Radiation Tolerance Tests of Small-Sized CsI(Tl) Scintillators Coupled to Photodiodes

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14 authors, including:


Juhani Huovelin
University of Helsinki

Seppo Nenonen
Oxford Instruments Analytical Oy


Rami Vainio
University of Turku

Ari Virtanen
University of Jyväskylä

Radiation Tolerance Tests of Small-Sized CsI(Tl) Scintillators Coupled to Photodiodes

E. Valtonen, J. Peltonen, O.V. Dudnik, A.M. Kudin, H. Andersson, Yu.A. Borodenko, T. Eronen, J. Huovelin, H. Kettunen, E.V. Kurbatov, J. Lehti, S. Nenonen, M. Rossi, R. Vainio, and A. Virtanen

***Abstract*—Radiation tolerance of small-sized CsI(Tl) crystals coupled to silicon photodiodes was studied by using protons. Irradiations up to the fluence of 10^{12} protons/cm^2 were used. Degradation of light output by less than 5 % was achieved.**

***Index Terms*—Cesium iodide, crystals, scintillation detectors, radiation effects.**

I. Introduction

RADIATION environment in space can cause deterioration of the performance of scientific instruments. Common radiation effects are loss of sensitivity of detectors, increased noise of the measured signal, and induced high background. It is therefore essential to test the behavior of the instruments at radiation levels expected to be encountered during flight.

CsI(Tl) scintillators have been used for measuring energetic particles on many space flights starting from an early phase of the space age [1]. The response of CsI(Tl) to protons and heavier ions is well-known, e.g., [2], [3], and references therein. The main advantages of CsI(Tl) are the high light output and the wavelength well matching the response of silicon photodiodes. A drawback is the long decay time of the light pulse limiting the use in high-intensity applications. Alarming results have also been published on the decrease of CsI(Tl) light output already at low absorbed doses [4], [5]. More recent results, however, indicate a higher radiation tolerance [6]-[11] although showing a large scatter depending, e.g., on the purity and the Tl concentration of the material. It has also been concluded that the deterioration of light yield in CsI(Tl) at doses below 10^5 Gy is caused by the loss of transparency due to color center formation, and that deterioration due to decrease of scintillation efficiency does not set in until above a dose of ~10^5 Gy [8], [11]. It might then be expected that radiation effects in small-sized (dimensions less than ~ 5x5x5 mm^3) CsI(Tl) crystals below the dose of ~10^4 Gy would not be significant due to the short light path in the scintillator. This paper presents some evidence that such assumption is valid for selected crystals.

The Solar Intensity X-ray and particle Spectrometer (SIXS) [12] onboard BepiColombo will measure the solar X-ray and particle fluxes during the mission to Mercury. The SIXS particle detector, measuring protons in the energy range 1-30 MeV and electrons between 0.1 and 3 MeV, consists of silicon detectors and a CsI(Tl) scintillation crystal with the size of 5.0x5.0x6.3 mm^3 coupled to a photodiode. In order to verify the acceptable performance of the instrument over the entire mission duration in the expected radiation environment [13], we have carried out radiation tolerance tests of CsI(Tl) crystals coupled to photodiodes in two runs at the RADEF facility of the University of Jyväskylä. As opposed to the investigations [6]-[11], which were performed by using gamma radiation, we used proton beams up to the level of proton fluences expected to be encountered during the BepiColombo mission [13]. Solar protons will be the most significant source of radiation during the mission. In this paper we briefly describe the tests and present the results achieved in the two runs. The test setup, test samples, and the measurements to verify the performance of the test samples after each irradiation are described in Section II. In Section III, we summarize the observed effects of radiation on the overall performance of the test samples. Conclusions are presented in Section IV.

II. Test Arrangements

A. Test Setup

Two runs were performed at the RADEF facility of the University of Jyväskylä. In both runs the primary proton beam energy was 55 MeV. The test samples were installed in ambient air. In the first run, after passing through the beam line end-window and reaching the test samples at the distance of 1.8 m, the beam energy was estimated to be 50 MeV. This

E. Valtonen and T. Eronen are with the Department of Physics and Astronomy, University of Turku, FI-20014 Turku University, Finland (phone +358 2 333 5644; e-mail: Eino.Valtonen@utu.fi).

J. Peltonen and J. Lehti are with Aboa Space Research Oy, Lemminkäisen-katu 14-18, FI-20520 Turku, Finland.

O.V. Dudnik and E.V. Kurbatov are with the Kharkiv National University named V.N. Karazin, Svobody sq., 4, Kharkiv, Ukraine.

A.M. Kudin and Yu. A. Borodenko are with the Institute for Scintillation Materials, Lenin ave., 60, Kharkiv, Ukraine.

H. Andresson and S. Nenonen are with Oxford Instruments Analytical Oy, P.O. Box 85, FI-02631 Espoo, Finland.

J. Huovelin is with the Observatory, University of Helsinki, P.O. Box, 14, FI-00014 University of Helsinki, Finland.

H. Kettunen, M. Rossi and A. Virtanen are with the Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 University of Jyväskylä, Finland.

R. Vainio is with the Department of Physics, University of Helsinki, FI-00014 University of Helsinki, Finland.

was well sufficient for protons to penetrate entirely through the CsI(Tl) samples and the photodiodes opposite to the beam entrance face of the crystals. The energy loss was roughly uniform (within 25 %) throughout the small scintillator crystals.

In the second run, a rotating variable-thickness polyethylene degrader was used in front of the test samples. The degrader had a stepwise thickness from 3.5 mm up to 30.5 mm. Thus, in this case, protons reaching the samples had energies from a few MeV up to about 46 MeV. However, due to the stepwise thickness of the degrader the spectrum was not smooth. Also, due to scattering from the plastic, the intensity decreased with decreasing proton energy. This setup in the second run was used in order to test the effects of non-uniform energy loss in the crystals, in particular near the entrance surface. The proton spectrum in the BepiColombo mission is expected to be relatively soft leading to energy losses mostly near the surface of the scintillator.

The beam intensity was measured before the test runs using scintillators and photomultiplier tubes as particle detectors at the test sample position. During the test runs the beam intensity was monitored using an ionization chamber at the beam line end-window. The beam intensity accuracy was typically 10%.

B. Test Samples

In the first run, three samples of CsI(Tl) crystals were irradiated together with two CsI(Na) crystals for comparison (see Table I). All samples were of standard quality without any selection rules or traceability requirements applied. Two of the CsI(Tl) samples were purchased from Scionix, NL [14]. They were coupled to custom silicon photodiodes by Scionix. One CsI(Tl) and two CsI(Na) crystals were provided by the Institute for Scintillation Materials, UA, (ISMA hereafter) through the Kharkiv National University. These scintillators were coupled to PDC 50s-CR silicon photodiodes manufactured by Detection Technology, Inc. [15]. For the irradiation tests, the samples were placed in plastic holders with a 5-mm diameter opening for the beam. The photodiodes were coupled to the crystal face opposite to the beam entrance, thus receiving the same fluence of protons as the scintillators, because all incident protons traversed the scintillators. Therefore, the test results represent the combined effects of radiation on the scintillator and the photodiode. This situation corresponds to the flight conditions, where both the scintillator and the photodiode are exposed to radiation.

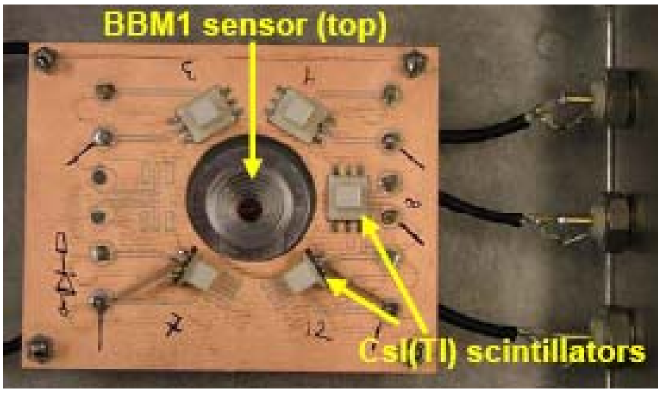

Fig. 1. Test samples in the second test run. BBM1 is the breadboard model of the sensor head with one of the samples mounted inside. Five other samples were mounted on a printed circuit board around the aperture of the sensor.

TABLE I
SUMMARY OF TEST SAMPLES

Scintillator	Crystal size (mm^3)	Photodiode	PD active area (mm^2)
Run 1			
Scionix1-2	4.0x4.0x4.0	Scionix custom	8.5x8.5
ISMA1-3[1)]	5.0x5.0x5.0	PDC 50s-CR[2)]	5.0x5.0
Run 2			
Scionix	5.0x5.0x5.0	S5106[3)]	5.0x5.0
ISMA1-5	5.0x5.0x6.3	S5106[3)]	5.0x5.0

1) ISMA1 CsI(Tl), ISMA2-3 CsI(Na)
2) Detection Technology, Inc. [15]
3) Hamamatsu Photonics [16]

In the second run, six CsI(Tl) samples were irradiated. One of the crystals was mounted in the breadboard model (BBM1, Fig. 1) of the instrument with a special aluminum collimator. This crystal was purchased from Scionix and was coupled to a Hamamatsu Photonics silicon photodiode S5106 [16]. Five samples from ISMA were coupled to the same type of Hamamatsu photodiodes. These crystals, with white reflective coating, were mounted on a printed circuit board close to the breadboard sensor aperture in order to achieve as uniform irradiation as possible for all the samples. Four samples, including the one in the sensor head, were mounted in the beam with the photodiode on the crystal face perpendicular to the beam (opposite to the beam entrance) and two with the photodiode active surface parallel with the beam (Fig. 1). The dimensions of the scintillator crystals and the photodiode active areas used in the two runs are summarized in Table 1.

C. Irradiations and Measurements

In both runs the samples were irradiated up to proton fluences of 10^9, 10^{10}, 10^{11}, and 10^{12} protons/cm^2 in consecutive steps. Dose rate effects were not studied in these tests. After the initial beam adjustments, during the main phases of the irradiations, the beam intensities were typically between 3.3×10^7 and 3.3×10^8 protons/cm^{2}s. However, in the second irradiation of the first run the average flux was 1.45×10^9 protons/cm^{2}s. The total durations of the irradiations in the first run were 755 s, 112 s, 1284 s, and 3128 s and in the second run 177 s, 241 s, 504 s, and 3832 s. Before starting the irradiation and after each step, the response of the crystals was measured by using the same proton beam as in the irradiations, but at sufficiently low intensity to avoid pile-up in the electronics (< 1000 counts/s). The shaping time of the scintillator signal amplifiers was 2 μs in the first run and 3 μs in the second run. The photodiodes were characterized by measuring their leakage current. In addition, a test pulser was used to determine the electronic noise.

During all irradiations the photodiodes were kept under the nominal operational bias voltage. A bias voltage of 30 V was used for the Detection Technology diodes and 23 V for the Hamamatsu diodes.

III. Results

The positions of the peaks in the energy loss distributions observed in the response measurements were taken as the measure of the light output of the scintillators and compared after each irradiation to the initial value. Peaks moving to lower channels with increasing fluence would indicate reduced light output due to radiation damage. The peak positions were determined by fitting Gaussian distributions to the observed peaks. From the fits, the Full Widths at Half Maximum (FWHM) of the distributions were also calculated, which are expected to be mainly affected by electronic noise due to the leakage current of the photodiode. The same quantities were determined for the test pulser peaks, assumed to be only affected by the photodiode properties. In general, when we discuss in the following the effects of radiation on the response of the test samples, it is the combined response of the scintillator-photodiode system, because radiation may affect both devices.

No pre-selection to reach good radiation tolerance was performed for the samples used in the first run. It turned out that all samples suffered significant loss of light output at the highest proton fluence used. All samples behaved similarly. Up to the fluence of 10^{11} protons/cm^2 no significant change occurred in the position of the single peak corresponding to the energy loss of 50 MeV protons penetrating the crystal and the photodiode. However, after 10^{12} protons/cm^2 the light output was reduced by 12-20 % compared to the initial value before irradiation. The smallest reduction in the light output was in one of the CsI(Na) samples, whereas the other CsI(Na) sample had larger loss of light output than some of the CsI(Tl) samples, although CsI(Na) is generally known to have higher radiation tolerance than CsI(Tl). This may be related to the samples originating from different manufacturing batches and reflecting differences in the characteristics of different ingots. The light outputs of the Scionix CsI(Tl) samples were closely equal before and after the irradiations. The ISMA CsI(Tl) sample had significantly higher initial light output than the Scionix samples, but also larger relative light output reduction after the fluence of 10^{12} protons/cm^2.

The FWHM values (~9 %) of the energy loss peaks of the Scionix scintillators did not change significantly as the function of the fluence, while those of the ISMA samples increased from the initial values of 9-12 % by a factor of 1.2 to 1.4 at the highest fluence. The FWHM values of the test pulser peaks started to increase already after the fluence of 10^{10} protons/cm^2 and at the maximum tested fluence reached values by a factor 1.6-2.0 larger than the initial ones. This reflects the large rise of the leakage currents of the photodiodes already at relatively low fluences. The leakage current increased roughly by a factor of ten in the last three irradiations.

The ISMA scintillators used in the second run were selected for good radiation tolerance. The crystals were tested for radiation hardness, and the selection criterion used was that no observable change in the light output or change of color was allowed at the dose of 100 Gy. Expected change of light absorption coefficient at 550 nm was $\ll 0.01$ cm^{-1} after the dose of 1 kGy. The samples used in the tests were from the same production lot as intended to be used in the flight model of SIXS. The crystal mounted in the sensor head (BBM1) was of standard quality.

In the second run a rotating variable-thickness degrader was used to modify the beam energy. Due to the stepwise thickness of the degrader the energy loss distribution in the samples consists of several peaks. An example of the energy loss distribution in one of the ISMA scintillators is presented in Fig. 2. Five peaks are clearly visible corresponding to protons penetrating the five thinnest sectors of the degrader. Possible shifts in the positions of each of these peaks can be used for tracing changes in the light output as function of the received fluence. To determine the peak positions and widths, a Gaussian function was fitted to each peak as demonstrated in Fig. 2. As in the first run, Gaussian fitting was also applied for the pulser peaks and used to evaluate the effect of potential increase of the leakage current on the electronic noise of the photodiode signals.

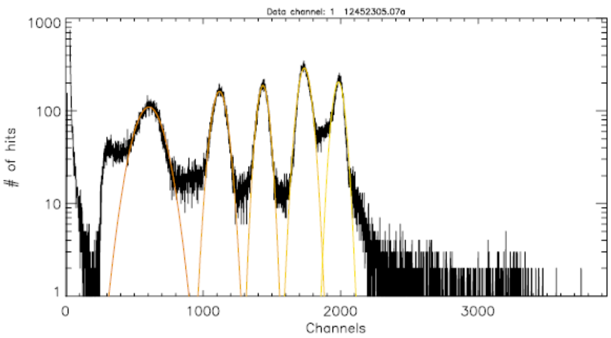

Fig. 2. Observed energy loss distribution in one of the ISMA scintillators with Gaussian fits on the peaks.

At the highest absorbed energy, a significant decrease was observed in the light output of the crystal mounted in the sensor head. After the fluence of 10^{12} protons/cm^2 the light output was reduced by 15 % compared to the initial value. There was also a clear trend of increasing FWHM of the pulser peak of this sample, reaching at the maximum fluence a value by a factor of 2.2 larger than the initial one. The scintillator of course does not contribute to the FWHM of the pulser peak, and this result indicates increasing noise caused by the strongly growing leakage current of the photodiode. Unfortunately, however, direct measurement of the current was not possible.

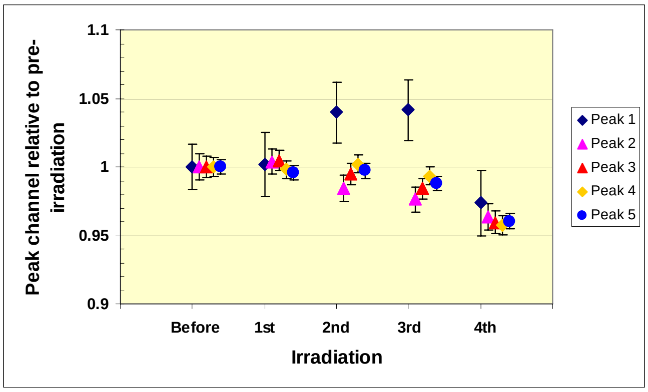

Fig. 3. Worst case changes in the positions of the five peaks of Fig. 2 in the ISMA scintillators as function of fluence. For clarity, each data point has been shifted to the right on the x-axis with respect to each lower peak number.

Fig. 3 shows the worst case behavior of the ISMA CsI(Tl) scintillators in the second run. This sample was one of the two mounted with the photodiode active surface in parallel with the beam. Peaks 1-5 in Fig.3 refer to the peaks in Fig. 2 counted from left to right. Estimated errors in determining the peak positions are given in Fig. 3 by the error bars. The estimated errors in Peak 1 position are largest because of the broadness (Fig. 2) and relatively poor fit of a single Gaussian curve to this peak. The observed increase of the channel number of Peak 1 in the 2nd and 3rd irradiation may be related to a surface effect of the crystal. The radiation disintegrates the absorbed OH^- ions at the surface and thus improves the light output until the dominant light attenuation due to color center formation sets in during the 4th irradiation. All the test samples had a similar trend. However, verification of this interpretation needs further investigation. From Fig. 3 it can be seen that in this worst case crystal some degradation in the light output at higher energies occurs already at the fluence of 10^{11} protons/cm^2. The maximum degradation, however, is only 3-4 %, which is by a factor 3-5 smaller than observed in the first run. No significant degradation was observed in the light output of the other ISMA scintillators below 10^{12} protons/cm^2. At this maximum tested fluence the degradation was for all samples of the same magnitude as shown in Fig. 3. The FWHM of the pulser peaks of all ISMA samples increased consistently with increasing fluence reaching at the highest fluence a factor of 1.3 to 1.5 higher values than the initial ones. This again indicates increased electronic noise due to increasing leakage current of the silicon photodiodes. The measured currents of the diodes are shown in Fig. 4.

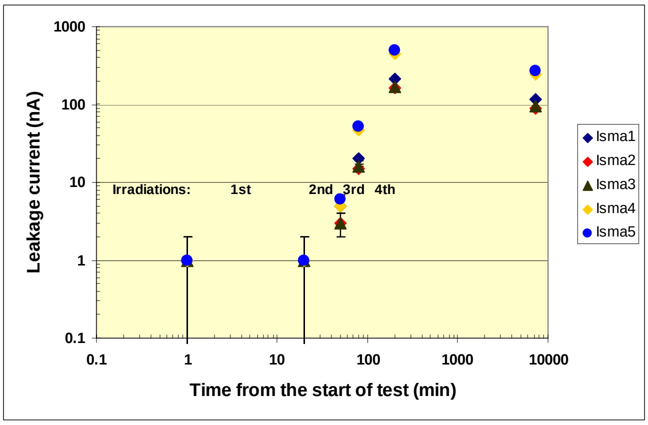

Fig. 4. Leakage currents of the ISMA scintillator photodiodes as function of time. Note the large error bars in the initial value (at time 1 min) and the value after the first irradiation (at time 20 min). The irradiations were carried out after the 1st, 2nd, 3rd, and 4th data point from the left. The leakage currents were measured before the irradiations, after each irradiation, and five days after the tests.

The initial current and the current after the first irradiation (both 1 nA) are not accurate values, but rather indicate the resolution of the current meter. However, it is clear that after the second (10^{10} protons/cm^2), third (10^{11} protons/cm^2), and fourth (10^{12} protons/cm^2) irradiation the leakage current has strongly increased. It is also worth noting that those diodes (ISMA 4 and -5), which had their active surfaces parallel to the beam are more sensitive to radiation than those with active surface perpendicular to the beam. This can be explained by protons with long path lengths causing more damage in the active chip volume than those just passing nearly perpendicularly through the thin depletion layer.

IV. Conclusion

When using small-sized CsI(Tl) crystals coupled to photodiodes, it is possible to achieve radiation hardness at least up to the proton fluence of 10^{12} protons/cm^2 without a major degradation in the light output. The results of the irradiation tests reported in this paper give confidence that the scientific goals of the SIXS particle instrument can be achieved by using a CsI(Tl) scintillator. However, when using standard silicon photodiodes for the light readout from the scintillator, the associated analog electronics need to be capable of handling leakage currents up to the μA- range without excessive increase of the electronic noise in order to preserve good energy resolution.

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