Evaluating vacuum phototriodes designed for the PANDA electromagnetic calorimeter

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Abstract

In this work properties of a vacuum phototriode (VPT) and preamplifier unit designed for the electromagnetic calorimeter of the PANDA experiment being built at FAIR are investigated. With the use of lead tungstate and lanthanum bromide scintillators the VPT properties are studied at low photon energies, from tens of keV in the lanthanum bromide measurements and between 10 MeV and 60 MeV in the lead tungstate measurements. At these energies the noise of the VPT unit can be expected to influence its performance significantly. It is shown that the noise contribution to the measured energy resolution, under optimal conditions, is consistent with a fluctuation of (one standard deviation) approximately 200 electrons at the VPT anode. For a lead tungstate crystal this is equivalent to a noise of 1.2 MeV. For lanthanum bromide this makes it possible to use VPTs for gamma ray spectroscopy above a few hundreds of keV without noticeable effects on the energy resolution compared to measurements with a standard photomultiplier.

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1. Introduction

The vacuum phototriode (VPT) is a one stage photomultiplier. Its design allows for operation in magnetic fields where the performance of a multi-stage photomultiplier tube (PMT) would not be acceptable.

A VPT, typically operating at a cathode–anode voltage around 1000 V, has a gain factor of the order of 10 which is small compared to that of a multi-stage device (10^5 or more for a conventional PMT). In comparison, the lower number of stages and the lower overall gain make the VPT gain less sensitive to drifts in the supply voltage and change in rate. However, the energy equivalent noise becomes larger and sets limits on the energy threshold.

VPTs are used for parts of the electromagnetic calorimeters of the CMS experiment [1–3] at LHC and currently operating in a magnetic field of 3.8 T. VPTs have been used for the DELPHI [4] and OPAL [5] experiments at LEP and in the CMD-2 detector [6] and the KEDR detector at [7] VEPP. Some characteristics of these experiments concerning the VPTs are given in Table 1.

Common to most of these applications of VPTs is the detection of GeV-energy particles. Reported characteristics, cf. Table 1, are consistent with an rms noise at the VPT anode, σ_{noise}, in the range of 260–480 electrons. This noise restricts the possibilities of setting low single-crystal energy thresholds.

In this paper we present results of investigations of two applications of VPTs at much lower energies. Firstly, the use in the PANDA forward endcap electromagnetic calorimeter (FwEEMC), equipped with lead tungstate (PbWO_4 or PWO) scintillators, for photon energies down to a few MeV. Secondly, for read-out of lanthanum bromide (LaBr_3) scintillators at photon energies of the order 100 keV. In both cases VPTs from Hamamatsu,^1 designed for the PANDA FwEEMC, have been used.

PWO and LaBr_3 represent two rather extreme scintillator materials with respect to the light yield. According to the Particle Data Group the light output, relative to NaI, is 0.00377 for PWO and 1.3 for LaBr_3. Some characteristics of these experiments concerning the VPTs are given in Table 1.

Table 1: Characteristics of VPTs used in various applications

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Scintillator</th>
<th>Energy range</th>
<th>Noise (σ_{noise}, electrons)</th>
<th>Gain factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>PbWO_4</td>
<td>100–300 GeV</td>
<td>260–480</td>
<td>10^5</td>
</tr>
<tr>
<td>DELPHI</td>
<td>PbWO_4</td>
<td>100–300 GeV</td>
<td>260–480</td>
<td>10^5</td>
</tr>
<tr>
<td>OPAL</td>
<td>PbWO_4</td>
<td>100–300 GeV</td>
<td>260–480</td>
<td>10^5</td>
</tr>
<tr>
<td>KEDR</td>
<td>PbWO_4</td>
<td>100–300 GeV</td>
<td>260–480</td>
<td>10^5</td>
</tr>
<tr>
<td>PANDA</td>
<td>PbWO_4</td>
<td>100 keV–60 MeV</td>
<td>1.2 MeV</td>
<td>10^5</td>
</tr>
<tr>
<td>PANDA</td>
<td>LaBr_3</td>
<td>100 keV–60 MeV</td>
<td>1.2 MeV</td>
<td>10^5</td>
</tr>
</tbody>
</table>

^1 Hamamatsu, http://www.hamamatsu.com,
The hadron-physics PANDA experiment at FAIR [9] investigates the strong interaction in annihilations of cooled antiprotons with momenta in the range 1.5–15 GeV/c. Here precision electromagnetic calorimetry over a large energy range, from a few MeV up to several GeV, is required [10]. Due to the expected high count rate, magnetic calorimetry is needed and the NaI(Tl) calorimeters used to date do not satisfy the required resolution [11]. However, the NaI(Tl) calorimeters used to date do not satisfy the required resolution [11].

### 2. Experiment

#### 2.1. Photosensors

##### 2.1.1. The VPT unit

The VPT units used in this work consist of a Hamamatsu R11357 MOD3 VPT, with an outer diameter of 23.8 mm, and a preamplifier and voltage divider SP883d produced at Basel University. The circuit diagram of the voltage divider is shown in Fig. 1 and the characteristics of the VPT and the preamplifier are summarized in Table 2.

A schematic illustration of a VPT is shown in Fig. 2. As scintillation photons hit the photocathode, electrons are emitted and accelerated towards the anode. The anode consists of a fine metal-mesh with geometrical transparency of roughly 50%. About 50% of the electrons are collected directly by the anode. The remaining electrons pass through the mesh and impinge on a dynode located behind the mesh. Secondary electrons from the dynode are ejected and accelerated toward the anode.

With an effective multiplication factor \( \delta \) at the dynode, the described process leads to a gain of

\[
g = \frac{N_A}{N_C} = \frac{1}{2} (1 + \delta)
\]

where \( N_C \) and \( N_A \) are the (average) number of photoelectrons emitted from the cathode and the final number of electrons at the anode, respectively.

A fluctuation in the number of electrons at the anode, \( \sigma_A \), is thus related to a fluctuation in the number of photoelectrons at the cathode, \( \sigma_C \), by

\[
\sigma_A = g \sigma_C \sqrt{2 - \frac{1}{g^2} - \frac{1}{2g^2}}
\]

For a given scintillator coupled to the VPT, with a ph.e. yield \( \beta = N_C/E \) (i.e. the average number of photoelectrons emitted at the cathode per unit energy deposited in the scintillator), the stochastic contribution to the relative energy resolution (in terms of deposited energy \( E \)) is then expected to be

\[
\frac{\sigma_E}{E} = \frac{\sqrt{\frac{N_A}{N_C}}}{\beta E} = \sqrt{\frac{2}{\beta E} \left(1 - \frac{1}{2g^2} - \frac{1}{4g^2} \right)}
\]

which to zeroth order in \( g^{-1} \) equals \( \sqrt{2/N_C} \). The corresponding value for a PMT is \( \sqrt{1/N_C} \). It should be noted that \( \beta \) may be different due to e.g. size, window and cathode material.

In the present setup, the VPT anode is connected to the preamplifier and voltage divider which is soldered directly to the pins of the VPT. To minimize the pick-up noise, the VPT unit was placed in a cylindrical Faraday cage consisting of a copper tube (shielding the preamplifier) extended with an aluminium foil (shielding the VPT), cf. Fig. 3. The coaxial power cables and signal cable were additionally shielded by a flexible metal hose. The preamplifier was powered by batteries to avoid disturbance from the power grid.

#### 2.1.2. The PMT

For all measurements presented here, we have, for possible comparisons, also used PMTs as light sensor. The PMTs used were the 19 mm tubes Photonis' XP1912 and Hamamatsu R1450, both equipped with the Hamamatsu E974-13 voltage divider. Characteristics of the R1450 PMT are summarized in Table 2. Both tubes have a photocathode diameter of 15 mm (minimum).

The voltage was set below 1000 V to avoid a nonlinear energy response. In order to have similar shaped pulses, for VPTs and

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**Table 1** Reported and estimated (denoted by ‘\( \ast \)) characteristics of some experiments using VPTs.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Scintillator</th>
<th>VPT Type</th>
<th>rms noise at the cathode, ( \sigma_C ) [photoelectrons]</th>
<th>Energy-equivalent noise, ( \sigma_{\text{eq}} ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS [^{\ast}1-3]</td>
<td>PbWO(_4)</td>
<td>RIE FEU 388</td>
<td>80(^{\ast})</td>
<td>1100(^{\ast})</td>
</tr>
<tr>
<td>OPAL [5]</td>
<td>Pb-Glass</td>
<td>RTC 1501/LF</td>
<td>250</td>
<td>0.6</td>
</tr>
<tr>
<td>CMD-2 [6]</td>
<td>BGO</td>
<td>produced by BINP</td>
<td>34(^{\ast})</td>
<td>360(^{\ast})</td>
</tr>
<tr>
<td>KEDR [7]</td>
<td>CsI</td>
<td>Hamamatsu R2184-01</td>
<td>20(^{\ast})</td>
<td>0.02</td>
</tr>
</tbody>
</table>

\[^{\ast}\] Results correspond to a 3 \( \times \) 3 matrix of individual detectors.

\[^{\ast}\] Estimated from reported numbers.

\[^{\ast}\] Presently Photonis.

\[^{\ast}\] Result from separated test of individual crystals.
Table 2
Some characteristics of the Hamamatsu R1450 PMT, R11357 MOD3 VPT and the SP883d preamplifier.

<table>
<thead>
<tr>
<th>PMT characteristics, Hamamatsu R 1450</th>
<th>300–650 nm</th>
<th>420 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral response</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength of maximum response</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photocathode</td>
<td>Bialkali</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum effective diameter</td>
<td>15 mm</td>
<td></td>
</tr>
<tr>
<td>Window material</td>
<td>UV transmitting glass</td>
<td></td>
</tr>
<tr>
<td>Number of stages</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Quantum efficiency at peak wavelength</td>
<td>≈ 20%</td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>≈ 5 × 10^6 at 750 V</td>
<td></td>
</tr>
<tr>
<td>Anode dark current (after 30 min storage in darkness)</td>
<td>max. 50 nA, typ. 3 nA</td>
<td></td>
</tr>
<tr>
<td>VPT characteristics, Hamamatsu R 11357 MOD 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral response</td>
<td>300–650 nm</td>
<td>420 nm</td>
</tr>
<tr>
<td>Wavelength of maximum response</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photocathode</td>
<td>Bialkali</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum effective diameter</td>
<td>16 mm</td>
<td></td>
</tr>
<tr>
<td>Window material</td>
<td>UV transmitting glass</td>
<td></td>
</tr>
<tr>
<td>Number of stages</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Quantum efficiency at peak wavelength</td>
<td>20–23%</td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>6–8 at 750 V</td>
<td></td>
</tr>
<tr>
<td>Anode dark current (after 30 min storage in darkness)^a</td>
<td>Range 0.23–6.1 nA, median: 1.2 nA</td>
<td></td>
</tr>
<tr>
<td>Preamplifier characteristics, SP 883d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum bias voltage</td>
<td>+ 1500 VDC</td>
<td></td>
</tr>
<tr>
<td>Power supply, floating</td>
<td>max. ± 6 V, ± 6 mA, − 1.5 mA</td>
<td></td>
</tr>
<tr>
<td>Power consumption (depending on rate and energy)</td>
<td>90 mV with 50 Ω load</td>
<td></td>
</tr>
<tr>
<td>Maximum single pulse input charge</td>
<td>4 pC</td>
<td></td>
</tr>
<tr>
<td>Output signal</td>
<td>+0.5 V/pC at 50 Ω</td>
<td></td>
</tr>
<tr>
<td>Maximum output voltage (with ±6 V power supply)</td>
<td>&gt; +2.5 V at 50 Ω</td>
<td></td>
</tr>
<tr>
<td>Output impedance</td>
<td>50 Ω</td>
<td></td>
</tr>
<tr>
<td>Rise time (with input load/detector capacitance 22 pF)</td>
<td>&lt; 20 ns</td>
<td></td>
</tr>
<tr>
<td>Feedback time constant</td>
<td>25 μs</td>
<td></td>
</tr>
<tr>
<td>Input load/detector capacitance C_d</td>
<td>0–300 pF</td>
<td></td>
</tr>
<tr>
<td>Typical noise performance at C_d = 22 pF (shaping 650 ns)</td>
<td>σ_{A_{noise}} = 235 electrons at −25 °C</td>
<td></td>
</tr>
<tr>
<td>Typical noise performance at C_d = 22 pF (shaping 200 ns)</td>
<td>σ_{A_{noise}} = 450/300 electrons at −25 °C</td>
<td></td>
</tr>
</tbody>
</table>

^a For the studied batch of VPTs.
2.2. Properties of PWO and LaBr$_3$ scintillators

The properties of the VPT unit when used with two types of inorganic scintillating materials, PWO and LaBr$_3$, were investigated. The decay time of the scintillating light for the two materials is similar (10–30 ns) but the light yields differ significantly. From the relative light output [8], assuming a light yield for NaI of 4, significantly. From the relative light output [8], assuming a light yield for NaI of 4, the intrinsic light yield at room temperature of PWO is of the order of 150 photons per MeV, compared to approximately 5.2 × 10$^4$ for cerium-doped LaBr$_3$. The maximum luminescence occurs at 420 nm and 360 nm for the two materials.

In practice, with PMT light sensors covering the face of the crystal, a ph.e. yield $\beta \leq 90$ ph.e. per MeV (at $-25^\circ C$) [12] has been reported for PWO crystals, 200 mm long, of the improved composition, denoted PWO-II [13]. A corresponding number for a cylindrical LaBr$_3$ crystal (diameter 25.4 mm, length 25.4 mm) at room temperature is approximately 17 000 [11]. While the temperature dependence of the light yield is rather strong for PWO ($-2.0\%$ per degree C at room temperature [13]), the light yield of LaBr$_3$ does not change appreciably with temperature close to room temperature.

The PWO crystals used in this work were produced by BTCP$^4$ for the PANDA FwEEMC. These crystals are 200 mm long, slightly tapered, with a rear short-end area of 26.0 × 26.0 mm$^2$. For these crystals connected to the 19 mm PMTs used in this investigation, the ph.e. yield is approximately $\beta = 25$ ph.e. per MeV at $-25^\circ C$ was measured.

The LaBr$_3$ crystals used are of cylindrical shape, diameter 17 mm and length 10 mm, produced by Saint-Gobain. The crystals were coupled to the light sensor by an optical grease Visilox V–788.$^5$ The photoelectron yield of the LaBr$_3$ crystal equipped with the VPT unit was measured to be approximately 500 times larger than that of a FwEEMC PWO crystal with the same VPT attached, and operated at $-25^\circ C$. Thus, the energy range 10–100 MeV in a PWO crystal corresponds to a range 20–200 keV in LaBr$_3$.

In order to have the best possibility for comparisons, all measurements reported here are carried out at $-25^\circ C$.

2.3. Measurements with PWO

2.3.1. The tagged photon facility at the MAX IV Laboratory

At the tagged photon facility [14] a mono-energetic electron beam impinges on an aluminum radiator foil whereby bremsstrahlung photons are produced. The energy of a bremsstrahlung photon equals the energy loss of the corresponding electron. In order to obtain information on the photon energy, the energy of the post-bremsstrahlung electrons is analyzed in a magnetic spectrometer equipped with a detector hodoscope in the focal plane. The tagger hodoscope consists of 63 plastic scintillators and was positioned to enable the detection of electrons corresponding to photon energies between approximately 10 and 63 MeV in 63 tagger channels. The intrinsic energy resolution of each tagger channel was measured in a previous experiment [15] and can be compensated for in the analysis. A collimator with diameter 5.4 mm was used in order to narrow the photon beam to 7 mm in diameter (FWHM of the spatial intensity distribution) at the position of the experiment.

2.3.2. The PWO setup

A realistic prototype [15] of the central part of the PANDA FwEEMC consisting of 25 PWO crystals arranged in a 5 × 5 array was used in this work. All crystals were equipped with VPT units (cf. Section 2.1). In the analysis only data from the central 3 × 3 matrix was used.

The prototype was mounted on a coordinate table inside a climate chamber. By moving the prototype, any crystal could be placed in the photon beam. All measurements were performed at $-25^\circ C$.

Some of the crystals were equipped with PMTs in a separate run, for possible comparisons.

For both VPT and PMT read-out, two different shaping amplifiers were used: a Mesytec$^6$ MSCF16, with a shaping time of 0.8 µs and 0.4 µs in separate runs, and a shaper provided by KVI, University of Groningen, [16] with 40 ns shaping time (the shaping time is here defined as the standard deviation of the, approximately, Gaussian output pulse shape). The latter shaper was designed for the FwEEMC to minimize pile-up at rates up to 1 MHz [17]. A peak-sensing ADC (CAEN$^7$ V785) was used to digitize the amplified signal from the Mesytec shaper and a QDC (Caen V792) was used for the KVI shaper. The data were recorded by a VME based data acquisition system.

The trigger to the data acquisition system was generated by a hit in the tagger hodoscope. Approximately 6% of the triggers corresponded to a detected photon in the PWO array.

It should be noted that these investigations were done under favourable conditions, compared to what can be expected in the PANDA experiment, with very well shielded detector units in a field-free environment. The beam intensity was adjusted to obtain a count rate of 40–150 Hz in a single hodoscope detector,
corresponding to a tagged photon count rate below 1 kHz in the PWO matrix. All results presented in the following were obtained using the Mesytec shaper with 0.8 \( \mu \)s shaping time, unless otherwise stated.

### 2.3.3. Analysis and results

Fig. 4 shows the response to tagged 36 MeV photons of a single PWO detector, for VPT and PMT read-out, respectively. Comparing the two spectra, the noise contribution from the VPT unit is evident from the sharp rise of intensity below 10 MeV. The width of the peak is also slightly larger for the VPT case. However, the width of the peak is to a large extent governed by shower leakage out of the crystal, which depends on the distribution of tagged photons over the crystal surface. Care was taken to reproduce the experimental conditions in each measurement. The beam profile was defined by a collimator with an opening diameter of 5.4 mm. In this way only the central part of the photon beam was reaching the detectors. The distance between the collimator and detector setup was kept constant. The beam profile was measured at several occasions and the variations were small around a value of 7 mm for the full width half maximum of the intensity distribution, horizontally and vertically. By monitoring the shower distribution in neighbouring crystals, the centring of the beam in a given crystal could be done with a precision of approximately 1 mm.

The absolute energy scale for each PWO detector was obtained by assigning the expected energy deposition (using GEANT4 [18, 19] simulations with realistic conditions concerning e.g. beam intensity distribution and photoelectron statistics) to the location of each tagged photon peak. Quantitatively, to characterize peaks in the pulse-height spectra, these were fitted by a Novosibirsk function [20, 21], which contains four parameters: the mode \( \mu_0 \) (location of the function maximum), the width \( \sigma \) (which equals FWHM/2.35), a skewness parameter \( \tau \) and the amplitude. The calibration function was parameterized by a 2nd order polynomial. An example is shown for one of the PWO detectors in Fig. 5.

In Fig. 6 the single-crystal energy resolutions, \( \sigma \), as a function of deposited energy are shown for VPT and PMT read-out. At the higher energies the resolution is dominated by the contribution caused by fluctuations of the energy leakage out of the crystal, and no significant difference in resolution is observed for VPT and PMT read-out. The difference observed at lower energies is attributed mainly to the additional noise from the VPT unit. As an example, the resolution around 19 MeV (deposited energy) is 3.0(1) MeV and 2.6(1) MeV for VPT and PMT read-out, respectively. With the simplistic assumption that this difference is only due to the additional noise from the VPT unit, the energy equivalent noise of the VPT would be 1.5(2) MeV (assuming the PMT noise to be negligible in comparison). However, other differences might contribute. For instance, the stochastic term would be approximately (cf. Eq. (4)) \( \sigma = \sqrt{2 E / p_{\text{VPT}}} \) and \( \sigma = \sqrt{E / p_{\text{PMT}}} \) for VPT and PMT read-out, respectively. Taking the stochastic term into account, using \( \beta = 25 \) p.e. per MeV for both PMT and VPT read-out, the average VPT noise in the energy interval 10–40 MeV is 1.3(1) MeV.

The constant noise for VPT read-out has also been estimated by comparing the measured resolution to the results of realistic GEANT4 simulations. The measured spatial intensity distribution of the photon beam, the energy distribution of the beam as well as photoelectron statistics were implemented in the simulations. Different noise contributions were added in order to get an agreement with measured resolutions. In Fig. 7 results of the simulations for different noise contributions are compared to the
measured energy resolutions. The best overall agreement between simulated and measured resolutions is obtained for an rms noise of \( \sigma_{\text{noise}} = 1.0(2) \text{ MeV} \). From the two estimates we conclude that the energy-equivalent noise of this single crystal, read out by VPT, is \( 1.2(1) \text{ MeV} \).

In Fig. 8 the results for the single-crystal resolution using shorter shaping times are shown (400 ns and 40 ns). For 400 ns shaping time the resolution is slightly worse compared to using 800 ns. For 40 ns shaping time we show the results for the 5 highest energies only, where the almost constant resolution indicates that the noise is the dominating factor (\( \sigma_{\text{noise}} \approx 9 \text{ MeV} \)). As expected, the constant noise term increases as the shaping time decreases.

The response of the total 3 × 3 matrix with VPT read-out was obtained by summing the calibrated signals of all nine detector elements. An energy threshold was set on the signals of the detectors (except the central one where the photon beam was aimed) in order to avoid summing up noise only. The optimal threshold setting was obtained by determining the resolution at each tagged photon energy as a function of threshold (cf. the inlay of Fig. 9), and finding the threshold value giving the best resolution. In Fig. 9 the distribution of optimal thresholds for 58 tagged photon energies is shown. The optimal threshold varies strongly with photon energy in this energy region. At the lowest energies it is around 5 MeV and above. At the highest energies it tends to a value of 4 MeV, which is close to \( 3 \times \sigma_{\text{noise}} \), an often used relation between noise and threshold in high-energy physics. The overall optimal threshold is taken as the average value, 4.9 MeV. Using this threshold, common for all tagged photon energies, the resolution as a function of photon energy is determined. Fig. 10 shows the result for the relative energy resolution. We conclude that the relative resolution varies between 21% and 9% in the energy interval investigated (11–60 MeV). In a measurement with PMTs the corresponding values for the relative resolution were 7.7% and 3.3% [15].

2.4. Measurements with LaBr₃

2.4.1. The LaBr₃ setup

The LaBr₃ crystal was attached to the VPT unit. For comparison, the same crystal was also attached to the Hamamatsu R1450 PMT. The voltage of the VPT was set to +750 V. For the PMT we used a voltage of −900 V, which is significantly lower than the maximum rating of −1500 V. With a voltage of −900 V, where the nominal gain is less than \( 10^5 \), a highly nonlinear gain is avoided (since the scintillation pulses are short, momentarily currents are large). The preamplifier signals were shaped and amplified in an Ortec\(^5\) 572 spectroscopy amplifier, using a shaping time of 1.0 μs, and analyzed in a Tukan\(^6\) multi-channel analyzer. The measurements were done at −25 °C.

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2.4.2. Analysis and results

In Fig. 11 two gamma-ray spectra obtained using the radio-active source $^{137}\text{Cs}$ are shown. The two spectra correspond to VPT and PMT read-out. We observe that the 662 keV peaks are almost identical indicating that, at this energy and with the present electronics, all effects contributing significantly to the resolution are the same, i.e. the additional noise contribution from the VPT unit is negligible. On the other hand, for the X-ray line (combination of several discrete lines) at approximately 31 keV, the noise contribution from the VPT unit is evident. Below this energy, the spectrum corresponding to the VPT read-out is dominated by noise.

For a quantitative estimation of the contribution of the noise, the gamma-ray peaks have been fitted by the sum of a Gaussian and a polynomial background. The obtained width ($\sigma$ of the Gaussian) for the 31 keV line is 6.1 and 3.1 keV for the VPT and PMT read-out, respectively. The resolution as a function of energy was measured by using several gamma-ray sources. In Fig. 12 we show the result at energies between 59 and 344 keV (obtained using $^{241}\text{Am}$ and $^{152}\text{Eu}$ sources) both for VPT and PMT read-out, respectively. If we assume that the square of the resolution (variance) is the sum of an energy-independent term, i.e. the constant noise, and an energy-dependent term, the constant noise can be obtained by extrapolating the resolution to zero energy. Technically this was done by fitting a second order polynomial in energy to the square of the resolution: 

$$\sigma^2 = \sigma^2_{\text{noise}} + bE + cE^2.$$  

For the VPT data the fit yields an energy equivalent noise of $\sigma_{\text{noise}} = 4.0(1)$ keV. The second term, if interpreted as the stochastic contribution, corresponds to a photoelectron yield of (cf. Eq. (4)) $\beta_{\text{VPT}} = 2/b = 15(2) \times 10^3$ p.e. per MeV. For the PMT read-out the data correspond to a slightly lower photoelectron yield $\beta_{\text{PMT}} = 1/b = 7.1(1) \times 10^3$ p.e. per MeV.

3. Discussion and conclusions

In Section 2.3 we conclude for the application with PWO that the energy equivalent single-detector noise ($\sigma_{\text{noise}}$) using VPT read-out, under favourable conditions, can be restricted to approximately 1.2(1) MeV. The measured equivalent noise is consistent with the electronic noise stated for the preamplifier in Table 2. Using the estimated value $\beta = 25$ p.e. per MeV and a VPT gain of 7, together with an energy-equivalent noise of 1.2 MeV, we obtain $\sigma_{\text{noise}} = 1.2 \times 7 \times 25$ electrons = 210 electrons which is comparable to the value of 235 electrons listed in Table 2. The corresponding fluctuation at the cathode would be $\sigma_{\text{noise}}^2 = 1.2 \text{ MeV} \times 25$ p.e. per MeV $\times 2^{-1/2} \approx 21$ p.e.

With an optimal threshold setting of approximately 5 MeV, the resulting relative energy resolution of a PWO matrix is approximately 21% and 9% at a photon energy of 13 and 60 MeV, respectively.

However, based on these results, we conclude that the investigated VPT unit does not fulfill the requirements of the PANDA electromagnetic calorimeter, i.e. a single-crystal equivalent noise and threshold smaller than 1 MeV and 3 MeV, respectively. More realistic conditions (e.g. the presence of magnetic fields, shorter shaping time) will not improve the situation. Thus, these results suggest that the use of the VPTs in the FwEEMC of the PANDA electromagnetic calorimeter should be ruled out.

Applying VPTs for the read-out of high light-yield scintillators like LaBr$_3$ is proven to work well down to energies of a few tens of keV. In the application presented, the noise contributes less than 20% to the energy resolution already at a gamma-ray energy of 300 keV. The energy-equivalent noise corresponds to a fluctuation...
in the number of ph.e. of $\sigma_{\text{noise}} = 4.0 \text{ keV} \times 15(2) \text{ ph.e. per keV} \times 2^{-1/2} = 42 \text{ ph.e.}$ With a gain of 7 the corresponding noise at the anode is 416 electrons.

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**References**

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