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Nuclear instrumentation — Photomultiplier tubes for scintillation counting — Test procedures

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

NUCLEAR INSTRUMENTATION – PHOTOMULTIPLIER TUBES FOR SCINTILLATION COUNTING – TEST PROCEDURES

FOREWORD

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International Standard IEC 60462 has been prepared by IEC technical committee 45: Nuclear instrumentation.

This second edition cancels and replaces the first edition published in 1974 and constitutes a technical revision.

The main technical changes with regard to the previous edition are as follows:

- to review the existing requirements and to update the terminology, definitions and normative references.

The text of this standard is based on the following documents:

FDIS	Report on voting
45/706/FDIS	45/711/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

NUCLEAR INSTRUMENTATION – PHOTOMULTIPLIER TUBES FOR SCINTILLATION COUNTING – TEST PROCEDURES

1 Scope and object

This International Standard establishes test procedures for photomultiplier tubes (PMT) for scintillation and Cherenkov detectors.

This standard is applicable to photomultiplier tubes for scintillation and Cherenkov detectors.

Photomultiplier tubes are extensively used in scintillation and Cherenkov counting, both in the detection and analysis of ionizing radiation and for other applications. For such uses, various characteristics are of particular importance and require additional tests to those conducted to measure the general characteristics of PMT. This has made desirable the establishment of standard test procedures so that measurements of these specific characteristics may have the same significance to all manufacturers and users.

The tests described in this standard for PMT to be used in scintillation detectors are supplementary to those tests described in IEC 60306-4, which covers the basic characteristics commonly requiring specification for photomultiplier tubes.

This recommendation is not intended to imply that all tests and procedures described herein are mandatory for every application, but only that those tests carried out on PMT for scintillation and Cherenkov detectors should be performed in accordance with the procedures given in this standard.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60306-4, *Measurement of photosensitive devices – Part 4: Methods of measurement for photomultipliers*

3 Terms, definitions, symbols and abbreviations

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1.1
photomultiplier tube
multiplier phototube
PMT (abbreviation)
vacuum tube consisting of a photocathode and an electron multiplier intended to convert light into an electric signal

[IEC 60050-394:2007, 394-30-12]

3.1.2
Cherenkov detector
radiation detector designed to detect relativistic particles, using a medium in which the Cherenkov effect is produced

NOTE The medium is optically coupled to a photosensitive device, either directly or through light guides.

[IEC 60050-394:2007, 394-29-17]

3.1.3
scintillation detector
radiation detector consisting of a scintillator that is usually optically coupled to a photosensitive device, either directly or through light guides

NOTE The scintillator consists of a scintillating material in which the ionizing particle produces a burst of luminescence radiation along its path.

[IEC 60050-394:2007, 394-27-01]

3.1.4
light guide
optical device designed to transmit light without significant loss

NOTE It may be placed between a scintillator and a photomultiplier tube.

[IEC 60050-394:2007, 394-30-15]

3.1.5
dark current (of a photomultiplier tube)
electric current flowing from the anode circuit in the absence of light on the photocathode

[IEC 60050-394:2007, 394-38-14]

3.1.6
gain (of a photomultiplier tube)
ratio of the anode output current to the current emitted by the photocathode at stated electrode voltages

[IEC 60050-394:2007, 394-38-15]

3.1.7
collection efficiency (of a photomultiplier tube)
ratio of the number of measurable electrons reaching the first dynode to the number of electrons emitted by the photocathode

[IEC 60050-394:2007, 394-38-16]

3.1.8
light sensitivity (of a photomultiplier)
ratio of a photomultiplier cathode current by the corresponding incident light flux of a given wavelength

[IEC 60050-394:2007, 394-38-62]

3.1.9
spectral sensitivity (of a photomultiplier)
light sensitivity as a function of wavelength

[IEC 60050-394:2007, 394-38-63]

3.1.10
light sensitivity non-uniformity (of a photomultiplier)
variation of the light sensitivity over the photocathode surface

[IEC 60050-394:2007, 394-38-64]

3.1.11
transit time (in a photomultiplier tube)
time interval between the emission of a photo-electron and the occurrence of a stated point on the output current pulse due to that electron

[IEC 60050-394:2007, 394-38-12]

NOTE For example, peak maximum.

3.1.12
transit time jitter (in a photomultiplier tube)
variation in the transit times corresponding to different photoelectrons

[IEC 60050-394:2007, 394-38-13]

3.2 Symbols and abbreviations

3.2.1 Symbols

A	photomultiplier tube spectrometric constant;
C_{pho}	light output of the working standard in photon/MeV;
H	pulse height or peakposition without filter;
H'	pulse height or peak position with filter;
k	absorption factor of the filter;
n	total number of readings;
P	P is the pulse height corresponding to the peak-value of the distribution;
$\overline{P}$	mean pulse height averaged over n readings;
P_i	pulse height at the i^{th} reading;
P_{max}	maximum pulse height, recorded during the 16 h test interval;
P_{min}	minimum pulse height; recorded during the 16 h test interval;
P_T	pulse height at temperature T;
P_N	pulse height at temperature T = 20 °C;
P_{UP}	pulse height when PMT stands upright;
P_{NS}	pulse height when PMT lies along north-south direction;
R	pulse height resolution (*PHR*);
R_a	energy resolution of the scintillation detector;
R_d	intrinsic resolution of the measured housed scintillator;
R_{et}	intrinsic resolution of the working standard;
t	observed time;
t_r	photomultiplier rise time;
t_s	rise time of the source pulse;
t_{scp}	oscilloscope rise time;
X	pulse height linearity;
V	value of pulse height corresponding to total absorption peak maximum of the measured housed scintillator;

Δ	mean pulse height deviation;
Δ_{max}	maximum pulse height deviation, in percent;
ΔP	full-width at half-maximum (*FWHM)*;
Δ_T	pulse height shift, in percent;
$\Delta_{\mu\text{-metal}}$	deviation of pulse-heights.

3.2.2 Abbreviations

CFTD	constant fraction timing discriminator;
FWHM	full-width at half-maximum;
LED	light emitting diode;
MCA	multichannel analyzer;
PHD	pulse height distribution;
PHR	pulse height resolution;
PMT	photomultiplier tube;
s^{-1}	counts per second;
SPEPHR	single photo-electron pulse height resolution;
SPERT	single photo-electron rise time;
TAC	time-to-amplitude converter:
TTS	transit-time spread.

4 Test conditions

Test conditions for photomultipliers are specified in terms of environmental conditions that shall be met to enable accurate measurements of the photomultiplier parameters discussed in this standard.

Power supplies should be stabilized and, in particular, high-voltage power supplies should have regulations of 0,01 % or better, and ripple and noise should be not more than 10 mV_{pp}.

The test enclosure shall be free of detectable light leaks. This can be verified by half-hour photon counting periods, with and without bright ambient light incident on the enclosure.

The PMT should be stored in darkness for 1 h prior to measurement to avoid phosphorescence effects. Cleanliness of the PMT glass and sockets is essential in preventing external noise effects. Any material near the photocathode should be at photocathode potential to prevent electro-luminescence of the envelope and electrolysis or charge accumulation of the glass. To obtain the best conditions for reproducibility of tests, it is recommended that where feasible, a shield connected to cathode potential, be placed around and in contact with the glass envelope of the photomultiplier.

The PMT should be degaussed before using, and a magnetic shield should be employed. Note that even the earth's magnetic field is of sufficient strength to influence measurements. Tube temperature should preferably be maintained constant at ± 2 °C within the limits from 19 °C to 25 °C. This is important in instances where the voltage divider may raise the temperature of the test enclosure.

Caution should be used to avoid drifts or base line shifts in the electronic circuitry that significantly affects the measurements.

To prevent drifts or base line shifts in potentials between dynodes resulting from the electron multiplier current, the quiescent current drawn by the resistive voltage divider should be at least 20 times the DC anode current. Alternatively, the potentials between dynodes for the dynodes drawing the greatest current may be individually stabilized (as with separate power supplies).

Charge-storage capacitors may be effectively used across the dynodes or from the dynodes to ground when the ratio of the peak anode current to the average anode current is large and the capacitor can maintain the required dynode potentials for the duration of the pulse.

Pulse shaping methods and time constants suitable for optimum performance should be used and should be stated.

5 Test procedures for photomultiplier characteristics

5.1 General

In addition to the specifications and test methods of IEC 60306-4, complementary or extended specifications and tests required for photomultipliers used with scintillation and Cherenkov detectors are:

a) Pulse height characteristics[1].
b) Dark current.
c) Pulse timing characteristics.

5.2 Pulse height characteristics

5.2.1 General

Pulse height is used in counting and spectrometric applications.

5.2.2 Pulse height resolution measurement

5.2.2.1 General

In general there are four distinct *PHR* measurements to define the photon-and-electron resolution of PMT and scintillator/PMT combinations. These resolutions may be used separately or together.

5.2.2.2 ^{137}Cs PHR for a scintillator/PMT combination

This *PHR* is a function of the photocathode quantum efficiency, collection efficiencies of the dynodes and spatial uniformity, as well as the resolution of the scintillator.

For standard cases, measurement of ^{137}Cs pulse height resolution requires a ^{137}Cs source, a NaI(Tl) scintillator of 50 mm height and approximately the same diameter as the photocathode, a pulse height analyzer and the photomultiplier to be tested. The photomultiplier tube is optically coupled to the scintillator - for example, with the aid of silicone grease or viscous oil. The crystal housing should be at photocathode potential. The source is placed at a distance from the scintillator such that less than 1 000 pulses/s are encountered.

The PMT should be operated at a voltage such that a linear response is obtained, i.e. the output pulse height is proportional to input light intensity. Improper anode bias, excessive gain (and thus excessive anode current) or improper voltage divider circuits may give rise to a compression of the output pulse distribution, yielding an incorrect (low) value of *PHR*.

The tube/scintillator combination should warm-up for 1 h to obtain optimum *PHR*.

1 The terms “pulse amplitude” and “pulse height” are commonly used to designate the charge associated with a PMT output pulse.

Phosphorescence of the scintillator and the PMT window may require 12 h to decay to a sufficiently low level to permit accurate measurements to be made. Therefore, photomultipliers and scintillators should not be exposed to ambient light for 12 h before measurements are made.

The test enclosure shall be designed to avoid high electric fields in the region of the photocathode. If the PMT is operated with ground potential at the photocathode (positive high voltage) there is little problem with external electric fields at the photocathode. If negative high voltage is used, electric fields near the photocathode should be low. This may be accomplished by an electrostatic shield at photocathode potential. Otherwise, excessive noise on the output signal, followed by eventual loss of photosensitivity, may develop. As with all PMT measurements, a magnetic shield is required.

The ^{137}Cs distribution should be displayed on a pulse height analyzer and so positioned that the upper half of the full-energy peak distribution spans at least eight channels. The total counting rate should not exceed 1 000 s^{-1} and the integration and differentiation time constants should not exceed 5 µs. At least 50 000 counts shall be contained within the channels comprising the *FWHM*.

Pulse height resolution (*PHR*), in percent, is obtained from:

$$R = \Delta P/P \times 100 \qquad (1)$$

where

R pulse height resolution in percent;

Δ*P* *FWHM* as shown in Figure 1;

P pulse height corresponding to the peak value of the distribution.

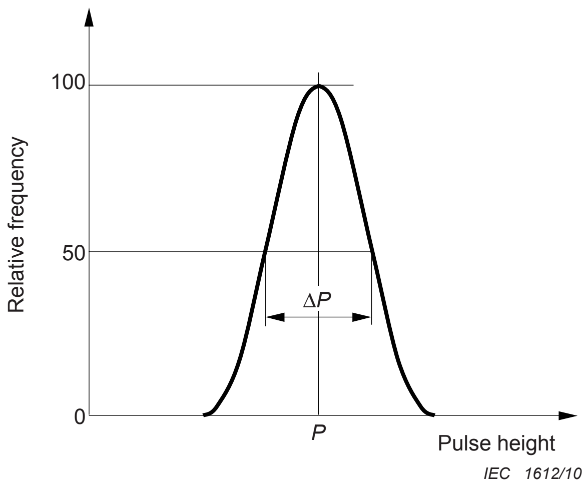


Figure 1 – Pulse height distribution

A linear interpolation should be made to determine the value Δ*P*. Alternatively, other curve-fitting techniques may be used. The method employed should be described.

In the case of a computer-controlled pulse height analyzer, a different method can be employed to determine the *FWHM* by assuming that the upper-part of the full energy peak approximates a Gaussian distribution. While the observed distribution is usually slightly skewed and not truly Gaussian, *PHR* values determined on the basis of a Gaussian distribution will, in general, agree closely with values obtained from the former method.

5.2.2.3 Light emitting source PHR

This *PHR* (intrinsic photomultiplier resolution) is obtained with a light emitting source such as a light emitting diode (LED) (see Annex A), calibrated to provide a ^{137}Cs- NaI(Tl) scintillator - equivalent signal (or stated number of photoelectrons per pulse). The light emitting source *PHR* is considerably smaller than the scintillator/PMT *PHR* because the contribution of the scintillator is not present.

The light emitting source *PHR* should be stated in terms of a ^{137}Cs-equivalent flash; the light emitting source should be adjusted in flash intensity until the resulting pulse height distribution exhibits a peak in the same channel as a NaI(Tl) scintillator and ^{137}Cs source combination. The light emitting source shall be positioned such that it uniformly illuminates the photocathode. *PHR* may be calculated from the previously discussed method (see equation 1). The integration time of the electronic circuits shall be much longer than the duration of the light flash and the time constant of the scintillator.

This measurement of *PHR* may be independently verified with another calibrated light emitting source, and good agreement should be obtained. This type of independent measurement is not as straightforward when NaI(Tl) scintillators are used owing to variations in resolution between different scintillators.

5.2.2.4 ^{55}Fe PHR for a scintillator/PMT combination

Pulse height resolution for a ^{55}Fe (5,9 keV, X-ray) source, using a NaI(Tl) scintillator coupled to the PMT, provides a figure of merit for resolution of low-energy events.

This is the *PHR* obtained using a scintillator/PMT combination with a ^{55}Fe source, and depends on both the scintillator and the photomultiplier.

Measurements are made as outlined in 5.2.2.2. The effect of scintillator resolution is more pronounced in the ^{55}Fe *PHR* measurement than in the ^{137}Cs *PHR* measurement. The ^{55}Fe source is placed at a distance from the scintillator so that less than 1 000 pulses/s are encountered.

The ^{55}Fe distribution is skewed, and a Gaussian distribution does not adequately describe the observed distribution. For this reason, resolution measurements based on assumptions of Gaussian distributions are not satisfactory, but the distribution shall rather be least-squares fitted with two peaks using appropriate software.

5.2.2.5 Single photo-electron *PHR*

Single photo-electron pulse height resolution (*SPEPHR*) has significance only for those photomultipliers that can resolve a single photo-electron peak. A weak DC light is used as the source of single photo-electrons for the photocathode for this measurement.

The single photo-electron peak is displayed on the pulse height analyzer system while DC light illuminates the photocathode. The tube dark pulses may be predominantly single photo-electron in origin, and software should be used to obtain a single photo-electron distribution; however, the DC light is required to verify the placement of the true single photo-electron peak on the analyzer display.

SPEPHR is the fractional *FWHM* of the single photo-electron distribution obtained from the photomultiplier. *SPEPHR* is calculated as stated in 5.2.2.2.

Some photomultipliers are able to resolve a single photo-electron peak, but the resulting distribution may not fall to one-half height on the low energy side due to noise contributions. In such cases, the quantity ΔP in equation 1 is undefined and calculation of *PHR* by means of the above method is impossible. As an approximation one may quote twice the one-half height measured on the high energy side. A statement of fractional width at some other height in the distribution (75 %, for instance) could be made, but it should be stressed that this figure is not *PHR*, which is defined in terms of the fractional *FWHM*.

5.2.3 Pulse height linearity measurement

The following test method is common as well as the two-pulse method using a transmittance filter:

1) Measure the ratio of output signal against two light source of different intensity illuminating the photo-cathode in turn.

Change the gap between the light source and the photo-cathode.

Then estimate the variation of the ratio of output signal.

2) Deviations from linearity are usually due to two effects:
   a) space charge effects associated with high-current pulses;
   b) resistive divider networks which cannot supply enough current to maintain the photomultiplier dynodes, and other elements, at constant operating potentials.

Assuming that a) is not the limitation (see Clause 4), the following measurement procedure of determining the peak "linear" current (charge) that can be obtained from a photomultiplier (see Figure 2) is used.

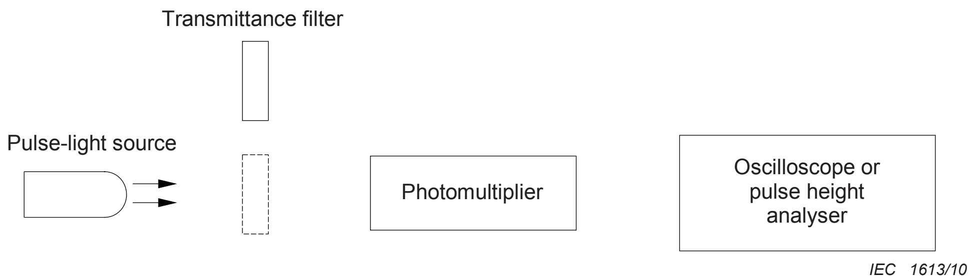


Figure 2 – Two-pulse method

The method is called the two-pulse technique and it requires a pulsed light source and a neutral-density filter that has an absorption factor in the range of 0,1 to 0,5 (i.e. transmission between 90 % and 50 %). The pulse width should not exceed 1 μs and the duty cycle should not exceed 1 %.

The output pulses are displayed on an oscilloscope or pulse height analyzer with and without the filter, and the ratio of the pulse heights or peak positions is noted.

Deviation from linearity (X) in percent is determined with equation (2):

$$X = (H' - k \times H) / H \times 100 \qquad (2)$$

where

H pulse height or peakposition without filter;

H’ pulse height or peak position with filter;

k absorption factor of the filter.

Expanded uncertainty of linearity measurement of pulse height should not exceed ±4 % with a level of confidence of 0,95.

5.2.4 Pulse height stability measurement

5.2.4.1 General

In scintillation counting it is particularly important that the photomultiplier has very good pulse height stability, especially when total absorption peaks produced by nuclear disintegrations of nearly equal energy are being distinguished. The pulse height stability is characterized by the properties listed below, which may be used separately or together. In production tests for 5.2.4.5 – 5.2.4.6 average current measurements, as specified in IEC 60306-4, may be used provided the manufacturer establishes their equivalence with the pulse height measurements described below. The caution regarding drifts or base line shift in the electronic circuitry (see Clause 4) is particularly important for these measurements. In a multi-channel analyzer the PMT pulse height is measured as the position in channels of the resulting peak.

5.2.4.2 Mean pulse height deviation at constant counting rate

A pulse height analyzer, a ^{137}Cs source and a NaI(Tl) scintillator are employed to measure the pulse height. The ^{137}Cs source is located along the major axis of the tube and scintillator such that a total counting rate of about 1 000 s^{-1} is obtained. The entire system is allowed to stabilize under operating conditions for a period of 1 h before readings are recorded. Following this period of stabilization, the pulse height (position of the total absorption peak) is recorded every 1 h for a period of 16 h. The spectrum is cleared after each 1 h measurement.

The mean pulse height deviation, in percent, is then calculated as follows:

$$\Delta = \frac{\sum_{i=1}^{n} \left| \overline{P} - P_{\mathrm{i}} \right|}{n} \times \frac{100}{\overline{P}}, \tag{3}$$

where

Δ mean pulse height deviation, in percent;

$\overline{P}$ mean pulse height averaged over n readings;

P_{i} pulse height at the i^{th} reading;

n total number of readings.

Maximum mean pulse height deviation values for photomultipliers with high-stability dynodes shall be less than 1 % when measured under the conditions specified above.

5.2.4.3 Maximum pulse height deviation at constant counting rate

Pulse height measurements are made as described above for mean pulse height deviation and the maximum pulse height deviation, in percent, is then calculated as follows:

$$\Delta_{\mathrm{max}} = \frac{P_{\mathrm{max}} - P_{\mathrm{min}}}{P_{\mathrm{max}} + P_{\mathrm{min}}} \times 100 \tag{4}$$

where

Δ_{max} maximum pulse height deviation, in percent;

P_{max} maximum pulse height, recorded during the 16 h test interval;

P_{min} minimum pulse height, recorded during the 16 h test interval.

Maximum pulse height deviation values for photomultipliers with high-stability dynodes shall be less than ± 2 % when measured under the conditions specified above.

5.2.4.4 Pulse height shift with counting rate

A pulse height analyzer, a ^{137}Cs source and a NaI(Tl) scintillator are employed to measure the pulse height. The ^{137}Cs source is located along the major axis of the tube and scintillator such that a total counting rate of about 10 000 s^{-1} is obtained.

The entire system is allowed to stabilize under operating conditions for a period of 1 h before readings are recorded. The pulse height is recorded for 1 h. Avoidance of base line shifts in the electronic circuitry is particularly important for this test. The photomultiplier tube gain at which the measurements are made shall be fixed.

The total counting rate is then decreased to about 1 000 s^{-1} by increasing the source to scintillator distance and the pulse height is recorded for 1 h. The pulse height is measured and compared with the measurement made at the total counting rate of 10 000 s^{-1}. The pulse height shift with counting rate is expressed as the percentage pulse height shift (plus or minus indicated) for the counting rate change.

Example: pulse height shift of – 1 % when going from 10 000 s^{-1} to 1 000 s^{-1}.

Photomultipliers designed for good pulse height stability should have a value less than 1 % pulse height shift.

5.2.4.5 Pulse height shift with temperature

A pulse height analyzer and a light emitting source held at constant temperature such as a LED or a radioactive source with scintillator are employed to measure the pulse height from the photomultiplier. A constant counting rate of between 1 000 s^{-1} and 10 000 s^{-1} is used, with the pulse height at least 10 times greater than that resulting from a single photo-electron. The PMT temperature is varied according to the range of interest and the corresponding pulse heights are noted.

The pulse height shift is the variation from the pulse height at 20 °C. It shall be calculated in accordance with the formula:

$$\Delta_{\mathrm{T}} = \frac{P_{\mathrm{T}} - P_{\mathrm{N}}}{P_{\mathrm{N}}} \times 100 \qquad (5)$$

where

Δ_{T} pulse height shift, in percent;

P_{T} pulse height at temperature T;

P_{N} pulse height at temperature T = 20 °C.

Pulse height shift with temperature should be such as specified in specification of manufacturer.

Care shall be taken to avoid pulse pile-up effects resulting from excessive thermionic emission at elevated temperatures.

5.2.4.6 Pulse height shift with magnetic field

A pulse height analyzer and a light emitting source such as LED or a radioactive source with scintillator are employed to measure the pulse height from the photomultiplier when PMT stands upright, i.e. the photocathode points towards the Earth, and when PMT lies along north-south direction.

The deviation of pulse-heights, in percent, shall be calculated in accordance with the equation:

$$\Delta_{\mu\text{-metal}} = ((P_{NS} - P_{UP}) / P_{UP}) \times 100 \quad (6)$$

where

$\Delta_{\mu\text{–metal}}$ deviation of pulse-heights;

P_{UP} pulse height when PMT stands upright;

P_{NS} pulse height when PMT lies along north-south direction.

Pulse height shift with magnetic field of the Earth should not exceed 2 %. Pulse height shift with various magnetic fields should be according to manufacturer specifications.

5.3 Test procedure for determination of dark current

Anode dark current is output current that flows in a PMT when the PMT is operated in a completely dark state and in the absence of external ionizing radiation.

Dark current is measured using a PMT, a divider voltmeter, a voltmeter, a PMT divider, an amperemeter. Power should be supplied in accordance with manufacturer's specifications. The PMT should be stored in darkness for 1 h. The value of anode dark current is determined.

The expanded uncertainty of anode dark current greater than 1 nA should not exceed 1 % and for anode dark current below 1 nA it should not exceed 10 %. Uncertainties are quoted with a level of confidence of 0,95.

5.4 Test procedure for time characteristics

5.4.1 General

For the following tests a fast, short light source is used such as e.g. LED, spark source, Cherenkov source, scintillator or a mode-locked laser (see Annex A). Pulses shall be less than 5 ns wide and rise time shall not exceed 500 ps.

5.4.2 Photomultiplier rise time measurements

Photomultiplier rise time is measured with a repetitive delta-function light source and a sampling oscilloscope. The trigger signal for the oscilloscope may be derived from the photomultiplier output pulse, so that light sources such as the scintillator light source may be employed.

Photomultiplier rise time is properly defined as the time required for the anode current to increase from 10 % to 90 % of its final value (see Figure 3).

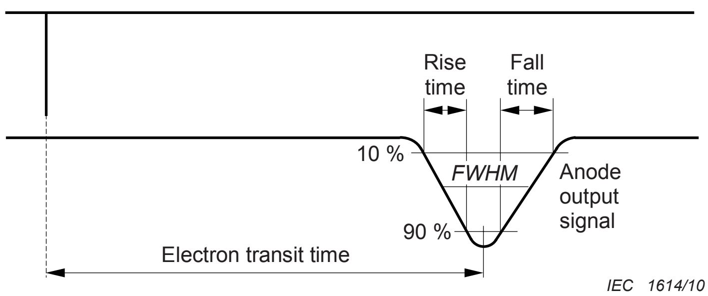


Figure 3 – Definition of rise, fall time and electron transit time

The rise time as measured from an oscilloscope photograph shall be corrected for the finite rise times of the individual elements comprising the system. The photomultiplier rise time is calculated from the relation:

$$t_r = \sqrt{t^2 - (t_s^2 + t_{scp}^2)} \tag{7}$$

where

t observed time;

t_s rise time of the source pulse as specified by the manufacturer of the light source;

t_{scp} oscilloscope rise time as specified by the manufacturer.

Equation (7) holds under the assumption that contributors exhibit Gaussian distributions, which is not strictly valid for the oscilloscope rise time.

Because of the uncertainties involved in correcting for the finite rise times of the individual elements, it is best to choose these elements such that their individual rise times do not exceed one third of that of the photomultiplier rise time. The rise times of the elements comprising the measurement system shall be stated.

Expanded uncertainty of rise time measurement should not exceed 15 % with a level of confidence of 0,95.

5.4.3 Fall time measurements

Photomultiplier fall time is the time difference between the 90 % and 10 % height points on the trailing edge of the output pulse waveform for full-cathode illumination and delta-function excitation (see Figure 3). The light source used should exhibit a fall time that is less than one-third of the photomultiplier fall time.

Fall time measurements are made in accordance with procedures outlined in 5.3.1.

Expanded uncertainty of fall time measurement should not exceed 15 % with a level of confidence of 0,95.

5.4.4 Single photo-electron rise time measurements

Measurement of single photo-electron rise time (*SPERT*) requires a photomultiplier having an adequate gain so that the single photo-electron events may be viewed on a sampling oscilloscope (see Figure 4). A pulsed-light source may be attenuated so that the average yield per pulse is much less than 1 photoelectron. Part of the PMT output is used to provide a trigger signal for a sampling oscilloscope while the larger part of the signal flows through a delay line to the vertical amplifier of oscilloscope.

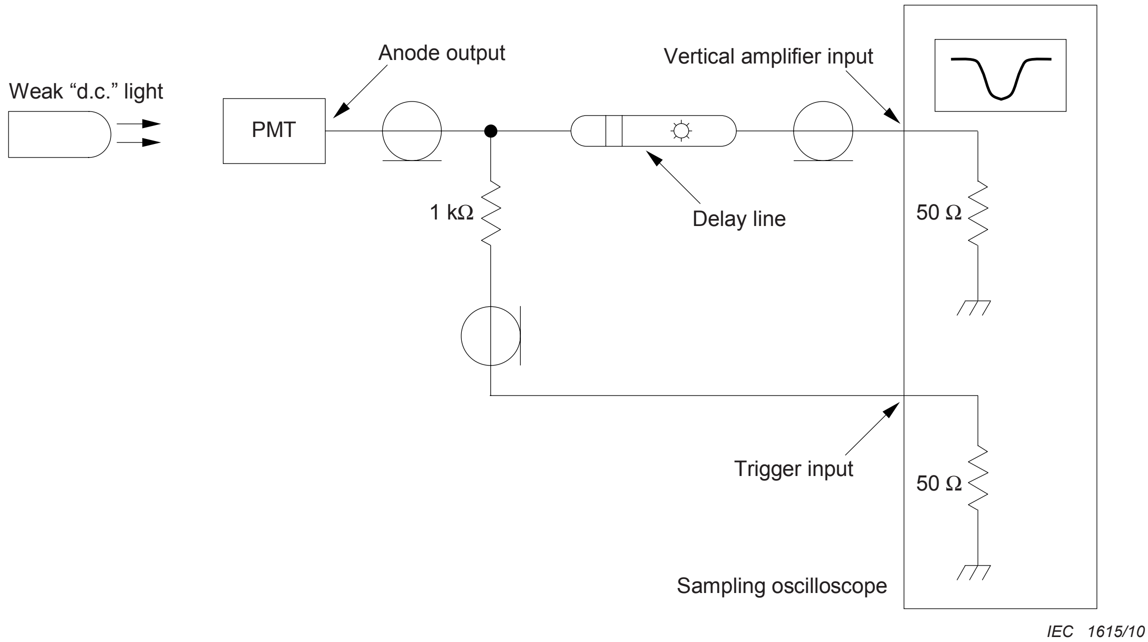


Figure 4 – Determination of single photo-electron rise time

Photocathode dark emission may also be used as a source of single photo-electrons. If the dark current is too low, a DC light may be used to increase the single photo-electron emission rate as in Figure 4. The use of a DC light is required to ensure that the output pulses are single photo-electron initiated. When dark current (or attenuated DC light) is used as a source of single photo-electrons, the trigger signal for the sampling oscilloscope shall be derived from the anode output pulse. A signal pick-off probe may be used, provided its rise time is small (one third or less) compared to the anode pulse rise time. A resistive divider is suitable, and may be fabricated in a manner to produce a rise time of less than 100 ps. Delay lines with internal trigger pick-offs are also available.

A description of the instrumentation and techniques used should accompany *SPERT* data.

Expanded uncertainty of single photo-electron rise time measurement should not exceed 15 % with a level of confidence of 0,95.

5.4.5 Transit time spread measurements

Transit-time spread (TTS), also called the transit time jitter, is measured by recording the intervals between a clocked series of light pulses and the corresponding series of anode pulses. The transit time probability distribution depends on the mean number of photoelectrons, emitted per light pulse, the variance being greatest for single photo-electron operation. The measured probability distribution can also depend to some extent on the statistics of photon emission because the timing reference chosen is a light pulse.

This is the fluctuation in transit time between individual pulses, and may be defined as the *FWHM* of the frequency distribution of electron transit times.

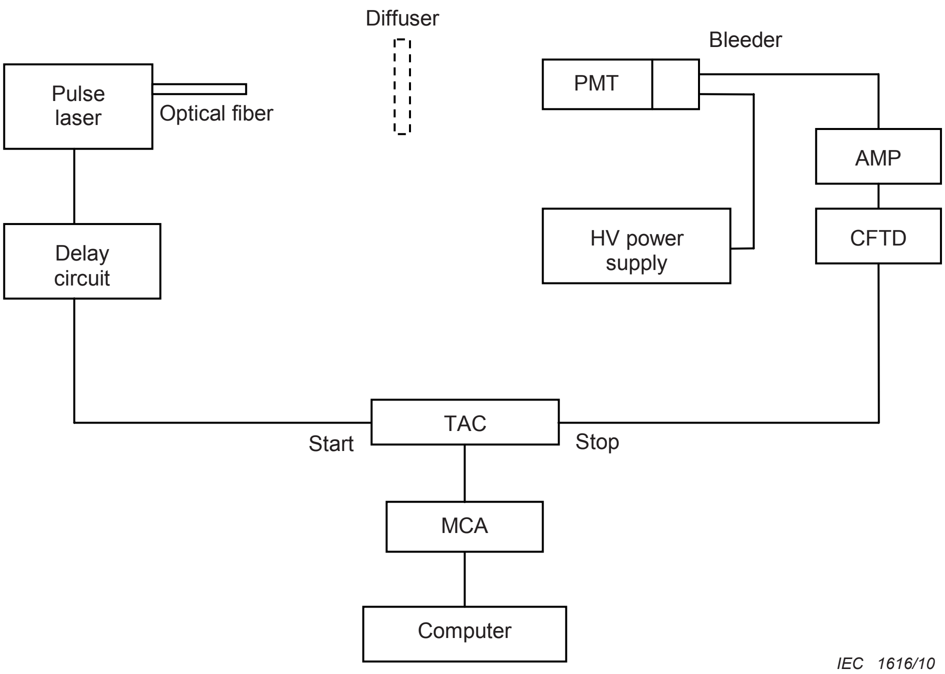
Photomultiplier transit time spread, also called photomultiplier time resolution, can be measured for a single photomultiplier, and also for a pair of photomultipliers. Both measurements are useful and are described hereafter. In performing these measurements, a number of techniques are available to designate the instant in time at which the output pulse reaches a given height. The recommended technique utilizes constant-fraction timing since this leads to the best timing performance for a wide range of pulse heights. The measurement method (single-tube or two-tube) should be stated. In a single-tube time resolution measurement (see Figure 5, Case 1), the trigger signal from the light source supplies the "start" signal to the TAC; the device output signal obtained from the constant-fraction timing discriminator supplies the "stop" signal. A statistically large number of TAC pulses are sorted by a multichannel analyzer and the resolution is given by *FWHM* of the time spectrum. The *FWHM* should span at least eight channels and at least 50 000 events should be contained within the *FWHM*. The intrinsic time spread of the light source and its trigger output should not exceed 30 % of the measured transit time spread and should be stated.

The resolution should be stated for full-cathode illumination.

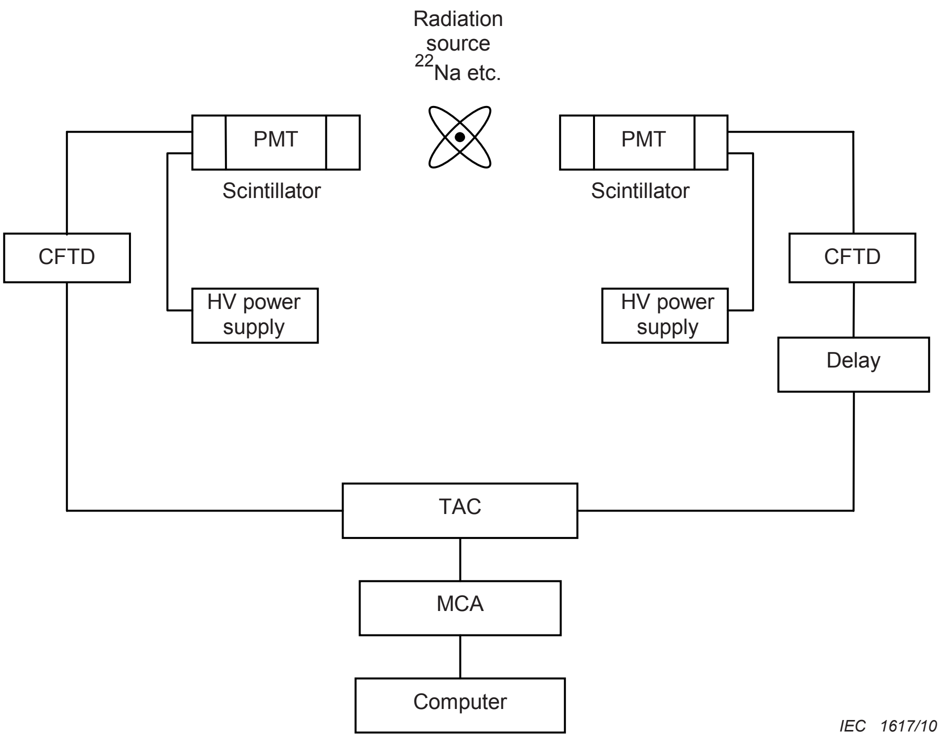
A second measurement of photomultiplier time resolution (see Figure 5, Case 2) involves the use of two photomultipliers viewing a common delta function light source. This technique allows one photomultiplier to activate the TAC "start", while the other activates the TAC "stop". Note that this technique does not require a trigger signal from the source, so that either Cherenkov or scintillation sources can be employed. As with the single-tube measurement, resolution improves with the number of photoelectrons per pulse, so this figure shall be stated. The *FWHM* of the distribution shall be stated, and the instrumentation shall be described. Calibration of the instrumentation shall be carried out according to the methods specified by the manufacturer.

Expanded uncertainty of transit time spread measurement should not exceed 15 % with a level of confidence of 0,95.

Case 1 – One tube



Case 2 – Two tubes



Key

PMT photomultiplier tube
TAC time-to-amplitude converter
CFTD constant fraction timing discriminator
MCA multichannel analyzer

Figure 5 – Transit time spread

Annex A
(informative)

Light sources

A.1 General

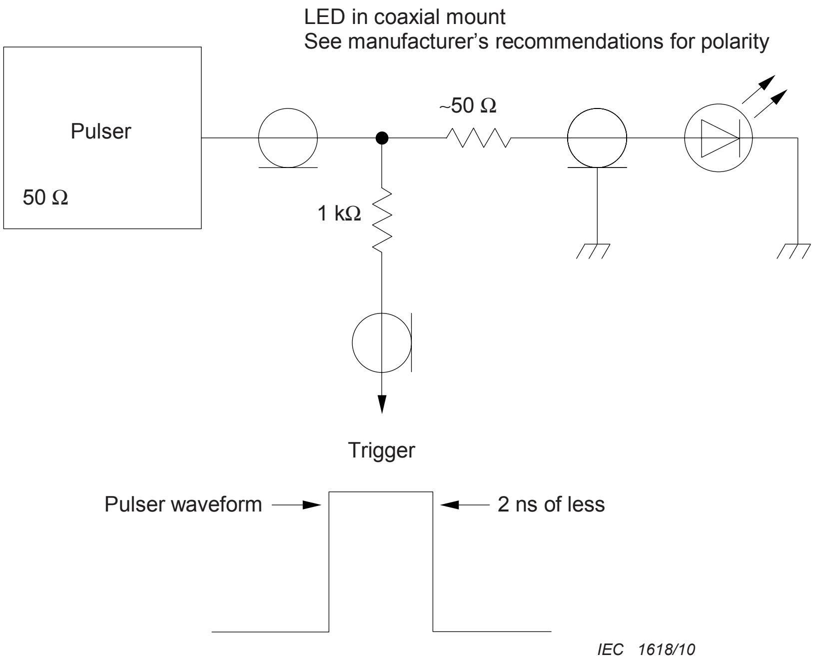
This Annex is concerned with "delta-function" light sources to be used for timing measurements. In general, no single source is suitable for all photomultiplier time measurements. Pulsed-light sources shall have a dispersion not greater than 1 % for a ^{137}Cs equivalent of NaI(Tl). Applicable sources are discussed below in order of increasing complexity and cost.

A.2 Light emitting diodes

The light emitting diode (LED) (see Figure A.1) is a convenient delta-function light source. Typical rise times are on the order of 500 ps for light flashes corresponding to less than 100 photons. The fall times are approximately equal to the rise times. Note that minimum rise times can only be obtained with delta-function current pulses. The rise time associated with a step function is considerably greater for all LEDs.

The light output can be varied from approximately 1 photon per pulse to over 1×10^5 photons per pulse. However, rise time begins to increase when the intensity exceeds a few hundred photons per pulse.

Pulse generators for LEDs may consist of mercury-switch pulsers as shown in Figure A.1, or avalanche transistor pulsers using either capacitors or charge lines for energy storage. Repetition rates of 400 Hz for a mercury-switch pulser and 10 kHz for avalanche transistor pulsers are typical. A trigger signal may be derived from either type of pulser to mark the occurrence of a light flash.



Rise time < 200 ps
Pulse height ~ 10 V

Figure A.1 – Light-emitting diode circuitry

A.3 Laser diode source

Some light pulsers based on laser diodes are available to accommodate various wavelengths, enabling optical output over a broad wavelength range of 375 nm to 1 550 nm, to reveal ultrashort pulses with *FWHM* of 100 ps or less. They may have high-repetition frequency up to 100 MHz.

A.4 Cherenkov source

The Cherenkov light source operates with energetic particles from a nuclear radiation source that create Cherenkov light when decelerated in a medium with high index of refraction. A beta source of ^{90}Sr may for example be used that is embedded between thin pieces of plastic.

The rate is governed by the radiation source intensity, and the flashes are random in time. No electrical trigger is available to mark the occurrence of a flash.

A.5 Scintillator light source

The scintillator light source utilizes a fast plastic scintillator and a nuclear radiation source to provide a light flash with a fall time longer than its rise time. A typical rise time is 400 ps; a typical fall time is approximately 1,5 ns with a characteristic long tail of several nanoseconds.

The rate of flashing is determined by the source intensity, and the flashes are random in time. No electrical trigger is available to mark the occurrence of a light flash.

A.6 Mode-locked laser

Mode-locking is achieved by applying a time-varying intensity or phase perturbation to the continuous-wave light signal within a laser cavity. When the perturbing frequency matches the resonant frequency $c/2l$ of the cavity, where c is the velocity of light and l is the cavity length, the nodes are brought into phase, resulting in intense light pulses occurring at a rate $c/2l$.

He-Ne (633 nm), Ar (588 nm and 514,5 nm) and Nd: YAG (1,06 μm) lasers may be mode-locked. Pulse widths for the He-Ne laser are of the order of 1 ns and pulse widths for the Ar laser are approximately 250 ps, while pulse widths for a Nd: YAG system range from 1 ps to 50 ps. The shorter pulse widths obtainable from a Nd: YAG system make this system most useful for high-speed time measurements on fast photomultipliers.

Repetition rates for a Nd: YAG system are usually in the range from 75 MHz to 200 MHz. Even the 75 MHz rate may be too fast for measurements with some photomultipliers. Lower repetition rates can be obtained by using fast electro-optical modulators to gate off unwanted pulses. An electrical trigger signal is available to mark the occurrence of each pulse.

The 1,06 μm radiation from Nd:YAG lasers can be doubled in frequency by employing a non-linear crystal to obtain pulses at 532 nm (green). These picosecond pulses may be very intense (10^8 photons per pulse) and may be used to obtain photo-emission from GaP (Cs) dynodes, as well as from photocathodes. The mode-locked laser can be used to probe the surface of a dynode to map its spatial timing characteristics.

Annex B
(informative)

Definition of the PMT spectrometric constant

B.1 General

The method of measurement of the PMT spectrometric constant using NaI(Tl) scintillators as standard scintillators is described in this Annex.

B.2 Equipment and measurement instrumentation

The measurements are made using the setup for measuring scintillation parameters of housed scintillators according to 5.2.2.2. Non-linearity and the initial point of the setup transformation characteristic shall be measured as specified in 5.2.3.

The setup is certified for making measurements if its non-linearity does not exceed 3 %. The setup non-stability is evaluated as specified in 5.2.4.3. The setup is certified for making measurements if its non-stability does not exceed 2 %.

B.3 Preparation and making measurements

1) The following measurements shall be used, if there is a working standard of the housed scintillator with known R_{et}. The measurements are made three times according to IEC 62372. The spectrometric constant *(A)* is obtained from the energy resolution (R_a) of the scintillation detector with the tested PMT and intrinsic resolution of the housed scintillator (R_{et}) according to formula:

$$A = (R_a^2 - R_{et}^2) \times C_{pho} \tag{B.1}$$

where C_{pho} is the value of the light output of the working standard (in photon/MeV units).

The energy resolution of the scintillation detector with the working standard, the intrinsic resolution and the light output of the working standard are determined for radiation of the same type and energy.

2) The method described in IEC 62372:2006, 5.3.3), shall be used, if there is no working standard.

Dependence graph $R_a^2 = f\left(\frac{1}{V}\right)$ is made on the basis of n results. A straight line is drawn through the experimental points, which can be approximated by the dependence as follows:

$$R_a^2 = R_d^2 + \frac{A}{V} \tag{B.2}$$

where the value R_d^2 is the intercept on the coordinate axis which corresponds to the intrinsic resolution of the measured housed scintillator *(R_d)*.

Value of *A* is determined as tangent of angle of the line slope.

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IEC 60050-394:2007, *International Electrotechnical Vocabulary (IEV) – Part 394: Nuclear instrumentation – Instruments, systems, equipment and detectors*

ISO/IEC Guide 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

IEC 62372:2006, *Nuclear instrumentation – Housed scintillators – Measurement methods of light output and intrinsic resolution*

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