CHAPTER 9
POSITION SENSITIVE PHOTOMULTIPLIER TUBES

The current multiplication mechanism offered by dynodes makes photomultiplier tubes ideal for low-light-level measurement. As explained earlier, there are various types of dynode structures available for different photometric purposes. Popular conventional dynode structures are the box-and-grid type, linear-focused type, circular-cage type and venetian-blind types. Furthermore, the MCP (microchannel plate) has recently been utilized as a dynode structure.

Two unique dynode structures are introduced in this chapter: the "metal channel dynode" and "grid type dynode". These dynode structures provide wide dynamic range, high gain, high position resolution, and are currently used in position-sensitive photomultiplier tubes.

Common methods for reading out the output signal from a position-sensitive photomultiplier tube are illustrated in Figure 9-1. In a multianode device, the output signal is read using independent multiple anodes. The cross-plate (wire) anode signal is read out by means of current or charge-dividing center-of-gravity detection.

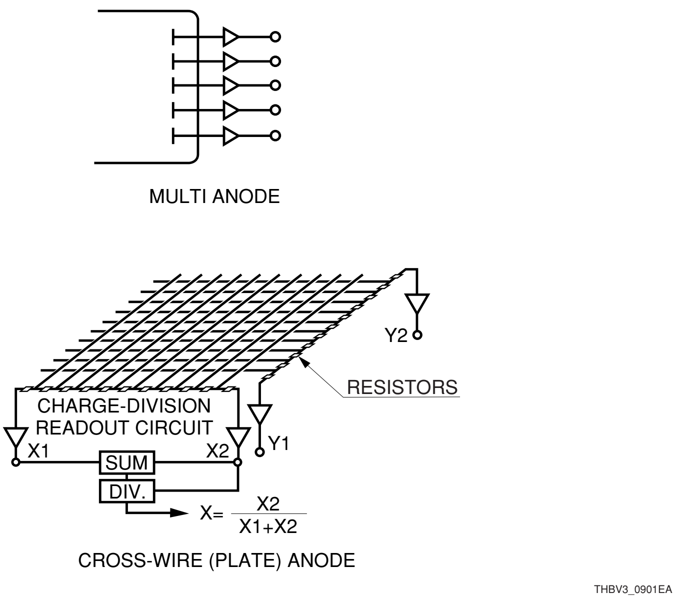


Figure 9-1: Anode output readout methods for position sensitive photomultiplier tubes

The following sections describe "metal channel dynode structures combined with multianode readout", "metal channel dynode structures combined with a cross-plate anode" and "grid type dynode structures combined with a cross-wire anode" for position sensitive photomultiplier tubes.

9.1 Multianode Photomultiplier Tubes

9.1.1 Metal channel dynode type multianode photomultiplier tubes

(1) Structure

Figure 9-2 shows the electrode structure for metal channel dynodes and the associated electron trajectories. Compared to the other types of dynodes, metal channel dynode type multianode photomultiplier tubes feature very low crosstalk during secondary electron multiplication. This is because the photoelectrons emitted from the photocathode are directed onto the first dynode by the focusing mesh and then flow to the second dynode, third dynode, . . . last dynode and finally to the anode, while being multiplied with a minimum spatial spread in the secondary electron flow.

The overall tube length can be kept short because the metal channel dynodes are very thin and assembled in close-proximity to each other.

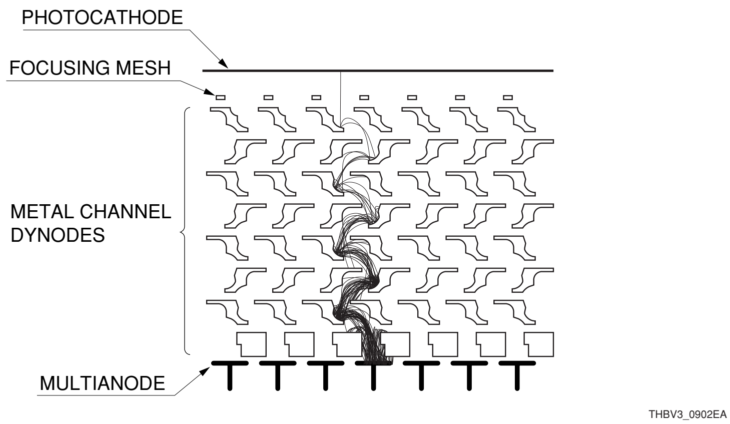


Figure 9-2: Electrode structure and electron trajectories

Multianode photomultiplier tubes using metal channel dynodes can be roughly classified into two groups. One group uses a matrix type multianode and the other group uses a linear type multianode.

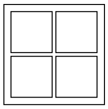
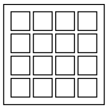
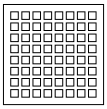
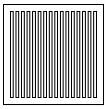
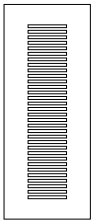
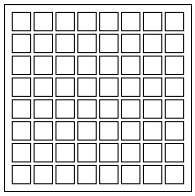
Type	Metal Channel Dynode Multianode Photomultiplier Tubes					
	Matrix			Linear		Matrix
	M4	M16	M64	L16	L32	M64
Anode Shape						
Number of Anodes	4	16	64	16	32	64
Pixel Size (mm)	9 × 9	4 × 4	2 × 2	0.8 × 16	0.8 × 7	5.8 × 5.8

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Figure 9-3: Anode patterns for metal channel dynode type multianode photomultiplier tubes

(2) Characteristics

In this section, we first describe basic characteristics of matrix type multianode photomultiplier tubes by discussing "crosstalk", "magnetic immunity" and "uniformity" in 64 channel matrix type multianodes.

"Crosstalk" is a measure to indicate how accurately the light (signal) incident on a certain position of the photocathode is detected while still retaining the position information. In photomultiplier tube operation, crosstalk is mainly caused by the broadening of the electron flow when light is converted into electrons and those electrons are multiplied by the dynode section. The incident light spread within the faceplate is another probable cause of crosstalk.

A typical setup for measuring crosstalk is shown in Figure 9-4 and an example of measurement data in Figure 9-5.

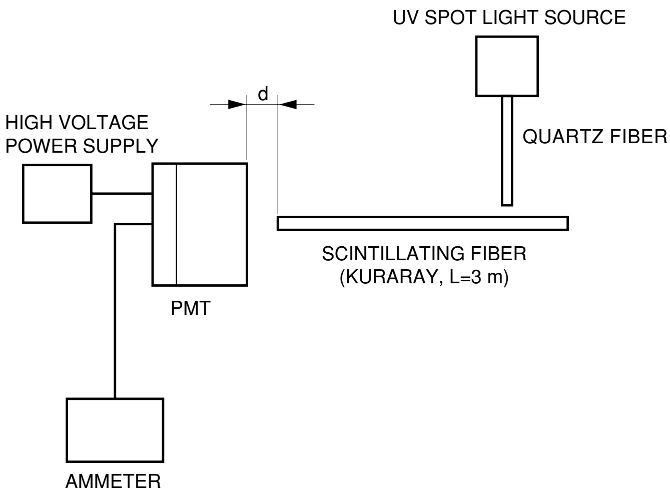

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Figure 9-4: Crosstalk measurement method

d=0 mm

0.3	1.4	0.4
0.8	100	1.2
0.2	1.1	0.3

SCINTILLATING FIBER (1.0 mm dia.)
SUPPLY VOLTAGE: 800 (V)
d: DISTANCE

d=0.5 mm

0.4	2.6	0.6
1.5	100	1.9
0.3	1.8	0.4

SCINTILLATING FIBER (1.0 mm dia.)
SUPPLY VOLTAGE: 800 (V)
d: DISTANCE

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Figure 9-5: Crosstalk measurement example

Data shown in Figure 9-5 is measured by irradiating a light spot (signal) on the photomultiplier tube faceplate, through a 1 mm diameter optical fiber placed in close contact with the faceplate. The output of each anode is expressed as a relative value, with 100 % being equal to the peak anode output produced from the incident light spot. Results show that crosstalk is 0.2 % to 1.4 % when the 1 mm diameter scintillating fiber is positioned in tight contact with the photomultiplier tube faceplate (d=0 mm). However, the crosstalk becomes 0.3 % to 2.6 % worse when the scintillating fiber is moved 0.5 millimeters away from the faceplate. This is of course due to light spread at the scintillating fiber exit. Bringing the optical fiber into tight contact with the photomultiplier tube faceplate is therefore recommended in order to make accurate measurements using scintillating fibers.

Next, let's discuss magnetic characteristics. Matrix type multianode photomultiplier tubes have excellent immunity to magnetic fields. This is because all parts except the photocathode are housed in a metal package and also because the distance between dynode electrodes is very short. Magnetic characteristics of a 64-channel multianode photomultiplier tube are explained below.

Figure 9-6 shows how the anode output is adversely affected by external magnetic fields applied along the three axes (X, Y, Z). Each data is plotted as a relative output value, with 100 % corresponding to an output with no magnetic field applied. Output is still maintained as high as 60 % versus 13 mT of the magnetic field in the X direction.

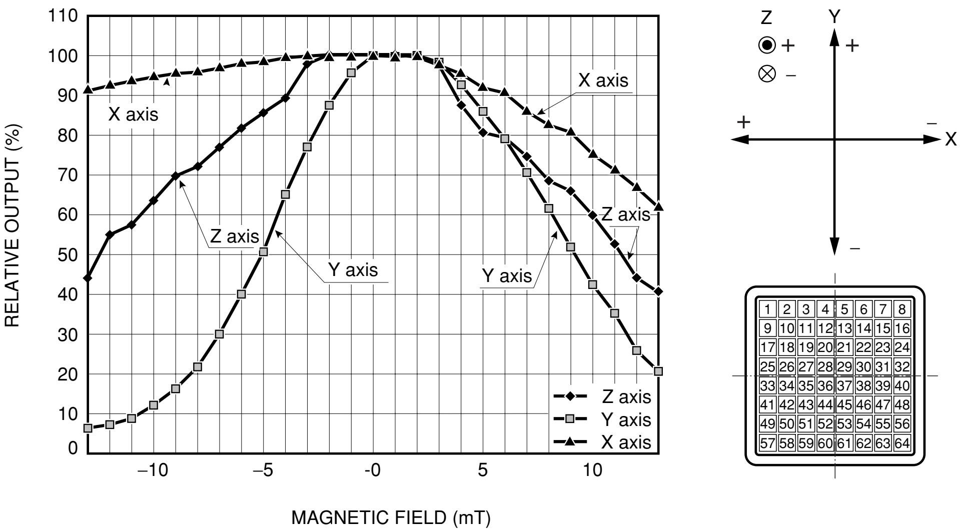

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Figure 9-6: Effects of external magnetic fields on anode output (anode channel No. 29)

Figure 9-7 shows typical uniformity data obtained from each anode when uniform light is illuminated over the entire photocathode of a 64-channel multianode photomultiplier tube. The non-uniformity observed here probably originates from gain variations in the secondary electron multiplier because the photocathode itself has good uniformity. Currently, non-uniformity between each anode is about "1:3" on average.

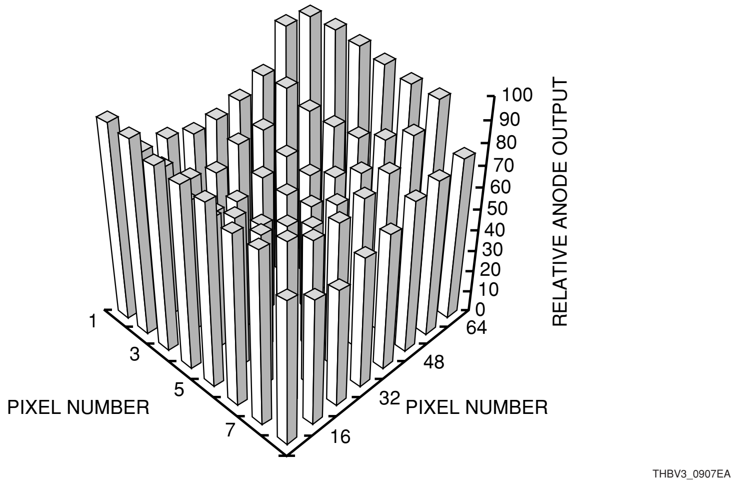


Figure 9-7: 64-channel multianode output uniformity

Uniformity of one pixel (one anode) is shown in Figure 9-8. This data is measured by input of weak DC light of 50 µm diameter to an anode of 2 square millimeters per pixel, while scanning the light every 0.1 millimeters on the photocathode.

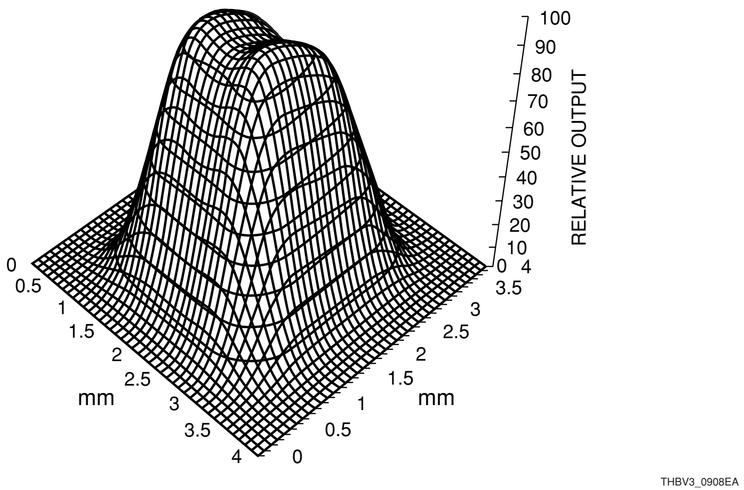


Figure 9-8: Anode output uniformity per pixel

We next describe basic "crosstalk" and "uniformity" characteristics of linear multianode photomultiplier tubes.

A typical setup for measuring crosstalk of a 16-channel linear multianode photomultiplier tube is shown in Figure 9-9 and the typical measurement data in Figure 9-10. In this measurement, a light spot emitted through the 100 μm aperture in the X-Y stage was scanned along the photocathode. Typical crosstalk obtained from the 16-channel linear multianode was approximately 3 %.

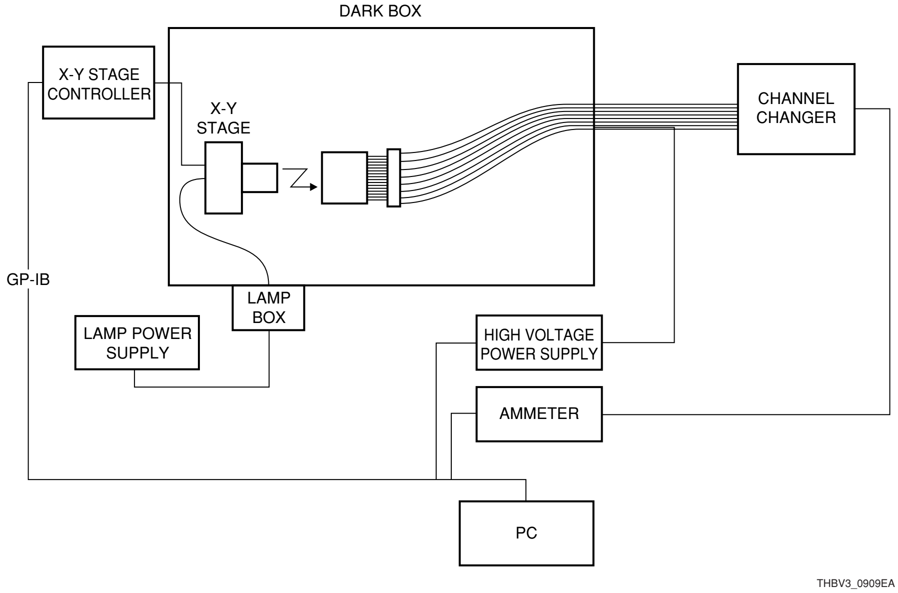
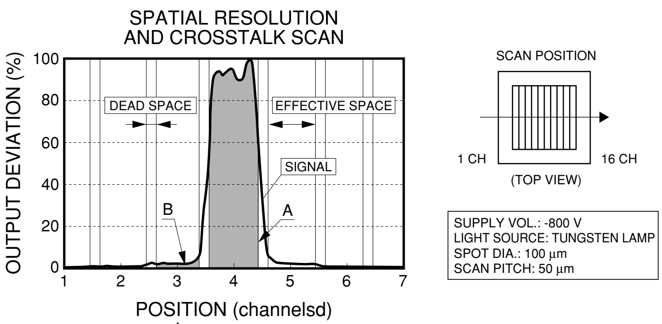


Figure 9-9: Crosstalk measurement method



	CROSS-TALK RATIO (%)															
CH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	100	2.9	0.6	0.2	0.1	—	—	—	—	—	—	—	—	—	—	—
2	2.9	100	3.1	0.5	0.2	0.1	—	—	—	—	—	—	—	—	—	—
3	0.8	2.8	100	2.8	0.6	0.2	0.1	—	—	—	—	—	—	—	—	—
4	0.3	0.8	2.7	100	3.2	0.6	0.2	0.1	—	—	—	—	—	—	—	—
5	0.1	0.3	0.8	2.9	100	3.1	0.6	0.2	0.1	—	—	—	—	—	—	—
6	—	0.1	0.3	0.8	2.7	100	3.0	0.6	0.2	0.1	—	—	—	—	—	—
7	—	—	0.1	0.3	0.8	2.7	100	3.0	0.6	0.2	0.1	—	—	—	—	—
8	—	—	—	0.1	0.3	0.8	2.9	100	2.9	0.6	0.2	0.1	—	—	—	—
9	—	—	—	—	0.1	0.3	0.8	2.9	100	2.9	0.6	0.2	0.1	—	—	—
10	—	—	—	—	—	0.1	0.3	0.8	3.1	100	2.7	0.6	0.2	0.1	—	—
11	—						0.1	0.4	0.8	3.3	100	3.8	0.6	0.2	0.1	—
12	—						—	0.1	0.4	0.9	3.2	100	2.8	0.6	0.2	0.1
13	—						—	—	0.1	0.4	0.8	3.1	100	2.8	0.6	0.3
14	—						—	—	—	0.1	0.4	0.8	3.1	100	2.7	0.6
15	—						—	—	—	—	0.1	0.4	0.9	3.2	100	2.9
16	—	—	—	—	—	—	—	—	—	—	—	0.1	0.4	0.9	3.1	100

CROSSTALK
AREA B / AREA A × 100

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Figure 9-10: Crosstalk of 16-channel linear anode

Some 16-channel and 32-channel linear multianode photomultiplier tubes are low crosstalk types. Some use a special faceplate containing black glass partitions or an electrode structure having shielding walls between the anodes of each channel. Typical crosstalk values measured with a low crosstalk type are shown in Figure 9-11.

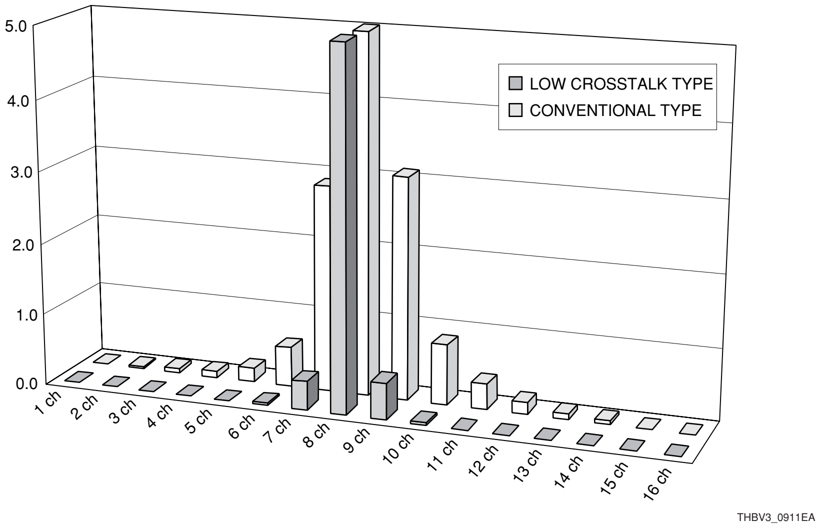

Figure 9-11: Crosstalk values of 16-channel low-crosstalk type

Figure 9-12 shows typical uniformity data of a linear multianode photomultiplier tube. This data was obtained from each anode when uniform light was illuminated over the entire photocathode of a 32-channel linear multianode photomultiplier tube. As with the matrix type, non-uniformity mainly originates from gain variations in the secondary electron multiplier. Currently, non-uniformity between each anode is about "1:1.7" on average.

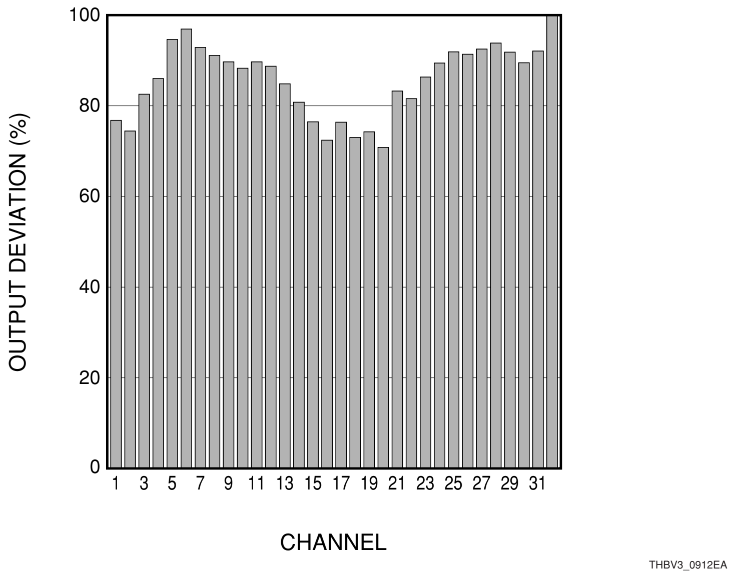

Figure 9-12: 32-channel linear multianode output uniformity

Since 16-channel and 32-channel linear multianode photomultiplier tubes have a one-dimensional array of anodes, they are mainly used as detectors for multichannel spectrophotometry. Due to its shape, the 32-channel type is often used in combination with a grating or prism, and recent applications include laser scanning microscopes.

Linear multianode photomultiplier tubes are also available with a band-pass filter attached to the face-plate. This allows detecting light only in the wavelength range of interest, just like using a grating or prism. There is no loss of light caused by the entrance slit which is used with the grating for separating the light into different wavelengths. Since light must uniformly strike the entire surface of the band-pass filter, Hamamatsu also provides a dedicated mixing fiber combined with a lens for this purpose. Figure 9-13 shows a photomultiplier tube with a band-pass filter and a dedicated mixing fiber combined with a lens.

Figure 9-13: Photomultiplier tube with band-pass filter **Mixing fiber + lens**

Dichroic mirrors can also be used for dispersing light into a spectrum. One example is illustrated in Figure 9-14 showing a very compact device containing an optical system and a detector.

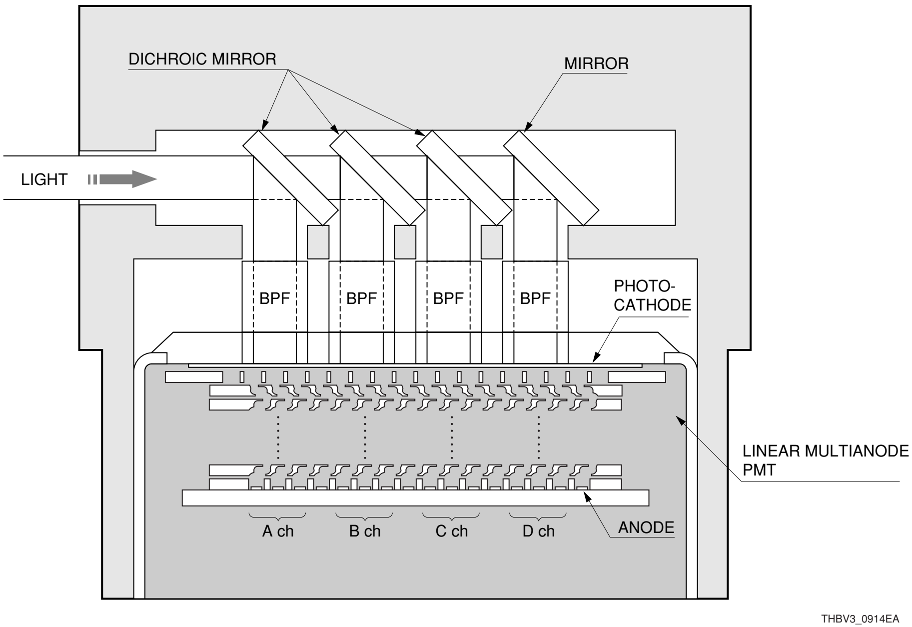

Figure 9-14: Multianode photomultiplier tube assembled with dichroic mirrors

9.1.2 Multianode MCP-PMT

The multianode MCP-PMT is explained in detail in section 10.4 of Chapter 10.

9.1.3 Flat panel type multianode photomultiplier tubes

(1) Characteristics

Metal channel dynodes are mainly used in 1-inch square metal package photomultiplier tubes and flat panel type (2 square inches) photomultiplier tubes, which can be selected according to the particular application.

This section introduces a flat panel type photomultiplier tube with an overall height as short as 15 millimeters. As shown in Figure 9-15, this photomultiplier tube features a large effective area and minimal dead area (insensitive area).

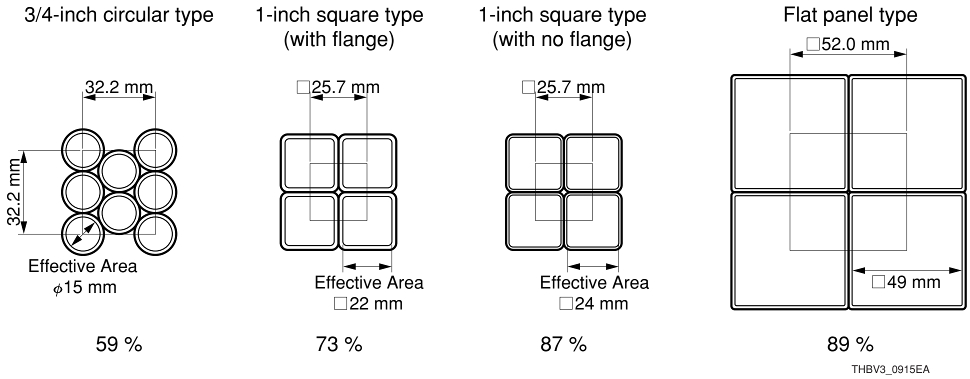

Figure 9-15: Comparison of effective area ratio

Typical spatial resolution obtained with a flat panel type 64-channel photomultiplier tube is shown in Figure 9-16. This spatial resolution data (output distribution of each anode) was measured by scanning the photocathode surface with a 1-millimeter collimated light beam emitted from a tungsten lamp through a blue filter.

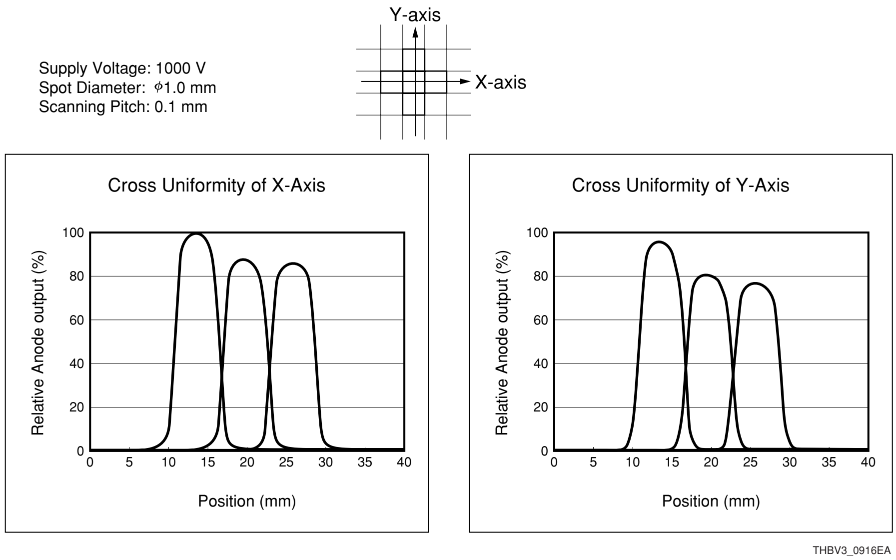

Figure 9-16: Spatial resolution of center anodes

Figure 9-17 shows typical crosstalk characteristics measured by irradiating the center of an anode (anode pitch 6 mm) with a light beam of 5 square millimeters. Relative outputs of adjacent anodes are shown in the figure by setting the output of this anode as 100 %,. As can be seen in the figure, this flat panel type 64-channel multianode photomultiplier tube has a crosstalk of 2 to 3 % at the center anodes.

—	—	—	—	—
—	0.2	1.8	0.2	—
—	1.5	100	2.7	—
—	0.2	2.6	0.3	—
—	—	—	—	—

Supply Voltage: 1000 V
Light Source: Tungsten Lamp
Spot Size: 5 square millimeters

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Figure 9-17: Crosstalk characteristics of center anodes

To take full advantage of the effective area, the photoelectrons emitted from the edges of the photocathode are focused toward the dynodes. This tends to increase anode crosstalk (3 % to 6 %) particularly in the corner areas. (See Figure 9-18.)

100	5.5	—
3.5	0.5	—
—	—	—

Supply Voltage: 1000 V
Light Source: Tungsten Lamp
Spot Size: 5 square millimeters

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Figure 9-18: Crosstalk characteristics of anodes in corner area

9.2 Center-of-Gravity Position Sensitive Photomultiplier Tubes

9.2.1 Metal channel dynode type multianode photomultiplier tubes (cross-plate anodes)

(1) Structure

Figure 9-19 shows the electrode structure of a metal channel dynode type multianode photomultiplier tube using a cross-plate anode.

In this photomultiplier tube, photoelectrons emitted from the photocathode are multiplied by each dynode and the multiplied secondary electrons are then reflected back from the last dynode and read out from the plate type anodes (cross-plate anodes) arranged in two layers intersecting with each other.

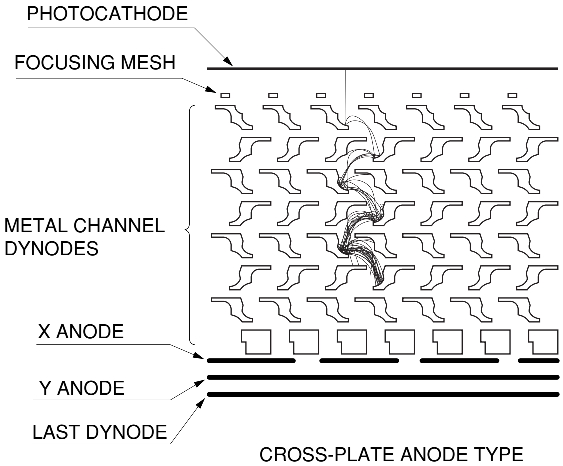

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Figure 9-19: Electrode structure

Figure 9-20 illustrates the center-of-gravity detection method for reading out the output signal from a position-sensitive photomultiplier tube using a cross-plate anode. The electron bunch released from the last dynode is collected by anodes linearly arranged in the X and Y directions. Since each anode in the same direction is connected by a resistor string, the collected electrons are divided into four signal components X1, X2, Y1 and Y2 corresponding to the anode position at which the secondary electrons arrive. By inputting these signals to summing (SUM) and divider (DIV) circuits, the center of gravity in the X and Y directions can be obtained from Eq. 9-1.

$$X = \frac{X_2}{(X_1+X_2)}$$
$$Y = \frac{Y_2}{(Y_1+Y_2)} \quad \text{(Eq. 9-1)}$$

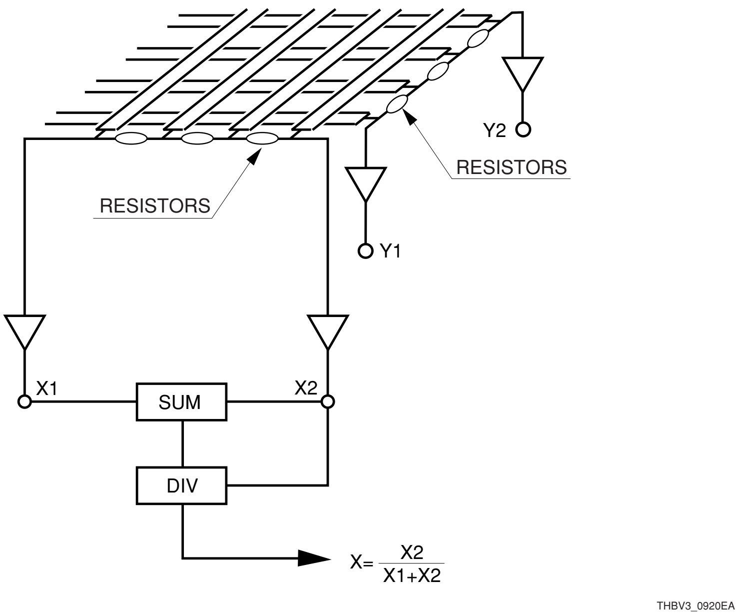

Figure 9-20: Center-of-gravity measurement method

(2) Characteristics

This section describes spatial resolution characteristics obtained by center-of-gravity detection using 6(X) + 6(Y) cross-plate anodes respectively arranged in the XY directions. This spatial resolution data (output distribution of each anode) was measured by scanning the photocathode surface with a 1-millimeter collimated light beam emitted from a tungsten lamp. Results are shown in Figures 9-21 and 9-22.

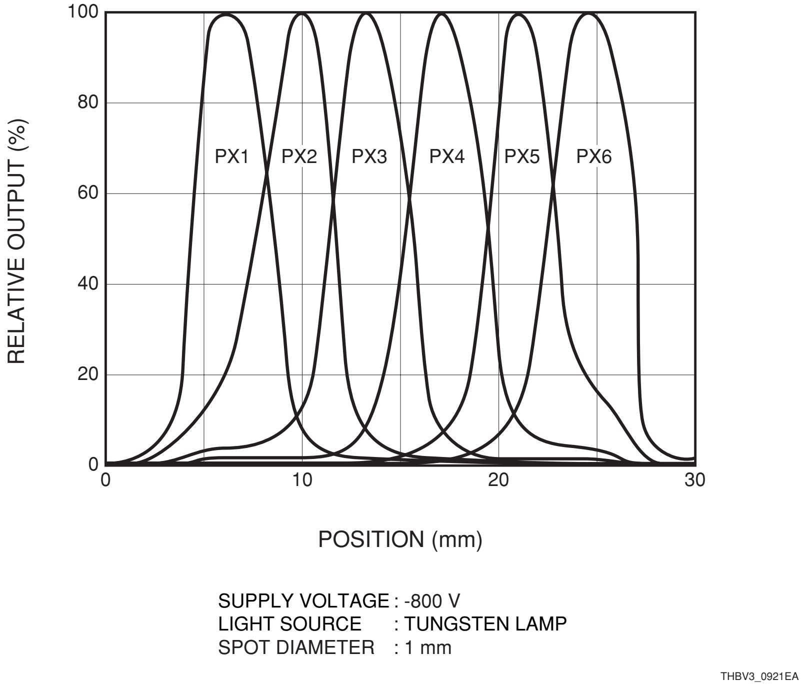

Figure 9-21: Spatial resolution of X anodes

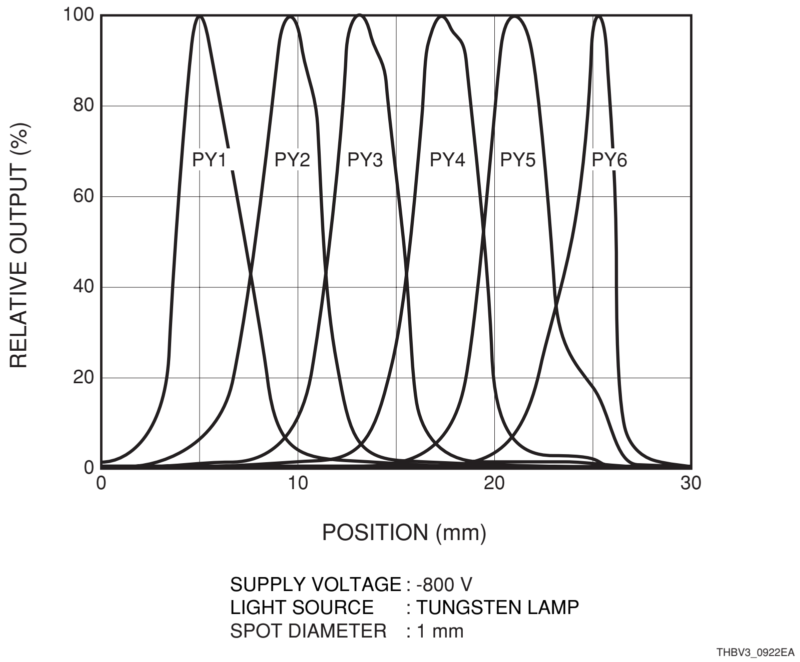

Figure 9-22: Spatial resolution of Y anodes

Figure 9-23 introduces a circuit diagram for scintillation imaging of 511 keV gamma-rays. It utilizes a position sensitive photomultiplier tube with 6(X) + 6(Y) cross-plate anodes and a mosaic array of scintillators (BGO of 2.2 mm×2.2 mm×15 mm arranged in a pattern of 9×9=81 pieces). An actual image obtained is shown in Figure 9-24.

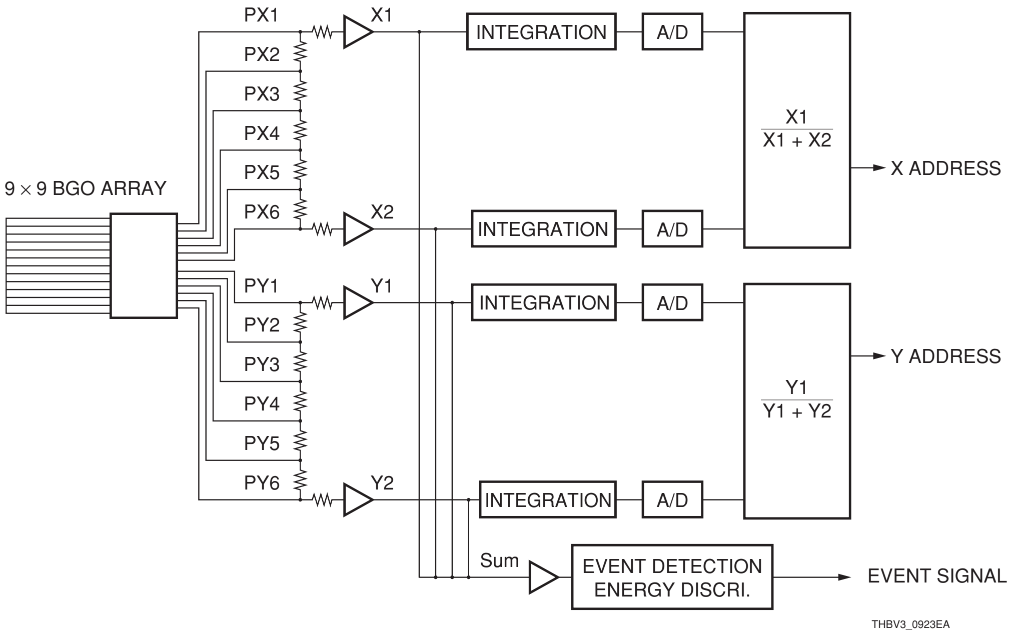

Figure 9-23: Scintillation imaging circuit using gamma-rays irradiated on mosaic pattern scintillators (BGO)

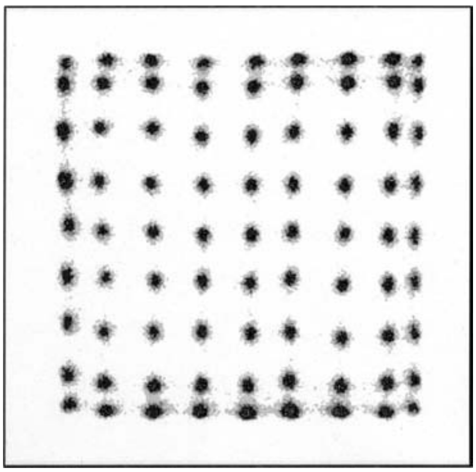

Figure 9-24: Scintillation image obtained by gamma-rays irradiated on mosaic pattern scintillators (BGO)

This scintillation imaging shows the mosaic pattern of 81 (9×9) BGO scintillators (2.2 mm×2.2 mm×15 mm). Off-center distortion in the image can be corrected by a lookup table.

9.2.2 Grid type dynode photomultiplier tubes (Cross-wire anodes)

(1) Structure

Figure 9-25 shows the electrode structure for grid type dynodes and the associated electron trajectories. The significant difference compared to ordinary box-and-grid dynodes is that the electron multiplier is fabricated from flat grid-like dynodes. These dynodes have a very fine structure that emits secondary electrons while suppressing the spatial spread of secondary electrons at each dynode.

In this photomultiplier tube, photoelectrons emitted from the photocathode are multiplied by each dynode (up to a total gain of 10^5 or more) and then the multiplied secondary electrons are reflected back from the last dynode (reflection type) and read out from the wire type anodes (cross-wire anodes) arranged in two layers intersecting with each other. The first dynode is placed in close proximity to the photocathode to minimize the spatial spread of photoelectrons.

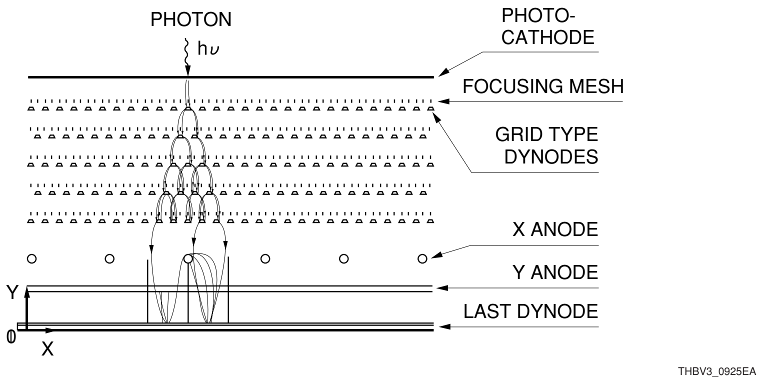

Figure 9-25: Electrode structure and electron trajectories

(2) Characteristics

A photomultiplier tube using a 12-stage grid type dynode yields a gain of 10^5 or more at 1250 volts. This type of photomultiplier tube is available in a circular envelope of 3 or 5 inches in diameter.

The number of wire anodes in the X and Y directions is 16(X) + 16(Y) for the 3-inch circular type (anode pitch: 3.75 millimeters) and 28(X) + 28(Y) for the 5-inch circular type (anode pitch: 4 millimeters).

Next, let's discuss the center-of-gravity detection method and spatial resolution characteristics. As shown in Figure 9-25, the electron flow spreads spatially between the photocathode and the first dynode and also between each grid dynode. When 50 μm diameter light spot scans the photocathode surface of the 3-inch circular type photomultiplier tube, the X and Y direction spatial resolutions are obtained as shown in Figures 9-27 and 9-28. Since the electron flow spreads in the multiplication process from the photocathode to the anode, the width of spatial resolution measured at each anode broadens to 9.5 millimeters in the X direction and to 8.6 millimeters in the Y direction.

Figure 9-26: Grid type dynode photomultiplier tube

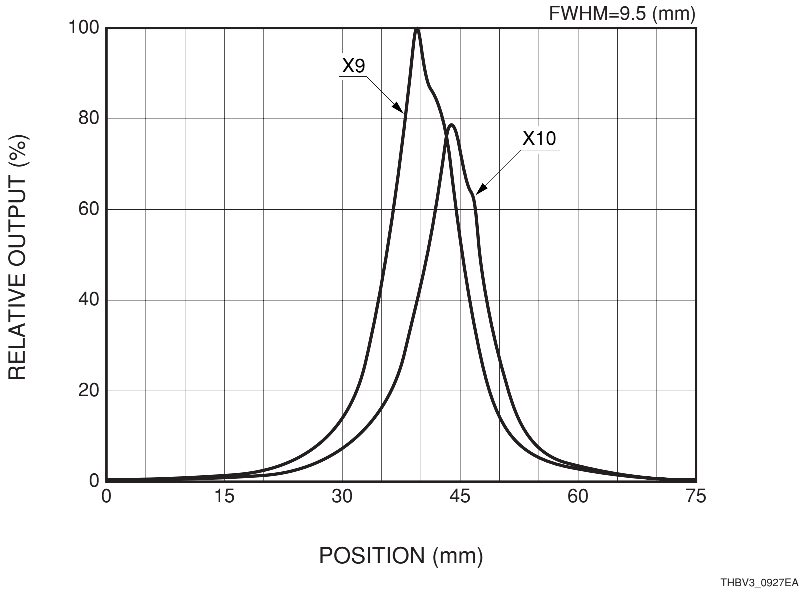

Figure 9-27: Spatial resolution in X direction

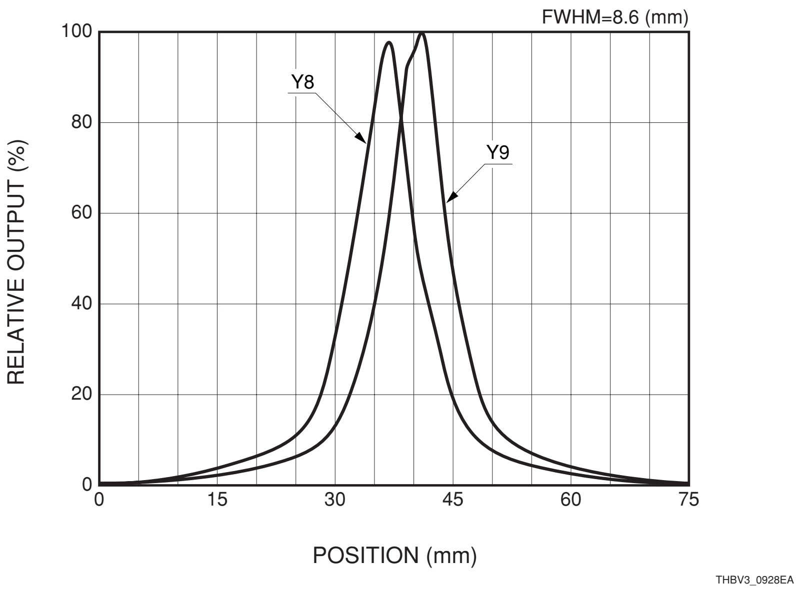

Figure 9-28: Spatial resolution in Y direction

To read out the signal from this photomultiplier tube, the center-of-gravity detection method is used, as described in the previous section 9.2.1, "Metal channel dynode type multianode photomultiplier tubes (cross-plate anodes)".

Figure 9-29 shows plots of spatial resolution measured with light emitted from a pulsed LED while changing the amount of light per pulse. This spatial resolution is determined by the center-of-gravity distribution in the output signal that broadens almost in inverse proportion to the square root of the amount of incident light according to the statistical theory. Figure 9-30 shows the center-of-gravity distribution characteristics measured while moving a light spot on the photocathode in 1 millimeter intervals. It proves that a resolution of 0.3 millimeters (FWHM) is obtained in the center at a light intensity of 4000 photons per pulse. A slight distortion occurs near the off-center region because there are fewer cross-wire anodes involved in the output signal. Figure 9-31 is a spatial linearity graph showing the electrical center-of-gravity position on the vertical axis and the light spot position on the horizontal axis.

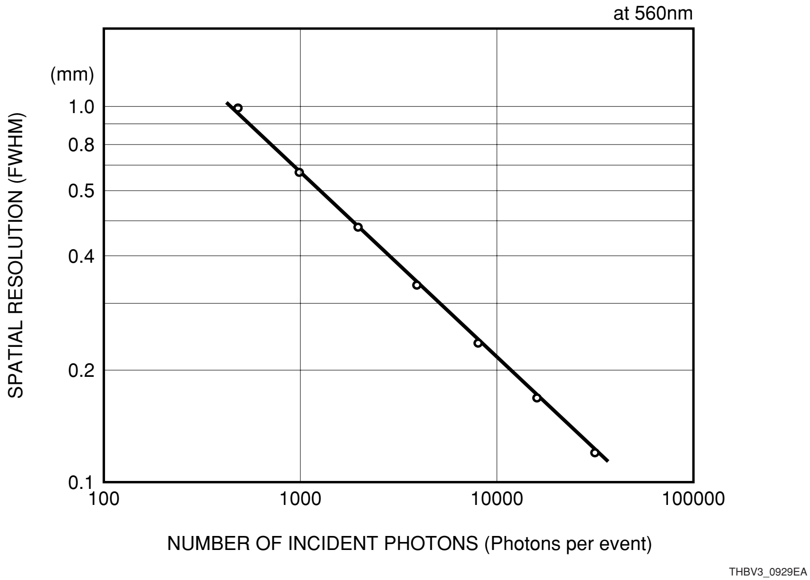

Figure 9-29: Spatial resolution vs. incident light level

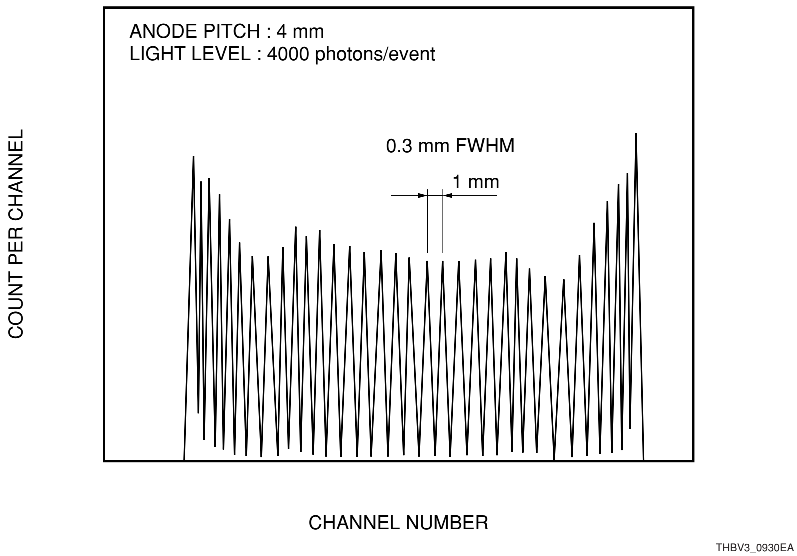

Figure 9-30: Center-of-gravity distribution with light spot movement

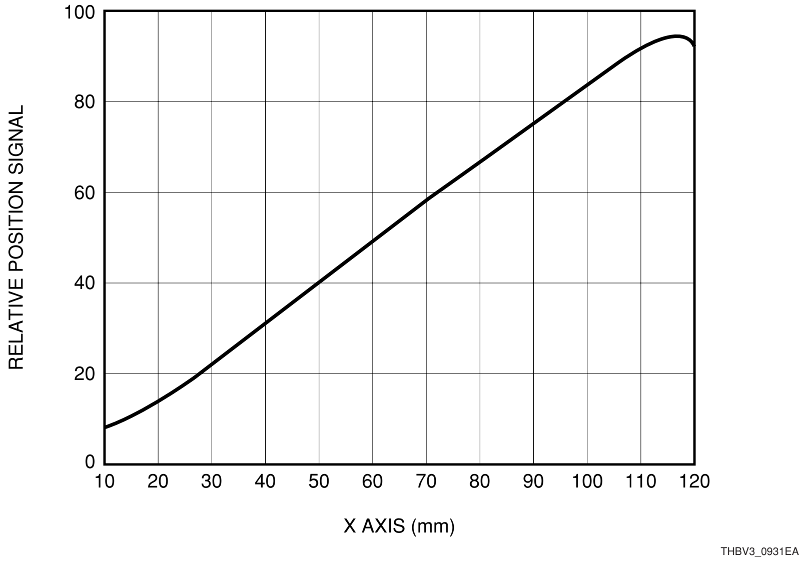

Figure 9-31: Spatial linearity of grid type dynode photomultiplier tube

In the peripheral portion of the photomultiplier tube, not all electrons are focused by the cross-wire anodes, and these electrodes cause distortion as if they are drawn toward the center. But this distortion level is small enough to be corrected by a lookup table or similar techniques.

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