AIP Review of Scientific Instruments

Experimental investigation of silicon photomultipliers as compact light readout systems for gamma-ray spectroscopy applications in fusion plasmasa)

M. Nocente, A. Fazzi, M. Tardocchi, C. Cazzaniga, M. Lorenzoli, C. Pirovano, M. Rebai, C. Uboldi, V. Varoli, and G. Gorini

Citation: Review of Scientific Instruments **85**, 11E108 (2014); doi: 10.1063/1.4886755
View online: http://dx.doi.org/10.1063/1.4886755
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/85/11?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in

Ion-induced gamma-ray detection of fast ions escaping from fusion plasmasa)
Rev. Sci. Instrum. **85**, 11E804 (2014); 10.1063/1.4886764

Improved time response for large area microchannel plate photomultiplier tubes in fusion diagnosticsa)
Rev. Sci. Instrum. **85**, 11E601 (2014); 10.1063/1.4886759

Ultra-high speed photomultiplier tubes with nanosecond gating for fusion diagnosticsa)
Rev. Sci. Instrum. **83**, 10D301 (2012); 10.1063/1.4728313

D-T gamma-to-neutron branching ratio determined from inertial confinement fusion plasmasa)
Phys. Plasmas **19**, 056313 (2012); 10.1063/1.4718291

Development and characterization of sub-100 ps photomultiplier tubesa)
Rev. Sci. Instrum. **81**, 10D318 (2010); 10.1063/1.3475718

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 149.132.2.36 On: Tue, 22 Jul 2014 15:33:31

Experimental investigation of silicon photomultipliers as compact light readout systems for gamma-ray spectroscopy applications in fusion plasmas[a)]

M. Nocente,[1,2,b)] A. Fazzi,[3,4] M. Tardocchi,[2] C. Cazzaniga,[1] M. Lorenzoli,[3,4] C. Pirovano,[3,4] M. Rebai,[1] C. Uboldi,[3] V. Varoli,[3] and G. Gorini[1,2]
[1]*Dipartimento di Fisica "G. Occhialini," Università degli Studi di Milano-Bicocca, Milano, Italy*
[2]*Istituto di Fisica del Plasma "P. Caldirola," EURATOM-ENEA-CNR Association, Milano, Italy*
[3]*Dipartimento di Energia, CeSNEF, Politecnico di Milano, Milano, Italy*
[4]*Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Milano, Italy*

(Presented 5 June 2014; received 31 May 2014; accepted 18 June 2014; published online 22 July 2014)

A matrix of Silicon Photo Multipliers has been developed for light readout from a large area 1 in. × 1 in. $LaBr_3$ crystal. The system has been characterized in the laboratory and its performance compared to that of a conventional photo multiplier tube. A pulse duration of 100 ns was achieved, which opens up to spectroscopy applications at high counting rates. The energy resolution measured using radioactive sources extrapolates to 3%–4% in the energy range $E_\gamma = 3$–5 MeV, enabling gamma-ray spectroscopy measurements at good energy resolution. The results reported here are of relevance in view of the development of compact gamma-ray detectors with spectroscopy capabilities, such as an enhanced gamma-ray camera for high power fusion plasmas, where the use of photomultiplier is impeded by space limitation and sensitivity to magnetic fields. [http://dx.doi.org/10.1063/1.4886755]

I. INTRODUCTION

Gamma ray spectroscopy is one of the few diagnostic techniques capable to measure suprathermal ions in high power fusion plasmas, as demonstrated at JET.[1–6] The instrumentation used typically consists of photomultiplier tubes (PMTs) for light readout coupled to inorganic scintillators, which view the plasma along a single line of sight. Information on the energy spectrum of gamma-ray emission is then complemented by profile measurements along multiple lines of observation by camera systems that, however, have null or very limited spectroscopy capabilities.[7] Clearly, combining spectral and profile information, for example, by enabling spectroscopy measurements in each channel of a gamma-ray camera, would be highly desirable.

A practical problem to achieve this goal is, however, space limitation, besides sensitivity to magnetic field, that often rule out the possibility to use PMTs as light readout systems in a gamma-ray camera and advocate for more compact solutions. A possibility may be represented by a recent development of light readout technology, Silicon Photomultipliers (SiPM), that are gaining an increasing role as possible replacements of PMTs. A SiPM is a two-dimensional array of a large number of cells consisting of a single photon avalanche diode (SPAD) and the relevant integrated quenching resistor. Each cell can be activated when hit by a single photon.[8] The output signal of a SiPM is proportional to the number of SPAD cells that get simultaneously activated, which in turn scales linearly with the number of impinging photons. Presently SiPMs, being also insensitive to magnetic fields, are widely used in Positron Emission Tomography,[9] where they are typically coupled to small size ($<$0.1 cm^2) LYSO crystals for measurements of the 511 keV electron-positron annihilation radiation. Their use for gamma-ray spectroscopy applications in fusion plasmas is new and not straightforward, as it requires the development of large area SiPMs to cover more extended crystal surfaces, needed to measure gamma-rays of energies higher than 511 keV. Besides, a fast ($\leq$100 ns) output signal and an energy resolution and linearity similar to that obtained with PMTs must be preserved.

In this paper we present a matrix of 12 SiPMs coupled to a large area (1 in. diameter) $LaBr_3$ crystal. The system has been characterized in the laboratory with radioactive sources and its performance compared to that of a conventional PMT, both in terms of time properties and energy resolution. Factors affecting the energy resolution of the system are identified and possible solutions for future improvements are indicated.

II. DEVICE PROPERTIES

The device developed is shown in Figure 1. It consists of a matrix of 12 SiPMs connected in parallel and arranged in a crossed shape.

Each of the twelve 5.1 mm × 5.1 mm SiPM units, built by ST Microelectronics,[10] is made of 4 × 830 SPAD cells. The matrix was characterized by measuring its current and capacitance as a function of the positive bias voltage V_{bias} applied to the cathode, as shown in Figure 2. The capacitance has the $1/\sqrt{V_{bias}}$ dependence expected for a semiconductor, approaching a value of 12 nF at $V_{bias} = 30$ V, that corresponds to 1 nF per SiPM unit. The current is constant (3 nA) up to $V_{bias} = 27.5$ V and then rises sharply up to about $V_{bias} = 29$ V.

[a)]Contributed paper, published as part of the Proceedings of the 20th Topical Conference on High-Temperature Plasma Diagnostics, Atlanta, Georgia, USA, June 2014.
[b)]Author to whom correspondence should be addressed. Electronic mail: massimo.nocente@mib.infn.it

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 149.132.2.36 On: Tue, 22 Jul 2014 15:33:31

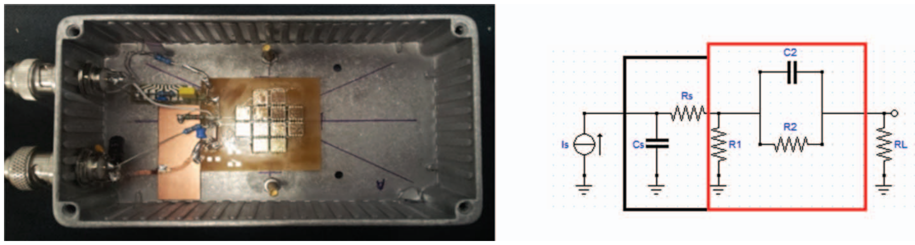

FIG. 1. Picture of the 12x SiPM matrix (left) with a simple circuital model of the device (right). The SiPM matrix is represented by the capacitance C_s and resistance R_s in the black box, together with the current generator I_s. The red box shows the pole-zero cancellation network installed right after the matrix. R_L is the load resistance.

This corresponds to the breakdown, i.e., the transition of each SPAD to its Geiger like regime of operation. After the breakdown, the current asymptotically follows Ohm's law.

It is worth noticing that the I-V curve of the device is very steep in the breakdown region, which implies that different SiPM units have the same breakdown point. This is an important requirement to ensure an overall uniformity of the response to light and is the result of individually selecting the SiPMs used to build the matrix from those processed on the same silicon wafer at the fabrication stage. In fact, the breakdown voltage is strongly sensitive to the distribution of impurities and defects in silicon and thus, even when the same wafer is used to fabricate SiPMs, a uniform response is not granted.

A 1 in. × 1 in. (diameter × height) $LaBr_3$ crystal was put in contact with the SiPM matrix using a thin layer of optical grease to optimize light transmission. The whole device was then sealed to ensure operation in a dark environment. The output signal was digitized using CAEN DT5751 (1 Gsample/s; 10 bits).

Figure 3 (left) shows a pulse from a ^{137}Cs radioactive source put in vicinity of the $LaBr_3$ crystal. The measured amplitude at the full energy peak was between 100 and 300 mV, depending on V_{bias} in the range 29–31 V. Setting $V_{bias} = 30$ V, the pulse has a rise time of 40 ns and a decay time of 550 ns, which significantly exceed those typically observed with the same crystal when coupled to a Hamamatsu R10233 PMT (rise time of 25 ns and decay time of 60 ns). The rise and decay times are here defined as the interval between the times at which the pulse reaches 10% and 90% of its maximum amplitude on the leading and falling edge, respectively.

The observed pulse shape and duration can be explained with the following simple circuital model of the device. Let assume the light emission from the $LaBr_3$ crystal to be represented by a single exponential $\exp(-t/\tau_C)$ and that the SiPM matrix consists of a capacitance $C_s = 12$ nF and resistance R_s connected in parallel as in Figure 1 (right), black box. In the domain of the complex frequency s, an output pulse V(s) $\propto 1/(s + 1/\tau_c) \cdot 1/(s + 1/\tau_S)$ with $\tau_S = R_S C_S$ is obtained, that can be Laplace transformed to time domain to give V(t) $\propto \exp(-t/\tau_C) - \exp(-t/\tau_S)$. The red curve in Figure 3 (left) shows a fit to data using a slightly modified version of this formula, i.e.,

$$V(t) = \begin{cases} A \quad if \quad t < t_0 \\ \mathrm{A+N} \cdot (\exp(-(t-t_0)/\tau_1) - \exp(-(t-t_0)/\tau_2) \;, \\ \text{if} > t_0 \end{cases} \tag{1}$$

in which A, N, and t_0 are fit parameters for the non zero offset, pulse amplitude, and start time, respectively. There is a good agreement between fit and data, which validates our simple model. From the fit, we obtain $\tau_1 = 26$ ns and $\tau_2 = 250$ ns. The simple model also suggests that the long decay time $\tau_2 = \tau_S$ is due to the large capacitance of the matrix, which is the result of summing up the capacitance of each SiPM unit connected in parallel in our matrix arrangement. As obtaining a fast output pulse is mandatory for high rate applications, a pole-zero cancellation network has been designed and tested (Figure 1 (right), red box).[11] The parameters of the network were chosen to cancel out the $1/\tau_S$ pole introduced by $R_S C_S \approx 250$ ns and to replace it with a shorter time constant of about 6 ns. The reduction in pulse amplitude after the network was compensated by use of a non-inverting fast amplifier based on the THS3001 Operational Amplifier by Texas Instruments, providing a gain of 40. The resulting pulse is illustrated in Figure 3 (right). The new rise time is 10 ns and the decay time is 90 ns, so that the pulse duration well compares to that typically achievable with a PMT. More

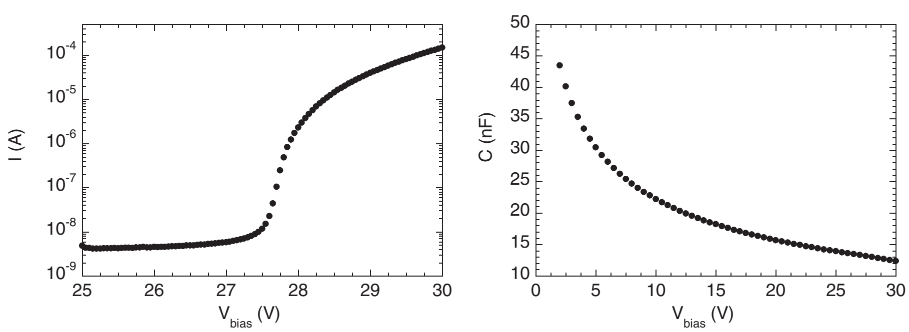

FIG. 2. Current vs. voltage (left) and capacitance vs. voltage (right) curves measured for the 12x SiPM matrix.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 149.132.2.36 On: Tue, 22 Jul 2014 15:33:31

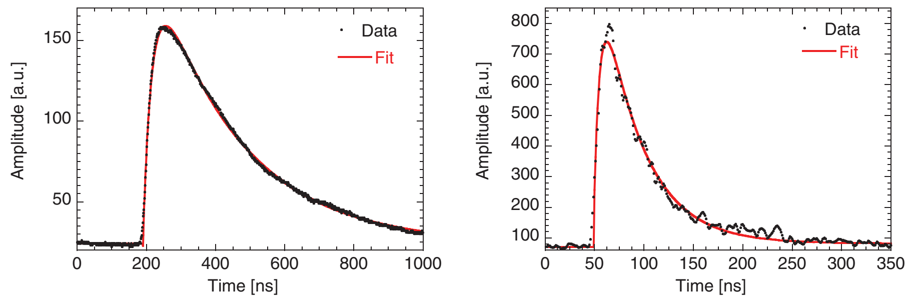

FIG. 3. Output pulses from a ^{137}Cs source using the 12x SiPM for light readout, before (left) and after (right) the installation of a dedicated pole-zero cancellation network. The red curves are fits to data using Eq. (1).

accurately, a fit to the data using Eq. (1) yields $\tau_1 = 6$ ns and $\tau_2 = 41$ ns. This result demonstrates that similar fast signals can be obtained using $LaBr_3$ coupled to a SiPM or PMT.

A closer inspection to Figure 3 (right) also shows that there are fluctuations superimposed to the predicted pulse shape, on a typical time scale of 10 ns. These are due to the combination of after pulsing and dark counts, both unavoidable in a SiPM device.[12] Similar fluctuations were observed on the oscilloscope even before the installation of the pole-zero network, but they were modulated over a much longer time scale, say >100 ns.

III. MEASURED ENERGY SPECTRUM AND RESOLUTION

The SiPM matrix was used to study the energy resolution achievable with this readout system coupled to a 1 in. × 1 in. $LaBr_3$ crystal. The experimental setup was the same as described in Sec. II. Laboratory radioactive sources of ^{22}Na (E_γ = 511 keV), ^{137}Cs (E_γ = 662 keV), and ^{60}Co (E_γ = 1173 and 1333 keV) were employed to obtain gamma rays of different energies.

The pulse height spectrum (PHS) was reconstructed from the waveforms recorded with the CAEN DT5751 digitizer based on a fitting procedure. In a first stage, a prefit with Eq. (1) was performed, at a given V_{bias}, to determine the τ_1 and τ_2 parameters for an average pulse. These parameters were then kept constant for all pulses. In a second stage, the fitting routine determined A, N, and t_0 for each pulse. A PHS spectrum was finally built from the height of each fitted pulse shape. A similar algorithm was used previously for $LaBr_3$ coupled to a PMT and was shown to provide an energy resolution matching the expected one.[13,14]

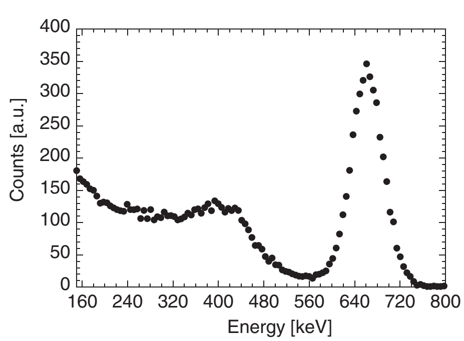

FIG. 4. Energy spectrum from a ^{137} Cs source measured in the laboratory using the 12x SiPM for light readout at V_{bias} = 31.5 V.

Figure 4 shows the energy spectrum of a ^{137}Cs radioactive source measured at V_{bias} = 31.5 V. The calibration was obtained based on the measured position of the full energy peaks of the ^{22}Na, ^{137}Cs, and ^{60}Co gamma-ray sources. The energy resolution (FWHM) is 8.6%, which can be compared to 4% obtained with ^{137}Cs using a Hamamatsu R10233 PMT for light readout. No significant difference was observed in terms of energy resolution before and after the installation of the pole-zero cancellation network.

The energy resolution R as a function of V_{bias} is shown in Figure 5 (left) for gamma-rays of different energies. The error bars are those derived from the Poisson statistics of the measured spectra. R improves with increasing V_{bias}, until a plateau region is reached for $V_{bias} > 31$ V, where the resolution is practically unchanged, within error bars. Here we note an added fluctuation in the case of ^{60}Co. The reason is the increased uncertainty in background subtraction due to the vicinity of the two 1173 and 1333 keV peaks in the energy spectrum of ^{60}Co. Although the plateau region of Figure 5 (left) may also extend above V_{bias} = 33 V, there is no advantage in operating the device in this region.

Figure 5 (right) shows the average value of the resolution at the plateau, as a function of energy. Data are well described by the $1/\sqrt{E}$ dependence expected from Poisson statistics (red curve), within the statistical uncertainties. From the $1/\sqrt{E}$ curve a resolution between 3% and 4% can be extrapolated in the energy range E_γ = 3–5 MeV, which is of interest for gamma-ray observations in fusion plasmas, for example, at JET.[1–6] Such energy resolution already enables spectroscopy studies in a gamma-ray camera system based on $LaBr_3$ coupled to SiPM. Here, with the word spectroscopy, we mean the capability to distinguish peaks with an energy separation of typically 200–300 keV, as for gamma-rays in the range E_γ = 3–5 MeV from fusion reactions, which is not possible in present gamma ray camera systems.

IV. DISCUSSION AND OUTLOOK

The count rate capability and energy resolution of the $LaBr_3$-SiPM system developed already meet the requirements envisaged for gamma-ray spectroscopy applications in camera systems of fusion plasmas. Improvements are, however, desirable, especially with regard to achieving the same energy resolution obtained by coupling $LaBr_3$ to PMTs. There are

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 149.132.2.36 On: Tue, 22 Jul 2014 15:33:31

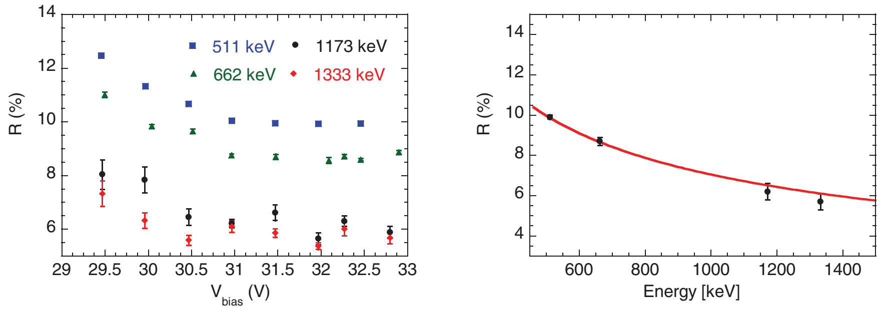

FIG. 5. (Left) Energy resolution R obtained in the laboratory as a function of V_{bias} for gamma-rays of different energies. A plateau in the data, which is reached for V_{bias} in the range 31–33 V, can be seen. (Right) Average energy resolution as a function of energy at the plateau shown with a $1/\sqrt{E}$ curve fit.

here two parameters affecting the resolution: the geometric efficiency, i.e., the ratio between the crystal area and that covered by the SiPM matrix; and the photon detection efficiency (PDE), that is the probability for a photon impinging on the matrix to give rise to an electric signal. The PDE is in turn the product of three factors: the quantum detection efficiency (QDE), the device fill factor, and the discharge probability.[12] A straightforward improvement for our device would be to achieve a wider coverage of the crystal surface by the SiPM matrix, contributing to an estimated gain of 20% at most in the geometric efficiency. As far as the PDE is concerned, a more substantial improvement of factor 2 may be achieved by better matching the crystal peak emission wavelength (380 nm) with the peak absorption wavelength of SiPMs (450 nm).[10] This can be obtained thanks to the recent development of new SiPMs, whose maximum QDE (≈18%) would be shifted towards blue light, thus closer to the emission wavelength of $LaBr_3$.[15] Alternatively, a wavelength shifter may be used to convert 380 nm photons to higher wavelengths. Both solutions will be tested in the near future. From these arguments, we may thus expect to decrease R by $\sqrt{(1.2 \times 2)} \approx 1.6$, yielding R ≈ 5.5% at $E_\gamma = 662$ keV, by the development of a new optimized SiPM matrix.

The remaining resolution gap between PMT and SiPM is more problematic and may be solved by an increase of the fill factor of the device by a further factor of 2, from typical present values of 35%. Such development is not available at the moment, but might be possible in a few years, depending on progress in the miniaturization technology. We shall, however, note here that, at higher PDE, nonlinearity,[12] which is observed when the number of detected photons is comparable to the amount of cells of the device, may become an issue for gamma-ray measurements in the 3–5 MeV range. From our measurements, we have extrapolated R ≈ 3%–4% at $E_\gamma = 3$–5 MeV, which corresponds to ≈6200 active cells over 39 840, i.e., 16%, very far from any nonlinearity concern. Achieving R = 4% at $E_\gamma = 662$ keV extrapolates to 1.5% at $E_\gamma = 5$ MeV, where the fraction of active cells would be ≈62%. In this condition, the effect of the device non linearity on the energy resolution would become an issue and may partly counteract the benefit of an increased fill factor.

V. CONCLUSIONS

A matrix of Silicon Photo Multipliers (SiPMs) for light readout from a large area 1 in. × 1 in. $LaBr_3$ crystal has been developed for applications to compact gamma-ray spectroscopy detectors. The system has been characterized in the laboratory and its performance compared to that of (non-compact) conventional photo multipliers (PMTs). Similarly to the PMT case, a fast pulse of 100 ns was obtained, using a dedicated pole-zero cancellation network, which opens up for high counting rate applications. The measured energy resolution at $E_\gamma = 662$ keV is 8.6%, that extrapolates to 3%–4% for E_γ in the range 3–5 MeV, enabling spectroscopy measurements in gamma-ray camera systems of present tokamak devices, such as JET, which are not possible at present using PMTs, due to their large dimensions. A comparison between the energy resolution of $LaBr_3$-SiPM and $LaBr_3$-PMT, however, revealed that there is still a factor two difference in favour of the latter. Solutions to overcome this gap have been pointed out, particularly with regard to improvements in the quantum efficiency and fill factor of SiPM devices.

ACKNOWLEDGMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed here do not necessarily reflect those of the European Commission.

[1] M. Tardocchi *et al.*, Phys. Rev. Lett. **107**, 205002 (2011).
[2] M. Nocente *et al.*, Nucl. Fusion **52**, 063009 (2012).
[3] M. Nocente *et al.*, Nucl. Fusion **52**, 094021 (2012).
[4] I. N. Chugunov *et al.*, Nucl. Fusion **51**, 083010 (2011).
[5] I. Proverbio, M. Nocente, V. G. Kiptily, M. Tardocchi, and G. Gorini, Rev. Sci. Instrum. **81**, 10D320 (2010).
[6] M. Tardocchi, M. Nocente, and G. Gorini, Plasma Phys. Controlled Fusion **55**, 074014 (2013).
[7] V. G. Kiptily, F. E. Cecil, and S. S. Medley, Plasma Phys. Controlled Fusion **48**, R59 (2006).
[8] P. Finocchiaro *et al.*, IEEE Trans. Electron Devices **55**, 2757 (2008).
[9] K. C. Burr and G. C. Wang, IEEE Nucl. Sci. Symp. Conf. Rec. **2**, 1095 (2007).
[10] See https://indico.cern.ch/event/117424/session/4/contribution/28/material/slides/0.pdf for information about the main properties of SiPMs developed by ST Microelectronics.
[11] C. Uboldi, "Caratterizzazione di fotorivelatori a valanga in silicio," Master degree thesis (Politecnico di Milano, 2010), see https://www.politesi.polimi.it/handle/10589/11686.
[12] G. F. Knoll, *Radiation Detection and Measurements*, 4th ed. (Wiley), Chap. 9.
[13] M. Nocente *et al.*, IEEE Trans. Nucl. Sci. **60**, 1408 (2013).
[14] M. Nocente *et al.*, Rev. Sci. Instrum. **81**, 10D321 (2010).
[15] M. Mazzillo *et al.*, IEEE Nucl. Sci. Symp. Med. Imaging Conf. Rec. **2012**, 391.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 149.132.2.36 On: Tue, 22 Jul 2014 15:33:31