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VACUUM PHOTO-TRIODE READ-OUT OF THE DELPHI LEAD GLASS CALORIMETER

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Abstract

In this paper we describe the low noise electronic amplification chain designed for the read-out of the one-stage vacuum photomultipliers (photo-triodes) of the DELPHI lead glass calorimeter. A mean open input electronic noise of 166 e^- RMS has been obtained with unipolar shaping. For completely mounted photo-triodes in a situation very close to the final experimental set-up and bipolar shaping we get a mean noise of 292 e^- RMS. Complete immunity against $1/f$ noise has been obtained. The gain stability during six months of operation is better than $\pm 0.3\%$.

determines the maximum collected charge and we have assumed for the final design:

$$Q_M = 8 \cdot 10^5 \text{ e}^-.$$

To keep a good energy and position resolution the counter noise has to be around 25 MeV hence the Equivalent Noise Charge (ENC) must be kept to around 250 e^- .

The dynamic range is of the order of 4000. The integral linearity is required to be better than 0.5% up to 120 fC of input charge. The triode dark current is typically 250 pA. We note also that the beam crossing interval in the LEP accelerator is 22 μs which allows one to use large shaping time constants.

Charge Amplification

The overall linear chain is shown in fig. 2. It consists of a preamplifier, located close to the triode to minimize the connecting lead capacitance, connected to a time-invariant filter through 50 m of twisted pair cable. The overall chain has a response such that the maximum of the output pulse is proportional to the injected charge. For a $Q\delta(t)$ input charge the output is $h(t)$. The Equivalent Noise Charge dependence on $h(t)$, neglecting the 1/f noise, is given by the general expression (3)

$$(1) \text{ ENC}^2 = \frac{2KT}{R_p} \int_{-\infty}^{+\infty} [h(t)]^2 dt + 2KT R_s C_i^2 \int_{-\infty}^{+\infty} [h'(t)]^2 dt.$$

where R_s and R_p are the equivalent noise generators that account for the series and parallel noise contributions of the whole amplification chain, see fig. 3, and C_i is the total (detector + FET + test + parasitic) input capacitance.

It is well known⁽³⁾ that to obtain the best signal to noise ratio, in the presence of series and parallel noise, the optimum measuring time constant is $T_m = T_c$ where $T_c = C_i \sqrt{R_s R_p}$.

Introduction

In the End-Cap electromagnetic calorimeter of the DELPHI experiment (FEMC)⁽¹⁾, based on lead glass counters, newly developed one-stage photo-multipliers ("photo-triodes")⁽²⁾ have replaced the popular multistage tubes because they can operate in a high magnetic field. It is important not to spoil the precision offered by lead glass counters and since the mean charge from such photo-triodes is in the fC range, high gain electronic amplification with very low noise is required in order to match the input ranges of commercial analog to digital converters (ADC's). For the 10000 channels of FEMC we have developed a special front-end to obtain a resolution and a dynamic range capability of 12 bits at a price significantly lower than currently available commercial products.

In this paper we will describe the performance of the analog part of such an electronic chain which includes the charge preamplifier, the filter amplifier and the track and hold of the charge for the multiplexed analog to digital conversion. This part is now available in the form of two hybrids at a total cost of about 60 SFx.

Detector parameters

The photo-triode consists of a photocathode, one dynode and an anode as shown in fig. 1.

The input capacitance for the 2" photo-triodes we use is determined by the distances between the electrodes which vary from one manufacturer to another. Typical measured values range from 5 to 15 pF. The triode gain in a magnetic field of 1.0 Tesla is in the range 7-10. An e.m. shower which develops in SF1 lead glass generates ~1000 photoelectrons/GeV on a bialkali triode photocathode. This

is the noise corner time constant. In these conditions the parallel and series noise contributions are equal and the ENC reaches a minimum. This is a general behaviour which is independent of the precise shape of the pulse response. It is also well known that the minimum ENC is obtained for the ideal cusp-shaped waveform (3) and is given by

$$(2) \quad ENC_{opt}^2 = 4KT C_i \sqrt{\frac{R_s}{R_p}}$$

The LEP beam crossing interval allows one to reach a satisfactory approximation to these conditions without using too complex circuitry: our solution is a double integration with optionally one or two differentiations to implement unipolar or bipolar shaping.

The preamplifier

We have adopted a JFET preamplifier in a charge sensitive configuration. The circuit is shown in fig. 4 together with the HV polarization circuit for the triode. The preamplifier, originally developed for μ -strip silicon detectors (4), is commercially available as a single channel hybrid (5).

In the charge sensitive loop, the AC feedback applied by C_f provides the charge integration while DC feedback via R_f allows the capacitance discharge with time constant $R_f C_f$. For good noise performance R_f should be as high as possible. The open input R_p is, in fact, given by R_f in parallel with the FET parallel equivalent resistance $R_{eq} \approx 10^9 \Omega$. In practice R_f is limited to 100 M Ω which is a value currently attainable with hybrid techniques.

The second stage is a pole-zero cancellation that reduces the signal length from 100 μ s to 10 μ s. This avoids pile-up effects in the output stage as well as amplification of the low frequencies. The gain which is determined by the ratio $\frac{R_c}{R_b}$ is chosen to give differential outputs of 90+90 mV for the maximum signal Q_M .

The final output buffer allows a symmetrical driving

of the twisted pair cable for lengths up to 50 m.

The AC coupling between anode and preamplifier, although it increases the noise slightly, is introduced to avoid a shift of the working point of the preamplifier, which would originate, through R_f , from the dark current of the tube.

The diode protects the input FET against the negative spikes that can occur when the HV for the triode is switched on/off. Since it injects noise directly into the preamplifier, it has been chosen to have small inverse current (50pA typical) and small capacitance $C_D \approx 1$ pF. The power dissipation of this preamplifier, determined essentially by the output stage, is about 300 mW.

Final Amplification

In the control room the signals are fed into the shaping amplifier cards containing in the prototype versions 16 or 24 channels. The schematics of the filter amplifier is shown in fig. 5. The jumper $j_{1,j2}$ allows the choice between unipolar and bipolar shaping. The first waveform in principle optimizes the noise performance of the chain and is limited to low-counting rates. The second one allows higher counting rates, very useful when calibrating the detector with an electron beam, and has a much higher rejection of low frequency components in the noise spectrum. This is useful because some versions of the photo-triodes are very sensitive to acoustic vibrations in the range 0-3000 Hz.

The first stage of the filter consists of a differential receiver performing a first integration with a time constant of 0.5 μ s. This assures good common mode rejection against interference such as external pick-up noise, cross talk between channels and ground loops.

After this stage there is a pole-zero circuit with time constant 1.5 μ s to perform a suitable shaping.

The final amplification stage for the unipolar shaping (jumper inserted) consists of an approximate integration to obtain the final waveform. The bipolar pulse is obtained by a further approximate differentiation through the 330pF capacitor that increases the rejection of low frequencies by

about 40 db.

The final stage is a track-and-hold circuit designed to keep the charge for at least 500 μ s with a loss smaller than one least count. During this time we intend to multiplex the 12 bit analog to digital conversion of about 100 channels.

Performance

The results we summarize here come from bench tests on single channels and from a series of measurements performed on a calorimeter module designed to contain 96 counters. This module, similar to the one described in ref. (6), was in operation in the DELPHI test beam H6 at the CERN North Hall from May to December 1985.

The unipolar and bipolar impulse response of the electronic chain to a square calibrated pulse, injected on the input test capacitance (1 pF), are shown in figs 6a and 6b respectively.

The unipolar shaping has the following typical characteristics

- peak at 2.12 μ s
- ratio $h(20\mu s)/h(2.12\mu s) = 0.9 \times 10^{-4}$
- charge gain: 2.25 μ V/ e^- .

The bipolar pulse is the approximate derivative of the previous one. It peaks at 1.25 μ s.

The measurements of the output signals were made under various experimental conditions with the different techniques summarized below.

- (a) Using a multichannel analyzer Silena 7412 operated in peak sense mode,
- (b) via a Lecroy 2282 12 bit charge sensitive ADC sensing through a resistor the hold voltage of the shaper with a 1 μ s gate
- (c) using the 50 Ω amplifier driver stage, shown in fig.5, as an alternative to the track-and-hold circuit, to feed the shaper output of fig. 6 directly into the Lecroy ADC. The peak was measured synchronizing a ~ 70 ns gate with the broad signal maximum.

For easy noise measurements a wideband RMS voltmeter HP 3400A has also been used.

In no case did one observe an appreciable difference in performance which might depend on the technique adopted.

Noise Results

The noise ENC, using the unipolar shaping, typical of FET's such as the MMBF4393 or BSR58 is given in fig. 7 as a function of the detector capacitance. The noise increases with the input shunt capacitance; the slope has a starting value of 2.2 e^- /pF and tends asymptotically to 6.0 e^- /pF.

The mean open input ENC and RMS spread for about 20 unselected hybrids is

$$\langle \text{ENC} \rangle = (166 \pm 9) e^-$$

with bipolar shaping the same measurements give

$$\langle \text{ENC} \rangle = (204 \pm 9) e^-$$

These values do not change when one varies the overall gain in the range 1:20 μ V/ e^- .

When the triodes are connected as in fig. 4 the ENC increases due to the contributions from additional noise sources. The most important are:

- (a) the triode dark current (I_{s1} nA)
- (b) the triode input capacitance ($C_{AK} \approx 5$ pF; $C_{AD} \approx 10$ pF)
- (c) the AC anode coupling
- (d) the diode reverse current and capacitance.

Individual bench measurements, made on a sample of about 50 completely mounted triodes, with bipolar shaping, give

$$\langle \text{ENC} \rangle = (270 \pm 20) e^-$$

The theoretical estimation of the noise using expression

(1) depends on the FET transconductance. Using a mean

value $G_m = 10 \text{ mA/V}$ which gives $R_s = 89 \Omega$, we obtain for unipolar

and bipolar shaping $ENC=209e^-$ and $ENC=240e^-$ respectively - very close to the experimental value.

With the optimal shaping given by expression (2) we would expect an $ENC_{opt}=169e^-$.

The system is in principle sensitive to mechanical vibrations that can cause oscillations of the triode capacitance value. This has been tested using a loud-speaker excited at varying frequencies. We observe a resonant behaviour of the system noise for unipolar shaping at discrete frequency values in the range 1-3 KHz. The exact values and the amplitude of the effect depend on the photo-triode type. In the presence of acoustic noise at resonance frequencies, therefore, the ENC for unipolar shaping increases with the applied HV. This behaviour is shown in fig. 8, where the noise dependence on the applied HV is shown for different conditions. The bipolar shaping effectively filters out the low frequency part of the signal, so that the noise is not affected by the presence of acoustic vibrations.

Dynamic range and linearity

The dynamic range capability of the electronic chain is given in fig. 9. The integral linearity is better than 0.5% over the whole dynamic range.

Track-and Hold

The main measured characteristics are:

- drop rate: 0.1 volt/sec
- charge injection: 3.5 pC
- feed-through less than 0.025%.

This assures 12 bit accuracy over a conversion time of at least 500 μ s.

Module performance

A module containing 72 counters, equipped with the electronics described above, has been in operation since June 1985. The same HV (800 V) was applied to all the triodes.

The signals from the preamplifiers, located inside the module, were sent through 50 meter cables, each containing 16 twisted pairs, to the cards performing the amplification with bipolar filtering, and the track-and-hold. The outputs of these cards were then digitized by 2282 Lecroy ADC's and read out via a VAX750 computer.

The mean ENC obtained in these conditions, which are very similar to those of DELPHI, is, for the 50 photo-triodes of the same type,

$$\langle ENC \rangle = (292 \pm 26) e^-.$$

This value is also compatible within 10% with the results of the remaining 22 photo-triodes made by different manufacturers or with different construction technique.

No variation in the ENC has been observed in six months of running time.

Fig. 10 shows the distribution of the electronic sensitivity, obtained by sending a calibration pulse into the test-input capacitances. The width is compatible with the tolerance (20%) of such components.

The system stability has been checked over a period of six months. The pedestal value of a typical channel is shown in fig. 11 as a function of running time. All the channels are stable within 2 ADC counts.

The sensitivity of a typical channel measured through the response to a calibrated pulse into the test input capacitance is shown in fig. 12 as a function of the running time. The amplification is stable at the $\pm 0.3\%$ level.

Conclusions

The performance of the electronic chain to be used in the lead glass e.m. calorimeter of the DELPHI experiment satisfies the tight constraints imposed by the required detector performance. The bipolar shaping gives an $ENC=270e^-$ RMS. The system is linear to better than 0.5% up to an input charge of $10^6 e^-$.

We are now developing the final version of the cards in FASTBUS format. Each card will serve 80 channels and will provide the amplification, the track-and-hold, the

Multiplexer and the 12 bit ADC.

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Figure Captions

Fig. 1. Construction of the Hamamatsu R2184 (type E) photo-triode;

Fig. 2. Block diagram of the photo-triode linear chain;

Fig. 3. Equivalent circuit of detector preamplifier and filter for noise analysis;

Fig. 4. The photo-triode electrical connections and pre-amplifier diagram;

Fig. 5. Filter amplifier and track-and-hold electrical diagram. The circuit enclosed in the dotted rectangle exists in hybrid form. The $50\ \Omega$ driving stage as an alternative output is shown outside the dotted rectangle;

Fig. 6. Analog chain response to an input charged of $2 \cdot 10^4$ electrons (gain = $15\ \mu\text{V}/e^-$)

(a) unipolar shaping

(b) bipolar shaping

Fig. 7. The noise ENC as a function of input capacitance;

Fig. 8. Noise ENC in the presence of resonant acoustic vibration as a function of the applied HV;

Fig. 9. Dynamic range capability; the points represent the deviation from the straight line fit to the first half of the range. The sensitivity for this measurement was 250 electrons/ADC count;

Fig. 10. Distribution of the electronic sensitivity of individual channels;

Fig. 11. Pedestal of a typical channel as a function of running time;

Fig. 12. Sensitivity of a typical channel as a function of running time.

TYPE R2184

(Unit: mm)

fig. 1

fig. 2

fig. 3

PREAMPLIFIER ELECTRICAL DIAGRAM

fig. 4

[illegible]

fig. 5

fig 6a

fig 6b

fig. 7

fig. 8

fig 10

fig. 9

fig. 11

fig. 12