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PMT-N2000 Neutron Detector Users Manual

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Summary

The PMT-N2000 is a family of scintillator-based neutron detectors with an embedded ARM processor for gain stabilization and autonomous alarm functions.

The detectors can act as a direct rplacement for ^{3}He tubes with a TTL pulse output but contain no pressurized gases nor toxic substances.

An embedded 32-bit ARM processor gives the detectors additional capabilities, such as gain stabilization and an alarm feature.

The ARM processor is programmed to track the neutron background over time and issue an alarm based on a statistical analysis of te current count rate. If the counts with in a programmable time window (typically 4s) are unlikly to be caused by background the device will raise an alarm. The false-alarm rate is programmable.

Finally, the ARM implements a 1020-point dual-channel logger with programmable dwell time, to record for example count rate changes in time steps as small as 50ms.

Feature summary – PMT-N2000

- Low-cost neutron detector
- ^{3}He-Replacement Tube
- ZnS:Ag + ^{10}B
- No ^{3}He, no ^{6}Li, no BF_3
- Gain stabilization
- Embedded ARM for autonomous alarm
- Software control for Portal Monitors
- ARM C-code customization possible
- Power consumption is only 250mW (5V@50mA)

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1. Supporting Documentation

Open-source software The software is open source and mostly written in Python. Bridgeport Instruments provides a software installer, which by default will create a C:\BPISoftV3 directory. That folder includes Python 3.7 with three added packages: ZMQ (www.zeromq.net), wxPython and Matplotlib v 3.2. ZMQ is used to implement the client-server behavior and it is accessible from more than 40 programming languages. Matplotlib is used for the graphics interface, and wxPython is used to create a traditional user interface with pull down menus.

The PMT-N2000 neutron detector is based on the PMT-2000 MCA, and all the MCA-2000 documentation applies.

In this document we describe the detector and showcase some of its performance.

2. Count rate measurement

The PMT-N2000 provides fast and accurate neutron counting. To measure count rates, select Display→Histogram from the menu bar. In response, a data panel will open. On that panel use "New" to erase old count rate data and begin a new acquisition. The panel does not automatically refresh, so click the "Refresh" button to receive updates. The panel also shows a measured energy histogram, which for the neutron detector has no significance.

More detailed count rate information can be found in the Status→Count_ Rates page.

Observe how the count rate accuracy improves with measurement time. The PMT-N2000 reports count rates together with their statistical errors. This gives users a useful tool. Manually, or programmatically, they can end a measurement precisely when the desired accuracy has been reached, which saves time and money.

The error (in %) is computed from the number of events as 100×2/sqrt(N), where N is the number of events. This is called the statistical 2-σ error. The true count rate lies within this error range with a 95% probability.

Note that the PMT-N2000 corrects the recognized count rate using the known dead time per event. Hence the reported count rate is greater than the recognized count rate. The reported count rate is also an accurate estimate of the true number of counts per second. In fact the reported count rate should match the true input count rate with about 1% accuracy (systematic error) for input count rates up to 100kcps. The statistical count rate error is computed correctly using the number of recognized events.

Use "Save" to append count rate data to a file.

2.1 Counting speed

Neutron dead time 3.0µs The PMT-N2000 has a non-extendable dead time of 3.0µs; per recognized neutron event,The resulting throughput for neutrons is well above 300kcps.

3. Sample vs Background

The instrument provides automatic background subtraction. To accurately measure the radioactivity of a weak source, or a weakly contaminated sample can be a complicated process. However, in all cases the process requires a precise measurement of the background and the ability to correctly subtract that background from the sample counts. And the PMT-N2000 greatly simplifies this task.

The PMT-N2000 stores sample and background data on the instrument and reports the difference. From the task bar, open the Display→Sample − Bck panel. You will see three set of count rates and their respective 2-σ errors: Sample, background and difference.

To acquire a background spectrum, remove all unwanted radioactive materials from near the detector and click on "Background". You can increase the accuracy of the results by measuring the background at least 4 times longer than a typical sample. Click "Refresh" to update the display.

Once you have counted the background long enough, click on "Sample". This starts a new sample acquisition and stops the background acquisition. The background counting will now have stopped and remain unchanged.

Every time the display is updated, the software reads all three sets of count rate data from the PMT-N2000: the background, the sample and the difference.

The instrument computes probabilities and alarms. The PMT-N2000 computes the probability that the sample count rate was caused by nothing but background. The message box next below the difference rate shows the result of that computation.

The instrument computes the probability that the observed sample count rate is caused by the just measured background. Instead of displaying the probability p it display -log10(p) and calls it the signal strength.

The instrument reports the signal strength and confidence interval. You will see that strength is quoted with a lower and upper boundary, such as 2.0 < 4.0 < 6.0. The excess of count rate over background caused by a small amount of radioactivity is called the signal. And like a weak radioactivity signal embedded in noise, the signal strength is what the instrument reports. Here the strength is reported as the negative logarithm of the above-mentioned probability. The instrument also reports the 95% confidence interval for the measured source strength. Users can thus make an informed choice on how to set alarm levels and thresholds for taking a decision. The mathematics is described in the math box below

Finally, you can set an alarm threshold. If the probability that the measured sample radioactivity is caused by nothing but background is too low, the PMT-N2000 can raise an alarm. The alarm threshold can be set in the alarm panel via the alarm_thr variable. For example, a value of 1.0e-3 is interpreted as a probability of 1 in 1000.

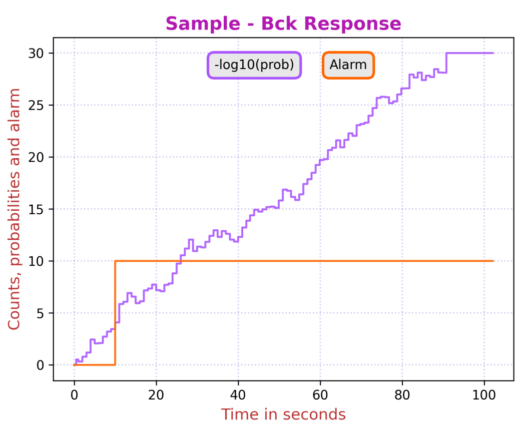

Fig. 1: THere is an example how the sample alarm strength keeps increasing with time when a sample is more radioactive than the background.

4. Mathematics of Errors and Alarms

This section is for the reader with an interest in the mathematics that is used by the instrument.

4.1 Count rates and their errors

When measuring count rates, the instruments counts events and the elapsed time. Systematic errors for measuring the run time are very small and are ignored here. The dominant variation come from the fact that the number of events during a given time interval is Poisson-distributed. When the total number of events counted is greater than 100, we can approximate the resulting Poisson distribution with Gaussian normal distribution with an average of (μ = number of events) equal to the number of events and a standard deviation of $\sigma = \sqrt{\mu}$ For a given measurement the instrument reports the 2-σ relative count rate error

$$\epsilon = 2/\sqrt{\mu}$$

Dead time does not contribute to statistical error. The instrument knows the incurred dead time per recognized event and computes a live time as run time minus dead time. The reported count rate is events/live_time.

4.2 Background subtraction

Background time can be different from sample time. The instrument can subtract the expected background counts from a sample count even when the two have been acquired for different amounts of time. The calculation for the difference count is

$$diff = sample - \frac{sample\_time}{back\_time} \cdot back$$

Here, $diff$, $sample$, and $back$ are the counts for all three cases.

Count rates are measured by summing all events within the alarm region of interest, and dividing by the respective live times. Count rate errors are computed from the number of events in the region of interest.

The difference count rate is computed as a direct difference, $R_D = R_S - R_B$, from the dead-time corrected sample and background rates.

The count rate error for the difference has to be computed from the two uncorrelated errors of the sample and the background counting:

$$\epsilon_d = \frac{\sqrt{(R_S \cdot \epsilon_S)^2 + (R_B \cdot \epsilon_B)^2}}{R_S - R_B}$$

Notice that for very small difference count rates the resulting relative error can be quite large. Further, a difference rate with a large relative error, eg 0.1cps ± 200%, simply means that the result is compatible with a difference of 0cps.

4.3 Computing probabilities

For a given sample measurement time, T_S, the PMT-N2000 knows how many background events to expect on average: $N_B = T_S \cdot R_B$. It compares that number to the number of actually measured events, N_S. Using correct Poisson statistics, not a Gaussian approximation, it calculates the probability that N_S could have been caused by the known background: $P = P(N \geq N_S | N_B)$. If $N_S \gg N_B$, this probability will be very small. If it falls below the given alarm probability (**alarm_thr** in arm_ctrl), the PMT-N2000 can raise an alarm. In other words, a stronger signal causes a lower probability.

However, a user might prefer to use a measure of the signal strength that increases with the signal strength. Hence we define a signal strength as $A = \log_{10}(1/P)$

For the confidence interval of the signal strength, the instrument reports a narrower measure. It computes the two opposites we get by assuming 1-σ errors in the background count and the sample count, but pointing in opposite directions. The resulting rectangular two-dimensional confidence interval contains about 71% of all cases.

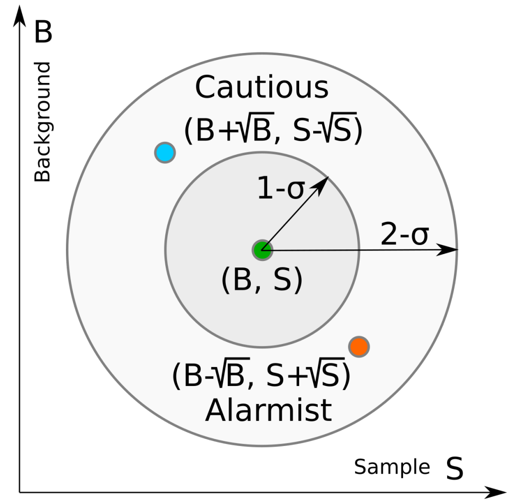

Fig. 2: Two dimensional confidence interval.

5. Radiation Portal Monitor

The PMT-N2000 can act as a radiation portal monitor with background tracking and a programmable alarm function. In a Radiation Portal Monitor (RPM) the data acquisition unit must perform a number of tasks:

- Continuous background measuring;
- Deliver an alarm within a few seconds after the time of closest approach by a source;
- Keep a few seconds of alarm history so that a polling host will not miss an alarm;
- Automatically reset the system on a continuous alarm to remain operational;
- Support a programmable alarm threshold based on a false-alarm rate;
- Support an adjustable background averaging time, eg 30s for a big gamma-ray detector vs 5 minutes for a neutron detector,
- Be able to recognize passing sources without the aid of an occupancy detector.

The PMT-N2000 implements all that functionality within its embedded 32-bit ARM processor. An alarm can be sent as digital pulse with a programmable width, from 1µs to infinity. Alarms can also be read via USB or the serial communications interface.

5.1 Theory of operation

In the discussion below, times are given in units of time slices. Typically a time slice is 50ms long and the ARM processor performs one RPM computation step every time slice.

At first the instrument measures the background. On start, after power on or a reset, the ARM processor begins to measure backgrounds. Until backgrounds are know with sufficient precision, the ability to alarm is disabled. This wait time is user programmable, cf **wait** in the RPM panel. Typically the wait time is a fraction of the background averaging time, eg 20% to 50%. A shorter wait time yields an active RPM earlier at an elevated risk for a false alarm until a full background averaging time has passed.

As long as there is no alarm, the events counted during one time slice are considered background events. Using the region of interest **(roi_low, roi_high)** in the RPM panel allows the user to constrain the attention on a part of the energy spectrum.

The background counts per time slice are averaged using geometric averaging. Using the $w = 1/Bck\_avg$ from the alarm panel the processor applies the formula: $B_{n+1} = B_n + w \cdot (N - B_n))$. The background averages are then stored in a 128-long FIFO. This way the instrument can look back 128 time slices to find an untainted background after an alarm has occurred.

We have $0 \leq w \leq 1$ for the weight. If the background at time $t = 0$ changes from B_0 to B_1, The background average responds to a step function with an exponential function of $B(t) = (B_1 - B_0) \cdot (1 - \exp(-t/\tau)$ where $\tau = 1/w$. The standard deviation of the averaged background, ie its noisiness, improves as if $1/w = Bck\_avg$ samples had been averaged.

What happens when a passing source causes an alarm? The instrument continuously computes a moving window sum of the last L time slices and compares that sum to the number of expected background counts during L time slices. For every time slice the instrument computes the probability that the observed counts could have been caused by the known background, cf the mathematics section above. It computes $P = P(N \geq N_L|N_B)$, with $N_B = L \cdot B$. If that probability is less than **epsilon** on the alarm panel, it will trigger an alarm.

An alarm is typically raised no later than $L/2$ time slices after the closest encounter. For a very strong signal, that alarm may be raised right at the leading edge of the L period; for a weak signal the alarm may be raised about $L/2$ time slices after the source has passed the point of closest approach. In many applications the allowed latency $L/2$ is about 2 seconds, which allows for a 4s summation time. At a time slice length of 100ms this means $L = 40$. In those applications, the time during which the radiation signal is detectable is 4s to 8s and and simulations show that 4s to 6s summation times produce the highest sensitivity; ie lowest minimum detectable activity.

No missed alarms. The instrument keeps a history of the alarm status with a maximum length of 128 time slices. This is controlled by the **history** parameter in the alarm panel. A polling device, via serial interface or USB, will be informed if there was an alarm present in the last **history** time slices. This way a polling host may have a a latency of 128 time slices (12.8s) and still will not miss an alarm.

As long as there is an alarm present in the alarm history FIFO, the instrument will suspend background updates and use the oldest background average in its memory as the best estimator of the background.

Automatic device reset ensures the instrument remains functional when the background suddenly increases. Consider the case of a radiation detection backpack. The wearer walks into a room where radioactive material is present, and this causes an alarm. After **history** time slices, the instrument automatically resets and starts to accept the elevated radiation level as the new background. After a **wait** period (30s typically) the instrument will again be ready to alarm if the operator suddenly encounters an even higher radiation level.

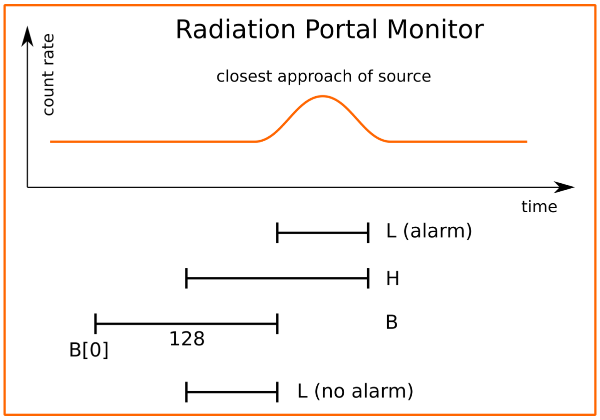

Fig. 3: Programmer's model of the Radiation Portal Monitor software.

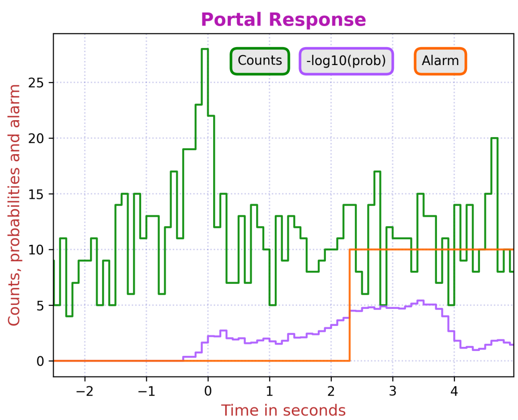

Fig. 4: Alarming on a neutron source that is barely above background. The alarm occurs within 2s of the time of closest approach. The time slice length was 100ms.

6. Gain Stabilization

All PMT-N2000 offer gain stabilization. All PMT-N2000 use at least one high voltage vs temperature lookup table to maintain a constant neutron sensitivity. Since code and data needed for the gain stabilization are embedded in the PMT-N2000, no user software is required and the calibration moves with the detector.

The PMT-N2000 also offers LED-based gain stabilization to counter PMT aging. Vacuum photomultiplier tubes lose gain over time, even under light to moderate loads. For example the popular R6231 PMT loses half its gain after an accumulated anode charge of about 50C. Distributed over one year, this equivalent to an average anode current of just 1.6µA, with a 6% gain loss per month. With a built-in LED that injects light into the back of the photomultiplier, the PMT-2000 can gain-stabilize on the LED response and counteract the PMT aging. In practice, PMT aging is only of concern if the detector is continuously operated above 45°C or is continuously subjected to very high neutron count rates (> 50kcps). As a diagnostic tool, the instrument reports the average PMT anode current.

6.1 General theory of operation

All types of gain stabilization use lookup tables, and users can supply their own. The standard code includes a 64-long float array with two look up tables **(LUT)**. The PMT-N2000 frequently determines the temperature and adjust the operating parameters according to the values found in the lookup tables.

If no LED is present, the ARM processor uses the HV vs temperature lookup table to determine the correct high voltage at the current operating temperature. If an LED is present, the ARM will use a temperature dependent LED target and adjust the high voltage so that the measured response to LED pulse equals the LED target.

How the LUT are constructed. The look up tables for HV and LED-target vs temperature were determined by BPI and are used on all detectors. The variation between detectors is small enough. For an application that needs to measure accurately a neutron flux, rather than performing an alarm function only, a developer might want to repeat temperature calibration.

Temperature calibration without LED Place the detector in a temperature chamber with a neutron source nearby and run the chamber through a temperature cycle. At each temperature, note the high voltage needed to maintain the constant room temperature neutron count rate. As the temperature increases, the high voltage needs to be inceased. Typically the effect is about

$$\Delta HV = HV \cdot 1 \cdot 10^{-3}/K$$

For a detector running at 1000V, this translates into 1V/°C

Temperature calibration with LED The procedure is similar to above. Adjust the high voltage as necessay to maintain count rate stability and record the resulting LED value at each temperature. In both cases, construct the LUT by proper linear extrapolation between your data points.

LUT length A lookup table (LUT) is limited to 20 entries. A typical grid is T0=−30°C with a step sizxe of 5°C for an inclusive range of −30°C to +65°C

Keep in mind that it takes a while for a detector to attain steady state. The vacuum PMT needs an hour and the deector characteristic time depends on the packaging and the size. Hence, it is necessary for a precise measurement, to maintain the detector at a fixed temperature for 2 to 4 hours before moving to the next.

Thermal equilibrium is necessary. Keep in mind that the PMT and the thermal neutron capture cross-section both have different temperature coefficients. If the PMT and the detector are not in equilibrium, there is no easy way to provide perfect gain stabilization. Hence an outdoor detector should be packaged with good thermal insulation to achieve thermal time constants of 2 hours or more – to ensure that all components are in a steady state situation. However, care must be taken not to insulate the electronics. Even if it only dissipates 250mW, that small amount of power stills needs to drain away to avoid self heating.

arm_cal registers and fields	
Index: name	***Description***
0: lut_len	Number of entries in the LUT; default is 20, 2..19 are allowed
1: lut_tmin	Minimum temperature in the lookup table; Typically -30°C
2: lut_dt	Temperature step size in the lookup table; Typically 5°C
[3:22]: lut_ov	Change of operating voltage vs temperature
[23:42]: lut_dg	Change of digital gain vs temperature
[43:62]: lut_led	Change of LED target vs temperature
63: lut_mode	int(lut_mode)&0x1 → lock bit, set to 1 to prevent the user from reading the arm_cal data from the PMT-N2000.

The arm_cal registers and fields.

6.2 Gain stab. summary

Standard software recognizes these gain stabilization modes (gsm):

- 0 ⇒ Off; Use when calibrating a detector.
- 7 ⇒ Suspend; Keep all parameters as they are.
- 1 ⇒ Use temperature lookup for change of operating voltage and digital gain; adjust hold-off if required.
- 2 ⇒ Compare measured LED value to expected value and adjust operating voltage accordingly. Use LUT for digital gain and compute hold-off time as needed.

arm_ctrl for detector calibration		
Name	***gsm***	***Description***
cal_ov	0,1,2	Operating voltage when the detector was calibrated
cal_temp	1,2	Temperature (in deg C) at which the detector was calibrated
cal_target	2	Target value for response to LED; used with gain_stab=2

The arm_ctrl registers and fields concerning detector calibration; The gsm column lists the gain stablization modes for which this parameter is used.

LUT needed for detector calibration		
Name	***gsm***	***Description***
lut_ov	1	Operating voltage
lut_led	2	LED average

The lookup tables (LUT) needed detector calibration; The gsm column lists the gain stabilization modes for a given LUT is used.

6.3 Gain stab. mode: gsm = 0

Off. Gain stabilization is turned off and the target operating voltage the PMT-N2000 will set is the one requested in arm_ctrl["fields"]["cal_ov"].

6.4 Gain stab. mode: gsm = 7

Suspend. This is different from gsm=0. During gsm $\neq$ 0 the gain stabilization algorithm may have changed the target operating voltage to a temperature dependent value that is different from arm_ctrl["fields"]["cal_ov"]. Setting gsm=0 would revert to that original value, while gsm=7 will leave the value unchanged.

6.5 Gain stab. mode: gsm = 1

This mode relies on just the look up tables and the measured temperature. It is implemented for all PMT-N2000. The units ship with LUT determined for NaI(Tl) at an integration time of 1.25µs

6.6 Gain stab. mode: gsm = 2

This mode adjusts the voltage using an LED measurement. This is an optional feature.

The driving circuit for the LED used in the gain stabilization is electronically temperature compensated, but the compensation is not perfect. Since also the thermal neutron capture cross-section changes with temperature, the ratio of the LED value and the count rate will be temperature dependent. Hence, there needs to be a lookup table to tell by how much the LED target value needs to be shifted as the temperature changes, in order to keep the neutron sensitivity constant.

Use an LED when expecting PMT aging. The purpose of the LED is to counteract PMT aging. This applies mostly to remotely installed detectors where a frequent recalibration is not possible. Whenever a detector can be recalibrated, or is used for alarming only, and only sees light to moderate loads (anode current < 1µA with round the clock operation), then an LED system is not required.

Manual vs algorithmic operation of the LED. When gain stabilization is off the user can set the LED pulse width. The LED blink frequency is fixed at 20Hz.To turn the LED off, set the width to 0. When the detector has been calibrated, read the LED value on the **ARM Status** panel and enter it into the **cal_target** field on the **ARM Ctrl** panel.

Operation with the LED ON When gain stabilization is turned off, and te LED is turned on, the LED pulses will be counted (adding to the overall count rate) and the LED energy values will appear in the energy histogram. When gain stabilization is turned on (gs=2), the LED pulses will no longer be counted and will disappear from the energy histogram.

Mode	*Operating conditions*
No gain stabilization	LED width = 0; gs=0
Gain stabilization without LED	LED width = 0; gs=1
Gain stabilization with LED	LED width = 2.0e-6; gs=2

Table 1: LED settings in different operating modes.

Keep the LED pulses short. The goal is that the LED pulses are measured with an "energy resolution" of 1% to 2% fwhm. The longer the LED pulse, the better the measurement precision. However, a resolution of 1.5% is enough and a highe precision does not result in a performance improvement. Typically, this is achieved at an LED width of around 2µs.

At high input count rates from a source (> 20kHz) there will be a small fraction of events classified as LED that are a pile up of an LED pulse with a gamma-ray or neutron. These are rare, but they do slightly affect the accuracy of the LED average measurement. Keeping the LED pulses short helps to suppress these unwanted events.

The LED pulse is shorter than the drive pulse. The LED light pulse about 0.9µs shorter than the drive pulse. Hence if you set the LED width too short you will see a measured LED average of zero.

Usually the pulse height is adjusted at the factory to about 300mV when the detector is calibrated. This allows operation with a higher or lower gain while keeping the LED pulse within ADC range.

7. Mechanical and Pin Outs

7.1 8-Pin Connector

The PMT-2000 uses a Bulgin PX0447 mini-B USB connector for power and USB communication. Mating cables are the Bulgin PX0441 (USB-A) and PX0442 (USB mini-A) series cables. They come in lengths from 2m to 4.5m.

The PMT-2000 uses a Switchcraft EN3P8MPX 8-pin connector for GPIO. The mating connector is part of the EN3C8 series.

Fig. 5: Pinout of the EN3P8 connector.

Connector J2, EN3P8MXPKG		
#	***Name***	***Description***
1	SWD_IO	Software Debug Data
2	SWD_RST	Software Debug Reset
3	Pin3	N_Out50# or RS485_A
4	Pin4	N_Out33
5	Pin5	N_Out50 or RS485_B
6	VD50	+ 5V power input (when not using USB)
7	GND	Ground
8	SWD_CLK	Software Debug Clock

Table 2: Pinout of the EN3P8 connector during operation.

By default, the PMT-N2000 ships with RS485 implemented on pins 3 and 5. Alternatively, these pins can carry 5V differential pulse signaling with programmable pulse width. The digital neutron pulse signal is always available with a 3.3V level at pin 4.

8. Product and Part Numbers

8.1 Product numbers

P/N	***Active element***
PMT-N2K-48x2	48-inch long, 1.875-inch Ø
PMT-N2K-24x2	24-inch long, 1.875-inch Ø
PMT-N2K-12x2	12-inch long, 1.875-inch Ø

Table 3: Part numbers for neutron detectors of different lengths. Add -LED to for the optional LED-based gain stabilization.

8.2 USB-ID

On the USB bus devices are recognized by their Vendor ID (VID), Product ID (PID) and Serial Number (SN). The vendor ID for Bridgeport Instruments is 0x1FA4. The Product ID's are shown in the table below. Within a product the serial number is fixed, unless BPI makes a custom device that requires a non-standard driver. Note that simple extensions, such as adding a variable to the controls, does not require a new driver.

The BPI software recognizes individual devices by the unique serial number burnt into each ARM processor. The device reports that when the host reads **arm_version**. The serial number communicated in response to USB setup commands is fixed for each part, to avoid that the host keeps adding every new device to an ever longer list of devices requiring a designated USB driver.

P/N	***PID***	***SN***
PMT-N2000	0x0102	PMT2K0001

Table 4: Product ID and USB bus serial numbers. The vendor ID is always VID=0x1FA4.

8.3 Device serial numbers

Each ARM processor has an immutable 128-bit unique serial number, which can be printed as a 32-character hexadecimal string. The MCA Data Server always uses the complete 32-character string to identify the device. Because of space constraints, the serial number printed onto the device is shortened to 8 hexadecimal characters. Alternatively, BPI may program a short, 32-bit serial number into the device, while keeping the unique 128-bit serial number.