Transactions of the Korean Nuclear Society Virtual Autumn Meeting
October 21-22, 2021

Light Output Evaluation of 3D-Printed Plastic Scintillators Irradiated with 100 MeV Proton Beams at KOMAC

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1. Introduction

Plastic scintillators have been used in various fields as radiation detectors for the use and control of radiation sources. The availability of plastic scintillator in extreme conditions such as space environments is emerging as a technical issue. In this environment, radiation hardness is an important issue to maintain the detector normal. There have been prior studies on the change of plastic scintillators by irradiation with electron beams [1] or gamma rays [2], but studies on high-energy protons are insufficient.

In this study, plastic scintillators made of different monomers were exposed to high-energy proton beams at different doses, and relative light output was observed for each plastic scintillator.

2. Material and method

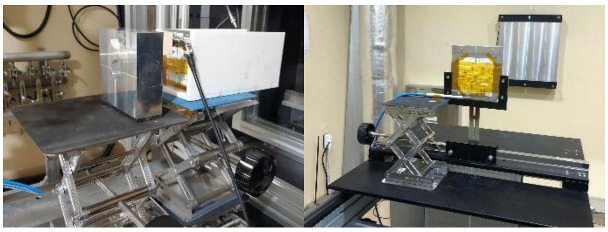

Figure 1. Irradiation setup of TR103 (left) & TR102 (right) proton beamline.

Three of these scintillators are made from different monomers (BPA(EO)$_{15}$DMA, D0241, OPPEA) using a 3D printer. Each scintillator contains 98.44 wt% of different type of monomers and has the same proportion of other components, PPO (primary dye), ADS086BE (wavelength shifter) and TPO (photoinitiator). BC408, a commercial plastic scintillator based on polyvinyltoluene, was selected as a comparator. BC408 is a general-purpose plastic scintillator with high light output [3]. All scintillators are made in sizes of 10 × 10 × 10 mm^3.

Table 1. Used beam line and irradiation method depending on irradiation dose

Total Dose	0.1k Gy	1k Gy	10k Gy	100 kGy
Beamline	TR102	TR102	TR103	TR103
Dose rate	1k Gy/h	1k Gy/h	200k Gy/h	200k Gy/h
Exposure time	6 min	60 min	3 min	30 min

Each scintillator sample was exposed 100 MeV proton beam conducted by Korea Multi-Purpose Accelerator Complex (KOMAC) (Figure 1). Doses were set to 0.1k Gy (6 minutes) and 1k Gy (60 minute) in TR102 with 1k Gy/h, and 10k Gy (3 minutes), 100k Gy (30 minutes) in TR103 with 200k Gy/h (Table 1). Other properties of beam lines are described in Table 2. During the irradiation, two beamlines had the uniformity of 8.86% in TR102 and 6.20% in TR103 at the sample position, and in terms of energy, 97.9 ± 1.0 MeV in TR102 and 96.4 ± 0.1 MeV in TR103 were measured (Figure 2).

Table 2. TR102 and TR103 proton beamline properties

Beam line	TR102	TR103
Available energy [MeV]	30 - 100	30 - 100
Exposed flux [#/cm^{2}sec]	2.6E+08	5.49E+10
Dose rate [Gy/h]	1k	200k
Beam shape	Flat	Gaussian
Exposed beam area	100 × 100 mm^2 (Plane)	d = 30 mm (Circle)

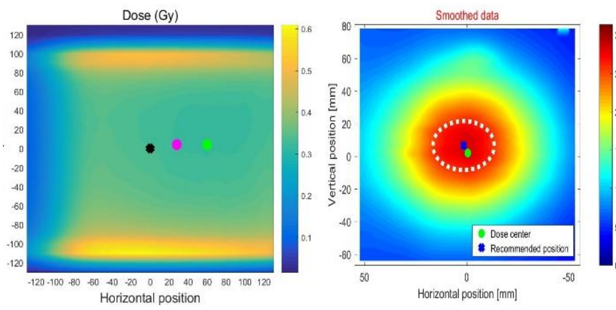

Figure 2. Beam profile on TR102(left) & TR103(right).

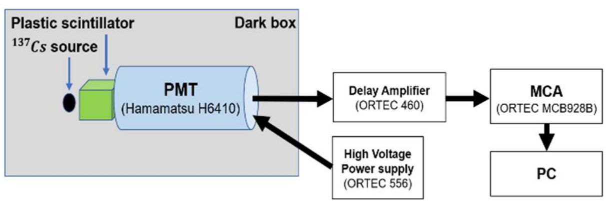

Figure 3. Schematic diagram of the measurement system for scintillation light output.

Figure 3 is an overview of the measurement system for scintillation light output. The 10 μCi ^{137}Cs gamma-ray check source was used and the photomultiplier tube (Hamamatsu, H6410) was applied with 1,500 V. The delay amplifier (ORTEC 460) was set with shaping time 0.1 μsec. The ^{137}Cs gamma-ray spectra for the tested scintillator samples was recorded with the multi-channel analyzer (ORTEC, MCB928B) with low level discriminator 30 mV. The measurement time of each sample was set to 900 seconds, and was carried out in a darkroom to minimize external influences. However, the measurement was carried out after two months from irradiation, because the sample was activated, and it took time to handling the sample.

Since the obtained energy spectrum represents continuous characteristics, graph fitting was performed to obtain Compton edge channel. In the fitted graph, the sum of the half of FWHM and the channel at the highest peak point was set to Compton edge. And this was used to calculate the relative light output of each sample.

Relative light output (Relative LO) of each scintillator sample was calculated as in the following equation considering the quantum efficiency of scintillator and the gain of amplifier.

$$\text{Relative LO }(\%) = \frac{C_{after}}{C_{before}} \times \frac{Q_{before}}{Q_{after}} \times \frac{G_{before}}{G_{after}} \times 100 \qquad (1)$$

where C is Compton edge channel, Q is quantum efficiency, G is amplifier's gain, *before* is non-irradiated samples and *after* is irradiated samples.

3. Result and discussion

As shown in Figure 4, BC408 and OPPEA did not show a decrease in light output until they received less than 1k Gy, but rather showed a light output of about 103%. This increase is expected to be due to the measurement error in the experimental environment and the human error in the production process due to the difference in the production date of the scintillator samples. $BPA(EO)_{15}DMA$ and D0241 showed slight decrease of about 95% at 1k Gy or less.

When 10k Gy was irradiated, BC408 and OPPEA still showed no significant change, but in the case of D0241, the light output decreased to about 82%. On the other hand, the measurement data after 10k Gy irradiation of the $BPA(EO)_{15}DMA$ scintillator sample was missed during the experiment, and the corresponding value was predicted by the dotted line by estimation.

When 100k Gy was irradiated, the light output of BC408 decreased to about 81%, and it was confirmed that BPA(EO)15DMA and OPPEA also decreased to about 78.7% and 89.3%. D0241 showed the biggest change with a decrease of about 24%. This is predicted to be due to disturbance in the molecular structure of plastic scintillators when exposed to higher than 100k Gy of high-energy protons. Also, since the intermolecular bonding structure and curing degree of each monomer are different, it is expected that there will be a difference in the rate of decrease in light output for each plastic scintillator sample. As shown in Figure 5, it can be confirmed that the D0241 sample irradiated with 100k Gy changes to the darkest color while other samples show little change.

Because BC408's known absolute light output is 10,000 photons/MeV [4], so finally, the rest of the sample's absolute light output could be calculated on Table 3 by applying the equation (1).

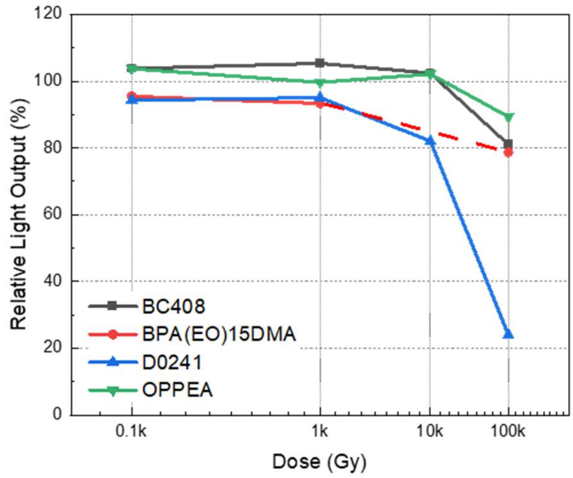

Figure 4. Relative light output of plastic scintillator according to proton dose compared to light output before irradiation of each scintillator.

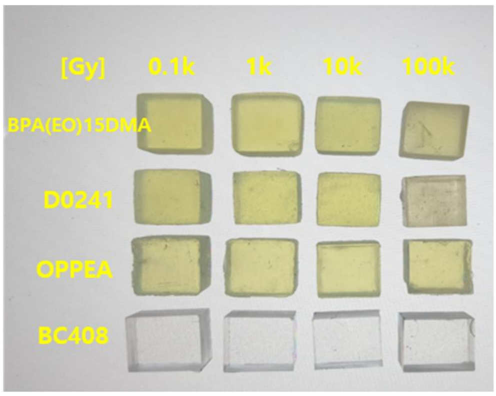

Figure 5. Appearance changes of scintillator after proton beam irradiation.

Table 3. Absolute light output (photons/MeV) according to the proton beam dose exposed to each sample.

	Non-irradiated	0.1k Gy	1k Gy	10k Gy	100k Gy
BC408	10,000	10,400	10,500	10,240	8,100
$BPA(EO)_{15}DMA$	1,750	1,670	1,630	7,600	1,380
D0241	7,170	6,760	6,810	5,880	1,720
OPPEA	6,870	7,130	6,850	7,020	6,140

4. Conclusion

In this study, we aimed to investigate the changes of relative light output from plastic scintillator when it exposed to high energy proton beam.

As a result, in BC408 and OPPEA, no significant light output changes were detected when it exposed less than 10k Gy, but a decrease was observed above 100k Gy.

$BPA(EO)_{15}DMA$ and D0241 had no significant changes in light output at below 1k Gy, but significant changes occurred when irradiated above 10k Gy. Specifically, D0241 had a significant decrease in light output at 100k Gy.

This shows that scintillators using D0241 are relatively vulnerable to high-energy protons compared to the rest types of scintillators. And finally, the long-term operation of plastic scintillation detectors in high-energy proton fields, such as the space environment, can be considered in the future.

REFERENCES

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