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PHOTOMULTIPLIERS GAIN MONITORING AT THE ONE PERCENT LEVEL WITH A BLUE LIGHT PULSER

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ABSTRACT.

We describe a method and an experimental layout allowing the monitoring of photomultipliers gain. We use artificial blue light (Spark-gap with filter : 436 ±20 nm) *and three reference detectors. Short term and long term measurements are presented. The results indicate a precision better than 0.5 % for the short term and 1.4 % for the long term determinations. This gain monitoring system has been developped for a new neutrino oscillation reactor experiment (600 photomultipliers) starting at the Bugey nuclear plant.*

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1. INTRODUCTION.

Light pulsers and optical fibres coupled to photomultipliers (PMs) or photodiode detectors have been extensively used in particle physics. In appropriate experimental situations such devices provide a way to regularly control the evolution of electronic detectors gains [Ref 1]. The absolute calibration of the detectors with particles of known energy remains essential but needs special running conditions. Generally, in between absolute calibrations, the gain evolution is frequently evaluated (each day for example). This is the case for the new Bugey neutrino oscillations programme [Ref 2], which uses several liquid scintillator detectors each having 200 PMs, on a long time scale (2 or 3 years of running time). We describe the methods to evaluate the PM's gain evolution. We used a prototype with 8 PMs and a network of optical fibres illuminated by blue light flashes. Our objective is to measure $R_i = \overline{G_i}/\overline{G_1}$ with a precision better than 1 % : $\overline{G_1}$ is the PM gain at the time t_1, $\overline{G_i}$ at the time t_i and R_i defines the monitoring parameter or the relative gain at the time t_i . We present two differents methods, a short term measurement which is valid under restrictive conditions and a long term measurement valid without these conditions but requiring more statistics. In the Bugey experiment, short term means a few weeks and long term several years.

2. PROTOTYPE AND LAYOUT.

Fig.1 sketches our experimental layout. A Bugey detector is simulated by a prototype of 4 cells filled with liquid scintillator (NE224) and viewed by a PM at both ends. Each of the 8 PMs (type XP3462-RTC) sees the light from one fibre fixed at the opposite side of the cell. Several fibres are connected to three reference detectors PR_1, PR_2 and PHR (PR_1,PR_2 are PMs type 150 AVP-RTC, PHR is a photodiode type S 1723.04 HAMAMATSU). In addition the gain of PR_2 is controlled with an ^{241}Am source deposited on a small NaI crystal. The gain of whole photodiode electronic chain is measured with the help of a ^{57}Co source (122.and 136.5 kev photons directly converted in the junction) [Ref 3]. Our light pulser is a spark-gap in a low nitrogen flow, connected to an interference blue filter [436±20 nm] and to a ground mylar sheet that allows a large angular scattering for any incident photon. The spark rate is about 60 per second and the discharge voltage about 2 KV. A typical flash produces a PM signal of 150 ns totale duration (22 ns fwhm) and 10 ns rise time. The amplitude is not constant from pulse to pulse. Figure 2a shows a standard ADC spectrum corresponding to 30 000 flashes. From time to time an AmBe source (4.43 Mev-γ) on each cell provides a direct and independant gain measurement.

Standard NIM and CAMAC electronics are used in the trigger logic and the events collection. We record the detector charge with an ADC (1024 channels LRS 2249A), and data taking is done with a Motorola 68000 VME computer [Ref 4] connected to the LAPP Vax .

3. THE EXPERIMENTAL METHOD.

We shall not , in the present paper, discuss the pedestals question . Due to the non-linearity of the ADC at low charge Q, we have used the "extrapolated" pedestal at $Q = 0$ and have applied corrections to the "measured" pedestal, obtained with a pulse generator, during the acquisition periods. In the following, any mention of a charge Q will mean a charge after pedestal substraction.

3.1 *The short term method.*

The definition of a short period is very dependant on each experimental situation. For us, it is assumed to be a few weeks. During such a period, we assume relative stability for the optics, the quantum efficiency of the prototype PMs and reference detectors. In other words, we make the assumption that any variations of the number of photoelectrons (in particularly due to the incident light source) on one detector correspond to a proportional variation on any of the other detectors. For reference detectors with radioactive sources we also assume, apart from the gain, the stability of responses. At present , we have no idea of such a stability over a long period (let us say several months). It was not the purpose of the present study. Many other authors have studied that aspect of the monitoring [Ref 5].

At each running period, we define the average charge values of : the PM under study $(\overline{Q})$, the reference detector $(\overline{Q_R})$ and its radioactive source signal $(\overline{S})$. $\overline{Q_1}, \overline{Q_{R1}}, \overline{S_1}$ are the values of the first running period (time $t = t_1$), and $\overline{Q_i}, \overline{Q_{Ri}}, \overline{S_i}$ those at any later period (time $t = t_i$), then it is easy to demonstrate that :

$$RS = \frac{\overline{G_i}}{\overline{G_1}} = \frac{\overline{Q_i} \cdot \overline{S_i}}{\overline{QR_i}} \Bigg/ \frac{\overline{Q_1} \cdot \overline{S_1}}{\overline{QR_1}} \qquad (1)$$

RS is the value of the parameter for short term monitoring. $\overline{Q_1}, \overline{Q_{R1}}$ $(\overline{Q_i}, \overline{Q_{Ri}})$ are the arithmetical averages of the charge spectra of the ADCs, and $\overline{S_1}$ and $\overline{S_i}$ are the averages found from fits. The Figures 3a and 3b show the fit (gaussian distribution and backround) of the ^{241}Am spectrum (reference PR2) and of the ^{57}Co peaks (reference photodiode PHR) respectively. With these two references we have two independant results for short term monitoring which we call RS2 and RS3. If all the previous assumptions are not verified, we can have biases in our results. Therefore, we will investigate a different monitoring method.

3.2 *The long term method.*

A long period is defined to be a period of several months or years. The long term method is based on the properties of the PM charge distribution when a constant number of photons impinges upon the photocathode [Ref 6]. To first order, in this case, the charge spectrum obeys to the two equations :

$$\overline{Q} = \overline{N} \cdot \overline{G} \qquad (2)$$

$$\frac{\sigma^2 Q}{\overline{Q}^2} = \frac{1}{\overline{N}} \cdot (1 - k) \qquad (3)$$

$\overline{Q}$ is the average of the charge distribution, $\sigma^2 Q$ its variance, $\overline{N}$ the average number of collected photoelectrons, $\overline{G}$ the average gain of the PM and of its chain. The factor $k = \varepsilon - \sigma^2 G/\overline{G}^2$ is a correction factor depending on ε which is the product of the quantum efficiency, and of the collection efficiency of the first stage. k also depends on the relative variance of the total gain of the PM chain. Typically for the RTC PM, $\varepsilon \sim 30\,\%$ (blue light) and $\sigma^2 G/\overline{G}^2 \sim 6\%$. It has already been suggested [Ref 7] to use relation (3) for the determination of the average number of photoelectrons $\overline{N}$ and relation (2) for the gain determination. Our experimental situation is a little more complicated because our light pulser is not a source emitting a constant number of photons. Nevertheless, we obtain an equivalent PM distribution when the PM signal is divided by the reference PM signal (QR_1 or QR_2) event per event. The corrected distribution $q_c = (Q/Q_R) \cdot \overline{Q_R}$ is in fact a gaussian distribution (at first order) with the following properties:

$$\overline{q_c} = \overline{Q} = \overline{N} \cdot \overline{G} \qquad (4)$$

$$\frac{\sigma^2 q_c}{\overline{q_c}^2} = \frac{\sigma^2 q_c}{\overline{Q}^2} = \frac{1}{\overline{N}} (1 - k) + \frac{1}{\overline{N_R}} (1 - k_R) \qquad (5)$$

The second term of (5) represents the square of the resolution of the reference PM and is a correction to the first term if $\overline{N_R} >> \overline{N}$. ($\overline{N_R}$ represents the number of photoelectrons on references and k_R is a factor similar to k). In our set-up, this correction is small because we have one optical fibre illuminating each prototype PM through the liquid scintillator and 7 fibres directly coupled to the references (PR1 and PR2). Our runs, on the average , have $\overline{N} \sim 700$ and $\overline{N_R} \sim 5\,000$ photoelectrons. $\overline{N_R}$ is calculated by using the two light pulser spectra of the two references (QR_1 and QR_2) and the σ of the event per event distribution (QR_1/QR_2), as explained in details by P.Besson [Ref 8]. Fig.2b displays the gaussian-like spectrum q_c

compared to the raw distribution Q (Fig.2a).This method is applied to each PM of the prototype. We define the RL long term monitoring parameter as

$$RL = \frac{\overline{G_i}}{\overline{G_1}} = \frac{\overline{N_1}}{\overline{N_i}} \cdot \frac{\overline{Q_i}}{\overline{Q_1}} \tag{6}$$

$\overline{N}$ is deduced from the variance of q_c and relation (5). $\overline{Q1}$, $\overline{N1}$, $\overline{G1}$ are the values of the first running period (time $t=t_1$) and $\overline{Qi}$, $\overline{Ni}$, $\overline{Gi}$ those at any later period (time $t=t_i$).With the two references PR1 and PR2 we obtain two long term monitoring parameters RL1 and RL2.

3.3 Verification of the monitoring with an Am-Be source.

We have used an Am-Be source (4.43 MeV γ) to irradiate the prototype cells from a fixed geometrical position. If we assume that the scintillation light (emission, transmission) and the PMs quantum efficiency (like in the short term method) are stable, we can define a monitoring parameter for the γ radioactive source as :

$$R\gamma = \frac{\overline{CH_i}}{\overline{CH_1}} = \frac{\overline{G_i}}{\overline{G_1}} \tag{7}$$

Here $\overline{CH_1}$, $\overline{CH_i}$ are charges associated with the γ spectra respectively at the times $t = t_1$ and $t = t_i$. Fig.4 displays a typical Am-Be spectrum obtained for one PM. The analysis of such distributions is difficult and is described in [Ref 8].

4. THE EXPERIMENTAL RESULTS.

The results are based on 12 runs taken during a data acquisition period of 20 days. At each run 30 000 light pulser events were recorded and immediately followed by the acquisition of source events of the two references PR_2 and PHR . From time to time that set of data was completed for the prototype PMs with the γ spectrum of the Am-Be source. During this period we have met problems of temperature and electric power instabilities. Fortunately, results do not seem to depend on these conditions.The first run, $t = t_1 = 0$, is defined to be the reference run with a gain value $\overline{G1}$.Then for each of the other runs we evaluate the monitoring parameters $R(t = t_i) = \overline{G_i} / \overline{G_1}$ at each time $t = t_i$. We calculate :

-The two short term monitoring parameters :

- RS2 obtained from the reference PR2 (PM),
- RS3 obtained from the reference PHR (photodiode).

-The two long term monitoring parameters :

- RL1 obtained from the reference PR1 (PM),
- RL2 obtained from the reference PR2 (PM).

-The source monitoring parameter (from time to time):

- $R\gamma$ obtained from the Am-Be source.

4.1 *Typical monitoring parameters for one prototype PM (PM1).*

Fig.5a shows the evolution, for the PM1, during 20 days, of the two short term parameters RS2, RS3 and the source monitoring parameter $R\gamma$. The error is statistical. We observe a good agreement between these three values at each run. For two measurements we have changed the high voltage (HV) on the PM (+20 and -20 volts) and we clearly see the corresponding variation of the monitoring parameters. The change due to the HV is also clear on Fig. 5b which displays the two long term monitoring parameters RL1 and RL2. We also notice good agreement between the two set of values. In fact this agreement allows us to define the mean value : RL = 1/2 (RL1+RL2) which has a better statistical significance. Fig.6a illustrates, the evolution of RL and $R\gamma$. The two results are in good concordance inside the experimental errors.During the whole test period the light pulser fluctuates and slowly changes. The mean values of the collected charge on a PM ($\bar{Q}$) and of the number of photoelectrons ($\bar{N}$) vary. Fig.7 indicates a typical behaviour of $\bar{N}$ as a function of $\bar{Q}$. Each point represents one run. Here, the two points which are far away from the averaged slope (proportional to $1/\bar{G}$) correspond to an appreciable change of the gain when the HV has been increased and decreased. The number $\bar{N}$ is not constant. We have studied a normalized number of photoelectrons $\overline{Nph} = \bar{N}.(\bar{S}/\overline{QR}\ )$ which should be constant if we have stability of the light transmission and stability of the PM quantum efficiency. Fig.6b shows the evolution of the ratio $R\bar{n} = \overline{Nph}\ (t{=}ti)\ /\ \overline{Nph}\ (t{=}t1)$ calculated with the PHR reference data . This evolution confirms, inside the stastistical errors, the fair stability of the optical light transmission and the stability of the photocathode efficiency .

4.2 *results for all the prototype PMs.*

In order to estimate the errors on our monitoring parameters, we have represented (fig.8 and fig.9) for 8 PMs of the prototype and 11 runs, the histograms of the following variables: RS2-RS3, RL1-RL2, RL-RS3, RS3-$R\gamma$, Rn-1. The corresponding mean value $\bar{m}$ and standard deviation σ are :

RS2-RS3 :	$\bar{m} = -0.1\ \%$	$\sigma = 0.5\%$	Fig.8a	(88 data points)
RL1-RL2 :	$\bar{m} = 0.1\%$	$\sigma = 1.1\%$	Fig.8b	(88 data points)
RL -RS3 :	$\bar{m} = 0.3\%$	$\sigma = 1.5\ \%$	Fig.8c	(88 data points)
RS3 -$R\gamma$:	$\bar{m} = 0.2\%$	$\sigma = 1.1\%$	Fig.8d	(20 data points)
Rn - 1 :	$\bar{m} = -0.3\%$	$\sigma = 1.5\%$	Fig.9	(88 data points)

Statistics are not very high but the histograms have a gaussian shape which indicates no large effect due to systematic error. Any deviation of $\overline{m}$ from zero reflects a possible bias between two measurements. On the other hand σ is correlated to the total error (statistics + systematic). The two short term monitoring parameters (Fig.8a) and the two long term parameters (Fig.8b) are in good agreement .The histogram X=RL-RS3 (fig.8c) has a mean value compatible with zero and the standard deviation σ=1.5 % includes the statistical errors (due to the counting, the pedestal substraction, the differential ADC linearity...etc) and also the systematic uncertainties . We have: $\sigma^2_X = (1.5\%)^2 = \sigma^2_{RL}(\mathrm{stat}) + \sigma^2_{RL}(\mathrm{syst}) + \sigma^2_{RS3}(\mathrm{stat}) + \sigma^2_{RS3}(\mathrm{syst})$.
We find $\sigma_{RL}(\mathrm{stat}) = 1.2\ \%$ and $\sigma_{RS3}(\mathrm{stat}) = 0.5\ \%$ as results of our calculations.
If we assume σ_{RS3} (syst) = 0 as suggested by the histogram (fig. 8a), we can estimate $\sigma_{RL}(\mathrm{syst}) \lesssim 0.5\ \%$. The total uncertainty associated to a single RL measurement is $\sigma_{RL} \leq 1.4\ \%$ and is dominated by statistics. Fig.8d displays the difference between the short term monitoring parameters RS3 and Rγ. The statistics are small (only 20 measurements) but the results show no appreciable error in the determination of the monitoring parameters. Finally , Fig.9 displays the histrogram of $R\overline{n} - 1$, the values $\overline{m} = -\ 0.3\ \%$ and $\sigma = 1.5\ \%$ are compatible with the validity of the short term method during our measurement period.

5. CONCLUSIONS.

We have described a method and an experimental layout allowing the control of the photomultipliers gain using an artificial blue light pulser and three reference detectors.The short term method (based on the signals average and several stability assumptions : - light transmission ,- quantum efficiency of the detectors,- references sources and their associated scintillators) has been compared to the long term determination (based on a fundamental equation of the PM charge at first order). In fact both methods, short and long term methods, are in good agreement during the 20 days of our study and verify the gain measurements obtained with an Am-Be source.

Finally with 88 gain measurements (each of 30 000 events) we arrive at the following conclusion :

1) over a 20 days period the basic assumptions concerning the short term method seem to be valid. The precision of the monitoring parameter is of the order of 0.5%

2) the long term method requires more statistics, has no stability assumption and is experimentally valid. The precision on the monitoring parameter is estimated to be better than 1.4 %. The long term monitoring parameter should be available, with such a precision, to control during a long period of time, the photomultipliers relative gain .

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FIGURE CAPTIONS.

1. The experimental layout.

2a. A typical charge spectrum of the light pulser on one prototype PM.

2b. The same distribution after correction is a gaussian-like spectrum corresponding to a light source emitting a constant number of photons.

3a. The fit of the ^{241}Am spectrum on Reference PR2 with a gaussian distribution and a background.

3b. The fit of the 122. and 136.5 keV γ rays of the ^{57}Co on reference PHR.

4. A typical γ spectrum of the Am-Be source with the pedestal, obtained on one prototype PM.The shoulder corresponds to the Compton edge of 4.43 Mev γ.

5a. The evolution of the two short term monitoring parameters RS2, RS3 and of the source monitoring parameter $R\gamma$ (PM1). $R\gamma$ errors correspond to an estimation of the fit errors.

5b. The evolution of RL1, RL2 the two long term monitoring parameters (PM1).

6a. The evolution of the average long term monitoring parameter RL = 1/2 (RL1+RL2) and of the source monitoring paramameter $R\gamma$ (PM1).

6b. The evolution of the ratio of the normalized number of photoelectrons $R\overline{n}$ (PM1).

7. The number of photoelectrons $\overline{N}$ as a function of the average collected charge $\overline{Q}$ (PM1). The straight line is hand-drawn.

8a. The histogram of the difference between the two short term monitoring parameters (RS2-RS3), (88 datas points : 11 runs - 8 PMs).

8b. The histrogram of the difference between the two long term monitoring parameters (RL1-RL2), (88 datas points: 11 runs - 8 PMs).

8c. The histogram of the difference between average long term RL and short term RS3 monitoring parameters (88 datas points: 11 runs - 8 PMs).

8d. The histogram of the difference between average short term RS3 and source $R\gamma$ monitoring parameters (20 datas points: 10 runs - 2 PMs).

9. The histogram of the difference $R\overline{n}$-1,$R\overline{n}$ being the ratio of the normalized number of photoelectrons (88 datas points : 11 runs - 8 PMs).

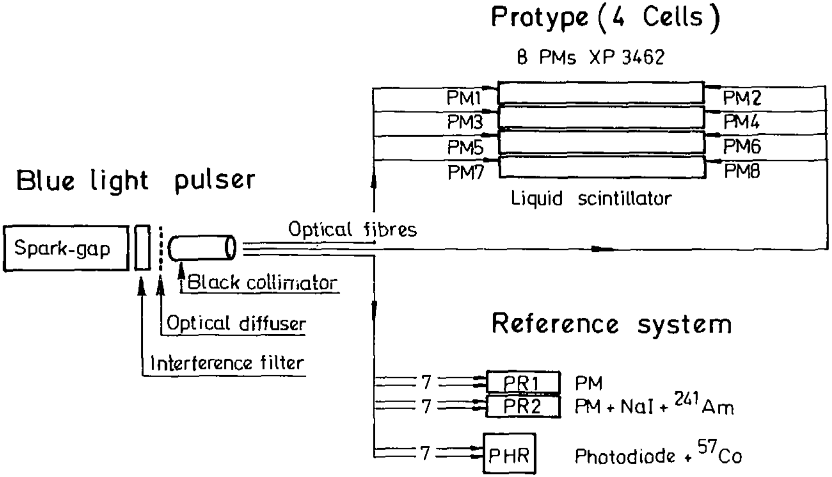

Protype (4 Cells)
8 PMs XP 3462
PM1
PM2
PM3
PM4
PM5
PM6
PM7
PM8
Liquid scintillator
Blue light pulser
Spark-gap
Optical fibres
Black collimator
Optical diffuser
Interference filter
Reference system
7
7
7
PR1
PR2
PHR
PM
PM + NaI + 241Am
Photodiode + 57Co

Fig. 1

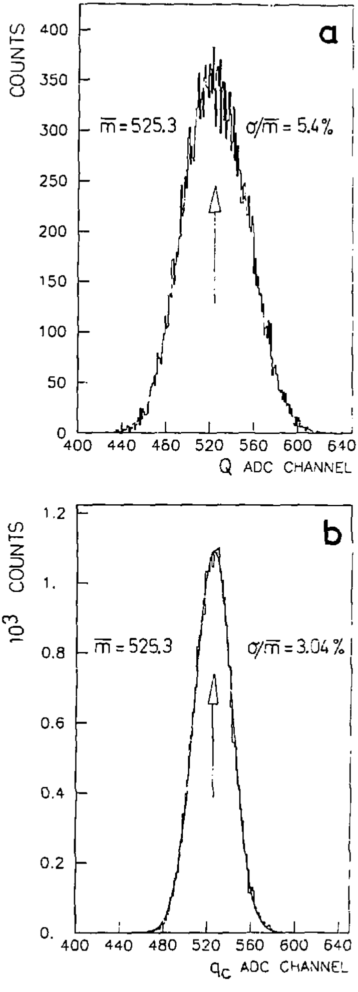

a
COUNTS
400
350
300
250
200
150
100
50
0
400
440
480
520
560
600
640
Q ADC CHANNEL
$\overline{m} = 525.3$
$\sigma/\overline{m} = 5.4\%$
b
10^3 COUNTS
1.2
1.
0.8
0.6
0.4
0.2
0.
400
440
480
520
560
600
640
q_c ADC CHANNEL
$\overline{m} = 525.3$
$\sigma/\overline{m} = 3.04\%$

Fig. 2

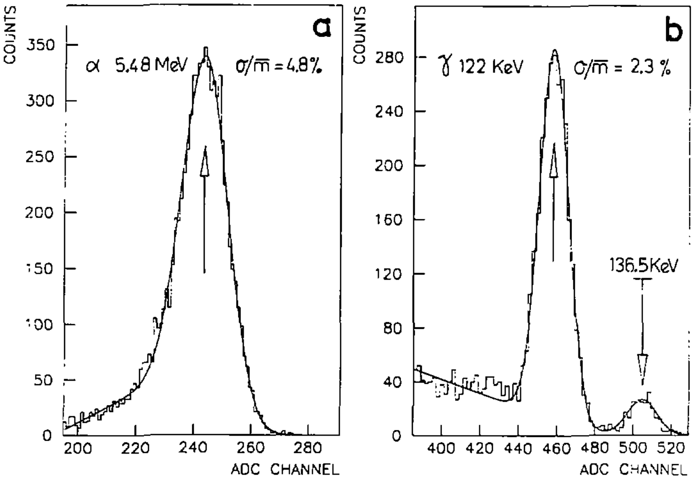

a
COUNTS
0
50
100
150
200
250
300
350
α 5.48 MeV
σ/m̄ = 4.8%
200
220
240
260
280
ADC CHANNEL
b
COUNTS
0
40
80
120
160
200
240
280
γ 122 KeV
σ/m̄ = 2.3 %
136.5 KeV
400
420
440
460
480
500
520
ADC CHANNEL

Fig. 3

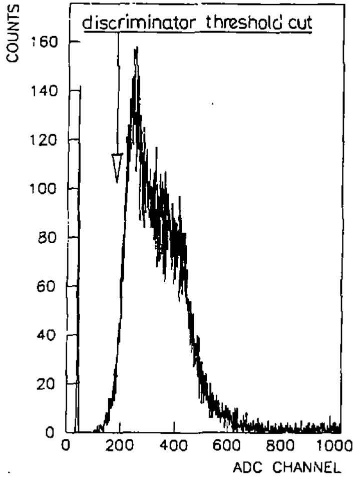

discriminator threshold cut
COUNTS
160
140
120
100
80
60
40
20
0
0
200
400
600
800
1000
ADC CHANNEL

Fig.4

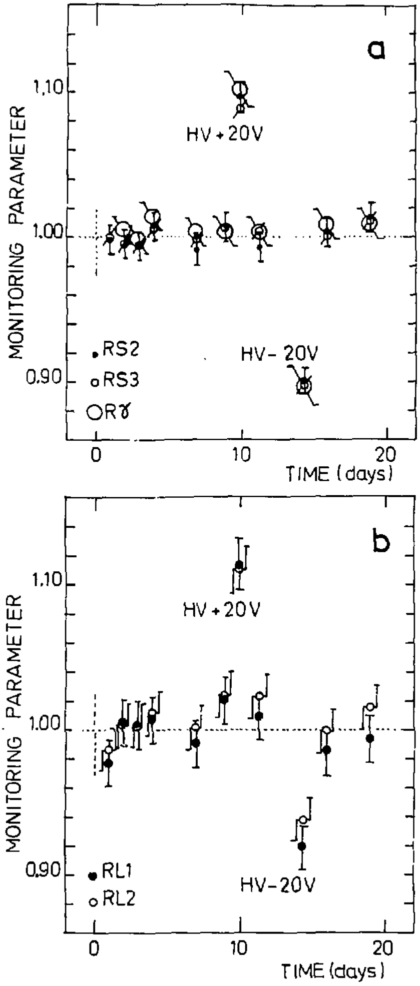

a
MONITORING PARAMETER
1.10
1.00
0.90
HV + 20V
HV - 20V
RS2
RS3
Rγ
0
10
20
TIME (days)
b
MONITORING PARAMETER
1.10
1.00
0.90
HV + 20V
HV - 20V
RL1
RL2
0
10
20
TIME (days)

Fig. 5

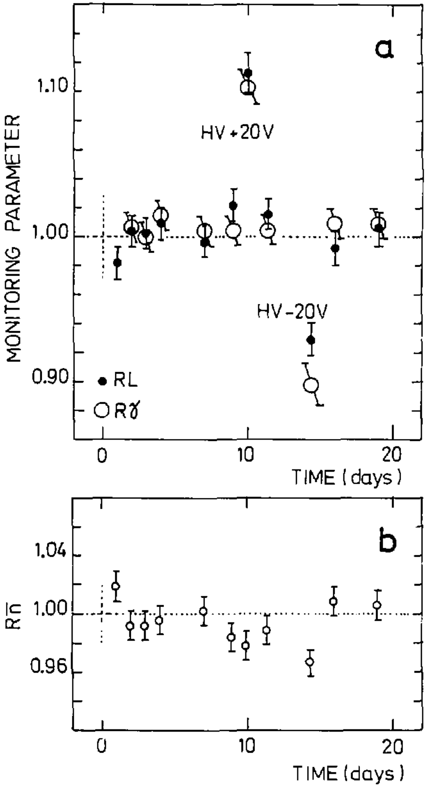
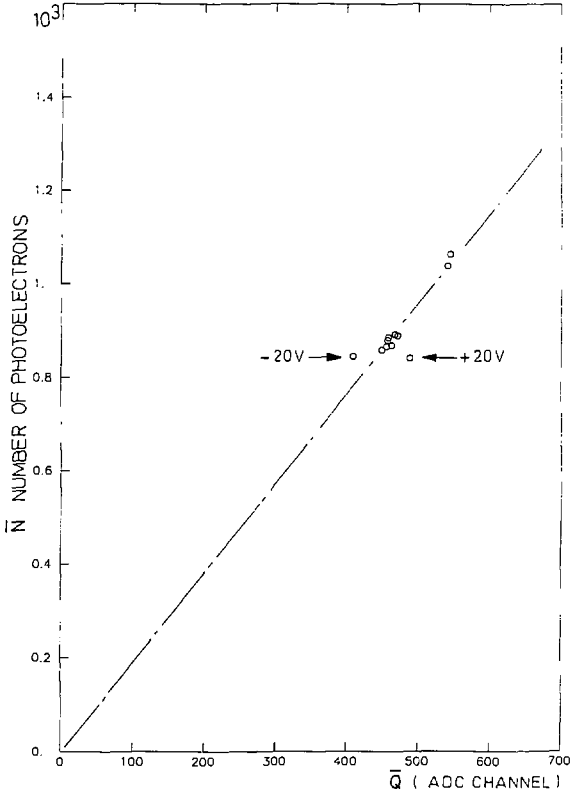

a
MONITORING PARAMETER
1.10
1.00
0.90
HV+20V
HV-20V
● RL
○ Rγ
0
10
20
TIME (days)
b
R$\bar{n}$
1.04
1.00
0.96
0
10
20
TIME (days)

Fig. 6



10^3
1.4
1.2
1.
0.8
0.6
0.4
0.2
0.
N̄ NUMBER OF PHOTOELECTRONS
-20V
+20V
0
100
200
300
400
500
600
700
Q̄ (ADC CHANNEL)

Fig. 7

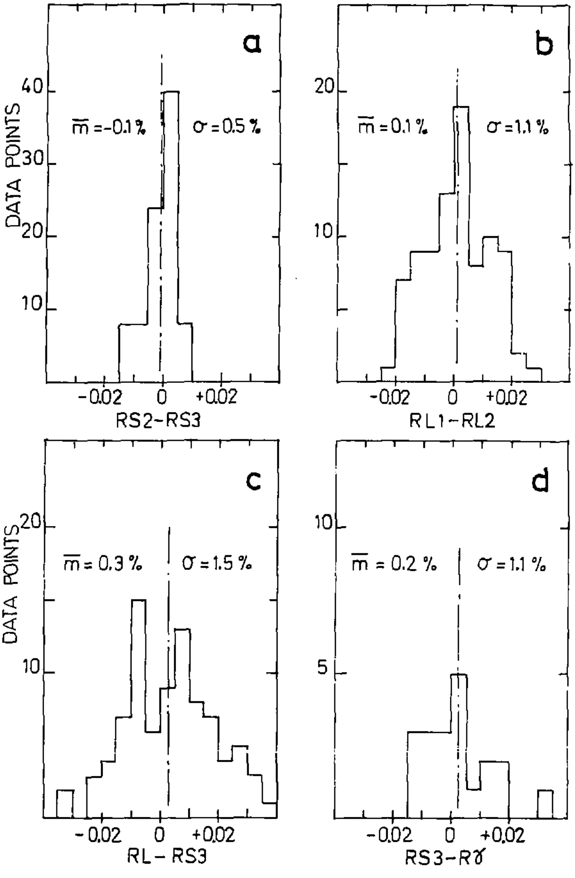

a
DATA POINTS
40
30
20
10
m̄ = -0.1 %
σ = 0.5 %
-0.02
0
+0.02
RS2-RS3
b
20
10
m̄ = 0.1 %
σ = 1.1 %
-0.02
0
+0.02
RL1-RL2
c
DATA POINTS
20
10
m̄ = 0.3 %
σ = 1.5 %
-0.02
0
+0.02
RL-RS3
d
10
5
m̄ = 0.2 %
σ = 1.1 %
-0.02
0
+0.02
RS3-Rγ

Fig. 8

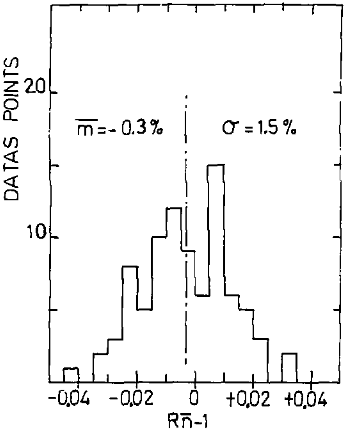


Fig.9