Nuclear Instruments and Methods 205 (1983) 443–449
North-Holland Publishing Company

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20 INCH DIAMETER PHOTOMULTIPLIER

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Received 14 July 1982

In the field of large scale water Cherenkov experiments such as proton decay, the detector is required to have a wide photosensitive area, high gain, low noise, fast timing, and good stability. The 20 inch diameter photomultiplier is developed and ascertained to have good characteristics as the detector component of the proton decay experiment. In this paper, various characteristics of the newly developed 20" PMT are described.

1. Introduction

A large underground Cherenkov detector system for proton decay studies was proposed by a group of the University of Tokyo [1,2]. It was recognized that the photomultiplier for the Cherenkov radiation detection should have the capabilities of "wide photosensitive area" detection, single photoelectron detection, fast timing property, tolerance against high pressure and long term stability.

The diameter of the photomultiplier is determined to be 20″ by the requirement in physics of efficient signal photon collection at huge amounts of radiation.

The 20″ diameter photomultiplier (20″ PMT) [3] has been developed while overcoming several problems on the production such as glass manufacturing and PMT construction that had not been encountered before.

2. The design of the PMT

The PMT is designed to fulfill the requirements mentioned in section 1. The picture and the construction of the PMT are shown in figs. 1 and 2 respectively. The glass envelope is made of borosilicate glass HARIO-32 (similar to Schott Duran-50) which is chosen because of its spectral transmittance and water-durability. The bi-alkali photocathode is chosen to match the water Cherenkov light spectrum. Fig. 3 shows both the spectral distribution of the Cherenkov light after the passage of 15 m water and the quantum efficiency of the photocathode.

The 20″ diameter quasi-hemipherical glass window and photocathode provide effective light collection (2π solid angle), measurement of timing property and tolerance against high pressure. The Venetian blind type

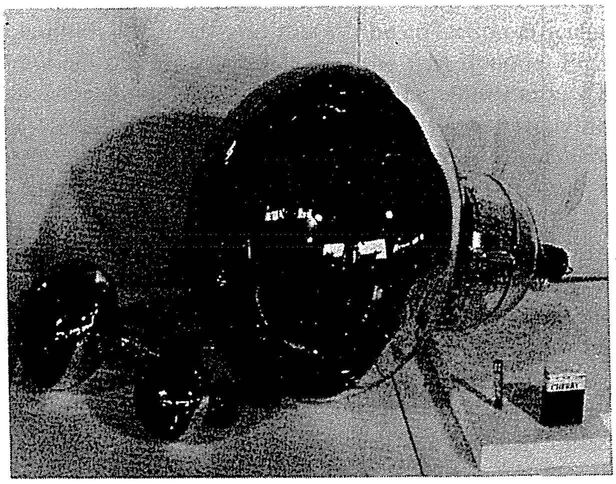

Fig. 1. Picture of the 20″ PMT with 8″ PMT, 5″ PMT and 1/2″ PMT.

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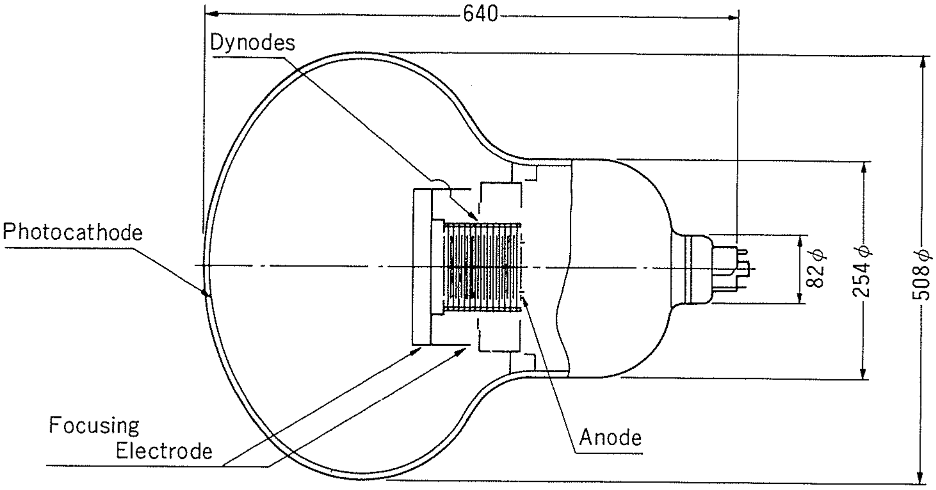


Fig. 2. The construction of the 20" PMT.

dynodes of 13 stages are installed to obtain a large photoelectron collection area as well as high current amplification. The structure and the arrangement of the focusing electrodes, which strongly affect the photoelectron collection efficiency and the timing property, are carefully designed on the basis of electron trajectory analysis. Fig. 4 shows the simulation of the electron trajectories from the photocathode to the first dynode with a voltage difference of 800 V. Photoelectrons are traced under an initial energy of 0.5 eV and emission angles of 0° and ±90°.

3. The PMT characteristics

Several characteristics of the PMT and measuring methods are discussed in this section. The following

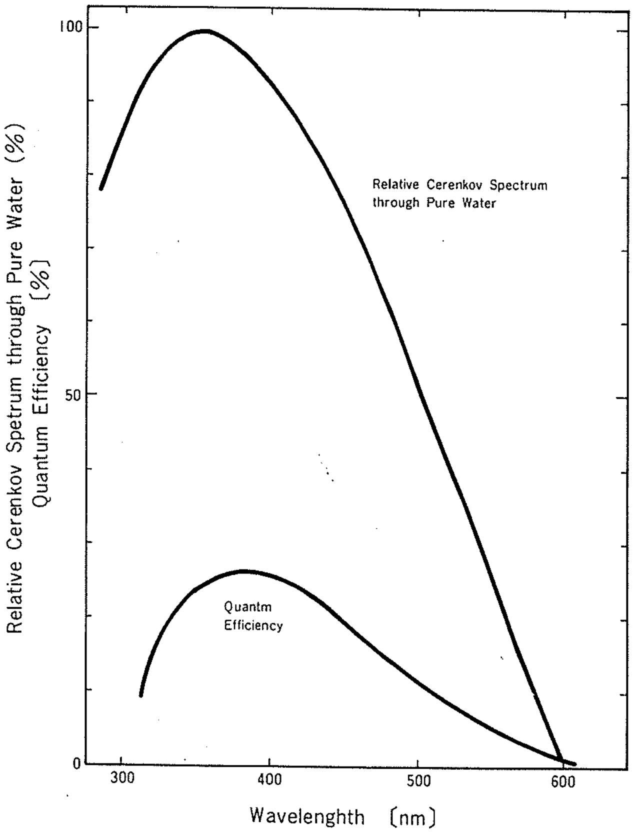


Fig. 3. Spectrum of Cherenkov light and measured photocathode quantum efficiency.

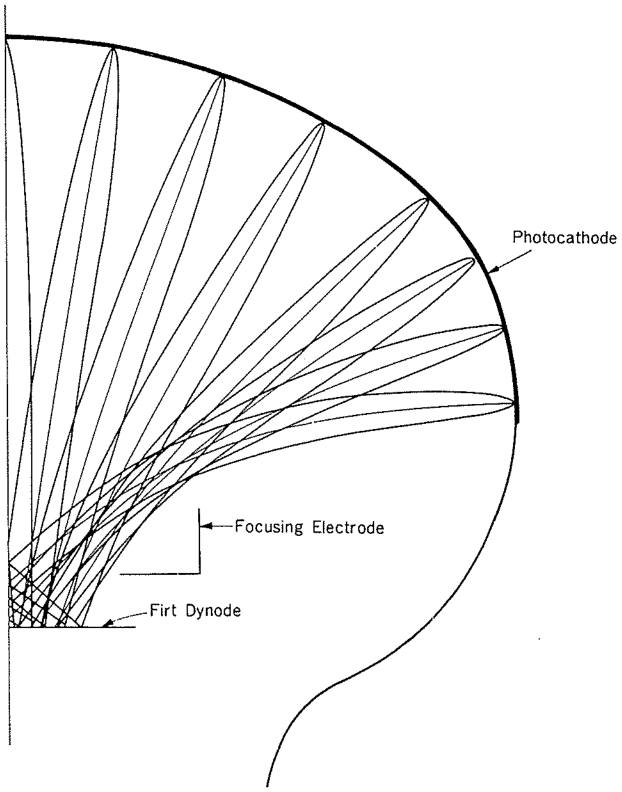
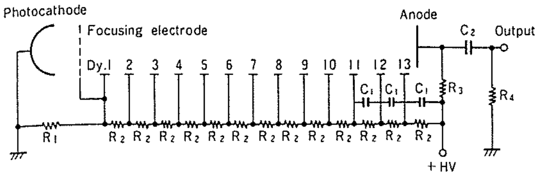


Fig. 4. Computer simulation of electron trajectories.



R1 : 800KΩ, R2 : 100KΩ, R3 : 10K ~ 100KΩ, R4 : Load.
C1 : 0.01μF, C2 : 0.047μF.

Fig. 5. Voltage divider used in the measurements.

measurements were done with the 13-stage voltage divider (8–1–1–...–1) shown in fig. 5, which provides optimum overall operation.

3.1. Gain

The gain of the PMT is defined by the ratio of the anode output current to the emitted photocathode current. The gain of the PMT is required to be 10^7 to detect single photoelectron events. Fig. 6 shows the gain of a typical PMT as a function of the applied voltage. The values of the applied voltage for obtaining a 10^7 gain are distributed around 2000 V. From this result the PMTs are found to be handled with standard techniques. Hereafter every measurement is carried out at 10^7 gain.

3.2. Dark pulses

The dark pulse counting rate should be, of course, low for a better S/N ratio. Many small dark pulses are distributed in any photomultiplier output. The discrimination level of 1/4 photoelectron equivalent is set for the elimination of these tiny dark pulses. The counting rate is found to lie between 5 kcps and 70 kcps at a temperature of 25°C. The dark pulse is mainly due to thermal emission from the photocathode and it is dependent on operating temperature as shown in fig. 7. The average value is around 20 kcps at 25°C. This dark pulse rate is satisfactorily small from the experimental point of view.

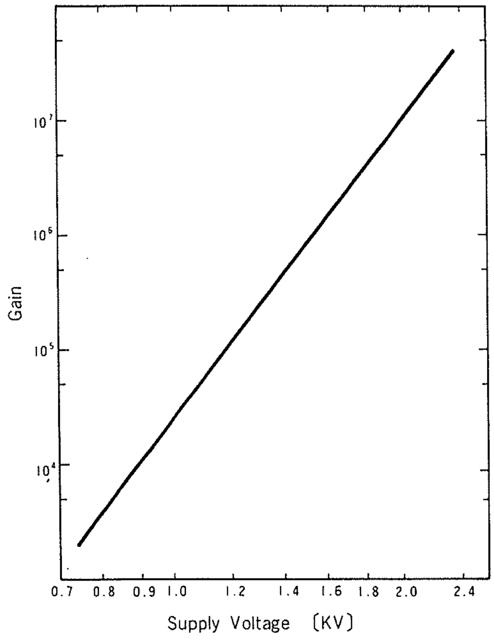


Fig. 6. Gain as a function of applied voltage.

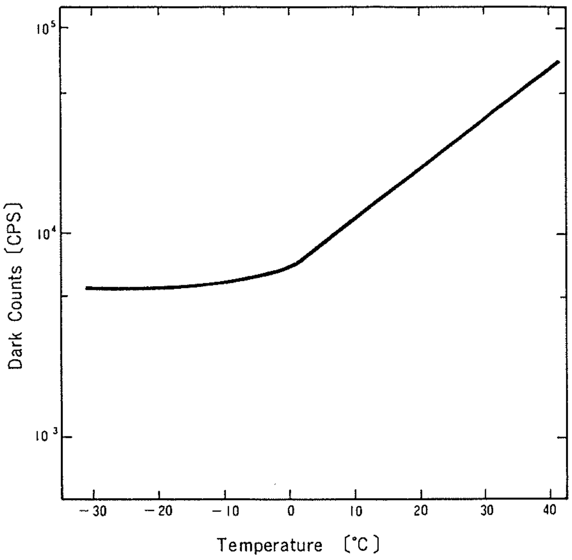


Fig. 7. Temperature dependence of dark counts.

3.3. Uniformity

When a large photomultiplier is constructed, it is a natural question whether a uniform sensitivity over the whole photocathode area is obtained or not. This uniformity is called anode uniformity and depends mainly on two factors, i.e. the uniformity of the photocathode quantum efficiency and that of the collection efficiency between the photocathode and the first dynode. Fig. 8 shows the measuring scheme of the uniformity. The photocathode is illuminated by a light spot through an optical fiber and the PMT is rotated to change the illuminated point on the photocathode around its spherical center. Fig. 9 shows the uniformity of the photocathode quantum efficiency. The anode uniformity is obtained by observing the change of output pulse height when an illuminated point on the photocathode surface is changed. Fig. 10 shows the anode uniformity of the PMT. The notations X and Y in fig. 9 represent the rotation direction of the PMT axis. The light position (θ) shows the angle between the incident optical axis and the PMT axis. From fig. 10 it is found that the change of anode uniformity is within 40%. The PMT has a good uniformity for its large dimension.

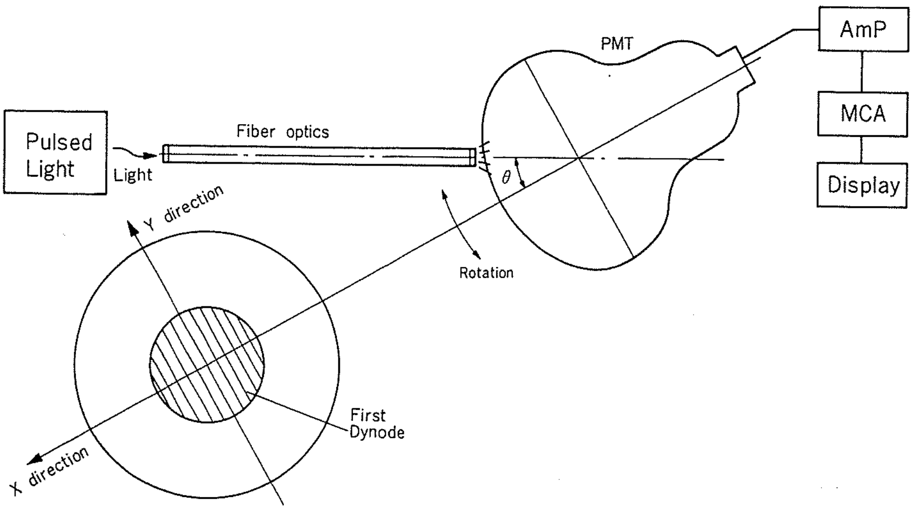


Fig. 8. Measuring scheme of the uniformity.

3.4. Timing characteristics

Fig.11 shows the output pulse waveform of the PMT when a δ-function-like light pulse (width less than 1 ns) is used. The whole photocathode is illuminated by this light pulse. The transit time is also measured. For a typical PMT the mean transit time is found to be 90 ns.

The transit time spread (distribution of transit time for a single PMT) is an important parameter when timing information is required. The measuring scheme of the single photoelectron transit time spread (TTS) is shown in fig. 12.

The intensity of the light pulse is attenuated and diffused, so most photoelectrons emitted from the photocathode are at the single photoelectron level. The time difference is measured by TAC (time-to-amplitude converter). TTS is obtained by measuring the fluctuation of this time difference. Fig. 13 shows TTS data, whose fwhm (full width at half-maximum) is 7 ns for a typical 20" PMT.

3.5. Energy resolution

In general, the energy resolution of a photomultiplier depends on several factors such as number of input photons, quantum efficiency, collection efficiency, mul-

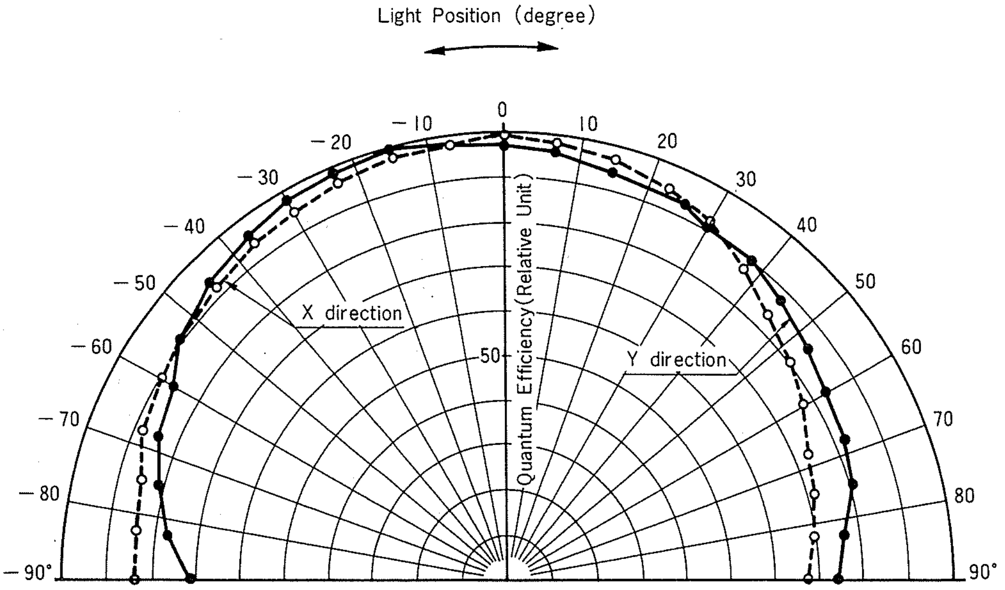


Fig. 9. Photocathode uniformity.

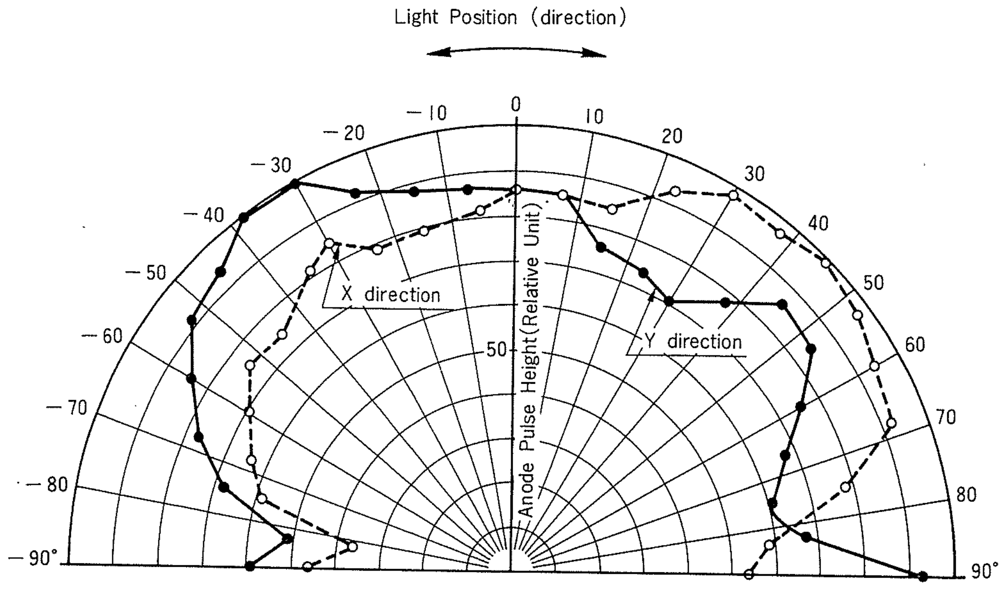


Fig. 10. Anode uniformity.

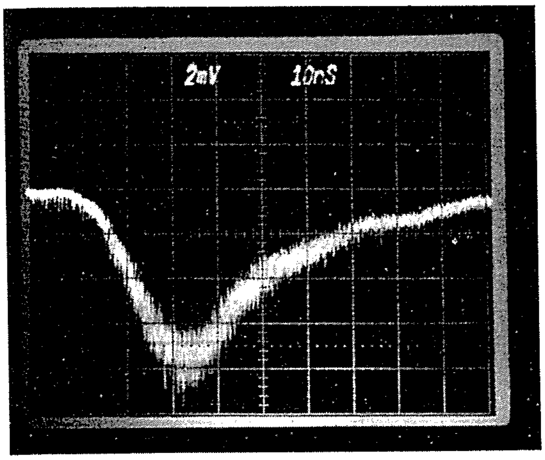


Fig. 11. Output pulse waveform for a δ-function-like light pulse.

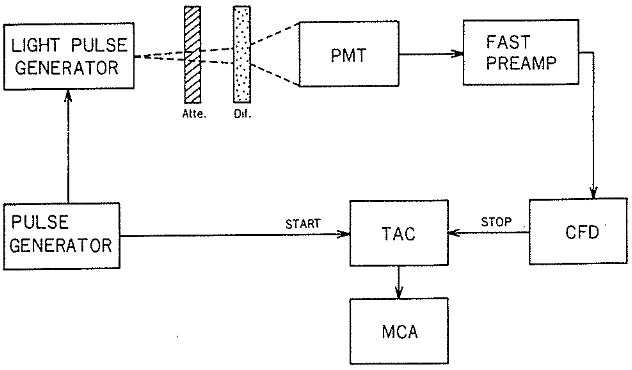


Fig. 12. Measuring scheme of transit time spread.

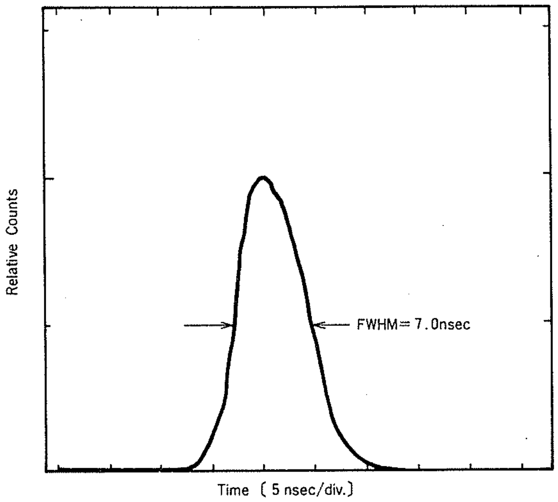


Fig. 13. Transit time spread for single photoelectron pulse.

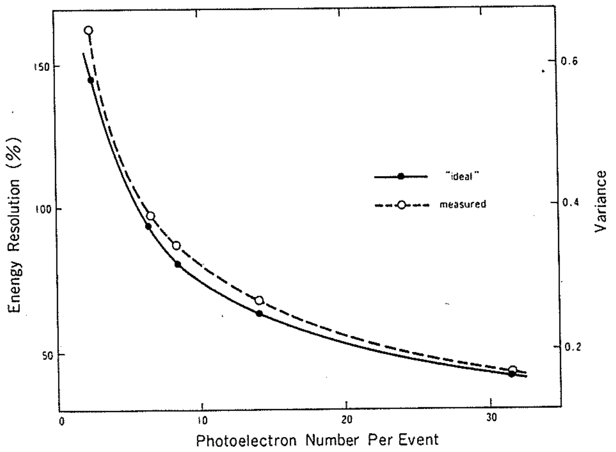


Fig. 14. Energy resolution.

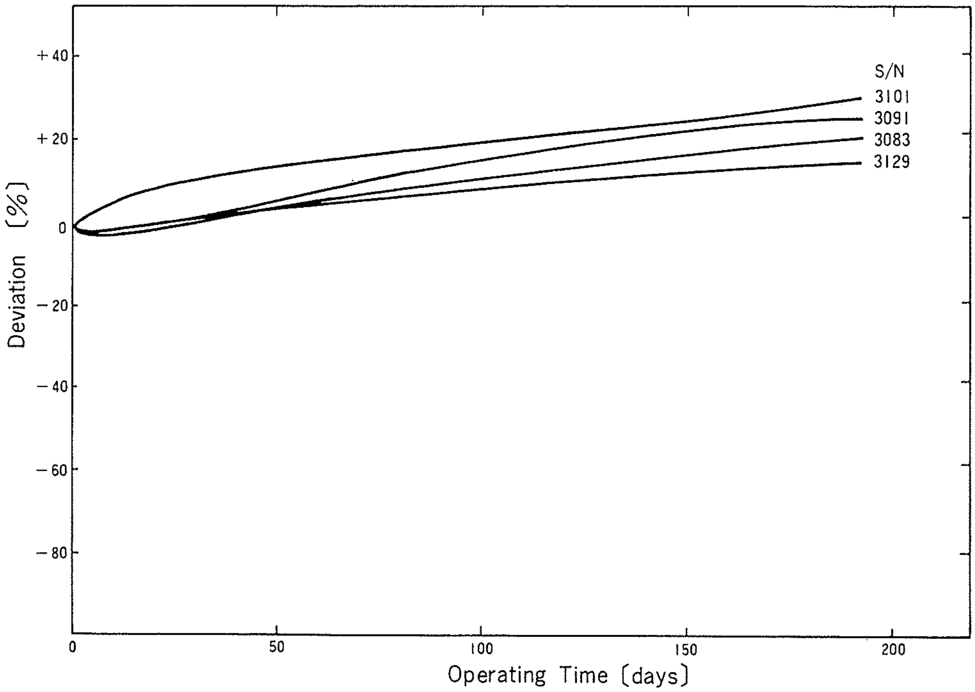


Fig. 15. Long term stability.

tiplication factors and their fluctuation at each dynode. Since it is difficult to know all these factors with enough accuracy, we restrict ourselves to know the spread of the ouput pulse distribution and to compare this with the "ideal" one. First, the average charge of the single photoelectron equivalent pulse is calculated from the output pulse distribution of a single photoelectron, which can be obtained with a very weak light input. Then we can extrapolate from this calculated single photoelectron pulse to N photoelectron pulses.

Let the variance of the distribution of N photoelectron pulses be written as $k\sqrt{N}$. In the "ideal" case, the value of k equals 1, which is not realized because of the photomultiplier systematics.

The measured resolution of output pulses is shown in fig. 14 in comparison with the "ideal" one. From fig. 14, k is obtained to be less than 1.1, that is, the energy resolution is only 10% inferior to the unrealizable "ideal" one.

3.6. Stability

Long term stability has been checked with several PMTs for a period up to 200 d. Fig. 15 shows the change of relative gain vs operating time for several PMTs. Judging from fig. 15, the PMTs seem to be so stable as to keep their characteristics during long running experiments. Further tests of the long term stability are continued.

4. Conclusion

For the experiment, around 1000 PMTs will be arranged under water. Protection against the earth magnetic field can be achieved by attaching a compensating coil or by enclosing a PMT with net and plate made of high magnetic permeability material.

There are no serious problems in using PMTs as detectors of Cherenkov radiation in the forthcoming experiment. After the discussions in the previous sections we conclude that the designed properties mentioned in the introduction are successfully accom-

Table 1
Characteristics of 20″ PMT

Diameter	50.8 cm
Shape of photocathode	quasi-hemispherical
Photocathode material	bi-alkali
Window material	borosilicate glass HARIO-32 (4–5 mm thick)
Dynodes	Venetian blind, 13 stages
Bleeder chain	8-1-1-...-1
Gain	10^7
Quantum efficiency	22% at $\lambda = 400$ nm
Mean transit time	90 ns
Transit time spread	7 ns fwhm
After pulse rate	less than 1% per photoelectron

plished. In table 1, we summarize the characteristics of the PMT. The remarkably wide photosensitive area of this PMT will be applicable to large scale experiments in other fields of science and industry.

We thank Prof. M. Koshiba of the University of Tokyo in connection with the foreseen nucleon decay experiment for his suggestion and promotion. We wish to thank the people of Hamamatsu TV, University of Tokyo and KEK (especially Prof. T. Nishikawa and Prof. K. Takahashi) for their support and encouragement.

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