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A SIMPLE LIGHT DETECTOR GAIN MEASUREMENT TECHNIQUE

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ABSTRACT

A simple but robust LED based light detector gain monitoring system capable of measuring gain to within a sensitivity of a fraction of a percent is presented. The absolute gain of the detector and its electronics can be measured with a systematic error from a fraction to a few percent depending on the photon to photon gain fluctuations. The method, based on intrinsic light and detector properties, does not require stringent mechanical or optical tolerances.

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INTRODUCTION

Calibration is a weak point in scintillation based calorimeters because most light detectors do not have sufficiently stable response. Knowledge of the light detector gain is necessary in order to discriminate between the light detector response and the changes in light output from the active component of the calorimeter.

For this reason, the LAA project sought a cheap but reliable method of precisely measuring and monitoring the gain of light detectors.

It was decided to base measurement methodology on quantum statistics alone in order to avoid systematic problems and obtain an absolute gain measurement. Some pioneering work was already done in the past[1] but those ideas have been further developed into a new and more effective gain monitoring system.

THE PERFECT DETECTOR CASE

Measurement conceptualization evolved from the following theoretical assumptions:

1) If an ideal noiseless and monochromatic gain light detector is exposed to a pulse of light its response to it will be:

$$R = G\ N_{pe}\ , \tag{1}$$

where R is the signal at the light detector output, G is the light detector gain and N_{pe} is the number of photoelectrons detected.

2) If a series of statistically equal light pulses (obtained, for example, by sending a train of equal electrical pulses in a LED) is used, the response of the light detector described in eq. (1) will vary from pulse to pulse because of the quantum fluctuations in the number of detected photoelectrons. The average response will be:

$$< R >= G < N_{pe} >\ , \tag{2}$$

where $< R >$ is the average detector response and $< N_{pe} >$ is the average number of detected photoelectrons.

Since the response variation of a perfect detector is caused by the statistical fluctuation of N_{pe}, the standard error, σ_R, of $< R >$ will be:

$$\sigma_R = G\sqrt{N_{pe}}\ . \tag{3}$$

Dividing the square of eq. (3) by eq. (2), the gain is obtained as:

$$G\ =\ \frac{\sigma_R^2}{< R >}\ =\ \frac{(G\sqrt{N_{pe}})^2}{G\ N_{pe}}\ . \tag{4}$$

In a perfect detector the gain can then be obtained by measuring its average response and its signal variance to a train of statistically equal light pulses.

It is important to note that the amplitude of the light pulses is completely factored out in eq. (4) which means that, in theory, light pulses of arbitrary amplitudes can be used provided that all the pulses of a train have statistically the same amplitude during

the measurement. This fact relieves experimenters from the necessity of engineering long term stability of the light pulser system.

THE REAL LIFE CASE

In an actual detector, the gain will differ photon to photon. In addition some electronics noise will be present. The measured average signal $< R >_{real}$ will be:

$$< R >_{real} = < G >< N_{pe} > + P \ , \tag{5}$$

where P is the ADC pedestal and $< G >$ is the average gain. The observed variance, $\sigma^2_{R\ real}$, will be:

$$\sigma^2_{R\ real} = < G >^2 < N_{pe} > + < G >^2 < N_{pe} > \delta^2_{SER} + \sigma^2_{elec} \ , \tag{6}$$

where the first term is given by the statistical fluctuation of the light signal, the second term is given by the Single Electron Response gain fluctuations:

$$\delta_{SER} = \frac{\sigma_{SER}}{A_{SER}} \ , \tag{7}$$

with A_{SER} and σ_{SER} being the Single Electron Response mean amplitude and standard error respectively. The last term, σ_{elec}, is the combination of the detector, amplifiers and ADC electronics noise.

Applying eq. (4) in the case of a real signal would give the wrong gain because of the external terms σ_{elec} and P.

This problem was turned around, taking advantage of the fact that P and σ_{elec} are not functions of N_{pe}. $< R >_{real}$ and $\sigma_{R\ real}$ were measured for a number of series [i] of light pulses (typically 5000 pulses/train). All pulses in each train were statistically equal (obtained with equal electric pulses in the LED) but every train had a different pulse height (different LED driver output pulse amplitudes). The data was taken with the apparatus shown in fig. 1.

$< R_i >_{real}$ plotted versus $\sigma^2_{i\ real}$ yielded the straight line shown in fig. 2 with slopes:

$$S = < G > (1 + \delta^2_{SER}) \ , \tag{8}$$

where $< G >$ is the average light detector gain (in ADC counts/photoelectron).

It is important to note that as a practical limitation, the light pulse intensities must be chosen so that for the smallest pulses:

$$< G >< N_{pe} > \geq \sigma^2_{elec} \tag{9}$$

and for the largest pulses, the fractional statistical fluctuation of the pulses $(1/\sqrt{N_{pe}})$ must be larger than the ADC resolution. If the electronics noise is small enough, this method can be pushed into the single photon region.

As a check of this method, the high voltage of a photomultiplier was increased until its single photoelectron response peak separated from the pedestal peak in the

pulse height spectrum. The gain was then measured both directly, observing the Single Electron Response pulse height spectrum (fig. 3) and with the afore mentioned method. The single electron response spectrum gave a signal amplitude of 10 ADC channels per photoelectron and a width $\delta_{SER} = .5$.

The new method showed a slope of 12.9 ADC channels per photoelectron, which after correction for the factor $(1+\delta^2)$, gave a gain of 10.3 ADC counts per photoelectron. In order to be able to measure the SER of fig. 3, the photomultiplier was operated at a voltage higher than its normal operating voltage. The high voltage was then progressively reduced and the results compared with the photomultiplier response to a fixed light pulse (fig. 4). As expected, the ratio between the two quantities varies little with high voltage[2].

MONTECARLO SIMULATION

The measurement was simulated with a simple Montecarlo where each light pulse had $N \pm \sqrt{N}$ photoelectrons and in which a different gain was applied to each pulse. The program was run with different gain distributions with $< G >= 1$ and δ_{SER} varying from 0 to 100%. The result, shown in fig. 5, is in perfect agreement with eq. (8).

FIRST APPLICATIONS

This technique was applied to determine the short term gain stability of an XP2282 photomultiplier and a gain variance of about 0.5% was found (fig. 6). It was concluded that the system described has a repetitivity better than 0.5%. The gain in ADC counts (left hand scale of fig. 6) was then converted into absolute gain by multiplying the ADC channel width (.25 pC/channel), dividing by the electron charge (1.6×10^{-19}Coulombs) (right end scale) and dividing by the correction factor $(1 + \delta^2) = 1.25$[3].

It should be stressed that the described method has a systematic error of $^{+0}_{-50}\%$ on the absolute gain measurement (unless δ_{SER} is independently known)*. If the light detector δ_{SER} is known or negligible, the entire electronics and detector chain gain can be measured with an error limited by the ADC channel calibration.

This method was used to measure the gain of all the 155 photomultipliers of the LAA Spaghetti Calorimeter Prototype with standard data taking voltages and cabling.

Since all photomultipliers were roughly set at the same gain by the beam calibration, they were assumed to have similar first dynode gain and hence the same $(1 + \delta^2)$ correction factor. Allowing for a tube-to-tube δ variation between 0.3 and 0.6, the correction factor $(1 + \delta^2) = 1.25 \pm .15$ was taken for all the 155 photomultipliers.

Because of the compact design of the prototype and due to base power dissipation, the photomultipliers in the beam were operating at 10-15 °C above room temperature. The photomultiplier gain variations with temperature were found to be -0.3% /^{0}C and a correction factor of 1.04 was taken.

Comparing the gain of the 155 photomultipliers (in pC/photoelectron) with the LAA Spaghetti calorimeter gains measured in the test beam calibration run (in

* In the assumption that the S.E.R. variance is smaller than the S.E.R. amplitude.

pC/GeV), it was possible to extract the LAA Spaghetti prototype light output which turned out to be about 320 photo-electrons/GeV (fig. 7)[4]. The large spread in light output was found to be correlated with the fibre production run number. To illustrate this point the oldest fibres have been represented with circles, the middle aged fibres with triangles and the newest fibres with square. The light output increases with time indicating a light output improvement during the six months of fibre production.

There is an important consequence of eq. 6; since σ_R is one of the components of the calorimeter resolution, the light detector δ_{SER} enters directly into the resolution limit of the calorimeter. For example, with a light output of 100 photoelectrons/GeV a perfect photon detector with $\delta_{SER} = 0$ will limit the calorimeter resolution to $10\%/\sqrt{E}$ while a photon detector with $\delta_{SER} = 100\%$ will result in a resolution limit of $20\%/\sqrt{E}$. In the case of the Spaghetti calorimeter mentioned above, the photon statistics limit would be $1/\sqrt{320} = 5.5\%$ with a perfect photon detector but it increases to 7% with a typical photomultiplier. As a consequence, a narrow S.E.R. will be a necessary photomultiplier requirement whenever the photon statistics limit will be a sizeable fraction of the calorimeter resolution.

This technique was also applied to the measurement of the gain of the Hybrid Photo Diode developed by LAA[5]. Some results are shown in fig. 8. In both measurements, the HPD was running at the same voltage. A single linear amplifier was used in fig. 8a. For fig. 8b an additional x10 amplifier was added and the LED light output was tuned down by a factor of ten in order to fit the data into the ADC range. The system automatically took into account the differing amplifier gains. Since, in the HPD, δ_{SER} is small, no correction need be applied. Applying this method in a range from a few thousand photoelectrons per pulse to a single photoelectron, a constant slope was found indicating a constant gain and confirming the HPD linearity for small light pulses.

CONCLUSIONS

A simple but effective light detector gain calibration and monitoring system has been developed. It is capable of sensitivity to within a fraction of a percent and of a precision on the order of a few percent.

The light pulses used have arbitrary, software adjusted amplitudes and no fixed light connection between the LED and the photocathode was necessary. The light connection can be allowed to change or to deteriorate between different measurements provided that it is stable during each measurement. This characteristic makes this calibration and monitoring system particularly simple, robust, resilient to abuses and suitable to large scale utilization.

Finally, it is important to remember that this method measures only the gain of the light detector and related electronics and that it is fully insensitive to the photocathode efficiency variations which need to be treated together with variations in light production.

REFERENCES

[1] R. DeSalvo, G.P. Ferri, *"Système de test pour PM"*, CERN/SPS/ELE/Note 82-23, 1982.
P. Sonderegger, D. Perrin, private communication 1982.

[2] δ^2 could be expected to vary like $^{n}\sqrt{G}$ if the n dynodes of the photomultiplier had all the same gain. In a real photomultiplier this would be an overestimation because the first dynode, main responsible for the SER fluctuations, is always tuned to the highest possible gain and it is closer to gain saturation than all the other dynodes. As a result the variation of the term $1 + \delta^2$ are quite limited.

[3] δ measured from a SER pulse height spectrum.

[4] The SPACAL prototype was built with fibres SCSF-38 from Kyowa-Kuraray. Kodak wratten # 3 yellow filtres cutting at 450 nm were used to reduce the attenuation length.

[5] R. DeSalvo et al., *"First results of the hybrid photo diode tube"*, CERN-LAA project, submitted to Nucl. Instr. and Meth., 1991.

FIGURE CAPTIONS

Fig. 1. Schematic diagram of the experimental apparatus for the photomultiplier gain measurements.

Fig. 2 Plot of the squared signal variance versus the signal amplitude. The observed slope is proportional to the gain and the intercept is function of the electronics noise and of the ADC pedestal.

Fig. 3. Single Electron Response spectrum of a photomultiplier. The SER amplitude is 10 ADC channels and the width is 5 ADC channels. The same photomultiplier shows a slope of 12.9 ADC channels/pe, becoming 10.3 channels/pe after δ^2 correction.

Fig. 4. Normalized gain (dots) and normalized pulse height (circles) versus voltage for the same photomultiplier of fig. 3.

Fig. 5. Montecarlo simulation of the squared signal variance versus the signal amplitude for different δ_{SER} values.

Fig. 6 Photomultiplier gain variations as a function of time.

Fig. 7. Measurement of the light output in photoelectrons per GeV of the modules of the LAA Spaghetti calorimeter prototype. The modules with oldest [middle aged - newest] fibers have been represented with circles [triangles - squares].

Fig. 8. Plot of the squared signal variance versus the signal amplitude of a prototype HPD: a) HPD with 1 amplifier, b) HPD with 2 amplifiers.

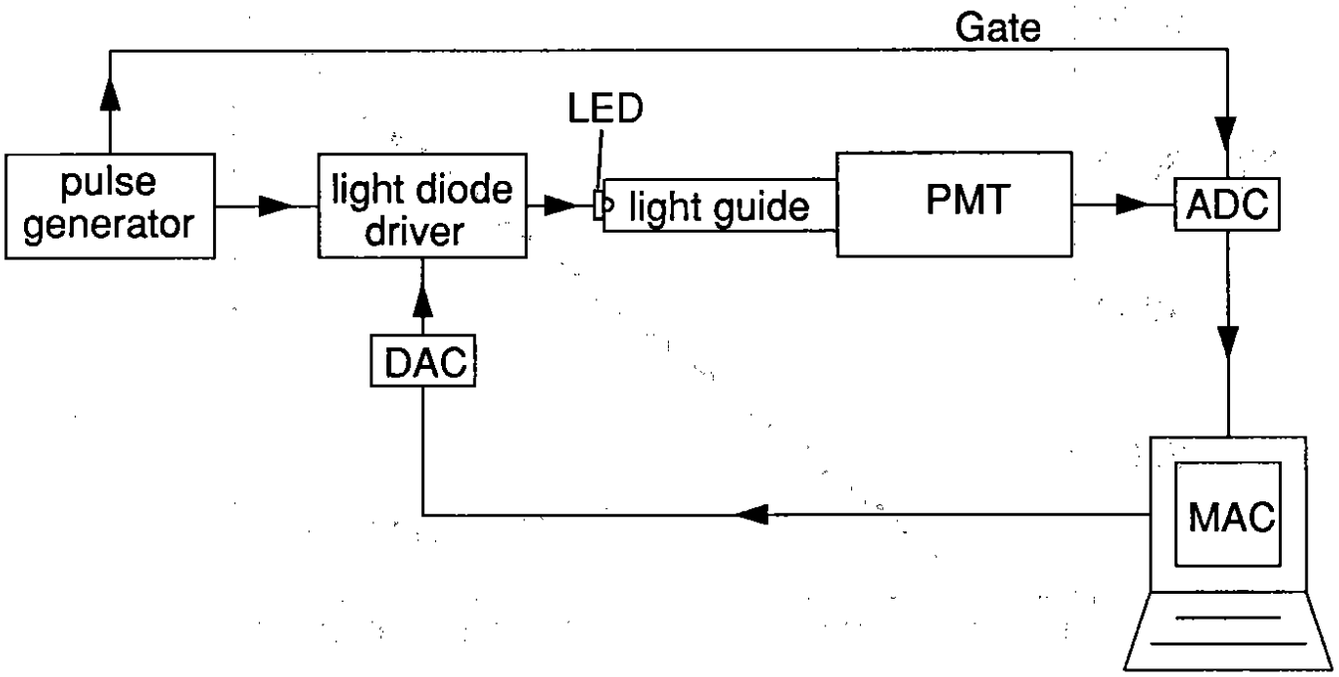

Gate
LED
pulse generator
light diode driver
light guide
PMT
ADC
DAC
MAC

Fig. 1.

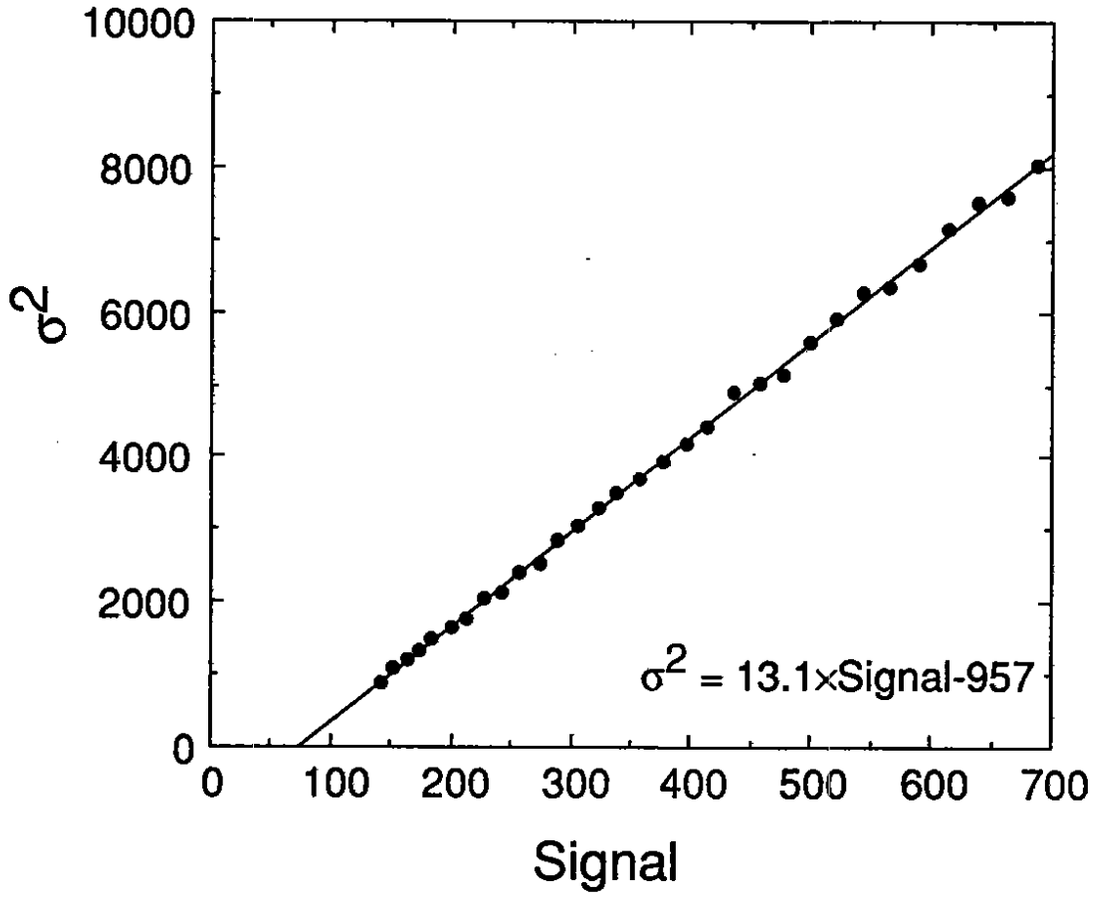

10000
8000
6000
4000
2000
0
σ2
0
100
200
300
400
500
600
700
Signal
σ2 = 13.1×Signal-957

Fig. 2.

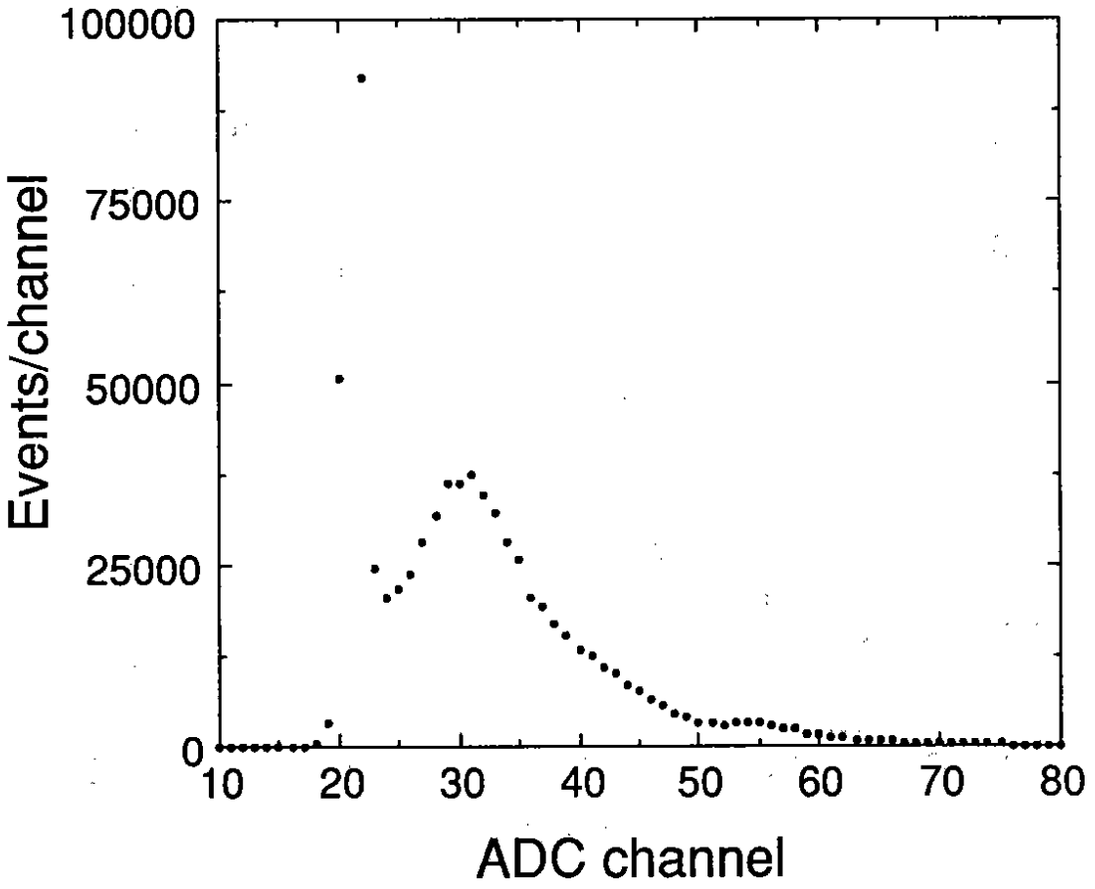

100000
75000
50000
25000
0
Events/channel
10
20
30
40
50
60
70
80
ADC channel

Fig. 3.

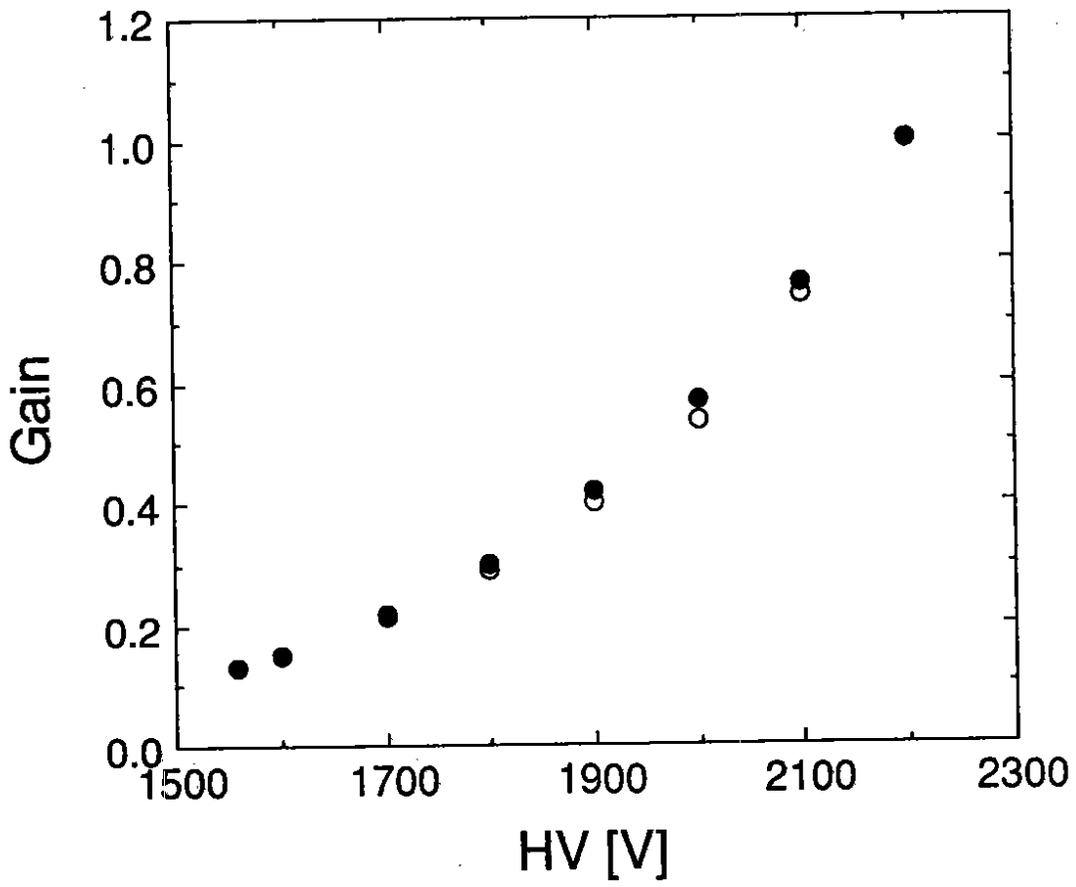


Fig. 4.

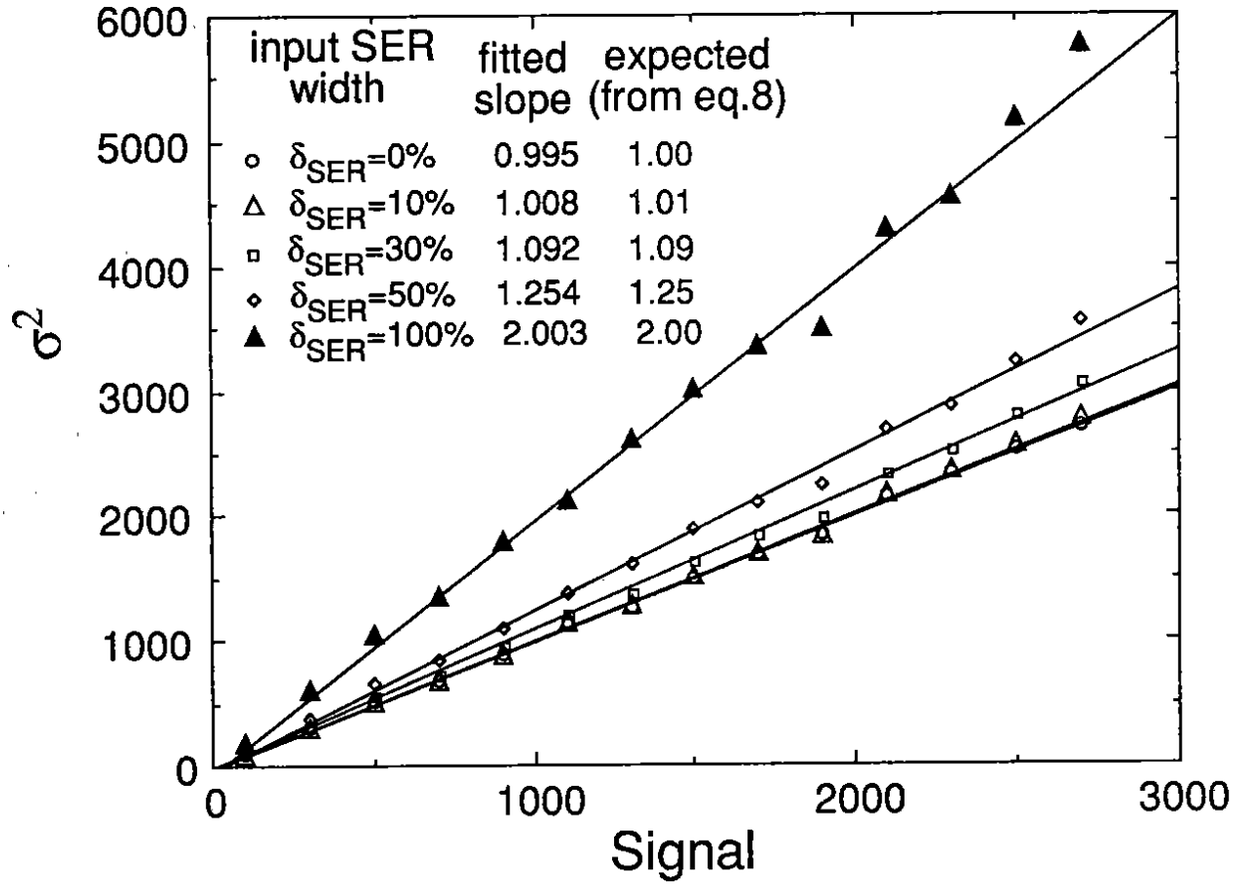

input SER width
fitted slope
expected (from eq.8)
δSER=0% 0.995 1.00
δSER=10% 1.008 1.01
δSER=30% 1.092 1.09
δSER=50% 1.254 1.25
δSER=100% 2.003 2.00
σ2
Signal
0
1000
2000
3000
4000
5000
6000

Fig. 5.

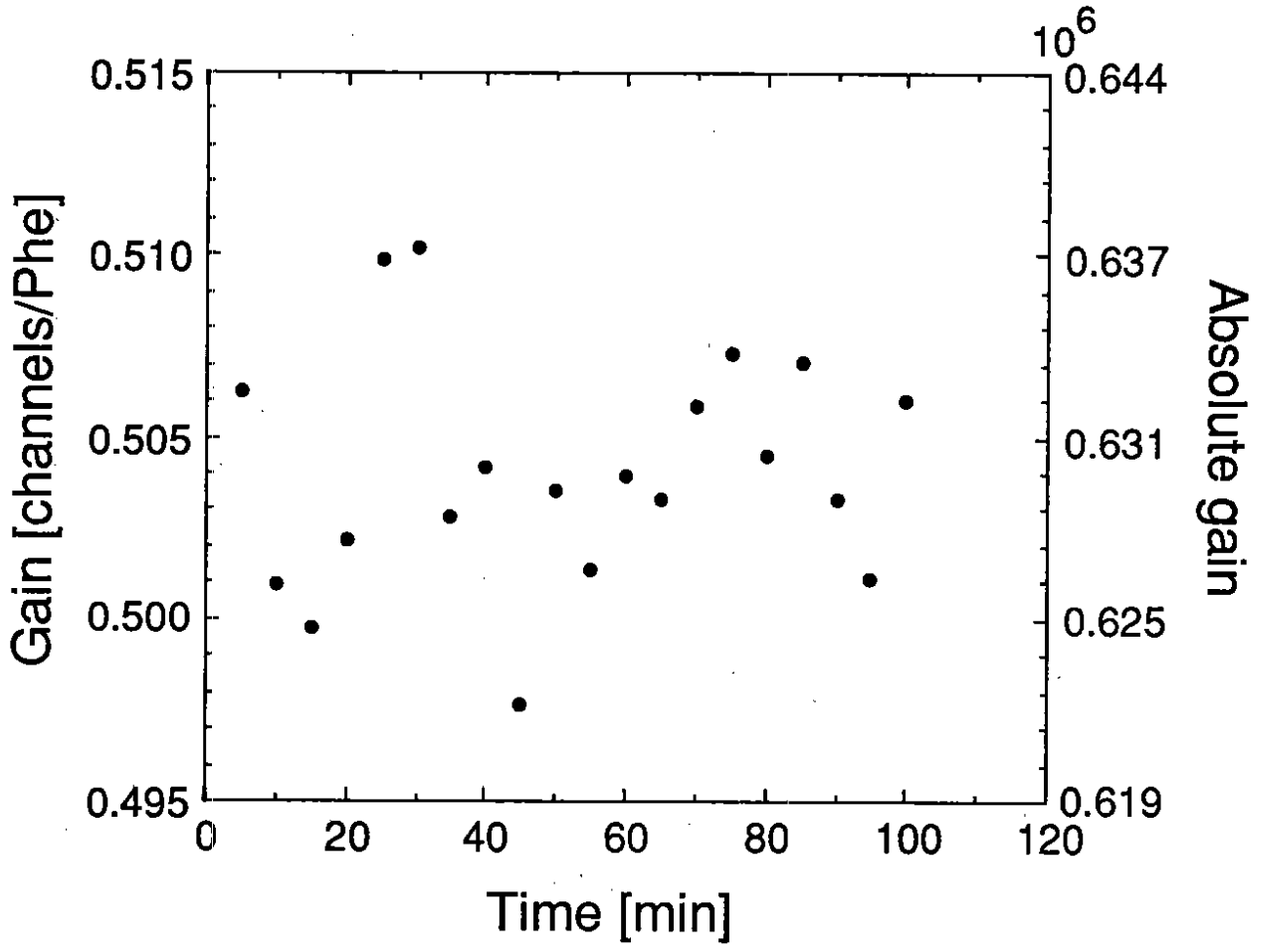

10^6
0.515
0.510
0.505
0.500
0.495
0.644
0.637
0.631
0.625
0.619
Gain [channels/Phe]
Absolute gain
0
20
40
60
80
100
120
Time [min]

Fig. 6.

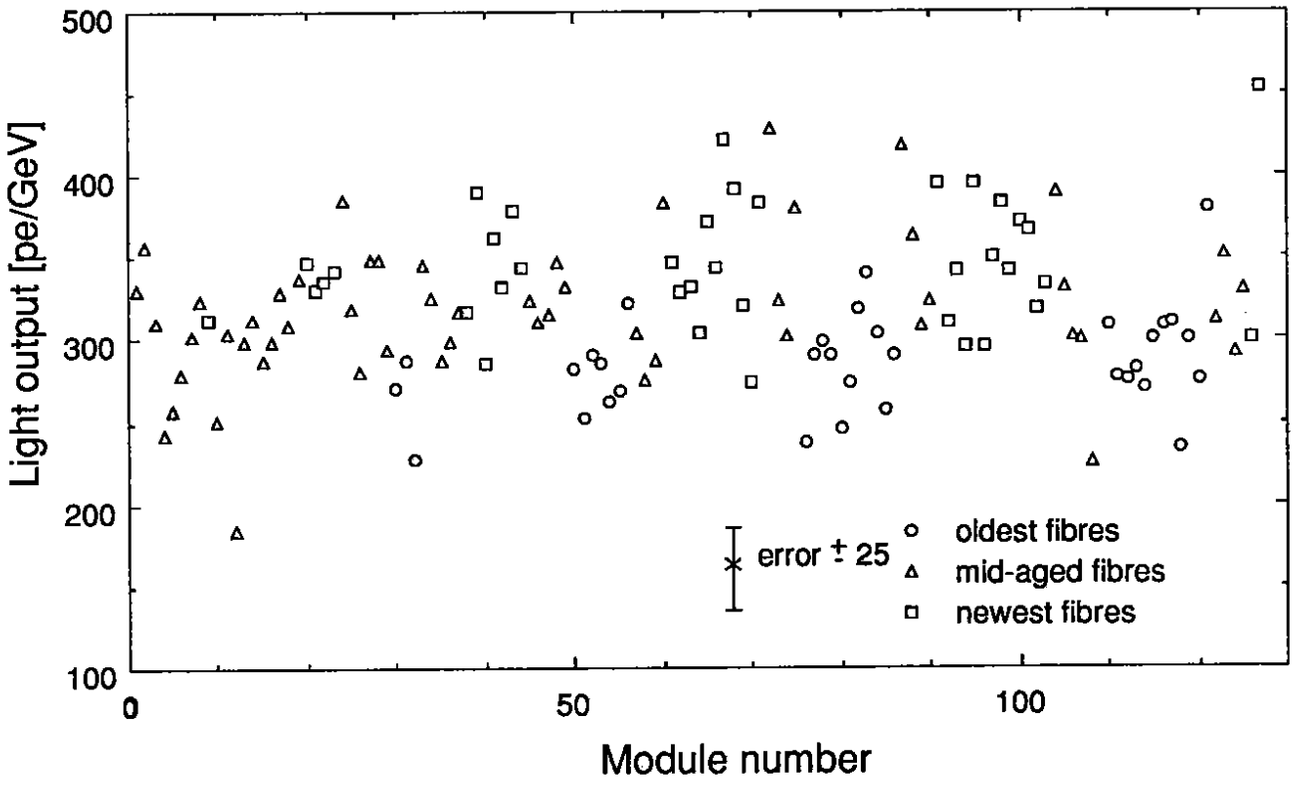
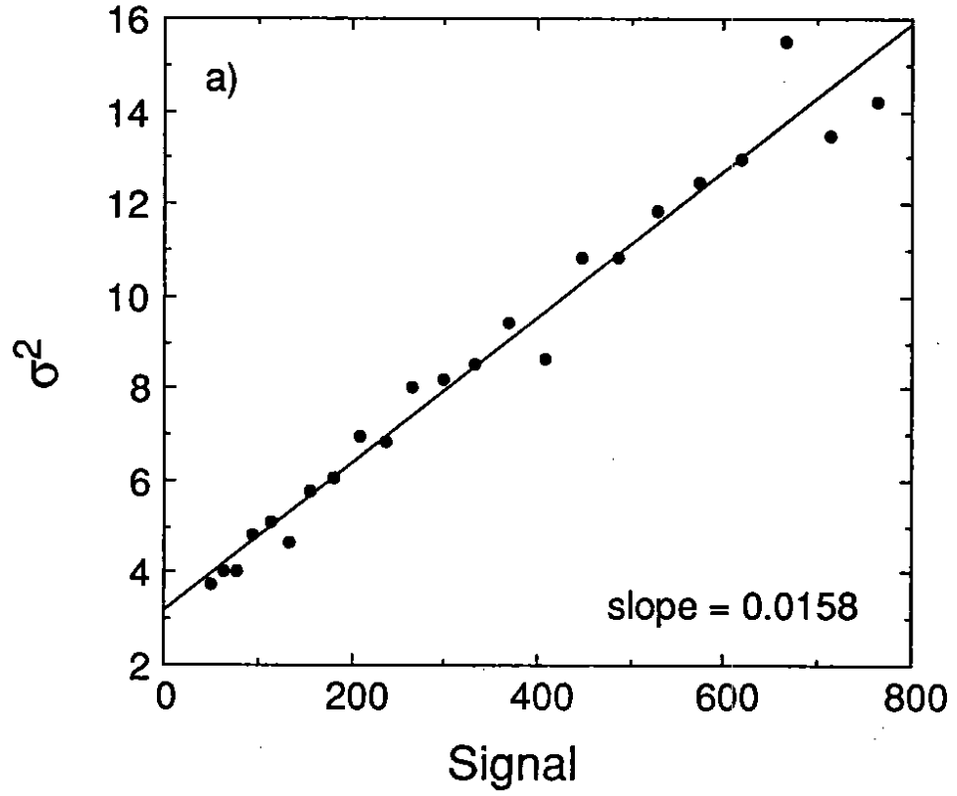

Light output [pe/GeV]
500
400
300
200
100
0
50
100
Module number
error ± 25
oldest fibres
mid-aged fibres
newest fibres

Fig. 7.


a)
16
14
12
10
8
6
4
2
σ^2
slope = 0.0158
0
200
400
600
800
Signal

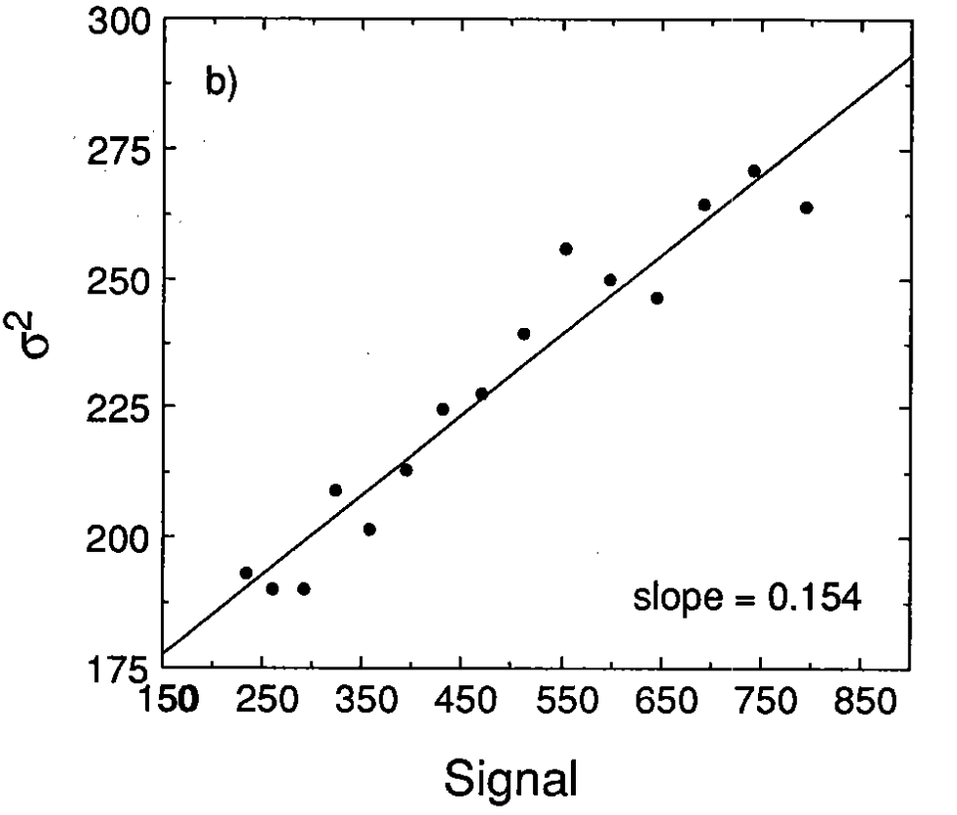

b)
300
275
250
225
200
175
σ^2
slope = 0.154
150
250
350
450
550
650
750
850
Signal

Fig. 8.