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Photomultiplier Tube Sorting for JEM-EUSO and EUSO-Balloon

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Abstract: The detector portion of JEM-EUSO is a focal surface made of 137 photo-detection modules of 9 elementary cells (EC), each composed of 4 Hamamatsu R11265-M64 multi-anode photomultiplier tubes (PMTs). JEM-EUSO's daughter experiment, EUSO-balloon, is a path-finder mission composed of a single JEM-EUSO photo-detection module with optics in a balloon-borne gondola. Each EC is powered by a single Cockcroft-Walton type high voltage power supply, and the gain of the EC can be adjusted as a unit by changing the power supply output. The ASIC readout electronics include a preamplifier which allows the gain of each pixel within the PMT to be equalized. There is up to a factor of 4 variation in gain between PMTs, and around a 20% variation in gain from pixel to pixel within a PMT. The gain and efficiency of each PMT is measured in single photon electron mode, and they are sorted so that each EC can be build from PMTs with a similar enough gain that all 256 pixels can be equalized using the dynamic range of the ASIC preamp. Sorting the PMTs in this way also allows a rejection defective PMTs. For JEM-EUSO the sorting requires measuring the gain and quantum efficiency of 64 pixels for over 5,000 photomultiplier tubes. The sorting of 40 PMTs for EUSO-balloon, serving as model and test run for future sorting for JEM-EUSO, included the building and calibration of a data acquisition system, the measurement of spectra in single photoelectron mode, and final analysis of the 64 resulting spectra for each of 40 PMTs.

Keywords: JEM-EUSO, UHECR, space instrument, photodetection, calibration

1 Introduction

The JEM-EUSO experiment is a ultra high energy cosmic ray (UHECR) observatory which will be placed on the International Space Station. It will observe fluorescence photons created in extensive air showers (EAS) induced by UHECR with energies above 10^{20} eV. The heart of the JEM-EUSO instrument [1, 2] is a focal surface composed of 137 photo-detection modules (PDM), the smallest self-triggering element. Each PDM is composed of 9 elementary cells (EC), the smallest flat surface, with each EC composed of 4 Hamamatsu M64 multi-anode photomultiplier tubes (PMTs). The readout of each PMT is through the dedicated *Spatial Photomultiplier Array Counting and Integrating Readout Chip* (SPACIROC) ASIC which has been developed for JEM-EUSO [3, 4].

EUSO-Balloon is a JEM-EUSO path-finder mission led by the French JEM-EUSO collaboration. The EUSO-Balloon detector is composed of a single JEM-EUSO PDM with optics launched in a balloon-borne gondola [5]. The philosophy in designing and building EUSO-Balloon is to follow as closely as possible the actual hardware design and requirements of JEM-EUSO.

2 Sorting as Calibration

Each EC of 4 PMTs is powered by its own Cockcroft-Walton type high voltage power supply (HVPS) which has been designed to meet the strict power consumption requirements of the JEM-EUSO mission [6]. The gain of the 4 PMTs within each EC can be adjusted together by regulating the HVPS output. In addition, the SPACIROC readout chip of each PMT includes a preamplifier with a range of a factor of 2, allowing the gain of each pixel to be modified individually.

Each PMT can be characterized by its measured gain and efficiency[1]. There is a factor of ≈ 4 variation in average gain between individual M64 PMTs. These differences in gain come from small manufacturing variations in the multiplication stage of the PMT, where a relatively small change in electrostatics between the dynodes can have a large impact on the overall gain of the PMT. Within each PMT there is a further variation of $\approx 25\%$ in gain from pixel to pixel. This variation is due mainly to the change in electrostatics with location on the photocathode. These same electrostatic variations also affect the total efficiency of the PMT, as they modify the efficiency of collecting converted photoelectrons (pe) from the photocathode into the multiplication stage of the PMT. Not only will the average efficiency vary from PMT to PMT, but the relative efficiency of each pixel within the PMT will vary as well.

The measured properties of the SPACIROC ASIC, particularly in terms of photon counting linearity, require that the working gain of the PMT be close to $1 \cdot 10^6$. Within a PMT the gain variation from pixel to pixel can be compensated in most cases by using the dynamic range of the ASIC preamp, but the larger factor of 4 variation between PMTs cannot. The PMTs must be sorted by gain so that each EC can be build from PMTs with gains (at same HV) which are similar enough that all 256 pixels can be brought to a working gain of $\simeq 1 \cdot 10^6$ using the ASIC preamp.

In addition, we have found during laboratory tests that in a small number (less than 1 in 10) of M64 PMTs one of the first dynodes draws a large current regardless of the incident light. This is due a to a low resistance between the dynode and the cathode, on the order of $\simeq 10$ MΩ rather than several GΩ. These PMTs still function for light detection (as

1. Where the efficiency can be either relative, i.e. compared to the other PMTs in the set, or absolute.

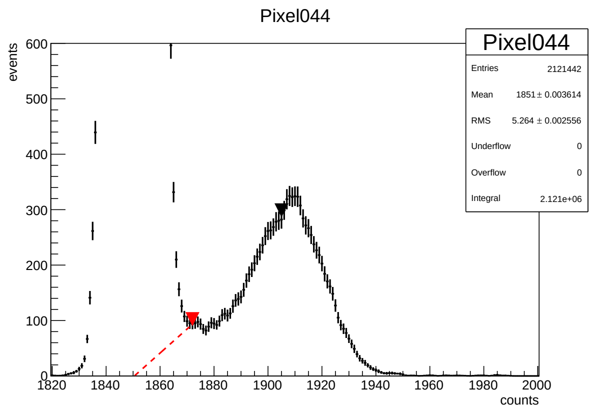

Figure 1: An example of a single photoelectron (pe) spectrum for one pixel of a M64 PMT, taken by the DAQ system discussed in section 4. The spectrum is shown as a histogram of the number of events (see section 3) with a given charge, in counts, returned by QDC. The first peak is the pedestal, corresponding to events in which no pe are collected at the anode of the pixel. The second peak, on the right, corresponds to events in which 1 pe is emitted. The 2 pe peak is not visible as a consequence of the Poisson statistics (see text). The gain of the pixel is the difference between the mean of the 0 pe and 1 pe peaks, while the efficiency of the pixel is proportional to the surface of the 1 pe peak. Here the mean of the 1 pe is shown by the black marker, with the valley between the two peaks taken at the location of the red marker. The red line shows a correction to the surface of the 1 pe peak assuming a linear dropoff from the valley.

evidenced by the fact that they passed Hamamatsu testing), but the large current drawn by the dynode is a potential problem, and these PMTs can not be used.

Due to this, sorting a sufficiently large number, in principle every PMT to be used in the experiment, is necessary before any EC can be constructed. This sorting can be thought of as a calibration of the EC units. For JEM-EUSO, sorting the PMTs requires measuring the gain and efficiency of 64 pixels for over 5,000 photomultiplier tubes. In EUSO-balloon the sorting of a total of 40 PMTs serves as model and test run for future sorting for JEM-EUSO. It includes: building and calibration of a data acquisition (DAQ) system, taking spectra for each pixel of each PMT, and final analysis to determine the gain and (relative) efficiency.

3 Single Photon Gain and Efficiency

In order to measure both the gain and efficiency separately we work in single photoelectron mode. Using the technique of Lefeuvre et al. [7, 8] the gain can be measured with a total error of $\simeq 2\%$, and the absolute efficiency can be measured to around 3% by using a comparison with 2 NIST photodiodes The PMTs to be sorted are received and measured with the BG3 filter glued on. The response of the PMT is measured as a charge spectrum using charge to digital conversion (QDC) electronics. A detailed explanation of the measurement technique can be found in Gorodetzky et al. ([9], this conference).

An example of a measured single photoelectron spectra is shown in figure 1. The gain, the average number of electrons arriving at the anode for a collected photoelectron, is the difference in charge between the 0 pe (the pedestal) and 1 pe peak. The total efficiency is the product of the quantum efficiency, i.e. the efficiency of converting photons to electrons at the cathode, and the collection efficiency, that of collecting emitted pe onto the first dynode. The total efficiency is proportional to the surface of the 1 pe peak.

For the error to be at the 1% level the number of 2 pe events (gates during which 2 pe are created and collected) in the spectrum must be negligible. As the emission of a pe is a Poisson process, for the number of 2 pe to be negligible requires that the average rate of pe be such that

$$n_{1\text{pe}} \leq 0.01 \times n_{0\text{pe}}.$$

As a 1% statistical error requires 10^4 signal events, and working in single photoelectron mode requires a signal to background ratio of 1%, we require at least 10^6 events per spectrum. To sort a reasonable number of PMT per day, the time per PMT should be on the order of minutes, which then requires a DAQ rate in the range of kHz.

The fact that we must measure 64 spectra in parallel (one for each pixel), makes the use of amplifiers difficult and, more importantly, expensive. This means that the resolution of the QDCs is a key component of the measurement. The M64 PMT has an typical gain of $\simeq 1 \cdot 10^6$ at a cathode voltage of 900 V. To be sure that the worst pixels of each PMT can be measured, we sort the PMTs at a cathode voltage of 1100 V, where the gain is factor ≈ 7 higher. At a gain of $1 \cdot 10^6$ the separation between the 0 pe and 1 pe peak is 160 fC, and the resolution of the QDC must be high enough to divide this charge into a enough bins that the 0 pe and 1 pe peak can be reliably separated.

4 The Data Acquisition System

The need for a data acquisition rate of several kHz can be easily satisfied by CAMAC or VME hardware. While VME is more modern and faster, we have found that the best available VME QDCs have a conversion resolution in the range of 100 fC per count. The high transfer rate of digital VME modules, and the fact that they are not shielded, makes VME less suited to precision charge measurements than CAMAC. To meet the needs of PMT sorting we used the CAEN model C1205 CAMAC QDC . The C1205 is a Wilkinson-type QDC with 3 independent charge ranges. The lowest of these is 0 to 80 pC with a 12 bit resolution, giving a theoretical conversion of 21 fC per QDC count. Each C1205 has 16 channels with inputs in Lemo format, meaning that 4 modules are needed per PMT. The Lemo format of the QDC inputs is an advantage in terms of signal quality and the ease with which a single pixel can manipulated.

In our DAQ the CAMAC crate is interfaced to VME using a CBD 8210 CAMAC branch driver, and the VME is readout by Motorola VME processor board. Using CAMAC has the advantage of its relative simplicity and the existence of a large library of CAMAC hardware in our laboratory. Readout of the CAMAC through VME gives a high speed and the possibility to include VME hardware if needed.

4.1 QDC Characterization

To extract the absolute gain from the measured spectra the conversion from QDC counts to Coulombs must be known

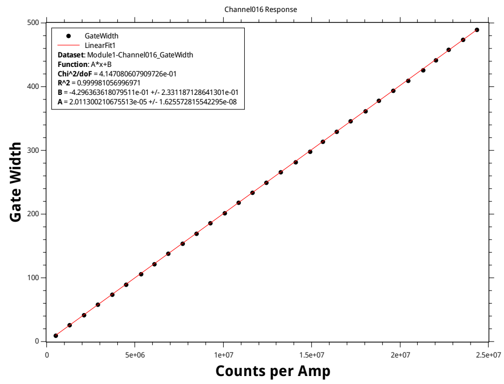

Figure 2: Example of the measured conversion curve for one input (here channel 16) of one QDC module. To have the required accuracy, and to account for the true integral nonlinearity of the QDC, the response is measured for ≥ 30 different input charges across the full range of the QDC. The measured data is shown by the black dots. The value of the conversion slope is taken from a least-squares fit to the data, shown in red.

with an accuracy of 1% or better. The conversion quoted by the manufacturer does not include the linearity properties of the QDC, nor the uniformity of channels within the same module, which is $\pm$ 5%. Any differential nonlinearity, the variation in width of each charge bin, in the QDC response can be reduced by using a built in sliding scale technique [10]. The integral nonlinearity, the total deviation from a linear response, must be measured across the full range of the QDC.

The response curve of each channel of each QDC was measured using a DC level with a resistor in series. The current through the input was measured with a picoammeter. An integration gate was created using a digital pulse generator, and for each gate width two spectra were taken, one with a high level and one at $\simeq 0$ mV to take the QDC pedestal. The resulting response curve for one channel of one module is shown in figure 2, plotted with the gate width in ordinates and the ratio of the QDC counts returned to the measured current in abscissa. The conversion slope was determined by performing a least squares fit of the measured curve. In order to reach a 1% accuracy on the slope, at least 30 data points per curve where needed, making more than 3840 measurements to complete a full characterization of all 64 QDC channels. To made this feasible, the readout of the picoammeter, control of the DC level, and the setting of the pulse generator where interfaced directly into the DAQ software, and the measurement of each response curve was scripted using the DAQ run control.

4.2 Data Acquisition Software

The data acquisition software has been written especially for this setup in C/C^{++} using the MIDAS data acquisition framework [11]. The software is divided into front-end programs which collect data, and back-end programs which handle background processes, run control, data analysis, and storage. The front-end which controls the CAMAC crate runs directly on the VME processor board and connects through Ethernet to the desktop which histograms, analyzes, and stores the data. Although in our case all the software has been developed on Linux, the entire system is portable

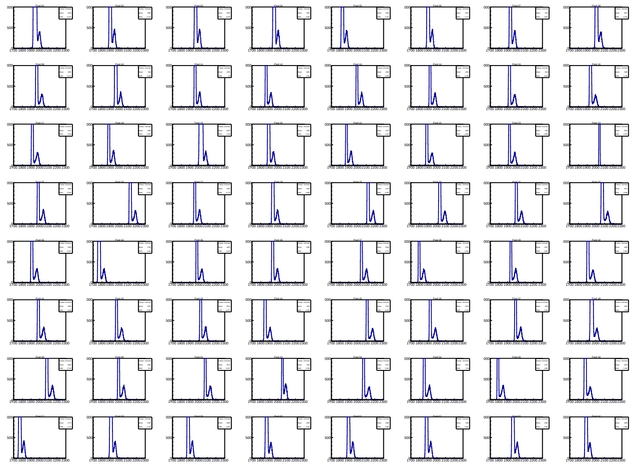

Figure 3: 64 spectra taken for one M64 PMT in a single run. Each pixel shows a good spe spectrum with a clearly visible pedestal and 1 pe peak.

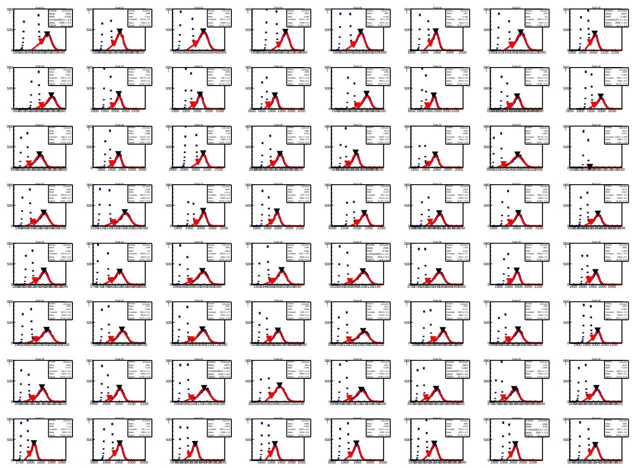

Figure 4: The 64 spectra of figure 3 after analysis by the routine discussed in section 4.2. For each pixel the location of the 1 pe peak mean and the valley have been found and marked. The red line shows a Gaussian fit to the 1 pe peak as a reference. One spectrum of these 64 can be seen in detail in figure 1.

and capable of running on any operating system.

This setup allows the acquisition to proceed to a rate of 2 kHz for all 64 channels in parallel with 100% efficiency. In this configuration, the rate is limited by the CAMAC signal definitions. As the C1205 is compatible with the FAST-CAMAC standard, a upgrade of the CAMAC crate controller to a FAST-CAMAC compatible model would increase the readout rate by a factor of 2 - 10 ,[12].

Other hardware is also interfaced to the DAQ software, such as the periodic readout of the NIST photodiode and control of the XY movement on which the light source is mounted. A full feed-back loop between the run analysis and control is possible. This allows complex tasks such as automatically centering on a given pixel with micron precision, and scanning the full photocathode of a PMT pixel by pixel.

An example of 64 spectra measured during one run are shown in figure 3[2]. Analysis poses a particular problem, as analyzing 64 spectra by hand for 5000 PMTs would be a huge task. We therefore developed a simple and robust software analysis using ROOT which searches within each measured spectrum for the valley between the 0 and 1 pe peak. The routine avoids using any fitting procedures to reduce the possibility of unphysical results which would require an external control by a physicist.

This analysis is performed automatically at the end of the run, and the routine has access to the NIST measurement results and the characteristics of the QDC so that it directly outputs a measured gain and efficiency for each pixel. The 64 spectra in figure 3 can be seen after analysis in figure 4. For each pixel the valley, shown by the red marker, has been found and the mean of the 1 pe peak has been determined, shown by the black marker. The red line shows a Gaussian fit to the 1 pe part, which is used only as a cross check.

5 Conclusion

The DAQ setup described works extremely well, and has already been used in the sorting of a number of PMTs. Results such as those shown in figures 1, 3, and 4 are typical. In addition to its use in sorting, this setup is a powerful tool to be used in all the photodetection test bench activities at APC.

In the near future the same system will be used to test the completed EC units for EUSO-balloon. This test is necessary because the potting which surrounds the ECs changes the electrostatic properties of the PMTs in the EC. The DAQ system developed for the sorting will be used to measure the gain of each pixel in the EC and the absolute efficiency of several pixels within each PMT. The relative efficiency of all pixels will then be measured using the ASIC readout electronics and this relative efficiency will be converted to an absolute one using the absolute efficiencies of the pixels measured with the QDC. In the farther future the tools developed here will be leveraged towards the task of sorting 5000 PMTs for JEM-EUSO. Here the flexibility and power of the DAQ system will be extremely important, especially in scaling up to simultaneously measure multiple PMTs.

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