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CHELSI : recent developments in the design and performance of a high-energy neutron dose meter

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Abstract

The intrinsic pulse shape discrimination properties of CsI(Tl) form the basis of a high-energy neutron (>20MeV) spectrometer (CHELSI) currently being developed at LANL that shows promise in satisfying the requirements of an ideal survey meter; lightweight, portable and real time display of dose.

Charged particle spallation products generated in the scintillator via neutron interactions are identified on the basis of pulse shape using digital pulse processing. Conservative estimates of dose rate can be given in real time based on count rates and pulse height distributions. More accurate dose measurements can be done off-line using unfolding methods to analyze stored pulse shape versus energy data.

As a precursor to the development of a portable instrument, data has been obtained using a 1”x1” CsI-based probe and a digital spectrometer. This system has been used to collect data on the 90-meter flight path at the LANSCE/WNR facility at average neutron energy of 335 MeV. The spectrometer has the capability, in addition to storing individual waveforms for off-line analysis, to record time-of-flight data and calculate a pulse shape parameter and pulse height for every scintillation event. Combining this data with traditional multichannel analyzer data has yielded a set of empirical response functions. Analysis of the charged particle spectra has shown that at in this neutron field an average count rate of 1.1 cps per mrem/hr is obtained for a 1”x1” CsI(Tl) scintillator.

Data recorded using monoenergetic protons from 30 to 75MeV has been used to further characterize scintillator performance.

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1. Introduction

With the recent interest in the design and construction of spallation neutron sources for such applications as the transmutation of nuclear waste, an examination of the current state of radiation protection regarding high-energy neutrons is prudent. Existing methods of area monitoring or surveying such as rem meters, foil activation-based methods or Bonner Spheres are not completely satisfactory for a variety of reasons. The ideal instrument should be lightweight, portable and give a real time indication of dose rate.

A program to develop such an instrument is underway at LANL [1]. Nicknamed CHELSI, the instrument is based on the well-known pulse shape discrimination properties of CsI(Tl) [2-5]. Incident neutrons above 10MeV produce charged particle spallation products that cause light emission in the scintillator as they slow down. These waveforms will be analyzed for pulse shape and pulse height in real time using a digital pulse processing.

Conservative estimates of dose rate can be given during field measurements solely on the basis of charged particle count rate and a rudimentary knowledge of charged particle pulse height distribution. For areas with elevated readings, better estimation of neutron fluence and dose can be gained by off-line deconvolution of the stored charged particle data. This approach requires that the scintillator energy response be well known. To this end, time-of-flight (ToF) data has been collected at the LANSCE/WNR facility. These measurements were also an opportunity to evaluate and compare on line pulse shape discrimination algorithms with off-line analysis of stored waveforms.

Monoenergetic proton data collected at the Northeast Proton Therapy Center has been used to further characterize CsI response.

2. Facility description

2.1. Northeast Proton Therapy Center (NPTC)

The Northeast Proton Therapy Center is located on the campus of the Massachusetts General Hospital in Boston MA. Designed around a 230MeV isochronous cyclotron, the facility is primarily dedicated to cancer patient therapy but grants experimenter access on weekends.

The Energy Selection System (ESS) [6] was used to set the primary beam energy to 108 MeV. This beam was degraded using a combination of plexiglass and lucite filters in the experiment room to generate beams of 30, 51, 60 and 75 MeV incident on the front face of the scintillator housing. Beam energies were calculated using the TRIM code[7] and later verified using MCNPX[8].

2.2. Los Alamos Neutron Science Center (LANSCE)

The irradiations at LANSCE were done on the 90m flight path at the Weapons Neutron Research (WNR) facility. This flight path, located at an angle of 15 degrees relative to the spallation target, is the longest beam line at LANSCE. Shielding (copper, lead and polyethylene) was inserted in the beam path to both harden the spectrum and reduce the neutron and gamma fluence at the detector location. In addition, stainless steel collimators were placed at the beam exit port to further limit fluence.

The beam time structure consisted of 590μs-long macro pulses emitted at a repetition rate of 100Hz. Each macro pulse consisted of a train of micro pulses separated by 1.8μs. Average beam current was about 3.2 μA.

3. Experimental details

The detector was based on a 1”x1” CsI(Tl) scintillator coupled to a Hamamatsu R6095 PMT as described previously [1]. The anode signal was fed to a current to voltage converter to preserve signal shape. This signal was processed using a Polaris™

digital spectrometer, controlled by a host laptop computer via a USB interface, operated in either of two basic modes.

The first mode was as a traditional multichannel analyzer. Typically 64K channels were used to obtain satisfactory resolution of the low energy gamma calibration lines. Calibration was done using low energy gamma sources (^{152}Eu, ^{60}Co and ^{137}Cs) and the 4.43MeV ^{12}C gamma ray. At NPTC, this gamma was generated by passing the proton beam through a thick lucite block and observing the beam at right angles to minimize the proton signal. At LANSCE, a PuBe neutron source provided the 4.43MeV gamma.

In the second mode of operation (list mode), individual waveforms were captured and stored for later pulse shape analysis off line. Each waveform was also analyzed on line for pulse shape and pulse height. In addition, ToF data was obtained which was stored with the waveform data along with the results of the on line analysis of shape and energy. The start signal for the ToF was the scintillation event while the stop signal was the next micro pulse. A TTL pulse, derived from the master micro pulse timer, was fed into the sync input of the Polaris spectrometer to provide the stop signal. Timing resolution was limited to 25ns as a consequence of the 40MHz clock speed of the spectrometer permitting only crude resolution (ΔE~150MeV) of the highest energy neutrons.

ToF-tagged ^{238}U fission chamber [9] data was collected simultaneously to yield beam fluence from which incident dose rates were calculated [10].

To bridge the large discrepancy in the fission chamber efficiency and that of the CsI scintillator, a SWENDI rem meter [11] was employed as a beam monitor. Positioned about 1.5m directly behind the CsI probe, SWENDI was calibrated (net counts per fission event) for each shielding configuration through a long run against the fission chamber. The delivered fluence during the relatively short scintillator runs could then be determined from the SWENDI counts.

4. Results

4.1. Monoenergetic proton data

Figure 1 shows the proton spectra recorded by the 1"x1" CsI(Tl)-based spectroscopy system. The indicated proton energies (E_p) are based on MCNPX calculations. Beam energies based on the gamma calibration were within ±5% of the MCNPX values except at 30MeV where the gamma-based result was about 20% lower. This was likely due to the relative sensitivity of the MCNPX calculation at this energy to uncertainties in material composition and thickness.

The FWHM at 75 MeV was found to be 2.5MeV on the assumption that the intrinsic resolution of the scintillator and the width of the proton beam added in quadrature.

4.2. WNR data

Analysis of the ^{238}U fission chamber data with 10cm of copper, 20cm of polyethylene and 10cm of lead in the beam line yielded the spectrum shown in Figure 2. All the data discussed below were taken with this shielding configuration.

The average beam fluence was calculated as 2.9×10^3 n cm^{-2} s^{-1} with a corresponding average H*(10) dose rate of 0.30 rem/hr [10]. A fluence-weighted mean energy of 335 MeV was calculated.

An overnight run with the fission chamber established a counting efficiency of 5.9×10^4 n cm^{-2} per fission event. Under the same experimental conditions, SWENDI accumulated 3.5×10^3 counts per fission event. Therefore, for short runs, the incident fluence was calculated from the SWENDI data using a conversion factor of 17 n cm^{-2} per count.

Figure 3 shows the pulse shape versus pulse height plot determined from an off-line analysis of 50000 waveforms recorded in list mode. A pulse identification index (PID) was calculated by dividing the signal integrated over a fast timing window by the total pulse energy so high PID values correspond to fast pulses. Optimum pulse shape discrimination was obtained by setting the fast timing window to 1.2μs in length.

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The dark band in Figure 3 with PID values near 0.5 is due to the relatively slow gamma signals. Lying above the gammas are two bands due to protons and deuterons respectively.

Figure 4 shows the PID vs energy (PID_E) plot for those events, based on ToF data, initiated by neutrons between 100 and 130 MeV. At these neutron energies the gamma, proton and deuteron bands are much more evident than in Figure 3. This is because as neutron energy increases, the probability of two or more charged particles being released simultaneously also increases. When these multi-particle events occur, the resultant pulse shape has a composite PID value (and energy) and will tend to fill the gaps between the single particle bands as demonstrated in Figure 3.

The on-line pulse discrimination results were not as impressive as the off line results. For example, the proton and gamma bands merged at pulse energies above 50MeVee. In the on line analysis, the signal is differentiated and a discriminator used to infer the time reference for the PID calculation. Jitter in this timing signal is manifested as a broadening of the PID result, an effect that is increasingly apparent with increasing pulse energy. Improvements to the on line analysis firmware are planned to improve performance.

The pulse height spectra shown in Figure 5 compare the spectrum recorded in MCA mode with that derived from an analysis of the waveform data (*i.e.* projecting the PID vs energy data onto the energy axis).

In MCA mode, an average input count rate of about 700 cps was measured at a threshold of 800keV. In the charged particle region of the spectrum, the combined count rate was 250 cps. This translates to a total charged particle count rate of 0.09 cps per unit fluence rate and 1.1 cps per mrem/hr for a 1”x1” CsI scintillator in the neutron field shown in Figure 2.

The upper range of the spectrum shown in Figure 5 is truncated due to signal saturation. When operated at lower gain, the spectrum extended as far as 250MeVee. This upper limit is far in excess of the amount of light that can be produced by a single proton (about 90MeVee for a 1”x1” CsI scintillator) and can only be explained by the combined light emission from multi-particle spallation events.

5. Discussion

The MCA and list mode data recorded under identical conditions can be combined to yield charged particle count rates as a function of neutron energy. List mode data gives the relative contributions to the MCA spectrum for any region of the PID_E plot. Normalizing this data to the dead time-corrected MCA spectrum (as shown in Figure 5) and to the fission chamber data allows the calculation of counting efficiency for any subsection of the PID vs energy plot per unit fluence or dose as a function of neutron energy. These response functions can then be used to unfold any PID_E plot to reveal the incident neutron spectrum. At low neutron energies (<150 MeV), the PID_E plot subsections could coincide with the charged particle bands. But with the increasing diffuseness of the PID_E plot at higher energies, a better approach might be to subdivide the charged particle region of into several rectangular zones. This approach has the advantage that it uses all the available charged particle data not just those events lying within the single particle bands. In addition, it makes less stringent demands on the degree of particle discrimination as it requires only a separation of gamma from charged particle events.

A prototype portable instrument based on a 2”x2” CsI(Tl) scintillator for improved detection efficiency is being assembled for evaluation. The probe includes a low power bias supply, rechargeable batteries and a μDXP™ card loaded with the firmware for real time shape and energy pulse analysis. This data, along with input and output count rate information, will be transmitted via a RS232 interface to a notebook PC or PDA for a conservative estimation and display of dose rate.

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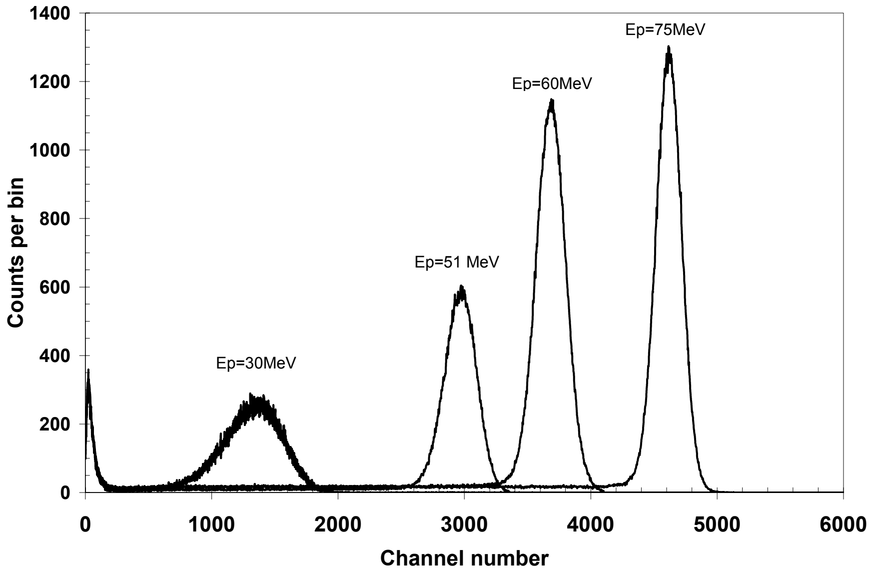


Figure 1. Monoenergetic proton spectra recorded by 1"x1" CsI(Tl)-based spectrometer.

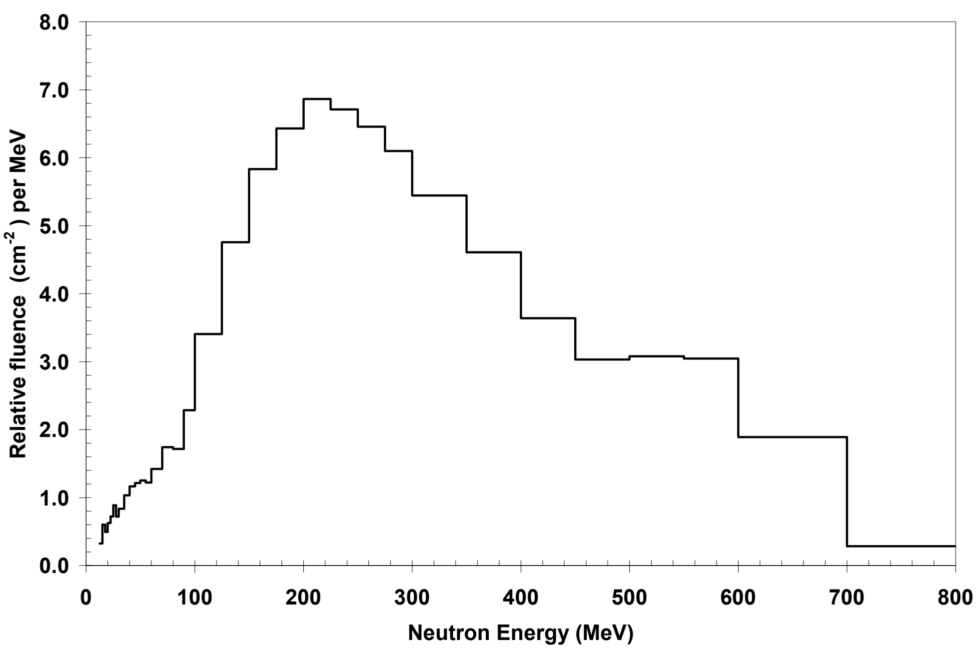
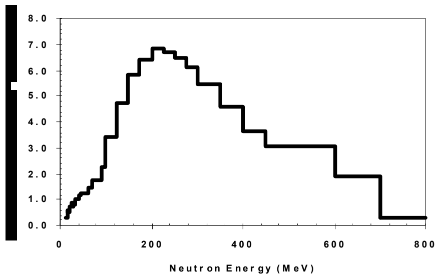


Figure 2. Neutron spectrum on 90m-flight path as measured by fission chamber with 10cm of copper, 20cm of polyethylene and 20 cm of lead in beam line



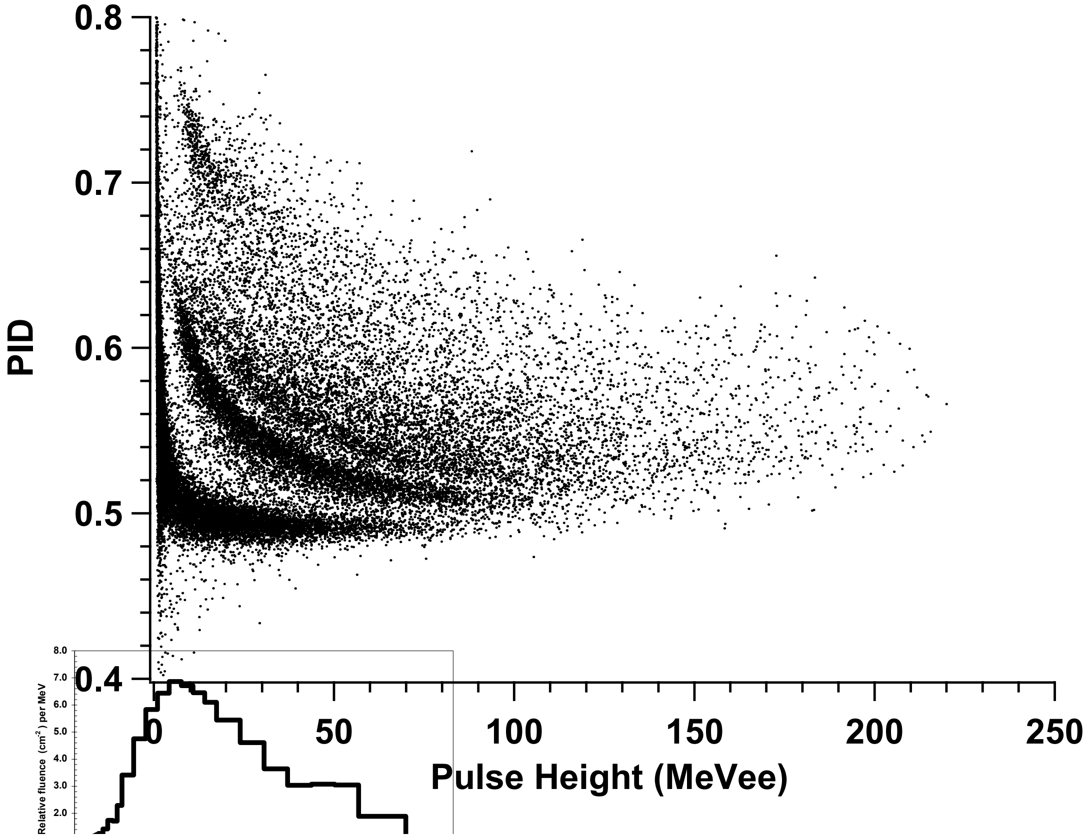


Figure 3. Plot of an off line analysis of pulse shape and energy. PID was calculated by integrating initial 1.2us of signal by total pulse energy.

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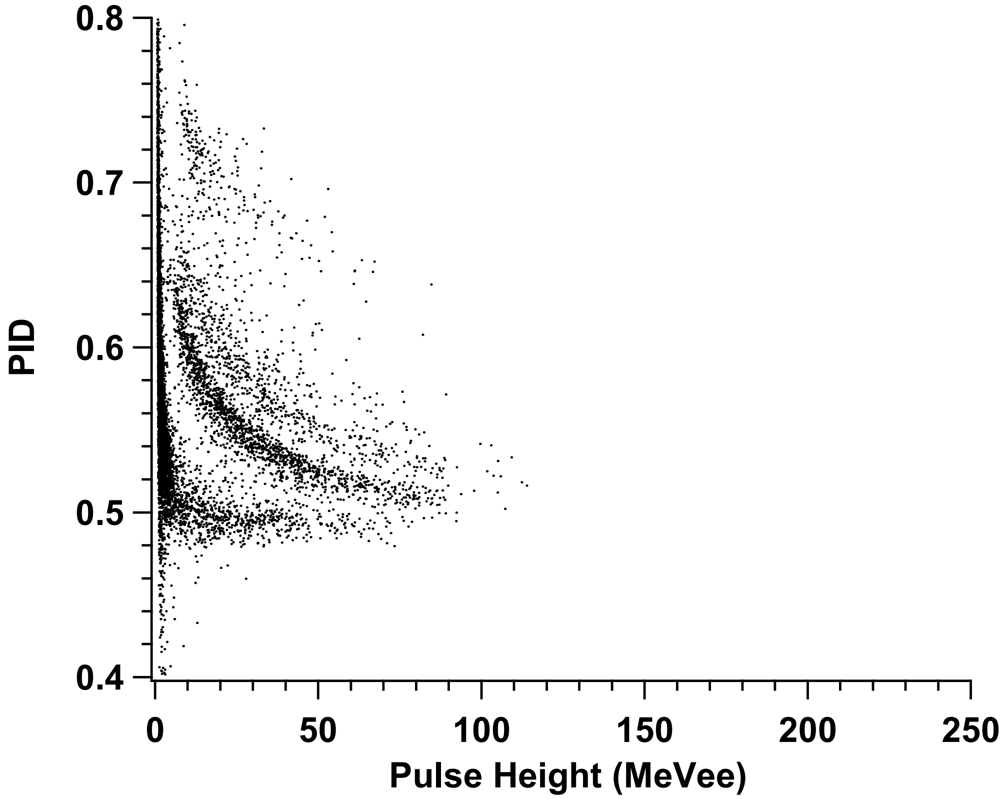

Figure 4. Off line analysis of pulse shape and energy for spallation events induced by neutrons between 100 and 130 MeV.

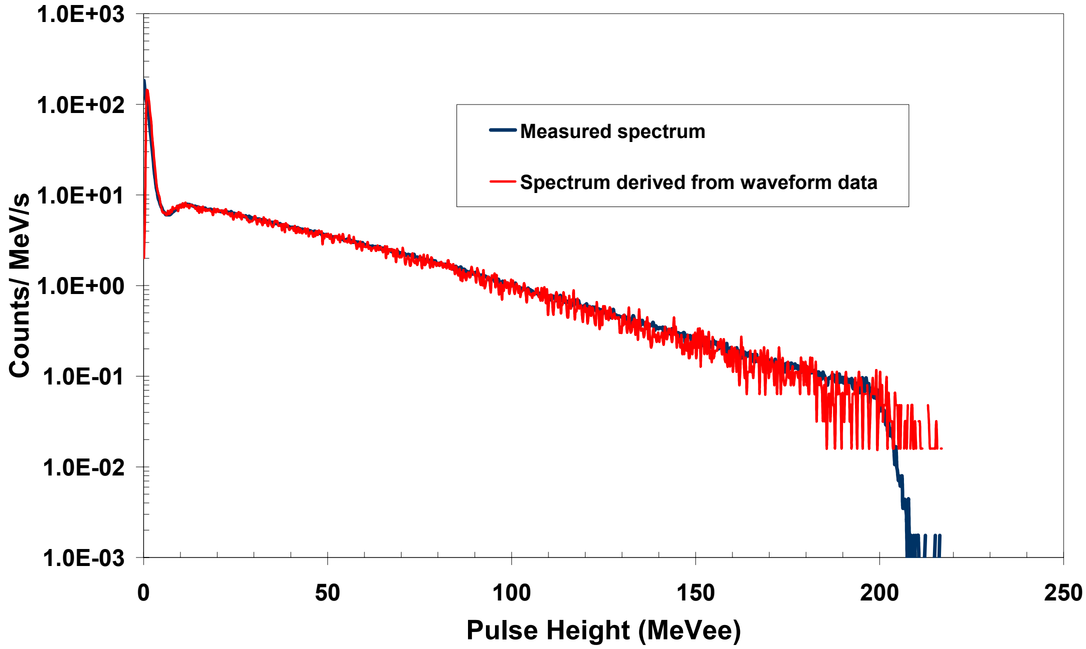

Figure 5. Comparison of the measured MCA spectrum and one derived from an analysis of waveform data recorded under the same conditions. The waveform-derived spectrum has been scaled to match the total number of counts in the MCA spectrum.

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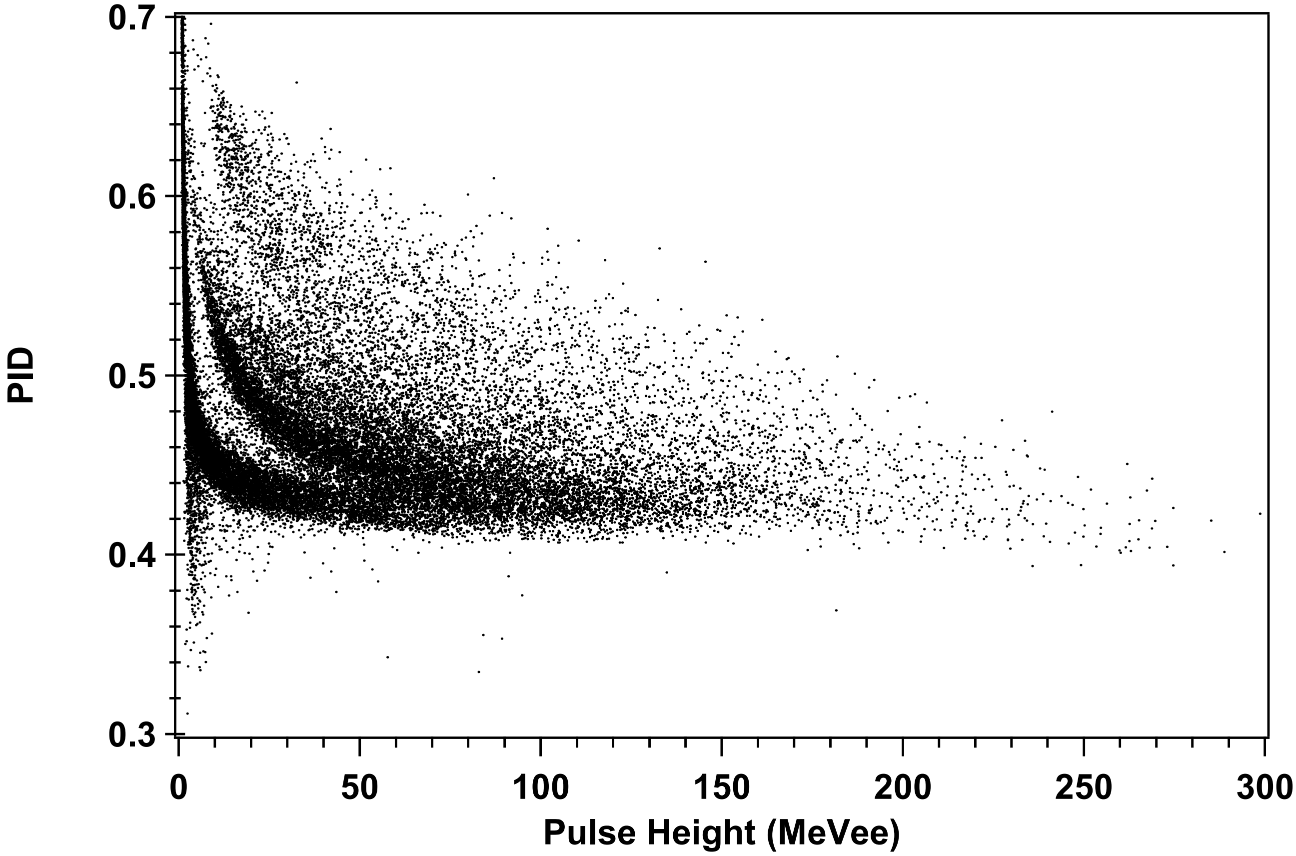

Figure 6. Online analysis of pulse shape and energy

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