Gamma single-hit detector for NDSE
Project #: LAO-034-21| Year 1 of 3 (1-year final)

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The use of a single-hit gamma detection system has been proposed by researchers at Los Alamos National Laboratory as a new approach to measuring the time history for Neutron Diagnosed Subcritical Experiments beyond Excalibur. A single-hit system will be relatively smaller and lighter and will not require complex calibrations. The existing current mode detector gives the time history of incident gammas by tracking current vs. time, which requires large volume detectors and digitizing of the entire waveform. A single-hit system tracks the rate of gamma-ray incidence vs. time, which requires small volume detectors and improves time resolution. Because a single-hit system only requires a time stamp for each incident gamma, a much less complex digitizer is required. This detector is potentially small enough to be used in parallel with the existing current mode detector wall for comparative measurements, or it could be used as a free-standing detector in the future.

Background

The concept of a single-hit gamma detector has been used previously to determine time history of mono-energetic neutrons with the Medusa detector at Omega Laser Facility (Knauer 1995). This project will apply a similar technique to determine time history of a Neutron Diagnosed Subcritical Experiment (NDSE) event by detecting fission-spectrum gamma-rays resulting from a quick burst of external neutrons injected onto fissionable material. Because gamma-rays are photons, arrival time at the detector is an accurate measure of time history at the source. The detector will be placed up to 20 meters from the source to allow accurate measurement of the gamma time history before the neutrons arrive contaminating the signal. Due to this distance, a large area detector was believed the only solution.
As the name implies, determining time history from a single-hit gamma detection system relies on only one gamma-ray being detected per time bin in each detector. The time bin is typically defined by the time resolution of the detector. The gamma time history is constructed by creating a histogram of the arrival times of the individual gammas observed by detector arrays. Because single-hit detection requires lower gamma flux to ensure that multiple gammas are not detected simultaneously, the large source-to-detector distance enhances the performance by reducing flux at the detector face.

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Project

In the first year of this project we developed experimental capabilities and design tools with the plan to apply these in the second year towards building a prototype, small single-hit detector array. The Los Alamos Operations (LAO) linac experimental facility was modified to meet the unique needs of this project, and experiments were performed to define limits on detector sizes for use as single-hit detectors. Simulations were developed to understand the X-ray flux from the linac, potential sources of scatter from the linac, and to understand interaction probability and energy deposit in the scintillation detectors.

LAO Linac Facility

The LAO linac is a variable energy electron linear accelerator that includes an injector, beam transport with a sub-harmonic buncher, and an s-band RF accelerator section, as shown in Figure 1. The linac was developed primarily to perform temporal studies on radiation detectors. The injector uses a gridded, thermionic cathode to deliver electron pulses with energies ranging from ~10 to 90 keV. There are two modes of operation of the injector, Short Pulse (SP) and Long Pulse (LP) depending on the needs of the experiment. SP mode as configured gives a fixed pulse width of 1.5 ns at higher accelerating potentials with longer pulses widths as the accelerating potential is reduced. Additionally, the electron pulse can be bunched using the sub-harmonic buncher giving pulse widths ranging from 100ps to 700ps depending on injected beam current and energy. The injected pulse can be used directly for experiments at the injected energy or the pulse can be injected into the RF sections and accelerated. Two s-band RF sections are used for bunching and acceleration. The RF power and phase for the two sections are independently controlled, allowing continuous adjustment of electron energy from ~0.5 MeV to 2.5 MeV. For this project the electron pulse was incident on a tungsten target to give a Bremsstrahlung X-ray spectrum. The time structure of the electron pulse will be imposed on the X-ray pulse giving the ability to study photon response of the detectors. The decision was made to use SP during the first year to characterize detectors and compare to simulations, while LP was expected to be used in the second year to test the ability to reconstruct the time history of an X-ray pulse with variable pulse width and pulse height.

Characterization of detectors using SP requires that the pulse-to-pulse jitter in amplitude is minimized. In this mode the time history of an X-ray pulse is not being measured but each pulse height represents a point on the time history curve. By varying pulse height, the response of a detector to the expected range of pulse heights can be studying by building good statistics at each pulse height. If pulse height jitter is not minimized, instead of building statistics at each selected pulse height each experiment will be spanning a range of pulse heights. When testing of detectors for NDSE applications was first studied, the LAO linac had pulse-to-pulse jitter in excess of 50% due primarily to the failures of the pulse synchronization system and of the phase shifters driving the sub-harmonic buncher. Further, single-hit studies required low X-ray flux which was achieved by reducing the linac beam current. Current was reduced by lowering the injector's accelerating voltage. This also led to the width of the pulse increasing, requiring the use of the sub-harmonic buncher to maintain of pulse width near 1 ns. Other projects shared interest in improving these two sub-systems primarily to attain narrow pulse widths. This project focused on optimizing these sub-systems for pulse height stability.

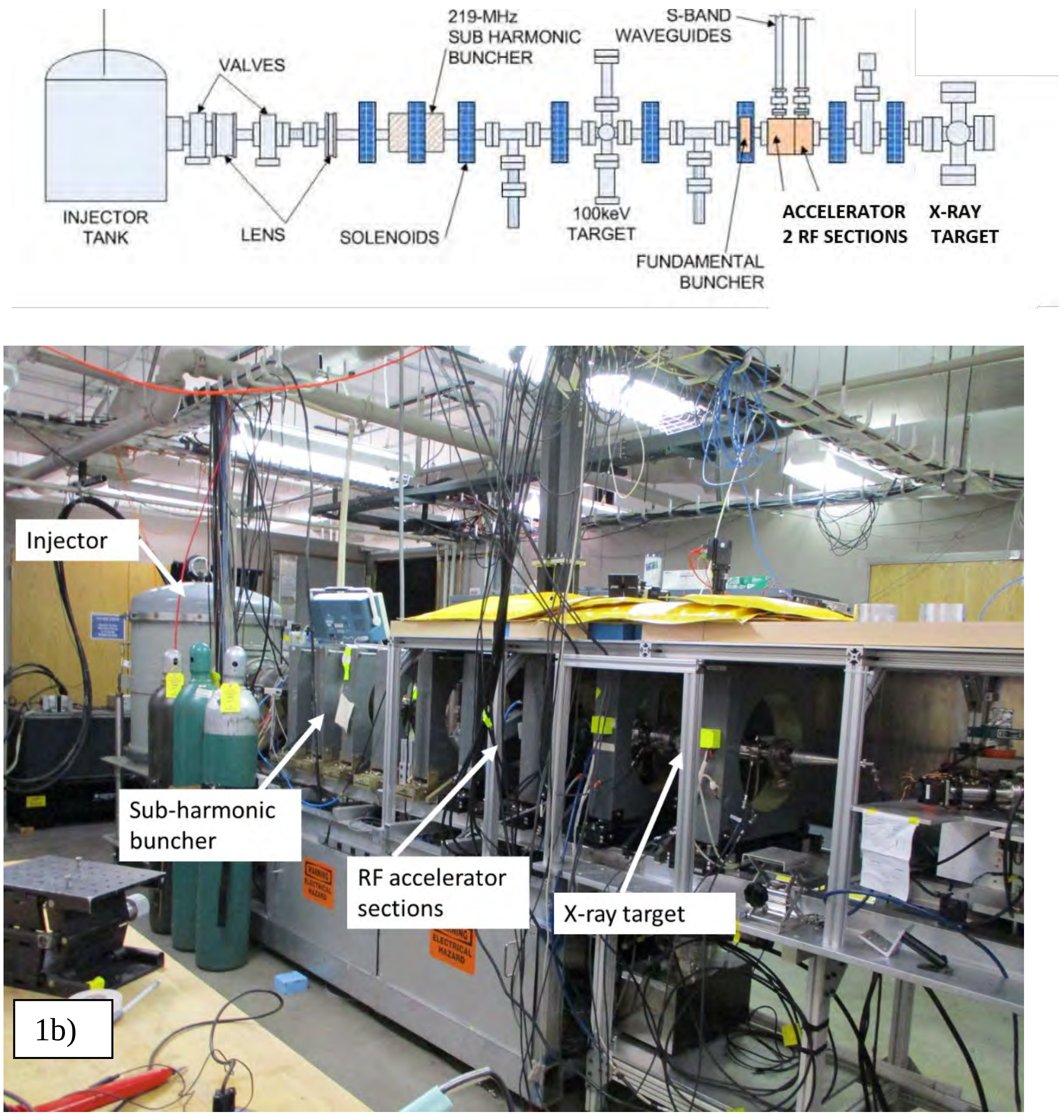

Figure 1. The layout of the LAO linac is shown. 1a) is a diagram showing the relative locations of the injector, sub-harmonic buncher, RF accelerator, and the X-ray target. 1b) shows these locations on a photo of the linac as configured during the experiments.

The pulse synchronization system uses a D flip-flop to synchronize the trigger pulse from a Quantum Composers 9520 pulse generator to the 219.7 MHz that drives the sub-harmonic buncher. The sub-harmonic buncher frequency is the 13th subharmonic of the 2856 MHz RF that drives the accelerating cavities. The phase shift system controls bunching by adjusting the timing of the injected pulse relative to the 219.7 MHz signal and the 2856 MHz signal independently. This ensures that the electron pulse is in the correct phase with the 219.7 MHz signal for optimal bunching, and simultaneously at the correct relative phase with the 2856 MHz for optimal acceleration. The earlier design was replaced with a system built from COTS components as shown in the block diagram (Figure 2). With this system, the pulse-to-pulse amplitude jitter was reduced to approximately 2%. Figure 3 shows a screen capture of 1,000 waveforms in infinite persistence on the Tektronix DPO71604 oscilloscope used to measure jitter. The histogram feature of the oscilloscope was used to measure mean and standard deviation of the amplitude.

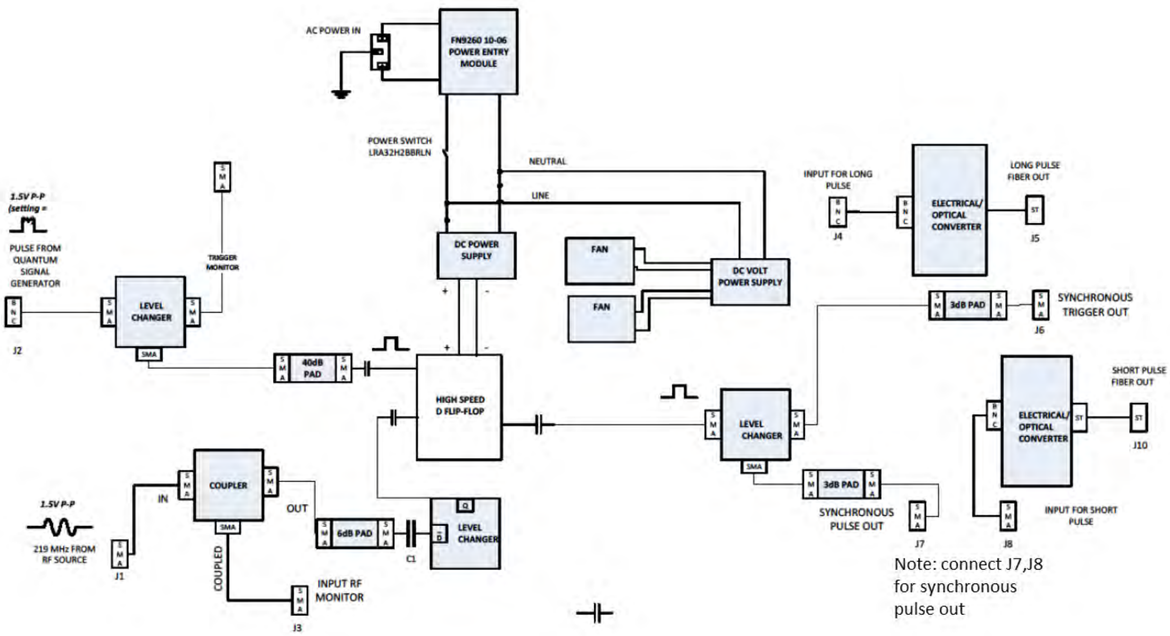

Figure 2. Block diagram of the pulse synchronization system used to synchronize the trigger signal for the electron pulse injector to the 219.7 MHz “clock,” the drive frequency of the sub-harmonic buncher. With this system, a time jitter of ~20 ps is maintained between the injected pulse and the RF drive.

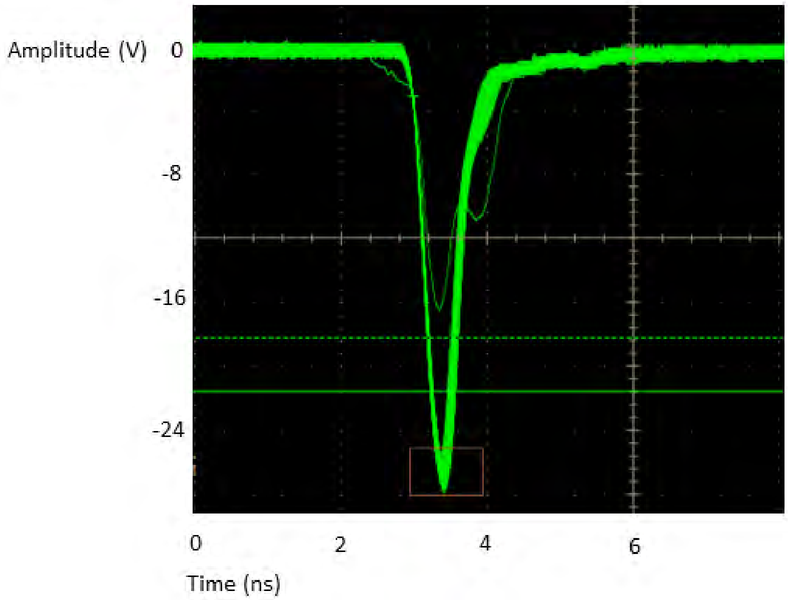

Figure 3. A Tektronix DPO71604 was used to measure amplitude jitter on the upgraded system. The pulse shown was measured on a fast faraday cup at the end of the beamline. Infinite persistence was used to give a visualization of the pulse amplitude jitter. The histogram mode of the DPO71604 was used to measure mean pulse height (26.1 V) and standard deviation (0.53 V) giving a 2% jitter in pulse amplitude over 1,000 waveforms. The anomalous pulse seen is due to occasional pulses not being synchronized. Further refinement of the system is needed to synchronize all of the pulses.

Experiments

The ultimate goal of this project was to determine the time history of the exponentially decaying gamma-ray flux after a fast burst of neutrons is incident on fissionable material (Figure 4). The target time resolution is 5 ns, based primarily on the expected pulse widths of detectors chosen for the preliminary work. When the capability is developed, time resolution can be changed to match new hardware performance. The experiments used to develop this capability are being performed using the LAO linac which, as noted above, has LP and SP capability. In LP mode the linac can produce electron pulses with widths up to several hundred ns, similar to the time range expected to be studied in an NDSE (Figure 4). However, duty cycle limitations imposed for radiation safety create additional challenges when operating at pulse widths greater than 100 ns. A typical long pulse would be a flat top pulse as shown to the left in Figure 5. Pulses with more time structure are possible by selective defocusing of the beam as shown to the right in Figure 5.

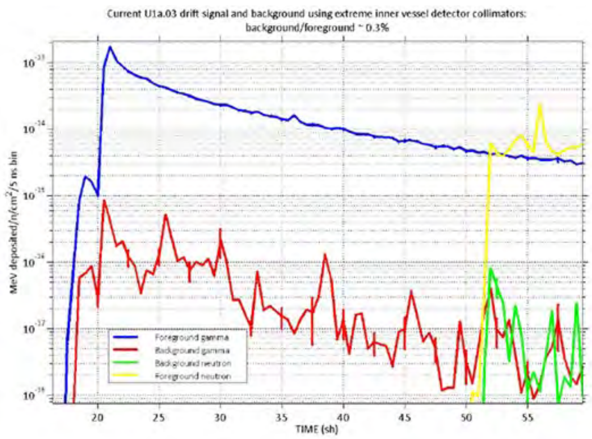

Figure 4. The upper (blue) curve shows simulated time history of fission gamma-rays from material irradiated with a short neutron pulse to illustrate a typical expected pulse shape.

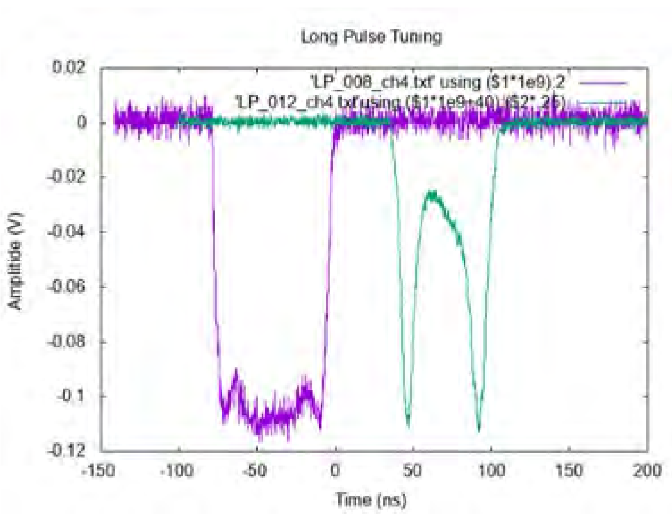

Figure 5. Two LP waveforms from the linac are showed superposed for comparison. The waveform to the left is representative of a flat-top pulse in the 50–100 ns range. The curve to the right was off steered to give an example of more time structure. The flat-top pulse will be useful for basic verification and troubleshooting of single-hit data collection, while the distorted pulse will test the ability to reconstruct an arbitrary shaped waveform.

Early in the project the decision was made to use SP for initial development with the use of LP used later to verify performance of full detector systems after development. In this context SP requires a pulse width less than the time resolution of the system to ensure all energy is deposited in one time bin. A time bin width of 5 ns is typical for this project based on the time response of detectors used in this project This will allow building good statistics at relevant flux levels by pulsing the linac and acquiring waveforms as required for the precision desired. Effectively, at each beam current level the time bin for a particular flux level is being explored. This requires pulse height stability, as discussed above, to assure consecutive linac pulses give statically similar doses to the detector. An additional benefit to the SP approach is that we can emulate an arbitrary number of detector pixels with one detector or a small array of detectors. For example, if 1,000 pulses are acquired and each acquisition saved, this will give statistically equivalent data to having a 1,000-pixel array. By selection of a relevant sample of beam currents, a wide range of array sizes can be studied with minimal initial hardware investment.

The first SP experiments were to explore the feasibility of single-hit detection for a variety of detector sizes. All detectors studied were plastic scintillators coupled to PMTs. Detectors with scintillator volume ranging from 20 cm^3 to 1500 cm^3 were studied with a range of beam currents from 1 mA to 250 mA. Fast frame mode was used on a Tektronix MSO58 (2 GHz) oscilloscope to acquire up to 1,000 waveforms at each beam current setting. The oscilloscope was triggered synchronously with the linac to assure that there was an acquisition for every linac pulse and that the oscilloscope was not triggered by background radiation. The acquired waveforms can be analyzed in parallel with simulations to analyze pulse shapes and determine flux ranges that are viable for single-hit detection. To determine in real-time if the detector was approaching its single-hit regime, the histogram feature of the oscilloscope was used to generate a pulse height spectrum for each data run with the detectors located 2 m from the target. For the 300 cm^3 detector, no evidence of single-hit mode was seen down to a 1 mA beam current. If lower fluxes are required, new tuning techniques will need to be developed, smaller Bremsstrahlung targets will need to be used, or larger beam-detector distances will be needed.

For the lower volume detectors, evidence of single-hit detection was seen at low beam currents. In single-hit mode it is expected that statistically all events can be categorized as either a hit (non-zero amplitude) or a no-hit (zero amplitude). We expect this to be clearly visible on the histogram with the no-hit bin showing more counts as current is decreased. Figure 6 shows three representative beam currents with a 100 cm^3 detector. At 11 mA beam current, no zero-amplitude events are detected indicating more than one X-ray is incident in each acquisition. At 2.4 mA, a gap is clearly seen between the zero-amplitude bin and the non-zero events, indicating single-hit X-ray detection is being observed. The zero-amplitude events increase relative to the hits at 1.7 mA, as expected.

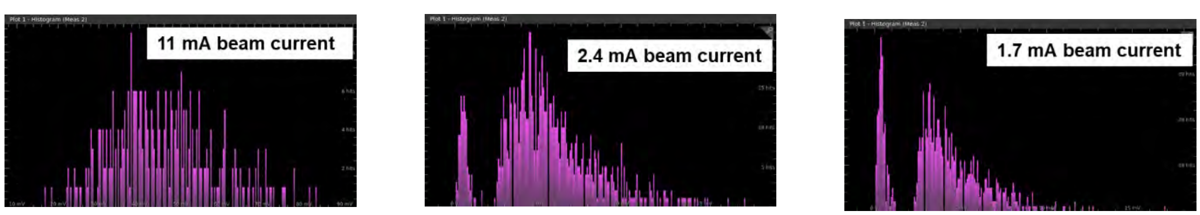

Figure 6. For representative beam currents the histogram shows no zero amplitude hits for 11 mA, the onset of zero amplitude hits at 2.4 mA, and increasing zero amplitude hits as the beam current is reduced to 1.7 mA. Having increasing zero amplitude hits is an indication that the detector is in single-hit mode. The detector has a scintillator volume of 100 cm^3 and was 2 m from the x-ray target These beam currents are within the range of expected fluxes on the detector based on tests performed previously on early Excalibur detectors.

With lower beam currents the zero-amplitude peak is well defined, while there is no distinct peak for the non-zero events. This is expected because at these energies the photopeak cross section is low and the Compton continuum is expected to dominate the spectrum. Additionally, when the electrons are incident on the tungsten target a Bremsstrahlung spectrum of X-rays is produced. Understanding the spectrum of the non-zero events is critical to verifying that the interactions are due to single-hit interactions. The continuum seen in the non-zero event spectrum could also be due to multiple X-rays being incident on the detector simultaneously (pile-up) which will introduce error into a time history constructed assuming single-hit events only. To understand the importance of multiple-hits, simulations will be developed for comparison with the experimental results.

Simulations

Simulations using GEANT4 and MCNP were developed to assist in the analysis of the experimental data. MCNP was used primarily to show the Bremsstrahlung spectrum expected when 2 MeV electrons are incident on the tungsten target as shown in Figure 7b. MCNP simulations were also used to identify possible sources of background noise such as electron directly scattered off of the tungsten target and X-rays that were scattering off of structures in the linac (primarily focusing magnets) and walls of the lab as shown in Figure 7a. Scattered X-rays would arrive later potentially distorting the measured time spectrum. Additionally, MCNP was used to predict energy deposit in the detector volume.

Simulations were performed using GEANT4 to understand the interactions of the incident photons with the detectors at the energies of interest. Figure 8 shows the relative number of interacting and non-interacting events as a function of energy for a 300 cm^3 detector where an event is defined as a photon incident on the detector. The energy spectrum used for these simulations was a fission spectrum similar to that expected for an NDSE event. Modifications to these simulations are needed to compare the simulations directly with the experimental data shown above. The simulations need to be modified to use the 2 MeV Bremsstrahlung spectrum, the flux needs to be scaled to the beam current, and the detector size needs to be adjusted. Further, when a photon interacted all electrons in the detector were saved. These electrons need to be tracked through the detector to give a pulse height spectrum. These are straightforward modifications that will allow direct comparison of experimental results to simulations and give a better understanding of whether single-hit or multiple-hit events are responsible for the shape of the experimental pulse height spectra shown above. These comparisons were planned for the second year of the project.

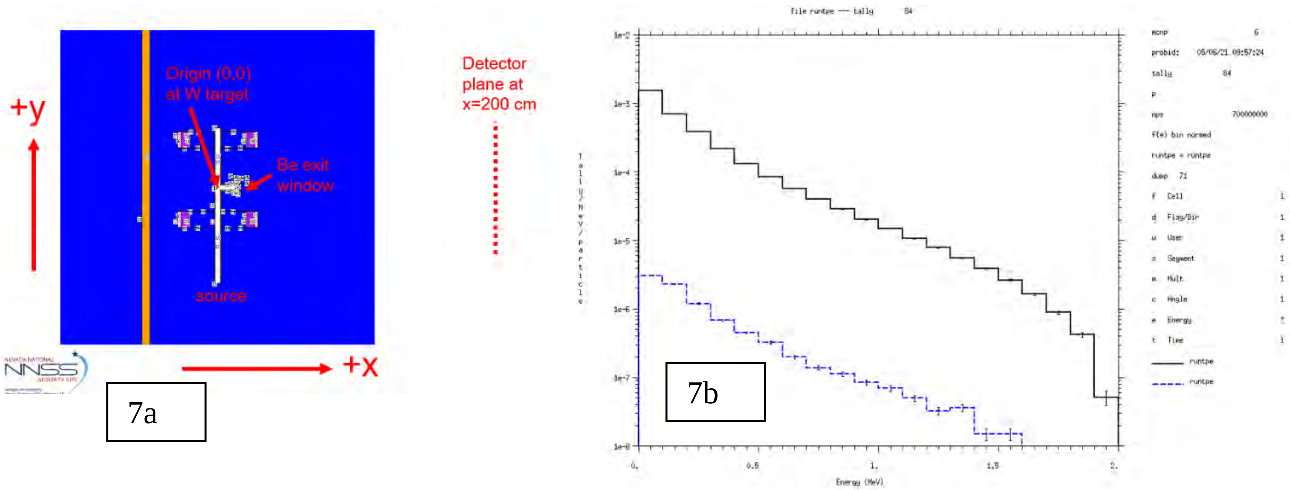

Figure 7. 7a) The linac system, including beam line, target, and windows, was modeled in MCNP. Relevant structures such as concrete walls and large magnets were also included to assess scattering. 7b) MCNP simulation showing X-ray flux with 2 MeV electrons incident on the tungsten target. The upper curve shows the flux directly outside of the X-ray window and the lower shows the flux at the face of the detector 2 m from the window.

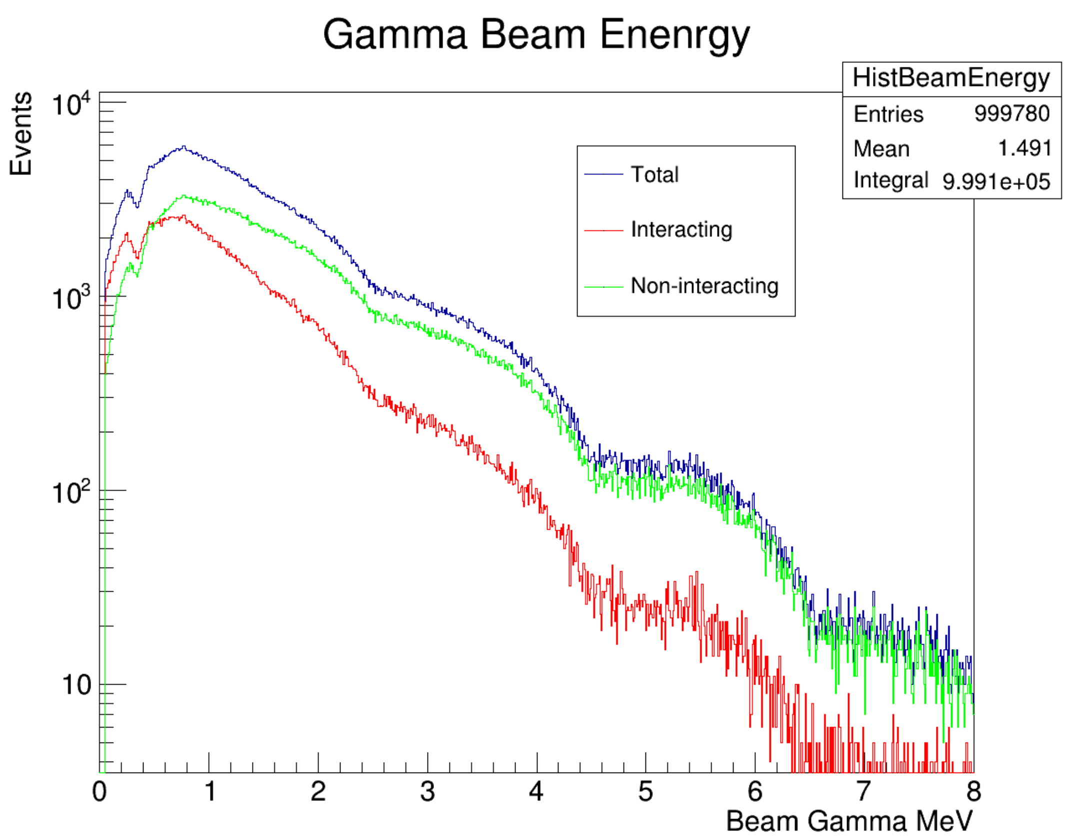

Figure 8. GEANT4 simulations comparing interacting to non-interacting events for photons incident on the 300 cm^3 detector. This is shown for a fission energy spectrum.

Conclusion

In year one of this project the linac facility was modified to provide the stable electron pulses required for single-hit experiments. Data were taken on a range of detector sizes and evidence of single-hit events was seen at lower beam currents. Based on previous work with Excalibur detectors developed for NDSE events, the single-hit events occur within the expected range of photon flux for NDSE. Simulations were developed to understand the experimental flux and to predict detector response. Plans were made to modify the simulations in year two to give a direct comparison of experimental and simulated pulse height spectra for the Bremsstrahlung spectrum of the linac. This would allow development of the design of a small array of detectors for testing.

The project's funding was not continued beyond the first year, so the tools developed are not expected to be directly applied to NDSE measurements. However, collaborators at LANL are considering developing the techniques for measurements in inertial confinement fusion research. The team is planning on submitting a publication to Review of Scientific Instruments and a poster presentation to the APS Division of Plasma Physics.

References

Knauer, J.P., R.L. Kremens, M.A. Russotto, and S. Tudman. 1995 "Using cosmic rays to monitor large scintillator arrays" *Rev. Sci. Instrum*. **66** (1): 926.