CLAS-NOTE 2001-011
pogorelk@jlab.org

Test of Low-Noise Readout of $PbWO_4$ Crystals at ITEP with APD's

V. Koubarovski, S. Kuleshov, O. Pogorelko, P. Shishov
Institute of Theoretical and Experimental Physics
Moscow, Russia
S. Boyarinov
Jefferson Lab, Newport News, VA 23606, USA

June 26, 2001

Abstract

A low-noise charge sensitive amplifier (CSA) and a current preamplifier for operating with Avalanche Photo Diodes (APD) and $PbWO_4$ crystals were developed. The amplifiers were tested at a 3 GeV electron beam and using a reference LED system. The results are in a good agreement. The equivalent noise level for the CSA is 6.3 MeV. The noise level for the current preamplifier with the emitter follower is close to the CSA.

1 Introduction

Test results for a single $PbWO_4$ crystal with an Avalanche Photo Diode (APD) and a low-noise Russian preamplifier (Garantiya) were presented in note [1]. The energy resolution was given approximately by the equation:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E(GeV)}} \oplus b \oplus \frac{c}{E} \tag{1}$$

where E is the energy in GeV, $\frac{\sigma}{E}$ is the energy resolution, a is the stochastic term (mainly governed by photostatistics and sampling fluctuations), b is the constant term (mainly from shower containment limitations and calorimeter non-uniformities), c is the noise term. From the test results we have estimated the noise term for the Garantiya current amplifier as 36 MeV.

At low energies (< 1 GeV) the contribution to the energy resolution from electrical noise dominates. Soft particle background also contributes to the noise term. At intermediate energies ($5 - 10$ GeV) the stochastic term a dominates. The constant term b is very important for higher energies. For the CMS ECAL [2] the noise term will not exceed 23 MeV/channel for the barrel calorimeter (two APD's photodetector) and 120 MeV/channel for the forward calorimeter (VPT photodetector). For the ALICE ECAL [3] the noise term is less than 10 MeV/channel (PIN diode).

Our goal was to reach a level of the noise term close to the contribution of the stochastic term $a = 3\%$ to the energy resolution. At an energy of 1 GeV the noise term c must be close to 30 MeV (10 MeV/channel).

2 Front-end and read-out electronics

The most important elements of the ECAL front-end and read-out electronics are the following:

2.1 Photodetectors

Only three types of photodetectors with low sensitivity to magnetic field (up to 1 T) can be used in the CLAS detector: VPT (Vacuum Photo Triode), PIN diode (p-n junction), and APD. All these photodetectors will be used in the CMS and ALICE detectors as photodetectors with $PbWO_4$ crystals.

The VPT has low quantum efficiency ($\sim$ 15%) and low gain ($\sim$ 10). The CMS ECAL group accepted this option for the End Cap calorimeter because of the high radiation resistance. The CMS group, using VPT readout, achieved an equivalent noise term of 360 MeV (120 MeV/channel). This term is not so important for the energy resolution at 100 GeV energies.

PIN diodes are an option for the ALICE ECAL. The PIN diode has no amplification, and its quantum efficiency is about $(50-70)\%$. To get a reasonably low noise level, the PIN diode must be used with a charge-sensitive preamlifier. This sets the low limit for the response time to more than 0.5 μsec. PIN diodes are sensitive not only to optical photons, but also to charged particles. The reason is that because of the 200 μm thickness of the $p-n$ junction, the passing particle deposits energy equivalent to 300 MeV in the PIN diode; this is known as the punch through effect.

The APD is a photodetector for the CMS barrel ECAL. The CMS team and the HAMAMATSU Corporation have been developing these photodetectors for ten years, and more than 120,000 APD's will be produced for the CMS barrel calorimeter (2 APD's per $PbWO_4$ crystal). The high level of gain (50-100) and the high quantum efficiency $(50-70\%)$ make the most attractive option.

2.2 Preamplifiers

The CMS and the ALICE collaborations will use charge-sensitive amplifiers. The ALICE ECAL group is planning to use charge-sensitive amplifiers with low noise and a low input current JFET transistor doublet at the input. The electronic noise is estimated to be less than 500 electrons within the 10 nsec rise time and the pulse duration of 0.2 msec. We used for our studies the ALICE preamplifier with a gain of 2 V/pC [4]. The ALICE group obtained a noise level of 8-9 MeV per channel.

CMS developed a charge-sensitive amplifier with 1900 electrons noise and 40 nsec time duration. As a result, 20 MeV noise per channel was achieved.

2.3 Bias voltage and signal circuits for the APD and preamplifier installation

To get a maximum linear range, the APD should be used at the short circuit regime. The high voltage power supply must provide 350-450 V bias on the APD. The APD installation circuit and the first amplifying element provide the main part of the noise term.

The various noise sources are the following:

- the noise developed in the first amplifying devices (FET or bipolar transistors);
- the noise coming from detector leakage current (APD noise) and the input current to the first amplifying element;
- the parallel resistance noise arising from any resistor shunting the input circuit;
- the so-called flicker noise, 1/f noise;
- the parasitic capacitor noise.

It is important to consider the APD installation circuits and the amplifiers together. To minimize parasitic installation capacity at the input of the amplifier, the APD surface should be perpendicular to the installation circuit and amplifier plate (or plates). Possible arrangements of of the ADP, bias circuit and amplifier assembly are shown in Fig. 1. The resistor $R1 = 110k\Omega$ provides protection from sparks. The capacitor $C1$ with the resistor $R1$ provides a high voltage power supply filter and creates a short circuit. For all preamplifiers used the low input impedance is important for limiting the short circuit operation of the APD. The Garantiya and CSA input impedances were 100Ω and 20Ω, respectively (Fig. 1b.). In Fig.1a, the collection of the current (charge) from both ends of the APD using two arms of the preamplifier is shown. Subtraction of in-phase noise by differential readout and reduction of noise by $\sqrt{2}$ using two amplifiers was realized. The input impedance was 10Ω. The above circuits were tested with the reference system and in beam tests. Later, the third circuit, of the amplifier was developed (Fig. 1c).

3 Tests of the preamplifiers

Our group tested the following low-noise preamplifiers:

- Wide-band preamplifier Garantiya
- Charge-sensitive amplifier with feedback resistor, $R_f = 50\ k\Omega$
- Wide-band preamplifier based on the MAR-8 with differential outputs of the APD
- Wide-band preamplifier Garantiya with an emitter follower and differential outputs of the APD

3.1 Garantiya

Garantiya is a Russian amplifier [5], manufactured as a microassembly using surface mounted technology. The gain is 0.8 V/pC, the rise time is 5 nsec, the time duration 20 nsec, the equivalent noise is 1800 electrons.

3.2 Charge-sensitive amplifier

We used a charge-sensitive amplifier obtained from the ALICE collaboration (Fig. 2), with the following parameters: electronic noise of 500 electrons, 30 nsec rise time, gain of 2 V/pC, output pulse width 200 μsec. In the ALICE calorimeter the value of the feedback resistor and capacitor were 200MΩ and $1pF$, respectively. We reduced the feedback resistor to 50kΩ which reduced the gain to 0.3 V/pC, and the pulse width to 300 nsec.

3.3 Wide-band preamplifier MAR-8

A two-arm amplifier is shown in Fig. 3. In the input circuit, BSF92 and BSF72 transistors were used. The next cascade used the monolithic amplifier MAR-8 (Mini-Circuits). This industrial 50 Ω amplifier was chosen because of low cost, low noise (2000 electrons), cascad-ability and excellent repeatability. The input transistors serve to reduce input impedance and cross talk between MAR-8 amplifiers. Without this transistors, cross talk was 3%, due to the amplifier feedback effect.

3.4 Garantiya with an emitter follower

The Garantiya with emitter follower is shown in Fig. 4. The APD cathode is connected to the base of the transistor. The APD anode is connected via the high voltage capacitor to the emitter of the transistor. The amplifier Garantiya was used as the second stage of the amplifier. Because the emitter follower gain is close to +1, and the output resistance is small, the short circuit operation is realized, although the input impedance of the emitter follower is high. This amplifier demonstrated low noise operation close to the CSA.

4 Noise measurements

The energy resolution (1) can be written as

$$\sigma^2 = a^2 \cdot E + b^2 \cdot E^2 + c^2 \tag{2}$$

or in amplitude units

$$\sigma^2 = a^2 \cdot A + b^2 \cdot A^2 + c^2 \tag{3}$$

The term b is small based on LED measurement

$$\sigma^2 = a^2 \cdot A + c^2 \tag{4}$$

A reference LED system (Fig. 5) for measuring the noise of the APD with the preamplifier was developed. The light from the blue LED was guided to the reference PMT, and tested the APD with the preamplifier, using transparent fibers. The position of the fibers at PMT and APD was fixed during the measurements. The PMT was used for monitoring and checking the linearity of the APD and the preamplifier. The LED amplitudes were changed using a pulse generator (rise time 6 nsec, duration 20 nsec, frequency 10 kHz) to study the dependence of the APD outputs with preamplifier vs. PMT outputs. The ADC spectra were fitted to a Gaussian to get the width σ and the mean amplitude A. The PMT high voltage was chosen to fully utilize the dynamic range of the ADC (LeCroy CAMAC 2249A) and was set at a constant value. From the dependence of the APD amplitude vs. amplitude of PMT (Fig. 6(a,c)) the relative gains $p1$ were obtained using the linear fit $A(APD) = p1 \cdot A(PMT) + p0$. The σ^2 (APD) dependence vs. A(APD) (the pedestals were subtracted) are shown in Fig. 6(b,d) The noise level for the APD with preamplifier was estimated from the linear fit as a constant term at $A(APD) = 0$. The normalization of preamplifier noise and APD was done using the ratio $Noise = \frac{\sigma}{p1}$. The main results for the noise level measurements of the APD and preamplifiers are presented in Table 1. The best results were reached for the charge-sensitive amplifier and the Garantiya with an emitter follower.

5 Beam test results

To test the preamplifiers we used the ITEP secondary electron beam. After some improvements of the electron beam alignment system, the beam at the front end of the $PbWO_4$ crystal was 5 mm in diameter and 10 mrad in angular divergence. A single $PbWO_4$ crystal was surrounded by 25 mm thick tungsten bricks. Data were taken with a 3 GeV electron beam [1] (see http://www.jlab.org/ pogorelk). The ADC spectra with single $PbWO_4$ crystal with PMT and APD and different preamplifiers are presented in Fig. 7-11. The main test beam results are shown in Table 2.

6 Conclusions

- The noise studies performed with the LED reference system and the beam tests are in a good agreement.
- The equivalent noise level for the CSA is 6.3 MeV.
- The equivalent noise level for the current preamplifiers is 16 MeV.
- The noise level for the amplifier with the emitter follower is close that of the CSA (Table 1, it was tested only with LED reference system yet).
- The current amplifier is ten times faster than the CSA, and can be used for $PbWO_4$ ECAL. The CSA needs more detailed studies of its rate capability.
- The above preamplifiers need to be tested under real conditions inside the CLAS detector, in the magnetic field and in the background created by particle beams.
- For the chosen preamplifier a microassembly with surface mounted technology must be developed.

References

[1] CLAS-NOTE 2000-005, Test Beam Results for the CLAS Electromagnetic Calorimeter Prototypes at ITEP.

[2] CMS Collaboration, TDR 4 CERN/LHCC 97-33, December 15 1997

[3] ALICE Collaboration, TDR2 CERN/LHCC 99-4, March 5 1999.

[4] Preamplifier for ALICE-PHOS project (CERN)

[5] 1st Workshop on Electronics for LHC Experiments, Lisbon, Portugal, 11-15 Sep 1995, CERN, Geneva.

Table 1: Noise measurements relative to Garantiya for different amplifiers using the reference LED system.

Amplifier	Photodetector	HV	Relative noise
CSA	EG&G	425	0.56
CSA	HAMAMATSU	370	0.24
Garantiya	EG&G	425	0.54
with emitter follower			
Garantiya	HAMAMATSU	365	0.17
with emitter follower			
Garantiya	HAMAMATSU	365	1.00
MAR-8	HAMAMATSU	365	0.93

Table 2: Energy resolution of a single $PbWO_4$ crystal with different preamplifiers. 3 GeV elecron beam.

Run	Photodetector	Amplifier	$\frac{\sigma}{E}$ %	Noise, MeV
763	PMT	-	4.34±0.2	3.17
773	PMT	-	6.44±0.2	4.44
	window $(5 \cdot 5) mm^2$			
729	APD	Garantiya	5.76±0.2	40.9
885	APD	Charge Sensitive	5.42±0.3	6.37
850	APD	MAR-8	4.61±0.4	16.1

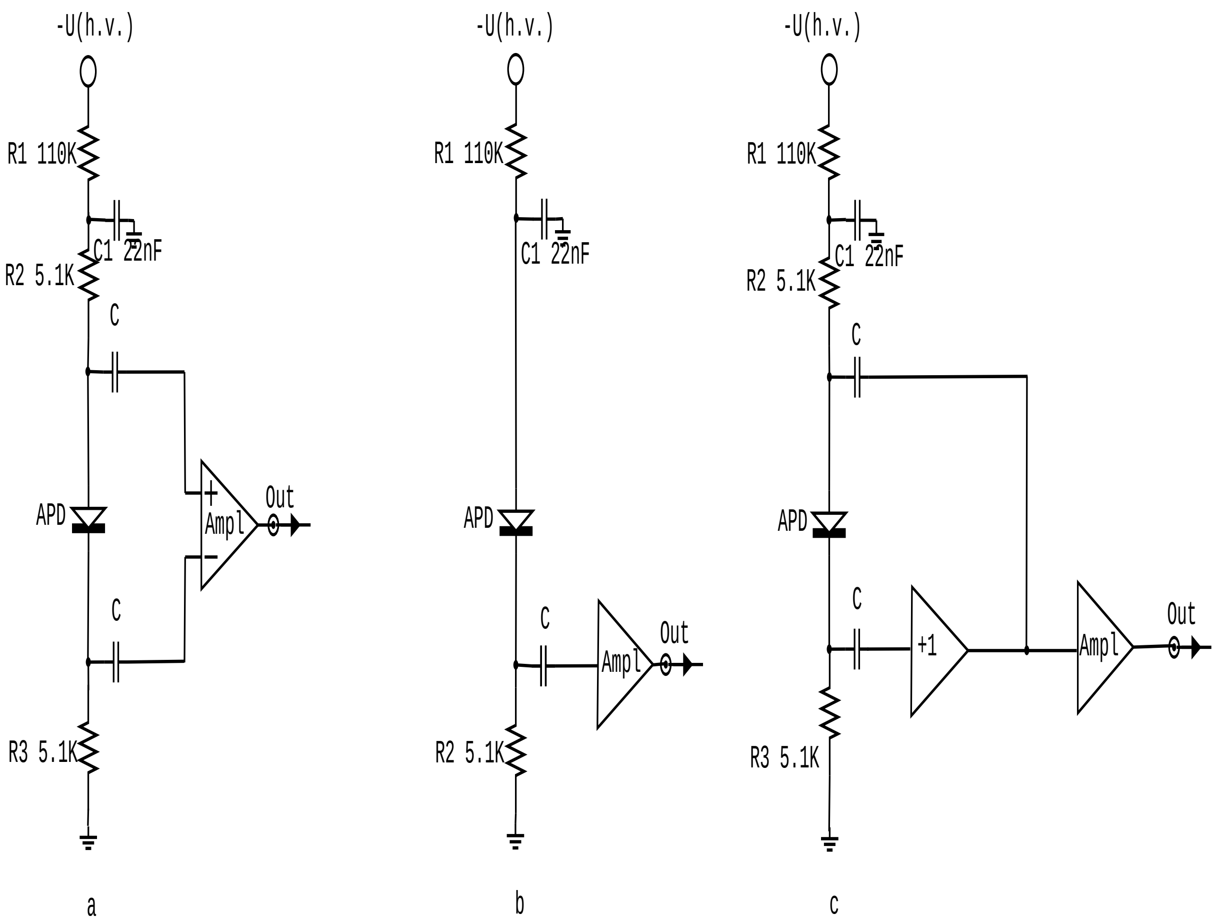

Figure 1: Schematic diagrams showing the connection of the APD and preamplifiers: a. two-arm preamplifier; b. typical circuit of the APD connection; c. circuit with buffer.

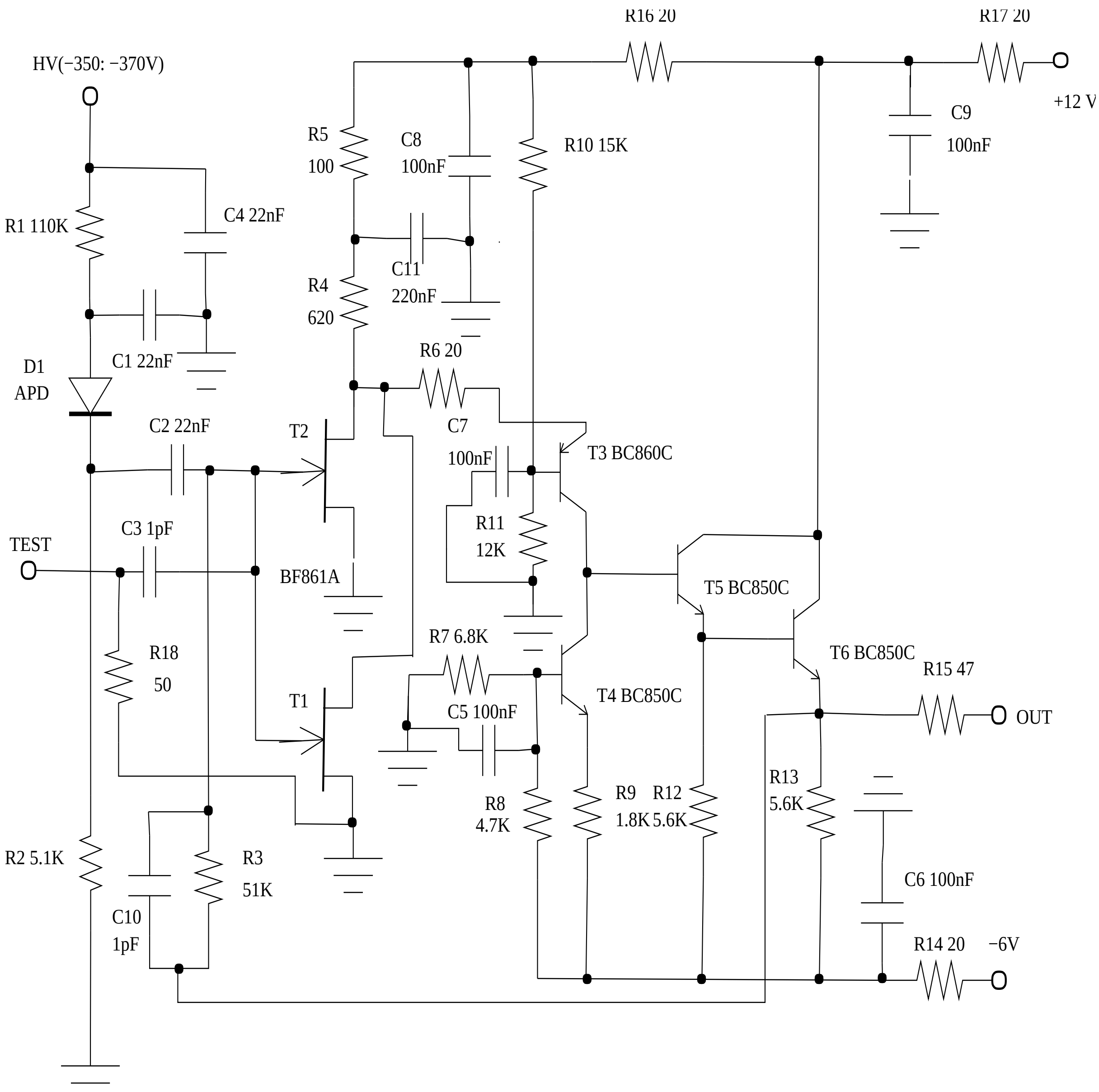

Figure 2: Charge sensitive preamplifier for the ALICE PHOS project (CERN).

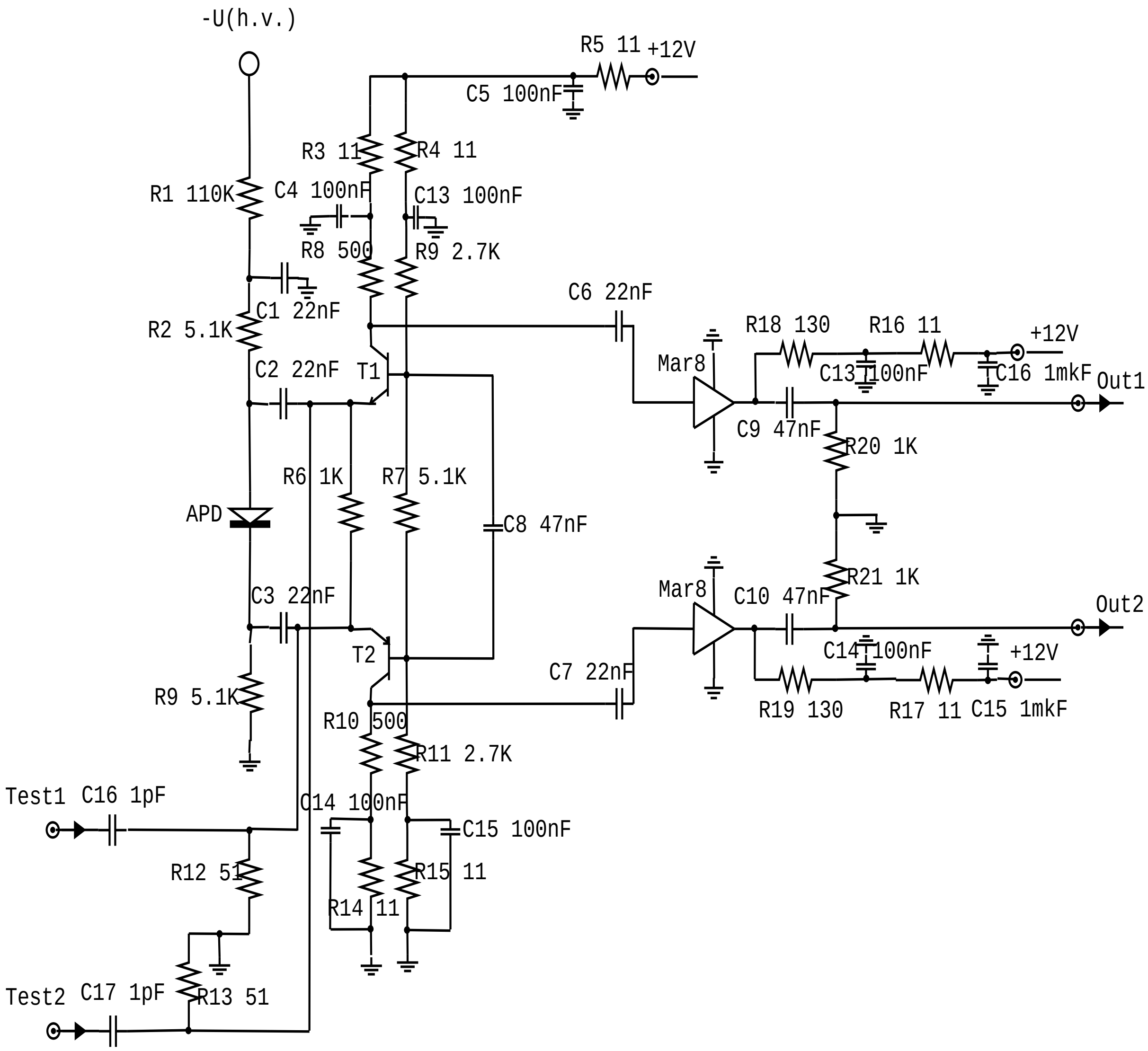

Figure 3: A two-arm preamplifier with monolithic amplifier MAR-8 (Mini-Circuit).

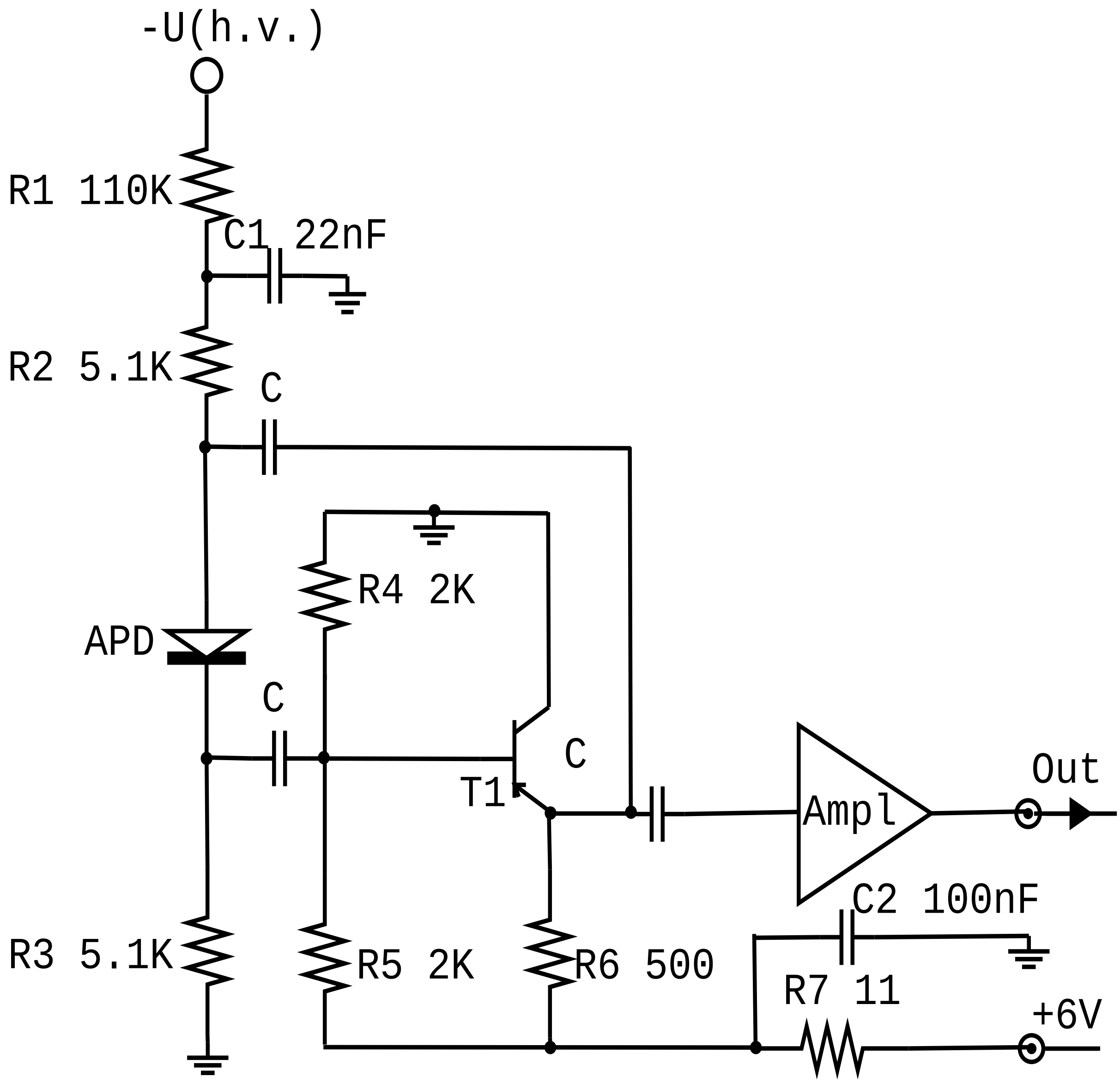

Figure 4: Preamplifier with emitter follower.

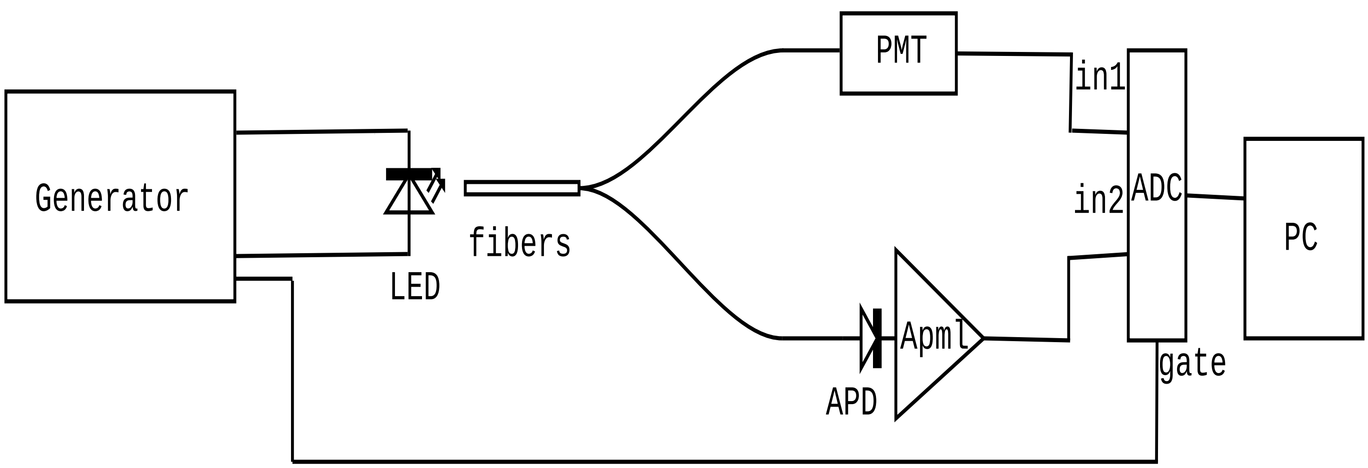

Figure 5: A reference LED system for noise measurements of the APD with the preamplifier.

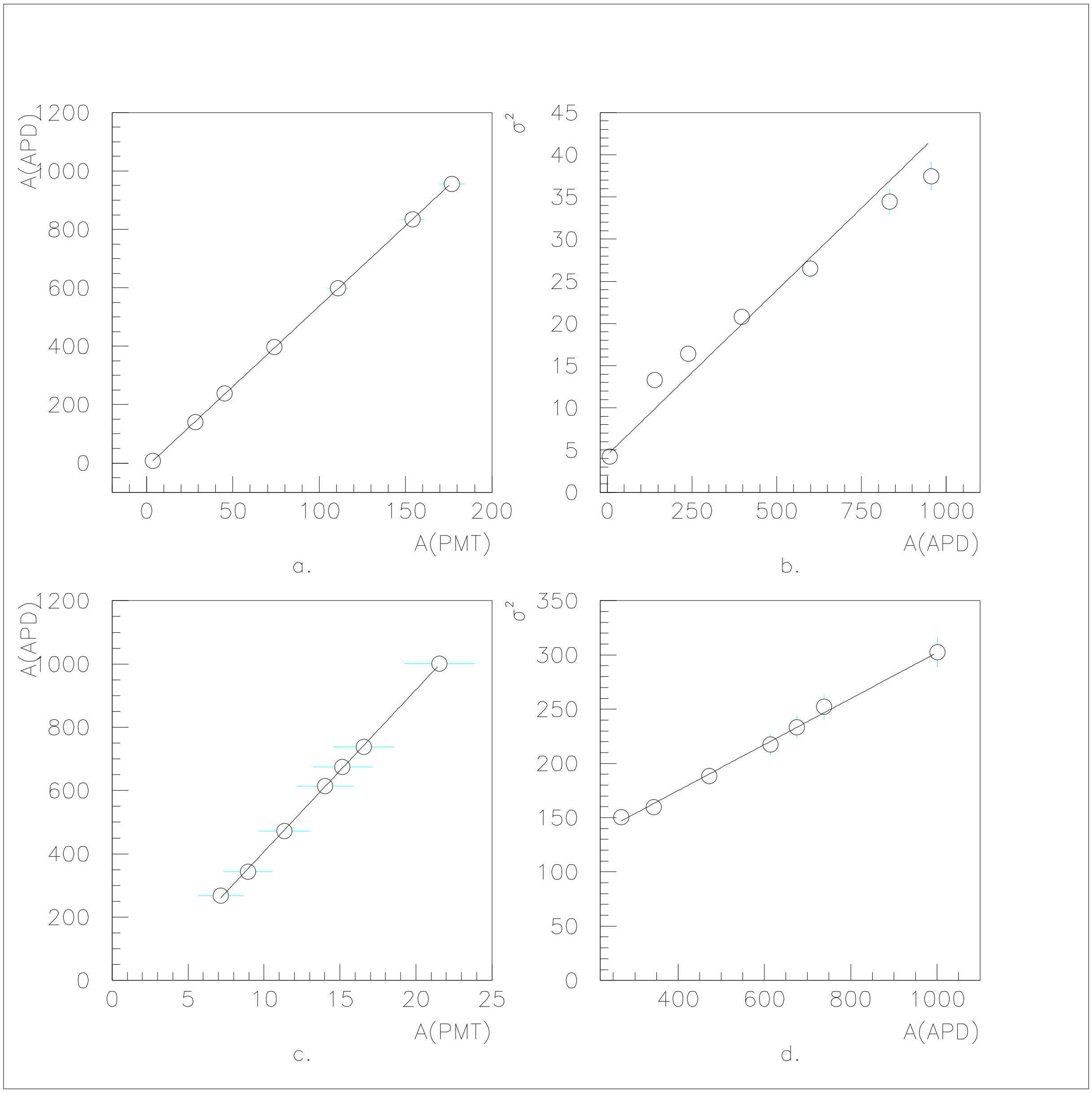

Figure 6: Noise measurement with the LED reference system: (a) The APD amplitude dependence vs. the amplitude of the PMT, and (b) the σ^2(APD) dependence vs. the APD amplitude for the charge sensitive amplifier with the APD (EG&G). (c) and (d) the same for the APD (HAMAMATSU).

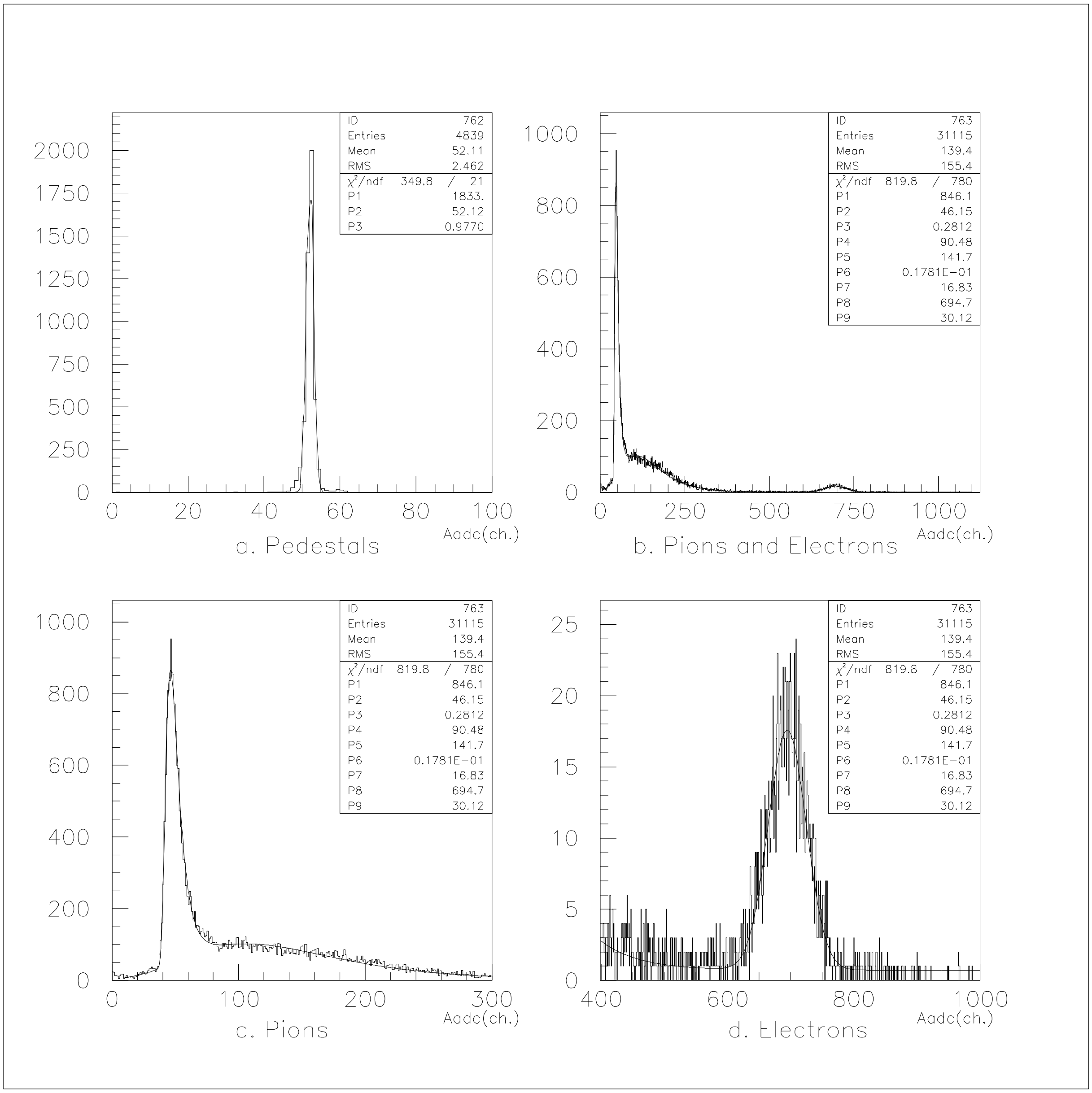

Figure 7: ADC spectra with a single $PbWO_4$ crystal and a PMT, 3 GeV beam.

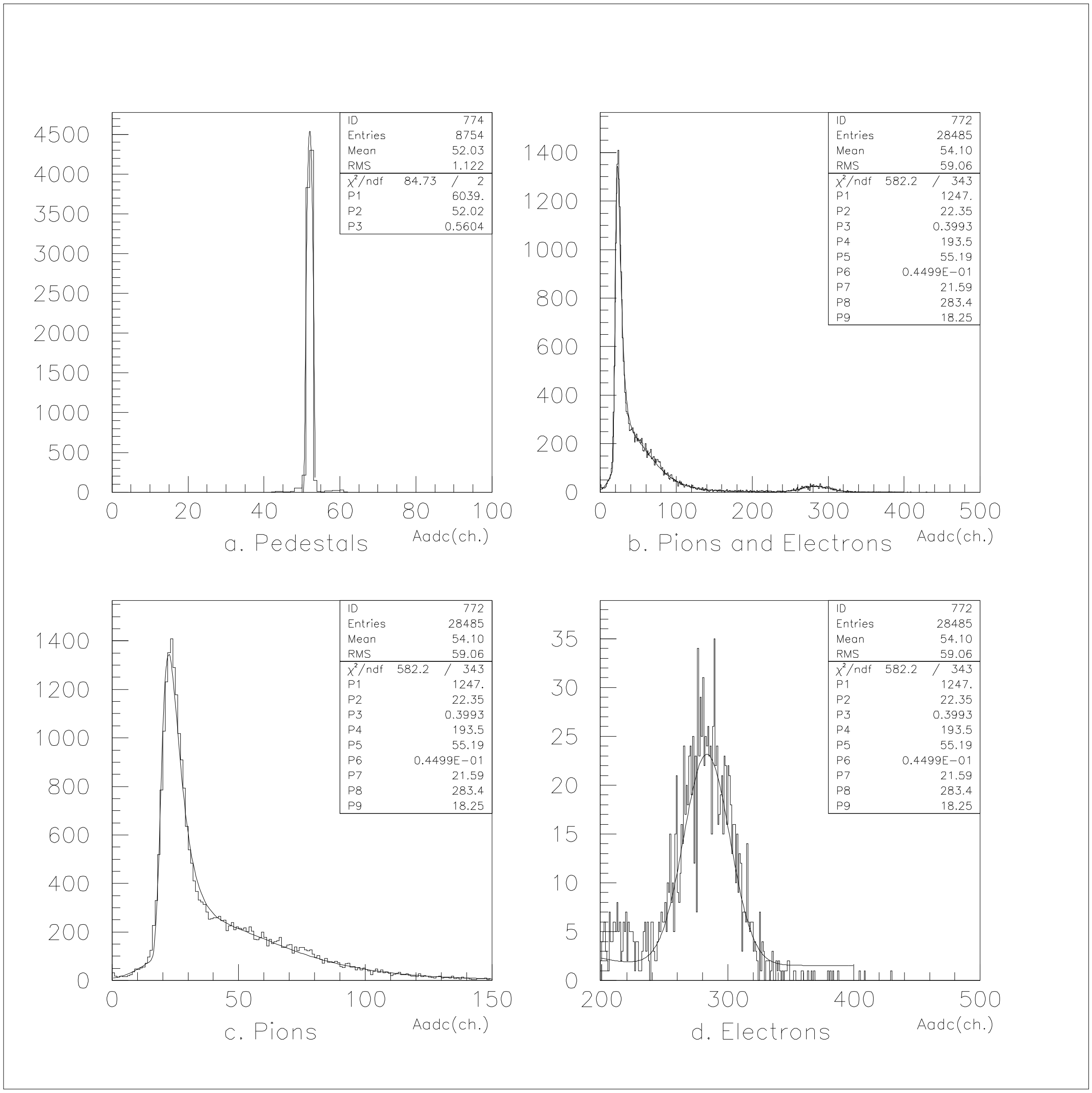

Figure 8: ADC spectra with a single $PbWO_4$ crystal and a PMT (window $5 \cdot 5\ mm^2$), 3 GeV beam.

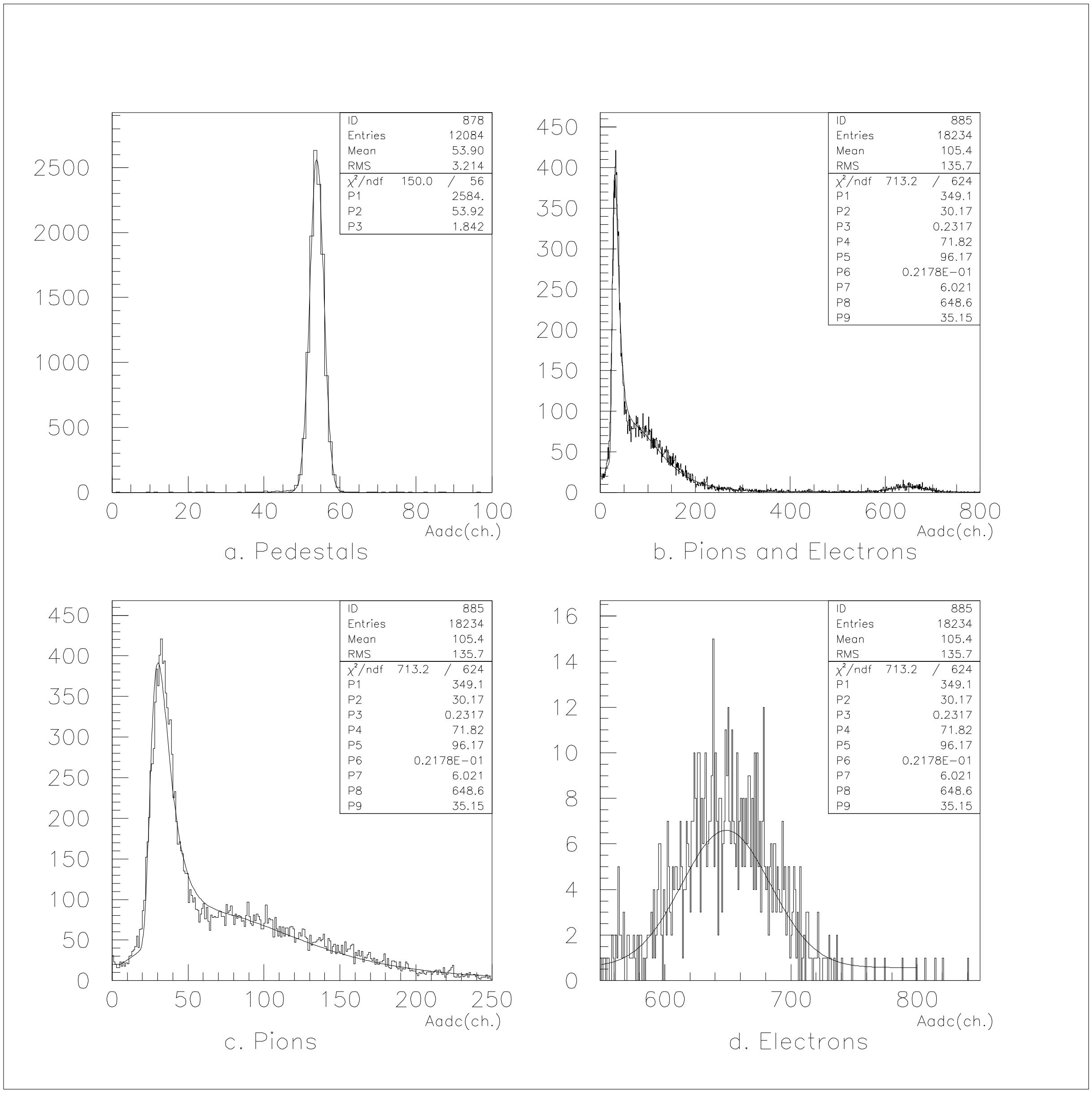

Figure 9: ADC spectra with a single $PbWO_4$ crystal, an APD and a charge sensitive amplifier, 3 GeV beam.

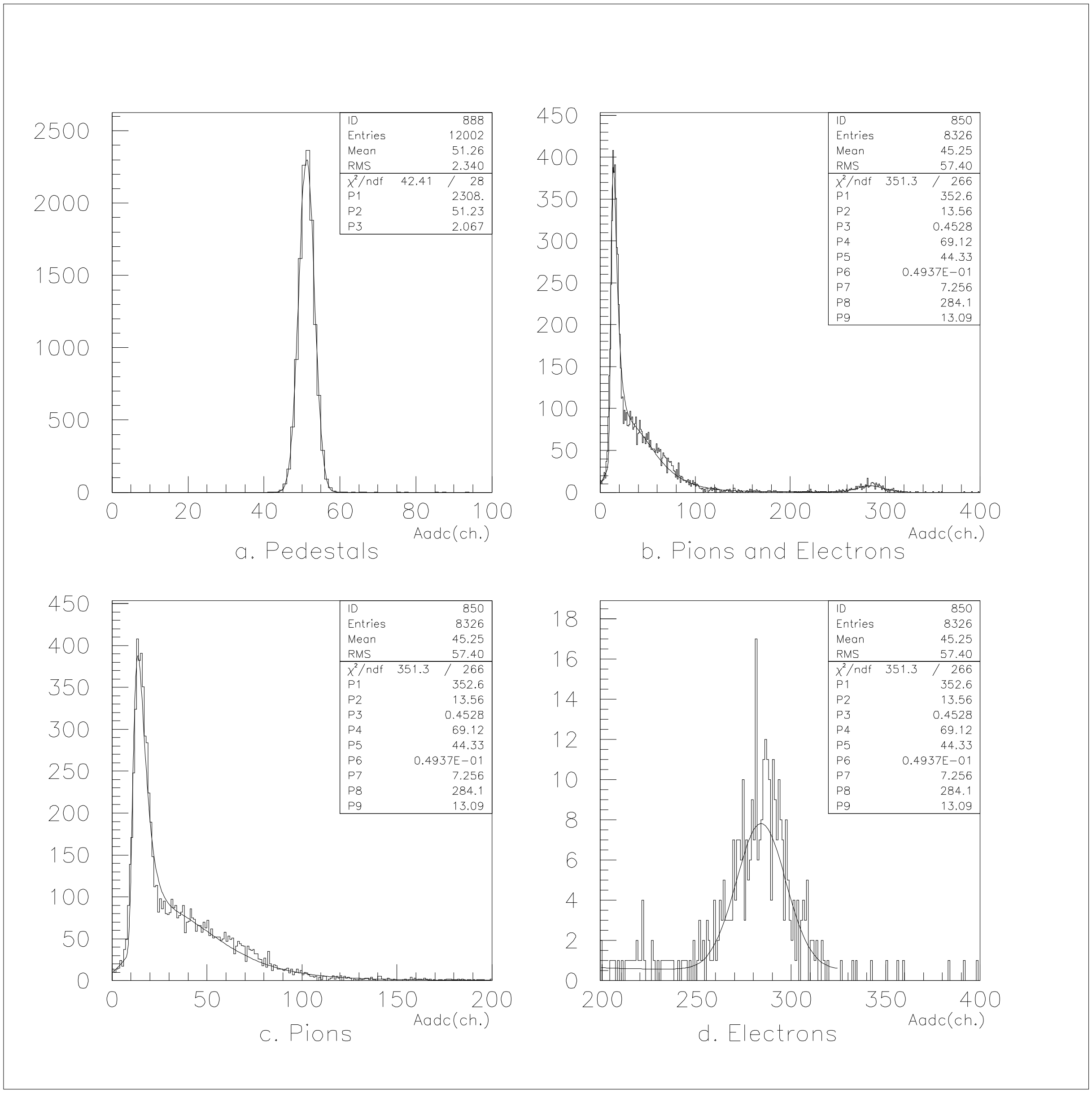

Figure 10: ADC spectra with a single $PbWO_4$ crystal and an APD and MAR-8 amplifier, 3 GeV beam.

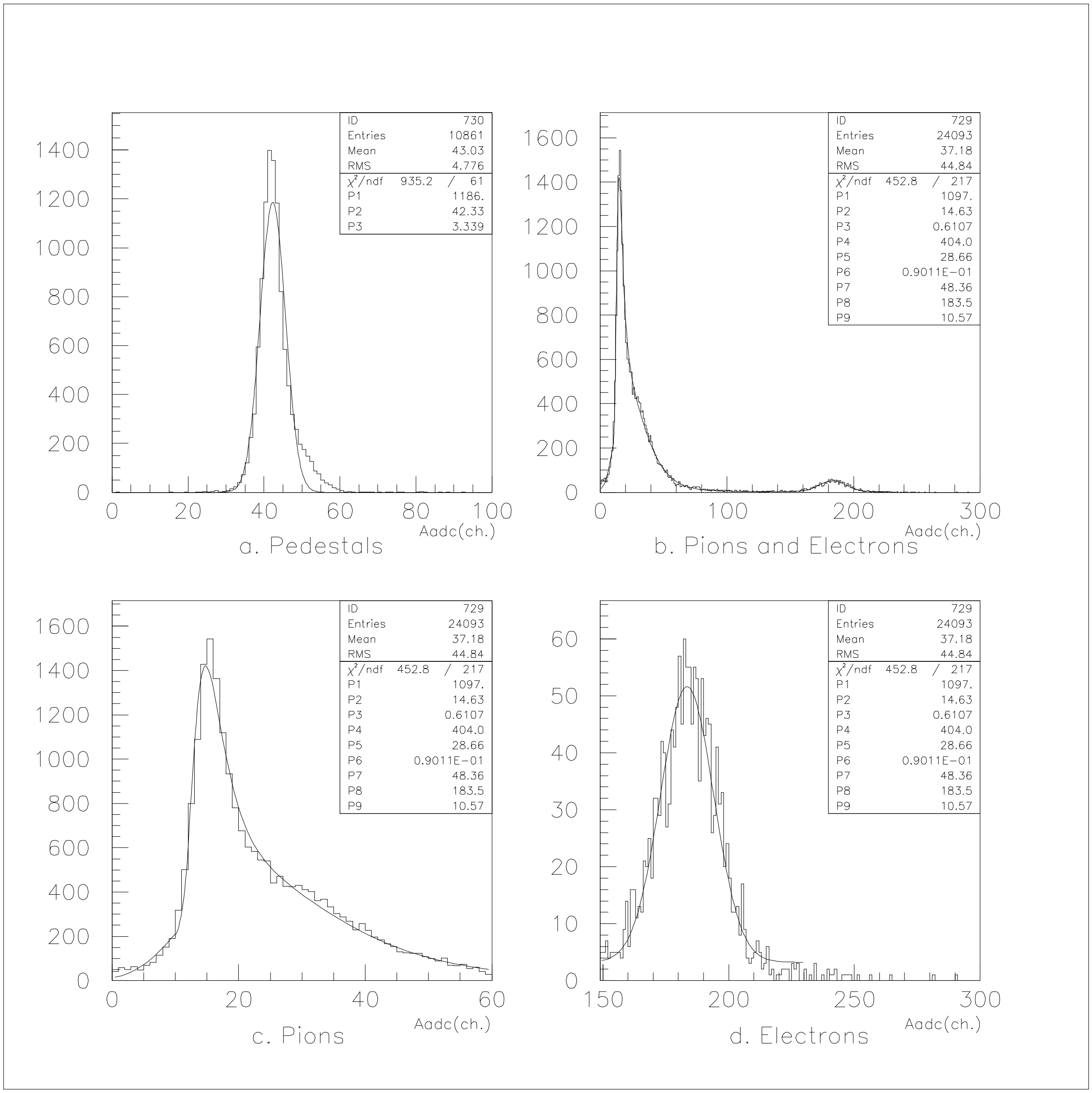

Figure 11: ADC spectra with a single $PbWO_4$ crystal and an APD and Garantiya amplifier, 3 GeV beam.