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Part IV. Photomultiplier tubes and other devices

RECENT DEVELOPMENTS IN PHOTOMULTIPLIERS FOR NUCLEAR RADIATION DETECTORS

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One of the recent developments in Hamamatsu photomultipliers for nuclear radiation detectors is a small photomultiplier developed for positron CT in nuclear medicine having excellent timing properties; the time resolution with BGO and CsF scintillators was observed for 511 keV positron annihilation γ-rays to be 2.24 ns and 0.34 ns, respectively.

Two types of new photomultipliers having special structures have recently been developed. One is a photomultiplier for high pressure use capable of withstanding up to 600 atm pressure while another is a "large-angle-of-view" photomultiplier for a proton decay experiment having a 20″ diameter hemispherical photocathode. A newly developed proximity focus type of microchannel plate photomultiplier provides a very fast time response of 130 ps and is usable in strong magnetic fields such as in calorimeters.

1. Introduction

As a nuclear radiation detector, the photomultiplier has been playing an important role because of its fast time response, and good characteristics for low noise amplification, with a wide dynamic range and good multi-decade linearity. Photomultipliers continue to be improved in response to extensive demands for better instrumentation.

Some characteristics of a photomultiplier are unique and a particular design is necessary for a particular application, e.g. a good timing property for positron CT, capacity to withstand high pressure for deep underwater use, a large angle of view for proton decay experiments and the ability to operate in strong magnetic fields in a calorimeter.

2. Photomultiplier for positron computed tomography (CT)

In positron CT(PCT) systems designed up to the present, NaI(Tl) or BGO scintillators have been used. Recently, small BGO scintillators are being used in most newly designed systems to get better spatial resolution because of high density and possibility for improvement in quality [1].

The projection data of positron sources in a patient are taken by using a coincidence technique and an axial tomographic image can be reconstructed from these data. There are two kinds of noises which may disturb the image quality; one is called "scattered event noise" and the other is called "accidental event noise". The accidental events decrease in proportion to the coincidence time width and the Compton scattered events are reduced by setting the lower energy discrimination level at a higher level. The detector, therefore, is required to have good time and energy resolution to improve the system performance.

Fig. 1 shows a newly developed photomultiplier for PCT applications. It is $1\frac{1}{8}''$ in diameter and has a special bialkali photocathode matching the BGO fluorescence. The coincidence timing properties and the pulse height distribution of these photomultipliers with Hitachi BGO [2] scintillators were measured, as shown in figs. 2 and 3. Results of 2.24 ns in time resolution and

Fig. 1. New small photomultipliers for positron CT.

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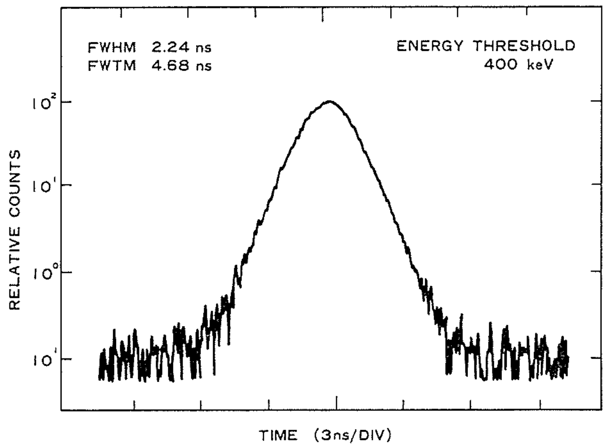

Fig. 2. BGO–BGO coincidence timing spectrum.

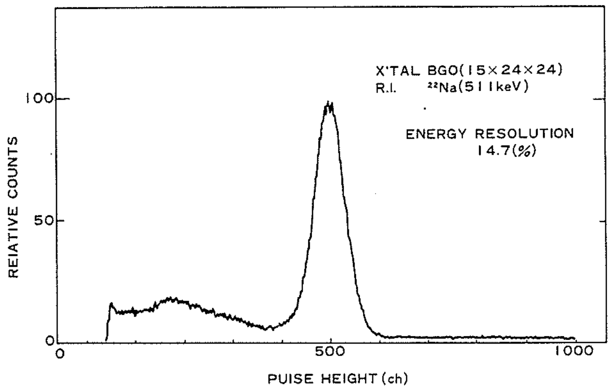

Fig. 3. Pulse height distribution for 511 keV gamma rays.

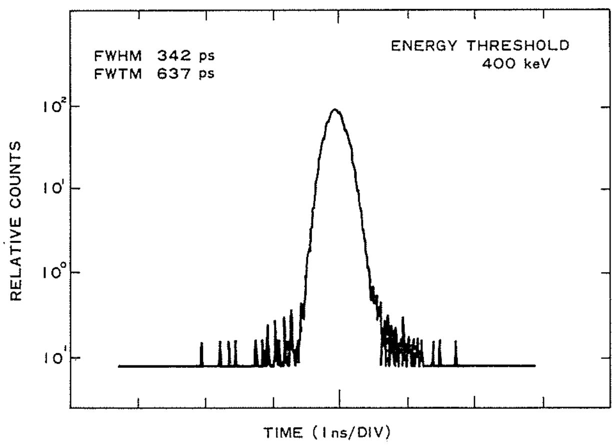

Fig. 4. CsF–CsF coincidence timing spectrum.

14.7% in energy resolution were obtained for 511 keV positron annihilation γ-rays.

Further, several researchers have suggested using the time-of-flight of the positron annihilation γ-rays to determine the location of the positron. Allemand et al. [3] have shown by mathematical simulation that the combination of time-of-flight data with computed tomography, results in a S/N improvement in the reconstructed image. They also suggested the use of CsF as a scintillator for the measurement of time-of-flight information [4]. In such a system, the photo-detector must have good time resolution.

Fig. 4 shows a coincidence timing spectrum for CsF coupled with the new photomultipliers which have UV transmitting windows to accept the CsF fluorescence. The observed fwhm for 400 keV and 140 keV energy thresholds were 340 ps and 398 ps, respectively.

3. Photomultipliers with special structures

A photomultiplier for high pressure use such as in "deep underwater muon and neutrino detection" (DUMAND) [5,6], was developed in collaboration with a group from the Institute of Cosmic Ray Research, University of Tokyo. The construction is shown in fig. 5. This photomultiplier is designed to withstand pressures up to 600 atm, equivalent to a pressure at 6000 m under water. Conventional tubes fail under a pressure of about 100 atm. No change in gain and pulse height resolution was observed in operation under 600 atm, as shown in fig. 6.

Fig. 7 shows three kinds of photomultipliers developed for proton decay experiments [7]. They are 5″, 8″ and 20″ in diameter, respectively and have hemispherical photocathodes for large-angle-of-view detection.

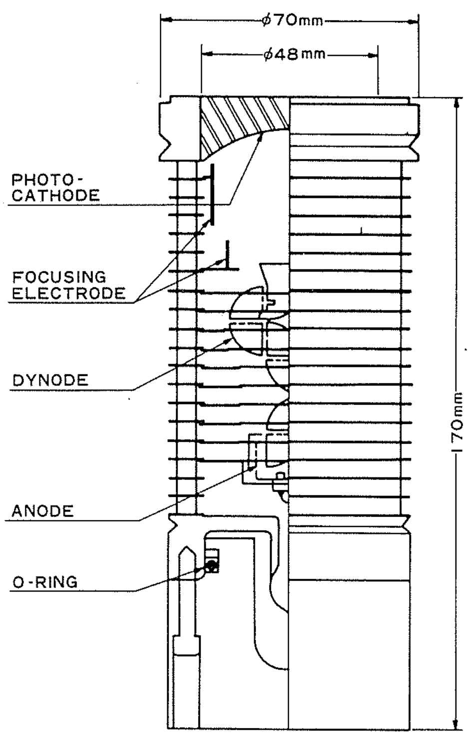

Fig. 5. Construction of 2″ photomultiplier for high pressure use.

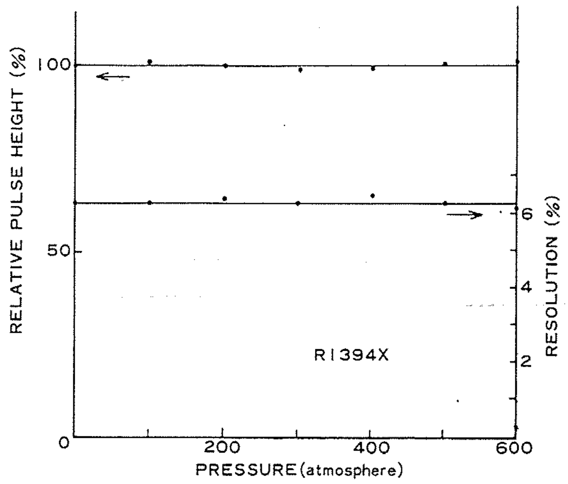

Fig. 6. Relative pulse height and resolution under pressure.

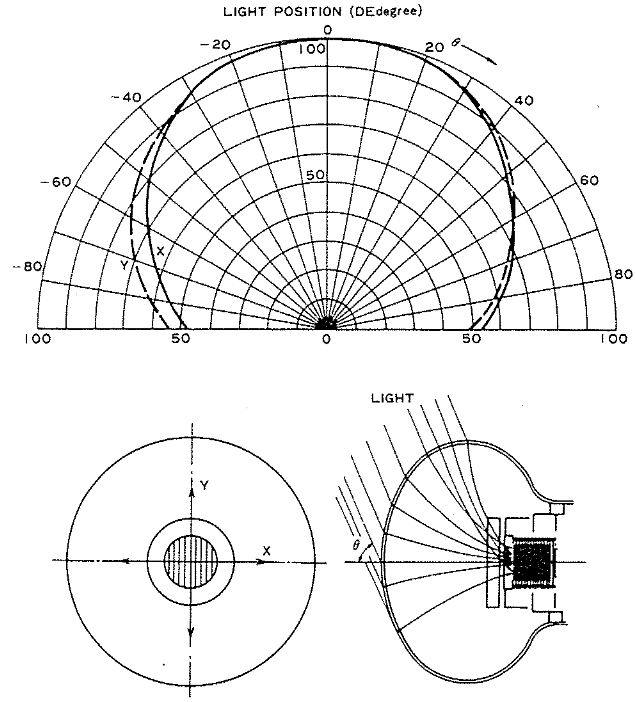

Fig. 8. Angular uniformity of 20″ PMT.

Both large angle of view and good angular uniformity are necessary for efficient observation of Cherenkov light signals in water. The angular uniformity measured with a 20″ photomultiplier is shown in fig. 8. Capability to withstand a water pressure at 20 m or more is necessary because some tubes should be settled at the bottom of the water vessel.

The petroleum exploration industry needs a rugged γ-ray detector that can be used in high temperature environments. They are used in nuclear oil well logging to search for possible oil presence down to a few miles deep underground [8]. The detector is, therefore, required to have a rugged structure and work in temperatures up to 150°C or more. (The temperature at the bottom of a drilled hole at 4500 m depth reaches 150°C). Fig. 9 shows newly designed photomultipliers for high temperature use which have Na_2KSb photocathodes and CuBe dynodes. The photomultipliers were cycled between 20°C and 175° while pulse height and pulse

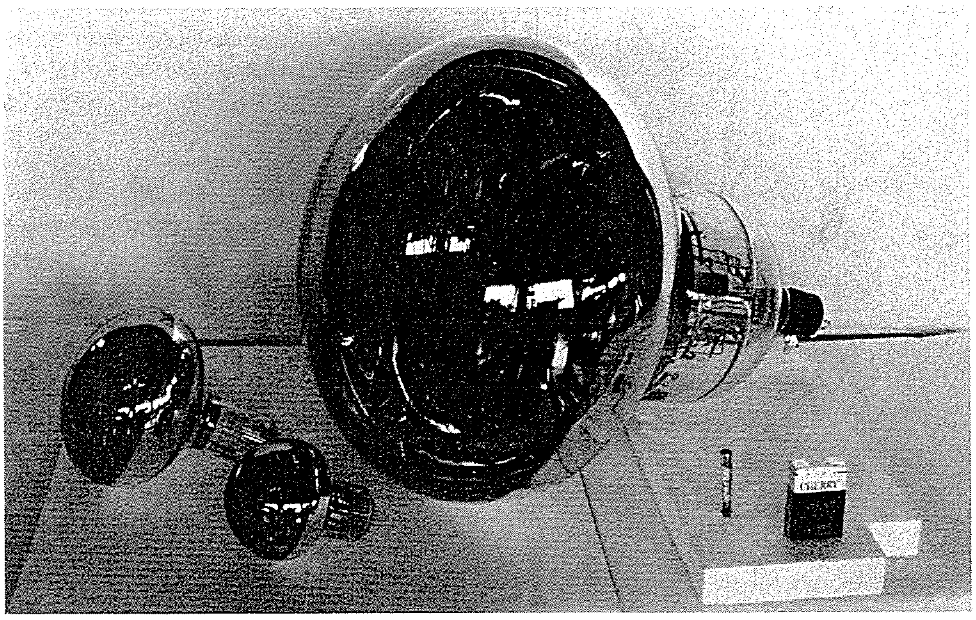

Fig. 7. 5″, 8″ and 20″ photomultipliers for proton decay experiment.

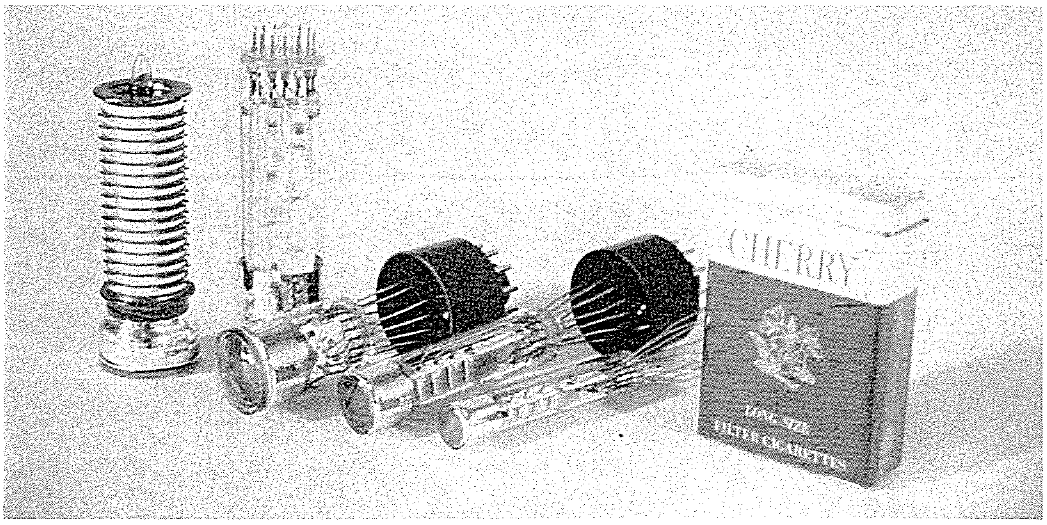

Fig. 9. Photomultipliers for high temperature use.

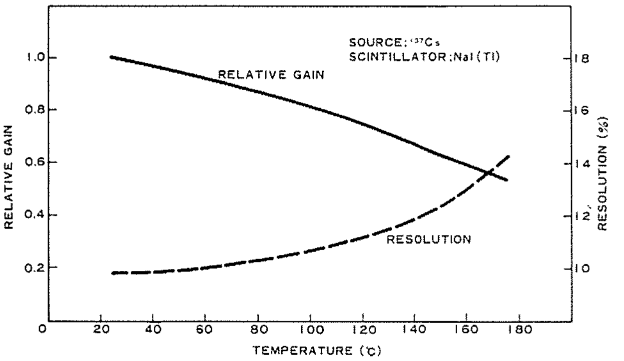

Fig. 10. Relative gain and energy resolution of R1288 as a function of temperature.

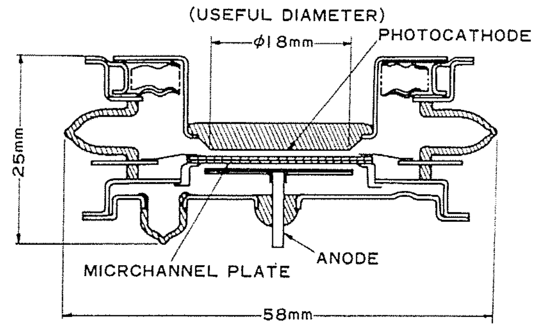

Fig. 11. Construction of proximity microchannel plate photomultiplier (R1564X).

height resolution with ^{137}Cs and NaI(Tl) scintillators were monitored (fig. 10).

4. New proximity focused MCP photomultiplier

A fast detector which can be operated in a high magnetic field is required in some high energy physics experiments. A microchannel plate (MCP) has a simple structure as an electron multiplier compared to the discrete dynodes of a conventional photomultiplier. This simple structure allows the design of an electron multiplier with a short, parallel electron trajectry so that better timing properties and less sensitivity to ambient magnetic fields can be obtained.

Fig. 11 shows a new proximity-focused MCP photomultiplier which has an 18 mm diameter bialkali photocathode and two stages of MCPs. The entrance part of the first MCP is covered with a thin Al film to prevent ion feedback to the photocathode.

In order to measure the timing property of this tube, a special light pulser was prepared (fig. 12).

Light pulses of 400 nm wavelength were generated from the second harmonic generator ($LiIO_3$) excited by a semiconductor laser. The pulse duration was measured to be 60 ps by a Hamamatsu streak camera system. Fig. 13 shows the output pulse shape from the new MCP photomultiplier for this light input. A fwhm transit time

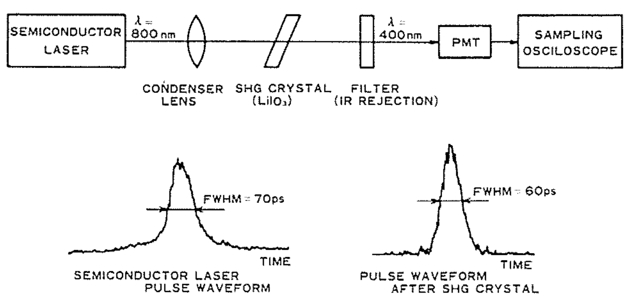

Fig. 12. Block diagram of pulse response measurement.

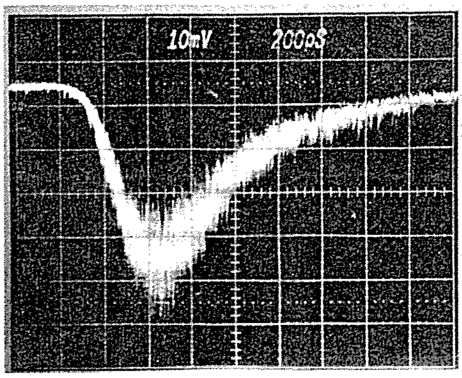

Fig. 13. Output pulse shape (of R1564X) observed on the sampling oscilloscope display.

spread of 130 ps was observed (fig. 14).

This photomultiplier was also tested in a magnetic field up to 0.9 T. Figs. 15 and 16 show the gain deviation as a function of transverse and parallel magnetic fields, respectively. With the transverse field, the gain begins to go down at around 0.04 T depending on the voltage between the photocathode and the first MCP. With the parallel field, the gain change is very small up to 0.9 T when the MCPs are operated at a voltage between 1400 V and 1500 V.

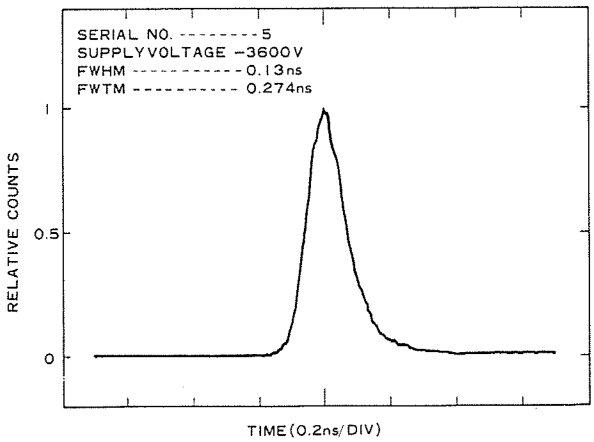

Fig. 14. R1564X transit time spread.

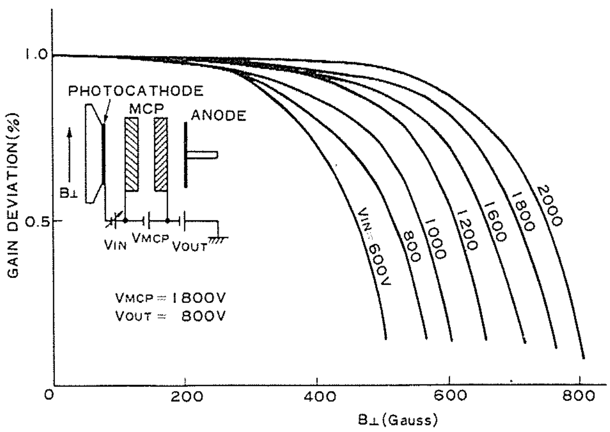

Fig. 15. Gain deviation of MCP PMT as a function of transverse magnetic field.

Until now, the life problem was always a drawback for MCP photomultipliers. Formerly MCP photomultipliers (without Al-film) showed gain fatigue after taking an integral output charge of 10^{-3} c/cm^2 and now those with Al-film have a longer life, up to 10^{-2} c/cm^2 as shown in fig. 17. The results of the life test with conventional photomultipliers are also shown in this figure for reference. At present, most of the degradation of MCP photomultiplier gain occurs in the MCP itself, rather than at the photocathode.

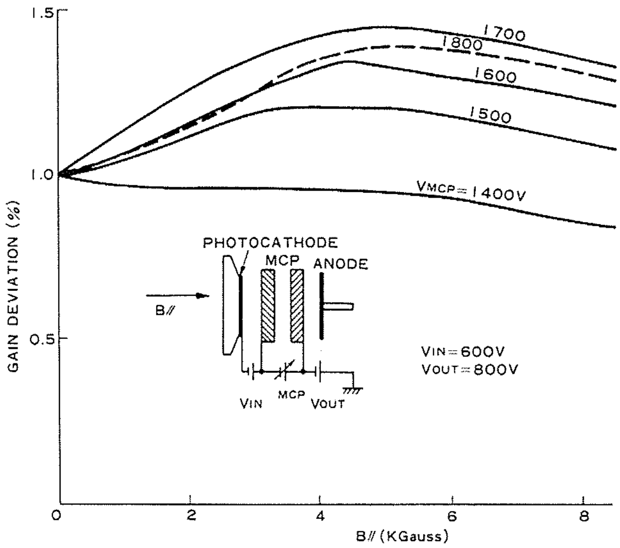

Fig. 16. Gain deviation of MCP PMT as a function of parallel magnetic field.

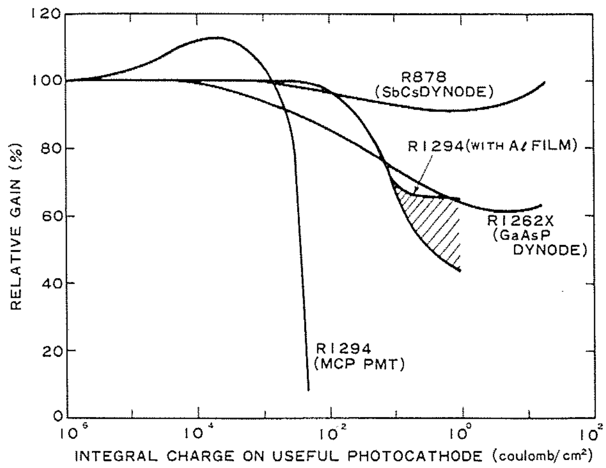

Fig. 17. Life test results for MCP PMT with an without Al film, and other PMTs.

5. Conclusion

Some recent developments in Hamamatsu photomultipliers for nuclear radiation detectors have been presented. For development and improvement of photomultipliers, empirical technology is just as important as scientific knowledge. The former is sometimes successfully pursued through intuitively clever trial and error. In response to increasing scientific demands, new and better photomultipliers will be designed and manufactured.

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