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Characterization of the new R5900 Hamamatsu photomultiplier in Pisa.

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Abstract

We report on a wide program of tests of the new conception Hamamatsu photomultiplier R5900. Fifteen of such photomultipliers have been characterized in Pisa testing their main parameters with a dedicated setup. Such a test program has been carried out in the framework of the study of a realistic prototype of the future ATLAS tile hadronic calorimeter (TILECAL).

1 The photomultiplier

The Hamamatsu R5900 is a new conception photomultiplier of extremely compact size ($28 \times 28 \times 20$ mm^3) due to the innovative metal envelope and the ultrathin electrodes allowing a downsizing of the device. The dynode geometry, a stack of extremely thin electrodes, allow a very good behaviour in magnetic field. These characteristics match the ATLAS hadronic calorimetry readout requirements and the collaboration started an intense study of such photomultiplier comparing it to other commercial products.

In September 1996 a test of a full scale slice of the barrel part of the calorimeter (for details about the detector see for example: ATLAS TP, RD34 Status Report), using a particle beam, will be carried out. The readout of half of such a slice has been set up using sixty-five of such phototubes. The sixty-five phototubes had to be characterized and classified following established criteria. The note reports about the test of fifteen out of sixty-five phototubes, done in Pisa last May-June 1996.

2 The test program

A testing protocol has been established for the photomultiplier characterization. The measurements are of two main types: a) a set of tests done using a DC mode operated light source and b) a set of tests done using a pulsed mode operated light source.

The light source is a blue LED LEDTRONICS BP280CWB1K-3.6VF050T, quite fast and intense [1]. In order to have a light with a wavelenght of the order of the real one an interferential filter (ANDOVER Co. 480FS10-50 selecting 480 ± 5 nm) has been used. A light mixer in front of the phototube window is used as in the real situation.

The goal is the measurements of the luminous characteristics of both the cathode and the anode, the gain and the efficiency of the photomultiplier.

3 The DC mode tests

At LHC a continous level of background and minimum bias events will be present, then the photomultipliers are expected to be continously illuminated by the light produced in the scintillator due to these background particles. Consequentely it has been decided to evaluate the phototube behaviour in such an enviroment. Moreover the DC mode allow an absolute gain measurement, useful to have a scale for the relative gain measurement done using a pulsed light.

3.1 The cathode luminous sensitivity

With the LED operated in continous mode and using a special divider, a measurement of the cathode luminous sensitivity has been done. The special divider is made connecting the anode and all the dynodes together to a positive voltage ranging 10-120 V, while the cathode is connected to ground. In that way it is possible to measure the photoelectron current variation by varying in step the applied voltage. This test allows to estimate the surface resistance of the photocathode and a precise tune of the voltage that can be applied to the first accelerating stage to have a satisfactory charge collection. In effect if the photocathode surface resistance is very large we will have a poor collection efficiency at the level of the first dynode and we have to increase the electrical field strength to correct for this effect.

Another important aspect of this measurement is that measuring the anode current (see below) we can extract directly the gain curve.

The required electronics consists in a digital multimeter channel (KEITHLEY 2001) per photomultiplier with a computer controlled readout and a stable HV channel per each phototube. A silicon photodiode with the related electronics is used to monitor the light level. A very precise digital voltmeter controls the low voltage power supply output to monitor eventual change in the LED supply.

In figure 1 we show the results obtained for the 15 phototubes: the photocathode current as a function of the voltage applied between the cathode and the first dynode is plotted for a saturation voltage of 10 nA and in figure 2 for a saturation voltage of 30 nA.

3.2 The anode luminous sensitivity and the gain

In a second step we measure the anode luminous sensitivity using the normal operation divider. In this measurement the light output of the LED is the same of the previous measurement. In order to decrease the light level, to avoid large anode current, we have used a neutral filter with a well known attenuation factor. In parallel the dark current is also measured (fig. 3).

The ratio of the anode efficiency and the cathode efficiency is the absolute gain. In figure 4 we show the gain curves as a function of the applied voltage for all our 15 photomultipliers.

Figure 5 shows the correlation between the measured gain and the gain measured by Hamamatsu. The clear correlation is a check of the test reliability. The gain measured by the firm is 10 times higher of the one measured during these tests because the firm used a different divider ratio.

4 Pulsed mode

4.1 Phototube efficiency and gain

The second part of the measurements consists in the evaluation of the photomultiplier efficiency and the relative gain using the LED in pulsed mode. This operation mode is near to the final use of the PM and it is important to evaluate the gain also in this mode to have a comparison and a more efficient characterization. At the end a normalization to the DC mode gain curve is needed.

The setup is the same as before, but while in the DC mode we could use a simple low voltage power supply, for the pulsed mode we have to use a LED driver. We used a LeCroy 9210/9211 pulse generator providing very precise output pulse and a fast pretrigger to form the gate for the ADC.

The gain measurement is made using a calibrated ADC channel per phototube. The measurement consists in the acquisition of a charge spectrum per channel at each voltage. In the offline data analysis stage we extract the number of photoelectrons and the charge, then the gain.

In figure 6 we report the light curves (number of photoelectrons vs the operating voltage) for 15 phototubes and in figure 7 the corresponding gain curves.

5 The Database compilation

A set of parameters has been required for the photomultiplier characterization. For the DC light mode the following quantities are required: once one obtains the plateau we can extract the voltage at which the plateau starts (*V1s*) and the value of the photocurrent at this voltage (*EPSp*), that is the value of photocurrent at the plateau.

The voltage (*V1s*) is the voltage at the first stage then knowning the voltage divider ratio it is possible to calculate the corresponding operating voltage for each phototube and check if this value is lower than the real operating voltage. This condition guarantees a satisfactory charge collection. All the phototubes satisfy this requirement.

In order to have an uniform sample we require that all the phototubes have similar photocathode sensitivity, otherwise the ones that are more sensitive as well as less sensitive, have to be rejected.

The pulsed light mode has been characterized through the voltage at which the plateau of the number of photoelectrons vs high voltage curves starts (*HVs*). Then a gain vs high voltage curve fit to the function:

$$G = \alpha(HV)^{\beta}$$

allows to extract the α and β parameters useful for the online database compilation.

Finally a parametrization of the dark current vs high voltage curve with the equation:

$$I_{dark} = a(HV)^{b} + c$$

provide the three parameters a, b and c characterizing the dark current behaviour.

Table 1 reports the value obtained.

Protocol based PMT characterization								
PM nr.	V1s (V)	EPSp	HVs (V)	$\alpha \times 10^{-15}$	β	a $\times 10^{-3}$	b	c
6A08CA	30	0.93	700	0.11	7.51	0.44	1.07	-0.32
6A31D4	20	0.95	700	0.12	7.55	0.10	1.21	-0.15
6A31C5	20	0.98	700	0.088	7.61	0.18	0.94	0.01
6A25D8	20	0.95	700	0.079	7.51	0.42	1.05	-0.26
6A31D5	20	0.98	700	0.091	7.57	0.43	1.05	-0.26
6A11C4	20	0.98	750	0.20	7.35	0.37	1.02	-0.13
6A31C4	20	0.99	700	0.086	7.63	0.42	1.04	-0.25
6A11C6	20	0.98	750	0.097	7.45	0.54	1.13	-0.68
6A26D7	30	0.97	700	0.084	7.59	0.43	1.05	-0.29
6A26C1	20	0.98	700	0.11	7.56	0.49	1.08	-0.43
6A31C6	10	0.98	650	0.085	7.67	0.61	1.20	-0.25
6A11C8	30	0.98	700	0.12	7.49	0.46	1.09	-0.41
6A11C9	10	0.98	700	0.13	7.47	0.39	0.97	-0.15
6A25DA	20	0.97	650	0.087	7.64	0.37	1.02	-0.19
6A26C4	40	0.97	650	0.091	7.58	0.43	1.06	-0.29

Table 1: The required database quantities

6 Additional measurements

Some additional measurements have been carried out to have a more precise evaluation of the phototube features.

In order to check the phototube efficiency dependence on the light level we measured it at three different levels (180, 300 and 900 photoelectrons). As it is possible to evaluate in figure 8 there is not a dramatic effect and that is a satisfactory result.

Based on our previous experiences [2] we performed a quantum efficiency (q.e.) measurement for each phototube to have an idea of their absolute q.e. value and the dispersion. A dedicated section is devoted to explain the basic idea and the procedures.

7 The quantum efficiency measurement

Besides the protocol measurement, we decided in Pisa to measure an additional important quantity: the quantum efficiency of the photomultiplier to check if it matches the TILECAL requirements and check what is the dispersion of such quantity in our sample. This important measurement characterizes the behaviour of a phototube.

The quantum efficiency of a phototube is a function of the wavelength and is defined as the percentage of produced photoelectrons for each incident photon. The quantum efficiency is measured by the producers on a sample of phototubes in the visible spectrum. The measurement is lengthy and for industrial production cannot be performed for each photomultiplier. The firm provides for each photomultiplier quantities that can be easily measured, as the photocathode sensitivity in the blue.

The aim of the measurement that we have made in our lab is to measure with good precision the photomultiplier's quantum efficiency for green light. In fact our WLS fibres, and more generally the scintillating fibres used in the tracking systems at colliders have an emission peak in the green. These fibres are more radiation hard and longer attenuation length than the blue fibres.

A complete program should also foresees a measurement of the detection efficiency of a photomultipliers operating in "photon counting" mode, but this part has been omitted for lack of time.

7.1 The q.e. definition

The photomultiplier quantum efficiency (ϵ_{pm}) measure the probability that a photon impinging the photocathode is converted in a photoelectron. The q.e. can be measured when the photomultiplier is operated as a vacuum photodiode, i.e. photocathode and all dinodes are kept at the same voltage such that the photomultiplier gain is 1. In these conditions, if the rate of photons is N, $\epsilon_{pm} = n/N$, where n is the average rate of photoelectrons.

The phototube operated as photodiode is powered at voltage V, corresponding to the plateau of the luminous sensitivity curve, such to have a complete collection of charge.

We measure the anode current I by recording a voltage drop on a load resistor R. Then we have:

$$n = \frac{I}{e} = \frac{V}{Re} \tag{1}$$

where e is the electron charge.

The rate of photons N can be measured using a photodiode whose quantum efficiency is well known. The experimental setup is shown in fig. 9. We have used a He-Ne laser as a stable light source at $\lambda = 543.5$ nm. The laser beam is attenuated by two polarimeters before hitting the photodiode. The axis of the first polarimeter is hold fixed, while the other one is rotated in order to vary in a controlled way the number of photons N.

To measure the rate of photons (N) we used a silicon photodiode (EG&G type UV-250BQ) whose active area is 4.6×4.6 mm^2. Its quantum efficiency at $\lambda = 543.5$ nm is provided by the manifacturer $\epsilon_{pd} = (60 \pm 5)$ %.

It is sufficient to position the photondetector with a precision of a few mm, since the laser beam divergence is very small and the beam transverse dimensions are about 3.0×3.0 mm^2. The maximum rate of photons is 10^{14}s^{-1}.

If N_0 is the rate of photons entering the second polarimeter, the rate of photons impinging the detector is: $N_0 \cdot (\cos^2 \phi + k)$, where ϕ is the angle between the two polarimeters and k is a constant. It is important that the laser beam intensity is large enough to allow a reliable measure of the diode current but not too large such to damage the photomultiplier. We have choosen $\Delta\phi = \pi/2$. The photodiode current (I) is given by:

$$I = e\epsilon_{pd} N_0 (\frac{1}{2} + k) \tag{2}$$

The constant k turns out to be very small (about 10^{-7}) and can be neglected, therefore we get:

$$\epsilon_{pm} = \frac{\epsilon_{pd} V}{RI} \tag{3}$$

In this measurement we have assumed that the phototube is linear. This is certanly true for the silicon photodiode whose response is linear but for the photomultiplier we have to operate with a low flux of photons and check the linearity of the response with a neutral filter. In addition the photocathode sensitivity is different for polarized light than for for unpolarized one, however the differences are of the order of few percent.

With this system we measured the quantum efficiency of the fifteen Hamamatsu R5900 photomultipliers.

The photomultiplier linearity has been checked by using a neutral filter with transmission coefficient equal to 0.2.

Finally we evaluated the uncertainty in the measure of the quantum efficiency. A possible source of uncertainty is related to the variation of quantum efficiency from the center to the border of the photomultiplier (the photomultiplier is positioned with a precision of about 1 mm in the vertical plane and of 100 μmin the horizontal one). As an example we measured such a variation for a photomultiplier Melz FEU184, whose photocathode window (2" in diameter) is larger than the one of the R5900, then the effects are more pronounced. We moved the photomultiplier in the horizontal (x) and vertical (y) plane in precise steps and we repeated the measurement of the quantum efficiency of the Melz photomultiplier. The results are summarized in figures 10 and 11 from which we see a variation of quantum efficiency of about 10 % . We assumed that this is the maximum spread of quantum efficiency.

Finally we were interested in the quantum efficiency at 480 nm, then once we obtained the quantum efficiency at the laser emission wavelength (543.5 nm) we rescaled the quantum efficiency curve to extract the interesting value. As a further check, using the testbench setup with the LED light filtered with a quite narrow band interferential filter, we performed a charge spectrum measurement for each photomultiplier from which we have the number of photoelectrons for each phototube for the same number of photons. It is straightforward to extract the correct value for the quantum efficiency.

In table 2 we report the obtained values for the Hamamatsu R5900 photomultipliers. The average quantum efficiency is about 16 %, which is lower than the required one (18 %) and in general is lower of the usual value for a good photomultiplier in this region, i.e. $18 \div 20$ %. Moreover the dispersion is about 13 %, that is a quite high value.

An explanation of the not very good quality of the photocathode can be traced to the possible fails in the production procedure. It is well known that the photocathode materials deposition have two different phases. During the first one the tube is empty and a first deposition of Antimonium (Sb) is made under vacuum. After that the vacuum condition are broken and the dynodes are inserted in the tube. Then, again in vacuum, there is the deposition of the other alcalyne materials on the photocathode and the dynodes. Finally the tube is closed. Due to the high occupancy of the dynodes we think that the second material deposition is quite difficult and surely subject to be not

Quantum efficiency	
PM nr.	Q.E. (%)
6A08C4	17.0
6A31D4	16.4
6A31C5	17.5
6A25D8	12.8
6A31D5	18.4
6A11C4	14.5
6A31C4	19.3
6A11C6	13.7
6A26D7	18.2
6A26C1	18.3
6A31C6	20.7
6A11C8	15.1
6A11C9	14.4
6A25DA	18.3
6A26C4	14.8

Table 2: The quantum efficiency measurement results

very well controlled. That can be an explanation for the low values of the absolute quantum efficiency for some of the photomultipliers and the high dispersion around the mean value. This problem will be reported to the firm.

8 Conclusions

The test carried out in Pisa characterized 15 Hamamatsu R5900 photomultipliers. Only three of them were rejected following the protocol criteria. The characteristics of the photomultiplier seem to be promising. Only the quantum efficiency behaviour is not matching the ATLAS requirements, but we are confident with a correct feedback and further developments to fix the problem.

References

[1] LEDTRONICS, LED BP280CWB1K-3.6VF050T data sheet.

[2] D. Autiero et al., Study of a possible scintillating fibre tracker at the LHC and tests of scintillating fibres, Nucl. Instr. and Meth. **A336** (1993) 521-532.

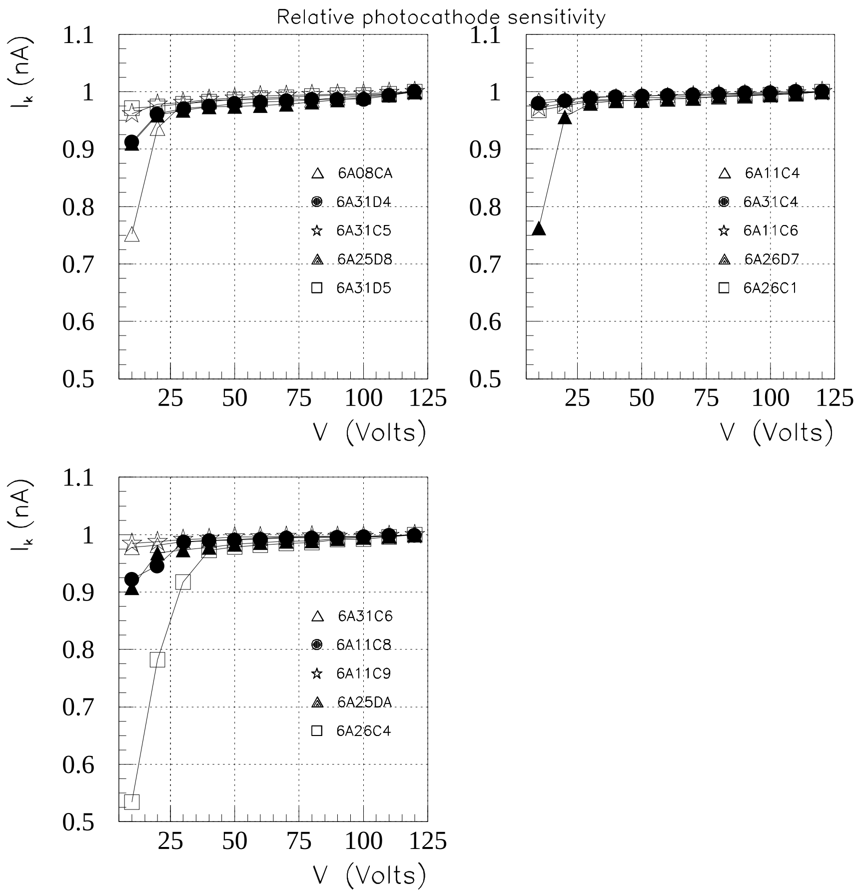

Figure 1: The photocathode luminous sensitivity (saturation value of the photocurrent of 10 nA). The curves are normalized to the saturation level.

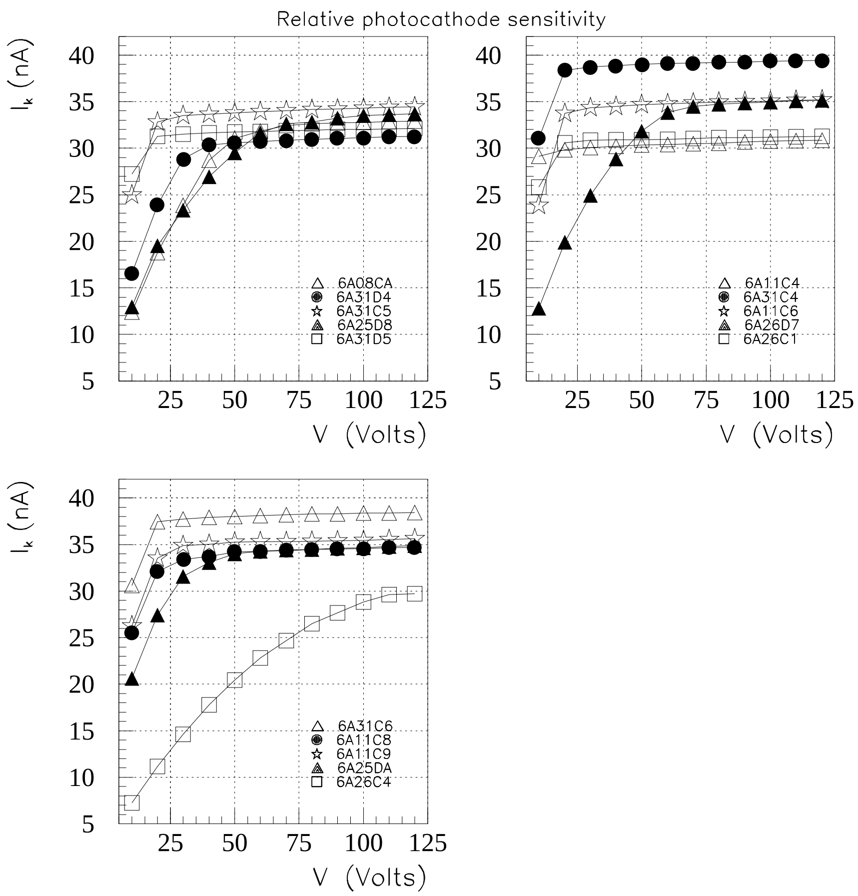

Figure 2: The photocathode luminous sensitivity (saturation value of the photocurrent of 30 nA. In this case the curves are not normalized to the saturation level.

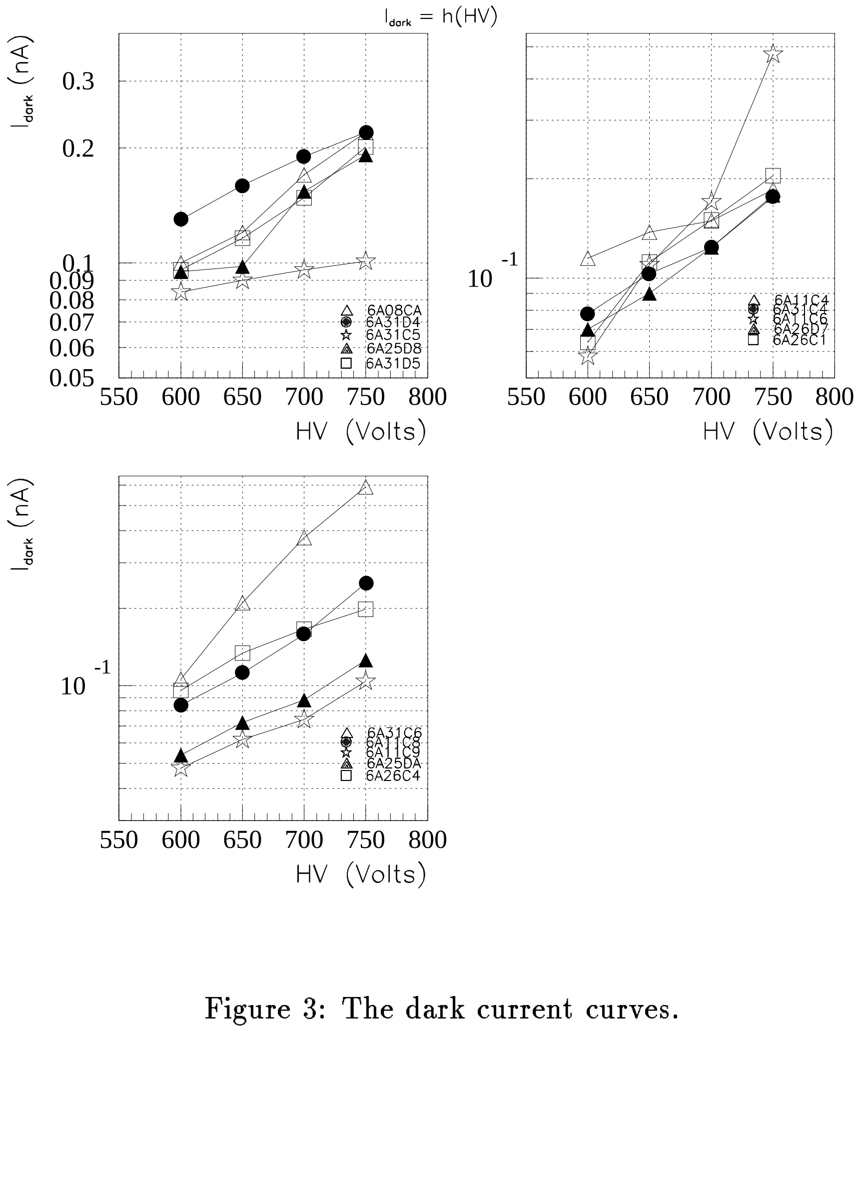

Figure 3: The dark current curves.

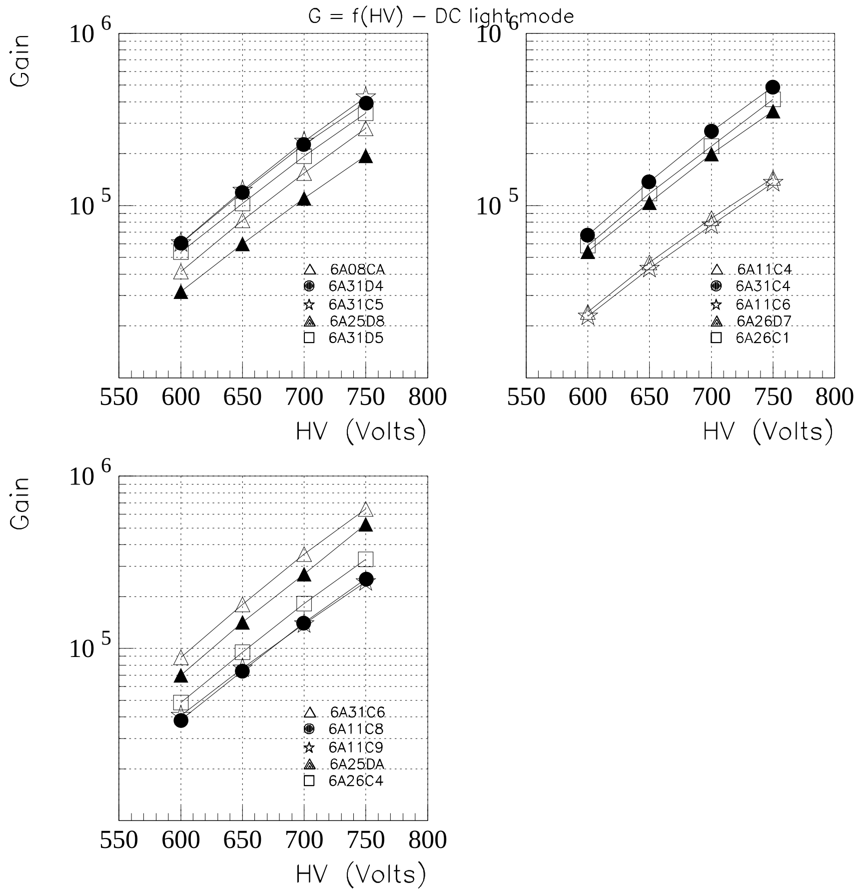

Figure 4: The gain curves.

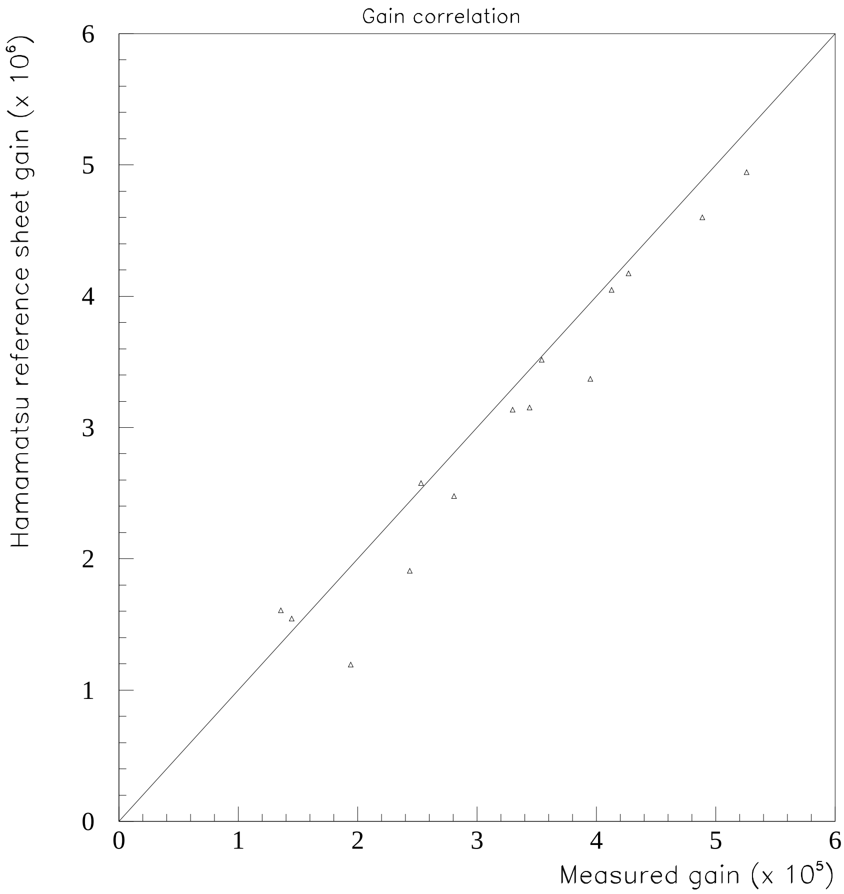

Figure 5: The correlation between the measured gain and the gain/10 measured by Hamamatsu.

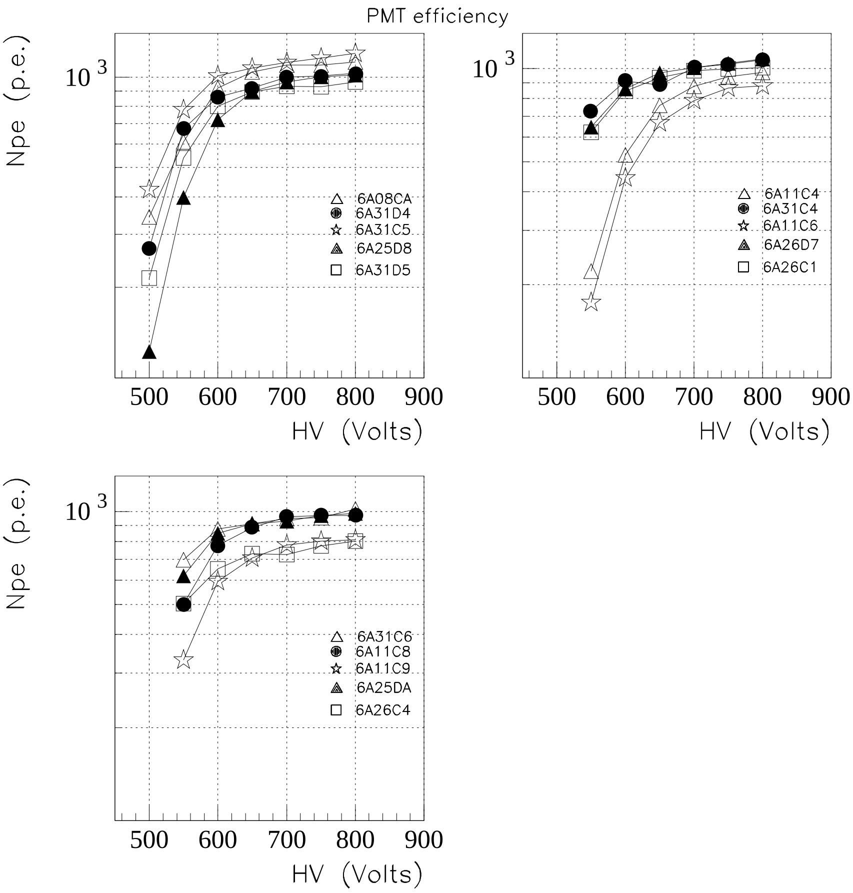

Figure 6: The efficiency curves in pulsed mode.

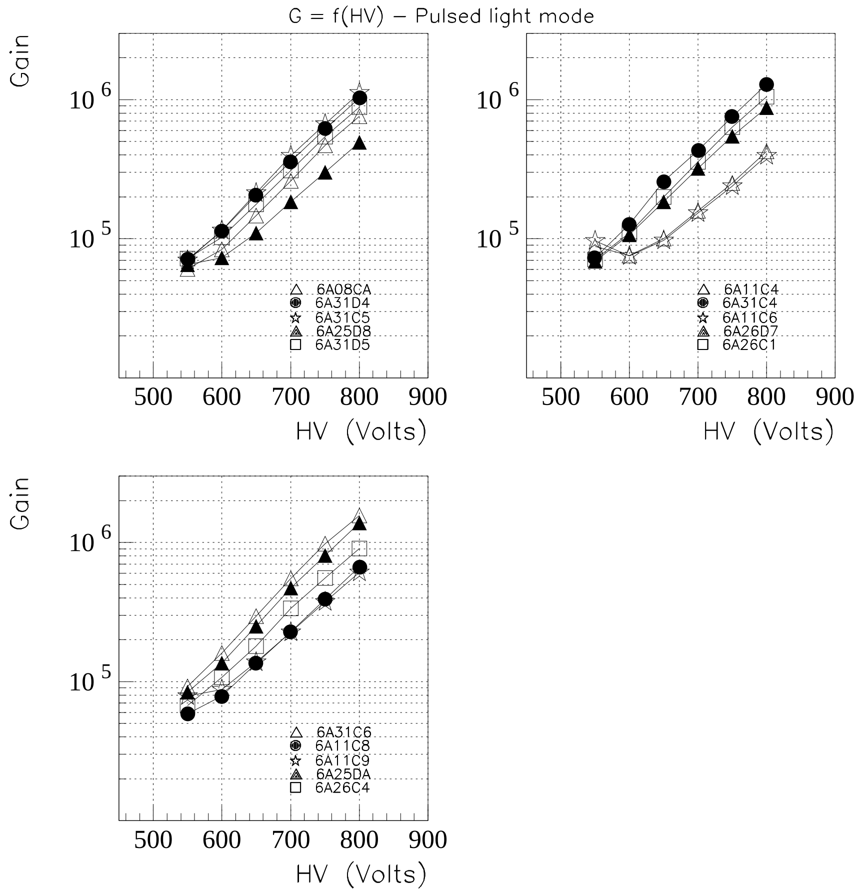

Figure 7: The gain curves in pulsed mode.

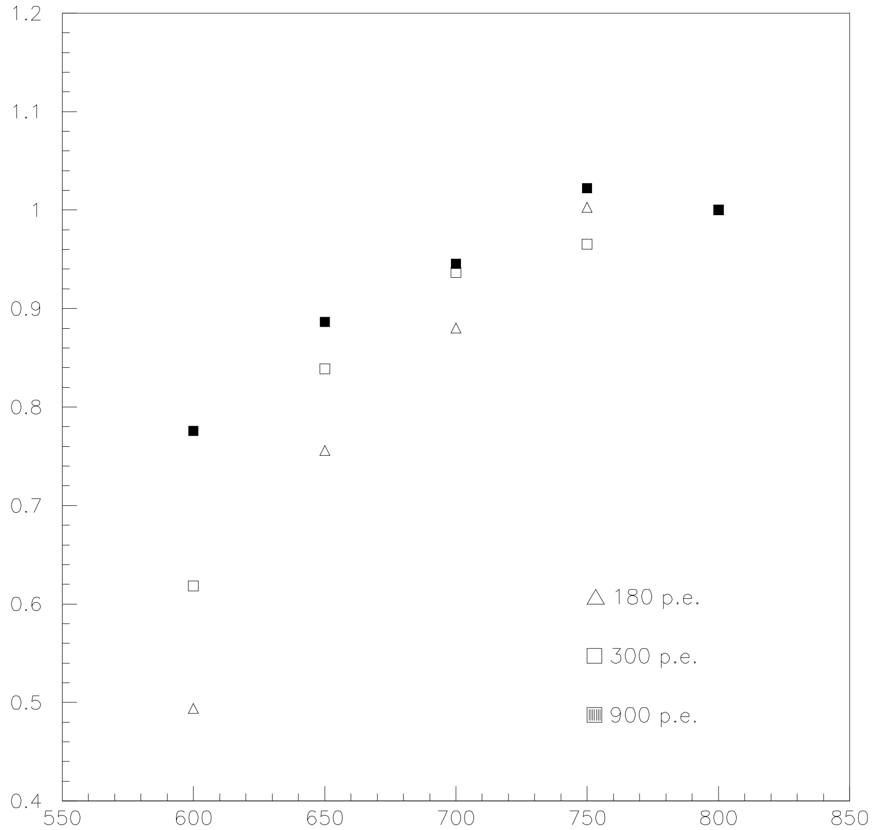

Figure 8: The phototube efficiency curves at different light levels (180, 300 and 900 photoelectrons). The curves are normalized to 900 photoelectrons (at 750 V).

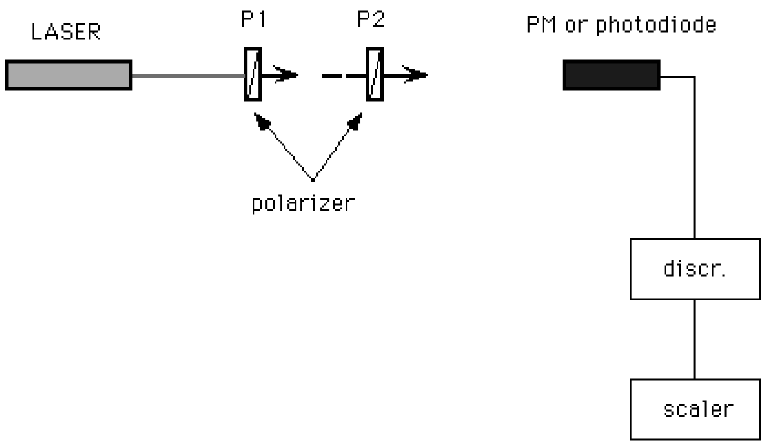

Figure 9: Experimental apparatus for the quantum efficicency measurement.

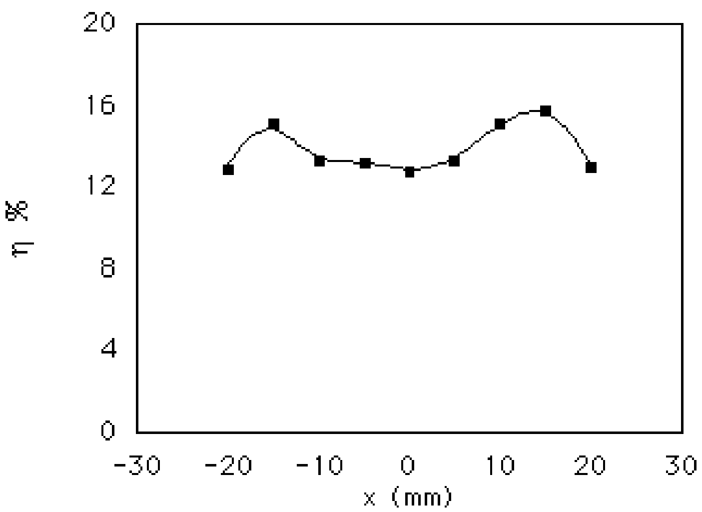

Figure 10: Variation of the quantum efficiency versus x of the laser beam incidence point on the photocathode surface.

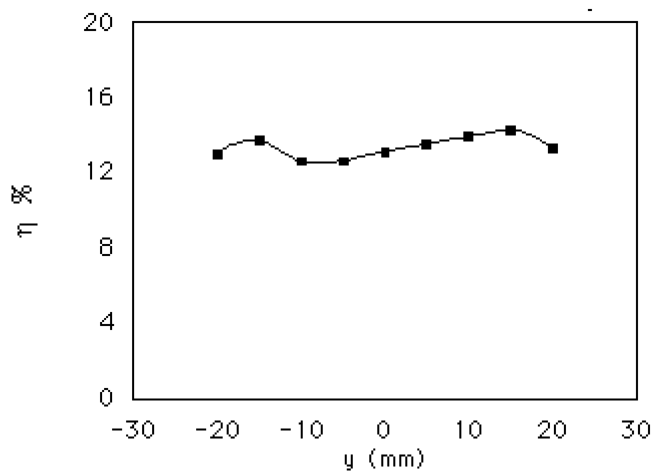

Figure 11: Variation of the quantum efficiency versus y of the laser beam incidence point on the photocathode surface.