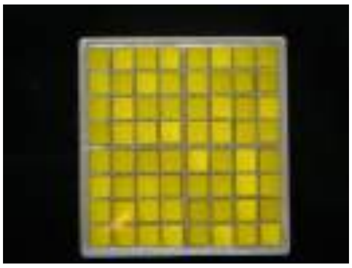
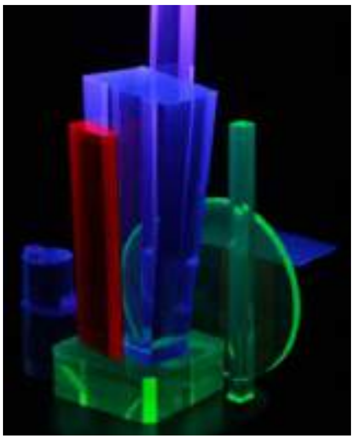
SCIONIX

Dedicated
Scintillation detectors





Content Page

1.0 Introduction, Who we are...

This tutorial of SCIONIX scintillation detectors is meant for users of radiation detection instruments to provide information on the different possibilities of scintillation materials and readout methods.

For the detection of radiation a great number of possibilities exist. Scintillators are often used for efficient detection of alpha- and beta-particles or electromagnetic radiation like gamma-rays or X-rays. For each application, a choice must be made for the type of scintillation material, its required size and the readout method. Also for the physical realization of the instrument numerous possibilities exist. The optimum choice often depends on the conditions in which your instrument should be used.

This tutorial provide you with some basic information about the physical properties of different scintillation materials and their typical applications. A limited number of standard detector configurations is presented. In practice, a scintillation detector is often "tailor made" for a specific application and the presented range is only a selection.

The SCIONIX philosophy is that the final detector is the result of close cooperation between us and you, the user of the instrument.

SCIONIX is a company producing equipment and components for radiation detection instruments employing **scintillation crystals and materials**. We are located near Utrecht in the center of the Netherlands, a 40 min drive from Amsterdam airport.

Scintillation detectors are being manufactured in The Netherlands since the 1960s. The design and fabrication of high quality scintillation detectors require a vast amount of expertise and experience. The long term presence of these qualities in the Netherlands forms the foundation on which SCIONIX was established in 1992.

Our product range consists of scintillation detection instruments with associated front-end electronics, often incorporated into the detector assembly. Key themes are: quick interaction on new scientific developments regarding materials and detection techniques; and close collaboration with end users.

We would like to invite you to learn more about SCIONIX and our products. Please feel free to call us for additional information, prices, and our exact capabilities.

2.0 Scintillation detectors

In this section, a short overview of the use and general principle of scintillation detectors is presented. Scintillation crystal parameters in relation to the application are discussed.

A scintillator is a material that converts energy lost by ionizing radiation into pulses of light. In most scintillation counting applications, the ionizing radiation is in the form of X-rays, γ-rays and α- or β-particles ranging in energy from a few thousand electron Volts to several million electron Volts (keVs to MeVs).

2.1 General

Pulses of light emitted by the scintillating material can be detected by a sensitive light detector, often a photomultiplier tube (PMT). The photocathode of the PMT, which is situated on the backside of the entrance window, converts the light (photons) into so-called **photoelectrons.** The photoelectrons are then accelerated by an electric field towards the dynodes of the PMT where the multiplication process takes place. The result is that each light pulse (scintillation) produces a charge pulse on the anode of the PMT that can subsequently be detected by other electronic equipment, analyzed or counted with a scaler or a rate meter.

Alternative ways to convert scintillation light into an electrical signal are Silicon photodiodes (PDs) or Silicon Photomultipliers (SiPms). The operation principles and different characteristics of these are discussed in a separate section. The combination of a scintillator and a light detector is called a **scintillation detector**.

Since the intensity of the light pulse emitted by a scintillator is proportional to the energy of the absorbed radiation, the latter can be determined by measuring the pulse height spectrum.

To detect nuclear radiation with a certain efficiency, the dimension of the scintillator should be chosen such that the desired fraction of the radiation is absorbed. For penetrating radiation, such as γ-rays, a material with a high density is required. Furthermore, the light pulses produced somewhere in the scintillator must pass the material to reach the light detector. This imposes constraints on the optical transparency of the scintillation material.

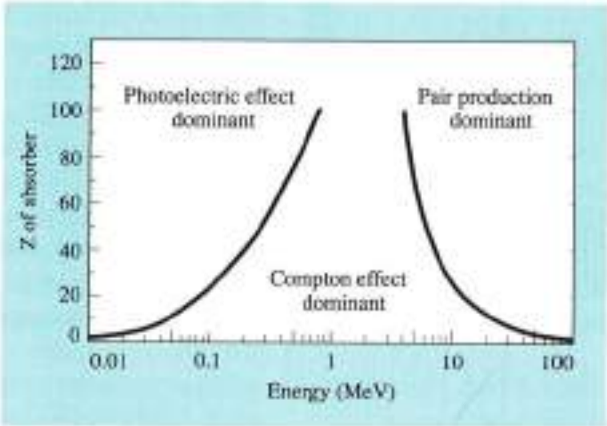
When increasing the diameter of the scintillator, the **solid angle** under which the detector "sees" the source increases. This increases the detection efficiency. The ultimate detection efficiency is obtained with so-called **"well counters"** where the sample is placed inside a well in the actual scintillation crystal.

The **thickness of the scintillator** is the other important factor that determines the detection efficiency. For electromagnetic radiation, the thickness to stop say 90% of the incoming radiation depends on the X-ray or γ-ray energy. For electrons (e.g. β-particles) the same is true but different dependencies apply. For larger particles (e.g. α-particles or heavy ions) a very thin layer of material already stops 100% of the radiation.

The thickness of a scintillator can be used to create a **selected sensitivity** of the detector for a distinct type or energy of radiation. Thin (e.g. 1 mm thick) scintillation crystals have a good sensitivity for low energy X-rays but are almost insensitive to higher energy background radiation. Large volume scintillation crystals with relatively thick entrance windows do not detect low energy X-rays but high energy gamma rays are measured efficiently.

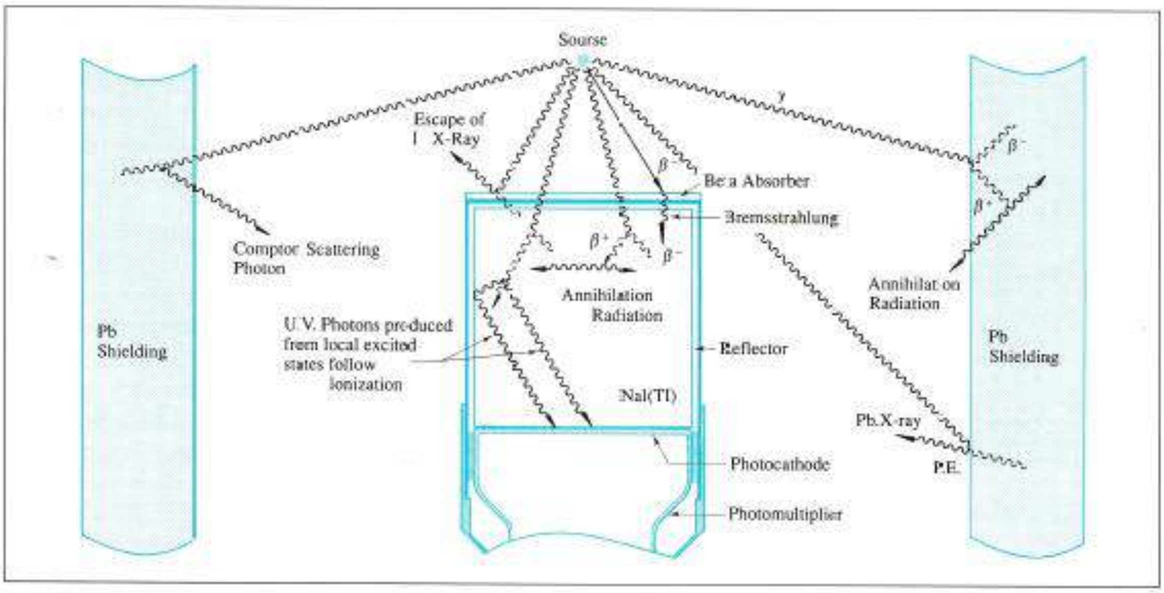
2.2 Interactions in scintillation materials

Electromagnetic radiation can interact with matter via **1. photoelectric effect**, **2. Compton effect** or **3. pair production**. Effect 3 only occurs at energies above 1.02 MeV. In practice, all effects have a chance to occur, this chance being proportional to the energy of the radiation and the atomic number (Z-value) of the absorber (the scintillation material).

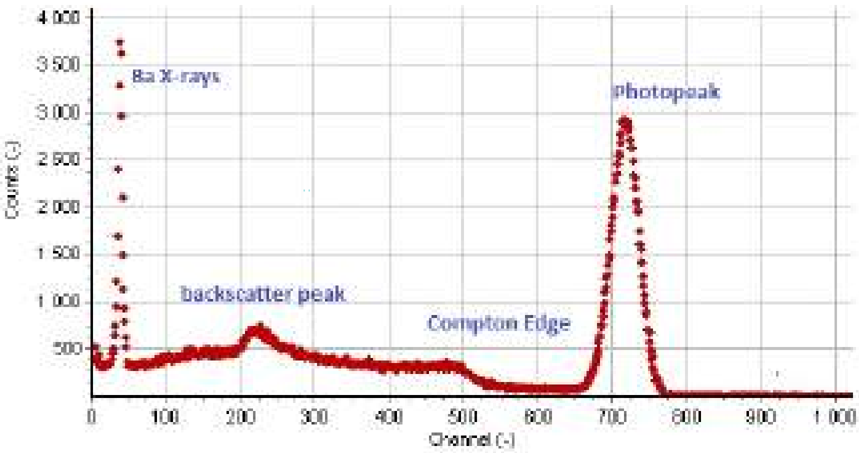


In the Photoelectric effect, all energy of the radiation is converted into light. This effect is important when determining the actual energy of the impinging X-ray or gamma-ray photons. The lower the energy and the higher the Z-value, the larger the chance on photo effect.

In real applications several interaction processes play a role as illustrated below.



Below shows a **typical pulse height spectrum** measured with a 76 mm diameter, 76 mm high NaI(Tl) crystal in which the radiation emitted by a ^{137}Cs source is detected. The photopeak, Compton maximum and backscatter peak are indicated. The lines around 30 keV are Barium X-rays also emitted by the source.

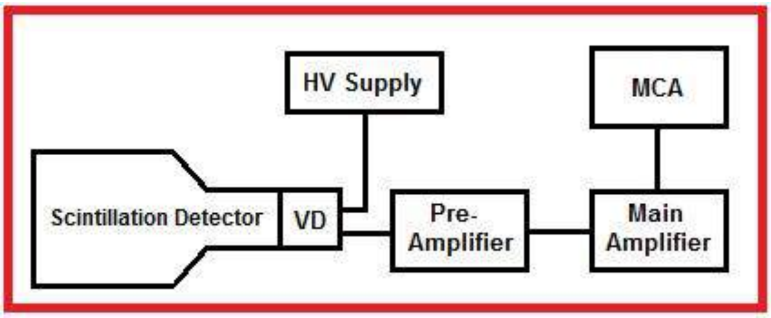


The total **detection efficiency** (counting efficiency) of a scintillator depends on the size, thickness and density of the scintillation material. However, the photopeak counting efficiency, important for e.g. gamma-ray spectroscopy, is a strong function of and increases with the Z^{4-5} of the scintillator. At energies below 100 keV, electromagnetic interactions are dominated by the photoelectric effect.
Electrons (e.g. β-particles) can be **backscattered** from a material which implies that no energy is lost in the interaction process and the particle is not detected at all. The backscattering fraction is proportional to the Z of the material. For NaI(Tl) the backscatter fraction can be as high as 30%! This implies that for efficient detection of electrons, low Z materials such as **plastic scintillators** or e.g. **CaF_2:Eu** or **YAP:Ce** are preferred. Also the window material is of importance.

2.3 Scintillator response to gamma-rays

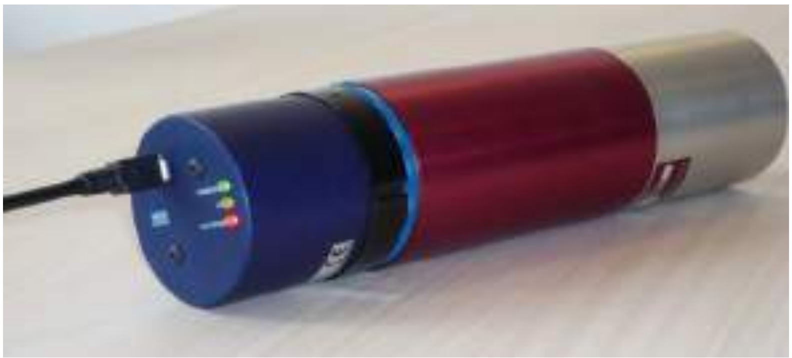
a. Pulse height spectrometry

The basic principle of pulse height spectroscopy is that the light output of a scintillator is proportional to the energy deposited in the scintillation material. The standard way to detect scintillation light is to couple a scintillator to a photomultiplier. Furthermore, a γ-ray spectrometer usually consists of a preamplifier, a main (spectroscopy) amplifier and a multichannel analyzer (MCA). The electronics amplifies the PMT charge pulse resulting in a voltage pulse suited to detect and analyze with the MCA. The schematic is shown below.



Alternatively, currently available digital techniques allow to directly digitize the (pre-amplified) pulses of the light detector (e.g. PMT or SiPm). Often programmable FPGA's are used for this. The optimum digital filtering constant (just as analog shaping time) depends on the speed of the scintillation material.

The combination of a 14 pins scintillation detector and a so-called "digital base" allows to construct a compact gamma spectrometer that can be operated via a USB or Ethernet port of a computer.



b. Energy resolution, proportionality

An important aspect of a γ-ray spectrometer is the ability to discriminate between γ-rays with slightly different energy. This quality is characterized by the so-called **energy resolution** which is defined as the (relative) width at half the height of the photopeak at a certain energy.

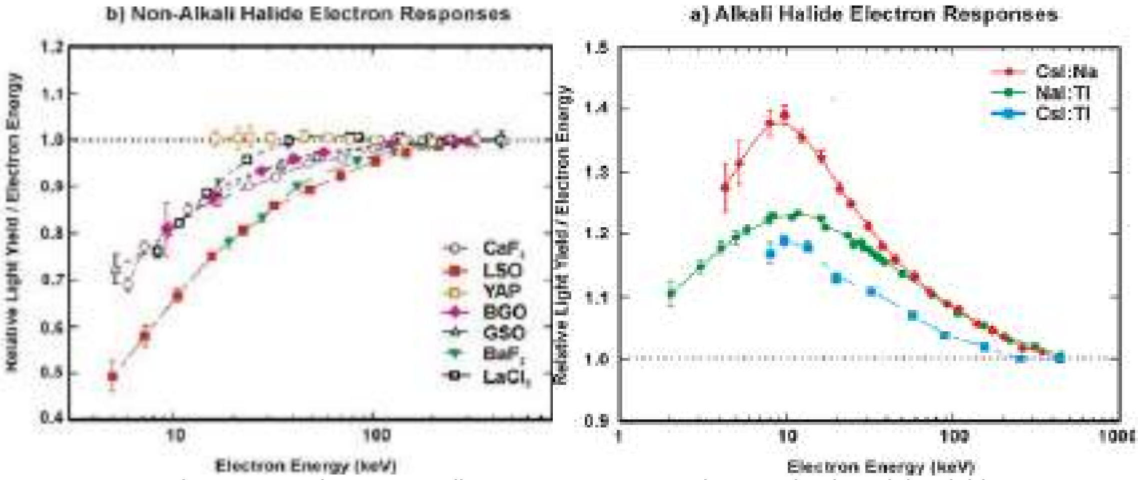
Besides by the γ-ray energy, the energy resolution is influenced by:

- The light output of the scintillator (statistics)
- Inhomogeneities in the scintillator light output and light detector response

At low energies where photoelectron statistics dominate the energy resolution, the energy resolution is roughly inverse proportional to the square root of the γ-ray energy.

In principle, the amount of light a scintillator emits per unit energy as a function of the energy is constant. However this is **not** the physical reality. This so called non-proportionality is vastly different for different scintillators and in the classic alkali halides it provides the limitation of the energy resolution in the MeV energy range. Below the proportionality of some typical scintillation materials is shown.

Gamma ray interaction in materials includes photo-electric effect, Compton effect and pair production. Usually a combination of several of them takes place. Gamma ray interaction in materials results in the production of energetic electrons. A non-proportional electron energy versus light response leads to a broadening of the photopeaks.



Ref. W. Mengesha, T.D. Taulbee, B .D. Rooney, and J.D. Valentine.*Light Yield Nonproportionality of CsI(Tl), CsI(Na), and YAP* IEEE Trans. Nucl. Sci. vol 45, no. 3, (1998) pp. 456–461

Scintillator proportionality is a material constant, different for each material

As such the energy resolution of a scintillator can be described with the formula below:

$$\left(\frac{\Delta E}{E}\right)^2 = \frac{\left(\frac{\Delta E}{E}\right)^2_{sci,intr}}{1} + \frac{\left(\frac{\Delta E}{E}\right)^2_{stat,N}}{2} + \frac{\left(\frac{\Delta E}{E}\right)^2_{PMT,sci}}{3}$$

Term 1 is the proportionality; term 2 the contribution by the statistics (amount of light produced per interaction) and term 3 inhomogeneity effects in for example PMT or scintillator.

The energy resolution of a scintillation detector is a true **detector property**, limited by the physical characteristics of the scintillator and the PMT or other readout device.

A typical energy resolution for 662 keV γ-rays absorbed in small NaI(Tl) detectors is 7.0 % FWHM. At low energies, e.g. at 5.9 keV, a typical value is 40 % FWHM. At these low energies, surface treatment of the scintillation crystal strongly influences the resolution. It may be clear that especially at low energies, scintillation detectors are low resolution devices unlike Si(Li) or HPGe detectors.

The use of more proportional crystals like e.g. $LaBr_3$:Ce, LBC, $CeBr_3$ or SrI_2(Eu) allows to achieve energy resolution numbers at 662 keV gamma rays down to the 3-4 % level. In the section on high resolution crystals more details are provided on proportional scintillation crystals.

c. Time resolution

The time resolution of a scintillation detector reflects the ability to define accurately the moment of absorption of a radiation quantum in the detector.

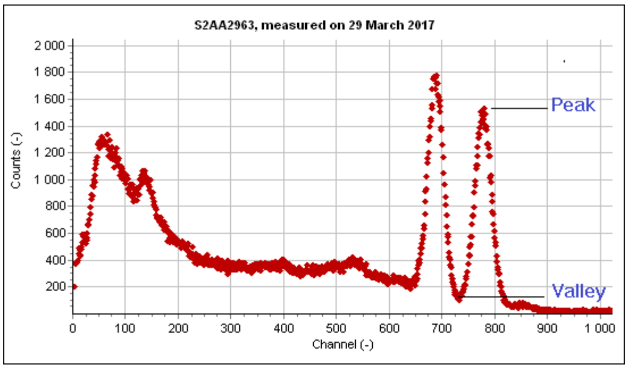
The light pulse of a scintillator is characterized by a rise time and by a 1/e fall time τ (decay time see the section on scintillation properties. It is obvious that the best time definition of an absorption event is obtained when the scintillation pulse is short (small decay time) and intense. Furthermore, the rise time and time jitter (also called transit time spread, TTS) of the PMT and of the electronics are important. For semiconductor readout similar properties apply.

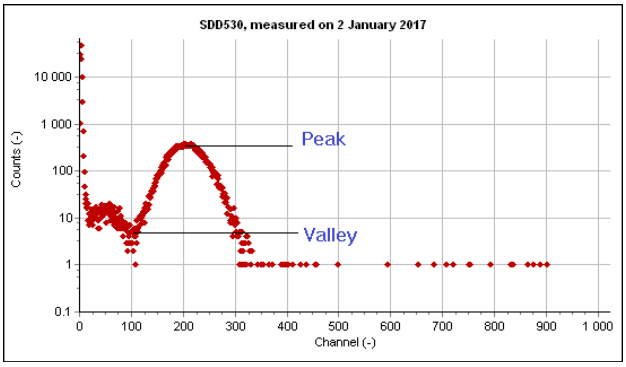
Small cm size NaI(Tl) detectors have typical time resolutions of a few nanoseconds for ^{60}Co (1.2 MeV). Much better time resolutions can be attained with organic - or **BaF_2** scintillation crystals. BaF_2 is presently the fastest known inorganic scintillator with detector time resolutions of a few hundred picoseconds. Also Cerium Bromide ($CeBr_3$) scintillators allow comparable time resolutions.

d. Peak-to-valley ratio

A sensitive way to check the energy resolution of a scintillation detector is to define a so-called peak-to-valley (P/V) in the energy spectrum. This criteria is not depending on any possible offsets in the signal. Either the peak-to-valley between two gamma peaks is taken or the ratio between a low energy peak and the PMT / electronical noise.

A good P/V ratio for a 76 x 76 mm NaI(Tl) crystal is 10:1. This is equivalent to an energy resolution of 7.0% at 662 keV. At 5.9 keV, a high quality NaI(Tl) X-ray detector can have a P/V ratio of 40:1.



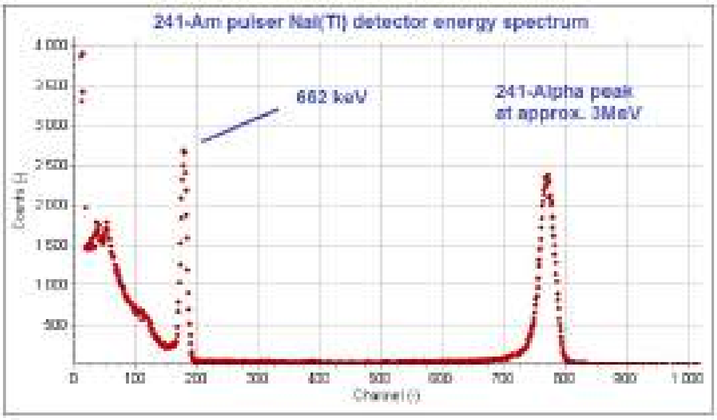


e. Spectrum stabilization

Large count rate changes and temperature variations may cause peak position variations in a spectrum. This effect is unavoidable in scintillation detectors since the light output of the scintillator and light detector amplification is (in most cases) temperature dependent. An additional program in the case of photomultiplier readout is hysteresis and memory effects in PMTs which complicates correction algorithms. In silicon photomultipliers this effect is not present.

To compensate for these effects it is possible to calibrate the peak position with a so-called **Am-pulser**.

This is a very small radioactive ^{241}Am source mounted inside a scintillation detector. The α-particles, emitted by the ^{241}Am, cause scintillations in the crystal that are detected by the PMT (or the photodiode) of the detector. For NaI(Tl), the **α-peak** is situated between a **Gamma Equivalent Energy (GEE)** of 1.5 and 3.5 MeV and can be specified. Count rates are typically 50, 100 or 200 cps. The position of the pulser peak is used as a reference to compensate for the above mentioned variations in detector response.



The above way of calibration is not ideal since the response of most scintillation crystals for γ-rays and α-particles is different. However, a second order compensation using e.g. a thermistor is only necessary for large temperature ranges.

For occasionally monitoring your system integrity, Light Emitting Diodes (LEDs) or laser ports can also be used. LEDs can be mounted inside scintillation detectors or a window for that purpose can be provided. Some special systems exist that intrinsically stabilize gain of the detector by injecting pulsed LED light into the light detector and by comparing it to the signal of a (stable) built-in semiconductor detector.

Besides the above described ways of pulse height stabilization, it is of course also possible to stabilize electronically on the peak of an (always present) external source. Sometimes the ^{40}K background line can be used for this purpose.

2.4 Scintillator interaction with charged particles: α- and β-particle detection

Charged particles such as electrons, muons or charged particles (e.g. α-particles) lose energy through Coulomb interactions with the atomic electrons in the surrounding matter. When selecting a detector for charged particles, the primary consideration is the type of particle to detect.

2.4.1 Weakly penetrating particles

This includes low energy electrons, protons, **α-particles** and heavy ions. The rate of energy loss in matter increases as the charge and mass of the particle increase, but the conversion of particle energy in scintillation light decreases. The number of photons produced by a 5.4 MeV α-particle is only a fraction that produced by a gamma photon with the same energy. This fraction varies per scintillator and the so-called alpha/gamma ratio can vary between roughly 0.1 (organic materials) and 0.8 for some alkali halides. Separate from the emitted energy and the specific scintillator, the energy resolution for particles also depends on the surface treatment of the material.

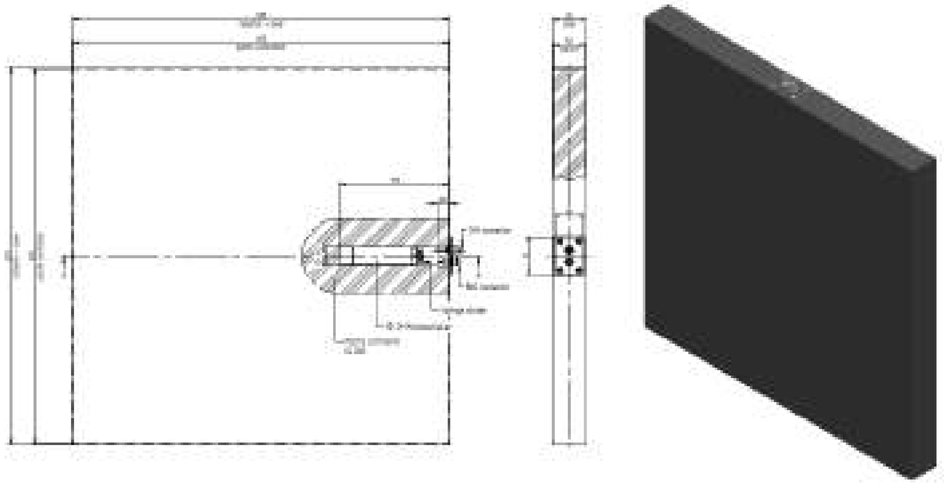
The following aspects should be considered. The entrance window of the detector should be very thin to minimize the energy loss. aluminized mylar windows are normally used. The thickness of mylar windows can vary between 2μm and 100μm. Layers of 2 micron double-sided aluminized mylar are never 100% light-tight.

2.4.2 Minimum ionizing particles

Particles in this group are usually single charged with a low mass and a high energy. Their energy loss per unit path length is small. Common examples of minimum ionizing particles are **cosmic muons and fast electrons**. In a plastic scintillator, minimum ionizing particles lose several MeV per cm material. Applications include calorimetry and electron spectroscopy.

Entrance window material and thickness are usually not that important since the particles normally pass through the window and the entire scintillator.

An example of the detection of muons are so-called "muon suppression shields" built up out of large are plastic scintillators read out by PMTs that can be built inside the plastic scintillator. Since the deposited energies are large small single PMTs are sufficient to discriminate the muon signal above the gamma background. Muons suppression shields are usually custom-made. SCIONIX can offer matching electronics for such applications.



3 Properties and use of scintillation materials

3.1 Scintillator properties

A large number of different scintillation crystals exists for a variety of applications. Some important characteristics of scintillators are:

- 1. Density and atomic number (Z)
- 2. Light output (wavelength + intensity)
- 3. Decay time (duration of the scintillation light pulse)
- 4. Mechanical and optical properties
- 5. Cost

1. Density & Atomic number

It is clear that for an efficient detection of γ-rays, a material with a **high density and high effective Z (number of protons per atom)** is required (see above). Inorganic scintillation crystals meet the requirements of stopping power and optical transparency, their densities ranging from roughly 3 to 9 g/cm^3 makes them very suitable to absorb penetrating radiation (γ-rays). Materials with high Z-values are used for γ-ray spectroscopy at high energies (> 1 MeV).

2. Light output

Since photoelectron statistics (or electron-hole pair statistics) plays a key role in the accurate determination of the energy of the radiation, the use of scintillation materials with a **high light output** is preferred for all spectroscopic applications. The scintillator emission wavelength should be matched to the sensitivity of the light detection device that is used (PM, SiPm or photodiode).

3. Decay time

Scintillation light pulses (flashes) are usually characterized by a fast increase of the intensity in time (pulse rise time) followed by an exponential decrease. The **decay time** of a scintillator is defined by the time after which the intensity of the light pulse has returned to 1/e of its maximum value. Most scintillators are characterized by more than one decay time and usually, the effective average decay time is mentioned. The decay time is of importance for fast counting and / or timing applications.

4. Mechanical, optical and scintillation properties

The most widely used scintillation material for gamma-ray spectroscopy NaI(Tl) is hygroscopic and is only used in hermetically sealed metal containers to preserve its properties. All water soluble scintillation materials should be packaged in such a way that they are not attacked by moisture. Some scintillation crystals may easily crack or cleave under mechanical pressure whereas others are plastic and only will deform like CsI(Tl).

Physical properties of the most common scintillation materials

Material	Density (g/cm^3)	Emission Maximum (nm)	Decay Constant (1)	Refractive Index (2)	Conversion Efficiency (3)	Hygroscopic
NaI(Tl)	3.67	415	0,23 µs	1.85	100	yes
CsI(Tl)	4.51	550	0,6/3.4 µs	1.79	45	slightly
CsI(Na)	4.51	420	0.63 µs	1.84	85	yes
CsI(Undoped)	4.51	315	16 ns	1.95	4-6	no
Cs_2LiYCl_6:Ce (CLYC)	3.31	275-450 nm	1,50,1000 ns	1.81	30-40	yes
CaF_2(Eu)	3.18	435	0.84 µs	1.47	50	no
$LaCl_3$:Ce(0.9)	3.79	350	70 ns	1.90	95-100	yes
SrI_2(Eu)	4.60	450	1-5 µs	1.85	120-140	yes
$LaBr_{2.85}Cl_{0.15}$:Ce (LBC)	4.90	380	35 ns	1.90	140	yes
^{6}Li-glass	2.6	390/430	60 ns	1.56	4-6	no
^{6}Li(Eu)	4.08	470	1.4 µs	1.96	35	yes
BaF_2	4.88	315 220	0.63 µs/ 0.8 ns	150 1.54	16 5	no
$CeBr_3$	5.23	370	18 ns	1.9	130	yes
YAP(Ce)	5.55	350	27 ns	1.94	35-40	no
LYSO:Ce	7.20	420	50 ns	1.82	70-80	no
BGO	7.13	480	0.3 µs	2.15	15-20	no
$CdWO_4$	7.90	470/540	20/5 µs	2.3	25-30	no
$PbWO_4$	8.28	420	7 ns	2.16	0.20	no
Plastics(*)	1.023	375-600	ns range	1.58	25-30	no

(1) Effective average decay time for γ-rays.
(2) At the wavelength of the emission maximum
(3) Relative scintillation signal at room temperature for γ-rays when coupled to a photomultiplier tube with a bi-alkali photocathode.
(*) approximate data

In the table, the most important aspects of commonly used scintillation materials are listed. The list is not extensive and new materials are developed regularly.

Each scintillation crystal has its own specific application. For high resolution γ-ray spectroscopy, NaI(Tl), or $CeBr_3$ (high light output) are often used. For high energy physics applications, the use of bismuth germanate $Bi_4Ge_3O_{12}$ (BGO) crystals (high density and Z) or Lead Tungstate ($PbWO_4$) improves the lateral confinement of the shower. For the detection of β-particles, CaF_2(Eu) or YAP:Ce can be used instead of plastic scintillators (higher density).

Scintillation materials and their most common applications

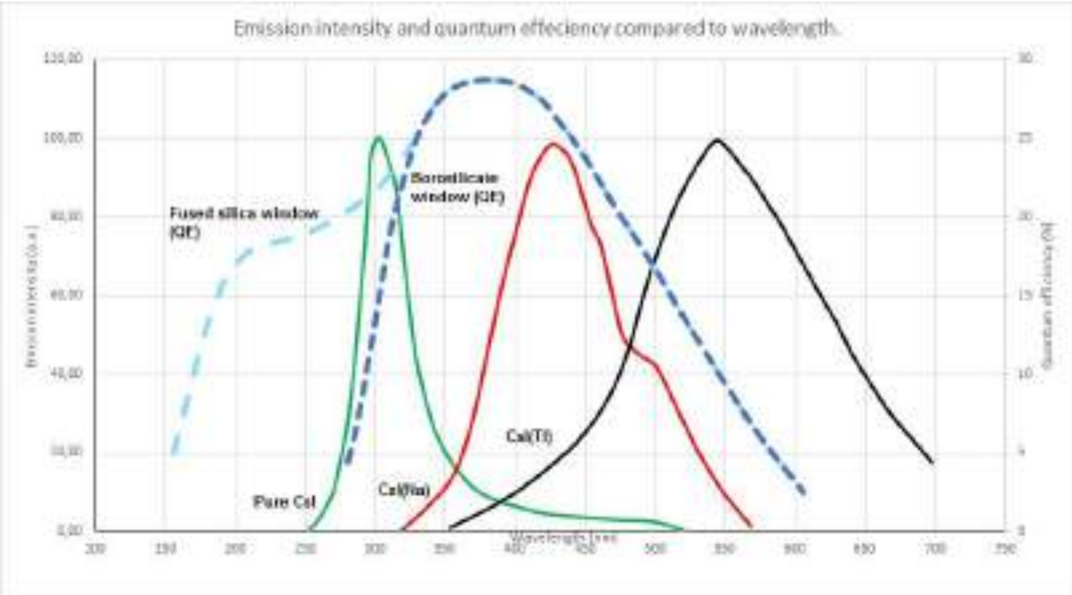
Material	Important Properties	Major Application
NaI(Tl)	Very high light output, good energy resolution	General scintillation counting, Health Physics, environmental monitoring, high temperature use
CsI(Tl)	Non-hygroscopic, rugged	Particle and high energy physics, general radiation detection, photo diode readout,
CsI(Na)	High light output, rugged	Geophysical, general radiation detection
CsI(undoped)	Fast, non-hygroscopic	Physics (calorimetry)
CaF_2(Eu)	Low Z, high light output	β detectors, α/β phoswiches
Cs2LiYCl6:Ce (CLYC)	Neutron detection capability High resolution	Nuclear identifiers, Physics
$LaCl_3$:Ce(0.9)	Very high light output, very good energy resolution	High resolution scintillation spectroscopy, Health Physics environmental monitoring
$CeBr_3$	Very high light output, very good energy resolution, low background	High resolution spectroscopy, low background applications
^{6}LiI(Eu)	High neutron cross-section, high light output	Thermal neutron detection and spectroscopy
$LaBr_{2.85}Cl_{0.15}$: Ce (LBC)	Bright, high resolution scintillator (La-138 background)	High resolution gamma spectroscopy
SrI_2(Eu)	Bright, high resolution scintillator	High resolution gamma Spectroscopy
^{6}Li-glass	High neutron cross section, non-hygroscopic	Physics, security
BaF_2	Ultra-fast sub-ns UV emission	Thermal neutral detection
YAP(Ce)	High light output, low Z, fast	Positron life time studies, physics, fast timing
LYSO	High density and Z, fast	MHz-X-ray spectroscopy, synchrotron physics
BGO	High density and Z	Physics research, PET, High Energy Physics
$CdWO_4$	Very high density, low afterglow Slow decay times	Particle physics, geophysical research PET, anti-Compton spectrometers.
$PbWO_4$	Fast, high density, low afterglow	DC measurement of X-rays (high intensity), readout with photodiodes, Computerized Tomography (CT)
Plastics	Fast, low density and Z high light output	Physics research (calorimetry) General counting, particle and neutron detection.

NaI(Tl) scintillation crystals are used in a great number of standard applications for detection of γ-radiation because of their high light output and the excellent match of the emission spectrum to the sensitivity of photomultiplier tubes, resulting in a good energy resolution. In addition NaI(Tl) is a relatively inexpensive scintillator. NaI(Tl) crystals show a distinct non proportionality (see below) which results in a limitation of the energy resolution at 662 keV to about 6% FWHM. NaI(Tl) crystals can be grown to large dimensions (400 mm diameter) in ingots of many hundreds of kg. The material can be cut in a great variety of sizes and shapes and cleaved in small diameters.

CsI(Tl) has the advantage that it is not really hygroscopic (its surface however is influenced by humidity on the long term), and does not cleave or crack under stress. It is a relatively bright scintillator but its emission is located above 500 nm where PMTs are not that sensitive. However due to this property it can effectively be read out by silicon photodiodes or SiPms. Thanks to its different decay times for charged particles having a different ionizing power, CsI(Tl) crystals are frequently used in arrays or matrices in particle physics research.

CsI(Na) is a hygroscopic high light output rugged scintillator like CsI(Tl) mainly used for applications where mechanical stability and good energy resolution are required. Below 120^{o} C it is an alternative to NaI(Tl). CsI(Na) has its emission peaking at 400 nm like NaI(Tl).

Undoped (pure) CsI is an intrinsic scintillator with same density and Z as CsI(Na). It has an emission at approx. 300 nm and since its intensity is strongly thermally quenched at room temperature it is relatively fast (ns decay time). There is a slow component present in this crystal that makes up at least 10% of the total light yield. The emission spectra below show how the emission spectrum of a scintillator can be influenced by its type of activation.

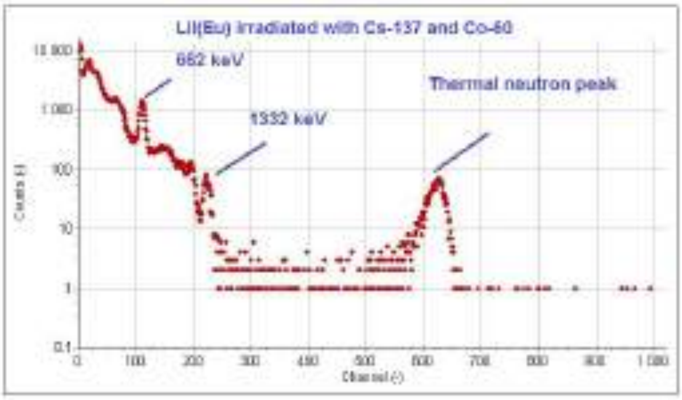


CaF_2(Eu), Europium doped calcium fluoride is a rather old low density scintillation crystal. Thanks to its low Z value it is well suited for the detection of electrons (beta particles) with a high efficiency (low backscatter fraction). CaF_2(Eu) is a relatively slow scintillator that is not hygroscopic and inert to many chemicals. It is brittle and cleaves relatively easy.

^{6}LiI(Eu) is used for the detection of thermal neutrons via the reaction

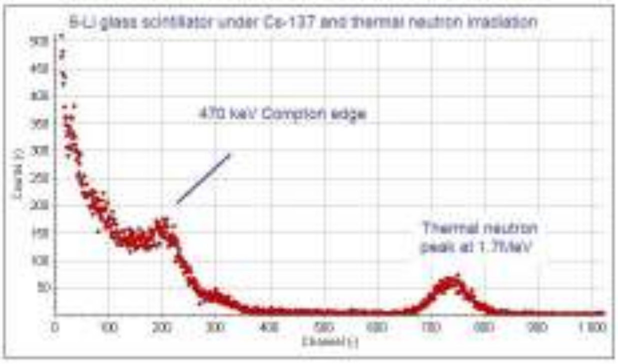
$$ {}^{6}_{3}Li + {}^{1}_{0}n \rightarrow {}^{4}_{2}He + {}^{3}_{1}H + Q \; (Q = 4.78 MeV) $$

The total Q-value of the alpha and the triton is 4.78 MeV. The resulting thermal neutron peak can be found at a Gamma Equivalent Energy larger than 3 MeV. This allows to separate neutron interactions from gamma events (< 2.6 MeV). Since the typical absorption length (90%) of thermal neutrons in 6-LiI(Eu) crystals is only 3 mm the efficiency for gamma rays can be made small. LiI(Eu) crystals are grown up to 25 mm in diameter.



6-Li glass scintillators offer the same possibility as 6LiI(Eu) crystals to detect thermal neutrons. However, the light output is much lower than of LiI(Eu) scintillators and therefore the neutron peaks are relative broad. In addition the scintillation efficiency for the resulting particles is low so that the neutron peak appears at a location of approximately 1.6 MeV in the gamma energy spectrum. 90% of thermal neutrons are absorbed in only 1 mm of material.

All 6-Li containing scintillators can also be used for the detection of fast neutrons but the efficiency of the nuclear reaction is smaller.



Further details on neutron detection can be found in the application note “neutron detection with scintillators”.

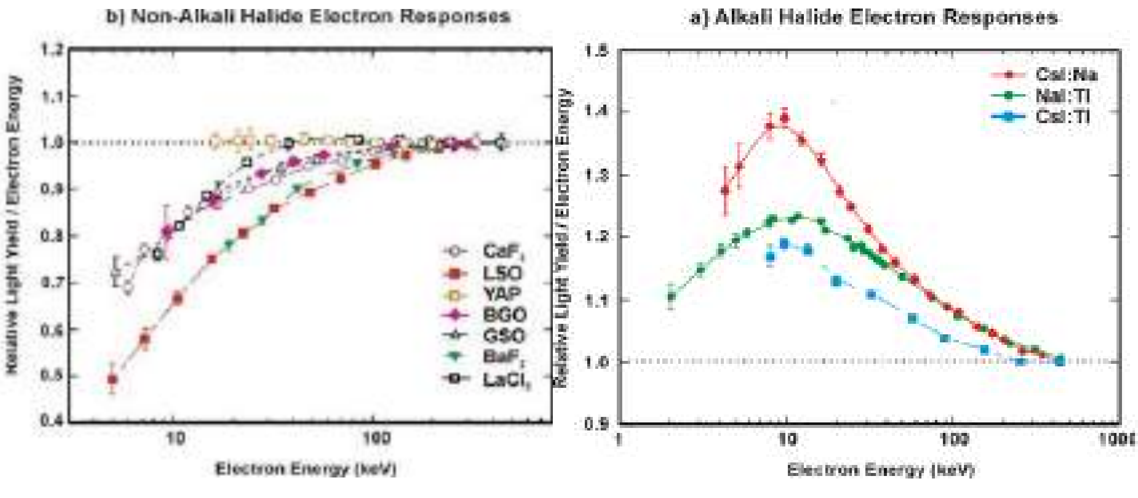
Barium Fluoride (BaF_2) is a non-hygroscopic scintillator with a very fast decay component located at 220 nm. To detect this component, light detectors with quartz windows are used. Barium Fluoride detectors allow fast sub-nanosecond timing for example for positron life time measurements. It is a weak scintillator with a modest energy resolution at 662 keV (typically about 10-12 % FWHM @ 662 keV.

BGO ($Bi_4Ge_3O_{12}$) has the extreme high density of 7.13 g/cm^3 and has a high Z value which makes these crystals very suited for the detection of **natural radioactivity** (U, Th, K), for high energy physics applications (high photo fraction) or in compact Compton suppression spectrometers. Since the light output of BGO is modest, the energy resolution is inferior to that of the standard alkali halides like NaI(Tl) or CsI(Tl).

YAP:Ce ($YAlO_3$:Ce) is a high density (5.5 g/cm^3) oxide crystal with a decay time about 10 times shorter than NaI(Tl) (23 ns) It is used in detectors for high count rate (up to several MHz) The non-hygroscopic nature of this material allows the use of thin mylar entrance windows. YAP:Ce can withstand gamma doses up to 10^4 Gray.

3.2 High resolution (proportional) scintillators

Currently there is an increased better understanding of the properties of scintillators and what determines their intrinsic energy resolution. A number of materials have been developed that exhibits a more proportional response to gamma rays than the classic alkali halides (NaI(Tl), CsI(Tl) etc). This has resulted in the availability of a class of proportional scintillators. New materials are being developed constantly and the list below is not extensive.
Bright proportional scintillator scan have energy resolutions around 3-4 % at 662 keV gamma rays under optimum light detection conditions. Just as other scintillators each have some advantages and disadvantages. Some typical proportionality curves are shown below.

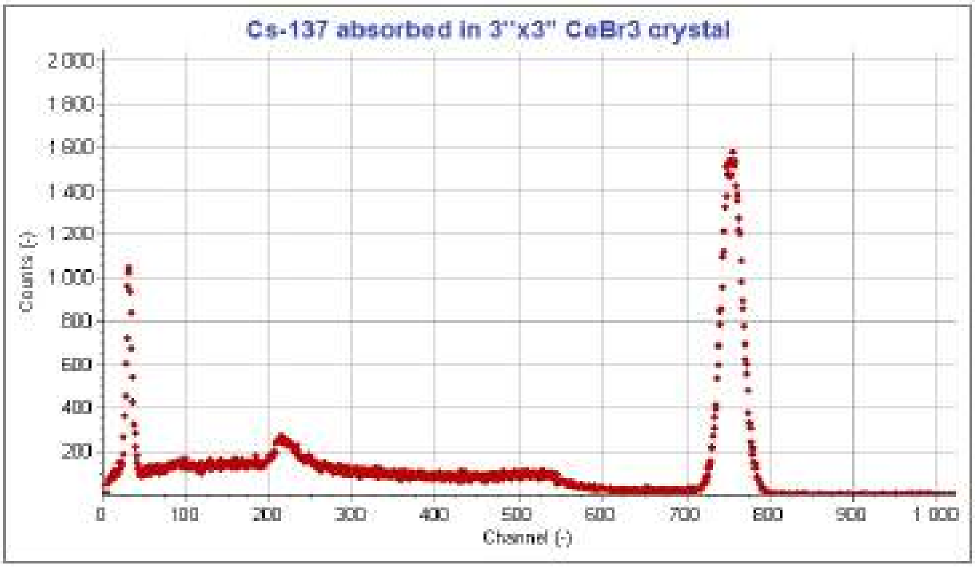


Ref. W. Mengesha, T.D. Taulbee, B .D. Rooney, and J.D. Valentine.*Light Yield Nonproportionality of CsI(Tl), CsI(Na), and YAP* IEEE Trans. Nucl. Sci. vol 45, no. 3, (1998) pp. 456–461

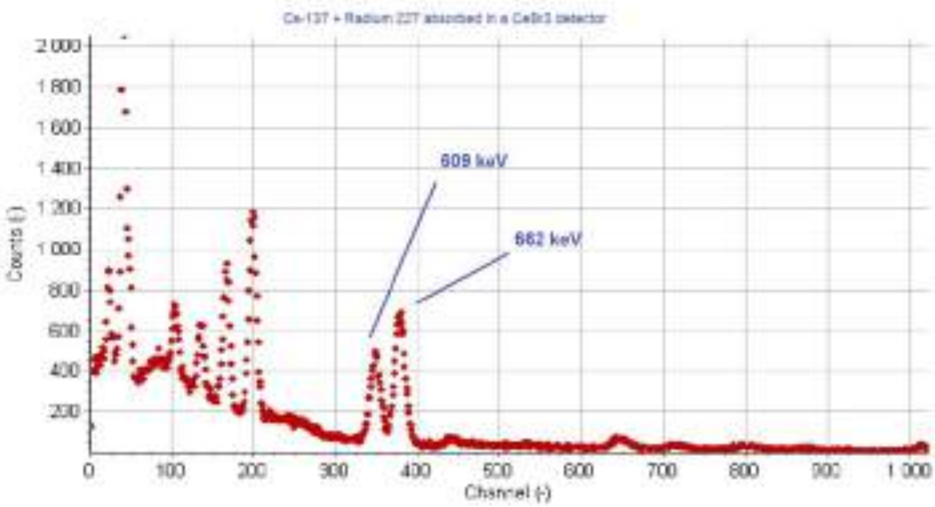
Proportional scintillators only offer their superior performance in energy resolution when the light detection is optimized by covering the largest possible area with light detector (PMT or SiPm).

LBC (Lanthanum BromoChloride) $LaBr_{2.85}Cl_{0.15}$:Ce scintillators have similar properties to the well-known $LaBr_3$:Ce crystals. Energy resolutions around 3.0% FWHM (662 keV) are standard and the material is mechanically a little stronger than $LaBr_3$. LBC crystals suffer from the same La-138 background as $LaBr_3$

$CeBr_3$ (Cerium Bromide) scintillators are characterized by a relatively high density and Z and a proportional response to gamma rays. Typical energy resolutions are 4% FWHM for 662 keV.



The material exhibits a fast decay of typical 20 ns (for 51 mm crystals) with a negligible afterglow. $CeBr_3$ is highly hygroscopic and provides the best performance when integrally coupled to PMTs. Thanks to its fast light pulse rise time, $CeBr_3$ detectors can provide sub nanosecond time resolutions, slightly worse than BaF_2 detectors. With $CeBr_3$ scintillators the 609 and 662 keV gamma lines from respectively radium and Cs-137 can easily be separated.



Cs_2LiYCl_6:Ce (CLYC) scintillation crystals offer a reasonable density of 3.3 g/cc. This proportional crystal offers an energy resolution of 4.5 - 5 % FWHM for 662 keV gamma rays. The thermal neutron peak due to the n-^{6}Li reaction produces a narrow peak at approximately 3.3 MeV. Its fast scintillation component is not excited by neutrons which opens PSD capabilities to further improve the neutron/gamma separation. CLYC has some slower emission components so larger signal shaping times are required. To absorb 90% of thermal neutron 12.5 mm of crystal is needed.

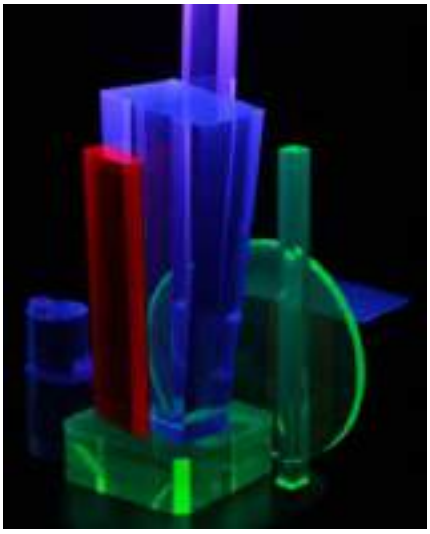
SrI_2(Eu), Europium doped strontium iodide is a very bright relatively slow scintillator with a very good proportionality. Typical energy resolutions are 3.5% @ 662 keV and 6% @ 122 keV. The material is quite radiopure. Due to its intrinsic self-absorption (small stokes shift), the crystal requires some special surface preparation techniques. The long decay time requires very long (digital) shaping time constants (> 10 µs) which complicates high count rate behavior. The self-absorption limits the maximum size of the crystal to approx. 4 cm.

3.3 Organic (plastic) scintillators

Organic scintillators (also called "plastic scintillators") consist of a transparent host material (a plastic) doped with a scintillating organic molecule (e.g. POPOP: p-bis [2-(5-phenyloxazolyl)] benzene). Radiation is absorbed by the host material, mostly via Compton effect because of the low density and Z value of organic materials. Therefore, plastic scintillators are mostly used for the either detection of β- and other particles or when very large volumes are needed since their material cost is relatively low.

Plastic scintillators are mainly used when large detector volumes are required e.g. in security or health physics applications. The cost of plastic scintillation detectors (per volume) is much smaller than that of e.g. NaI(Tl) detectors; plastic scintillators can be manufactured in several meter long slabs.

There exists a **large number of different organic scintillators** each with specific properties. The materials listed on the SCIONIX web site are a direct copy of the ELJEN website. SCIONIX is the European representative of ELJEN Technology.

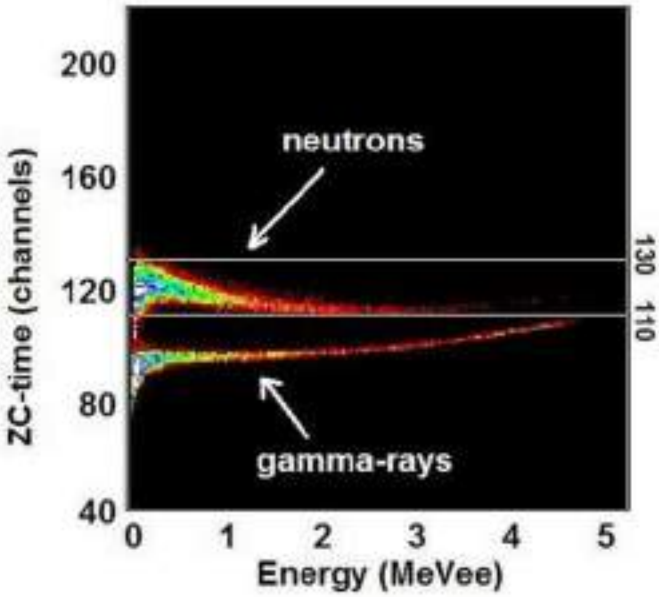


Organic scintillators can be doped with specific atoms like **6-Lithium** (EJ-270) or Boron (EJ-254) to make them neutron sensitive or with Pb (EJ-256) to improve the response at lower energies (tissue equivalent). This influences the scintillation properties.

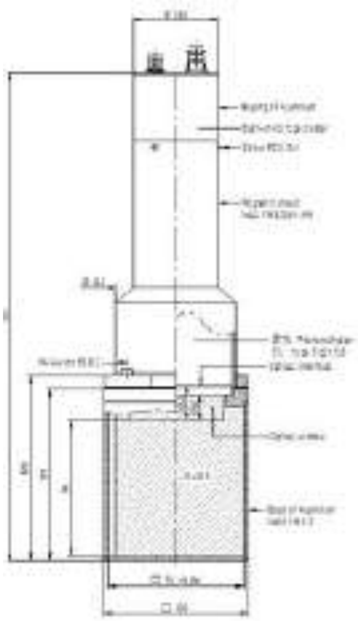
Also, plastic scintillators exist that can be used to **discriminate gammas from fast neutrons** via pulse shape analysis which is used in physics research and in some security applications. An example is EJ-276 (successor of EJ-299-33). See the datasheet on these materials.

3.4 Liquid scintillators

Also doped liquids are used as scintillators. Some liquid scintillators like E-J301 or EJ-309 offer fast neutron/ gamma discrimination properties based on their scintillation pulse shape. Using proper electronic techniques (digitizers), neutron pulses can be discriminated from gammas



Liquid scintillation detectors need provisions to allow expansion of the liquids under temperature variations. For further information see the technical datasheet of liquid scintillators.



3.5 Afterglow

To detect fast changes in transmitted intensity of X-ray beams, as e.g. in CT scanners or luggage X-ray detectors, crystals are required exhibiting low afterglow. Afterglow is defined as the fraction of scintillation light still present for a certain time after the X-ray excitation stops. Afterglow originates from the presence of millisecond to even hour long decay time components. Afterglow in most halide scintillation crystals can be as high as a 5-10 percent after 3 ms. The long duration afterglow in e.g. CsI(Tl) can be a problem for many applications. Afterglow in halides is believed to be intrinsic and correlated to certain lattice defects. BGO, $CeBr_3$ and Cadmium Tungstate ($CdWO_4$) crystals are examples of low afterglow scintillation materials.

4 Thermal Neutron detection

Neutrons do not produce ionization directly in scintillation crystals, but can be detected through their interaction with the nuclei of a suitable element. In a ^{6}LiI(Eu) scintillation crystal for example, neutrons interact with ^{6}Li nuclei to produce an alpha particle and a triton (tritium nucleus), which both produce scintillation light that can be detected. Another Li containing scintillator is the above mentioned CLYC.
Also enriched ^{6}Li containing glasses can be used, doped with Ce as activator. Alternatively, Boron or Gadolinium containing inorganic scintillators can be used but these scintillators are not common.

Al alternative technique to construct large area thermal neutron detectors is via ^{6}LiF/ZnS(Ag) screens called EJ-426, read out via green wavelength shifters by PMTs or SiPms. For more information see the datasheet on these materials.

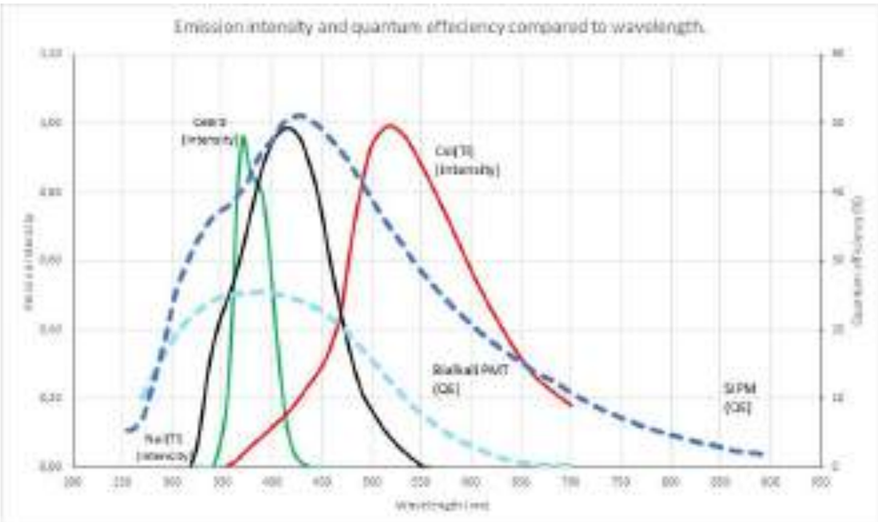
5 Radiation damage

Radiation damage is defined as the change in scintillation characteristics caused by prolonged exposure to intense radiation. This damage manifests itself by a decrease of the optical transmission of a crystal which causes a decrease in pulse height and deterioration of the energy resolution of the detector. Radiation damage other than radio-activation is usually partially reversible; i.e. the absorption bands often disappear slowly in time; some damage can be annealed thermally.

In general, doped alkali halide scintillators such as NaI(Tl) and CsI(Tl) are rather susceptible to radiation damage. All known scintillation materials show more or less damage when exposing them to large radiation doses. The effects usually can only be observed clearly with thick (> 5 cm) crystals. A material is usually called radiation hard if no measurable effects occur at a dose of 10.000 Gray. Examples of radiation hard materials are $CeBr_3$ and YAP:Ce.

6 Emission spectra of scintillation crystals

Each scintillation material has a characteristic emission spectrum. The shape of this emission spectrum is sometimes dependent on the type of excitation (photons / particles).



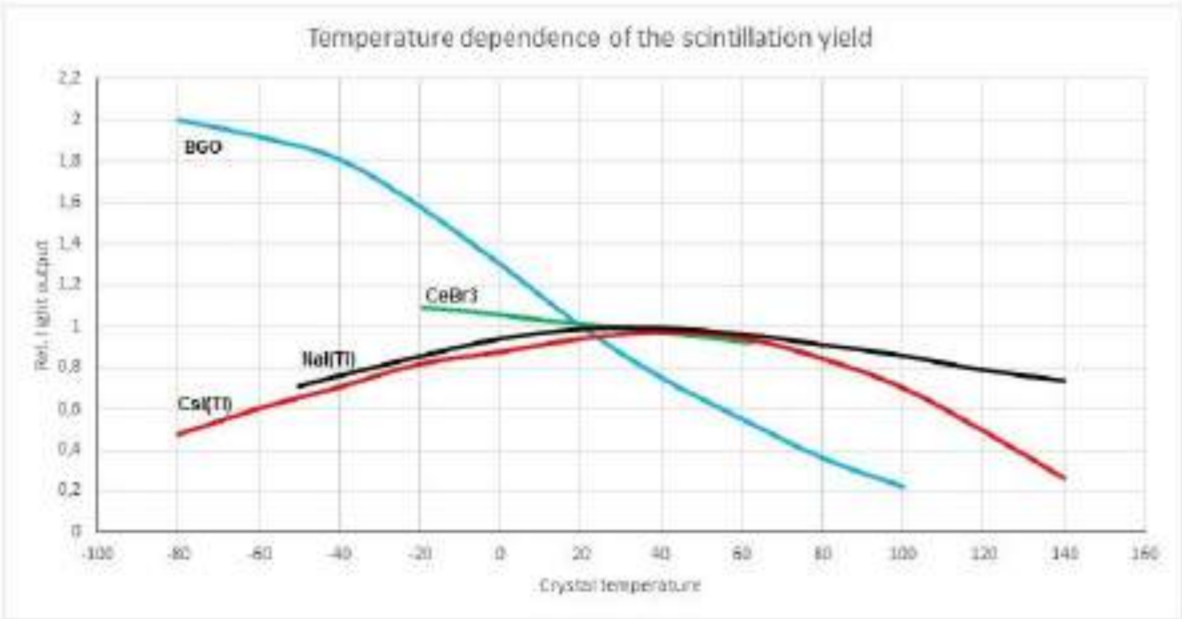
Emission spectra of NaI(Tl), CsI(Tl) and CeBr3, scaled on maximum emission intensity. Also a typical quantum efficiency curve of a bialkali photocathode and a Silicon Photomultiplier (SiPm) is shown.

This emission spectrum is of importance when choosing the optimum readout device (PMT / photodiode/SiPm) and the required window material. The graph shows the emission spectrum of some common scintillation materials.

7 Temperature influence on the scintillation response.

The light output (number of photons per MeV gamma) of most scintillators is a function of temperature. This is caused by the fact that in scintillation crystals, radiative transitions, responsible for the production of scintillation light, compete with non-radiative transitions (no light production). In most scintillation crystals, the light output is quenched (decreased) at higher temperatures. An example of the contrary is the fast component of BaF_2 of which the emission intensity is essentially temperature independent.

The scintillation process usually involves as well production, transport and quenching centers. Competition between these three processes each behaving differently with temperature, causes a complex temperature dependence of the scintillation light output. Below the temperature dependence of some common scintillation crystals is shown.



Temperature dependence of the scintillation yield of NaI(Tl), CsI(Tl), BGO and $CeBr_3$

For most applications, the combination of the temperature dependent light output of the scintillator together with the temperature dependent amplification of the light detector should be considered.

The doped scintillators NaI(Tl), CsI(Tl) and CsI(Na) show a distinct maximum in intensity whereas many undoped scintillators such as BGO show an increase in intensity with decreasing temperature. The temperature dependence of the Ce doped scintillators LBC, $CeBr_3$ and YAP:Ce is significantly less than that of other scintillators.

8 Which scintillator for your application?

When we observe the physical property table carefully, it is clear that none of presently known scintillation crystals possesses **all the ideal characteristics** such as high density, fast decay, low cost etc. The choice of a certain scintillation crystal in a radiation detector depends strongly on the **application**. Questions such as:

1. - What is the energy and type of the radiation to measure?

2. - What is the expected count rate?

3. - What are the experimental conditions (temperature, shock)?

4. - Can the scintillator be grown in the required size? and

5 - What is its cost?

are very important in this respect to determine the optimum choice.

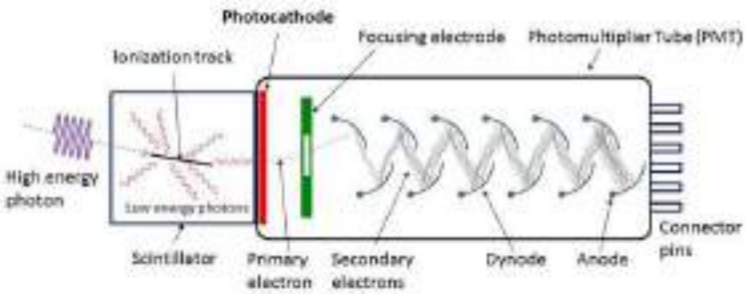
SCIONIX will be happy to assist you in making the best, most cost effective decision for your application.

9 Scintillation light detection devices

The light emitted by a scintillation material must be detected using some kind of sensitive light detection device. There are several options:

9.1 Photomultiplier Tubes (PMTs)

Light (photons) are converted into **photoelectrons** by absorbing them in a thin photocathode layer inside a (glass) vacuum tube. Most often a photocathode is semi-transparent and usually consist of a thin layer of evaporated Cs, Sb, and K atoms or a mixture of them. Each photoelectron is pulled by an electric field towards a dynode and subsequently amplified. In a 10 stage PMT, the net amplification is of the order of 5. 10^5. Each scintillation pulse produces a charge pulse at the anode of the PMT.
The process is illustrated below.



Besides in the above described pulse mode, PMTs can also be operated in **current mode** in which case the anode current is a measure for the radiation intensity absorbed in the scintillator. This can only be done when the photocathode is at negative potential. This allows to operate a scintillation detector is high radiation fields. The disadvantage is **that all spectroscopic information is lost.**

The energy resolution, coincident resolving time and stability of a scintillation detector depend to a great extent upon the type of photomultiplier tube. The selection of a proper type is fundamental to a good detector design.

The light conversion efficiency of a photomultiplier cathode is a function of the wavelength; the **Quantum Efficiency (Q.E.)** is defined as the chance that one photon produces one photoelectron. In the amplification process, one photoelectron produces per dynode step about 3 - 4 secondary electrons. With a 12 stage PMT, a typical gain in the order of 10^6 can be obtained. Fig.1 below shows a schematic of a PMT. It should be noted that PMTs are sensitive to magnetic fields; a μ-metal shield provides adequate protection from the earth magnetic field. For operation in high magnetic fields, special PMTs are available.

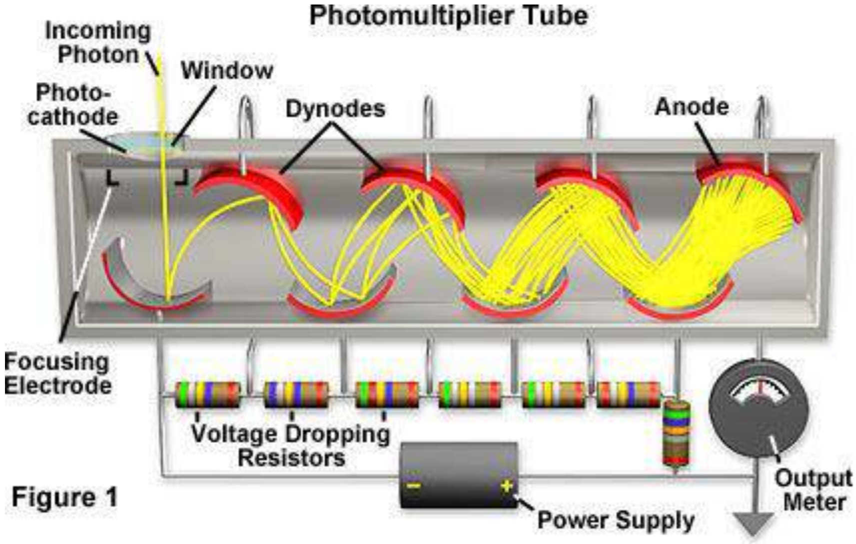


Figure 1

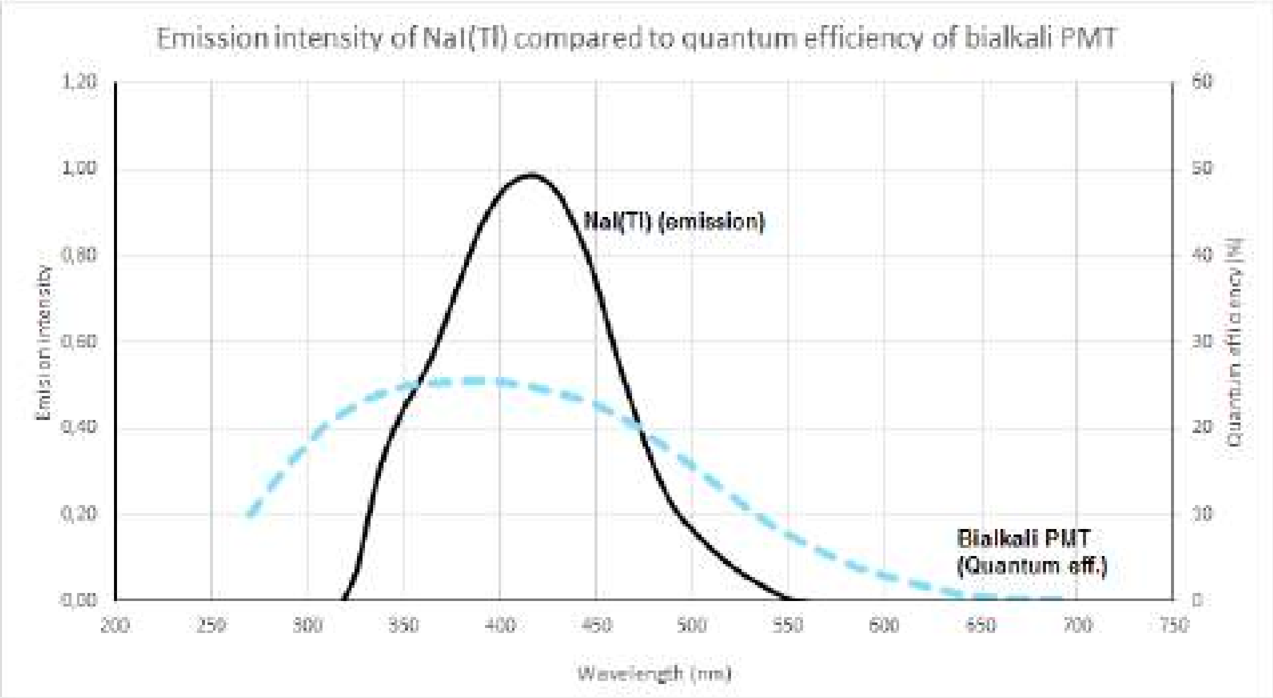
There exist a number of PMT dynode structures, each with their typical characteristics. Important PMT parameters are:

- Amplification as a function of voltage
- Dark current
- Pulse rise time
- Physical size
- Gain stability
- Radiological background

Gain, stability and dark current depend on the used dynode materials and are a function of temperature. Pulse rise time depends on the dynode structure. For fast timing applications, so called **"linear focused"** PMTs are advised.

A very important factor is the sensitivity as a function of the position on the PMT entrance window. A large variation can cause a degradation of the energy resolution of a scintillation detector. This variation can be caused by a change in quantum efficiency of the photocathode or a non-uniform photoelectron collection efficiency from the cathode onto the first dynode. The above effects can be important for both small and large diameter PMTs.

From the scintillation properties table is clear that each type of scintillator has a different emission spectrum. It is important for a good performance that the emission spectrum of a scintillator is well matched to the quantum efficiency curve (for definition see above) of the PMT. To detect the fast scintillation component of BaF_2 for example, it is necessary to use a PMT with quartz window since glass absorbs all light below 280 nm. The figure below shows the quantum efficiency (Q.E.) of a standard PMT with a bi-alkali photocathode. The emission spectrum of the most common scintillator NaI(Tl) is shown too. It can be seen that the overlap is very good. For other scintillation materials such as BGO, the match is less ideal.



Quantum efficiency curve of a bialkali photocathode together with the scintillation emission spectrum of NaI(Tl).

The gain of a PMT is temperature sensitive. The variation in gain, which depends on the photocathode and dynode material, amounts to typically 0.2 - 0.3 % per ^{o}C.

Due to their dynode stages, PMTs are usually quite bulky devices although some short versions and miniature types have been developed.

Care must be taken when PMTs are used inside **magnetic fields**. Although there are PMT types that have a high magnetic field immunity, this effect remains a problem.

The material of a PMT is usually glass. Glass has an intrinsic amount of ^{40}K which contributes to the **radiological background** of the scintillation detector. ^{40}K emits as well 1460 keV gamma rays as β-particles. The face-plate of the PMT can be constructed of special low-K glass. Furthermore, this background can be limited by using light guides absorbing the β-particles and creating a distance between the crystal and the PMT. The above techniques are used in so-called **"low background"** scintillation detectors.

Below we would like to summarize the advantages and disadvantages of PMTs in conjunction with scintillation crystals:

Photomultiplier Tubes

Advantages:

- Standard device
- Large signals
- Large active areas possible
- Fast rise times possible

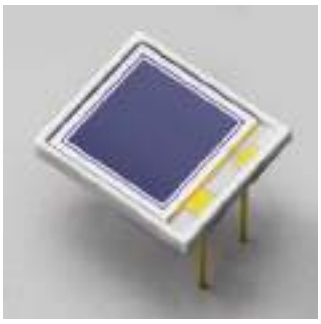
Disadvantages:

- Large physical dimension
- High Voltage (typical 700 V) required
- Gain instability as function of temperature
- Sensitive to magnetic fields
- Background radiation

For more information regarding PMTs we refer to the PMT manufacturer's literature.

9.2 Photodiodes

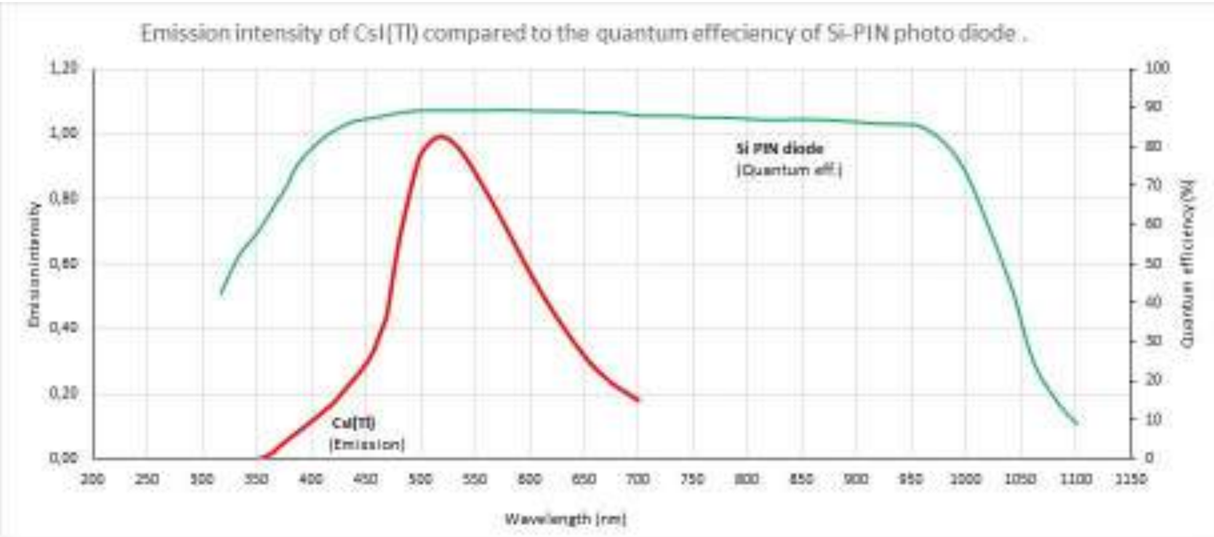
In a photodiode, the scintillation photons produce electron-hole pairs that are collected at respectively the anode and the cathode of the diode. Most frequently, reverse biased PIN photodiodes are used having a low capacitance and low leakage current.



When photodiodes are optically coupled to a scintillation crystal, each scintillation light pulse will generate a small **charge pulse** in the diode which can be measured with a charge sensitive preamplifier. Alternatively, the **current** produced in the diode can be measured.

The quantum efficiency of silicon photodiodes is typically 70% between 500 and 900 nm but decreases rapidly below 500 nm as shown in the figure below. It is clear that the highest signals can be expected from scintillation crystals that have an intense emission above 500 nm. CsI(Tl), characterized by a large scintillation intensity with a maximum at 550 nm, are therefore well suited to couple to photodiodes.

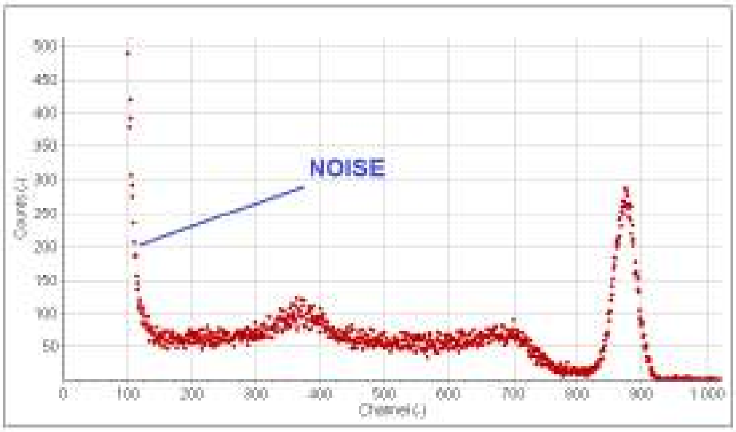
In contrary to photomultiplier tubes, photodiodes do not require a high voltage (HV) power supply but only a bias voltage of about 30 V. Photodiodes are thin, rugged and insensitive to magnetic fields. Furthermore, the output signal from a crystal/photodiode detector is very stable due to the absence of drift of the diode gain since no charge amplification takes place in the device itself. Photodiodes are thin (several mm) which can be advantageous.



Quantum efficiency curve of a silicon photodiode together with the emission spectrum of CsI(Tl)

Due to the small signal generated by the photodiode, it is necessary to employ a high quality charge preamplifier in order to keep the noise level as low as possible. **Noise** is an intrinsic problem to standard photodiodes. In silicon PIN photodiodes, the created number of primary electron-hole pairs (e-h pairs) is not increased by amplification. The PIN photodiode is a **unity gain device**. The thickness of the silicon used is typically 200 - 500 µm. Coupled to a conventional (low noise) charge sensitive preamplifier, the substantial capacitance of the device (40 - 50 pF/cm^2 for 200 and 300 µm wafer devices) is mainly responsible for the noise which determines for a large part the energy resolution of the detector. Also the dark current of PIN photodiodes (1 - 3 nA/cm^2 at full depletion) may contribute significantly to the noise, especially at larger shaping times. The dark current increases as well with increasing surface area as with increasing temperature.

As long as there is enough light per event available, every scintillation event can be detected using photodiodes. However, due to the intrinsic noise there is a lower limit on the energy of the radiation that can be detected. For a small (1 cm^3) CsI(Tl) cube coupled to a 10 x 10 mm^2 photodiode the best lower energy limit reported amounts to approx. 40 keV. From the above noise numbers and the electron-hole pair yield of the scintillator / photodiode combination, the noise contribution to the energy resolution can be calculated. The figure below shows a pulse height spectrum measured with a photodiode scintillation detector.



Example of a pulse height spectrum of 662 keV gamma rays absorbed in a 10x10x50 mm^3 CsI(Tl)scintillation crystal read out by a 10x10 mm PIN photodiode at 20 degrees C,

At increasing temperatures, the dark current of the photodiode increases. This limits the use of scintillation photodiode detectors to temperatures below 50 ^oC.

Below we summarize the advantages and disadvantages of photodiode scintillation detectors in conjunction with scintillation crystals for pulse counting:

Advantages:

- Small dimension (thin)
- Low Voltage operation
- Very stable signal height
- Rugged
- Insensitive to magnetic fields

Scintillator Detectors ***Photodiode***

Disadvantages:

- Limited surface area
- Low energy noise threshold
- Noise at elevated temperatures

Photodiodes can also be used in **DC mode** to read out a scintillation crystal. Capacitance and leakage current are less important then since the diode is used unbiased. This mode of operation is used for applications where radiation intensities are high and close packing of arrays is scintillation crystals is required such as in medical CT scanners.

The low level noise limit can be overcome by using so called **"Avalanche Photodiodes"**, APDs. In these devices an internal amplification enables to detect also X-rays of lower energy. However, an external voltage of at least several hundred Volts is required and the amplification is a strong function of temperature (gain stability). Also the leakage current of APDs at room temperature is relatively high. APDs are currently available in approx. 1 cm diameter size maximum. APD signals are much faster than signals from PIN diodes (ns range) and are mostly used for fast timing with small scintillation crystals or when operation in a magnetic field is mandatory.

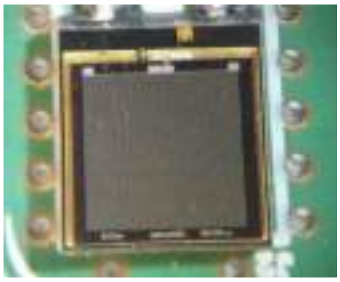
All diodes are susceptible to radiation damage induced by particles or gamma-rays which usually results in an increase in the dark current.

9.3 Silicon Photomultiplier SiPm

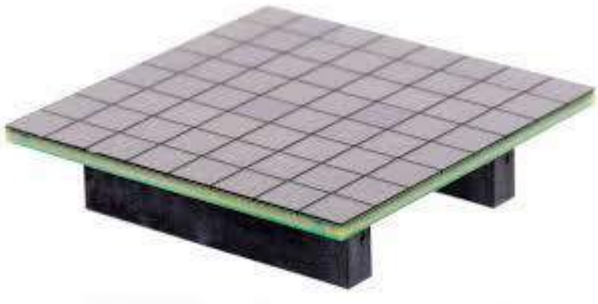
An alternative to the readout of scintillation crystals with photomultiplier tubes is the use of so-called silicon photomultipliers (SiPms)

Silicon photomultipliers are arrays of micron size self-quenched avalanche photodiode pixels operating in Geiger mode just above the breakdown voltage. When a photon is absorbed in a pixel it fires a defined charge. More pixels firing simultaneously implies a larger total charge pulse.

The typical properties of SiPms are:

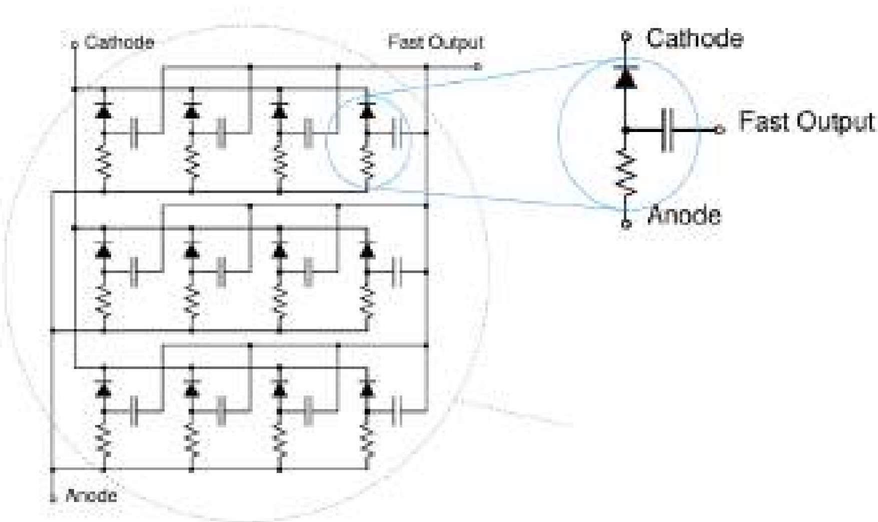


- Low voltage operation (25-30 V)
- Insensitive to magnetic fields
- High gains (10^6)
- Mechanically compact
- Elements 3x3 of 6x6 mm
- Micro cell size between 25 and 50 µm



SiPm elements can be combined into matrices. SiPms can be operated up to 60°C. For applications where small size and low voltage operations are required, SiPm readout of scintillators can be a good choice.
SiPms behave totally different from classical photomultiplier tubes, as well with respect to signal processing as to spectroscopic behavior. The gain of SiPms is a very strong function of the bias voltage which should be chosen carefully depending on the actual application of the detector. The number of SiPms needed on a scintillation crystal depends on the requirements.

SCIONIX has developed a range of sensors equipped with SiPms for a great variety of applications.



Advantages:

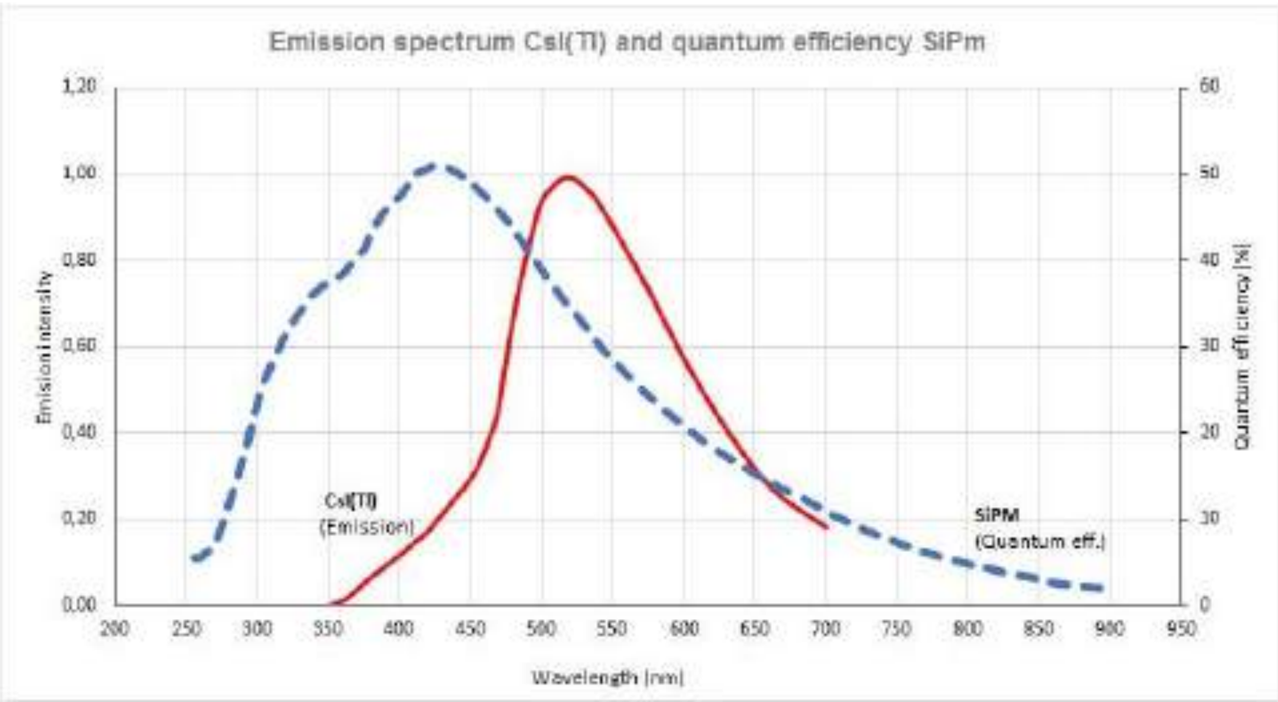
- Small dimension (thin)
- Low Voltage operation
- High QE (PDE) also > 500 nm
- Insensitive to magnetic fields

Silicon photomultipliers

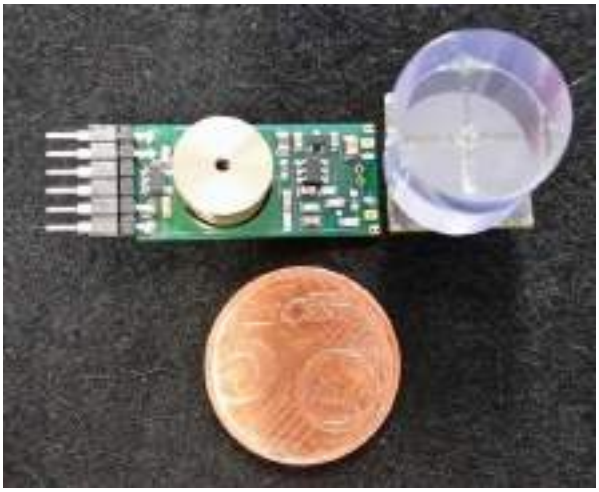
Disadvantages:

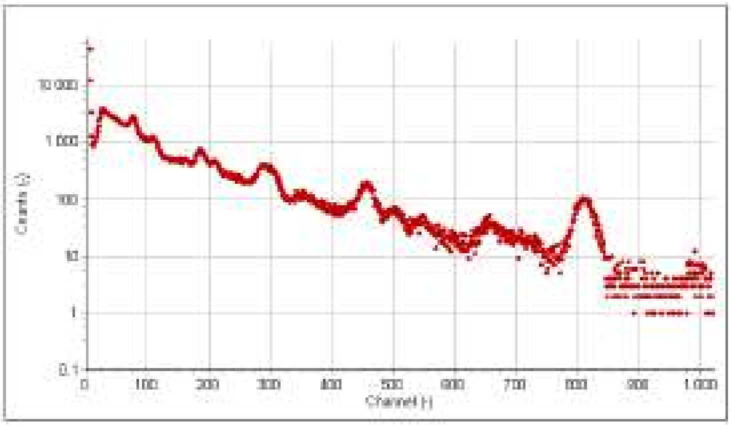
- Linearity of pulse height spectrum strongly depending on bias voltage and scintillator speed
- Temperature dependent gain typically -1.3 % per degree C
- Strong noise increase at elevated temperature. Maximum temperature approx. 50 degrees C
- Large cost per cm^2

SCIONIX has developed bias generator / preamplifier modules for SiPm scintillation detectors. The gain drift as a function of temperature is internally corrected. Such modules operate at voltage 5.2 – 16V and consume less than 30 mW.



Quantum efficiency curve of a silicon photomultiplier together with the emission spectrum of CsI(Tl).





Bias generator / preamplifier for SiPms

Thorium spectrum of a 51x102x406 mm CsI(Tl) SiPm detector

3”x3” SiPm scintillation detector

2”x4”X16” SiPm scintillation detector

9.4 Alternative readout methods

It is also possible to read out scintillators using CCD cameras when the intensities are large and when imaging is an objective. Usually energy information is lost in this case.

10 Detector Nomenclature / Type Numbering

SCIONIX scintillation detectors are characterized by a type number in which most of the properties of the instrument can be found. However, there remain features that are not "captured" in the type number (e.g. special geometries or electronic features) since there is a large number of ways a scintillation detector can be constructed. In this case the **suffix -Xxx** is added to the type number which refers to "special". Note that for some of the nine features below, more than one option may apply.

The following example, type number **V 50 BD 5 / 2 ME1 - CS - X** indicates a 50 mm square CsI(Tl) crystal, 5 mm high, integrally coupled to a 51 mm diameter (2") photomultiplier tube. The detector is provided with a beryllium entrance window, solid Mu-metal detector housing and built-in voltage divider. It is a customer special.

V 50 BD 5 / 2 ME1 - CS - X

1 2 3 4 5 6 7 8 9

1. Geometry of scintillator

V	=	Square
R	=	Rectangular
C	=	Spherical
Z	=	Hexagonal
-	=	Cylindrical (default)

2. Actual scintillation diameter in mm

3. Type of crystal / light detector coupling

A	=	Demountable light detector
B	=	Integrally mounted light detector
C	=	Crystal without light detector
K	=	Gamma camera crystal
P	=	Photodiode readout
T	=	High temperature detector
H	=	Crystal readout side perpendicular to PMT
F	=	Fiber optics light guide
Q	=	Quartz light guide or window

4. Type of window / housing

A	=	Thin window aluminum entrance window
D	=	Beryllium entrance window
M	=	Mylar entrance window
S	=	Stainless Steel housing
C	=	Copper housing/window
CF	=	Carbon Fiber window
P	=	Axial well in crystal
R	=	Ruggedized construction
-	=	Standard 0.5 mm thick aluminum housing (default)

5. Height of crystal in mm

In case of *phoswiches,* the height of the primary crystal precedes the letters **PH** followed by the height of the secondary (guard) crystal.

6. Size and Quantity of the light detector

When the readout is with a **photomultiplier (PMT)** the number here is the diameter of the PMT in inches. In case of more than one PMT, the number is indicated in brackets after the diameter; e.g. / 3(3) indicates three 76 mm PMTs

When the readout is with a silicon photomultiplier (SiPm), the type number shows here “**SiP**“ with in brackets the number of SiPm modules.

In case of photodiode readout, the size of the photodiode is indicated in mm.

7. Electronics/ features of PMT

M	=	External solid μ-metal shield
E1	=	Built-in Voltage Divider (VD)
E2	=	Voltage divider / preamplifier
E3	=	Special electronics module
Es	=	SiPm resistor / capacitors
HV	=	Built-in high voltage generator
-NEG	=	Negative high voltage operation (standard is positive)

8. Scintillation material

BGO	=	BGO
BAF	=	BaF_2
CaF	=	CaF_2 (Eu)
CEBR	=	$CeBr_3$
CLYC	=	CLYC:Ce
CN	=	CsI(Na)
CS	=	CsI(Tl)
LBC	=	Lanthanum BromoChloride
LYSO	=	LYSO

P	=	Plastic scintillator (general) or the specific type
SRI	=	$SrI_2(Eu)$
YAP	=	YAP:Ce
ZnS	=	ZnS(Ag)
-	=	NaI(Tl)

NOTE; frequently new materials are added to the list; SCIONIX offers all scintillation materials that are commercially available

9 Extra features

Am	=	Am light pulser
T	=	Built-in thermistor
O	=	Fiber optic for gain monitoring PMT
L	=	Built-in LED
Xxx	=	Non standard or custom configuration
LB	=	Special low background selected materials

Standard "off the shelf" scintillation detectors are provided with silver anodized aluminum housings, bialkali photocathode PMTs and positive (+) high voltage operation.

11 Detector configurations

Below some general aspects are mentioned regarding detector construction which may help you choosing the right detector for your application.

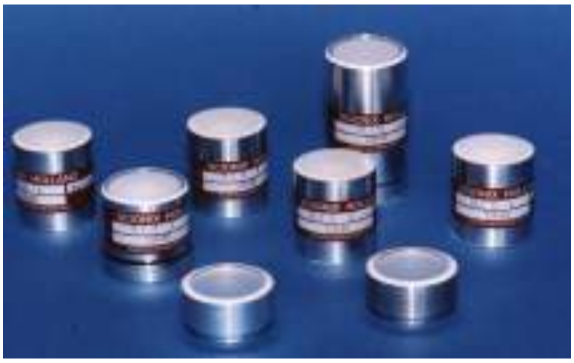
11.1 Scintillation crystals without photomultiplier tubes.

A scintillation crystal can be supplied to fit a specifically designed instrument of a user. Often, the scintillation crystal is supplied mounted in a hermetically sealed metal container with an optical window to protect the crystal from hydration or from other environmental influences. In case of non-hygroscopic crystals this requirement is less stringent.

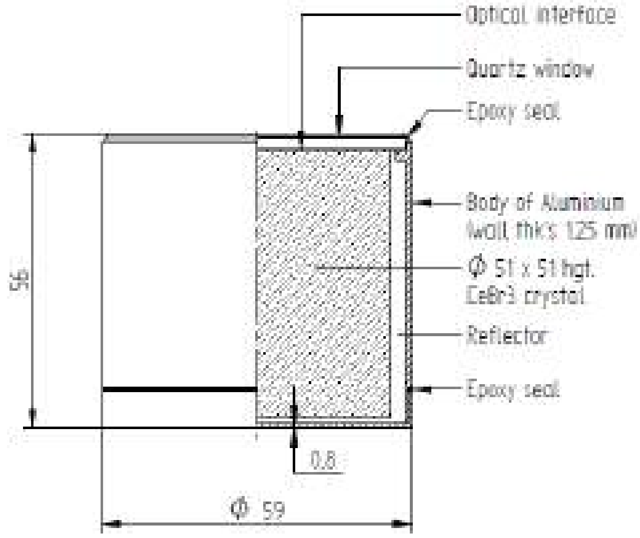
Because of statistics, it is always desirable to detect as much light as possible from a scintillation event in the light detection device. For this purpose, the scintillation crystal is covered on all sides, except the read-out side, with reflective material. This can be e.g. special white reflective materials like TYVEK, Teflon or reflective powder such as Al_2O_3. The surfaces in contact with the reflector can be optically polished or ground. The scintillation light is transmitted through a glass or quartz window to be optically coupled to the light detector.

Depending on the **shape of the scintillation crystal**, a certain surface treatment is required to obtain a large light output **and** a good uniformity. Both are important to achieve a good energy resolution. The optimization of scintillation crystal surfaces is based on experience with the material and not always obvious. SCIONIX will provide the optimum surface treatment of the crystal for your specific application.

Optical coupling to the PMT can be achieved by using optical grease or a special optically transparent glue. Below, an example of the general construction of a canned scintillation crystal is shown. Flexible optical coupling allows for different expansion coefficients between materials.



Standard C-style scintillation assembly

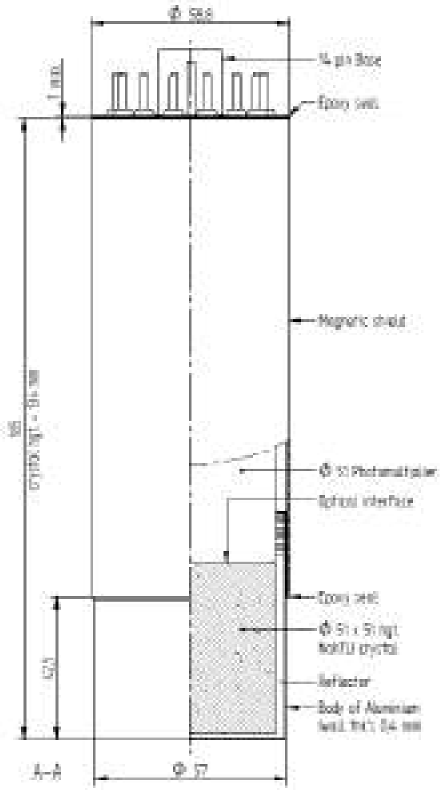


11.2 Scintillation crystals with photomultiplier tubes.

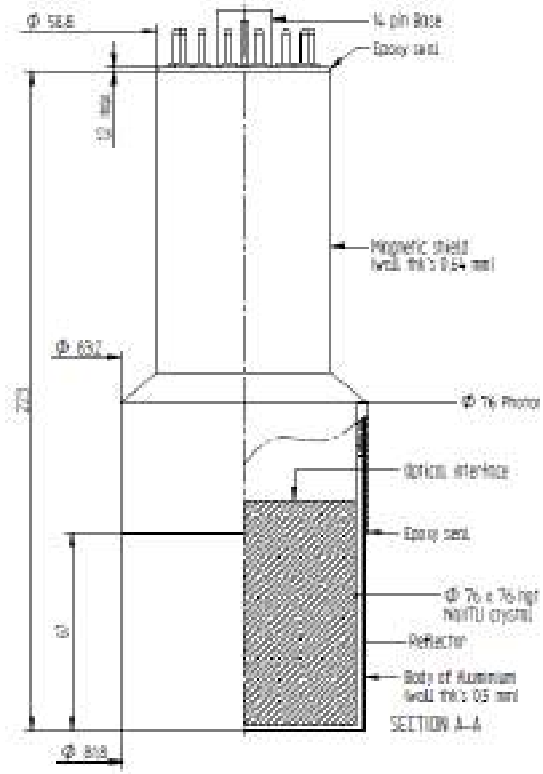
The most frequently used scintillation detector consists of a scintillation material integrally coupled to a Photomultiplier Tube (PMT). The scintillation crystal is mounted in a metal housing with µ-metal shielding against the influence of magnetic fields. For conditions where strong fields are expected, this shield can be increased in thickness for additional protection.

Standard scintillation detectors read out with PMTs can be provided with either an external so called "plug-on" **Voltage Divider (VD)** for the PMT or with a built-in one. In the first case, the detector itself ends in a 12, 14, or 20 pins connector that should be plugged into the socket of the VD or so called digital base”. This allows quick exchange of detectors and electronics but it makes the detector considerably longer (about 5 cm).

In addition to a **voltage Divider** it is possible to incorporate a **preamplifier / line driver** into the detector that converts the high impedance output signal of the PM to a 50 Ohms output signal that can drive over 100 m of cable.



Standard 51B51/2M scintillation detector

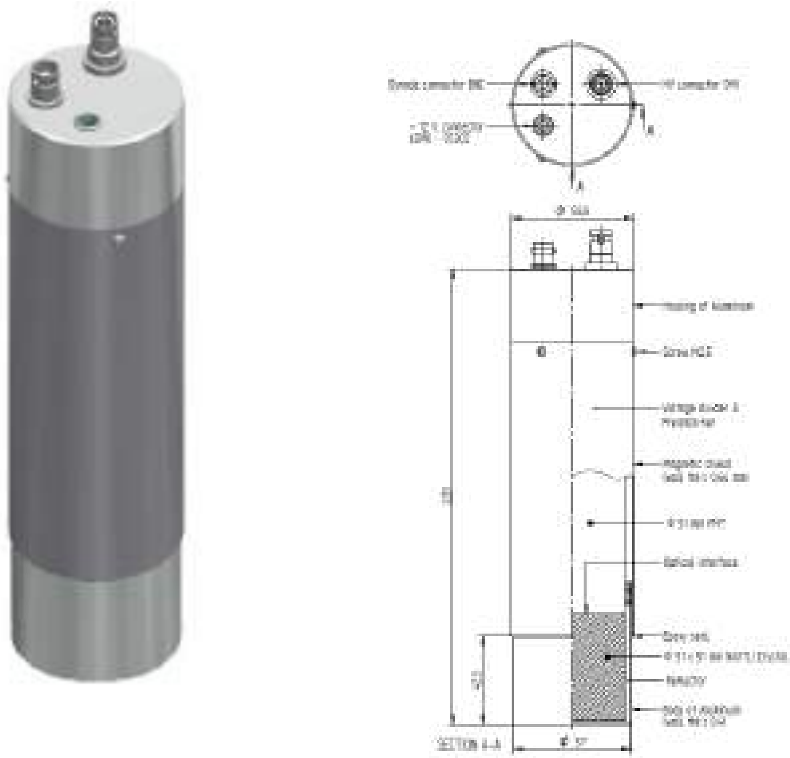


Standard 76B76 / 3M scintillation detector

Standard scintillation detectors read out with PMTs can be provided with either an external so called "plug-on" **Voltage Divider (VD)** for the PMT or with a built-in one. In the first case, the detector itself ends in a 12, 14, or 20 pins connector that should be plugged into the socket of the VD or so called digital base". This allows quick exchange of detectors and electronics but it makes the detector considerably longer (about 5 cm).

In addition to a **voltage Divider** it is possible to incorporate a **preamplifier / line driver** into the detector that converts the high impedance output signal of the PM to a 50 Ohms output signal that can drive over 100 m of cable.

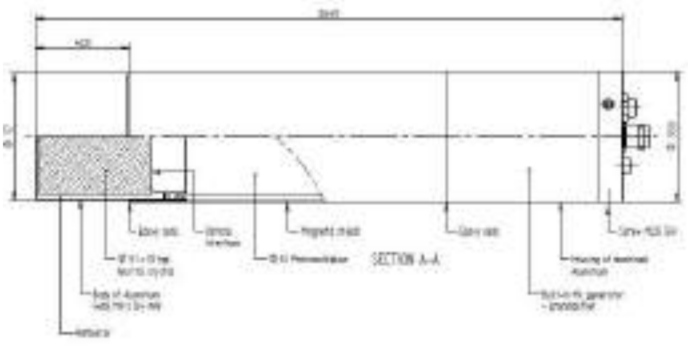
51x51mm scintillation detectors with built-in line driver



A **”digital base”** is a piece of electronics that is connected to a scintillation detector with 14 or 20 pins and which produces the required high voltage, processes the signals and digitizes them. It is connected via a USB, Ethernet port or sometimes via a Bluetooth connection to a computer or cell phone.

Example of digital bases

Besides built-in Voltage Dividers /preamplifiers), it is also possible to integrate **high voltage generators** (fed with +5 or +12 V) into the assembly or **spectroscopic amplifiers** and counters. Both can be fed with external voltages via a power connector or a USB connector.

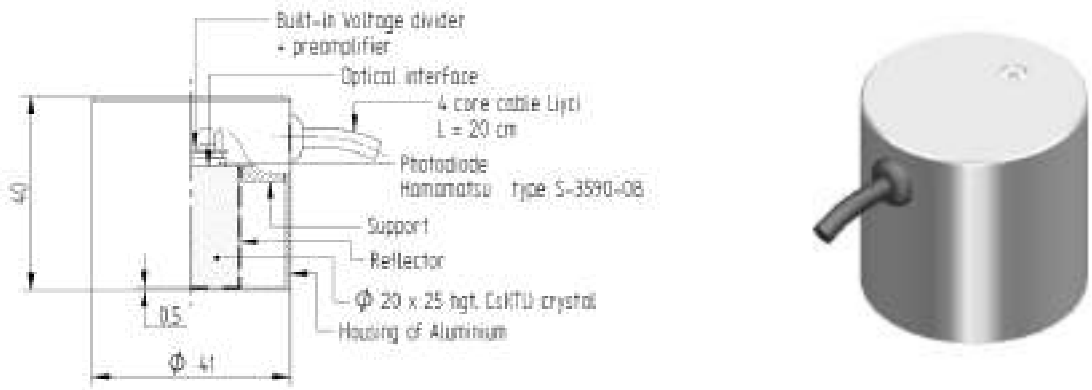


For more details regarding **detector electronics** we refer the respective section.

11.3 Photodiode detectors

The advantages and limitations of these instruments were already discussed in the section about light detectors In general. The required size of the scintillation crystal determines the possibility to use this readout technique. Small crystals perform best with good energy resolution and noise levels around 50 keV or slightly less. For medical applications these devices are well suited for measurement of 140 keV gamma-rays.

Photodiode detectors are also widely used for **heavy ion** detection in combination with thin Si detectors for E / ΔE measurements applied to particle identification. Compact size, good energy resolution and immunity to magnetic fields are pro's.



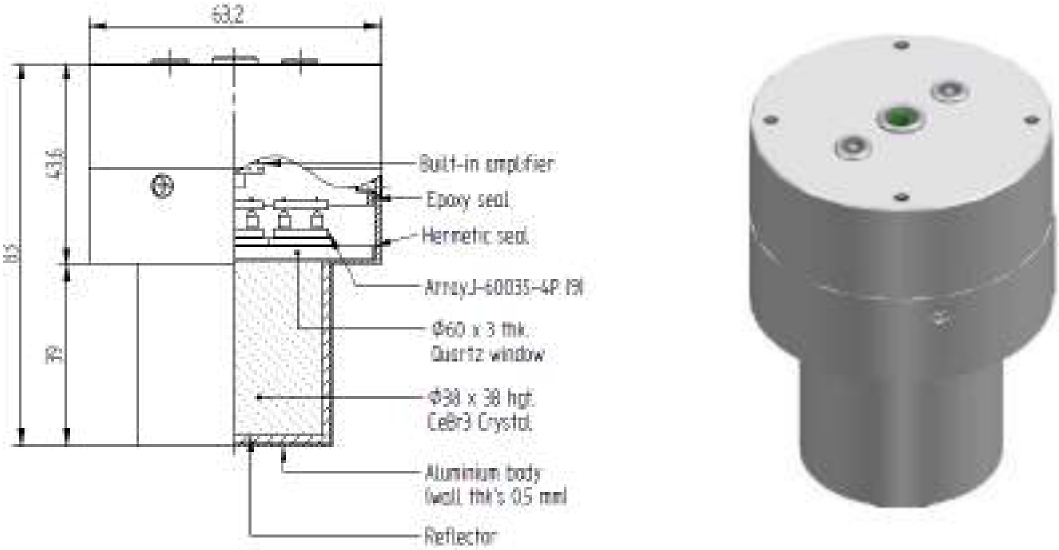
20x25 mm CsI(Tl) PIN Photodiode detector with built-in preamplifier

A totally different application is the measurement of high intensity X-ray beams. In this case, the photodiode is used in DC current mode (no pulse height discrimination). Longer wavelength emitting scintillation crystals like CsI(Tl), $CdWO_4$ or special ceramic scintillators are sometimes used in arrays coupled to photodiodes. Advantages are the good signal reproducibility, the absence of gain drift and the compact size.

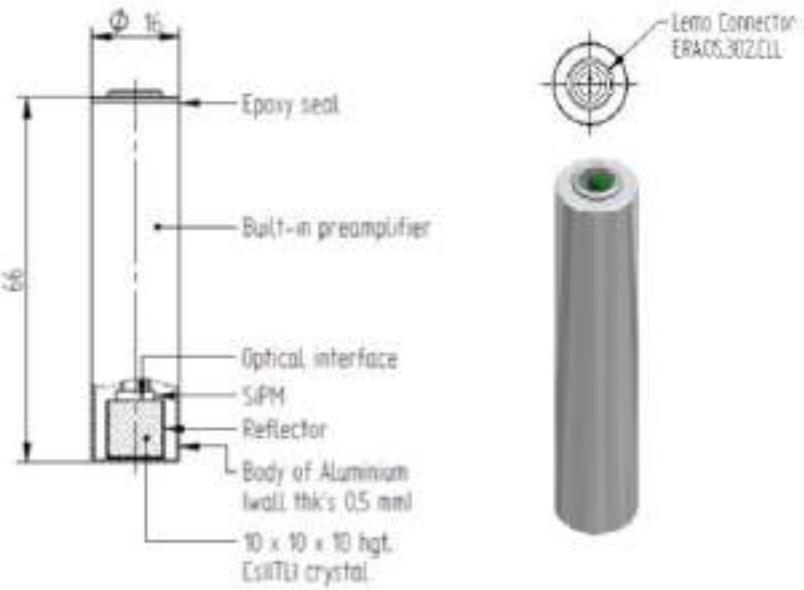
11.4 Silicon Photomultiplier (SiPm) readout

SiPm readout can result in compact mechanically robust scintillation detectors especially when rugged scintillators like CsI(Tl) are used. The required bias voltage that SiPms need (often 25-30 V) can be generated using built-in charge pumps operating at low voltages and consuming tens of mW. The raw SiPm signal, differentiated to increase is speed or a preamplified signal is fed out. The intrinsic large gain drift of SiPms (> -1% per degree C) can be overcome to a large extent by the built-in temperature compensation of the bias generator.

Usually only a fraction (20-30 %) of the total scintillator surface is covered with SiPm area to limit the cost of the sensor. This is sufficient for most applications. When more area of the scintillator is covered it increases the signal but also the noise. The optimum choice depends on the sensor requirements in terms of time- , energy resolution and noise.



38x38 mm $CeBr_3$ scintillator with SiPm readout

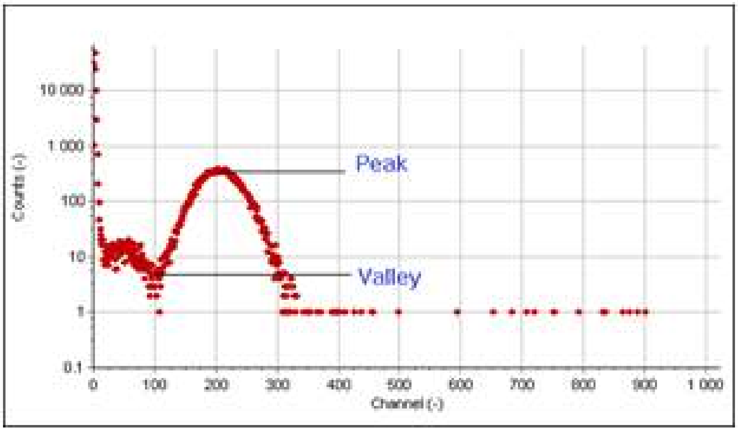


Miniature CsI(TI) SiPm detector with built-in power supply

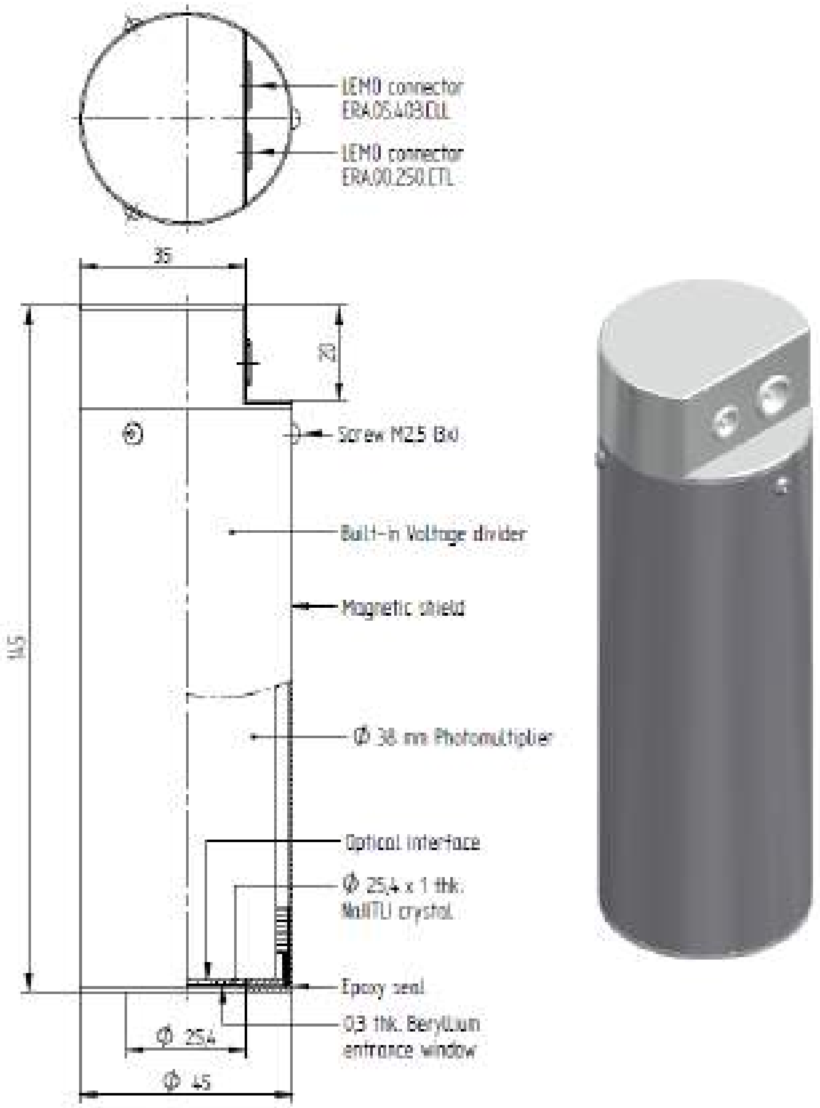
11.5 Detector entrance windows

The density and thickness of the detector entrance window determine the transmission of the radiation. For high energy gamma-rays say > 300 keV, the absorption of a mm or so entrance window can be neglected and the choice for a window is dictated by practical considerations.

For **lower energy X-rays** this choice is more critical. Below, the transmission of a range of standard detector windows is presented from which you can determine the optimum window for your application. The thinnest Aluminum window normally used has a thickness of 25 -30 µm. This window can be used down to 10 keV X-ray energy. Below this energy, 0.2 or 0.3 mm thick Beryllium is required. The advantage of a Beryllium window above a thin aluminum one is that is it less fragile.



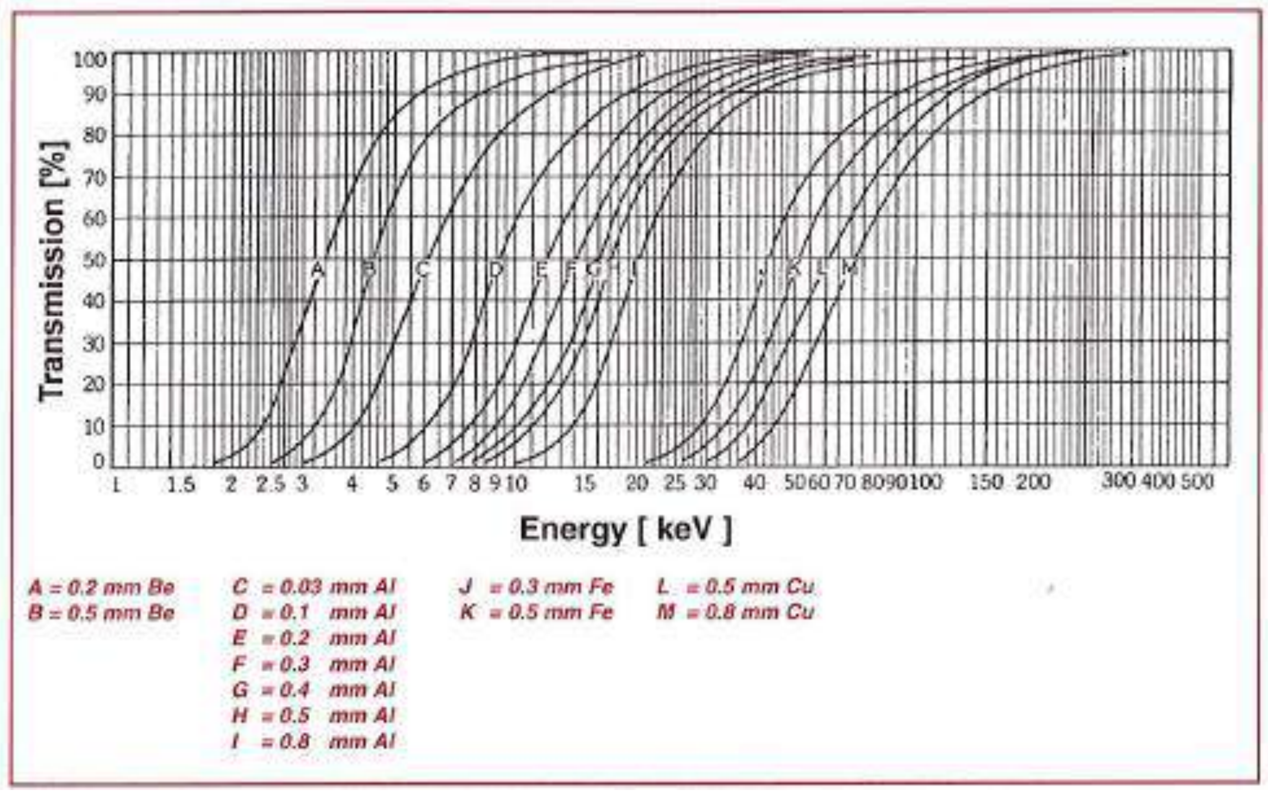
Typical 5.9 keV ^{55}Fe energy spectrum measured with a NaI(Tl) scintillation detector showing a typical energy resolution < 40 % FWHM and peak-to valley ration > 45



NaI(Tl) X-ray detector with built-in Voltage Divider

For the detection of **alpha particles** or low energy **electrons** (beta particles), a thin aluminized (light tight) mylar window is used. Mylar windows however can only be applied for **non-hygroscopic** scintillation materials. Standard thickness is 2, 4, 6 or 18 μm. Light tightness can only be achieved by using at least 2 or 3 layers. The thinnest available mylar window has a thickness of 2 μm. This means that light tightness can only be achieved from 6 micron onwards but for larger areas this can even be a problem.

Some crystals are suitable to coat with several hundreds of nm evaporated aluminum for the detection of very low energy beta's (e.g. from Tritium).



11.6 Crystal dimensions, housing materials

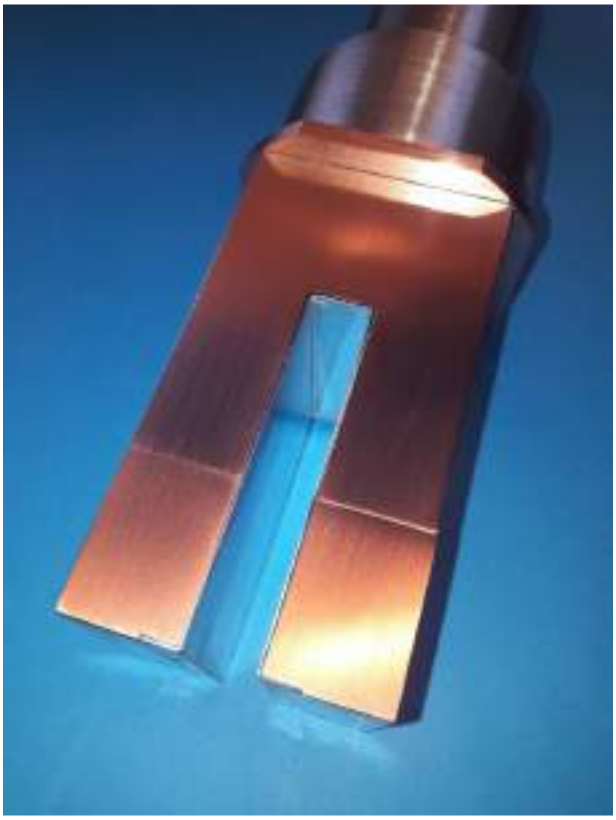
The surface area (solid angle) and the thickness of a scintillation crystal determine its detection efficiency. Normally, a scintillation crystal is read out with a PMT or photodiode in dimension equal to one of its sides. However it is common practice to use light guides or to taper a crystal without much too loss of performance. This can save space and cost, especially when resolution is not of prime importance. In case of SiPm readout, usually only part of the crystal is covered to keep the sensor cost to a reasonable level.

The maximum size of a scintillation crystal varies very much between different materials. NaI(Tl) crystals can be manufactured up to around 0.5 m in diameter whereas e.g. the limit for good quality BGO crystals is around 15 cm. This all has to do with crystal growing physics related to the physical properties of the material. The limit for Ce doped crystals like YAP:Ce is even smaller, 7 cm in diameter. Sometimes it is easier and less expensive to construct a large detector surface area by combining smaller detectors.

We always advise to consult us for the optimum detector configuration for your application.

Detectors are usually manufactured in cylindrical housings made of e.g. **plastics** (only non-hygroscopic crystals), **aluminum**, **stainless steel or (OHFC) copper**. Square or rectangular housings add to the cost. Aluminum has excellent radiation transmission properties but is relatively soft and can corrode, even when anodized. For aggressive or rough environments (shocks), 316 type stainless steel is advised. Copper is useful for low background applications.

All detectors can be provided with customer defined mounting flanges or other means to support the instrument.



11.7 Light pulsers

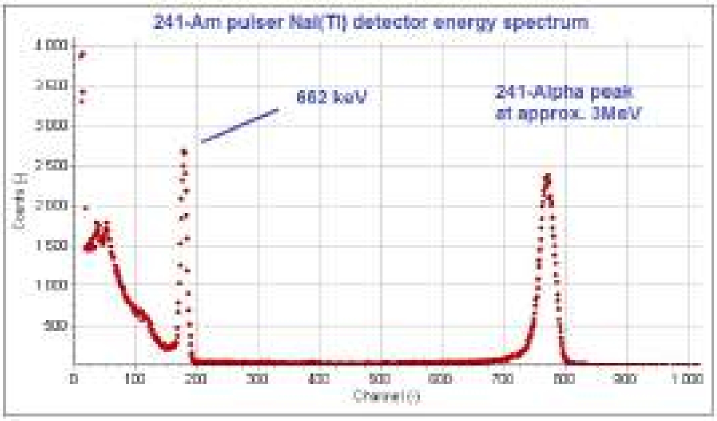
The light yield of a scintillation material and the gain of a light detector with amplification (e.g. PMT, SiPm) is a function of temperature. As discussed in earlier, it is possible to calibrate a scintillation detector on a light pulse emitted by e.g. a stabilized LED or by the light emitted by a **radioactive pulser**. This can be:

1. A low activity built-in gamma source producing a line outside the region of interest; the energy is usually < 1 MeV.

2. An alpha particle emitting nuclide like ^{241}Am in contact with the primary scintillation crystal

The advantage of method 1 is that one calibrates on the true response of the primary crystal. However, many gamma sources have more than one line and there is also Compton background.

The advantages of alpha sources is the absence of Compton background and their high energy (usually around 5 MeV) which implies narrow lines. The disadvantage is that the temperature response of many scintillation crystals is different for gammas and alphas. The optimum choice depends on the energy of interest and on the temperature region in which the detector should be stabilized.



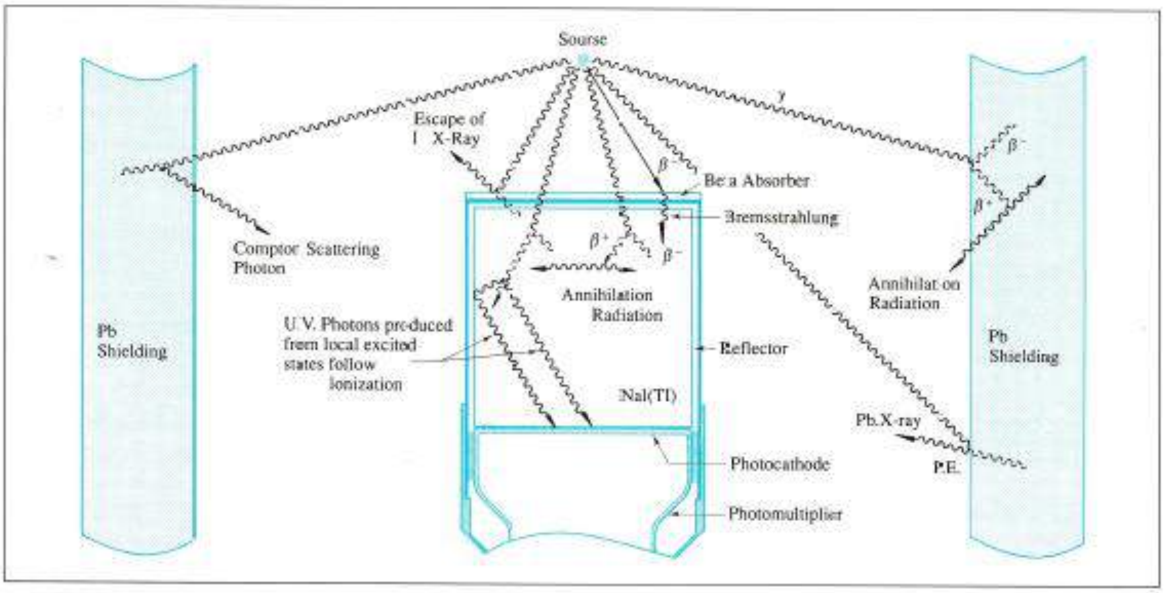
LEDs are intrinsically unstable (temperature, ageing) and cannot be used for an absolute calibration of a scintillation detector without measuring the emitted light in another way (e.g. with a diode).

11.8 Low background detectors

The term low background in itself needs to be specified in detail. A proper specification is the number of counts within a certain energy window with a well-defined shielding around the instrument (Pb, Fe and Cu).

Below a schematic shows the different sources of background in a shielded scintillation detector set-up.

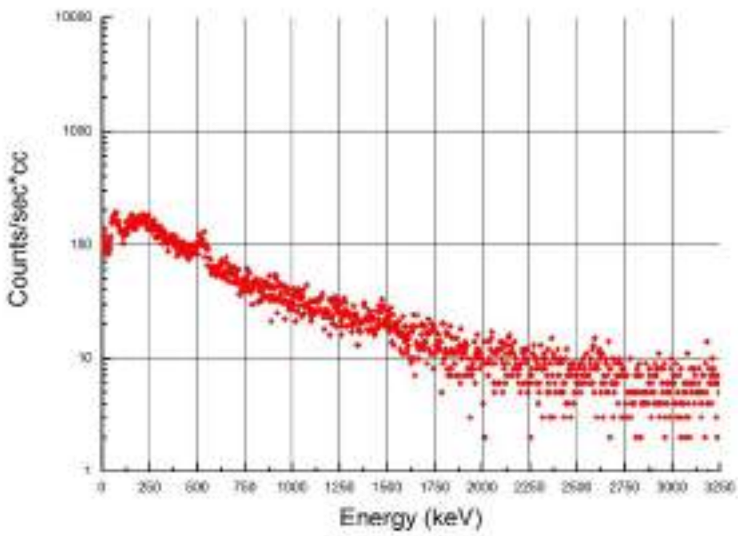
Sources of background from within the detector are the photomultiplier tube or other light detector, the detector housing and the scintillator. The main contributing nuclides are ^{40}K (mainly from the PMT glass) and U and Th which are present in small quantities in the housing and window materials. Special PMTs can be selected with an ultra-low K content and all other materials can be pretested prior to assembling. Plastics should be avoided because they often contain K. Aluminum has a larger U and Th content than steel so for low background applications, steel housings are the best choice.



SiPms and photodiodes have little mass and are relatively background free.

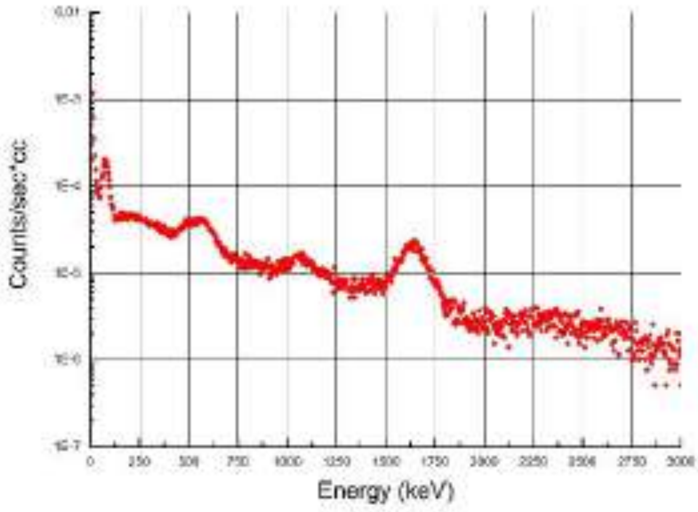
In low background detectors special precautions are taken to reduce the internal background. Between PMT and crystal quartz or undoped NaI, light guides are used to absorb the beta radiation from ^{40}K and to increase the distance between the PMT and the scintillation crystal. Below a typical NaI(Tl) background spectrum is shown. The continuum is caused by cosmic interactions (muons) in the scintillator and the shielding.

The scintillation crystal is a source of internal contamination too. NaI(Tl) crystals have a low background with their ^{40}K content typically less than 1 ppm.



Typical NaI(Tl) background spectrum in shielding

Other scintillators have typical radiological background issues. All CsI(Tl) crystals have some Cs-137 contamination due to nuclear fallout incidents over the last decades. BGO crystals have an internal background caused by traces of ^{206}Pb that are transmuted by cosmic radiation into ^{207}Bi, resulting in gamma lines at 570, 1060, 1630 (sum peak) and 2400 keV. Typical net count rates in the above peaks are approx. 0.01 c/s/cc.



Typical BGO background spectrum in 10 cm thick Pb shielding

BaF_2 crystals have an intrinsic background of Radium causing a set of alpha lines with a total count rate of 0.25 c/s/cc typical.

$CeBr_3$ crystals have a typical Ac-227 background due to alpha particles of at best < 0.001 c/s/cc whereas $SrI_2(Eu)$ crystals are very radiopure. The best large volume scintillation crystal for very low background applications is still NaI(Tl).

12 Examples of standard detector configurations

Below some standard scintillation detector assemblies are presented.

12.1. Assemblies without photomultiplier tubes

C-styles and CP-styles

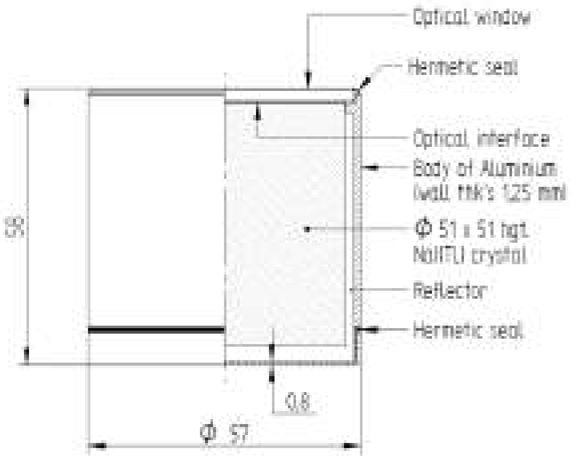
SCIONIX **C-style** detector assemblies basically consist of a scintillation crystal which is machined and mounted in a housing of aluminum, stainless steel or copper. In case of hygroscopic crystals the assembly is sealed by a glass or quartz window for optical coupling to a photomultiplier tube or other light detection device. A C-style assembly can be manufactured from low background materials (LB steel or copper).

C-style assemblies are intended for use in combination with customer's photomultiplier tube in demountable assemblies. The optical contact to the PMT is accomplished by using optical coupling compound or customers own optical glue.

C-style assemblies can be provided with an **axial well** called **CP styles**, or with thin (25 µm thick) aluminum entrance windows at the flat side of the crystal called **CA styles**.

The standard thickness of an aluminum housing is 0.5 mm, that of a stainless steel housing (harsh environments) is 0.8 mm. C-style assemblies can be provided is ruggedized version (CR styles).Housings can be equipped with flanges or grooves for O-rings in order to facilitate a demountable coupling to the PMT and its housing.

The optical window can be extended in height or tapered to form an optical light guide to a different diameter than that of the crystal. For optimum energy resolution, the diameter of the crystal is chosen equal or slightly smaller than the diameter of the PMT.



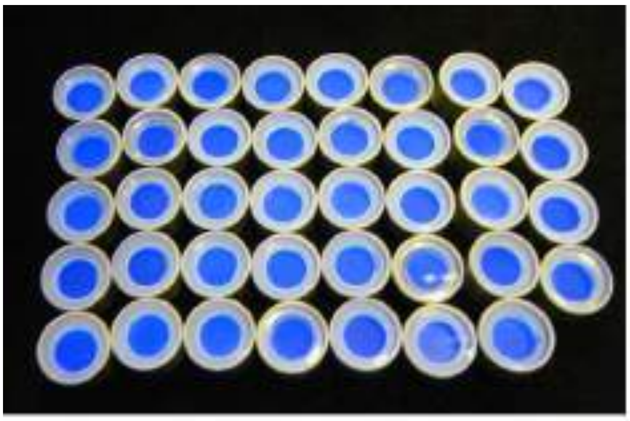
Example of C-style assembly

Standard inner well dimensions for CP-style assemblies are:

51 CP 51 : 25.4 mm diameter, 39.3 mm deep,
16.6 mm diameter, 39.3 mm deep.

76 CP 76 : 25.4 mm diameter, 52 mm deep.

The standard well thickness is 0.3 mm (Aluminum).



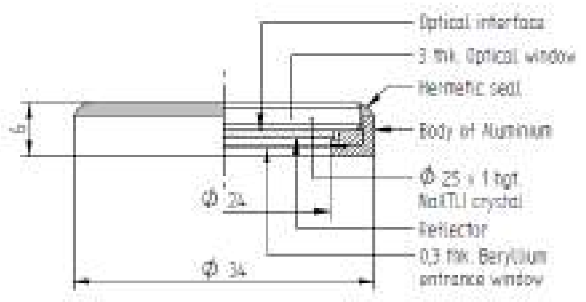
Application

Standard C-style assemblies are used for detection of gamma-rays and X-rays between 30 keV and 2 MeV. For higher energies, BGO can be chosen as the scintillator of choice in which case the optical window is omitted. CP-styles are used in **well counters** for e.g. medical applications or wipe test detectors.

Thin window crystal assemblies: CA-styles, CD-styles

For the detection of low energy X-ray radiation, a detector can be made intrinsically insensitive to higher energy radiation by choosing the scintillation crystal only a few mm thick. For optimum energy resolution, also at very low (several keV) energies, NaI(Tl) scintillation crystals are often used.

For transmission of the radiation of interest, 25 µm thin Aluminum (Al) windows or 0.25 - 0.3 mm thick Beryllium (Be) windows are used. Al windows are suitable for energies down to 10 keV whereas Beryllium windows can be used down to 3 keV. The advantage of Al windows is their low cost but Beryllium windows are less easily damaged. For non-hygroscopic crystals, aluminized mylar entrance windows or titanium foil windows can also be used.



12.2 Assemblies with photomultiplier tube(s)

Detectors with photomultiplier tubes exist basically in two versions: demountable called **A-styles** and integrated called **B-styles**.

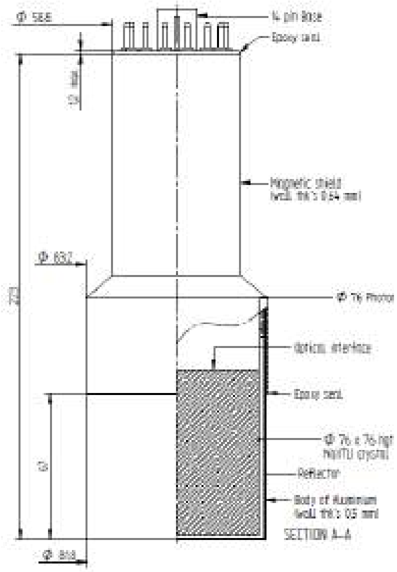
Assemblies with integrated photomultiplier tubes: B-styles

Scintillation detectors with integrated photomultiplier tube(s) consist of a scintillation crystal, coupled directly to a photomultiplier tube with a slightly flexible, high refractive index optical coupling medium. The crystal and PMT are hermetically sealed (gas tight) in a light-tight housing with an aluminum or beryllium entrance window. Detectors have either an internal or solid external µ-magnetic housing around the PMT and can be supplied with 12, 14 or 20 pins connectors to connect to a plug-on Voltage Divider or with a built-in voltage divider (see the section on electronics)

The advantages of this construction are:

- Permanent light sealing
- Improved energy resolution due to direct coupling to the PMT
- Guaranteed energy resolution
- Simplification of detector design by eliminating support hardware to maintain contact between crystal and PMT
- No problems with degradation of optical contact between crystal and PMT

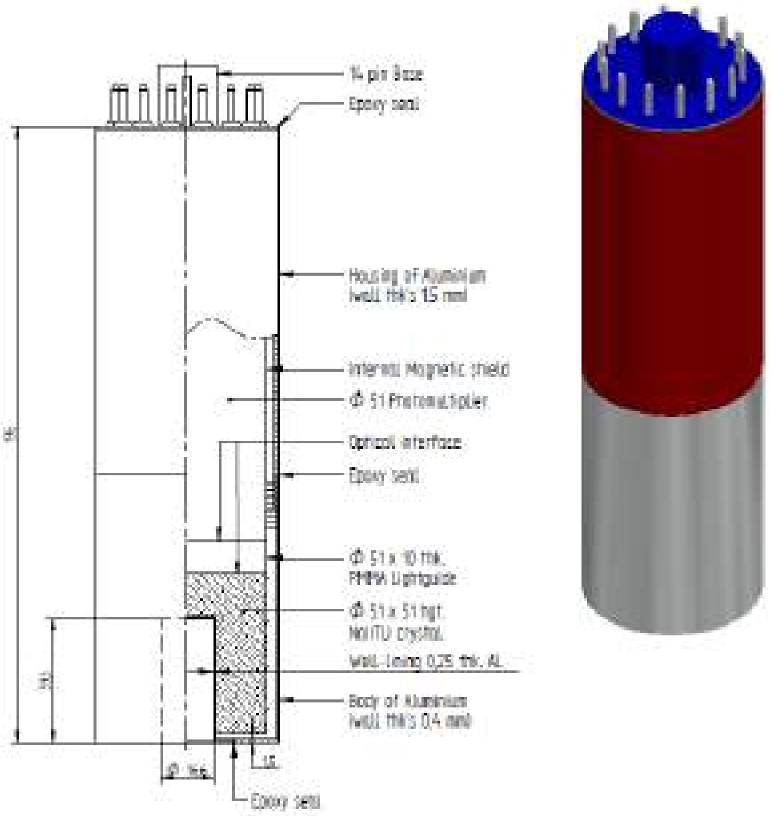
One of the most frequently used scintillation detectors world-wide is the 76 x 76 mm NaI(Tl) detector (SCIONIX type 76 B 76 / 3M) which is **THE** scintillation detector standard for general gamma spectroscopy having excellent efficiency and energy resolution.



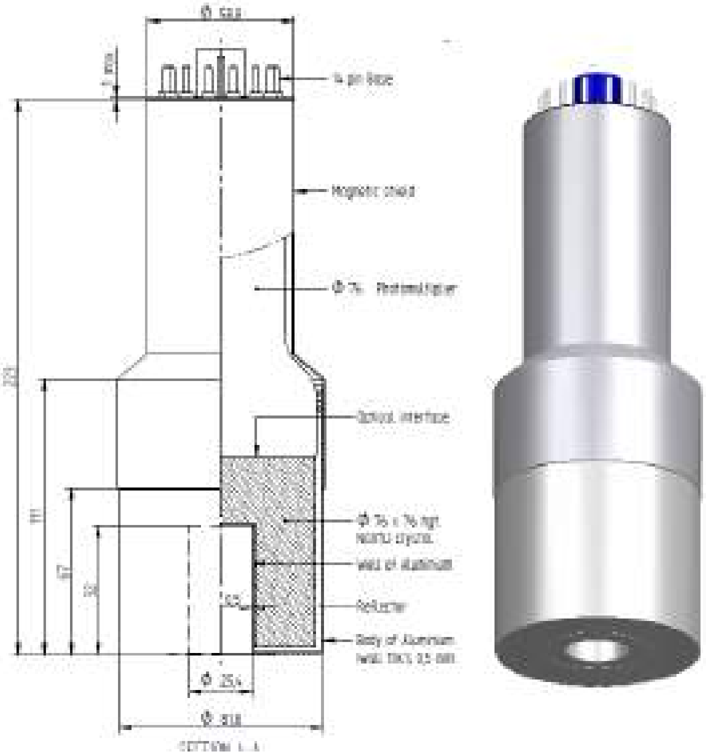
Standard 76 B 76 / 3M scintillation detector

For low background (LB) applications, B-style assemblies can be supplied in low background steel or electrolytic copper housings. All detector components can be selected on the lowest possible radioactive background. In LB units, quartz or undoped NaI light guides are used to reduce the background from the PMT

Below some standard B-style detectors are shown as well as an example of an assembly equipped with an axial well (**BP style**).

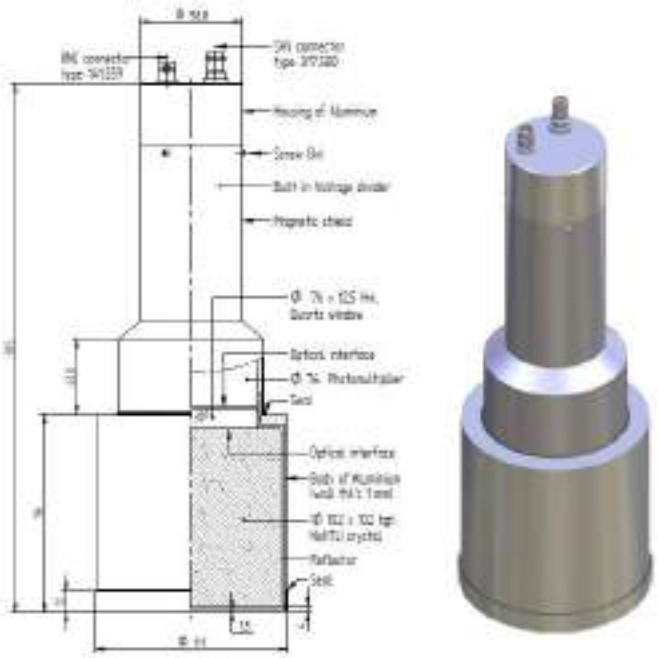


2”X2” NaI(Tl) detector with axial well



76 x 76 mm integrated NaI(Tl) detector with axial well

Many other PMT diameters are possible. Standard PMT diameters are: 10, 13, 19, 25, 28, 38, 51, 76, 90, and 127 mm.

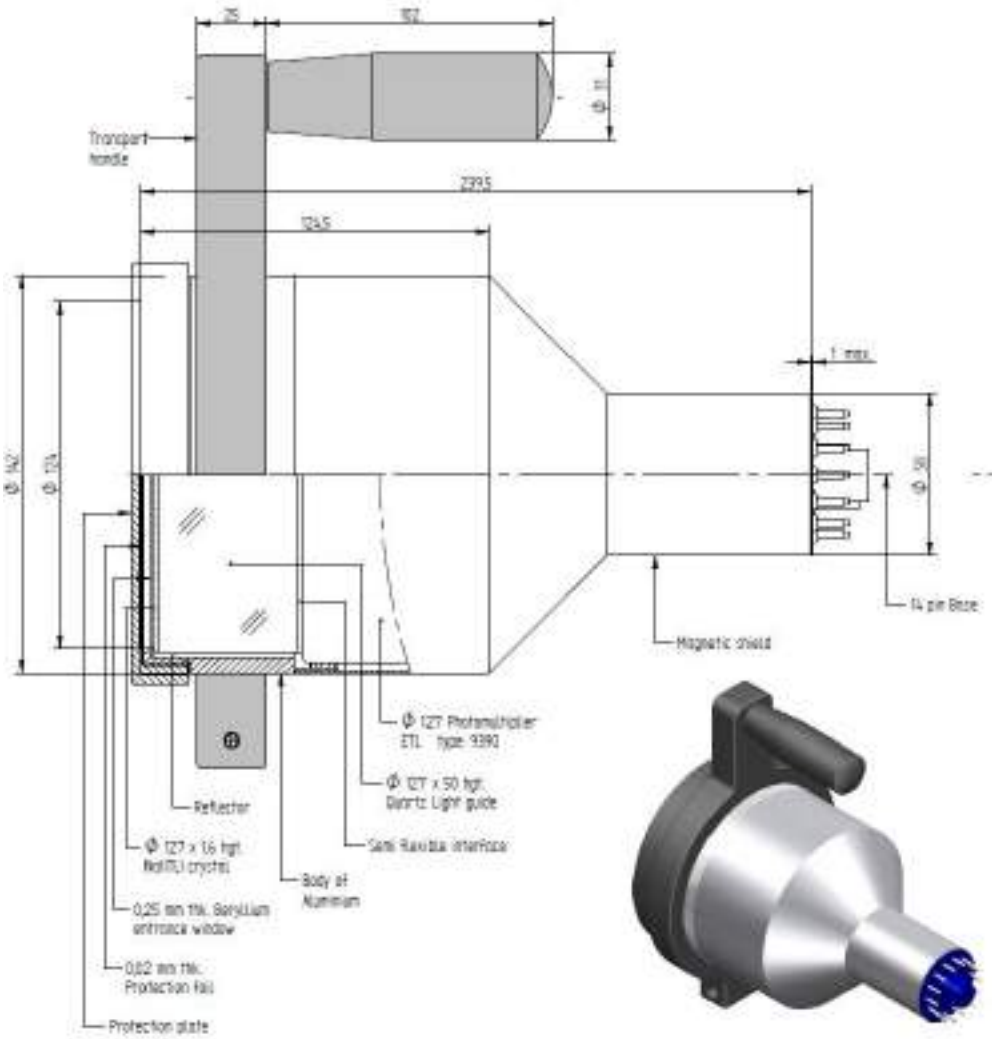


102 x 102 mm integrated NaI(Tl) detector with built-in Voltage Divider

Thin window B-style assemblies: BA-, BD- and BM-styles

For the detection of low energy radiation, thin scintillation crystals are combined with PMTs in a thin-window assembly. For the detection of X-rays > 10 keV, 30 μm thick Aluminum windows (**BA styles**) are used. For lower energies, the **BD-style** with a 0.2 or 0.3 mm thick Beryllium window is the detector of choice. **BM** is the notation for a thin mylar entrance window for the detection of heavy ions of low energy β-particles with non-hygroscopic crystals. The thickness of the above materials is not fixed and can be modified to your application.

Thin window B-style assemblies are often constructed with light guides to compensate for local inhomogeneities in the response of the photocathode of the PMT.



Large area X-ray detector probe for low level detection (Fidler probe)

Assemblies with demountable photomultiplier tubes: A-styles

Detectors with more than one PMT are often constructed as demountable assemblies. The advantage is that in case of break-down of one PMT, it can be replaced easily by the user without having to take apart the entire crystal assembly. Especially for complicated detectors such as Anti-Compton shields or large whole body counters, this is the normal approach. A-styles are also available with axial well (AP-style) or thin entrance window AA-styles.

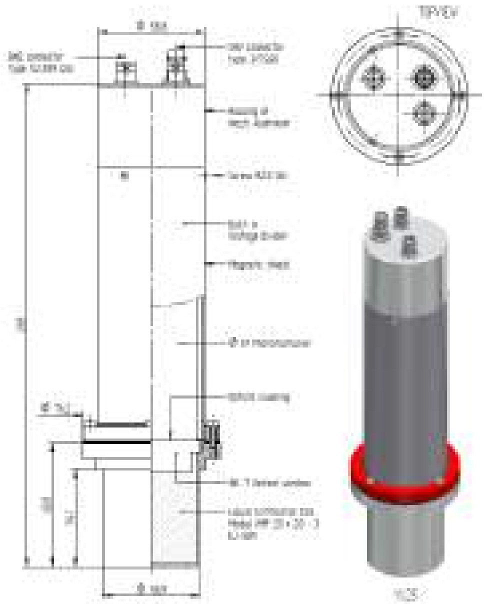
Example of an A-style assembly with 127 mm diameter PMT: 127 A 127 / 5M

12.3. Liquid Scintillation detectors

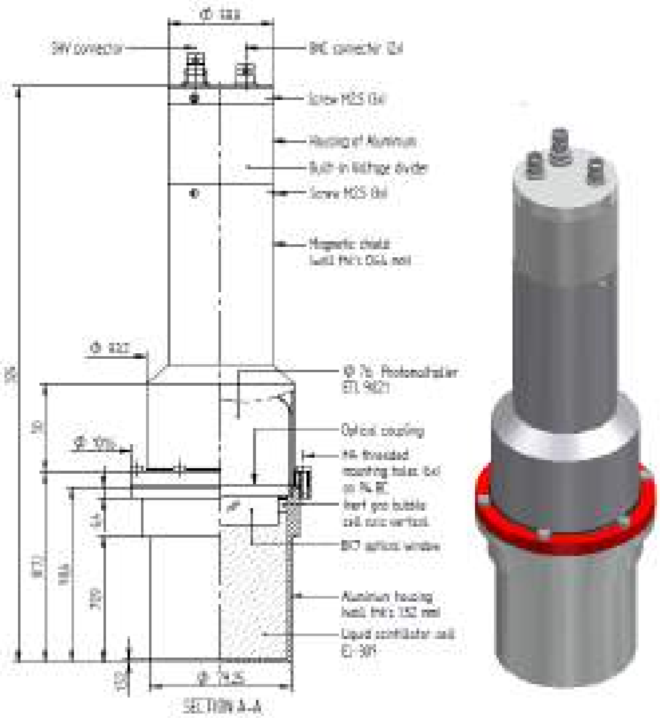
For (fast) neutron / gamma discrimination liquid scintillators in combination with pulse shape discriminating electronics are an effective solution. These days' nonflammable / nontoxic liquids are available like EJ-309.

All liquid scintillators are hermetically sealed from ambient air. Liquid scintillators exhibit more thermal expansion than inorganic scintillators and every liquid scintillation cell needs an expansion reservoir. SCIONIX has developed a construction that guarantees 100 % optical contact between the liquid and the optical window under all orientations of the cell.

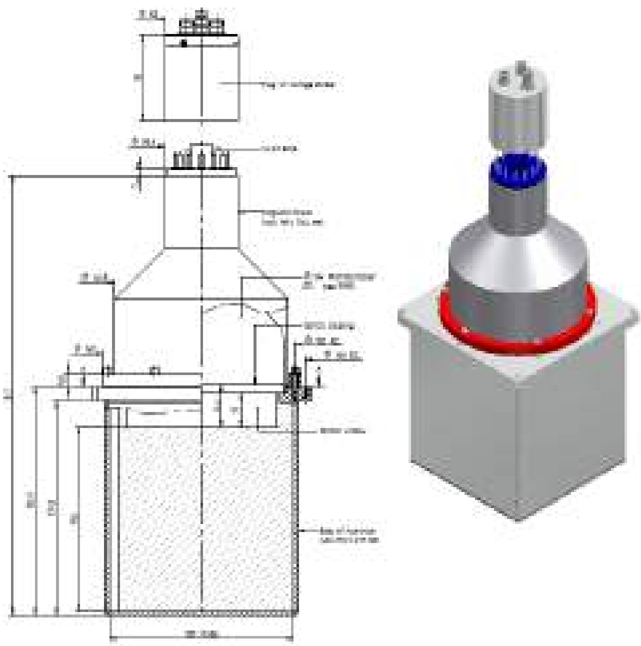
In order to allow at the same time neutron / gamma PSD and time-of-flight information, liquid scintillation detectors are usually equipped with fast (2-3 ns rise time) PMTs and transistorized Voltage dividers operated at negative high voltage.



51 x 51 mm active volume EJ-309 liquid scintillation detector



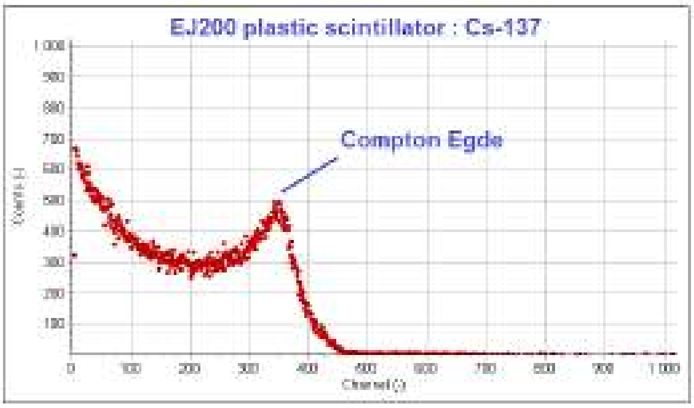
76 x 76 mm active volume EJ-309 liquid scintillation detector



150x150x150 mm active volume EJ-309 liquid scintillation detector

12.4. Solid organic scintillation detectors in short

Solid organic scintillators exist in many varieties. What they have in common is that they consist of mainly carbon and hydrogen atoms and have therefore a relatively low density (roughly 1 g/ cc) and a low Z value. This means that interaction with gamma-rays is for the largest part via Compton interaction which explains the absence of photo-peaks in the energy spectrum. Spectroscopy with organic scintillators is therefore challenging. This means that plastic scintillators are mostly used for gross counting not for spectroscopy.



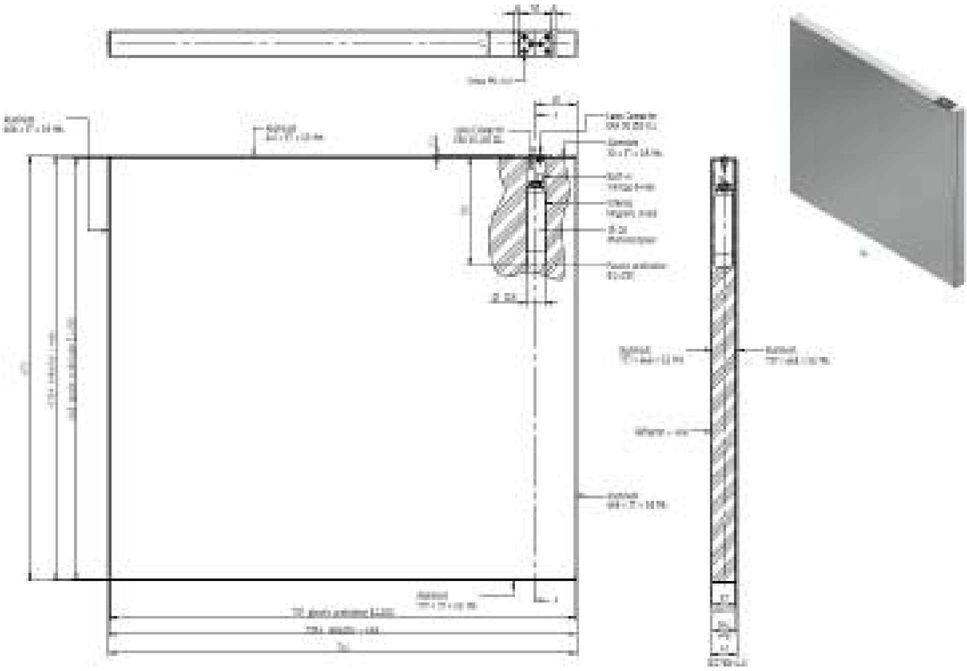
Typical pulseheigth spectrum of 662 keV gamma-rays in a plastic scintillator

PolyVinylToluene (PVT) based and PolyStyrene (PS) based scintillators are called **"plastic scintillators".**

In the ELJEN part of the SCIONIX web site a detailed description of the available plastic scintillators can be found. Here we just mention briefly some important characteristics.

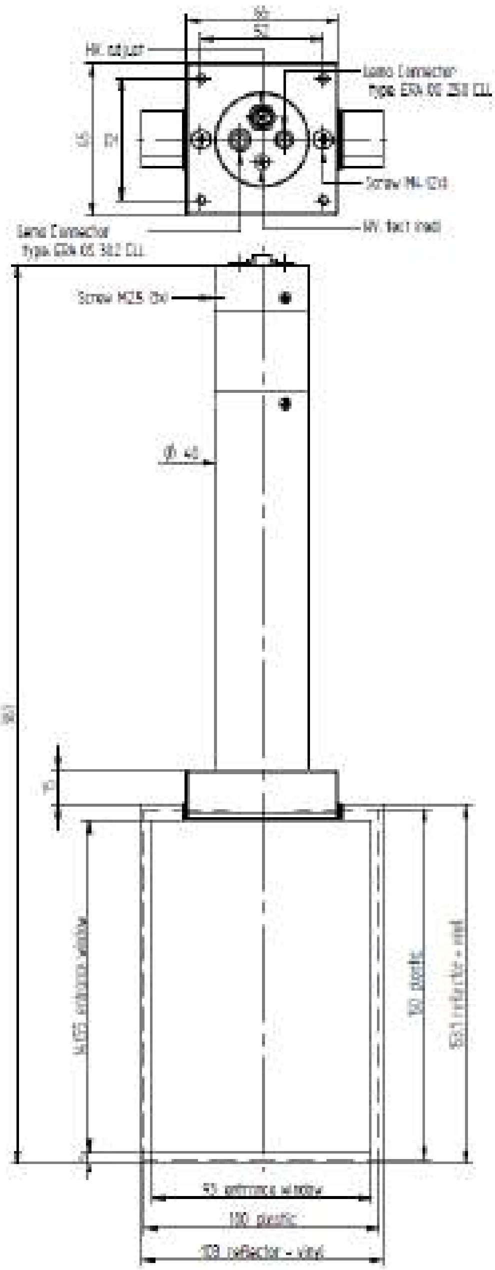
The main reason to choose plastic scintillators is their low cost and the fact that they are available in very large sizes (meters long). In general plastic scintillators emit between 8.000 and 12.000 photons per MeV gamma rays and the maximum of their emission is around 420 nm. When a wavelength shifter is added to the material, the maximum of the emission is shifted to about 490 nm. This can be advantageous for readout using silicon based devices (photodiodes, APDs, some SiPms). The above means that plastic scintillators are mostly used for gross counting not for spectroscopy.

Due to their large size choices have to be made for the way the scintillation light is read out.
Sometimes multiple PMTs are needed to detect signals above the noise but this totally depends on the actual application. Since cosmic muons deposit several MeV per cm of material, the readout requirements for muon shields are less stringent than for other applications and small PMTs embedded inside the plastic scintillator are often used.
Muon shields are used to reduce the background of Shielded HpGe detectors and are in practice always “custom designed”.

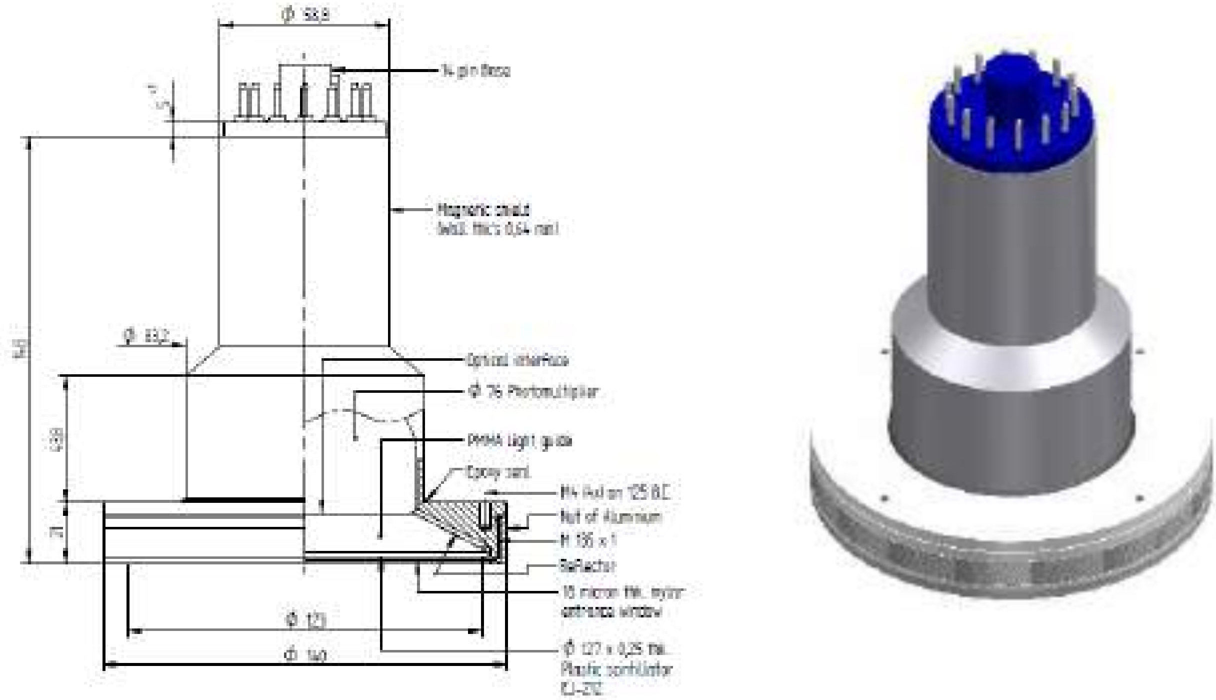


Example of plastic scintillator muon shield segment

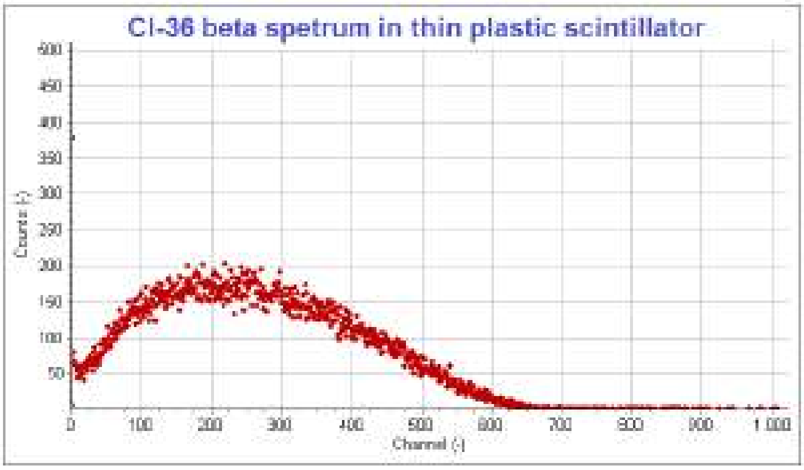
Thin (0,25 mm thick) plastic scintillators coupled to PMTs can be used for low background detection of beta particles in the presence of gamma rays. The entrance window is usually aluminized mylar.



Thin plastic scintillation detector with built-in high voltage generator



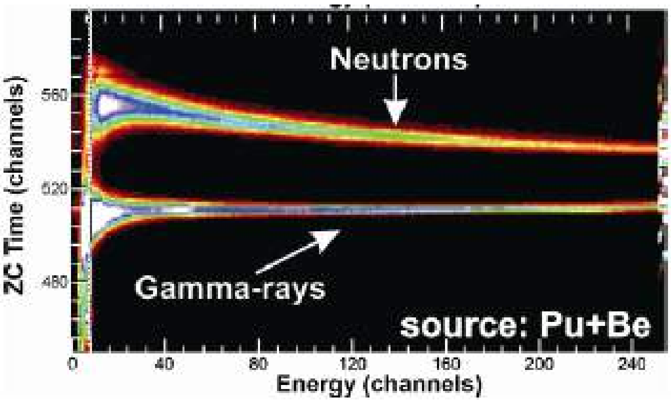
Large area thin plastic scintillation detector



Example of ^{36}Cl beta spectrum (endpoint energy 714 keV) in 5 mm thick plastic scintillator

Plastic scintillators can be read out by SiPms but the signal-to-noise ratio should be considered carefully and sometimes signal coincidence electronics is required.

Stilbene (C_4H_{12}) and **Paraterphenyl** are solid organics crystals that have recently gotten some more attention due to their excellent neutron / gamma discrimination properties. SCIONIX offers these materials in conjunction with PMTs and SiPms.



Neutron / gamma PSD spectrum of Stilbene read out by a PMT

12.5. Photodiode detectors

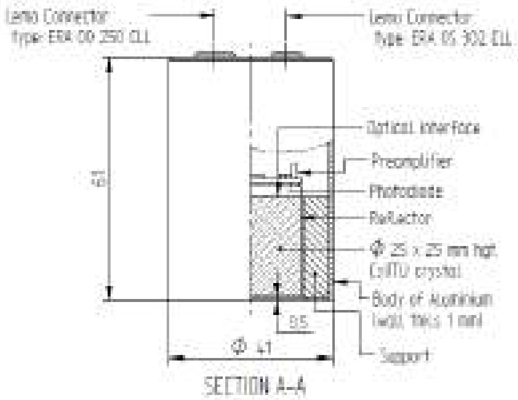
The advantages and limitation of photodiode detectors were discussed in a previous section. In general, photodiode scintillation detectors consist of a small PIN photodiode, integrally coupled to a scintillation crystal, often CsI(Tl). As a standard rule, a charge sensitive preamplifier is incorporated in the assembly.

The **intrinsic noise** of the photodiode/preamplifier combination **prohibits** the use of large scintillation crystals for detection of low energy (< 1 MeV) gamma-rays. This noise determines the lowest energy that can be detected with the device. CsI(Tl) crystals of 1 cm^3 coupled to 10x10 mm^2 PIN photodiodes can be used down to 40 keV; for larger crystals (e.g. for 2x2x2.5 cm^3 coupled to 18x18 mm^2 diodes, this number is about 70 keV.

Photodiode scintillation detectors can be used e.g. in applications where:

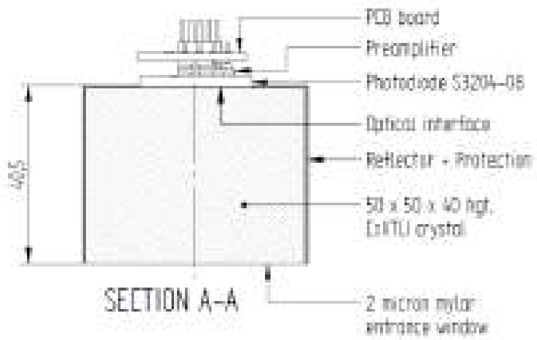
- No high Voltage is available or desired (medical applications)
- Stable gain is essential (long term environmental monitoring)
- High magnetic fields are present (physics research)
- A rugged detector is required

CsI(Tl) crystals do not crack or cleave and photodiodes are shock resistant. Many configurations are possible. The noise level and energy resolution of the detector depend very much on the crystal/diode configuration. Contact SCIONIX for your specific requirement. The noise of photodiode scintillation detectors increases with temperature. Above 50 ^oC these instruments are not advised.

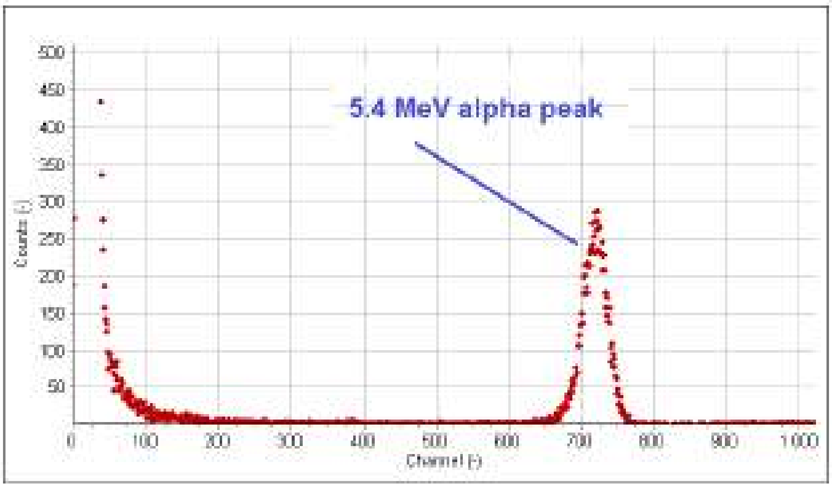


CsI(Tl) Photodiode detector for gamma rays

An important application of photodiode detectors is in physics research for the detection of **charged particles**. A thin silicon detector is placed in front of a CsI(Tl) crystal read out with a photodiode to perform an E / ΔE measurement.



Heavy ion detector and typical energy spectrum for 5.4 MeV alpha particles below

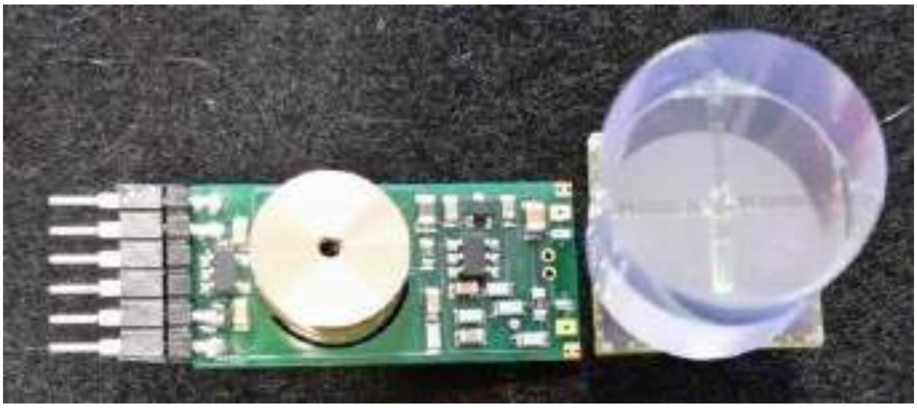


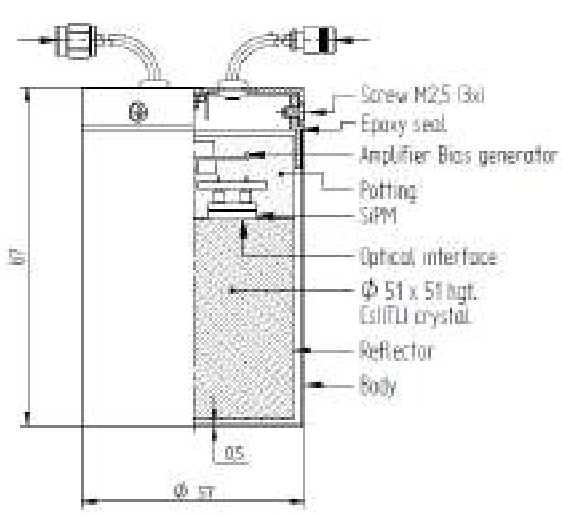
CsI(Tl) crystals can be cut into a variety of shapes. Since CsI(Tl) is not very sensitive to moisture Cs(T) equipped photodiode detectors are wrapped only in special reflector materials and provided with thin (aluminized) mylar entrance windows (0.35 mg / cm{3})

12.6. Silicon photomultiplier detectors

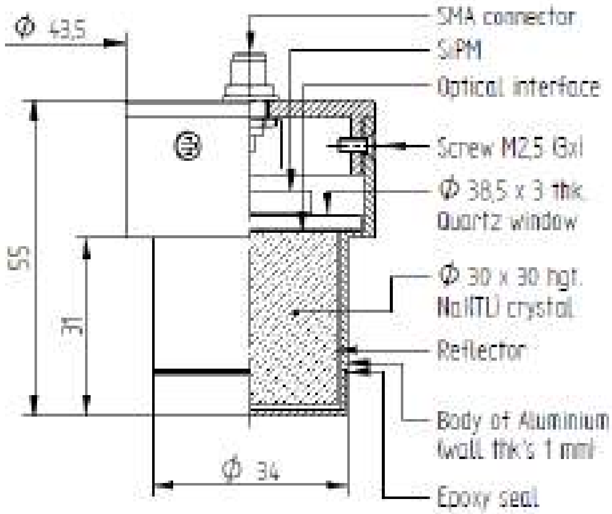
Last years an increasing number of low noise silicon photomultipliers (SiPms) has become available. SCIONIX offers a large range of SiPm assemblies using these devices of which the properties, advantages and drawbacks were discussed in the section on scintillator readout. Low voltage operation, compact size and insensitivity to magnetic fields are the most important advantages. Below some concepts are shown.

SCIONIX offers built-in a (first order) temperature compensated bias generators / preamplifier in conjunction with the SiPm / scintillator combination.

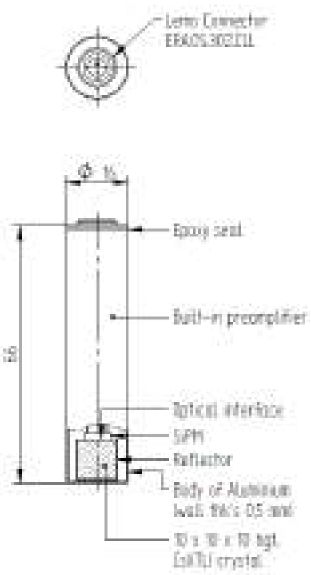


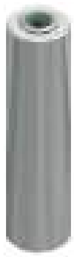


51 x 51 mm SiPm scintillation detector



30x30 mm NaI(Tl) / SiPm detector



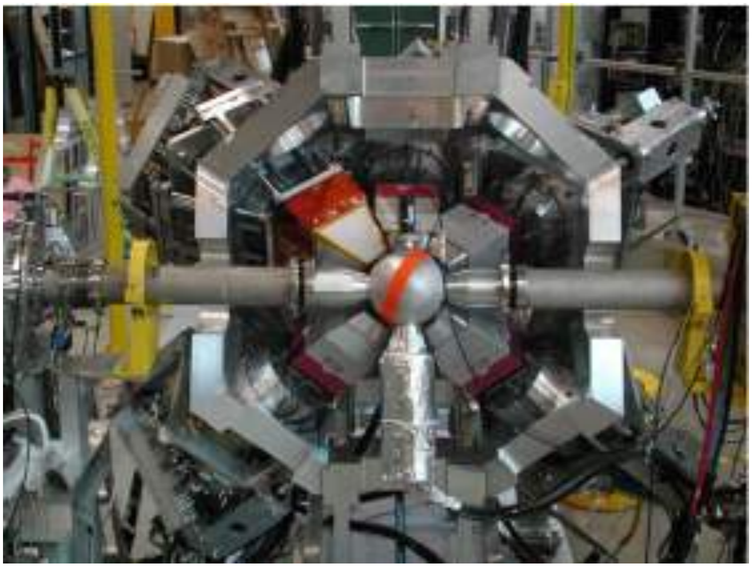


Miniature CsI(Tl) / SiPm detector

12.7. Specials

In fact, many SCIONIX scintillation detectors are specials with detector configuration and materials adapted to the specific requirements of the user. Among the special applications we would like to mention here **anti-Compton shields,** and **phoswhiches**.

Compton Suppression systems are scintillation detector assemblies mounted around a **High Purity Ge-detector (HPGe)** that detect the gamma rays Compton scattered by the Ge crystal and generate a **veto signal** when such a Compton event occurs. This improves the peak-to-total ratio in the pulse height spectrum of the Ge detector significantly.

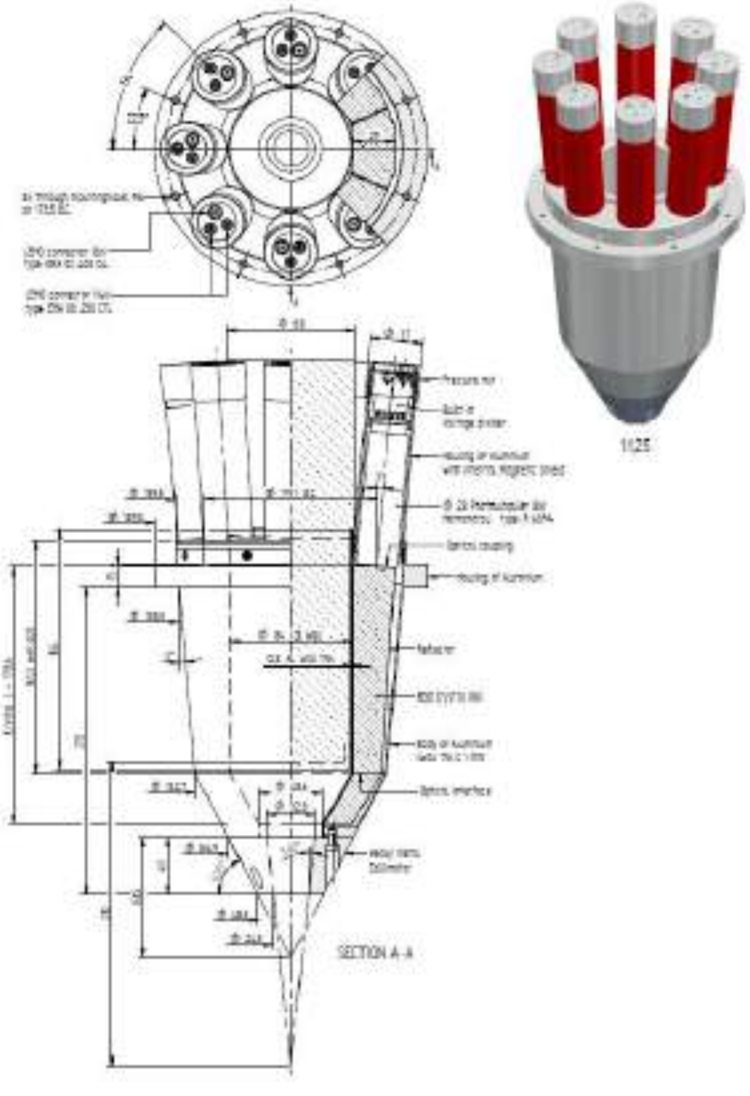


Compton suppression shields in Physics (Tigress experiment)

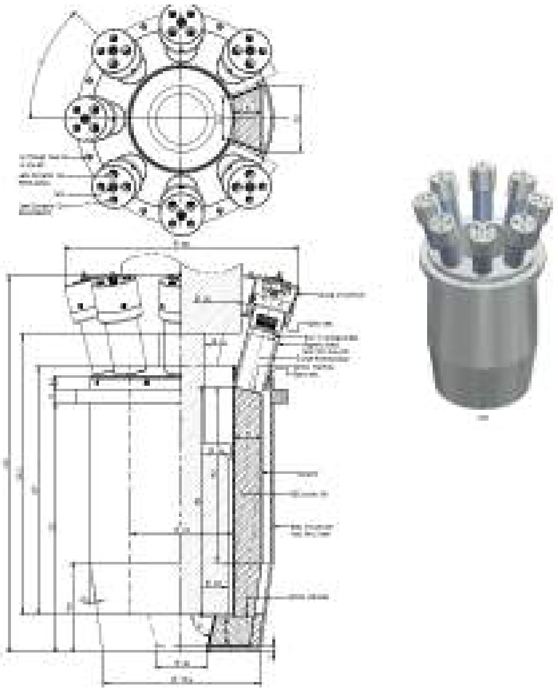
Crucial parameters are a large solid angle coverage around the HPGe detector and high stopping power. The use of segmented well-type BGO detectors is the generally accepted optimum approach, except for **low background systems** where the intrinsic high background of BGO is prohibitive and NaI(Tl) is normally used.

Another very important parameter is the lowest (Compton scattered) X-ray energy that can be detected. For optimum suppression one should be able to distinguish 15 keV from the noise. Below some examples are shown.

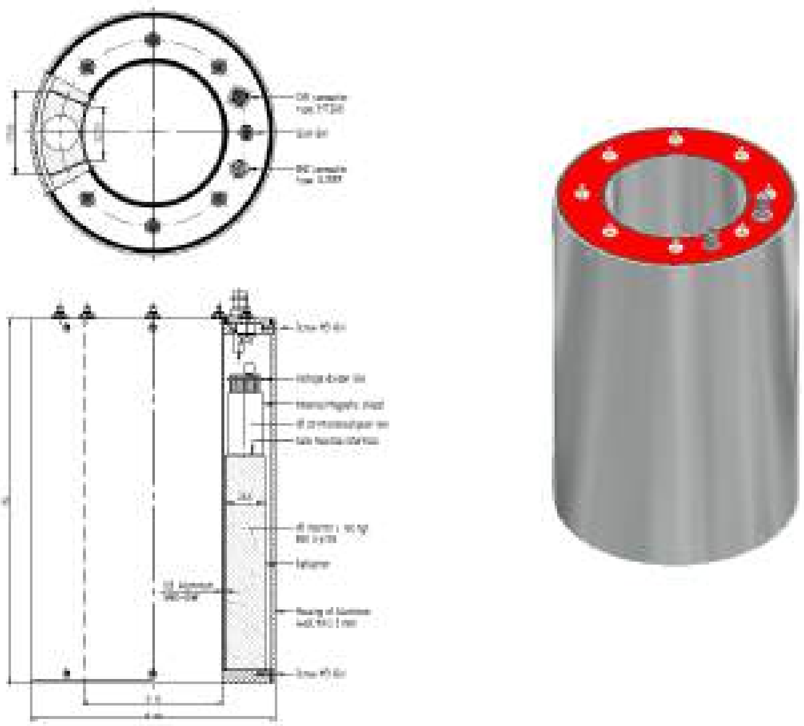
Compton suppression shields can be provided with **special backcatcher detectors** around the cryostat arm for optimum solid angle coverage. Many options are possible and we advise to contact SCIONIX to discuss the optimum configuration for your HpGe detector assembly.



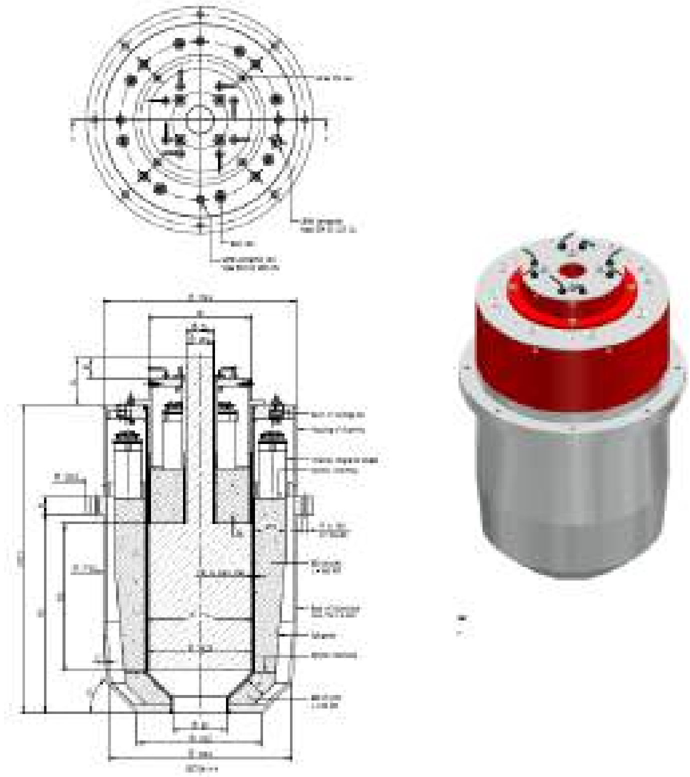
Standard BGO Compton suppression shield around a 83 mm diameter HpGe detector with "nose piece"



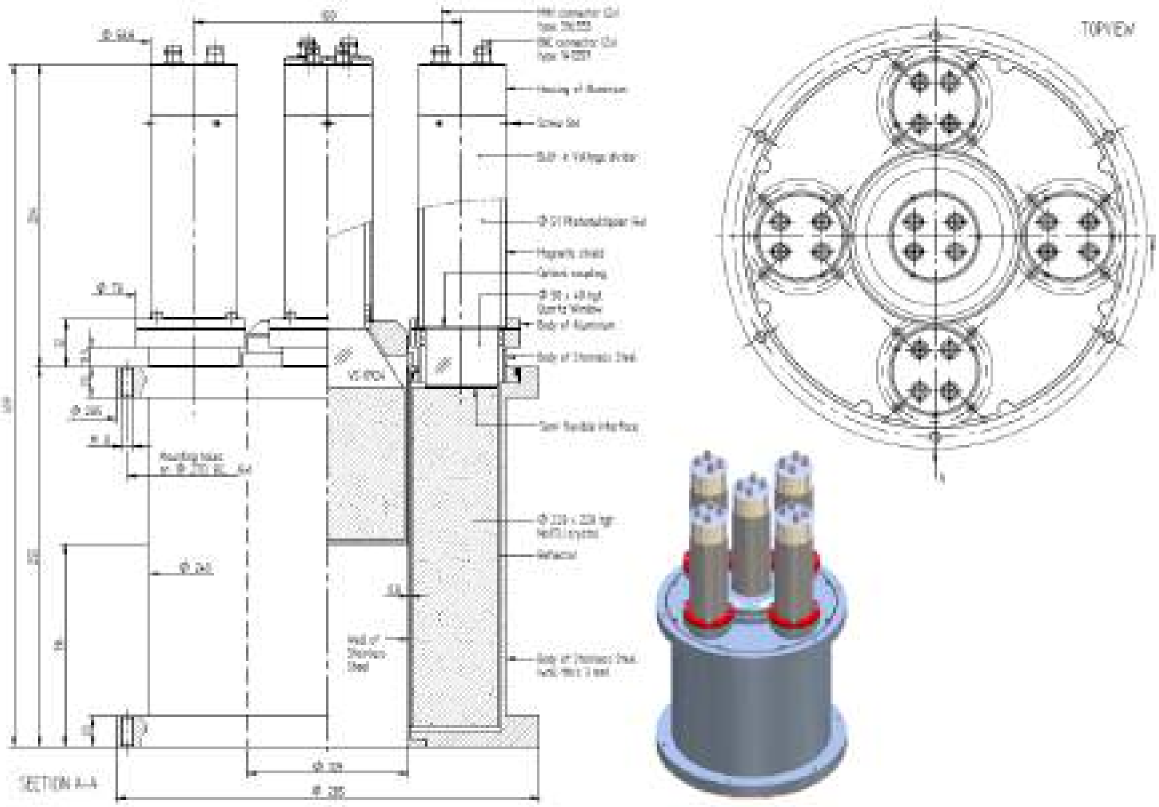
Standard BGO Compton suppression shield around a 78 mm diameter HpGe detector with flat "nose piece"



Straight annular BGO suppression shield around a 96 mm HpGe detector



BGO Compton suppression annulus with backcatcher



Low background NaI(Tl) annulus with backcatcher

Phoswiches are detectors employing a combination of two different scintillation materials. The application is low intensity detection of X-rays in the presence of a gamma-ray background. The (thin) primary scintillation crystal detects the radiation of interest and the secondary (guard) crystal detects background absorptions in the guard crystal and radiation that is scattered by the primary crystal and is absorbed in the guard crystal. This last aspect implies that by setting a **veto** in case of a **time coincidence** in signals between primary and guard crystal, the background contribution from the primary crystal can be reduced.

Both primary and guard crystal are read out with the same PMT. Whether a signal in the PMT originated from the primary or the guard crystal is determined by choosing scintillation materials having **different decay times**. Important is that the primary crystal cannot excite the secondary one optically. The most frequent combination is a NaI(Tl) and CsI(Tl) phoswich (effective decay time 0.27 μs and 1 μs) for low energy X-ray detection.

Signal separation is done by (digital) pulse shape discrimination for which it is important that the decay times of the two scintillators are sufficiently different.

Another classic example of a phoswich is the use of a ZnS(Ag) coated plastic scintillator in alpha/ beta detection (EJ444). Alpha particles are stopped in the thin ZnS(Ag) layer producing pulses with a decay time of approximately 100 ns whereas beta particles that loose energy in the plastic scintillator produce pulses with decay times of the order of a few ns.

Also other combinations of crystals are possible like $CeBr_3$ and NaI(Tl) crystals (decay times 23 ns versus 270 ns) in physics experiments.

13 Detector electronics

Scintillation detectors usually employ a Voltage Divider (VD) network to operate the photomultiplier tube. This sometimes called "bleeder network" defines a potential (voltage) difference between the cathode, dynodes and anode of the PMT. The exact design of this network is of influence for proper working of the scintillation detector. Some details of voltage divider networks are discussed below. The descriptions below are not exhaustive; for more details we refer to the photomultiplier manufacturer's literature.

13.1 Positive or Negative High Voltage?

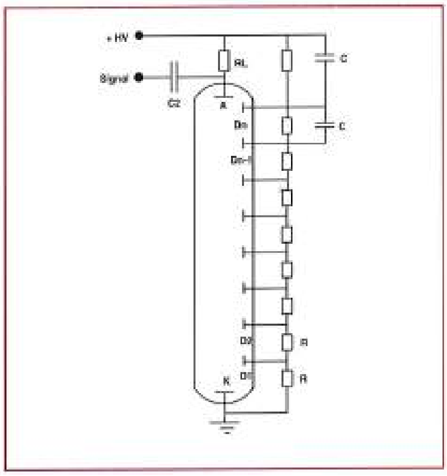
It is possible to operate a photomultiplier tube with either **A. anode at positive potential** (cathode at ground) or **B. anode at ground** (cathode at positive potential). For measurements of DC anode current such as in some X-ray applications, option B is the only choice since in the first option the anode must be separated from the follow-up electronics by means of a high voltage capacitor.

On the other hand, option A is used for most standard applications since the μ-metal shield should be preferably at cathode potential. Option A implies that cathode, detector mass (ground) and shield are all connected together. In option B, the shield must be very well insulated from the detector mass and special construction requirements apply.

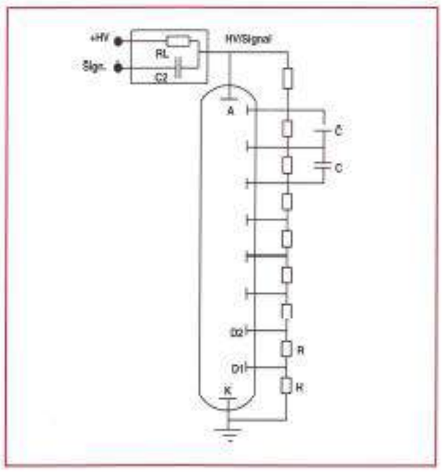
In all cases, a detector designed for POSITIVE high voltage operation, should NEVER be connected to a Plug-in Voltage divider wired for negative High Voltage since this will cause a dangerous situation with the detector housing at live potential!

All standard SCIONIX detectors with photomultiplier readout are designed for POSITIVE high voltage. A detector designed for NEGATIVE High Voltage has the suffix -NEG at the end of the type number.

Negative high voltage is preferred for fast timing applications to avoid poles in the output signal. Voltage dividers for Detectors operated at positive high voltage can be wired with a **single connector** for signal and HV. At the electronics' side, these can be separated using a simple splitter, as illustrated below.



Example of voltage divider for positive HV



Example of voltage divider with single connector and signal/HV splitter

13.2 Design of voltage dividers

The design of the voltage divider influences the performance of a detector. At high count rates, the voltage across dynodes may drop and the average bleeder current should be always defined as at least 10 times larger than the average anode current in the detector. A standard resistor value between dynodes is 470 kΩ which is a compromise between bleeder current and gain stability which is sufficient for count rates up to approx. 50.000 c/s.

Voltage dividers may be linear (most common), tapered or specially stabilized with Zener dynodes or transistors. The number of possibilities is large. A very important aspect is the potential (electric field) between the cathode and the first dynode of the PMT. In any case, this potential should be sufficient to ensure a good photoelectron collection efficiency. Usually, this voltage is defined by the PMT manufacturer.

The **gain** of a scintillation detector varies with each PMT and is also strongly influenced by the exact design of the voltage divider. If the absolute detector gain is of importance, it can be defined as: ***the output voltage (in e.g. 1 MΩ) at a specific operating voltage of the PMT for a certain energy absorbed in the detector.***

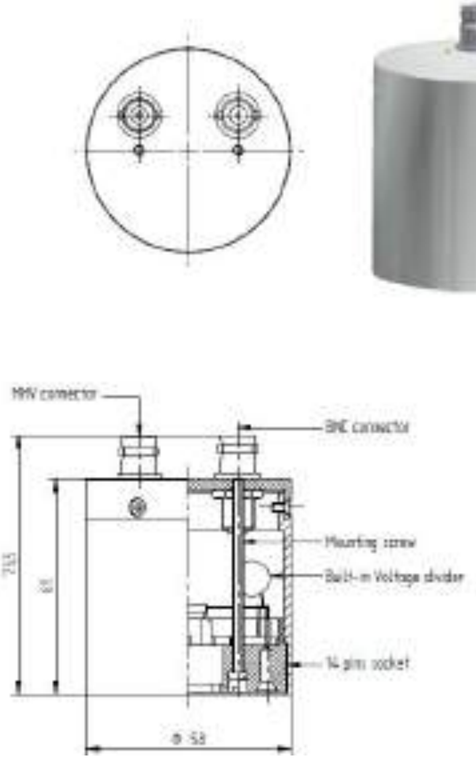
PMTs can be **selected** on gain but adjustment of the gain of the detector by varying the voltage in the VD by means of a precision potentiometer is much more convenient. **Extra options** on voltage dividers are e.g. a gain potentiometer, an extra dynode output or a focus potentiometer.

When asked for advice, SCIONIX can design the voltage divider best suited for your application without any additional cost.

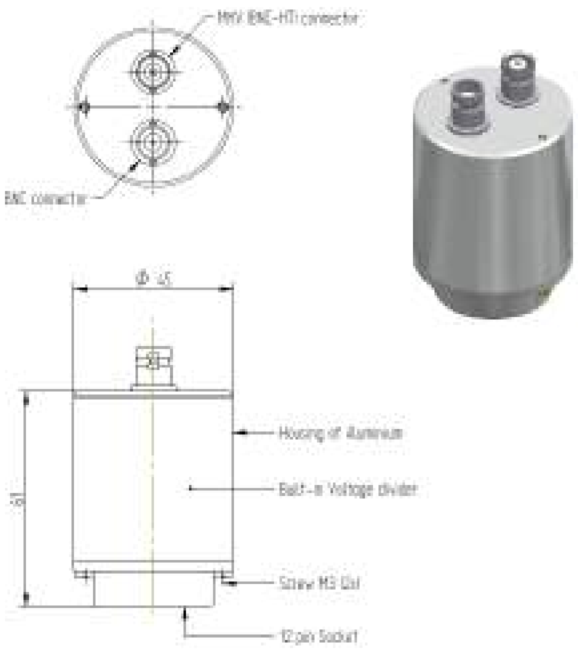
13.3 Plug-on or integrated?

Voltage Dividers and other electronics can be **incorporated** into the scintillation detector. In this case, the resistor network is **directly** soldered onto the pins of the PMT which implies a minimal length of the assembly. Also for low background applications this is the preferable option. The connector(s) for high voltage and signal are located at the back of the assembly. Also flying leads is an option.

When it is expected that detectors have to be interchanged often it may be preferable to use a so-called **"plug-on"** option in which case the voltage divider and associated electronics are mounted in a small base with the same diameter as the detector which is plugged on the pins of the socket of the PMT. Most frequently used PMT sockets in this respect are the 12 pins JEDEC B12-43 base for 38 mm diameter PMTs and the 14 pins JEDEC B14-38 base for 51, 76 and 127 mm diameter PMTs. These are also the standard sockets for scintillation detectors supplied without voltage divider. Below some examples are presented.



Standard plug-on voltage divider for 14 pins PMT sockets, VD 14 - E1.



Standard plug-on Voltage divider for 12 pins PMT sockets, VD 12 - E1.

13.4 Voltage dividers & preamplifiers.

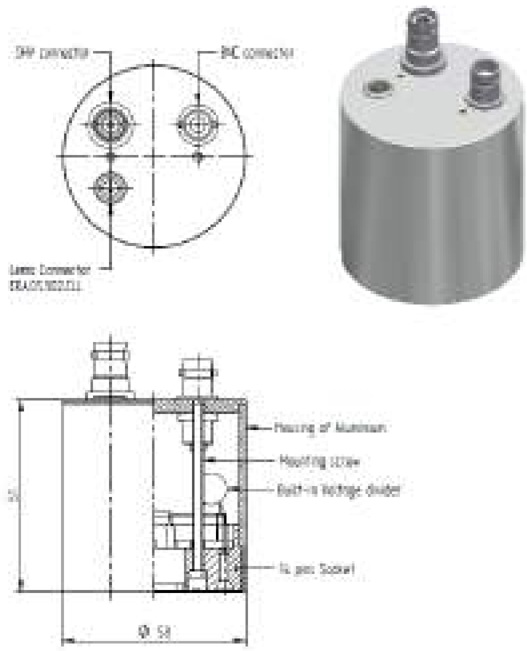
A detector signal will be attenuated in a long cable and when signals have to be transported over more say than 10 m of cable this effect cannot be neglected. Signals even may become deformed and signal differences between a set of detectors having different cable lengths can be a problem.

Furthermore, the signal that is to fed into a main amplifier (also called shaping amplifier or spectroscopic amplifier) needs to have a certain pulse fall time (typically 50 μs) in order to allow proper pole-zero and base-line correction. This effect is especially important at high count rates. For digital signal processors the preferable pulse fall times are usually of the order of a microsecond.

To solve the above problems, scintillation detectors can be supplied with a built-in (or plug-on) **preamplifier/buffer amplifier**. This amplifier has an output impedance of 50 Ω for proper matching to the most frequently used cable impedance (reflections).

The standard SCIONIX voltage divider/ preamplifier the VD (12) 14 - E2 is an example of this suited for a wide variety of PMTs. This amplifier operates with a wide variety of voltages, is very fast (rise time < 50 ns) and can drive cable lengths of 100 m or more. Varieties for ultra low power consumption exist and the amplifier is very small so that it will fit in almost every scintillation detector.

Please consult SCIONIX for your specific requirements regarding signal shape, power consumption etc.



Standard PLUG-ON voltage Divider / preamplifier model VD14-E2

13.5 Connectors

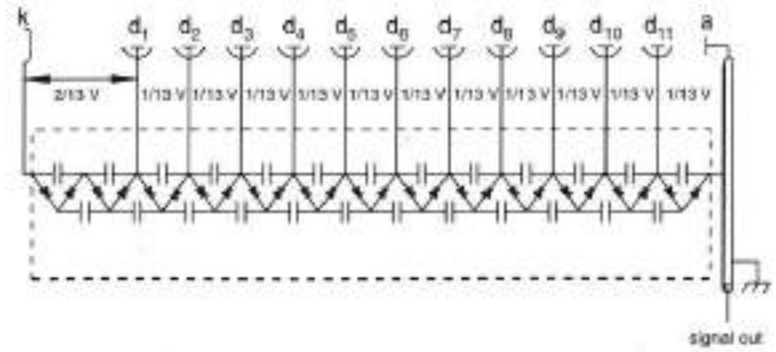
Often, high voltage, signal and preamplifier power are fed in via separate connectors The SCIONIX standard connector for high voltage is the **SHV** (Super High Voltage) connector, the most frequently used standard in nuclear electronics. For signals, **BNC** connectors are the standard and for preamplifier power signals, the **dual LEMO type 0S** and the **9 pins sub-D** connector are normally used.

Many other possibilities exist such as flying leads options, water-tight connectors, MHV, TNC, PET-100 and different types of LEMO or FISHER connectors.

13.6 Built-in High Voltage generators and other electronics

Recent developments in hybrid circuitry have allowed to incorporate a number of other electronic components **into** the scintillation detector assembly which eliminates in some applications the necessity of NIM based electronics.

An example of the above is the scintillation detector with a **built-in High Voltage Generator** (- HV option,). This can be a small Cockcroft - Walton (CW) generator which produces the high voltage required to operate a PMT. This unit only requires a DC voltage of + 5 V or + 12 V and requires only 100 mW of power. The unit is fully integrated with the PMT so there are no high voltage leads anywhere in the assembly. The gain of the PMT is maintained also at high anode currents (up to 100 μA) and the unit adds only 50 mm to the length of the PMT. The high voltage can be factory set, precision potentiometer adjustable or set by a (0-5V) regulating voltage. Below the advantages are summarized.



Advantages built-in (CW based) high voltage generators:

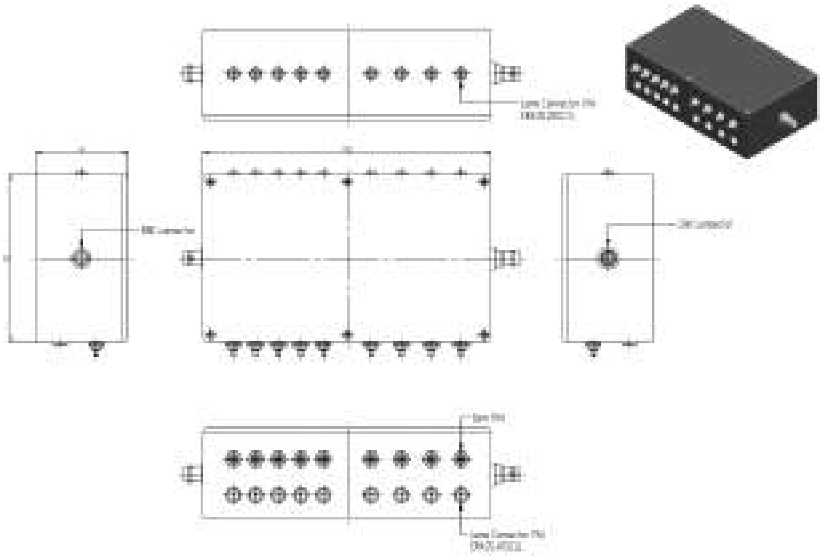
- Compact
- Low power consumption
- Sealed
- High gain stability versus count rate

When there is not enough space available also conventional high voltage generators can be incorporated in a detector assembly in combination with a voltage divider chain.

Besides the above mentioned preamplifiers it is also possible to incorporate e.g. **shaping amplifiers (spectroscopic amplifiers) or Single Channel Analyzers (SCAs)** into a detector assembly. All these components constructed as small SMD or hybrid circuits are very small in dimension. Specific parameters of these devices can be defined by the user Please consult SCIONIX for more details.

Scintillation detectors with **PIN photodiode** readout or with **SiPms** can be equipped with built-in charge sensitive preamplifiers or built in bias generator / preamplifiers.

For the effective operation of series of scintillation detectors with a single high voltage power supply SCIONIX offers junction boxes to sum signals and high voltage inputs. These modules can be equipped with built-in preamplifiers or high voltage modules.



Author: P. Schotanus

Note:

SCIONIX is not limited to manufacturing only the designs we present in this book.
The models illustrated only represent examples of types of detectors.
Many other options are possible.

The performance data we present in this handbook are Typical and not necessary guaranteed. Scionix reserves The right to alter designs and specifications without notice.

Whilst every effort is made to ensure accuracy of published information, Scionix cannot be held responsible for errors or consequences arising therefrom.

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