WPJET4 Gamma Camera Upgrade (GCU)

D05	*Report on M5:* Simulations of the best scintillator material for gamma ray spectroscopy measurements in the camera *31.12.2014*

1. Introduction

The DT-experiment in 1997 has shown that direct measurements of confined alpha particles are very difficult. Alpha-particle studies require a significant development of dedicated diagnostics. JET has now an excellent set of confined and lost α-particle diagnostics. However, in order to take full benefit from the future extensive DT campaign in 2017, a number of diagnostic upgrades are necessary, as stated in the "Work Plan for the implementation of the fusion roadmap in 2014-2018", see *GCU Project Management Plan* and references therein. Among these necessary upgrades, the gamma ray camera plays an important role as a very useful diagnostic tool for the study of confined α-particles as well as fast ions. The information provided by the upgraded gamma-ray camera, namely gamma ray spatial emissivity energy resolved, will complement the high resolution spectroscopy measurements provided by KM6S and KM6T spectrometers along radial and oblique line of observation, respectively. The gamma ray emission spectra of Gamma Camera are associated with specific reactions among fast ions or fusion alphas with impurities, e.g., $^{9}Be(\alpha, n\gamma)^{12}C$, and thus reconstruct the energy. From these data it is possible to measure the spatial distribution/redistribution of the fast ions and fusion alphas in selected ranges of their energy and to follow their evolution in time.

The energy and spatial distributions of fast ions in plasma are now measured in JET with the Gamma Camera, equipped with a detector array. The array comprises 19 CsI:Tl with a diameter of 20 mm and a thickness of 15 mm coupled to photodiodes. CsI:Tl crystals are characterised by a comparatively long scintillation decay time, about 1000 ns.

From a diagnostic point of view a high power D-T plasma represents a rather harsh environment. For operating the Gamma Ray Camera diagnostic at the high D-T neutron fluxes expected in the next high-power D-T campaign on JET and to improve its spectroscopic capability specific hardware improvements are needed. In particular, it is proposed to enhance the existing spectroscopic and count rate capability by replacing the 19 CsI detector with new faster and better energy resolution detector modules, e.g., $CeBr_3$ or $LaBr_3$:Ce detectors with a scintillation decay time about 20 ns. This is a challenging upgrade due to available space for detectors and shielding. The new detector must be able to sustain count rate in excess of 500 kHz and energy resolution equal or better than 5% at 1.1 MeV. New detector material should not contain oxygen to avoid unwanted background due to a reaction on oxygen. For both $LaBr_3$ and $CeBr_3$ scintillators, light yield is high and comparable, about $6\text{-}7\times10^4$ photons/MeV.

The $CeBr_3$ scintillator was found to fulfil low noise measurement conditions. It shows 30 times reduction in internal activity in comparison with $LaBr_3$. The $CeBr_3$ scintillator has a similar energy resolution, sensitivity and decay time as the $LaBr_3$ scintillator. Moreover, the $CeBr_3$ scintillator seems to be more resistant for gamma radiation than $LaBr_3$. A 1 kGy dose of gamma radiation deteriorates the yield of $LaBr_3$ by ~10% and worsens its energy resolution from 3.0 to 3.8%, while is almost negligible for $CeBr_3$.
$CeBr_3$ may also be more resistant to neutron radiation because of lower neutron capture cross section in Ce (~12 mb) than in La (~100 mb) at E_n ~30 keV [1-2]. These features make $CeBr_3$ an interesting alternative for JET plasma applications in spite of the excellent spectroscopic performances of $LaBr_3$ scintillator.

At NCBJ we performed both measurements and Monte Carlo simulations to find the best scintillator material for gamma ray spectroscopy measurements in the camera.

2. Measurements at NCBJ

All measurements were done at our laboratory at NCBJ. The list of gamma-ray sources used for evaluation of response of the detectors comprised:

- standard radioactive sources: ^{137}Cs (661.7 keV), ^{22}Na (511 keV and 1275 keV), ^{65}Zn (1116 keV) and ^{152}Eu (1408 keV),
- natural background gamma-rays from ^{40}K (1461 keV) and ^{208}Tl (2615 keV),
- PuBe: 4.4 MeV from $\alpha+^{9}$Be reaction,
- PuC: 6.1 MeV from $\alpha+^{12}$C reaction.

The measurements were performed using three samples of $CeBr_3$ scintillator, with crystal dimensions:

- cuboid 10×10×5 mm,
- cylinder Ø20×20 mm,
- cylinder Ø25×25 mm.

An important note

Due to high hygroscopicity of $CeBr_3$ material, all samples were encapsulated by the manufacturer (SCIONIX Holland B.V) in aluminium containers with quartz windows. As an example, a cylindrical shape $CeBr_3$ sample of 20 mm diameter and 20 mm height is presented in Fig. 1. The outer size of the container is 28 mm diameter and 24 mm height.

Fig. 1. Ø20×20 mm $CeBr_3$ scintillator, encapsulated in aluminium container with quartz window. The outer size of the container is 28 mm diameter and 24 mm height.

2.1. PIN-diode readout

The measurements with a PIN-diode readout were performed for all 3 scintillator samples. The tested $CeBr_3$ scintillators were coupled to a HAMAMATSU PIN-diode S3590-18 with 10×10 mm photosensitive area. The signal from the PIN-diode was sent to a CREMAT CR-110 preamplifier and was subsequently passed to an ORTEC 672 spectroscopy amplifier. Gaussian shaping of 1 μs was used for optimal signal-to-noise ratio and data was recorded with a TUKAN8K multichannel analyser (MCA).

High energy gamma-rays are registered by scintillators mainly due to electron-positron pair creation. Positron is than subject to annihilation with another electron into two 511 keV gamma-ray quanta. Detection of full gamma-ray energy requires that both of these 511 keV quanta are absorbed in the scintillator. In case when one or two of these 511 keV quanta escape, single escape (SEP) or double escape (DEP) peaks can be observed in the spectrum.

The energy spectra recorded with 3 $CeBr_3$ samples under irradiation of PuBe source emitting 4.4 MeV gamma-rays are presented in the left part of Fig. 2. The full energy peak (FEP) at 4.4 MeV is recorded only for 2 largest samples. Besides FEP, the SEP and DEP are observed at energies of 3.9 MeV and 3.4 MeV, respectively. For the smallest sample, only DEP is registered by the scintillator due to a low probability of 511 keV quanta absorption.

The right part of Fig. 2 shows the response of the tested $CeBr_3$ samples to PuC source that emits 6.1 MeV gamma-rays. The peaks corresponding to the detection of 6.1 MeV gamma-rays are substantially less intense. There are two reasons:

- the stopping power for 6.1 MeV is smaller,
- the intensity of our PuC source is much smaller compared to PuBe source (lower integrals despite longer measurement live time (LT)).

Measurements done with PuC source do not show any peaked structures in the region-of-interest (RoI) that is important for the GCU project, i.e. between 3.4 MeV (DEP) and 4.4 MeV (FEP), marked with vertical dashed lines in Fig. 2.

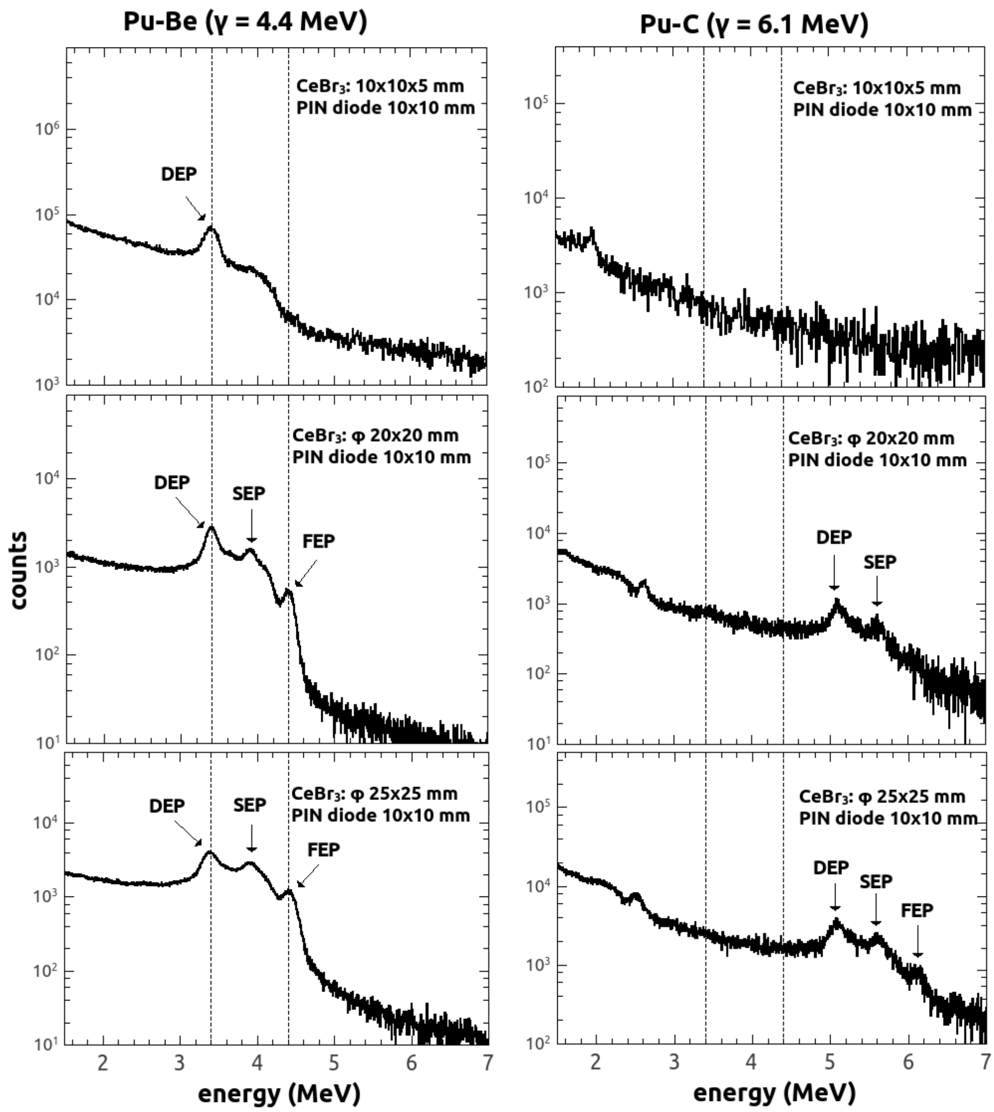

Fig. 2. Comparison of gamma spectra from PuBe and PuC sources for $CeBr_3$ scintillators: 10×10×5 mm, Ø20×20 mm, Ø25×25 mm, coupled to 10×10 mm PIN-diode. Dashed vertical lines are limiting the GCU region-of-interest.

Table 1 presents the integral numbers (netto) after background subtraction as measured for 3 tested samples with PuBe and PuC sources. Table 2 gives the ratio of number of counts, normalized to unity at the value registered for FEP for used detectors and sources.

Table 1. Number of counts (netto) from gamma spectra registered for PuBe and PuC sources for $CeBr_3$ scintillators and 10×10 mm PIN diode. Sources were placed at distance of 14 cm from a scintillator top surface.

Scintillator size [mm]	Number of counts							
	PuBe				PuC			
	Live time [s]	3.4 MeV (DEP)	3.9 MeV (SEP)	4.4 MeV (FEP)	Live time [s]	5.1 MeV (DEP)	5.6 MeV (SEP)	6.1 MeV (FEP)
10x10x5	80000	1048000 +/-430	-	-	70000	-	-	-
Ø20x20	7900	64700 +/-1100	18100 +/-1800	14000 +/-1800	70000	35100 +/-700	13200 +/-1000	2700 +/-700
Ø25x25	7200	102500 +/-5400	36500 +/-4500	27500 +/-1900	70000	93500 +/-2400	25700 +/-1600	11400 +/-700

Table 2. Relative intensity of gamma rays normalized to 1 for FEP.
Number of counts: from Table 1.

Scintillator size [mm]	Relative intensity					
	PuBe			PuC		
	3.4 MeV (DEP)	3.9 MeV (SEP)	4.4 MeV (FEP)	5.1 MeV (DEP)	5.6 MeV (SEP)	6.1 MeV (FEP)
10x10x5	-	-	-	-	-	-
Ø20x20	4.62 +/-0.60	1.29 +/-0.21	1	13 +/-3.4	4.9 +/-1.3	1
Ø25x25	3.73 +/-0.32	1.33 +/-0.19	1	8.20 +/-0.55	2.30 +/-0.20	1

2.2. Comparison between PIN-diode and PMT

The energy resolution of the cylindrical shaped $CeBr_3$ was measured using two types of photodetectors, a PIN-diode (HAMAMATSU S3590-18) with photosensitive area size of 10×10 mm and a photomultiplier (PMT – HAMAMATSU R6231-100) of 52 mm diameter. Fig. 3 presents the results obtained for several gamma-ray transitions, along with the fit to experimental data. The values registered in the energy range between 3.4 MeV and 5.6 MeV were not taken into account in the fitting procedure, as they are subject to deterioration caused by the Doppler effect [3].

The measured energy resolutions are summarized in Table 3. Despite the fact, that the PMT readout gives substantially better energy resolution than PIN-diode for gamma-ray detection below 2 MeV, the energy resolutions at higher energies are close for both photodetectors coupled to $CeBr_3$ crystals.
The drawback of using a PIN-diode for scintillation readout is a lack of the internal gain of a signal, therefore it is necessary to use a preamplifier close to the photodetector. Limited space available for detector module installation in the Gamma Camera is then a source of additional

constraints on the choice of a suitable preamplifier. The main problem that remains open for solving is maintaining of a good energy resolution at high count-rates.

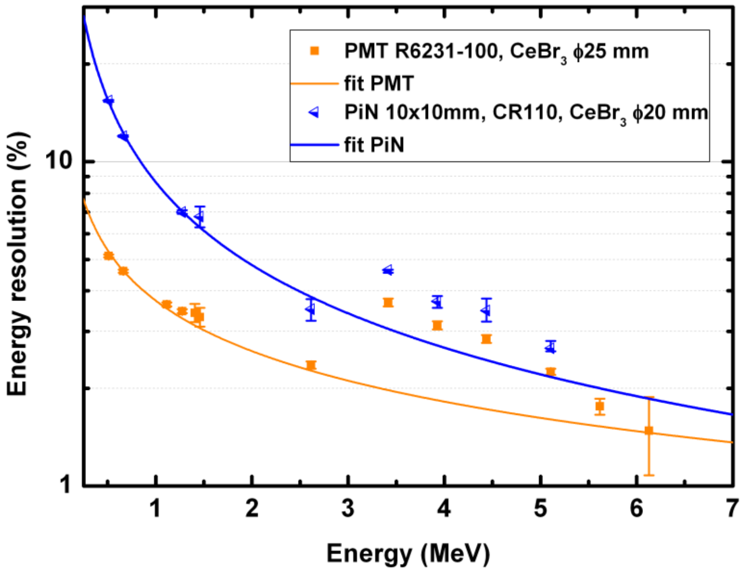

Fig. 3. The energy resolution of CeBr3 scintillator coupled to a PMT and a PIN-diode.

Table 3. Energy resolution measured for CeBr3 scintillators coupled to PMT and PIN-diode.

Source	E_γ (keV)	Energy resolution (%)	
		PMT Ø52 mm $CeBr_3$ Ø25×25 mm *)	PIN-diode 10×10 mm $CeBr_3$ Ø20×20 mm
^{22}Na	511	5.1 ± 0.1	15.4 ± 0.1
^{137}Cs	661.7	4.6 ± 0.1	12.0 ± 0.1
^{65}Zn	1116	3.6 ± 0.1	-
^{22}Na	1275	3.5 ± 0.1	7.0 ± 0.1
^{152}Eu	1408	3.4 ± 0.2	-
^{40}K	1461	3.3 ± 0.2	6.8 ± 0.3
^{208}Tl	2615	2.4 ± 0.1	4.3 ± 0.5
PuBe (DEP)	3416	3.7 ± 0.1	4.6 ± 0.1
PuBe (SEP)	3927	3.1 ± 0.1	3.7 ± 0.2
PuBe (FEP)	4438	2.8 ± 0.1	3.5 ± 0.3
PuC (DEP)	5106	2.3 ± 0.1	2.7 ± 0.1
PuC (SEP)	5617	1.8 ± 0.1	-
PuC (FEP)	6128	1.5 ± 0.4	-

*) The energy resolution is expected to be the same for Ø20×20 mm and Ø25×25 mm $CeBr_3$ scintillator coupled to a Ø52 mm PMT, assuming equal quality of tested samples.

2.3. MPPC readout

The measurements with MPPC photodetector were done using HAMAMATSU MPPC array S12642-0404PA made in Through Silicon Via (TSV) technology.
The tested MPPC array consisted of sixteen single 3×3 mm MPPC elements placed in 4×4 matrix that was used as a single photodetector with 12×12 mm photosensitive area.
The scintillator used for the tests was Ø20×20 mm $CeBr_3$. For the purpose of described below tests, a signal from the MPPC was preamplified using a CANBERRA 2005 preamplifier and was subsequently sent to a CANBERRA 2022 spectroscopy amplifier. The amplifier output was read out by a TUKAN8K MCA. However, in principle signal produced by the MPPC photodetector does not need to be amplified, as the gain of this device can be as high as that of typical PMT (~10^6).

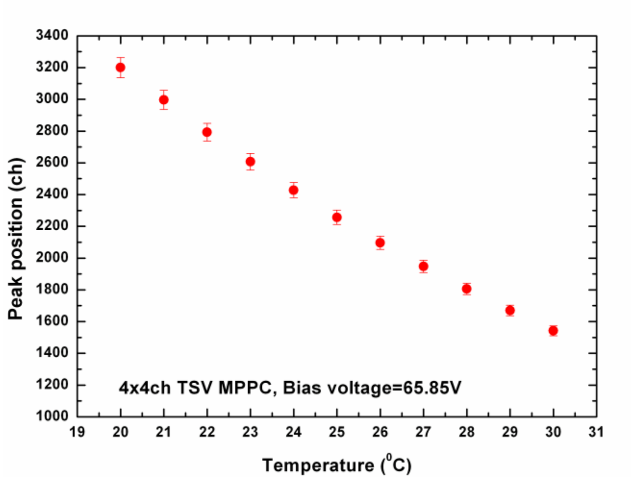

Fig. 4. Peak position as a function of temperature.

Fig. 4 presents the dependence of the pulse amplitude registered for 662 keV gamma-rays with MPPC as a function of ambient temperature. Measurements were done in a climatic chamber at temperatures varied from +20^{0}C to +30^{0}C with 1^{0}C step. The accuracy of temperature readout was equal to 0.2^{0}C. Bias voltage was constant and equal to 65.85 V. The temperature change by +1°C resulted in the shift of the peak position by (-7.6±0.7)% due to three reasons:

- reduction of the overvoltage (gain) of the MPPC,
- reduction of the photon detection efficiency (PDE),
- increase of the range of linear response.

Due to the fact that the gain of the MPPC depends on the bias voltage, the relation between the amplitude of 662 keV gamma-rays and bias voltage was investigated. The measurements were performed in a climatic chamber, the temperature was kept constant at +25°C. In Fig. 5 a peak position vs. bias voltage is plotted in the range between 65.75 V to 65.95 V. Change of the bias voltage by +10 mV shifts the position of the registered peak by +1 %.

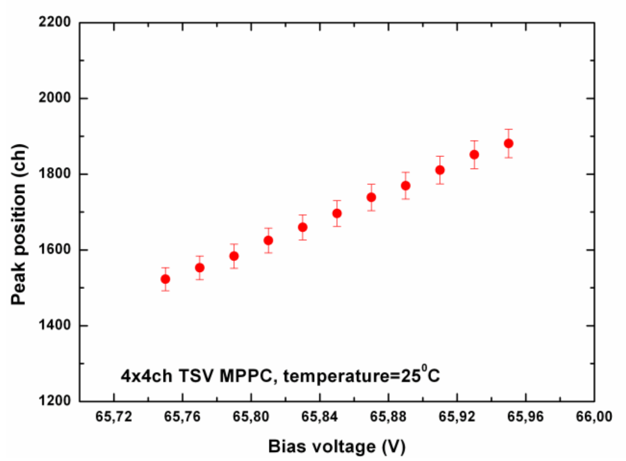

Fig. 5. Peak position as a function of bias voltage.

The studies on the response of $CeBr_3$ coupled to MPPC will be continued with measurements for high energy gamma-ray sources. MPPC photodetectors require optimization in order to increase the range of a linear response to absorbed energy and ensure a sufficient energy resolution. Further tests are planned to quantify the performance of MPPC in terms of linearity and energy resolution at the Gamma Camera energy of interest.

Application of MPPC photodetector has significant advantages in comparison with PIN-diode for scintillation readout, because MPPC has a large internal gain (~10^6) and PIN-diode gain is equal to unity. Therefore, MPPC output signal should be easily driven through 80 m cables even without a preamplifier. This useful feature results in high count rate capability. However, there are few problems that need to be addressed:

- gain stabilization upon temperature fluctuations,
- correction for non-linear response at high gamma-ray energy,
- evaluation of MPPC sensitivity to neutron damage.

3. Monte Carlo Simulations with Geant4 scintillator irradiated by gammas with energies of 4.4 and 6.0 MeV

To find geometrical dimensions for the scintillator which are optimal for measurements in the energy range 1-6 MeV, the Monte Carlo simulations were performed with the Geant4 code. An energy resolution of 4% was assumed in simulations. The 10^6 parallel gammas with energy of 4.4 and 6.0 MeV were incident on a scintillator surface.
As an example, in Fig. 6 gamma spectra obtained from Monte Carlo simulations are shown for scintillators with dimensions, as described in the figure caption.

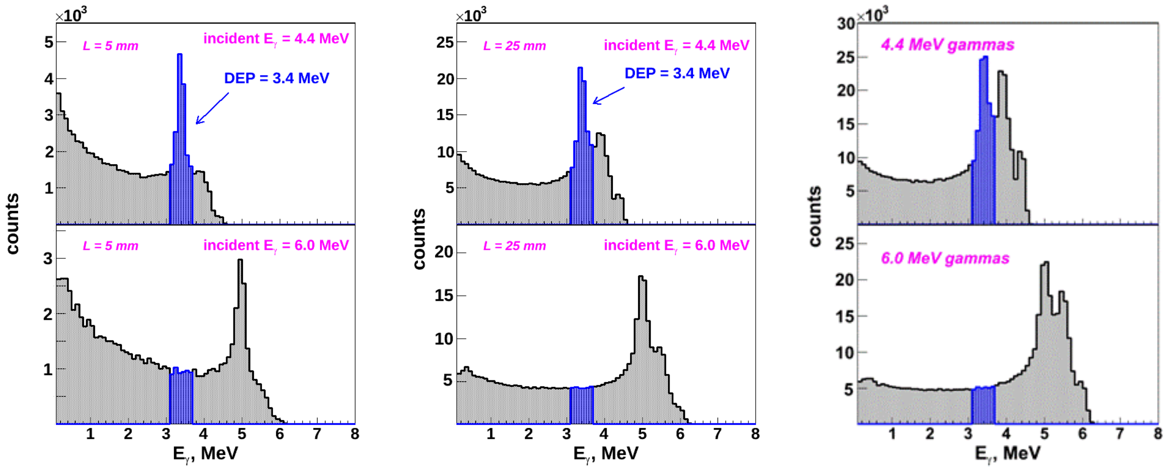

Fig. 6. In the left part, spectra obtained for a scintillator with a diameter of 20 mm and a thickness of 5 mm irradiated by gammas with energies of 4.4 (upper) and 6.0 MeV (lower) are compared. In the central part, such a comparison is shown for a scintillator with a a diameter of 20 mm and thickness of 25 mm. In the right part, the scintillator has dimensions of 35×35 mm.

To find an optimal thickness of the scintillator, a figure of merit (FoM) equal to a ratio between a DEP intensity for 4.4 MeV gamma-ray, located at 3.4 MeV, and a number of events in the background, at the same energy range produced in the detector by 6.0 MeV gammas, is considered. The simulation results for scintillators with a thickness from 5 to 28 mm show that the optimal scintillator thickness is around 25 ~~5~~ mm for FoM defined above.

4. Conclusions

1. From measurements and simulations, including existing space constraints, we will be able to find an optimal detector setup, based on crystals with a relatively short scintillation decay time.
2. $CeBr_3$ scintillator coupled to PIN-diode readout provides sufficient energy resolution less than 5% at Gamma Camera energy of interest.
3. The drawback of using a PIN-diode for scintillation readout is a lack of the internal gain of a signal, therefore it is necessary to use a preamplifier close to the photodetector, not in a separate location in a cubicle.
4. Limited space available for a detector module installation in the Gamma Camera is a source of additional constraints choosing a suitable preamplifier.
5. Problem that remains open for a solution with a PIN-diode photodetector is maintaining of a good energy resolution at high count-rates.
6. MPPC photodetector has a significant advantage over PIN-diode used for scintillation light readout: MPPC has a large internal gain ($\sim 10^6$) and does not need a preamplifier.
7. Problems that remain open for solving with MPPC photodetector are:
   - gain stabilization upon temperature fluctuations,
   - correction for non-linear response at high gamma-ray energy,
   - evaluation of MPPC sensitivity to neutron damage.

References

[1] H. Beer et al., „Neutron capture cross section on 138 Ba, 140,142Ce, 175,176Lu and 181Ta at 30 keV", Phys. Rev. C 21 (1980) 534.
[2] A. Musgrove, „Resonant neutron capture in 139La", Australian Journal of Physics 30 (1977) 599.
[3] Glenn F. Knoll, „Radiation Detection and Measurement", 3rd edition (2010).