PMT electronics for high-resolution powder diffraction of CRISTAL and MARS beam-lines

M Bordessoule, T Bucaille, E Elkaïm and B Sitaud
Synchrotron Soleil, l'Orme des Merisiers, Saint-Aubin
BP 48, 91192 Gif-sur-Yvette cedex, France
E-mail: michel.bordessoule@synchrotron-soleil.fr

Abstract. The design and performance characterization of a multi-crystal X-ray scintillation detector are presented. These set-ups are used on the CRISTAL and MARS beam-lines of SOLEIL. Main topics, such as the measurement of the dead-time of the amplifier, the compromise between the energy resolution and the dead-time, are addressed in this article.

1. Introduction

Our goal was to build a multiple analyzing crystal stage for high resolution powder diffraction at the CRISTAL beam-line and the MARS beam-line at Synchrotron SOLEIL. Both the mechanical set-up and the electronics were locally designed. The photo-multiplier tubes (PMT) and scintillator crystal assemblies were provided by SCIONIX. The 21 scintillating crystals used on the CRISTAL beam-line are YAP:Ce crystals, with a scintillation decay time of 25ns, while the 24 used on the MARS beam-line are NaI:Ti crystals, with a scintillation decay time of 240ns. A classical amplifier design, with fixed time shaping, fulfilled our requirements for a suitable amplifier that delivers short pulses while providing good energy resolution. The shaped pulses are observable through a multiplexer. For each detector channel, an energy window discriminator validates the shaped pulse, and generates a 30ns TTL pulse as long as the maximum of the pulse is within the upper and lower discriminating levels. Thus, the associated cPCI standard cards provide, for each channel, the high voltage, the two levels of the window discriminator, the TTL counter, and the multiplexer.

2. Electronics

These in-house electronics are similar to a fast spectroscopy shaping amplifier, although without the need for a base-line restorer, since with the grounded anodes PMTs each amplifier is DC-coupled to the PMT by a 50Ω cable. The input impedance of the amplifier is 50Ω. Both the high-voltage (HV) and signal cables are enclosed in a supplementary shield. The gain and the time constant of the amplifiers are fixed. The height of the output pulse can be adjusted with the HV of each PMT.

The principle of this implementation relies on cascading filters of the second order. This design has better features than the classical CR-RC design, because it needs a smaller number of amplifiers for a given degree of shape approximation, and has a much faster baseline return, since each amplifier has a heavily damped sinus impulse response. Let us decide to design a filter with a Gaussian impulse response, whose standard deviation is σ.

The frequency synthesis technique used here allows us to define a realizable filter with a frequency module similar to a Gaussian. Other symmetrical pulse shapes could be approximated as
well, from their frequency module. Using three operational amplifiers, each for a filter of the second order, limits to six terms the Taylor series $Q_2(p)$ approximating a Gaussian function $Q_1(p)$, with $p = \sigma s$ where $s$ is the Laplace variable. The function $Q_2(p)$ is the product of three Hurwitz second order polynomials.

\[
Q_2(p) = \exp\left( -p^2 \right) = Q_2(p) = \sum_{i=0}^{i=6} \left( -1 \right)^{i} \frac{p^{2i}}{i!} = \prod_{i=1}^{i=3} \frac{(p+a_i)^2 + b_i^2}{a_i^2 + b_i^2}
\]

(1)

The conjugate values ($\pm a_i, \pm b_i$) are the three pairs of solutions of $Q_2(p)=0$. Only the positive real parts are considered. The zeroes of (1) are readily found with a mathematical program, and are tabulated. The values of the passive components of the filter are defined by identifying each $a_i$ and $b_i$ pair to each of the three cascaded Sallen-Key filters. The product of the three transmittances is the Laplace transform of the approximation of the Gaussian function. By definition, the frequency response approximates a Gaussian up to the 6th term.

3. Choice of the shaping time, example of a CeBr$_3$ scintillator

The counting precision is limited on the one end by the dark count rate, linked to the radioactivity of the scintillator and the dark current of the PMT, and is measured in Figure 3 with the amplifier for the YAP. On the other end, the electronics dead-time, as shown in Figure 5, is another limitation. It is necessary to determine a compromise between a short dead-time, and a sufficient energy resolution.

The fluctuation of the output pulses height is due to the varying number and time of arrival of the photoelectrons, described by a non-constant parameter Poisson distribution, whose parameter is the scintillator's decay time. The energy resolution is defined as the distribution of the maxima of the output pulses. A short shaping time does not allow collecting all the photoelectrons and lowers the contribution of the second term of (2). Also, a short shaping time is equivalent to a large bandwidth filter, illustrated in Figure 1, and degrades the signal over noise ratio, raising the contribution of the third term of (2). The PMT bandwidth is under 100MHz. To give an example with a recent scintillator, a 1GHz sampling oscilloscope recorded 4,000 events, off-line at 6keV, from a CeBr$_3$ scintillator and PMT assembly from Scionix. The PMT is a low dark current Hamamatsu R1924. Each event was convoluted with a Gaussian of standard deviation $\sigma$, and the resolution plotted in Figure 2.
In order to simulate each PMT event, a Monte-Carlo program was written. The main parameters are the decay constant of the scintillator as previously recorded, the PMT noise factor, and the dark current noise. The first task is to generate sets of non-homogeneous i.e. a non-constant parameter Poisson distribution, whose parameter is N3=22 the mean number of photoelectrons per event. The sum of Poisson distributions also is a Poisson distribution, whose parameter is the sum of the component parameters. A matrix of N1 rows and N2 columns is filled with values representing the number of photoelectrons for each ∆t=1ns. N1 is the number of trials and N2 defines a time span of (N2-1)∆t, suitable for representing both the exponential of the scintillator (τ=20ns) and the Gaussian filter. Each column is a classical Poisson toss, so each row is a non-homogenous Poisson set, with N3 as the mean number of photoelectrons per event. Hence, the sum of the rows has the shape of the mean output pulse of the PMT. Each row is then multiplied by a set of Gaussian noise values, whose mean is one, representing the noise factor $N_{FPMT}=1.2$ of the PMT, and a Gaussian noise of 75eV is added. Then, each noisy event is convoluted with a Gaussian of standard deviation $\sigma$, and the corresponding energy resolution is plotted in Figure 2.

4. Linearity and energy resolution measurements on the PMTs of the CRISTAL beam-line

The energy resolution is linked to the efficiency of the optical coupling between the YAP:Ce crystal and the PMT. The variance $\sigma_{keV}^2$ of the measured energy $E_{keV}$, stated in keV, is given by (2). The parameter $N_{FPMT}=1.45$ is the noise factor of the PMT Hamamatsu R647, measured as the broadening of the single electron peak. The scintillator yield is $SY=25$ photons per keV at 370nm.

$$\sigma_{keV}^2 = \left( IR \cdot E_{keV} \right)^2 + E_{keV} \cdot \frac{N_{FPMT}}{SY \cdot CE \cdot QE} + \sigma_{amp}^2$$  \hspace{1cm} (2)

$QE=25\%$ is the quantum efficiency of the photocathode at 370nm. The data of Figure 4, taken on the CRISTAL beam-line, fits with (2) for a collection efficiency $CE=32\%$. The amplifier noise is 4mV$_{rms}$ i.e. $\sigma_{amp}=53eV$. The small coefficient $IR=0.55\%$ is the rms intrinsic energy resolution of the YAP:Ce crystal. The mean number of photoelectrons is the product ($E_{keV} \cdot SY \cdot CE \cdot QE$).
5. Dead-time measurements on the electronics of the MARS beam-line (NaI)

A Poisson-like impulse generator triggered a fast Canberra 2126 CFD discriminator, whose pulse-pair resolution is about 15ns. Two sets of data were recorded off-line, for different output signals and discriminator levels. The rates at the input and the output of the amplifier are corrected for the fixed 15ns dead-time of the CFD. Then these records are compared to the Takács\textsuperscript{8,9} formula of (3) in which $OR$ and $IR$ are the input and output rates, $\tau_1$ is a time constant around 250ns, and $\theta$ is a coefficient allowing a smooth transition between the extended and non-extended dead-time classical formulas.

\begin{align}
OR = \theta \cdot IR \left[ \exp (\theta \cdot \tau_1 \cdot IR) + \theta - 1 \right]^{-1}
\end{align}

The shape of Figure 6 shows, for a low input rate, the dependence of the model on the parameters. This threshold influence on the dead-time model limits the acceptable precision of a realistic correction, at an input rate of around 1MHz, over the aim of our detector systems.

6. Conclusion

Two acquisition chains, designed in-house at a fraction of the price of commercial offers, are reliably delivering data on MARS and CRISTAL. The thoroughly investigated main characteristics are determined by the quality of the scintillator and PMT assembly, not by the ancillary electronics. Measurements with the same electronics and a recent CeBr$_3$ scintillator are also presented.

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