Analyzing the Sensitivity of a Hard X-Ray Detector Using Monte Carlo Methods

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1. Abstract

An improved sensitivity function was created for the HERIE hard x-ray detector used in direct-drive inertial confinement fusion experiments done on the Omega and Omega-EP laser systems at the Laboratory for Laser Energetics (LLE). In order to infer the spectrum of x rays emitted from the target, data was gathered from the HERIE and HXRD hard x-ray detectors. A sensitivity function was used to infer the slope of the x-ray spectrum from the measured signals. Based on previously calculated sensitivity functions for these detectors, there was a discrepancy between the spectra inferred from the two diagnostics. To better understand this discrepancy, Monte Carlo simulations of the HERIE setup were performed using the GEANT4 framework. Tests were performed on the simulated image plate in order to validate the simulation against published experimental data. Once validated, the detector's sensitivity was calculated at various energy levels and compiled into an improved sensitivity function. Using data derived from the simulation of the detector has significantly reduced the difference between the inferred spectra from the HERIE and HXRD detectors. This will aid in the analysis of future experiments.

2. Introduction

During direct-drive fusion experiments on the Omega and Omega-EP laser systems, hard x rays are emitted from the target as a result of the interaction of the high-intensity laser beams with the target. On the Omega system, the 4-channel HXRD[1] and the 9-channel HERIE[2] detectors are used to measure the hard x rays. Because of their unique geometries, data from each detector needs to be interpreted with a sensitivity function in order to infer the spectrum of the x rays. The expected result is an identical spectrum inferred from both detectors. Currently, a significant discrepancy is observed between the two diagnostics. A Monte Carlo simulation was set up using GEANT4[3] in order to create a more accurate sensitivity function for the HERIE detector.

3. HERIE Physical Setup

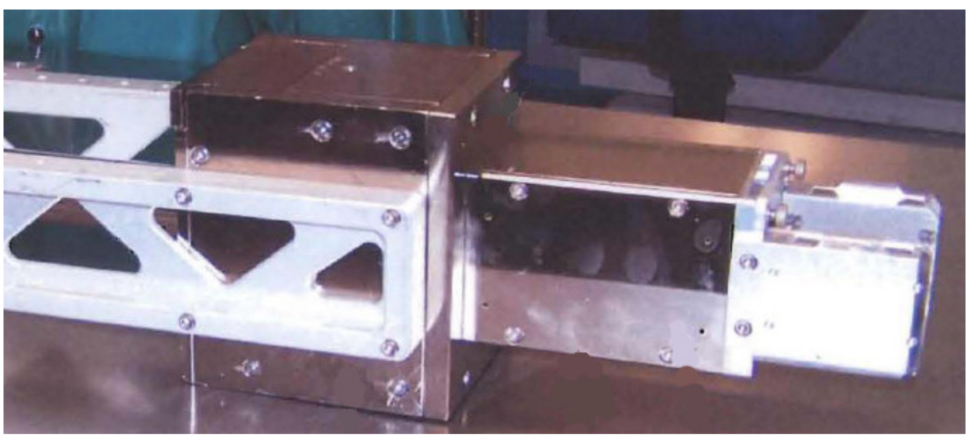

Figure 1. *Physical HERIE hard x ray detector*

The HERIE detector, shown in Figure 1, consists of a lead shell that houses an image plate. Inside this shell, there are three layers made of copper, aluminum, and plastic that help shield the image plate. The image plate itself consists of multiple layers of plastics and a single sensitive layer as listed in Table 1. This sensitive layer absorbs the x ray photons and stores the absorbed energy to be read out later.

Table 1. *Composition of the image plate.*[4]

	Composition	Density (g/cm^3)	Thickness (μm)
Mylar Layer	$C_{10}H_8O_4$	1.64	9
Sensitive Layer	$BaFBr_{0.85}I_{0.15}$:Eu	3.18	124
Back Layer	$C_{10}H_8O_4$	1.4	12
Base Layer	$C_{10}H_8O_4$	1.4	190
Ferromagnetic Layer	MnO, ZnO, Fe_2O_3 + Plastic	3.0	80
Back Protective Layer	$C_{10}H_8O_4$	1.4	25

In front of the lead shell and image plate sits a filter stack that has nine channels. The stack consists of 30 plates of either tungsten, aluminum or copper. Each plate has a different configuration of nine holes, creating nine channels with different thicknesses. This in turn creates nine different regions of sensitivity on the image plate. When the image plate is scanned and the data is retrieved, nine values for deposited energy will be collected for each experiment.

4. Simulation Model

The simulations were carried out in the GEANT4 framework. This was chosen because GEANT4 has historically been used to model the HXRD x-ray detector. GEANT4 has the capability to model the passage of particles through matter and is often used in areas dealing with high energy, medical studies, and nuclear physics.[3] Previous simulations of the detector included only the filter stack and the image plate, but the current model, as seen in Figure 2, includes the full geometry of the detector.

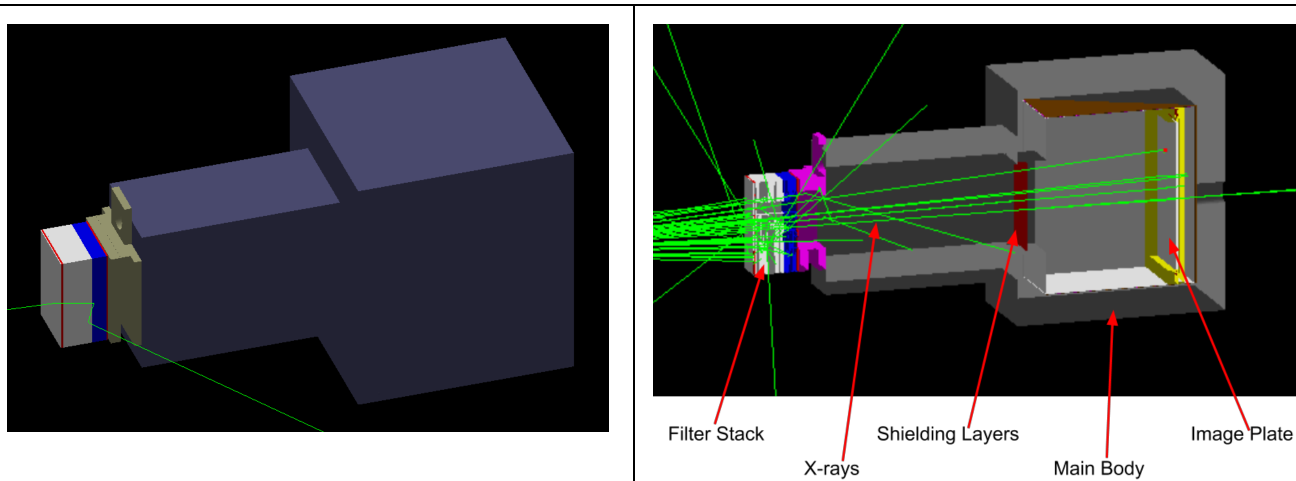

Figure 2. *Visual representation of GEANT4 simulation. The full HERIE detector is seen with a filter stack (left). The cross section (right) has multiple x rays running through it.*

Figure 2 also shows visuals from a simulation with multiple beams running through the detector. Each beam of energy has the possibility of deflecting from, passing through, or being absorbed into each layer of matter it encounters. GEANT4 handles every interaction and ultimately determines how much energy was absorbed in the sensitive layer.

4.1 Validation Using the Image Plate

The simulation model was validated by being used to simulate the image plate before it was incorporated into the full geometry of the detector. This was done by comparing values taken from the simulation with experimental data published by *B. R. Maddox et al.*[4] The first test was of the image plate's absorption, i.e., how much energy is trapped in an isolated image plate. This was done by creating a large second sensitive layer behind the image plate in GEANT4. A known amount of energy would be sent towards the image plate and any energy that was not absorbed would be detected by the second sensitive layer.

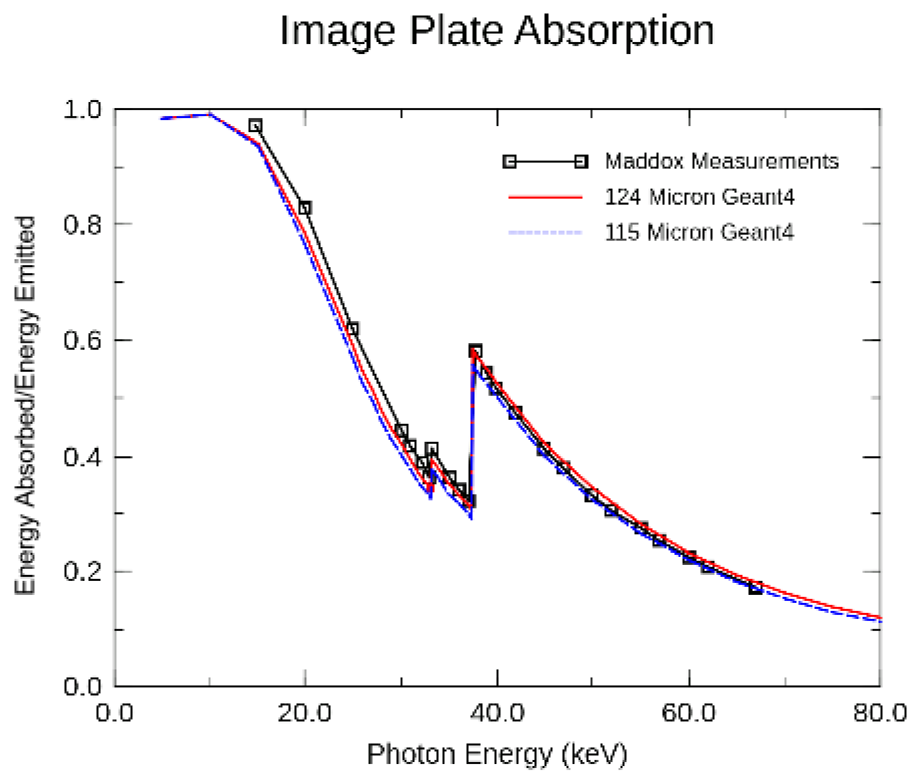

Figure 3. *Graph of absorption functions for the image plate calculated by GEANT4 for image plate thicknesses of 124 and 115 microns. Published data from B. R. Maddox et al[4] are included.*

Figure 3 shows the results of two simulations done in GEANT4 compared to the published data. Like the measurements, the simulated values show sharp increases, known as absorption edges, near energies of 32 keV and 38 keV, which is a characteristic created by the composition of the plate.[4] This implies a good match between the composition of the physical plate and the simulated plate. The two simulations differed only in the thickness of the image plate, since the published values for the thickness vary.

A second test was done to validate the image plate's sensitivity, i.e., the amount of energy absorbed by the image plate alone compared to the amount of energy directed towards it. The second sensitive layer was removed and the energy deposited in the sensitive layer of the image plate was recorded. Published data from the experiment, as well as a model described in *B. R. Maddox et al.,* is compared to the GEANT4 data in Figure 4.The sharp increases in sensitivity correspond to the

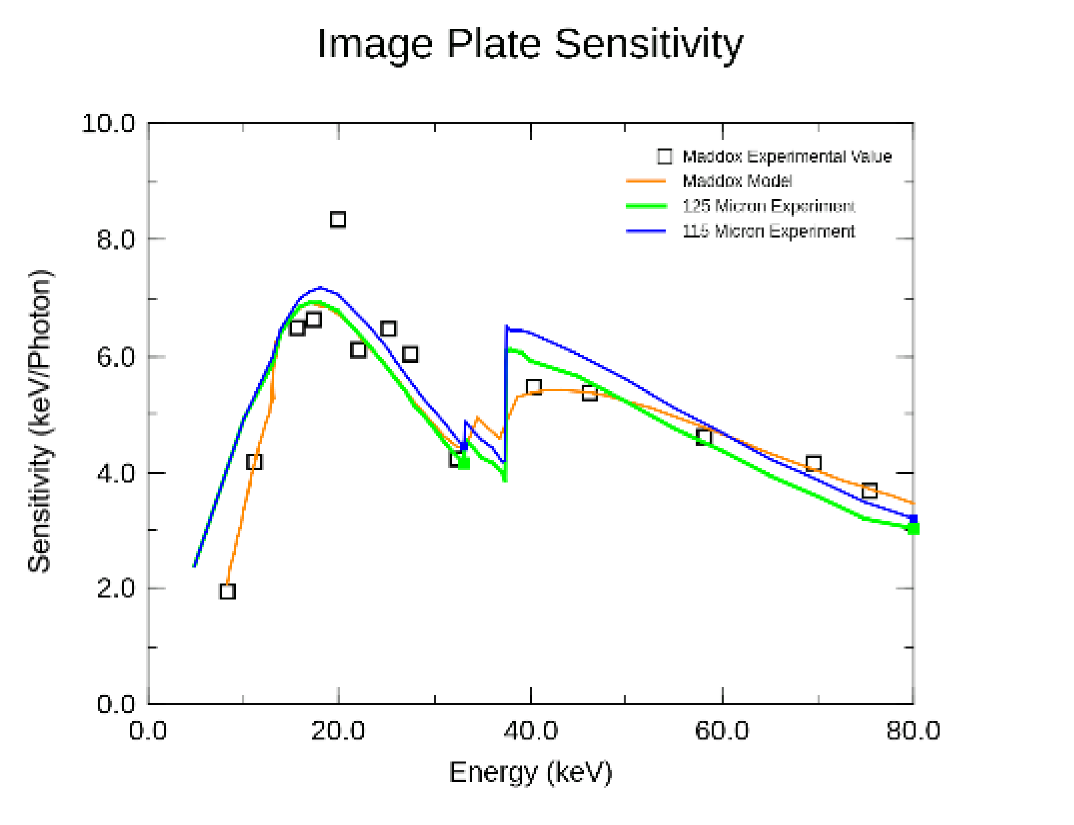

Figure 4. *Graph of sensitivity values for the image plate calculated by GEANT4 for image plate thicknesses of 125 and 115 microns. Published data from B. R. Maddox et al*[4] *are included.*

absorption edges found earlier. The difference between the two thicknesses appears larger in this test, but both are very close to the experimental data. The 125 micron thick plate was chosen for the rest of the simulations.

4.2 Validation Using the Full Geometry

Once the model of the image plate was confirmed to be accurate, the full geometry was added in and the model was tested against experimental data generated at LLE. This data was collected from the emission of a predetermined spectrum of x rays corresponding to typical inferred spectra from experimental HERIE data. This hard x-ray spectrum was used in the GEANT4 model.

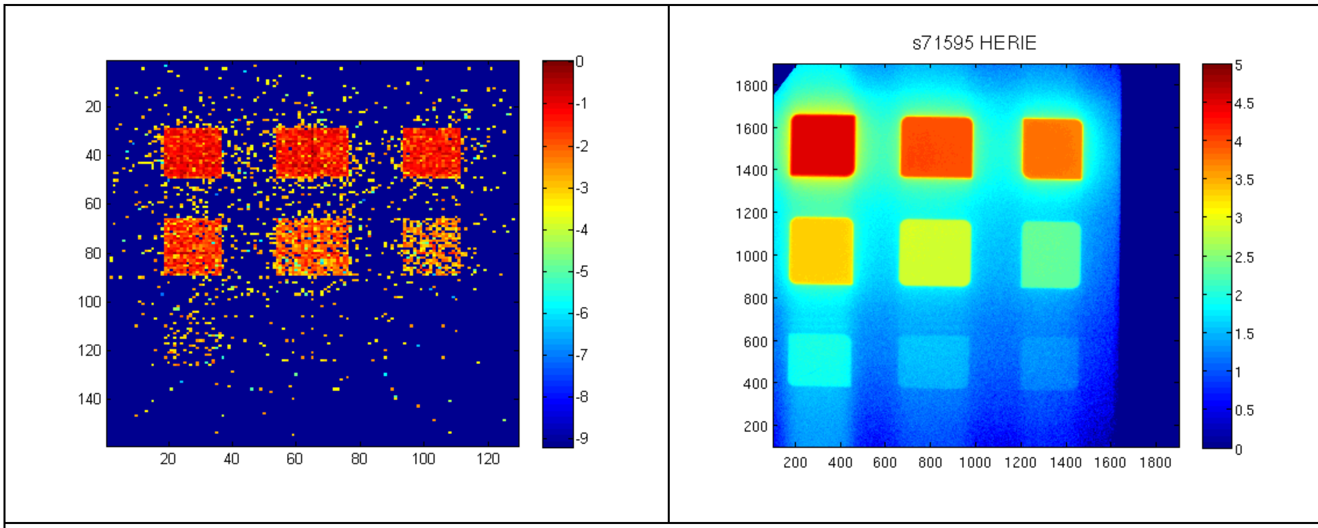

Figure 5. *Visual representation of energy deposited in image plate. GEANT4 simulation (left). LLE experiment (right). The scales are logarithmic to base 10.*

Shown in Figure 5, the simulation produced the same pattern of energy deposition in the image plate as the experiment did. The data collected from GEANT4 was plotted using a much lower spatial resolution compared to the experiment. However, the average values in each channel were compared to each other and the error was found to be small. This indicates that the full geometry properly accounts for the spread and deflection of beams within the detector and can be used to generate accurate sensitivity functions.

5. Creating the Sensitivity Functions

The full geometry was incorporated into the simulation with GEANT4 handling the probability of every interaction between energy and matter. In order to produce a realistic and accurate model of the sensitivity functions for each individual channel, the simulation stepped through small increments of x-ray energy and ran millions of x-ray photons during each step.

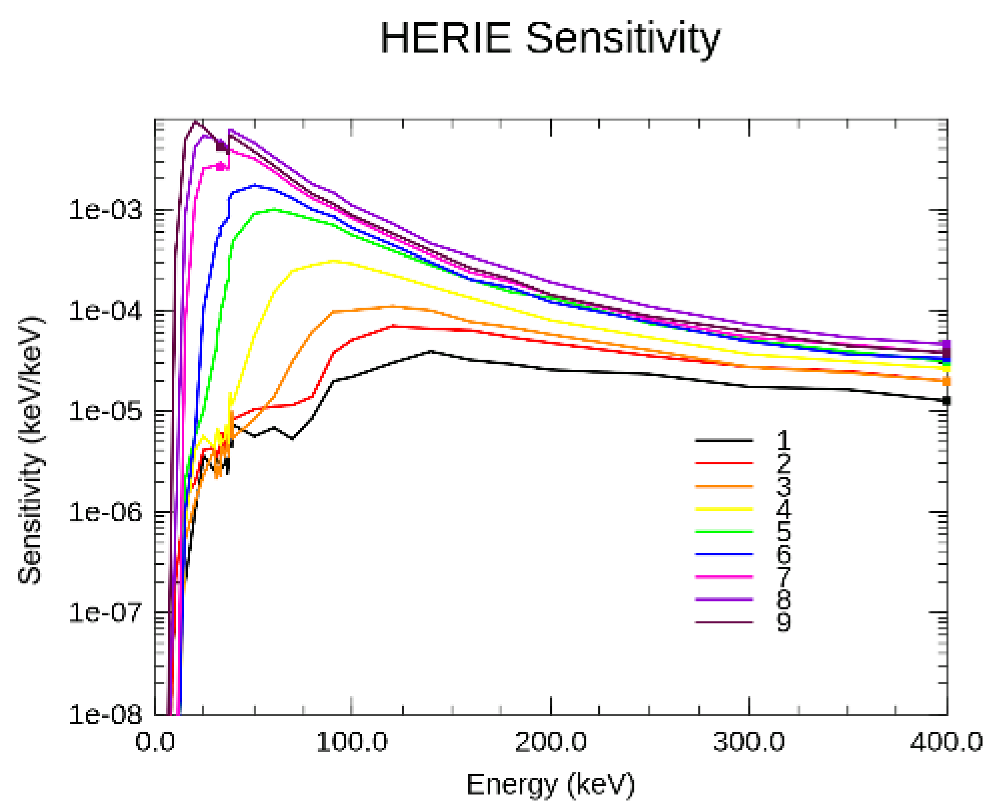

Figure 6. *Sensitivity functions generated by GEANT4 for all 9 channels.*

The combination of the functions shown in Figure 6 with the x-ray spectrum emitted by the target gives the total energy deposited in the image plate, which can compared to the data collected during an experiment. The x-ray spectrum emitted from the target can be approximated by an exponential function of energy

$$I \propto e^{\frac{-E}{kT}}, \tag{1}$$

where *I* is intensity, *E* is x-ray energy, and *kT* is a slope parameter. Summing up the squares of the differences between the measured signals on the different channels and the estimated signals as a function of slope parameter kT generates an error sum, which can drive an optimization procedure. The slope parameter kT that produces the smallest error is determined to be the best representation of the actual x-ray spectrum (see Figure 7).

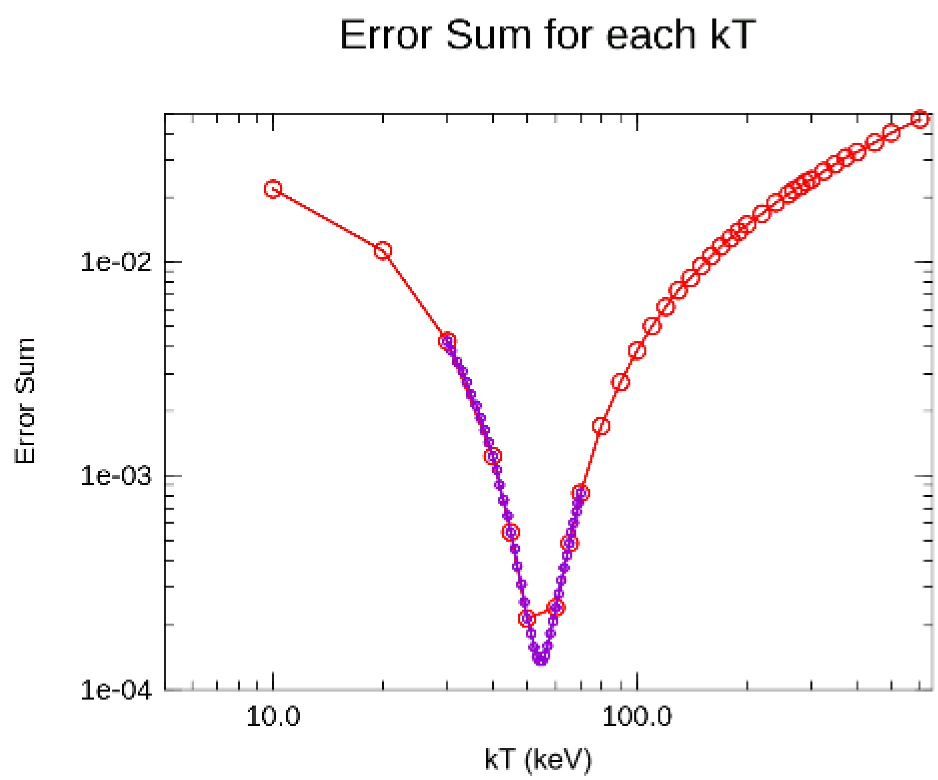

Figure 7. *Error sum for a sample spectrum. The red model uses larger increments as a function of slope parameter kT to guess what the slope parameter kT is while the purple model uses smaller increments around the prediction of the red model to determine kT more precisely.*

6. Results

After the new sensitivity functions were generated, slope parameters were calculated for multiple experiments and compared to slope parameters calculated for the same experiments using the old sensitivity functions (see Figure 8).

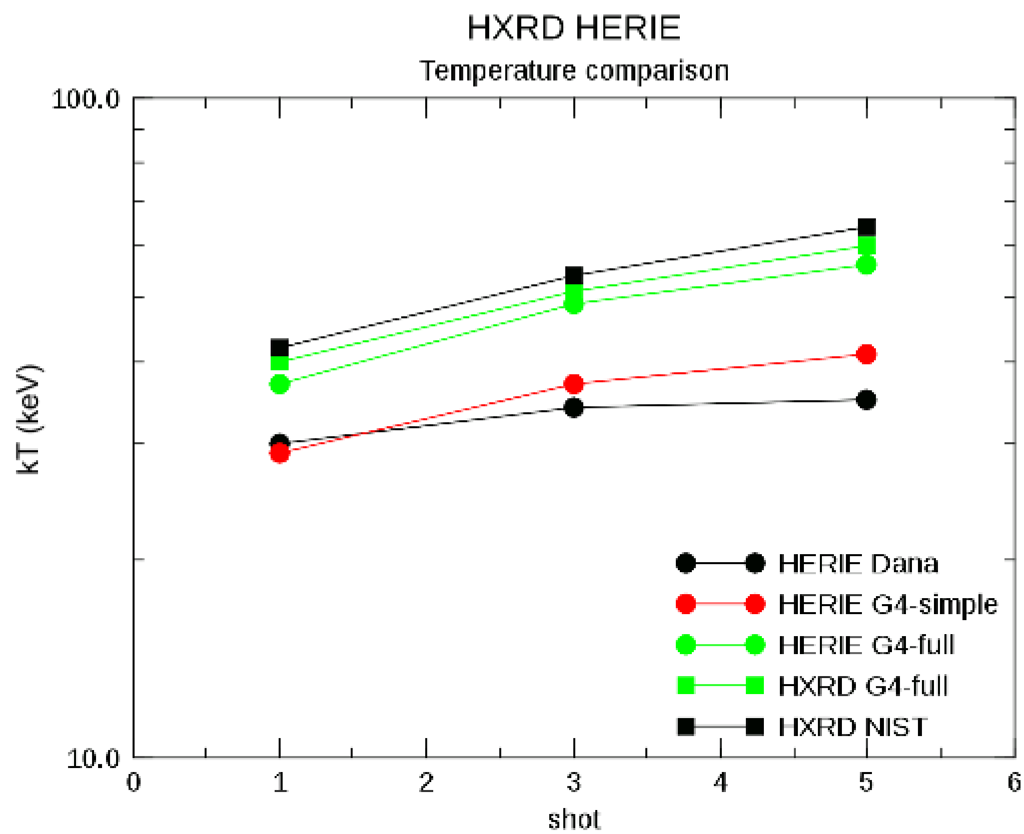

Figure 8. *Comparison of inferred slope parameter (kT) during multiple experiments using different sensitivity functions.*

The two black lines used the original sensitivity functions generated without the use of GEANT4 and demonstrate the discrepancy between the HERIE and HXRD detectors. The red line is produced by the function created by GEANT4 when only the filter stack and image plate are included. It only had a minor effect on the inferred spectra of the HERIE detector. The two green lines are the result of GEANT4 simulations that involve the full geometry. The HXRD simulations were created in parallel but separate from the simulations described by this paper. The adjustment on the HERIE detector appears greater because the HERIE geometry is more complicated and the difference between using the full geometry and the simplified geometry is greater than with the HXRD detector. Using the newly corrected sensitivity functions involving the full geometry (green lines) demonstrates a very close agreement between the detectors.

7. Conclusion

The discrepancy between the HERIE and HXRD hard x ray detectors was significantly reduced by improved sensitivity functions generated through GEANT4 simulations. The Monte Carlo simulations created in the GEANT4 framework accurately modeled the image plate and the full geometry of the HERIE detector. This created a more accurate sensitivity function for each channel that can be used to accurately infer the spectrum of incident x rays. These new sensitivity functions will be used in future experiments on the Omega and Omega-EP system that involve the HERIE detector.

8. Acknowledgements

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9. References

[1] C. Stoeckl et al., "*Hard x ray detectors for OMEGA and NIF*", Review of Scientific Instruments **72**, 1197 (2001)

[2] Dana Edgell, private communication

[3] GEANT4 Applications and User Support, Page last modified 01/09/15, Website

http://geant4.cern.ch/

[4] B. R. Maddox et al., "*High-energy x ray Backlighter Spectrum Measurements Using Calibrated Image Plates*", Review of Scientific Instruments **82**, 023111 (2011).