A New Four Channel Pulse Shape Discriminator

Andreas Ruben, Timothy E. Hoagland, Ron Fox, Phillip L. Kerr, Gregor Montermann, Robert Schneider

***Abstract*–A renewed interest in neutron - gamma discrimination and the need to process rates up to several MHz per channel led to the development of a new, four channel pulse shape discriminator (PSD) in 1/12 NIM format. By revisiting old techniques and running simulations of new ideas, it was determined that the best PSD performance is obtained by measuring the time between the rising edge of the pulse and the intersection point of the curves of the integrated short component with the trailing edge of the pulse. Pulse shape discrimination can be performed at up to 4MHz detector rate. The module was tested with different neutron and gamma sources as well as at high neutron flux and was found to provide good energy independent neutron / gamma discrimination in a wide energy range with low dead time. A 96-channel system using 24 of these modules is now being operated**

I. INTRODUCTION

Over the past few years', research and development for Homeland Security Instrumentation has increased the interest in neutron detection. At LLNL active detection of small quantities of shielded highly enriched Uranium was studied using a low-dose 60-keV Neutron interrogation technique. The fissile material can be identified by detecting the prompt and delayed fission neutrons, however those have to be discriminated from background gamma radiation and from the low-energy 60-keV primary neutrons by using pulse shape discrimination technique and energy thresholds respectively [1].

The neutrons are detected with a liquid scintillator detector made of EJ301, which is similar to NE213. The light emission of this scintillator is characterized by a fast and a slow decay component, which depend on the dE/dx of the detected radiation, i.e. neutrons have a stronger slow component compared to photons resulting in a longer decay time.

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A. Ruben is with WIENER, Plein & Baus, Ltd., Springfield, OH 45505 USA (telephone: 937-324-2420, e-mail: aruben@wiener-us.com).

T. Hoagland is with WIENER, Plein & Baus, Ltd., Springfield, OH 45505 USA (telephone: 937-324-2420, e-mail: thoagland@wiener-us.com).

R. Fox, is with Michigan State University, East Lansing, MI 48824 USA. (telephone: 517-333-6349, e-mail: fox@nscl.msu.edu).

P. Kerr is with the Lawrence Livermore National Laboratory, Livermore, CA 94551 USA, (telephone: 925-423-6534, e-mail: kerr12@llnl.gov).

G. Montermann is with Mesytec GmbH & Co. KG, Putzbrunn, 85640 Germany (telephone: [49] 89-45600730, e-mail: g.monterman@mesytec.com).

R. Schneider is with Mesytec GmbH & Co. KG, Putzbrunn, 85640 Germany (telephone: [49] 89-45600730, e-mail: r.schneider@mesytec.com).

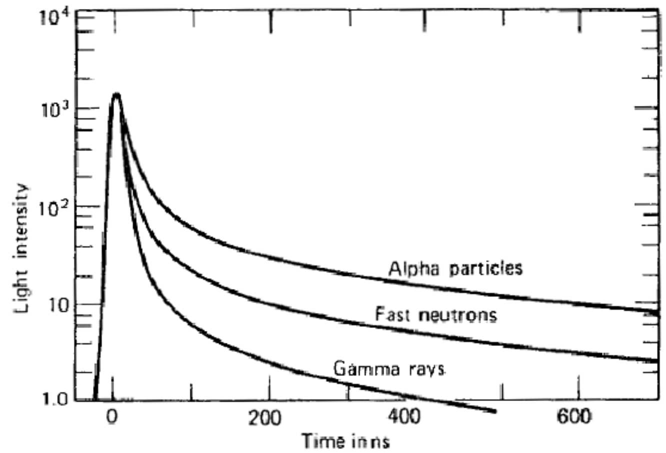

Fig. 1. PMT output signals from NE213 type liquid scintillator for selected particles [2].

Several pulse-shape discrimination methods were considered and studied. Traditional analog pulse-shape discrimination measures the tail length or decay time of the pulse. Two logic signals (Start / Stop) are created from two trailing edge constant fraction discriminators (CFD) set at different fractions. The measured time is proportional to the tail length of the particle. Another, more modern approach is to digitize detector pulses and develop an algorithm to determine the particle type based on the shape of the pulse. However, this method requires a channel of fast sampling ADC (200MHz or higher) for each detector and on-line pulse shape analysis.

A slightly cheaper method uses charge integration of both the fast component as well as of the complete pulse for each detector. By sending the same signal into two charge integrating ADC's (QDC's) with two different gates to integrate the full signal as well as the fast component only, one can derive information about the pulse shape. This method also requires off-line calculation to determine particle type.

II. PULSE SHAPE DISCRIMINATION PRINCIPLE & MPD-4 OPERATION

A new 4-channel analog pulse shape discrimination module MPD-4 was developed. For the MPD-4 the traditional method was modified in order to get good and energy independent resolution, wide dynamic range and also fast neutron – gamma discrimination performance. Shaping the pulse and adding a "fast component integrator" to subtract the fast component from the shaped pulse allowed to determine the decay time independent from the pulse amplitude.

Fig. 2. 4 channel pulse shape discrimination module MPD-4.

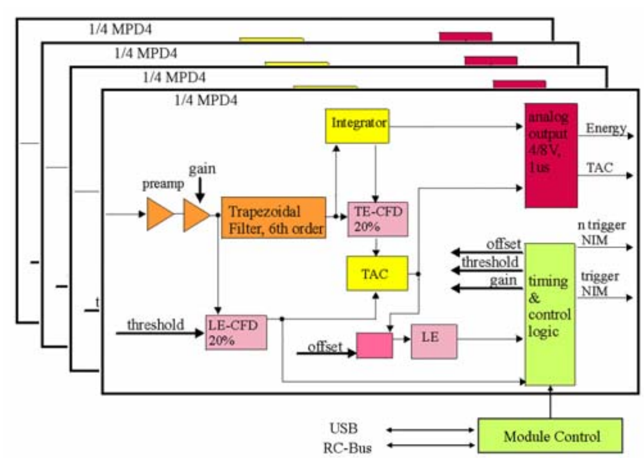

Fig. 3. MPD-4 block diagram.

The detector signal after passing a pre-amplifier and gain stage is split into two branches. One is connected into a constant faction discriminator (CFD), which triggers on the leading edge of the signal and provides the “Start” signal to the Time-to-Amplitude converter (TAC). The other branch goes into a high order trapezoidal filter. This filter is needed to reduce the photon quantization noise, which limits the resolution at low photon statistics. The filter also preserves the rise and decay time of the signal.

The fast component of the signal (first 20ns) is integrated and then subtracted from the shaped signal. The zero crossing point of the resulting signal is used to provide the “Stop”. This method results in a pulse height independent timing of the “Stop” signals. The TAC output is proportional to the length of the trailing edge of the detector signal and thus a measure for the particle type. The following simulated timing diagram illustrates this principle for both a gamma and neutron pulse.

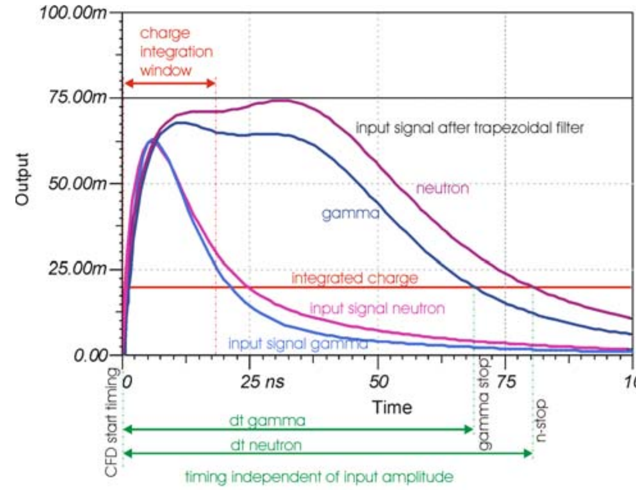

Fig. 4. Timing diagram with input pulses (light color) and shaped pulses (dark) for a typical neutron (purple) and gamma (blue) event. All timing signals are shown in green. The integral of the fast component is indicated by the red horizontal line.

The integrated fast component, which is proportional to the particle energy, is wired to an output as "Energy" signal. Commercial peak-sensing multi-channel ADC’s can be used to digitize both the “Energy” and “TAC” signals with high precision.

Further the precise CFD timing signal from the leading edge (“Start”) is provided as a “Trigger” for the external ADC’s but can also be used for time-of-flight measurements or to determine the position in long detectors with dual PMT readout. The logic “OR” of all 4 “Trigger” signals is available as “Common Trigger”. A programmable leading edge discriminator on the TAC signal generates a logic signal “n-Trigger” to indicate a neutron or gamma event. All logic signals are available both in fast NIM and ECL levels.

In addition to the spectroscopic mode with “Energy” and “TAC” signal outputs the MPD-4 can be switched into a fast mode without analog signals. All logic signals are then generated with a much shorter pulse length of 50ns, which is reducing the dead time to 250ns. A further reduction to about150ns is possible when optimizing the module for a specific detector and PMT.

TABLE I
MPD-4 MODES AND TIMING

Signal	Spectroscopic Mode	Fast Mode
Amplitude	1us shaped pulses	-
TAC	1us shaped pulses	-
Trigger / Gate	1us long pulses	50ns
gamma/neutron	1us long pulses	50ns
Common Trigger	1us long pulses	50ns
Position TAC	1us long pulses	-
ECL signals	50ns	50ns
Dead Time	1.15us (+ ADC + DAQ)	250ns (150ns)

III. Data Acquisition System

A VME based DAQ system was built to read-out a 96 channel neutron detector array for a DHS/DNDO funded project at LLNL. Both the Energy and TAC signals for each detector were digitized with commercial 32-channel VME peak-sensing ADC. In addition all triggers, neutron and gamma events flags were counted in latching scalers to determine individual and overall rates and to calculate dead times of the system.

The detector read-out was done with a WIENER VM-USB controller and a PC running the Linux based MSU NSCL data acquisition and histogramming software [3]. In order to achieve the highest possible data rates an interrupt triggered VME list sequencer read-out method was used.

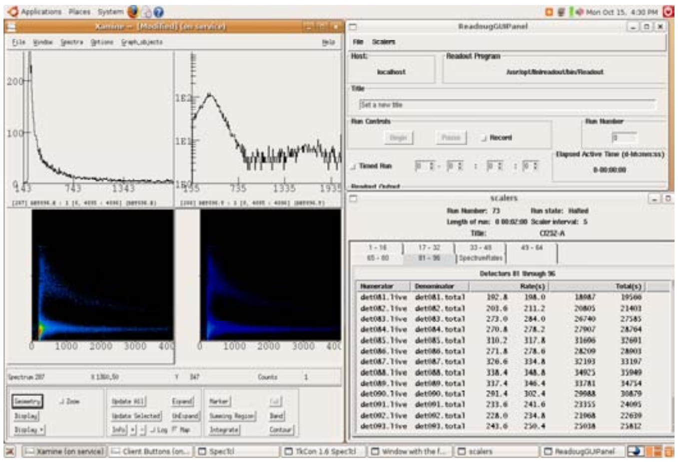

Fig. 5. NSCL DAQ software screen dump with on-line monitoring and experiment control GUI.

All MPD-4 parameters can be set manually on the front panel or remotely via the built-in USB-2 interface or the proprietary Mesytec RC control bus. A TCL script based graphical user interface was written to allow easy module configuration and saving of configuration settings to file.

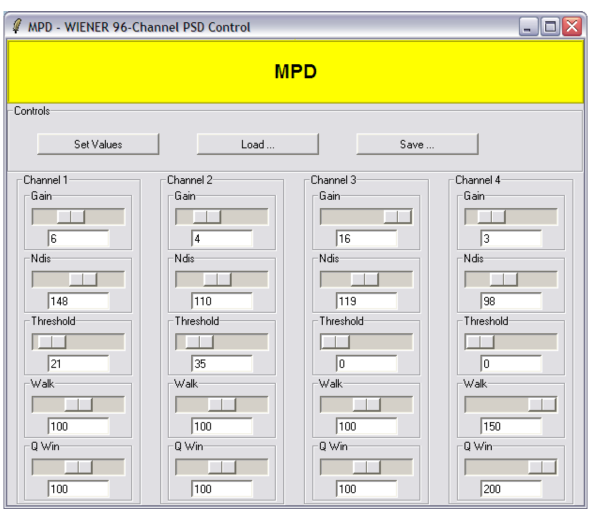

Fig. 6. TCL script GUI for MPD-4 setup via USB-2 or RC-bus link

A first beam test with 4 detectors was done at the Wittenberg University Accelerator Laboratory in Springfield, Ohio and proved both operation of the MPD-4 modules as well performance of the VME DAQ system. The 400kV Cockcroft-Walton accelerator produced neutrons at about 3MeV energy with a d+d → n+^{3}He reaction. Tests were done with individual detector rates of up to 75kHz.

The full DAQ system for the 96-channel detector array was installed at LLNL in December 2006 and running there since then in different configurations.

IV. Results

In all performed tests the MPD-4 showed good neutron gamma discrimination in a wide dynamic range. Plots of “TAC” (y-axis) output vs. “Energy” (x-axis) are presented in Figure 7 and 8. They show the neutron and gamma regions with good separation and no curvature in the gamma band. This indicates that the module produces good particle discrimination without energy dependence.

Using a ^{252}Cf spontaneous fission source to generate neutrons with a Maxwell distribution at an average energy of 1.42MeV Figure 57 shows a clear separation of neutrons and gammas up to highest energies.

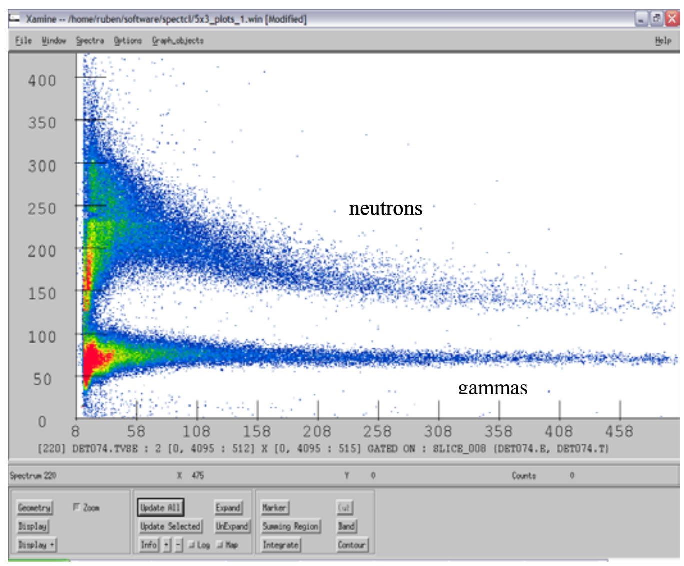

Fig. 7. “TAC” versus “Energy “plot for 252Cf source.

Figure 8 shows the similar plot for the 2.9MeV neutrons from the d+d → n+^{3}He reaction measured at the Wittenberg University Accelerator Laboratory. A large paraffin block located close to the detectors moderated a part of the fast neutrons to lower energies. Visible is the neutron energy cut-off at the maximum energy of 2.9MeV as well as the large low energy neutron contribution.

The “TAC” spectrum, which corresponds to the y-axis projection of the 2-dimensional plot, is given in Figure 9 and shows again good neutron - gamma separation.

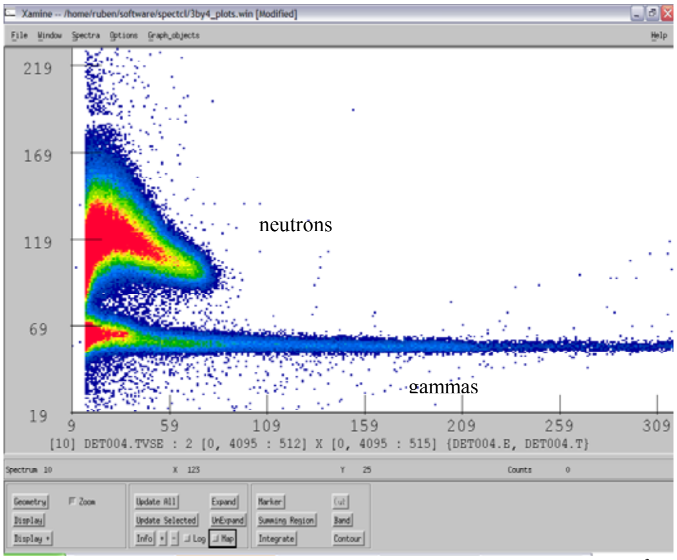

Fig. 8. "TAC" versus "Energy "plot for neutrons from d+d→n+^{3}He reaction with a neutron energy of about 2.9 MeV.

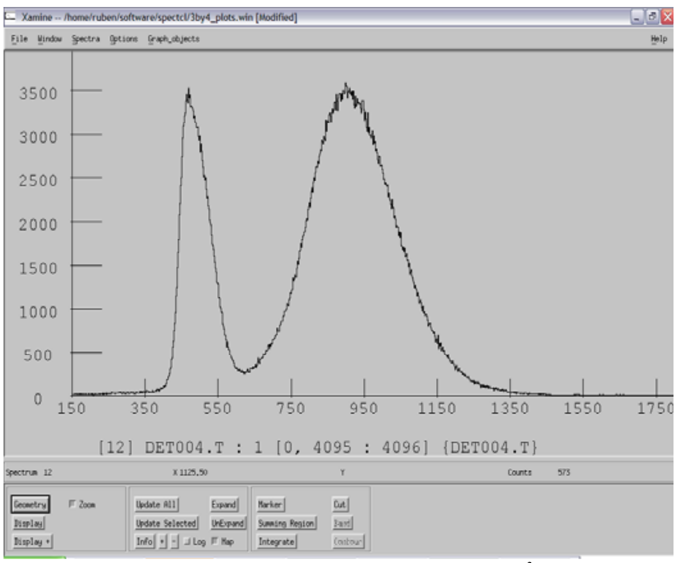

Fig. 9. TAC spectrum for neutrons from the d+d→n+^{3}He reaction and background gamma radiation. The gamma peak is at the left (channel 400 to 550), the neutron TAC distribution on the right.

Early tests show that neutron/gamma discrimination is very clean up to low neutron energies of a few 100keV. A measurement has not yet been performed to determine the lowest possible energy for which the MPD-4 is able to discriminate between the two particles.

For high rate applications, the module can be set to fast mode. Then TAC and energy outputs are switched off and a logic signal for neutron and gamma events is generated on ECL or NIM outputs that can be used with scalers. In fast mode each incoming signal results in 250ns dead time meaning each channel can handle up to 4MHz detector rate. A reduction to 150ns dead time is possible, but at the cost of slightly higher noise at the internal TAC signal.

V. Summary and Outlook

The improved analog pulse shape discrimination technique proved to provide excellent neutron - gamma discrimination in a wide dynamic range, going down to lowest energies (not yet measured). The developed module, MPD-4, furnishes all analog electronics for 4 channel pulse shape discrimination in a compact NIM design. Knowing the detector characteristics and optimizing the MPD-4 settings accordingly the module can be operated in a fast mode, in which a logic signal for a neutron or gamma event is provided within 150ns for counting purposes or to trigger neutron events.

The next upgrade of MPD4 will provide internal counters for neutrons and gammas and a basic ADC / multi-channel analyzer to monitor and adjust the discrimination spectra without external ADC's. All internal parameters and data can be accessed via USB-2 and the Mesytec RC control bus.

Acknowledgment

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References

[1] Kerr, Phil. "Active Detection of Small Quantities of Shielded Highly-Enriched Uranium Using Low-Dose 60-keV Neutron Interrogation". CAARI 2006, Fort Worth, TX. To appear in Nuclear Instr. and Meth. in Phys. Res. B, 54634, 2007.
[2] L.M. Bollinger and G. E. Thomas, Reviews of Scientific Instruments 32, 122 (1972).
[3] R. Fox et al. Real-Time Results Without Real-Time Systems, IEEE Transactions on Nuclear Science, Vol. 51, No. 3, June 2004