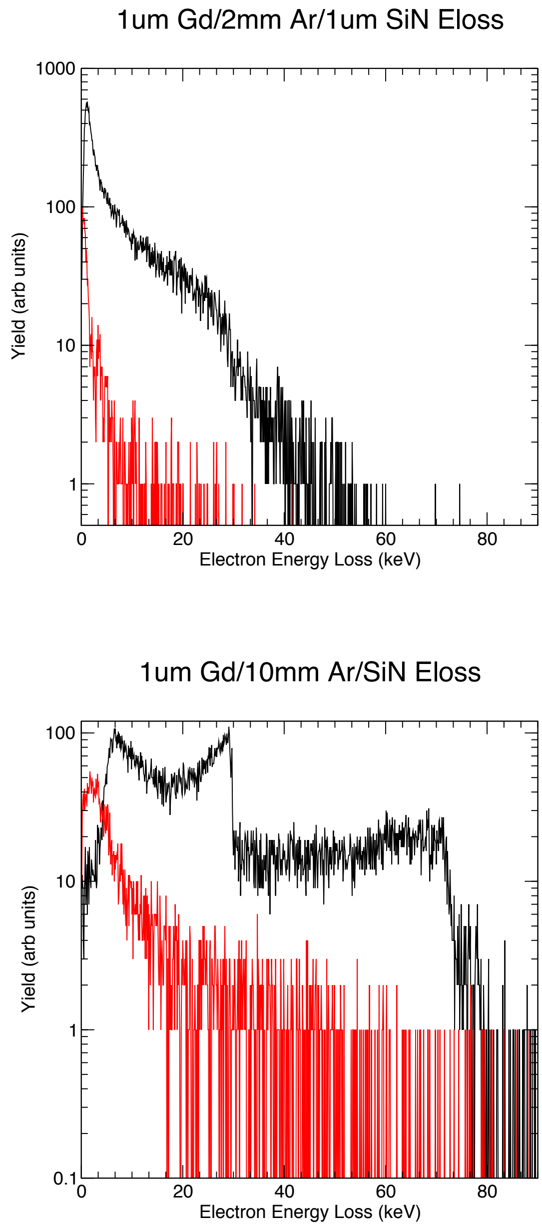

Fig. 10. Simulation of electron energy deposited in the Ar gas of the PPS using Si_3N_4 windows. Upper is with 2mm of Ar gas, lower is 10mm of Ar gas. The red data are as described in Fig. 7.